GTI
Sub-6GHz 5G Device
White Paper

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1 Executive Summary

In recent years, 4G has profoundly changed our daily life, and stimulate people's desire for higher performance and better user experience for more innovative services and applications. Towards 2020, the mobile communication will rapidly penetrate to more and more elements of the human's daily life and the society's operation, which will create the opportunities for the mobile industry and other vertical industries. With the new capabilities, e.g. extremely high data rate, extremely low latency and extremely high reliability, massive connection and traffic density, the 5th generation mobile communication technology (5G) will shine a light on the great change on both our daily life and the whole society's operation.

Targeting for commercial launch of 5G in 2020, the global telecommunication operators, network, chipset and device vendors, test instrument manufacturers and solution providers are deeply involved to promote end-to-end maturity of standard and industry. 5G technology development and trial activities comprise some main phases, such as Key technology feasibility validation, Prototype development and trials, Pre-commercial product development, Lab tests and Field trials for pre-commercial and commercial product, Commercial Launch and so on.

In the face of 5G services and market trends, there are many key capabilities and performance indicators for 5G network, base station and device. And there are also many challenges for 5G Device Design and Implementation, so 5G Device Whitepaper is necessary to define the technical requirements for 5G Device and direct the research and analysis on key points. GTI encourages the industry partners to participate the 5G activities and work together to make contributions to the 5G Device White Paper.

2 Abbreviations

Abbreviation	**Explanation**
2/3G	The 2/3rd Generation Telecommunication
3GPP	The 3rd Generation Partnership Project
4G	The 4th Generation Telecommunication
5G	The 5th Generation Telecommunication Technology
AR	Augmented Reality
CC	Component Carrier
CP	Control Plane
CPE	Customer Premise Equipment
DC	Dual Connectivity
eMBB	Enhanced Mobile Broadband
gNB	NR node
GP	Guard Period
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
LDPC	Low Density Parity Check
MAC	Medium Access Control
MCG	Master Cell Group
ME	Mobile Equipment
MIMO	Multiple-Input Multiple-Output
mMTC	Massive Machine Type Communication
mmWave	Millimeter Wave
MN	Master Node
MR	Mixed Reality
MU-MIMO	Multi-User MIMO
NAS	Non Access Stratum
NG Core	Next Generation Core Network
NR	New Radio
NSA	Non-Standalone
OFDM	Orthogonal Frequency Division Multiplexing
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PLMN	Public Land Mobile Network

PoC	Proof of Concept
RLC	Radio Link Control
RRC	Radio Resource Control
SA	Standalone
SCG	Secondary Cell Group
SN	Secondary Node
SU-MIMO	Single-User MIMO
UE	User Equipment
UP	User Plane
URLLC	Ultra-Reliable and Low Latency Communications
VR	Virtual Reality

3 Introduction

Targeting for the 5G industrialization, this White Paper is necessary to facilitate the development of 5G chipset/device and the corresponding test instruments. This document targets enhanced Mobile Broadband (eMBB) scenario for Sub-6GHz 5G pre-commercial and commercial products, which is conducted to be the technical references for the development of chipset/device and the basis for the 5G pre-commercial and commercial products specs.

Form Factor of 5G Device, the communication functions and performance requirements of 5G devices are described in this White Paper. And it focus on discussion about the key research points of 5G Device, including Multi-Mode Multi-Band, Network Access Capability, Inter-working and Voice Solutions, RF Requirements, Demodulation Performance, Power Consumption and Device Testing Requirements.

5G device will follow 3GPP 5G NR Release 15 and later releases. This document will be updated according to the progress of 3GPP 5G NR standardization and the findings from the development and trials.

4 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

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5 Form Factor of 5G Device

There are three main classes of new 5G applications: Extreme Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC) and Massive Machine Type Communication (mMTC). mMTC can mostly be fulfilled by modification and optimization of existing cellular technologies (e.g. NB-IoT), however URLLC and eMBB require new technologies to break new bandwidth and latency boundaries. These will unlock new, potential applications and services that require 5G infrastructure. In this white paper we are focused on potential use cases and applications of eMBB devices, potential use of URLLC is also discussed.

5G infrastructure has significant benefits for a number of applications that are already limited in some capacity by existing 4G services. However this is only the beginning, as every generational shift that grants more capacity and speed always grants unforeseen and unpredictable applications that will only be realized later.

Known applications that will benefit demand high bandwidth and/or ultra-low latency include

1. Virtual, mixed and augmented reality
2. Autonomous driving
3. Infotainment services for public and private transportation
4. 360-degree, 4K/8K resolution live entertainment and sports
5. Alternative to landline fiber services
6. Game-streaming services
7. Thin/zero client for mobile devices

More information on these applications are provided below:

1. Augmented Reality (AR), Mixed Reality (MR) and Virtual Reality (VR) devices

One of the biggest upcoming technological revolutions is AR, MR or VR devices. Each has its own unique applications and opportunities, but all are still in their infancy and currently range from proof-of-concept devices to immature platforms. 5G eMMB can help unlock further advancements to yield new opportunities.

As smartphone performance increases, they are transforming into devices that can be used with VR/AR headsets. Currently, Google's Tango technology uses a Visual Positioning Service[1] (VPS) for in-door navigation, but it relies heavily on local Wi-Fi networks to define its location and the spaces it maps out. Using 5G technologies will enable more consistent signal coverage allowing VPS to be mapped via a combination of camera(s), cellular location and GPS.

Generally speaking, AR/MR/VR are all data rate hungry, which translates to power and battery limitations in smartphones and wearable devices (for example: Samsung Gear VR or Microsoft Hololens). A revolutionary 5G use-case could instead offload the AR/MR/VR sensor inputs and graphics rendering to a Cloud server, which would require only a much simpler, low power user-device that acts only as sensor recorder, 5G cellular transmitter and video decoder. This design would significantly lower the cost of ownership, enabling a much greater market potential and service-style models based on Cloud-server use time. However to enable Cloud-based processing without upsetting user experience, 5G eMMB with lower latency will be required as they provide the necessary streaming bandwidth and low reaction time.

2. Autonomous driving

Autonomous driving will greatly depend on wireless connectivity. Enabling vehicles to communicate with each others could result in considerably more efficient and safer use of existing road infrastructure. If all the vehicles on a road were connected to a reliable network incorporating a traffic management system, they could potentially travel at much higher speeds and within greater proximity of each other without risk of accident. Potential dangers spotted by the increasing number of vehicular sensors could immediately be relayed to other vehicles in the vicinity.

While such systems would not require very high data bandwidth, providing a reliable infrastructure with a low response time would be crucial for their safe operation. Such applications require the millisecond-level response addressed in the 5G specification.

3. Infotainment services for public and private transport

While current personal media needs are mostly being serviced by smartphones and tablets, private vehicles increasingly have infotainment functions built in as natural extension to the legacy of radio, CD and DVD. While air travel has embraced in-seat infotainment for many years and subscription based services for private vehicles is gaining traction, public ground transportation services could also provide in-seat infotainment as a source of additional revenue. Streaming data in both these scenarios would require the multi-Gigabit bandwidth addressed in the 5G specification. Bandwidth requirements are dictated not only by the number of people serviced (5 people per car, 50 per coach or 500 per train for example) but also the quality of streaming media: Full HD, UltraHD 4K and future 8K (with respective quality increments in digital audio as well).

4. 360-degree, or 4K/8K resolution live entertainment and sports

Major sporting and entertainment events are both big value investments and have historic president. The potential market is very significant, with regular events in the hundreds of millions of viewers: the 2017 American Super Bowl had 111.3 million people watching, F1 motorsport has 425 million fans globally, and Manchester United soccer club alone has over 650 million global fans.

They are also frequently the perfect opportunity by the host to showcase the latest technologies. For example, the Tokyo Olympics is already set to become the first sporting event to broadcast in 8K, and one of the first to have 5G network coverage.

Smartphones displays are moving towards ever higher resolutions with HDR quality (for example: Sony Xperia XZ Premium, LG G6, Samsung Galaxy S8), with video streaming services such as Netflix following as sufficient devices reach the hands of consumers. Some operator has already committed to the 2020 Olympics streamed over 5G to VR devices, which will let users feel like they are actually in the stadium with the athletes.

4K/8K broadcasting and 360-degree drone-enabled live video streaming requires extreme levels of bandwidth only 5G technologies can service, with multi-Gigabit throughput sufficient to make such systems a reality.

5. Alternative to landline fiber services

eMMB wireless can be an attractive alternative to fiber roll-out. Fiber roll-out can incur a significant cost, with a long roll-out time, or is simply unviable due to environmental, regulatory or other economic factors such as small subscriber numbers (small/remote towns and villages) or factors such as fixed infrastructure where it’s too difficult to retrofit, such as tall, inner-city apartment blocks or commercial buildings.

Since there is already ongoing investment in worldwide cellular services to increase coverage and reliability, the use 5G eMMB could provide an alternative backbone to fiber, giving these locations fast connectivity for home and office use; enabled by low-cost, fixed antenna to the apartment or as a service for the whole building.

High-bandwidth and reliable internet services can allow for more efficient remote-working and inter-office collaboration tools; which is an attractive investment for local or national governments looking to stimulate business and job opportunities outside of cities.

6. Gaming as a Service (GAAS)

For consumer devices, video games are a rare use case of high power computing. The video game industry has consistently pushed of performance for premium PCs, games consoles and premium mobile products.

Game streaming services (GAAS), however, moves the core processing onus from the user device into the Cloud. The user input/action is recorded and sent to the remote Cloud-server, where the game environment is rendered and only the display and audio output – essentially a livestream video feed – is sent to the user device. This means the user device requires only state of the art connectivity and simple AV decoding.

This type of service model is very attractive to many game publishers, infrastructure operators and users as it greatly lowers the ownership cost to a regular service fee, but previous attempts of services such as Sony PSNow and Nvidia GeForce GRID have only achieved limited success. A user experience that mirrors a local gaming device has not yet been met, often due to latency and bandwidth limitations even when using fixed line connections.

5G eMMB with low latency will meet the requirements of these services, finally unlocking their market potential.

7. Thin/zero client for mobile devices

Thin or zero clients have specific advantages in device cost and data security. With little to no locally stored user files, corporate devices can be very efficiently managed and monitored. 5G eMMB could potentially provide users their apps and data, or even an entire OS state, every-time they turned on their device with little delay.

This is attractive if data-security and corporate device control is an essential consideration, as lost or stolen devices are simply locked out of the network with no local data risk.

Based on the envision of potential 5G eMBB scenario described above, the main form factor of 5G device will be similar as smart handheld device today because consumers have been used to such kind of device and establish their daily behavior. For other scenarios, there will be more different devices such as module used to provide communication access service for vertical industry and consumer electronics terminal.

6 General Description

3GPP has been working on an accelerated path of developing 5G NR specifications. The Initial work is concentrated on NSA (Non-standalone) mode, followed by Standalone (SA) mode soon after. NSA is expected to be an intermediate step for smooth transition of existing networks to 5G. It is also expected that LTE Advanced pro deployments are going to be around for many coming years and hence could benefit from NSA. However, some operators may also choose to directly deploy a dedicated network for 5G services using Standalone mode. It is an end state to reap full potential of 5G network.

With this in mind, GTI sub-6GHz device is expected to support both NSA and SA mode of operation. NSA mode relies on Dual connectivity for its operation while SA may involve Inter-RAT mobility management. This section will provide high level guidelines for supporting NR in SA mode as well as NR-LTE in NSA mode.

6.1 System Description

This subsection will focus on high level NR system requirements to be supported in initial 5G UE for eMBB use case.

6.1.1 Key System Requirements

This subsection will provide key system requirements for 5G NR device support when may be common among GTI operators.

- Frequency bands and System bandwidth:

Table 6-1 5G NR Band list

RAT	Band	Max BW for 15kHz	Max BW for 30kHz	Max BW for 60kHz
NR	Band n77 (3.3 GHz ~4.2GHz)	50MHz	100MHz	100MHz
	Band n78 (3.3 GHz ~3.8GHz)	50MHz	100MHz	100MHz
	Band n79 (4.4GHz~5GHz)	50MHz	100MHz	100MHz
	Band 1	20MHz	20MHz	20MHz
	Band 3	25MHz	25MHz	25MHz
	Band 8	20MHz	20MHz	20MHz
	Band 41	50MHz	60MHz	60MHz

NOTE 1: Table 6-1 will be updated according to NR bands and Bandwidths defined in 3GPP and operators’ deployment.

NOTE 2: The actual system bandwidth for one operator depends on how much 5G frequency is allocated for this operator.

- MIMO configurations:
    - UL: 2 layers required, 4 layers recommended
    - DL: 4 layers required, 8 layers recommended

6.1.2 Performance requirements

- Latency requirements
    - Control plane: <=10ms
    - User plane: <=4ms for one way
- Single user peak data rate

The recommended UL and DL single user peak data rates for different MIMO layers are given below.

- DL peak data rate for 4 layers: >=1.3Gbps
- DL peak data rate for 8 layers: >=2Gbps
- UL peak data rate for 2 layers: >=175Mbps
- UL peak data rate for 4 layers: >=350Mbps

Configurations: 100MHz BW: 70% DL; Uplink 64QAM; DL 256QAM for 4 layers and 64QAM for 8 layers.

6.2 Physical Layer Requirements

For 5G Devices in eMBB usage scenario, key physical layer characteristics have been well studied in the NR study item in 3GPP Release 14 and are now being standardized in NR work item in Release 15. In this subsection, we briefly illustrate the key requirements on the agreed design, from the UE perspective.

6.2.1 Multiple numerologies

- A numerology is defined by sub-carrier spacing and CP overhead and multiple numerologies should be supported in NR. For sub-6GHz, the UE should support the following features:
  - Available subcarrier spacing values include 15 KHz, 30 KHz and 60 KHz. The values are configured by gNB and notified to the devices. 30 KHz subcarrier spacing is important to support large channel BW of 100MHz (e.g. 3.5 GHz). In the band lower than 3.5 GHz such as n41, 15 KHz should be supported. 60 KHz may also be required in supporting some high speed and low latency scenarios.
  - All numerologies with 15 kHz and larger subcarrier spacing, regardless of CP overhead, align on symbol boundaries every 1ms in NR carrier.

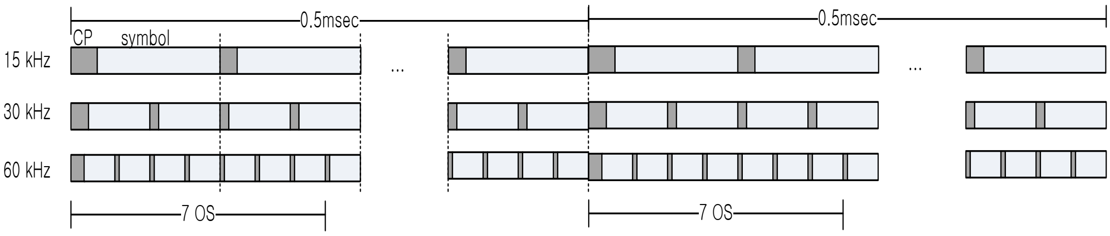

Figure 6-1 Illustration of the symbol alignment

More specifically, for the normal CP family, the following is adopted.

- For subcarrier spacing of 15 kHz * 2^{μ} (μ=0,1,2),
  - Each symbol length (including CP) of 15 kHz subcarrier spacing equals the sum of the corresponding 2^{μ} symbols of the scaled subcarrier spacing.
  - Other than the first OFDM symbol in every 0.5ms, all OFDM symbols within 0.5ms have the same size
  - The first OFDM symbol in 0.5ms is longer by 16Ts (where Ts is the time unit assuming 15 kHz and FFT size of 2048) compared to other OFDM symbols.

Normal CP can be used with any numerology and the extended CP value will be only one in given subcarrier spacing. LTE scaled extended CP is supported at least for 60 kHz subcarrier spacing in Rel-15. The CP type can be semi-static configured with UE-specific signaling. UE supporting the extended CP may depend on UE type/capability.

6.2.2 Flexible frame structure

In NR, a frame consists of 10 subframe with length of 10ms and each subframe duration is fixed to 1ms.

A slot is defined as 14 OFDM symbols for the same subcarrier spacing of up to 60kHz with normal CP and 12 OFDM symbols for at least 60kHz with extended CP. Table 6-2 and Table 6-3 illustrate the values of number of OFDM symbols per slot, the number of slot per frame and the number of slots per subframe for normal CP and extended CP, respectively. NR UE should support all the slot configurations in Table 6-2 and Table 6-3.

Table 6-2 Number of OFDM symbols per slot, $N_{\text{symb}}^{\text{slot}}$, for normal cyclic prefix.

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

Table 6-3 Number of OFDM symbols per slot, $N_{\text{symb}}^{\text{slot}}$, for extended cyclic prefix.

μ	$N_{\text{symb}}^{\text{slot}}$	$N_{\text{slot}}^{\text{frame},\mu}$	$N_{\text{slot}}^{\text{subframe},\mu}$
2	12	40	4

NR UE should support the slot format that a slot can contain all downlink, all uplink, or at least one downlink part and at least one uplink part. Slot aggregation should also be supported, i.e., data transmission can be scheduled to span one or multiple slots.

6.2.3 Bandwidth part configuration and adaptation

- Bandwidth part properties include numerology (SCS, CP type), frequency location (e.g. center frequency), and bandwidth (e.g. number of PRBs), etc. A UE can be configured with one or more carrier bandwidth parts in the downlink with a single downlink carrier bandwidth parts being active at a given time. The UE is not expected to receive PDSCH or PDCCH outside an active bandwidth part.

- A UE can be configured with one or more carrier bandwidth parts in the uplink with a single uplink carrier bandwidth parts being active at a given time. The UE shall not transmit PUSCH or PUCCH outside an active bandwidth part.

- For unpaired spectrum, a DL BWP and an UL BWP are jointly configured as a pair, with the restriction that the DL and UL BWPs of such a DL/UL BWP pair share the same center frequency.

6.2.4 Initial access

- NR UE should support synchronization on time and frequency and the detection of the physical cell IDs from 1008 candidates. Besides, NR UE should support the detection of the SS/PBCH block under different numerologies and time locations in various frequency carriers and bandwidth configurations.
- NR UE should support obtaining the essential minimum system information, including at least SFN, SS block time index and configuration information of PDCCH for RMSI (Remaining minimum System Information) from PBCH.
- NR UE should support the detection of the RMSI from PDSCH.

6.2.5 Waveform

- NR UE should support CP-OFDM-based waveform in both DL and UL. With CP-OFDM based waveform, spectral utilization should be equal or greater than that of LTE (90% for LTE) which is defined as transmission bandwidth configuration / channel bandwidth * 100%. Transparent spectral confinement technique(s) (e.g. filtering, windowing, etc.) for a waveform can be used at the UE side in either UL transmission or DL reception. CP-OFDM waveform can be used for single-stream and multi-stream transmissions.
- NR UE should also support DFT-S-OFDM based waveform for eMBB uplink transmission. DFT-S-OFDM is limited to a single stream transmissions.
- NR UE should support the switching between CP-OFDM and DFT-S-OFDM in UL, following the network configuration.

6.2.6 Modulation

- For NR DL, UE should have the capability to demodulate the symbols with constellation mapping of QPSK, 16QAM, 64QAM and 256QAM.
- For NR UL, UE should have the capability of modulate the information bits with QPSK, 16QAM, 64QAM and 256QAM (optional) mapping.

6.2.7 Multiple antenna techniques

- NR UE should support 4 layer DL transmission and 2 layer UL transmission, and consider support up to 8 layer DL transmission and up to 4 layer UL transmission.
- NR UE should support DL DMRS based spatial multiplexing (SU-MIMO/MU-MIMO) with close-loop or semi-open loop transmission.
- NR UE should support the channel estimation for demodulation for at least 8 orthogonal DL DMRS ports.

- NR UE should support aperiodic/semi-persistent/periodic CSI-RS/IMR and CSI reporting with up to 32 CSI-RS ports.
- NR UE should support SRS transmission with antenna switching over multiple Tx antennas.

6.2.8 Scheduling and HARQ timing

- NR UE should support the dynamic timing between receiving the DL signaling and ACK/NACK feedback ranging from n+2 slot to n+4 slot, where n is the slot of receiving the DL signaling for slot-based scheduling in the non-CA case with single numerology for PDCCH and PDSCH.
- NR UE should support DL assignment and the scheduled DL data in the same slot.
- NR UE should support the dynamic timing between receiving the UL grant and UL data transmission ranging from n+2 slot to n+4 slot, where n is the slot of receiving the UL grant for slot-based scheduling in the non-CA case with single numerology for PDCCH and PUSCH.
- NR UE should support asynchronous and adaptive HARQ in DL/UL
- NR UE should support code block group based transmission with single/multi-bit HARQ-ACK feedback and transport block (TB) based transmission.

6.3 Upper Layer Requirements

UE shall support 3GPP Release 15 NR non-standalone mode and NR standalone mode. For the impact of SA and NSA to UE and the device implementation consideration, refer to chapter 8. In this chapter, general upper layer requirements are discussed.

6.3.1 Control Plane

- UE shall support three states in RRC: NR_RRC_IDLE, NR_RRC_INACTIVE, NR_RRC_CONNECTED, and the transition between each other except from NR_RRC_IDLE to NR_RRC_INACTIVE.
- UE shall support 5GC-initiated paging. When UE is inactive state, UE shall support RAN-based location area update and RAN-initiated paging.
- UE shall support on-demand SI. In NR_RRC_IDLE and NR_RRC_INACTIVE, the request is through a random access procedure; In NR_RRC_CONNECTED, the request is through dedicated RRC signaling.
- UE shall support unified access barring mechanism for all RRC states in NR (NR_RRC_IDLE, NR_RRC_CONNECTED and NR_RRC_INACTIVE).
- UE shall support the following characteristics for cell reselection: Intra-frequency

reselection based on ranking, Inter-frequency reselection based on absolute priorities and inter-RAT cell reselection between NR and E-UTRAN. UE may also support cell reselection based on service specific prioritization.

- UE shall support to measure multiple beams (at least one) of one NR cell and derive cell quality from these multiple beams (above one threshold). Cell quality from beam measurements is derived in the same way for the serving cell(s) and for the non-serving cell(s). UE shall support to report beam information (beam ID and measurement results) in addition to cell quality results.
- UE shall support beam level mobility within serving cell and cell level mobility.
- UE shall support inter RAT handover between NR and E-UTRAN.
- UE shall support all mandatory integrity/cipher algorithm defined in TS 33.501. Ciphering and integrity protection of RRC and NAS-signaling shall be supported.
- Carrier Aggregation (CA) is optional to be supported. UE shall support PDCP packet duplication once CA is configured.
- UE shall support radio link failure detection.
- UE can support Automatic Neighbor Relation (ANR) function.
- UE shall support single registration mode.
- UE shall support emergency service and SMS, voice and video service over IMS in 5G system via NR.
- UE shall support at most eight Network Slices simultaneously. UE shall support three Session and Service Continuity modes, i.e. SSC 1, SSC 2 and SSC3.
- UE shall support secondary authorization/authentication by a DN-AAA server during the PDU session establishment introduced by 5GS.
- Positioning: reserved

6.3.2 User Plane

- UE can support ROHC as Header compression and decompression in PDCP.
- UE can support UDC equivalent implementation for NR in UL.
- UE shall support different TTI duration length as different numerology corresponds to different TTI duration length.
- UE shall support scheduling information report such as multiple scheduling request report associated to multiple scheduling request configurations, buffer status report, power headroom report.
- UE shall support Semi-Persistent Scheduling (SPS).

- UE shall support DRX in NR_RRC_CONNECTED for power saving.
- UE shall support contention-based random access procedure and contention-free random access procedure.
- UE shall support Logical Channel Prioritization procedure.
- UE shall support 5G QoS.
- UE shall support ciphering and integrity protection of user data between the UE and gNB. UP integrity is mandatory to support and optional to use by 5G UEs and 5G networks, with the exception of 5G UEs that can only access the EPC.

6.4 Summary

This section provides a high level summary of the key requirements for a sub-6GHz 5G device.

(1) The device is required support for HPUE (26dBm) on TDD bands.

(2) To take full advantage of MIMO, the device shall support SRS with Tx antenna switching across multiple Tx antennas.

(3) In NSA mode, device shall be capable of simultaneous transmission (and reception) across LTE and NR.

(4) LTE and NR may be deployed in same band and hence in-device co-existence is critical for its operation.

(5) Initial NSA deployments are expected to use dual connectivity architecture option 3/3a/3x.

(6) For LTE in dual connectivity，it is expected to support up to LTE 3CA DL (contiguous and non-contiguous) and LTE 2CA UL (contiguous). LTE 4CA DL is optional.

(7) 1Tx LTE and 1Tx NR would be a default dual connectivity configuration. However, reusing the Tx chains, 2Tx (UL MIMO) can be used in “LTE only” coverage area or in “NR only” coverage area. 2Tx can also be used in TDM mode between LTE and NR. Please note that 2Tx is anyways a key requirement for standalone NR operation.

(8) The device shall support 15 KHz and 30 KHz subcarrier spacing for NR. 60 KHz is optional.

(9) Channel coding requires support for LDPC (eMBB data) and Polar coding (Control channel).

(10) UL RoHC as well as Uplink Data Compression (UDC) schemes as defined in 3GPP is optional.

7 Multi-Mode Multi-Band

Telecommunication industry, in general, is moving towards 5G rapidly. At the same time, existing LTE Advanced pro deployments continues to grow and is expected to last for another decade or more. Initial 5G deployments are expected to start from 2018-2019. Depending on operator's network architecture, there would be different mainstream approaches for 5G deployments, such as Standalone (SA) and Non-Standalone (NSA) 5G networks. A 5G UE should support both standalone and non-standalone 5G operations. For the Non-standalone 5G operations, LTE carrier(s) is mandatory to be the anchor carrier for 5G UEs. Besides LTE and 5G, there may be operators around the globe which relies on 3G and other 2G services (though 2G services may be obsolete or refarmed to LTE in near future). All these diverse RATs are potentially also using different bands / channels globally.

To summarize, 5G UE should support some of the following networks:

- 5G/NR (standalone and non-standalone)
- LTE FDD
- TD-LTE
- WCDMA/HSPA
- TD-SCDMA/HSPA
- GSM/EDGE/GPRS
- CDMA1X/EVDO

In order to support global roaming as well as local services, 5G UE should support the core bands of 4G/3G/2G being used worldwide. For 5G bands, it should focus on potential core bands which will be deployed within 3-5 years.

Based on last GTI MMMB requirements, a set of seven core LTE bands were identified which included four key TD-LTE band (Bands 38, 39, 40 and 41) as well as three FDD LTE bands (Bands 3, 7 and 20). Additional bands were identified as core roaming bands (Bands 1, 2, 4, 5, 8, 12, 13, 17, 25, 26, 27, 28, 42 and 43). Support for 2G and 3G may still be required, however, some operators may have re-farmed their legacy 2G networks to LTE. Table 7-1 is below is some GTI operators' recommended bands/RAT list. It is important to understand other GTI operator's requirements to build a global MMMB device.

Table 7-1 MMMB device Band list

RAT	Band
NR	Band n77 (3.3 GHz~4.2GHz)
	Band n78 (3.3 GHz~3.8GHz)
	Band n79 (4.4GHz~5GHz)
	Band 1

	Band 3
	Band 8
	Band 41
TD-LTE	Band 40
	Band 38
	Band 39
	Band 41
	Band 34
TD-SCDMA/TD-HSPA	Band 34
	Band 39
GSM/GPRS/EDGE	Band 8
	Band 3
	Band 2
	Band 5
LTE FDD	Band 7
	Band 1
	Band 3
	Band 17
	Band 4
	Band 20
	Band 8
	Band 25
	Band 26
	Band 12
WCDMA/HSPA	Band 1
	Band 2
	Band 5
	Band 8

The above-listed bands for 5G are only Sub-6GHz. The millimeter wave (mmWave) bands provide plentiful spectrum for 5G, which will rise the requirement of supporting mmWave for 5G UEs. The specified requirements for mmWave will be updated according to the progress of spectrum allocation and operators' deployment.

RF front end architecture to support these various RAT and bands in a discrete manner may provide good RF performance but at the same time pose huge challenges in terms of cost, space and parts availabilities. Multi-mode Multi-band integrated RF architecture could help overcome many of the challenges posed by discrete design. Such architecture would combine several bands into a single chain, independent of RAT.

RF front-end subsystem consists of a combination of power amplifiers (i.e P.A), filters, duplexers, RF switches, resistors, capacitors, and inductors that helps with device conformance to 3GPP and national regulatory emission specifications. Figure below represents a logical partition of bands required in a multi-mode multi-band global smartphone device. It is understandable that various OEMs may combine RF front-end components in different grouping depending on component selection and functionality provided by those components for CA and connectivity purposes. Various architectures currently also combines mid bands (1.7-2.1 GHz) and the mid-high bands (2.3-2.7 GHz) into a single module to simplify CA. Similarly, high bands could be combined with Wi-Fi or even with mid-high bands and hence share antennas. It should be mentioned that the architecture below may not support multi-RAT simultaneous transmission / dual connectivity but may be suitable for Standalone architecture.

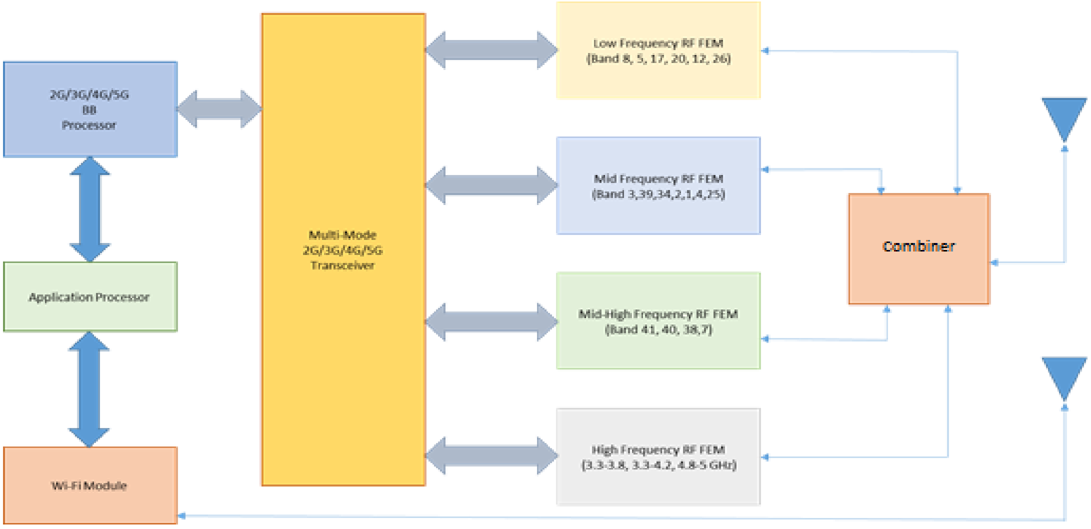

Figure 7-1 MMMB architecture 1

Figure below illustrates a variant of MMMB architecture. The main difference between this architecture (below) and the one described above is the simultaneous handling of multi-mode 2/3/4/5G technologies through single / multiple baseband chipset. While this architecture provides simultaneous transmission support for 2/3G or 5G and LTE, it may require analysis on power consumption and space. Non-standalone / Dual connectivity architecture may benefit from such architecture. It should be noted that this complexity and extra cost is well understood in the industry and smartphones using such designs have progressed significantly in the last years.

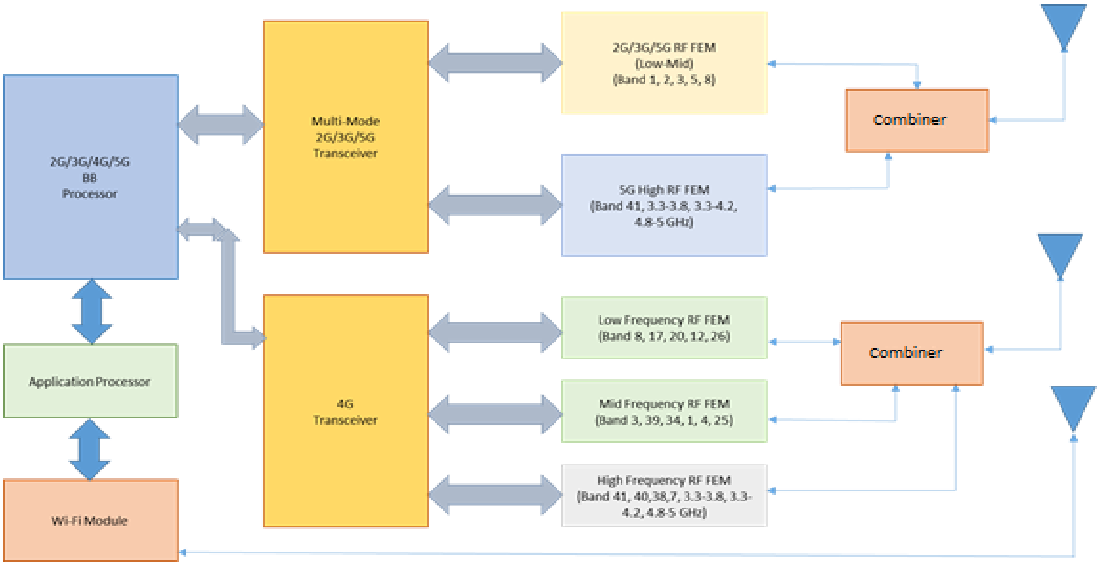

Figure 7-2 MMMB architecture 2

In this example, same baseband processor and multiple transceivers are required to simultaneously support 4G and 5G as well as 2/3G technologies. It should be mentioned that other functionality partition on baseband processors is possible. For instance, 5G and LTE could be part of a single processor while 2G/3G is addressed by a separate processor. Also, the application processor may well be integrated as part of baseband processor. Also, in some cases, the transceiver and the baseband processor could be integrated in a single chipset.

Besides Band and RAT support, it is also important to account for Channel BW, number of Rx/Tx antennas, UL Tx power, MCS, CA configurations per RAT, other connectivity and co-existence requirements when designing a mulit-mode multi-band device supporting NR and LTE.

8 Network Access Capability

This section looks at 5G Network Architecture options supporting standalone and non-standalone mode of operation.

8.1 Connectivity Options in 3GPP

3GPP defines both Standalone (SA) and Non-Standalone (NSA) deployment configurations for NR.

8.1.1 Standalone NR

A standalone NR deployment configuration would not require an associated LTE network. The NR-capable UE could use random access to directly establish a radio link with a gNB, and attach to the 5GC to establish service. This would be the simplest configuration architecture, and would allow the simplest UE implementation.

Standalone NR requires a complete set of specification from 3GPP for all interfaces in the network. 3GPP plans to complete specifications for basic standalone NR in Rel-15, to be approved in June 2018.

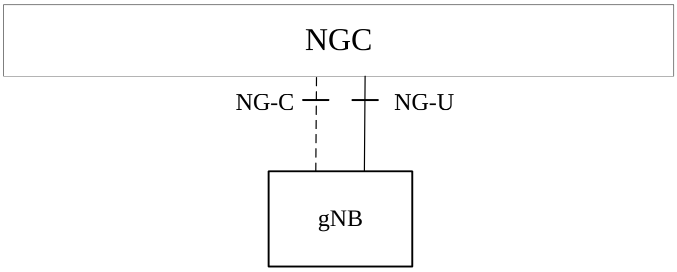

Figure 8-1 Standalone NR – 3GPP Option 2

For Standalone operation, the basic network access principles/procedures follow LTE counterparts. The additional requirements mainly include:

1. System information (SI) broadcasting: NR system Information is divided into Minimum SI and Other SI.
    - Minimum SI: periodically broadcast and comprises of basic information required for initial access and the scheduling information for other SI.
    - Other SI: encompasses everything not broadcasted in the Minimum SI, which may either be broadcasted, or provisioned in a dedicated manner. Both manners can be either triggered by the network configuration or upon request from the UE (i.e., on-demand)

    Compared to LTE SI broadcasting method, on-demand SI broadcasting is a new mechanism introduced in NR to deliver “other SI” by UE request. For UEs in RRC_CONNECTED, dedicated RRC signaling is used for the request and delivery of the Other SI. For UEs in RRC_IDLE and RRC_INACTIVE, making the request will trigger a random access procedure.

2. Access control: Unlike LTE, one unified access barring mechanism will be introduced in NR to address all the use cases and scenarios that E-UTRA addressed with different specialized mechanisms. And, the unified access barring mechanism should be applicable for all RRC states in NR (RRC_IDLE, RRC_CONNECTED and RRC_INACTIVE).
    - *Editor’s note: The details are still under discussion in 3GPP.*

3. RRC_Inactive: This is a new RRC state in NR, in addition to RRC_Idle and RRC_Connected. It is a state where a UE remains in CM-CONNECTED and able to move within an area configured by NG-RAN (i.e., RAN-based notification area, RNA) without notifying NG-RAN. In RRC_INACTIVE, the last serving NG-RAN node keeps

the UE context and the UE-associated NG connection with the serving AMF and UPF. The UE notifies the network via “RAN-based notification area update (RNAU)” procedure if it moves out of the configured RNA.

4. Inter-RAT mobility: for NR, the main inter-RAT scenario is handover-to-LTE. For the more detail, please refer to Chapter 9.

8.1.2 Non-Standalone NR

As an interim step for NR deployments, 3GPP has defined non-standalone deployment configurations, using Dual Connectivity (DC) between the UE and both an NR gNB and LTE eNB.

Because initial NR networks may not have complete coverage, DC can be used to combine the coverage advantage of existing LTE networks with the throughput and latency advantages of NR. However, it requires more complex UE implementations to allow simultaneous connections with both LTE and NR networks, potentially increasing the cost of UEs. This will require more complex UE radio capabilities, including the ability to simultaneously receive DL from NR and LTE on separate bands.

NSA networks use architectures where NR gNBs are associated with LTE eNBs and do not require a two separate signalling connection to the 5GC. These architectures are enumerated based on the control plane and user plane connections used between eNB, gNB, EPC, and 5GC, as shown in Table 8-1 below.

Table 8-1 C-Plane / U-Plane Connections

Dual Connectivity RAN-CN Architecture Options		**Core Network**	
		4G EPC	**5G 5GC**
RAN BS with C-Plane and U-Plane connection to Core	**LTE eNB**	Option 3	Option 7
	NR gNB	N/A	Option 4
“A” suffix means User Plane direct connection with Core exists for both eNB and gNB			
“X” suffix means User Plane direct connection with Core exists for both eNB and gNB with split bearer used for gNB SCG.			

Option 3 architectures use the 4G EPC as the Core Network, with the S1-C control plane connection for the UE between the LTE eNB and the EPC. The gNB acts as Secondary Cell Group (SCG) connected to the Master Cell Group (MCG) at the eNB. Control plane information is exchanged between the eNB and the NR gNB, and no direct control plane interface exists between the gNB and EPC. User Plane bearers are supported between eNB and EPC over S1-U. In option 3A, the gNB also terminates User Plane bearers with the EPC directly. In Option 3X, those gNB terminated S1-U bearers may be split, and carried over the Xx interface to the eNB and over the LTE air interface.

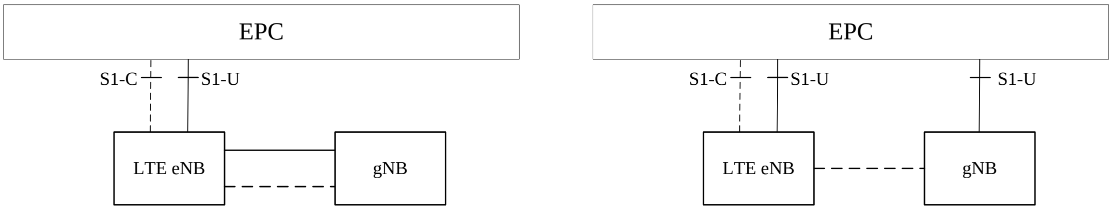

Figure 8-2 Non-Standalone NR – 3GPP Option 3 and 3A

Option 4 is essentially the inverse of Option 3, with the gNB representing the MCG and the eNB representing the SCG. The Control Plane connection is between the gNB and the 5GC over the NG-C, and the eNB gets its control plane information over Xx with gNB. In Option 4A, direct User Plane bearers with the 5GC are terminated at the eNB.

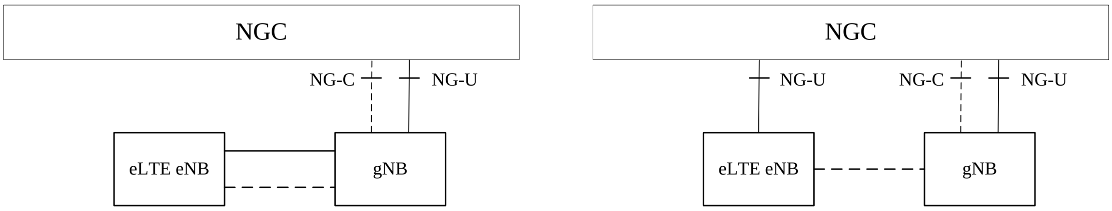

Figure 8-3 Non-Standalone NR – 3GPP Options 4 and 4A

Option 7 uses the same topology as Option 3, with the eNB acting as MCG and the gNB acting as SCG. The difference is that the 5GC Core is used instead of the EPC, requiring the eNB to support eLTE interfaces with the 5GC.

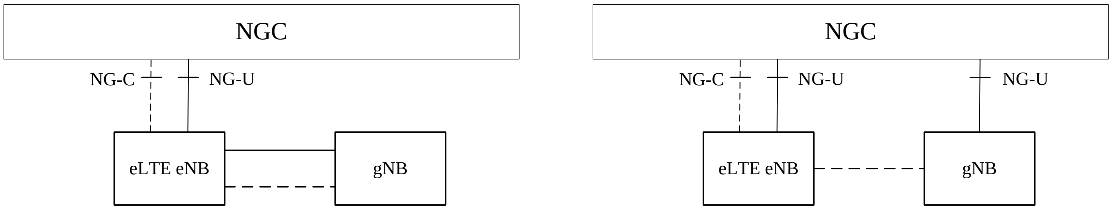

Figure 8-4 Non-Standalone NR – 3GPP Options 7 and 7A

Option 3 does not require interfaces with the 5GC, and allows service over the NR air interface with only the Uu (between UE and gNB) and the Xx (between gNB and LTE eNB) interfaces fully defined. Other network interfaces needed for SA deployment are not needed. As such, it is seen as a likely common architecture for early NR deployments.

From C-plane viewpoint (option 3), there is only one RRC state in UE, which is based on the LTE RRC. And, there is only one C-plane connection towards the Core Network (i.e., EPC for Option-3). **错误!未找到引用源。** illustrates the relevant architecture. Each radio node has its own RRC entity which can generate RRC PDUs to be sent to the UE. Note that, RRC PDUs generated by the gNB (SN) can be transported via the LTE Uu interface or NR Uu interface to the UE if configured.

The eNB (MN) always sends the initial SN RRC configuration via MCG SRB (SRB1), but subsequent reconfigurations may be transported via MN or SN. Additionally, the UE can be configured to establish a SRB with the SN (i.e., SRB3) to enable RRC PDUs for the SN to be sent directly between the UE and the SN.

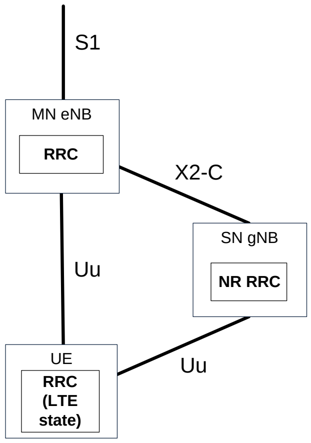

Figure 8-5 Control-plane viewpoint of non-standalone mode

Impacts to RRC procedures for non-standalone operations support include [8]:

1. Secondary Node Addition: The procedure is initiated by the MN eNB (MeNB) and is used to establish a UE context at the SN gNB (SgNB) to provide radio resources from the SgNB to the UE. This is the first procedure to enable non-standalone operation. After a SN is added, it can be modified or released later.

2. Secondary Node Modification: The procedure may be initiated either by the MeNB or by the SgNB and be used to modify, establish or release bearer contexts, to transfer bearer contexts to and from the SgNB or to modify other properties of the UE context within the same SgNB.

3. Change of Secondary Node: The procedure is initiated either by MeNB or SgNB and used to transfer a UE context from a source SgNB to a target SgNB and to change the SCG configuration in UE from one SgNB to another. Note that, it always involves signalling over MCG SRB towards the UE.

4. Inter-Master Node handover without Secondary Node change: The procedure is used to transfer context data from a source MeNB to a target MeNB while the context at SgNB is kept.

More noticeable requirements in RRC layer to support non-standalone operation are listed below [9]:

1. System information: For non-standalone operation, UE mainly gets the system information via LTE, except for radio frame timing and SFN from the NR-PSS/NR-SSS

and PBCH of NR cell. After LTE RRC connection is established, system information for initial SN configuration is provided to the UE by dedicated RRC signalling via the MN. Additionally, in non-standalone operation, upon change of the relevant system information of a configured SN, the network releases and subsequently adds the concerned SN cell (with updated system information).

2. SRB3 via SN: SRB3 can be used to send SN RRC Reconfiguration, SN RRC Reconfiguration Complete and SN Measurement Report messages. The objective is to provide a direct signaling link between NR Uu interface. Similar to one of the SRBs defined in TS 38.331, SRB3 uses NR-DCCH logical channel type, and the RRC PDUs on SRB3 are ciphered and integrity protected using NR PDCP, with security keys derived from S-KgNB. The SgNB selects ciphering and integrity protection algorithms for the SRB3 and indicates them to the MeNB within the SCG Configuration. There is no requirement on the UE to perform any reordering of RRC messages between SRB1 and SRB3.

3. Combined message handling: When both MN and SN reconfigurations are required, the SN RRC reconfiguration message is encapsulated in an MN RRC message that also carries the corresponding MCG reconfiguration that ensures the combined configuration can be jointly processed by the UE. The UE uses a joint success/failure procedure for messages in an encapsulating MN RRC message. A failure of the MN RRC messages, including one encapsulated SN RRC message with or without any MCG reconfiguration fields, triggers a re-establishment procedure. Each SN RRC reconfiguration message should have its own RRC response message even when the SN RRC message is encapsulated in an MN RRC message. And also, if a SN RRC reconfiguration message is contained in a MN RRC message, the UE sends a MN RRC response message that encapsulates the SN RRC response message.

Measurement: It can be configured independently by the MN (for inter-RAT measurement) and by the SN (intra-RAT measurements on serving and non-serving frequencies). As for the total number of measured carriers across E-UTRA and NR, it is assumed that MN and SN shall coordinate based on UE capabilities. Moreover, if MN and SN both configure measurements on the same carrier frequency, then the configurations need to be consistent. Measurement report can be delivered via SRB1 or SRB3 if configured.

3GPP is prioritizing the specifications for Option 3 NSA networks, scheduled for approval by December 2017 as part of Rel-15.

8.2 Uplink Strategies for NR deployment

As part of the Study Item for NR, 3GPP defined multiple scenarios for uplink connectivity between LTE and NR. This subsection will focus on Uplink strategies for NR deployment.

8.2.1 Uplink strategies for Standalone Operation

It is known that there is a coverage gap issue between DL and UL. For NR, the gap could be up to 7dB. Two possible uplink strategies can be considered in NR standalone deployments:

- High-band/low-band carrier aggregation: It follows LTE CA concept by aggregating high-band/low-band downlink carriers but only transmitting uplink via a low-band carrier. Since low-band carrier has better penetration characteristic, better uplink coverage can be achieved.
- Supplementary uplink (SUL): In SUL, one downlink is paired with two possible uplink carrier candidates (one is in low-band and the other is in high-band). Similar to CA concept, better uplink coverage can be achieved by selecting low-band carrier for uplink transmission. However, unlike CA concept, there is no direct reference from downlink carrier. Relevant PHY/protocol enhancements are needed, and the details are FFS. Regarding to SUL detail, please refer to Chapter 11.

8.2.2 Uplink strategies for Non-Standalone Operation

For Non-standalone operation, there is inter-modulation (IMD) issue for some specific band combination. For example, if LTE UL is @1.8GHz and NR UL is @3.5GHz, there could be a severe IMD interference to LTE DL @1.8GHz. Currently 3GPP prefer to consider the fall back to single uplink transmission for the problematic band combination, the details will be further specified later. Some further optimization may be considered, but may not be included within 3GPP Rel-15 NR specification:

1. Uplink transmission is alternating between two uplink carriers by semi-static TDM pattern.
2. LTE uplink and NR uplink both transmit onto the same LTE UL carrier, and uplink resource is shared in in TDM manner. In order to achieve this, sub-carrier alignment (shift 7.5kHz) to align the sub-carrier locations for LTE and NR will be necessary. Further details are still under 3GPP standardization process.

Since non-standalone operation is based on EN-DC model, two uplink Tx is the basic assumption. For two uplink transmission, power consumption is a concern. Regarding to the uplink power analysis and possible power reduction solution is discussed in Chapter 13.

9 Inter-RAT Interworking

9.1 NR mobility state transition

This section will look at LTE and NR interworking scenario as supported by 3GPP. LTE-NR interworking is important for standalone mode of operation between LTE and NR unlike for dual connectivity where there is simultaneous transmission across both RAT’s most of the time. Inter-working between LTE and NR is not expected to be significantly different from what is defined in LTE specifications for interworking with other 3G networks. The Inter-RAT mobility is expected to be supported both, in Idle mode as well as connected mode. Figure below illustrates possible mobility scenarios across LTE and NR.

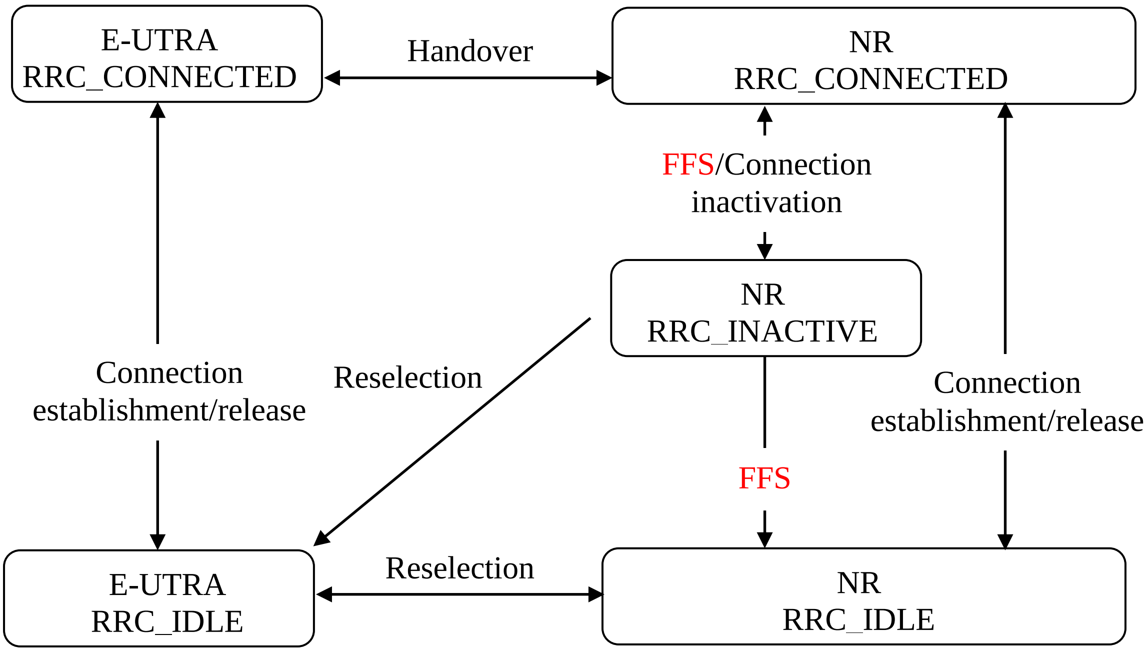

Figure 1-1 LTE-NR mobility state diagram

Connected mode mobility is expected to occur over 'Xn' interface between LTE eNB and NR gNB where both (eNB & gNB) are connected to 5GC core network. It is also expected that S1/NG (CN based) based Handover will be supported (SA2 decision pending) where LTE eNB is connected to EPC and NR gNB is connected to 5GC. Xn and CN HO over NG Core (eNB & gNB connected to 5GC) is supported by RAN2, which is transparent from UE perspective. Lossless HO is expected based on tight interworking between RATs when connected to 5GC core. Source RAT shall support configuring target RAT measurement and reporting for inter-RAT HO. High level call flow for both scenarios are illustrated in the figure below.

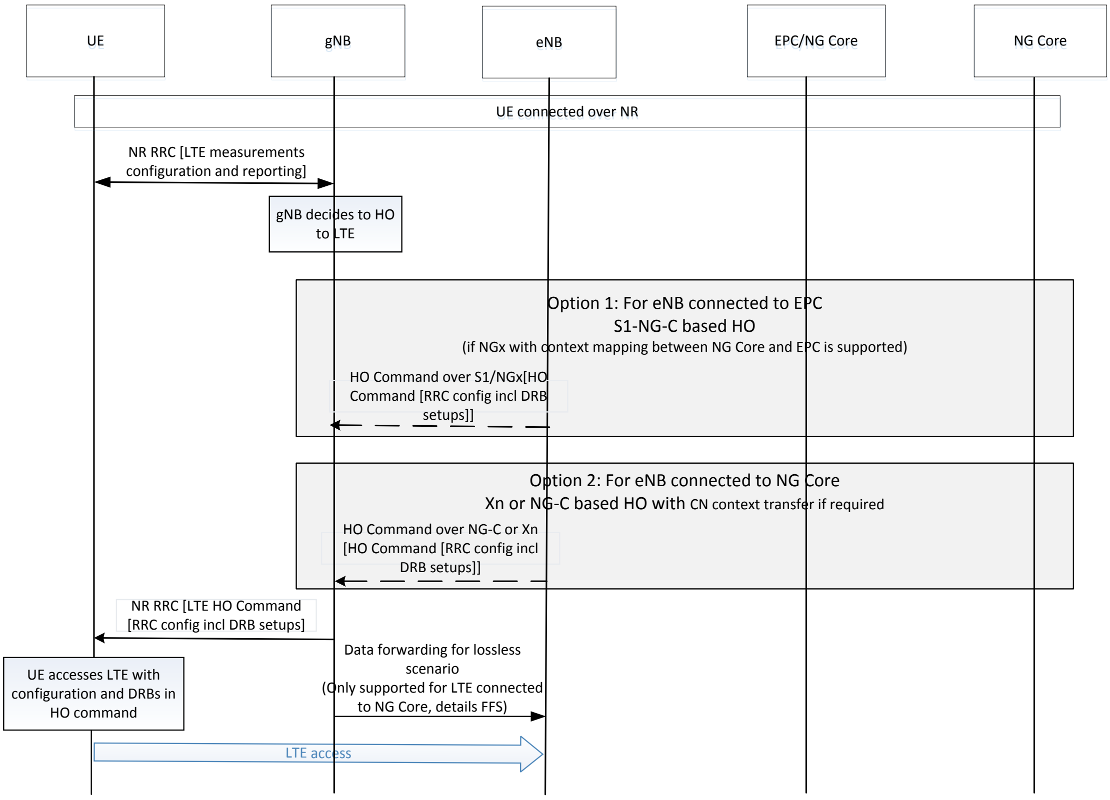

Figure 9-2 NR to LTE Connected state mobility

Interworking between NR and LTE is expected to also support both collocated and non-collocated site deployments.

For Standalone Option-2 handover between NR and LTE mode, in addition to RAN-level handover, CN change is also included. The procedures for inter-system change are described in sub-section below.

9.2 Inter-System Procedure

If the UE supports both 5GC and EPC NAS, it can support inter-system interworking and operates in either single-registration mode or dual-registration mode.

- In single-registration mode, UE is either in 5GC NAS mode or in EPC NAS mode. Therefore, UE is required to handle only one active MM state (either RM state in 5GC or EMM state in EPC).
- In dual-registration mode, the UE may be registered to 5GC only, EPC only, or to both 5GC and EPC. Therefore, UE is required to handle independent registrations for 5GC and EPC.

Because 3GPP SA2 already have clear preference to use single-registration mode, the following introduction will only base on single registration mode. N26 interface is an inter-CN interface between the MME and 5GS AMF in order to enable interworking between EPC and the 5GC. Support of N26 interface in the network is optional for interworking.

9.2.1 Interworking Procedures with N26 interface

Interworking procedures using the N26 interface enables the exchange of MM and SM states between the source and target network (i.e., between 5GC and EPC). When interworking procedures with N26 is used, the UE operates in single-registration mode.

Mobility for UEs in single-registration mode:

When the UE supports single-registration mode and network supports interworking procedure with the N26 interface:

- For idle-mode mobility from 5GC to EPC, the UE performs TAU procedure with EPS GUTI mapped from 5G-GUTI sent as old Native GUTI if the UE has a PDU session established or if the UE or the EPC support "attach without PDN connectivity". The UE performs an attach procedure if the UE is registered without PDU session in 5GC and the UE or the EPC does not support attach without PDN connectivity.
- For connected-mode mobility from 5GC to EPC, inter-system handover is performed.
- For idle-mode mobility from EPC to 5GC, the UE performs registration procedure with the EPS GUTI sent as the old GUTI.
- For connected-mode mobility from EPC to 5GC, inter-system handover is performed. During the Registration procedure, the HSS+UDM cancels any MME registration.

9.2.2 Interworking Procedures without N26 interface

For interworking without the N26 interface, IP address continuity is provided to the UEs on inter-system mobility by storing and fetching PGW-C+SMF and corresponding APN/DDN information via the HSS+UDM.

Mobility for UEs in single-registration mode:

- For mobility from 5GC to EPC, the UE that has received the network indication that dual registration mode is supported may either:
    - Perform Attach in EPC with Request type "Handover" in PDN CONNECTIVITY Request message and subsequently moves all its other PDU session from 5GC to EPC, or.
    - Perform TAU with 4G-GUTI mapped from 5G-GUTI, in which case the MME instructs the UE to re-attach. IP address preservation is not provided in this

case.

- For mobility from EPC to 5GC, the UE performs Registration of type "mobility registration update" in 5GC with 5G-GUTI mapped from EPS GUTI. The Registration Accept includes "Handover PDU Session Setup Support" indication to the UE. Based on this indication, the UE may subsequently either:
    - move all its PDN connections from EPC to 5GC, or
    - Re-establish PDU sessions corresponding to the PDN connections that it had in EPS. IP address preservation is not provided in this case.

For PDN connection transfer from EPC to 5GC:

- UE may register in 5GC ahead of any PDN connection transfer using the “Registration procedure without establishing a PDU session” in 5GC.
- UE performs PDN connection transfer from EPC to 5GC using the “UE initiated PDU session establishment” procedure with "Existing PDU Session" indication.
- If the UE has not registered with 5GC ahead of the PDN connection transfer, the UE can perform Registration in 5GC with "Existing PDU Session" indication in the PDU Session Request message.
- UE may selectively transfer certain PDN connections to 5GC, while keeping other PDN Connections in EPC.
- UE may maintain the registration up to date in both EPC and 5GC by re-registering periodically in both systems. If the registration in either EPC or 5GC times out, the corresponding network starts an implicit detach timer.
- When sending a control plane request for MT services (e.g. MT SMS) the network routes it via either the EPC or the 5GC.

10 Voice Solution

The voice service is not only a traditional and typical service but also a reliable and high quality telecommunication service, and it will continue to serve in 5G era.

The proposed basic principle and goal for voice service:

- IMS based
- Mobility and seamless continuity between 5G and 4G
- The interrupt duration up to 300ms

During the standard discussion, operators show different preferences on the network architecture options. For example, some operators show interests on Option 3 (Non-Standalone) which requires gNB connect EPC/LTE; and some operators show preference on Option 2 (Standalone) which 5GC connects gNB. More preference also be identified during the discussion since operators have different deployment strategies. We can foresee the 5G network might be much more complicated than the network we have now. This section looks at the potential voice solutions for the different network scenarios.

10.1 Potential solutions

Based on 3GPP Rel-15, we summarize the potential solutions as follows:

- VoNR
- EPS Fallback
- Dual Standby

For other network options, the voice solution might be different due to operators might have different deployment preference.

1. VoNR

Generally, the procedure of VoNR is similar with VoLTE with little updates.

UE reports the IMS voice capability and UE usage setting information to the AMF during the registration procedure, and then AMF requests the UE radio/RAN capability and Compatibility for IMS voice of PS session. The serving PLMN AMF is expected to send an indication toward the UE during the Registration procedure to indicate the availability of IMS voice over PS session.

To allow for appropriate domain selection for originating voice calls, the UE shall attempt initial registration in 5GC. If the UE fails to use IMS for voice, e.g. due to "IMS voice over PS session supported indication" indicates voice is not supported in 5G System, the UE behaves as described below for "voice centric" for 5GS or "data centric" for 5GS:

- A UE set to "voice centric" for 5GS shall always try to ensure that Voice service is possible. A voice centric 5GC capable and EPC capable UE unable to obtain voice service in 5GS shall not select a cell connected only to 5GC. By disabling capabilities to access 5GS, the UE re-selects to E-UTRAN connected to EPC first (if available). When the UE selects E-UTRAN connected to EPC, the UE performs Voice Domain Selection procedures as defined in TS 23.221.
- A UE set to "data centric" for 5GS does not need to perform any reselection if voice services cannot be obtained.

2. EPS Fallback

The Handover could be triggered by voice bearer establishment, gNB can initiate an inter-RAT HO procedure to EPC, or fall back the call to LTE. The voice will be delivered over

EPC if EPC supports VoLTE (In case EPC does not support VoLTE, the voice may be delivered over 2/3G via EPC).

3. Dual-Standby

From the experience from the early stage of LTE deployment, some dual-standby solutions like PS + CS solution (SG-LTE/SV-LTE) are reasonable before VoIP (VoLTE or VoNR) becomes mature. These solutions only require limited standard efforts and network investment but can provide stable voice in early stage of each generation.

As operators may need some time to deploy a 5G network to provide stable VoNR service, the dual-standby solution (e.g. PS+CS or VoLTE+NR concurrence) could be a promising way when operators start to deploy 5G network.

Generally, the dual-standby solution provides a single link for voice by CS or CSFB or VoLTE/SRVCC, and the rest link is for NR PS data. The dual-standby solution can be a single RF chain or multiple RF chain, and the UE can disable the data connection when voice link is activated and resume back when voice finishes.

Dual registration is one of the dual-standby solution which requires standard efforts before deployment.

10.2 Summary

For SA:

- Scenario 1: SA with N26 between AMF in 5GC and MME in EPC

  With the N26 interface between AMF and MME, the session can be seamlessly transferred from source network to target network when inter-system change occurs. The UE maintains a single registration for 5GC and EPC.

  The voice service can provided over 5G NR(VoNR) with single registration mode. If 5GS is not ready for VoNR, gNB can trigger the fall back to EPS and voice service can provided with VoLTE.

- Scenario 2: SA without N26 between AMF in 5GC and MME in EPC

  Without the N26 interface between AMF and MME, the session could not be seamlessly transferred from source network to target network when inter-system change occurs.

  In 3GPP, how to support voice is under discussion for the dual registration UE. when UE register on 4G and 5G concurrently, the session context maybe transferred and resumed by UE from source network to target network, but the session interruption duration depends on UE itself design.

For NSA:

In NSA, for example option 3, the dual connectivity would be supported, primary one for

CP(signal) over LTE an secondary one for UP(media) over NR. As to Voice service, the dual connectivity may be not required, and voice service would be provided on LTE connectivity with VoLTE.

11 RF Performance

11.1 High Power UE

11.1.1 Motivation

Due to different TX/RX configurations and network deployment between downlink (DL) and uplink (UL), for example, transmitted power and antenna numbers, 4G LTE coverage in general limited in UL. According to the evaluation done for LTE Band 41 Power Class 2 (+26dBm) [4], the coverage asymmetry could be up to 5 dB based on the network deployment parameters. To improve UL coverage, an effective way is to increase its transmitted power.

Based on some initial analysis of 5G NR link budget, it would suffer the same system bottleneck. Therefore operators proposed to specify both Power Class 2 (+26 dBm) and Power Class 3 (+23 dBm) UE in 3GPP RAN4 [5].

11.1.2 3GPP Status

Power Class 2 has been introduced to LTE Band 41 to enhance UL coverage. Currently, the NR work item of high power UE for 3.5 GHz frequency range has been approved in RAN4 and other bands such as n41 are expected to be added in the specifications as well. Several other topics will be evaluated in the following RAN meetings, including the co-existence of NR-to-NR and NR-to-LTE, UE TX/RX characteristics, and specific absorption rate (SAR) related issue, etc. The work plan is expected to be completed by March 2018 [6].

11.1.3 TX Front-end Status and Architecture for HPUE

Power amplifier (PA) would be the most critical FE component to support NR HPUE. In Table 11-1, preliminary power gain and maximum output power of 3.5 GHz PA from two vendors are summarized. Depending on different front-end architecture/component, the post-PA insertion loss will be different. However, around 4 to 6 dB loss should be a reasonable number at this frequency range. In that case, it is actually marginal or even not feasible to achieve 26 dBm antenna power with any one of these two PAs. We expect the PA Pmax should be further improved for NR HPUE application.

Table 11-1 Preliminary Power Amplifier Data in NR 3.5 GHz Band

Vendor	PA Gain (dB)	Pmax (dBm)
A	30	30.8

B	26	30

According to the agreement in 3GPP RAN4, NR non-standalone mode, i.e., NR and LTE dual connectivity, would be the first priority in Release 15. Figure 11-1 shows an example of front-end architecture that can support NR 2x2 MIMO and LTE dual connectivity. One of the advantage to have NR 2x2 MIMO is that 26 dBm transmitted power can be achieved with two Power Class 3 PAs, which significantly relieves PA Pmax requirement.

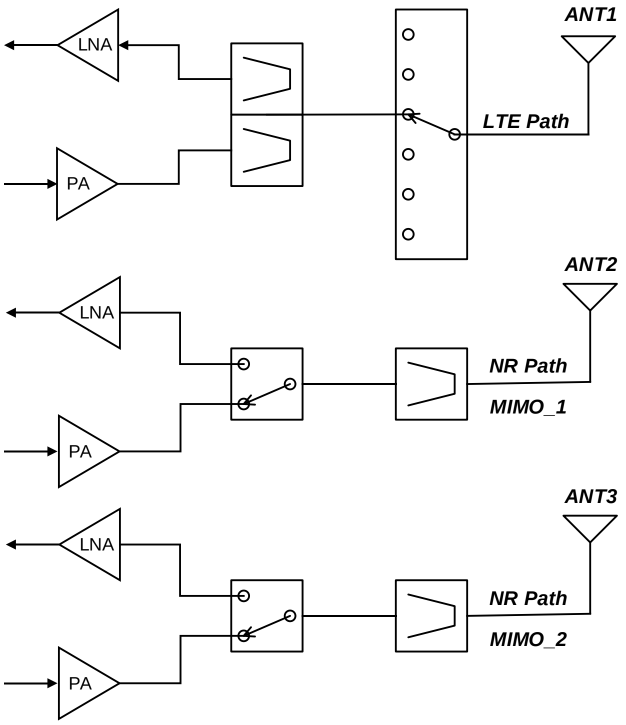

Figure 11-1 Example of front-end architecture supporting NR 2x2 MIMO and LTE dual connectivity

11.1.4 Consideration on Thermal for HPUE

It is intuitive that one side effect of HPUE is the total power consumption increase, especially from the power amplifier. Moreover, it is also expected that the power consumption of MODEM will increase significantly due to the wider transmission bandwidth in 5G NR. Thermal becomes a challenging issue from UE manufacturer point of view.

In this section, a preliminary thermal budget and the corresponding phone surface temperature was analysed based on a 5.5 inch phone model. The evaluation considers UE operating in NR NSA mode. The output power of LTE FDD TX is 23 dBm, while the output power of NR TDD TX is 23/26 dBm, as shown in Figure 11-2. Assuming a 45°C phone surface temperature design target in real network application, it can be seen in Table 11-2 that only the lowest NR UL duty cycle, 11.67%, can meet the requirement if UE TX transmits LTE 23 dBm and NR 26 dBm (23+23) simultaneously. On the other hand, when UE TX power is backed off to LTE 23 dBm and NR 23 dBm (20+20), then NR UL duty cycle can be increased to

31.67% as shown in Table 11-3. According to the analysis, it seems that total TX transmitted power of 26 dBm is more feasible for implementation. Another viewpoint is that the chance to continuously transmit maximum output power for a long period for an UE should be low in real network. Therefore, the data in Table and Table could be considered as worst case and define a relaxed target of 52°C phone surface temperature. Then the applicable NR UL duty cycle can be further improved.

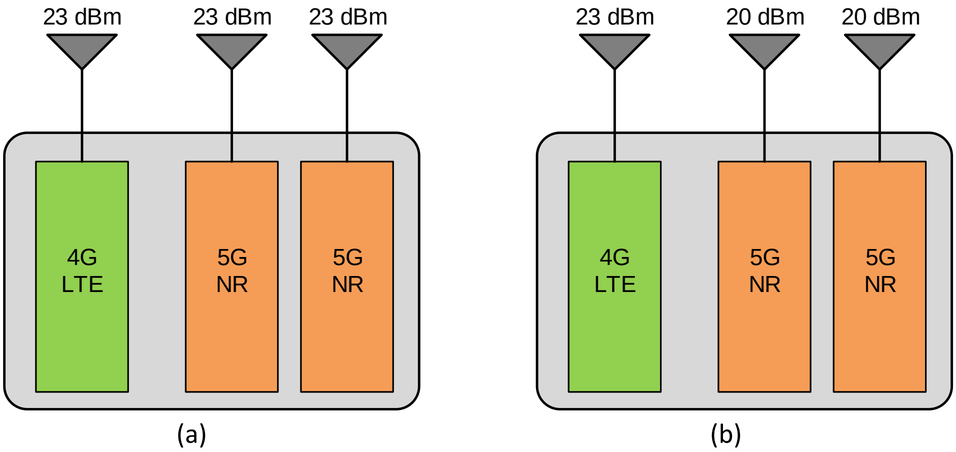

Figure 11-2 (a) Total transmitted power 27.8 dBm (LTE 23 dBm + NR 26 dBm) (b) Total transmitted power 26 dBm (LTE 23 dBm + NR 23 dBm)

Table11-2 LTE FDD (23 dBm) + NR TDD 2x2 MIMO (23 + 23 dBm)

LTE FDD 23 dBm NR TDD 23+23 dBm	NR UL Duty Cycle (Re-use LTE TDD Configuration)						
	63.33 %	53.33 %	43.33 %	31.67 %	23.33 %	21.67 %	11.67 %
Phone Surface Temperature (°C)	61.5	57.7	53.9	49.5	46.3	45.7	41.9

Table 11-3 LTE FDD (23 dBm) + NR TDD 2x2 MIMO (20 + 20 dBm)

LTE FDD 23 dBm NR TDD 20+20 dBm	NR UL Duty Cycle (Re-use LTE TDD Configuration)						
	63.33 %	53.33 %	43.33 %	31.67 %	23.33 %	21.67 %	11.67 %
Phone Surface Temperature (°C)	52.7	50.2	47.8	45.0	43.0	42.6	40.2

11.1.5 Consideration on SAR for HPUE

Due to the higher transmitted power than nominal Power Class 3 UE, SAR evaluation for NR HPUE is quite critical. In a similar fashion, UE with transmitted power of LTE FDD 23 dBm and NR TDD 26 dBm (63.33% UL duty cycle) is treated as a baseline. Please be noted that WiFi TX is also considered in this analysis. The results in Table 11-4 compare the SAR value varying with different NR UL duty cycle. The duty cycle has to be lower than 31.67% in order to pass the SAR limit, 2 mW/10g. In summary, a total TX transmitted power of 26 dBm is more practical in terms of SAR. Otherwise, the UL duty cycle would be quite limited.

Table 11-4 Body SAR Analysis – LTE FDD (23 dBm) + NR TDD 2x2 MIMO (23 + 23 dBm) + WiFi

	Total SAR (mW/10g)	SAR limit (mW/10g)	NR UL Duty Cycle
Body SAR	2.841	2	63.33 %
Body SAR	2.592	2	53.33 %
Body SAR	2.342	2	43.33 %
Body SAR	2.051	2	31.67 %
Body SAR	1.843	2	23.33 %
Body SAR	1.802	2	21.67 %
Body SAR	1.552	2	11.67 %

11.2 In-Device Interference

There are two basic deployment policies for 5G network depending on the preferences of each operator: standalone deployment and non-standalone deployment.

For standalone deployment, the NR system can work independently with LTE. Thus a single connectivity with NR network is the basic operation for the UE. In this case, single UL transmission mode is sufficient as baseline.

To further enhance the standalone deployment, there may be various ways for different targets, e.g.:

- Throughput enhancement: Carrier aggregation of NR-NR can be used to boost user data rate.
- Coverage enhancement: SUL (Supplementary Uplink) is using a lower-frequency carrier for NR UL transmission in addition to NR’s dedicated UL carrier. Due to the lower frequency, the UL coverage can be significantly improved by transmission on SUL.

For the above enhancements, UE may support simultaneous transmission of more than one UL in different bands, which may potentially lead to in-device interference.

For non-standalone deployment, UE should support the dual-connectivity of LTE and NR, where LTE carrier is always the anchor carrier. In this case, UE may also encounter the in-device interference issue.

In summary, except the standalone NR operation with one UL band, UE may suffer from in-device interference due to simultaneous UL transmissions in the non-standalone deployment and some enhancements of standalone deployment.

There are three different types of in-device interference due to simultaneous UL transmission over different bands:

- Interference from Harmonic

This kind of interference comes from the harmonic of lower- frequency UL signals to the higher- frequency DL signals when the harmonic of UL frequency falls into the DL frequency. Figure 11-3 shows the case with LTE on a lower- frequency carrier and NR on a higher- frequency carrier. One example is that when a UE is simultaneously transmitting on B3 (LTE) and receiving on NR sub-6G band B42 (3.4G~3.6G), interference from H2 of B3 will fall into NR receiver.

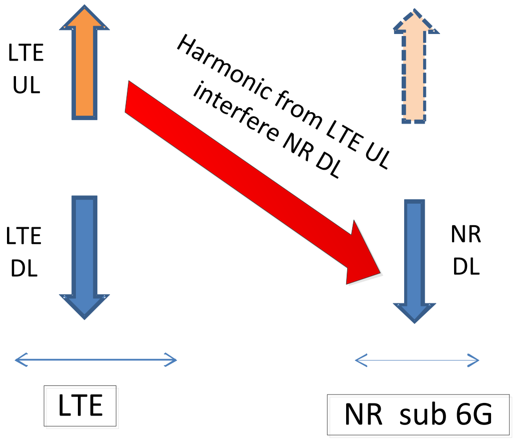

Figure 11-3 Illustration of interference from Harmonic

- Interference from Harmonic mixing

This kind of interference comes from higher frequency UL signals to the lower-frequency DL signals when the higher frequency is multiple of the lower frequency. Figure 11-4 shows the case with LTE on a lower- frequency carrier and NR on a higher-frequency carrier. One example is that when a UE is simultaneously transmitting on 3.3G~4.2G and receiving on LTE B26, interference from UL will fall into LTE B26 receiver and be demoded by receiver which causes sensitivity degradation.

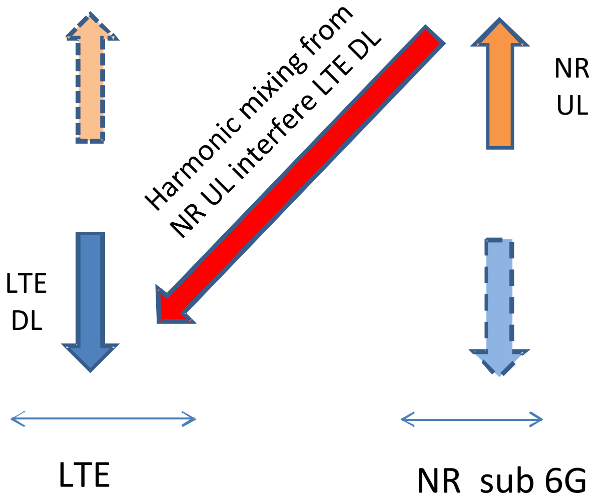

Figure 11-4 Illustration of interference from Harmonic mixing

To address the interference from Harmonic or Harmonic mixing, the main solution is based on the transmission coordination between UL and DL transmission. Two different approaches have been identified as the solutions:

- TDM
- FDM

It means NW can schedule the DL and UL to avoid the interference. However, these solutions will require the LTE NW and NR NW to share/exchange information, which may lead to some potential challenges in the multi-vendor deployment scenarios.

- Interference from Intermodulation (IMD)

This kind of interference comes from the intermodulation (IMD) product between lower-frequency and higher-frequency UL carriers which may fall into the DL carrier. Figure 11-5 shows the case with LTE on a lower- frequency carrier and NR on a higher-frequency carrier. One example is that when a UE is transmitting simultaneously on B3 (LTE) and NR sub-6G band (3.3G~4.2G), interference of IM2/IM4/IM5 will fall into B1 LTE receiver.

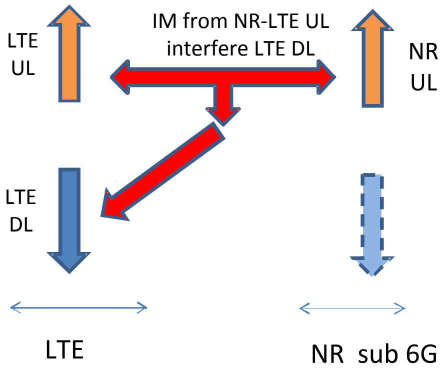

Figure 11-5 Illustration of interference from IMD

To address the IMD issues, there are some potential ways

- Spectrum allocation
- Single UL transmission

However, spectrum allocation is not always useful due to too many limitations. Thus single UL transmission has been agreed as an solution in 3GPP. Since the IMD interference is highly related to the band combinations, UE may support simultaneous UL transmissions for some band combinations while can only support single UL transmission for other band combinations. To facilitate NW's scheduling, UE can report its capability whether or not support simultaneous UL transmissions based on the band-combination basis, and NW decide the configuration/scheduling based on UE's capability report.

11.3 SUL

High frequency band provides massive resource for NR deployments. However, high frequency leads to larger pathloss and smaller coverage. For NR DL, there may be several alternatives to improve the coverage, e.g., larger base station transmit power, massive MIMO. In contrast, UL coverage will be more serious due to the limited transmit power of UE and limited number of transmit antennas. Thus there will be an imbalance between DL and UL coverage.

In order to improve the UL coverage, a lower-frequency carrier can be used for NR UL transmission in addition to NR dedicated UL carrier, where the lower-frequency carrier is a supplementary uplink (SUL). Some typical use cases are as follows:

- For a cell-center UE, NW can configure SUL for higher UL throughput.
- For a cell-edge UE, NW can configure SUL for UL coverage improvement when the NR dedicated UL carrier is unavailable.

A typical deployment is that NR carrier is on 3.5GHz and SUL is on 1.8GHz, where DL and UL are expected to achieve comparable coverage.

In addition to data transmission, SUL can be used for initial access. UE can choose SUL or NR dedicated UL to access the network based on its measurement and NW’s configuration.

To effectively support SUL operations, there will be more requirements for UE implementation, e.g.:

- Different RF chains: As the main motivation of SUL is to improve UL coverage, the SUL and NR dedicated DL/UL are usually in different frequency bands. Depending on the specific band combination, UE may need two different RF chains, each of which is for one frequency band.
- Synchronization of two UL chains: The PHY scheduling depends on various types of timing, thereby requiring synchronization of two UL carriers/chains.
- Simultaneous UL transmission: one is SUL and the other is dedicated UL.
- Dealing with different numerologies for different UL transmissions.

11.4 LTE and 5G NR RF path co-banding

Spectrum allocation in sub-6 GHz, in general, is very scarce and possibly requires co-existence of multiple RAT within the same / adjacent block of channels. In this section, support for LTE and NR within the same band or block of spectrum is discussed since it is expected to be legitimate scenario. For example, Band 41, 42/43 with such large spectrum block can be utilized for LTE and NR in the same band. This requires tight co-operation and interference mitigation amongst LTE and NR. Besides operator sharing band for LTE and NR, different operator may have deployed different RAT within a given band or block of spectrum, and hence could benefit from economies of scale due to sharing the same RF front end architectures between RATs. For example, Operator deploying LTE in Band 42 / 43 may currently face difficulties in terms of cost and availability/demand. Having other operators requiring to deploy 5G NR using the same band, would result in higher demand for RFFE components and hence larger economies of scale.

This following subsections will look at both scenarios of shared as well as dedicated RAT use for a given spectrum block.

11.4.1 Concept and Architecture of RF Path Co-banding

RF path co-banding refers to the scheme of sharing the same RF path (from the transceiver to the antenna) by carriers of different RATs (Radio Access Technologies), which operate with overlapped frequency range. In conventional UE designs, such as case of B1, single Tx RF path can transmit B1 LTE carrier and B1 WCDMA carrier; likewise single Rx path can receive signal for B1 LTE and WCDMA. In 5G NR system, the co-banding concept is applicable for the spectrum of 3.5 GHz as well 2.5 GHz in sub-6GHz range. That means LTE can share RF path with 5G NR working at these frequency bands. As an illustration, the spectrum range of relevant 3.5 GHz bands is as follows：

Table 11-5 3.5 GHz spectrum band

LTE Band number	UL	DL	Duplex mode
B42	3.4-3.6 GHz	3.4-3.6 GHz	TDD
B43	3.6-3.8 GHz	3.6-3.8 GHz	TDD
B48	3.55-3.7 GHz	3.55-3.7 GHz	TDD

NR Band number	UL	DL	Duplex mode
n77	3.3-4.2 GHz	3.3-4.2 GHz	TDD
n78	3.3-3.8 GHz	3.3-3.8 GHz	TDD

Actually B48 is within the frequency range of B42+B43， therefore analysis is focused on the co-banding between NR band n77/n78 and LTE B42/B43. A typical RF architecture for 3.5 GHz RF path co-banding is shown in Figure 11-6.

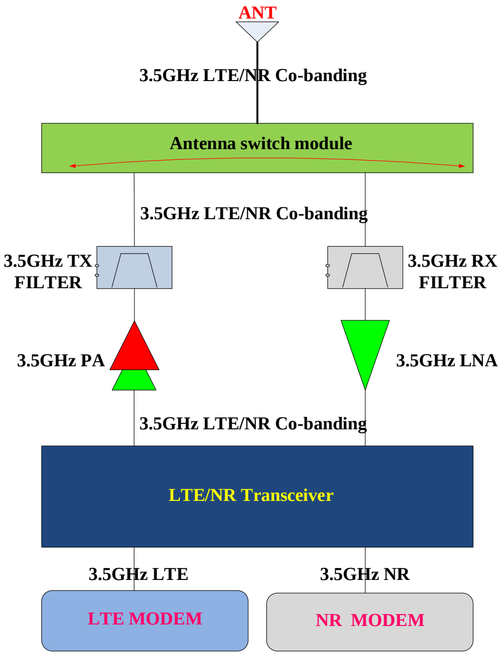

Figure 11-6 3.5GHz typical RF architecture

As shown in Figure 11-6, 4G LTE and 5G NR have separate modem. The co-banding path starts at the transceiver, through PA/LNA and the same filter/ switch/antenna. The advantage of RF path co-banding is obvious that the cost and PCB area are saved by sharing the same components, and the UE design can leverage the experience of 4G LTE and 3G WCDMA co-banding. On the other hand, there are plenty of challenges when migrating the design considerations from LTE/WCDMA co-banding to the LTE/NR co-banding, for example the increased bandwidth of NR compared to the LTE, the PAPR (Peak to Average Power Ratio) difference of uplink signal, etc., as analyzed in following sections.

11.4.2 System-level Challenges

At system level, the main challenges of LTE/NR co-banding come from the 5G NR requirements. The differences between 5G NR and 4G LTE include:

- Compared to the LTE system with a maximum channel bandwidth of 20 MHz, 5G NR has a higher maximum channel bandwidth of up to 100 MHz;
- Compared to the LTE system with the uplink carrier of DFT-SC-OFDM, 5G NR is to support both CP-OFDM and DFT-S-OFDM, and there will be a PAPR shift for CP-OFDM modulation on the baseline of LTE DFT-S-OFDM;
- Compared to the LTE system with the maximum RF output power of 23dBm, 5G NR is supposed to output a power up to 26dBm of power class 2.

Therefore the RF-path co-banding design needs to utilize a common path to reach different targets of LTE and 5G NR. A systematic approach is necessary to decompose the RF chain and analyze the impact to key components. The main considerations are presented next.

- Transceiver

A key challenge is to support the bandwidth up to 100 MHz with a single carrier. If the bandwidth of 100 MHz for a NR carrier can be supported, then the bandwidth of 20 MHz for LTE should not be the bottleneck. Furthermore, special attention should be paid to Tx noise/emission and Rx out of band blocking performance, with broadband filter configured for Tx and Rx.

- Power Amplifier (PA)

Both the channel bandwidth and the wide frequency range will be the challenge. For example, for NR band n77 's frequency range 3.3-4.2 GHz, it is quite difficult for a single PA to cover such a wide bandwidth of 900 MHz, compared to the bandwidth of 200 MHz in LTE B42 or B43. A suggested way is to split the full frequency range into two parts, and apply two PAs to meet the requirements, but this needs more investigations. About the single channel bandwidth, 100 MHz per NR channel requires much wider effective bandwidth possessed by biasing and supply feeding circuits, compared to 20 MHz in LTE case. That also necessitates schemes to mitigate the memory effect and ensure the linearity performance.

The exact maximum output power of 5G NR is to be determined by standardization bodies. Even if targeting at the same level as LTE power class, generating enough output power for such wide NR channel bandwidth is not easy task for the component vendors. Aforementioned 5G NR uplink will use the waveform of CP-OFDM, which has a much higher PAPR than SC-FDMA of LTE, necessitating higher peak power capability of PA. If the PA is specified as same power class for NR and LTE, its power added efficiency (PAE) in LTE mode will normally degrade due to operating away from relevant optimum output power level.

- Filter

In the co-banding scenario of 3.5 GHz LTE/NR, the total bandwidth of 900 MHz of n77 is problematic for conventional SAW/BAW filter design. Ceramic technology based filter is considered but the performance of insertion loss and out of band attenuation needs to be balanced. For a single carrier of 100 MHz, the challenge comes from the group delay parameter which typically degrades the uplink EVM performance.

- Low Noise Amplifier (LNA)

The main concern of LNA for 3.5 GHz LTE/NR co-banding is its gain and noise figure performance, due to the wide frequency range coverage. LNA commonly gets integrated into the transceiver, so this aspect shall be considered into the transceiver design as well.

- Antenna switch module

The power handling of ASM should cover the peak power of NR, which would increase the area, cost and design complexity of the switches. On the other hand, the switching speed need to be faster than LTE to satisfy the NR system requirements.

- Antenna design considerations for LTE/NR co-banding

  NR band n77's bandwidth of 900 MHz is significantly wider and more challenging than n78's bandwidth of 500 MHz; n77 deserves more attention than n78 accordingly. For NR band n77, its relative bandwidth percentage is 24.0%, which is close to the relative bandwidth percentage of 23.7% for the existing and common LTE mid bands ranging from 1710 MHz to 2170 MHz. Therefore, similarly, it should be achievable to enable efficient radiation for n77 by the solution of a single antenna. Besides, two separate antennas covering 3.3-3.8 GHz for n78 and 3.8-4.2 GHz for the rest of n77 respectively connected to the ASM directly and individually can be also the option to meet n77's wide-band requirement with the decent antenna efficiencies. However, when the architecture of two separate antennas is employed, the isolation between the two antennas should hence be taken into design consideration and overall performance balance. Last, no matter the architecture of the single antenna or two separate antennas is used, the risk of antenna isolation should not be ignored compared to the existing LTE architecture and placement because more antennas will be requested by sub-6 GHz 5G communication systems.

11.4.3 Way Forward on standalone support

The RF path co-banding of LTE/NR can better utilize the spectrum allocated globally and reuse the overall UE system architecture for simplification. As stated, there are challenges due to the new requirements of NR quite different from LTE. It will be valuable to investigate more into the system level analysis, component level design and practical implementation so as to achieve good RF performance with the co-banding of LTE/NR.

11.4.4 Co-banding with simultaneous operation

So far, the previous subsections focused on non-shared use of RF front end for a given spectrum block/band. Another important scenario is support for simultaneous operation of multi-RAT within a given block of spectrum. From a device architecture point of view, it may be possible to re-use / share the same RF front end architecture components / transceivers across different RATs within shared spectrum. However, there may be co-existence/interference concerns if multiple RAT are not synchronized in terms of DL / UL operation. This would require the device to adhere to in-band RF performance specifications as defined by 3GPP, while maintaining good spectral efficiency. Some of the key requirements are as follows:

In-band Emission (NR & LTE): Meet SEM requirements. MPR/AMPR values yet to be defined.

Adjacent channel selectivity (NR & LTE): 27 dB (LTE) and 33dB (NR)

ACLR (NR & LTE): 31dB for 20MHz channels. FFS for other CBWs

Guard band requirement (NR & LTE): FFS in 3GPP

In-band blocking: FFS in 3GPP

In-channel selectivity: FFS in 3GPP

Beside these adjacent channel requirements, co-channel deployment of LTE and NR may be possible. This would require a use of TDM approach between LTE and NR (using MBSFN subframes). However, this may have impact to overall system efficiency and hence, it is not recommended to use such deployment scenario.

12 Demodulation Performance

In some countries, several vehicles move with the speed over 300km/h, e.g., Japan Tohoku Shinkansen (320km/h), German ICE (330km/h), AGV Italo (400km/h), and Shanghai Maglev (430km/h). With the increase of high speed moving environment, the demand of using mobiles is growing larger. Therefore, it is important to guarantee the performance under the high speed scenarios.

High speed leads to high Doppler Shift, which may significantly decrease the demodulation performance of UE and affect user experience in the high-speed train scenario. For 5G, the UEs' demodulation performance should meet the relevant requirements of 3GPP in the scenarios where the mobility speed is up to 500km/h. In Table 12-1, we calculate the Doppler shift under different speed and frequency. For 3.5GHz, the scope of Doppler Shift is up to ±1620 Hz with 500 km/h mobility speed.

Table 12-1 Doppler shift under different speed and frequency

Speed (km/h)	Doppler shift (Hz)		
	1.9GHz	2.6GHz	3.5GHz
100	176	241	324
200	352	481	648
300	528	722	972
350	616	843	1134
400	704	963	1296
450	792	1083	1458
500	880	1204	1620

In order to have better network performance, dedicated network is deployed along the high speed railway. To avoid interference, separate carriers are utilized for dedicated network and public network. To avoid frequent handover, cell combination is applied: multiple RRHs are connected to one BBU with fiber. The coverage of a single cell can be extended significantly, and no handover is necessary within several RRUs belonging to the same BBU. Figure shows the dedicated high speed train scenario in our network. [14]

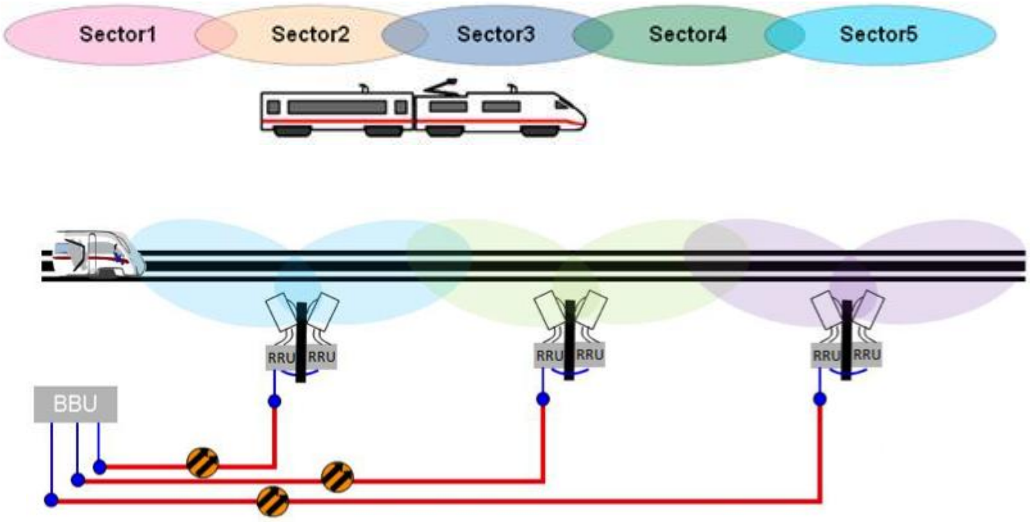

Figure 12-1 Dedicated high speed train scenario

The above high speed scenario has multiple taps. The UEs' demodulation performance should meet the needs of multi-path signals with opposite Doppler Shifts.

As a summary, high speed train scenario is a changeling scenario for demodulation. However, through carefully designed reference signal and receiver algorithm, most of the negative impact can be mitigated. More future studies are needed for NR demodulation.

13 Power Consumption

13.1 Introduction

The main topic of this chapter is the changes that we might expect to see in the power consumption of the NR modem compared to its predecessors. In the UE as a whole, significant power may also be consumed in the display and the applications processor, but these will not be considered here, other than to mention that higher data rates in the modem are likely to be accompanied in the UE by higher resolution displays and graphics engines driven by faster applications, and these will also have an impact on UE power consumption.

The modem becomes a significant contributor to the power requirement once connectivity is involved, and can be the dominant user of power when data rates are very high, or when channel conditions are poor. The challenge facing NR is not simply to deliver higher instantaneous data rates, but to ensure that data transfer happens in an energy efficient way whether the average data rate is very high or very low. In this section we will be taking a closer look at the factors affecting the power requirements of the NR modem in different use cases, and some of the ways in which the UE and the network can help each other to ensure that the energy in the UE battery is used as efficiently as possible.

13.2 Key scenarios and performance metrics

The power consumption in a UE depends on a number of variable factors, among them the radio environment between the UE and the gNB, user data throughput and usage patterns, quality of service requirements, network coverage provision and user mobility. A user on the edge of a cell will inevitably experience slower throughput and higher power consumption than one who is near a gNB and has a good multipath environment. For a better understanding of UE power consumption patterns it is helpful to standardise environmental factors as far as possible and look at a few simple scenarios.

13.2.1 A figure of merit (FOM) for power consumption

The simplest case to consider is that of maximum power consumption, which occurs when the modem is receiving and transmitting data at the maximum rate, with transmit power set to the maximum level. If the transmit power is kept constant, a reduction in uplink data rate will not have a significant effect on power demand, as the power is simply redistributed among fewer bits. Unless the UE is sufficiently close to the gNB that the transmit power level can be reduced, this configuration represents the most energy-efficient mode of transferring data, and dividing the total power drawn from the battery by the UE downlink data rate gives a representative figure of merit, which for current LTE UEs might be of the order of 1nJ-10nJ/ received bit [13]. The precise figure would vary with UE category and model - it could be higher than the stated range, but the power required from the battery for uplink transmission alone means that it is unlikely to fall below 2nJ/bit for an LTE handset. It should be noted that even at 1nJ/bit, an NR UE operating at 4Gbps would have a power consumption well in excess of 4W, after adding in the power for the display and applications processor. An average UE battery today has a capacity of around 12Wh, so this rather extreme use case would only allow a maximum of 3 hours of continuous use before recharging.

But most users who do not have exclusive occupancy of the cell will only experience the maximum throughput in short bursts – if the throughput reduces to 200Mbps, can we expect a 95% reduction in UE power consumption? A 200Mbps connection at 200mW would allow nearly 60 hours of data transfer (up to 40Tbytes) on a 3000mAh battery before recharging, which most of today’s users would find very attractive.

13.2.2 The power vs latency trade-off

Sadly the answer to the question in the previous paragraph is no – there are some unavoidable energy costs in the UE that worsen the figure of merit as the data rate falls - but using some of the features of NR with cooperation between the UE and the network we could come close in some cases. The main reason for reduced energy efficiency of data transfer at lower rates is that the UE does not know when incoming data will be arriving, so it needs to monitor the control channel frequently to find out when data is present. It also has to receive the data channel at full bandwidth for at least as long as it takes to decode the control channel, in case the control channel carries a data assignment. If there is a low latency requirement (sub-1ms), it might be necessary do this in every TTI, which is detrimental to power consumption when data rates are low.

In LTE, the downlink assignment has always been sent in the same TTI as the associated data. NR introduces the possibility of cross-slot scheduling, where the assignment can refer to the next TTI, or a later one [14]. This can help the UE to save power in two ways – firstly, in control-only periods, it can turn off its receivers as soon as the control channel symbols have been captured, and secondly, the control channel can be transmitted over a reduced bandwidth, allowing the UE to sample and process at a reduced rate for those TTIs in which the data channel is not needed. The combination of these two features means that receiving the control channel can be much more power efficient, and full bandwidth reception and processing is only needed when there is actually data present. The penalty is an increase in latency of at least one TTI, but since NR can accommodate shorter TTIs than LTE, sub-1ms latency is still achievable. This is illustrated below in Figure , the upper graph showing the UE power profile with same-slot scheduling and the lower graph showing the savings that result when cross-slot scheduling is enabled.

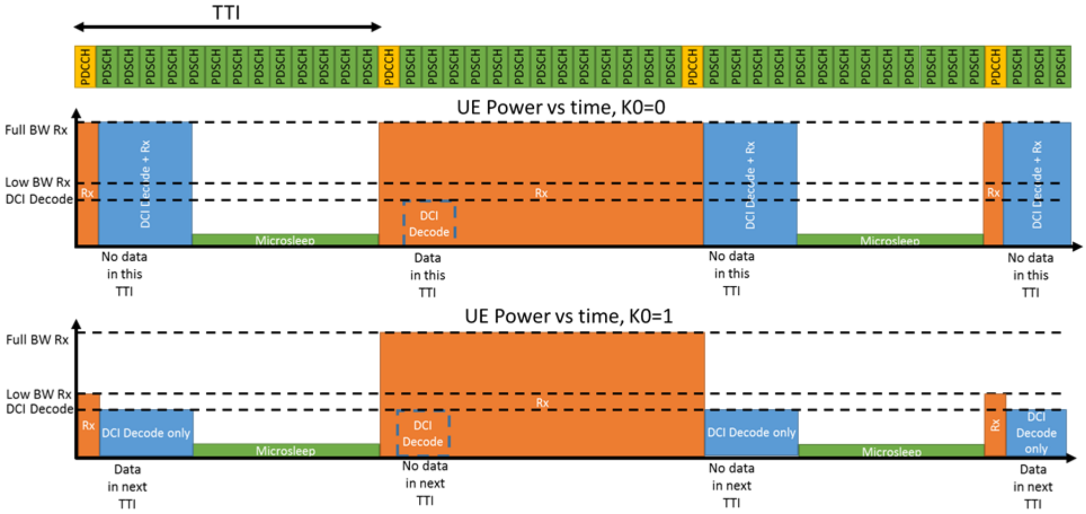

Figure 13-1 Power saving from Cross-slot scheduling

Where the latency requirement can be relaxed, further power savings can be made by implementing a DRX cycle. This will reduce the active duty cycle for control channel-only monitoring, and if cross-slot scheduling is active then data channel reception is only needed when UE data is present. With this configuration the modem might spend 90% of its time in a low power sleep state, with corresponding power savings, but the penalty would be substantially increased latency – perhaps several 10's of milliseconds. For many popular applications (social media, YouTube, file transfer….) strict low latency is not a user requirement, and most users would find this a price worth paying for increased battery life.

For other applications, practical considerations sometimes impose a lower limit on the latency that can be tolerated. For example, in high quality audio or video telephony, round trip delays of more than 100ms or timing offsets between the audio and video streams can become very noticeable, and since speech is processed in frames of 20ms duration a latency of one or two speech frames is significant. Semi-persistent scheduling can reduce the level of signaling required, but even so it would be necessary to process the control channel and data channel at least once every 20 or 40 ms.

13.2.3 Achieving power efficient VoNR and ViNR

Today's UEs (2G, 3G or 4G) claim talk times of up to 30 hours for voice calls, and setting this against the typical battery capacity this equates to an average power consumption of around 300-400mW. When moving from LTE to NR it is important to remember that the energy cost of processing one TTI at 100MHz will be higher than the cost of processing a TTI of the same duration at 20MHz, even though the energy per bit will be lower. Shorter NR TTIs will help in this respect, but the key to low power consumption for NR voice will be to keep the data that the UE has to process for a voice call to a minimum.

If power consumption for VoNR (Voice/video over NR) is to be competitive with VoLTE and older technologies, bandwidth adaptation will be highly desirable to make the best use of the processing resources in the UE. If the network can deliver 4Gbps, then a single 250us TTI can deliver 1 Mbit of data, and if that happens once every 20ms (1.25% of network capacity), that is sufficient to support a high definition video connection. If all that is needed is a 250 bit speech frame, it makes no sense for the UE to receive and process the full bandwidth simply to discard 99.9% of the sampled data that is processed. It would be more power efficient to receive a narrower bandwidth containing the required resource blocks and sample and process these at a lower rate to save power.

13.2.4 Spectrum usage for NR

Fortunately for the first generation of NR UEs, most of the high bandwidth spectrum under 6GHz is found in TDD-only bands. This results in a tradeoff between uplink and downlink data rates, but it also means that receive and transmit will not both occur at the same time, reducing both the peak and the average power requirement in the UE. Even so, a UE operating at maximum throughput for prolonged periods (for example, when transferring large data files) may still experience a large increase in its internal temperature, and would then need to negotiate with the network to reduce its data throughput temporarily to allow its temperature to stabilise at an appropriate level.

These examples illustrate how some of the key features of NR can be used to adapt UE behavior so that power efficiency can be optimised to deal with the traffic that is present. Cross-slot scheduling allows more efficient use of the physical receive and transmit resources in the UE. Bandwidth adaptation means that irrelevant resource blocks can be excluded from the sampling process, resulting in a lower processing load, and DRX allows appropriate tradeoffs to be made between power consumption and latency.

In practice a single UE can carry several different types of traffic concurrently, and a fully optimised solution may require unacceptably high levels of signaling, or be beyond the capabilities of existing scheduling algorithms. The improvements that have already been made for NR include many of the building blocks that are needed to improve power efficiency - it will be up to network operators and UE manufacturers to use them wisely.

13.3 Power scaling from LTE to NR

The first mainstream NR UEs are likely to offer peak data rates of around 2Gbps downlink and 1Gbps uplink, with premium devices offering maybe 5Gbps downlink and 1.5Gbps uplink. Depending on the network rollout, these may be either non-standalone devices, using the LTE network as an anchor for initial access and mobility, but supplemented by one or more NR carriers for high data rates and low latency, or standalone devices which use only NR carriers.

13.3.1 Example power breakdown for an LTE UE

Figure 13-2 below shows a typical power breakdown for a Cat4 LTE UE in 2013 [11], with the LTE modem accounting for approximately 2.7W of the total. Since that time, smaller process geometries and design improvements have resulted in power savings in the modem, but over the same period higher throughput from carrier aggregation has increased the processing load, cancelling out many of the savings as the price for increased capability. Modem power consumption can still reach 3W or more (3nJ/bit at peak LTE data rates for the previously discussed figure of merit).

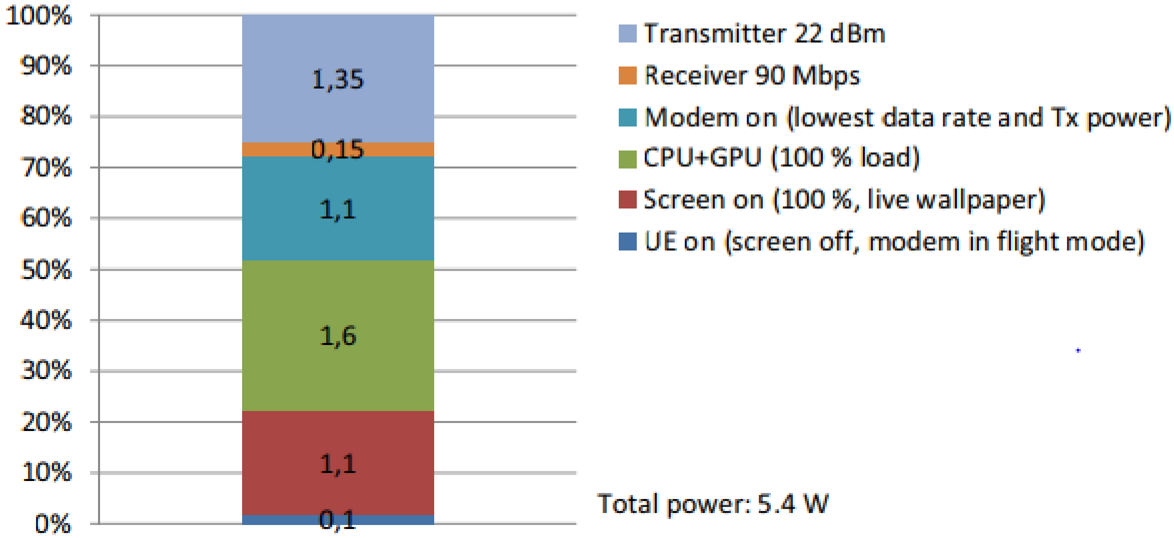

Figure 13-2 LTE UE power consumption

It is therefore of interest to consider how the modem power might scale with the move to NR and a 4 to 5 times increase in data rates, using the model described in the previous section.

13.3.2 RF front end

From 错误!未找到引用源。, 160mW of transmit power (22dBm) requires 1.35W from the battery, so for a 23dBm average we would need approximately 1.7W of battery power.

13.3.3 Transceiver subsystem

The transceiver for a non-standalone NR UE requires at least two LTE receivers (2x2 MIMO) and one transmitter. Additional LTE carriers may be supported for cases where there is no NR coverage, but in NR mode the total transceiver power will be minimised if the other active receivers and transmitters are assigned to NR carriers.

200MHz of NR bandwidth at 4x4 DL MIMO is needed for 4Gbps throughput – with 15 kHz subcarrier spacing the widest supported carrier is 50MHz and so 4 carriers would be needed, implying 16 receivers, and 4 synthesisers in receive mode, if the carriers are noncontiguous. With 30 or 60 kHz subcarrier spacing 100MHz carriers can be supported, meaning that only 8 receivers and 2 synthesisers would be needed. Achieving the required antenna isolation for MIMO operation at sub-6GHz frequencies may limit the number of independent antennas that can be offered in small-footprint devices. This in turn would restrict the total number of transmitters/receivers that could be supported.

The 150mW receiver power from Figure represents the power for 2 receivers and one synthesiser, together with the ADC and baseband interface. 16 receivers and 8 synthesisers (1.2W) is an overestimate of the power for the 15 kHz case (only 4 synthesisers are needed). If we allow for improvements in receiver efficiency since 2013, we might expect a receive mode power of around 800mW for the 15 kHz case and 400mW for the 30 and 60 kHz case.

Transmit mode power is harder to extract from these figures, but we need the same number of synthesisers in transmit mode as we do in receive mode, and 2x2 MIMO means we only need half the number of transmitters as receivers. For maximum power in the PA the power in a transmitter is likely to be higher than a receiver, so the corresponding figures in transmit mode might be 600mW for the 15kHz case and 300mW for the 30 and 60kHz cases.

13.3.4 Baseband processing

From **错误!未找到引用源。**, baseband processing accounts for 1.1W of power consumption in the 2013 handset, with most of the complexity residing in the downlink. A Cat4 LTE UE has a downlink throughput of 150Mbps – a straightforward scaling with data rate might lead us to expect that at 4Gbps, the modem power would increase to almost 30W.

However, the baseband for the UE measured in 2013 came from a 28nm silicon process, and NR UEs will be using smaller and more power-efficient geometries – a factor of 4 reduction from geometry scaling (not unrealistic) would bring this down to a slightly more manageable 7.5W. Further gains can be made from architectural improvements using more efficient processors and hardware accelerators.

In addition to this, the lower complexity of NR decoding should lead to substantial power reductions in downlink processing [16], and may bring the 1nJ/bit barrier within reach.

13.4 Managing UE power efficiently

The simple power model presented here suggests that NR UE power consumption at peak throughput may be higher than for an LTE UE offering lower throughput, but the energy per bit at maximum performance will be significantly better. The key to competitive NR UE performance will be how well the power consumption scales with data rate at lower throughputs. Most users do not currently require sustained high throughput for long periods, and experience with LTE devices indicates that for many typical use cases a significant proportion of UE power is spent monitoring the control channel during periods when user data is absent [18].

A UE that uses power efficiently needs to turn on receivers and transmitters only when necessary, and to discard any downlink data that is not intended for it at the earliest opportunity.

13.4.1 Overtemperature protection

With increasing peak data rates, UE overheating remains a possibility. A UE must have options to reduce its power consumption in a controlled manner without terminating connectivity if it experiences overtemperature as a result of prolonged high throughput.

13.4.2 Bandwidth adaptation

The sampling rate in the analog-digital interface has a direct effect on power consumption. Bandwidth adaptation can be used to confine the control channel for a specific UE or group of UEs to a narrow bandwidth which can be received with minimum resources at a lower sample rate to reduce the cost of control channel-only cycles where no data is present.

13.4.3 Cross-slot scheduling

Cross-slot scheduling allows similar savings can be made on the data channel, with receive and transmit resources only being enabled for the resource blocks that have been allocated. This can be particularly advantageous for data traffic consisting mainly of small packets, where receiving and processing over the full channel bandwidth may require disproportionate levels of power. The network can assist the UE in this respect by scheduling the UE resource block allocation appropriately, confining it to narrow bandwidths wherever possible.

13.4.4 Power vs data rate

With these features in place, power consumption for the UE then consists of two main components. The first is a baseline power level for control channel monitoring, which can be further reduced if the network sets a DRX cycle which is compatible with the latency requirements of the traffic. The second is a data component which is much more closely related to actual volumes of data traffic, and scales well as the data rate changes. This is illustrated in Figure 13-3 below.

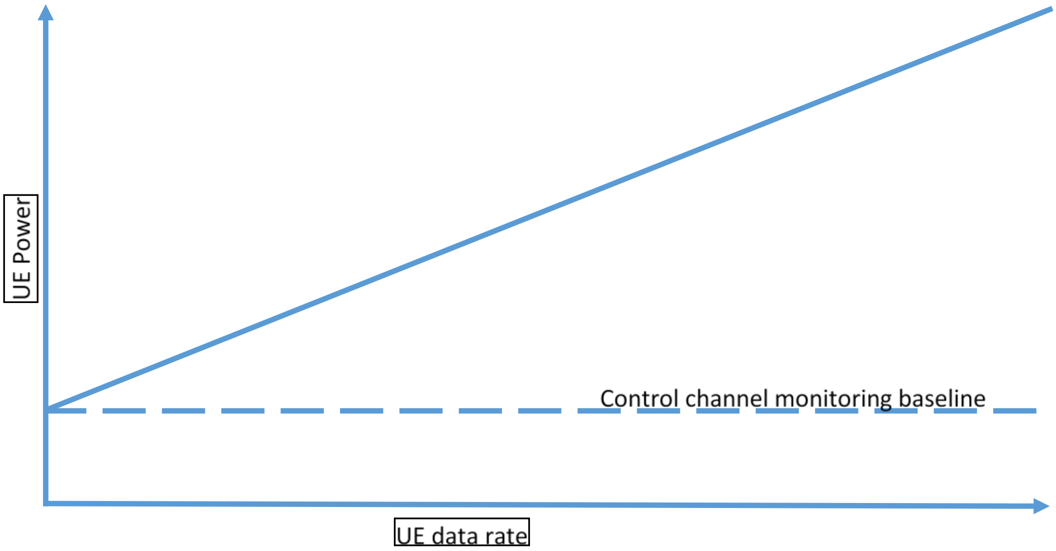

Figure 13-3 UE power variation with data rate

The behaviour illustrated can be applied equally well to uplink or downlink data. The baseline power intercept at zero data throughput is set by the control channel monitoring power, which is a function of the DRX cycle, channel bandwidth and the channel conditions. The maximum data rate in the downlink is set by the channel bandwidth, transmission mode, the coding rate, modulation scheme and the channel conditions, which also determine the downlink power at the maximum data rate. The maximum data rate in the uplink is also determined by these parameters, but may be further limited by the maximum power that the UE can transmit.

The power relationship is, however, not perfectly linear, because data is generally unevenly distributed over successive TTIs. Bandwidth adaptation can reduce power in those TTIs where the full complement of resource blocks is not used by the UE. The shared objective of the UE and the network should be to keep the baseline as low as possible and to minimize energy consumption on a per-TTI basis.

Full bandwidth reception of NR is likely to require more power than for LTE, owing to the higher sample rate and increased volumes of data across the baseband interface. For low data rate applications, such as VoNR, it will be important to take full advantage of bandwidth adaptation and scheduling options to ensure that power consumption in these scenarios remains competitive with older technologies.

If intensive data activity causes the UE temperature to rise unacceptably, it can request a temporary performance restriction from the network to allow its temperature to return to more normal levels. This restriction could be in the number of active carriers, the MIMO order, the bandwidth, the duty cycle or a combination of these – each would have the effect of reducing either the number of active resources in the transceiver, or the data bandwidth crossing the baseband interface, leading to a reduction in power consumption.

13.5 Implications for NR UEs

The analysis presented here is approximate, but it still allows us to draw some useful conclusions. Firstly, it seems likely that, at least for the first generation NR devices, a UE operating at 4Gbps will require more power from its battery than an LTE UE operating at 1Gbps or below, simply due to the increased processing requirement. However, if the two devices operate at comparable data rates, the NR UE will require less power, since it will have fewer receive and transmit resources active for less of the time, and there will be efficiency gains in the baseband processing.

In principle a standalone UE should consume less power than a non-standalone UE, requiring fewer receive and transmit resources for equivalent bandwidth. However, if both cases use an anchor carrier in the lower frequency bands for improved coverage, the anchor bandwidth would probably be significantly lower than 100MHz whether it was NR or LTE, and this would tend to reduce any differences.

Silicon processing advances continue to deliver improvements in power consumption, but at an increasing cost. The power requirement for downlink processing will reduce over time, although history suggests that future bandwidth increases will continue to present challenges for battery technology and thermal management in the UE.

Since average transmit power is limited by RF regulations, and the total carrier bandwidth is increased, there will be less energy per uplink subcarrier in the NR bands than in the LTE bands. TDD operation in the NR bands will allow the PA to increase its peak power output, and this may be necessary to maximise the coverage area over which full bandwidth uplink communication can be sustained. The average power will be kept within limits by adjusting the TDD duty cycle.

Most of today’s use cases can be accommodated comfortably if the user has reliable access to a 50Mbps data bandwidth, even allowing for the impact of high definition video on bandwidth requirements. Users will appreciate the benefits that higher bandwidth can deliver in terms of response times and file transfer speeds, but the single-user applications that stretch the capabilities of a multi-gigabit connection are probably still to be written. Power consumption in NR UEs will need to be competitive for all patterns of traffic from gigabits per second down to bits per second, and this will require cooperation between networks and UEs to match UE resource allocation to data traffic patterns in ways that allow the UE to reduce the data bandwidth that it has to process, and the time for which it is active, so that it can further optimise its power consumption. This will be particularly important when competing with established low data rate services such as voice telephony.

Networks that make the best use of the new features that NR offers to optimize UE power consumption will gain a competitive advantage, benefitting from more satisfied customers and increased revenues per user.

14 Test Requirements

With the implementation of 5G over the next decade, device manufactures will face new challenges in testing their hardware, software, and end-to-end deployments. 5G technology, as currently envisioned, is quite different from 4G and will bring together some of the most challenging aspects of existing test approaches and test equipment. It will also introduce new challenges, requirements and risks described further here.

14.1 Test areas for 5G sub-6G and challenges

Test solutions must evolve and adapt for 5G, effectively handling the three major use cases identified by 3GPP. It is obvious that 5G is not going to have a monolithic, one-size-fits-all deployment, and any test area, equipment and approach must reflect this. There will be very different requirements with regard to bandwidth, latency, radio characteristics, energy use and mobility.

14.1.1 Test challenges

Traditional device characterization in lower frequency devices has been limited to narrow band and Continuous Wave (CW) modes, but now it is expected that wide band modulated characterization of devices is required to ensure the device technology suitable for the new 5G waveforms. High bandwidth place challenging demands on components such as filters, mixers, power amplifiers and antennas that are used in mobile devices. To efficiently and reliably characterize these components, measurement systems must offer wide frequency coverage, high dynamic range, high output power, signal stability and signal quality with as little distortion and as few harmonics as possible.

14.1.2 Requirement for test equipment

Technological innovations combined with close and trustworthy customer relationships requires innovative test and measurement solutions that allow customers to launch their products more quickly, safely and economically.

Test equipment should be capable to generate and analyze wideband signals. Power amplifiers are crucial to link performance. By using CW and modulated stimuli to characterize power amplifiers (PA) in detail, test equipment should efficiently determine amplifier KPIs such as EVM, AM/AM plus AM/PM conversion and gain compression from a single measurement.

Besides providing sufficient measurement accuracy, test equipment need to keep the test cost low enough to meet the demands. Today’s market requires test solutions that address legacy technologies, while also supporting numerous verification requirements. Controlling the cost of test is the key attribute.

14.2 Device test cycle and test solutions

To develop a new product such as a wireless communication device, it will typically start with feasibility leading to development and implementation phase to commercial quality which will be tested against industry standards and specific customer requirements.

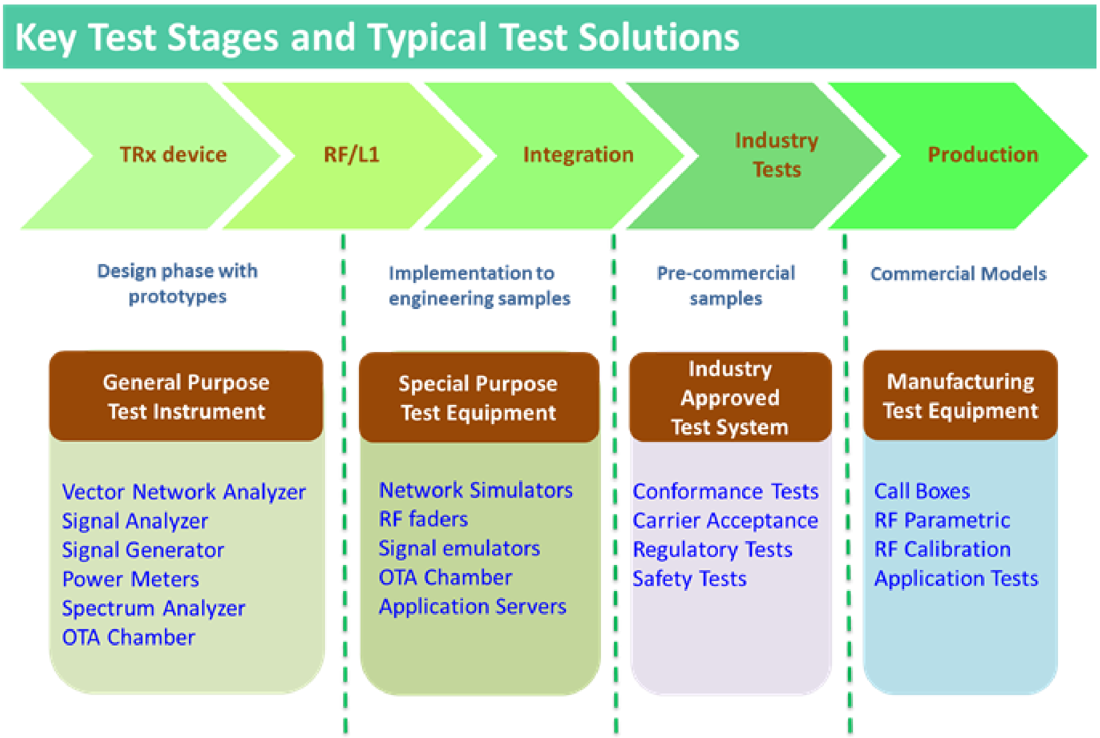

Figure 14-1 Stages of Test solutions

The above diagram illustrates the product development stages and the different test equipment and solutions required for each of the stages.

The initial stages tend to require general purpose test equipment which the test equipment vendors could develop based on the early of 5G requirements such as waveforms, modulations, etc. As the development stages progress, the complexity of the test solutions required would increase. Similar to the device development, the test equipment development would need to closely follow the development of the technical standards of 5G by 3GPP. The testing involved will move from basic tests to more focused tests for the different layers of the protocol.

The entire protocol stack would then be tested in an integrated form which would normally require industry defined tests, such as conformance tests specified by 3GPP RAN WG5 (RAN5). Test equipment vendors would typically work closely with RAN5 and other industry bodies such as GCF to provide test solutions to enable device manufacturers and operators to carry out such tests. In addition, the mobile operators around the world may have additional tests defined as Carrier Acceptance which they would require the device manufacturers to run.

When the new device development is complete and move into production, specific test solutions will be required to check the critical parameters and fucntions of the products for quality assurance purpose.

14.3 Risks

With any new technology, there will be the usual technical risks associated with a new design and problems encountered during the implementation. There is however some risks which are unique to the development of 5G NR.

The first major risk for 5G NR is whether the commercial service target will be met with working solutions. This is largely caused by the very tight timescale for the definition 5G specifications and the development of new devices following these specifications. For 3G and LTE, there was a period of about 4-5 years from the development of the 3GPP core specifications to the general commercial service launch. However, for 5G NR, the current plan suggests that this period will be reduced to 3 years. It means that the development of the new specifications and new devices, both user equipment and network equipment, will have to take place in parallel. The risk is particularly increased with the introduction of mmWave for the higher frequency bands. It is because mmWave is an entirely new technology for mass cellular mobile communication.

Many vendors are closely tracking the progress of the 3GPP core specifications in order to minimize the risks in developing their devices in parallel. Nevertheless, in order to meet the timescale, there will be a level of speculative development involved in trying to predict what may or may not be included in the 3GPP standards. The speculative nature means that the development team must build in flexibility in their design to allow rapid changes to be made at a later stage.

Another way to mitigate the risks is for the test equipment and the device vendors to work closely from early stages of the development. They will each independently monitor and interpret the output of 3GPP from each meeting. When working together, they can compare the understanding and cross validate with each other in order to have a better chance to arrive at a common correct interpretation. This will minimize the necessity of rework during development. It will also ensure a smoother path during the test phase.

The second key risk is the introduction of mmWave in a mass cellular communication network. mmWave as technology has been used in many high frequency applications such as satellite and short-range radio communication applications. But it has not been used in a highly dense and flexible cellular communication application where the geographical coverage will be wide and user behavior is extremely unpredictable. The industry has been doing extensive investigations on mmWave in the last few years to characterize it behavior in a cellular environment. Whilst these investigations are no doubt very valuable to assess the suitability and the risks, it is simply not possible to cover every eventual use cases involved. For this and other reasons such as costs of deployment, the initial application for mmWave operation tend to focus on fixed point-to-point such as home broadband where the geographical environment can largely be pre-determined.

15 Other Aspect

GTI Sub-6GHz 5G Device Whitepaper targets enhanced Mobile Broadband (eMBB) scenario for Sub-6GHz 5G pre-commercial and commercial products, which discusses Form Factor of 5G Devcie, Communication Function and Performance requirements and the hot topics of 5G Devcie Implementation. This document conducted to be the technical references for the development of chipset/device and the basis for the 5G pre-commercial and commercial products specs. According to the progress of 3GPP 5G NR standardization and the findings from the development and trials, there will be more key issues need to be discussed in the updated version of this Whitepaper in the next step.