Simplifying spectrum migration from 5G to 6G

White paper

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As the research and development of 6G networks progress, it is crucial to address the challenges related to spectrum scarcity. While new spectrum bands may be allocated for 6G, the existing frequency ranges utilized by 5G remain important for 6G coverage and capacity. To ensure a seamless transition between 5G and 6G without compromising network performance, Nokia recommends Multi-RAT Spectrum Sharing (MRSS) and 6G Carrier Aggregation (CA) as preferred solutions.

This white paper offers an overview of the technical merits and deployment aspects associated with MRSS. It draws valuable insights from the migration experience from 4G to 5G with DSS, highlighting the improved coexistence capabilities of 5G's New Radio (NR) standard with future generations. The paper explores various physical layer facets, including waveforms and numerology, energy efficiency aspects, as well as strategies to minimize signalling overhead. Practical deployment considerations such as frequency bands and network architecture are also discussed.

By addressing these essential elements, the paper emphasizes the importance of MRSS in achieving a seamless migration path towards 6G while maximizing the potential of existing infrastructure.

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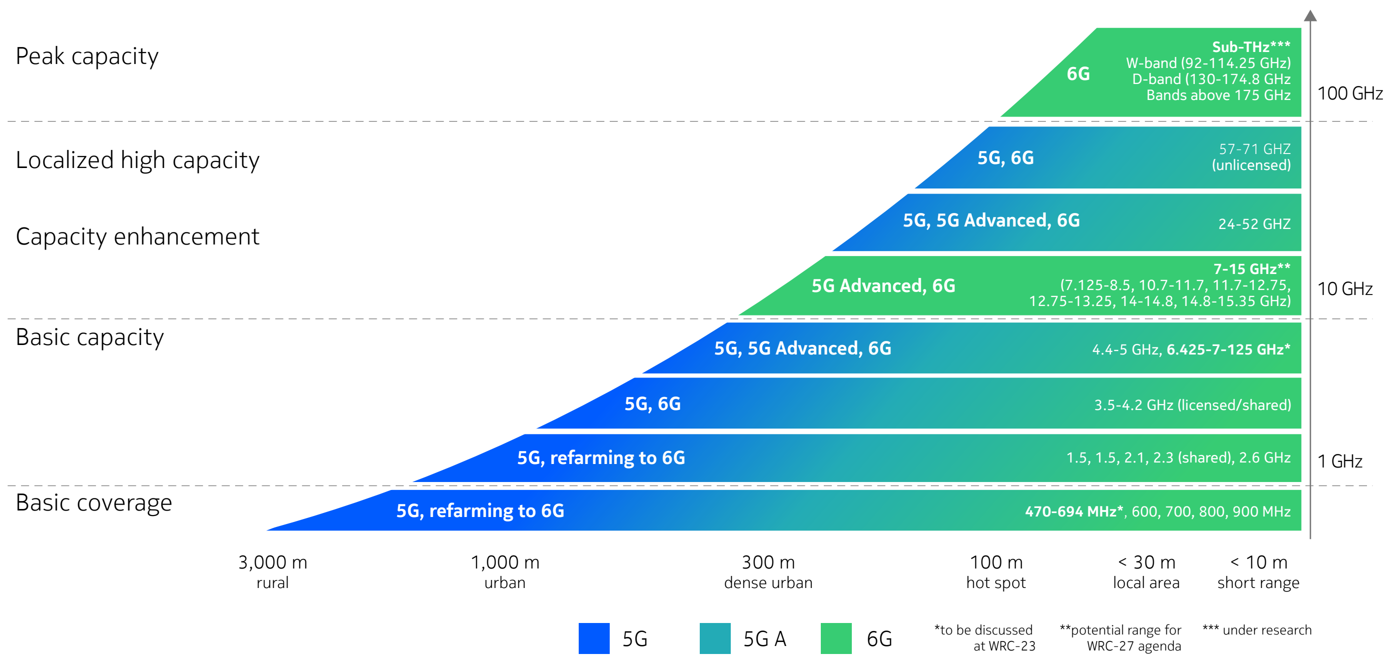
The sixth generation of mobile communication networks (6G) is currently in pre-standardization phase and concept research is actively ongoing in both industry and academia. 6G work within 3GPP is expected to start in 2024 with definition of the overall 6G timeline and start of the requirements work in SA1. 6G will be an evolutionary expansion of the 5G ecosystem and is set to integrate the digital, physical, and human worlds. Like any other wireless technology, however, it is an inescapable fact that 6G deployments require large amounts of spectrum. The interested reader can learn more about Nokia's Vision for 6G and Spectrum in [1] and [2], respectively.

Prior to 5G, the introduction of radio access technology generations was driven in part by the availability of new spectrum and static refarming of existing spectrum resources to the new generation. Spectrum scarcity and device penetration have increased significantly since those days. While new licensed frequency bands are envisioned for 6G in the 7.125-15.35 GHz band, spectrum is an extremely valuable and strategic resource and not all regions may allocate new spectrum for 6G in a timely manner. These aspects will become clearer after global spectrum discussions take place at ITU-R WRC-23, later this year.

Figure 1. Spectrum wedding cake for 3GPP systems [2],



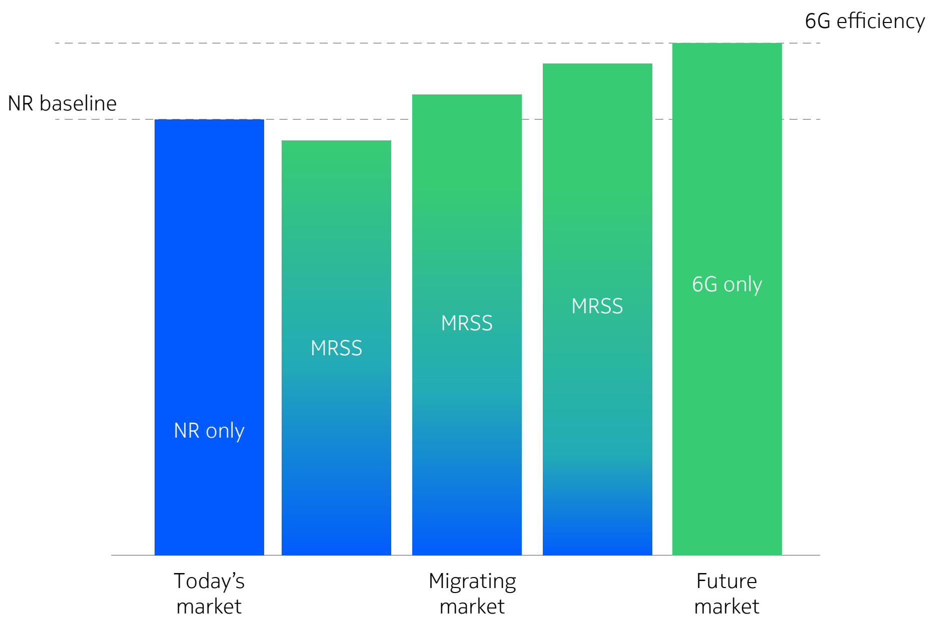
Irrespective of the outcome of WRC-23, two key learnings from the introduction of 5G are:

1. Reusing the existing network site infrastructure is a priority for operators
2. Enough spectrum to provide expanded capacity and sufficient coverage from Day-1 is essential.

Bearing in mind that no new low-band spectrum is expected to become available in the key 6G markets by 2030, the ability to leverage existing 5G spectrum will play a pivotal role in the successful and cost-efficient migration to a new Radio Access Technology (RAT).

While traditional static spectrum refarming is, in theory, always an alternative, it might not be justifiable in practice due to the disruption to existing services during the initial stage of 6G device adoption. In other words, real-time sharing is advantageous as it adapts seamlessly to RAT-specific traffic variations and gradual 6G uptake.

Figure 2. MRSS allows for gradual and efficient introduction of new 6G equipment



Owing to 5G's flexible and lean-carrier design, a spectrally and energy-efficient MRSS solution between 5G and 6G is not only possible, but also needed to ensure 5G user performance is not compromised and added-value goes beyond a 6G logo.

Figure 2 illustrates this migration, which starts with 5G. The endgame is limited by the final efficiency of 6G. In the wireless world, one commonly looks at it in terms of spectral efficiency (bits/s/Hz). However, in a broader sense, the efficiency gains could also be observed from an energy efficiency angle, e.g., bits/Joule. Regardless, MRSS cells should approach the pure 6G performance asymptotically as 6G devices take over 5G ones and 6G efficiency enhancements offset any overheads arising from sharing the same frequency band.

Finally, another essential lesson from the 4G to 5G migration is that simplicity is key. Multiple architectural options lead to uncertainties and complexities that can have long-lasting impacts on the entire ecosystem well beyond the early migration phase. Therefore, a single step migration based on a 6G Standalone (SA) architecture is the preferred way forward. This path naturally leads to the initial 6G coverage question.

This is where 6G carrier aggregation (CA) comes into the picture. In practice, MRSS is envisioned to be deployed in low frequency bands for coverage and then aggregated with MRSS and/or pure 6G carriers in mid and high bands for capacity. This minimizes the need for new site acquisitions and/or hardware (HW) installs and paves the way for a smooth mostly software (SW) rollout of 6G cells during the early 2030s.

4G-5G migration and lessons from DSS

The laws of physics imply that lower frequency bands are ideal to provide nationwide coverage and deep indoor penetration of 5G NR signals. When 5G was introduced, however, the spectrum between 700-2600 MHz was already occupied due to the tremendous commercial success of 4G /LTE. For some operators, being able to roll out 5G sites without switching off LTE or acquiring new mid-band spectrum was important. Therefore, in addition to new mid-band spectrum support, 3GPP Rel-15 specifications standardized a framework to enable dynamic spectrum sharing (DSS) between 4G and 5G with the objective to provide faster and simpler migration to 5G. The discussion that follows aims to uncover both the strengths and weaknesses of the original DSS concept to unveil fresh insights for enhancements.

Nokia discusses DSS more extensively here [3], but in simple terms, DSS is a feature that enabled the coexistence of LTE and NR in the same frequency band. Both RATs share spectrum resources and leverage a common radio unit for transmission and reception. DSS introduced the ability to distribute orthogonal resources between both radio technologies based on near-real-time traffic conditions.

The 3GPP specifications did not prescribe a single method to deploy DSS, but instead developed a framework to support multiple options. Four options were discussed, although the first two proved to be the most practical solutions for transmitting 5G NR signals and channels in LTE subframes:

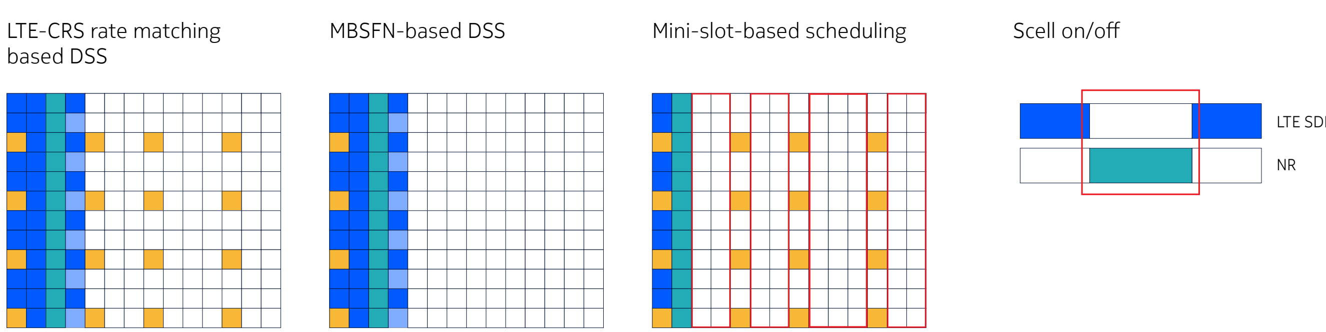
a) Rate matching (RM) around the LTE cell-specific reference signal (CRS)

b) Multi-Broadcast Single Frequency Network (MBSFN) frames, which allow the absence of LTE-CRS outside the LTE control symbols

c) Mini-slots-based scheduling using type B physical downlink shared channel (PDSCH) mapping

d) Secondary Cell (SCell)l on/off.

Figure 3: DSS different deployment options



Even though DSS was a good idea on paper, the practical implementation was plagued by fixed 4G overhead and limited by LTE legacy user equipment (UE) capabilities and initial 5G UE capabilities. For example, options c and d were abandoned because mini-slot scheduling introduced larger demodulation reference signal (DMRS) overheads and higher layer overheads due to reduced transport block sizes (TBS), while legacy 4G devices did not support Rel-12 Discovery Reference Signals (DRS).

With the initial rollouts of 5G, the shortcomings and downsides of DSS soon became evident. Table 1 captures some of the key technical challenges and mitigation options that were identified during DSS tests and deployments.

Table 1. Issues and lessons Learned from DSS

Key issues	Impact	Migrations
Overheads	The fixed overhead from the LTE-CRS and the LTE physical downlink control channel (PDCCH) and the Rel-15 NR PDSCH mini-slots (2,4 or 7 symbols), restricted NR PDSCH slot configurations	3GPP Rel-16 enhanced the options for mini-slot duration
Restrictions to NR PDCCH	LTE control region spans the entire bandwidth and at least the first symbol of the slot must be dedicated to LTE PDCCH. NR PDCCH monitoring for UEs not supporting optional features was restricted to the first three symbols of the slot. This limited NR PDCCH resources in DSS cells since overlapping with the LTE-CRS was not allowed	Several solutions were specified to help reduce the PDCCH scheduling burdens. For example, Rel-17 cross-carrier scheduling from a secondary to a primary cell (SCell to PCell) and the Rel-18 framework to enable decoding NR PDCCH candidates overlapping with LTE-CRS
Inability of 5G chipsets for LTE-CRS cancellation	The NR performance was impacted by the presence of interference from LTE neighbour cell LTE-CRS transmissions. Early 5G chipsets did not have the ability for LTE-CRS cancellation	3GPP Rel-17 introduced the UE capability for LTE-CRS interference mitigation and options to configure UE with LTE neighbour cell information to assist the UE
LTE-CRS RM in idle mode	For NR DSS deployments in standalone mode, a 5G UE is not aware that its camping on an NR DSS cell until after it enters radio resource control (RRC) Connected mode. This impacted the design (e.g., higher latency or overhead or reduced reliability) for the transmissions of messages expected by a UE in RRC IDLE or during transition to RRC Connected before it is aware of the CRS RM pattern to apply	No mitigations. Although an option to support this was discussed during 3GPP Rel-15, it never materialized
Lack of tested capabilities of commercial LTE devices	The transmission mode 9 (TM9) and Rel-12 discovery signals could have enabled other sharing schemes for DSS; however, these features were either not widely tested on all devices or not supported	No 3GPP mitigation was possible for this scenario since the issue was due to lack of market adoption of standardized features
Over protection of LTE	Rel-15 specifications for DSS ensured there was minimal impact to LTE performance. As 5G device penetration increases over time and LTE device penetration reduces, there are challenges to trade-off some LTE performance for NR performance in DSS cells	This design choice has not been revisited

While a comprehensive examination of the DSS framework can significantly advance our understanding, another game-changing aspect deserves to be highlighted: when compared to LTE, NR establishes a much more solid basis for coexistence with the next generation. The 5G air interface is significantly more flexible than LTE. Almost everything is configurable: from reference signal positions, the synchronization raster, the synchronization signal block (SSB) periodicity and bandwidth parts, to control resource set (CORESET) and sub-slot, with the caveat that some of the flexibility requires UEs to support optional features.

As it can be observed, although solutions for some of the issues were defined in 3GPP, the need to support backward compatibility with legacy Rel-15 DSS devices meant that the adoption of the mitigation solutions is scarce. In other words, the capabilities of 5G legacy devices when 6G is introduced will also determine which type of MRSS frameworks can be deployed and hence the success of MRSS, just as they did for DSS. In this sense, the industry should now start identifying key features that may impact this migration to ensure high penetration of devices supporting these features.

Ultimately, the MRSS framework must effectively utilize the available flexibility to circumvent the pitfalls of DSS. It should possess the necessary adaptability to determine the degree of protection afforded to specific 5G resources and grant operators the capability to alter their prioritized air interface as needed over time.

Deploying 6G with MRSS

The deployment of 6G will be influenced by multiple factors, encompassing commercial considerations, sustainability objectives, and spectrum-related factors. The initial rollouts are expected to deliver superior data rates, reduced latency, and decreased energy consumption compared to 5G, while maintaining existing coverage capabilities. Additionally, these initial deployments may need to support novel beyond-communication services. The MRSS approach should strive to attain maximum spectrum sharing dynamicity with 5G, accompanied by minimal overhead. In this section, we will first delve into the necessary adaptations required at the physical layer (PHY) to achieve these objectives, followed by a discussion of various deployment strategies.

PHY aspects

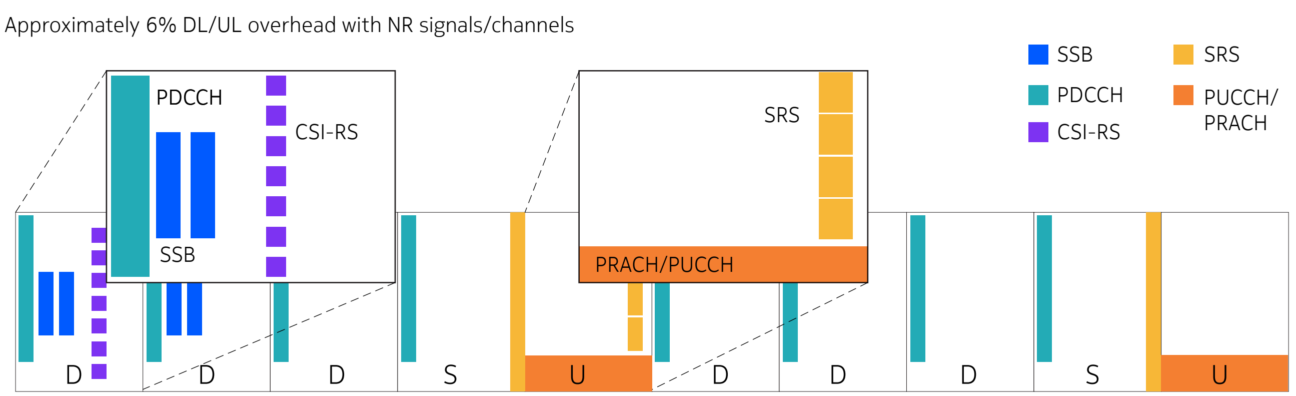
6G PHY design is still in research phase, and, hence, concrete details regarding 6G waveforms, numerology, and reference signals are not yet defined. However, employing orthogonal frequency-division multiplexing access (OFDMA) in 6G would make it backward compatible with 5G and enable an alignment with NR waveforms and numerologies. In practice, this means additional guard overhead in (frequency or in time) can be avoided and coexistence in the same bands can be more spectrally efficient. This would allow the reuse of much of the existing radio infrastructure and provide a smooth upgrade path.

Therefore, a possible evolutionary path from 5G could employ orthogonal frequency-division multiplexing (OFDM) with compatible numerology, or at least waveforms based on Fast Fourier Transform (FFT) like Discrete Fourier Transform (DFT)-spread-OFDM, using the same frequency raster defined for NR. This is desirable for frequency ranges already supported by NR, particularly FR1 (frequency range 1). Moreover, the combination of multiple-input, multiple-output (MIMO), OFDM and near-Shannon codes has proven to bring the physical layer close to its theoretical bounds, and modest improvements can be expected from other waveforms in terms of spectral efficiency.

As mentioned before, early 6G rollouts should provide at least the same coverage and capacity performance as 5G. To achieve this goal, overheads from sharing the spectrum must be rigorously minimized. This cannot be overstated. Fortunately, the potential for overhead reduction in MRSS is high when compared with DSS. At the same time, proven methods previously applied in DSS to optimize resource efficiency, like rate matching in PDSCH on a resource element (RE) level, could be further leveraged in MRSS.

In MRSS, the fixed downlink overhead in 5G could be attributed to SSB, system information, and paging transmissions along with the 5G PDCCH symbols. Other reference signals can be flexibly configured with different periodicity, hence reducing the overhead. Figure 4 illustrates the minimal overhead in a 5G time division duplex (TDD) frame. On top of the flexibility provided by NR, additional room for further improvement can be identified. For instance, one possibility is to reuse to some extent 5G reference signals. Primary and Secondary Synchronization Signals (PSS and SSS) of an NR cell are promising candidates. Not only would this approach minimize physical layer overheads, but it may also improve the overall energy efficiency in certain scenarios.

Figure 4. Minimal overhead in 5G TDD frame[1]



Many deployments that support massive antenna configurations naturally demand efficient methods of network energy utilization. Network energy saving (NES) techniques are being introduced in Rel-18 [4]. They span time (e.g., micro-Tx, symbol or subframe switch off), frequency (e.g., dynamic transmit/receive (Tx/Rx) bandwidth adjustment), power (e.g., dynamic adaptation of transmission power for signals/channels) and spatial domains (e.g., dynamic antenna elements/panel/Tx/RX point (TRP)/beam ON and OFF). Because NES is pivotal for environmental sustainability and operational cost savings, the specified MRSS framework should be backward compatible with at least the commercially adopted NES techniques while allowing for the extension of new 6G-specific energy-saving features.

During the initial stages of 6G deployment, it is important to prioritize 5G performance due to the low penetration of 6G devices. However, as the adoption of 6G devices grows, the focus should shift towards prioritizing 6G performance. Given that MRSS encompasses multiple frequency bands as discussed subsequently it is essential for the framework to strike a balance and avoid excessive protection of 5G. Flexibility within the MRSS framework is crucial, allowing operators to determine the extent to which any of the RATs sharing spectrum can be degraded.

1 For a reference calculation, a 40MHz Ch Bandwidth, TDD DDDSU format with 20ms SSB/PRACH periodicity considered.

Finally, another forward-looking issue to be considered is that 3GPP cellular systems can offer services beyond communications [5]. While the relevance of enhanced mobile broadband (eMBB) is undisputed, additional 5G-Advanced services could gain commercial traction prior to 6G introduction. It remains open whether MRSS cells should also support these services and to what extent the existing frameworks can be leveraged to minimize overheads.

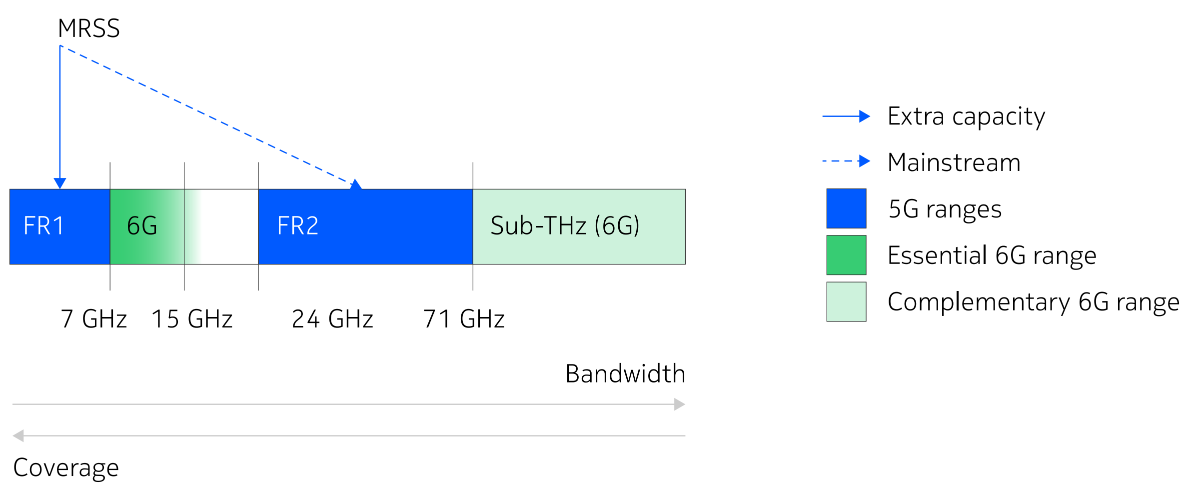
Deployment and implementation aspects

Akin to the 6G physical layer design, the exact architecture options remain undefined. One can safely assume, however, that 6G will be deployed in the existing frequency ranges 1 and 2 (FR1, FR2) as well as new candidate bands including the essential 7-15GHz range, as depicted in Figure 5. As stated earlier, the recommended approach moving forward is to adopt a single-step migration based on 6G SA. While this implies a simplified migration and avoids coexistence issues between definitive and interim architectural solutions, it also means that:

- MRSS is needed to provide 6G coverage via FR1
- Day-1 support for uplink and downlink (UL, DL) CA is essential to aggregate FR1 carriers with mid- and high-bands for enhanced capacity.

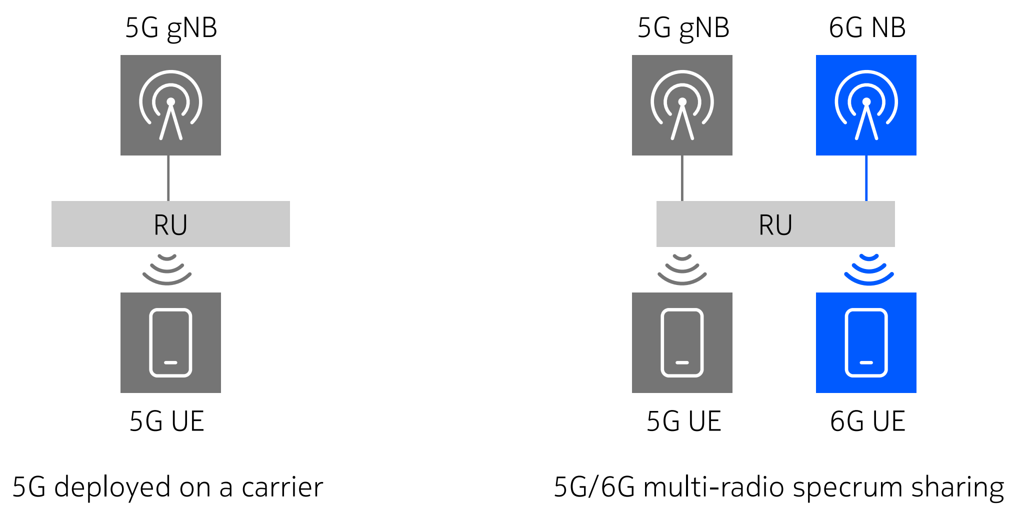
In other words, MRSS and 6G CA are key technology components for migration. Moreover, MRSS shall not require any changes to 5G UEs, and 6G UEs shall support MRSS through 6G radio design and basic 6G radio functionalities.

Figure 5. Existing 5G spectrum, expected 6G ranges and MRSS



Given that FR1 includes frequency and time division duplex (FDD, TDD) bands, MRSS solutions must work with both duplexing schemes. In particular, 15kHz and 30kHz sub-carrier spacing (SCS) support is important for FDD and TDD bands, respectively. Moreover, while a frequency-agnostic framework would be preferable, band-tailored approaches may be useful due to the different characteristics of FR1 and FR2.

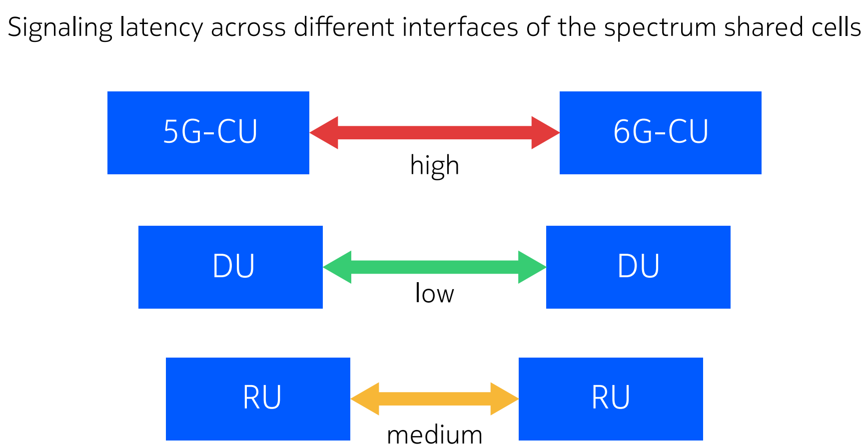
Figure 6. Migration from 5G spectrum to 5G/6G MRSS spectrum



6G is also likely to support higher bandwidths and larger antenna arrays with narrower beams, which will have to be supported in the MRSS framework. Because user and control plane (U-plane and C-plane) beamforming is extensively supported by 5G-NR, spatial domain spectrum sharing techniques could be leveraged by MRSS in addition to the well-known time- and frequency-domain approaches. This poses some strict requirements, however, in terms of coordination between L2 packet schedulers.

Although MRSS deployments share a common radio unit (RU), the distributed unit (DU) could be shared or independent for both RATs. The former would facilitate coordination across packet schedulers, but the latter case would, for example, entail a high-speed low-latency interface. For DSS, no such interface was standardized and the existing network interface (Xn) would fall short of expectations given the additional delay introduced by the higher layers and the potential routing delays. As depicted in Figure 7, an interface between DUs would be optimal, but this may be challenging to realize and implement. Avoiding new interfaces is preferable, given the associated standardization, implementation, testing, and integration costs.

Figure 7. Signalling interface between the MRSS cells



Finally, it is likely that 6G will have to coexist with 4G for some time, as many legacy 4G devices are expected to remain in use during initial deployments. For these scenarios, it is recommended to avoid 4G-6G MRSS and to handle the migration from 4G to 6G via static refarming, because overhead challenges such as LTE-CRS would severely impact 6G performance.

Conclusions

As 5G rolls out, industry and academia have started to pave the way to 6G. Nokia expects the new generation to be launched commercially by 2030 following 5G-Advanced. To make 6G a reality and to fully exploit its benefits, repurposing existing 5G spectrum will be essential.

Armed with 5G's flexible and lean-carrier air interface, plus the lessons from the migration from 4G to 5G, Nokia has been tackling the 5G-6G coexistence topic. Our conclusion is that MRSS is going to be a key tool to ensure an uncompromising and cost-efficient migration to a new RAT.

Table 2: 6G Spectrum and migration summary

6G spectrum and migration	
Topic	**Nokia's recommendation**
5G spectrum	Existing spectrum must be leveraged efficiently.
5G-6G coexistence	MRSS is essential for a smooth migration path.
Carrier aggregation	Availability of CA configurations (DL+UL) on 6G UEs from Day-1 is key.
Looking back (lessons from DSS)	
Topic	**Main take-away**
Dynamic Spectrum Sharing	DSS allows two RATs to share the same spectrum and radio unit and adapt allocations based on near-real-time traffic conditions.
Fixed overheads	DSS performance was severely limited by fixed 4G overhead challenges, e.g., LTE CRS.
Legacy and day-1 features	Capabilities of 5G legacy devices and features supported by Day-1 6G UEs will determine the nature and success of MRSS frameworks.
Revisiting adaptability assumptions	Grant operators the capability to alter their prioritized air interface as needed over time, adapting the level of protection afforded to specific 5G resources.
Looking ahead (designing MRSS)	
Topic	**Nokia's recommendation**
Numerology and waveforms	Compatibility with NR waveforms and numerologies avoids additional guards and facilitates spectrally efficient sharing.
Overhead minimization	Physical layer overhead must be kept as low as possible. The potential for overhead reduction in MRSS is high when compared with DSS.
Energy efficiency	MRSS deployments should not prevent the utilization of energy saving gains introduced by 5G-Advanced. The framework should also be flexible enough to accommodate new 6G-specific energy-saving features.
Access to lower bands	MRSS and 6G CA are recommended to constitute the key technology components for migration.
Open interfaces	The Xn interface would fall short of expectations. The standardization of new interfaces between schedulers comes with realization and implementation challenges.
4G to 6G migration	Avoid 4G-6G MRSS due to fixed LTE overheads.

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Abbreviations

3GPP	3rd-Generation Partnership Project
CA	Carrier Aggregation
C-Plane	Control Plane
CORESET	Control Resource Set
CRS	Cell Specific Reference Signal
DFT	Discrete Fourier Transform
DMRS	DeModulation Reference Signal
DRS	Discovery Reference Signal
DSS	Dynamic Spectrum Sharing
DU	Distributed Unit
eMBB	enhanced Mobile Broadband
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FR	Frequency Range
HW	Hardware
ITU-R	International Telecommunication Union Radiocommunication Sector
LTE	Long Term Evolution
MIMO	Multiple-Input, Multiple-Output
MBSFN	Multicast Broadcast Single Frequency Network
MRSS	Multi-RAT Spectrum Sharing
NES	Network Energy Saving
NR	New Radio
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	OFDM Access
PCell	Primary Cell
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PSS	Primary Synchronization Signal
RAT	Radio Access Technology
RCC	Radio Resource Control
RE	Resource Element
RM	Rate Matching
RU	Radio Unit
Rx	Receive
SA	Standalone
SA1	Technical Specification Group Service and System Aspects Work Group 1
SCell	Secondary Cell
SCS	Sub-Carrier Spacing
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
SW	Software
TBS	Transport Block Size
TDD	Time Division Duplex
TM9	Transmission Mode 9
TRP	Tx/Rx Point
Tx	Transmit
UE	User Equipment
U-Plane	User Plane
WRC	World Radiocommunication Conference
Xn	Network interface

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