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Dynamic Spectrum Sharing for 5G NR and 4G LTE Coexistence - A Comprehensive Review

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ABSTRACT In the early phase, the number of new radio (NR) users is considerably low compared to the long-term evolution (LTE) users. Hence, allocating the LTE spectrum to a small number of NR users will have a detrimental effect on the LTE users. To overcome this backdrop, dynamic spectrum sharing (DSS) between LTE and NR has become an emerging technology where both systems can coexist on the same LTE spectrum. However, the most critical factor for LTE and NR coexistence is to share the spectrum resources of LTE systems with data and control signals necessary to operate NR systems subject to not impacting LTE operations. In line with this, a comprehensive understanding of DSS for LTE and NR coexistence taking into account diversified concerns is presented in this paper. First, an overview of the technological background of essential signals and channels of both LTE and NR systems to enable DSS for their coexistence is given. Numerous deployment options and potential design considerations of DSS are then discussed. The application of DSS to both multicast-broadcast single-frequency network (MBSFN) and non-MBSFN LTE subframes under NR with and without synchronization signal/ physical broadcast channels (PBCH) block (SSB) transmissions is examined. Further, the third-generation partnership project (3GPP) standardization activities towards DSS in its different releases are discussed, numerous use cases are highlighted, and the significance and limitations of DSS are identified. To provide additional insights, the relative comparison of potential aspects of several DSS concerns including, deployment options, design considerations, DSS applications, and 3GPP standardization efforts, is carried out. Finally, a summary of key lessons learned is provided in terms of numerous facts and figures.

INDEX TERMS 4G, 5G, coexistence, dynamic spectrum sharing, LTE, new radio, review.

I. INTRODUCTION

A. BACKGROUND

With ever-increasing user demand for diverse mobile services, mobile network operators have been facing difficulty in ensuring the user demand, caused by various characteristics (e.g., path loss, amount of bandwidth, etc.) of the available mobile spectrum at different bands [1]. The fifth generation (5G) mobile provides three major categories of service [2], [3], including enhanced mobile broadband (eMBB), ultra-reliable and low latency (URLLC), and massive machine-type communications (mMTC) [4], [5], [6]. The importance of the coexistence of 5G and fourth generation (4G) depends on the 5G new radio (NR) implementation possibility [7], [8]. Therefore, large coverage for eMBB and mMTC services to ensure network access for most mobile users [9] and a high data rate for eMBB and URLLC services are required. However, low frequencies including those below 2 GHz (e.g., 450 MHz [10]) are suitable for large coverage whereas high frequencies such as those above 3 GHz are suitable for high data rates because of their easy availability of huge bandwidth. Low frequencies are widely occupied by 4G long-term evolution (LTE) [11], whereas high frequencies suffer from larger path loss resulting in smaller coverage [12], [13]. Hence, to address the demand for large coverage and high data rate along with low latency and high reliability of 5G services, 5G needs to be operated on both low and high frequencies.

Given that 4G services still dominate the mobile communications market and are expected to continue for the next several years, to ensure large coverage, 5G NR requires coexisting with 4G LTE in the same low-frequency bands. However, in the early phase of 5G NR, the number of 5G users is very low as compared with that of 4G LTE, and the static allocation of 4G spectrum for 5G services may result in a negative effect on 4G users' performances [14], [15]. On the other hand, compared to 4G LTE systems, 5G allows its users enhanced service experiences [16] as aforementioned, requiring a smooth transition from LTE to NR. In this regard, spectrum refarming is a straightforward way where users in the previous generation (e.g., 4G LTE) are gradually reduced while users in the next generation (e.g., 5G NR) increase correspondingly until all users are transferred to the next generation system. However, like acquiring a new spectrum, spectrum refarming from LTE to NR is expensive and could take a decade, making it difficult to realize the demand for continuous coverage rapidly [14]. To overcome this backdrop, dynamic spectrum sharing (DSS) in the scarce spectrum has evolved such that both LTE and NR can operate and coexist on the same spectrum [17], [18]. In DSS, based on the user demand for LTE and NR services, time and frequency resources are allocated dynamically to both systems. Such dynamic resource allocation to users of existing systems is called dynamic spectrum management (DSM).

DSS is a feature for the early stage of 5G network deployments [19] and hence is advantageous in an early NR market by allocating necessary time and frequency resources commensurate with the traffic demand of NR user equipment (UE), leading to an improved spectrum utilization. DSS is designed to be backward compatible with existing LTE UEs. Further, because 4G and 5G are likely to coexist for a long time, adopting spectrum sharing is sensible to promote the transition period from 4G to 5G [20]. Furthermore, the 5G layer is similar in design to the 4G layer such that DSS is adaptable with the LTE subcarrier spacing (SCS) and similar time-domain (TD) structure. Nevertheless, the major challenges that DSS causes are to reduce the network capacity and the achievable peak throughput by individual users because of the overhead generated from control channels of both NR and LTE. Depending on the DSS implementation and configuration, the actual reduction in capacity varies.

The role of DSS is to allow the scheduling of 5G NR users to the spectrum of 4G LTE without affecting the essentials of one system by the other. In LTE, for example, a cell reference signal (CRS) is such a kind of essential signal, and the DSS design concept evolves mainly around the positions of CRSs in the time-frequency grid. Another feature of DSS design is to place reference signals of NR properly such as SSBs and demodulation reference signals (DMRS) into the LTE resource grid without being affected by LTE systems [21]. The performance of DSS between NR and LTE depends on how optimally resources of LTE can be allocated to NR for its data transmissions subject to avoiding collisions with LTE reference signals.

In LTE, subframes are categorized into two, namely Multicast-broadcast single-frequency network (MBSFN) (because it is single-frequency network-based) [18] and non-MBSFN [22]. The positions of CRS and other control signals such as PDCCH differ for these subframes. Likewise, essential broadcast signals such as SSB span over a specific number of resource blocks (RBs) and subframes in the NR resource grid. To avoid collisions of NR SSBs with LTE CRSs when transmitting using the LTE spectrum, the impact of DSS is different for LTE MBSFN and non-MBSFN frames. Likewise, DSS can be deployed in several options based on the type of LTE subframes. Further, an SCS has a direct impact on the operation of NR SSB. In general, SSBs use a different SCS from that of the one used to transmit NR data traffic with physical downlink shared channels (PDSCHs). Moreover, the benefits of DSS can be exploited further if DSS is employed with technologies such as standalone architecture and carrier aggregation (CA) on the device side [23], [24].

In line with so, the third-generation partnership project (3GPP) has been continuing its standardization activities towards DSS between LTE and NR in its different releases, including defining several functions in Release 15, approving additional features in Release 16, and proposing further enhancement in Release 17 [25]. To support LTE and NR coexistence, 3GPP introduced several requirements in the standardization of 5G NR including support for the coexistence of uplink/downlink of both LTE and NR within an LTE carrier bandwidth, with no impact on the legacy LTE devices, and so on. Hence, though in principle, the idea of DSS is simple, a detailed understanding of DSS at the resource element (RE) level or RB level under different LTE subframes and the CRS positions to transfer the NR SSBs and other control channels including PDCCHs using the LTE spectrum is critical.

B. RELATED STUDY

Numerous surveys on spectrum sharing have been carried out from holistic viewpoints such as [26], [27]. Moreover, several surveys such as [28], [29], [30] on coexistence studies in unlicensed frequency bands have been addressed in the existing literature. Regarding DSS for LTE and NR coexistence, numerous research works, including [1], [22], [31], [32], [33], [34], [35] have also addressed the DSS for the coexistence of LTE and NR systems from a specific set of viewpoints. For example, in [31], authors have proposed a novel DSS scheme using the dual bargaining game approach to address diversified service requirements in LTE and NR coexisting network platforms by adopting the idea of cooperative game theory and different allocation rules. The proposed scheme is formulated as a two-level dual bargaining model that facilitates the coordination and cooperation among network entities to share effectively the limited wireless spectrum resource, which results in improved performance measures in the LTE and NR coexisting platforms. Specifically, comparing with the existing state-of-the-art spectrum sharing protocols, simulation results show that the proposed scheme can improve throughput, payoff, and service provision by about 5%, 10%, and 10%, respectively, under the dynamically changing network environment.

Unlike one-way traffic offloading from the NR system to the LTE band, authors in [32] proposed a cross-band spectrum sharing scheme by sharing spectrum in both LTE and NR bands to allow two-way traffic offloading to offload the LTE traffic to the NR band and vice versa. To enable this technique, for the NR band, the multicast and broadcast services (MBS) feature of the NR network released in 3GPP Release 17 is exploited and a muted MBS subframe-based coexistence scheme is proposed. Muted MBS subframes are assigned on the NR band by the NR resource controller for the LTE traffic. Likewise, for the LTE band, muted MBSFN subframes are assigned on the LTE band by the LTE resource controller for the NR traffic. Unlike the traditional practice that requires coordination between LTE and NR systems, this scheme instead uses a machine learning-based technology recognition and traffic characterization (TRTC) system to identify and characterize traffic patterns. The NR resource controller uses the TRTC system to sense the available spectrum in the LTE band, whereas the LTE resource controller uses the TRTC system to sense the available spectrum in the NR band. Since no coordination is required for DSS between NR and LTE networks, unlike traditional DSS methods, this scheme does not suffer from additional signaling overhead. In comparison with the static band configuration, it is shown that the proposed cross-band spectrum sharing scheme on average can improve LTE throughput, NR throughput, LTE band spectrum utilization efficiency, and NR band spectrum utilization efficiency by 13.5%, 8.3%, 11.8%, and 20.7%, respectively.

Likewise, a proactive DSS scheme is proposed in [22] for the bandwidth split between NR and LTE systems at every subframe level using a controller that takes into account future states for LTE and NR spectrum sharing. Introducing a deep reinforcement learning algorithm based on Monte Carlo tree search, the controller distributes the communication resources over time and frequency between NR and LTE in a dynamic manner over a specific time horizon. The results show that the proposed scheme can improve the system-level performance. To serve both eMBB and Internet-of-Things (IoT) applications through an efficient 5G deployment, in [33], an innovative spectrum-exploitation mechanism such as spectrum-sharing between NR and LTE is introduced. It is shown that the proposed spectrum-sharing mechanism can balance various conflicting requirements, including uplink/downlink traffic asymmetry, uplink/ downlink coverage imbalance, and transmission efficiency versus latency. Further, subject to using the spared LTE uplink resources as a 5G NR supplemental uplink carrier paired with a wide band time-division duplexing (TDD) carrier above 3 GHz, the proposed spectrum sharing between LTE and NR can allow operators to retain their investment on LTE without refarming the LTE spectrum to NR. Furthermore, it is demonstrated that the proposed spectrum-exploitation mechanism can support seamlessly compelling IoT and eMBB services.

The authors in [17] studied the basic architecture of DSS, analyzed DSS interference, and proposed two interference mitigation solutions, namely, buffer setting and rate matching. To determine the feasibility of both solutions, the performance of both systems is verified in a commercial network. Based on theoretical, simulation, and practical analysis, it is shown that both solutions can effectively reduce inter-system interference introduced by DSS. More specifically, it is shown that the network rate is increased by 60% in an interference environment, whereas, user experience is improved in the DSS architecture. Likewise, a comprehensive analysis of the interference avoidance for DSS between frequency division duplex (FDD) LTE and NR is presented in [34] to overcome the coverage problem for NR standalone (SA) networks by operating in low-frequency LTE bands. In addressing so, the authors presented detailed collisions between FDD LTE and NR and proposed the corresponding collision avoidance principle by exploiting the flexible configuration of the NR physical layer. To address the collision with CRS, which exists across the whole LTE bandwidth, LTE CRS puncturing or NR puncturing is employed. The impact of LTE CRS puncturing or NR puncturing on the overall performance as well as the capacity loss based on the essential overhead are presented.

The concept of DSS for the coexistence of LTE and 5G NR is studied in [35], and a solution is presented to allow operators to offer both LTE and NR services on the same frequency bands. A sharing ratio is defined as the ratio of shared resources between NR and LTE systems. A common resource manager is considered whose function is to compute the sharing ratio between LTE and NR and update it based on respective traffic demands. Similarly, in [1], the authors introduced the efficient coexistence between LTE and 5G NR in two coexistence scenarios, namely co-carrier sharing and adjacent carrier sharing. In the co-carrier sharing scenario, two cases termed uplink spectrum sharing and downlink spectrum sharing in 3GPP are considered. In uplink spectrum sharing, NR shares the uplink carrier with LTE, whereas in downlink spectrum sharing, NR shares the downlink carrier with LTE. Through uplink sharing, NR can extend its coverage with C-Band (3.2GHz $\sim$ 5GHz) deployment and deploy using the LTE sites a C-band NR network, resulting in facilitating seamless coverage, reducing NR network cost, as well as speeding up NR commercialization. Moreover, simultaneous uplink/ downlink sharing between NR and LTE opens up early and low-load NR deployment. To the best of the authors' knowledge, no survey works have yet been addressed in the existing literature to give a holistic technical viewpoint on DSS for LTE and NR coexistence at the RB level, which is aimed to be addressed in this paper based on several key contributions, including [36], [37], and [38].

C. CONTRIBUTION

In this paper, an in-depth understanding of DSS for LTE and NR coexistence is presented by taking into account diversified concerns, including technological background, deployment options, potential design considerations and effects, DSS applications, 3GPP standardization activities towards DSS, and finally, DSS use cases, significance, and limitations. Relative comparisons of potential aspects of several DSS concerns including, deployment options, design considerations, DSS applications, and 3GPP standardization works in different releases in tabular forms are carried out. More specifically, the following regarding DSS for the coexistence of 5G NR and 4G LTE systems is contributed in this paper.

- A brief overview of the technological background of essential signals and channels of both LTE and NR systems that play a key role in enabling DSS for the coexistence of LTE and NR systems is given.
- Secondly, possible DSS deployment options for LTE and NR coexistence are discussed, and relative performances for the CRS rate-matching deployment option are presented in terms of spectral efficiency for numerous CRS configurations.
- Thirdly, numerous potential DSS design considerations and corresponding effects on designing LTE and NR coexistence are discussed.
- Fourthly, the application of DSS to both LTE MBSFN and LTE non-MBSFN subframes when considering NR with SSB as well as with SSB transmissions is discussed.
- Fifthly, 3GPP standardization activities towards DSS for LTE and NR coexistence in different releases are pointed out.
- Sixthly, numerous use cases, significance, and challenges with DSS along with highlighting future research directions on DSS for LTE and NR coexistence are highlighted.
- Finally, key lessons learned throughout the paper are summarized.

Though DSS for the coexistence of NR and LTE is not new, the novelty in the contribution of this paper can be justified by the fact that no paper in the existing literature has yet reviewed comprehensively the technical viewpoints of the use of DSS for the coexistence of NR and LTE systems. Rather, numerous contents concerning the application of DSS for the coexistence of NR and LTE have been addressed in the literature from either specific or partial, but comprehensive, technical viewpoints. In the authors' best view, this paper is a first of its kind that aims at addressing this research scope – a comprehensive review of technical understanding of DSS for the coexistence of NR and LTE systems - by reviewing relevant work either proposed, discussed, or demonstrated in the existing literature. In doing so, other than the authors' viewpoints, all sources of content used in the paper have been cited properly for clarity as well as easy navigation for the prospective readers to get further insights on a particular topic of interest. Existing works discussed in the related works section of this paper are compared and are given in Table 1 to show how this paper differs in scope from these existing works. Additionally, a list of abbreviations is given in Table 2.

D. ORGANIZATION

The paper is organized as follows. An overview of the technological background of essential signals and channels of both LTE and NR systems is given in Section II. In Section III, numerous DSS deployment options and their relative performances in terms of spectral efficiency are discussed. DSS design considerations and corresponding effects on the LTE and NR coexistence are discussed in Section IV. The application of DSS to both MBSFN and non-MBSFN LTE subframes under NR with and without SSB transmissions in Section V is examined. Section VI discusses the 3GPP standardization activities towards DSS in different releases. Section VII highlights numerous use cases, identifies the significance and challenges, and points out future research directions on DSS for LTE and NR coexistence. Key lessons learned throughout the paper in terms of numerous facts and figures are summarized in Section VIII. Section IX concludes the paper.

II. PRELIMINARIES

This section gives a brief overview of relevant signals and channels of both LTE and NR systems that play a key role in DSS between them. More specifically, frame structure, MBSFN reference signals, physical downlink control channel (PDCCH), and cell-specific reference signals of LTE are discussed. Likewise, along with the frame structure and PDCCH, CORESET, downlink control information (DCI), SSB, and DMRS of NR are detailed.

A. LTE AND NR FRAME STRUCTURES

1) LTE FRAME STRUCTURE

LTE uses 10 ms of frame duration to transmit uplink and downlink information. The duration of each subframe is 1 ms such that there are 10 subframes per radio frame. Each subframe consists of two consecutive slots of 0.5ms, resulting in 20 slots per radio frame. The length of cyclic prefix and SCS defines the number of orthogonal frequency division multiplexing (OFDM) symbols in a slot. For a normal cyclic prefix and SCS of 15 kHz, there are 7 symbols per slot such that each subframe consists of 14 symbols. However, for an extended cyclic prefix, there are 12 symbols per subframe [36].

LTE supports two radio frame structures, including Type 1 and Type 2. Type 1 is used for both half-duplex and full-duplex FDD operations. However, frame type 2 applies to TDD. For FDD, both downlink and uplink transmissions separated in the frequency domain can take place on 10 subframes per 10 ms interval. On the contrary, in TDD, each radio frame comprises two half-frames, each consisting

TABLE 1. A comparison of this paper with existing works.

Article	Major focus		Contribution
31	DSS for LTE/NR coexistence from a specific set of viewpoints	DSS scheme	A novel DSS scheme that satisfies diversified service requirements in the 4G and 5G (4G/5G) coexisting networks is proposed in the paper. The following are also addressed in the paper. • Formulate a two-level bargaining process for the LTE resource allocation; • Explore the interaction between 4G and 5G operators using a joint-bargaining procedure; • Show the outperformance of the proposed approach over the existing protocols.
33			A cross-band DSS scheme is proposed in the paper. The scheme utilizes LTE MBSFN and NR MBS features. Moreover, to enable the cross-band DSS scheme, novel uncoordinated LTE and NR resource controllers are proposed.
22			A proactive DSS scheme between 4G and 5G systems is proposed. A deep reinforcement learning algorithm based on Monte Carlo Tree Search is proposed for this problem.
35			An innovative spectrum-exploitation mechanism, e.g., the NR/LTE spectrum-sharing philosophy, is introduced for efficient 5G deployment to serve both eMBB and IoT applications. The key concept relies on accommodating the uplink resources in an LTE FDD frequency band as a supplemental uplink carrier along with the NR operation in the TDD band above 3 GHz.
32		DSS interference	A comprehensive interference avoidance analysis is presented for DSS between FDD LTE and NR to address NR SA networks' coverage concerns. Detailed collisions between FDD LTE and NR are presented, and the corresponding principle of collision avoidance is proposed. Finally, a capacity loss is explained taking into account vital overheads.
17			The basic architecture of DSS is studied in the paper. Addressing the theoretical analysis of DSS interference, two interference mitigation solutions, namely buffer setting and rate matching, are proposed.
1		Coexistence of LTE and 5G NR	Efficient LTE-NR coexistence is introduced in the paper. Two coexistence scenarios, namely co-carrier and adjacent carrier sharing are presented.
34			NR-LTE DSS concept is studied in the paper. A solution is then presented to offer both LTE and NR services in an interleaved mode on the same frequency. Finally, employing the feature of DSS, the performance evaluation of a communication system is carried out.
26	Spectrum sharing from holistic viewpoints with a focus on standardization and implementation aspects		Emphasizing mainly standardization and implementation features, in this paper, a comprehensive survey of existing licensed and unlicensed spectrum sharing techniques in mobile systems is carried out.
27			A comprehensive survey examining existing spectrum sharing scenarios under various network topologies as well as coordination protocols for the licensed spectrum is carried out.
30	Coexistence studies in unlicensed frequency bands		A comprehensive survey concerning the coexistence of cellular and IEEE 802.11 standards in all the available unlicensed frequency bands is carried out.
28			A comprehensive survey of the coexistence of LTE licensed assisted access (LTE-LAA) and wireless fidelity (WiFi) in 5 GHz bands and an analysis of numerous deployment scenarios are provided.
29			An in-depth summary of numerous coexistence scenarios in 5 GHz unlicensed bands, including the coexistence of LTE, radar, and dedicated short-range communication with WiFi, as well as the coexistence among numerous 802.11 protocols in 5 GHz bands is addressed.
This paper	DSS to coexist 4G LTE and 5G NR systems from holistic viewpoints		A comprehensive understanding of DSS at the RE level or RB level under different LTE subframes and CRS positions is carried out. The following are addressed in this paper. • An overview of the technological background of essential signals and channels of both LTE and NR systems. • Possible DSS deployment options for LTE and NR coexistence; • Numerous potential DSS design considerations; • Application of DSS to both MBSFN and non-MBSFN LTE subframes under NR with SSB as well as NR without SSB transmissions; • 3GPP standardization activities towards DSS for LTE and NR coexistence; • Highlight numerous use cases along with the significance and limitations of DSS; • Summarize key lessons, in terms of facts and figures, learned throughout the paper.

of 5 subframes, and hence, has a length of 5 ms [36]. Since LTE operates mainly on FDD bands unless stated otherwise, frame structure type 1 by default, which is shown in the following Fig. 1.

2) NR FRAME STRUCTURE

Unlike LTE, which considers only 15 kHz SCS, multiple OFDM numerologies are supported in NR to provide flexibility. More specifically, multiple SCSs, defined as $\Delta f = (2^{\mu} \times 15)$, are adopted in NR where $\mu \in \{0, 1, 2, 3, 4\}$. NR is designed to incorporate SCS of variable length, including 15kHz, 30kHz, 60kHz, 120kHz, and 240kHz. Supported transmission numerologies are shown in Table 3 [39].

Like LTE, NR also uses a 10 ms long radio frame for uplink and downlink transmissions, each consisting of 10 subframes. Each subframe lasts for 1 ms. For a given numerology, μ, slots within a subframe are denoted as $n_s^{\mu} \in \left\{0, \ldots, \left(N_{\text{slot}}^{subframe,\mu} - 1\right)\right\}$ and within a frame are denoted as $n_{s,f}^{\mu} \in \left\{0, \ldots, \left(N_{\text{slot}}^{frame,\mu} - 1\right)\right\}$. Each slot consists of a set of consecutive symbols denoted as $N_{\text{symb}}^{\text{slot}}$. Like LTE, cyclic prefix length defines symbols per slot in NR. Based on the above numerologies for NR, Table 4 shows the number of OFDM symbols per slot, slots per subframe, and slots per frame for the normal cyclic prefix (CP).

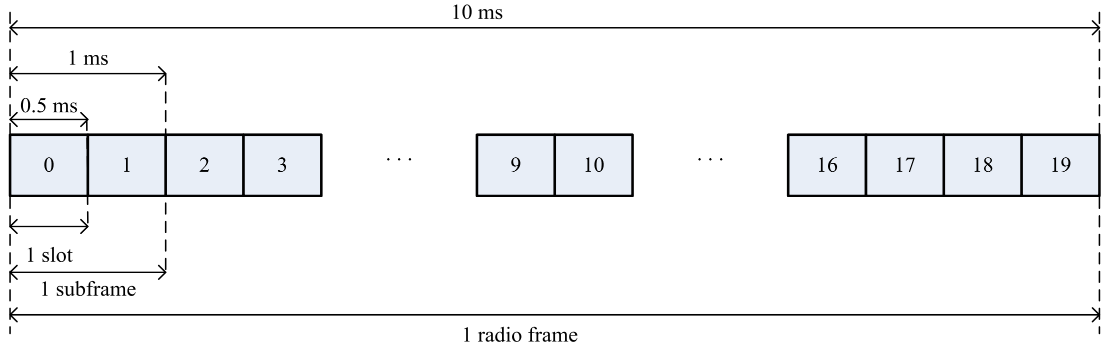


FIGURE 1. LTE frame structure type 1 [36].

TABLE 2. List of abbreviations.

Name	Description
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
CA	Carrier Aggregation
CC	Component Carrier
CCE	Control Channel Elements
CORESET	Control Resource Set
CP	Cyclic Prefix
CRS	Cell Reference Signal
CSI-RS	Channel State Information Reference Signals
DC	Dual Connectivity
DCI	Downlink Control Information
DMRS	Demodulation Reference Signals
DSM	Dynamic Spectrum Management
DSS	Dynamic Spectrum Sharing
eMBB	Enhanced Mobile Broadband
FDD	Frequency Division Duplex
HARQ	Hybrid Automatic Repeat Request
LTE	Long-Term Evolution
LTE-LAA	LTE Licensed Assisted Access
MBSFN	Multicast-Broadcast Single-Frequency Network
MBS	Multicast Broadcast Service
MIB	The Master Information Block
mMTC	Massive Machine-Type Communications
mmWave	Millimeter Wave
Non-MBSFN	Non-Multicast-Broadcast Single-Frequency Network
NR	New Radio
NSA	Non- Standalone
OFDM	Orthogonal Frequency Division Multiplexing
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channels
PCI	Physical Cell ID
PBCH	Physical Broadcast Channel
PSS	Primary Synchronization Signal
RB	Resource Block
RE	Resource Element
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
SA	Standalone
SCS	Subcarrier Spacing
SS	Synchronization Signals
SSB	Synchronization Signal/PBCH Block
SSS	Secondary Synchronization Signal
TD	Time-Domain
TDD	Time Division Duplex
TRS	Tracking Reference Signals
UE	User Equipment
URLLC	Ultra-Reliable and Low Latency Communications

Note that, because 15kHz SCS is considered in LTE, the following analysis considers SCS of 15kHz for NR as well to reduce complexity in DSS. Also, like LTE, NR uses a radio frame duration of 10 ms and a subframe duration of 1 ms. Fig. 2 shows the frame structure for NR in the time domain with a corresponding change in subcarrier spacings mentioned above. As the transmission is addressed in every slot level and the slot duration decreases by half as the SCS increases by twice, the number of symbols (i.e., data) transmitted per radio frame [36] can be increased by considering longer subcarrier spacing. Because a normal cyclic prefix is considered, each slot in NR incorporates 14 OFDM symbols.

TABLE 3. NR transmission numerologies [39].

μ	$\Delta f = (2^{\mu} \times 15)[\text{kHz}]$	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

TABLE 4. The number of OFDM symbols, slots, subframes, and frames in NR for normal CP [39].

μ	$N_{\text{symb}}^{\text{slot}}$	$N_{\text{slot}}^{\text{frame},\mu}$	$N_{\text{slot}}^{\text{subframe},\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

Recall that, the number of slots per subframe in LTE is 2, each incorporating 7 OFDM symbols for normal cyclic prefix. Because a SCS of 15kHz for NR is considered, each subframe of both LTE and NR consists of 14 OFDM symbols, which eventually makes the spectrum sharing between LTE and NR systems simple. Yet, it is to be pointed out that, theoretically, other subcarrier spacings in NR (Fig. 2) can be used at the cost of additional complexity [40].

Considering 15 kHz SCS for the duration of N subframes, Fig. 3 shows the resource grid for NR. The smallest unit shown in a rectangle in the resource grid is called the RE. A RE consists of a subcarrier of 15 kHz that spans over one OFDM symbol duration. When grouping contiguously, a set of 12 subcarriers of 180 kHz spanning over one subframe duration, is referred to as a resource block (RB). The performance of DSS between NR and LTE depends on

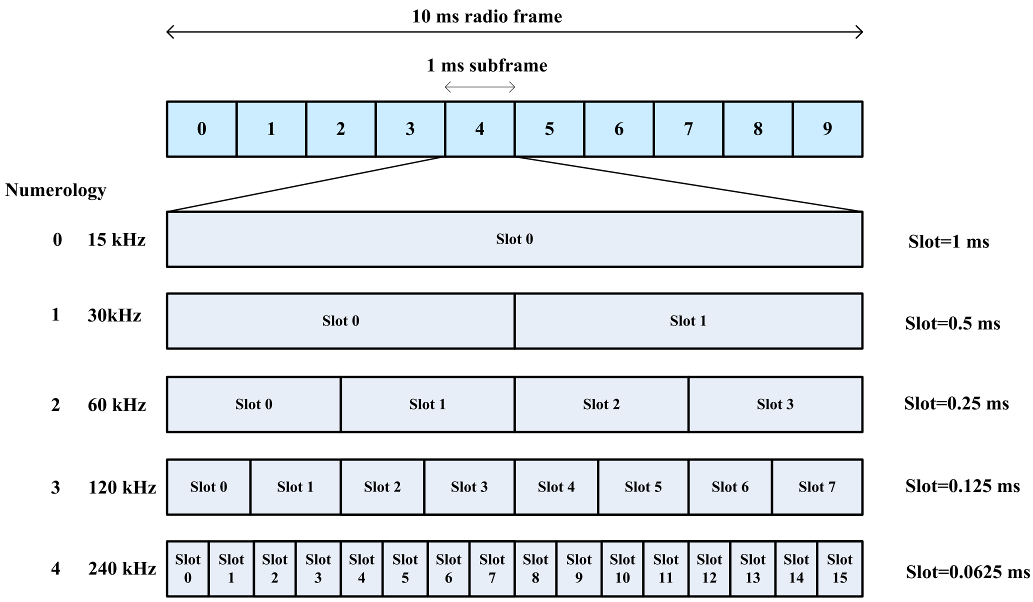


FIGURE 2. NR frame structure in the time domain [37].

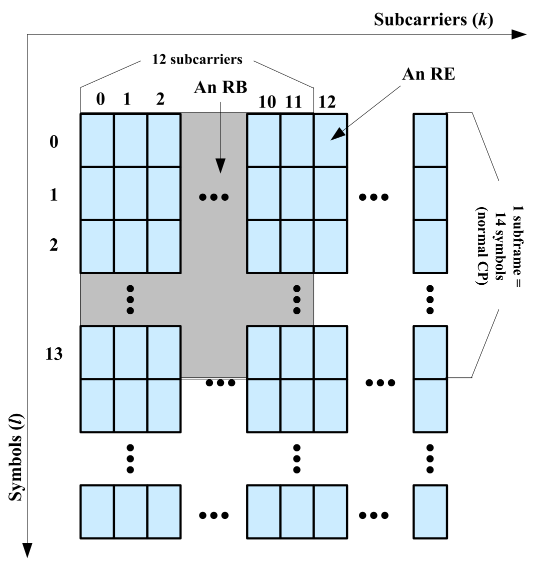


FIGURE 3. 5G resource grid [37].

how optimally REs or RBs of LTE can be allocated to NR for its data transmissions subject to avoiding collisions with LTE reference signals, which are discussed in detail in the following sections.

B. LTE CELL-SPECIFIC REFERENCE SIGNAL

In LTE, CRSs are transmitted always in all downlink subframes for frame structure type 1 (Fig. 1) in a cell to synchronize any User Equipment (UE) with the serving Base Station Transceiver (BTS). Moreover, UEs utilize CRSs to support the transmission of PDSCH, e.g., to estimate the downlink channel condition [40], [41], [42], [43]. Depending on the number of antenna ports, the number and position of CRSs differ. In LTE, the position of CRSs is fixed. Because, in LTE, SCS of 15 kHz is used [43], CRS reference signals are defined for only 15 kHz. For multiple antenna ports, a RE used for the CRS transmission on one antenna port cannot be used in the same time slot on any other antenna port and is usually set to zero.

Fig. 4 shows the LTE control signals mapping, particularly CRSs, for one RB over one subframe in a time-frequency resource grid based on the number of antenna ports and the length of the normal cyclic prefix. The normal cyclic prefix differs from the extended cyclic prefix by one symbol more than that in the extended cyclic prefix per slot. Hence, for the extended cyclic prefix $l \in \{0, 1, 2, 3, 4, 5\}$. It is to be noted that all reference signals do not support the same number of antenna ports. For example, CRS can support a configuration of one, two, or four antenna ports, transmitted respectively, on ports 0, {0,1} and {0,1,2,3} as shown in Fig. 4.

In Fig. 4, R_p denotes an RE used for the transmission of CRS on port p. CRSs are shown in different colors for different ports spanning one RB in LTE for the number of antenna ports 1, 2, and 4. For 1 and 2 antenna ports, CRSs are present at symbols 0, 4, 7, and 11 whereas CRSs are present at symbols 0, 1, 4, 7, 8, and 11 for 4 antenna ports. Note that, with an increase in the number of antenna ports, the density of CRSs per RB increases both in frequency and time. In other words, though the number of REs to serve NR traffic per RB decreases with an increase in the number of antenna ports, because of spatial multiplexing, the actual number of REs for NR traffic increases as the number of antenna ports increases.

LTE PDCCHs are mapped partly, only to REs unoccupied by CRSs, at symbol 0, whereas fully to all REs at symbol 1. Symbol 2 is used by PDCCHs of 5G NR. REs mapped

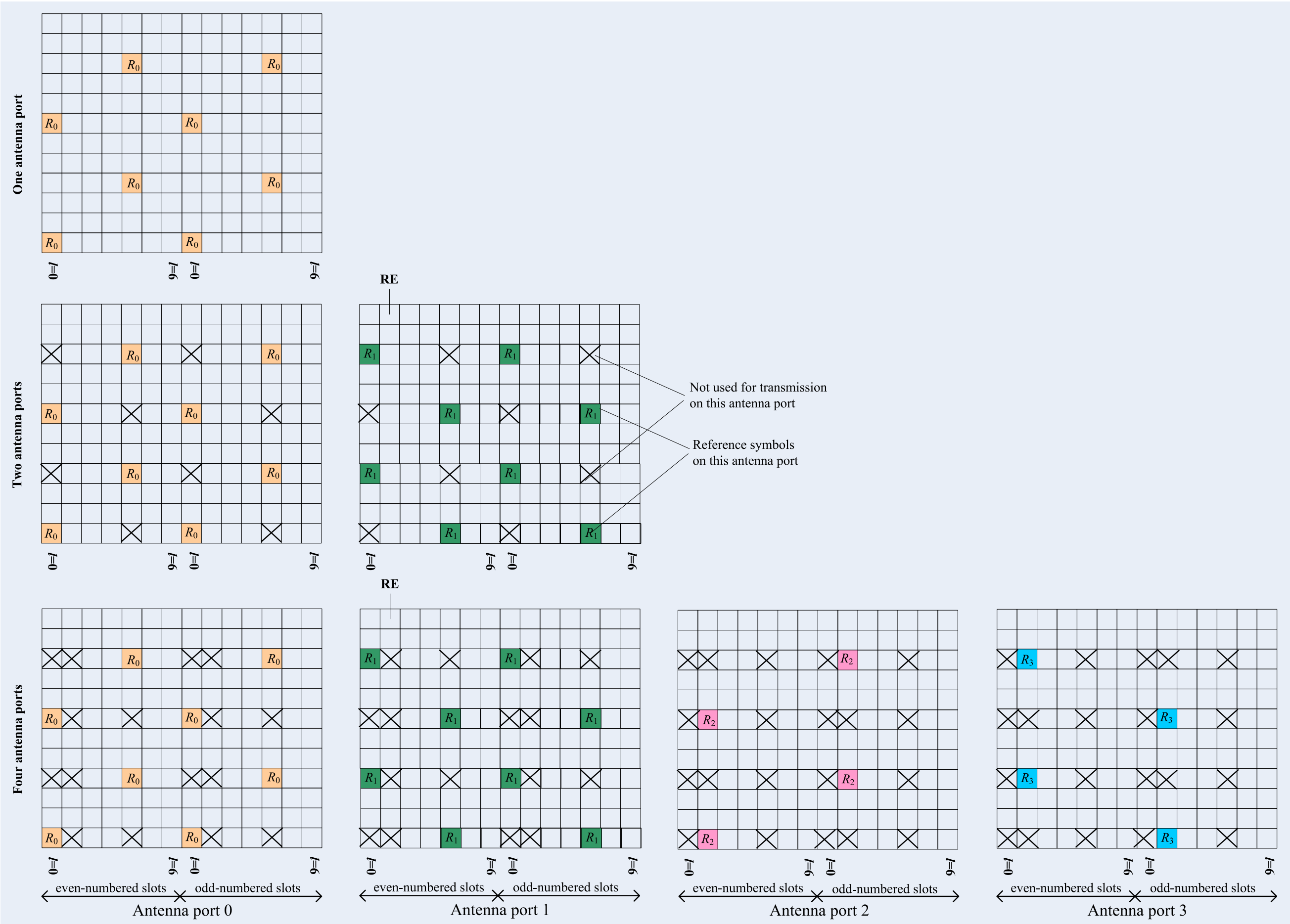


FIGURE 4. Mapping of downlink reference signals (normal cyclic prefix) [36].

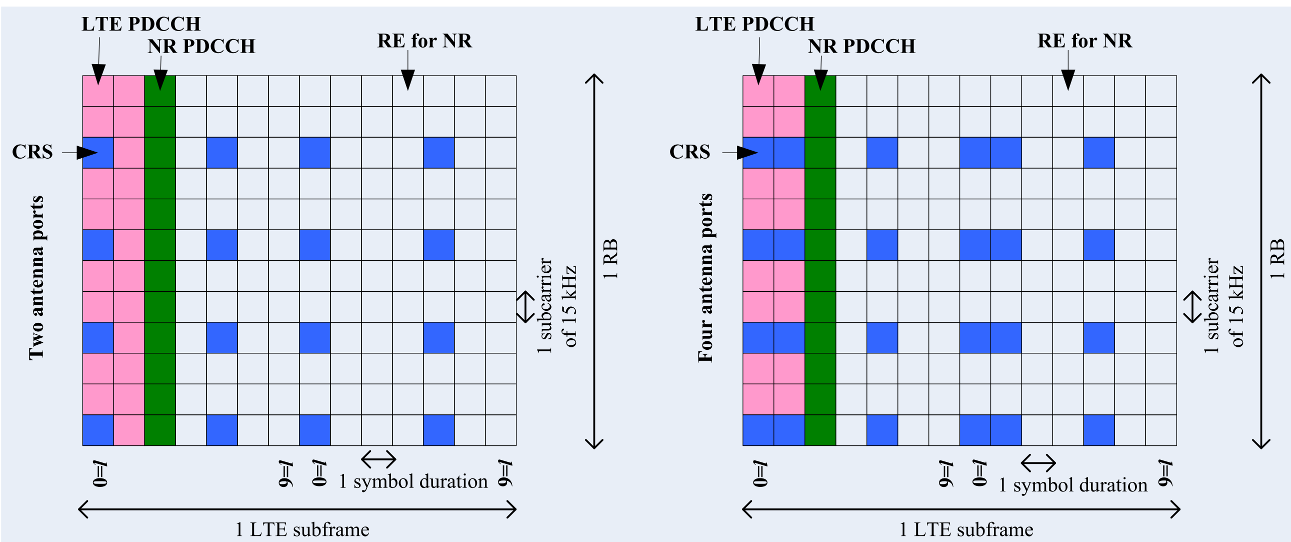


FIGURE 5. LTE Control signals and resources (i.e., REs) for NR data transmission in LTE using DSS for different LTE antenna configurations [37].

to these control signals, i.e., CRSs (shown in color) and PDCCHs of LTE cannot be used to serve NR traffic to avoid collision and interference. Note that CRSs are not used for MBSFN subframes. Including PDCCHs, Fig. 4 is redrawn as shown in Fig. 5 for antenna ports two and four. Fig. 5 shows that, in LTE, when employing DSS using 2 antenna ports, there are only 120 REs ($(12 \times 14) - (3 \times 12) - (3 \times 4) = 120$ REs) remaining per RB to serve NR data traffic. Similarly, it remains only 116 REs ($(12 \times 14) - (3 \times 12) - (4 \times 4) = 116$) per RB when employing four antenna ports. Recall that though the number of REs to serve NR traffic per RB decreases with an increase in the number of antenna ports, because of spatial multiplexing, the actual number of REs for NR traffic increases as the number of antenna ports increases. This can be found reflected in Fig. 5 where the number of REs to serve NR traffic for 2 and 4 antenna ports are, respectively, 240 (2×120) and 464 (4×116).

Because the number of CRSs spanning an RB per symbol duration (i.e., CRS rate) varies with the number of antenna ports, CRS rate matching is needed to serve NR in places other than occupied by CRSs and control channels [44]. CRS rate matching can be done either at the RE level or the symbol level [17]. At the RE level, CRS rate matching is difficult. This can be made simpler by matching the CRS rate at the symbol level such that no serving of NR data traffic can be performed at symbols incorporating CRSs and control channels of LTE and NR. CRS rate matching in detail in a later section is discussed. Recall that LTE CRSs and PDCCHs occupy symbols 0 and 1 whereas symbol 2 is occupied by NR PDCCHs. Hence, at the symbol level rate matching, in effect, there are 96 REs ($168 - (3 \times 12) - (3 \times 12)$=96 REs) and 84 REs ($168 - (3 \times 12) - (4 \times 12)$ REs) of LTE per RB per symbol, respectively, for 2 and 4 antenna ports that can be allocated to serve NR data traffic using DSS (i.e., to provide 5G coverage using 4G LTE spectrum) (Fig. 5).

C. LTE MBSFN REFERENCE SIGNALS

A base station can use either unicast or multicast approach to deliver multiple users the same content [45]. In unicast, multiple copies are sent to the UEs, one per UE whereas one copy of interest is sent to all UEs in multicast. Among multicast technologies, LTE adopts MBSFN because of its basis on the single frequency network and cell edge performance improvement [18]. 3GPP has defined MBSFN reference signals to deliver simultaneous transmission of the same content to a set of users over the same radio resources within multiple cells [45], [46], [47]. Such a cooperative transmission can provide very large coverage and is a good feature for enabling broadcasting services nationwide [48]. MBSFN reference signals are transmitted only on antenna port 4 when the physical multicast channel (PCH) is transmitted. MBSFN reference signals are defined only for the extended cyclic prefix and transmitted using SCS of either 15 kHz or 7.5 kHz [36]. Fig. 6 shows the mapping of LTE MBSFN reference signals for the SCS of 15 kHz.

D. NR DMRS FOR DSS

In NR, DMRS is used for channel estimation and demodulation of physical channels (i.e., how to demodulate the data signal in the NR system) [49], [50], [51], [52]. DMRS accompanies every piece of information in 5G NR as the standard assumes that the precoding is used. Unlike LTE, the number, position, and density of DMRS in NR are highly configurable [53]. There are two types of PDSCH mapping in NR, namely Type A and Type B. In Type A, DMRS is allocated to either symbol 2 or symbol 3 in a slot. This DMRS allocation is good for transmissions of slots occupied mostly by data. In Type B, DMRS maps to the first symbol of the PDSCH allocation irrespective of where in the slot it appears [53]. This is particularly useful when allocation starts midway through a slot. This can help fast demodulation by having DMRS in the first place to reduce latency. This Type B mapping is helpful for transmissions of data that may appear anywhere in the slot. Note that in both types, DMRSs are at the beginning of a slot in NR.

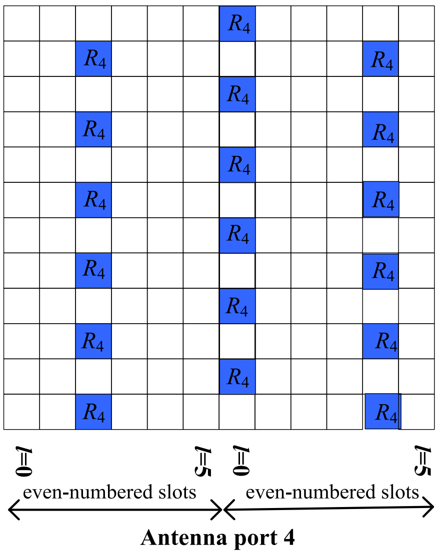


FIGURE 6. Mapping of MBSFN reference signals (extended cyclic prefix, Δf =15kHz) [36].

When DSS is being employed, according to 3GPP Release 15, in general, one DMRS at a single symbol (particularly, at symbol 3) is sufficient. However, when using more of the LTE REs per RB for NR data traffic, in addition to the DMRS at symbol 3, one more DMRS needs to be transmitted at symbol 11. The positions of 5G DMRSs are fixed at symbols 3 and 11 per RB per subframe for 15kHz SCS in the LTE. However, it is known that in the LTE non-MBSFN subframe, as shown in Fig. 5, CRSs already exist at symbol 11, which results in making the NR DMRS difficult to position at symbol 11 in any LTE RB. To avoid this, though it is not specified in the 5G specification, 5G NR leaves a provision for shifting the position of the DMRS in NR from symbol 11 to symbol 12 in LTE when DSS is being employed (i.e., when NR data is transmitted using LTE subframes) as shown in Fig. 7 [36].

E. NR CORESET, PDCCH, AND DCI

Control resource sets (CORESETs) are a set of time and frequency resources where physical downlink control channel PDCCH is transmitted. Using the CORESET feature, network operators can configure and allocate time and

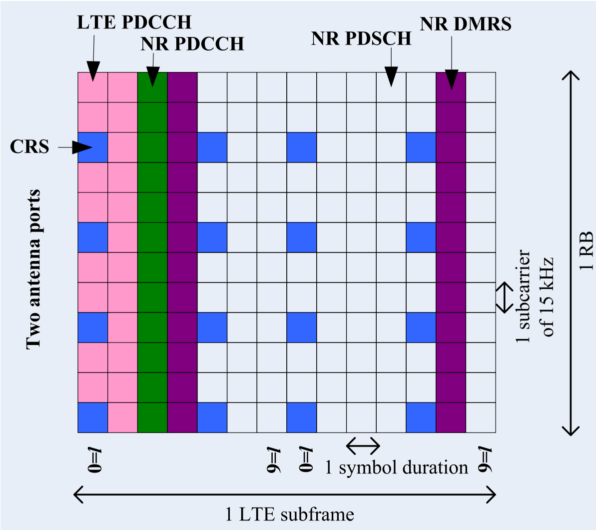


FIGURE 7. 5G NR in LTE subframes with DMRS shifted (from symbol 11 to symbol 12) in Type A PDSCH [36].

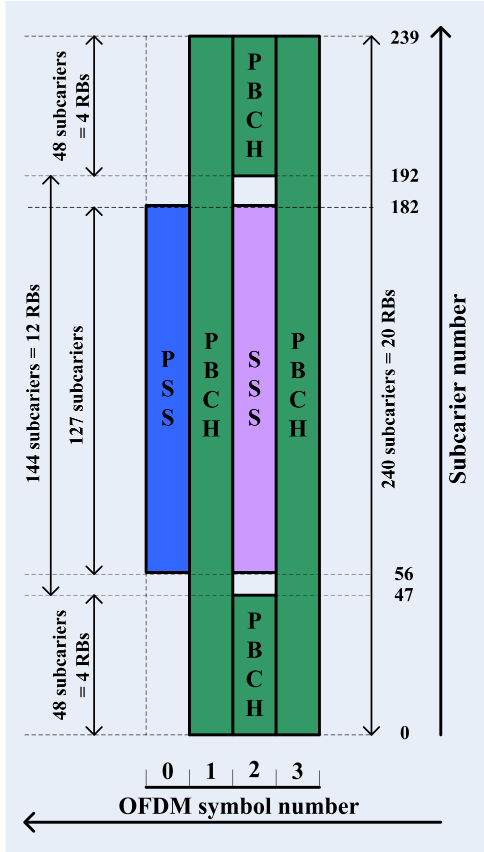


FIGURE 8. Time-frequency structure of an SSB [63].

frequency resources [3], [54]. CORESETs can be more than one and may occur anywhere in the time and frequency grid of the carrier. CORESETs are at most three OFDM symbols long. PDCCH is transmitted within CORESETs. PDCCH may occupy part or all of the frequency locations of the CORESETs at different time instants. The basic unit of CORESETs is Resource Element Groups (REG). A REG is a set of 12 contiguous REs (or 1 RB) in one symbol duration [55]. A CORESET may span up to 6, possibly noncontiguous, RBs in frequency [55], [56] and between 1 and 3 contiguous OFDM symbols in time.

CORESETs represent locations where a UE may receive PDCCH. There may not be any PDCCH in some CORESET locations. A CORESET may not span the whole bandwidth. This is particularly important when the bandwidth is large (e.g., 400 MHz), which not all UE may support, as a UE needs to be able to decode all control information.

The PDCCH channel carries scheduling assignments and other control information [57]. A PDCCH is mapped to a specific CORESET. A PDCCH may map to one or more control channel elements (CCEs). NR standards define several aggregation levels like LTE except for the introduction of a new aggregation level 16 (not available in LTE), resulting in aggregation levels of 1, 2, 4, 8, or 16 CCEs where 1 CCE corresponds to 6 REGs, i.e., 6 RBs. Of these 72 (6×12) REs, 54 are for PDCCH itself, and 18 are reserved for associated DMRS. DMRS helps UE to estimate the channel, which accounts channel propagation effect including beamforming.

DCI carries control information about scheduling PDSCH [57], [58]. DCIs are carried by PDCCH [59]. DCIs indicate the location of user data in time and frequency, modulation and coding scheme, hybrid automatic repeat request (HARQ), antenna ports and the number of layers, CSI requests, and so on. A UE needs to decode DCI to decode downlink data or transmit uplink data.

Like LTE, NR UE needs to identify and decode PDCCH. However, NR PDCCH differs in many aspects from LTE PDCCH. For example, in NR, PDCCH may not span the whole bandwidth of 5G NR, which LTE always does. This is because NR UEs are not required to decode the full NR bandwidth leaving flexibility in making UE devices much simpler and cheaper. Secondly, NR PDCCH supports device-specific beamforming.

F. NR SYNCHRONIZATION SIGNAL/PBCH BLOCK

NR also adopts two types of synchronization signals (SSs) like LTE, namely, primary synchronization signal (PSS) and secondary synchronization signal (SSS). The synchronization signal/physical broadcast channel (PBCH) block (SSB) comprises 20 contiguous RBs (i.e., $20 \times 12 = 240$ subcarriers) [60], which can start from any RB index but spans over 20 RBs contiguously over four contiguous symbols (symbol indices 0, 1, 2, and 3) as shown in Fig. 8 [60]. An SSB consists of PSSs, SSSs, and Physical Broadcast Channels (PBCHs) [61], [62]. A UE uses PSSs for the downlink frame synchronization (i.e., the position of the first symbol in a radio frame of 10 ms) and SSSs for the downlink subframe synchronization (i.e., the position

TABLE 5. The maximum allowable number of SSBs in an SS burst [63].

Carrier Frequency	Maximum number of candidates SSBs within an SS Burst set
3GHz $\leq fc$	4
3GHz $< fc \leq$ 6GHz	8
$fc >$ 6GHz	64

of the first symbol in a subframe). PBCH gives additional information about the system. To measure reference signal received power (RSRP) and reference signal received quality (RSRQ) by a UE, SSs can also be used.

A UE in a cell synchronizes in time and frequency with the cell and detects the physical cell ID (PCI) of the cell using SSs and PBCH to acquire relevant cell access information [60]. In contrast to LTE, which has 504 PCIs, NR has 1008 unique PCIs. These PCIs are divided into 336 unique PCI groups, each containing 3 unique PCIs. Let PCI group numbers be represented as $N_{\text{ID}}^{(1)} = \{0, 1, 2, \ldots, 335\}$, and each group of PCIs is represented as$N_{\text{ID}}^{(2)} = \{0, 1, 2\}$. Then, the PCI of a cell can be calculated as $N_{\text{ID}}^{\text{Cell}} = 3 \times N_{\text{ID}}^{(1)} + N_{\text{ID}}^{(2)}$. A UE derives $N_{\text{ID}}^{(2)}$ from the PSS and $N_{\text{ID}}^{(1)}$from the SSS. With these three, PSS, SSS, and Cell ID, a 5G UE can latch onto the 5G NR network. Fig. 8 shows the time and frequency structure of an SSB. From Fig. 8, the following can be observed.

- PSS, SSS, and PBCH always stay consecutively. Each SSB lasts for 4 symbols in TD and 20 RBs or equivalently 240 SCSs in FD.
- Out of 240 subcarriers, PSS occupies the first OFDM symbols and spans over 127 SCSs. Like PSS, SSS is located in the third OFDM symbol and spans over 127 SCSs as well. Note that there are white portions (i.e., unused 8 and 9 SCSs), respectively, below and above the SSS, which define blank subcarriers in an SSB.
- PBCH occupies full second and fourth OFDM symbols, each spanning 240 SCSs. In addition, PBCH spans in the third symbol over 48 SCSs both below and above the SSS. This implies that PBCH occupies a total of 576 (240+48+48+240) SCSs across OFDM symbols 1, 2, and 3.
- In the time domain, each SSB spans across 4 OFDM symbols. SSBs are transmitted with a periodicity of 5ms,10ms, 20ms, 40ms, 80ms, and 160ms. Note that longer SSB periodicities help enhance network energy performance whereas shorter one helps facilitate faster UE cell search. In general, a UE can assume a default periodicity of 20ms during initial cell search or idle mode mobility.
- A set of SSBs forms an SS burst, which is defined to enable beam-sweeping for PSS/SSS and PBCH. Each SSB in an SS burst is transmitted on a different beam following the time division multiplexing (TDM) technique. An SS burst is always confined to a 5ms window located either in the first half or in the second half of a 10 ms radio frame.
- Depending on the carrier frequency, the maximum allowable number of the candidate SSBs in an SS burst is varied as shown in Table 5.

For any candidate SSB, the starting OFDM symbol index can be defined based on the SCS and carrier frequency as given in Table 6 where each entry within a set, represented in curly brackets, denotes the starting OFDM symbol index for the candidate SSBs of the corresponding SS burst. For example, for SCS=15kHz and carrier frequency 3GHz $<$ $fc \leq$ 6GHz, there is a maximum of eight SSBs in the SS burst (see Fig. 9). The set of the starting OFDM symbols corresponding to each of the eight candidate SSBs of this SS burst can be defined using the following formula {2, 8}+14n where n={0,1,2,3}, resulting in a set of starting OFDM symbols of {2, 8, 16, 22,30,36,44,50} as shown in Table 6.

As an example, the timing of candidate SSBs within the SS burst set is shown in Fig. 9 for SCS=15 kHz and carrier frequencies of 3GHz to 6 GHz. From Fig. 9, it can be found that the starting OFDM symbol indices for the candidate SSBs are given by 2, 8, 16, 22, 30, 36, 44, and 50, as mentioned in Table 6. Note that if the network is not using beamforming, only one SSB may be transmitted. This means that there can be only one SSB in an SS burst.

Note also that the use of SCSs as shown in Table 6 is constrained by the channel bandwidth. Since each SSB always consists of 20 RB, and there are 12 SCS per RB, the bandwidth occupied by an SSB=240 $\times$ SCS. Hence for SCS of 15 kHz, the channel bandwidth of an SSB is 3.6 MHz whereas for SCS of 30kHz, the channel bandwidth of an SSB is 7.2 MHz. This implies that for any carrier frequency with SCS of 30 kHz or higher, 5MHz channel bandwidth cannot be used since the minimum bandwidth required by an SSB is 7.2 MHz. Similarly, it can be shown that SCSs of 15 kHz and 30 kHz can be applied to carrier frequencies of sub-6 GHz whereas SCSs of 120 kHz and 240 kHz (required bandwidth of an SSB of 28.8MHz and 57.6MHz, respectively) apply to FR2 frequency bands, i.e., higher frequency bands such as millimeter wave (mmWave) bands.

Additionally, in LTE, the positions of PSS and SSS are always fixed [64]. However, in NR, a set of possible frequency locations for SSBs is defined. This is referred to as a synchronization raster. A UE needs to search for SSBs on this raster [65]. Since a UE may not be able to decode all SSBs at the same time because of the beamforming of SSBs, it is not unusual that the received SSB could be anywhere within the SS burst set, resulting in no frame synchronization. Hence, to achieve frame synchronization, the master information block (MIB) includes a time index to let a UE know the relative position of the SSB in time.

In the following section, the use of DSS in LTE in the presence or absence of NR SSB is examined and the required considerations for implementing the DSS in LTE subframes for NR transmissions are identified.

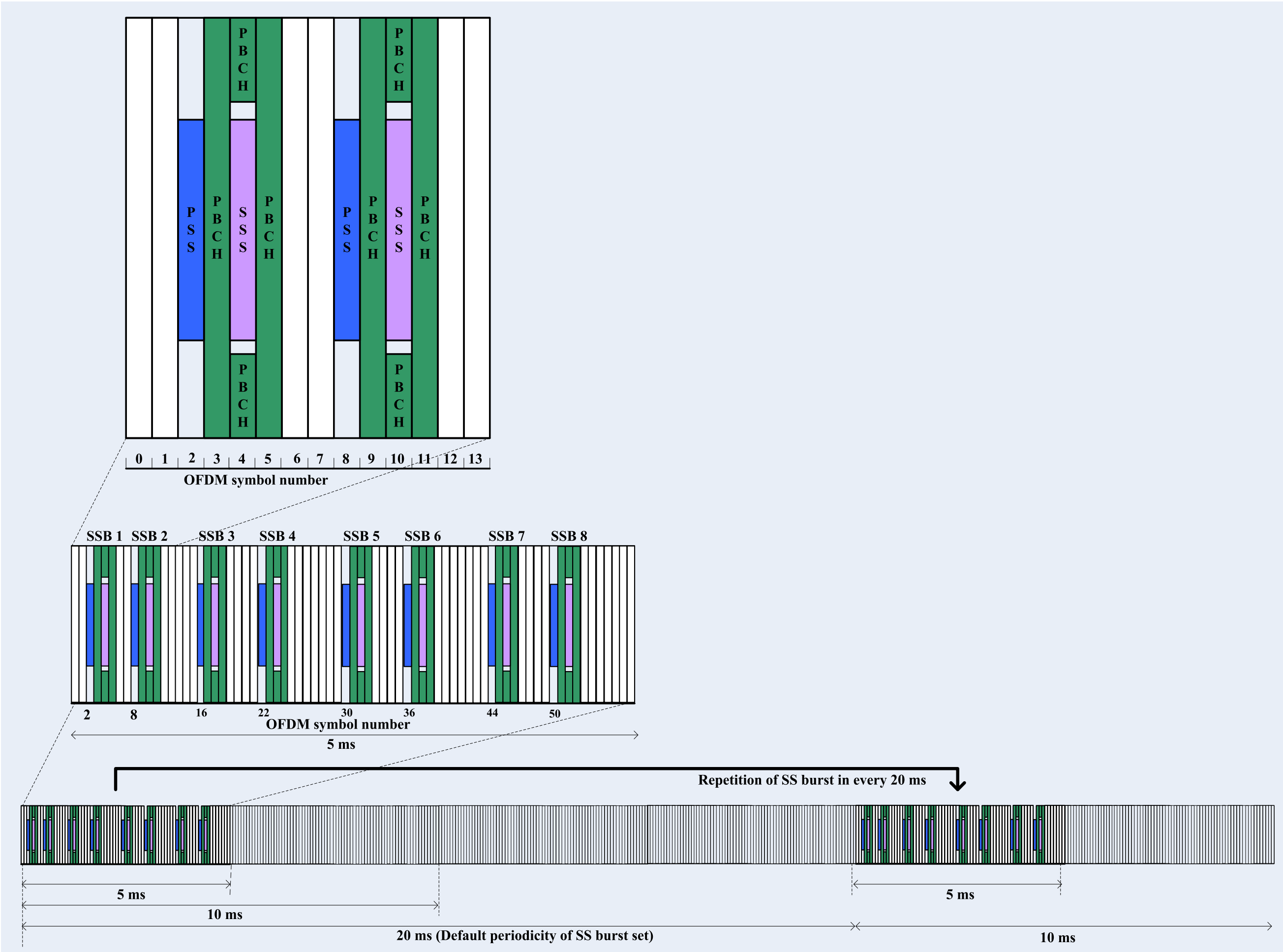


FIGURE 9. SS burst set for SCS=15khz and carrier frequencies between 3ghz and 6 GHz (Maximum number of SSBs in SS burst set=8; SSB starting symbol index set: {2, 8, 16, 22, 30, 36, 44, 50} [63].

TABLE 6. Estimation of starting symbol indices for the candidate SSBs within an SS burst [63].

Subcarrier spacing	Starting OFDM symbols of the candidate SSBs	3GHz $\leq fc$	3GHz $< fc \leq$ 6GHz	$fc >$ 6GHz
15 kHz (case A)	{2,8}+14*n*	*n*=0,1 {2,8,16,22}	*n*=0,1 {2,8,16,22,30,36,44,50}	NA
30 kHz (case B)	{4,8,16,20}+28*n*	*n*=0 {4,8,16,20}	*n*=0,1 {4,8,16,20,32,36,44,48}	NA
30 kHz (case C)	{2,8}+14*n*	*n*=0,1 {2,8,16,22}	*n*=0,1 {2,8,16,22,30,36,44,50}	NA
120 kHz (case D)	{{4,8,16,20}+28*n*	NA	NA	*n*=0,1,2,3,5,6,7,8,10,11,12,13,15,16, 17,18 {4,8,16,20,…,508,512,520,524}
240 kHz (case E)	{8,12,16,20,32,36,40,44} +56*n*	NA	NA	*n*=0,1,2,3,5,6,7,8 {8,12,16,20,…,480,484,488,492}

G. TYPES OF NR PDSCH MAPPING FOR DSS

There are two types of data scheduling in NR, including Type A and Type B [66], [67]. Type A or slot-based mapping where PDSCH can be started allocating at the slot level from symbols 0, 1, 2, and 3 that lasts from 3 to 14 OFDM symbols. In general, NR eMBB services use Type A mapping. Note that for 15 kHz subcarrier spacing, the slot size is 1 ms.

The second thing is when the data can be started to send. It can start from the symbols 0, 1, 2, or 3 and can schedule a minimum of 3 to a maximum of 14 symbols per subframe. This is called Type A or slot-level mapping. This mapping is used for MBSFNs as shown in Fig. 7 where symbols 0 and 1 can not be used because of the presence of CRS and PDCCH of 4G LTE. In addition, symbol 2 is used for the PDCCH of NR, and symbol 3 is used for NR DMRS. Hence,

TABLE 7. A multilayer approach for 5G scenarios [68].

5G service	Service requirement	Spectral layer	Spectrum band	Spectrum amount	DSS
eMBB	Extremely high data rates	Superdata layer	Above 6 GHz	800 MHz (contiguous)	5G deployment without 4G
eMBB, URLLC, mMTC (wide area but no deep coverage)	A compromise between capacity and coverage.	Coverage and capacity layer	2-6 GHz	100 MHz (contiguous)	
eMBB, URLLC, mMTC	Wide area and deep indoor coverage.	Oversailing layer	Below 2 GHz	Up to 20 MHz (paired/ unpaired)	Usually applied up to below 3 GHz (e.g., 2.6 GHz)

CRS rate matching can not be used for Type A since time allocation must start at either 0, 1, 2, or 3. However, such kind of problem does not exist for MBSFN.

To overcome this problem, there is a concept of Type B /mini-slot where the transmission can start at any symbol in a slot. However, the length must be limited to 2, 4, or 7 symbols to avoid any delays. This is normally used for URLLC, which are time-sensitive services.

H. DSS UPLINK

There is no complexity in the uplink to use DSS as there is no concept of CRS and others except that 5G needs to shift by 7.5kHz since 4G uses 7.5 kHz raster shift as well [1], [14].

III. 5G SPECTRUM AND DSS DEPLOYMENTS

This section covers a brief discussion on the 5G spectrum, particularly, relevant to the potential deployment of DSS for LTE and NR coexistence. Potential deployment options for the DSS between LTE and NR are then discussed, followed by a performance analysis of the DSS deployment options in terms of spectral efficiency. The section ends by providing a comparison of the DSS deployment options.

A. 5G SPECTRUM AND DSS

5G operates on spectra ranging from 1 GHz up to millimeter waves. 5G can be deployed in shared spectrum, licensed spectrum, and unlicensed spectrum bands. For paired spectrum, 5G can use the FDD technology while for unpaired spectrum, TDD technology is used. In general, based on different 5G service requirements, a triple-layer concept as shown in Table 7 [68] can be applied to spectral resources. More specifically, for massive machine-type communication (mMTC) and URLLC services, an oversailing layer below 2 GHz to provide coverage both to wide areas and indoors is considered an essential layer. The coverage and capacity layer ranging from 2GHz to 6GHz is a good compromise between capacity and coverage. The superdata layer above 6 GHz can be used for services requiring extremely high data rates but relaxed coverage. Such a triple-layer concept allows accommodating 5G services (i.e., eMBB, mMTC, and URLLC) requiring different coverage and data rate capability in the appropriate layer.

On the contrary, a service-based single-layer operation would be inefficient in providing services requiring both coverage and high data rates along with low latency, and so on. Hence, to fulfill the diverse requirements of 5G services, the use of joint and multiple spectral layers becomes crucial for 5G networks. DSS is mainly relevant for low band FDD usually ranging from 600-2600 MHz spectrum where DSS can flexibly provide refarming from LTE to 5G.

B. LTE-NR DSS DEPLOYMENT OPTIONS AND PERFORMANCES

1) DSS DEPLOYMENT OPTIONS

Adopting various numerologies, a scalable and flexible physical layer design is offered by NR**.** Depending on the operating band, several SCSs for data and synchronization channels are defined. However, such flexibility comes with increased complexity caused by ensuring tight coordination between gNB and eNB for reliable synchronization [21].

Recall that the role of DSS is to allow NR users to be scheduled in the LTE spectrum without affecting the essentials of one system by the other. In LTE, for example, a CRS is a kind of essential signal that is used for the downlink channel measurement. CRSs have a specific time-frequency resource assignment. DSS design concept evolves mainly around the positions of CRSs in the time-frequency grid. Typically, the density of CRSs over an RB in frequency, and radio frame duration in time increases with an increase in the number of antenna ports. CRSs generate 4.76% overhead in time and frequency with a single antenna port, whereas 14.29% for 4 antenna ports. Moreover, DSS design enables fitting reference signals of NR such as SSBs and DMRS into the LTE resource grid without being affected by LTE systems by placing them in time and frequency away from any collision with the LTE systems [21]. There are three options for the DSS between LTE and NR as follows [26].

2) OPTION 1 (MULTICAST-BROADCAST SINGLE-FREQUENCY NETWORK-BASED)

MBSFN subframes are used in LTE for point-to-multi-point transmission [69]. Recall that the key concept of MBSFN is that in a certain number of subframes within an LTE frame, 12 OFDM symbols other than the first two symbols of the corresponding subframes are reserved [70], [71] such that no LTE transmission can take place. Such MBSFN subframes are intended to serve broadcast services while muting regular LTE data transmission. This concept is applied to the DSS

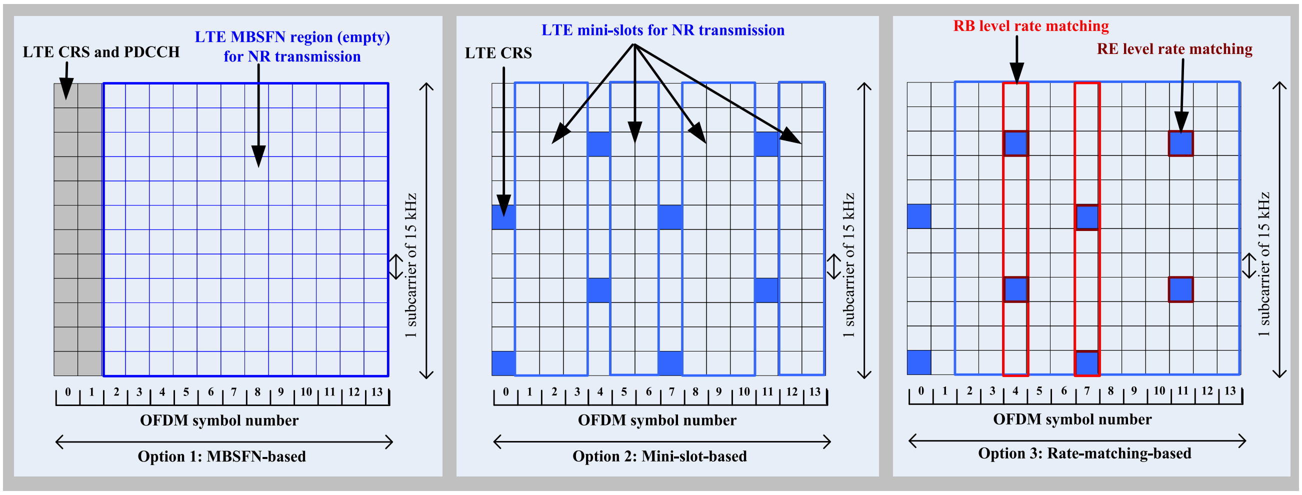


FIGURE 10. DSS deployment options. (a) Option 1 deals with MBSFNs, (b) Option 2 using Mini-slot, and (c) Option 3 using CRS rate matching [21], [38].

between LTE and NR such that MBSFN subframes can be used for carrying data of NR users, instead of LTE users [72]. MBSFN subframes are transparent to legacy LTE UEs, i.e., LTE UEs know that such MBSFN subframes are for other purposes than for the LTE data transmission.

Because MBSFN subframes are opted for addressing DSS operations, there is no need for LTE MBSFN Reference Signals and LTE CRSs are transmitted only in the non-MBSFN region (i.e., the first two symbols) of the MBSFN subframe as shown in Fig. 10(a) [21]. A major downside of using MBSFN subframes comes from using them very often, which may result in taking away resources from LTE UEs and hence reduced LTE user-only throughput.

3) OPTION-2-MINI-SLOT-NON-MBSFN-BASED

In option 2 (also referred to as mini-slot-based), the transmission of NR data can take place anywhere in an LTE slot except at those symbols that contain LTE CRSs. In other words, only symbols free of scheduling CRSs in an LTE slot can be used for scheduling NR data (Fig. 10(b)) [69]. This option is based on the fact that in NR, mini-slot scheduling where NR data scheduling can take place anywhere inside an NR slot, is available to address extremely low latency for URLLC applications [73]. The major downside of this option is that the wastage of resources is too high for NR data scheduling and hence is not suitable for eMBB applications. However, this option is suitable as well for certain cases such as the insertion of 30 kHz SSB.

4) OPTION-3-CRS-RATE-MATCHING-NON-MBSFN-BASED

In option 3, an NR UE carries out puncturing of LTE REs [70] to detect the presence of LTE CRSs so that the corresponding REs allocated to CRSs can be avoided by the NR scheduler to schedule NR data on PDSCH. The option can be executed in two levels, namely, RE-level and RB-level. At the RE-level, only REs allocated to LTE CRSs are avoided from NR data scheduling [69]. However, at the RB-level [14], the entire RB (or the subframe) carrying CRSs is avoided from NR scheduling as shown in Fig. 10(c). Hence, RB-level rate matching is simpler than that of RE-level. This, however, comes at the cost of fewer REs available for NR data scheduling than that at RE-level. Note that the major difference between the mini-slot-based option and RB-level CRS rate matching option is that subframe 2 (reserved for the LTE PDCCH) in an LTE slot can also be scheduled for NR data in the mini-slot-based option, which is not possible in the RB-level rate matching.

5) SPECTRAL EFFICIENCY PERFORMANCE OF DSS OPTIONS

The number of REs in a slot per RB for NR data transmission depends on LTE CRS configurations as a function of the number of antenna ports as shown in Fig. 4 for Mapping of downlink reference signals (normal cyclic prefix). From Fig. 4, the following observations can be identified.

- For antenna ports 1 and 2, CRS exists in four symbols with indices $\{0, 4, 7, 11\}$ per RB.
- In addition to the above symbols, CRS exists in two other symbols with indices $\{1, 8\}$ for 4 antenna ports.
- There are two CRS subcarriers per symbol for each antenna port configuration.
- LTE PDCCH occupies the first two symbols and NR PDCCH occupies the third symbol in an LTE slot. So, they cannot be taken into consideration for NR PDSCH overhead estimation. Hence, 11 symbols can be used to schedule NR PDSCH.
- In these 11 symbols per LTE slot, there are 3 symbols for antenna ports 1, 2, and 4 symbols for antenna port 4 that carry CRSs.
- Hence, in these 11 symbols per LTE slot, for RE-level CRS rate matching, the total number of REs carrying CRSs overhead for antenna port 1 is $(3 \times 2) = 6$, for

TABLE 8. LTE CRS rate matching [38].

CRS Configuration	Rate matching	
	RE-level	RB-level
LTE 1 CRS port	126 RE	96 RE
LTE 2 CRS port	120 RE	96 RE
LTE 4 CRS port	116 RE	84 RE

TABLE 9. Comparison among DSS deployment options.

Option 1	MBSFN	High data rates applications	Frequent use results in reduced LTE throughput	eMBB	Exists in the first two symbols per LTE subframe	Takes place only within the MBSFN region without CRSs
Option 2	Non-MBSFN	Extremely low latency applications	Too high wastage of resources for NR data scheduling	URLLC	Presence throughout the LTE slot	Anywhere in an LTE slot except symbol 2 and symbols for LTE CRSs
Option 3	Non-MBSFN	High data rate applications, suitable for RE-level CRS rate matching	Few resources are available when using RB-level CRS rate matching	eMBB	Presence throughout the LTE slot	Anywhere in an LTE slot except symbol 2 and symbols for LTE CRSs

antenna port 2 is $(3 \times 4) = 12$, and for antenna port 4 is $(4 \times 4) = 16$.

- Similarly, for RB-level CRS rate matching, the total number of REs carrying CRSs overhead for antenna port 1 is $(3 \times 12) = 36$, for antenna port 2 is $(3 \times 12) = 36$and for antenna port 4 is $(4 \times 12) = 48$.
- The number of REs per RB per symbol is equal to 12. So, there is a maximum of$(11 \times 12) = 132$ REs per LTE slot for NR PDSCH transmissions.
- For RE-level CRS rate matching, the total number of REs for NR PDSCH transmissions for antenna port 1 is $(132 - 6) = 126$, for antenna port 2 is $(132 - 12) = 120$ and for antenna port 4 is $(132 - 16) = 116$.
- For RB-level CRS rate matching, the total number of REs for NR PDSCH transmissions for antenna port 1 is $(132 - 36) = 96$, for antenna port 2 is $(132 - 36) = 96$and for antenna port 4 is $(132 - 48) = 84$.

Table 8 [38] shows the above estimation for the number of REs in an LTE slot per RB in both RE-level and RB-level CRS rate matching. From Table 8**,** it can be found that more REs are available for NR PDSCH within an LTE slot per RB in RE-level rate matching than that available in RB-level rate matching irrespective of antenna port configurations. This results in higher NR PDSCH transport block size and hence better spectral efficiency in RE-level rate matching than that in RB-level rate matching.

Given that each option has its relative merits and demerits, based on the particular configuration, each option can have its application. It is not uncommon that, in some circumstances, an optimal DSS solution can be achieved by applying more than one or all of the above options together [21]. A comparison among DSS deployment options is given in Table 9.

IV. DSS DESIGN AND EFFECT

The most critical factor for LTE-NR coexistence is to share the spectrum resources of LTE systems with data and control signals necessary to operate NR systems subject to not impacting LTE operations. This requires design considerations on how to allocate time and frequency resources to NR systems on top of the LTE framework. In line with so, this section covers a concise discussion of several potential DSS design considerations.

A. TRANSMISSION OF NR BROADCAST AND SIGNALING MESSAGE

For designing NR-LTE coexistence, firstly, it is needed to consider supporting the transmission of common signal as well as the initial access method of 5G NR in view of the frame structure along with signal transmission properties of 4G LTE [36]. Note that a basic downlink reference signal in LTE is CRS. This implies that when designing DSS, NR signals and channels need to be allocated on top of the LTE time-frequency grid that avoid overlapping the LTE CRSs, resulting in no effect on the LTE operation because of transmitting NR using LTE. In this regard, CRS rate matching can be an example method. However, an NR device is unaware of the type of cell it has accessed during the initial access phase, be it either a clean NR or a shared LTE-NR cell.

NR SSBs are essential broadcast signals that allow an NR device to detect a cell. Recall that an SSB is a one-shot transmission lasting for 20 ms (default) when considering an SCS of 15 kHz for spectrum sharing [74], [75], [76], [77]. To detect properly, SSBs need to be transmitted collision-free of the inherent LTE system. However, an SSB lasts for 4 OFDM symbols contiguously in the time domain and 20 RBs in the frequency domain making it impossible to transmit using a normal subframe because of overlapping with the CRS (Fig. 11) [36]. To overcome this problem, SSBs need to be transmitted using LTE MBSFN subframes since, in MBSFN, CRSs are restricted only within the control region of LTE represented by the PDCCH of LTE (Fig. 11). MBSFN allows LTE devices to skip certain subframe patterns.

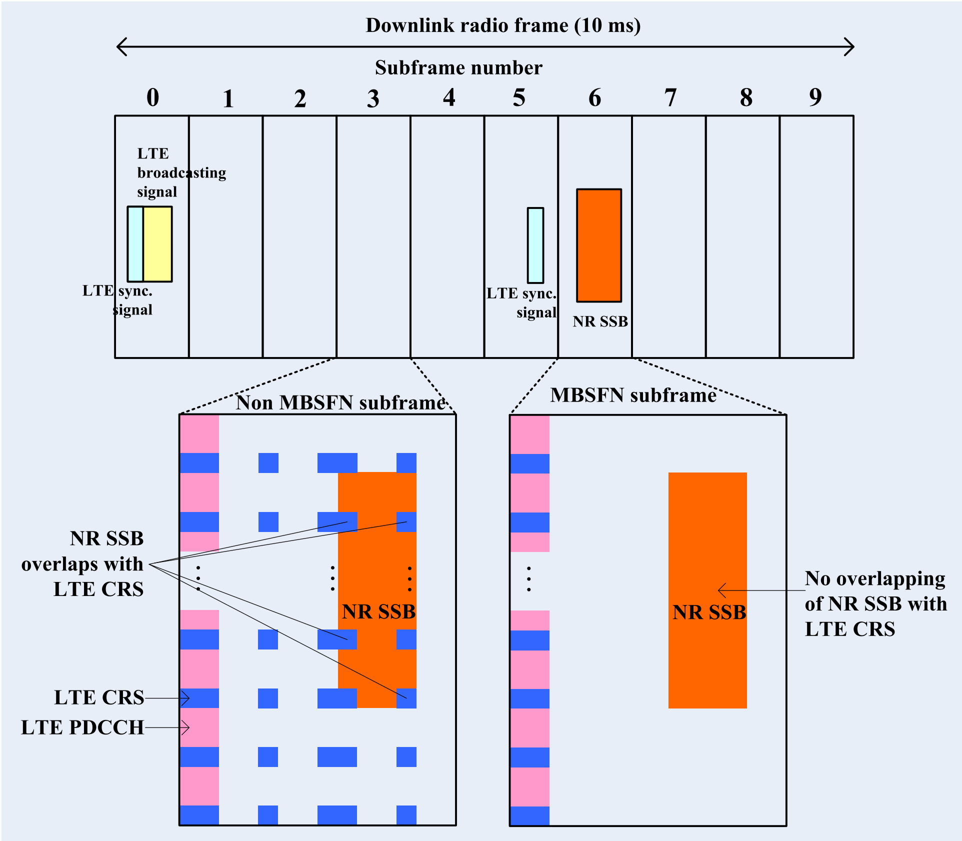


FIGURE 11. Transmission of SSB and broadcast signals of NR in LTE MBSFN subframe [36].

TABLE 10. Broadcast channels or signaling messages in NR [36].

Signal/Channel	NR SA/NSA
SSB	SA and NSA
RAR	SA and NSA
SIB1	SA
OSI	SA
Paging	SA

During the initial access, broadcast channels and signaling messages transmitted are given in Table 10. Note that, the initial stage of 5G NR is going to be in the non-standalone (NSA) mode [78] in which SSB and random-access responses (RARs) are transmitted while LTE acts as an anchor node. However, for NR SA, system information block 1 (SIB1), other system information (OSI), and paging channels are transmitted in addition to SSB and RAR in NR NSA mode. All of them need to be transmitted using LTE MBSFN subframes as LTE CRS rate matching for these signals is not defined.

Each of these signals is transmitted at a regular interval defined in standards. For example, SSB and RAR are transmitted every 20 ms. Note that RAR and SSB can be transmitted on the same MBSFN to reduce resource allocations. To support NR, all these above signals are important even though they act as control overhead for the LTE. For example, a DSS overhead of 5% will be incurred even when both SSB and RAR are transmitted on the same MBSFN. Requesting these signals by the network with shorter periods will further increase the overhead imposed on the LTE system.

Since OSI, SIB1, and the paging channel, need to be transmitted additionally when operating in NR SA mode, the overhead increases even further than that in NR NSA mode. An example of all these essential signal transmissions for NR operations is shown in Fig. 12. Note that the overhead imposed because of these essential signals to operate NR is the minimum amount that is generated even in the absence of NR downlink transmissions, which has a direct impact on the LTE downlink peak throughput, varying with the mode (NSA and SA) of operation of NR.

B. NR DOWNLINK CONTROL AND DATA TRANSMISSION

NR data and signaling messages are carried in the downlink and uplink physical channels [79]. Among these channels, the PDCCH controls the transmission and reception of uplink and downlink data through the transmission of DCI and is responsible for scheduling the control information of the physical layer [57]. In DSS, when transmitting the NR downlink control channel (i.e., PDCCH) on the LTE spectrum, it is necessary to make sure that PDCCHs do not collide with the CRS of LTE. According to the specification, a UE needs to monitor the first three symbols per slot. Given

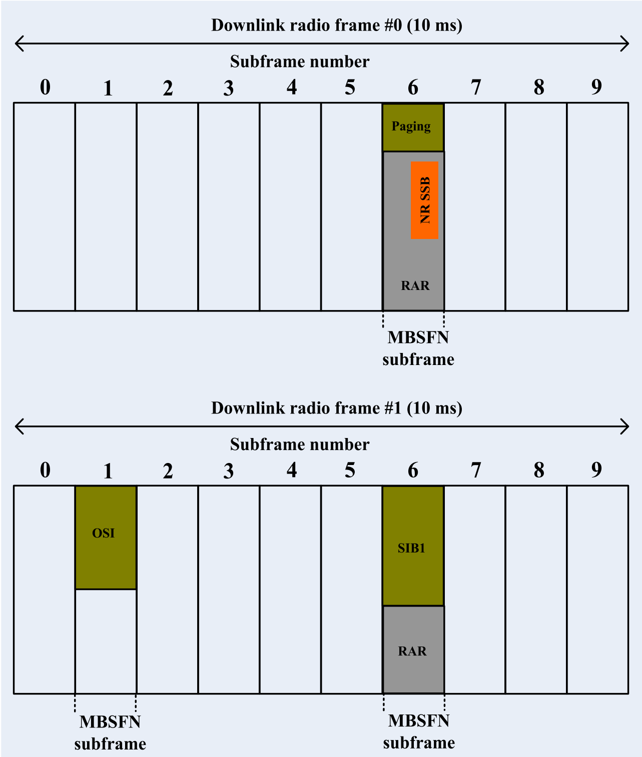


FIGURE 12. An illustration of the transmission of broadcast channels or signaling messages of NR using MBSFN subframes of LTE [36].

the CRS configuration, NR PDCCHs may need to allocate to the second or third symbols to avoid a plausible collision. Fig. 13 shows how the NR PDCCH varies with the CRS configuration. For 2 CRS port configurations, NR PDCCH can be allocated to either symbols 2 and 3 or symbol 3 only depending on whether LTE PDCCH is scheduled to symbol 1 or symbols 1 and 2, respectively, without affecting the collision with CRS.

Moreover, if any extra DMRS is needed for the PDSCH of NR in the downlink, it should be allocated to the 13^{th} symbol in a subframe such that no collision occurs with the CRS [80]. For MBSFNs, since CRSs do not exist in MBSFN subframes, no CRS rate matching is needed for NR PDSCH transmissions. However, like non-MBSFN subframes, additional DMRS should be allocated to symbol 13 to sync with non-MBSFN subframes.

An important issue with PDCCH allocation is that PDCCHs of NR as well as LTE are allocated to only symbols 1, 2, and 3 in a subframe when employing DSS. This *restricts* the capacity of PDCCH in DSS as compared to that in non-DSS. Fig. 14 shows the limitation of supportable UEs in DSS. For the 4CRS LTE (see Fig. 13) configuration, only one symbol (symbol 2) can be assigned for NR PDCCH. Intuitively, this is one-third of the capacity of NR PDCCH when operating in non-DSS or NR-only mode as all three symbols can be assigned to only PDCCH.

Note that the transmission of NR PDCCH of any UE's is carried out by aggregating either 1, 2, 4, 8, or 16 CCEs, respectively, corresponding to aggregation levels of 1, 2, 4, 8, and 16 [81] where a CCE is a basic unit of PDCCH [57], which consists of 6 RBs or 72 REs [79], [82]. As the channel condition gets poor, the aggregation level increases proportionately. As shown in Fig. 14(a), to support a UE with the weak channel condition, a level-8 aggregation for the PDCCH may be needed because of limited bandwidth resources. However, when operating in non-DSS or NR-only mode, because PDCCH can be allocated to all the first three symbols in a subframe, in addition to the UE with the weak channel condition, other UEs can also be supported because of being allocated with more resources to PDCCH.

Note that, since in the early 5G market, the number of NR UEs is low as compared to LTE UEs, the limitation in PDCCH when using DSS may not be critical. However, as the NR market grows, the PDCCH enhancement can be addressed using the optional NR CORESET feature such that OFDM symbols beyond the first 3 in a subframe can be configured. Moreover, to achieve more efficient DSS between LTE and NR systems, 10 symbols PDSCH mapping type B with shifted DMRS (defined in release 16) can be used along with the above configured NR CORESET.

C. ON-DEMAND TRANSMISSION OF NR DOWNLINK REFERENCE SIGNAL

Reference signals of NR include channel state information reference signals (CSI-RS) and tracking reference signals (TRS). Devices use CSI-RS to acquire downlink channel information. After decoding, CSI-RS is sent by the devices as feedback to the base station via the PUSCH and PUCCH channels [53]. Transmissions of CSI-RS can be carried out in the last symbol of an MBSFN subframe whereas the transmission of TRS is addressed periodically in consecutive slots allowing UEs to track and compensate for time and frequency variations. Note that, LTE cannot use RBs of the transmitted TRS whereas NR can. Hence, the transmission of TRS should be on demand, specifically, transmitted when there are connected NR UEs to minimize the impact on LTE.

D. LTE ALWAYS-ON SIGNAL TRANSMISSION

The CRS of LTE is transmitted irrespective of the UE and network status when a base station is turned on [83] because of their requirements by UEs in the cell to demodulate control signals, measure mobility, and estimate channel quality [40]. Moreover, LTE PDCCH is transmitted to control channel symbols. Because NR channels cannot be transmitted through REs occupied by CRSs and PDCCHs, both are considered overhead for NR transmission using DSS.

Fig. 15 shows the resources occupied by CRSs and PDCCHs for the MBSFN and the normal subframe of LTE with the variation of LTE CRS configurations. As an example, for 4CRS configuration, the number of REs occupied by CRSs and PDCCHs is 24 for MBSFN whereas

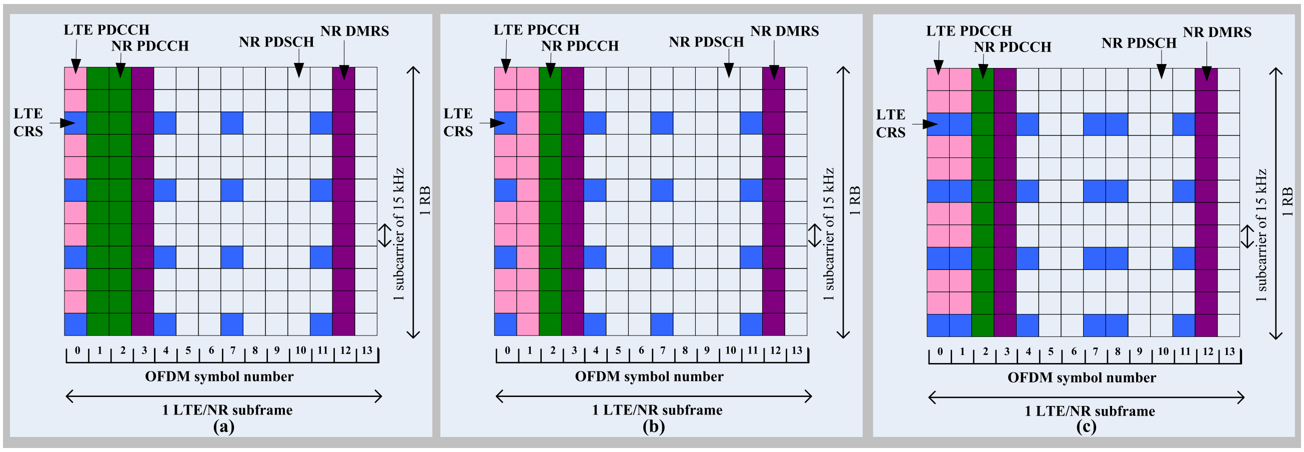


FIGURE 13. Transmissions of NR PDCCH and PDSCH design [36]. (a) 2 antenna ports configuration, 1 PDCCH for LTE and 2 PDCCHs for NR; (b) 2 antenna ports configuration, 2 PDCCHs for LTE and 1 PDCCH for NR; (c) 4 antenna ports configuration, 2 PDCCHs for LTE and 1 PDCCH for NR.

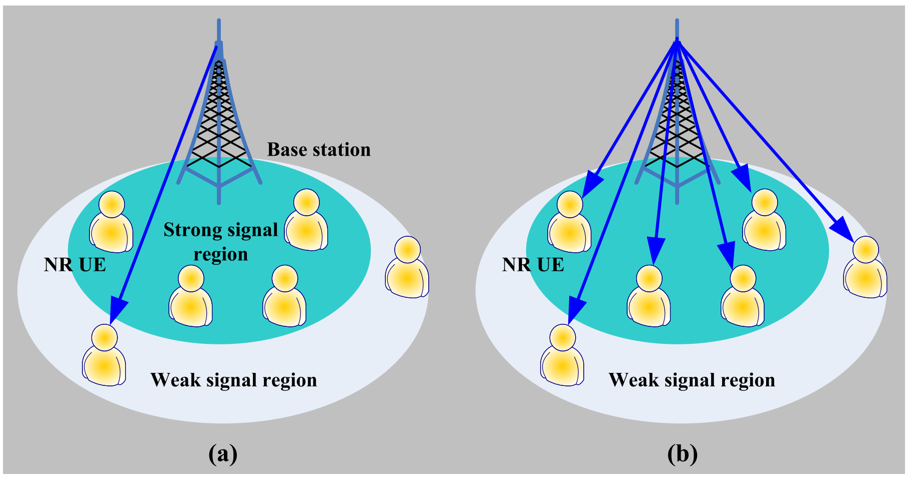


FIGURE 14. Limitation in DSS to support the number of NR UEs depending on available resources for the NR PDCCH [36].

TABLE 11. NR downlink overhead in an RB, which is caused by LTE CRS and PDCCH (for LTE normal subframe) [36].

Configuration	Average overhead in an RB
2 antenna ports, 1 LTE PDCCH	14%
2 antenna ports, 2 LTE PDCCH	21%
4 antenna ports, 2 LTE PDCCH	23%

40 for normal subframes per RB. Considering one normal subframe used for the NR transmission using DSS, the percentage overhead concerning NR only for different CRS configurations is shown in Table 11. These LTE overheads have a direct impact on the available resources for NR PDSCH. This results in a proportionate reduction in expected NR downlink peak throughput with CRS configurations. It is to be noted that If CRS positions in a slot between adjacent cells are different, then the CRS of one cell interferes with the data of its neighboring cell, causing CRS interference. This CRS interference may have not occurred if the whole LTE spectrum had been re-farmed for NR transmission. In Table 12, major signals of LTE and NR involving DSS design considerations are given.

V. APPLICATION OF DSS IN LTE SUBFRAMES FOR NR WITH/WITHOUT SSB TRANSMISSIONS

Recall that there are two types of subframes in LTE, including non-MBSFN and MBSFN, each having a different time-frequency grid structure, i.e., the position of CRSs in an LTE subframe is different for MBSFN and non-MBSFN. Moreover, a 5G UE cannot latch onto the LTE spectrum if SSBs for NR on the LTE spectrum cannot be positioned. All these require a different slot mapping when employing DSS to transmit NR PDSCH in the presence or absence of NR SSBs on the LTE spectrum. These critical aspects of DSS are analyzed and possible solution alternatives are discussed in this section. In doing so, the section starts with a basic discussion on the location of NR SSBs for numerous antenna ports and ends with a comparative analysis of the impact of DSS on LTE subframes in the presence or absence of NR SSBs.

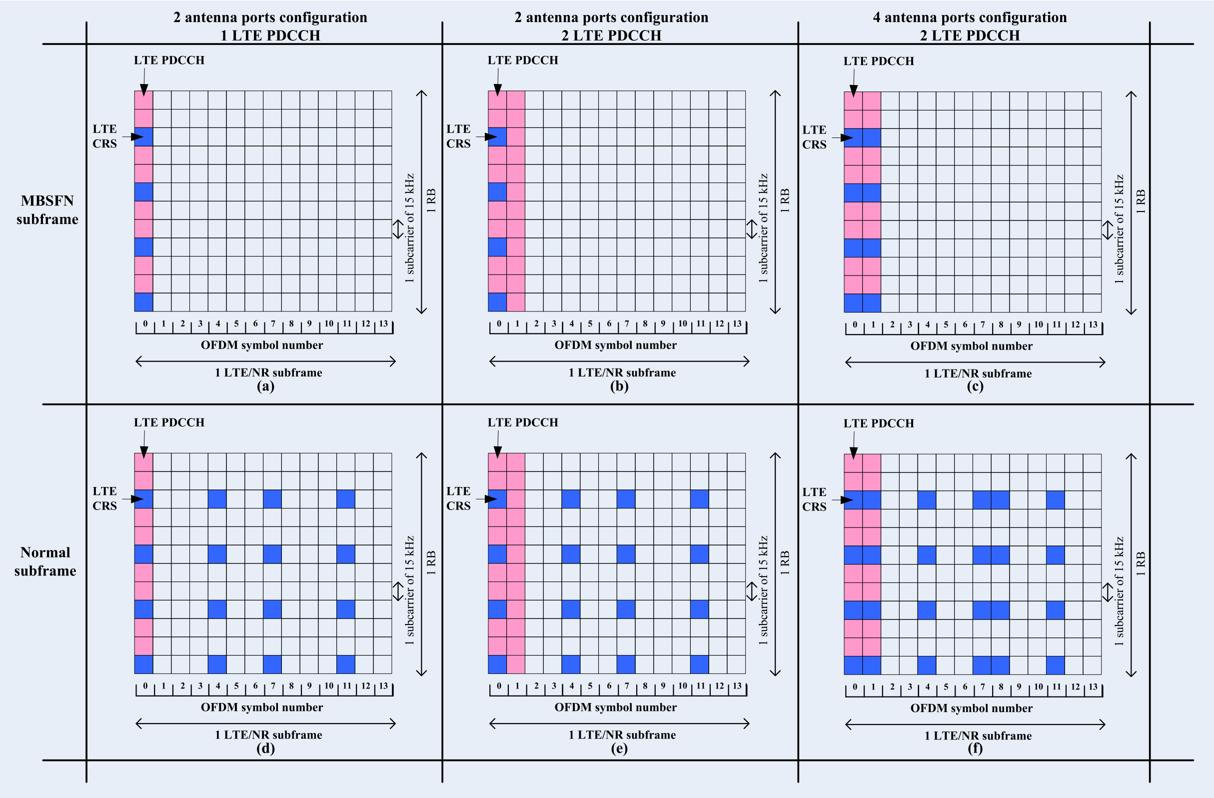


FIGURE 15. Resource distribution of LTE CRS and PDCCH [36].

TABLE 12. Major LTE and NR signals involving DSS design considerations for LTE and NR coexistence.

LTE and NR Signals	Type	Position in the resource grid	Transmission subframe	Application
NR SSB	Broadcast signal	Spans over 4 symbols and 20 RBs continuously in the time-frequency resource grid	MBSFN	Used to detect a cell
LTE and NR PDCCH	Control channel	The first three symbols in a subframe	Non-MBSFN	Used to control channel symbols
LTE and NR	Reference signal	Throughout a subframe for LTE non-MBSFN subframes, and the first two symbols in a subframe for LTE MBSFN subframes	Non-MBSFN	Demodulate control signals; measure mobility and, estimate channel quality
NR CSI-RS	NR reference signals on demand	The last symbol of LTE MBSFN subframes	MBSFN	Used to estimate channel quality by a UE
NR RAR	Broadcast channel and signaling message	Transmitted every 20ms	MBSFN	Used for initial access to the network. Transmitted in both standalone and non-standalone modes.
NR OSI, S1B1, and paging channel		Transmitted at regular intervals		Transmitted when operating in standalone mode. S1B1 is used to provide essential system parameters and configuration information to the UE; OSI is scheduled for other system information, and the paging channel is used to trigger radio resource control (RRC) setup.
NR DMRS	Reference signal	Usually, one DMRS at symbol 3. Additional DMRS must be located at symbol 13 in an LTE non-MBSFN subframe when employing DSS between LTE and NR systems	Non-MBSFN	Demodulation of the classical channel.

A. FITTING NR PSS, SSS, AND SSB FOR DSS

Both MBSFN and non-MBSFN subframes of LTE can used to deploy DSS for NR and LTE coexistence. Recall that, for NR PDSCH transmissions, an effective option to deploy DSS is CRS rate matching that allows for avoiding collisions of NR PDSCH with LTE CRSs. However, it is quite impossible

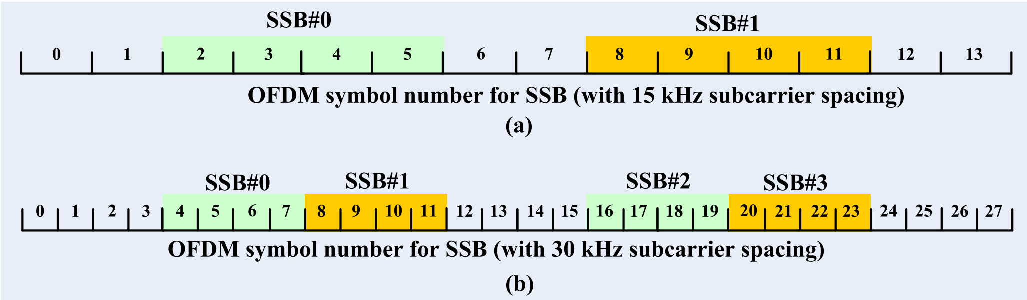


FIGURE 16. Location of NR SSB for four antenna ports [37].

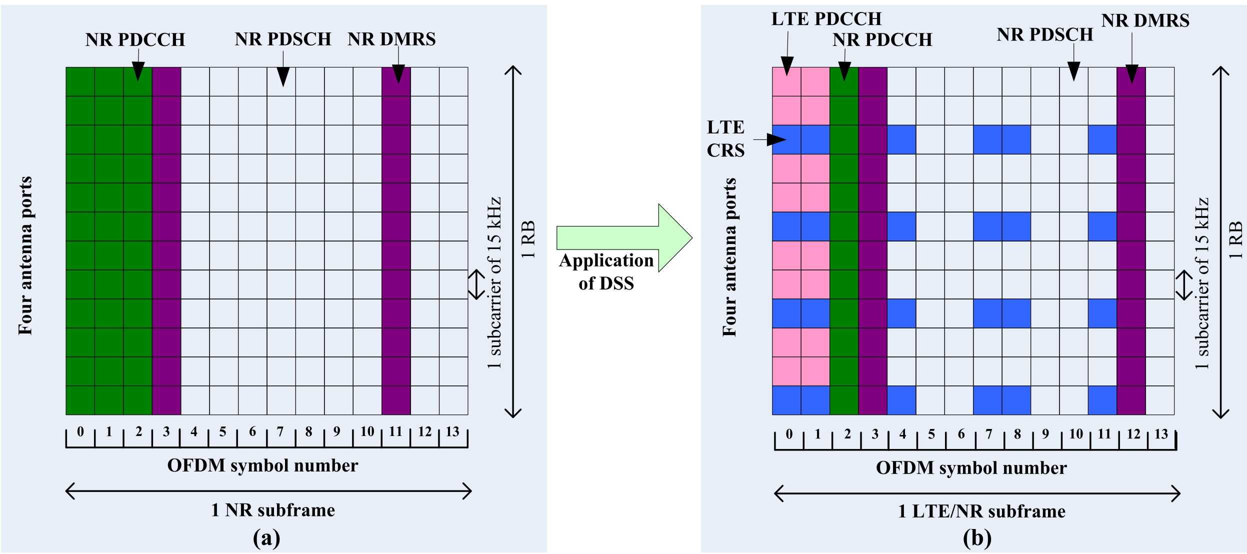


FIGURE 17. 5G NR when employing DSS to the LTE spectrum for *NR without SSB Transmissions* and SCS=15kHz for four antenna ports [21], [37]. (a) NR cells without DSS and (b) LTE and NR cells with DSS.

to puncture the channel for NR SSB as it affects the downlink measurements and synchronization. In other words, at least continuous 20 RBs in frequency and four symbols in time in the LTE frame are needed to latch any 5G UE onto the LTE spectrum (Fig. 8).

In the time domain, the location of SSBs is fixed in NR (i.e., in which symbols SSBs do exist). For example, for the frequency band n41 TDD (ranges from 2496 MHz to 2690 MHz) and SCS of 15 kHz, there are two SSBs, one of which spans over symbol indices 2, 3, 4, and 5 whereas the other SSB spans over symbol indices 8, 9, 10, and 11, in a subframe of 14 symbols (Fig. 16(a)). However, for the same n41 TDD band, if 30 kHz subcarrier spacing is considered, four SSBs spanning over sets of symbol indices of {4, 5, 6,7}, {8, 9, 10, 11}, {16, 17, 18, 19}, and {20, 21, 22, 23} in a subframe can be transmitted as shown in Fig. 16(b).

Depending on the SCS (15 kHz, 30kHz, 60kHz, and so on) and the number of beams being formed, an SS burst set (with length L) is transmitted on different beams [60]. A UE looks for SSB signals and latches onto the SSB with the strongest one (beam) to connect to the 5G network. A UE needs at least one SSB out of L SSBs to synchronize with the network. One of the challenges with the SSB is that it needs four symbols contiguously. Now how the position of SSBs has an impact on the LTE spectrum when using DSS will be discussed.

B. APPLICATION OF DSS IN LTE NON-MBSFN SUBFRAMES FOR NR WITHOUT SSB TRANSMISSIONS

Fig. 17 shows an example scenario of dedicated NR carrier transmissions *when DSS is employed or not* without considering the SSB transmission. In a normal scenario where no DSS is used in the LTE spectrum, either any of the symbols 0, 1, and 2 or all of them can be used for NR control channels (Fig. 17(a)). Also, DMRS is fixed at symbols 3 and 11 (Fig. 17(a)). The rest of the 9 symbols can be used for NR PDSCH, i.e., NR data traffic. However, when DSS is employed in the LTE spectrum, symbols 0 and 1 for the CRS and PDCCH of LTE, symbol 2 for the NR PDCCH, symbols 3 and 12 (assuming employing the alternative DMRS location feature described above) for the NR DMRS, and some REs of symbols 4, 7, 8, and 11 for the LTE CRS, are used when considering the four antenna ports configuration as shown in Fig. 17(b) [37].

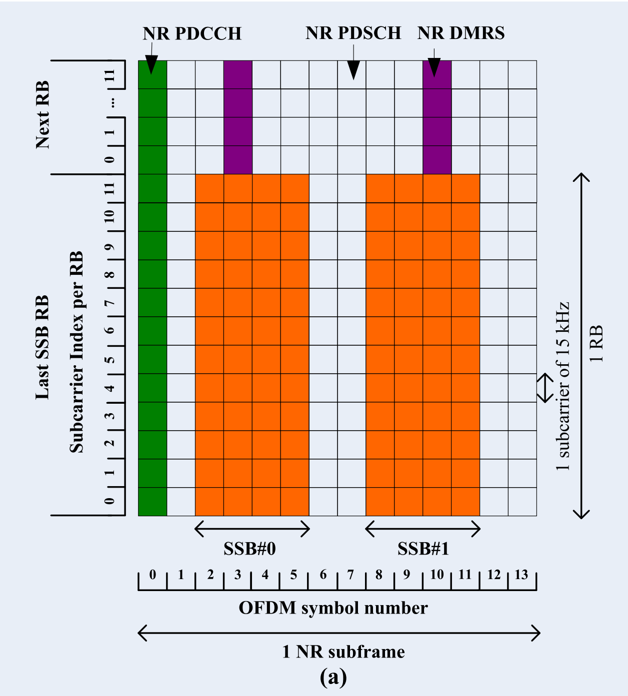


FIGURE 18. 5G NR when employing DSS to the LTE spectrum *without NR SSB transmissions* for four antenna ports [21]. (a) NR cells without DSS and SCS=15 kHz [38].

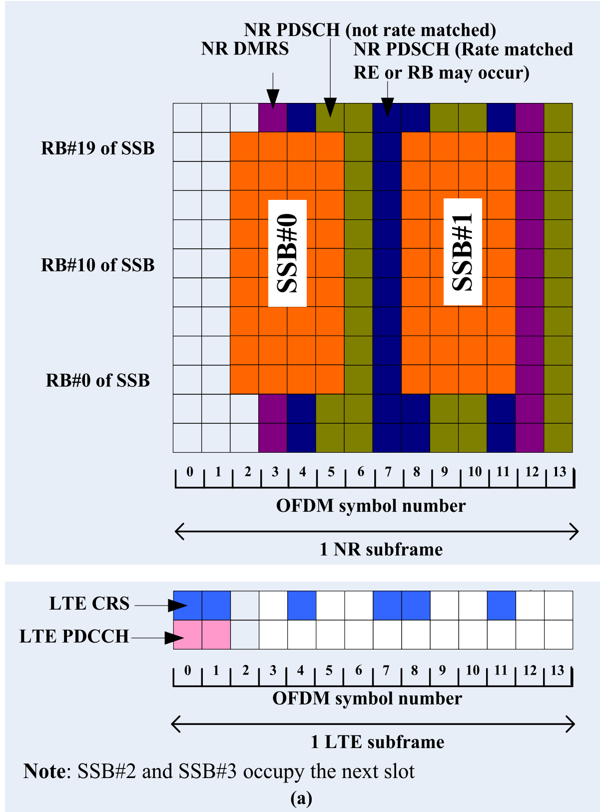


FIGURE 19. Spectrum sharing on SSB channel of NR for LTE non-MBSFN subframes. NR PDSCH with 15 kHz and SSB with 15 kHz [37].

As mentioned earlier, the collision of NR PDSCHs with LTE CRSs can be avoided using either RE- or RB-level CRS rate matching. Note that when employing DSS using RE-level CRS rate matching, REs available for NR PDSCHs will be reduced further (e.g., by 16 REs because of LTE CRS) in this non-MBSFN region in a slot.

C. APPLICATION OF DSS IN LTE NON-MBSFN SUBFRAMES FOR NR WITH SSB TRANSMISSIONS

For the transmission of NR SSB, a different slot mapping needs to be employed. Fig. 18 shows NR SSB in slots without employing DSS where two SSB beams each with 4 symbols (ranges from symbols 2 to 5 and from symbols 8 to 11) are occupied by SSBs in NR. Recall that, for NR, either 0, 1, 2, or all symbols are assigned with NR PDCCH, and symbols 4 and 11 are positioned for DMRSs. Also, in LTE, for four antenna ports, CRSs exist in symbols 0, 1, 4, 7, 8, and 11.

For 15 kHz SCS and the number of antenna ports of 4, from Fig. 19, it can be shown that SSB0 collides with the CRS at symbol 4 whereas SSB1 collides with symbols 8 and 11. Note that the upper part and lower part of Fig. 19 illustrate, respectively, NR resource grids and LTE non-MBSFN subframes. Hence, it cannot be positioned SSBs for NR on the LTE spectrum. Since SSBs cannot be positioned on the LTE spectrum, a 5G UE cannot latch onto the LTE spectrum no matter how many RBs are available in any LTE band, and hence no DSS can be performed. This is the complexity of employing DSS in NR/LTE systems.

This can be avoided by using *mixed numerology* where the term numerology defines physical layer waveform parameterization [84], [85]. Note that, unlike LTE, which uses single numerology in downlink, 5G adopts a scalable or mixed numerology such that different SCSs [68], [86], symbol durations, and number of symbols per slot can be chosen. For example, SCSs can be varied by scaling the baseline SCS of 15 kHz by a factor of $2^{(x-1)}$ where x is any non-negative integer ranging from 1 to 4 [46], [84], [87], [88], [89]. Hence, to support multiple services over the same carrier, 3GPP has proposed using mixed numerology for frequency multiplexing [3], [54], [84], e.g., for the data traffic signal, 15kHz is used whereas, for the control signal, 30kHz is used to perform DSS in NR/LTE systems. More specifically, for NR SSBs, 30kHz can be used instead of 15 kHz. In that case, from Fig. 20, it can be found that at least SSB0 can be positioned at symbols 2 and 3 (so avoiding collision with symbol 4 if 15 kHz were used as before) as shown in Fig. 21. This way at least one SSB can be transmitted in each subframe as the other three SSBs, SSB1, SSB2, and SSB3 collide with the CRSs of LTE (Fig. 20).

This may delay the transmission of SSBs, for example, the first 20 ms for antenna 1 (SSB0), the next 20 ms for antenna 2 (SSB1), and so on. However, 5G UE can extract all SSBs with some delays and can use the LTE spectrum for DSS. In short, only 30 kHz for SSBs and 15 kHz as

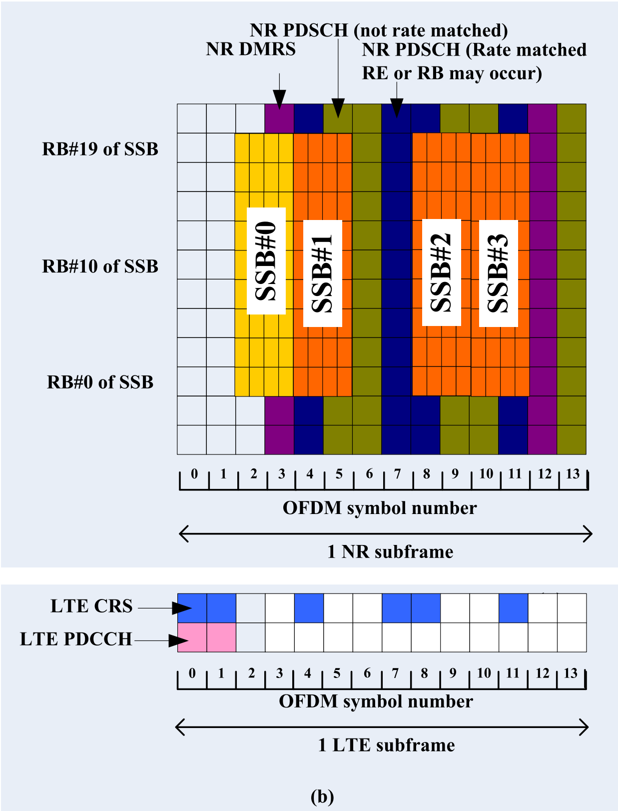


FIGURE 20. Spectrum sharing on SSB channel of NR for LTE non-MBSFN subframes. NR PDSCH with 15 kHz and SSB with 30 kHz [37].

usual for NR data can overcome the problem with SSB to address DSS. Note that with the change in numerology from 15 kHz to 30 kHz, symbols 0 and 1 occupy LTE PDCCH, and symbols 2 and 3 occupy an SSB.

It is to be noted that because of the presence of CRSs, NR PDCCH cannot be shifted to symbol 4 to avoid collision with CRSs. In such a situation, a shortage of required symbols for NR PDSCH Type A mapping arises because of shifting NR PDCCH to symbol 5 while NR PDSCH by at least at symbol 6 (Fig. 18). This causes us to move to Type B mapping without any other alternative options. However, moving to Type B mapping raises a new concern as the maximum number of symbols with Type B is limited to 7. This implies that if starting with symbol 6, Type B mapping can last up to symbol 12, leaving symbol 13 effectively empty. The above limitations clarify further the effectiveness of using LTE MBSFN subframes for NR SSB transmissions on the LTE spectrum.

D. APPLICATION OF DSS IN LTE MBSFN SUBFRAMES FOR NR WITH/WITHOUT SSB TRANSMISSIONS

The simplest way of implementing DSS is using an MBSFN as follows. Most mobile operators deploy DSS in the early phase by accommodating NR on the LTE spectrum using MBSFN (Fig. 22) [90]. In 4G LTE, a particular subframe can be configured as an MBSFN, which is designed to broadcast Television (TV) channels. In an MBSFN subframe, the first two symbols are reserved for the CRS and PDCCHs of LTE, and the remaining 12 symbols in the subframe are kept blank to allow TV transmissions using 4G LTE networks, i.e., mobile TV. These 12 symbols are muted or ignored by LTE devices.

More specifically, if an LTE UE finds a subframe configured as MBSFN, the UE simply ignores the corresponding subframe as an MBSFN subframe is designed only to provide live TV/broadcast services. Hence, these MBSFN subframes, each having completely blank 144 REs (i.e., $(14 \times 12) - (2 \times 12) = (168 - 24) = 144$REs), can be used to carry 5G NR traffic. In short, 4G LTE subframes configured as MBSFNs can be used for the transmission of 5G NR traffic without SSB.

Fig. 23 shows the e-SSB cases when MBSFN subframes are considered instead of non-MBSFN for NR with SSB. Because MBSFN mutes all 12 symbols for NR PDSCH, there will be no collision from LTE CRSs and PDCCH as in the case of non-MBSFN, resulting in minimal impact on NR SSBs. Hence, 5G traffic can be served very conveniently using MBSFN subframes.

Given the above explanation, it may be an obvious question: can all the LTE subframes be configured as MBSFN subframes? The answer to this question is no. This is because certain symbols, including subframes 0, 4, 5, and 9, cannot be configured as MBSFN subframes as they are used to carry LTE system-specific information such as paging and SSs in LTE. As shown in Fig. 24, in a radio frame of 10 ms, subframes 0 and 5 are used to carry PSS, SSS, and broadcasting channel (BCH) in LTE FDD whereas subframes 4 and 9 are used to carry paging information in LTE [91]. Hence, only the remaining 6 subframes, namely 1, 2, 3, 6, 7, and 8, can be configured as MBSFN subframes for the NR traffic. Depending on the 5G NR traffic requirement, an operator can configure 1, 2, ... up to 6 subframes on an LTE radio frame as MBSFN subframes to carry 5G NR data traffic.

Hence, for MBSFN cases, it is crucial to align LTE subframes with NR SSB slots since all SSB beams are not eligible for LTE MBSFNs. The use of many MBSFN subframes results in reduced throughput for LTE users. However, the MBSFN subframe is important to allow SSB transmission very smoothly. This implies that an optimal DSS solution would be to mix both Non-MBSFN and MBSFN methods [21]. In Table 13, the effect of DSS on LTE subframes in the presence or absence of NR SSBs is given.

VI. STANDARDIZATION ACTIVITIES TOWARD DSS

In the NR standardization, 3GPP recommends numerous functions and requirements in its different releases starting from Release 15 onward for the use of DSS to coexist NR and LTE on the same LTE spectrum. More specifically, in Release 15, several functions are defined to support LTE and NR coexistence in the FDD bands. To improve performance

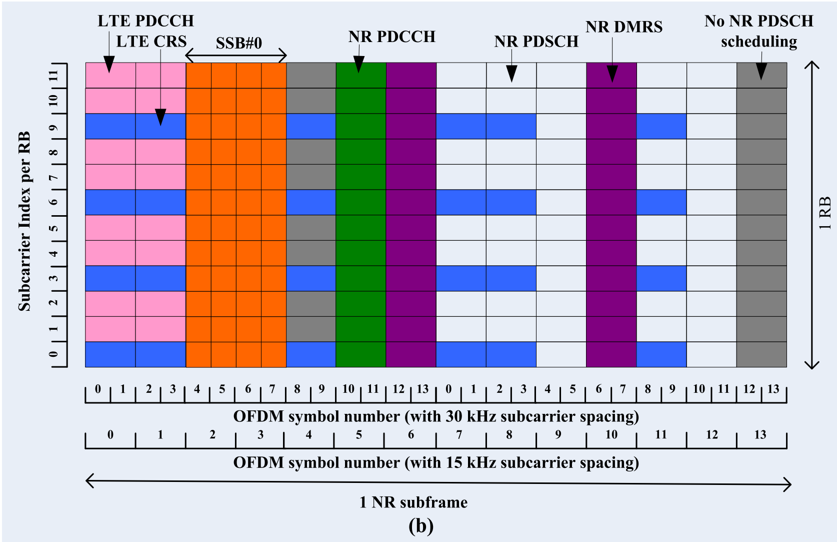


FIGURE 21. 5G NR when employing DSS to the LTE spectrum *without NR SSB transmissions* for four antenna ports [21]- LTE and NR cells with DSS and SCS=30 kHz [38].

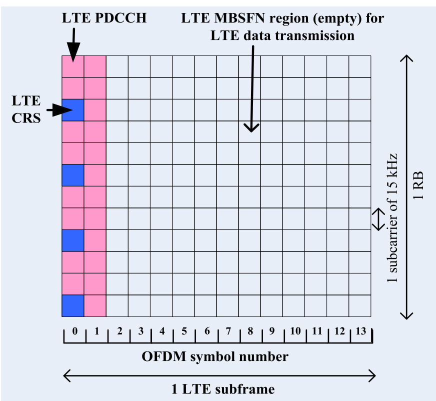


FIGURE 22. MBSFN subframe [37].

and to address new use cases, additional features approved in Release 16 and further enhancement proposed by 3GPP in Release 17 for DSS are discussed. In this section, standardization activities toward DSS in 3GPP Releases 15, 16, and 17 are covered.

A. 3GPP STANDARDS FOR DSS

To allow LTE spectrum sharing in designing the NR, 3GPP introduced specifications as follows. Recall that NR initially adopted OFDM waveform as a baseline and 15 kHz SCS as the basic numerology, which is compatible with that of LTE. This resulted in a highly aligned LTE and NR resource grid structure to support efficient LTE-NR coexistence. In the NR standardization, the following requirements are described [36], [92].

- Within the bandwidth of an LTE carrier, it is needed to support LTE uplink and NR uplink as well as LTE downlink and NR downlink. Also, identify and specify at least one NR band/LTE-NR band combination to operate this coexistence.
- The impact of physical layer design for NR should be minimal to enable coexistence.
- There should be no impact on the ability of the legacy LTE devices.
- Supporting simultaneous connections to LTE and NR of all UEs in the same LTE bandwidth is not obligatory.

Note that the terms NR-LTE coexistence and LTE-NR spectrum sharing mean the same, and hence, are used interchangeably. In the 3GPP Release 15, several functions are defined to support LTE and NR coexistence in the FDD bands as follows.

1) NR 100 KHZ CHANNEL RASTER FOR FDD BANDS

In LTE the channel raster granularity is 100 kHz [11]. However, for NR the channel raster granularity can be a minimum of 5 kHz [93]. To share any LTE bands with NR, existing FDD bands need to be redefined. In this case, the same channel raster of 100 kHz in LTE can be used for deploying NR on the LTE spectrum (Fig. 25) [36], [94].

2) NONCOMPULSORY 7.5 KHZ SHIFT IN NR UPLINK

Recall that, in LTE, to reduce the power consumption caused by the high Peak-to-Average power ratio of OFDM, the single carrier-frequency division multiple access (SC-FDMA) in the uplink is used, which causes a shift of 7.5kHz. Hence, to coexist with LTE, in addition to the OFDMA, an optional 7.5kHz channel raster shift in NR uplink for FDD bands is supported [14] to ensure that NR and LTE grids are aligned as shown in Fig. 26 [36], [94].

3) PDSCH WITH LTE CRS RATE MATCHING FOR NR

Rate matching matches the number of bits in the transport block to the number of bits that can be transmitted in the

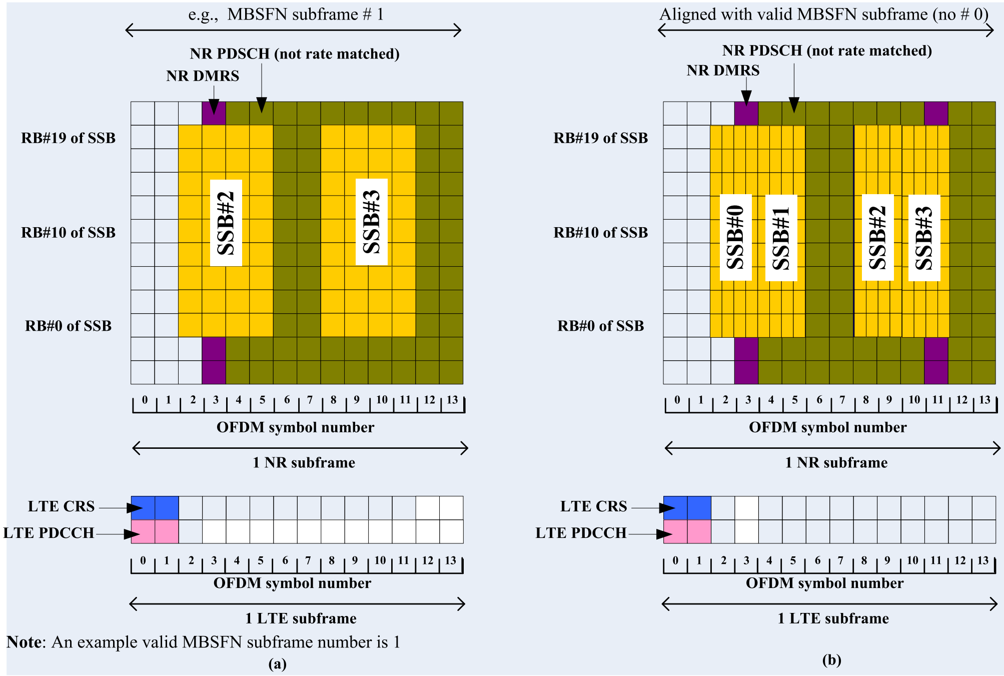


FIGURE 23. **Spectrum sharing on NR SSB Channel for LTE MBSFN subframes. (a) PDSCH with 15kHz and SSB with 15 kHz-case A and (b) PDSCH with 15 kHz and SSB with 30 kHz-case B [38].**

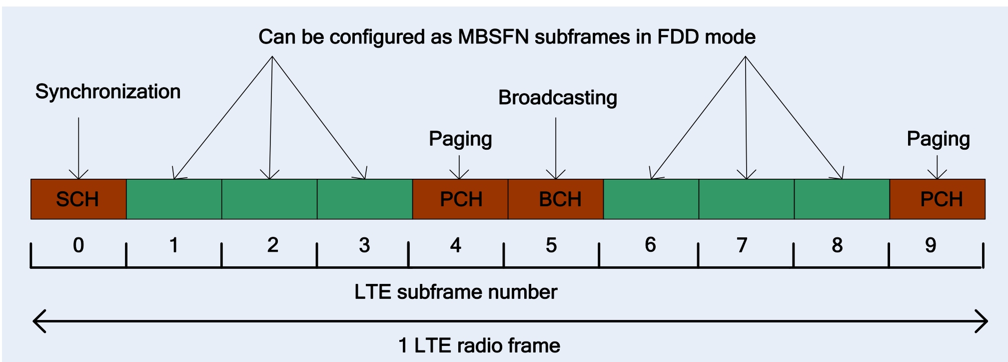


FIGURE 24. **Possible MBSFN subframes in an LTE FDD radio frame [37], [91].**

given resource [16], [95]. The most basic reference signal in LTE downlink is CRS; hence, it is necessary to avoid these CRSs in LTE when allocating NR transmission to LTE time-frequency resources.

Rate matching allows NR to transmit data to be allocated and is the most important feature for the coexistence of NR and LTE in downlink. The bandwidth of LTE, CRS port number, and location are major CRS-related information, which is sent to NR UEs to carry out CRS rate matching through RRC configurations [96]. Several CRS rate matchings are given below as examples (Fig. 27) [16].

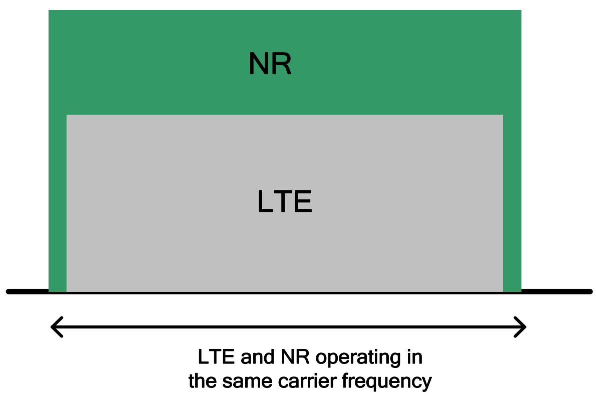


FIGURE 25. **Coexistence of LTE and NR with the same carrier frequency [94].**

4) ADDITIONAL DMRS LOCATION

In NR PDSCH, if required, a provision for an additional DMRS location is defined in the specification on the 12th symbol in a slot. However, the last LTE CRS location is specified at the 12th symbol, causing interference with the additional DMRS location described above. To avoid this clash such that NR PDSCH can be transmitted on the LTE spectrum, an alternative DMRS location is specified at the

TABLE 13. Impact of DSS on LTE subframes in the presence or absence of NR SSBs for LTE and NR coexistence.

LTE	NR	
	With SSB	Without SSB
MBSFN	• No collision from LTE CRS and PDCCH with NR SSBs. • Minimal impact on NR SSBs. • A maximum of six out of ten subframes in a radio frame can be used as MBSFNs for DSS • Not all LTE subframes can be configured as MBSFN. • Alignment of LTE subframes with NR SSB slots is essential since SSB slots may overlap within possible MBSFN subframes other than 0, 4, 5, and 9 subframes in an LTE frame of 10ms. • Using the mixed numerology, it is possible to transmit all four SSBs (for four antenna ports) in one LTE subframe.	• The simplest way to perform DSS between LTE and NR is using MBSFN. • Most operators deploy DSS in the early phase using LTE MBSFNs. • Except for the first two symbols, the rest 12 symbols can be used for DSS.
Non-MBSFN	• Mixed numerology (15kHz SCS for PDSCH and 30kHz SCS for SSB) is useful for the SSB transmission using LTE non-MBSFNs. • Only Type B mapping for PDSCH is possible. Hence, the wastage of resources occurs as symbol 13 remains unused. • It can transmit only one SSB in each subframe, resulting in a delay in SSB transmissions.	• Collision of NR PDSCHs with LTE CRSs can be avoided using either RE- or RB-level CRS rate matching. • The same numerology (i.e., 15kHz SCS) can be employed for both NR and LTE for DSS. • Both Type A and Type B mapping for PDSCHs can be employed.

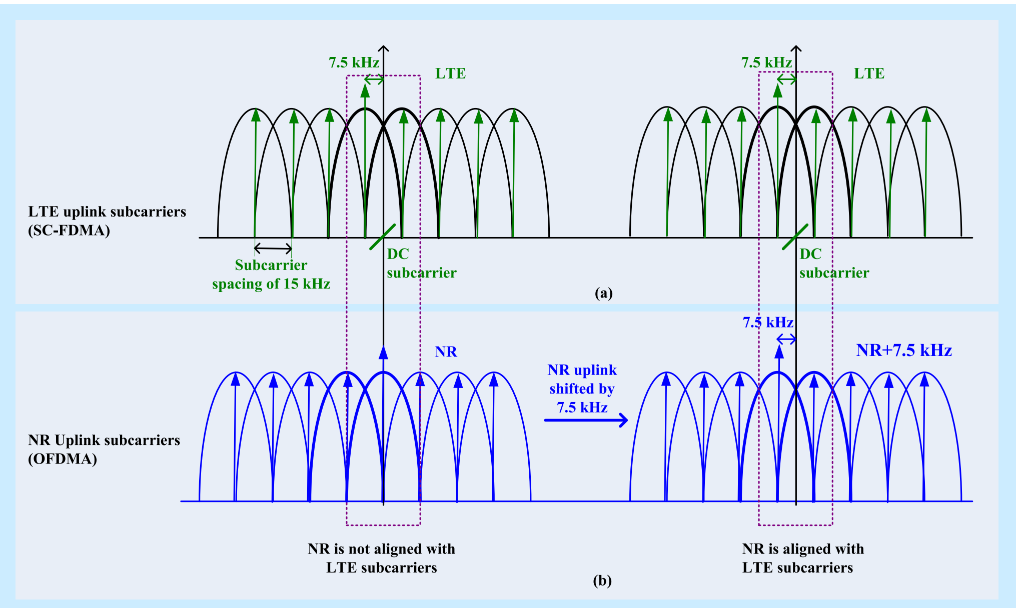


FIGURE 26. Aligning NR uplink with that of LTE by shifting 7.5 kHz rightward [36].

symbol location 13th [5], [97] instead of the 12th symbol as shown in (Fig. 13) for the LTE 2 CRS port configuration.

5) CONFIGURATION OF FLEXIBLE CORESET/PDCCH

Configuration of NR CORESET can be carried out in both RB and symbol levels. For NR UEs, the first three OFDM symbols are obligatory to support. Considering basic CORESET configuration, the first three symbols are divided into LTE PDCCH and NR PDCCH. Recall that NR PDCCH can be located in symbols 2nd and 3rd so long as it does not overlap the CRS position. As an optional feature, NR CORESET with up to three contiguous symbols can be configured beyond the first three OFDM symbols. This in turn relaxes the limitation that LTE PDCCH and NR PDCCH should share the first three OFDM symbols and hence provides more NR flexibility [98] and PDCCH capacity to both LTE and NR.

B. 3GPP RELEASES 16 AND 17 ENHANCEMENTS

After completing the first release of 5G in Release 15 [99], to improve performance and to address new use cases further, 3GPP has been working on the evolution of 5G [100], [101]. Additional features approved in Release 16 and further enhancement proposed in Release 17 for DSS [25] are discussed in the following.

1) NUMEROUS CRS RATE MATCHING PATTERNS

In Release 15, CRS matching is configured only for the same bandwidth size of NR as that of an LTE component carrier (CC). However, if the bandwidth of an NR carrier is

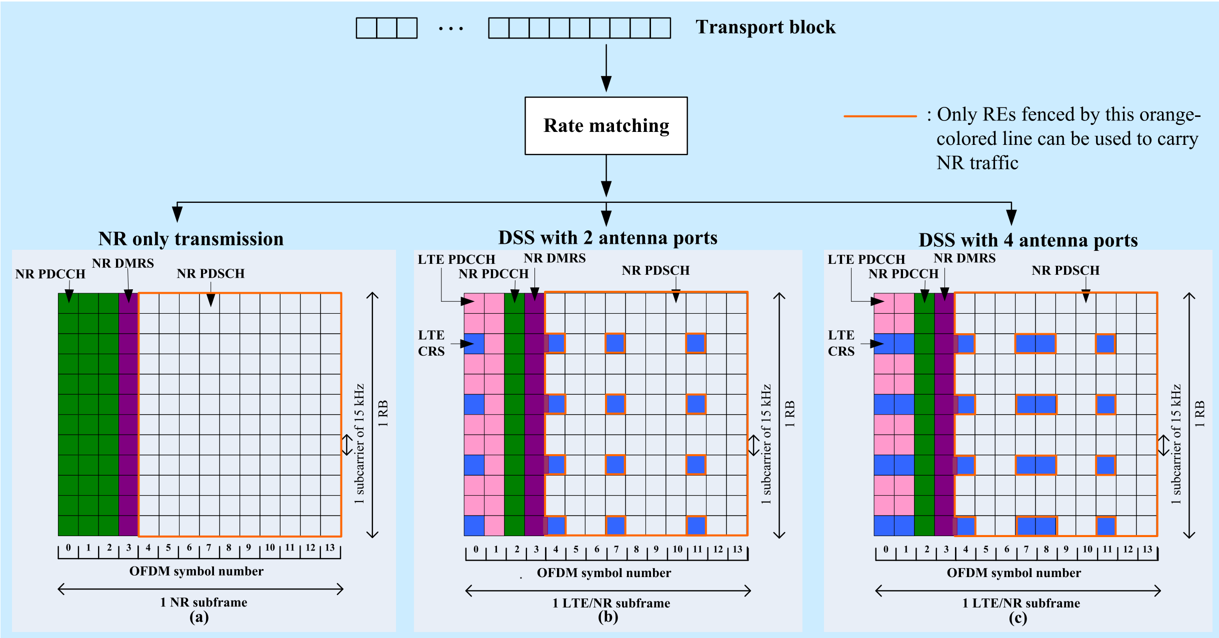


FIGURE 27. Illustrations of the CRS rate matched NR PDSCH [36].

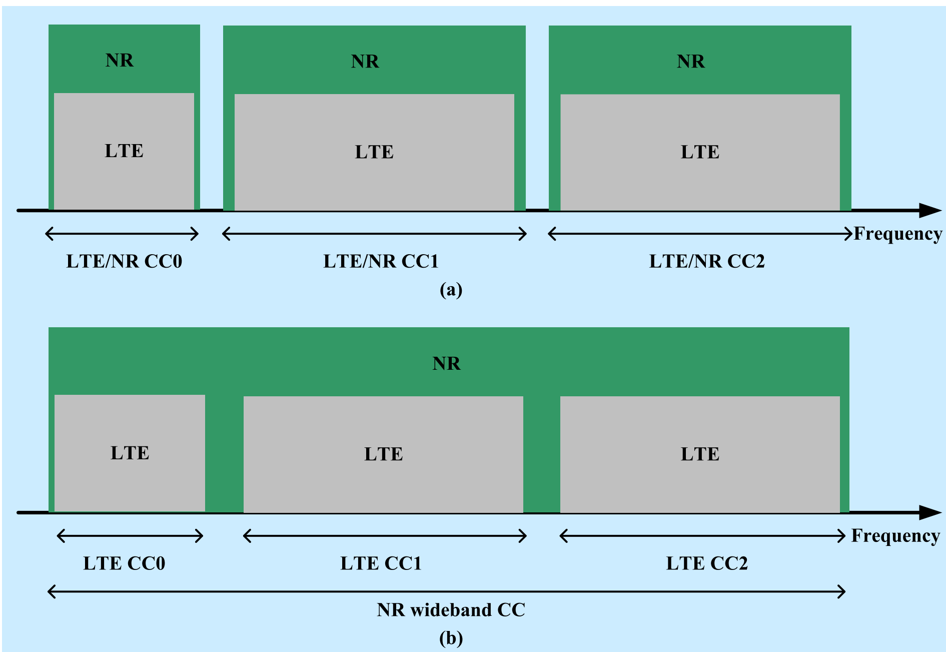


FIGURE 28. NR with CRS rate matching [36]. (a) single LTE CRS rate matching pattern per NR CC in 3GPP Rel-15 and (b) multiple LTE CRS rate matching patterns in a single NR CC in 3GPP Rel-16.

larger than that of an LTE CC, multiple CRS rate matching is needed. For example, an NR carrier having a bandwidth of *50 MHz* may coexist with two 20 MHz CCs and one 10 MHz CC of LTE as shown in Fig. 28. Because of this reason, in Release 16, LTE CRS rate matching patterns are defined for a wider bandwidth such that an NR carrier may include multiple CCs using CA [102]. A maximum of three CRS rate matching patterns was agreed to configure within an NR carrier.

2) ENHANCEMENT OF PDSCH MAPPING TYPE B

In Release 15, PDSCH mapping Type B is used when the PDCCH is used in symbols other than the first three symbols.

- For example, in Fig. 29, 3rd and 4th symbols can be used to allocate NR PDCCH. However, in Release 15, only a PDSCH of lengths 2, 4, and 7 symbol durations is considered, which in turn causes underutilization of available resources as the full utilization of remaining resources in a slot cannot be possible.

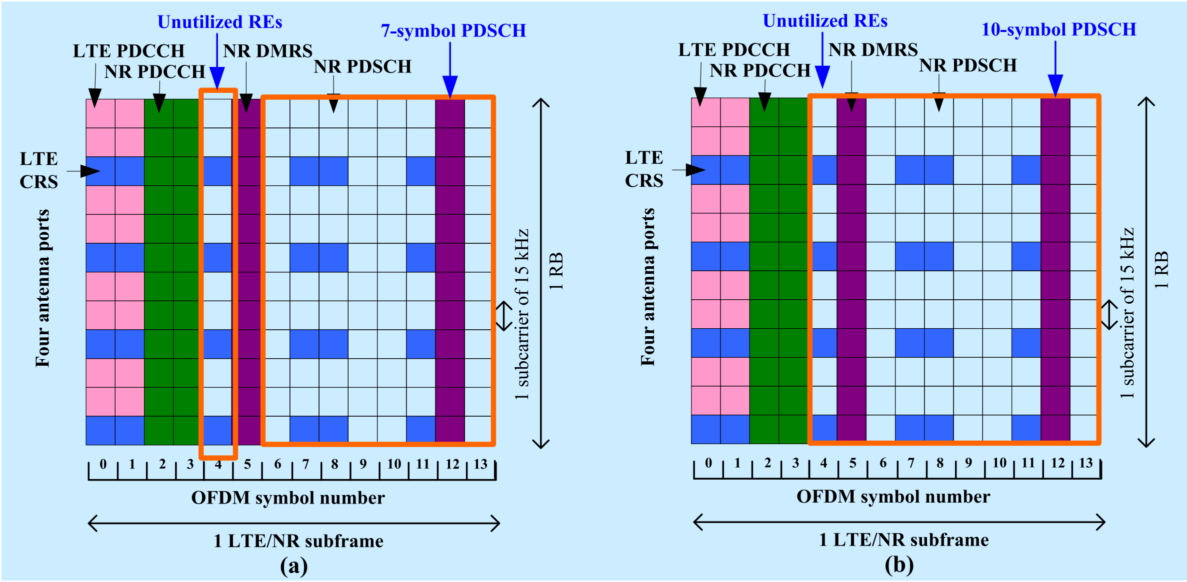


FIGURE 29. Enhancement of PDSCH mapping type B in Rel-16. (a) PDSCH mapping type B in Rel-15 and (b) PDSCH mapping type B in Rel-16 [36].

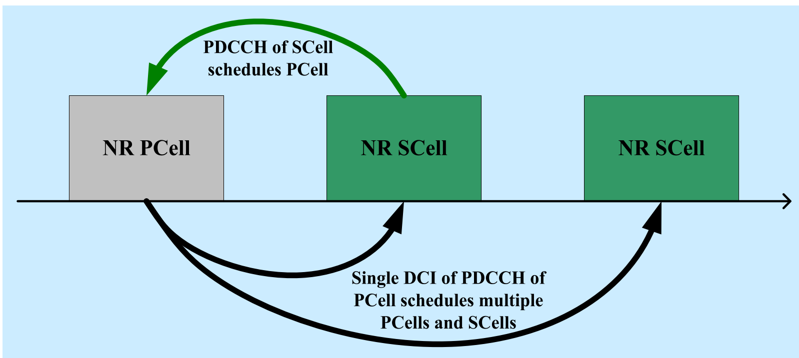


FIGURE 30. Cross-carrier scheduling to improve the scheduling capacity of NR [36].

- For example, symbol 5th remains unutilized when considering a possible combination of 7 symbols for PDSCH as it cannot make the remaining 10 symbol lengths as shown in Fig. 29(a)).
- Because of this reason, additional symbol length (e.g., PDSCH of 10 symbols long [36], [102]) for PDSCH mapping type B is defined to fully utilize available resources as shown in Fig. 29(b).

3) CROSS-CARRIER SCHEDULING

Caused by the limited shared resource usage of PDCCHs for NR and LTE, sufficient NR scheduling in the shared resources may not be possible with an increase in NR devices [103]. To increase NR scheduling capacity, in Release 17, cross-carrier scheduling has been proposed [20]. Cross-carrier scheduling helps overcome the limitation of PDCCH resources of primary cells (PCell) of NR by secondary cells (SCells). For example, in Fig. 30, the PDCCH of SCell schedules the PDSCH on the P(S)Cell. Another way could be to schedule PDSCH on multiple cells by the PDCCH of P(S)Cell/SCell using a single DCI as shown in Fig. 30 [36].

4) EMPLOYING DSS ON MID-BAND TDD

In addition to deploying in LTE low-band, a number of network operators who deployed LTE in mid-band TDD would like to deploy DSS in mid-band TDD as well [104]. A comparison of 3GPP standardization activities in different releases toward DSS is shown in Table 14.

VII. DSS USE CASE, SIGNIFICANCE, CHALLENGE AND FUTURE RESEARCH DIRECTION

A. DSS USE CASES

DSS at 4G low bands provides great coverage caused by the continuous uplink and downlink signal transmission using the FDD technology [105]. Full benefits of DSS can be exploited when DSS is employed with technologies such as standalone architecture with a 5G core network since standalone architecture brings new 5G services as well as great coverage and CA on the device side since CA of both low-band and high-band at the device level help provide

TABLE 14. 3GPP standardization activities toward DSS for LTE and NR coexistence in different releases.

Attribute	3GPP Release 15 (Basic)	3GPP Releases 16 and 17 (Enhancement)
LTE CRS rate matching configuration	Single CRS rate matching: the same bandwidth of NR and a CC of LTE	Multiple CRS rate matching: The bandwidth of NR can be larger than one CC of LTE. A maximum of three CRS rate matching can be possible to apply
PDSCH mapping Type B	Only PDSCH of lengths 2, 4, and 7 symbol duration are considered.	In addition to 2, 4, and 7 symbols, a PDSCH of 10 symbols long is defined.
PDCCH cross-carrier scheduling	PDCCH cross-carrier scheduling is not possible, i.e., the PDCCH of one cell cannot schedule the PDSCH of another cell.	The PDCCH of the secondary cell can schedule the PDSCH of the PCell or the PDCCH of the PCell can schedule the PDSCH of multiple cells using a single DCI.
DSS band and duplexing	DSS is deployed mostly in low-band LTE FDD.	DSS is being considered to deploy in the midband TDD in addition to low-band FDD.

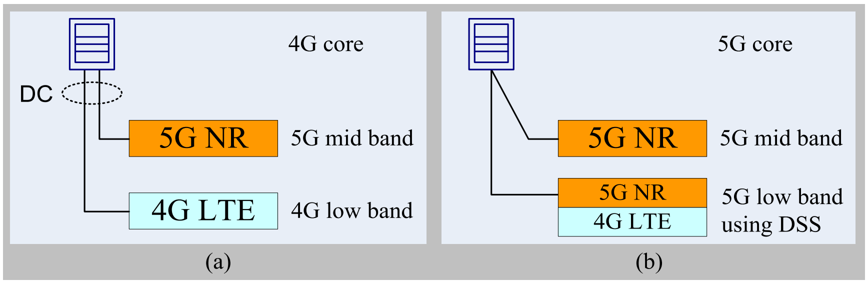


FIGURE 31. (a) NSA with low band 4G, which is good for mobile broadband, and (b) SA with low band 5G using DSS, which is good for 5G slicing and services [113].

high data rates by aggregating spectrum at low-and-high bands [23], [24].

1) 5G STANDALONE ARCHITECTURE WITH DSS

In the first phase of 5G, NSA architecture is considered where 4G and 5G radios are connected using dual connectivity (DC) [106], [107], and the existing 4G core network is used by both radios (5G NR and 4G Radio) [108]. Fig. 31 shows NSA architecture combining the mid-band 5G with the low-band 4G using DC for mobile services. Note that with DC in place, devices can continue connection simultaneously to both 4G LTE and 5G NR [109]. On the other hand, SA architecture has its own 5G core network allowing it to bring new services [110] because of its enhanced support for network slicing, along with dynamic scalability and adaptability. In SA, there is no DC in the radio [111] since no connection exists with the 4G radio, resulting in obtaining no additional advantages from low-band 4G. This, however, can be resolved by applying DSS with all or part of an existing low-band 4G radio to enhance 5G coverage [112] (Fig. 31). Fig. 31 shows 5G FDD operating in low bands (currently used by 4G services), which is required for SA deployments since DC between mid-band 5G and low-band 4G does not exist [106].

2) 5G CA WITH DSS

4G CA is a basic capability that exists in both 4G and 5G NSA devices. Using 4G CA, NSA can combine spectrum from multiple 4G bands to boost its capacity [105]. This is not the case for 5G FDD devices (particularly, those available in the first part of 2020) that are not 5G CA-supported (i.e., they do not support CA between 5G bands). Because 5G FDD at a low band plus 5G TDD at 3.5GHz band together is optimally utilized, this device limitation downgrades user performance. In other words, it is preferable to support 5G CA when a low band is converted from 4G to 5G usage to improve user performance. Moreover, 5G FDD and 4G FDD bands are combined with DC, not with CA, resulting in 20-30% lower downlink throughput [113]. This is because, unlike CA having a single MAC entity [114], DC does not allow common scheduling and requires two separate uplinks causing a 3 dB coverage loss.

B. DSS SIGNIFICANCE

1) EFFICIENT USE OF AVAILABLE SPECTRUM

Network operators are facing continuous pressure to deliver seamless connectivity to their customers with an ever-increasing demand for faster and more reliable wireless communications. An effective solution to this problem is DSS [17]. DSS enables efficient use of available spectrum by dynamically allocating spectrum based on the actual needs or the service ratio [115] of the mobile networks such that no valuable spectrum resources are wasted on underutilized bands [116].

2) COEXISTENCE OF MULTIPLE GENERATIONS OF WIRELESS TECHNOLOGY

Conventionally, mobile network operators use dedicated spectrum bands [117] for each generation (e.g., 698MHz-793MHz [118] and 2GHz [119] bands for LTE), which were once effective. However, with an increased demand for mobile services, such allocation of dedicated spectrum for each generation is found inefficient and limits the potential for innovation and growth in the mobile industry. DSS provides solutions to this problem by allowing multiple generations of mobile technology to coexist with the same spectrum band [34], such as operating 5G NR within 4G LTE spectrum bands by allocating radio resources dynamically to NR and LTE without degrading the performance of LTE. [120].

3) REDUCTION IN DEPLOYMENT COST AND TIME OF 5G

Employing DSS, mobile operators can deploy 5G services using their existing 4G infrastructure and spectrum resources. This reduces the cost and shortens the time for 5G deployments in NSA mode [106] caused by not having to wait for the release of the new and dedicated 5G spectrum [116].

4) ACHIEVING EXTENDED 5G COVERAGE BY USING A LOWER FREQUENCY BAND

Typically, 5G is co-located in LTE sites. Because mid-band and mmWave bands face higher propagation loss and 5G were to utilize only mid-band TDD, the 5G coverage is lower than that of LTE, which operates only below the 3 GHz low-frequency band reserved only for it. Hence, research on the coverage performance of 5G is critical [121], and in this regard, DSS can solve this problem by operating 5G within 4G low-frequency bands to extend the coverage of 5G.

5) FACILITATING 4G TO 5G SMOOTH TRANSITION

In the early NR market, the demand for 5G traffic may not be high enough to use the whole spectrum re-farmed from LTE (i.e., 5G may need to coexist with LTE [122]), resulting in a waste of spectrum that may otherwise be used for LTE traffic. Contrary to this, in a refarming scenario, the available re-farmed spectrum may be insufficient to fulfill NR traffic demand while some portion of LTE resources remain unused because of a low LTE traffic demand. DSS can solve such setbacks through dynamic spectrum resource allocations depending on the actual LTE and NR traffic demands across the entire band, which results in high spectrum utilization.

6) FACILITATING SA NETWORKING

In contrast to NSA, which is a continuation of 4G technology to provide mainly eMBB services, SA mode is the final networking architecture of 5G [123] to enable diversified vertical industry applications and increase revenue sources for operators [121]. Because SA does not rely on 4G networks [120], [124], [125], it is necessary to deploy a complete 5G network with a wide coverage area from the beginning. However, because of higher frequency bands of 5G, the coverage area of a base station is smaller, resulting in greater network investment. This can be solved by employing DSS between 4G LTE and 5G NR such that a wide coverage for 5G SA mode can be provided using lower frequency bands of 4G.

7) EASY TO SUPPORT 5G CA

NSA mode provides 5G services by EN-DC, i.e., LTE and 5G DC [126], [127], [128], [129]. However, DC has lower performance than carrier aggregation. DSS, by dynamically allocating the 4G spectrum to 5G, can realize CA in 5G between the FDD low band and TDD mid-band to improve performance.

8) SPEED

DSS allows NR to serve more users without physically upgrading mobile network operators' equipment. Additionally, the speed and performance of NR devices on the DSS networks are improved because of taking advantage of the NR service [130].

9) FASTER ROLLOUT OF 5G NETWORK

In the traditional approach, NR and LTE networks are rolled out independently with a new spectrum, new antenna, and new radio frequency (RF) nodes. However, in the DSS-based network rollout, NR can be rolled out faster using the existing spectrum, current antennas, and current RFs. Resources are shared between NR and LTE dynamically [131].

10) MAXIMIZED NETWORK CAPACITY

DSS allows simultaneous operation of LTE and NR networks in the same LTE spectrum, providing additional capacity for NR services without compromising the quality of LTE services. This in turn maximizes the overall network capacity to support the growing demand for high-speed data services [132].

11) IMPROVED USER EXPERIENCE

By allocating resources dynamically based on user demand, DSS ensures a better user experience, resulting in faster data speed, reduced latency, and enhanced overall service quality for both LTE and NR users [132].

The aforementioned performance gains of DSS for LTE and NR coexistence are summarized in Table 15.

C. DSS CHALLENGES

1) CAPACITY AND DATA RATES

One of the major impacts of employing DSS is originating control overhead. The overhead caused by DSS affects directly the cell capacity and peak data rate [133]. This is because DSS causes inevitable overhead that requires allocating for the DSS a certain portion of the total available resources, resulting in a reduction in the total amount of resources that can be allocated to both LTE and NR systems.

Fig. 32 shows an example scenario considering evenly distributed traffic for both NR and LTE systems. In such a case, when serving using DC, the whole spectrum resource can be assigned equally to both systems, i.e., 10 MHz each, for example (Fig. 32). However, if DSS is employed, the total cell capacity of both systems will be reduced by the ratio of DSS overhead and gets even further deteriorated with an increase in cell loading and network traffic demand [134]. The deterioration also affects the peak data rate. This is because when the frequency band is divided statically, a maximum peak data rate can be achieved by aggregating the spectrum of both systems.

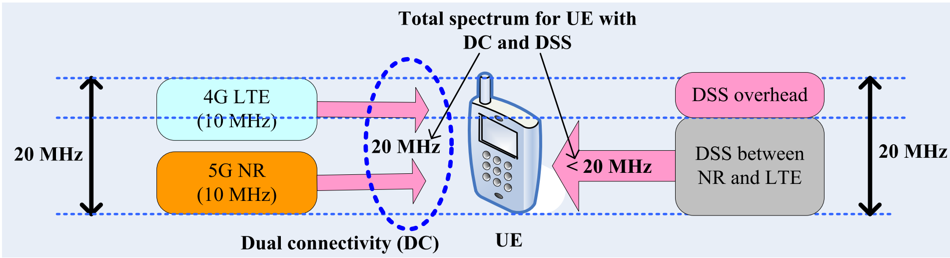


FIGURE 32. DSS and low-band DC data rates [36].

TABLE 15. A summary of DSS performance gains for LTE and NR coexistence.

DSS Performance Gain	Method	Purpose
Efficient spectrum use	Dynamic spectrum allocation based on the actual needs or the service ratio of the mobile networks.	Seamless connectivity and faster and more reliable communications.
Coexistence of multiple mobile generations	Allow the coexistence of multiple generations of mobile technology with the same spectrum band.	To avoid static spectrum allocation for each generation, which is found inefficient and has limited potential for innovation and growth.
Reduced cost and time for 5G deployments	Mobile operators are allowed to deploy 5G services using LTE infrastructures and spectrum resources.	To avoid waiting for the release of the new and dedicated 5G spectrum.
Extended coverage for NR	Operation of NR within LTE low-frequency bands.	Mid-band and mmWave bands face higher propagation loss resulting in lowering the 5G coverage than that of LTE.
Smooth transition from LTE to NR	DSS can solve these setbacks through dynamic spectrum resource allocations depending on the actual LTE and NR traffic demands across the entire band, which results in high spectrum utilization.	In the early NR market, the demand for 5G traffic may not be high enough to use the entire spectrum re-farmed from LTE which results in a waste of spectrum.
SA networking	Employing DSS between LTE and NR such that a wide coverage for NR SA mode can be provided at the lower frequency bands of LTE.	SA mode is the final networking architecture of 5G to enable diversified vertical industry applications and increase revenue sources for operators.
Supporting CA in NR	Dynamic allocation of the LTE spectrum to NR using DSS, CA can be realized in NR between FDD low band and TDD mid-band to improve performance.	CA has better performance than dual connectivity and LTE.
NR rollout	In the DSS-based network rollout, NR can be rolled out faster using the existing spectrum, current antennas, and current RFs [131].	Faster rollout of NR networks [131].
Maximized network capacity [132]	DSS allows simultaneous operation of LTE and NR networks in the same LTE spectrum, providing additional capacity for NR services without compromising the quality of LTE services.	Maximizing the overall network capacity for high-speed data services.
Improved user experience [132]	Dynamic resource allocation based on the user demand.	Ensuring a better user experience.

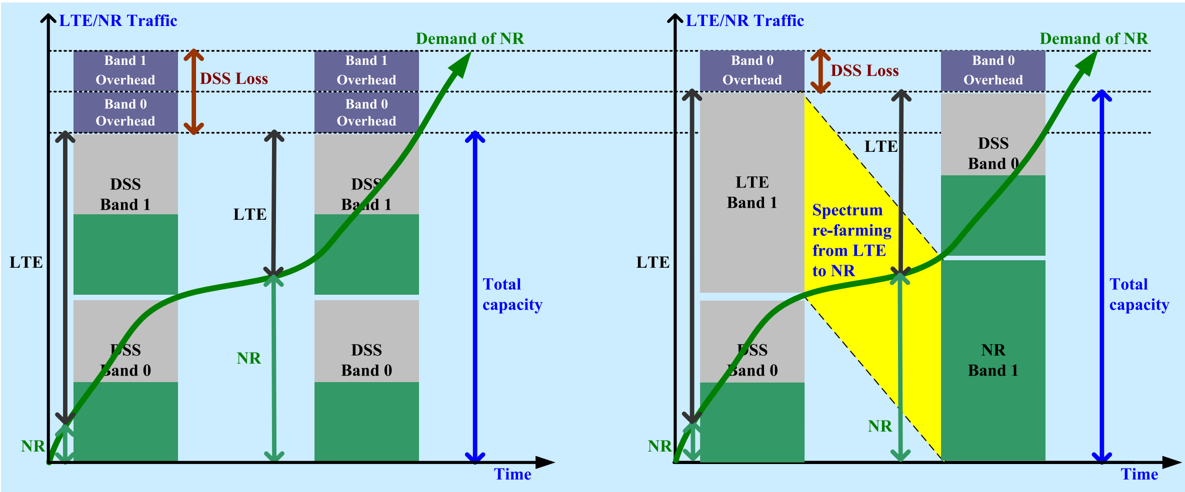
2) DSS OPERATION WITH SINGLE VERSUS MULTIPLE SPECTRUM BANDS

A noticeable feature of DSS is that expected benefits may not be guaranteed even if DSS is employed in more than one spectrum. As shown in Fig. 33, the left graph shows the operation of DSS on both NR and LTE systems (Multiband DSS) whereas the right graph shows the operation of DSS only on a single band (Single band DSS).

In either case, if the demand for NR traffic is low, spectrum resources can be allocated flexibly to both systems. However, when both bands employ DSS, the DSS overhead increases because of operating DSS on the LTE spectrum as well, resulting in a reduction in total cell capacity. With an increase in NR traffic, the re-farming of the LTE spectrum (shown in the right picture) serves the additional capacity of NR systems, resulting in an improvement in the total capacity (Fig. 33) compared to a multi-band DSS (shown in the left picture).

3) DEPLOYMENT AND OPERATION

1) Technical-and-economic-perspectives:
   - Deployment of DSS imposes an additional burden both technically and economically since it requires replacing hardware and upgrading key LTE software.
   - In addition, in certain scenarios, the replacement of existing LTE radio units may be required with new ones compatible with NR, and a new baseband unit needs to be deployed to accommodate the new low band.
   - Furthermore, a real-time signaling interface and synchronization addressing NR and LTE resource coordination may be required.
2) Service/operation perspectives:
   - *Real-time coordination:* DSS has a direct impact on LTE and NR services [135]. For optimal operation, dynamic coordination of resource changes in real-time between NR and LTE is required, which can otherwise disturb resource-related LTE and NR services.



(a) (b)

FIGURE 33. Capacity responses of single-band and multi-band DSS operation. (a) multi-band DSS and (b) single-band DSS [36].

- *Lock-in nature of Vendors:* Operating DSS successfully between LTE and NR, a prerequisite is tight internet-working between these systems [136]. This can only be guaranteed through unified scheduling or vendor-proprietary interface.

4) INCREASED OVERHEADS

To enable DSS, both LTE and NR systems transmit various control and reference channels, particularly, in the downlink for coordination and control purposes to support operating the network properly. Depending on the DSS implementation technique, there may be a drop in the network capacity from 10% to 40% [104]. Ideally, NR capacity and LTE capacity are, respectively, reduced by 20-30% and by 5-10% caused by DSS operations. Note that the control channels share the system spectrum that could otherwise carry user payload. Overhead from control channels increases in DSS because, in DSS, transmissions of control channels for both NR and LTE are required. The overhead can add up to several tens of percentage points. The exact reduction in capacity varies depending on the DSS implementation and configuration. To limit the overhead, always-on periodic channels or channel resources are required to be managed efficiently by the scheduler [103].

5) LTE AND NR DIRECT-CARRIER SUBCARRIERS

In LTE, the direct-current subcarrier, which is located at the center frequency, is not used for the downlink, and hence, usable subcarriers are located around the center frequency [137]. For LTE uplink, no direct-current subcarrier exists as the whole LTE spectrum is shifted down in frequency by a half subcarrier spacing, i.e., 7.5 kHz [138] as shown in Fig. 26. Contrary to the LTE, NR does not avoid the direct-current subcarrier since each NR device may have its direct-current subcarrier located at various locations in the carrier [138]. Further, when employing DSS for the coexistence of NR and LTE (i.e., to operate both on the LTE spectrum), it is necessary to align uplink subcarriers of LTE and NR to minimize inter-subcarrier interference [139]. Adding a 7.5 kHz frequency shift to the NR uplink can address this challenge as shown in Fig. 26.

6) LOCAL OSCILLATOR (LO) LEAKAGE

The position of direct-current subcarriers was known prior to the LTE devices as they were initially designed to support all available bandwidth. However, unlike LTE devices, NR devices are flexibly allocated with their bandwidth within a huge bandwidth of up to 400 MHz. So, it is highly probable that direct-current subcarriers may fall outside the NR UE bandwidth. This raises the concern of how to deal with the degradation due to the local oscillator (LO) leakage both for the uplink and downlink NR transmission [140].

7) MIXED NUMEROLOGY

LTE uses a fixed numerology of 15 kHz subcarrier spacing, whereas NR can use 15 kHz or 30 kHz subcarrier spacing. LTE and NR can become orthogonal only when NR uses 15 kHz subcarrier spacing as NR can use the same time and frequency grid as used by LTE. However, when NR uses 30 kHz subcarrier spacing, the situation becomes different. So, developing mechanisms to share resources between LTE and NR when NR and LTE use different subcarrier spacings is critical. A possible solution is that NR and LTE can share the same time and frequency resources if the UE can be able to decode LTE and NR transmissions simultaneously [141].

8) INTERFERENCE AVOIDANCE AND SUBCARRIER SPACING

DSS enables NR and LTE to share the same LTE spectrum. Because LTE and NR use distinct modulation methods so that their transmissions can interfere with one another. As a consequence, throughput and network efficiency may

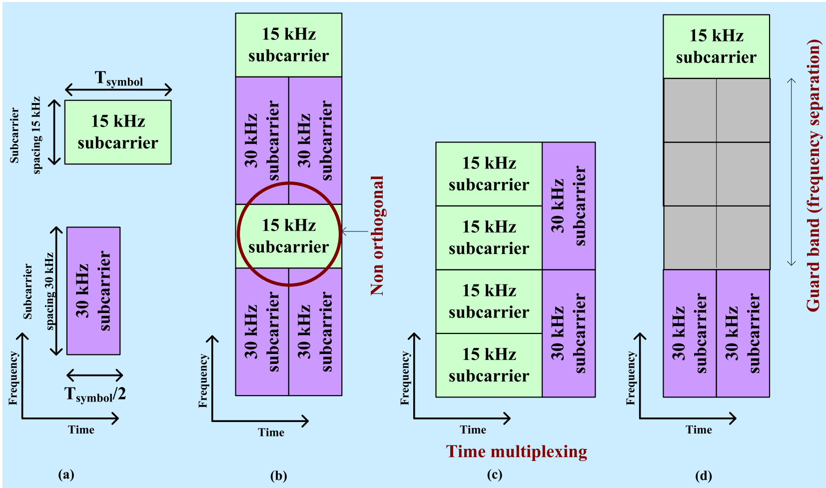


FIGURE 34. Interference avoidance in DSS 5G NR 30 kHz subcarrier spacing. (a) guard band (b) time multiplexing [141].

suffer [142]. This necessitates managing mutual interference generated from both LTE and NR signals, which otherwise degrades each other's performance [143]. When NR uses 30 kHz subcarrier spacing, NR then occupies twice the spectrum in the frequency domain and a half duration in the time domain as compared to when using 15 kHz subcarrier spacing. Hence, the mixed numerology generates interference, resulting in breaking the orthogonal property (Fig. 34). To avoid this mutual interference when LTE and NR operate on the same LTE frequency, it is a persistent challenge that needs to be addressed for an efficient coexistence of NR and LTE networks [143]. Hence, techniques that can address the impact of mixed numerology need to be developed. For example, time multiplexing separating two transmissions in the time domain and guard band causing frequency separation in the frequency domain can avoid such interference as shown in Fig. 34 [141].

9) BACKWARD COMPATIBILITY

Backward compatibility is the primary concern for DSS. Because of the huge number of LTE devices in operation, it is almost impossible for network operators to alter the LTE transmission mechanism. This necessitates a transparent spectrum sharing between NR and LTE and an adaptive NR transmission to coexist NR with LTE [141].

10) SYSTEM COMPLEXITY

LTE and NR spectrum sharing necessitates a complicated system capable of handling changing spectrum resource sharing. This implies that network operators will need to invest in cutting-edge hardware and software to enable LTE and NR spectrum sharing [142].

11) REGULATORY AND INCENTIVIZING CHALLENGES

From the regulatory perspective, to accommodate the DSS concept, laws and regulations governing spectrum usage need to be adapted. Likewise, for incentivizing, it is necessary to create new incentive models to initiate cooperative spectrum sharing for network operators to become willing to collaborate [144].

12) OTHER CHALLENGES

There are also other numerous challenges concerning DSS for LTE and NR coexistence as pointed out in the following.

1) Hardware Compatibility: Many cellular infrastructures probably are not yet compatible with the DSS, and some equipment may need necessary upgrades or replacements to put up DSS functionalities [143]

2) Regulatory and Policy Considerations: Regulatory bodies in different parts of the world have different terms and conditions imposed on the use of spectrum. Hence, it is critical to comply with DSS with such rules in regions particularly where the spectrum licensing protocols are stringent [143]

3) Return on Investment: Though DSS might avoid the necessity of dual infrastructure, the deployment of DSS still requires a certain level of cost. Specifically, in regions where the adoption rate of 5G is slow enough, the deployment of DSS causes a great challenge on the return on investment (ROI) for DSS from the economic viewpoint, which necessitates an in-depth market study before deciding to deploy the DSS [143]

4) Evolution and Long-term Strategy: With the continual evolution of cellular standards by standardization bodies like 3GPP, confirming the integration of DSS seamlessly with new features and enhancements is paramount. Moreover, when most users move to 5G, evaluating the continual relevance and efficiency of DSS as well as planning for eventual phase-out is critical [143]

5) Challenges for operators and users: DSS presents several challenges for operators and users, including increased complexity and coordination, lower peak performance and latency, and higher interference and power consumption [145].

6) Spectrum sharing and switching: To manage spectrum sharing and switching between LTE and NR, additional effort is needed. This is equally applicable to ensuring the compatibility of different radio access network (RAN) and core network components [145].

7) Overhead and delay: Overhead and delay for the subframe switching and signaling are introduced because of the limited maximum bandwidth and subcarrier spacing for NR [145].

8) Active transmitters and receivers: Because of the increase in the number of active transmitters and receivers in the same band, UEs need to operate in both LTE and NR modes, which in turn increases the power consumption [145].

9) DSS implementation: Implementation of DSS in LTE for NR presents some challenges as follows [146].

- Affecting spectral efficiency performance, which may result from the additional management overhead traffic required by DSS [146].
- Optimizing traffic management policies, particularly, trading off capacity versus user experience as well as overall LTE and NR user experience [146].
- Isolating performance issues, including interference, signal quality, or network, for both LTE and NR at the same time as well as the mutual effect of NR and LTE on each other [146].

D. FUTURE RESEARCH DIRECTIONS

Some major research directions are highlighted in the following as potential research studies.

- Developing flexible spectrum sharing solutions of DSS for a smooth migration from 4G LTE to 5G NR systems such that DSS can allocate radio resources to NR users following the rate at which the number of NR users increases over time.
- Developing a mechanism for an optimal allocation of time and frequency resources dynamically to LTE and NR systems.
- Designing an effective cross-carrier scheduling mechanism to enhance the scheduling capability of NR UEs since limited resources are usually shared by PDCCHs of NR and LTE.
- For proper DSS, schedulers of LTE and NR need to coordinate with one another to exchange traffic information. Hence, a sophisticated coordination mechanism between NR and LTE schedulers is a promising research direction.
- Like CA, DC cannot allow common scheduling and hence cannot provide the same capacity performance. This requires an in-depth investigation of the performance of NR with CA and DC individually.
- A maximum of six LTE subframes per frame can be assigned as MBSFNs for NR transmissions. Since an increase in LTE MBSFN subframes per frame enhances the capacity performance of NR users whereas it degrades correspondingly the capacity of LTE users, finding an optimal number of LTE MBSFNs in each radio frame is critical to trade-off the capacity between NR and LTE users.
- Because spectrum re-farming is a traditional and simplest option to support different cellular generations to operate on the same spectrum [126], [147] whereas DSS generates additional control overhead, a deep understanding of the spectrum utilization under spectrum re-farming and DSS is one of the vital research directions.
- The major drawback with DSS is the generation of control overhead, which reduces the overall resources that can be allocated to LTE or NR users. However, the control overhead depends on several factors, including coordination between schedulers of NR and LTE and the complexity of the developed DSS mechanism. Hence, how to develop an efficient DSS mechanism with a minimal control overhead is a potential research direction.
- For an optimal operation of DSS, resource changes between LTE and NR dynamically are needed, which may disturb resource-coordinated LTE and NR services, making it difficult for operators to adopt both the resource-coordinated features and DSS simultaneously. Developing a holistic approach to overcome this concern is a potential research scope.
- When the CRS position of any LTE cell (cell 1) is different from that of its neighboring cell (say cell 2), the CRS of cell 1 may coincide with the data of cell 2, resulting in CRS interference. Such interference can be avoided when the entire LTE carrier is re-farmed to serve NR services. However, so long as the 100% migration of the LTE spectrum happens, adjacent cell CRS interference occurs. Hence, developing novel approaches that can address avoiding such CRS interference is a crucial future research direction.

VIII. LESSONS LEARNED

In this section, a summary of major lessons that have been discussed and learned throughout this paper in different sections is discussed.

A. 5G SPECTRUM

Broadly, spectrum bands in 5G (NSA can be categorized into three.

1) CATEGORY 1

This portion of frequency bands, also termed low-frequency bands, lies below 3 GHz, which operates in an FDD mode and is used mainly by LTE services. DSS for the NR and LTE coexistence is working on this category.

2) CATEGORY 2

This portion of frequency bands, also termed mid-frequency bands, lies from 3 GHz to 5 GHz and operates in a TDD mode.

3) CATEGORY 3

This portion of frequency bands, also termed high-frequency millimeter-wave bands, lies between 24 GHz to 40 GHz. It is also operated in a TDD mode.

B. 5G STANDALONE VERSUS NON-STANDALONE AND USE OF DSS

5G NR operates in both standalone and non-standalone modes. In standalone, NR works autonomously of the core network of LTE, whereas in non-standalone, it uses the core network of LTE. Hence, DSS is operated on the LTE spectrum in non-standalone mode for the coexistence of LTE and NR networks.

C. USE OF LTE CARRIERS FOR NR TRANSMISSIONS

Currently, mobile communication markets around the world are mostly served by LTE and are expected to continue the same trend for the next several years. Because NR is in the early stage of deployment in most parts of the world, NR users are relatively lower in number than LTE. This leads to hindering LTE users if allocating the LTE spectrum to NR users only and requires DSS to be in place to allocate the LTE spectrum to LTE and NR users based on their respective traffic demands.

D. FUNDAMENTAL BASIS TO SUPPORT LTE-NR COEXISTENCE

Like LTE, which uses the OFDM wave with a fixed 15 kHz SCS, NR also adopts the OFDM considering 15 kHz as the basic numerology. This enables the resource grid structures of both NR and LTE systems greatly aligned, leading to a fundamental basis for their coexistence.

E. FUNCTIONS NECESSARY FOR SUPPORTING LTE-NR COEXISTENCE IN FDD BANDS

To coexist NR with LTE in FDD bands using DSS, 3GPP recommended in Release 15 the following functions.

- Channel raster of 100 kHz for NR,
- 7.5 kHz shift in uplink for NR (optional), and
- Rate matching of LTE CRS with NR PDSCH.

F. LTE-NR COEXISTENCE SUPPORT IN 3GPP RELEASE 15

To avoid the requirement of PDCCH of both NR and LTE to be shared within the first three symbols in an LTE subframe, optionally, NR CORESET ranging contiguously up to 3 symbols can be configured outside the first three symbols, leading to an enhanced LTE and NR PDCCH capacity.

G. FLEXIBLE SPECTRUM-SHARING AND SMOOTH 5G MIGRATION

DSS allocates LTE time-frequency resources to NR users based on their traffic demands. The remaining LTE resources are then allocated to LTE users. With an increase in NR users over time and consequently a corresponding decrease in LTE users, DSS allocates more resources to NR users dynamically. Such a flexible allocation of LTE spectrum to NR users enables a smooth migration toward 5G NR from the existing 4G LTE.

H. COEXISTENCE OF MULTIPLE RATS

DSS has been considered an effective technique to coexist multiple radio access technologies (RATs) [148], and hence, enables NR to utilize low-frequency bands to coexist with LTE. This results in no further requirement for a new low-frequency spectrum to address large NR coverage.

I. COVERAGE HOLES

Typically, NR is installed on existing LTE sites to reuse LTE infrastructure [31]. Coverage holes [126], [149] could exist because of operating NR at the mid-band frequency only as shown in Fig. 35. Nevertheless, operating at mid-band frequency results in an indoor coverage hole caused by external wall penetration loss of a building, and the coverage reduction increases even further with an increase in the frequency bands, e.g., mmWave bands.

J. IMPACT OF LOW-FREQUENCY BANDS

By employing DC and CA techniques, the coverage of mobile networks operating at the mid-band or mmWave bands can be extended as shown in Fig. 36. However such coverage can be extended even further by operating mobile networks at a low-frequency band as shown in Fig. 36. Hence, if all low-frequency bands are occupied by LTE services such that they are difficult to use for NR services, DSS can be employed to share the low-frequency bands with NR to expand its coverage.

K. DSS DEPLOYMENT

Most deployment of NR FR1 in the early stage is based on TDD, typically operating in the 3.5 GHz. However, LTE operates on most of the spectrum below 6 GHz, which is configured as the FDD mode. This causes DSS to be deployed using the FDD mode in the low-frequency bands.

L. SPECTRUM UTILIZATION UNDER SPECTRUM RE-FARMING AND DSS SCENARIOS

Fig. 37 shows the variation in traffic of both LTE and NR systems with an increase in the demand for NR as well as the utilization of spectrum under the scenarios of spectrum re-farming and DSS. Recall that in the early NR deployment, NR traffic may be too small to require the available re-farmed spectrum resources, which results in a scarcity of available spectrum to serve LTE traffic whereas an underutilization of the re-farmed spectrum resources by NR. In other words, this leads to leaving some unused re-farmed spectrum resources by NR. However, as the NR traffic demand increases and eventually exceeds that of LTE, NR will face a scarcity of spectrum resources to serve its traffic whereas LTE will

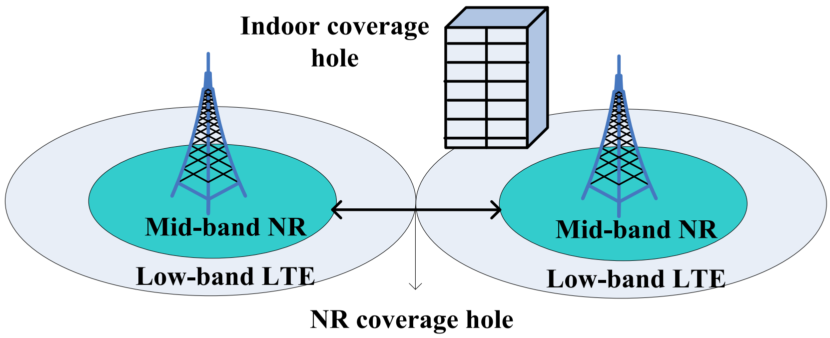


FIGURE 35. Coverage hole of mid-band NR [36].

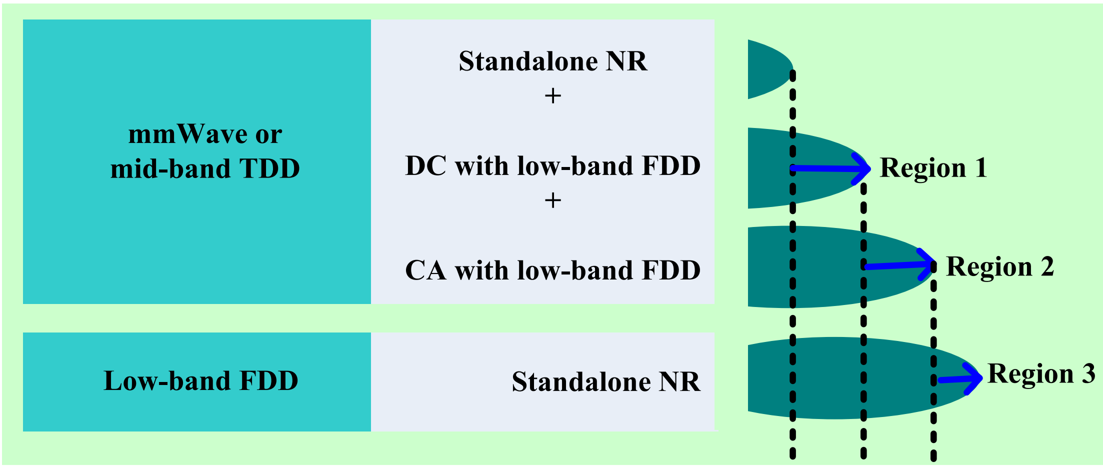


FIGURE 36. Coverage extensions in different deployment scenarios [36].

cause an underutilization of the re-farmed spectrum because of the reduced demand for LTE traffic (Fig. 37(a)).

DSS plays an important role in avoiding this scenario by allocating spectrum to LTE and NR dynamically across the whole band following their respective traffic demands (Fig. 37(b)). To implement so, schedulers of LTE and NR need to coordinate with one another to update the traffic status so that spectrum resources can be assigned dynamically to NR and LTE in a synchronized way (Fig. 38). Such a dynamic resource allocation using DSS allows NR and LTE to adjust the amount of spectrum to serve their respective traffic demands over time.

M. CROSS-CARRIER SCHEDULING

Since a limited amount of radio resources is shared by PDCCHs of NR and LTE, there can be a scarcity of available scheduling resources for NR in the shared carrier with an increase in the number of NR devices. To address this issue, in Release 17, cross-carrier scheduling has been discussed to enhance the scheduling capacity of NR UEs. More specifically, the cross-carrier scheduling addresses the limitation of PDCCHs of NR PCell with the help of SCells.

N. AVOID COLLISION OF NR PDCCH WITH LTE CRS

One of the major concerns in DSS that needs to be addressed is to make sure that the PDCCH of NR does not collide with the CRS of LTE. This can be addressed by configuring NR CORESET to avoid collision of NR PDCCH with LTE CRS.

O. NR/LTE PDCCH CONFIGURATIONS

In accordance with the 3GPP specifications, since a UE needs to monitor only the first three OFDM symbols of a subframe/slot for the NR PDCCH, having known the PDDCH configuration of LTE, NR PDCCH can be configured in either one or two symbols. An example scenario could be to assign NR PDCCH to either the second and third symbols or across the third symbol based on the number of symbols assigned to LTE PDCCH for the 2CRS antenna port configuration. Likewise, for a 4CRS configuration, only the third symbol can be assigned to NR PDCCH.

P. LTE CRS RATE MATCHING AND DMRS LOCATIONS

CRS rate matching is not needed for LTE MBSFN subframes to transmit NR PDSCH as no CRS exists in LTE MBSFN subframes. Moreover, additional DMRS if required can be allocated to the 13^{th} symbol position in a subframe to stay in sync with any additional DMRSs in non-MBSFN subframes.

Q. IMPACT OF ALWAYS-ON LTE CRS TRANSMISSIONS

If DSS is employed, in comparison with the re-farmed networks to NR, CRS may cause adjacent channel

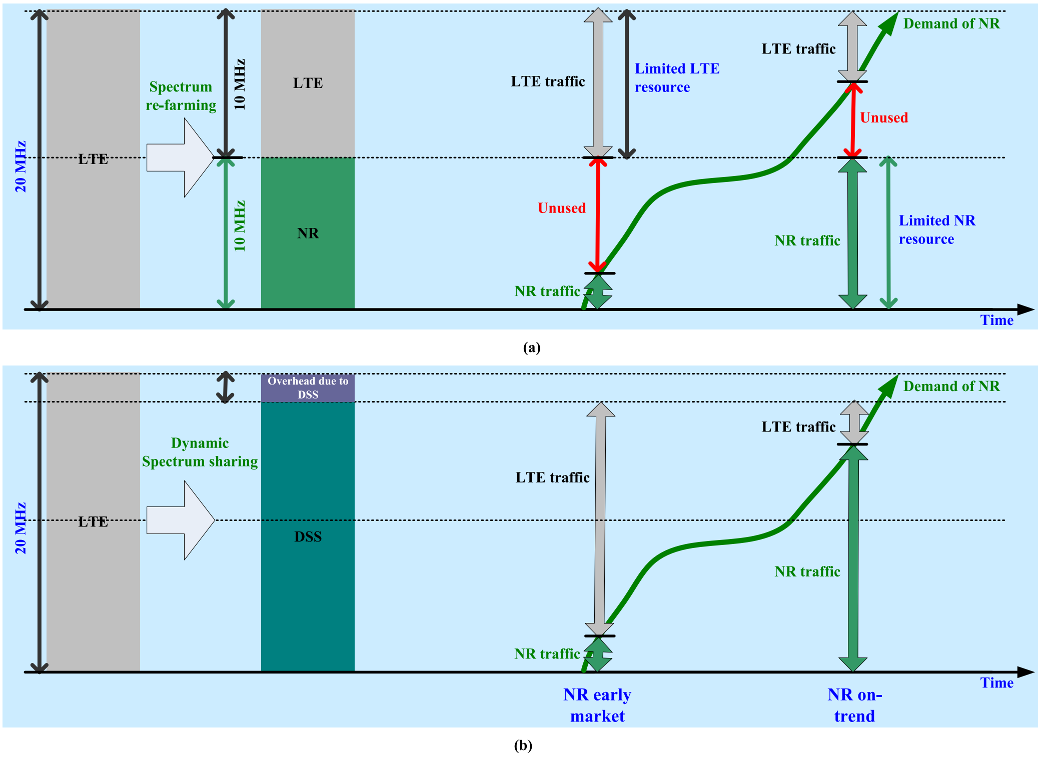


FIGURE 37. Spectrum re-farming and DSS with an increase in NR traffic demand. (a) spectrum re-farming (DSS) [36].

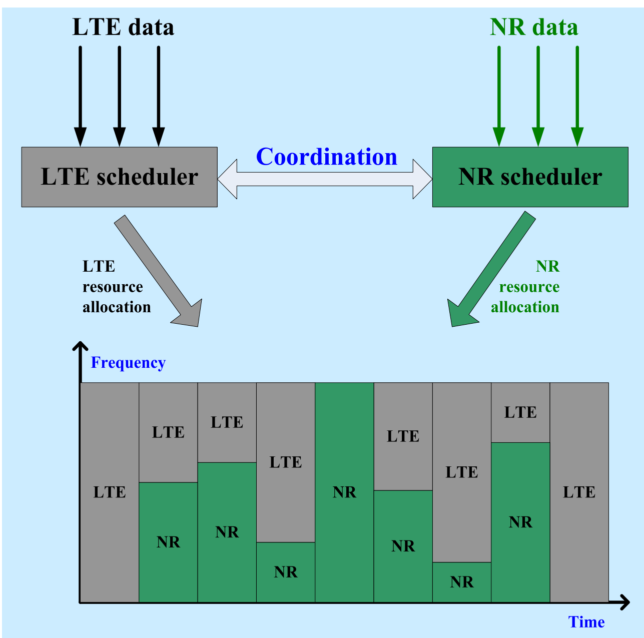


FIGURE 38. Dynamic resource allocation using DSS-an example [36].

interference. Each cell may be configured differently with the CRS placement to avoid CRS interference between neighboring cells. otherwise, CRS interference may occur between serving and neighboring cells. Such CRS interference is a characteristic of always-on transmissions of LTE CRS, which could be avoided if the LTE carrier could have been replaced fully with NR.

R. VARIATION IN CCE FOR PDCCH

Recall that by aggregating one or more consecutive CCEs where a CCE consists of 6 RBs or 72 REs, a PDCCH for a UE is transmitted. Depending on the UE channel condition, the number of CCEs assigned to a PDCCH varies. More specifically, for a good UE channel condition, the aggregated number of CCEs allocated to a PDCCH can be reduced to a minimum of 1 CCE whereas for a poor UE channel condition, the aggregated number of CCEs can be increased to a maximum of 16 (a new aggregation level for NR, which is absent in LTE).

S. PDCCH CAPACITY LIMITATION

In the early deployment of NR, the capacity limitation of NR PDCCH may not be critical. However, with an increase in NR users, the limited capacity of NR PDCCH may not be able to serve many NR UEs operating under diverse channel conditions. In such a scenario, features such as optional NR CORESET configuration may be considered for the configuration of OFDM symbols beyond the default first three symbols in a subframe for PDCCHs.

T. ADDITIONAL PDSCH SYMBOL LENGTH AND DMRS CONFIGURATION

For more efficient DSS, in addition to implementing the optional NR CORESET configuration, an additional symbol length of 10 symbols with shifted (additional) DMRS defined in 3GPP Release 16 can be employed. To avoid collision with CRS, the additional DMRS needs to be shifted to the 13^{th} symbol in an LTE subframe.

U. DSS ADVANTAGES

Notable advantages of using DSS to operate NR on the LTE spectrum are listed below.

- Smooth migration from LTE to NR.
- Enabling fast implementation of 5G services based on already existing LTE networks.
- Providing both LTE and NR services simultaneously using the same LTE spectrum.
- Improving both low-and mid-band spectrum utilization.
- Allowing network operators to offer NR services using low-band LTE spectrum without spectrum re-farming.
- Overcoming the limited coverage issue when operating NR on mid-band and mmWave band spectrum by enabling DSS on LTE low bands as well as aggregating low-band and high-band spectrum.

V. DSS DRAWBACKS

DSS operation faces numerous drawbacks as described below.

- Generation of inherent control overheads.
- Reduction in the total capacity of a band because of the generation of control overheads. That's why, though dynamic switching is a key feature of DSS, it reduces the total capacity of the band.
- High migration costs and time-to-deployment.
- DSS may disturb resource-coordinated LTE and NR services leading to the loss of key NR features.
- Vendor lock-in nature of DSS.
- Tight internetworking, a prerequisite, between LTE and NR is necessary for the successful operation of DSS.

W. OTHER FACTORS AND METHODS NECESSARY FOR THE LTE-NR CO-EXISTENCE

For NR-LTE coexistence, LTE frame structure and signal transmission properties need to be considered, which is detailed in short, in the following.

- LTE operation should not be affected while sharing LTE's resources for NR operation.
- Any CRS rate matching cannot simply be assumed to avoid LTE CRS.
- To ensure relevant detection performance, SSBs each occupied 20 RBs and 4 OFDM symbols, are required to be transmitted without any collision with LTE.
- For only NR-dedicated use, DSS may utilize MBSFN subframes of LTE so that the whole LTE subframe can be used.
- In an NSA-based NR system, an LTE serves as a control anchor whereas additional messages such as SIB1, paging, and OSI are transmitted in an NR SA system.

IX. CONCLUSION

This paper presents a comprehensive overview of DSS for the coexistence of LTE and NR systems. Major concerns for the realization of DSS to coexist LTE and NR on the same LTE spectrum, including, the technological background of essential signals and channels of both LTE and NR systems, possible DSS deployment options for LTE and NR coexistence, potential design considerations and effects, DSS applications to both LTE MBSFN and LTE non-MBSFN subframes when considering NR with SSB as well as without SSB transmissions, 3GPP standardization activities towards DSS for LTE and NR coexistence in different releases along with highlighting relevant use cases, significance, and limitations.

Comparative studies of numerous concerns, including deployment options, design considerations, DSS applications, and 3GPP standardization works, are carried out. Finally, a summary of key lessons learned throughout the paper is given, namely real-time coordination for tight internetworking and dynamic resource changes between LTE and NR to achieve optimal DSS solutions, ensuring the minimum impact of NR physical layer design on LTE, no impact on the ability of the legacy LTE devices, adoption of scalable or mixed numerology (only 30 kHz for NR SSBs and 15 kHz for NR data), 4G LTE MBSFNs for the transmission of 5G NR traffic without SSB, optional NR uplink 7.5kHz shift for FDD bands, replacement of legacy radio units with new ones to support NR, no complexity in the uplink to use DSS, operation of non-standalone NR initially in the low-frequency bands, allocation of the PDCCH of both LTE and NR to the first three symbols in DSS, not all SSB beams can be valid for MBSFN subframes, and so on.

Though in principle, the idea of DSS is simple, as presented throughout this paper, a detailed understanding of DSS at the RE level or RB level under different LTE subframes and the CRS positions to transfer the NR SSBs and other control channels including PDCCHs using the LTE spectrum is critical. Numerous research works have also addressed the DSS for the coexistence of LTE and NR systems from a specific set of viewpoints. However, no survey works have yet been found in the existing literature that has given a holistic technical viewpoint on DSS for LTE and NR coexistence at the RB level, which has been provided in this paper. It is expected that this paper will serve as a benchmark for researchers of similar interests in both industry and academia, which will result in generating further research directions on DSS for LTE and NR coexistence.

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