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Three Decades of 3GPP Target Cell Search through 3G, 4G, and 5G

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ABSTRACT This survey provides the reader with the open literature on the detailed operational scenarios of Target Cell Search (TCS) in both 3G and 4G systems, with a particular emphasis on the DownLink (DL). There is no completely latest survey of the TCS scenarios. Therefore, we examine the TCS-involved solutions which have been chosen for Wideband-Code Division Multiple Access (W-CDMA), Time Division-Synchronous Code Division Multiple Access (TD-SCDMA), Long-Term Evolution Frequency Division Duplex (LTE-FDD), and Time-Division Long-Term Evolution (TD-LTE). Especially for TD-SCDMA, there is no concrete literature demystifying the details of TCS scenario. Accordingly, this survey aims for repairing the associated crack in the literature. Moreover, as a recent evolution from the operational systems, we also focus on the TCS scenario which can be exploited in New Radio (NR) systems operating at both sub-6 GHz and millimeter-Wave (mmW) spectrum bands. A taxonomy diagram is also provided to classify relevant target cell search scenarios in 3G, 4G, and 5G as well as followed by those in inter-Radio Access Technologies (RATs). In a nutshell, our endeavors definitize the first comprehensive survey on the TCS progress tailored to the evolution of commercial mobile communication systems over three decades. It is worth mentioning that this survey is also informative for engineers and researchers to design practical mobile station modem.

INDEX TERMS LTE-FDD, millimeter-wave, new radio, target cell search, TD-LTE, TD-SCDMA, W-CDMA.

I. INTRODUCTION

The 3rd Generation Partnership Project (3GPP) has broadly supported Code Division Multiple Access (CDMA) aided mobile communication systems, resulting in the 3G systems [1], [2], that is to say the Wideband-CDMA (W-CDMA) [1] and the Time Division-Synchronous CDMA (TD-SCDMA) [2] operating models. Then, for the sake of specifying 4G systems, the 3GPP has standardized the Orthogonal Frequency Division Multiplexing (OFDM) assisted Long-Term Evolution (LTE) and their derivatives [3]. Recently, by the vigorous 3GPP standardization activities, 5G systems, also known as New Radio (NR), have been stipulated [4]–[8]. In the aforementioned 3G, 4G, and 5G systems, the first operational stage of mobile communication systems is the Initial Cell Search (ICS), commenced by the User Equipment (UE)[1] for the sake of attaining both the appropriate time and frequency synchronizations as well as of identifying a serving cell ID. In order to substantially diminish the entire cell search complexities and the related power consumption, hierarchical cell search procedures have been suggested and used in all the systems covered in [4], [7]–[12], [14]. After ICS procedure, which is activated for the initial synchronization to detect a best possible serving cell, the Target Cell Search (TCS) is invoked for detecting adjacent cells required to support potential handovers and guaranteeing seamless mobility.

Based on the following two clearly evidenced rationales, this survey paper only emphasizes the TCS procedures and scenarios being employed in 3G, 4G, and 5G systems.

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[1]In 3GPP terminology, UE is the same meaning as mobile station.

TABLE 1. A concise comparison of our survey with the existing relevant papers.

Relevant Paper	Year	Key Topic	Main Issues Addressed
Park *et al.* [21]	2008	Efficient coherent neighbor cell search	Substantial performance enhancement of the coherent neighbor cell search has been investigated.
Li *et al.* [22]	2011	Secondary synchronization signal detection scheme for neighbor cell search	An iterative secondary synchronization signal detection scheme constituting three stages for each iteration has been characterized for enhanced neighbor cell search performance.
Shen *et al.* [23]	2012	Neighboring cell search	First establishment of a general framework for neighboring cell search in LTE systems has been illustrated to formulate sufficient signal metrics under diverse channel conditions and devise cell search algorithms based on it.
Das *et al.* [24]	2012	Closed subscriber group proximity detection enhancement using out-of-band radio of home Node-B	A macro cell based fingerprint method for improved proximity detection has been proposed for offering higher precision and better network performance.
Qualcomm [25]	2013	Neighborhood small cells for hyper-dense deployments	In order to realize efficient network densification, a new network deployment model referred to as neighborhood small cells comprising very dense deployment of small cells has been presented for offering both indoor and outdoor coverage to satisfy enormous data demand.
Prasad *et al.* [26]	2013	Energy-efficient inter-frequency small cell discovery techniques	Diverse cell search and discovery schemes tailored for energy-efficient detection of small cells configured in a carrier other than the serving macro cell have been investigated to manifest better offloading opportunity utilization and savings in UE battery power consumption.
Xenakis *et al.* [27]	2014	Mobility management for femto-cells	A comprehensive illustration on the core aspects and research challenges of mobility management support under the existence of femto-cells has been characterized with the special focus on 1) cell identification, 2) access control, 3) cell search, 4) cell selection and reselection, 5) handover decision, and 6) handover execution.
Mikami *et al.* [28]	2015	A cell identification performance improvement in co-channel heterogeneous cellular networks	Cell identification performance enhancement has been analyzed by having transmission power coordination of synchronization signal symbols under heterogeneous cellular networks in conjunction with cell range expansion.
Takeda *et al.* [29]	2015	Small cell discovery in LTE-Advanced Rel-12	Small cell enhancement scenarios in Rel-12 have been detailed to design small cell discovery techniques based on a new cell discovery signal.
This survey	2020	Three decades of 3GPP target cell search through 3G, 4G, and 5G	Full details of target cell search procedures of W-CDMA, TD-SCDMA, LTE-FDD, TD-LTE, and NR operating especially at mmW spectrum bands are surveyed in a consistent manner.

(1) Details on detection schemes of the cell search constituting two essential synchronization signals' detection and carrier frequency offset compensation with cell identification have been investigated in [15]–[20]. Furthermore, enormous research endeavors have been dedicated to the related detection schemes and to TCS algorithms [15]–[20] and [21]–[29], respectively. A concise comparison of our survey with the existing relevant papers manifesting those TCS algorithms is offered in Table 1. Surprisingly, however there is no open literature providing an extensive survey of the detailed TCS procedures and scenarios utilized in practical mobile station modems fulfilling the 3G, 4G, and 5G specifications, which is actually a critical aspect of commercialization.

(2) Very recently, there were investigations in the open literature to introduce how the ICS in NR system operates [14], [30]–[34]. However, as opposed to the significance of NR TCS design on the mobile station modem, there is still no study to deal with the issue in depth.

Accordingly, this survey aims for filling the associated gap in the literature. More specifically, it elucidates the existing TCS scenarios of 3G, 4G, and 5G systems, where 5G system also embraces the latest contribution on the millimeter-Wave (mmW) spectrum bands constituting one of the essential parts for mobile communications [4]–[7], [13]. By contemplating not only basic principles for beginners but also core implementation elements for practical modem engineers, we elaborate key issues for comprehending the fundamental principles of the TCS. The corresponding TCS scenarios are visualized in three individual flow charts with demystified descriptions as shown in Figs. 4, 7, and 19.

Main contributions of this survey are summarized as follows:

- Theoretical perspective: The underlying comprehension of the TCS procedure is portrayed based on radio resource control states and their state transitions in 3G, 4G, and 5G. We manifest how the TCS operates in the sense of the theoretical view.
- Standard perspective: From the point of view of the bridge that links the fundamental theories and implementation elements, we demonstrate three decades of TCS in the perspective of the 3GPP standardization. More explicitly, we delve into the TCS scenarios based on TCS framework provided by the 3GPP standardization. The detailed illustration can be beneficial to practical model design for attaining commercially reliable TCS performances.
- Implementation perspective: For the sake of stable and reliable operation of the TCS, we demonstrate leading challenging technical issues to be pondered with feasible ways. Moreover, with the aid of a conceptual sketch of our proposed intelligent TCS system controller, we shed lights on the future research direction as a better evolutionary way in NR.

For the sake of leading explicit presentation, a taxonomy diagram to classify the associated TCS scenarios in 3G, 4G, and 5G as well as those in inter-Radio Access

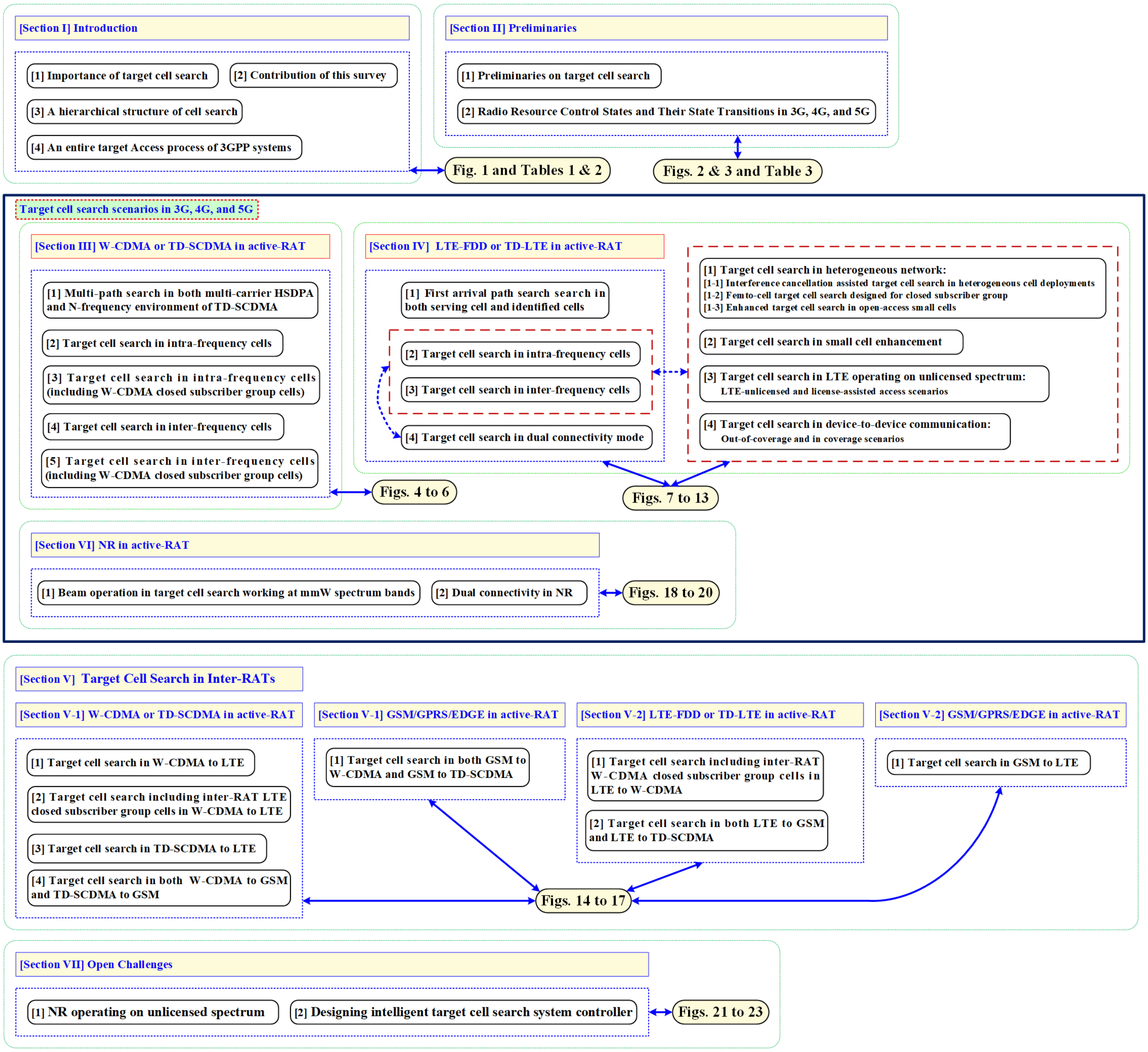

FIGURE 1. Taxonomy of associated target cell search scenarios in 3G, 4G, and 5G and followed by those in inter-RATs as well as overall structure of this survey.

Technologies (RATs) is visualized in Fig. 1. An overall structure of this survey is also portrayed in Fig. 1, where all the relevant figures in conjunction with Tables 1, 2, and 3 are indicated together. Table 2 provides a complete list of acronyms exploited for the survey. The remainder of the survey paper is organized as follows: In Section II, we provide a survey by introducing preliminaries on TCS, which constitutes the associated definitions, its importance, main TCS issues, and ways of resolving these issues. Subsequently, radio resource control states and their state transitions in 3G, 4G, and 5G are demystified. Table 3 also manifests key comparisons among the main features of W-CDMA, TD-SCDMA, LTE-FDD, TD-LTE, and NR in terms of both ICS and TCS. In Section III, we exhibit the TCS procedures of the W-CDMA and the TD-SCDMA systems. With contemplating an overview of entire TCS scenarios operating at these two 3G systems, we then continue further to provide insight into the TCS and multi-path search operational procedures and scenarios. Likewise, we begin with a complete literature survey by illustrating the operational scenarios of TCS techniques of both Long-Term Evolution Frequency Division Duplex (LTE-FDD) and Time-Division Long-Term Evolution (TD-LTE) in Section IV, which are classified into two categories, namely both normal TCS and specialized TCS scenarios. Then, we review TCS scenarios in inter-RATs including both 3G as active-RAT and 4G as active-RAT in

TABLE 2. List of essential acronyms.

Acronym	Definition	Acronym	Definition
3GPP	3rd Generation Partnership Project	**N2WT**	NR to W-CDMA or TD-SCDMA
CDMA	Code Division Multiple Access	**NR**	New Radio
CELL_DCH	Cell Dedicated CHannel	**OFDM**	Orthogonal Frequency Division Multiplexing
CELL_FACH	Cell Forward Access CHannel	**PBCH**	Physical Broadcast CHannel
CELL_PCH	Cell Paging CHannel	**P-CCPCH**	Primary Common Control Physical CHannel
D2D	Device-to-Device	**PCI**	Physical-layer Cell-Identity
DL	DownLink	**P-CPICH**	Primary Common PIlot CHannel
DRS	Discovery Reference Signal	**PSBCH**	Physical Sidelink Broadcast CHannel
DwPTS	Downlink Pilot Time Slot	**PSC**	Primary Scrambling Code
EDGE	Enhanced Data rates for GSM Evolution	**PSS**	Primary Synchronization Signal
E-UTRA	Evolved UMTS Terrestrial Radio Access	**PSSS**	Primary Sidelink Synchronization Signal
G2L	GSM/GPRS/EDGE to LTE	**RAT**	Radio Access Technology
G2N	GSM/GPRS/EDGE to NR	**RRC**	Radio Resource Control
G2T	GSM/GPRS/EDGE to TD-SCDMA	**SCH**	Synchronization CHannel
G2W	GSM/GPRS/EDGE to W-CDMA	**SS**	Synchronization Signal
GPRS	General Packet Radio Service	**SSS**	Secondary Synchronization Signal
GPS	Global Positioning System	**SSSS**	Secondary Sidelink Synchronization Signal
GSM	Global System for Mobile communications	**T2G**	TD-SCDMA to GSM/GPRS/EDGE
HSDPA	High Speed Downlink Packet Access	**T2L**	TD-SCDMA to LTE
ICS	Initial Cell Search	**TCS**	Target Cell Search
L2G	LTE to GSM/GPRS/EDGE	**TD-LTE**	Time-Division Long-Term Evolution
L2N	LTE to NR	**TD-SCDMA**	Time Division-Synchronous Code Division Multiple Access
L2T	LTE to TD-SCDMA	**UE**	User Equipment
L2W	LTE to W-CDMA	**UL**	UpLink
LAA	License-Assisted Access	**UMTS**	Universal Mobile Telecommunications System
LBT	Listen-Before-Talk	**UNII**	Unlicensed National Information Infrastructure
LTE	Long-Term Evolution	**URA_PCH**	UTRAN Registration Area Paging CHannel
LTE-FDD	Long-Term Evolution Frequency Division Duplex	**UTRA**	UMTS Terrestrial Radio Access
LTE-U	LTE-Unlicensed	**W2G**	W-CDMA to GSM/GPRS/EDGE
mmW	millimeter-Wave	**W2L**	W-CDMA to LTE
N2G	NR to GSM/GPRS/EDGE	**W-CDMA**	Wideband-Code Division Multiple Access
N2L	NR to LTE	**WT2N**	W-CDMA or TD-SCDMA to NR

Section V. In Section VI, we also examine an overview of TCS procedures and scenarios in NR, followed by beam operation in TCS working at mmW spectrum bands. Section VII offers open challenges, which highlight NR operating on unlicensed spectrum scenario and a great potential on deep learning aided intelligent TCS system controller in NR. In Section VIII, our conclusions are provided to summarize our survey and to manifest profound insights.

II. PRELIMINARIES

A. PRELIMINARIES ON TARGET CELL SEARCH

We introduce brief preliminaries on TCS procedure, followed by radio resource control states and their state transitions in 3G, 4G, and 5G. We strive to elucidate a definition of TCS procedure, its importance, and main TCS issues in a simple and concise manner. Fig. 2 illustrates a hierarchical structure of cell search and an entire target cell access process of 3GPP systems in both DownLink (DL) and UpLink (UL). More explicitly, the target cell access procedure in DL constitutes both TCS and adjacent cell selection followed by system information reception. In the forthcoming Sections III, IV, V, and VI, full details of TCS scenarios are described in 3G, 4G, inter-RATs, and NR, respectively. The target access processing stage of 3G/4G/5G mobile communication systems is portrayed as follows: Besides the serving cell detected during the ICS procedure, the UE should search and track multiple adjacent target cells around the UE, which provide informative resources for activating handover, maintaining multiple robust links to cooperate nearby Node-Bs,[2] and reasoning possible locations. To illustrate it a little bit further, adjacent target cell detection to ensure the sufficient number of detected cells is capable of supporting an efficient handover to the best possible adjacent target cell in terms of reliable and seamless connectivity over multiple cells. Especially, in case of heterogeneous and hierarchical cell configurations, the role of TCS to secure more reliable cells bestows Node-B a better flexibility to offload the traffic in terms of the network throughput optimization. Similarly, the TCS is also able to support efficient maintenance of multiple reliable links in terms of the best possible multiple Node-Bs' cooperation. In addition, enhanced UE's location inference is highly strengthened by the higher number of detected cells. Even though further complicated time scheduling, more power consumption as well as more time and frequency resources are required to be managed efficiently, the exploitation of TCS is reliably to make the communication system mobile, which manifests a top priority on the design. Such additional requirements lead only to tolerable impact on the entire system burden.

[2]In 3GPP terminology, Node-B is the same as base station.

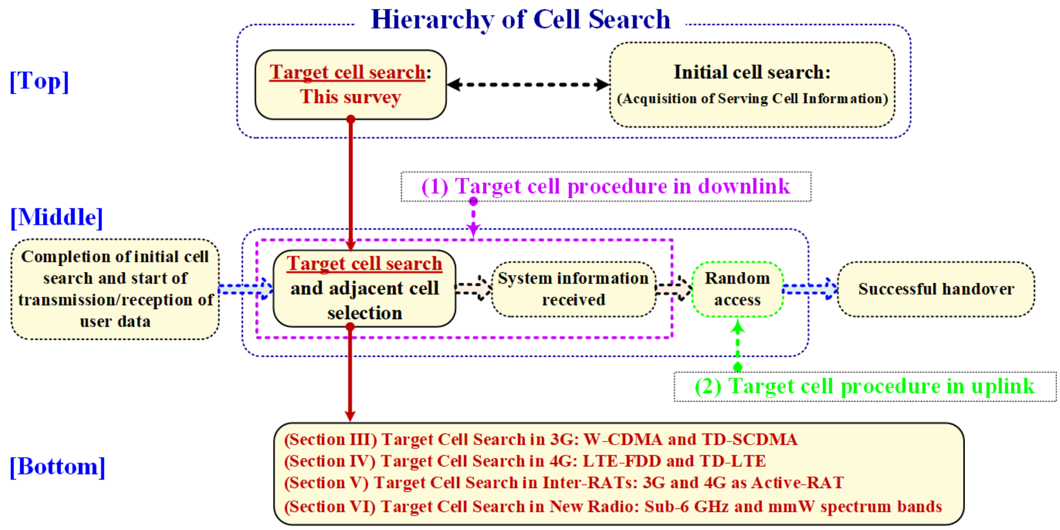

FIGURE 2. Hierarchical structure of cell search and entire target access process of 3GPP systems in both downlink and uplink.

From both ICS and TCS perspectives, essential comparisons among the main features of W-CDMA, TD-SCDMA, LTE-FDD, TD-LTE, and NR in Table 3 are articulated as follows:

Firstly, when contemplating the sensitivity to multi-paths on both ICS and TCS, owing to substantially higher time resolution in two CDMA systems, collecting all the reliable multi-paths received is to maximize the receiver's performance. On the other hand, two OFDM based systems are to acquire only first arrival path for their discrete fast Fourier transform window alignment.

Secondly, due to periodic transmissions of uniquely designed synchronization channel or signals in W-CDMA, TD-SCDMA, LTE (LTE-FDD and TD-LTE), and NR, maximal time uncertainty durations for conducting ICS procedures are set to 0.67 ms, 5 ms, 5 ms, and 20 ms, respectively [8], [35]–[37]. By contrast, their TCS counterparts manifest a completely different behavior in the corresponding time uncertainty durations. More explicitly, in case of two CDMA based systems, acquiring the accurate timing positions of reliable multi-paths in both serving cell and adjacent target cells is a critical role for TCS. Furthermore, both maintaining the number of the robust multi-paths and finding a precise location of a dominant path having the highest channel gain lead to better performance of 3G receiver [38], [39]. For the sake of satisfying those requests, a predefined reduced region surrounding the time position of the first received path is defined as reduced time uncertainty window on which TCS is processed. On the other hand, the TCS issue on cyclic prefix aided OFDM systems such as LTE and NR becomes especially critical for the synchronous operation mode, where the arrivals of the synchronization signals from adjacent cells are primarily positioned within a cyclic prefix period to make those signals detected in a single symbol duration. In other words, a maximum of one single symbol duration is sufficient for the reduced time uncertainty window. In such systems, TCS is considered as a joint detection of the cell IDs and their corresponding timings of adjacent target cells based on the superimposed synchronization signals received [23].

Lastly, since the degree of uncertainty in frequency domain depends highly on system's carrier frequency, we would like to highlight that initial carrier frequency offset compensated for performing ICS procedure is dozens of times larger than that alleviated for doing TCS counterpart. More specifically, in case of W-CDMA system leveraging a substantial benefit of continuous synchronization channel, one-shot based coarse frequency offset mitigation approach is feasible, however TD-SCDMA, LTE, and NR systems experiencing scarceness of synchronization signal caused by its time division approach need further remedy, namely a concatenated approach compensating for the existing very high initial carrier frequency offset, comprising both coarse and fine frequency offset mitigation schemes. On the other hand, owing to substantially reduced frequency offset range at TCS stage, at most either fine or residual frequency offset is required to be mitigated depending on the corresponding scenarios. Accordingly, for the sake of implementing mobile station modem to satisfy a commercial-level, a successful and reliable completion of the TCS procedure plays a pivotal role in guaranteeing reliable and seamless connectivity over multiple cells.

B. RADIO RESOURCE CONTROL STATES AND THEIR STATE TRANSITIONS IN 3G, 4G, AND 5G

The principal roles of the Radio Resource Control (RRC) protocol encompass (1) establishment of RRC connection, (2) release of RRC connection, (3) reselection, (4) broadcast of system information, and so on. The basic operation of the RRC protocol is illustrated by a state diagram, which

TABLE 3. Key comparisons among the main properties of W-CDMA, TD-SCDMA, LTE-FDD, TD-LTE, and NR with respect to both ICS and TCS.

	Sensitivity to multi-path	Uncertainty in time domain		Uncertainty in frequency domain	
	ICS & TCS	ICS	TCS	ICS	TCS
W-CDMA	Reliable multi-paths	0.67 ms	A predefined reduced region surrounding the time position of the first received path	Coarse freq. offset	Fine or residual freq. offset
TD-SCDMA	Reliable multi-paths	5.0 ms	Same as that of W-CDMA	Coarse and fine freq. offsets	Fine or residual freq. offset
LTE	First arrival path	5.0 ms	A single symbol duration	Coarse and fine freq. offsets	Fine or residual freq. offset
NR	First arrival path	20.0 ms	A single symbol duration	Coarse and fine freq. offsets	Fine or residual freq. offset

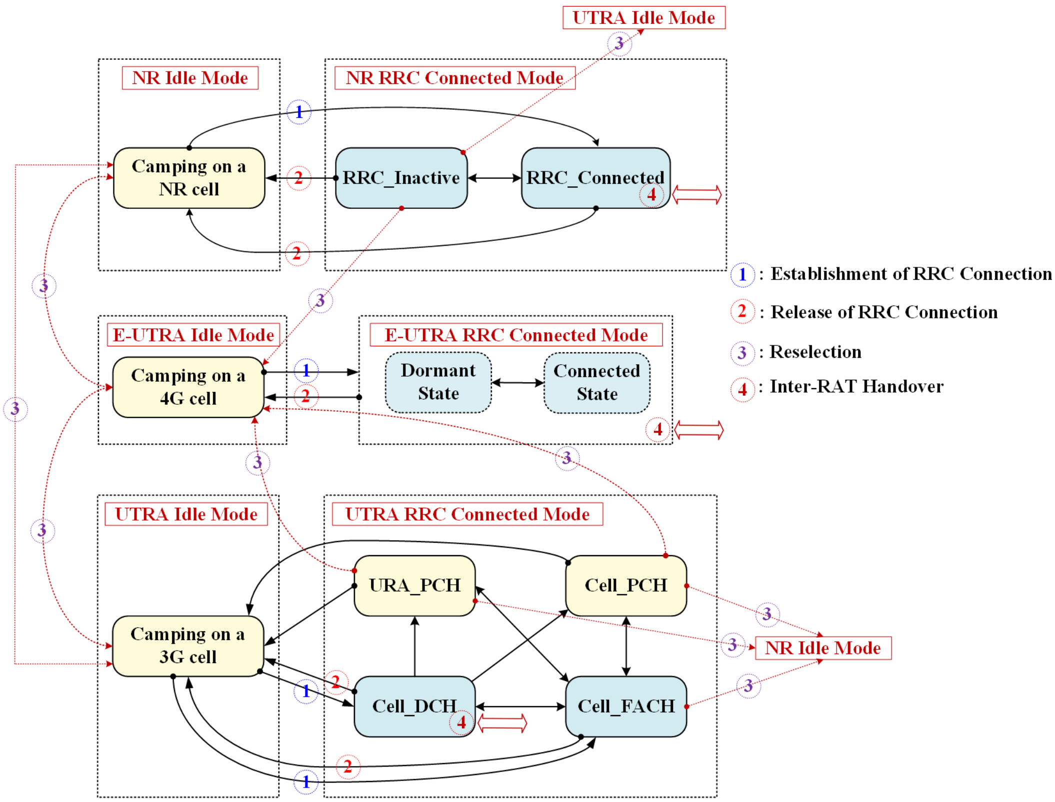

FIGURE 3. RRC states and their transitions in 3G UTRA, 4G E-UTRA, as well as NR RRC_CONNECTED and RRC_IDLE modes.

portrays specific states that a UE may ride in. The diverse RRC states in the state diagram handle different amounts of radio resources related to them. Both RRC states and their transitions play a pivotal role in allowing 3G, 4G, and 5G networks to balance radio resources between mobile users connected and to support power-efficient operation when user data is not allocated. Before moving into the main context of TCS scenarios in detail, we would like to introduce the RRC states and their state transitions in RRC_CONNECTED and RRC_IDLE modes of 3G Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access, those of 4G Evolved UMTS Terrestrial Radio Access (E-UTRA), as well as those of 5G NR, which are exploited in illustrating entire cell search scenarios used in 3G, 4G, and 5G systems, respectively. As portrayed in Fig. 3, the RRC_CONNECTED mode's states in 3G UMTS Terrestrial Radio Access (UTRA) constitute Cell Dedicated CHannel (`CELL_DCH`), Cell Forward Access CHannel (`CELL_FACH`), Cell Paging CHannel (`CELL_PCH`) and UTRAN Registration Area Paging CHannel (`URA_PCH`) [40]–[42]. Entire states in 4G E-UTRA consist of only the RRC_CONNECTED and RRC_IDLE modes [43]. Those in 5G NR are composed of the RRC_CONNECTED, RRC_INACTIVE, and RRC_IDLE modes [44]. Moreover, numbers one to four inside round brackets in Fig. 3 represent establishment of RRC connection, release of RRC connection, reselection, and inter-RAT handover, respectively, which illustrate how the RRC states and their state transitions interwork in 3G UTRA, 4G E-UTRA, and 5G NR RRC modes. When UE is turned on, it enters RRC_IDLE mode and tries to camp on either a 3G, 4G, or 5G cell, which is directly associated with ICS procedure. Then, the RRC connection becomes established between the UE and its serving radio network controller. The UE switches to the RRC_CONNECTED mode, in which UEs in 3G UTRA may be in either CELL_DCH or CELL_FACH of the RRC_CONNECTED mode.

3G UTRA RRC states and their state transitions are illustrated as follows. When the UE is in the CELL_DCH state, user data are transmitted through dedicated channel(s). Hence, for the sake of conveying high data traffic, the UE must stay in the CELL_DCH state. On the other hand, if several UEs share common channels, for example, random access channel for UL and forward access channel for DL, the UE switches to CELL_FACH. It is noted that data transmission is only carried out in these two states. In the CELL_PCH state, the UE listens to a paging channel in order to monitor specific paging messages transmitted from radio network controller, while UL access is not allowed in the state. It is noted that in the aforementioned three states, the UE updates location information whenever its serving cell is changed. Finally, in case of the UE receiving packets infrequently, the 3G cell may rule out the cell update overhead by commanding the UE to switch to the URA_PCH state. Owing to limited battery capacity, UE's power consumption always leads to a critical issue for UE's data transmission. Power saving techniques are typically aimed to reduce power consumption. Accordingly, 3G UTRA exploits discontinuous reception in order to maintain the power of UE as long as possible [9], [41]. More explicitly, discontinuous reception allows an idle UE to turn off its receiver chain for a predefined duration, which is also referred to as the discontinuous reception cycle rather than continuously monitoring the radio channel. Furthermore, a UE is capable of negotiating its own discontinuous reception cycle length with a serving network. Consequently, the network performs sleep and wake-up scheduling of each UE connected and delivers a paging message whenever the UE wakes up. With the aid of four RRC state transitions as portrayed in Fig. 3, the efficiency of discontinuous reception scheme is substantially improved. The following TCS operational scenarios in 3G UTRA are based on these four RRC states and their state transitions.

Even though 4G E-UTRA constitutes two RRC modes, namely RRC_CONNECTED and RRC_IDLE modes, the RRC_CONNECTED mode is further divided into two subcategories, expressed as connected and dormant states [45]. More clearly, the former and the latter manifest active and discontinuous reception operation states, respectively. In the connected state of the RRC_CONNECTED mode, a UE is continuously transmitting and receiving signals to/from adjacent Node-Bs. Accordingly, a fully tightened TCS schedule is activated as long as the UE stays in the state. On the other hand, whenever the UE is in the dormant state of the RRC_CONNECTED mode, connected state discontinuous reception mechanism starts to perform, which is capable of substantially reducing the tail energy. If any data packet does not exist during a predefined time period set by the connected state discontinuous reception inactivity timer, the UE only wakes up periodically to monitor the existence of newly incoming signal. Until the connected state discontinuous reception inactivity timer is expired, a connected state discontinuous reception cycle is repeated periodically and a dedicated TCS schedule should also follow the cycle. Specifically, when a periodic wake-up commences, in order to recover both the timing and frequency deviations induced by clock drift and mobility, reacquisition procedure has to be activated to achieve the latest timing and frequency information. Simultaneously, the predefined TCS schedules are also performed to find better candidates of a prospective serving cell. In the RRC_IDLE mode, no RRC connection is established. When a UE wakes up and needs to monitor paging information regularly but sparsely, the role of UE is to monitor a paging channel to detect incoming calls, to perform cell (re-)selection, and to obtain system information [43]. Hence, similar reacquisition procedure adopted in the connected state discontinuous reception and all the categories of TCS in the RRC_IDLE mode must be performed together.

5G NR interworking with the legacy should satisfy the requirements of diverse 5G services such as enhanced mobile broadband, ultra-reliable low-latency communication, and even massive internet of things services [4], [5], [46]. Hence, efficient control of connectivity for the future 5G services is guaranteed by exploiting a flexible way of RRC management. In order for UEs to achieve a wide variety of 5G NR services having different requirements associated with flexibly configurable discontinuous reception cycles, the new mode is simultaneously to minimize power consumption and signaling burden as well as to optimize mobility and system access latency during the NR RRC connection. It is also considered as an optimization of RRC state transitions for the case that the UE stays at the same geographical position after inactivity timer expires. Besides RRC_CONNECTED and RRC_IDLE modes exploited in 4G E-UTRA, 5G NR has adopted a new RRC state referred to as RRC_INACTIVE mode [44]. Therefore, three RRC modes are available, namely NR-RRC_CONNECTED, NR-RRC_INACTIVE, and NR-RRC_IDLE. The strategy of camping for UEs in NR-RRC_IDLE mode is extended to that in the NR-RRC_INACTIVE mode. It is noted that Fig. 3 also manifests multi-RAT access and camping based on 3G UTRA and 4G E-UTRA tightly integrated to the 5G NR. When the UE is turned on, it enters NR-RRC_IDLE mode and tries to camp on a 5G NR cell, which is directly involved in ICS procedure. Then, the UE move into NR-RRC_CONNECTED mode having establishment of RRC connection. If no UE's activity is detected until a predefined expire time, there will be a transition from NR-RRC_CONNECTED mode to NR-RRC_INACTIVE mode. Whenever its activity is resumed, the state will be changed to NR-RRC_CONNECTED mode. It is also noted that UE in NR-RRC_IDLE cannot move to NR-RRC_INACTIVE mode as portrayed in Fig. 3.

III. TARGET CELL SEARCH IN W-CDMA AND TD-SCDMA

In this Section, as portrayed in Figs. 1 and 4, both taxonomy and hierarchical structure of the entire TCS scenarios in W-CDMA and TD-SCDMA systems are introduced and then full details of multi-path search and TCS in four typical scenarios are illustrated with the aid of Figs. 4, 5, and 6. The main differences of TCS scenarios between W-CDMA and TD-SCDMA systems are also clarified. It is noted that three main characteristics of two CDMA systems in terms of both ICS and TCS have been articulated in Table 3.

A. TARGET CELL SEARCH IN 3G

Fig. 4 portrays an entire state transition diagram of all the cell search scenarios in active-RAT mode of 3G systems (either W-CDMA or TD-SCDMA) and their related inter-RAT TCS scenarios such as 2G to 3G and LTE to 3G, in which 2G and LTE are in active-RAT, respectively [47]–[50], [53]. Here, 2G, 3G, and 4G systems represent Global System for Mobile communications (GSM)/General Packet Radio Service (GPRS)/Enhanced Data rates for GSM Evolution (EDGE), W-CDMA/TD-SCDMA, and LTE-FDD/TD-LTE, respectively. It is noted that G, W, T, and L represent GSM/GPRS/EDGE, W-CDMA, TD-SCDMA, and LTE-FDD/TD-LTE, respectively. To elaborate the diagram a little bit further, every square bracket of Fig. 4 represents specific conditions and RRC state given to each mode of operational scenarios. Furthermore, numbers 1, 2, and 3 inside parenthesis manifest additional information to be exploited in the mode, namely (1), (2), and (3). More explicitly, (1) represents that a list of monitored set[3] is provided. (2) indicates that in case of closed subscriber group cell search,[4] at least one closed subscriber group ID is included in the UE's whitelist. Finally, (3) means that no explicit neighbor list for achieving closed subscriber group IDs is provided.

Let us introduce all the TCS scenarios in RRC states constituting `CELL_DCH`, `CELL_FACH`, `CELL_PCH`, and `URA_PCH` of Fig. 4. There are ten operational scenarios available in `CELL_DCH` and(/or) `CELL_FACH` of TCS scenarios, namely [C1] Multi-path search in serving cell(s) and identified cells, [C2] TCS in intra-frequency cells under `CELL_DCH`, [C3] TCS in intra-frequency cells (including W-CDMA closed subscriber group cells) under `CELL_FACH`, [C4] TCS in inter-frequency cells under `CELL_DCH`, [C5] TCS in inter-frequency cells (including W-CDMA closed subscriber group cells) under `CELL_FACH`, [C6] TCS in W-CDMA to LTE (W2L) under `CELL_DCH`, [C7] TCS including inter-RAT LTE closed subscriber group cells in W2L under `CELL_FACH`, [C8] TCS in TD-SCDMA to LTE (T2L) under `CELL_DCH` and finally [C9/C10] TCS in W-CDMA to GSM/GPRS/EDGE (W2G) and TD-SCDMA to GSM/GPRS/EDGE (T2G), respectively. In order to perform W2G and T2G for 2G target cell detection, the employment of absolute radio frequency channel number and base station identity code is required to facilitate those particular TCS operations. More explicitly, a pair of the carrier frequencies exploited in the UL and DL of GSM/GPRS/EDGE is specified by the absolute radio frequency channel number and the base station identity code indicates a code employed in GSM/GPRS/EDGE to uniquely identify a Node-B. This is because a UE may receive the broadcast channel of more than one Node-Bs on the same carrier frequency [54].

Similarly, seven TCS operational scenarios are available in the idle mode, `CELL_PCH` and `URA_PCH`. Specifically, [I1] Multi-path search in serving cell, [I2] TCS in intra-frequency cells (including W-CDMA closed subscriber group cells), [I3] TCS in inter-frequency cells (including W-CDMA closed subscriber group cells), [I4] TCS in inter-frequency cells including inter-RAT LTE closed subscriber group cells in W2L, [I5] TCS in T2L and finally [I6/I7] TCS in W2G and T2G, respectively. Furthermore, we also need to see TCS scenarios when either GSM/GPRS/EDGE or LTE is in active-RAT. Specifically, in connected and idle modes of GSM/GPRS/EDGE systems, there are [G1/G3] TCS in GSM/GPRS/EDGE to W-CDMA (G2W) and [G2/G4] TCS in GSM/GPRS/EDGE to TD-SCDMA (G2T). Similarly, in `RRC_CONNECTED` and `RRC_IDLE` modes of LTE systems, there are [L1/L3] TCS including inter-RAT W-CDMA closed subscriber group cells in LTE to W-CDMA (L2W) and [L2/L4] TCS in LTE to TD-SCDMA (L2T). According to Fig. 4, it is noted that TCS scenarios for closed subscriber group cells are not contemplated for `CELL_DCH` of W-CDMA, TD-SCDMA, and GSM/GPRS/EDGE.

When TCS scenarios are performed based on predefined schedules, there are three exclusive types of cells classified in 3G systems: (1) Active cell represents at least a single cell or multiple cells with which a UE is currently communicating. In case of W-CDMA, there are multiple active cells to be connected owing to its soft-handover support. On the other hand, only a single active cell exists in TD-SCDMA network. (2) Monitored cells indicate cells that are included in the cell information list. (3) Detected cells represent cells that the UE has detected, which are neither active nor monitored. In fact, the cells may be missing neighbors. Accordingly, intra-frequency target cells constitutes active, monitored, and detected cells. By contrast, only monitored cells are included in inter-frequency target cells [50]–[52].

B. MULTI-PATH SEARCH IN W-CDMA AND TD-SCDMA

The objective of the multi-path search is to seek for the accurate timing instances of the multiple non-negligible delayed paths and to identify the suitable paths reserved not only for the maximum ratio combining scheme of the Rake receiver but also for the best possible performance of the equalizer. More explicitly, once the first received path is acquired, the uncertainty region that has to be searched will be shrunk to a predefined reduced region surrounding the time position, where the first received path was identified. This shrunk search window width is determined by multiple factors, namely the maximal allowable dispersion of the multi-path propagation environment encountered, the appearance and

[3]Monitored set (a.k.a. neighbor set) represents cells to be detected and monitored by a UE, which are known to the network and not part of the active set.

[4]Full details of the closed subscriber group cell search are elucidated in Section IV, because the concept has been adopted in LTE and followed by in W-CDMA.

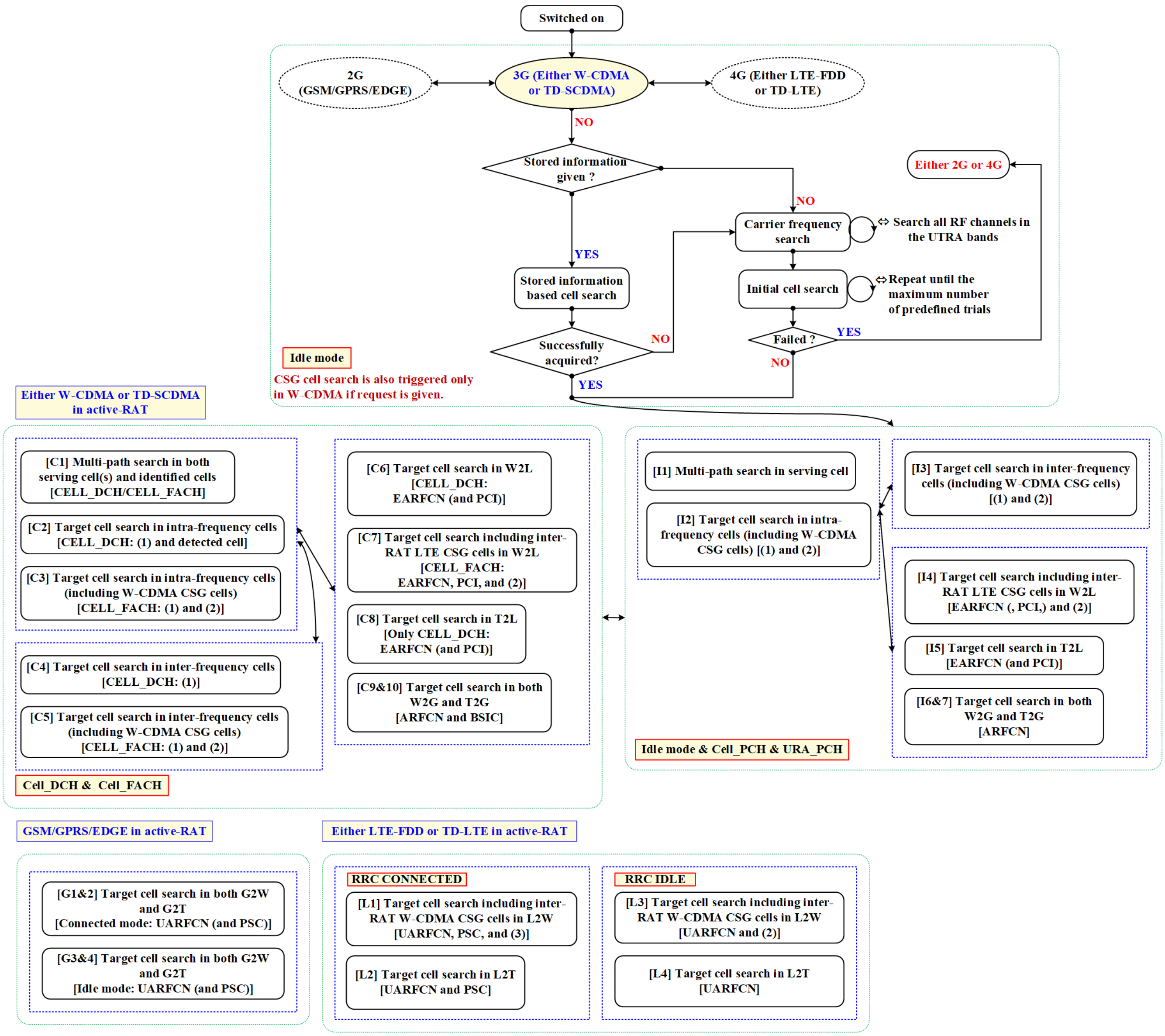

FIGURE 4. **Entire cell search scenarios used in 3G system, where ARFCN, BSIC, CSG, EARFCN, and UARFCN represent Absolute Radio Frequency Channel Number, Base Station Identity Code, Closed Subscriber Group, E-UTRA Absolute Radio Frequency Channel Number, and UTRA Absolute Radio Frequency Channel Number, respectively.**

disappearance of propagation paths induced by corner effect and(/or) shadow fading, Relay induced dispersion of the multi-paths, and so on [38], [39], [55]–[57]. The multi-path search plays a pivotal role in both tracking dynamically changeable multi-path positions and maintaining seamless support of handovers. It is noted that a bank of correlators can be exploited to boost the performance of multi-path search substantially.

Dual-cell High Speed Downlink Packet Access (HSDPA) (also referred to as dual-carrier HSDPA) is a multi-carrier version of HSDPA introduced in 3GPP Rel-8 [1]. The dual-cell HSDPA is the natural evolution of HSDPA in terms of carrier aggregation in the DL. Fig. 5 illustrates the so-called DL dual-cell operation scenario of Rel-8 [1], illustrating both the UL and DL carrier frequency allocations. It is noted that this terminology, called dual-cell, is somewhat deficient, because a "cell" typically refers to a geographic traffic-cell, but we adopted the terminology in compliance with the standard. When a UE is operating in its dual-cell HSDPA mode, it is capable of receiving two separate HSDPA transmissions from two adjacent carriers, both of which may have different powers. The two cells of dual-cell HSDPA are handled by the same Node-B. As seen in Fig. 5, the primary serving cell has a full set of common control channels such as the Synchronization CHannels (SCHs), Primary Common PIlot CHannel (P-CPICH), Primary Common Control Physical CHannel

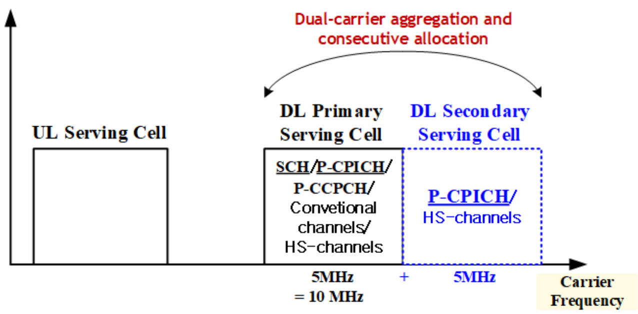

FIGURE 5. **Downlink dual-cell operation scenario of Rel-8, where HS represents High Speed.**

(P-CCPCH), and other existing physical channels. It is worth noting that Two SCHs, P-CPICH, and P-CCPCH constitute key physical channels used for both ICS and TCS procedures in W-CDMA. By contrast, in case of the secondary serving cell, P-CPICH is only transmitted to the UE except for high speed channels. Both the primary and the secondary cells are capable of transmitting simultaneously their high speed channels to the UE. In order to facilitate multi-path search operations, an RRC signaling flag referred to as "(1) Adjacent frequency measurements without compressed mode" has been introduced in Rel-8 [40], [51], [58]. Activation of the flag does not need compressed mode to conduct P-CPICH measurements on another carrier frequency, which is adjacent to the anchor carrier frequency corresponding to the primary cell. A concept of using a dual-multi-path search aided UE has been devised in [58]. Specifically, similar to multi-path search's operation in normal mode, the dual-multi-path search acts as in intra-cell search environment at the cost of additional hardware complexity. With the capability of searching without compressed mode, the search performance of the dual-multi-path search is twice higher than that of single-multi-path search. Likewise, carrier aggregation across multiple frequency bands leads to the concept of dual-band dual-cell HSDPA in Rel-9. In this situation, as visualized in Fig. 6, the primary serving cell is allocated to a single carrier frequency in one frequency band and the secondary serving cell to a single carrier frequency in another frequency band. A new RRC signaling flag referred to as "(2) Inter-band frequency measurements without compressed mode" has been added to Rel-9. Activation of the flag does not need compressed mode to conduct P-CPICH measurements on two inter-band carrier frequencies chosen by a predetermined band combination list [40], [51], [59]–[61]. Hence, the dual-multi-path search also works on the dual-band dual-cell configuration.

In case of Rel-10, for the sake of supporting its multiple multi-path searches' operation, a new RRC signaling flag referred to as "(3) Enhanced inter-frequency measurements without compressed mode" has also been included to perform P-CPICH measurements on two additional carrier frequencies other than the carrier frequency related to the serving high speed cell, where each carrier frequency belongs to either the frequency band including the currently used carrier frequency or another frequency band in the band combination list [40], [51], [59]–[61]. It is noted that these two additional carrier frequencies to be measured without compressed mode and the currently used carrier frequency cannot be allocated to more than two frequency bands. As an example of the configuration, with the aid of higher layer signaling, the exploitation of the triple-multi-path search's operation is maintained at three individual carrier frequencies in up to two frequency bands. Finally, in Rel-11, an RRC signaling flag referred to as "(4) Inter-frequency measurements on configured carriers without compressed mode" has been introduced to conduct parallel P-CPICH measurements on two carrier frequencies, which are configured for both serving high speed operation in a frequency band and the secondary serving high speed operation in another frequency band, respectively. These two frequency bands are also determined by the band combination list [40], [51], [59]–[61]. Accordingly, the above four different scenarios are carried out under all the possible carrier aggregation configurations in Rel-8, Rel-9, Rel-10, and Rel-11 of multi-carrier HSDPA as portrayed in Fig. 6, where 3C, 4C, and 8C represent three-, four-, and eight-carriers, respectively as well as a square in each frequency band occupies a 5 MHz bandwidth. Separate frequency bands referred to as Bands A and B manifest a variety of carrier aggregation configurations defined in 3GPP specifications. It is also noted that NC-3C and -4C indicate non-contiguous three- and four-carrier configurations, respectively. New scenarios introduced in Rel-11 are capable of supporting up to the four carrier HSDPA operation having two non-contiguous carriers in a single frequency band, which is referred to as single band non-contiguous four carrier HSDPA as visualized in Fig. 6. In this situation, there are three main assumptions to be considered. Firstly, the entire bandwidth per sub-block cannot exceed 15 MHz. Secondly, only contiguous carriers within each sub-block are available. Finally, the maximum number of aggregated carriers is set to four. The employment of multiple multi-path search's operation in diverse carrier aggregation configurations is capable of boosting multi-path search's efficiency substantially owing to its parallel processing without compressed mode.

We introduce only different parts in TD-SCDMA compared with those of W-CDMA illustrated above. Multi-path search in TD-SCDMA has been used to enhance the step 2 searcher's performance by finding non-negligible multi-path positions [62]. In order to reduce the complexity of entire ICS procedure, hierarchical cell search procedures have been chosen and realized in all the 3GPP systems [4]–[13]. The ICS procedure of TD-SCDMA is typically implemented by exploiting three stages for the hierarchical cell search approach to acquire the serving cell ID. Similarly, step 1, 2, and/or 3 searchers are employed for its TCS procedure. More explicitly, rather than using inaccurate multi-path timings obtained in the step 1 search stage, the step 2 searcher is capable of performing its role at reliable multi-path timings. Furthermore, it is noted that different positions having the same SYNC-DL code index can correspond to

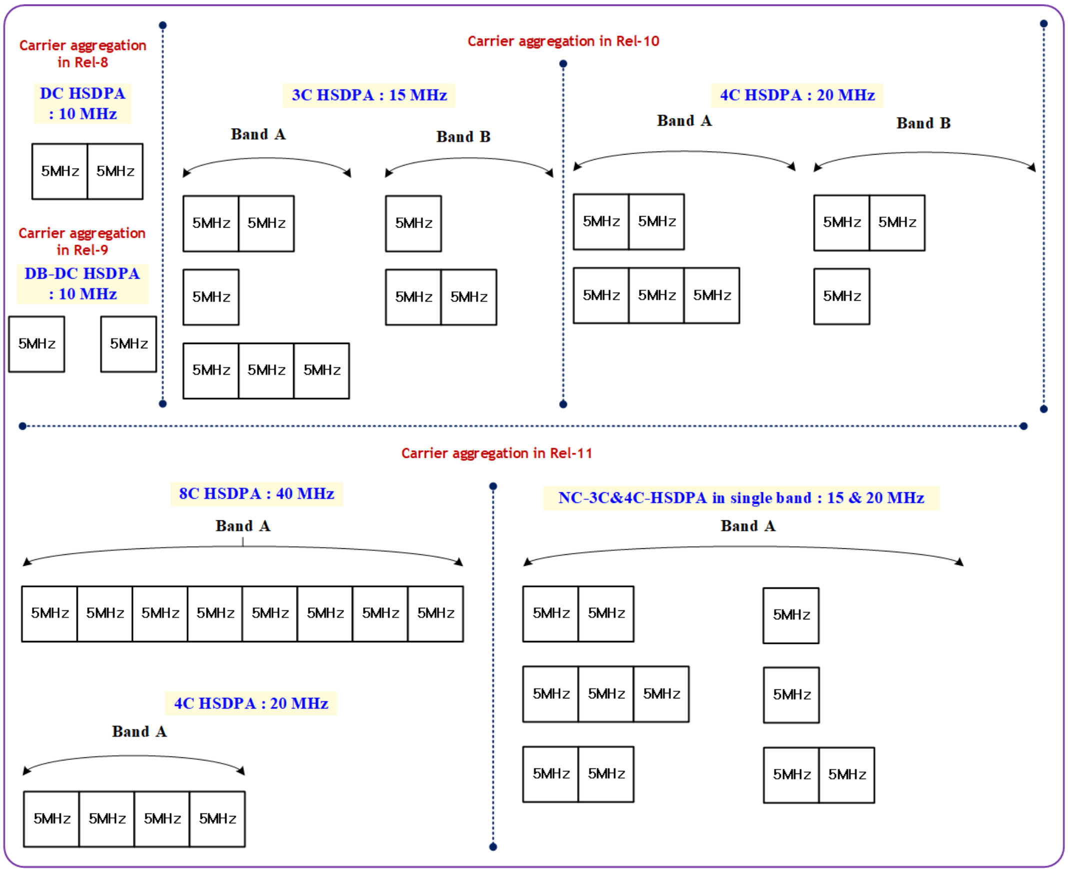

FIGURE 6. Visual illustration of all the possible carrier aggregation configurations in Rel-8, Rel-9, Rel-10, and Rel-11 of multi-carrier HSDPA, where each square represents a single 5 MHz bandwidth and each band encompasses a combination of both consecutive and non-consecutive 5 MHz bandwidths. DC and DB-DC represent dual-cell and dual-band dual-cell, respectively.

different midamble indices. Hence, under realistic multi-cell environments, an identification of each multi-path position having different midamble index can also be carried out by the multi-path search [62], [63]. In order to support seamless handover scenario, the multi-path search is to focus mainly on reliable multi-paths gained from a single target cell because TD-SCDMA does not support soft-handover used in W-CDMA. In case that an advanced multi-cell interference cancellation aided receiver is considered, even though the soft-handover is not supported, the multi-path search scheduler has to maintain multi-path timings from several dominant adjacent cells. This is because the interference cancellation assisted cell searcher removes all the multi-paths from other cells to improve the achievable detection probability of the multi-paths in a target cell. Under the N-frequency environment, it is highly likely that the primary carrier frequency of adjacent cells is not the same as that of the current serving cell. Accordingly, the multi-path search in inter-frequency cells can be activated frequently.

C. TARGET CELL SEARCH IN TYPICAL SCENARIOS OF W-CDMA AND TD-SCDMA

Let us portray further the details of TCS scenarios in Fig. 4. Even though full details of [C1/I1] have mainly been illustrated in the previous Section, with the aid of Figs. 3 and 4 in terms of RRC states, we further delve into its behaviors in a slightly different manner. During [C1] scenario, multi-path search operations in both serving cell(s) and identified cells are activated. On the other hand, during [I1] scenario, multi-path search in serving cell is only performed to acquire renewed multi-path timing information. It is worth noting that the role of multi-path search in W-CDMA is further extended to intra-frequency TCS operations. To illustrate it a little bit further, rather than using step 1/2/3 searchers, TCS for both intra-frequency active cell and intra-frequency identified cells can be performed by the multi-path search, because cell specific information such as both the active cell(s) and the identified cells has already been obtained, where the serving cell is contemplated as active cell in W-CDMA and TD-SCDMA as well as the identified cells represent monitored cells already found by previous cell search operations. Accordingly, only updated appropriate timing positions need to be acquired instead, which is feasible by careful selection of search window size for a practical use. Additionally, when the secondary common pilot channel exists, multi-path search in W-CDMA is also carried out by exploiting the channel [1]. During discontinuous reception mode, whenever 3G mobile station modem wakes up, previous timing information must be updated. Hence, acquisition of the new timing positions is also conducted by the multi-path search.

[C2/C3/I2] illustrates TCS in intra-frequency cells. In case of [C2], TCS is performed based on the condition (1).[5] In order to find active and monitored cells non-identified, only step 1 and 3 searchers may be required owing to cell information provided. On the other hand, step 1, 2, and 3 searchers are used for attaining only detected cells, because this kind of cell is not recognized in a given neighbor cell information list. By contrast, [C3/I2] scenarios are associated with the conditions (1) and (2). It is noted that the number of serving cell in W-CDMA depends entirely on that of active cells associated with soft-handover. On the other hand, the number in TD-SCDMA is always set to one. Furthermore, W-CDMA closed subscriber group cells may be detected only if the request of finding such cells is signaled from their serving cell. The details of the closed subscriber group TCS are illustrated in the following Section IV. In case of TD-SCDMA TCS in intra-frequency cells, the employment of step 1 and 2 searchers covers detection of both active and monitored cells non-identified as well as that of detected cells. It is highly likely that the number of TD-SCDMA target cells to be detected will be decreased owing to adjacent cells having different primary carrier frequencies. Closed subscriber group cell detection in TD-SCDMA is excluded in all the TCS scenarios as specified in [50].

Inter-frequency TCS scenarios of [C4/C5/I3] are quite similar to those of [C2/C3/I2] except for two factors, namely the employment of compressed mode and the exclusion of detected cells. It is worth noting that the compressed mode is not required in TD-SCDMA TCS scenarios owing to its inherent time division duplex behavior. As visualized in Fig. 14, the compressed mode in W-CDMA is utilized for the sake of making a sufficient transmission gap to search target cells in predefined inter-frequencies. The inter-frequency TCS is conducted by exploiting both UTRA absolute radio frequency channel number and Primary Scrambling Code (PSC) (in TD-SCDMA, scrambling code) as well as given conditions. More specifically, the carrier frequencies employed in the UL and DL of 3G systems are designated by the UTRA absolute radio frequency channel number. Carrier center frequency used is allocated based on an integer multiple of 200 kHz [64]. In order to identify serving cells in W-CDMA DL system, a set of 512 PSCs is generated on the basis of truncated $(2^{18}-1)$ Gold sequences, which match to a single frame period consisting of 38400 chips for the chip rate 3.84 M chips per sec. An individual PSC is allocated to each cell and utilized to scramble P-CPICH and P-CCPCH together. The role of the inter-frequency TCS is to find all the candidates for potential handover in indicated inter-frequencies (in W-CDMA scenarios closed subscriber group cells are also encompassed) [49], [51]. During CELL_DCH, closed subscriber group cell search is not allowed in TCS scenarios. It is noted that in W-CDMA only step 1 and 3 searchers are used to perform the inter-frequency TCS scenarios with the aid of cell-specific information available. Furthermore, compared to search space of the ICS scenario, that of TCS is much narrower. Hence, if suitable memory space is feasible, stored information based TCS can be exploited for the sake of improving the inter-frequency TCS performance. In case of TD-SCDMA, the observation window of TCS in Fig. 15 constitutes idle time slots during which the UE shall identify new detectable cells in monitored sets indicated from higher layer signaling. The step 1 and 2 searchers can also be utilized as in the intra-frequency TCS scenarios.

[5] See the details of the conditions (1), (2), and (3) in Section III-A.

D. SUMMARY AND LESSONS LEARNED

In Section III, all the TCS scenarios in RRC states constituting CELL_DCH, CELL_FACH, CELL_PCH, and URA_PCH of Fig. 4 were classified into two main categories, namely (1) Ten operational scenarios available in CELL_DCH and/or CELL_FACH of TCS scenarios as well as (2) Seven TCS operational scenarios available in the idle mode, namely CELL_PCH and URA_PCH. By employing an entire state transition diagram of all the cell search scenarios in active-RAT mode of 3G systems (either W-CDMA or TD-SCDMA) of Fig. 4, we have proceeded by offering an insight into the TCS and multi-path search operational procedures and scenarios. Figs. 5 and 6 detailed how all the possible carrier aggregations of multi-carrier HSDPA are configured in terms of multi-path search operations. We have introduced that the objective of the multi-path search is to seek for the accurate timing instances of the multiple non-negligible delayed paths and to identify the suitable paths reserved. In addition to its basic role, its more important but not well known roles have also been demystified. More specifically, with the aid of all the possible carrier aggregation configurations in Rel-8, Rel-9, Rel-10, and Rel-11 of multi-carrier HSDPA as portrayed in Fig. 6, classic multi-path search's operation in normal mode has been extended to satisfy all the scenarios established at the cost of additional hardware complexity. In case of Rel-11, in order to reinforce the multiple multi-path searches' operation in diverse carrier aggregation configurations, full parallel processing is able to boost multi-path search's efficiency substantially. The aforementioned facts manifest how the role of the classic multi-path search has been evolved in the standardization of 3G systems.

Only different parts in TD-SCDMA compared with those of W-CDMA illustrated above were also highlighted in Section III as follows: (1) Multi-path search in TD-SCDMA has been used to enhance the step 2 searcher's performance by finding non-negligible multi-path positions. (2) For the sake of enhancing seamless handover scenario, the multi-path search has been used to aim mainly for reliable multi-paths collected from a single target cell, because TD-SCDMA does not provide soft-handover exploited in W-CDMA. On the other hand, the role of multi-path search in W-CDMA has been further extended to intra-frequency TCS operations. More specifically, TCS operations for both intra-frequency active cell and intra-frequency identified cells can be performed by the multi-path searcher, because cell specific information such as both the active cell(s) and the identified cells has already been obtained, which is capable of increasing the utilization of the existing hardware substantially.

IV. TARGET CELL SEARCH IN LTE FDD AND TD-LTE

In this Section, as described in Figs. 1 and 7, both taxonomy and hierarchical structure of the entire TCS scenarios in LTE-FDD and TD-LTE systems are introduced and then full illustrations of three Subsections, namely (A) Target Cell Search in 4G, (B) Normal Target Cell Search, and (C) Specialized Target Cell Search are provided with the aid of Figs. 8 to 13. Through continuous evolution of LTE systems adopting heterogeneous and hierarchical cell environments, typical TCS scenarios for detecting classic intra- and inter-frequency cells have further diversified and categorized as specialized TCS scenarios comprising four distinguishing cases in Subsection (C), which is visualized as brown-colored dashed two boxes inside a bigger box named 'Target cell search scenarios in 3G, 4G, and 5G' of Fig. 1. More specifically, as mentioned in Fig. 1, Subsection (B) constitutes 1) Target Cell Search in Typical Scenarios and 2) Target Cell Search in Dual Connectivity Mode. Similarly, Subsection (C) consists of 1) Target Cell Search in Heterogeneous Network Scenario, 2) Target Cell Search in Small Cell Enhancement Scenario, 3) Target Cell Search in LTE-Unlicensed Spectrum Scenario, and 4) Target Cell Search in Device-to-Device Communication Scenario. It is worth noting that three main characteristics of two OFDM based systems in terms of both ICS and TCS have been manifested and compared with their CDMA counterparts in Table 3.

A. TARGET CELL SEARCH IN 4G

We introduce detailed TCS scenarios of two 4G systems.

In Fig. 7, we assume that there exist three main RATs, namely 2G, 3G, and 4G systems. Fig. 7 portrays an entire state transition diagram of almost all the cell search scenarios in active-RAT mode of LTE systems and their related inter-RAT target cell search scenarios such as 2G to LTE and 3G to LTE, in which either 2G or 3G is in active-RAT [47]–[53], where every square bracket represents specific conditions given to each mode of operational scenarios. Furthermore, a specific condition inside parenthesis manifests an optional information to be exploited in the mode. Additionally, there are three conditions represented as (1), (2), and (3). More explicitly, (1) represents that an explicit intra-frequency neighbor list including Physical-layer Cell-Identities (PCIs) can be optionally provided, where the PCI means the identifier of each cell in LTE system, which corresponds to the scrambling code exploited to differentiate among Node-Bs in W-CDMA and TD-SCDMA systems. The number of PCIs is constrained to 504 owing to its construction method. (2) indicates that in case of closed subscriber group cell search, at least one closed subscriber group ID is included in the UE's whitelist, where a closed subscriber group represents a set of subscribers of an operator who are allowed to access one or more cells having restricted access, referred to as closed subscriber group cell [47], and the whitelist is a list encompassing all the closed subscriber group identities and their related public land mobile network IDs of the closed subscriber groups for the subscriber registered [47]. Finally, (3) means that no explicit neighbor list for achieving closed subscriber group IDs is provided. It is also assumed that popular combinations of multi-mode mobile station modem may be classified into two modes, namely 1) GSM/GPRS/EDGE, W-CDMA/High Speed Packet Access, and LTE-FDD (or TD-LTE) as well as 2) GSM/GPRS/EDGE, TD-SCDMA/Time Division-High Speed Packet Access, and TD-LTE. It is noted that the second mode only exists in China.

Let us introduce almost all the TCS scenarios in RRC_CONNECTED and RRC_IDLE modes of Fig. 7. There are seven operational scenarios available in both modes of TCS scenarios, namely [C1/I1] First arrival path search, [C2/I2] TCS in intra-frequency cells including small (even closed subscriber group) cells, [C3/I3] TCS in inter-frequency cells including small (even closed subscriber group) and LTE-Unlicensed cells,[6] [C4/I4] TCS including inter-RAT W-CDMA small (even closed subscriber group) cells in L2W, [C5/I5] TCS in LTE to GSM/GPRS/EDGE (L2G), [C6/I6] TCS in L2T, and finally [C7/I7] TCS in Device-to-Device (D2D) communications. Furthermore, we also need to see TCS scenarios when GSM/GPRS/EDGE, W-CDMA, or TD-SCDMA is in active-RAT, namely [G1/G2] TCS in GSM/GPRS/EDGE to LTE (G2L), [T1/T2] TCS in T2L, and [W1/W2/W3] TCS in W2L, where except for CELL_DCH mode inter-RAT LTE closed subscriber group cells are also searched in W2L mode. From now on, we delve deeper into all the TCS scenarios illustrated in Fig. 7.

B. NORMAL TARGET CELL SEARCH

1) TARGET CELL SEARCH IN TYPICAL SCENARIOS

Even though RRC transition state of LTE constitutes two modes, namely RRC_CONNECTED and RRC_IDLE modes, the RRC_CONNECTED mode is further divided into two subcategories, expressed as connected and dormant states [45]. More explicitly, the former and the latter manifest active and discontinuous reception operation states, respectively. In the connected state, a UE is continuously transmitting and receiving signals to/from adjacent Node-Bs. Accordingly, a fully tightened TCS schedule is activated as long as the UE stays in the state, where [C1] to [C7] depicted in Fig. 7 are properly allocated depending on their priorities defined in [49]. According to the schedule, TCS blocks commence by searching all the candidates of adjacent cells included in a list of both intra- and inter-frequencies indicated by higher layer signaling. On the other hand, whenever the UE is in the dormant state of the RRC_CONNECTED mode,

[6]The details of LTE-Unlicensed will be explained in the Section IV-C-3.

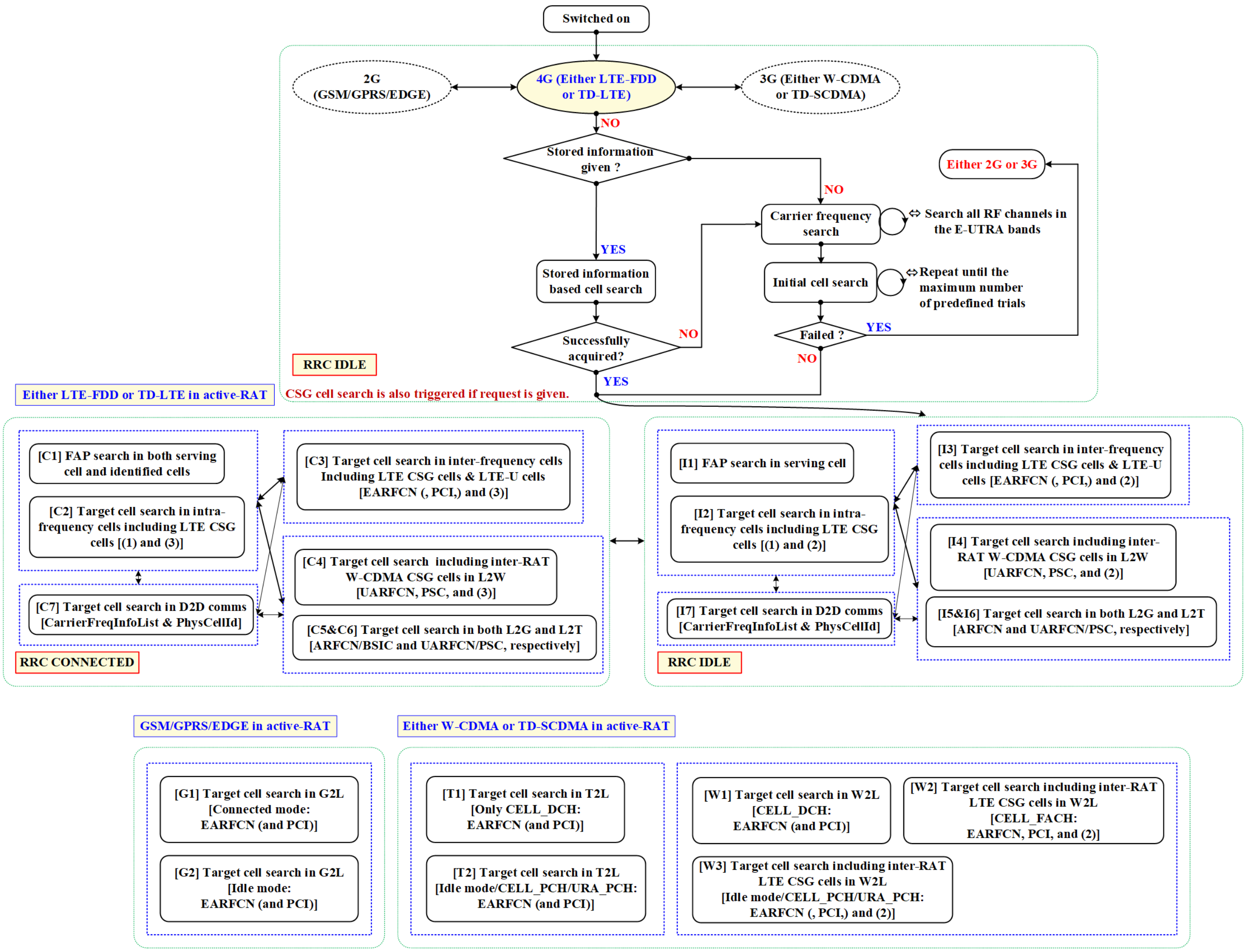

FIGURE 7. Entire cell search scenarios used in 4G system, where [C2/I2] and [C3/I3] also operate under diverse small cell deployment with heterogeneous network. CarrierFreqInfoList, FAP, and PhysCellID represent Carrier Frequency Information List, First Arrival Path, and Physical Cell ID, respectively.

connected state discontinuous reception mechanism starts to perform, which is capable of substantially reducing the tail energy. If any data packet does not exist during a predefined time period set by the connected state discontinuous reception inactivity timer, the UE only wakes up periodically to monitor the existence of new incoming signal. Until the connected state discontinuous reception inactivity timer is expired, a connected state discontinuous reception cycle is repeated periodically and a dedicated TCS schedule should also follow the cycle. Specifically, when a periodic wake-up commences, in order to recover both the timing and frequency deviations induced by clock drift and mobility, both first arrival path searcher and residual frequency offset compensator have to be activated in order to achieve the latest timing and frequency information, which may be referred to as reacquisition. Simultaneously, the predefined TCS schedules are also performed to find better candidates of a prospective serving cell. In the RRC_IDLE mode, when a UE wakes up and needs to monitor paging information regularly but sparsely, similar reacquisition procedures adopted in the connected state discontinuous reception and all the categories of TCS in the RRC_IDLE mode must be performed together, where [I1] to [I7] portrayed in Fig. 7 are properly scheduled to conduct the corresponding TCS operations.

From now on, we portray further the details of the TCS scenarios in Fig. 7. More explicitly, in case of [C1/I1], the main objective of first arrival path search is to achieve the largest receive energy in the multi-path propagation environments [65], [66]. For the sake of supporting seamless handover, discrete fast Fourier transform window alignment with the first arrival path is also performed in adjacent identified cells. Therefore, periodic first arrival path search in both a serving and identified cells is necessary for the UE to maintain timings of the first paths received in order to maintain the best possible link quality. [C2/I2] illustrates that the TCS in intra-frequency performs based on conditions (1) and (3). In order to support seamless handover, its performance requirement is much stricter than other types of TCS. Its procedure is almost the same as that of ICS with only residual frequency offset compensation. Similarly, [C3/I3] follows the TCS procedure mentioned in [C2/I2], which is conducted by using E-UTRA absolute radio frequency channel number. More explicitly, the carrier frequencies in the UL and DL are specified by the channel number ranging from 0 to 65535. Carrier center frequency used in LTE systems is allocated based on an integer multiple of 100 kHz [48], (3), and optionally PCI. The TCS searches candidates for handover in all indicated inter-frequencies encompassing diverse small and LTE-Unlicensed cells.

2) TARGET CELL SEARCH IN DUAL CONNECTIVITY MODE

Dual connectivity mode in Rel-12 version of LTE systems is capable of substantially improving per-user throughput and robustness of mobility by allowing UEs to be linked to both master cell group and secondary cell group via master enhanced Node-B and secondary enhanced Node-B, respectively. The dual connectivity mode is configured for the UE being in the RRC_CONNECTED mode [53]. The master cell group in the dual connectivity mode represents a group of serving cells related to the master enhanced Node-B, constituting the primary (serving) cell and optionally one or more secondary cells [53]. Similarly, the secondary cell group in the dual connectivity mode indicates a group of the serving cells related to the secondary enhanced Node-B, comprising the primary secondary cell and optionally one or more secondary cells [53]. The dual connectivity mode may be deployed in three typical scenarios, namely (1) Co-channel deployment in coverage of macro cell, (2) Inter-frequency deployment in coverage of macro cell, and (3) Small cell out of coverage of macro cell, where the small cell can be configured in either intra- or inter-frequency allocation. After the ICS procedure has been conducted, a UE commences by performing both intra- and inter-frequency TCS in order to acquire appropriate small cells to be used for determining the secondary cell group. If the dual connectivity capable UE is allocated with the primary secondary cell, whenever the measurement gap length is activated in the master cell group, the UE cannot transmit and receive any data in the secondary cell group during the corresponding interruption time period [49]. More explicitly, in case of the synchronous dual connectivity mode, the interruption time period is exactly the same as the measurement gap length. On the contrary, the asynchronous dual connectivity mode leads to mismatched subframe timing, which makes its entire interruption time period seven subframes, namely 7 ms. The UE is only capable of searching inter-frequency and inter-RAT cells in the master cell group. As long as the dual connectivity mode is activated, TCS will follow the existing scenarios except for the case that the master cell group discontinuous reception cycle is exploited. Similarly, in case of the intra-frequency TCS on the primary secondary cell, its TCS may be possible to find suitable intra-frequency adjacent cells. The TCS will also follow the existing scenarios except for the case that the secondary cell group discontinuous reception cycle is utilized.

According to the maximum reception timing difference of two modes in the dual connectivity operation [53], in the synchronous dual connectivity operation, the UE is capable of dealing with the timing difference up to at least 33 μs between cell groups. On the other hand, in case of the asynchronous dual connectivity operation, the UE is able to handle the timing difference up to 500 μs between cell groups. Hence, when determining the cell search window sizes of two modes under the given timing mismatch conditions, the former should be set to (33 + margin1 μs) wider than that of the single connectivity mode. Similarly, the latter should be set to (0.5 + margin2 ms) wider than that of the single connectivity mode, where both margins 1 and 2 may be determined based on information collected in real field tests. For the sake of supporting the dual connectivity operation, it is noted that an individual cell search module is assigned to each cell group, which may result in two sets of first arrival path search, TCS, and residual frequency offset compensation operated in parallel.

C. SPECIALIZED TARGET CELL SEARCH

1) TARGET CELL SEARCH IN HETEROGENEOUS NETWORK SCENARIO

Details of TCS in heterogeneous network scenario are further classified into 1-1) Interference cancellation assisted TCS in heterogeneous cell deployments, 1-2) Femto-cell TCS designed for closed subscriber group, and 1-3) Enhanced TCS in open-access small cells as follows:

1-1) Interference Cancellation Assisted TCS in Heterogeneous Cell Deployments: Through the evolution of LTE systems, the efficient deployment of small cells over macro-cell layout has given rise to high interests to mobile communication society. After a concept of heterogeneous network has been adopted in 3GPP, cells having diverse sizes have been configured, for example, mixed deployment of macro-, pico-, and(/or) femto-cells. Especially, the mixture of the diverse cells operating at the same carrier frequency, i.e., intra-frequency leads to severe inter-cell interference in heterogeneous network. In order to mitigate the interference effectively, enhanced inter-cell interference coordination has been adopted in Rel-10, where the enhanced inter-cell interference coordination enables a UE to compensate for strong interference induced by both control and traffic channels. More explicitly, the enhanced inter-cell interference coordination is capable of mitigating severe intra-frequency interference by employing frequency, power, and time domain based approaches. Additionally, a concept of almost blank subframe has been included, where the almost blank subframe does not transmit any traffic channels and does only control channels such as Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), Physical Broadcast CHannel (PBCH) and related reference signals for backward compatibility. The transmission of only the predetermined control channels manifests that PSS, SSS, and

PBCH comprise fundamental physical channels exploited for ICS and TCS procedures in LTE. Therefore, when the almost blank subframe pattern is scheduled on macro-cell, UEs staying in pico-/femto-cells transmit their data during the almost blank subframe period even though the UEs are sensitive to macro-cell induced interference. A similar manner is also used for almost blank subframe pattern configured by pico-/femto-cells. Furthermore, in Rel-11 for the sake of improving enhanced inter-cell interference coordination approach, further enhanced inter-cell interference coordination has been adopted to cancel inter-cell interference. Accordingly, interference cancellation capable functionality is added to the receiver, aimed for the cell-specific reference signal, PSS, SSS, and PBCH cancellations [67]–[69], where the cell-specific reference signal represents a specific reference signal corresponding to each cell to measure the corresponding channel quality in DL. A variety of the interference cancellation schemes targeted for dominant interference cells can be exploited for diverse heterogeneous network deployment scenarios.

Now, we take a closer look at the interference cancellation assisted TCS approaches. In order to improve the SSS detection performance in the TCS scenarios, frequency domain SSS cancellations have been analyzed in [21]–[23]. More explicitly, after the SSS detection is performed successfully, a regenerated SSS of the detected cell is subtracted from the entire received signals in the frequency domain and in the next round SSS detections for other adjacent cells having less interference are carried out. It is repeated until all of the non-negligible cells are acquired. However, either under enhanced inter-cell interference coordination or further enhanced inter-cell interference coordination situation having almost the same frame timing, both the PSS and SSS cancellations of the dominant interference cells are capable of substantially enhancing the detection performances of the TCS. According to [70], the time domain interference cancellation scheme has been used to improve the ICS detection performance. More explicitly, after the first cell information is detected, the following cell detection eliminates both the PSS and SSS regenerated from previous detected cell until a certain criterion is met. By efficiently removing both PSSs and SSSs of dominant inference cells, a UE is able to identify a proper cell. Similarly, for the sake of improving the TCS detection performance in the synchronous heterogeneous network deployment, the time domain interference cancellation based approach is capable of resolving hidden cell problem, which represents that candidates of cells to be detected may not be found owing to stronger serving and adjacent cells. Furthermore, the time domain interference cancellation is also exploited to suppress longer delay dispersion induced interferences exceeding cyclic prefix length under multi-cell environment. Further enhancement of detection is achieved in case of having bigger power offsets among adjacent cells [71]. On the other hand, the frequency domain interference cancellation technique was exploited in tracking mode [70]. Hence, unwanted PSSs are regenerated and aggregated to subtract all the PSSs from received signals in the frequency domain. Then, further accurate PSS position is determined under a situation without having dominant interferences, followed by the elimination of unwanted SSS. Moreover, a new approach demonstrate that a PSS, SSS, and PBCH interference cancellation assisted cell search has to be assumed under further enhanced inter-cell interference coordination environment in which scenario additional cancellation of PBCH is required for better master information block decoding performance [68]. Accordingly, diverse interference cancellation aided cell search strategies will be possibly proposed in the future heterogeneous network deployment scenarios.

The existence of different cell types in heterogeneous network requires UEs to follow more sophisticated cell search strategies. Here, small cell is classified into three categories, namely closed subscriber group/hybrid small cell, open-access small cell, and a cluster of densely placed small cells, where the small cell itself represents pico-/femto-cell [3], [47], [49], [51]–[53]. Additionally, one of main features adopted in Rel-10 is the employment of in-band relay to support cell coverage enhancement. A single relay is considered as a separate cell different from the donor cell, where the donor cell represents a macro-cell having an enhanced Node-B and relays are linked to the enhanced Node-B via radio interface. Namely, the relay cell has its own PCI. UEs can directly be synchronized to relays in all the possible cell search scenarios [72], [73]. Accordingly, the relay can be shown as an open-access small cell.

1-2) Femto-Cell TCS Designed for Closed Subscriber Group: As one of home enhanced Node-B categories, the deployment of femto-cells especially designed for closed subscriber group has been highlighted in Rel-9. Even though the deployment of femto-cells paves the way for leading to substantial capacity increment, its deployment also causes several downsides. More explicitly, most of the femto-cells are deployed in unplanned manner and the number of the femto-cells is presumably larger than an entire set of PSC in W-CDMA or that of PCI in LTE. Such the high number may result in PSC and PCI confusion [27], [47]. In case that there exist several closed subscriber group cells having the same PSC or PCI in the vicinity of the serving macro-cell, it is impossible to identify a target closed subscriber group cell based on the PSC or on PCI detected. Furthermore, guaranteeing high mobility and seamless handover supports on the femto-cells play a pivotal role in deploying the femto-cells over a macro-cell. For the sake of facilitating the femto-cell detection in W-CDMA/LTE system deployments,[7] there exists six ways of improving the femto-cell TCS performance as follows [25], [27], [47], [74], [75].

(1) A configuration of high search threshold set to macro-cells can be considered. However, its disadvantage is

[7]In Rel-9, femto-cell and closed subscriber group cell are used interchangeably. The femto-cell TCS procedure in W-CDMA is similarly exploited for that in LTE.

to consume battery inefficiently owing to frequent cell search trials.

(2) Dedicated TCS for carrier frequency bands having high priority is used for finding the femto-cells. Accordingly, the UE is capable of searching the specific carrier frequency bands every predetermined period, which is referred to as slow background search [27], [74].

(3) Cell reselection beacon has been proposed in [25], [74], where the femto-cell broadcasts the cell reselection beacon on its macro-cell's carrier frequency. More explicitly, the cell reselection beacon has two-layer structure constituting sparsely allocated periodic peaky signal burst having very short duration and low power beacon occupying the remaining duration in the time domain in order to detect UEs located in both the femto-cell edge and close vicinity, respectively.

(4) Neighbor cell list targeted for the femto-cells is capable of reducing candidates of PSC or those of PCI in order to support the femto-cell TCS [27], [75].

(5) Manual closed subscriber group search is elucidated in W-CDMA and LTE, where a UE is able to find a dedicated closed subscriber group cell manually. The manual search request allows the UE to scan closed subscriber group IDs available by searching all the possible carrier frequency bands reserved for closed subscriber group cells [27], [75]. The search is only required in idle mode [47].

(6) UE based autonomous cell search is currently considered as a promising solution to perform both intra- and inter-frequencies as well as inter-RAT femto-cells' detection. In case of W-CDMA being in active-RAT, only LTE is considered as inter-RAT and vice versa. [25], [47], [74], [75]. The method can be activated in either event-trigger or periodic mode. The UE based autonomous cell search is capable of determining when and(/or) where to search for closed subscriber group cells previously visited.

Among these six methods, we focus on the UE based autonomous cell search in cognitive radio and a cooperative manner, because the approach has been interested in 3GPP standardization society [47], [75]. UEs are capable of storing a list of available closed subscriber group IDs and its accessibility is directly related to whether the closed subscriber group ID received is encompassed in the UE's closed subscriber group whitelist or not. It is noted that at least one closed subscriber group ID should be encompassed in the whitelist. Otherwise, the UE based autonomous cell search should be disabled [47], [49], [51]. Activation of the UE based autonomous cell search allows UEs to camp in closed subscriber group cells with the aid of fingerprint information. When the UE visits a closed subscriber group cell for the first time, the first manual selection of the target closed subscriber group cell is mainly carried out by users. During the selection, the UE must acquire fingerprint information of the closed subscriber group cell and the information collected is stored in the UE. In order to detect closed subscriber group cells, how to efficiently use proximity detection features based on fingerprint is under a crucial UE design issue. By utilizing the features, a UE determines whether it is in the vicinity of the target closed subscriber group cells whose closed subscriber group IDs are in the UE's whitelist. More explicitly, the reason why the proximity detection for finding closed subscriber group cells has been proposed is to restrict the geographical range of the possible candidates for closed subscriber group cell handover. The employment of multiple fingerprints is further to reduce the range.

For the sake of supporting inbound handover procedure to a target closed subscriber group cell, a UE has to proceed the followings. When entering the range of all the possible candidates for the closed subscriber group cell handover based on fingerprints measured, a UE reports a proximity indication to the serving macro-cell. Then, the UE tries to detect either PSC or PCI of the target closed subscriber group cell. When uniquely identifying the closed subscriber group cell ID, the UE has to receive the details of system information broadcast from the closed subscriber group cell, for example, cell global identity/evolved UTRA network cell global identity, tracking area identity, and closed subscriber group ID, where each identity represents a unique identifier to distinguish the closed subscriber group cell from all other cells. Both the cell global identity and the evolved UTRA network cell global identity are used in W-CDMA and LTE-Advanced, respectively. The tracking area identity means area unit to register UE's location in LTE, which constitutes one or multiple cells. By exploiting the information obtained, the serving macro-cell identifies the target closed subscriber group cell in order to support UE's mobility and handover [24], [27], [47], [76]. Fig. 8 (a) illustrates a brief procedure of the cell search for finding the target closed subscriber group cell. Fingerprint information is classified into two categories, namely 3GPP and non-3GPP based information. The employment of only macro-cell based fingerprints provides quite reliable, but inaccurate decision of proximity indication. On the other hand, the additional use of non-3GPP based fingerprints enhances its accuracy but consumes non-3GPP related resources. Fig. 8 (b) visualizes a concrete relationship among two fingerprint zones and the corresponding target closed subscriber group cell.

Now, let us commence by portraying 3GPP and non-3GPP based fingerprints. According to [77]–[85], the 3GPP based fingerprints may be classified into seven categories as follows:

(1) A certain range of PSC/PCI value, (2) Neighbor cell list associated with macro- and closed subscriber group cells, (3) A list of carrier frequencies and RAT information (E-UTRA absolute radio frequency channel number/UTRA absolute radio frequency channel number), (4) E-UTRA network cell global identity/cell global identity of macro-cell, (5) reference signal receive power/reference signal receive quality/received signal code power, (6) Registered public land mobile network, and (7) Enhanced cell ID and observed time difference of arrival. Among those seven categories, the enhanced cell ID denotes a positioning feature of LTE [86] and the observed time difference of arrival represents another

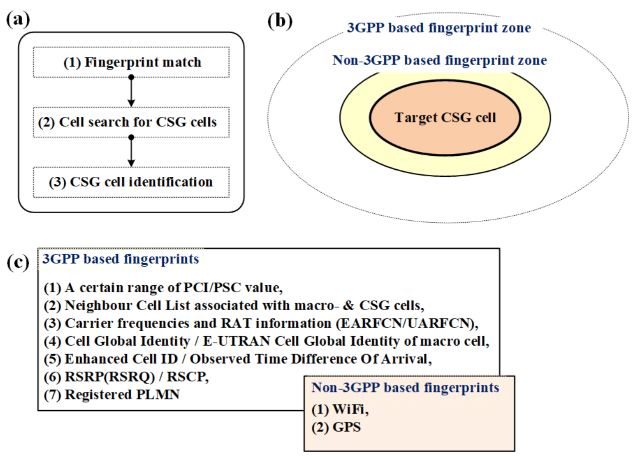

FIGURE 8. UE based autonomous cell search, where (a) represents an entire procedure of the cell search for finding the target closed subscriber group cell, (b) portrays a concrete relationship among two fingerprint zones and the corresponding target closed subscriber group cell, and (c) illustrates 3GPP and non-3GPP based fingerprints. E-UTRAN, PLMN, RSCP, RSRP, and RSRQ represent E-UTRA Network, Public Land Mobile Network, Received Signal Code Power, Reference Signal Receive Power, and Reference Signal Receive Quality, respectively.

positioning feature used in W-CDMA and LTE [86], [87]. In LTE, the reference signal receive power indicates the average power of resource elements carrying cell-specific reference signals over the entire bandwidth. Hence, the reference signal receive quality is defined as reference signal receive power over received signal strength indicator, where the indicator means total received wide-band power [84]. Similarly, the received signal code power represents the average power measured based on P-CPICH received in W-CDMA [85]. The macro-cell based approach (equivalent to 3GPP based one) has been considered as a reference scenario [53], [78]. The main design issue exhibits what minimum set of the macro-cell based fingerprint information should be known by the UE in order to identify its fingerprint matching. For the sake of further localizing the fingerprint zone as illustrated in Fig. 8 (b), the additional employment of the non-3GPP based fingerprints is a critical UE implementation issue. The non-3GPP based fingerprints may be categorized into two approaches, namely WiFi and Global Positioning System (GPS) [79], [80], [82], [83]. Fig. 8 (c) summarizes the 3GPP and non-3GPP based fingerprints. More explicitly, out-of-band radio assisted proximity indication detection approach has been proposed in [24]. Under the scenario, a UE commences by searching for the target closed subscriber group cell over the out-of-band link, namely WiFi signal link, because the WiFi signal coverage is quite similar to that of the typical closed subscriber group cell. Accordingly, the frequency of the proximity indication report to the serving macro-cell is substantially reduced and therefore an activation of the measurement gap is also proportionally decreased. It is especially crucial for the UE to minimize macro-cell's capacity loss. Another approach for enhancing the closed subscriber group cell fingerprinting matching is based on additional positioning information exploiting the GPS signal. Hence, the employment of GPS signal aided geography is also feasible to further localize the fingerprint zone. However, GPS receiver could also lead to substantial accuracy errors inside houses or buildings. If a UE is capable of determining further accurate fingerprint matching by using WiFi and(/or) GPS information having a high confidence, its proximity indication may be reported in spite of not having PSC/PCI matched to the previously visited closed subscriber group cells because femto-cells may change its PSC/PCI owing to its reset [79]. Accordingly, the efficient use of multiple 3GPP and non-3GPP based fingerprints is very beneficial for the UE to guarantee more accurate fingerprint matching. It is noted that the best possible combination has to maintain the best possible battery efficiency with respect to UE's implementation.

1-3) Enhanced TCS in Open-Access Small Cells: There have been diverse ways of improving successful discovery rate of the open-access small cells such as open home enhanced Node-Bs and pico-cells [26], [88]–[90]. According to [88], with some modification of the current specifications, ten potential solutions have been discussed for enhancing the open-access small cell discovery and identification. Among them, particular interests have been highlighted to (1) The employment of longer measurement period, (2) UE mobility state estimation, (3) An extension of UE based proximity detection used in detection of closed subscriber group/hybrid cells, and (4) The proximity detection based on macro and open-access small cell listening. Furthermore, we also would like to spotlight (5) Power boosting mode of synchronization related signals [28], (6) Interference cancellation aided detection [68], and (7) The use of initial frequency offset estimated at carrier frequency of a serving macro-cell [91]. More explicitly, the method (1) is also referred to as background inter-frequency cell search. Compared with the currently standardized scheme supporting frequent inter-frequency measurement gap patterns, the use of the longer measurement period is capable of reducing UE's power consumption at the cost of the number of the inter-frequency TCS and their measurements [26], [88], where its search period may be set to 60 sec. The method (2) represents that mobility state aided flexible TCS is used for detecting small cells mainly deployed in a dedicated carrier [26], [88], [90]. Specifically, the mobility state is estimated by counting the number of handovers or that of cell reselection conducted during a predefined time period, where the mobility state estimation constitutes the normal (or low), medium, and high mobility states. The TCS is activated only if its mobility status indicates the normal mobility state. Otherwise, the TCS is suspended. It is also noted that the method (2) can be performed with other methods (1), (3), or (4) to improve its cell detection probability. This method (3) is almost the same as that of the UE based proximity detection for closed subscriber group/hybrid cell detection, in which multiple reference signal receive power sets and its corresponding macro-cell ID are exploited [26], [88]. In the method (4), the proximity detection for inter-frequency open-access small cells is conducted by a serving macro enhanced Node-B. By exploiting a periodic measurement report sent from UE(s), the serving macro enhanced Node-B is capable of activating the inter-frequency small cell discovery and the following measurements for associated UE(s). Network operators guarantee better control to mobility in heterogeneous network. The details of the network based proximity detection scheme are under enhanced Node-B implementation issue [88], [89]. In addition, a combination of both the network-oriented and UE-aided RF fingerprinting schemes has been proposed to reduce the small cell discovery time substantially [89], which is a joint approach to exploit the methods (3) and (4) portrayed above.

In case of a macro-cell enhanced Node-B overlaid with open-access small cell such as pico-cell operating at the same carrier frequency band, either inter-site enhanced Node-Bs' synchronization or at least its partial synchronization has to be maintained owing to the support of several multi-cell cooperative schemes adopted in LTE systems [28], [92], [93]. Under the heterogeneous network deployment, cell range expansion is the most popular technique to offload cellular traffic to small cells [28], [92]. Even though the pico-cell range is successfully extended by the cell range expansion scheme, at cell edge of the pico-cells enlarged by the cell range expansion bias value, the pico-cell's signals overlaid to a macro-cell severely suffer from huge inter-cell interference induced by a serving macro-cell. The inter-cell interference also leads to substantial TCS performance degradations. For the sake of improving all the cell search performances, from enhanced Node-B perspective, the method (5) referred to as power boosted mode of cell search related signals such as PPS, SSS, and cell-specific reference signals becomes a feasible solution to mitigate the cell search performance deterioration at cell edge of the pico-cells expanded by the cell range expansion approach [28]. Furthermore, the method (6), namely interference cancellation aided cell search operation plays a pivotal role in further enhancing the cell search performance at the cost of additional complexity and power consumption on the UE side [68]. Hence, a reasonable combination of both approaches enables the UE to increase the cell search performance substantially. On the other hand, in case of a macro-cell based enhanced Node-B overlaid with the pico-cells operating at the different carrier frequency band, a typical approach manages two separate cell search operations corresponding to both macro- and small cells, respectively. The method (7) exploits the initial frequency offset measured at a carrier frequency of 2 GHz in order to achieve further accurate frequency offset estimate at a carrier frequency of 3.5 GHz, because the autocorrelation of the PSS may cause proportionally higher false correlation peaks under higher frequency offset value [91]. Therefore, according to a comparison between two PSS correlation peaks attained at these two carrier frequencies, the step 1 and 2 of the ICS employing both the PSS and SSS are performed at a carrier frequency having the highest PSS correlation peak. Similarly, in case of TCS operations, the behavior may lead to similar issue.

2) TARGET CELL SEARCH IN SMALL CELL ENHANCEMENT SCENARIO

According to standardization of Rel-12, one of important ways for increasing cell capacity is deployment of densely located small cells in a cluster, which is referred to as small cell enhancement [29]. Even though several small cell deployment scenarios exist, presumably the most popular scenario becomes a deployment of small cells operating at a specific higher carrier frequency of 3.5 GHz under a serving macro-cell as visualized in Fig. 9 (a) [29], [94]. Fig. 9 illustrates deployments of a group of small cells overlaid in a serving macro-cell, where (a) represents a cluster of three small cells synchronized in terms of allowable time and frequency errors [95] and (b) portrays a periodic Discovery Reference Signal (DRS) transmission constituting PSS, SSS, cell-specific reference signals on antenna port 0 in a predetermined consecutive subframes, and channel state information reference signals in the same consecutive subframes under a synchronized small cell cluster, where the synchronization of the DRSs in a cluster may be maintained by assistance control information such as periodic transmission interval ranging from 40, 80 to 160 ms and starting timing of the DRS. Owing to the same cell ID shared by adjacent small cells in a cluster, channel state information reference signal is optionally employed to identify each small cell and measure the corresponding signal quality. It is also noted that a set of the predetermined consecutive subframes is referred to as DRS window duration denoted as "D" in Fig. 9 (b). In the situation, the DRS must be transmitted periodically in order to guarantee that UEs entering a small cell acquire the cell's system information without severe delay even if some of adjacent small cells are alternately deactivated to minimize adjacent small cell induced interferences as portrayed in Fig. 9 (b) [3], [29], [94], [96], [97]. Finally, Fig. 9 (c) visualizes detection of DRS at three different carrier frequencies represented as F1, F2, and F3, where small cells in different carrier frequencies are not synchronized especially in the time domain. Specifically, an observation of the DRS at F1 is repeated every 40 ms and those of the DRSs at both F2 and F3 are done every 80 ms. It is also assumed that the length of the measurement gap is set to 6 ms. By employing both PSS and SSS transmitted from each small cell in a cluster, coarse time and frequency synchronizations are attained and then the exploitation of cell-specific reference signals enables UE to achieve accurate time and frequency synchronizations. In case that small cells configured in multiple carrier frequencies are required to search, in order to support an efficient discovery of densely located small cells in a cluster, a combination of synchronized DRS transmission and additional network aided control information such as transmission timing and associated configuration has been analyzed [94]. A specific grouping method to reduce severe inter-small cell induced interference has also been proposed [98]. Even though research efforts

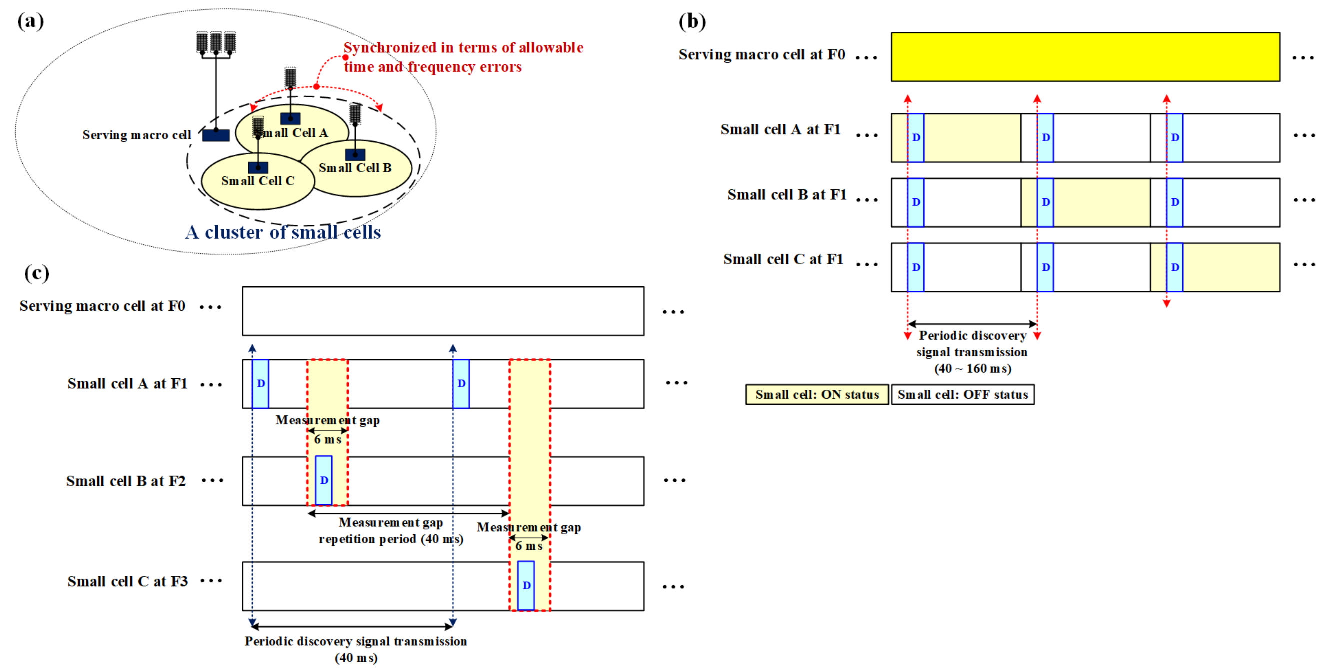

FIGURE 9. Deployment of small cells overlaid in a serving macro cell, where (a) represents three small cells synchronized in a cluster, (b) portrays a periodic DRS transmission constituting PSS, SSS, CRS, and CSI-RS in a synchronized small cell cluster, and (c) illustrates detection of DRS at different carrier frequencies. It is noted that the small cells in different carrier frequencies are not synchronized especially in time domain as well as CRS and CSI-RS represent Cell-specific Reference Signal and Channel State Information Reference Signal, respectively.

on diverse designs for better synchronization signals such as an introduction of auxiliary SSS to increase the entire number of cell IDs have been investigated under heterogeneous network environments, our main attention on cell search strategies has been limited to the current 3GPP specifications. Further details of the new design issues are portrayed in [96], [99]–[101].

3) TARGET CELL SEARCH IN LTE OPERATING ON UNLICENSED SPECTRUM SCENARIO

With the advent of small cell based capacity boosting approaches, the 3GPP has also manifested higher interest to unlicensed bands available. Especially, the 5 GHz spectrum band used mainly in WiFi systems is considered for open-access indoor small cells or outdoor hot spots to utilize extensive amount of unlicensed spectrum bands available around the globe, where the small cells represent both femto- and pico-cells. Deployment of LTE and its evolutions in the unlicensed spectrum bands is capable of aggregating the unlicensed band with the licensed one to leverage the DL only carrier aggregation scheme adopted in Rel-10 [102]–[106], [109]. Specifically, the primary (serving) cell operates at the licensed anchor carrier, whereas the secondary cell does at the unlicensed one. The above assumption means that LTE and its evolutions do not work as a stand-alone system on the unlicensed spectrum bands. There are two ways of realizing LTE and its evolutions in the unlicensed spectrum bands.

3-1) The first approach of LTE operating on unlicensed spectrum scenario is not to modify the existing specification, namely LTE-Unlicensed (LTE-U). The LTE-U without any modification can be deployed in regions such as the US, South Korea, China, and India. More specifically, without modifying Rel-10 protocols a fair coexistence with unlicensed technologies such as WiFi systems becomes feasible only with additional software based functionality. For the sake of minimizing detrimental co-channel interference induced to both WiFi access points and other LTE-U enhanced Node-Bs in the proximity, it is crucial for LTE-U capable enhanced Node-B and UEs to search the best possible channel operating at 5 GHz bands available. LTE-U utilizes Unlicensed National Information Infrastructure (UNII)-1 and UNII-3 radio bands, which correspond to 5150 to 5250 MHz and 5725 to 5850 MHz, respectively [109]. Even though a 100 kHz frequency channel raster is exploited for LTE-Advanced, it leads to extremely large search space in a very wide spectrum of 5 GHz unlicensed band. When assuming that LTE-U deployment in the unlicensed spectrum is set to 20 MHz, it is reasonable for LTE-U to align the channel raster with WiFi channel having 20 MHz. Additionally, in case that carrier spacing of the intra-band contiguous carrier aggregation should be a multiple of 300 kHz, it is also required to allocate adjacent carrier frequencies with the 20 MHz channel raster. To elaborate it a little bit further, the operations of LTE-U are restricted only to the following carrier frequencies. For UNII-1 radio band, $f_{(UNII-1)}$ is set to 5160, 5180, 5200, 5220, and 5240 MHz. By exploiting these five values, we further contemplate $f_{(UNII-1)}, f_{(UNII-1)} \pm 1$ and $f_{(UNII-1)} \pm 2$ to calculate the corresponding search space. Similarly, in case of

UNII-3 radio band, $f_{(UNII-3)}$ is set to 5745, 5765, 5785, 5805, and 5825 MHz. Then, $f_{(UNII-3)}$, $f_{(UNII-3)} \pm 1$ and $f_{(UNII-3)} \pm 2$ are used for determining its search space. Accordingly, there exists only 50 hypotheses for carrier frequency search and inter-frequency TCS procedures of LTE-U scenario, which substantially reduces the search space to be considered.

During the secondary cell activated, LTE-U DRS is periodically transmitted by the LTE-U enhanced Node-B to support proper secondary cell's detection and measurements [107]. More explicitly, detection of the LTE-U DRS is capable of achieving the secondary cell's time and frequency alignments and then also conducting the secondary cell's time and residual frequency offset trackings as well as their associated measurements. The LTE-U DRS constitutes cell-specific reference signal, PSS, and SSS as well as physical downlink control channel and physical downlink shared channel in the fifth subframe, where both channels are utilized for system information block type 1 transmission. Its definition is quite similar to that of the DRS used in a cluster of small cells as portrayed in Fig. 9 except for channel state information reference signal. Its transmission may be maintained by assistance control information such as periodic transmission interval ranging from 40, 80 to 160 ms. The intra-frequency TCS and related measurements are conducted within a configured measurement window duration as well as the inter-frequency TCS and related measurements are also carried out within a configured measurement gap duration. Furthermore, both master information block and system information block type 1 on the secondary cell are broadcast at least once every 160 ms. LTE-U capable UE needs to distinguish transmissions from LTE-U enhanced Node-Bs associated with other public land mobile networks. The UE must gain a capability of inter-frequency automatic neighbor relation opted for available LTE-U unlicensed bands. A summary of the automatic neighbor relation procedure may be portrayed as follows [107]: (1) The LTE-U capable enhanced Node-B asks UEs to conduct related measurements for an allocated carrier frequency, (2) The UEs try to acquire timing, frequency, and PCI information of the current LTE-U transmissions on the carrier frequency, (3) Detected information encompassing PCI is fed back to the enhanced Node-B, (4) The enhanced Node-B further commends the UEs to obtain cell global identity IDs and public land mobile network IDs of the previously detected LTE-U enhanced Node-Bs operating in inter-frequency LTE-U bands, (5) The cell global identity is finally reported to the enhanced Node-B via the cell global identity report.

Fig. 10 illustrates an example of clear channel assessment at LTE-U enhanced Node-B side as well as the following cell search operation scenarios at both carrier-sensing adaptive transmission and clear channel mode when a specific channel is allocated. Fair coexistence mechanism constitutes (1) Clear channel assessment, (2) Carrier-sensing adaptive transmission, and (3) Opportunistic supplementary DL [102], [108]. More explicitly, the supplementary DL transmission is managed opportunistically by monitoring the traffic demand. Therefore, when the LTE-U small cell is lightly loaded, the secondary cell in the unlicensed spectrum band is switched off to avoid the existing interference to adjacent WiFi access points. UEs are only linked to the primary (serving) cell in the licensed spectrum band.

As portrayed in Fig. 10, the clear channel assessment determines the cleanest channel by using WiFi and LTE measurements, because its policy avoids interference among the LTE-U small cell, adjacent WiFi access points as well as other LTE-U small cells. Specifically, the LTE-U enhanced Node-B searches predetermined candidates of the unlicensed bands comprising UNII-1 and UNII-3 as well as detects the cleanest channel for the supplementary DL carrier to be used in carrier aggregation. When measured interference level is higher than a predefined threshold value on the existing carrier frequency and then there exists another cleaner channel found, the new channel is allocated to the secondary cell by employing Rel-10/11/12 procedures, in which the process also needs to avoid channels occupied by strong LTE-U small cells of other mobile network operators. Accordingly, the clear channel assessment plays an essential role in performing efficient channel sensing. The clear channel assessment procedure is mainly implemented by reusing the existing energy detectors and(/or) matched filters of LTE-U enhanced Node-Bs, LTE-U UEs, and WiFi access points [109].

Now, let us investigate both energy detector and matched filter a little bit further. Among diverse channel sensing methods [110], the matched filter dedicated to specific waveform is the most robust with the highest complexity owing to its priori information regarding predefined synchronization signal patterns. By contrast, the energy detector becomes the most common way of spectrum sensing due to its lowest complexity, however it has the lowest detection capability. For the sake of measuring interferences and detecting the existing signals in each channel, diverse combinations of the energy detector and the matched filter have been proposed. There exists two stage aided interference and the existing signal detection method [102], [108]. At the beginning of the measurement procedure, the interference level in an individual channel is measured by employing energy detection. Therefore, the energy detector is capable of acquiring received signal strength indicator values of all the existing channels. Then, the matched filters dedicated to LTE-U and WiFi receivers are used to enhance interference detection sensitivity and additional specific information. More explicitly, from LTE-U capable enhanced Node-B perspective, its WiFi preamble detector using matched filters identifies the existences of all nearby WiFi access points operating in an assigned channel and an LTE-U network listening module is also exploited to acquire PSS, SSS, and PBCH channels of neighboring LTE-U enhanced Node-Bs. Similarly, the corresponding LTE-U capable UE is enabled to address the hidden node effect and facilitate better channel selection by reusing the existing PSS/SSS/PBCH detectors and WiFi preamble detector. There are three clear channel assessment detection schemes on the WiFi receiver [37], [111]–[114],

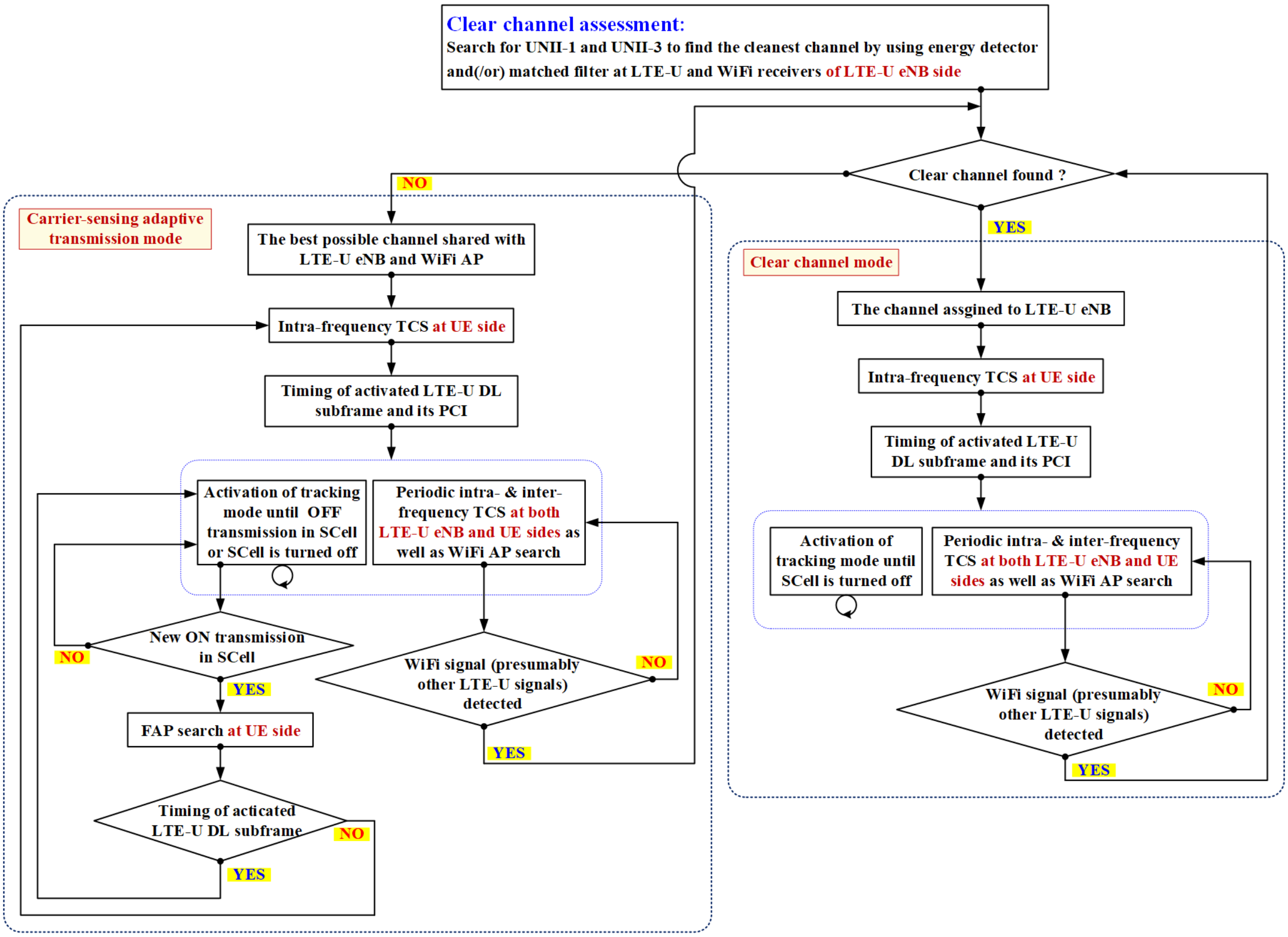

FIGURE 10. **Illustration of clear channel assessment at LTE-U enhanced Node-B side as well as the following operation scenarios at both carrier-sensing adaptive transmission and clear channel modes, where AP, eNB, and SCell represent Access Point, enhanced Node-B, and the secondary cell, respectively.**

that is to say, (1) Energy detection using non-coherently accumulated energy measurement irrelevant to the nature of transmitted signal, (2) Preamble detection exploiting matched filters dedicated to a predefined preamble constituting repetitions of pseudo noise code, (3) Decorrelation-based detection employing all pairs of matched filters for detecting transmitted signal in which the detection finds specific spreading characteristics of an 802.15.4 signal. Depending on specific scenarios, one of them can be chosen for its realization.

After a clear channel is assigned to LTE-U enhanced Node-B, intra-frequency TCS at UE side commences by acquiring timing of activated LTE-U DL subframe and its PCI. Then, the following tracking mode is capable of maintaining timing and frequency information of the detected DL subframe until the secondary cell is switched off. At the same time, periodic intra- and inter-frequency TCS at both LTE-U enhanced Node-B and UE sides as well as WiFi access point search are performed to monitor the change of interference level and find the best possible channel. If either WiFi signal or other LTE-U signals are detected, the current LTE-U enhanced Node-B has to move onto the best possible channel. On the other hand, in case that no clean channel exists, as illustrated in Fig. 10, the best possible channel is shared with LTE-enhanced Node-B and WiFi access points. Carrier-sensing adaptive transmission scheme applies adaptive time division multiplexing based transmission to LTE-U small cells, which is able to exploit long-term carrier sensing of co-channel WiFi access points' activities. Specifically, for the sake of supporting fair coexistence with other LTE-U enhanced Node-Bs and WiFi access points operating on the same unlicensed channel, the LTE-U enhanced Node-B conducts adaptive ON and OFF transmission based on the subframe in which LTE-FDD subframe format is only considered in LTE-U secondary cell's operation. It is noted that the maximum secondary cell ON-state period shall not be longer than 20 ms, whereas the minimum secondary cell ON-state period shall not be shorter than 4 ms. On the other hand, the minimum secondary cell OFF-state period is set to 1 ms. The maximum secondary cell OFF-state period depends on the LTE-U DRS periodicity [107]. Every ON status, the start timing of activated LTE-U DL subframe is deviated from the previously used timing owing to clock drift and mobility. Therefore, the employment of first arrival path searcher at UE side seems to be inevitable to acquire new timing of DL subframe on the secondary cell. If the trial may fail, intra-frequency TCS is activated to reacquire proper timing information of the activated DL subframe. All the intra- and inter-frequency TCS having their measurements on the secondary cell comply with the existing 3GPP specifications.

3-2) The second approach of LTE operating on unlicensed spectrum scenario represents License-Assisted Access (LAA) with a modification of the specification adopted in Rel-13 to provide a unified global solution complying with the regulatory requirements. More explicitly, Rel-10/11/12 based LTE-Advanced employing additional unlicensed spectrum bands cannot be exploited in specific markets such as Europe and Japan because there exist strict unlicensed band restrictions on the channel occupation, which requires Listen-Before-Talk (LBT) and minimum bandwidth occupancy [102], [106]. Accordingly, the cognitive radio assisted spectral management approach adopted in LTE-U is insufficient. Transmissions under unlicensed spectrum scenario must be handled in further finer time scale level, which leads to change at both media access control and physical layers. LAA also exploits both UNII-1 and UNII-3 radio bands, which are the same as those of LTE-U. The LBT adopted as a coexistence mechanism for LAA is a regulation for unlicensed spectrum bands, which periodically measure whether other signals are busy or not in the channel (known as 'Listen') before transmitting (also known as 'Talk') at millisecond scale [104], [105], [115]–[118]. When the LTE licensed cell and LAA assisted cells are configured in non-collocated situations, sufficiently large propagation delay is capable of arising timing discrepancy of up to tens of microseconds, which manifests an unavoidable rationale for the employment of LAA DRS transmission. A DRS introduced in Rel-12 provides the capability of time and frequency synchronizations cell identification, as well as radio resource management measurement for relevant UEs when the small cells are in a dormant state. Similarly, the DRS is reused to allow UEs to search and measure the dormant unlicensed cells. That is, the role of the LAA DRS is exactly the same as that of the Rel-12 DRS as visualized in Fig. 9. Hence, LAA DRS transmission is exploited for meeting the purposes of the DRS adopted in Rel-12. In addition, the LAA DRS can be utilized for signal quality measurements. More explicitly, in case that measured values such as reference signal received power and reference signal receiving quality are higher than their predetermined thresholds, an event-triggered measurement report at the UE will be sent back to the LAA capable enhanced Node-B via licensed carrier in order to aid suitable cell selection, carrier selection, and radio resource allocation involved directly in a given set of unlicensed carriers.

In order to satisfy the more rigorous timing requirement specified in Rel-13, a periodic LAA DRS transmission has been shown as portrayed in Fig 11 visualizing opportunistic LAA DRS transmissions at LAA capable enhanced Node-B [115]–[118]. To elaborate it a little bit further, transmission of LAA DRS can be placed in a DRS measurement timing configuration window anywhere if LBT procedure is successfully complete, where the window has a predetermined duration of 6 ms and a configurable periodicity of 40/80/160 ms. Therefore, its transmit timing is predetermined and known to the UE, which enables to monitor each DRS based on the timing from the licensed carrier. It is noted that the transmission of LAA DRS is opportunistic as a result of the clear channel assessment by sensing the channel during a single slot duration as illustrated in Fig. 11. More specifically, if a success of clear channel assessment is reported, LAA DRS transmission in a particular subframe is activated and followed by dedicated TCS operation. Otherwise, UE needs to wait for the next LAA DRS transmission. Further details of the clear channel assessment and the following TCS scenarios are detailed in Fig. 10, where the TCS operations of the clear channel mode under LTE-U are the same as those under LAA. That is, with respect to TCS scenarios in unlicensed spectrum, both LTE-U and LAA configurations are mainly similar to each other. Only difference in TCS operations is directly associated with the non-clear channel mode, because both carrier-sensing adaptive transmission mode in LTE-U and LBT mode in LAA follow their own different protocols, respectively. Even though a single DRS transmission is scheduled during a DRS measurement timing configuration window, time and frequency drifts between two consecutive DRSs are still under tracking capability. Hence, reliable TCS performance based on LAA DRS can be attained. For the sake of incrementing the number of the successful LAA DRS transmissions and enhancing the corresponding LAA DRS detection performance, the transmission of LAA DRS in any subframe should be guided by the network command within the DRS measurement timing configuration window. An exemplification of LBT operations in Fig. 11 demonstrates a variant of frame based LBT transmission [115]–[118]. Under the particular configuration, if an unlicensed small cell B is not synchronized to adjacent cell A in time domain, namely within the DRS transmission subframe duration of cell A, the corresponding time unsynchronization between cells A and B enables to generate a failure of clear channel assessment and the following deactivation of TCS repeatedly. Accordingly, the transmission of LAA DRS should be subject to LBT operation to minimize a collision probability. For example, a concrete configuration of the unlicensed small cell C manifests how a collision event is avoided. Even though a minimization of the blocking event is under implementation issue, the remedy of LAA DRS transmission is to compensate for the blocking event through the increased opportunities of DRS transmissions within a single DRS measurement timing configuration window. As demystified by cases of those cells B and C, a specially chosen subframe at LAA capable enhanced Node-B can be exploited for conducting clear channel assessment until a successful clear channel

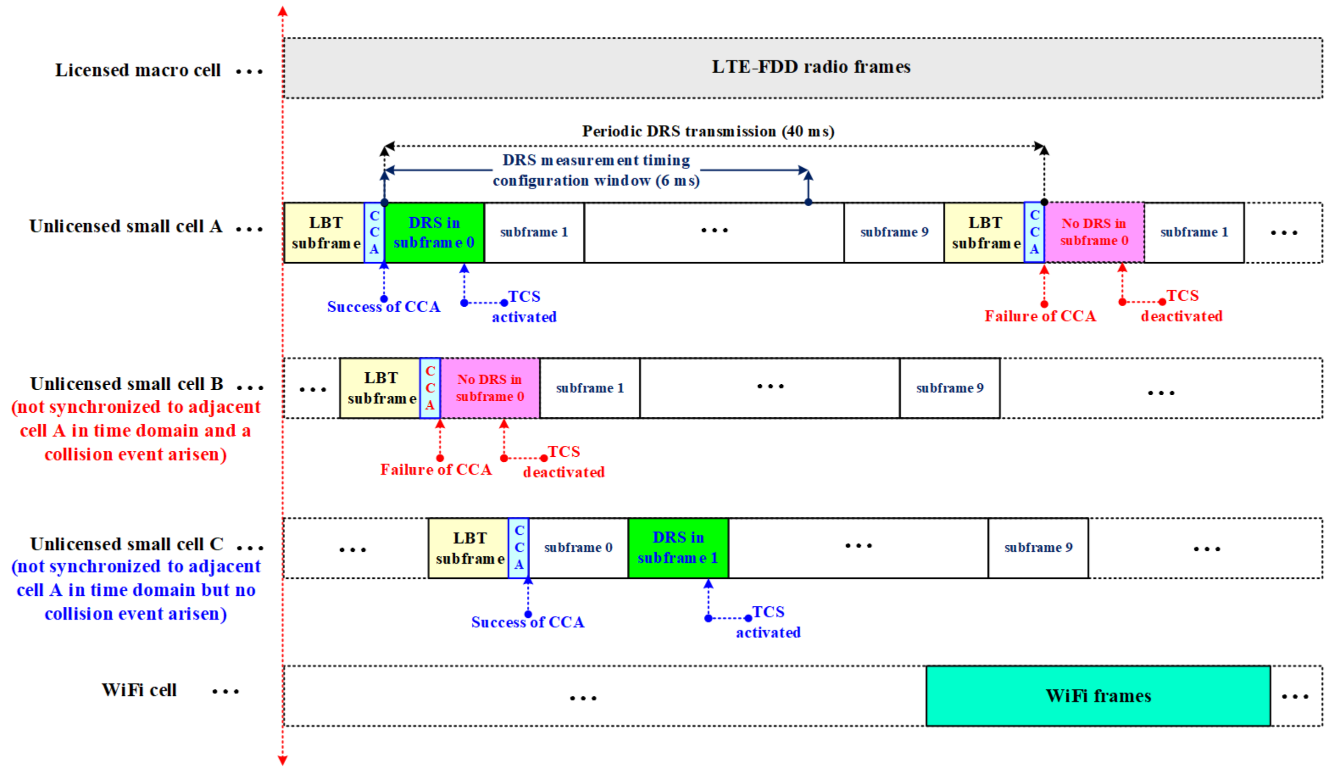

FIGURE 11. Visualization of opportunistic LAA DRS transmissions at LAA capable enhanced Node-B, where CCA represents Clear Channel Assessment.

assessment achievement or the expiration of entire clear channel assessment trials. The second clear channel assessment trial in cell A elucidates how a DRS transmission is not successful and finally the following TCS operation is also deactivated while active WiFi frames exist. Under heterogeneous configurations of multiple unlicensed small cells and WiFi cells, the LBT approach leveraging the opportunistic DRS transmission results in the increase of the successful DRS transmission possibility to alleviate the harmful blocking issue at the cost of incremented complexity of multiple DRS detections.

4) TARGET CELL SEARCH IN DEVICE-TO-DEVICE COMMUNICATION SCENARIO

[C7/I7] of Fig. 7 represents TCS scenarios in D2D communications employing a list of the carrier frequencies and physical cell IDs predetermined. Proximity-based technique has become a promising approach targeted for both public safety and commercial purposes. As a real implementation of D2D communication systems, FlashLinQ has been proposed by Qualcomm, which constitutes a synchronous peer-to-peer wireless physical and medium access control architecture to support distributed channel allocation [113]. Moreover, the 3GPP has also led to dynamic research activities focused on D2D proximity services, whose results have been included in Rel-12 of LTE systems [3], [43], [53], [114]–[120]. Owing to tight time constraint of 3GPP standardization, only a limited set of D2D techniques has been introduced in Rel-12. D2D communications in Rel-12 encompasses two scenarios, namely enhanced Node-B aided D2D communications at in-coverage of enhanced Node-B and autonomous D2D communications at out-of-coverage. For the sake of utilizing frequency resource efficiently and minimizing additional implementation burden, D2D communications in Rel-12 exploits part of UL resource [119]. Specifically, in case of LTE-FDD, UL spectrum is exploited for D2D transmission. Similarly, UL subframe is also utilized in TD-LTE.

When starting cell search for D2D communications especially under out-of-coverage scenario, two sidelink synchronization signals consisting of a sidelink physical channel and sidelink synchronization signals are required to reuse the principles of the existing PBCH, PSS, and SSS. More explicitly, Physical Sidelink Broadcast CHannel (PSBCH) carrying system information, Primary Sidelink Synchronization Signal (PSSS), and Secondary Sidelink Synchronization Signal (SSSS) to be transmitted by UE have been introduced in Rel-12 [3]. Fig. 12 illustrates D2D channel structure designed for D2D synchronization signals and channels constituting PSSS, SSSS, demodulation reference signal, PSBCH, and guard period, which correspond to P, S, D, B, and G, respectively. This transmission pattern is periodically transmitted every 40 ms, where both (A) and (B) represent Normal and Extended cyclic prefix cases, respectively. Both PSSS and SSSS are capable of carrying a physical layer sidelink synchronization ID corresponding to the physical

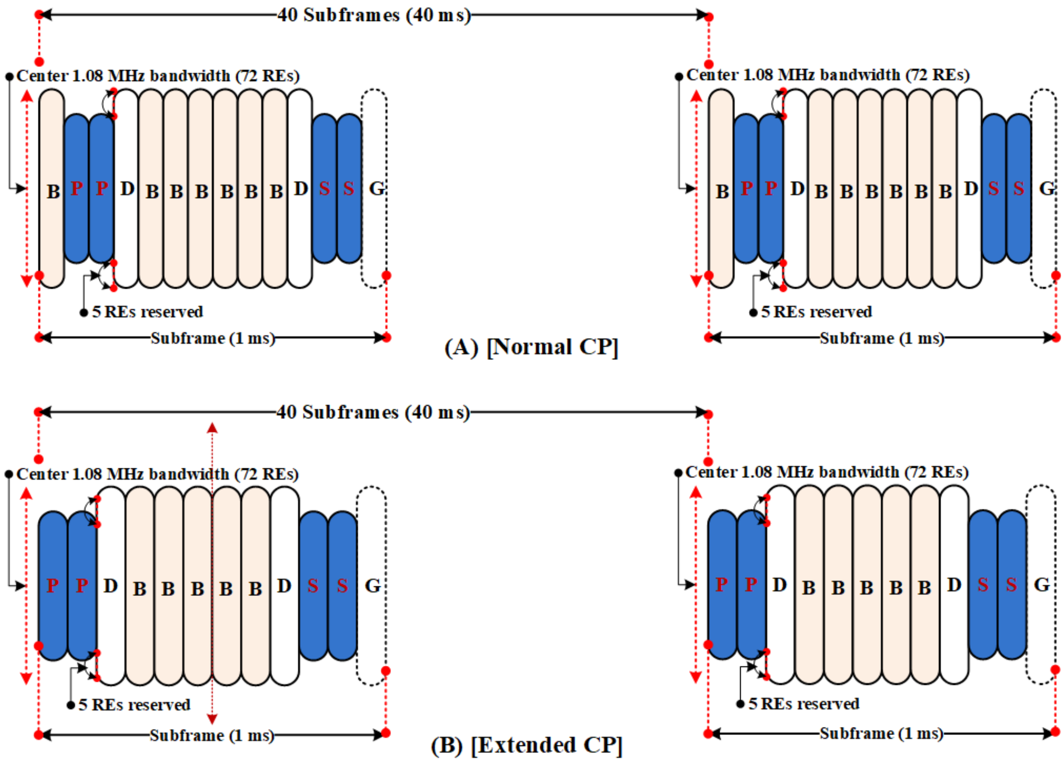

FIGURE 12. D2D channel structure designed for D2D synchronization signals constituting PSSS, SSSS, demodulation reference signal, PSBCH, and guard period: (A) Normal cyclic prefix case and (B) Extended cyclic prefix case, where CP and RE represent Cyclic Prefix and Resource Element, respectively.

layer cell ID obtained in enhanced Node-B based normal cell search scenario. The physical-layer sidelink synchronization ID constitutes $N_{ID}^{SL} \in \{0, 1, \ldots, 335\}$, which is classified into two sets $id_{(I-C)}$ and $id_{(OoC)}$ corresponding to identities $\{0, 1, \ldots, 167\}$ and $\{168, 169, \ldots, 335\}$, respectively, where the former is employed for 'in-coverage' and the latter is reserved for 'out-of-coverage' [3], [121], [122]. The PSSS is transmitted in two consecutive Single-Carrier Frequency Division Multiple Access symbols in a subframe as depicted in Fig. 12. Two sequences exploited for the PSSS in the two Single-Carrier Frequency Division Multiple Access symbols $d_i(0), \ldots, d_i(61)$, where i $= 1, 2$ are generated by the same method used in PSS generation having new root index $u = 26$ if $N_{ID}^{SL} \leq 167$ and $u = 37$ otherwise. The PSSS is also generated from Zadoff-Chu sequences having a length 62 and located on the 62 carriers in the center of the spectrum resource. Similarly, the SSSS is also transmitted in two adjacent Single-Carrier Frequency Division Multiple Access symbols in the same subframe as described in Fig. 12. Two sequences employed for the SSSS $d_i(0), \ldots, d_i(61)$, where i $= 1, 2$ are generated by the same method used in the existing SSS generation having $N_{ID}^{1} = N_{ID}^{SL}$ mod 168 and $N_{ID}^{2} = \lfloor N_{ID}^{SL}/168 \rfloor$, where $\lfloor \cdot \rfloor$ represents a floor operation [3], [121], [122]. PSBCH represents a broadcast channel transmitted by UE, where the PSBCH is also allocated in the six inner resource blocks at the center of the spectrum resource of the same subframe, as portrayed in Fig. 12. Two demodulation reference signals are utilized for the purpose of received signal quality measurement. The last Single-Carrier Frequency Division Multiple Access symbol in a sidelink subframe is void to guarantee transmission and reception transition time for forthcoming subframes, which is referred to as a guard period [3], [123]. It is also noted that the resource mapping for both normal and extended cyclic prefixes is a little bit different in terms of the number of symbols as illustrated in Fig. 12. More explicitly, in case of extended cyclic prefix, locations of both PSSS and SSSS are shifted by one symbol to the left. Parameters used in D2D communication are broadcast from a serving enhanced Node-B to UEs in cell coverage. By contrast, UEs situated outside a serving enhanced Node-B's coverage exploit parameters preconfigured for D2D communications. Subframes allocated to transmit both sidelink synchronization signal and PBSCH are configured by higher layer signaling and transmissions of other sidelink physical channels are not allowed in these subframes. For an allocated carrier frequency, a UE shall comply with half-duplex based transmission because sidelink signals and channels partially or completely overlapped with an UL transmission in time cannot be transmitted simultaneously. Fig. 13 manifests D2D cell search scenario based in both 'in-coverage' and 'out-of-coverage' situations, where '$*$' represents that a block showing reception of PSS, SSS, and PBCH for target cell search has been omitted. Similarly, '$**$' indicates that another block describing reception of PSSS, SSSS, and PSBCH for

D2D cell search has been dropped. '(1)', '(1C)', and '(1I)' as well as '(2 − 1)' and '(2 − 2)' represent in-coverage situation, RRC_CONNECTED and RRC_IDLE in in-coverage situation as well as both the initial and following modes in out-of-coverage situation, respectively. '(1D)' and '(2D)' also indicate D2D TCS block in in-coverage situation and a decision routine for D2D synchronization transmission in out-of-coverage situation, respectively. Based on the aforementioned, we would like to illustrate an example of D2D cell search scenarios [3], [37], [43], [47], [121], [122]. The D2D cell search will reply heavily on predefined coverage scenarios and the scenarios are directly associated with how synchronization between two UEs is obtained. As indicated in Fig. 13, a UE to be employed as a D2D Synchronization Reference is referred to as synchronization reference UE [43], [122]. Before going into the details of the D2D cell search scenarios, now let us introduce how to determine a synchronization reference UE in brief. According to [43], [122], there are three priority criteria to choose the best possible synchronization reference UE. If UEs are in in-coverage situation and are signaled by higher layer, the UEs are considered as top candidates of being a synchronization reference UE. Otherwise, in case that UEs get physical-layer sidelink IDs related to in-coverage situation, the UEs can be a potential candidate. Then, if the above cases are still not found, the remaining UEs may become a set of candidates having the lowest priority. When UEs' priority class is determined, within the class of the candidates sidelink reference signal received powers based on all received signals are measured and sorted. Then, a UE having the highest sidelink reference signal received power is determined as a synchronization reference UE to broadcast PSSS, SSSS, and PSBCH. As portrayed in Fig. 13, after enhanced Node-B based cell search has been completed successfully and tracking mode starts in the RRC_CONNECTED status, specific RRC signaling is delivered to a target UE to activate D2D communication, which leads to 'in-coverage' situation. Then, when the higher layer signaling command activates a role of synchronization reference UE, the UE starts to broadcast PSSS, SSSS, and PSBCH. Otherwise, with the aid of reference signal receive power measurement conducted on the DL signal of the serving enhanced Node-B, the resultant reference signal receive power is compared with a predefined threshold denoted as $TH_{(I-C)}$. In case that the reference signal receive power is below the threshold, the UE performs a role of synchronization reference UE, which enables the UE to provide a way of cell range extension. By contrast, if the measured reference signal receive power is higher, the UE may follow either of two possible scenarios depending on whether new non-serving carrier frequency is assigned for the D2D communication or not [47]. Namely, the former embarks upon TCS and the following measurement on the allocated non-serving carrier frequency. Depending on the existence of enhanced Node-B, the UE can decide whether D2D synchronization procedure of out-of-coverage is chosen or not. In case of in-coverage, additional intra-frequency TCS is required to find a better cell. It is noted that D2D synchronization procedures of both out-of-coverage and in-coverage situations corresponding to '(1)' and '(2 − 1)'&'(2 − 2)' are rather similar. On the other hand, in case of not supporting additional non-serving carrier frequency, the UE tries to receive PSSS, SSSS, and PSBCH to find a new synchronization reference UE and then if found, the UE will be synchronized with the new synchronization reference UE and its physical-layer sidelink ID will be assigned. Presumably, periodic intra- and inter-frequency TCS procedures and tracking mode will also be performed whenever scheduled by the UE, where physical-layer sidelink IDs reserved for both in-coverage and out-of-coverage scenarios range from 0 to 167 as well as 168 to 335, respectively.

If all the scenarios of the in-coverage situation are failed and a UE finally decides to be in out-of-coverage situation, namely an initial mode of out-of-coverage '(2 − 1)', the UE commences by searching for another UE to be a synchronization reference UE by detecting PSSS, SSSS, and PBSCH transmitted by adjacent UEs and measuring their signal qualities until a final candidate is chosen as a synchronization reference UE. When the sidelink reference signal received power value measured falls under a predefined threshold denoted as $TH_{(OoC)}$, the synchronization reference UE commences by transmitting PSSS, SSSS, and PSBCH. Otherwise, the UE is synchronized with the new synchronization reference UE. The same transmission can also start when data is needed to transmit under a case of being a synchronization reference UE not found. After the initial mode has been conducted, a scenario of an additional non-serving carrier frequency allocated is almost the same as that of in-coverage situation. Similarly, when not supporting additional non-serving carrier frequency, any of three modules portrayed in a box having round corners may be activated, namely D2D mode, normal TCS mode, or tracking mode. However, in a case of having a better synchronization reference UE, new additional procedure is required for completing an entire D2D cell search scenario.

It is noted that physical-layer sidelink ID currently exploited for the UE is exactly the same as that obtained from its synchronization reference UE, which manifests how multiple UEs are linked to one another in D2D communication. More explicitly, if several UEs share exactly the same ID together, the ID has been originated from a synchronization reference UE determined at an initial D2D synchronization stage. The ID propagates from the synchronization reference UE to other UEs consecutively. Finally, all these UEs are linked together in terms of the identical ID. When a UE is synchronized with new synchronization reference UE, new physical-layer sidelink ID will be assigned to the UE. However, an exception exists as follows: New synchronization reference UE is currently in in-coverage situation and includes a physical-layer sidelink ID derived from the in-coverage range represented as a specific $ID_{(I-C)}$. On the other hand, a UE being synchronized with the new synchronization reference UE stays in out-of-coverage situation.

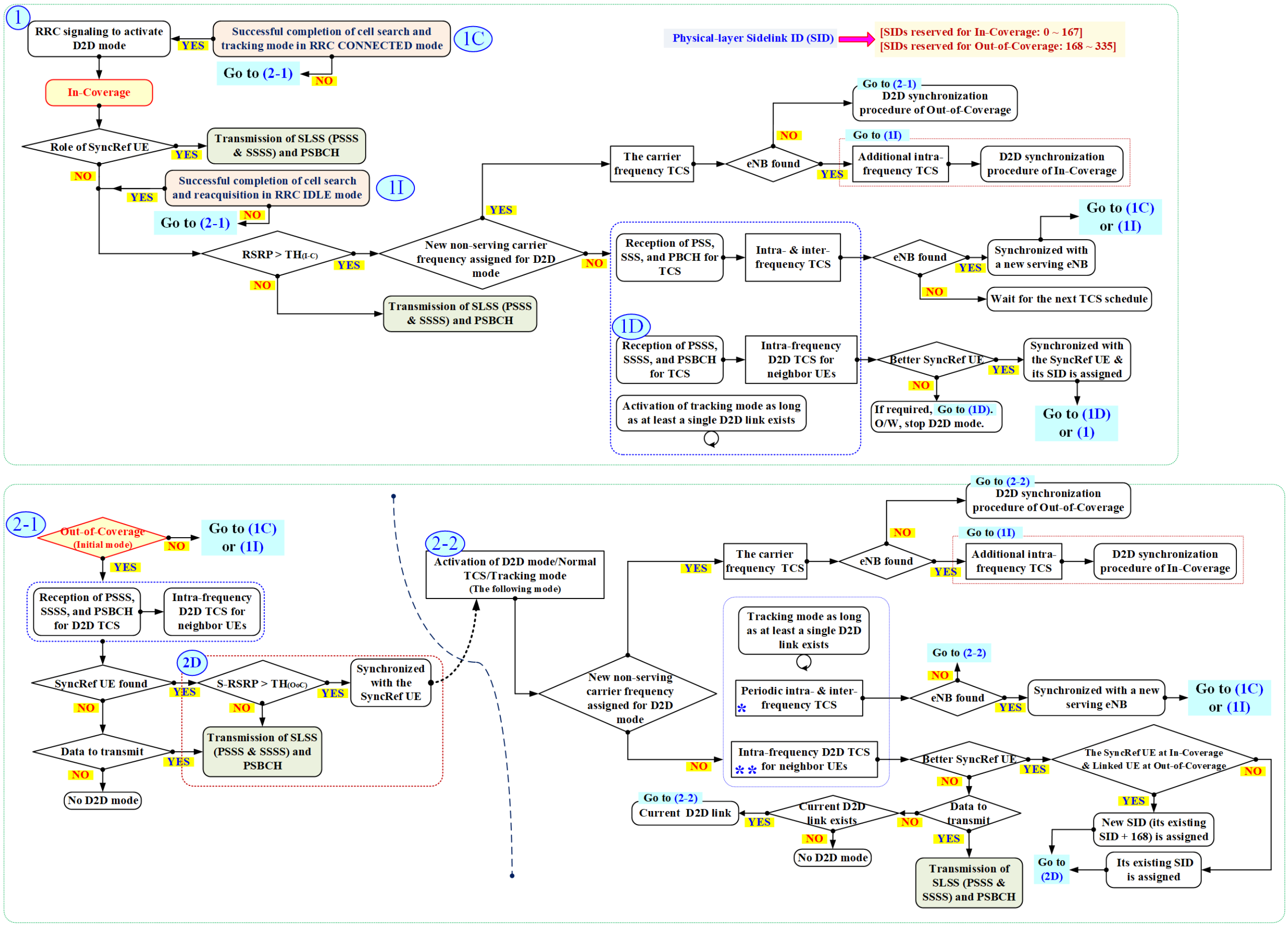

FIGURE 13. D2D cell search scenario based on both in-coverage and out-of-coverage situations, where SID, SLSS, S-RSRP, and SyncRef represent physical-layer Sidelink ID, SideLink Synchronization Signal, Sidelink Reference Signal Received Power, and Synchronization Reference, respectively.

Under such a situation, the UE must get a new ID 168 higher than the originally received one, which is one of $ID_{(OoC)}$. Accordingly, by checking an assigned ID, we are capable of identifying whether UE is located in either in-coverage or out-of-coverage situations. Finally, in case that a UE does not find any synchronization reference UE until a predetermined timer is expired, the UE may start to broadcast PSSS, SSSS, and PBSCH at the moment of having data to send. Its ID is determined in a random manner based on the ID set reserved for out-of-coverage situation [3], [37], [43], [47], [121], [122]. By employing the above-mentioned ID allocation rule, when a better synchronization reference UE is found, the following procedure checks whether the synchronization reference UE and the linked UE are in in-coverage and out-of-coverage situations, respectively. If the condition is met, new physical-layer sidelink ID is assigned to the linked UE.

D. SUMMARY AND LESSONS LEARNED

In Section IV, as visualized in Figs. 1 and 7, a hierarchical structure of entire TCS in LTE-FDD and TD-LTE systems has been introduced and then full details of three Subsections, namely (A) Target Cell Search in 4G, (B) Normal Target Cell Search, and (C) Specialized Target Cell Search were demystified through Figs. 8 to 13. More explicitly, as mentioned in Fig. 1, Subsection (B) constituting 1) Target Cell Search in Typical Scenarios and 2) Target Cell Search in Dual Connectivity Mode were elucidated. Similarly, with further evolution of LTE systems, Subsection (C) consisting of 1) Target Cell Search in Heterogeneous Network Scenario, 2) Target Cell Search in Small Cell Enhancement Scenario, 3) Target Cell Search in LTE-Unlicensed Spectrum Scenario, and 4) Target Cell Search in Device-to-Device Communication Scenario were also demonstrated. Especially, details of TCS in heterogeneous network scenario were further classified into 1-1) Interference cancellation assisted TCS in heterogeneous cell deployments, 1-2) Femto-cell TCS designed for closed subscriber group, and 1-3) Enhanced TCS in open-access small cells.

Among normal TCS scenarios, there are two main findings to emphasize. (1) There is an explicit distinction between the role of multi-path search and that of first arrival path search. Compared with diverse roles of the multi-path search operating in 3G systems, the latter's objective is limited only to maintain timings of the first paths received from several adjacent cells and to achieve the largest receive energy in the multi-path propagation, which is associated with OFDM's relative insensitiveness in timing issues compared with inherent sensitiveness in CDMA systems. (2) TCS in dual connectivity mode is analogue to TCS in dual-cell HSDPA configuration. Hence, an individual TCS module is assigned to each of two cell groups and those two modules are operated in parallel.

Throughout the evolution of LTE system, the considerations on heterogeneous network, small cell enhancement, the exploitation of unlicensed spectrum bands, and D2D communication have been adopted, which led to new requirements for dedicated TCS receivers and the resulting TCS scenarios. The first issue of TCS in heterogeneous network scenario has confronted severe inter-cell interference in complicated heterogeneous network deployment scenarios. Interference cancellation assisted TCS approach optimized for removing hazardous impact originated from dominant interference cells has been a popular remedy at the expense of increased hardware complexity. The second issue caused by unplanned deployment of femto-cells and cell identification confusion led to a special design request of dedicated femto-cell TCS. Among these six methods, UE based autonomous TCS in cognitive radio and a cooperative manner has been considered as a promising solution to perform both intra- and inter-frequencies as well as inter-RAT femto-cells' detection. The efficient exploitation of multiple 3GPP and non-3GPP based fingerprints was to guarantee more accurate fingerprint matching and to achieve better TCS performance. The third issue of TCS in heterogeneous network scenario had a request for improving TCS performance in open-access small cells, namely pico-cells severely suffered from huge inter-cell interference induced by a serving macro-cell. Accordingly, one of two efficient remedy was to exploit interference cancellation aided TCS operation proposed in the first issue. In addition, from enhanced Node-B perspective, power boosted mode of TCS related signals became a feasible solution to mitigate the TCS performance deterioration. Hence, a reasonable combination of both approaches was capable of increasing the TCS performance substantially.

Under densely located small cells in a synchronized cluster, referred to as small cell enhancement in Rel-12, TCS operation has been supported by a periodic DRS transmission constituting PSS, SSS, cell-specific reference signals. Even though several small cell deployment scenarios exist, the most prominent scenario may be a deployment of small cells operating at a specific higher carrier frequency of 3.5 GHz under a serving macro-cell. The synchronization of the DRSs in a cluster may be maintained by assistance control information such as periodic transmission interval and starting timing of the DRS. Exploiting the transmission of DRS has also been adopted in TCS operation of LTE operating on unlicensed spectrum scenario. With the advent of small cell based capacity boosting approaches, the 3GPP has expressed higher interest to unlicensed spectrum bands available. Especially, the 5 GHz spectrum band used mainly in WiFi systems was considered for open-access indoor small cells or outdoor hot spots leveraging extensive amount of unlicensed spectrum bands available around the world. There were two ways of implementing LTE and its evolutions in the unlicensed spectrum bands. The first approach of LTE operating on unlicensed spectrum scenario was not to modify the existing specification, namely LTE-U. The second approach of LTE operating on unlicensed spectrum scenario represented LAA with a modification of the specification adopted in Rel-13 to provide a unified global solution complying with the regulatory requirements. This is because the cognitive radio assisted spectral management approach adopted in LTE-U was insufficient. Hence, the LBT adopted as a coexistence mechanism for LAA was a regulation for unlicensed spectrum bands. Furthermore, the role of both the LTE-U and LAA DRSs was exactly the same as that of the Rel-12 DRS. The TCS operations of the clear channel mode under LTE-U were the same as those under LAA. That is, with respect to TCS scenarios in unlicensed spectrum, both LTE-U and LAA configurations were mainly similar to each other. Only difference in TCS operations was directly associated with non-clear channel mode owing to both carrier-sensing adaptive transmission mode in LTE-U and LBT mode in LAA following their own different protocols.

On the other hand, D2D proximity services in 3GPP have been specified in Rel-12 of LTE system. D2D communications in Rel-12 encompasses two scenarios, namely enhanced Node-B aided D2D communications at in-coverage of enhanced Node-B and autonomous D2D communications at out-of-coverage. In order to leverage frequency resource and minimize additional implementation burden, D2D communications in Rel-12 have employed part of UL resource. Parameters used in D2D communication were broadcast from a serving enhanced Node-B to UEs in cell coverage. By contrast, UEs situated outside a serving enhanced Node-B's coverage exploited parameters preconfigured for D2D communications. If all the TCS scenarios of the in-coverage situation were failed and a UE finally decided to be in out-of-coverage situation, namely an initial mode of out-of-coverage. When commencing TCS for D2D communications especially under out-of-coverage scenario, two sidelink synchronization signals were required to reuse the principles of the existing PBCH, PSS, and SSS. With the aid of a predetermined list of carrier frequencies and physical cell IDs, TCS operations in D2D communications of Fig. 13 have been designed for covering both 'in-coverage' and 'out-of-coverage' situations. Compared with all the heterogeneous small cell scenarios aforementioned, an adoption of D2D communications in the evolved LTE system manifested a unique configuration, which also led to a disparate style of TCS operations and relevant scenarios. In a nutshell, throughout the evolution of LTE system in conjunction with heterogeneous mixture of different sizes of cells having special purposes, the corresponding TCS operations and scenarios have also been diversified as summarized above. Such a diversification enables to boost an optimal design of TCS system controller.

V. TARGET CELL SEARCH IN INTER-RATs

In this Section, both taxonomy and parallel structures of the entire TCS scenarios depending on selected active-RATs are introduced in the light of these classifications of Figs. 1, 4, and 7. According to roles of 3G and 4G as active-RAT, full details of the TCS scenarios are illustrated through Figs. 14 to 17. We also articulate how 2G systems being in active-RAT schedule their observation time windows to activate TCS operations for detecting both 3G and 4G cells. Before delving into TCS scenarios in inter-RATs, let's commence by introducing a fundamental role of TCS in inter-RATs.

A RAT represents the underlying physical connection process designed for a single radio based wireless communication network. Similar to the role of generic TCS, that of TCS in inter-RAT is also mainly supporting an efficient handover functionality to guarantee reliable and seamless connectivity as well as offloading the traffic to balance the entire network throughput under all the existing 2G, 3G, 4G, and even 5G networks. More explicitly, before a UE leaves a coverage area of a serving RAT and then enters that of a neighbor RAT, with the aid of predetermined system information portrayed in Figs. 4 and 7, the UE must conduct TCS in inter-RAT to search and find a set of properly selected carrier frequency, timing information, and cell ID of the neighbor RAT during predefined measurement gaps generated by a Node-B of the serving RAT. The followings manifest two main scenarios, namely 3G as active-RAT constituting 3G to 4G and 3G to 2G TCS scenarios as well as 4G as active-RAT consisting of 4G to 3G and 4G to 2G TCS scenarios.

A. 3G AS ACTIVE-RAT

In Fig. 4, TCS scenarios illustrated in [C6 to C10] and [I4 to I7] are associated with inter-RAT TCSs aiming for 2G and 4G. According to a specified RAT to be selected, given information is different as portrayed in four RRC states of TCS scenarios in Fig. 4. When TCS scenarios aimed for W2L, T2L, W2G, and T2G are determined, an allowable observation period is generated at each scenario and during the period a dedicated TCS operation is performed to find target inter-RAT cells. When comparing TCS scenarios in `CELL_DCH` and `CELL_FACH` states with those in IDLE, `CELL_PCH`, and `URA_PCH` states, there exist two key differences between them. First, given information for supporting the TCS is usually different between two categories. Second, scheduling and detection schemes of the TCS are quite different each other for the two categories, because depending on the observation period allocated to two categories, only limited detection schemes can be adopted to `CELL_DCH` and `CELL_FACH` states. Specifically, in `CELL_DCH` state of inter-RAT TCS scenario, due to its highly restricted observation period sophisticated detection approach may not be considered for enhancing TCS performance. Figs. 14 and 15 manifest two typical examples of observation periods assigned when W-CDMA and TD-SCDMA are in active-RAT, respectively. Whenever predefined observation periods are activated, the dedicated TCS algorithms are used to detect either 2G or 4G cells.

At the bottom of Fig. 4, two boxes demonstrate TSC scenarios for 2G and 4G being in active RAT modes. More explicitly, when GSM/GPRS/EDGE is in active RAT, inter-RAT TCS is aimed to detect either W-CDMA or TD-SCDMA cells. [G1/G2] and [G3/G4] correspond to Connected and Idle modes, respectively. These two TCS scenarios are referred to as TCS in G2W and G2T, respectively. Similarly, when either LTE-FDD or TD-LTE is in active RAT, inter-RAT TCS is aimed to acquire either W-CDMA or TD-SCDMA cells, expressed as TCS in either L2W or L2T, respectively. Hence, [L1] and [L3] represent L2W TCS scenarios in RRC_CONNECTED and RRC_IDLE modes, respectively. Likewise, [L2] and [L4] correspond to L2T TCS scenarios in RRC_CONNECTED and RRC_IDLE modes, respectively. Similar to the inter-frequency TCS scenarios, owing to its highly limited observation period, the stored information based TCS can be exploited to boost their inter-RAT TCS performances. Each scenario is capable of employing different information supporting its dedicated TCS operation [51]. Minimum requirements of TCS capabilities are elucidated in [49]–[51]. To elaborate the details of G2W, G2T, L2W, and L2T a little bit further, first of all, we portray a typical example of observation window generation of TCS in which [G1] G2W and [G2] G2T scenarios of Fig. 4 are involved. As portrayed in Fig. 17, transmitted signal in GSM/GPRS/EDGE systems constitute a multi-frame having 26 time division multiple access frames. An entire duration of the multi-frame is set to 120 ms and only a single frame (named Frame 25) is unused during the entire duration. Each frame comprises eight time slots and the length of each time slot is 0.5777 ms. Therefore, the length of each frame becomes 4.615 ms. The inter-RAT TCS for observing either W-CDMA or TD-SCDMA signals is performed once during a duration of Frame 25. Accordingly, in case of W-CDMA, multiple sets of SCHs as well as continuous P-CPICH can be detected every 120 ms. Even though its highly limited observation time window duration is only available, a UE is capable of acquiring system information from W-CDMA cells relatively easier than from TD-SCDMA cells, because in case of TD-SCDMA only a single Downlink Pilot Time Slot (DwPTS) and midamble in time slot 0 are available during the same period. As visualized in Figs. 15 to 17, both DwPTS and midamble in time slot 0 correspond to the essential synchronization resources utilized for ICS and TCS procedures in TD-SCDMA. Hence, the UE detects system information from TD-SCDMA cells only if the UE receives sufficiently high strength signals owing to its one-shot based detection. Fig. 16 also manifests an instance associated with [L1] L2W and [L2] L2T scenarios of Fig. 4. The

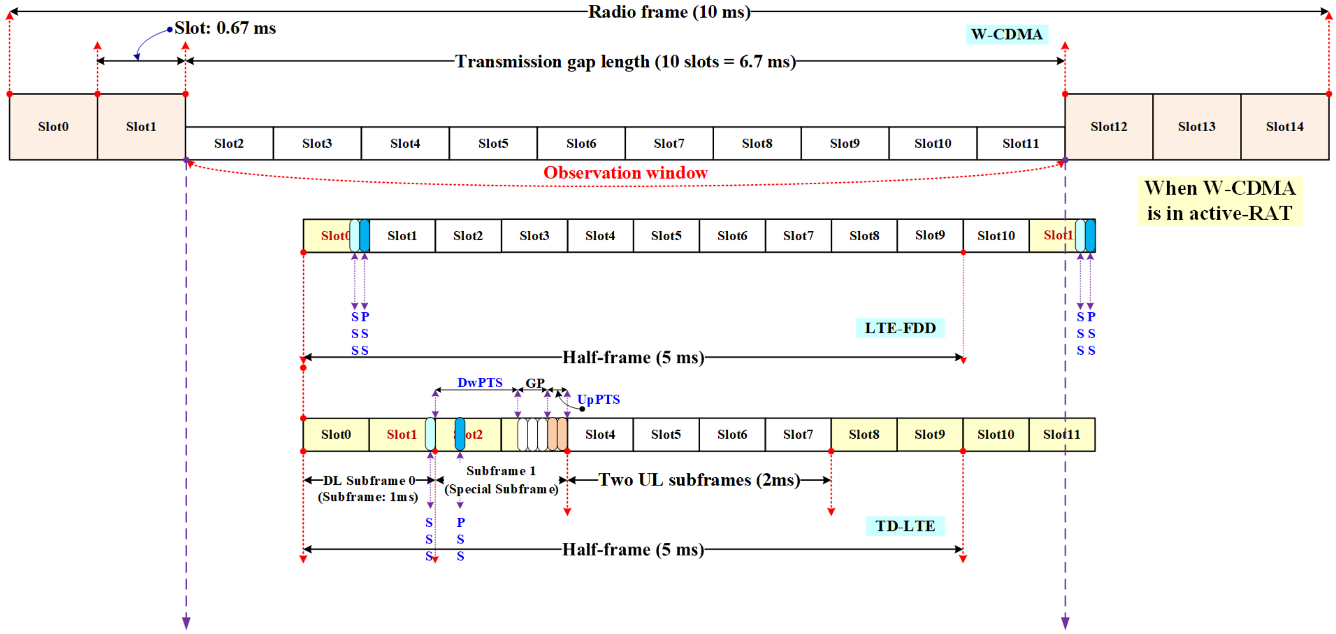

FIGURE 14. Observation window timing of target cell search when W-CDMA is in active-RAT, where GP and UpPTS represent Guard Period and Uplink Pilot Time Slot, respectively.

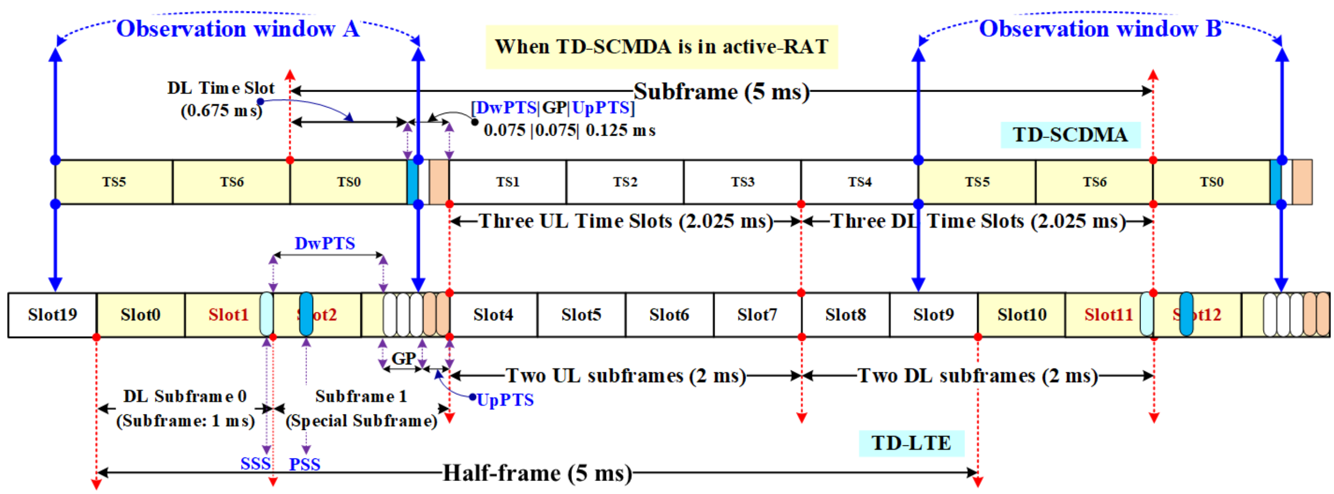

FIGURE 15. Observation window timing of target cell search when TD-SCMDA is in active-RAT, where synchronous mode between TD-SCDMA and TD-LTE is configured as well as TS represents Time Slot.

TCS situation is almost the same as those of G2W and G2T except for the exploitation of the observation window period predefined in 4G. With the aid of cell-specific information available, both step 1 and 3 searchers of W-CDMA as well as step 1 and 2 searchers of TD-SCDMA are used to perform the inter-RAT TCS scenarios of Fig. 4.

B. 4G AS ACTIVE-RAT

In Fig. 7, TCS scenarios described in [C4/I4], [C5/I5], and [C6/I6] are associated with inter-RAT TCSs aimed for 2G and 3G. Depending on a specified RAT to be chosen, given information is different as portrayed in the RRC_CONNECTED mode of the TCS scenarios. When comparing the TCS scenarios in the RRC_CONNECTED mode with those in the RRC_IDLE mode, there exists two key differences between them. First, given information for supporting the TCS is different between two modes. Second, scheduling and detection schemes of the TCS in the RRC_CONNECTED mode are quite different from those in the RRC_IDLE mode. This is because depending on the observation period allocated in either the RRC_CONNECTED or RRC_IDLE mode, only limited detection schemes can be adopted. For example, in the RRC_CONNECTED mode of the inter-RAT TCS scenario, owing to its highly restricted observation period

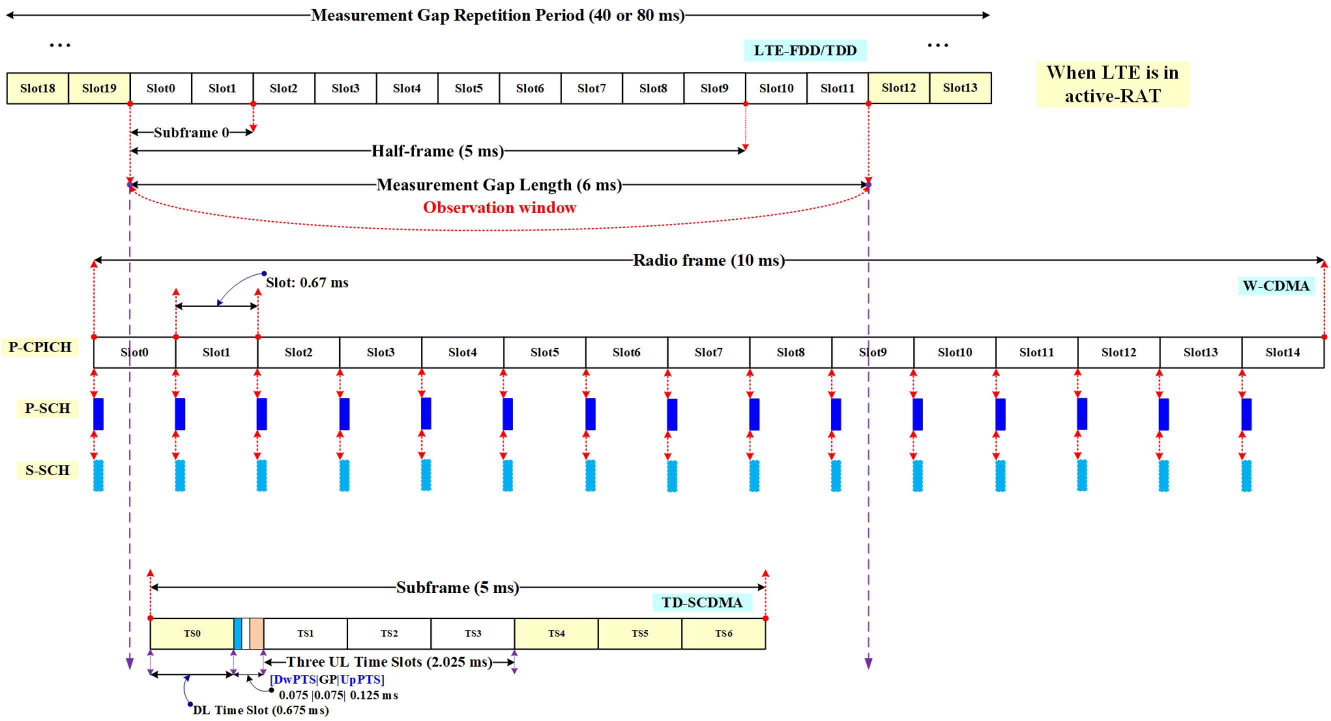

FIGURE 16. Observation window timing of target cell search when LTE is in active-RAT, where both P-SCH and S-SCH indicate primary synchronization channel and secondary synchronization channel, respectively, used for ICS and TCS procedures of W-CDMA.

sophisticated detection approaches may not be chosen. When either LTE-FDD or TD-LTE is in active RAT, an inter-RAT TCS aimed to detect GSM/GPRS/EDGE cells is referred to as TCS in L2G. Similarly, inter-RAT TCS aimed to acquire either W-CDMA or TD-SCDMA cells is expressed as TCS either in L2W or in L2T, respectively. Fig. 16 illustrates an example of the observation window generation of the TCS in which [L1] L2W and [L2] L2T scenarios of Fig. 4 are involved. According to UE measurement procedures in the RRC_CONNECTED state [49], there are two gap pattern configurations used by the UE, which represent gap pattern IDs 0 or 1, respectively. The gap pattern ID 0 is repeated every 40 ms. Similarly, the gap pattern ID 1 is performed every 80 ms, which is referred to as measurement gap repetition period. Every measurement gap repetition period having 6 ms of the measurement gap length is allocated to identify and measure either inter-frequency LTE FDD and TD-LTE, W-CDMA, TD-SCDMA, or GSM/GPRS/EDGE cells. More explicitly, as illustrated in Fig. 16, the UE is capable of observing multiple sets of SCHs as well as continuous P-CPICH for TCS of W-CDMA cells during the observation window. Owing to RF transition time, duration of just over 5 ms is only guaranteed. On the other hand, in case of TD-SCDMA, only a single DwPTS and midamble in time slot 0 are detected during the same period as that allowed in W-CDMA. In other words, only a single shot aided detection is allowed. Hence, the target cell detection performance of W-CDMA is much better than that of TD-SCDMA owing to the amount of physical channels observed.

At the bottom of Fig. 7, two boxes manifest the TSC scenarios for either 2G or 3G being in active RAT mode. More explicitly, when GSM/GPRS/EDGE is in active RAT, the inter-RAT TCS is aimed to detect either LTE-FDD or TD-LTE cells. [G1] and [G2] correspond to Connected and Idle modes, respectively. The TCS scenario is referred to as TCS in G2L. Similarly, when either W-CDMA or TD-SCDMA is in active RAT, the inter-RAT TCS is aimed to acquire either LTE-FDD or TD-LTE cells, it is expressed as TCS in either W2L or T2L, respectively. The W2L constitutes three different operational scenarios depending on their RRC transition states, which are indicated as [W1] to [W3] in Fig. 7. Each scenario is able to use different information supporting its TCS operation [51]. On the other hand, in case of TCS in T2L, CELL_FACH state is not included and hence only [T1] and [T2] modes are available [50]. Minimum requirements of the TCS capabilities are elucidated in [49]–[51]. To elaborate the details of W2L, T2L, and G2L a little bit further, we portray examples of the observation window generation of TCS when W-CDMA, TD-SCDMA, and GSM/GPRS/EDGE are in active-RAT, which correspond to Figs. 14, 15, and 17, respectively. As portrayed in Figs. 17, the inter-RAT TCS for observing LTE signals is performed once only during Frame 25. According to the hierarchical frame structure, a pair of the PSS and SSS can be detected every 120 ms. The fact manifests that

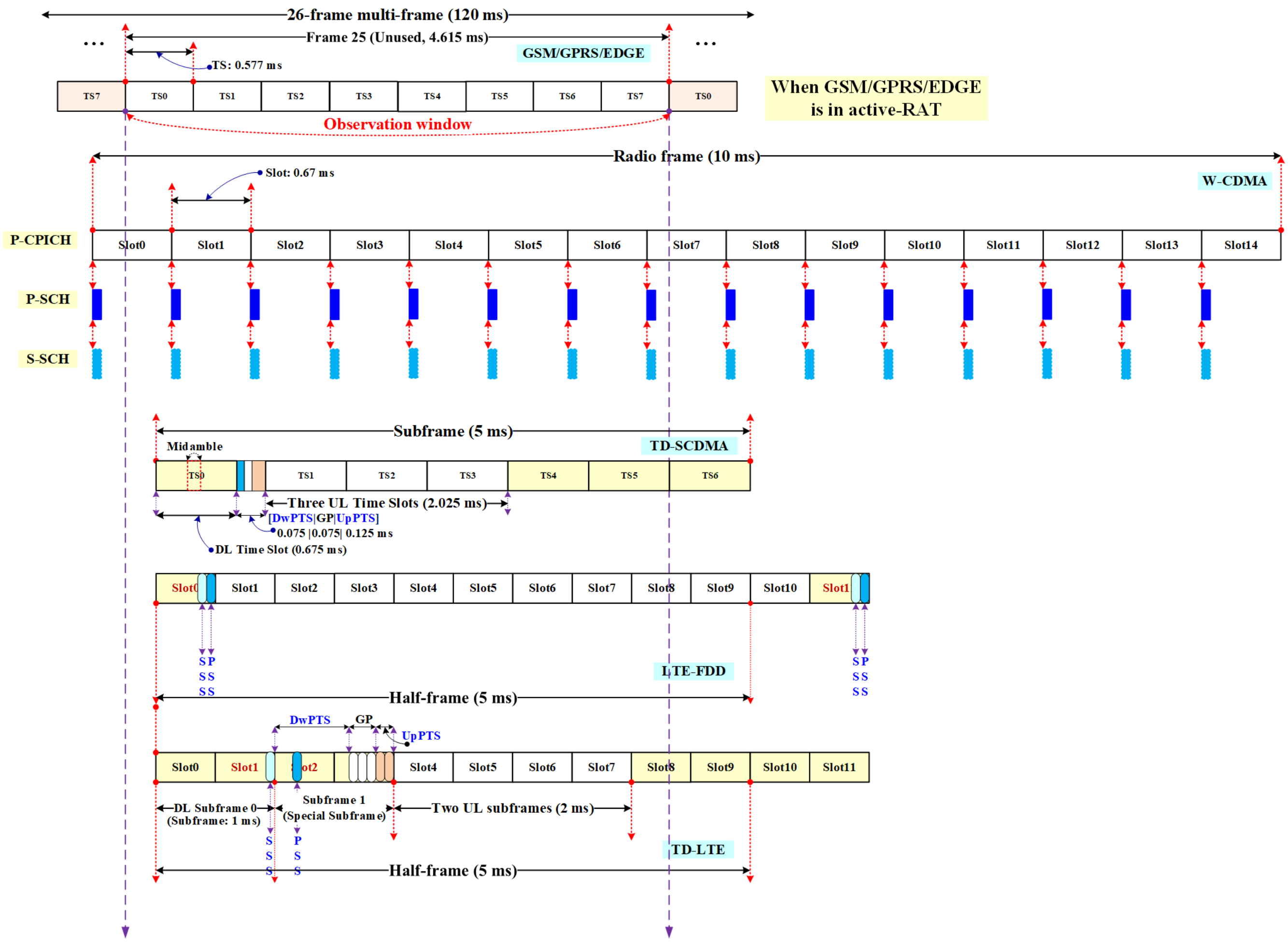

FIGURE 17. Observation window timing of target cell search when GSM/GPRS/EDGE is in active-RAT, where both P-SCH and S-SCH indicate primary synchronization channel and secondary synchronization channel, respectively, used for ICS and TCS procedures of W-CDMA.

only one-shot based detection is available owing to its highly limited observation time window duration. A UE is capable of acquiring system information from LTE cells only if the UE receives signals with sufficiently high signal strength. On the other hand, in order to support the inter-frequency and inter-RAT TCSs in W-CDMA systems, compressed mode is scheduled for generating sufficient length of gap not to be exploited for transmission of data. As illustrated in Fig. 14, the instantaneous transmit power is incremented in the compressed frame(s) so as to maintain the same quality of data transmission. In the compressed mode, compressed frame(s) are periodically scheduled for generating transmission gap position, where the transmission gap position represents the number of consecutive idle slots during the compressed mode ranging from 3, 4, 5, 7, 10 to 14 slots [124]. Fig. 15 demonstrates a detailed example of the observation window timing of the TCS when TD-SCDMA is in active-RAT. As visualized in Fig. 15, during the observation window A of the synchronous mode, a UE can observe both DL subframes 0 and 1 of TD-LTE, where the subframe 0 includes the SSS and in the subframe 1 (also expressed as special subframe), a ratio of DwPTS, guard period, and uplink pilot time slot length expressed in OFDM time symbol is shown as 9:3:2 [3]. The subframes 0 and 1 of Fig. 15 are considered as core physical channels for ICS and TCS procedures in TD-LTE. DL time slots in TD-SCDMA and DL subframes in TD-LTE are roughly time-aligned in the synchronous mode configured [125], [126]. The illustration exhibits how a switching point alignment between TD-SCDMA and TD-LTE systems interrelates. It is noted that TD-LTE coexists with a legacy TD-SCDMA system only in China. Consequently, an entire search space in the synchronous mode is substantially reduced compared with that in the asynchronous mode. Whenever the inter-RAT TCS for observing TD-LTE signals is conducted, the UE is capable of detecting both the PSS and SSS during the observation window. However, as analyzed in GSM/GPRS/EDGE systems, owing to lower scheduling priority and highly restricted observation window duration of W-CDMA and TD-SCDMA systems, the UE is usually able to detect a pair of the PSS and SSS. The fact explicitly means

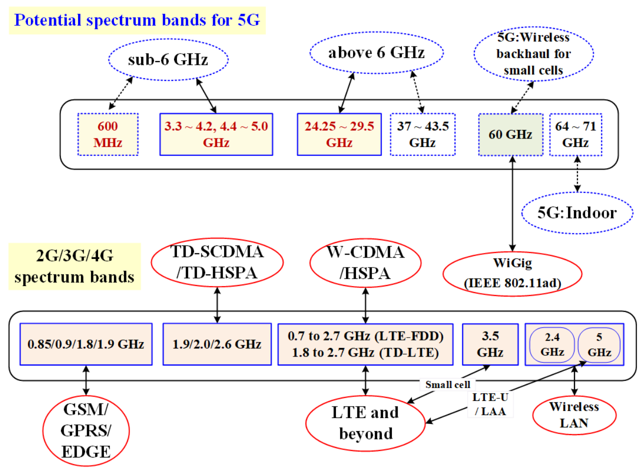

FIGURE 18. Spectrum bands allocated over 2G, 3G, 4G, and 5G systems, where (TD-)HSPA and WiGig represent 3.5G (Time Division-)High Speed Packet Access and 60 GHz WiFi, respectively. The latter is mainly based on IEEE 802.11ad standard.

that successful handover to a suitable inter-RAT cell is only feasible for the UE to be located within the target inter-RAT cell.

C. SUMMARY AND LESSONS LEARNED

Entire TCS scenarios in inter-RATs have been described in the light of these classifications of Figs. 4 and 7. There exist two main scenarios, namely 3G as active-RAT constituting 3G to 4G and 3G to 2G TCS scenarios as well as 4G as active-RAT consisting of 4G to 3G and 4G to 2G TCS scenarios. Similar to the role of the inter-frequency TCS scenarios, that of TCS in inter-RAT is also mainly supporting an efficient handover functionality to guarantee reliable and seamless connectivity as well as offloading the traffic to balance the entire network throughput under all the existing 2G, 3G, 4G, and 5G networks. Whenever predefined observation periods are activated for 3G or 4G being in active RAT mode, the dedicated TCS algorithms are used to detect either (2G or 4G) or (2G or 3G) cells, respectively. Due to its highly limited observation period, the stored information based TCS can be exploited to boost their inter-RAT TCS performances.

VI. TARGET CELL SEARCH IN NR

In this Section, as portrayed in Figs. 1, 18, and 19, both taxonomy and hierarchical structure of the entire TCS scenarios in NR system are introduced. Then, as a distinct feature introduced in NR system, beam operation in TCS working at mmW spectrum bands is detailed through Figs. 19 and 20 as well as dual connectivity in NR is also portrayed in a concise manner. It is worth noting that three main properties of two OFDM based systems with respect to both ICS and TCS have been illustrated and compared with their CDMA counterparts in Table 3.

Before delving into details of TCS in NR, let us look over spectrum bands allocated over 2G, 3G, 4G, and NR systems, which are visualized in Fig. 18. The bottom trace manifests how spectrum bands are assigned over 2G, 3G, and 4G systems. Traditionally, sub-3 GHz spectrum bands had been allocated to 2G, 3G, and even 4G systems. However, 3.5 and 5 GHz spectrum bands have been assigned to 4G systems to boost user throughput substantially. In case of NR systems, spectrum bands are classified into two categories. For example, sub-6 GHz spectrum bands are mainly capable of covering 600 MHz, 3.3 to 4.2 GHz, and 4.4 to 5.0 GHz bands. Similarly, above 6 GHz spectrum bands may encompass 24.25 to 29.5 GHz, 37 to 43.5 GHz, 60 GHz, and 64 to 71 GHz [127], [128]. Accordingly, for the sake of optimizing the overall cell search performance over multi-RAT scenarios, a harmonization of well-structured TCS flows and enhanced detection schemes will play a pivotal role in designing the best possible NR capable cell searcher.

A. OVERVIEW OF TARGET CELL SEARCH

Entire cell search scenarios in NR are quite similar to those in 3G systems and LTE, evidenced by Figs. 4 and 7. Owing to similarities between LTE and NR such as the employment of cyclic prefix aided OFDM as well as RRC states and their state transitions of Fig. 3, full details of NR TCS scenarios are mainly a direct extension of LTE ones. With the aid of the simplified cell search scenarios of Fig. 19, its hierarchically structured NR TCS scenarios based on RRC sates and main key difference are elucidated. We assume that there exist four main RATs, namely 2G, 3G, 4G, and NR systems. In order to complement two existing LTE RRC modes, RRC_IDLE and RRC_CONNECTED, a new RRC_INACTIVE mode has been adopted in NR. The new mode allows a NR capable UE to benefit from several aspects of the two original modes, which will be further elucidated in the forthcoming standardization meetings [13], [46]. More explicitly, Fig. 19 portrays the simplified state transition diagram of almost all the cell search scenarios in active-RAT mode of NR systems and their related inter-RAT TCS scenarios such as 2G to NR, 3G to NR, and 4G to NR, where either 2G, 3G, or 4G is in active-RAT and every square bracket encompasses a specific RRC status relating to each mode of operational scenarios. Furthermore, the first mode inside each square bracket manifests RRC status of a particular active-RAT and the second one indicates the corresponding RRC status in NR.

Let us introduce TCS scenarios in three RRC modes, namely RRC_CONNECTED, RRC_INACTIVE, and RRC_IDLE modes of Fig. 19. Inter-RAT TCS scenarios are a little bit different from the LTE counterpart, illustrated in Fig. 7. Specifically, the inter-RAT TCS scenario in RRC_CONNECTED mode is restricted to TCS only for NR to LTE (N2L). On the other hand, the inter-RAT TCS scenarios in RRC_INACTIVE and RRC_IDLE modes are capable of handling N2L, NR to W-CDMA or TD-SCDMA (N2WT), and even NR to GSM/GPRS/EDGE (N2G) [13], [46]. We also need to define TCS scenarios when either GSM/GPRS/EDGE, W-CDMA, TD-SCDMA,

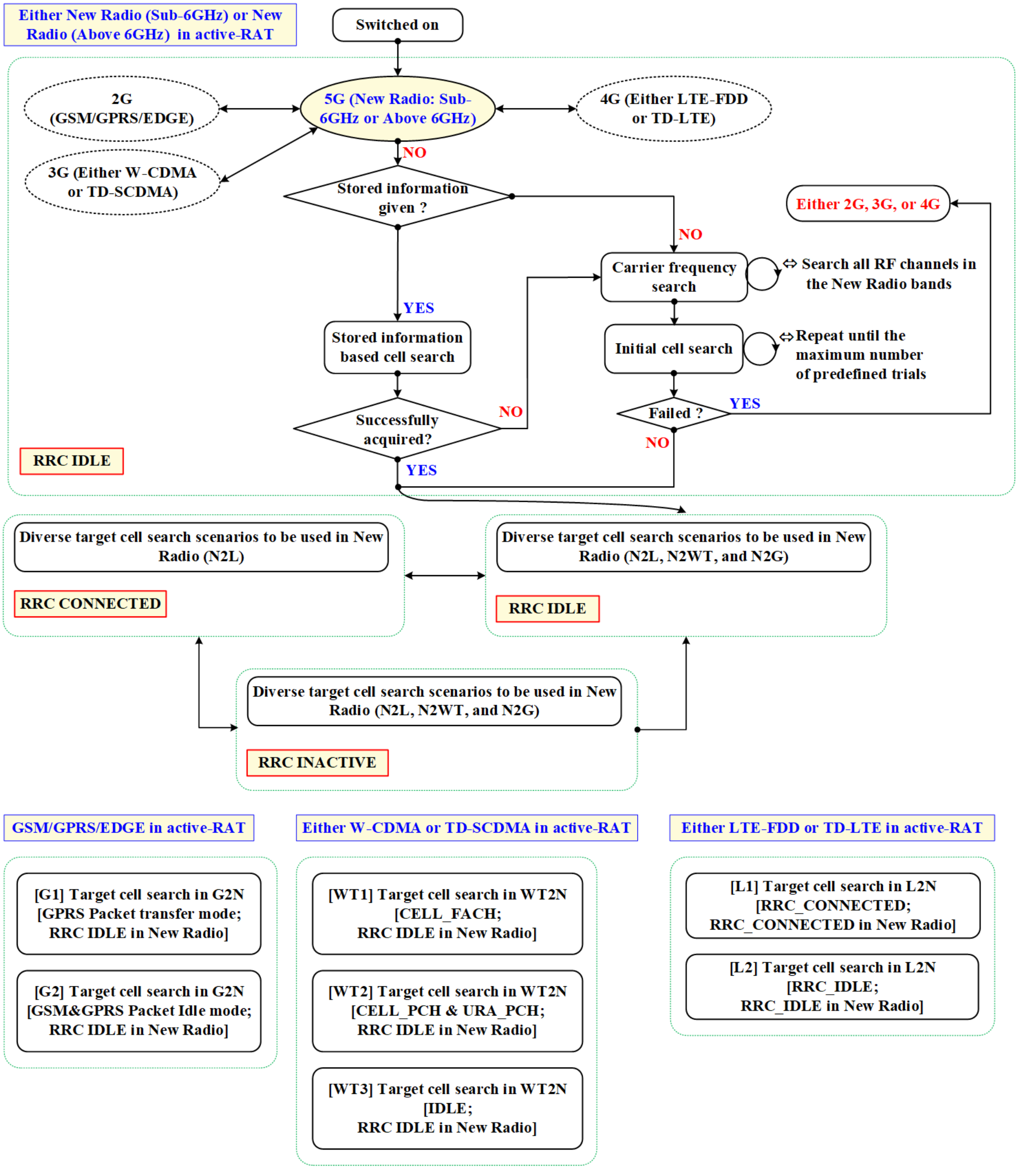

FIGURE 19. Entire cell search scenarios used in 5G system.

or LTE is in active-RAT. More explicitly, [G1/G2] represents TCS scenarios in GSM/GPRS/EDGE to NR (G2N), where G1 and G2 correspond to GPRS packet transfer mode to RRC_IDLE mode in NR and GSM/GPRS packet Idle mode to RRC_IDLE mode in NR, respectively. Similarly, [WT1/WT2/WT3] manifests TCS scenarios in either W-CDMA or TD-SCDMA to NR (WT2N), where WT1, WT2, and WT3 correspond to CELL_FACH mode to RRC_IDLE mode in NR, CELL_PCH and URA_PCH modes to RRC_IDLE mode in NR, as well as IDLE mode to RRC_IDLE mode in NR, respectively. In case of LTE being in active-RAT, [L1/L2] also means TCS scenarios in LTE to NR (L2N), where L1 and L2 correspond to RRC_CONNECTED mode to RRC_CONNECTED mode in NR and RRC_IDLE mode to RRC_IDLE mode in NR, respectively.

B. BEAM OPERATION IN TARGET CELL SEARCH WORKING AT mmW SPECTRUM BANDS

As portrayed in Fig. 20, Synchronization Signal (SS) burst set constitutes half radio-frame duration of 5 ms. The SS/PBCH blocks in a half radio-frame are numbered in an ascending order in time ranged from 0 to $(L - 1)$. A concrete instance of Fig. 20 is visualized based on the subcarrier spacing of 120 kHz with $L = 64$. Through the SS burst, there exist four groups of SS/PBCH blocks. Inside each group, there are 16 SS/PBCH blocks. When contemplating beamformed signals, every UE may not recognize the number of physical beam(s) to be generated and sent at NR Node-B, which has a similar functionality as employed in enhanced Node-B of LTE as well as it is also not guaranteed whether the UE receives the same physical beam(s) across different SS/PBCH blocks within a SS burst set. During the TCS procedure especially operating at 28 GHz, in order to mitigate harsh path loss, the exploitation of beamforming functionality is definitely one of the pivotal capabilities [13]. Detection of beamformed synchronization signals plays an essential role in the TCS procedure to provide sufficient coverage extension [129]. For the sake of further increasing beamforming gain, the additional beamforming at the UE side should be considered and is beneficial for extending NR cell coverage. NR also should contemplate both single-beam and multi-beam based ways to transmit multiple synchronization signals. When pondering the multi-beam based operation, UEs are capable of receiving synchronization signals for a shorter duration if NR Node-B transmits synchronization signals periodically in a beamformed manner. Better orthogonality among adjacent cells results in significant reduction of inter-cell induced interference, which also leads to beneficial performance gain under heterogeneous multi-cell environments [130], [131]. Single beam approach is a special case of multi-beam approach. It may be postulated that NR Node-B sends predetermined information about preferred beam patterns for a UE during the TCS stage.

UE must settle the best possible pair of transmitted and received beams as follows [4], [13], [129], [132]:

- 1) Beam sweeping: In order to guarantee a sufficient spatial coverage, the SS/PBCH blocks can be transmitted by leveraging multiple beams at both the NR Node-B and the UE. Beam sweeping can be consecutively conducted with a predetermined set of transmitted and received beams during a fixed time period. In other words, NR Node-B periodically transmits SS burst carrying multiple SS/PBCH blocks, where each SS/PBCH block is sent via the corresponding beam having predetermined interval and direction. Inherently, there exists on a trade-off between coverage extension from the narrow beams and mean cell search time. Specifically, coarse beam sweeping granularity having wider beam width can be chosen to reduce the entire cell search space even if the use of finer beam sweeping granularity leads to the coverage extension at the cost of cell search time increment. For the support of the efficient beam sweeping, the hierarchical structures of SS burst set period, SS burst set, and SS/PBCH block are organized and they should also be periodically transmitted as visualized in Fig. 20 [6]–[8], [133]. On the other hand, in case of sub-6 GHz spectrum bands, a single SS/PBCH block can periodically be transmitted by a single beam operation without activating any beam switching.
- 2) Beam measurement: A UE measures all the possible sets of transmitted and received beams in a predetermined manner. In idle mode, both synchronization signal and specified NR reference signals are employed for serving and neighbor cell measurements. These measurements are based on either cell- or on beam-level approach for radio resource management reporting with a unit of an SS/PBCH block. More explicitly, by measuring reference signal receive powers of multiple SS/PBCH blocks, the best possible transmit beams are selected by NR Node-B. Then, the NR Node-B lets the UE know the beam information applied to the DL channel, which makes the UE choose the corresponding reception beam to attain the DL channel [134].
- 3) Beam determination: UE finally chooses the best possible pair of the transmitted and received beam(s) among all the possible sets.

Let us illustrate how beam sweeping works in detail. The employment of beamforming is an attractive way of resolving cell coverage issue of the TCS procedure in power restricted scenarios. DL sweeping time interval is required by transmission and reception point, which represents an antenna array installed at NR Node-B having one or more antenna elements available to NR network, where NR Node-B usually constitutes one or multiple transmission and reception points. in order to transmit synchronization signals associated with the TCS procedure. A DL sweeping time interval constitutes multiple sweeping blocks. If either analog or hybrid beamforming is considered for the TCS procedure, the synchronization signals should be transmitted or received along only one or few beam direction(s) in one sweeping block owing to the limited number of RF chains [135]. The narrow beams in all the sweeping blocks during a sweeping time interval are capable of covering the entire serving area as visualized in Fig. 20. Hence, with the aid of the steering of phase shifter the multi-beam transmissions on a predetermined pattern of sweeping blocks are referred to as beam sweeping. In case of digital beamforming providing higher flexibility, all the narrow beams can be transmitted or received simultaneously in a single sweeping block at the cost of increased number of RF chains, directly proportional to the entire number of multi-beams even if the use of it usually becomes infeasible [130], [131], [135]–[140].

After the aforementioned procedure has been completed, whenever normal communication starts, a UE moves into the connected mode. Then, depending on data services, a state of the UE moves back to the idle mode or keeps staying in

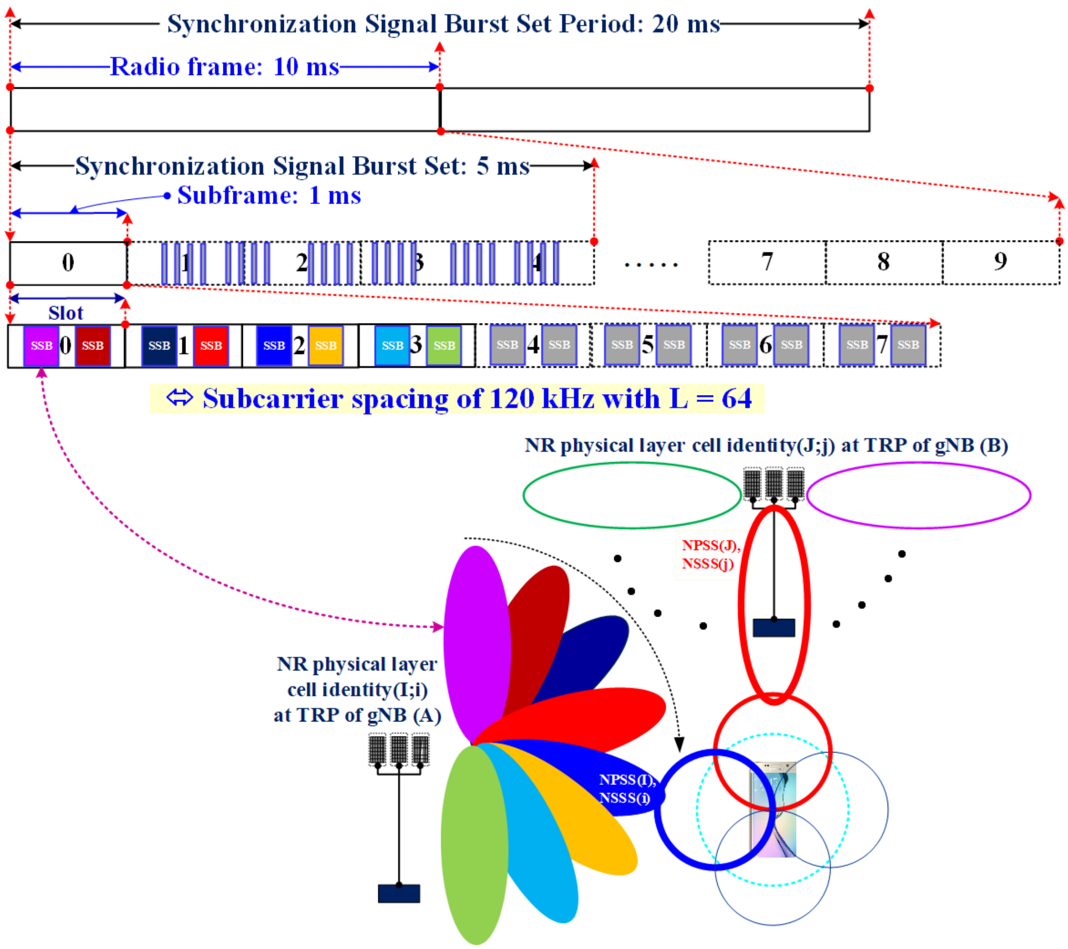

FIGURE 20. Visual illustration of both transmission and reception point as well as UE's beam sweepings during target cell search procedure in NR, where *I* and *J* represent NR physical layer identities assigned to a particular transmission and reception point of NR Node-B(A) and that of NR Node-B(B), respectively as well as *i* and *j* indicate NR physical layer cell identity groups allocated to a particular transmission and reception point of NR Node-B(A) and that of NR Node-B(B), respectively. gNB, NPSS, NSSS, and TRP represent NR Node-B, NR-PSS, NR-SSS, as well as Transmission and Reception Point, respectively.

the connected mode. In the connected mode, for the sake of guaranteeing the best possible radio links continuously, the required procedures are compensations of residual timing error and frequency offset as well as beam management controlling the beams' candidate set used for transmission and reception points and(/or) UE. TCS for handover is further activated in a scheduled fashion to support seamless mobile connections over multiple cells. In case of beamforming operating at transmission and reception point, the procedure usually includes an intra- and inter-transmission and reception points' transmitted beam sweeps obtained from a set of different beams. Similarly, for the sake of beamforming operating at UE, it typically encompasses a UE's received beam sweeps attained from a set of different beams. Both procedures of this particular configuration in Fig. 20 illustrate how a mmW capable NR Node-B is able to transmit synchronization signals in a predefined beamformed manner, where highlighted beams specify a set of beam sweeps obtained. Here, I and J represent NR physical layer identities assigned to a particular transmission and reception point of NR Node-B(A) and that of NR Node-B(B), respectively as well as i and j indicate NR physical layer cell identity groups allocated to a particular transmission and reception point of NR Node-B(A) and that of NR Node-B(B), respectively. It is also noted that by employing the same color pattern, SSB located at each slot of Fig. 20 is exactly matched to the corresponding beam transmitted at transmission and reception point of NR Node-B(A), where SSB represents an instance of SS/PBCH block. When SS/PBCH blocks are transmitted, every sweeping time interval a transmission and reception point sweeps all of the beams in a predefined manner and keeps the same operation of beam sweeping irrespective of the number of UE's beams. A UE stays with the same beam during the sweeping time interval of SS/PBCH blocks to receive all the transmission and reception point beams. In other words, whenever a complete cycle of the sweeping time interval comes to an end, the UE switches the beams step by step. The beam width at UE side may relatively be wider than that at transmission and reception point side owing to relatively smaller number of antenna arrays. Hence, a single beam at UE side is capable of covering multiple narrower transmission and reception points' beams as portrayed in Fig. 20. The order of beam sweeping depends mainly on a trade-off between its TCS performance and latency required for the NR TCS procedure. Accordingly, the order of beam sweeping is under an implementation issue [130], [131], [136]–[140]. By exploiting both the identities and the identity groups, NR physical layer cell ID $N_{ID}^{(CELL)}$ can be attained. Fig. 20 manifests an explicit illustration of finding the best possible pair between transmission and reception points and the corresponding UE at the end of the beam sweeping procedure. A set of the transmitted and received beams having blue color is selected as a matched beam pair.

During the TCS procedure, we also need to contemplate the following two operations.

- 1) Beam change (or switch): When NR network sets up a UE having a new serving beam among the currently existing candidate beams or requires the UE to observe alternative serving beams still available, the UE may have multiple serving beams involved in different received beams. Both NR network and the UE should identify requests for the beam change whenever necessary.
- 2) Beam recovery: When the current beam link quality is recognized as below the minimum requirement or the beam is completely blocked, UE should acquire alternative potential candidate beams not currently established for reception and indicates these beams to NR network via specific signaling [138]–[140].

Compared with always-on cell-specific reference signals in LTE, reference signals in NR are on-demand reference signals when required as well as their time and frequency distributions are configurable to satisfy NR performance requirements having minimized overhead [6], [134], [141]. There are mainly three reference signals to be utilized for tracking and managing multiple beams.

- 1) Channel state information reference signal in NR is used for supporting reference signal receive power measurements for seamless mobility, beam management encompassing analog beamforming, as well as both time and frequency trackings for demodulation.
- 2) Phase-tracking reference signal is a new UE-specific reference signal to mitigate adverse phase noise and common phase error impact on NR performance at higher carrier frequency bands. Its configuration has high density in the time domain, however low density in the frequency domain. Its time and frequency densities depend mainly on signal-to-noise-ratio and scheduling bandwidth.
- 3) Tracking reference signal is employed for performing both fine time and frequency tracking procedures as well as both multi-path delay and Doppler spread measurements.

Accordingly, how to leverage these three reference signals for optimizing the above-mentioned beam operations is under a critical implementation issue. As an example of how to track multiple beams in connected mode, the beam management operations employ channel state information reference signal in DL and sounding reference signal in UL to transfer the latest beam and channel state information report as well as the DL control information between the NR Node-B and the corresponding UE. Then, based on the above-mentioned, the following is to update the connection via the strongest selected beam among the existing candidates [14], [140] which enables handover, beam adaptation, and beam failure recovery procedures. Specifically, the beam failure recovery stage is activated as soon as a UE recognizes deterioration of quality on a NR Node-B's transmit beam, which allows to request a switch to a different beam having the best possible quality. When there is an indication assigned for a particular carrier frequency band, a UE is also capable of exploiting serving cell timing to derive the indices of SS blocks transmitted by neighbor cells. In other words, the UE enables to achieve radio-frame or symbol-level synchronizations so as to find a group of candidates for the best possible beam pair. Due to the additional beam operations in NR working at mmW spectrum bands, the TCS operations defined in NR manifest more complicated procedures and its overall detection performance mainly depends on how the beam operations work robustly.

C. DUAL CONNECTIVITY IN NR

As further extension of dual connectivity mode in Rel-12 version of the LTE counterpart, a dual connectivity between LTE and NR has been adopted in NR [13], [46]. NR capable UE operates in either standalone NR or dual connectivity of LTE and NR, where the former represents that UE is capable of accessing only NR carrier. On the other hand, the latter means that UE can accesses LTE and NR together [4]. In case that both master cell group and secondary cell group constituting LTE cell(s) and NR cell(s), respectively, NR Node-B is considered as the secondary node not broadcasting system information. NR capable UE is capable of attaining radio-frame timing and other information of the secondary cell group by exploiting both SSs and PBCH of NR primary secondary cell, where the definition of the primary secondary cell is exactly the same as that of the LTE counterpart in Section V.B-2).

On the other hand, in case that both master cell group and secondary cell group constituting NR cell(s) and LTE cell(s), respectively, NR Node-B is now the master node. Similarly, NR capable UE is capable of obtaining radio-frame timing and other information of the secondary cell group by employing PSS, SSS, and master information block of LTE primary secondary cell. According to the selection of being the master node, the corresponding TCS procedure of the secondary cell group will be activated. In order to detect NR cell in the dual connectivity scenario, NR network should also provide UE network indication of SS burst set periodicity per carrier frequency band and related information to derive measurement timing and duration such as time window size for synchronization signal detection. UE also postulates the same periodicity and timing for all of cells on the same carrier.

D. SUMMARY AND LESSONS LEARNED

Entire TCS scenarios in NR are quite similar to those in 3G and 4G systems, corroborated through Figs. 4 and 7. Due to similarities between LTE and NR such as the employment of cyclic prefix aided OFDM as well as RRC states and their state transitions of Fig. 3, full details of NR TCS scenarios can be thought of as an extension of LTE ones. In order to complement two existing LTE RRC modes, for example RRC_IDLE and RRC_CONNECTED, a new RRC_INACTIVE mode has been adopted in active-RAT mode of NR system. The new mode allows a NR capable UE to benefit from several aspects of the two original modes. Our main focus on TCS operation in NR system is beam operation in TCS working at mmW spectrum bands owing to its unique channel characteristics. Accordingly, during the TCS procedure especially operating at 28 GHz, in order to mitigate severe path loss, the employment of beamforming functionality is definitely one of the key capabilities. Detection of beamformed synchronization signals plays an essential role in the TCS procedure to provide seamless connectivity. In order to further increment beamforming gain, the additional beamforming at the UE side should be contemplated and is helpful for extending NR cell coverage for the seamless connectivity. When conducting the multi-beam based operations, UEs are able to receive synchronization signals for a shorter duration if NR Node-B sends synchronization signals periodically in a beamformed manner. UE must establish the best possible pair of transmitted and received beams by using beam sweeping, beam measurement, and beam determination. The exploitation of beamforming is an attractive way of resolving cell coverage issue of the TCS procedure in power restricted scenarios. Due to the additional beam operations in NR operating at mmW spectrum bands, the TCS operations defined in NR system manifest more complicated procedures and its overall detection performance mainly depends on how the beam operations work robustly. As further extension of dual connectivity mode in Rel-12 version of the LTE counterpart, a dual connectivity between LTE and NR has been adopted in NR. Therefore, an individual TCS module of each RAT is assigned to each of two cell groups and those two TCS modules operate in parallel.

VII. OPEN CHALLENGES

A. NR OPERATING ON UNLICENSED SPECTRUM SCENARIO

Owing to the vast spectrum bands available, the design of NR-Unlicensed system operating in mmW spectrum bands ranged from 30 to 300 GHz is indispensable for the sake of attaining several tens of Gbps data rates. Differently from the well-known classification as sub 6 GHz and above 6 GHz spectrum bands of Fig. 18, the operational unlicensed spectrum bands of NR-Unlicensed are categorized into sub 7 GHz and above 7 GHz spectrum bands, where the spectrum bands of sub 7 GHz indicate the unlicensed spectrum bands in the 6 GHz regime exceeding 7 GHz such as 7.125 GHz. The standardization of NR-Unlicensed working at sub 7 GHz spectrum bands was developed as one of Rel-16 work items. Similarly, NR-Unlicensed operating in above 7 GHz spectrum bands is considered to be addressed in Rel-17 and beyond. Both LTE-U and LAA were especially aimed for operating in the 5 GHz spectrum band. On the other hands, as visualized in Fig. 21, NR-Unlicensed contemplates more complicated arrangements of multiple spectrum bands, which can be any combinations of 2.4 GHz (unlicensed spectrum band global), 3.5 GHz (shared access spectrum band in the USA), 5 GHz (unlicensed spectrum band global), 6 GHz (unlicensed spectrum band in the USA and Europe), 37 GHz (shared access spectrum band in the USA), and 60 GHz (unlicensed spectrum band global). Hence, the sub 7 GHz spectrum bands are categorized into 2.4, 3.5, 5, and 6 GHz spectrum bands while above 7 GHz bands include 37 and 60 GHz spectrum bands [142]–[146]. Similar to the purposes of LTE-U and LAA, the main goals of standardizing NR-Unlicensed are naturally to facilitate the availability of NR towards diverse unlicensed spectrum bands and fair coexistence across different RATs. Even though both LTE-U and LAA have focused only on carrier aggregation exploiting a particular unlicensed 5 GHz spectrum band, NR-Unlicensed leverages potential on multiple spectrum bands and diverse deployment configurations. More specifically, as illustrated in Fig. 21, the configurations are classified into (1) Carrier aggregation of licensed NR Node-B and NR-Unlicensed Node-B, (2) Dual connectivity of licensed NR Node-B and NR-Unlicensed Node-B, (3) Dual connectivity of licensed LTE Node-B and NR-Unlicensed Node-B, (4) Standalone of

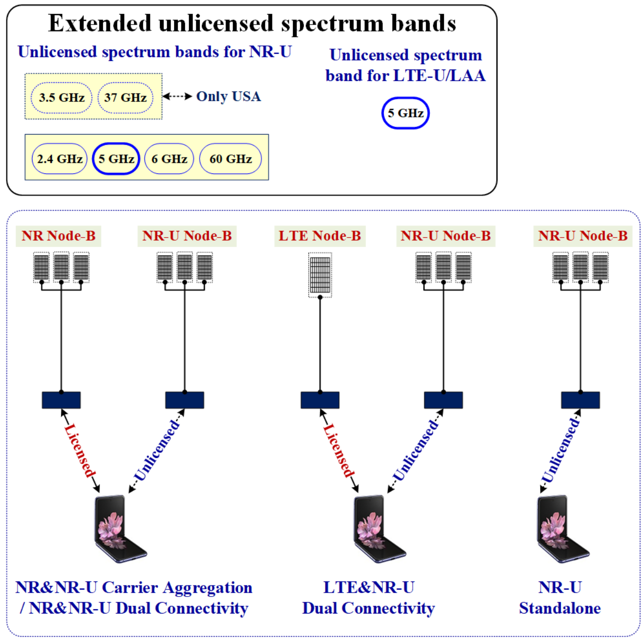

FIGURE 21. NR-U deployment scenarios in conjunction with extended unlicensed spectrum bands, where NR-U represents NR-Unlicensed.

NR-Unlicensed Node-B. From TCS operation perspective, critical issues to be resolved can be summarized as follows:

(1) Due to the exploitation of directional beam based transmissions in NR-Unlicensed working in mmW spectrum bands, there exists a clear distinction for NR-Unlicensed coexistence involved in multiple RATs as compared to LTE-U and LAA as well as WiFi coexistence operating only in the 5 GHz spectrum band. As visualized in Fig. 20, with the aid of NR capable Node-B and UE's beam sweeping, the first critical issue manifests a new request of beamformed TCS procedure. More explicitly, search dimension for carrier sensing and the following TCS operation are also different between LTE counterparts and NR-Unlicensed. The former only covers both time domain and a particular spectrum band, however the latter further encompasses time domain, multiple spectrum bands, and even space domain, which leads substantially to longer mean cell search time. Hence, the specialized and independent target cell searcher operating only at unlicensed bands may be required.

(2) For the sake of NR-Unlicensed operating in the standalone deployment configuration, all the signals must be transmitted in the allocated unlicensed spectrum band, which results in a substantial impact on design of dedicated TCS procedure. More specifically, dedicated SS blocks should always be transmitted in the standalone configuration of Fig. 21. In the NR-Unlicensed standardization, the SS block is referred to as NR-Unlicensed DRS. Especially, the standalone operation of NR-Unlicensed also encompasses beam assisted transmissions working at multiple mmW spectrum bands. Accordingly, the second critical issue is involved in designing new SS block transmitted in 60 GHz band, which arises owing to the occupied channel bandwidth requirement and the excessively large channel bandwidth. When reusing the existing SS block in 60 GHz, the SS block only occupies a part of the channel bandwidth. Accordingly, an optimized SS block resource mapping design in frequency domain should be required for NR-Unlicensed operation especially at a wide 60 GHz spectrum band.

(3) The third critical issue is directly associated with an explicit relationship between the transmission of the SS blocks and relevant LBT requirement on multiple unlicensed spectrum bands. Since the transmission of SS block can be blocked by the existing channel occupancy, periodic transmission of SS block may not be successful. The aforementioned can be resolved by employing a solution realized in LAA DRSs. However, configurations of NR-Unlicensed are far more complicated than a single 5 GHz spectrum band based on configurations for LTE-U and LAA. For the sake of reducing the LBT impact on multiple unlicensed spectrum bands, the improvement of successful channel access probability can be achieved by better carrier and channel sensing based multiple SS block transmissions.

(4) The fourth critical issue represents dynamic integration of both licensed and unlicensed spectrum bands in conjunction with sub 7 GHz and mmW spectrum bands, which is to maximize the utilization of NR-Unlicensed and to suggest a promising further research topic. A specialized design of intelligent TCS system controller plays a pivotal role in realizing the purpose, which is another open challenge towards a unified TCS operation scenario.

B. DESIGN OF INTELLIGENT TARGET CELL SEARCH SYSTEM CONTROLLER

In a design philosophy of classic TCS system controller for typical scenarios of the aforementioned Sections, the system controller has mainly focused on support of an efficient handover capability to guarantee robust and seamless mobility. As the evolution of LTE system, new role of the system controller was to offload heavily biased traffic to balance the entire network throughput under all the existing 2G, 3G, 4G, and 5G licensed networks in conjunction with diverse unlicensed ones. However, without harmonizing both the roles flexibly at the system controller, the optimization of the entire network throughput becomes infeasible. Moreover, trite approaches of balancing numerous parameters in a classic manner cannot guarantee a timely efficient harmonization through dynamically configured heterogeneous networks.

Powerful machine learning techniques have been conceived for enhancing the performance of wireless communications. Deep learning assisted systems have been manifested to outperform their existing counterparts dispensing with deep learning owing to the fact that they are inherently data-driven rather than relying on specified model approximations and assumptions, where the systems implicitly catch the environmental effects. Especially, deep learning algorithms have recently attracted enormous interest in the design of efficient wireless systems and even optimized networks [147]–[153]. With the aid of the huge volume of data collected from NR network and the associated intelligent decision making system controller, big data and relevant deep learning techniques can be considered as the two linchpins of NR network [147]–[153]. Big data analysis may be illustrated as a closed-loop process. In the entire process, the first stage is to attain the huge volume of data based on both UE and the existing NR network. The collected data can be transformed into accessible data by exploiting specialized data preprocessing and filtering techniques. Then, deep learning aided analysis is to process the massive data and to extract meaningful hidden features. Based on those features, intelligent decision-making task is conducted to optimize the NR network in terms of radio resource scheduling and allocation, traffic load balancing, power efficiency, and so on. Furthermore, invoking systematic approach for optimizing deep learning and other machine learning techniques jointly is a critical issue for the design of efficient intelligent transceivers exploited for self-organized user- and network-centric configurations in intelligent standalone and microwave-overlaid mmW networks [148], [154]. The inherent nature of the collected data can also be modeled as non-stationary time series data having time-varying data distribution. Accordingly, one of the popular solutions to handle the time-varying behavior can be to choose deep learning technique in conjunction with

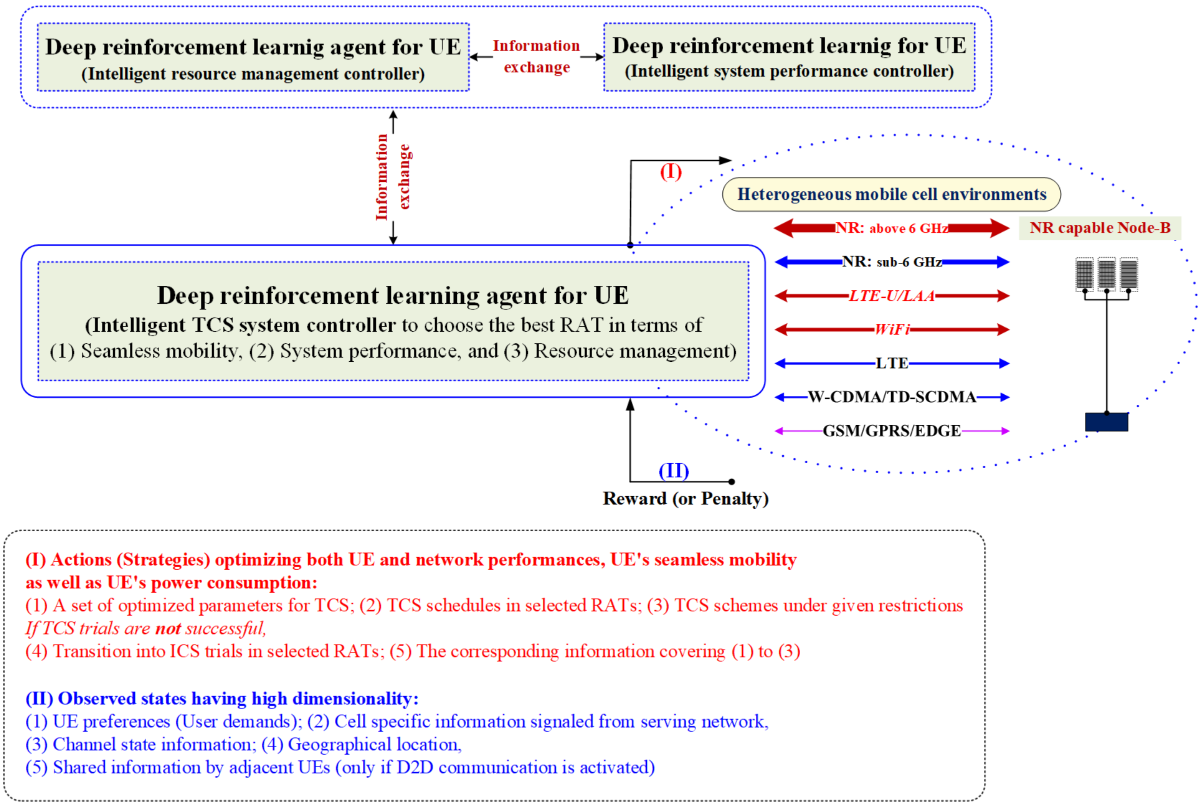

FIGURE 22. A visual diagram of our proposed intelligent TCS system controller leveraging deep reinforcement learning's potential.

online learning, where data are gained and processed consecutively [150], [151], [155]. In order to boost the proactive exploitation of data-rich NR network environment and to leverage deep learning's full potential, the optimal design of the intelligent TCS system controller becomes the most important open challenge in order for UE to choose the best possible RAT in terms of (1) Seamless mobility, (2) System performance, and (3) Resource management. From the mobile station modem perspective, a top-level intelligent controller can be composed of (1) Intelligent system performance controller, (2) Intelligent resource management controller, and (3) Intelligent TCS system controller, each of which may have its own deep reinforcement learning agent and collected information can be exchanged among three intelligent controllers. It is noted that the design of the intelligent controller is under implementation issue and our interest is only to concentrate on key roles of the intelligent TCS system controller. A conceptual illustration of our proposed intelligent TCS system controller is visualized in Fig. 22.

First, we can consider adding intelligence to the TCS designs by combining with diverse combinations of deep learning and other machine learning techniques, where the TCS system controller can intelligently support the best possible handover decision as well as the seamless connection and mobility in order to maximize the throughputs of individual user and entire NR network simultaneously. Therefore, the active employment of the high volume of relevant data will pave the way for building an intelligent TCS system controller. More explicitly, let us consider a system, where cell-specific information is transmitted by the existing cellular network. For instance, we can make use of cell/sector IDs, timings, and reference signal's received powers for both the serving macro-cell and all the identified intra- and inter-frequency cells. By adopting the intelligence aided TCS system controller leveraging all the cell specific information, the search scope required for both the sub-6 GHz and mmW channel environments may be reduced substantially. Moreover, with the aid of the intelligence, event-triggered TCS scheduling is capable of optimizing the entire scheduling management of diverse TCS scenarios in terms of maximized throughput of either individual UE or the existing cellular network. As reasonable candidates for enhancing intelligence of the TCS system controller, both reinforcement learning and deep reinforcement learning can be contemplated in wireless communication networks.

Before moving into its applications in wireless communication environments, key essences on both reinforcement learning and deep reinforcement learning are illustrated as follows.

- *Reinforcement Learning*: As portrayed in Fig. 23, reinforcement learning agent becomes a decision-maker taking actions iteratively in a particular environment and employing the return attained from the environment, which finally provide the agent rewards (or penalties) as results of its corresponding actions to resolve a targeted issue. Both action and reward represent all the possible

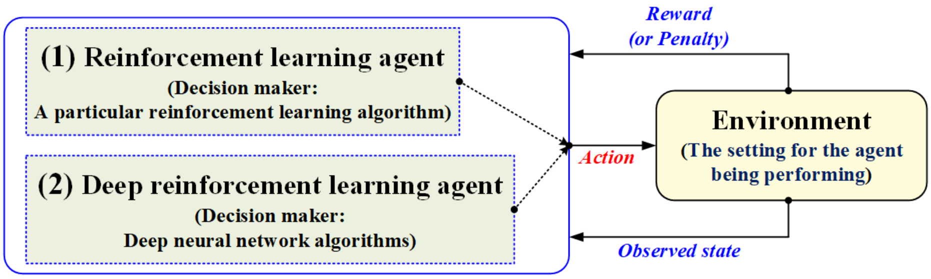

FIGURE 23. Both reinforcement learning and deep reinforcement learning architectures adopted under heterogeneous mobile cell environments, where a deep reinforcement learning agent represents a deep neural network approximating the specified function.

moves to be taken by the agent and an instantaneous feedback sent back from the environment to evaluate the last action, respectively. After a series of trial-and-error is conducted to learn the correct sequence of actions maximizing an accumulated long-term reward, it approaches the best possible result, which is the sequence of actions maximizing the total reward [155], [156]. In short, reinforcement learning is considered as an experience-driven way of optimizing problems by performing trial-and-error. Accordingly, reinforcement learning is suitable for decision making, planning, and scheduling.

- *Deep Reinforcement Learning*: The exploitation of both function approximation and representation learning characteristics obtained by powerful deep learning has inspired inventions of several famous deep reinforcement learning algorithms [155]. Deep reinforcement learning approach represents a set of ways of approximating specified functions being used in diverse deep reinforcement learning methods through deep neural networks [155]. As visualized in Fig. 23, the main feature of the deep reinforcement learning algorithms is to introduce the deep neural network as a novel agent in classic reinforcement learning algorithms, i.e., a set of convolutional neural networks can be selected as a novel deep learning capable agent [148], [150], [151], [155]. The deep neural network iteratively interacts with a particular environment and gleans reward as its feedback. More explicitly, the network chooses an action at each instant, which leads to change of the state in the environment. The trained network is to optimize the network's parameters, and hence it is capable of choosing actions potentially generating the best possible future outcome. Therefore, the deep reinforcement learning algorithm is an appropriate way of resolving critical issues raised by the classic reinforcement learning approaches. To illustrate it a little bit further, for the sake of attaining compact low-dimensional characteristics of high-dimensional raw data, the employment of the deep reinforcement learning methods is an attractive remedy of resolving high-dimensionality curse in a given environment, to which there are a massive number of possible states related [148], [155].

With the aid of a conceptual diagram of the intelligent TCS system controller in Fig. 22, when multiple RATs such as 2G, 3G, 4G, and 5G networks are co-located at the same geographical region, decision to which one of the multiple RATs is configured enables to make their communication link establishments to guarantee their reliable connections and maximized throughput, defined as selection of the RAT. Moreover, the RAT selection is highly associated with complicated access control as well as radio resource scheduling and allocation in multi-RAT access, which leads to substantial complexity issue due to too many requirements to satisfy. For the sake of reducing network signaling and processing load at each RAT, the RAT decision is usually controlled by UE, which may result in overall performance inefficiency owing to UE's selfish nature. In order for either UE or cellular network to make an optimal decision for multi-RAT access, recent efforts of [157], [158] have taken advantage of enormous power of machine learning techniques. Among diverse machine learning techniques, classic reinforcement learning has been chosen for their proposed solution to resolve the above-mentioned issues [156], because the reinforcement learning approach does allow reinforcement learning agent to properly monitor any change in multi-RAT access and hence intelligently schedule radio resource in both UE and cellular network. According to [157], [158], a reinforcement learning agent can be either UE or any cellular network. Hence, the agent in reinforcement learning approach is capable of learning environmental variations to explore potential answers. Employing it has been shown as a useful tool for sequential decision making under uncertainty. Reinforcement learning have obtained successful outcomes of a variety of use cases. Specifically, even though network parameters may not be easily attained or even not timely updated, the exploitation of reinforcement learning based approach is able to derive relevant information to be signaled. On the other hand, classic reinforcement learning approaches manifest a lack of scalability and are inherently restricted to low-dimensionality issues. This is because the reinforcement learning algorithm does share the same complexity dilemma as other machine learning algorithms. To illustrate it a little bit further, the action space for each reinforcement learning agent is significantly huge and hence a very long operational time is required to achieve globally optimized results. Namely, sudden parameter changes usually lead to critical latency issue. It makes computational-complexity reduction the top priority on the use of reinforcement learning approach in a time-varying and dynamic environment. Accordingly, its critical disadvantages in the reinforcement learning approach can make grave restrictions to diverse applications under specific circumstances.

As portrayed in the crucial property of the deep reinforcement learning approaches above, the exploitation of the deep reinforcement learning algorithms is capable of addressing complicated mobile network control and management issues efficiently, and hence employing it enables to extract abundant key characteristics from heterogeneous mobile cell environments [148], [155], [159]. Moreover, a novel multi-objective reinforcement learning algorithm utilizing deep learning aided approach has been characterized in radio resource allocation issue of space communication scenarios [160]. The main role of the deep reinforcement learning algorithms adopted in our proposed intelligent TCS system controller is timely decision making under unknown and unexpected NR network environments, which cannot be executed by classic reinforcement learning approaches. Specifically, from NR network perspective, a combination of diverse RAT related radio resource scheduling and allocation as well as even different types of heterogeneous mobile cells is capable of generating tremendous amount of timely urgent management requests. Under the circumstances, the intelligent TCS system controller operating on UE must leverage big data generated from NR network and even a legacy of the existing ones. As portrayed in Fig. 22, the deep reinforcement learning agent for UE represents the intelligent TCS system controller and the environment is considered as heterogeneous mobile cell environment constituting 2G (GSM/GPRS/EDGE), 3G (W-CDMA/TD-SCDMA), 4G (LTE/LTE-U/LAA), 5G (NR: sub-6 GHz and above 6 GHz), and WiFi systems. Observed states having high dimensionality may consist of (1) UE preferences (User demands), (2) Cell specific information signaled from serving network, (3) Channel state information, (4) Geographical location, and (5) Shared information by adjacent UEs (only if D2D communication is activated). Finally, actions are interpreted as strategies optimizing performances and resource managements at both UE and network as well as seamless mobility and power consumption at UE. For example, the TCS is activated based on the followings: (1) A set of optimized parameters for TCS, (2) TCS schedules in selected RATs, and (3) TCS schemes under given restrictions Additionally, if TCS trials are not successful, an alternative is to conduct a transition into ICS trials in a selected RAT. The ICS can be performed based on the corresponding information covering (1) to (3) above. Accordingly, the systematic use of big data as well as relevant deep learning and machine learning algorithms are capable of shedding light on the optimization of intricate management requests under the future heterogeneous mobile cell environment in diverse manners.

VIII. CONCLUSIONS

In this paper, we have presented a complete survey of the related open literature that is closely associated with the entire TCS scenarios, which can be employed in a concrete design of commercial mobile station modems operating under 3G, 4G, and 5G specifications. Moreover, we also highlighted the latest contributions of 5G systems employing the essential features of mmW spectrum. A brief comparison of our survey with the existing relevant papers emphasizing significant TCS algorithms has been provided in Table 1. With the aid of Fig. 1 summarizing an explicit classification of all the associated TCS scenarios based on the proposed taxonomy diagram, importance of TCS, contributions of this survey, a hierarchical structure of cell search, and an entire target access process of 3GPP systems have been underlined in Section I.

In Section II, we have begun our discussion by summarizing preliminaries of TCS, which consists of a hierarchical structure of TCS, the related definitions, its significance, core TCS issues, and ways to solve those issues as portrayed in Fig. 2. Table 3 also focused on key comparisons among the main properties of W-CDMA, TD-SCDMA, LTE-FDD, TD-LTE, and NR in terms of both ICS and TCS. Subsequently, Fig. 3 visualized how RRC states and their state transitions are interrelated in 3G, 4G, and 5G. Following these preliminaries, in Section III, we have demystified the TCS procedures of W-CDMA and TD-SCDMA systems, which are further categorized into multi-path search and TCS in typical scenarios. By exploiting an overview of entire TCS scenarios operating at both the 3G systems of Fig. 4, we proceeded by offering an insight into the TCS as well as multi-path search operational procedures and scenarios. Especially, we have learned further extended roles of the multi-path search in conjunction with all the possible carrier aggregation configurations of multi-carrier HSDPA in Figs. 5 and 6. Also, the unique feature of the multi-path search in TD-SCDMA system has been highlighted. Both are crucial points for commercially designed multi-path searcher.

Likewise, we have proceeded to offer the full details of the operational scenarios of TCS techniques of LTE-FDD and TD-LTE in Section IV, which are portrayed in Figs. 7 to 13. The structure of Section IV is further classified into two normal TCS operational scenarios and four specialized TCS operational scenarios. In the normal TCS scenarios, we have characterized two main findings as follows: (1) An explicit distinction between the role of multi-path search and that of first arrival path search, (2) A particular configuration of TCS modules in dual connectivity mode.

Throughout the evolution of LTE system, the considerations on four specialized TCS operational scenarios have been adopted, which leads to new requirements for dedicated TCS receivers and the following TCS scenarios. We have seen the following three cases, namely (1) TCS performance degradation in heterogeneous network scenarios led by severe inter-cell interference, (2) Unplanned deployment of femto-cells and cell identification confusion, and

(3) TCS performance degradation in open-access small cells. For the sake of resolving the above-mentioned, we investigated (1) Interference cancellation assisted TCS approach, (2) UE based autonomous TCS operation, and (3) Power boosted transmission mode of TCS related signals. Under densely located small cells in a synchronized cluster in Rel-12, TCS operation has been supported by a periodic DRS transmission, which is also reused in TCS of LTE operating on unlicensed spectrum scenario. We also elucidated the same and different features of TCS operational scenarios between LTE-U and LAA. With respect to TCS scenarios in unlicensed spectrum, both LTE-U and LAA configurations were observed to be similar to each other. Only difference in TCS operations was directly associated with non-clear channel mode owing to the employment of different protocols. D2D communications in Rel-12 encompasses two scenarios, namely enhanced Node-B aided D2D communications at in-coverage of enhanced Node-B and autonomous D2D communications at out-of-coverage. With the aid of predetermined and given information, TCS operations in D2D communications in Fig. 13 have been designed for covering both 'in-coverage' and 'out-of-coverage' situations. In a nutshell, throughout the evolution of LTE system in conjunction with heterogeneous mixture of different sizes of cells having special purposes, the corresponding TCS operations and scenarios have also been diversified.

Subsequently, we have also reviewed TCS scenarios in inter-RATs constituting 3G as active-RAT and 4G as active-RAT in Section V, which are supported by Figs. 14 to 17. Similar to the role of the inter-frequency TCS scenarios, that of TCS in inter-RAT is also mainly supporting an efficient handover functionality to guarantee reliable and seamless connectivity as well as offloading the traffic to balance the entire network throughput under all the existing 2G, 3G, 4G, and 5G networks.

In Section VI, we have outlined an exemplified spectrum band allocation over 2G, 3G, 4G, and 5G systems as evidenced in Fig. 18. We then elucidated an overview of TCS procedures and scenarios in NR, followed by beam operation in TCS working at mmW spectrum bands, which are illustrated in Figs. 19 and 20. Entire TCS scenarios in NR are quite similar to those in 3G and 4G systems, confirmed by Figs. 4 and 7. Due to similarities between LTE and NR such as the employment of cyclic prefix aided OFDM as well as RRC states and their state transitions of Fig. 3, full details of NR TCS scenarios are mainly a direct extension of LTE ones except for an introduction of RRC_INACTIVE mode as a newly defined RRC state. Our main focus on TCS operation in NR system was beam operation in TCS working at mmW spectrum bands owing to its unique channel characteristics. By leveraging the additional beam operations in NR working at mmW spectrum bands, the TCS operations defined in NR system manifest more complicated procedures and its overall detection performance mainly depends on how the beam operations work robustly. As further extension of dual connectivity mode in Rel-12 version of the LTE counterpart, a dual connectivity between LTE and NR has been adopted in NR.

In Section VII, similar to the purposes of LTE-U and LAA, the main goals of standardizing NR-Unlicensed are naturally to facilitate the availability of NR towards diverse unlicensed spectrum bands and fair coexistence across different RATs. NR-Unlicensed leverages full potential on multiple spectrum bands and is associated with four deployment configurations as illustrated in Fig. 21. From TCS operation perspective, we have seen four critical issues as follows: (1) A new request of beamformed TCS procedure in enormous mmW spectrum bands, (2) A new request of NR-Unlicensed DRS in the standalone deployment configuration, (3) A new request of designing better carrier and channel sensing based multiple SS block transmissions, and (4) A new request of dynamic integration of both licensed and unlicensed spectrum bands. Those four issues are expected to be research topics.

With the advent of artificial intelligent era, Section VII also introduced another open challenge, which may shed light on a highest attractiveness of leveraging deep reinforcement learning assisted intelligent TCS system controller in NR as visualized in Figs. 22 and 23. In order to boost the proactive exploitation of data-rich NR network environment and to leverage deep learning's full potential, the optimal design of the intelligent TCS system controller becomes one of the important open challenges, where UE is to choose the best possible RAT in terms of (1) Seamless mobility, (2) System performance, and (3) Resource management. With the aid of the intelligence, event-triggered TCS scheduling is capable of optimizing the entire scheduling management of diverse TCS scenarios in terms of maximized throughput of either individual UE or the existing cellular network. Accordingly, the systematic use of big data and relevant deep learning algorithms is capable of shedding light on the optimization of intricate management requests under the future heterogeneous mobile cell environment. Based on the essence of the aforementioned, the thorough comprehension of the TCS scenarios in 3G, 4G, and 5G systems will play a crucial role in designing the mobile station modem with a commercial level.

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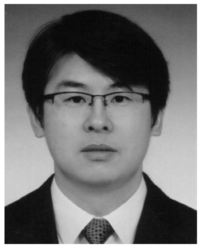

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