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5G

5G New Radio Solutions: Revolutionary Applications Here Sooner Than You Think

Sky5™

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Executive Summary

As demand grows for ubiquitous wireless connectivity and the promise of new and previously unimagined applications – such as autonomous vehicles, artificial intelligence, telemedicine and virtual reality – so does the anticipation for 5G. 5G will be revolutionary, delivering higher data throughput, extremely low latency and speeds up to 100 times faster than 4G. As a result, 5G is moving toward commercial reality faster than many expected. With that in mind, mobile operators are implementing near-term, tactical efforts to ensure that 5G demonstration hardware becomes available by late 2018 and throughout 2019.

This paper explores the practical first steps of any rollout, focusing on the spectrum below 6 GHz as standards for mmWave applications have yet to be defined. Our approach is not intended to subscribe to any particular solution; rather, it is an introduction to what Skyworks believes will likely transpire over the next several years. In addition, our framework focuses primarily on the practical solutions for the 5G RF front-end (RFFE) in the sub-6 GHz arena. To help readers better understand what that practicality means, Skyworks presents its perspective on how early 5G will be implemented with particular emphasis on enhanced mobile broadband applications, or eMBB, in 3GPP parlance. Our goal is to provide some reasonable expectations of the future and correlate it to current 4G LTE Advanced Pro to see how manufacturers will address the new requirements. We will describe how the early rollout for 5G will proceed, how the standards will be translated into networks and devices, and what we can expect to see over the next several years as 5G becomes commercialized.

With decades of experience over previous standards coupled with our systems and technology expertise, Skyworks is well-positioned to deliver the significantly more powerful and complex architecture demands associated with 5G.

3GPP Release 15 Summary: The Framework for Early 5G

Release 15 of 3GPP marks the commercial beginning of 5G. Its impact will be felt for the next several decades across multiple markets – from telecommunications to industrial, health, automotive, the connected home and smart cities as well as other emerging, yet unforeseen ones.

We expect this framework to underpin commercial 5G networks being deployed in 2020, even though additional network configurations have extended completion of the standard by approximately six months. The changes were incorporated to ensure delivery of all new radio (NR) architecture options and the finalization of option 3a (non-standalone) and option 2 (standalone). The updates will also include further development of the standalone 5G NR specifications as well as refinements to some of the earlier work. Release 16 will likely be used for application of NR to unlicensed bands, minor changes and improvements, with more substantial changes expected in Release 17.

With Release 15 in hand, mobile operators, device manufacturers, and chipset providers have the confidence and ability to move forward with concrete developments to support commercial deployments. We fully expect to see commercial products and announcements in 2019, ahead of larger scale network deployments in 2020.

In the following section, we explore some of the key takeaways from Release 15 with particular emphasis on the impact to the RF front-end.

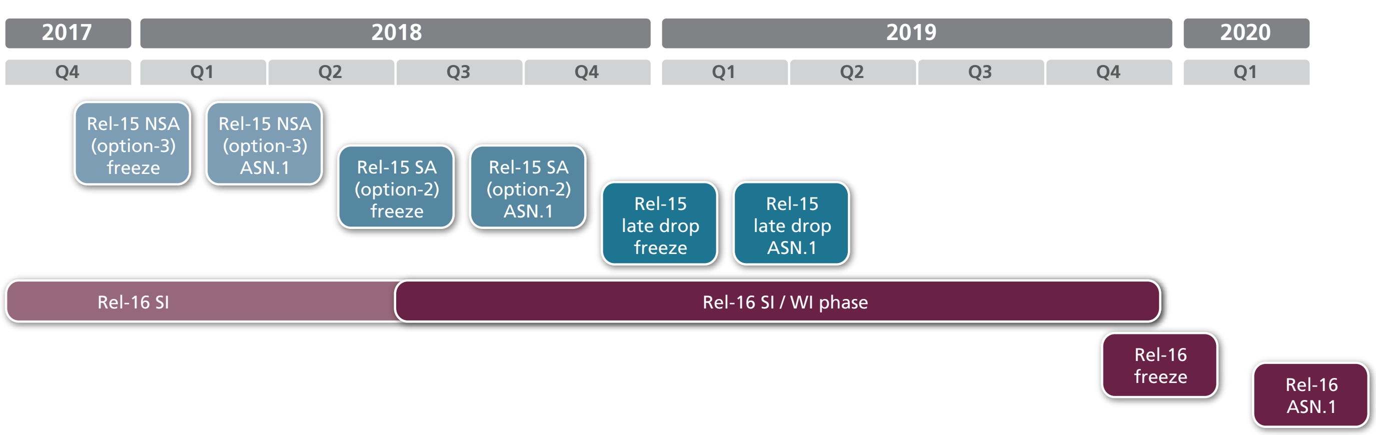


Figure 1. 3GPP Multi-Phased Development of the 5G Standard Across Rel-15 and Rel-16

Key RFFE Takeaways from Release 15

5G standards draw heavily upon the experiences and lessons learned from 4G LTE, including many of the concepts successfully proven to support increased data rates. This evolution and reliance upon existing technology allows several techniques from 4G to be integrated into the initial rollout of 5G, providing immediate benefits without the need to wait for future releases. The rollout is also supported by the use of E-UTRA (Evolved Universal Terrestrial Radio Access) NR Dual Connectivity (EN-DC) combinations where NR is always associated with an LTE link.

Multiple Input Multiple Output (MIMO) and Antenna Implications

A key takeaway from the early draft of Release 15 is that 4x4 downlink MIMO, particularly at frequencies above 2.5 GHz (which include n77/78/79 and B41/7/38), will be mandatory. Draftees of the specification recognize the benefit of 4x4 downlink, as well as its impact on the data rate and network capacity, and have thus made this a requirement for the first implementation phase of 5G.

The presence of four MIMO layers not only enables expanded downlink data rates, it also means there will be four separate antennas in user equipment (UE), opening up additional degrees of freedom for the RF front-end design community.

An additional feature that is strongly desired by mobile operators, though not mandatory, is the deployment of 2x2 uplink MIMO. Having 2x2 uplink MIMO in UE requires two 5G NR transmit power amplifiers (PAs) to transmit from separate antennas. This is particularly beneficial in cases where higher frequency time division duplex (TDD) spectrum is used – as is the case with n41, n77, n78, and n79 as well as other TDD bands. The effective doubling of the uplink data rate enables shorter uplink bursts and flexible use of the 5G frame timing to increase the number of downlink sub-frames, potentially increasing downlink data rates by up to 33 percent. However, when the downlink data rate becomes extremely high, the uplink is challenged by the requirement of rapid and constant CQI and ACK/NACK response from UE and will be required to support 5 to 6 percent of the downlink data rate. As a result, the uplink data rate can eventually limit the downlink data rate and, without uplink MIMO, the coverage area and maximum downlink data rates will be limited by the uplink data rate performance.

A further use of the available second transmit path is a new transmission mode called "2Tx coherent transmission." This effectively uses the principles of diversity, which are heavily leveraged on the downlink side of the network and enable up to 1.5-2 dB of additional transmit diversity gain, which is critical to address the fundamental uplink limited network performance. Studies[1] have shown that such improvements in uplink channels equate to an approximate 20 percent increase in range at the cell edge. Why is this so important? Operators report that most mobile calls originate from within building structures (approximately 75 percent of calls are made from inside a home or an office), which causes signal degradation and decrease in cell radius. In other words, the call is operating from the cell's edge, which is physically located further away from the base station. Thus any adjustment made toward that end will be viewed positively by the operators and help to minimize costs of 5G networks.

Beyond improving cell edge performance, 2x2 uplink MIMO improves spectrum efficiency. Since 5G NR is mostly a TDD technology above 2 GHz, and TDD cells are likely to be configured in a highly asymmetrical configuration with priority to downlink (e.g., 80 percent downlink, 20 percent uplink), improving spectrum efficiency is key to delivering high cell capacity.

Key Insights

- *5G devices will require 4x4 downlink MIMO and most will support 2x2 uplink MIMO, at least in the 2.5 GHz to 6 GHz spectrum.*

Dual Connectivity (4G/5G) in Non-Standalone Modes

In the initial phase of Release 15, mobile operators emphasized the need to establish the framework for the dual connectivity non-standalone (NSA) method of operation. Essentially, network deployment with dual connectivity NSA means that the 5G systems are overlaid onto an existing 4G core network. Dual connectivity implies that the control and synchronization between the base station and the UE are performed by the 4G network, while the 5G network is a complementary radio access network tethered to the 4G anchor. In this model, the 4G anchor establishes the critical link using the existing 4G network with the overlay of 5G data/control. As you can imagine, the addition of a new radio, in this case 5G new radio, alongside the existing 4G LTE multi-band carrier aggregation baseline, stresses system performance, size and interference mechanisms – posing additional challenges to be resolved when designing the new 5G NR RF front-end.

A simplified view of NSA option-3a network topology (see Figure 2) shows that in early generations of 5G networks, mobility will be handled by LTE radio anchors (control and user planes). This architecture leverages the LTE legacy coverage to ensure continuity of service delivery and the progressive rollout of 5G cells. It certainly seems the most plausible method of implementing 5G while at the same time ensuring that the integrity of data connections is maintained in areas where the backhaul and network infrastructure is not yet upgraded to 5G. However, this requires UE by default to support simultaneous dual uplink transmissions of LTE (Tx1/Rx1) and NR (Tx2/Rx2) carriers in all possible combinations of standardized bands and radio access technologies (FDD, TDD, SUL, SDL). As you might expect, this raises the technical barrier of getting multiple separate radios and bands functioning in a small device. When combined with a TDD LTE anchor point, network operation may be synchronous, in which case the operating modes will be constrained to Tx1/Tx2 and Rx1/Rx2, or asynchronous which will require Tx1/Tx2, Tx1/Rx2, Rx1/Tx2, Rx1/Rx2. When the LTE anchor is a frequency division duplex (FDD) carrier, the TDD/FDD inter-band operation will require simultaneous Tx1/Rx1/Tx2 and Tx1/Rx1/Rx2. In all cases, since control plane information is transported by LTE radio bearers, it is critical to ensure that LTE anchor point uplink traffic is protected.

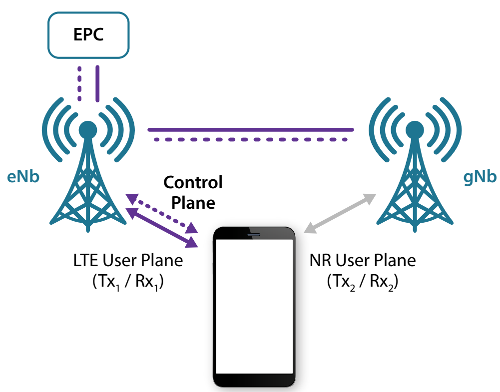


Figure 2. NSA Option-3a Dual Connectivity Network Configuration

Depending on Tx1 and Tx2 carrier frequencies and their relative spacing, intermodulation distortion (IMD) products may fall onto the LTE Rx anchor point frequency band and cause LTE desensitization. Figure 3 shows an example of IMD products generated by an intra-band LTE-FDD 10 MHz (left carrier) and NR-FDD 10 MHz (right carrier) NSA configuration.

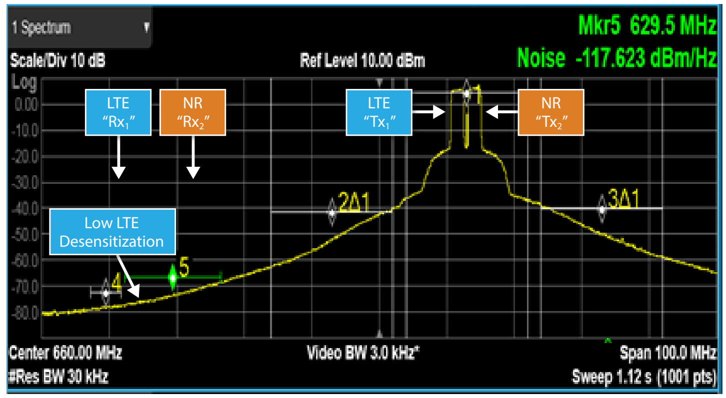


Figure 3. Example of IMD products observed at power amplifier output for dual LTE 10 MHz (left carrier) and NR 10 MHz (right carrier) transmissions for intra-band quasi contiguous resource block (RB) allocations.

In the example below, noise rise falling into LTE Rx1 band leads to moderate desensitization. However, there are multiple potential combinations of NR and LTE uplink allocations which, in some cases, may result in high desensitization. Figure 4 illustrates an example of high LTE receiver (anchor point) desensitization caused by non-contiguous RB operation of an intra-band EN-DC.

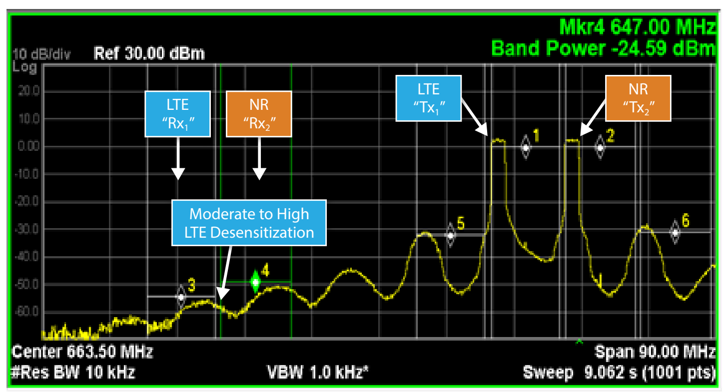


Figure 4. Example of IMD products observed at power amplifier output for dual LTE 10 MHz (left carrier) and NR 10 MHz (right carrier) transmissions for non-contiguous resource block allocations.

RFFE solution providers are accountable for mitigating as much interference as possible to allow for optimal signal usage in the UE. The complex nature of dual transmit LTE/NR concurrency and 5G-capable UE constitutes an even greater challenge for the NR RF front-end.

The second phase of Release 15 will include standalone (SA) operation, which uses a 5G core network that will not require backward compatibility to 4G LTE. However, the assumptions used in this paper are based on the initial implementation of 5G with NSA, which is the principal deployment strategy for re-farmed bands, since SA is anticipated for new spectrum above 3 GHz.

While the sheer volume of Tx/Rx combinations resulting from 4G carrier aggregation, the addition of 5G NR and the potential challenges posed by 2x2 uplink MIMO would give anyone pause, Skyworks' systems and engineering teams have worked diligently to resolve many of the issues in the RFFE and are described in the following sections.

Key Insights

- *Dual connectivity implies that the control and synchronization between the base station and the UE are performed by the 4G network, while the 5G network is a complementary radio access network tethered to the 4G anchor.*

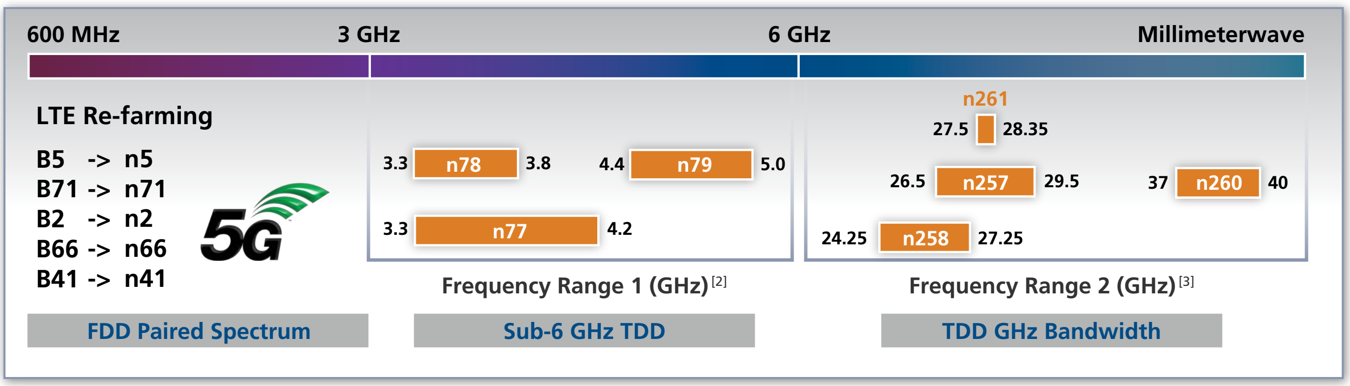


Figure 5. High Level Spectrum Overview of 5G NR

All Spectrum is 5G, but Not All Spectrum is Equal

In just a year, the blueprint for 5G implementation has evolved notably. Discussions in early 2017 focused on TDD spectrum and 3.5 and 4.5 GHz ranges, which amounted to three bands. At the time, this was a manageable, targeted introduction of a disruptive technology. Fast forward to 2018, and it is safe to say that any and all mobile-owned operators will be candidates for 5G NR (see Figure 5).

A quick review of 5G announcements indicate that operators are targeting not only the sub-6 GHz spectrum, but, in order to support 5G NR, will also utilize new swaths of millimeter wave spectrum and look to re-farm their LTE assets in a lower frequency band. Hence, all spectrum assets owned by operators will be brought to bear in 5G networks.

One can expect that a combination of these spectra will be used to give consumers enhanced mobile data experience. Previous discussions have indicated that wider bandwidth and higher order MIMO are key to delivering this enhanced user experience; and a combination of 4G and 5G-based dual connectivity systems will be integrated, in ways unique to each operator, to deliver the transformative experience.

New Challenges for 5G NR

With the previous information, now is a good time to reflect on what the new 5G radio challenges present for both smartphone designers and their counterparts in the RF front-end community. The list below is not intended to be exhaustive; rather it indicates some issues as we start development of commercial 5G products.

Wider Channel Bandwidth

- The new bands in the sub-6 GHz region will feature much larger relative percent bandwidth (n77 = 24%, n78 = 14%, n79 = 12.8%) than existing bands (B41 = 7.5%, B40 = 4.2%, 5 GHz Wi-Fi = 12.7%).
- The instantaneous signal modulation bandwidth for NR is extended up to 100 MHz in bands n41, n77, n78, n79.
- Contiguous intra-band EN-DC instantaneous bandwidth is 120 MHz and 196 MHz for non-contiguous.
- Conventional envelope tracking (ET) technologies are hard pressed to expand beyond 60 MHz. While the industry waits for new ET technologies to meet the 100 MHz challenge, average power tracking (APT) will be required for early proof of concept work.

High Power User Equipment (HPUE) – Power Class 2

(Specific to TDD bands n41/77/78/79)

- As mentioned previously, HPUE or power class 2 (+26 dBm at a single antenna) will increase radiated power out by +3 dB relative to power class 3 operation.
- PAs will need to be designed to meet higher operating power output with more stringent waveforms.
- Optimized system design will be critical to achieving minimal post-PA loss to deliver HPUE benefits.

5G NR Inner Allocations Away from Channel Edge Can Be Transmitted at Higher Power

- 5G NR requires less Maximum Power Reduction (MPR), or power back-off, when reduced waveform allocations are a specified offset away from the channel edge. This enables much higher power across uplink modulation orders and addresses a fundamental coverage issue in LTE networks: the uplink power limited transmission and SNR for reduced RB allocations at cell edge.

5G NR New Waveforms and 256 QAM Uplink

- The new 5G waveforms, especially cyclic prefix orthogonal frequency division multiplexing (CP-OFDM), have a higher peak-to-average ratio and will, therefore, require more power back-off than conventional LTE waveforms.
- 256 QAM modulation will be employed in uplink signals to increase data rates. This will challenge the RF front-end to maintain total error vector magnitude (EVM) below 3 percent including PA and transceiver.
- Other issues such as in-band distortion, frame rate and clipping must be managed to achieve optimum efficiency.

Cost-effective Support for 4x4 Downlink MIMO, 2x2 Uplink MIMO and Coherent 2Tx Transmission Modes

- 4x4 downlink MIMO is required in 3GPP for n7, n38, n41, n77, n78, n79 – either operating as a standalone band or as part of a band combination. This feature has been prioritized due to the significant benefits of doubling the downlink data rate and spectral efficiency, as well as the up to 3 dB advantage in receive diversity gain versus 2x2 downlink modes.
- Emphasis will be placed on size and cost reduction for the additional content to achieve this new feature set.

New 5G NR Spectrum

- New bands for sub-6 GHz will extend the frequency from 3 GHz up to 6 GHz in the device.
- This increase in frequency will push improvements in the complete radio front-end as the industry tries to maintain current performance while operating at a higher frequency.
- There will also be new antenna multiplexing and tuning challenges, as well as in-device coexistence with 5 GHz Wi-Fi.

Non-standalone Dual Connectivity and Uplink Carrier Aggregation (CA) Intermodulation

- Non-standalone operation requires dual connectivity, implying uplink CA between an LTE anchor and 5G. With the number of operating radios increasing over a substantially larger bandwidth, the challenge to maintain acceptable power for intermodulation products becomes even more complex.

Intra-band Coexistence in Re-farmed 4G LTE Bands

- Intra-band coexistence will be imposed in many bands as operators struggle to find available 5G spectrum.
- Intermodulation distortion (IMD) and RF front-end linearity will become pain points in the new 5G NR RFFE.

New Technologies Required for 5G NR – Enabling RFFE

This leads us to the discussion of what technologies, both current and new, will be required for dual connectivity 5G RFFE. At a high level, it makes sense to review the technology requirements from two separate frequency bandwidths – below 3 GHz and 3 GHz to 6 GHz – as shown in Figure 6.

When thinking about 4G LTE re-farming, it is important to understand that it will take place in relatively narrow channels using conventional PA and filter technology. While some improvements in PA output power and linearity can be expected in FDD bands below 3 GHz, sufficient performance in 4G LTE and 5G NR from the same PA duplexer paths that exist today, can be generally achieved. This means that current low band technology is not only adequate even if not optimized for 5G, but with small improvements in output power and linearity it can be optimized for 5G NR performance.

Elements of a Sub-6 GHz 5G NR RF Front-end

You may now be asking: if bands below 3 GHz can be optimized for 5G NR performance, then what are the requirements for a sub-6 GHz RFFE?

To simplify the discussion, the following section focuses on a practical example of a sub-6 GHz radio front-end with n77, n78 and n79 frequency bands. This example is intended to illustrate the important criteria for designing a 5G NR in sub-6 GHz, as shown in Figure 7. We will also discuss the impact of 5G spectrum, waveform and modulation on the constituent parts of the radio front-end module.

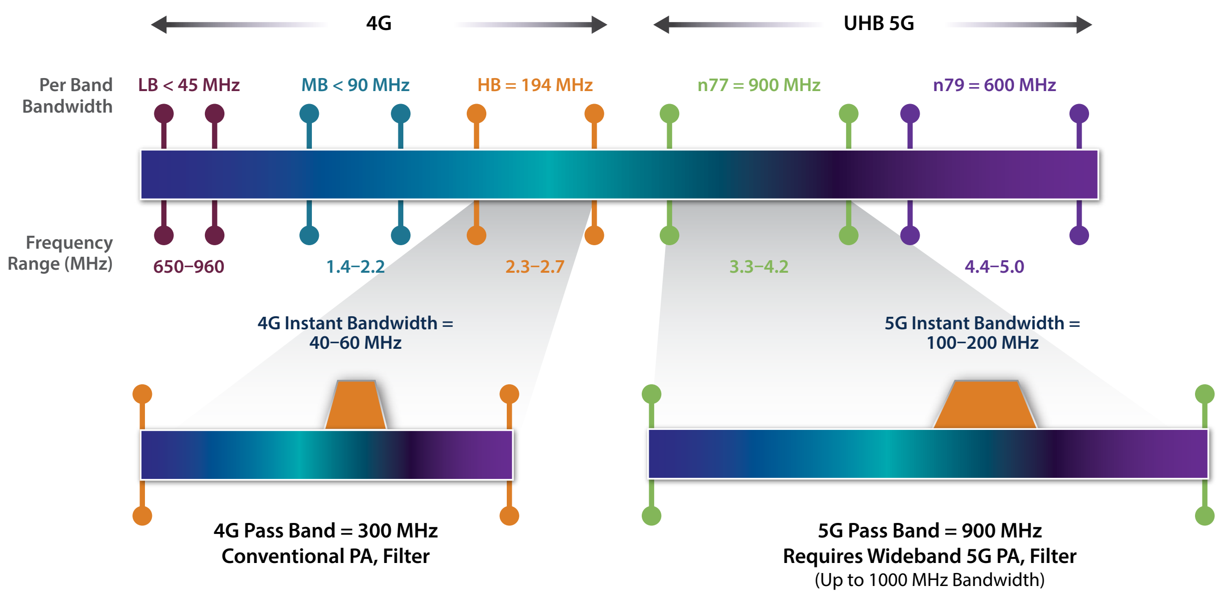
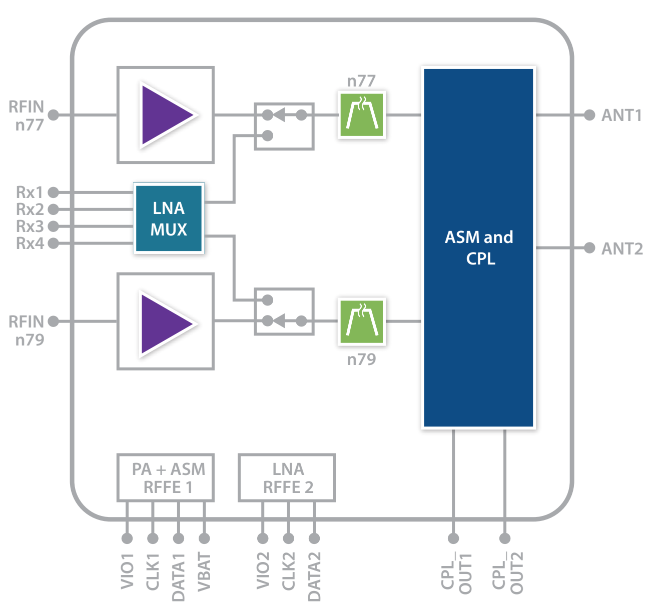


Figure 6. 5G NR Requires Wideband Topologies



Wideband PA

- 100 MHz instantaneous bandwidth with CP-OFDM
- Up to 900 MHz passband
- PMIC limitations (100 MHz APT)
- HPUE

Integrated LNA

- Proven performance boost overcoming systems loss
- ~2 dB Noise figure improvement over TRx based LNA

Wideband Filter

- Tough coexistence driven by dual connectivity
- Up to 900 MHz bandwidth
- Lowest insertion loss

Antenna SRS Support

- Facilitate signal channel sounding for improved Rx in MU-MIMO
- Operator requirements
- Dependent upon coexistence and antenna interface

Figure 7. Elements of Sub-6 GHz 5G NR Transmit/Receive Module

Wideband PA

3GPP requirements for n77 and n79 spectrum indicate 100 MHz instantaneous bandwidth for the component carrier in the uplink. This is much more rigorous than current LTE standards that use carrier aggregation of 20 MHz channels to extend support for 40 to 60 MHz.

It is anticipated that early 5G systems will require the PA to operate in APT mode to accommodate the wider bandwidth signals. Accordingly, users can expect a 100 MHz channel when the PA is operating under APT conditions. Conversely, conventional ET is challenged to perform beyond 40 to 60 MHz. In order to extend the ET modulator bandwidth to reach 100 MHz, additional power consumption would be required, in addition to addressing amplitude/phase delay mismatch sensitivity, management of memory effects, limitations in capacitive supply loading, out-of-band Tx emissions and intermodulation into the LTE anchor band. Though there are several promising new techniques in development to extend ET to the operating bandwidth, it is projected that it will take several more years before commercialization is achieved. Designers are thus left with the challenge of delivering a better performing PA at two to three times the present state-of-the-art instantaneous bandwidth, while operating with a higher peak-to-average CP-OFDM modulation and over much larger passbands than present for 4G LTE sub-3 GHz.

Beyond the wider channel bandwidth, operators have shown significant interest in high power UE capabilities, especially as it pertains to TDD bands in the sub-6 GHz region. Currently, there is some uncertainty as to whether the bands will be 2x2 uplink (two transmitters on at the same time) or a single Tx placement, which means that the PAs will not only need to deliver industry-leading output powers compared to their 4G counterparts, but they will have to do so over a wider bandwidth and at higher frequencies. Meeting higher output power at higher frequencies without ET modulation has given the design community problems to solve.

In order to meet the new, challenging performance requirements of wider channel bandwidth and HPUE, Skyworks engineers have developed new PA topologies that deliver linear PA performance at higher frequencies and over much greater channel bandwidth. These new architectures must be capable of significantly outperforming their LTE counterparts though under more rigorous operating conditions.

Integrated High Performance Low Noise Amplifier

When placing the sub-6 GHz modules, integrating the receive LNA functionality inside the module allows for considerable flexibility and adds value in performance. In Figure 7, there are two receive LNAs optimized for n77, n78 and n79 bands. Integrated LNAs have been proven to boost performance when overcoming system loss, especially in high frequency areas where there is generally more insertion loss due to the high frequency roll off of various RF structures.

Typically, integrated LNAs also contribute about 1.5 to 2.0 dB system noise figure enhancement, which translates directly to improved receive sensitivity when compared to alternative methods such as populating discrete LNAs at or near the transceiver.

Wideband Filter Technology

In the case of sub-6 GHz applications utilizing new TDD spectrum, legacy 4G is virtually nonexistent, except in specific regions such as Japan. While many of the defined 3GPP bands exist (B42/43/48), they have yet to be rolled out commercially in large volumes for LTE and only represent a small subset of the much larger NR band definitions. This is where we will see rapid deployment of n77, n78 and n79 RF front-end modules. We should note, however, that the passbands are significantly larger for these new 5G NR bands. For example, n77 has a passband of 900 MHz – almost 25 percent relative bandwidth, which is twice as large as the 5 GHz Wi-Fi band – and n79 has a passband of 600 MHz. In both instances, we find that conventional acoustic filters are not well-suited for these extremely wide pass bands.

There are additional complexities that will determine the extent of 5G NR wideband filter requirements. For example, one can derive a simple filter response if we assume an ideal environment with a separate high band antenna and no coexistence requirements. On the other hand, if we consider a more complex radio environment, such as a multi-radio atmosphere with simultaneous Wi-Fi transmission, you will see the filter requirements become much more strenuous.

Thus, it is important to take note of the radio environment, antenna topology and coexistence requirements in order to specify the optimum filter. In other words, the filter design and antenna topology into which the FEM will be subsequently mated must be customized to the specific use case or application. Skyworks has the expertise to tailor 5G NR filters to accommodate either end of these extreme use cases.

Antenna Outputs and Fast Sounding Reference Signal (SRS) Hopping

Antenna configurations will play a vital role in the mainstream 5G products. While market requirements will slowly become clear over the next 18 months, there is already some uncertainty as to which of the optional features will be supported.

One feature is the fast hopping sounding reference signal (SRS), which uses the transmitter to send a series of known symbols across all of the downlink receive antennas in the UE in order to better calibrate the MIMO channel and improve the downlink SNR. This process is key to enhanced MIMO and beam forming operation. SRS carrier switching (SRS-CS) was recently introduced in LTE Release 14 to assist the eNodeB (eNB) in obtaining the channel state information (CSI) of secondary TDD cells in TDD LTE CA scenarios. Prior to Release 14, only the primary cell benefits from SRS UE transmissions, and therefore downlink transmissions on secondary cells are done without prior knowledge of the CSI (Figure 8).

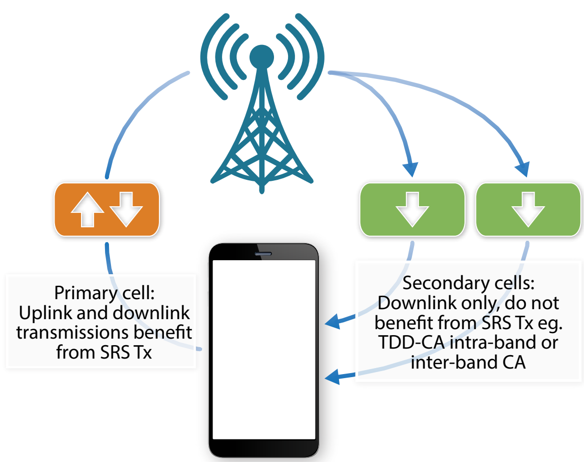


Figure 8. NSA Option-3a Dual Transmission

SRS transmit switching (SRS-TS) allows UE to route its SRS transmissions to all other available antenna ports. Assuming channel reciprocity holds, as should be the case for TDD operation, this feature enables gNB, or 5G NR base station, to estimate CSI on secondary downlink "only" cells. Applying that concept to multi-user MIMO (MU-MIMO) offers yet another network performance enhancement, which in turn will enhance the 5G consumer experience.

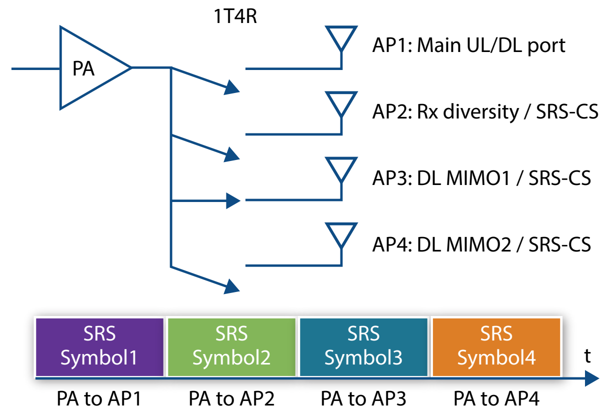


Figure 9. Example of SRS-TS to the remaining 3 Rx antenna ports (AP) available in 1 Tx / 4x UE architecture

Figure 9 provides an example of fast SRS hopping transmissions to any receive downlink antenna port for a UE architecture supporting 1 Tx/4 Rx operation. This scheme requires an RF switch to route the UE transmitter chain to each of the remaining 3 Rx antenna ports.

In 5G NR, the same architecture is relevant – SRS-TS allows gNB to evaluate cell CSI, assuming channel reciprocity applies. This is essential for MU-MIMO performance and MIMO performance at high frequency, particularly as the channel coherence time is short and only fast SRS hopping can provide sufficient MIMO channel estimation.

Implementation Scenarios: What Will a 5G Enabled UE Look Like?

Now let's take a look at what we envision a typical implementation of new 5G NR features would be in several different usage cases.

Implementation in FDD LTE Re-farming Bands Below 3 GHz

The previous section covered greenfield operation in new TDD bands called the sub-6 GHz range. In this section, we take a quick look at a different usage case – specifically, how some operators plan to re-farm their LTE bands into 5G NR. There are two key differences when running 5G NR modulation through an existing 4G PA path: (1) the filter bandwidth and isolations may have to change on the receive side and (2) on the transmit side, the PA may require some incrementally increased linearity and power capability.

Initially, LTE re-farming for 5G NR can be accomplished using the low, mid and high band power amplifier modules with integrated duplexer (PAMiD) structures currently utilized in the market. However, as we get closer to commercial network rollout in 2020 and beyond, improvements will need to be made in the PAMiDs to accommodate for both 4G and 5G LTE re-farmed operations.

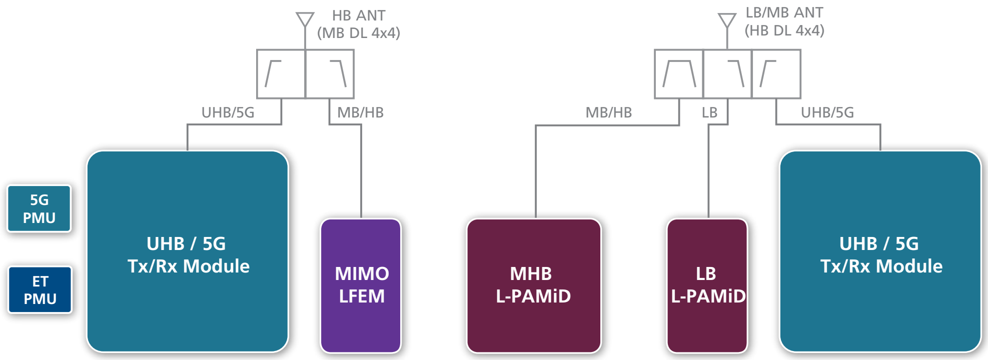


Figure 10. Transmit (Tx) Block Diagram

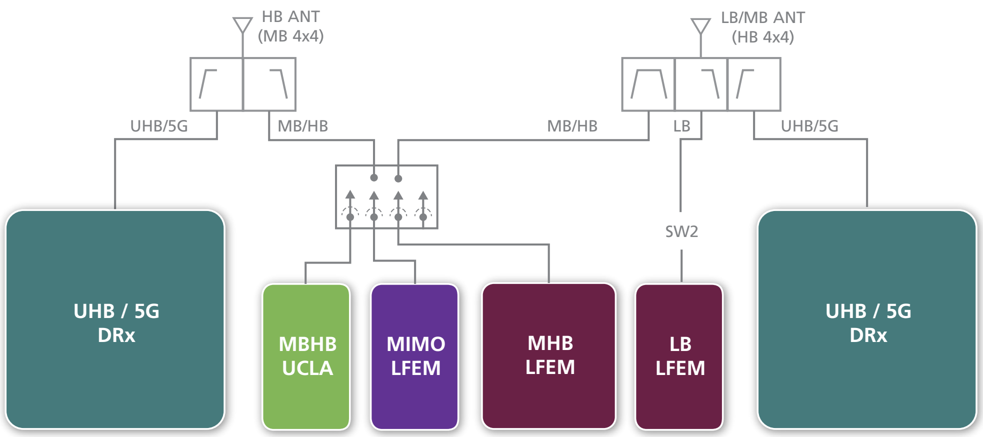


Figure 11. Receive (Rx) Block Diagram

Putting It All Together: What Does a Dual Connectivity 4G LTE/5G NR RF Front-end Look Like?

In Figures 10 and 11, Skyworks illustrates a possible solution for dual connectivity smartphones. There are many ways to achieve the same goal. However, using a 4G core front-end with the addition of 5G NR modules to support overlaid 5G performance and dual connectivity offers a simple, straightforward solution. Figures 10 and 11 show conventional PAMiD devices in the primary transmit path and diversity receive components on the diversity antenna side. This is standard implementation of the core 4G content of a dual connectivity RFFE.

In order to achieve full performance sub-6 GHz UE, there are additional placements required for the transmit capability in bands n41, n77, n78 and n79 to support 2x2 uplink MIMO. In the new n77, n78, and n79 bands in particular, this means an additional 5G NR PAMiD module, as well as two additional diversity receive components are needed to support downlink 4x4 MIMO capability.

A Look Forward to 5G Commercial Networks

How might 5G requirements evolve as we get closer to commercial implementation?

As mentioned earlier, the standards, operator requirements, device manufacturer plans and chipset architectures will be finalized throughout 2018 and 2019. In the interim, the industry is moving forward with demonstrating practical 5G compliance and testing methodologies and projects in order to achieve commercialization in the second half of 2019 and early 2020 timeframe.

This is a very compressed timeline to establish all the components of the ecosystem, as well as to standardize equipment, install small cells, test devices and chipsets and align smartphone OEMs in order to deliver groundbreaking solutions.

While we anticipate changes, we are confident that the course defined in this paper is one that can deliver pragmatic, yet groundbreaking performance solutions to the market in a timely manner.

Summary: Enabling a New Era of Disruptive Communications Technology

Throughout many conversations with mobile network operators, UE device manufacturers and chipset partners, it is clear that 5G will be here sooner than many predict. As with previous generations, the transition to a new technology presents opportunities as well as challenges. With decades of experience spanning multiple generations of wireless standards, Skyworks possesses the technology breadth and expertise to meet these challenges and deliver increasingly sophisticated solutions to advance both the vision and promise of 5G.

From the early days of 2G communication to the more digital wireless standards of 3G WCDMA and 4G LTE, Skyworks has been at the center of innovation and manufacturing scale with each generation (see Figure 12). 5G will be no exception. 5G will raise the bar on system performance and push improvements in size, integration, coexistence and modulation distortion in order to meet design criteria for expanding markets such as enhanced mobile broadband (eMBB), cellular vehicle-to-everything (C-V2X) and low latency communications. Skyworks, via its Sky5™ unifying platform, is working diligently to ensure the ecosystem and platforms are in place to ensure a seamless transition to this new era of exciting and previously unimagined applications.

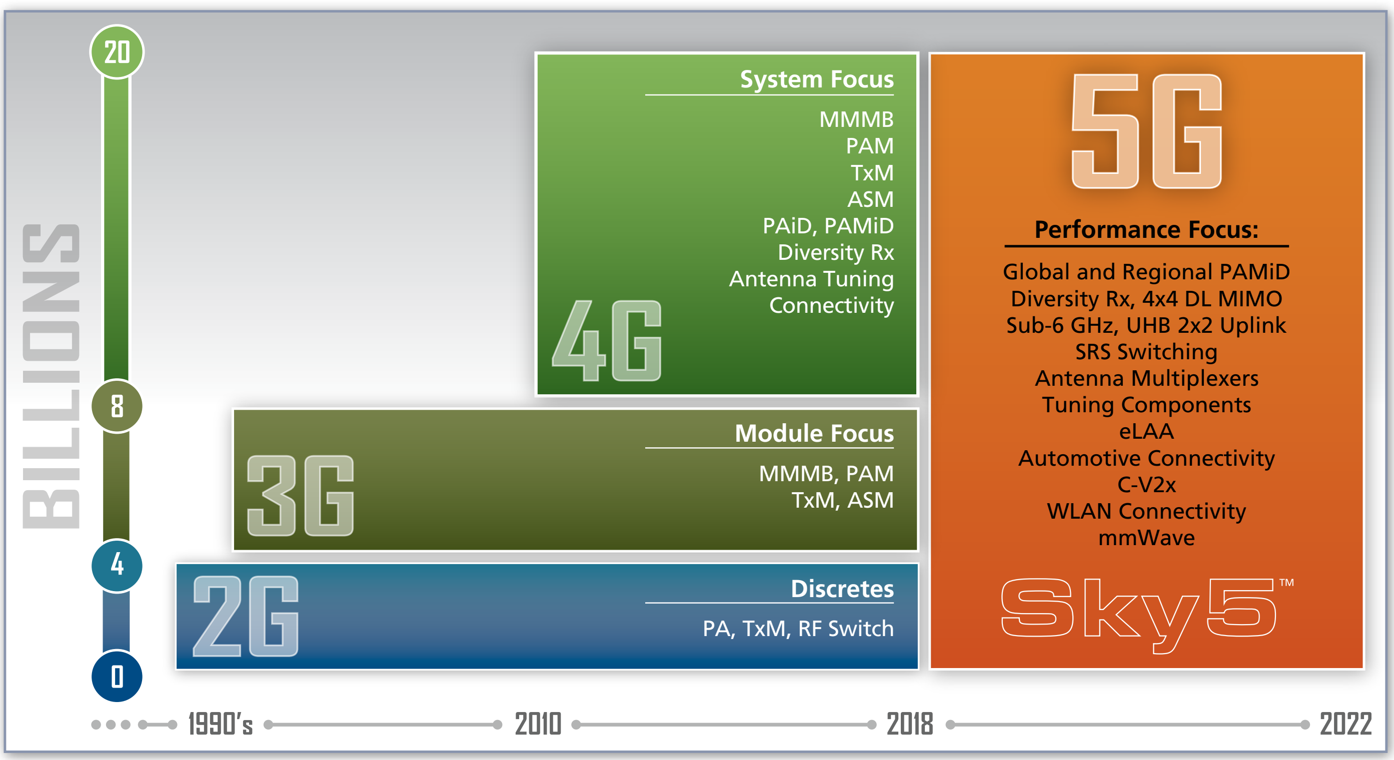


Figure 12. Cumulative Shipments

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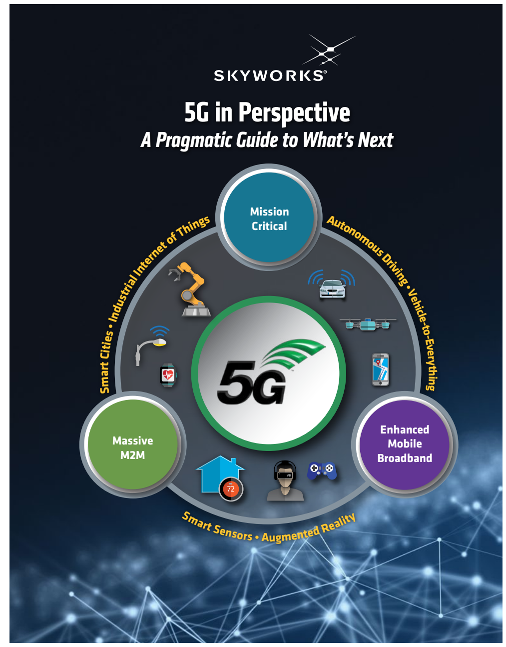
For more information about our solutions, please visit us at www.skyworksinc.com/5g

Additional Resources

5G in Perspective: *A Pragmatic Guide to What's Next*

Skyworks' first 5G technology paper examines the current state of LTE networks, discussing ways it could evolve to deliver a 5G user experience, and identifying the tools and techniques required to support a 100x data throughput improvement. Given that much has transpired with cellular standards, Skyworks answers the question "What's Next?" as the industry evolves to 5G.



5G in Five Minutes!

Want a simple explanation about 5G and how it will revolutionize wireless connectivity in our daily lives? Skyworks has as easy-to-understand video to help!

We invite you to watch "5G in Five Minutes" - the first in a series of videos where Skyworks CTO Peter Gammel explains the critical components for 5G and their importance in the evolution of 5G technologies. Please visit our video page at www.skyworksinc.com/skyworks_video.aspx to watch today!

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