Applications of Intelligent Radio Technologies in Unlicensed Cellular Networks - A Survey

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Abstract

Demands for high-speed wireless data services grow rapidly. It is a big challenge to increasing the network capacity operating on licensed spectrum resources. Unlicensed spectrum cellular networks have been proposed as a solution in response to severe spectrum shortage. Licensed Assisted Access (LAA) was standardized by 3GPP, aiming to deliver data services through unlicensed 5 GHz spectrum. Furthermore, the 3GPP proposed 5G New Radio-Unlicensed (NR-U) study item. On the other hand, artificial intelligence (AI) has attracted enormous attention to implement 5G and beyond systems, which is known as Intelligent Radio (IR). To tackle the challenges of unlicensed spectrum networks in 4G/5G/B5G systems, a lot of works have been done, focusing on using Machine Learning (ML) to support resource allocation in LTE-LAA/NR-U and Wi-Fi coexistence environments. Generally speaking, ML techniques are used in IR based on statistical models established for solving specific optimization problems. In this paper, we aim to conduct a comprehensive survey on the recent research efforts related to unlicensed cellular networks and IR technologies, which work jointly to implement 5G and beyond wireless networks. Furthermore, we introduce a positioning assisted LTE-LAA system based on the difference in received signal strength (DRSS) to allocate resources among UEs. We will also discuss some open issues and challenges for future research on the IR applications in unlicensed cellular networks.

Keywords: Unlicensed cellular network, Intelligent radio, LTE-LAA, 5G NR-U, Wi-Fi coexistence, Listen-before-talk (LBT), Artificial intelligence, Positioning assisted resource allocation.

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1. Introduction

The rapid proliferation of mobile/wireless devices has created a huge demand for spectrum resources. To cope with severe spectrum resource shortage for cellular networks, licensed assisted access (LAA) of long term evolution (LTE) in the unlicensed spectrum, also known as LTE-U, was proposed for a more flexible spectrum resource access and more efficient unlicensed spectrum utilization. The LAA was initially added to the long-term evolution (LTE) standard, and thus it is widely called LTE-LAA. Specifically, the LTE-LAA was proposed by 3GPP to support the large capacity required in 5G and beyond, as clearly specified in 3GPP Releases 13 to 15. One of the major concerns about the LTE-U standardization is whether LTE-U will be able to share the unlicensed spectrum with IEEE 802.11 users in a fair manner [1]. On the other hand, artificial intelligence (AI) technologies, in particular Machine Learning (ML), will play an increasingly important role to assist user terminals (UEs) to access the unlicensed spectrum, and thus it has attracted a lot of attention in 5G and beyond research. The UEs with AI capabilities are commonly named in intelligent radio (IR) in the literature. At the beginning of this paper, we are going to give a brief introduction about the background and challenges for IR assisted unlicensed cellular networks, before we dive into the very details of the subjects.

1.1 Background

When we talk about the unlicensed spectrum, it normally refers to industrial, scientific, and medical (ISM) (9 KHz - 300 GHz) and unlicensed national information infrastructure (UNII) (2400 MHz - 2483.5 MHz and 5150 MHz - 5850 MHz) bands. More detail discussions will be given in Section 2. As the demands for high-speed data services increase, government agencies, industry sectors and operators are looking for the ways to share and utilize the unlicensed spectrum for capacity enhancement. The concept of LTE-U appeared for the first time in 3GPP documentations in 2014 [2]. The LTE-U standardization was accomplished based on LAA protocol in 3GPP Release 13, which includes carrier aggregation (CA) to utilize secondary carriers, targeting downlink (DL) operation in 5 GHz band. Furthermore, uplink (UL) operation was defined in enhanced-Licensed Assisted Access (eLAA) in 3GPP Release 14, and its continued development was presented in Further Enhanced LAA (feLAA) of 3GPP Release 15. Along with the development of 5G, New Radio-Unlicensed (NR-U) has been scheduled to appear in 3GPP Releases 16 and 17, which is expected to specify the necessary technologies for cellular operators to completely integrate the unlicensed bands into 5G networks.

Despite the merits of capacity increase via unlicensed spectrum access, interferences and coexistence problems exist. Several works studied the issue to share spectrum resources and mitigate co-channel interferences between BSs [3]. The tradeoff between QoS, interferences, and collision probability need to be considered as well [4] [5]. Apart from this, many works considered compatibility with Wi-Fi systems in the designs of coexistence framework in MAC protocols to obtain better spectrum efficiency and system throughput, such as hyper access point (HAP) scheme [6] [7], which integrates the functionalities of an LTE-U SBS and a commercial Wi-Fi AP. This coexistence framework is not only backward compatible with Wi-Fi user devices but also amendable to the LTE CA specifications.

Due to the complicated environment in 5G/B5G networks, reconfigurability in future wireless communications becomes a must. Traditional cognitive radio users detect and sense channels through licensed spectrum to make sure whether it is occupied or not and then make decisions in accordance with the sensing results. However, the conventional dynamic spectrum management (DSM) mechanism is not applicable to the diverse RF environments in 5G networks [8]. In other words, CR users should be more intelligently assisted with AI or machine-learning (ML) technologies to use the licensed and unlicensed spectra opportunistically. In this article, we aim to give a comprehensive survey on the applications of intelligent radio technologies in unlicensed cellular networks.

1.2 Related Works

Different from licensed cellular networks, LTE-LAA and NR-U are two cellular systems designed to work specifically in unlicensed cellular spectrum. It is obvious that coexistence and interference are usually the two important issues discussed in various researches within LTE-LAA and NR-U systems. Several solutions such as offloading [9], interferences control [10], beam-based transmission using directional antennas [11], network slicing and spatial multiplexing [12], hybrid channel access mechanism [13] had been proposed. Besides, to ensure fair operation in unlicensed spectrum with the coexistence between LTE-LAA and Wi-Fi systems, we note that several works used Markov chain as their analytical models [14] [15] [16] [17]. Several researches proposed modified LBT protocols based on LAA frame structure, such as an adaptive *p*-persistent LBT channel access scheme [14], anti-slot-jamming LBT scheme [15], linear backoff based LAA scheme [16] and enhanced clear channel assessment (eCCA) based LAA scheme, to fulfill fairness and coexistence.

Intelligent radio (IR) or smart radio (SR) based on AI technologies has been viewed as a vast unexplored frontier for futuristic wireless communications. Several works had employed AI technologies and ML algorithms in wireless networks, such as intelligent UE and intelligent BS design in IR [18], heterogeneous CR based spectrum resource allocation [19] and the envisioning structure of IR [8]. Among those fantastic AI technologies, Q-Learning (QL) algorithms, which is one of the most commonly used Reinforcement Learning (RL) algorithms, have widely been employed in IR-based LTE-LAA/NR-U networks. Similar works had been presented in literatures, such as the QL based dynamic duty cycle selection scheme [20], QL based TXOP period [21], frequency-reuse-1 mechanism [22], and QL based LAA scheme for sharing unlicensed spectrum [23].

1.3 Motivations

[24] predicted how rapidly the growth of mobile data traffic will be. This requires a significant improvement of capacity and spectral efficiency in current cellular infrastructure. Technologies such as massive MIMO, Ultra Dense Network (UDN), Non Orthogonal Multiple Access (NOMA), Cognitive Radio (CR), AI and Carrier Aggregation (CA) are the enablers to achieve the goals. In this regard, CR techniques had been widely used to provide priori information for optimizing spectrum utilization, which can be appropriately adopted in unlicensed systems to solve spectrum scarcity, traffic offloading, and coexistence and interference issues between licensed and unlicensed bands.

We admit that the original intention of CR is to make a better use of the spectrum resources by cognitive sensing the environment and adjusting its transmitter parameters accordingly. Unfortunately, the original CR techniques fail to deliver a real "cognitive" capability, which is normally associated with a much higher level of intelligence. Therefore, the traditional CR techniques must be revitalized before we can turn UEs to IR units. As a matter of fact, AI can explore the "cognitive" functions in machines, which can not only perceive or sense its working environment, but also "learn from experiences" and "take needed actions to solve problems" to extend the essence of CR networks. This is what we call it as AI-enabled radio and networks, also named as Intelligent Radio (IR) or Smart Radio (SR). In this paper, we also make a comprehensive survey of the research works on IR applications in underlined unlicensed cellular networks.

There are two major research directions related to IR and unlicensed cellular networks. One is IR enabled unlicensed cellular applications based on LTE-LAA systems; the other is that based on 5G NR-U systems. In the survey for AI enabled LTE-LAA and NR-U systems, reinforcement learning and Q-learning algorithms have been widely utilized in the literature. Reinforcement learning is a type of AI algorithms, which learn from experiences and select proper actions from rewards through training process to maximize rewards. In this paper, we aim to provide readers with the information on how IR will work jointly with unlicensed cellular networks in 4G/5G/B5G wireless networks.

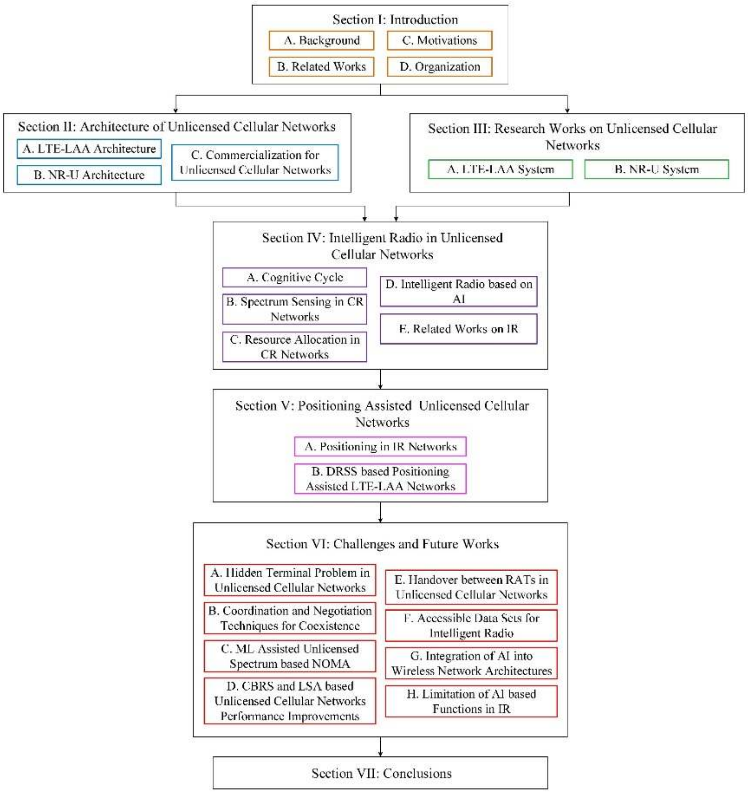

Fig. 1. Structural organization of this paper.

1.4 Organization

The rest of this paper can be outlined as follows. In Section II, we present the design of unlicensed cellular networks based on LTE-LAA as specified in 3GPP Releases 13 and 14. 3GPP NR-U standardization progress for sub 7 GHz and mmWave bands will be introduced as well. The major acronyms and abbreviations used in this paper are listed in **Table 1**. The overall organization of the paper is shown in **Fig. 1**. Section III provides an overall introduction for the methodologies used in the current research on LTE-LAA and NR-U systems. Associated IR or CR techniques as well as general AI applications in unlicensed cellular networks are discussed in Section IV. A positioning assisted LTE-LAA system will be given in Section V. The major challenges and future works are summarized in Section VI, followed by the conclusions as presented in Section VII.

Table 1. Major acronyms used in this paper.

Acronym	Definition	Acronym	Definition
ABS	Almost blank subframe	LWA	LTE-WLAN aggregation
AI	Artificial intelligence	MAC	Medium access control
AIFS	Arbitration inter frame spaces	MARL	Multi-agent reinforcement learning
AMM	Alternative mode monitoring	MBS	Macro base station
A-MPDU	Aggregate MAC protocol data unit	MIMO	Multiple-input multi-output
ANN	Artificial neural network	MISO	Multiple-input single-output
AOA	Angle of arrival	ML	Machine learning
AP	Access point	MLPN	Multi-Layer linear perceptron network
ARI	Alignment reference interval	mMTC	massive Machine-type communication
ARIA-LAA	Alignment reference interval adaptation-based LAA	mmWave	Millimeter wave
AWGN	Additive White Gaussian Noise	MN	Moving network
BS	Base station	MNO	Mobile network operators
CA	Carrier aggregation	MT	Mobile terminal
CBR	Case-based reasoning	MUST	Multiuser superposition transmission
CBRS	Citizens broadband radio service	MVUE	Minimum variance unbiased estimation
CBS	Case-based system	NOMA	Non orthogonal multiple access
CC	Component carrier	NR	New radio
CCA	Clear channel assessment	NR-U	New radio-based access to unlicensed spectrum
CDP	Cycle frequency domain profile	OBR	Ontology-based reasoning
CDSA	Control-data separation architecture	OBS	Ontology-based system
CI	Co-channel interference	OCHM	Orthogonal code hopping multiplexing
COT	Channel occupancy time	OMA	Orthogonal multiple access
COTA	Channel occupancy time adaptation	omniLBT	Omnidirectional LBT
CP	Collision probability	OS	Operating system
CR	Cognitive radio	OSA	Opportunistic spectrum access
CRLB	Cramer Rao lower bound	OVSF	Orthogonal variable spreading factor
CRN	Cognitive radio network	PAL	Priority access license
CRS	Cell-specific reference signal	PCF	Point coordination function
CS	Carrier sense	PDP	Power delay profile
CSAT	Carrier sensing adaptive transmission	PHY	Physical layer
CSI	Channel state information	PN	Pseudo-noise
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance	PPDU	Physical protocol data unit
CSTON	Coordinated space, terrestrial and ocean network	PSD	Power spectral density
CW	Contention window	PSS	Primary synchronization signals
DBS	Data base station	PU	Primary user
DC	Duty cycle	QL	Q-Learning
DCF	Distributed coordination function	QoE	Quality of experience
DFS	Dynamic frequency selection	QoS	Quality of service
DIFS	Distributed inter frame space	RAT	Radio access technology
dirLBT	Directional LBT	RB	Resource block
DL	Downlink	RBS	Rule-based system
DRL	Deep reinforcement learning	RF	Radio frequency
DRS	Discovery reference signals	RL	Reinforcement learning
DRSS	Difference received signal strength	RLAN	Radio local area network
DSA	Dynamic spectrum access	RNNs	Recurrent neural networks
DSM	Dynamic spectrum management	RRM	Radio resource management
DTX	Discontinuous transmission	RSSI	Received signal strength indicator
DwPTS	Downlink pilot time slot	RTS/CTS	Request to Send/Clear to Send
eCAA	Enhanced clear channel assessment	RTTOA	Round trip time of arrival
E-CRN	Enhanced cognitive radio network	SA	Spectrum aggregation
ED	Energy detection	SAS	Spectrum access system
EDCA	Enhanced distributed channel access	SBS	small cell base station
EDTA	Energy detection threshold adaptation	SCUE	Small cell user
EE	Energy Efficiency	SDL	Supplementary downlink
EHN	Energy harvesting network	SDR	Software defined radio
eICIC	Enhanced inter-cell interference coordination	SIC	Successive interference cancellation
eLAA	Enhanced licensed assisted access	SINR	Signal to interference plus noise ratio
eNB	Evolved node B	SON	Self organizing networks
ESN	Echo state network	SR	Smart radio
ETSI	European telecommunications standards institute	SS	Spectrum sharing
E-UTRA	Evolved universal terrestrial radio access	SSS	Secondary synchronization signals
FBE	Frame based equipment	SST	Statistical signal transmission
FCC	Federal communications commission	SU	Secondary user
FDD	Frequency division duplexing	SWIPT	Simultaneous wireless information and power transfer
feLAA	Further enhanced LAA	TDD	Time division duplexing
FH	Frequency hopping	TDMA	Time division multiple access
FP	Frequency planning	TDOA	Time difference of arrival
GA	Genetic algorithm	TH	Time-hopping
GAA	General authorized access	TIX	Triangular interpolation and extrapolation
GAN	Generative adversarial network	TM	Transmission mode
GP	Guard period	TOA	Time of arrival
GSA	Global mobile suppliers association	TPC	Transmit power control
HAP	Hyper access point	TRUST	Transparent ubiquitous terminal
HARQ	Hybrid Automatic Repeat Request	TSTA	Transmission start time alignment
HCF	Hybrid coordination function	TXOP	Transmission opportunity
HetNet	Heterogeneous network	UCCS	Unlicensed component carrier selection
HMM	Hidden Markov model	UDN	Ultra dense network
ICI	Inter-cell interference	UE	User equipment
ICW	Intelligent-CW	UL	Uplink
IE	Inference engine	UNII	Unlicensed national information infrastructure
IMI	Initial mode identification	UPCS	Unlicensed personal communication system
IR	Intelligent radio	UpPTS	Uplink pilot time slot
ISM	Industrial, scientific, and medical	UPT	User perceived throughpu
KF	Kalman filtering	URLLC	Ultra reliable and low latency communications
LAA	Licensed assisted access	VANET	Vehicular ad hoc network
LACA	Learning-assisted clustered access	VCFG	Virtual coalition formation game
LBE	Load based equipment	WAS	Wireless access system
LBT	Listen-before-talk	WLAN	Wireless local area network
L-M	Levenberg-Marquard	WSS	Wide-sense stationary
LTE	Long-term evolution	3GPP	Third Generation Partnership Project
LTE-LAA	LTE for licensed assisted access	5G-U	5G networks in Unlicensed spectrum
LTE-U	LTE in Unlicensed spectrum		

2. Architecture of Unlicensed Cellular Networks

Before we start our discussion on the architecture of unlicensed cellular networks, let us introduce the names of the unlicensed spectrum frequency bands in the sequel, which have been illustrated in **Fig. 2**.

- Industrial Scientific Medical Band (ISM Band).
- Unlicensed National Information Infrastructure Bands (UNII Bands).
- Millimeter Wave Band (mmWave Band).
- Unlicensed Personal Communication System Band (UPCS Band).

In the text followed, two main architectures of unlicensed cellular networks, i.e., LTE-LAA and NR-U, are introduced with the corresponding technical regulation and operation descriptions in the networks. **Fig. 3** shows the transmission signaling architectures of these two systems exemplified in accordance with 3GPP specifications TR 36.889 V13.0.0 [25], TR 38.889 V16.0.0 [26], and TS 37.213 V16.3.0 [27], respectively. At the end of this section, the progressive status of commercialization for the unlicensed cellular networks is described.

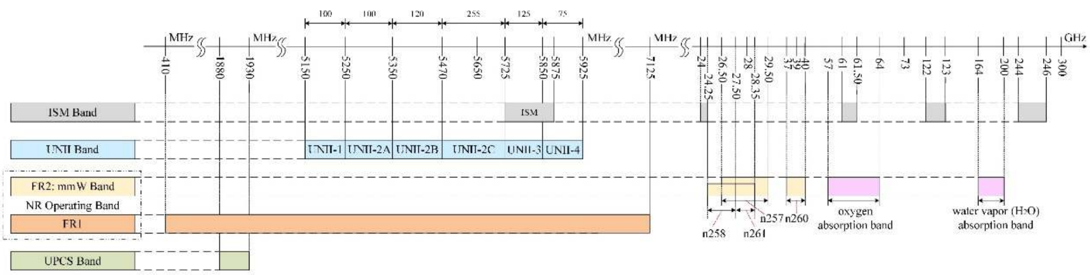

Fig. 2. Illustration of unlicensed spectrum frequency bands, where the NR band includes FR1 and FR2 bands. FR1 covers n1~ n95 (410 ~ 7125 MHz) bands. FR2 covers n257 ~ n261 (24250 ~ 52600 MHz) bands, including the mmWave bands.

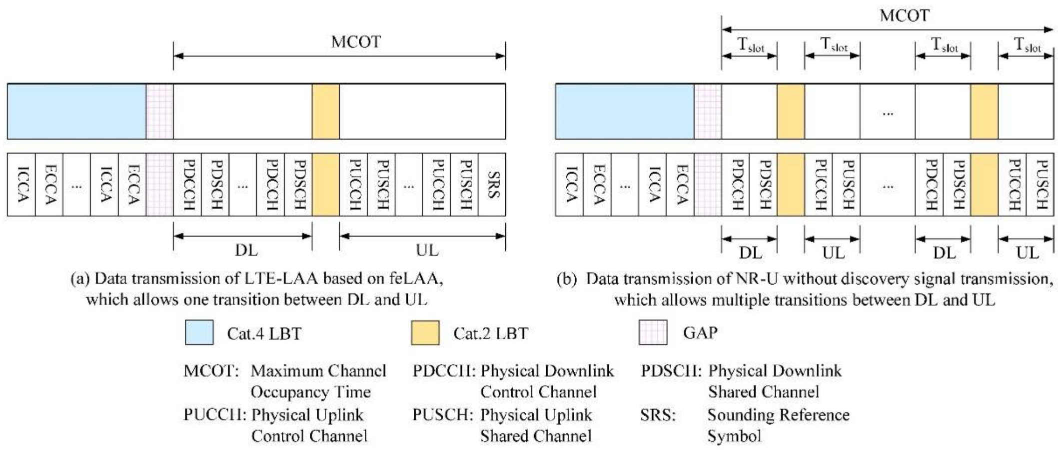

Fig. 3. Illustration of transmission signaling architectures of LTE-LAA and NR-U systems, where (a) is for data transmission in LTE-LAA based on feLAA, and (b) is for data transmission of NR-U without discovery signal transmission.

2.1 LTE-LAA Architecture

The idea to extend the LTE protocol to unlicensed spectrum can be traced back to year 2014, when companies like Ericsson, Qualcomm, Huawei and Alcatel-Lucent came up with a plan to extend cellular networks from licensed spectrum to unlicensed bands in 3GPP TSG RAN Meeting #65 [28]. Driven by spectrum limitation and shortage, a new standard specification called Licensed assisted access (LAA) has been proposed in 3GPP TR 36.889 (Release 13) to deliver a better performance and system capacity for long-term evolution (LTE) systems to operate on unlicensed bands [25].

2.1.1 Overview on LTE-LAA Technology

2.1.1.1 LTE unlicensed spectrum

The unlicensed spectrum has its traditional convenience to support low-cost wireless applications, such as Zigbee, Bluetooth and Wi-Fi devices. The Federal Communications Commission (FCC) in the USA has gradually released unlicensed bands for commercial use. First, the 2.4 GHz ISM band was released, then the 5 GHz UNII band, as well as the 60 GHz mmWave band recently.

Compared to the 2.4 GHz band, the 5 GHz band is relatively underutilized, mainly used by Wi-Fi. Considering less congested channels and wider bandwidth for practical implementation, LTE-LAA currently focuses mainly on the 5 GHz bands to provide broadband multimedia services [29]. Besides, more and more wireless carriers and vendors want to use a higher frequency band, normally higher than 3 GHz to avoid crowded and almost saturated user traffic in lower frequency bands. Those higher frequency bands include 28 and 60 GHz mmWave bands. Comparing these two unlicensed spectrums, the 60 GHz band has more available bandwidth than the 28 GHz band, making it feasible for supporting bandwidth-intensive services [30]. However, oxygen absorption and atmospheric attenuation parameters in 57-64 GHz band and water vapor absorption in 24 GHz and 164-200 GHz bands pose a significant challenge to meet physical layer specifications, as shown in **Fig. 2**.

2.1.1.2 Spectrum allocated for LTE-LAA and Wi-Fi systems

Since 2.4 GHz band has been widely used by many other wireless techniques and the 5 GHz band has a wider available bandwidth but with a shorter communication range, 5 GHz bands had been included in the operating band for LTE-LAA in several countries [29]. **Fig. 4** shows the unlicensed 5 GHz spectrum applications between LTE-LAA and Wi-Fi in respective regions.

2.1.2 Long-Term Evolution (LTE) Physical Layer

There are three radio frame structure types defined in 3GPP TS 36.201 V14.0.0 [31] as listed in the follow-up text. The detailed descriptions of the frame structure Types 1-3 are included in 3GPP TS 36.211 V14.4.0 [32] [33]. For downlink and uplink transmission, the eNB and the UE perform the channel access procedures prior to transmitting as specified in [34].

- Frame Structure Type 1 (FDD),
- Frame Structure Type 2 (TDD),
- Frame Structure Type 3 (LAA only).

2.1.3 LTE-LAA Channel Bands

Release 12 of 3GPP TS 36.101 V12.9.0 [35] defines the operating bands of evolved universal terrestrial radio access (E-UTRA) from band 1 to 44, separately. Among the E-UTRA operating bands, Band 1 operates at 1920 MHz - 1980 MHz for uplink, and at 2110 MHz - 2170 MHz for downlink in FDD duplex mode. Band 44 operates at 703 MHz - 803 MHz for uplink, and at 703 MHz - 803 MHz for downlink in TDD duplex mode. The operating bands 45 - 67 of E-UTRA are going to be included in Release 13 of the 3GPP Standard TS 36.101 V13.2.0 [36]. Furthermore, bands 69 - 70 will be included in Release 14 of the 3GPP Standard TS 36.101 V14.0.0 [37]. The all E-UTRA operating bands are listed in Chapter 5.5 of the 3GPP Standard TS 36.101 V14.5.0 [38]. The operating band 46 for LAA is shown in **Table 2**. Chapter 5.6 in 3GPP TS 36.101 V14.1.0 [39] and TS 36.101 V14.5.0 [38], defines several requirements for the channel bandwidths, as listed in **Table 3**. The 3GPP Standard TS 36.101 V14.5.0 [38] defines channel bandwidth for each E-UTRA band. Accordingly, E-UTRA band 46, allocated for LTE-LAA systems, is allowed to use 10 MHz and 20 MHz bandwidth.

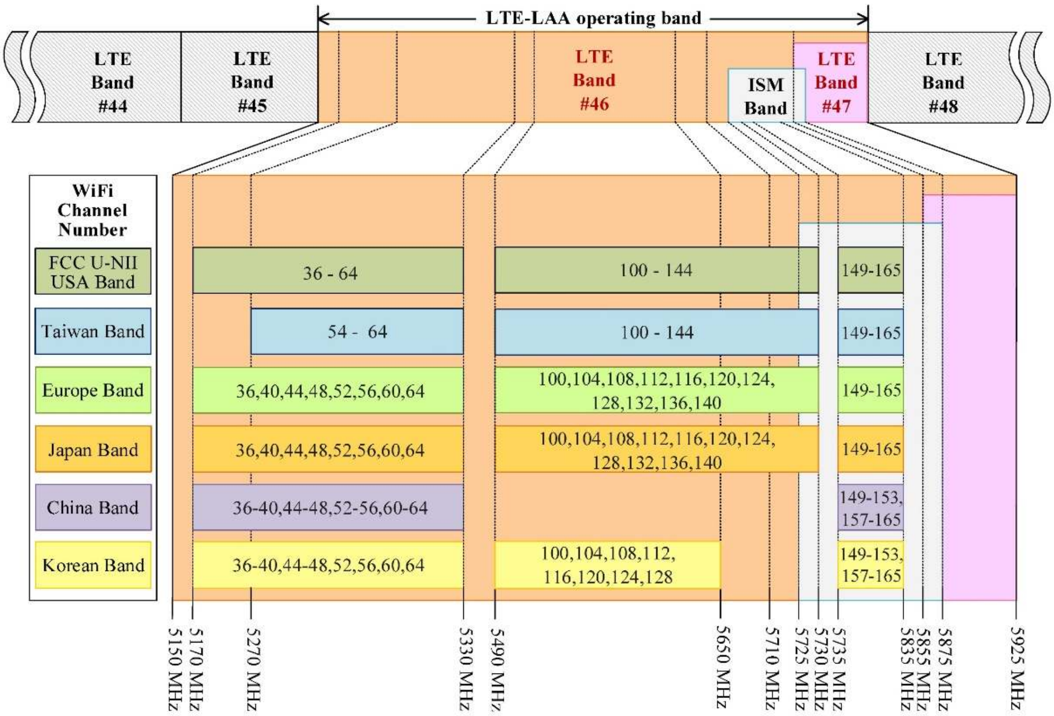

Fig. 4. Spectrum for LTE-LAA systems, which is regulated in E-UTRA band 46 and coexists with Wi-Fi channels as shown in the overlapping parts of the figure. E-UTRA band 47, which is defined for V2X communication from 5855 to 5925 MHz, is included in band 46.

Table 2. The operating band 46 for LAA in E-UTRA.

E-UTRA operating band	Uplink (low-high MHz)	Downlink (low-high MHz)	Duplex mode
#44	703-803	703-803	TDD
#45	1447-1467	1447-1467	TDD
#46	5150-5925	5150-5925	TDD[1]
#47	5855-5925	5855-5925	TDD[2]
⋮	⋮	⋮	⋮

#64	Reserved	Reserved	Reserved
#65	1920-2010	2110-2200	FDD
#66	1710-1780	2110-2200	FDD
#67	N/A	738-758	FDD
#68	698-728	753-783	FDD
#69	N/A	2570-2620	FDD
#70	1695-1710	1995-2020	FDD

1. This band is an unlicensed band limited to authorized licensed-assisted activities utilizing frame structure Type 3. This detail for this specification is limited to E-UTRA DL activities when carrier aggregation is used.
2. This band is unlicensed spectrum utilized for V2X communication networks. There is no prospective network arrangement for this band, and thus both frame structure Type 1 and frame structure Type 2 can be utilized.

Table 3. Applications in each class Bandwidth configuration in E-UTRA channels, where N_{RB} is the number of resource blocks in the given bandwidth.

Channel bandwidth BW (MHz)	1.4	3	5	10	15	20
Number of resource blocks in BW	6	15	25	50	75	100

2.1.4 Licensed-Assisted Access (LAA)

According to 3GPP TR 36.889 [25], the goals of a LAA system include: (1) a single frame design integrating regional regulatory requirements as the global solution; (2) effective and fair coexistence with inherent Wi-Fi networks; and (3) coexistence mechanisms to achieve beneficial performance of throughput and latency among LAA networks for different operators to address the compatibility of fairness and effectiveness. Some more specific design targets and functionalities are listed as follows.

- LBT design with clear channel assessment (CCA): The LBT mechanism requires to utilize a CCA to analyze the state of the channel before accessing it. Energy detection can be used by CCA to decide whether other signals are present or absent in the channel.
- Discontinuous transmission (DTX) on a carrier with limited maximum transmission duration: DTX operated on unlicensed carriers with the finite maximum transmission length in time affects a few functionalities required by LTE, such as Automatic Gain Control (AGC) settings, channel reservation, downlink discovery signals, frequency & time synchronization, etc.
- Radio resource management (RRM) measurements including cell identification: Release 12 Discovery Reference Signals (DRS) can be used as a starting point for providing RRM functionality, including cell identification. Some modifications of the Release 12 DRS signal and/or the transmission/reception may be necessary to support RRM functionality for LAA.
- Channel-State Information (CSI) measurements and reporting: If LAA supports CSI measurements, the aspects about Cell-specific Reference Signal (CRS) should be considered. The UE should be informed about the presence of CRS in a subframe implicitly or explicitly, in which the transmission of CRS may be subject to LBT.

2.1.5 Standardization for LTE-LAA Towards 5G NR-U

LTE-LAA was proposed formally in 3GPP Release 13 TR 36.889 [25]. It was modified as enhanced LAA (eLAA) in 3GPP Release 14 to specify how DownLink (DL) and UpLink (UL) work for LTE-LAA small cell in 5 GHz unlicensed spectrum [40]. In March 2017, another enhancements known as Further Enhanced LAA (feLAA) was concluded in 3GPP work item of TSG RAN Meeting #75 in 3GPP Release 15 [41]. However, considering large capacity and high data rate demands for the new generation wireless communications such as 5G NR, it was motivated to enable unlicensed spectrum utilization as the enhancements. Meanwhile, it is expected to keep some peculiarities of LTE-LAA for NR-U, especially its channel access mechanism and Hybrid Automatic Repeat Request (HARQ) scheduling process with some revisions adapted to 5G NR-U requirements. In this regard, new work items of NR-U approved by 3GPP provide a much broad spectrum including 2.4 GHz, 5 GHz, and 6 GHz unlicensed bands. An overview on the 5G NR-U was presented in [42]. The scenarios of 5G NR-U can be categorized into two operation modes:

- Licensed assisted access NR-U: LAA NR-U will offer a satisfactory network performance in transmission rate and capacity through carrier aggregation function to add up unlicensed band with the existing licensed band to assist licensed based traffic transmission for both NR and LTE networks. It can be implemented either utilizing carrier aggregation in small-cells supporting both unlicensed and licensed bands or realizing dual-connectivity between a single licensed macro-cell and an unlicensed local small-cell.
- Stand-alone NR-U: Stand-alone NR-U is the extended development of cellular mobile communication technologies from anchoring in licensed spectrum into totally independent operation in unlicensed spectrum. Further detail regulation of stand-alone NR-U operation specified by 3GPP can be referred to 3GPP TR 38.889 V16.0.0 [26] and the corresponding channel access process can be referred to 3GPP TS 37.213 V16.3.0 [27].

2.2 NR-U Architecture

2.2.1 Overview of NR-U Technology

Although in the study item on LAA (RP-141646) [28], which first introduced the cellular network access to unlicensed spectrum to assist operators for licensed service offloading [28]. However, considering development of 5G NR to maximize the feasibility of NR-based unlicensed access, the study item in 3GPP RP-170828 [43] focused on the issue of NR-based access to unlicensed spectrum, such as dual connectivity of regular NR operation, CA based aggregation with a 5G NR anchor, and standalone scenario of NR in unlicensed spectrum. The detailed work is scheduled to be followed by another work item completed in Release 16.

2.2.2 Characteristics of NR-U Technology

As we mentioned previously, there are two modes, (1) LAA NR-U and (2) Stand-alone NR-U, which are included in 5G deployment in unlicensed spectrum. In 3GPP plenary meeting in the end of 2018, it has decided to kick off the work item for 5G NR unlicensed spectrum in Release 16 [42]. Providing unlicensed spectrum services for 5G brings in benefits on flexible framework scenarios deployment, spectrum utilization efficiency increase, and better data rates and QoS quality.

2.2.3 Prospect and Time table of NR-U Technology

According to the announcement in 3GPP website [44], Release 16, the second phase of 5G, had been completed on July 3, 2020, with Stage 3 freeze (TSGs#88e). NR-based operation in unlicensed spectrum is one of the Release 16 features and study items, which had been completed already. The newest related active program documentation and detail specification of NR-U operation can be referred to 3GPP TR 38.889 [26]. Besides, in a recent 3GPP webinar

[45], the TSG RAN Chair Balazs Bertenyi mentioned that the topic, such as general enhancements to NR-Unlicensed operation, will be included in Release 17 work area.

In 3GPP TR 38.889 [26], it describes five possible deployment scenarios for NR-U as follows.

- Scenario A: Carrier aggregation (CA) between licensed band NR for primary cell (PCell) and unlicensed band NR-U for secondary cell (SCell), in which unlicensed NR-U SCell may have either DL/UL scheme or DL-only mechanism.
- Scenario B: Dual connectivity between licensed band LTE for PCell and unlicensed band NR-U for primary secondary cell (PSCell).
- Scenario C: Stand-alone NR-U.
- Scenario D: An NR cell with unlicensed DL transmission and licensed UL transmission.
- Scenario E: Dual connectivity between licensed band NR for PCell and unlicensed band NR-U for PSCell.

On the other hand, the channel access schemes for NR-based access for unlicensed spectrum are classified into 4 categories as follows [26].

- Category 1: Immediate transmission after a short switching gap that is no longer than $16\mu s$.
- Category 2: LBT without random back-off, in which the length of CCA detection duration is deterministic (for instance, fixed to $25\mu s$).
- Category 3: LBT with random back-off with a contention window of fixed size. The transmitting entity draws a random number N within a contention window whose size is fixed and designated by the maximum and minimum value of N . The length of the random number N deployed in the LBT process is to determine the period of detection time for the channel to be sensed idle by the transmission entity before transmission starts.
- Category 4: LBT with random back-off with a contention window of variable size. The transmitting entity draws a random number N within a contention window whose size is specified among the maximum and minimum value of N . The transmitting entity will change its contention window size after it draws a random number N which is utilized as the channel detection period for sensing the channel as idle before transmission starts.

2.3 Commercialization for Unlicensed Cellular Networks

A lot of companies and operators have put their efforts to unlicensed cellular networks commercialization. LTE-LAA network is one of the pioneers.

In 2017, AT&T announced its commercial LTE-LAA technology deployment in Indianapolis, USA [46]. In the same year, the first commercial LTE-LAA network was rolled out by companies such as Qualcomm, Ericsson, and MTS in the Ufa City of Russia to support Gigabit LTE peak download speeds [47]. As indicated by the news in Ericsson's site [47], Andrey Ushatsky, the Vice President for Technology and IT, MTS, declared that the business based gigabit LTE-LAA network participated by Qualcomm and Ericsson Technologies has been the principal LAA network dispatch in Eastern Europe and Russia, and this is a significant achievement in the transition to 5G. Meanwhile, Yulia Klebanova, the Vice President of Business Development, Qualcomm Europe, Inc., indicated that Gigabit LTE network can help operators achieve a higher spectral efficiency and increase network throughput by serving clients of cellphones controlled by Qualcomm Snapdragon Gigabit LTE modems with LAA service, including Snapdragon 835 and 845 Mobile Platforms. The gigabit-per-second-based transmission rates in the implementation were accomplished utilizing Ericsson Radio System programming software [47], comprising 256-QAM and 4CC Carrier

Aggregation of 10 streams with 4x4 MIMO on a licensed 20 MHz carrier combined with 3x20 MHz LAA. These operators have sufficient confidence in commercial LAA deployment and take it as an essential bridge to 5G networks.

Depending on the announcement in Global Mobile Suppliers Association (GSA) report [48], as of January 2019, 32 operators have invested in LAA across 21 countries, and this has expanded to 37 operators in 21 nations by July 2019 [49]. Then, the number goes to 38 operators in 21 countries by December 2019 [50], in which 8 of these declared LAA network deployments in 6 nations. Up to July 2019, 11 operators have invested in LTE-U networks; One LTE-WLAN aggregation (LWA) network has launched in Taiwan; One eLAA has been in its trial in South Korea; 11 companies have invested in Citizens Broadband Radio Service (CBRS) trials in the United States; 22 commercially available modem-containing chipsets support unlicensed access; 122 devices support LTE in unlicensed spectrum technology offered by 29 vendors.

3. Research Works on Unlicensed Cellular Networks

In this section, we give a survey on the existing research works on unlicensed cellular networks proceeding in the two directions, i.e., LTE-LAA and NR-U systems, respectively.

Table 4. Major research issues and contributions of LTE-LAA related works.

Summary of study issue	Description	Advantage	Disadvantage	References
Survey articles	Overview and evaluation of the design challenges and key LTE enhancements for LAA.	Provide a comprehensive introduction on LTE-LAA in terms of technical designs and challenges.	Absence of modeling and discussions about key issues in LTE-LAA.	[51][52]
	Overview of the impact of unlicensed spectrum operation on the LTE physical layer architecture based on coexistence with WiFi.	Provide the technical specifications of LTE-LAA on physical layer.	Lack of in-depth modeling and discussions on future works and challenging issues.	[53][54]
Coexistence mechanisms	Several algorithms design proposed to solve the coexistence challenges between WiFi and LTE-LAA systems based on methods related to WiFi-like techniques (EDCA, WiFi systems TXOP).	Provide several solutions to address coexistence issue due to the lack of coordination among LAA UEs.	The proposed scheme might not be compatible with 3GPP regulations.	[55][56] [57][58]
	Algorithms design related to frame structure or MAC layer deployment.	Realize a controllable coexistence mechanism.	The design might not be compatible with 3GPP standards.	[59]
	Interference impact of LTE-LAA coexisting with WiFi in the unlicensed band under various network conditions.	Provide insights to configure a network for interference mitigation.	Analysis of co-channel interference to MBS can not be extended from licensed to unlicensed bands for general cases.	[4]
	Design and settings of LBT mechanisms for LTE-LAA to ensure fair coexistence.	1. Analytical performance for different LBT schemes are given to provide references for	High complexity and cost to implement multi-LBT mechanisms (even in hybrid	[60][61][62]

		selecting various network planning priority. 2. Designs of distinct LBT schemes considering practical channel and cell load factors for better fairness and QoS.	LBT or adaptively switch LBT).	
	To improve the energy efficiency (EE) and achieve fair resource sharing of LAA systems by leveraging licensed resource blocks (RBs) allocation with unlicensed bands based on an EE optimization method.	Effective criterion to improve EE and allocate RBs properly.	The assumption of duty cycle is not realistic.	[63]
Carrier selection	A dynamic carrier selection scheme is proposed to maximize spectral utilization instead of maintaining frequency reuse factor of one.	1. Improve edge user performance. 2. Reduce energy consumption.	1. Lack of centralized control and coordination. 2. Difficult to achieve a stable QoS.	[64][65][66]
	A centralized channel selection mechanism is proposed to increase network capacity.	Increase spectral efficiency.	A suboptimal approach was proposed to approximate its optimal solution.	[67]
	Frequency reuse for transmission by neighbouring nodes of the same operator is proposed to increase the spectral efficiency of LAA.	Increase spectral efficiency of LAA.	Require accurate and effective energy detection.	[68]
	Utilizing LTE directly in an unlicensed band, without any assistance from a licensed band, i.e., the stand-alone unlicensed LTE.	1. Access without licensed control by operators. 2. Enhanced unlicensed band utilization.	1. High complexity and cost in hardware. 2. Capacity is not fully used.	[69]
CW size adaptation	A contention window (CW) size adaptation algorithm based on LBT channel access scheme is proposed to achieve higher throughput gain.	1. Fair channel access with Wi-Fi. 2. Fair cell-load based service differentiation.	High complexity.	[70][71]

3.1 LTE-LAA System

We can classify the existing works done on LTE-LAA networks, as shown in **Table 4**. We discuss each category in the following text.

3.1.1 Coexistence Mechanisms

Coexistence has been a focus of discussions on unlicensed cellular networks for a long time. In order to avoid the performance degradation caused by the systems coexistence, and guarantee a fairness between WLAN systems and LTE networks, it is necessary to design a channel access mechanism for LTE-LAA systems [62]. In the text followed, several research works dealing with the fairness issue toward Wi-Fi networks will be introduced.

3.1.1.1 Surveys on Coexistence Issues

[51] performed a comprehensive survey on LTE-LAA/Wi-Fi coexistence performance evaluation methodologies according to the indoor scenario described in 3GPP TR 36.889 [25].

The simulation results showed that the throughput for Wi-Fi users is not degraded over a flexible range of selected LAA channel access parameters including energy detection threshold and maximum channel occupancy time [51]. The authors in [52] corroborated the performance enhancement of an implementation carried out on a co-located LTE-A and Wi-Fi systems with CA implemented between LTE licensed and unlicensed bands. They observed that the lower Wi-Fi activity they detected, the better the throughput became [52]. To this end, optimal learning algorithms can be incorporated in the system [52]. In [53], the authors presented exhaustive buffer occupancy and system-level throughput evaluations based on indoor and outdoor coexistence schemes, which were done with the same parameters used in 3GPP LAA (TR 36.889) simulation assumptions [25].

Table 5. Coexistence mechanisms used in unlicensed cellular networks.

Mechanisms	Description	References
Listen Before Talk (LBT)	A LBT mechanism is an adaptive DCF protocol adopted for small base stations (SBSs) whose backoff time is a random variable taken from CW.	[54][63]
Distributed Coordination Function (DCF)	DCF is a fundamental random access based MAC protocol used in IEEE 802.11, which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to resolve multiple stations contention.	[72]
Duty Cycle (DC)	DC is implemented by splitting the common radio channel through air time sharing between Wi-Fi and LTE-U subsystems.	[73][74]
Almost Blank Subframe (ABS)	ABS introduces a concept of muting some frames in one layer and prevent the interference to others.	[75]

3.1.1.2 Coexistence Mechanisms in Unlicensed Bands

In the text followed, we will categorize the coexistence mechanisms into four groups and introduce each of them briefly. These four classifications include listen-before-talk (LBT), distributed coordination function (DCF), duty cycle (DC), and almost blank subframe (ABS) schemes.

- Listen Before Talk (LBT)
  In [63], LBT access component with versatile DCF convention was received for SBSs. The backoff window size can be adaptively adjusted according to Wi-Fi traffic status and accessible authorized spectrum bandwidth. To achieve fair coexistence for LTE-LAA systems, the LAA LBT procedures for both data and DRS should be made as comparable as conceivable to the process such as DCF and enhanced distributed channel access (EDCA) protocols utilized in Wi-Fi [54].
- Distributed Coordination Function (DCF)
  DCF is fundamental random access based MAC protocol utilized in IEEE 802.11 [72]. It utilizes Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to resolve multiple stations contentions [76]. DCF employs a slotted backoff time for stations to allow transmit after the backoff waiting period in order to achieve fair channel access and collision avoidance with a random integer uniformly selected in the range $[0, CW-1]$, where CW refers to the current contention window, which relies upon the number of successive transmissions encountering failures for the packet.
- Duty Cycle (DC)
  DC is implemented by splitting up the shared channel resources through time duration partition among LTE-U and Wi-Fi systems [73]. In [74], Qualcomm proposed a coexistence technique called Carrier-Sensing Adaptive Transmission (CSAT) inspired by duty cycle (DC). The CSAT algorithm was utilized in LTE-U small cells incorporation with flexible Time Division Multiple Access (TDMA) transmission,

depending on long-term carrier detection of Wi-Fi activities in the common channel spectrum.

- Almost Blank Subframe (ABS)
  ABS manages frames in silent and active modes to achieve interferences control. In [75], the authors proposed an ABS scheme eliminating co-channel interference between small cells and Wi-Fi networks without priority setting. In [75], according to the 3GPP Release 10 TDD scheme, an LTE system conducting ABSs achieves autonomous (without coordination) coexistence between LTE and Wi-Fi networks. Normally, these ABS schemes are set with reduced power or content. However, ABSs need to be transmitted randomly without coordination and compatibility with previous releases [75].

3.1.1.3 LBT Framework

In Chapter 8 of 3GPP Technical Report 36.889 [25], the evaluated channel access schemes are classified into 4 categories as follows, in which the detail description can referred to [25].

- Category 1: No LBT.
- Category 2: LBT without random back-off.
- Category 3: LBT with random back-off with a fixed sized contention window.
- Category 4: LBT with random back-off with a variable-size contention window.

Category 4 performs the best in fairness, and then comes Category 3, followed by Category 2. The fixed CW in Category 3 still offers waiting time for secondary users (SUs), protecting the channel access rights of primary users (PUs). The worst could be Category 1, since the spectrum resource is open randomly for any user. We will summarize the works on LBT protocol in the literature as follows.

- *Frame Based Equipment (FBE) and Load Based Equipment (LBE)*: According to technical reports written by European Telecommunications Standards Institute (ETSI) [77] [60], two broad types of LBT schemes were proposed. One is FBE and the other LBE. For FBE, the equipment performs channel sensing at fixed instants in time, where the transmit/receive structure is not directly demand-driven. For LBE, the equipment performs channel sensing at any instant in time, where the transmit/receive structure is demand-driven. Based on FBE and LBE operations, several works are referred in **Table 5**. In 3GPP Release13 specification, LAA was designed to implement CW mechanism based on LBE framework.
- *Fair and efficient LBT*: [60] proposed an LBT mechanism, which attempts to share the medium in a fair manner. It improves the Wi-Fi as well as the combined Wi-Fi-LAA performances significantly. [61] proposed an analytical model to evaluate the performance of an LBT based coexistence scheme with multiple LTE SBSs. [62] analyzed and optimized the throughput performance of LTE-LAA networks coexisting with WLAN under imperfect spectrum sensing.
- *LBT with TXOP backoff*: There are two more configurable parameters of carrier sense multiple access with collision avoidance (CSMA/CA) for different QoS provisions, including (1) arbitration inter-frame spaces (AIFS), and (2) transmission opportunity (TXOP). AIFS is the time a device must wait before reoccupying the channel after a successful transmission. A small value of AIFS represents a high priority. TXOP represents the number of frames a device is allowed to transmit, once it gets access to the channel. In the proposed scheme [55], the LBT coexistence mechanism adopts an adaptive CW and serves an exponential number of backoff subframes for an LAA device that transmitted in a unit of TXOP period time

3.1.2 Carrier Selection

In [64], the authors proposed a fully distributed base station (BS) activation and user scheduling framework to perform Inter-cell interference (ICI) management. In this framework, BSs will determine whether to turn on or off their transmit power in a competition period independently. Also, interference brings in challenges to LTE-LAA operators on component carrier selection in case of a dense deployment. Therefore, authors in [65] proposed an algorithm called dynamic unlicensed component carrier selection (UCCS). When UEs in the licensed carrier experience poor throughput, an offloading mechanism will be activated. Dynamic carrier selection for each cell was proposed by [66].

3.1.3 Contention Window (CW) Size Adaptation

Normally, a general LBT channel access scheme adopts a fixed CW size, which gives the same channel access opportunity to all LTE-LAA eNBs, but it has no flexibility to adapt according to load intensity change appropriately. [70] proposed a contention window (CW) size adaptation algorithm based on an Cat.4 LBT channel access scheme by sensing and calculating the current load intensity with respect to the slot utilization in a period of time. Similarly, [71] proposed a CW size adaption based LBT enhancement approach for LTE-LAA UEs, to balance channel access fairness with the QoS.

Table 6. Major research works on NR-U networks.

Study issues	Description	References
Spectrum sharing	Share and manage spectrum for licensed and unlicensed bands to enable 5G network deployment, such as IOT, factory automation, autonomous vehicular networks, etc.	[78][79]
	Resource management and control to fulfill spectrum sharing with spectrum fragility characteristics to support dense network environments.	[80][81]
	Study different strategies for the integrated use of licensed and unlicensed mmWave bands.	[82]
	Propose an inter-operator network slicing framework over licensed and unlicensed bands.	[83]
	Discuss LAA configurations in different RAN configuration modes to meet latency and reliability requirements of 5G networks.	[84]
Coexistence mechanisms	Several algorithms to explore MAC mechanisms were proposed to address the coexistence challenges for multi-channel strategies to achieve low latency LTE unlicensed band access.	[85][86]
	Use LBT of LAA to coordinate unlicensed spectrum channel access to address coexistence issue.	[13][87]
	Report standardization status of NR-U including channel access mechanism enhancements.	[88]
	Propose the ways to achieve harmonious coexistence of unlicensed bands in 5G heterogeneous networks.	[89][90]
Intelligent contention window	Design an intelligent-CW framework to ensure fair channel share time.	[91]

3.2 NR-U System

As an important part of 5G solutions, NR-U technology was proposed by 3GPP. In this subsection, we aim to offer a survey on the NR-U systems. The existing works on NR-U networks are summarized in **Table 6**. In this subsection, we will discuss the NR-U system, focusing mainly on its several important features.

3.2.1 Spectrum sharing

Spectrum sharing is one of the most important issues when NR-U was proposed originally. Numerous research works have been published to discuss how to realize spectrum sharing and management in the NR-U system. The related works in this topic are listed in **Table 6**.

Authors in [78] proposed a smart spectrum sharing scheme for 5G based on use cases with associated technologies to implement affordable wireless broadband access. Similarly, an algorithm was proposed to manage spectrum grants in an unlicensed spectrum environment for 5G autonomous network deployment [79]. And [92] focused on 5G PHY/MAC designs to combine the unlicensed and licensed bands to enable large-scale deployments for factory automation applications. In [93], a mathematical queuing theoretic framework was developed with three distinct strategies (i.e., based on sequential service, probabilistic offloading, or proportional splitting) to integrate licensed and unlicensed mmWave bands usage. Besides, an adaptive scheme was proposed to include spectrum sharing and energy consumption conservation for mmWave radio over fiber system coverage enhancement [82]. The authors in [83] worked out an enhanced cognitive radio networks (E-CRNs) framework with dynamic spectrum management (DSM), including licensed spectrum sharing (SS) and unlicensed spectrum aggregation (SA) for 5G wireless networks. Moreover, [84] recommended LAA configurations as different RAN configuration modes to serve latency and reliability sensitive 5G networks. Some other researches aimed to design a control framework to enable spectrum sharing. [80] proposed a resource management and control framework to address spectrum fragility based on a resource pricing concept. On the other hand, [81] suggested a concept of control-data separation architecture (CDSA) comprising of a control base station overlaying data base stations (DBSs) to support dense network environments.

3.2.2 Coexistence mechanisms

Coexistence mechanism is also an important issue in NR-U systems, on which many works have been reported in the literature. Some works focused on MAC layer protocol design to enable multiple channel access for both Wi-Fi UEs and NR-U UEs. Some others proposed the ideas to extend some related LTE-LAA techniques, such as LBT, to NR-U to increase compatibility between LTE-LAA and NR-U systems. Yet some others promoted the standard development of NR-U.

In [85], a weight based channel selection method was proposed to improve the fairness of coexistence between diverse networks, which is an unsolved problem existing in multi-channel contention between the enhanced LAA (eLAA) and the Wi-Fi systems. On the other hand, a MAC mechanism related to multi-channel strategies designed for WLAN and LTE was explored to achieve Ultra-Reliable and Low Latency Communications (URLLC), particularly in the unlicensed spectrum [86]. In [13], the author recommended a hybrid channel access mechanism to take advantage of LBT in LAA, which can achieve a higher user perceived throughput (UPT) and a lower delay. On the other hand, a cooperative LBT protocol was designed to characterize the effective capacity of NR-U in unlicensed bands [87]. Considering the standardization development of NR-U, [88] provided a comprehensive overview on the related topics.

Additionally, other researchers discussed several aspects to facilitate harmonious coexistence of unlicensed bands in 5G heterogeneous networks. [89] proposed a model with its focus on network densification, which aims to optimize the maximum node density to maximize throughput performance for high density networks. In [90], a statistical signal transmission (SST) technique was proposed to promote harmonious coexistence in 5G unlicensed bands.

3.2.3 Intelligent contention window (CW)

In several technologies using the variant of CSMA/CA protocol, such as Wi-Fi and LTE-LAA, the selection of contention window size $CW_{\min}$ is extremely important to improve the overall performance of a NR-U network. To this end, the authors in [91] proposed an intelligent contention window (ICW) framework to adapt $CW_{\min}$ values to ensure the fairness in sharing channel time with neighbor nodes. In the framework, nodes are aware of the aggressive behavior of their neighboring nodes by detecting the unlicensed channel status, and non-aggressive nodes adapt their $CW_{\min}$ values accordingly. The fairness in sharing channel time could be guarantee with the help of the mechanism.

4. Intelligent Radio in Unlicensed Cellular Networks

The research on intelligent radio (IR) or smart radio (SR) can be traced back to 2000, when Joseph Mitola proposed a concept of cognitive radio in his PhD thesis as an embryonic form of cognitive radio architecture [94]. A few years later, cognitive radio (CR) had been described by Federal Communications Commission (FCC) as a system or radio which detects its functional electromagnetic environment and then vigorously and autonomously tunes its corresponding radio execution parameters to modify system operation, such as facilitate interoperability, access secondary markets, mitigate interference, and maximize throughput [95]. Haykin in [96] gave a definition of cognitive radio as follows. Cognitive radio, a clever wireless communication system, which can perceive its neighboring environment (i.e., the external world), and adopt the procedure of understanding-by-building to learn and pick up from the environment and adjust its inner states to statistical modifications in the advent RF incentive through modifying relevant operating parameters (e.g., modulation scheme, transmit-power, and carrier-frequency) immediately with two main purposes: 1) highly reliable and firm communications systems, and 2) efficient radio frequency spectrum utilization.

Before diving into the topic of IR, let us start with some terminologies often used in CR networks. Different from conventional communication paradigms, CR devices are able to adjust their transmitter parameters, such as modulation type, transmission power, transmission frequency, etc., to fit neighboring radio environment in which it operates [97]. Those operations include active negotiation with other UEs or passive detection and decision making procedure in the CR devices itself [97]. In order to intelligently and efficiently utilize the spectrum resources, a CR unit should provide functionalities with cognitive capability and reconfigurability [96] [98]. According to the descriptions in [98], the cognitive capability denotes the ability to detect and gather information data from the neighboring environment, such as transmission power, transmission frequency, carrier bandwidth, modulation type, etc. Reconfigurability refers to the ability to respond to the sensed information by dynamically adjusting the operational parameters to achieve optimal performance. With these capabilities, CRs put primary users (PUs) and secondary users (SUs) in different operating modes based on environment variations [96] [98].

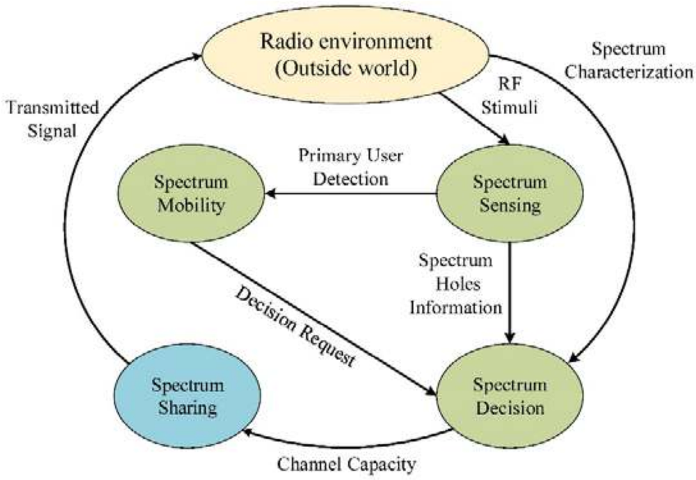

Fig. 5. Cognitive cycle framework for dynamic spectrum management, whose basic idea is introduced by Haykin [96].

4.1 Cognitive Cycle

Within a cognitive cycle as shown in **Fig. 5**, cognitive radios can not only sense their environments, obtain knowledge and adjust their radio parameters intelligently, but also perform spectrum characterization, spectrum selection and CR reconfiguration, respectively [99] [100] [101].

The tasks required for adaptive operation in a cognitive cycle can be briefly discussed as follows [96] [99] [101].

4.1.1 Spectrum Sensing and Monitoring

Spectrum sensing is a technique, which provides the capability to determine whether a particular band of the channel is occupied. Spectrum monitoring is defined as monitoring accessible frequency bands to obtain spectrum information and discover the spectrum holes.

4.1.2 Spectrum Analysis and Decision

Based on the local partial information and measurements obtained through spectrum sensing, the spectrum model with characteristics of the spectrum holes in the wireless communication scene can be built up and estimated. And the spectrum decision is defined as the detail for spectrum usage and access methods, such as the bandwidth of a channel, the data rate, and the transmission mode. The optimal spectrum access preference denotes the option that maximizes user application requirements base on the constraints of spectrum policy or environment [102].

4.1.3 Spectrum Mobility

Spectrum mobility is defined as the process when the SU senses that a specific spectrum is reclaimed by PU. SU then should change its frequency to another vacant spectrum. Normally, spectrum mobility occurs when either a PU appears or the present channel statuses get worse off. Spectrum mobility requires a new sort of spectrum handoff scheme to detect the reliability of PUs' connection, and switch the current communication to a new spectrum within an allowable QoS impairment.

4.2 Spectrum Sensing in CR Networks

When spectrum sensing is considered with CR technique, it not only serves more comprehensive applications and lower infrastructure requirements, but also involves spectrum usage characteristic features, including signal modulation, waveform, bandwidth, carrier frequency, etc. [103]. In the text followed, we summarize existing solutions for spectrum sensing in CR, such as energy detection based sensing, matched-filtering based sensing, waveform based sensing, cyclostationarity based sensing, radio identification and feature detection based sensing, and cooperative sensing.

In general, energy detection is one of the most common methods for spectrum sensing. Its implementation has a low cost and a low computational complexity [104] [105]. And matched-filtering based sensing helps finding the probability of miss-detection in a shorter period of time than other sensing methods. Especially, when considering the probability of false alarm happened in a relatively low SNR, matched-filtering requires a smaller number of target signal samples than other sensing techniques. Next, waveform based sensing correlates a known pattern with the received signal pattern, and makes a decision from the output in comparison to the threshold. This technique is applicable to the systems with known signal patterns. And cyclostationarity based detection is more robust and reliable to noise uncertainty, in which utilizes the cyclostationary features of the received signals to implement air interface recognition. On the other hand, radio identification and feature detection based sensing identifies the transmission parameters and technologies utilized by PUs to capture a complete knowledge about the spectrum characteristics. Such an identification is the greatest power for cognitive radio to gain an extended and higher dimensional knowledge. Finally, cooperative communication is a paradigm which facilitates distributed transmission by collaborations with each other between distributed devices in a specific wireless network [106]. Cooperative spectrum sensing based CR networks significantly enhance the reliability of detection in the presence of PUs [106]. In **Table 7**, we compare these spectrum sensing approaches.

Table 7. References on spectrum sensing methods in cognitive radio [103] [101].

Taxonomy	Summary of the work	Pros and cons	References
Energy detector based sensing	Obtain energy of the received signal as test statistics.	Pros: 1) Non-coherent. 2) Low implementation complexities. 3) No need to know prior knowledge of PU. Cons: 1) Noise uncertainty causes a high false alarm probability. 2) Poor performance under a low SNR. 3) Unable to differentiate PU from other signals and noises.	[104][105]
Matched filter detector based sensing and waveform detector based sensing	It is known as an optimal coherent detector for detecting presence of PUs. MF can be implemented by correlating the PU signal with the received signal. If a correlation peak appears, it means a PU signal is present. It has robust performance with a low SNR to detect very weak signals.	Pros: 1) Optimal sensing performance with maximized received SNR in the presence of additive stochastic noise. 2) Better detection robustness against noise uncertainty. 3) Better detection robustness in a low SNR circumstance. Cons: 1) It requires prior knowledge of the primary network.	[107]
Cyclostationarity based sensing	A detection method for detecting PU trans missions through utilizing the cyclostationarity characteristics of the received	Pros: 1) Able to differentiate noise from primary users' signal. 2) Able to distinguish among different types of transmissions and PUs.	[103][106]

	signals. Cyclostationary characteristics are produced by the periodicity that exists in the signals or in its corresponding statistics such as autocorrelation function and mean value.	3) Better detection robustness under a low SNR. Cons: 1) Implementation complexity is high. 2) Require a large sample set for better estimation precision of the features.	
Feature detection based sensing	A detection method uses distinctive features of signals for identifying the presence of transmitted signals. Normally, the cyclic spectral density function is obtained as the matching features.	Pros: 1) Better detection robustness against noise uncertainty. 2) Better detection robustness under a low SNR circumstance. Cons: 1) Requirement of specific system features associated with PU signals.	[108]
Cooperative sensing	A detection method allows multiple CR UEs to collaborate in spectrum sensing, which improves the probability of detection in fading channels and mitigates the impact of multipath fading, shadowing and hidden terminal issues.	Pros: 1) Effective detection performance by exploring spatial diversity. Cons: 1) User selection impacts cooperative sensing as gain-limiting factors. 2) Require extra sensing time, delay, energy, etc., which incurs cooperation overhead.	[104][106]
Other sensing methods	Learning-based sensing, Measurement-based sensing.	Pros & Cons: 1) Suitable for a dynamically changing environment. 2) Higher operational complexity. 1) Interference challenges across a broad spectral range. 2) Higher complexity.	[109]

4.3 Resource Allocation in CR Networks

In a cognitive radio network (CRN), SUs continuously monitor the presence of PUs and opportunistically access the unused licensed bands of the primaries under the condition that SUs must not interfere with PUs transmission [99]. Therefore, a prior knowledge of possible transmission activities of the PUs is desirable for the SUs to effectively access the available channels and predict the expected radio and network performance for QoS provisioning [110].

Considering the access approaches of SUs, resource allocation can be generally divided into two categories: centralized and distributed, as shown in **Table 8**. In centralized resource allocation, a central entity such as BS or eNodeB manages resource allocation. Distributed resource allocation does not rely on a central entity that controls scheduling. Instead, each node and UE performs measurements and calculations toward making resource allocation decisions autonomously. Some even share the information among its neighbors. In **Table 8**, we compare the two approaches. In **Fig. 6**, we classify resource allocation schemes based on the concept of competition between SUs. From this point of view, resources such as time, frequency, code, space, and geolocation maps can be made available to SUs.

Table 8. Existing resource allocation schemes in cognitive radio [98].

Taxonomy	Summary of the work	Pros and cons	References
Centralized	A central entity exists and take the responsibility to manage the resource allocation process.	Pros: 1) Optimized solution in terms of its desired performance metrics (e.g., network sum rate). 2) Able to minimize interference and achieve an optimal overall network performance. 3) Readily achieve global optimal fairness. 4) Can handle priorities more efficiently	[111][112]

		5) Suitable for highly loaded networks only. Cons: 1) Produce a large signaling overhead which wastes resources. 2) The crash of central entity may have a serious impact on the entire network performance.	
Distributed	No central entity in charge of controlling the scheduling process. Each node performs resource allocation autonomously. Some nodes make decision via limited cooperation by exchanging information with neighboring nodes.	Pros: 1) Better flexibility over the centralized one. 2) Offer more robust and steady communications due to resource allocation signals are transmitted via each node. 3) Reduce overhead and delay in the information exchanging process. Cons: 1) Cannot obtain an optimal solution because each node has limited information. 2) Can only achieve local fairness. 3) Suitable for lightly loaded networks only.	[113][114]

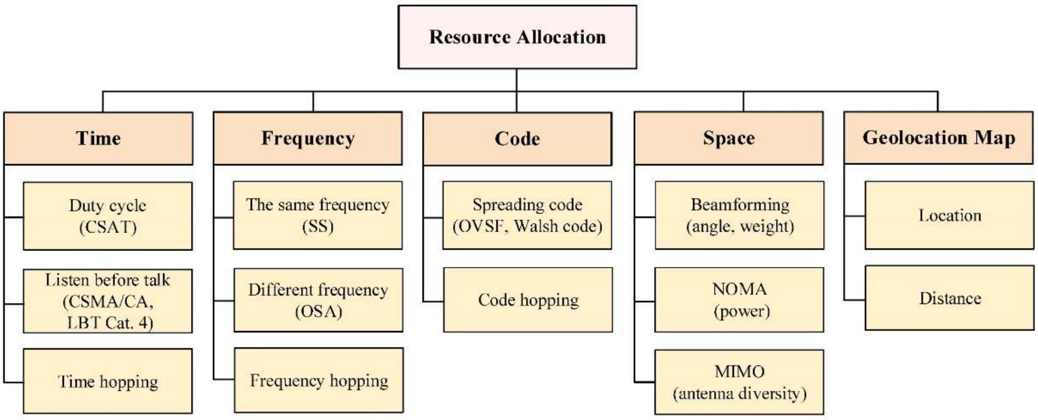

Fig. 6. Classification of resource allocation schemes in terms of competitions between UEs in cellular networks.

4.4 Intelligent Radio based on AI

Featured by massive connectivity with densely deployed UEs and small cell base stations (SBSs), 5G promises to serve more than one million devices per square kilometer to support emerging machine-type communication (MTC), which again requires a large amount of spectrum resources. Obviously, a fundamental and critical issue arises on how to accomplish such great amount of wireless access in the case of limited spectrum resources [8]. As 5G and B5G networks need to support an enormous number of devices and connections in an extremely complex RF environment, a lot of challenging issues, such as different QoS requirements, fast-changing traffic dynamics, and spectrum heterogeneity across networks, need to be taken into account. We need to not only renovate the current wireless communication systems but also make use of artificial intelligence technologies to revolutionize wireless system design following an IR (or SR) paradigm [8]. From a perspective of cognitive radios, the authors in [115] reviewed numerous CR implementations using a variety of AI techniques, including artificial neural networks (ANNs), metaheuristic algorithms, hidden Markov models (HMMs), rule-based systems (RBSs), ontology-based systems (OBSs), and case-based systems (CBSs).

4.4.1 AI Assisted CR

4.4.1.1 Artificial Neural Network (ANN)

In 1943, W. McCulloch (a neurophysiologist) and W. Pits (a logician) presented for the first time an idea of artificial neural for studying human brains. Their idea was adopted later in computational models known as artificial neural networks (ANNs) [116]. An ANN is a set of nonlinear functions modeled based on each nerve plexus. According to different network configurations and training methods, there are many types of ANNs, which can be possibly applied to communication networks, including CR networks. One of the most common ones is Multi-Layer Linear Perceptron Network (MLPN), which consists of multiple layers of neurons using a nonlinear activation function. For every single layer of neurons, it is composed of the outputs from the former layer in the form of linear combinations whose weights can be tuned by several approaches such as back propagation (BP) [116], genetic algorithm (GA), or hybrid methods. The size of the network and the application to which it applies will affect the performance of the training network model.

4.4.1.2 Metaheuristic Algorithms

Finding the precise relations and parameters through desired performance metrics describing a specific CR network is normally inaccessible. That is to say, it is very difficult to use mathematical search algorithms to get the optimal parameters regarding the performance measurements. Thereupon, metaheuristic algorithms [117] were proposed to obtain the optimal solution in solution search space through learning and constructing the critical relationships for many computationally hard problems. The term “metaheuristic” appeared early in the work of stochastic optimization approaches in the 1950s [118]. Within multiple metaheuristic algorithms, GA is often adopted to configure CR parameters dynamically and solve a multi-objective optimization problem.

4.4.1.3 Hidden Markov Model (HMM)

Hidden Markov Model (HMM) [119] is a statistical model augmenting the Markov chain, which can characterize and dissect complicated random behaviors of a sequence of events. Essentially, this statistical model is a Markov process including observable and hidden states. HMM observes symbols through their transitions from one state to another and then generates corresponding sequences. In the whole process, we can only observe the output value while all the states are hidden. In 1989, [119] introduced three fundamental problems in the proposed tutorial to characterize the hidden Markov models. They are (1) evaluation problem: forward-backward algorithm, (2) decoding problem: Viterbi algorithm, and (3) learning problem: EM algorithm, whose details can be referred to [119]. HMM could be applied to CR to solve a variety of problems such as spectrum sensing and spectrum occupancy prediction.

4.4.1.4 Rule-Based System (RBS)

A Rule-Based System (RBS) provides specific rules corkscrewed from a particular application field, which can be applied as the basis of decision making process in the same domain. It is a natural and intuitive idea to transfer existed knowledge of human beings into a machine recognized automated system. RBS could be used in the reasoning processes of CR.

4.4.1.5 Ontology-Based Systems (OBSs)

Based on Gruber’s definition given in 1995 [120], Feilmayr gave his definition on OBS as follows. An ontology is a formal, explicit specification of a shared conceptualization that is characterized by high semantic expressiveness required for increased complexity [121]. An ontology comprises the following components [122]:

(i) Classes: A set of substances in the modeled area.
(ii) Instances: The distinct subjectives included in classes within the modeled area.
(iii) Attributes: Characteristics that substances can have.
(iv) Relations: Links related to one another entities for being which classes and subjectives.

A typical OBS is the ontology language, which has been probed during CR development for logical facts information inference [123].

4.4.1.6 Case-Based System (CBS)/Case-Based Reasoning (CBR)

Case-Based System (CBS) or Case-Based Reasoning (CBR) was proposed in the early 1980s by Schank's work on dynamic memory model. The idea of CBS is to acquire a solution with the guidance of the former similar experiences or cases in the problem-solving process [124]. During the process of CBS, solutions are sought by selecting the most relevant case to the problem and adjusting the case to adapt to the current situation. The case adaptation for finding the proper parameters could be taken as a typical optimization problem. The target of the optimization process is to reduce both time and procedure to find the optimal parameters, for which the desired system is searching. The properties of CBS [124] include 1) the ability to resolve problems within incompletely apprehended domains, 2) the ability to supply a distinct explanation, and 3) the close semblance to the real human inference process.

4.4.2 Intelligent Radio Architecture

Intelligent radios was envisioned by Haykin as brain-empowered wireless devices [96]. In [8], the authors proposed three stages to categorize intelligent radio (or smart radio) according to several implicated technologies and diverse levels of intelligence.

- Stage 1: Human-oriented Classical Signal Processing.
- Stage 2: Machine Learning (ML).
- Stage 3: Contextual Adaptation.

In Stage one (i.e., human-oriented classical signal processing), knowledge is elaborated by a set of rules in specifically well-defined domains through limited intelligence and people. Whereas in Stage two (i.e., machine learning), it deploys a network with partial intelligence by creating statistical models for specific problem domains and gain the optimal solution from training through big data. Finally, in Stage three (i.e., contextual adaptation), the intelligence is extended completely to represent a plenty of parameters regarding real complex RF environments. It is expected as a potential solution to address spectrum management issues and other challenges in the future.

Via a mimic of the recognition process in a human brain, the authors separated the stage two, ML-based technology, into three hierarchical levels listed as follows [8].

(i) RF Landscape Perception.
(ii) RF Environment Understanding.
(iii) Reasoning for Instantaneous Spectrum Access.

Perception will enable devices sensing multiple features of signals autonomously. In the RF environment understanding level, it learns the complex structure and establishes a transmission activity map in the intricate RF environment. Finally, reasoning builds on perception and understanding to coordinate the channel access into the shared spectrum resources for both PUs and SUs in a tolerant interferences with each other. The relationship amongst the three stages can be illustrated further in **Fig. 7**.

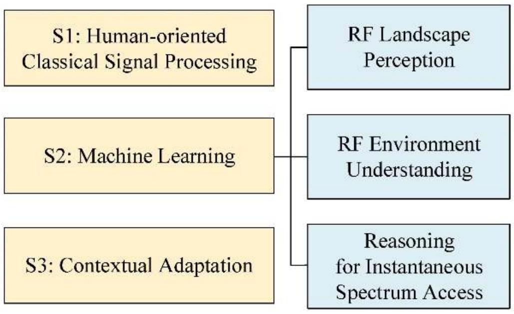

Fig. 7. An intelligent radio architecture proposed in [8].

Besides, [125] presented another framework for IR (or SR), which is an algorithm-hardware separation architecture. In this framework for IR, an operating system (OS) was proposed as the interface between the device hardware and the transceiver algorithms. The OS is capable to estimate the requirements and capabilities of local hardwares, such as RF chains, phase shifters, antennas, and so on. The OS then configures its own transceiver algorithms according to the estimated results from hardware and those useful AI techniques. The transceiver algorithms can be viewed as a software running over the OS.

4.5 Related Works on IR

In this subsection, we present a survey on the related works about reinforcement learning based unlicensed cellular systems in **Table 9**.

4.5.1 AI Enabled LTE-LAA Systems

In general, machine learning (ML) algorithms can be categorized into three types: 1) unsupervised learning, 2) supervised learning, and 3) reinforcement learning (RL). Supervised learning can learn from labeled data sets whose characteristics of each sample can be taken as the descriptive information of the situation. However, supervised learning is not applicable for tackling interactive problems. Moreover, RL learns from experiences, which is suitable for solving interactive problems. And RL learns from the unlabeled training data sets too; however, RL works based on the idea that the agent decides the future actions with a maximal reward according to both real-time states and rewards from the environment, which resembles the human learning process. These ML algorithms had been implemented in wireless networks extensively. Among them, RL has been applied to enhance LTE-LAA wireless network performance due to its human-learning like characteristic, which reacts from the interactions within fluctuating wireless environment.

RL is one type of ML algorithms, which is characterized by goal-oriented learning and decision making algorithms. Normally, a framework of RL comprising the fundamental elements such as Policy, Reward, Value Function, and Model of the environment. The way these elements work in the strategy decision process is described as follows.

- Agent: It can act with “environment” through “action”.
- Environment: The range that the agent moves around. Environment will give different rewards according to actions that the agent takes.
- State: The status in which the agent is for a specific time.
- Action: The movement that the agent takes through its policy.
- Reward: The encourage or punishment that the environment gives the agent as the feedback of its actions.

An agent obtains its reward by interacting with an environment continuously until it has learnt the best policy. In other words, the agent practices to obtain the best policy according to its state for making a decision on the actions. Actions have influences on both the direct reward and the next state, and then proceed to affect the entire subsequent rewards. The main characteristics of RL are summarized as follows. 1) RL usually takes a closed loop form. 2) It learns and explores from environment but does not specify a specific action. 3) It is affected by decayed actions and rewards for its future states.

Table 9. Recent works related to AI enabled LAA systems.

Objective	Summary of the works	Citation	Year	References
Specify coexistence requirements between LAA and Wi-Fi networks.	Maximize TxOP based on Q-learning and expected capacity.	0	2016	[126]
Maintain a satisfactory throughput for both LAA and Wi-Fi in a time division duplex LTE system.	Q-learning based dynamic duty cycle selection technique.	61	2015	[20]
Provide LAA functional implementation and an enhanced learning technique for efficient coexistence between LAA and Wi-Fi.	Q-learning mechanism and a double Q-learning method.	23	2016	[58]
Decouple resource allocation in uplink and downlink of heterogeneous small cell networks in both licensed and unlicensed bands.	A distributed algorithm based on a machine learning framework of echo state networks (ESNs).	48	2017	[127]
Coordinate coexistence between LAA and Wi-Fi networks using common channel by offloading downlink traffic in unlicensed bands.	A channel selection strategy based on Q-learning method to determine the most appropriate channel for traffic offloading in downlink transmission.	6	2015	[9]
A Q-learning based method to select the appropriate channel for downlink traffic offloading in a non-stationary wireless network.	A distributed Q-learning mechanism that exploits prior experience to support channel selection functionality.	34	2015	[128]
Develop a game theoretic framework for load balancing between LAA and Wi-Fi.	A regret-based learning (RBL) dynamic duty cycle selection (DDCS) method to solve the game theoretic problem.	23	2016	[129]
Adjust channel-access probability with time alignment and detection threshold adaptation to ensure fair sharing of unlicensed bands.	A frequency-reuse-1 scheme (ARIA) with fuzzy Q-learning algorithm to adapt to a dynamic network.	6	2018	[22]
Study an mLTE-U scheme with an adaptive LTE LBT scheme in coexistence with Wi-Fi.	Use Q-learning for self-adaptive mLTE-U for proper TXOP and muting period in co-located mLTE-U and Wi-Fi networks.	10	2018	[21]
Investigate the coexistence mechanism for LTE-LAA based heterogenous networks.	A two-level Q-learning based framework to solve optimization problem and determine transmission time for LTE-LAA system.	2	2018	[130]
Find an unlicensed spectrum-efficient coexistence scheme between LTE and incumbent users with the help of AL technologies.	A Q-learning based LAA scheme with a chaotic motion model to study its ergodicity, regularity and randomness.	1	2019	[23]

RL can also be defined as a process to characterize a learning problem, in which decision making is sequential and the goal is long-term. In some RL learning problems, several decision makers may possess conflicting objects and need to make decisions autonomously under the constraint of limited information to optimize a particular reward or cumulative objective function [131] [132]. In every step, a RL agent must perceive entire states of the environment and take an action, which generates a new state for the environment to which it may transit into [133]. In [132], the authors proposed a cross-system learning paradigm to achieve a leverage between LTE SBSs and Wi-Fi in a cellular network by implicitly coordinating their transmissions with no information exchange. Hence, RL can be applied to solve the capacity leverage problem in the self-organizing HetNets, which enhances network performance for operators.

Multi-agent reinforcement learning (MARL) is a research area that has been widely used, which can deal with higher complexity tasks via increasing the scalability of those already-problematic single-agent RL algorithms to achieve a realistic size. In [133], the authors provided an exhaustive survey on MARL, whose vital issue is to define a multi-agent learning goal. Besides, some researchers tackled the spectrum access problem with MARL based channel selection, in which multi-user and multichannel CR systems work without negotiations [134]. In such a scheme, it is expected for SUs to learn how to avoid transmitting at the same time according to its experience [134]. Due to privacy and safety concerns, most agents may not be willing to share agent value functions and state information in practice, which can be challenging in MARL. On the contrary, most existing MARL algorithms [135] [134] demand agents to obtain other agents' value functions and state information [133] when distributed agents are considered [127]. Consequently, an efficient multi-agent RL algorithm based on recurrent neural networks (RNNs) was proposed in [127]. RNNs, which can store state information of the users without having to share value functions with other agents due to their recurrent connections, are hopeful candidates for firmly storing the moments of a succession of observations [133] [127].

Q-Learning (QL) is a model-free RL algorithm, which updates the Q value function based on a specific equation (for example, Bellman equation). Meanwhile, the value of a Q function is used to state the quality that how useful a given action is in obtaining the future rewards. In addition, QL is an off-policy Temporal Differences (TD) control algorithm [131], which means that the behavior of learning the value of the optimal policy is independent of the agent's actions. The objective of an agent is defined as obtaining the maximum received reward within a given time duration. By training over a long run, the Q matrix will reach its convergence, and the agent will find the fastest route to the goal state.

QL can be used to deal with joint resource allocation and network access issue in heterogeneous networks to accomplish coexistence. The authors in [130] developed a two-level QL based mechanism to solve resource allocation and network access problem with the unlicensed spectrum in LTE-LAA networks. On the other hand, in [58], the authors used a QL mechanism to monitor the unlicensed spectrum activities, contributing to an effective coexistence between LTE-A and Wi-Fi systems. Furthermore, in their research works, a double QL method was devised through optimizing the learning of Channel Occupancy Time (COT) and the adaption of interference power level jointly. Besides, some innovative idea to accelerate the training speed of QL on the constraint of exploration and exploitation has been proposed. In [23], the authors proposed a QL framework-based coexistence scheme by dividing the state space into six states based on the predefined throughput and fairness thresholds. The ergodicity, regularity, and randomness of the chaotic motion was introduced in the Q-Learning framework to accelerate the training process of Q table to achieve convergence.

Other than RL, QL, some researchers proposed alternative learning based algorithms to realize the idea of AI in unlicensed assisted network. In [129], authors proposed a regret-based learning (RBL) dynamic duty cycle selection (DDCS) method, which is a learning algorithm based on the notion of regret matching, to obtain a sustainable throughput in an LTE-U based UAV-assisted heterogeneous network. Simulation results showed that the proposed RBL-DDCS outperforms fixed duty cycle based LTE-U transmission.

4.5.2 Machine Learning Assisted NR-U Networks

After having discussed about the research works on AI enabled LTE-LAA systems, we go ahead to do a survey on the existing research efforts on machine learning assisted NR-U networks. We listed the related works for the machine learning assisted NR-U networks in **Table 10**.

Table 10. Recent works related to machine learning assisted NR-U networks.

Objective	Summary of the works	Year	References
Leverage learning-assisted clustered access (LACA) of SBSs to improve interoperability between licensed and unlicensed access.	Design of an LACA to provide SBS clusters with fast converging operation and facilitate the coordination among SBSs.	2020	[136]
Improve cellular spectrum efficiency and energy efficiency in 5G-enabled vehicular networks.	Give an intelligent offloading framework by utilizing licensed and unlicensed spectrum jointly.	2020	[137]
Ensure end-to-end secure delivery of critical data to meet URLLC requirements in mmWave bands.	Give an adaptive channel assignment method using machine learning and fountain codes for mmWave hybrid access.	2019	[138]
Perform unlicensed band selection and resource allocation to maximize LTE users' quality of experience (QoE).	Use a virtual coalition formation game and Q-learning algorithm to solve a unlicensed band selection optimization problem with multi-player interaction.	2018	[139]
Allocate spectrum channels efficiently among unlicensed users considering interferences as well as economic impact.	A deep feedforward network algorithm was used to perform waveform and air-interface data analysis in multi-slot spectrum auction.	2018	[140]
Leverage resources and ensure coexistence for the cross-technology over unlicensed bands.	Proposed a Sensing Fingerprint (SF) profile for ML-based algorithms to characterize the state of networks.	2020	[141]
Adjust contention window to achieve fair spectrum access of coexisting networks.	Proposed an Intelligent-CW (ICW) framework, allowing UEs to adapt their CWs according to observed transmissions.	2019	[142]

As the deployment of NR-U will form an enormous network size, inter- and intra-system competitions in the unlicensed and licensed spectrum will formulate a complex multi-system coexistence (possible with hidden node) problem. Due to numerous features, included in the NR-U system, such as mobility induced constantly changing channel conditions and contention-based access for WLANs, machine learning is expected to be adopted in management and topology control across the entire network. As a result, [136] proposed learning assisted clustered access (LACA), a mechanism addressing the required interoperability of licensed and unlicensed access, to substantially improve coexistence performance with Wi-Fi and LTE-LAA systems in the unlicensed spectrum. Several ML based clustering techniques have been developed and discussed, including K-means, Gaussian Mixture Model (GMM), Expectation Maximization (EM), Hierarchical Clustering Analysis (HCA), and Q-Learning Based Online Clustering (QBC).

In 5G enabled vehicular networks with an explosively increasing data traffic, deep reinforcement learning (DRL) can be used to ensure QoS and save the energy cost in a distributed offloading network architecture. In order to minimize the cost for vehicular traffic offloading in transmission and computation, the authors in [137] constructed an intelligent offloading framework and formulated an optimization problem, which were divided by the authors into two subproblems to use a distributed DRL based resource allocation algorithm to solve it. The simulation results approved that DRL-based method greatly decrease the communication overhead.

To satisfy 5G URLLC stringent requirements, ML can be implemented for ensuring an efficient access scheme in both licensed and unlicensed mmWave spectrum. The authors in [138] introduced ML and fountain codes to an mmWave hybrid access scheme based on an adaptive channel assignment method. ML can predict power proactively and fountain codes can guarantee transmission reliability without retransmission. With the help of these methods, the spectrum efficiency is significantly improved as a bid to meet the URLLC criterion.

From a spectrum sharing viewpoint, QL algorithms are often used to solve optimization problem of quality of experience (QoE) and resource allocation over unlicensed bands in 5G networks. The authors in [139] formulated an unlicensed band selection and resource allocation (in licensed/unlicensed bands) optimization problem with the objective of maximizing users' QoE while preserving incumbent wireless systems in unlicensed spectrum. To solve the optimization problem, a virtual coalition formation game (VCFG) was used in modeling together with cooperative Kalai-Smorodinsky bargaining and QL algorithms. The authors justified a better performance of the proposed approach with various simulation results.

In addition, spectrum auction is another interesting concept to allocate unlicensed spectrum, which can be dealt with deep learning algorithm. In [140], the authors studied the spectrum auction based on UE's waveform and wireless air-interface, and combined these multiple factors to formulate a multi-slot spectrum auction problem. Simultaneously, a deep feedforward network algorithm was adopted to analyze this dynamic multislot spectrum auction problem. The deep learning algorithm, a pattern recognition approach, considers the factors such as bidder's economic capability, the interests of the channel, and the interferences they suffer during communications.

Unlike the traditional methods to solve the coexistence issue between Wi-Fi and NR-U networks, a lot of researchers aim to adopt AI and ML techniques to track dynamics of wireless networks. In [141], the authors proposed the Sensing Fingerprint (SF) profile to describe the state of NR-U and Wi-Fi networks, which can be feasible for AI-/ML-based algorithms to track their dynamics for the state of the wireless environment. Simulations and extensive experiments were shown to demonstrate the effectiveness of SF profile in network dynamics tracking processes.

Additionally, adopting contention window size to vary channel access probability based on real observed transmissions has been taken as a key parameter in fair sharing of unlicensed networks, which can be assisted by AI and ML techniques. In [142], authors propose an Intelligent-CW (ICW) framework adapting corresponding $CW_{\min}$. Simulation results revealed that ICW provides a higher throughput and a lower frame latency than standard techniques. By utilizing ICW to proper adjusting contention window size $CW_{\min}$, the fairness in aggressive network scenarios can be improved.

5. Positioning Assisted Unlicensed Cellular Networks

The main idea of reinforcement learning assisted LTE-LAA networks, as listed in Subsection 4.5, lies on the fact that SUs learn from previous experience and try to improve its learning strategy to maximize the resource allocation efficiency. However, in AI enabled IR (or SR) systems, the resource allocation may be done based on spectrum maps generated by multiple sensors. Therefore, the information collected to establish spectrum maps will play an extremely role in IR applications in unlicensed cellular networks. Based on this understanding, we proposed an approach to integrate spectrum sensing techniques, positioning information, and spectrum maps in LTE-LAA networks. In particular, we designed a positioning assisted

LTE-LAA system, and we obtain positioning information on the basis of DRSS method to identify Wi-Fi APs transmission power and location. Although the works was carried out in the context of CR enabled LTE-LAA system, it is equally applicable to any IR enabled unlicensed cellular networks, such as NR-U systems.

5.1 Positioning in IR Networks

Location awareness is one of the essential characteristics of an IR network [143]. As the wireless channel parameters are environment-dependent, IR techniques should provide an empirical model and outline adjacent propagation environments. Therefore, a location awareness architecture was proposed for the realization of location awareness [144], and can be exploited to improve the wireless communication system design in CR networks [145]. The higher accuracy the cognitive positioning system can provide a better efficiency CR network can obtain. We identify the tasks of positioning into positioning principles, parameter measurement & extraction, and positioning tracking [146], as shown in **Fig. 8**.

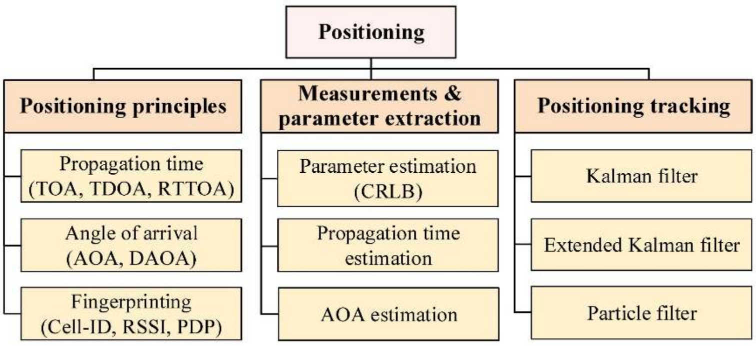

Fig. 8. Different task of positioning algorithms.

5.1.1 Basic ideas of Positioning

Positioning requires observations of several physically dimensional quantities [146]. The obtained measurement values characterize a certain type of positioning information in the given environment [146]. Let us focus on the positioning principles based on electromagnetic waveform observation. First, we discuss about the propagation time, the angle of arrival, and the signal finger-print.

5.1.1.1 Propagation Time

We measure the propagation time by accessing one of the following information: 1) Time of arrival (TOA); 2) Time difference of arrival (TDOA); and 3) Round trip time of arrival (RTTOA). TOA measures the propagation time along the line segment between Tx and Rx. Different from TOA, the main idea of TDOA is to measure signal propagation delay time differences to identify the points of equal distance to the BSs of interest, which gives the definition of a hyperbola. Compared to TOA, RTTOA method is also a circular positioning method, which avoids the need for time synchronization between wireless nodes. In practical systems, the nodes in RTTOA scheme may have different processing delays, which entails a drift in time.

5.1.1.2 Angle of Arrival (AOA)

Besides distance and time, the angle of the signal propagation direction, from which the signal arrives at the target receiver, is another relevant parameter. The problem of an unknown receiver orientation was discussed in [146].

5.1.1.3 Signal Finger-Print

Similarly to the uniqueness of human finger-prints, we expect to reconstruct a finger-print for a signal relevant to some parameters of the signal. The RSSI and the power delay profile (PDP) are two common finger-prints of transmitted signals. The average received signal power (such as RSSI) is reversely proportional to the distance d between the transmitter and the receiver. PDP is another finger-print based method for positioning. Once measuring the time differences and power ratios between incoming/arriving paths, we can obtain the relative values of PDP at the transmitter and the receiver for a given channel model with multipath propagation.

5.1.2 Measurements and Parameter Extraction

The strength of received radio signals depends on the position of the receiver. This influences the observed positioning parameters in terms of delay, amplitude, and phase of a signal [146]. Usually, the observed signal is presented by noisy samples, which is not deterministic but is a kind of distortion. However, we can consider such distortions as stochastic processes, where information about the parameters is known or can be estimated. A well-known example is additive white Gaussian noise (AWGN). Other than measurements, the accuracy of estimation is vital. The main goal in estimation theory is to find a minimum variance unbiased estimator (MVUE). The variance $E\left\{|\alpha-\hat{\alpha}(r)|^2\right\}$ of an estimate is a usual characteristic to quantify the accuracy [146]. A particular lower bound $\hat{\alpha}(r)$ is called Cramer Rao lower bound (CRLB), which was derived by the Cauchy-Schwarz inequality. If an estimator can reach the CRLB, it is called a MVUE.

5.1.3 Positioning Tracking

In general, we assume that MT is static during the estimation process, and we treat it as a deterministic parameter [146]. However, in real applications, MTs like mobile UEs move along time. Positioning tracking obtains the current position information from the past estimated states. The first order hidden Markov model is commonly used in positioning tracking. A classical approach to tracking is represented by Kalman Filtering (KF). Recently, Bayesian Filtering and Particle Filtering have also received more attentions in positioning tracking research. The detailed contents of these techniques please referred to [146].

5.2 DRSS based Positioning Assisted LTE-LAA Networks

We proposed a positioning assisted LTE-LAA system model, including energy detection spectrum sensing, differential received signal strength (DRSS) positioning, and spectrum allocation algorithms, as shown in **Fig. 9**.

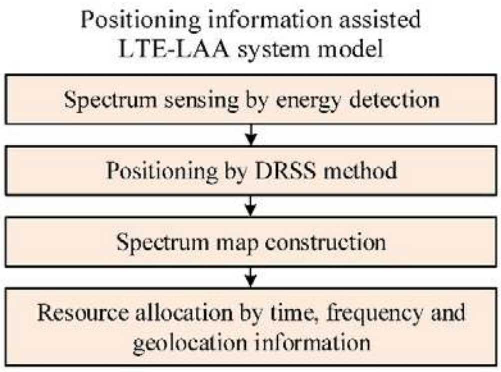

Fig. 9. A proposed model for positioning information assisted LTE-LAA system.

Compared to other positioning methods such as TOA and DOA, DRSS has the following advantages. (1) It can be measured without using any array antennas or directional antennas. (2) It does not need a perfect synchronization between transmitters and sensors. (3) DRSS can be captured by available fingerprints in measurements, whereas TOA and DOA measurements suffer from severe multipath fading. Overall, the low-complexity and cost-effectiveness with the DRSS method makes it in particular suitable for our system model.

With the help of CR techniques, an LTE-LAA system will possess a capability on obtaining spectrum information and performing dynamic channel access in unlicensed spectrum. To implement the method, we used idle LTE-LAA UEs to perform spectrum sensing for Wi-Fi APs and feedback the channel information to LTE-A BSs, which will allow LTE-LAA UEs to allocate the best possible channels different from Wi-Fi signals.

5.2.1 Spectrum Sensing by Energy Detection

To construct a spectrum map, information of the PUs and the channel occupancy must be obtained. In the proposed system model, the channel model can be obtained as shown in the channel model of (1), which includes the information of Wi-Fi AP transmission power P_t, Wi-Fi APs locations (X,Y), and the path loss exponent α. In this channel model, S denotes a shadowing random variable, d is the distance between a Wi-Fi AP and a BS, and κ is a parameter related to carrier frequency and propagation environment.

$$P_r = P_t \frac{\kappa 10^{-S/10}}{d^{\alpha}} \tag{1}$$

An LTE-LAA BS assigns idle UEs to do spectrum sensing and send back the spectrum information to the BS periodically. We assume that each LTE-LAA UE scans the unlicensed band and records the RSSI in each unlicensed channel, which is then transmitted back to LTE-LAA BS to find the Wi-Fi APs locations and transmission powers. If multiple Wi-Fi APs are transmitting in the same unlicensed channel, the LTE-LAA UEs have to distinguish them among the signals coming from different Wi-Fi APs. When the BS gets the spectrum map information, it sends it to all LTE-LAA SBSs in its coverage. Finally, the LTE-LAA SBSs selects a best possible access channel for a particular LTE-LAA UE, avoiding the interferences from/to the Wi-Fi APs nearby.

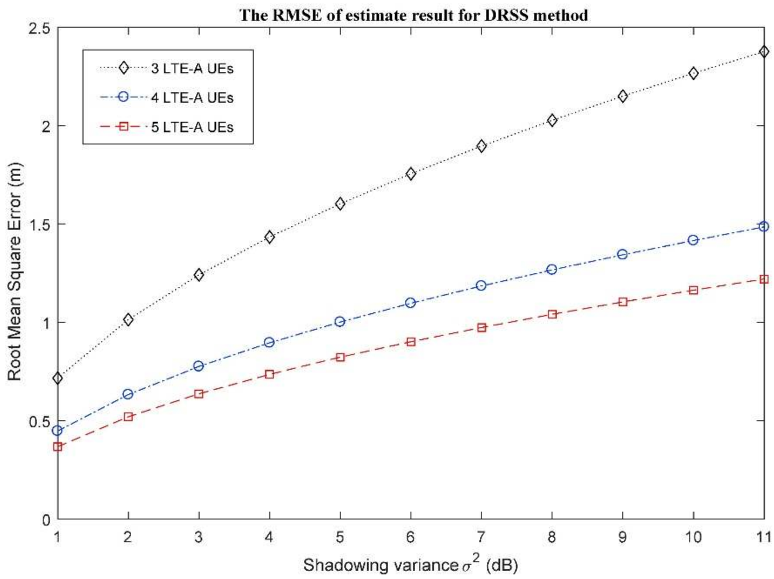

Fig. 10. Results for RMSE versus shadowing variance in the DRSS method, where the results obtained with 5 UEs outperform that with 3 UEs.

5.2.2 Positioning Techniques Based on DRSS

With the help of DRSS positioning algorithm, Wi-Fi APs' locations can be estimated accurately by idle UEs. In case that the AP locations are sometimes unavailable, we used estimation theory to formulate an optimal problem for AP locations with a minimum error. To solve this non-linear optimal problem, we used the Levenberg-Marquard (L-M) iteration algorithm. We express the covariance matrix as the root mean square error of the estimated result, which is written as $RMSE_{\mathbf{A}} = \sqrt{(\hat{X}-X)^2 + (\hat{Y}-Y)^2} \geq \sqrt{(F)_{11}^{-1} + (F)_{22}^{-1}}$, where $\mathbf{A} = (\hat{X}, \hat{Y})^T$. We used simulations to test our DRSS method, as shown in **Fig. 10**. We found that sensors (i.e., idle UEs) locations can affect sensitively the estimated results. In **Fig. 10**, the RMSE of the estimated results is shown. When we used more LTE-LAA UEs as the sensors, we could improve the performance of the proposed DRSS scheme.

5.2.3 Spectrum Map Construction and Resource Allocation for Unlicensed Channels

After obtaining the Wi-Fi AP transmission power $P_t^{(db)}$, the Wi-Fi AP location (X,Y), and the path loss component α, the LTE-LAA BS can construct a spectrum map and identify vacant channels for LTE-LAA UEs. The Wi-Fi AP location can be obtained using the DRSS method as the example shown in **Fig. 11**. By constructing an accurate spectrum map, LTE-LAA MBS sends the spectrum map information to LTE-LAA SBS such that each LTE-LAA SBS can allocate channels to its LTE-LAA UEs appropriately. Obviously, the more accurate Wi-Fi AP position we obtain, the more accurate the Wi-Fi AP transmit power and spectrum map we can obtain. In this way, the QoS can be maintained from the LTE-LAA SBS's point of view, which means that LTE-LAA SBS can properly allocate channels to UEs in its coverage. By properly allocating channels to UEs, the collisions between them can be avoided to guarantee QoS for the UEs.

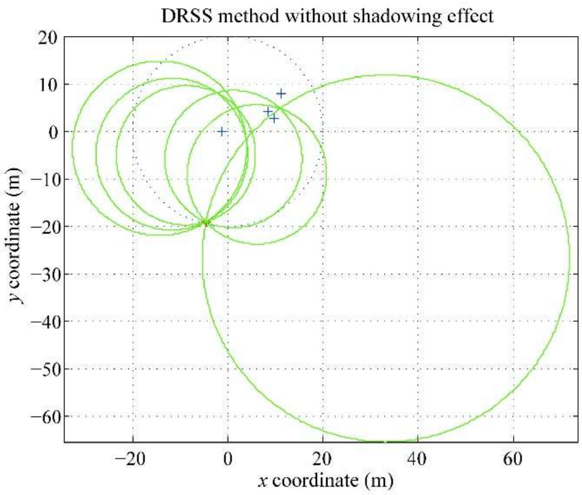

Fig. 11. Spectrum map construction based on DRSS method, where the figure shows four LTE-A UEs with six green cycles intersected in the red point, which is the Wi-Fi AP location.

In order to allocate channels according to spectrum map information, we formulate an optimization problem to find appropriate transmission power $P_k^{(n)}$ [147]. We should consider the total interference $I_s^{(n)}$ due to the transmission from Wi-Fi APs to LTE-LAA SBS on channel n. On the other side, as we perform channel sensing based on energy detection method, we define a threshold T_L as -75 dBm. Taking into account $I_s^{(n)}$ and T_L, we concluded that different scenarios resulted in different throughputs $R_k^{(n)}$. To solve the above optimal problem and find the optimal power when LTE-LAA UE k wants to access channel n, we formulate a channel allocation problem as

$$\max_{[x_k^{(n)}]} \sum_{n=1}^{N} \sum_{k=1}^{K} \left[R_k^{(n)} \right]^* x_k^{(n)}, \quad (2a)$$

$$\text{s.t.} \quad \sum_{n=1}^{N} x_k^{(n)} \leq 1, \quad \forall k \in \mathbf{K}, \quad (2b)$$

$$\sum_{n=1}^{N} x_k^{(n)} \leq 1, \quad \forall n \in \mathbf{N}, \quad (2c)$$

$$x_k^{(n)} \in (0,1), \quad \forall n \in \mathbf{N}, \quad k \in \mathbf{K}, \quad (2d)$$

where $x_k^{(n)}$ is the channel allocation indicator. Namely, $x_k^{(n)} = 1$ means that channel n is assigned to LTE-LAA UE k. Otherwise, $x_k^{(n)}$ is equal to zero. Equation (2) sets up an integer linear programming problem. Under the condition that the constrain matrix $\mathbf{A}$ is a totally unimodular matrix, we may relax the integer constrains in an integer programming problem into a linear constrain in a linear programming problem. And we can get the result effectively by solving the linear programming problem. The detail process to solve such an integer programming problem can be referred to [147]. The further system analysis, including single MBS and multiple LTE-LAA SBSs considering interferences between LTE-LAA SBSs, is shown in [148].

6. Challenges and Future Works

Although AI technologies will surely play an extremely important role in futuristic unlicensed cellular networks such as LTE-LAA and NR-U systems, there are still many open issues and challenges need to be addressed. In this section, we summarize the key challenges and future research directions related to the AI enabled unlicensed cellular networks as follows.

6.1 Hidden Terminal Problem in Unlicensed Cellular Networks

The hidden primary user issue is similar to the hidden terminal problem in a traditional CSMA/CA network [103]. With CSMA/CA protocol utilized in a Wi-Fi network, hidden terminals occur when a device transmits to an AP, but the neighboring devices can not hear its transmission. Consequently, collision could happen at a node even when it follows the LBT CSMA/CA protocol for accessing the medium in an LTE-LAA or NR-U system. **Fig. 12** illustrates a scenario with the hidden terminal problem, where the dashed circles represent the operating ranges of an SBS in LTE-LAA (or NR-U) or a Wi-Fi AP, respectively. As shown in **Fig. 12** (b), the transmission from a Wi-Fi AP generates unwanted interferences to a SBS UE, as the Wi-Fi AP's signal could not be detected by the SBS. Some works suggested to use cooperative sensing to deal with the hidden terminal problem, and readers can refer to Section 4 and the given literatures [104] [106]. A cost-effective coordination scheme must be in place to overcome the hidden terminal problem before an AI enabled unlicensed cellular network can operate successfully.

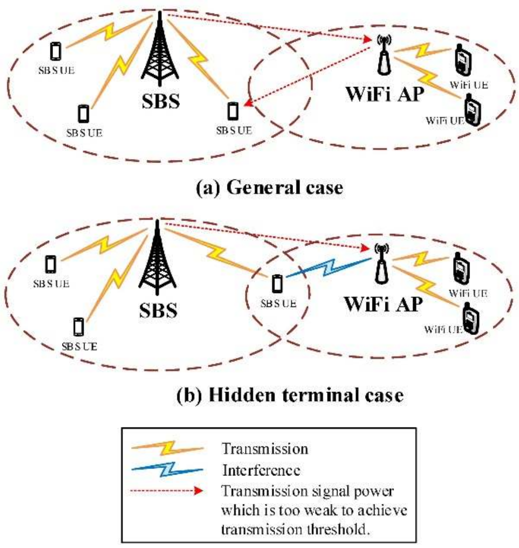

Fig. 12. The scenarios with and without hidden terminal problem in an unlicensed cellular network.

6.2 ML Assisted Unlicensed Spectrum based NOMA

Power-domain NOMA, with its earlier version called multiuser superposition transmission (MUST), was proposed for3GPP LTE-A networks in 2015 [149]. The basic idea of the power-domain NOMA is to allocate powers to different UEs based on their channel conditions. In particular, users with poor CSI get a higher transmission power, otherwise a lower power. This ensures that a user can detect its own message by cancelling other users' signals one-by-one, also called successive interference cancellation (SIC). The power domain NOMA assisted with SIC yields a better overall system throughput than OMA with the same frequency bandwidth resource. The power-domain NOMA working at the same channel is similar to a CR system, and some even treated NOMA as a special case of CR, which allocates explicit powers to users to achieve users' predefined quality of service (QoS) [150].

Nevertheless, due to the random property of 5G/B5G wireless channel, the variation of channel and wireless environment may take place rapidly. The traditional technology might not be sufficient to adapt itself promptly to the variation of the channel. CR or IR becomes a promising solution to work with NOMA. Some preliminary studies on CR-NOMA [151] and cooperative CR-NOMA [152] have been done. In a two-scheduled users scenario of CR-NOMA, a more generic CR-inspired power allocation scheme was proposed for both uplink and downlink NOMA in [153]. Although several works related to CR-NOMA focused on performance analysis such as throughput and data rate analysis, very few work addressed the error rate performance of a CR-NOMA system [154], which is a critical and challenging issue as bit error rate (BER) governs the reliability of individual secondary user. In this regard, the algorithms such as SIC schemes should be enhanced significantly.

In addition to BER performance issues, secondary users, which receive other users' signals to perform SIC for interference elimination, may have security and privacy issue. How to maintain both information safety and fairness between primary and secondary users has not yet been thoroughly studied. The ways to facilitate cooperation between primary and secondary users in scenarios such as ultra dense heterogeneous networks can be another challenging issue. The use of NOMA in unlicensed cellular systems can be a challenging issue as well, as indicated in [155].

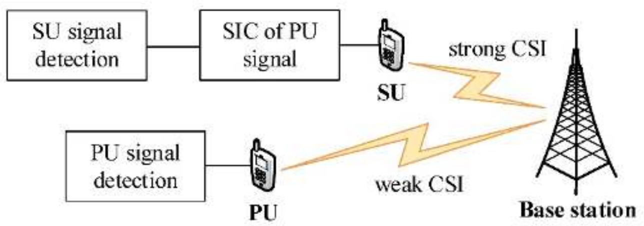

Fig. 13. Implementation of a CR based NOMA network.

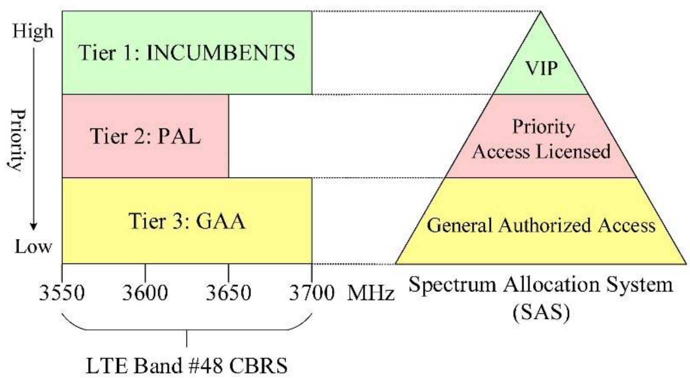

Fig. 14. Spectrum Allocation System (SAS) for CBRS.

6.3 CBRS and LSA Based Unlicensed Cellular Networks Performance Improvements

Citizens Broadband Radio Service (CBRS) [156] was proposed in April 2015 by FCC for commercial use of 150 MHz from 3550 to 3700 MHz in the 3.5 GHz band [157]. Originally, the 3.5 GHz band was limited for military applications only. CBRS managed by FCC includes 15 channels of 10 MHz bandwidth and utilizes 3GPP LTE protocol which is the first to share the RF spectrum between military and commercial users. The rules of CBRS comprise three tiers, namely, incumbent users, Priority Access License (PAL) users, and General Authorized Access (GAA) users as shown in **Fig. 14**.

CBRS utilizes spectrum access system (SAS), a combination of controlling intentions and a database for the purpose of interference coordination [158] to control the spectrum access for both PAL and GAA UEs. Simultaneously, incumbent systems are protected by Citizens Broadband Radio Service Device (CBSD). Although both CBRS alliance and others discussed and proposed new approaches focusing on interference management issues in SAS and CBSD, there still exists critical problems like privacy and fairness that has not sufficiently considered when dealing with interference management. Furthermore, coexistence methods to achieve a tradeoff between spectral efficiency, flexibility, and discriminatory for various CBDSs, and contiguity of channels correspond to geographically contiguous PAL UEs requested by FCC [159] are also challenging issues.

The CBRS, as an emerging standard, encounters the coexistence issues of GAA users similar to LTE-LAA system. However, unlike coexistence between LTE-LAA and Wi-Fi which possesses the same priority for the two independent systems, CBRS considers a LTE node coexisting with another LTE node in a higher priority (for instances, GAA and PAL nodes). Hence, the authors in [160] introduced LBT schemes and a Q-learning algorithm to improve user perceived throughput for PAL/GAA spectrum sharing in CBRS networks. Nevertheless, because CBRS is not widely available all over the world, no extensive studies for CBRS system performance enhancement have been done, except for some field trial demonstrations, such as the SAS protocol based broadband radio testbed in [161] and the Verizon's deployment in Florida [162].

Similarly, Licensed Shared Access (LSA) was proposed by Radio Spectrum Policy Group (RSPG) of European Union (EU) in 2011. It is an emerging spectrum sharing approach for incumbent UEs at the first tier to access the spectrum resources while regulator authorizes individual licensing to limited LSA licensees at the second tier to get permission from the incumbents to share underutilized frequency band. The incumbents assess issues, such as the geographical areas, the technical protection, and the mechanism to vacate the occupied channels when the incumbents need to access the same spectrum in the same area, are also widely open for more further investigations. Some more challenges exist for the LSA concept, which can be listed as follows. How to coordinate the LSA spectrum for multiple UEs when they are located in proximity to neighbor countries and regulation domains? How to design the LSA policies and protection zones to minimize the interferences to incumbents? These challenge issues are important for managing spectrum but have not been investigated comprehensively [163].

6.4 Handover between RATs in Unlicensed Cellular Networks

As more and more operators are expecting to access the unlicensed spectrum, handovers between different radio access technologies (RATs) to ensure user's QoS in radio links could be a challenging issue. 3GPP standard TS 23.401 [164] illustrates seamless and non-seamless handover solutions for a UE transfer from a source eNodeB to a target eNodeB continuing data services when across macrocells, small cells and Wi-Fi hotspots. In an inter-RAT handover, those indirect forwarding signals could be embedded into part of downlink data forwarding. The detailed process and regulation could be referred to 3GPP TS 23.401 [164].

Despite the regulations in 3GPP TS 23.401 [164], the mobile channel and environment vary quickly in heterogeneous IR networks which has a big impact to existing handover procedure. Normally, in the traditional LTE networks, handover is triggered by user mobility in licensed bands, while the authors in [165] considered handover process in LTE-LAA unlicensed networks triggered by availability of unlicensed bands. Adopting IR in an unlicensed cellular network could complicate cross-layer and cross-RATs deployment in a real communication system, which might lead to handover failures that increase probability of packet loss and service interruption. How to integrate these cross-layer parameters (e.g., PHY layer and MAC layer), coordinate independent radio interfaces for different layer's handovers, organize different RATs's handover to ensure diverse coverage conditions and QoS requirements are critical issues to ensure handover success. These issues have not been studied intensively in the literature. It is an open issue to design a new and efficient handover procedure considering not only timevarying fading channels, traffic dynamics and QoS assurance, but also other factors, such as spectrum availability triggering handovers [165], packet-wise based handover [166], and IP combined coding techniques based handover [167] to enhance handover performance.

6.5 Accessible Data Sets for Intelligent Radio

Variety of data sets are free to access, which provides a basis to evaluate different learning algorithms in computer vision or image processing research. However, IR based wireless communications data sets are still under construction. The measurement campaigns to gain large data sets for wireless communication networks could be expensive and time-consuming, especially in outdoor environments. Owing to the variable property of wireless channels, it is also costly to get accurate measurement data for different coherence times of the channels [168]. To share the data sets for public, several issues need to be considered, such as the privacy protection in the real cellular communication data [169].

In addition to the privacy issues, some proposed to use transfer learning with a joint data-driven and model-driven approach to solve the training data problems. The authors of [170] proposed some approximate mathematical models containing useful prior information, which can be transformed to deep learning techniques to reduce the amount of data required in the training process. Several other issues exist, such as the amount of training data, the number of neurons and layers in a deep transfer learning neural network have not been investigated. Another issue in hyper-parameters in transfer learning could be tuning balance proportion between data-driven and model-based neural network model [169].

6.6 Integration of AI into Wireless Network Architectures

Integration of AI module in wireless networks is normally implemented in an ad hoc fashion, which has an impact to the control method of a communication system through signal feedback process. Due to the training of single node in a distributed network requires data sets from local measurements, an individual node has different learning capacities [170]. Meanwhile, the data sets for particular nodes have different sizes and quality metrics based on diverse measurements and storage capabilities owing to non-ideal measurement sensors [170]. One challenge issue is tailor-made optimization from the viewpoint of each node in a distributed wireless system. This issue has not been studied due to the distinct natures of wireless networks, multiple access techniques, and their different parameters such as modulations, coding schemes, channel variation, delay and so on.

Besides, in a wireless network with multiple nodes, a general pair of transmitter and receiver could be taken as an end-to-end learning based wireless communication system, which takes a lot of time in its training process for the whole communication network operating through all nodes [169]. In this way, some nodes might be active and some might be inactive to work with a model-driven DL scheme. How to coordinate multiple ML frameworks with different wireless communication blocks is a challenging issue. On the other hand, communication metrics learning is critical for IR operation. In an end-to-end wireless communication system, the metrics learning with specific requirements to reflect the properties of wireless communication networks need to be done in a timely manner [169].

To implement 5G/B5G wireless networks, some issues related to AI-enabled wireless network design are still widely open. How to implement AI module functions to substitute some function blocks of wireless communication systems, part of which can be intra-layer function blocks or the cross layer function blocks, is an important issue. Some works classified the issues as 1) layer-free AI, 2) layered AI, and 3) cross-layer AI based wireless communication systems [171]. Different layer design patterns contribute to different data-model trainings.

6.7 Limitations of AI based Functions in IR

Currently, most works on intelligent radio focused on improving the functional capabilities to make radio more intelligent. They made their efforts to improve the accuracy of spectrum sensing [172], reduce interferences in signal processing [173], predict or acquire fading channel state information (CSI) [174], or decrease the transmission latency of vehicular-to-vehicular communication networks [175]. Take spectrum sensing function as an example, which plays a vital role in IR. According to the requirements of spectrum sensing, there are three working scenarios to achieve the diverse optimization targets: 1) throughput-oriented scenarios, 2) energy-saving-oriented scenarios, and 3) sensing-accuracy oriented scenarios [176]. In the past, traditional broadcasting scenarios yield a low utilization rate of spectrum for users. While users are assumed to have the same priority to occupy the spectrum resources, energy saving becomes dominant, which was investigated in autonomous uplink transmission [177]. On the other hand, if coexistence is a critical issue for wireless communication networks (especially in unlicensed spectrum), sensing accuracy affects coexistence performance sensitively.

Conventional studies relied on model-dependent methodologies, such as congestion control, game theory, greedy strategy, graph coloring schemes, and matching theory, etc, to solve their optimization problems, which require the priori parameters of the networks, such as UEs' activities in specific spectrum chunk. However, in reality, it is hard to obtain enough knowledge beforehand to establish a network evolution model due to the complexity of a spectrum environment and fast-changing RF dynamics. In addition, realistic limitations such as computational power, hardware capability, sensing time, and decentralized multi-user scenarios (e.g., mMTC networks) make spectrum sensing and decision making more challenging [8]. To satisfy the optimization targets and solve the optimization problem, which should adapt to the ever-changing channel states correspond to time and space, a model-free idea allowing an entity to interact with the environment without pre-defined a network model, was suggested. Several works focused on reinforcement learning or deep reinforcement learning based spectrum sensing [176].

Next, we identify several other challenges in training process of AI technologies as follows [178].

- Training Issues: Two important impediments that may affect the training AI models for cellular networks could be system overhead and training data availability. The over-the-air feedback in transmission and the separation of information across network protocol layers in wireless communication networks could generate a large amount of system overheads and thus make it harder to obtain the underlined training data.
- Lack of Bounding Performance: Due to the non-linear characteristics, it is difficult or even infeasible for AI methods to offer the worst-case performance guarantee.
- Lack of Explainability: Due to the intrinsic nature of AI training processes which behave just like black box, it is hard to develop analytical models or tools to either examine their correctness or illustrate their behaviors.
- Uncertainty in Generalization: It is normally unclear to know whether the datasets used in a training model is general enough to conform to the distribution of signals as encountered in the real world cellular networks.
- Lack of Interoperability: Inconsistency among AI modules may come from diverse vendors, and it may possibly undermine the whole network performance.

7. Conclusions

In this paper, we made a comprehensive survey on the potentials and challenges associated with AI enabled LTE-LAA/NR-U systems, where intelligent radio can be applied to both LTE-LAA and NR-U systems to optimize the performance of an unlicensed cellular system. The pros and cons of the AI techniques suitable for LTE-LAA and NR-U systems are discussed in different aspects. It was shown that the coexistence between different unlicensed systems is the core issue for successful operation of the unlicensed cellular networks, in which the recent works were categorized and discussed in Sections 3 and 4.

Smart radio is an intelligent technique for improving spectrum efficiency and optimizing opportunity based spectrum access performance. AI enabled CR/IR plays a vital role in spectrum sensing in a radio environment and performs resource allocation adaptively to assign access channels to UEs. In this paper, three of the most important elements of CR/IR, including spectrum sensing and positioning assisted resource allocation, are introduced respectively. The intelligent radio architecture for unlicensed cellular systems was introduced, which provides a great departure point for those who are interested in working in this fascinating research areas.

Reinforcement learning could been implemented into unlicensed cellular networks to address the coexistence issues for both LTE-LAA and NR-U systems. Many related works were discussed in this paper. AI enabled IR will be a very important research direction to employ LTE-LAA and NR-U in 5G and beyond networks. Moreover, major challenges in CR/IR based unlicensed cellular systems were identified and discussed, such as hidden terminal problem, AI enabled NOMA systems, CBRS and LSA based unlicensed cellular networks, handover between RATs in unlicensed cellular networks, accessible data sets in IR, AI based wireless network architectures, and limitations of AI based functions in IR.

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