4G/5G Spectrum Sharing for Enhanced Mobile Broad-Band and IoT Services

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Abstract—5G has been developed for supporting diverse services, such as enhanced mobile broadband (eMBB), massive machine type communication (mMTC) and ultra-reliable low latency communication (URLLC). The latter two constitute enablers of the Internet of Things (IoT). The new spectrum released for 5G deployments, primarily above 3 GHz, unfortunately has a relatively high path-loss, which limits the coverage, especially for the uplink (UL). The high propagation loss, the limited number of UL slots in a TDD frame and the limited user-power greatly limit the UL coverage, but this is where bandwidth is available. Moreover, the stringent requirements of eMBB and IoT applications lead to grave 5G challenges, such as site-planning, ensuring seamless coverage, adapting the TDD DL/UL slot ratio and the frame structure for maintaining a low bit error rate (BER) as well as low latency, etc. This paper addresses some of those challenges with the aid of a unified spectrum sharing mechanism, and by means of an UL/DL decoupling solution based on 4G/5G frequency sharing. The key concept is to accommodate the UL resources in an LTE FDD frequency band as a supplemental UL carrier in addition to the New Radio (NR) operation in the TDD band above 3 GHz. With the advent of this concept, the conflicting requirements of high transmission efficiency, large coverage area and low latency can be beneficially balanced. We demonstrate that the unified 5G spectrum exploitation mechanism is capable of seamlessly supporting compelling IoT and eMBB services.

Index Terms—5G-NR, coverage enhancement, NR/LTE frequency sharing, DL/UL decoupling, supplemental uplink, Internet of things

Introduction

The fifth-generation (5G) concept has been developed by the International Telecommunication Union (ITU) known as “IMT-2020” since 2012. Diverse 5G use-cases have been envisioned, spanning from enhanced mobile broadband (eMBB) to massive machine type communication (mMTC) as well as ultra-reliable and low latency communication (URLLC) [1-4]. The latter two use-cases constitute major components of the Internet of Things (IoT). Accordingly, the 5G radio interface has to have quite diverse capabilities, including 20 Gbps peak data rate, 100 Mbps user-rate, up to 500 km/h velocity, less than 4 ms latency, and 100-fold improved network energy efficiency to enable the seamless delivery of large amounts of data for eMBB. Additionally, it also has to be capable of supporting 1,000,000/km2 connection density, low power consumption for mMTC and at least 99.999% reliability within 1 ms latency for URLLC. Vehicular communications which are referred to as Vehicle to Everything (V2X) also constitute a compelling 5G application. V2X communications defined in 3GPP include V2N (Vehicle-to-Network), V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), V2P (Vehicle-to-Pedestrian), complemented by the integrated cellular interface and the direct link interface [15].

In the 3rd Generation Partnership Project (3GPP), 5G New Radio (5G-NR) has been developed relying on a common air-interface aiming for addressing such diverse requirements. The first version of NR specifications was frozen in December 2017. On the other hand, regional regulators invested a lot of efforts in 5G spectrum planning for the first wave of 5G-NR deployments, including the C-band (3 GHz-5 GHz) and millimeter wave (mmWave) bands around 26 GHz and 39 GHz. The mmWave bands have very large available bandwidth and usually adopt time division duplexing (TDD) for exploiting the channel-reciprocity to support both multiple-input multiple-output (MIMO) techniques and asymmetric downlink (DL)/uplink (UL) resource-allocation. However, those high frequency bands also experience high propagation loss and are typically configured to have a small number of UL transmission slots in a 10 ms time-frame due to the heavy DL traffic load, which will result in a limited UL coverage. Hence a high infrastructure cost is imposed by the dense base station (BS) deployment required for continuous coverage.
Additionally, the limited UL coverage also hampers both the low latency of URLLC and the massive connection requirements of mMTC, especially in the light of cost-efficiency. Several challenging issues such as large coverage and low latency, have to be tackled in order to support robust vehicular communications, especially for autonomous driving applications. As it will be analysed later, critical challenges are experienced by the TDD wideband operation above 3 GHz in efficiently delivering 5G services in wide-area coverage.

Hence innovative air interface design is expected for the efficient support of 5G-NR eMBB and IoT services. Given that the majority of operators are expected to deploy 5G as an over-sailing layer on top of their existing long term evaluation (LTE) network using frequency division duplexing (FDD) below 3 GHz, there is an opportunity to share the low frequency band with part of the 5G-NR users or devices, as a complementary band to the TDD band above 3 GHz. LTE/NR frequency sharing, also known as “DL/UL decoupling”, was consequently proposed during the standardization of 3GPP and was accepted in Release 15. The concept of LTE/NR frequency sharing detailed in Section III is to employ a part of the existing LTE frequency band (most of them are below 2 GHz and are allocated as paired spectrum) into NR operation in addition to the new un-paired NR bands above 3 GHz. Since the lower-frequency bands experience a lower propagation loss, by exploiting this concept, the coverage can be substantially extended and the challenges involved in 5G deployments can also be conveniently circumvented. The frequency sharing mechanisms can also be used jointly with previous studies [5-7] for further enhancing the coverage for frequency bands above 3 GHz. This paper focuses on the standardization progress of the first version of NR, thus it does not include the mMTC part. However, it is clear that most IoT applications (low power wide area, mMTC and even URLLC) need a large continuous UL coverage. In this sense the LTE/NR UL sharing will indeed benefit diverse IoT applications.

In this paper, the potential benefits of 4G/5G spectrum sharing are investigated. Firstly the challenges ahead for 5G deployments are analysed in Section II, and LTE/NR frequency sharing is proposed for addressing these challenges. Their key concepts and benefits are briefly introduced in Section III, while the technical enablers of LTE/NR frequency sharing are discussed in Section IV. The standardization process as well as the regulatory framework of LTE/NR frequency sharing are summarized in Section V. Finally, Section VI concludes the paper.

5G Spectrum and Challenges

5G candidate spectrum

The IMT spectrum identified in the ITU’s World Radiocommunication Conferences (WRC) 2015 and 2019 (which are below 6 GHz and above 24 GHz, respectively) are applicable for 5G deployments. 3GPP defines frequency bands for the 5G-NR interface according to the guidance both from ITU and from the regional regulators, with prioritization according to the operators’ commercial 5G plan. According to [8], three frequency ranges are identified for 5G deployments for both eMBB and IoT applications, including the new frequency ranges of 3-5 GHz and 24-40 GHz, as well as the existing LTE bands below 3 GHz.

As illustrated in Figure 1, generally, a triple-layer concept can be applied to the spectral resources based on different service requirements. An “over-sailing layer” below 2 GHz is expected to remain the essential layer for extending the 5G mobile broadband coverage both to wide areas and to deep indoor environments. This is especially important for mMTC and URLLC applications. On the other hand, the “coverage and capacity layer” spanning from 2 to 6 GHz can be used for striking a compromise between capacity and coverage. However, compared to the range below 2 GHz, these bands suffer from a higher penetration loss and propagation attenuation. The “super data layer” above 6 GHz can be invoked for use-cases requiring extremely high data rates but relaxed coverage. Given this triple-layer concept, the eMBB, mMTC and URLLC services that require different coverage and rate-capability can be accommodated in the appropriate layer. However, a service-based single-layer operation would complicate the 5G deployments and it is inefficient in delivering services that simultaneously require both good coverage and high data rate as well as low latency, etc. To accommodate these diverse services, the employment of joint multiple spectral layers becomes a “must” for a meritorious 5G network.

![Figure 1 Multi-layer approach for 5G scenarios.](image)

Coverage analyses for 5G spectrum

Let us define the coverage of a communication link as the maximum tolerable power attenuation (in dB) of an electromagnetic wave, as it propagates from the transmitter to the receiver, whilst still guaranteeing the transmission rate target, which is given by

\[ C_{\text{coverage}} = P_{\text{TX}} + G_{\text{RX}}^\text{eff} + G_{\text{TX}}^\text{eff} - N_{\text{RX}} - N_{\text{TX}} - L_{\text{path}} - L_{\text{FCS}} - L_{\text{NLOS}} - L_{\text{delay}} \]

(1)
where $P_{tx}$ is the transmission power per subcarrier, $\gamma$ denotes the receiver sensitivity, $G_{tx}$ and $G_{rx}$ are the transmitter and receiver antenna gains, respectively, $N_{th}$ and $N_r$ denote the thermal noise and the noise figure of each subcarrier, respectively. Furthermore, $L_{tx}$ and $L_{rx}$ are the cable-loss at the transmitter and receiver side, while $L_p$, $L_f$, $I_m$ and $L_g$ represent the penetration loss, shadowing loss, interference margin and propagation loss difference due to the sub-carrier frequency offset with respect to the reference frequency, respectively.

According to Eq. (1), the coverage is affected by numerous factors, including the transmission power, propagation loss and receiver sensitivity. Since the propagation loss varies with the frequency, the coverage substantially differs in different frequency bands. Therefore, the provision of a good performance in all frequency bands remains a key challenge for 5G deployments. Furthermore, due to the limited UL transmission power and higher path-loss in NR than in LTE, the UL coverage is usually the bottleneck in 5G deployments.

In Figure 2, we portray the coverage performance of the 3.5 GHz TDD band and compare it to that of the 1.8 GHz FDD band. Part of the parameters assumed for this comparison are shown in Figure 2, while the rest are given in Table 1. In the link budget, the UL coverage is calculated when the UL data

$$
\text{Figure 2 Link budgets for different frequency bands, where 1Mbps throughput is assumed}
$$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1.8 GHz with 4T4R</th>
<th>3.5 GHz with 4T4R</th>
<th>3.5 GHz with 64T64R</th>
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<tr>
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<td>PUSCH</td>
<td>PDCCH</td>
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<td>26</td>
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<td>Noise figure $N_r$ (dB)</td>
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$Table 1$ Parameters assumed in the link budgets.
rate is set to 1 Mbps for supporting typical uplink video traffic. By contrast, the DL coverage is usually limited by the physical downlink control channel (PDCCH) quantified in terms of the block error rate of the primary PDCCH. It can be observed that the UL coverage and DL coverage are balanced over the 1.8 GHz FDD band with the aid of 4 transmit and 4 receive antennas. For the 3.5 GHz TDD band using the same transmit and receive antennas as that of 1.8 GHz scenario, in excess of 10 dB coverage gap is observed. This is mainly due to the large propagation loss, the penetration loss and the limited number of UL transmission slots in a frame of the 3.5 GHz TDD band. By comparison, for the 3.5 GHz TDD band using 64 transmit and 64 receive antennas, a similar DL coverage performance can be achieved to that of 1.8 GHz, owing to the beamforming gain provided by massive MIMOs and by the DL interference margin difference. Explicitly, since massive MIMOs also reduce the inter-cell interference, they reduce the DL interference margin. However, the UL coverage is poorer compared to the DL of 3.5 GHz, even when massive MIMOs are employed, because the UL power spectral density of the 3.5 GHz TDD band is lower than that of the 1.8 GHz FDD band at the same maximum device transmission power. This is partly due to having less UL slots in a TDD-frame than in an FDD-frame, which means that more frequency resources per slot should be allocated for a given UL throughput of say 1 Mbps. Therefore, how to improve the UL coverage is indeed an important issue for 5G deployments.

5G spectrum duplexing and DL/UL asymmetry

Duplexing is another key factor affecting the performance of 5G networks in terms of their wide-area coverage. 5G NR supports multiple duplex modes, including static TDD, FDD and flexible duplexing. In 3GPP, the same frame structures and resource allocation mechanisms are invoked for both FDD and TDD. It is expected that early 5G deployments are very likely to start from the new TDD spectral bands (e.g., 3.5 GHz). Therefore in the following we will discuss both static and dynamic 5G TDD networks.

For static TDD, the UL/DL traffic ratio is usually decided by the statistical UL/DL traffic load ratio among multiple operators in a specific country or region. As discussed in [9], the DL traffic constitutes a large portion of the entire teletraffic. With the popularity of video streaming increasing, it is forecast that the proportion of DL content will grow even further in the future, hence it is natural that more resources should be allocated to the DL. Therefore, a smaller proportion of the resources is left for the UL, which will further affect the UL coverage performance. On the other hand, for LTE FDD band, the same bandwidth is allocated to both the UL and DL, which means that the UL spectrum is under-utilized and will be even severe in the future.

Hence dynamic TDD mechanisms have been specified from 3GPP Release 12 onwards, especially for the hotspots where the TDD DL/UL ratio can be adapted based on the actual traffic. However, it has not yet been deployed in practical systems due to its severe inter-carrier and intra-carrier interference.

5G deployment challenges

In the following, we will discuss a few challenging issues that have to be considered in 5G deployments, particularly for the TDD mode and in higher frequency bands.

A. 5G Band selection: Wideband spectrum availability vs coverage. The availability of the bands below 3 GHz remains limited for 5G-NR in the near-future and the lower bands fail to support high data-rates due to their limited bandwidth. On the other hand, the wider NR bands above 3 GHz experience increased propagation losses, leading to a limited coverage. Therefore, independent usage of the spectrum below and above 3 GHz fails to strike a compelling trade-off between a high data rate and large coverage.

B. TDD DL/UL ratio: Spectrum utilization efficiency vs DL/UL coverage balance. As discussed, the NR TDD operation is usually configured for a limited number of UL transmission slots (e.g., DL:UL=4:1) in a frame due to the heavy DL traffic load, even though more slots should be allocated to the UL for improving the UL coverage. This can increase the UL data-rates, when the bandwidth cannot be further increased due to the maximum transmission power constraint. While the DL spectral efficiency is usually higher than that of the UL, having more UL slots would further reduce the spectral utilization efficiency. Therefore, there is a clear trade-off between the UL coverage and spectral utilization efficiency.

C. TDD DL/UL switching period: Transmission efficiency vs latency. For the TDD operation, frequent DL/UL switching is required for low-latency DL and UL transmission. However, a certain guard period is needed at each DL/UL switching point (e.g. 130 us is used in TD-LTE networks) for avoiding serious blocking of the UL receiver due to the strong DL interference emanating from other cells. Frequent DL/UL switching would lead to a high idle-time (14.3% vs 2.8% for 1 ms and 5 ms switch period), which is undesirable in efficient eMBB services.

D. Site planning: seamless coverage vs deployment investment. For early 5G-NR deployment, co-site installation with the existing LTE networks would be cost-effective and convenient. However, due to the higher propagation loss above 3 GHz, one has to introduce denser cells and new sites. Otherwise, 5G-NR cannot attain the same seamless UL coverage as that of LTE.

To circumvent this challenge, a new LTE/NR frequency sharing concept was accepted by 3GPP, which will be elaborated on below.
NR/LTE Frequency Sharing: Addressing Deployment Challenges

The concept of LTE/NR frequency sharing is to exploit the spare resources in the existing LTE frequency band for 5G-NR operation as a complement of the new 5G wideband spectrum. For example, as shown in Figure 3, the C-band (frequency ranges of 3-5 GHz) TDD carrier can be paired with the UL part of a FDD band overlapped with LTE (e.g., 1.8 GHz). In other words, an UL carrier within the lower frequency FDD band is coupled with a TDD carrier in the higher frequency band for NR users. Then a NR user has two UL carriers and one DL carrier in the same serving cell. By contrast, only one DL carrier and one UL carrier are invoked for a traditional serving cell. With the advent of this concept, the cell-edge NR users can employ either the lower frequency FDD band carrier (UL part) or the higher frequency TDD band carrier to transmit their uplink data. In this case, since the UL propagation loss on the lower frequency band is much lower than that of the higher frequency TDD band, the coverage performance of NR users can be substantially extended and a high UL data-rate is guaranteed even if this user is relatively far from the BS. On the other hand, the cell-centre users can rely on the higher-frequency TDD band to take advantage of its higher bandwidth.

\[
\begin{align*}
\text{NR DL} &: 3400-3800 \text{ MHz} \\
\text{NR UL} &: \text{LTE low frequency band} + 3400-3800 \text{ MHz}
\end{align*}
\]

Figure 3 LTE/NR uplink spectrum sharing to extend 5G coverage at higher frequencies (e.g. 3.5 GHz)

Usually, it is not necessary to allocate the low-frequency FDD band for the DL of NR, since as discussed in Section II, the DL coverage in the C-band is good. Then the low-frequency FDD band is employed in NR only for the UL. In 3GPP, the UL-only carrier frequency is referred to as the supplementary uplink (SUL) frequency from a NR perspective.

Given the concept of LTE/NR frequency sharing, the four challenging issues described in Section II can be dealt with appropriately.

Balance between wideband spectrum availability and coverage quality.

With the advent of LTE/NR frequency sharing, the spectrum availability vs. coverage trade-off can be well balanced. In this case, the 5G-NR DL traffic is scheduled on the higher TDD bands, and a high DL/UL tele-traffic ratio facilitates the efficient exploitation of the large bandwidth. The DL coverage quality remains similar to that of LTE with the aid of massive MIMO and multiple beam scanning (for example, 3D beam forming [7]). Additionally, the 5G-NR UL traffic can be supported by either a low-frequency SUL carrier or by a high-frequency TDD carrier. The cell-edge users rely on lower-frequency bands for ensuring that their spectral efficiency can be maintained at the same level as that of LTE, and their UL scheduling opportunities can be increased compared to that in the high-frequency TDD-only system. Consequently, both higher data-rates and large coverage are achieved.

Balance between spectrum utilization efficiency and DL/UL coverage

LTE/NR frequency sharing is instrumental in striking a compelling trade-off between high spectrum exploitation efficiency and wider DL/UL coverage. For the high-frequency TDD carrier, the DL/UL time-slot (TS) ratio configuration only has to take into account the long-term DL/UL traffic statistics for guaranteeing the DL spectrum exploitation efficiency (usually 4:1). The cell-edge users and IoT devices may opt for the SUL carrier philosophy for their UL transmission. In this case, the high DL/UL TS ratio on the TDD carrier does not impose any detrimental effects on IoT services. In addition, the lower propagation loss of the lower carrier is helpful for improving the spectrum efficiency. As a result, given a certain packet size, the requirements imposed on the scheduled bandwidth, or the UE’s transmit power are reduced on the lower band compared to that on the higher band.

Let us now observe the UL user throughputs of various UL channel allocations in the 3.5 GHz band, the joint 3.5 GHz and 0.8 GHz bands and joint 3.5 GHz and 1.8 GHz bands seen in Figure 4. OFDM waveform is adopted for both the LTE DL as well as for the 5G-NR DL and UL, while the LTE UL adopts the SC-FDMA (single carrier frequency division multiple access) waveform based on similar frequency-domain subcarrier mapping as that of OFDM waveform. The UE’s maximum total transmission power for all cases is 23 dBm and the DL/UL TS ratio of the 3.5 GHz TDD system is 4:1. The channel bandwidths of the 3.5 GHz, 0.8 GHz and 1.8 GHz scenarios are 100 MHz, 10 MHz and 20 MHz, respectively. Observe in Figure 4 that the UL throughput of the cell-edge UEs relying on the SUL is substantially improved compared to that of the UEs operating without SUL, which is a joint benefit of the additional bandwidth, of the lower propagation loss and of the continuous UL resource of the SUL. Additionally, the UL throughput of UEs relying on the SUL at 0.8 GHz is better than that of the UEs with SUL at 1.8 GHz at lower throughput, but it is lower than that of UEs with SUL at 1.8 GHz at higher throughput. The reason for this trend is that when the UL throughput is low, the UEs are usually power-limited and the propagation loss is lower at low frequencies, hence the throughput of the SUL at 0.8 GHz is better than at 1.8 GHz. By contrast, when the throughput is high, the uplink transmission...
power is not an issue and it is the bandwidth that becomes the bottleneck, thus the throughput of the SUL at 1.8 GHz within a 20 MHz bandwidth outperforms that at 0.8 GHz with 10 MHz bandwidth. Therefore, with the advent of the LTE/NR frequency sharing concept, the spectrum exploitation efficiency and DL/UL coverage can be beneficially balanced.

Therefore, with the advent of the LTE/NR frequency sharing concept, the spectrum exploitation efficiency and DL/UL coverage can be beneficially balanced.

Balance between transmission efficiency and latency

Low latency is a critical requirement for URLLC services. In 5G-NR design, a self-contained TDD frame structure [10] is proposed, where in each sub-frame/slot, both DL and UL can be included. As indicated, frequent DL/UL switching may help reduce the UL latency, but it also introduces a non-negligible overhead, which is inefficient for both of eMBB and URLLC services in a unified system. Under the LTE/NR frequency sharing concept, the URLLC devices can be scheduled at the SUL carrier for the UL data or control messages, which means that UL resources always exist, whenever an UL message arrives. Thus, the latency due to the discontinuous UL resources of the TDD carrier is beneficially reduced and simultaneously, the overhead caused by the frequent DL/UL switching on the higher-frequency TDD band can also be avoided.

Figure 5 shows both the latency and the overhead comparison of various TDD frame structures. For the “TDD carrier only” system associated with a 5 ms switch period, the round trip time (RTT) cannot be tolerated by the URLLC services, due to the long feedback latency. If a self-contained TDD frame is applied in the “TDD carrier only” system having a 1 ms switch period, although the RTT is reduced, the overhead increases dramatically due to the frequent DL/UL switch. For the proposed LTE/NR frequency sharing concept, the SUL can provide timely UL feedback without frequent DL/UL switching, which hence beneficially reduces the RTT without any extra overhead. Therefore, the transmission efficiency and latency become well-balanced.

Balance between seamless coverage and deployment investment

Seamless coverage is highly desirable for 5G NR in order to provide a uniform user experience. Again, it is difficult for 5G NR to achieve seamless coverage in case of co-site deployment with LTE by only using the frequency band above 3 GHz. With the advent of the LTE/NR frequency sharing, the 5G-NR UL becomes capable of exploiting the precious limited spectrum resources in the lower frequency bands that the operators have been using for LTE. Therefore, the NR UL coverage can be improved to a similar level as that of LTE. This implies that the seamless NR coverage can be supported in co-site NR/LTE deployment.

Mobility improvement

With the advent of LTE/NR frequency sharing, seamless NR coverage is achieved and the mobility-related user-experience is also improved. As illustrated in the co-site deployment example of Figure 6(a), due to the limited UL

![Figure 4 UL user throughput comparison](image4.png)

![Figure 5 Latency comparison of different TDD frame structures](image5.png)
coverage, the radius of 5G C-band cells is much smaller than that of the LTE 1.8 GHz cells. When a UE moves to the boundary of the cells, inter-Radio Access Technology (RAT) handovers will occur. Note that each inter-RAT handover will impose interruptions in excess of 100 ms, which is much higher than that of the intra-RAT handover. With the advent of the LTE/NR spectrum sharing concept, the SUL carrier beneficially extends the coverage of 5G cells. As shown in Figure 6(b), with the help of SUL, the coverage range of 5G cells and LTE cells becomes similar. Then inter-RAT handovers will occur much less frequently, because handovers are only encountered when the UE goes beyond the boundary of the area contiguously covered by multiple 5G-NR cells. Thus the probability of the inter-RAT handovers is significantly reduced, consequently the UE’s mobility-related experience is remarkably improved with the aid of LTE/NR spectrum sharing mechanisms.

Unified support for IoT and eMBB

LTE/NR frequency sharing also provides a unified support for diverse IoT and eMBB services, including the following aspects:

- In 5G-NR operation a cell can include both a TDD carrier and a SUL carrier.
- A unified eMBB and IoT TDD DL/UL frame structure configuration can be used at a high-frequency TDD carrier. The eMBB-optimized configuration imposes no detrimental impact on low-latency IoT devices, because a pair of uplinks are available for transmission and the tele-traffic of the low-latency IoT devices can be offloaded to a SUL carrier. Moreover, the unified eMBB and IoT TDD DL/UL ratio eliminates the potential network synchronization or inter-carrier synchronization problems of multiple operators.
- A unified site planning can be arranged for 5G-NR deployment in harmony with the existing LTE networks to meet the diverse requirements of both eMBB and IoT services.

Technical Enablers of NR/LTE Frequency Sharing

To enable LTE/NR spectrum sharing, the relevant LTE/NR coexistence mechanisms have been specified in 3GPP Release 15. In this section, some key mechanisms, including efficient spectrum sharing management, frequency sensing and UL frequency selection as well as service-oriented dynamic scheduling are introduced.

Efficient LTE/NR frequency sharing management

As for the LTE/NR frequency sharing, the specific resource sharing philosophy is of prime concern [11]. Based on statistical spectral-activity results of practical LTE networks, the UL resources in the paired spectrum are typically underutilized. This offers opportunities for exploiting the idle LTE UL resources for the UL transmission of 5G-NR. According to the 3GPP specification ratified for LTE FDD bands, there is a provision for feedback information in all the UL sub-frames. Thus, it is important to reserve UL feedback resources in all sub-frames for legacy LTE UEs for improving the network’s performance. As illustrated in Figure 7(a), frequency division multiplexing (FDM) between LTE and NR is recommended either in a semi-static or in a dynamic manner. Semi-static sharing is suitable for multiple vendors’ deployment, because it requires no frequent scheduling information exchange between the LTE and NR equipment, while dynamic sharing is more suitable for the deployment of NR and LTE equipment from the same vendor and it typically achieves a higher spectral efficiency. In addition, the LTE/NR frequency sharing will cause little burden on inter-operator cooperation. On one side, almost all the operators who have 5G NR deployment plan today also have existing LTE network at low frequency bands and there is no need for inter-operator cooperation. On the other side, if LTE and 5G-NR belong to...
different operators, it is difficult for LTE UL and 5G-NR-SUL to conduct the dynamic TDM carrier sharing. Static or semi-static frequency domain reservation for 5G-NR-SUL carrier can be used, which can relax the tight inter-operator coordination requirement significantly.

Figure 7 LTE-NR FDM sharing: semi-static or dynamic

In order to make full use of the spectral resources, it is expected that the LTE and NR UEs are scheduled in orthogonal frequency resources without any extra overhead at the boundaries between the frequency resources allocated to LTE and NR. Accordingly, as shown in Figure 7(b), the subcarrier spacing (SCS) of NR SUL can be configured in the same way as in LTE. The NR SUL scheduling granularity is designed to be aligned with the physical resource block (PRB) boundary of LTE, otherwise wasteful guard bands would be needed. In Figure 7(b), the abbreviations represent the: physical uplink control channel (PUCCH), physical random access channel (PRACH), and physical uplink shared channel (PUSCH).

In NR, different SCSs are specified for different frequency ranges, while only 15 kHz SCS is defined in LTE. In order to coexist with LTE, the SCS of the SUL carrier is recommended to be 15 kHz, which is likely to be different from that of the new TDD band for NR, e.g. 30 kHz SCS for 3.5 GHz TDD band. As a consequence of different SCSs on the SUL and on the TDD carrier, the parameters, including the lengths of orthogonal frequency division multiplexing (OFDM) symbols and slots on the two carriers are different. 3GPP Release 15 defined the corresponding mechanisms for supporting efficient scheduling, and the feedback for UL and DL.

Additionally, for the LTE UL carrier, there is a half-SCS (7.5 kHz) shift of the subcarriers to reduce the impact of the direct-current leakage to the discrete Fourier transform-spread-OFDM (DFT-S-OFDM) waveform. Hence a 7.5 kHz shift is also required for the SUL bands. Otherwise, the subcarriers of LTE and NR would not be orthogonal [12]. Additionally, the LTE frequency bands will be re-farmed for NR in the future. In this case, the 7.5 kHz shift should also be introduced for the LTE re-farmed bands in order to support its coexistence with the narrow band internet of things (NB-IoT) and enhanced MTC.

The UE implementation design of the SUL and TDD UL transmission is another important issue. A potential prototype design is portrayed in Figure 8. To facilitate the prompt UL carrier switching, the 7.5 kHz subcarrier shift of the SUL carrier can be more beneficially carried out in the digital domain. This is because if the frequency shift is implemented in the RF domain, much longer retuning time would be imposed between the LTE UL and NR SUL [14].

Figure 8 Joint LTE-NR UE architecture [14].

Single uplink transmission

Another challenge for LTE/NR uplink frequency sharing is the deleterious interference. Simultaneous UL transmissions on the 1.8 GHz SUL band and the 3.5 GHz TDD band will impose serious in-device inter-modulation interference, which may degrade the 1.8 GHz DL reception quality. 3GPP Release 15 has specified that LTE/NR uplink sharing is only allowed to select a single UL carrier to transmit at any instant in a UE. Additionally, prompt carrier switching between an SUL and TDD carrier is supported, if an SRS is needed at a TDD carrier for the specific cell-edge UEs, which are scheduled on the SUL carrier. The standard UE architecture design has already supported individual RF chains for the SUL band and TDD band, which supports prompt UL carrier switching, hence it is very convenient for scheduling.

Frequency sensing and UL frequency selection

For a 5G NR system having a combined TDD carrier and SUL carrier, frequency sensing is required for the UL frequency selection and random access [11].

For initial access, it is best for cell-edge users to transmit the random access preamble on the SUL carrier, while the cell-center users may be better served by selecting the higher-frequency TDD carrier for random access. Therefore, during the initial access, each UE compares its DL reference signal...
received power (RSRP) measurement on the TDD carrier to the RSRP threshold configured by the network to select the UL carrier for random access. If the RSRP is lower than the threshold, the UE is classed as a cell-edge UE and will request random access on the SUL carrier, while if the RSRP is higher than the threshold, the UE is treated as a cell-center UE and will select the TDD carrier for random access.

**Service-oriented dynamic scheduling**

5G NR provides a unified air interface for the flexible support of various services. Additionally, to support the various services by appropriate system configurations, scheduling and resource allocation relying on Quality of Service (QoS) awareness is supported. 3GPP Release 15 defines three slice types for the so-called 5G new core, including eMBB, URLLC and mMTC. Each slice type is configured to meet a specified set of QoS parameters. The QoS of each slice type can be passed down from the core network to the radio access network. Then, based on the QoS requirements, the BS can perform either QoS-prioritized scheduling or service-oriented scheduling. Such a service-oriented scheduling mechanism can work together with the UL carrier selection in the above-mentioned LTE/NR uplink sharing. For example, the URLLC service can automatically select the SUL carrier from the outset without the need for comparing the RSRP to the appropriately configured threshold.

**Independent configuration of non-SUL and SUL**

To support a pair of UL carriers in a serving cell, various specific configurations are needed. In the standardization, some of the parameters, such as the random access related configurations, data transmission bandwidth, transmission power settings, downlink to uplink scheduling timing etc. are configured for the SUL and non-SUL (TDD carrier) independently. Given these carefully specified configurations, the SUL and non-SUL can seamlessly work together for improving the system performance.

**Standardization of NR/LTE Frequency Sharing**

<table>
<thead>
<tr>
<th>5G NR New bands</th>
<th>5G NR Band combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band number</td>
<td>Frequency</td>
</tr>
<tr>
<td>n77</td>
<td>3.3 - 4.2 GHz</td>
</tr>
<tr>
<td>n78</td>
<td>3.3 - 3.8 GHz</td>
</tr>
<tr>
<td>n79</td>
<td>4.4 - 5.0 GHz</td>
</tr>
<tr>
<td>n80</td>
<td>1710 - 1785 MHz</td>
</tr>
<tr>
<td>n81</td>
<td>880 - 915 MHz</td>
</tr>
<tr>
<td>n82</td>
<td>832 - 862 MHz</td>
</tr>
<tr>
<td>n83</td>
<td>703 - 748 MHz</td>
</tr>
<tr>
<td>n84</td>
<td>1920-1980 MHz</td>
</tr>
<tr>
<td>n257</td>
<td>26.5 - 29.5 GHz</td>
</tr>
<tr>
<td>n258</td>
<td>24.25 - 27.5 GHz</td>
</tr>
<tr>
<td>n260</td>
<td>37 - 40 GHz</td>
</tr>
</tbody>
</table>

**Standardization progress on LTE/NR coexistence**

On December 21st, 2017, the first version of non-standalone (NSA) 5G was declared to be frozen and the LTE/NR coexistence is one of the important features on the completed list. The completed technology components include the spectrum to be used for standalone NR and for the non-standalone LTE/NR dual-connectivity mode, as well as for HARQ feedback, power control, UL scheduling mechanisms and so on. In the following, we will mainly discuss the LTE/NR coexistence band combinations specified in 3GPP Release 15.

**LTE NR coexistence band combination definition**

As shown in Table 2, 3GPP Release 15 has defined a number of bands for SUL and for the corresponding SUL and TDD band combinations conceived for NR standalone and non-standalone deployment, respectively [13].

In the “5G NR New bands” column of Table 2, typical examples of the frequency bands specified for the NR operation are given. The frequency bands include the C-band frequencies spanning from 3.3 GHz to 5 GHz, and the millimeter wave band having frequencies around 26 GHz and 38 GHz. The SUL bands spanning from 700 MHz to 2 GHz are also specified, as shown in the “5G NR New bands” column of Table 2. As described above, when SUL is used, there are two UL carriers in a serving cell. Then the frequency band combinations for the two UL carriers in a serving cell are defined in the column of “5G NR Band combinations”. In order to make the band combination definitions more clearly, some examples are given in the following. Taking SUL, n78-n80 of Table 2 as an example, in a serving cell, the non-SUL carrier is on band n78 and the SUL carrier is on band n80. Another example is DC, 1-SUL, n78-n84, where DC means that the dual-connectivity-aided UE is configured with both LTE and NR. The LTE cell is on LTE Band 1 and the NR cell is on band n78 with an additional SUL carrier on band n84. Since the NR SUL carrier n84 overlaps with LTE Band 1, the LTE UL carrier and the NR SUL carrier share the same frequency resources.
Summary and Future Work

This paper introduced an innovative spectrum exploitation mechanism, namely the LTE/NR spectrum sharing philosophy, for efficient 5G deployment in order to serve both eMBB and IoT applications. This solution eminently balances the various conflicting requirements, such as DL/UL traffic asymmetry, DL/UL coverage imbalance, transmission efficiency versus latency, etc. The proposed spectrum sharing between LTE and NR also allows operators to retain their LTE investment without "re-farming" the LTE band to NR, given that the spared LTE UL resources can be used as a 5G NR SUL carrier paired with a wideband TDD carrier above 3 GHz.

As to future work, firstly, it is expected that more spectrum combinations can be introduced. For example, the SUL carrier can be paired with the DL-only band in order to form an independent cell. Another promising technique of LTE-NR coexistence is to combine the SUL carrier with the mmWave band in order to improve both the UL coverage and the mobility, whilst simultaneously reducing the number of mmWave base stations required for providing seamless coverage. In this case the SUL receiver and the mmWave transceiver may be deployed at non-collocated base stations. There are several challenges for the non-collocated scenario, such as the provision of power control, uplink synchronization, uplink access point switching, etc. Other evolving scenarios may include multiple SUL carriers being paired with higher frequency bands within the same cell. The strategies of traffic and user allocation among multiple SUL and UL carriers also have to be studied. The evolution of LTE/NR frequency sharing can also aim for supporting the IoT services at a low latency in a large coverage area, in addition to supporting eMBB operation.

References