GTI 5G Global device Whitepaper

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1 Executive Summary

This whitepaper identifies and explores the 5G multi-mode multi-band device requirements of wireless network operators and service providers deploying the latest generation of mobile broadband technology. By defining a common set of 4G/5G frequency bands, 2G/3G technologies and other capabilities that should be supported by the 5G multi-mode, multi-band mobile global roaming smartphone devices, the GTI anticipates that the development of a device eco-system and certification process will be accelerated, while regional deployments and roaming capabilities will be facilitated. In addition, the paper highlights certain key 5G technological requirements related to multi-mode mobility and MIMO support required by GTI operators.

Through surveys of GTI member companies, a set of recommended requirements was developed for the 5G multi-band, multi-mode device designs to meet the immediate needs of operators currently engaged in 5G network deployments as well as the longer-range needs of operators still in the planning phase of their 5G rollout. These recommended requirements include:

5G Bands: A total of 15 NR bands were identified based on GTI operator's survey. These are n77, n78, n41, n1, n3, n28, n66, n40, n79, n8, n71, n25, n38, n70 and n74. The mmWave frequencies will be updated later based on the progress of global spectrum allocation and operators' deployment plans.

LTE Bands: A total of 20 LTE bands were identified for inclusion in devices based on GTI operator's feedback. These are B3, B1, B8, B40, B7, B41, B2, B39, B42, B28, B71, B34, B5, B25, B66, B20, B38, B43, B70, and B11.

Air Interface Technologies: Support for TDD/FDD 5G NR in SA and NSA mode based on 3GPP Release 15 features, TDD / FDD LTE, 3G UMTS (in Bands 1,2,4,5 and 8) and 2G GSM/EDGE/GPRS (in Bands 2, 3 and 8), along with Wi-Fi, were identified as critical for the majority of GTI operators.

Voice and Data Applications and mobility: As both voice and data transmission capability were determined to be important to the majority of GTI operators and because, along with VoLTE and VoNR, 2G/3G technologies are expected to support voice services in many networks, , SRVCC, CSFB and EPS fallback mode support was identified to meet deployment needs. Devices are also expected to support handover and cell reselection / redirection for supporting mobility across various supported access technologies.

MIMO: The majority of GTI operators listed MIMO technology as essential for achieving the throughput and efficiency targets for 5G NR. Many bands require support for 4Rx. NR TDD bands shall also support 2Tx and UL MIMO. The channel state information shall be supported based on CSI-RS as well as SRS and device shall support SRS antenna switching (2T/4R or 1T/4R).

Product Requirement: Product requirements are expected to evolve in subsequent versions of this whitepaper, however, based on limited response from GTI operators, the device shall support IEEE (Wi-Fi) version 801.11a/b/g/n/ac/ax. The display shall support resolution up to 3168*1440 using OLED with refresh rate of 120Hz and screen size of 6.5-6.8”. The battery capacity shall be greater than 4000mAh for the initial devices.

Device testing: Testing is a crucial part of device development**.** 3GPP RAN5 has been developing TC for conformance. Such conformance testing certification is performed through various certification bodies such as GCF and PTCRB, depending on each operator’s preference. Each region may also have their own specific regulatory requirements for device performance in terms of Tx and Rx that every regional operator needs to abide by. In addition, each operator may define operator-specific testing for the device to operate optimally on their own network.

Device challenges and architecture: Global device definition and high levels of required performance make the architecture design challenging in areas such as support multi-mode, numerous bands, band combos for CA and ENDC, antenna switching, higher in-line losses, need for higher Tx/Rx performance, reduced PCB area while increasing need for more antennas, co-existence and improved battery performance. These complex challenges demand proper selection of components and performance tradeoffs to meet the global needs.

2 Abbreviations

Abbreviations	Explanation
3GPP	3rd Generation Partnership Project
5GC	5G Core
ACLR	Adjacent Channel Leakage Ratio
AMF	Access and Mobility management Function
AP	Application Processor
BP	Baseband Processor
BWP	BandWidth Part
CA	Carrier Aggregation
CBW	Channel Bandwidth
CP-OFDM	Cyclic-Prefix Orthogonal Frequency Division Multiplexing
CSFB	Circuit Switched FallBack
CSI-RS	Channel State Information - Reference Signal
CTIA	Cellular Telecommunications and Internet Association
DFT-S-OFDM	Discrete Fourier Transform spread Orthogonal Frequency Division Multiplexing
DRX	Discontinuous Reception
DUT	Device Under Test
EDGE	Enhanced Data rates for GSM Evolution
EN-DC	E-UTRAN New Radio – Dual Connectivity
EPS	Evolved Packet System
EUTRA	Evolved Universal Terrestrial Radio Access
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FR1	Frequency Range 1
GCF	Global Certification Forum
GERAN	GSM EDGE Radio Access Network
GPRS	General Packet Radio Service
GSM	Global System for Mobile
GTI	Global TD-LTE Initiative
GUMMEI	Globally Unique MME Identifier
GUTI	Globally Unique Temporary Identifier
HPUE	High Power User Equipment
HSS	Home Subscriber Server
IEEE	Institute of Electrical and Electronics Engineers
IMS	IP Multimedia core network Subsystem
ISM	Industrial, Scientific and Medical
LNA	Low Noise Amplifier

LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MM-MB	Multiple Mode - Multiple Band
MNO	Mobile Network Operator
MSC	Mobile Switching Center
NR	New Radio
NSA	Non-StandAlone
OEM	Original Equipment Manufacturer
OTA	Over The Air
PA	Power Amplifier
PCB	Printed Circuit Board
PDN	Packet Data Network
PDU	Packet Data Unit
PLMN	Public Land Mobile Network
PMI	Pre-coding Matrix Indicator
PTCRB	PCS Type Certification Review Board
QAM	Quadrature Amplitude Modulation
QOS	Quality Of Service
QPSK	Quadrature Phase Shift Keying
RAT	Radio Access Technology
RF	Radio Frequency
RFFE	Radio Frequency Front End
RFIC	Radio Frequency Integrated Circuit
ROHC	Robust Header Compression
SA	StandAlone
SAR	Specific Absorption Rate
SCS	Sub-Carrier Spacing
SMF	Session Management Function
SRS	Sounding Reference Signal
SRVCC	Single Radio Voice Call Continuity
TAU	Tracking Area Update
UDC	Uplink Data Compression
UDM	Unified Data Management
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
VOLTE	Voice Over LTE
VONR	Voice Over NR
WLAN	Wireless Local Area Network

3 Introduction

The Global TD-LTE Initiative (GTI) is an organization of wireless broadband operators worldwide cooperating in the promotion and development of a robust ecosystem based on the TD-LTE standard. Founded in February of 2011 by leading international mobile network operators, the GTI's 2.0 mission is to:

- Continue to promote development of TD-LTE enhanced technologies and global deployment
- Continue to enlarge the scale of converged TDD/FDD terminal and network
- Promote and utilize the advantages of TDD to facilitate 5G development
- Promote 5G unified standard and end-to-end ecosystem
- Explore 5G cross-industry market and opportunities

Initial 5G deployments occurred starting in mid-2019 and have been increasing at a pace that makes 5G, besides LTE, the fastest developing mobile communication technology ever. However, these early deployments have largely been uncoordinated and have occurred in an ever-increasing number of frequency bands, making the implementation of the RF portion of 4G/5G devices significantly challenging. To further complicate the device architectures, different mobile operators have different requirements with regard to support for voice services as well as interoperability with 2G and 3G networks.

Recognizing the complexity of developing devices that will address the disparate needs of 5G operators worldwide, GTI has formed several Task Forces to bring operators and vendors together for objectives such as sharing development strategies and technology know-how, expediting the development of terminals, and fostering global roaming and low-cost terminals. One of these Task Forces, called "5G Global Device", has focused on defining a common set of 5G bands and other device requirements in order to support regional deployments and roaming by accelerating the development of a device ecosystem, including a certification process.

A number of surveys of the GTI operators were conducted to identify and harmonize common device requirements, architectures, and multi-mode multi-band needs. These requirements constitute the foundation for designing and manufacturing global multi-mode multi-band devices serving the GTI community and beyond. This whitepaper is the culmination of the work of the 5G Global Device task force and includes individual sub-sections summarizing the survey results on the following topics:

- 5G bands and feature requirements
- LTE bands and feature requirements
- Multi-Mode 2G/3G support
- Support for voice services
- Support for MIMO configurations
- Testing and regulatory requirements

This paper is organized as follows:

- Section 4 focuses on GTI requirements for multi-mode multi-band devices in cellular networks, specifically for the smartphone which is the main global device form factors. Requirements are presented in key areas that affect smartphone design, architectures, and functionality such as; multi-band 5G-LTE support, support for legacy wireless technologies, voice and data services, MIMO configuration to be supported on those devices, interoperability and co-existence requirements. All these requirements were derived as part of an extensive operator survey.
- Section 5 addresses some of non-cellular product requirements that could be useful to implement GTI global device.
- Section 6 focuses on testing requirements in terms of conformance testing and regulatory testing. It also specifies national / operator specific requirements.
- Section 7 lists some of the device architecture recommendations and analyzes the challenges.
- Section 8 then summarizes key recommendations of this work and highlight future areas that GTI will focus on in order to achieve its goal and objectives.

4 GTI MM-MB Device Requirements

GTI has established a working group to analyze common operator requirements and harmonize device requirements, architectures, and multi-mode multi-band needs among its members. Those requirements constitutes the foundation for designing and manufacturing global roaming multi-mode multi-band devices serving the GTI community and beyond.

In order to gather GTI's operator requirements, a comprehensive survey was conducted gathering information on key technological areas that have a direct implication on device architectures and MM-MB support. In addition, the survey took into account various timeframe requirements (i.e. 2020, 2021/22) in order to use an incremental approach where applicable. It is well understood that device requirements and MM-MB support will evolve over time and such evolution, along with device market lifespan, should be considered when deciding global device requirements. The following requirement areas were covered as part of the survey:

- 5G bands and feature requirements
- LTE bands and feature requirements
- Multi-mode 2G/3G support
- Support for voice services
- Support for MIMO configurations
- Product requirements
- Testing and regulatory requirements

The following subsections of this paper summarize some of the survey results pertaining to the above mentioned areas.

4.1 LTE /3G / 2G Multi-Band Requirements

This subsection will summarize requirements as it pertains to the main LTE bands of interests, roaming LTE bands, and 2G/3G bands of interest, based on the deployment plans from GTI members.

4.1.1 LTE Multi-Band Requirements

Initial LTE deployments occurred in mid-2010, and since then the technology has been deployed at a pace that is makes it the fastest developing mobile communication technology ever. However, these deployments have happened in a disjoint fashion, with an ever increasing number of frequency bands which makes RF implementations of devices even more challenging. In this context, GTI's has engaged with its operator base - a base that today encompasses more than one billion customers - to define a common set of multi-mode multi-band device requirements in order to accelerate the creation of global device ecosystems and device development by maximizing economics of scale.

Table 4-1 summarizes the operator responses regarding their immediate needs for LTE band support as well as what is expected to be needed by 2021 and beyond.

# of Operators	LTE Band	TDD/FDD	Band name	DL Freq	UL Freq
5	B3	FDD	1800	1805-1880	1710-1785
5	B1	FDD	2100	2110-2170	1920-1980
4	B8	FDD	900 GSM	925-960	880-915
3	B40	TDD	2300	2300-2400	
3	B7	FDD	2600	2620-2690	2500-2570
3	B41	TDD	2600	2496-2690	
2	B2	FDD	1900 PCS	1930-1990	1850-1910
2	B39	TDD	1900	1880-1920	
2	B42	TDD	3500	3400-3600	
2	B28	FDD	700	758-803	703-748
2	B71	FDD	600	617-652	663-698
1	B34	TDD	2000	2010-2025	
1	B5	FDD	850	869-894	824-849
1	B25	FDD	1900	1930-1995	1850-1915
1	B66	FDD	AWS-3	2110-2200	1710-1780
1	B20	FDD	800	791-821	832-862
1	B38	TDD	2600	2570-2620	
1	B43	TDD	3700	3600-3800	
1	B70	FDD	AWS-4	1995-2020	1695-1710
1	B11	FDD	1500	1475.9-1495.9	1427.9-1447.9

Table 4-1 LTE Bands - GTI operator survey

Thus, a total of 20 LTE bands have been requested by GTI operators for the 5G Global device.

4.1.2 2G/3G Multi-Band Requirements

The global device supporting 5G/LTE should also be compatible with 2/3G mode at the initial stage of deployment, which means not only support for 5G and LTE bands but also 2/3G bands are required by GTI members. Some 2/3G bands are re-farmed for LTE deployment, and can co-band with LTE in the device, which will not necessarily cause any additional increase of cost.

Table 4-2 below summarizes the survey results in this area. Based on survey results, GSM/EDGE/GPRS/UMTS constitute the 2/3G technologies required by GTI for global configuration devices.

Technology	Bands
2G GSM	B2, B3, B8, B5 (optional)
3G UMTS	B1, B2, B4, B5 and B8

Table 4-2 2G / 3G Bands - GTI operator survey

Thus, the GTI global multi-mode multiband device shall require support for 4 GSM bands and 5 UMTS bands.

4.2 5G Multi-Band Requirements

GTI along with its partners, is focused on promoting a global 5G Ecosystem and exploring cross-industry market opportunities.

Since 5G specifications were first released, there has been rapid deployment of 5G networks around the world. These initial launches have provided good insight on 5G network, base station, and device performance and capabilities. They have also helped further understanding of the challenges of a 5G device design and implementation.

This subsection will define common devices requirements as pertains to the main 5G NR SA bands of interests, roaming 5G bands, and EN-DC combos, based on 5G deployment plans from GTI members.

MULTI-MODE:

A 5G UE should support both standalone (SA) and non-standalone (NSA) 5G operations. For NSA 5G operations, LTE carrier(s) are mandatory to be the anchor carrier for 5G UEs. In addition to LTE and 5G, some operators around the globe may rely on 3G and 2G services, as seen in section 4.1.2.

Non-independent network architecture (NSA) Option 3X has been the first choice all over the world for 5G deployment, followed by independent 5G network architecture (SA) Option 2;

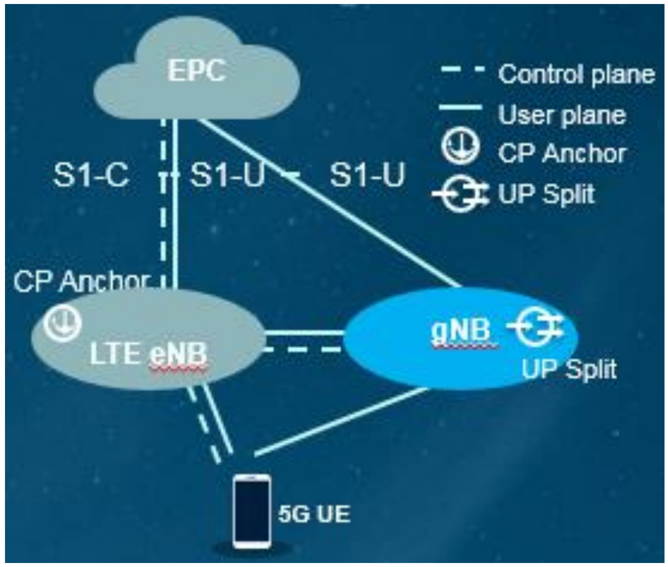

Figure 4-1 Option 3X - User plane connection to the EPC via gNB

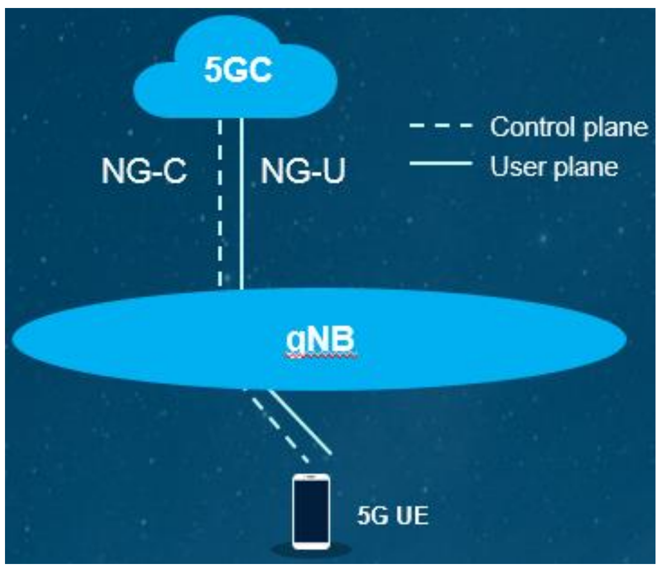

Figure 4-2 Option 2: 5G independent network

a. Devices and Chipsets:

From Table 4-3 it is clear that NSA/SA multi-mode chipsets are available to the open market. And also there are multiple 5G NSA/SA multi-mode terminals available or announced.

Vendor	Chipset	Frequency	5G Mode
Hisilicon.	Balong 5000	SUB 6G 200Mhz mmWave 800Mhz	NSA/SA
Hisilicon.	Kirin 990	SUB 6G 100Mhz	NSA/SA
MediaTek	Helio M70	SUB 6G 200Mhz	NSA/SA

MediaTek	Dimensity1000	SUB 6G 200Mhz	NSA/SA
Qualcomm	X50	SUB 6G 100Mhz mmWave 400Mhz	NSA
Qualcomm	X55	SUB 6G 200Mhz mmWave 800Mhz	NSA/SA
Samsung	Modem 5100	SUB 6G 100Mhz mmWave 400Mhz	NSA/SA
Samsung	Modem5123	SUB 6G 200Mhz mmWave 800Mhz	NSA/SA
Samsung	Exynos 980	SUB 6G 100Mhz	NSA/SA

Table 4-3 Chipset Information from Open Information source

The 5G UE should support some or all of the following access technology modes to meet global operator's requirements:

- 5G NR: SA (standalone) and NSA (non-standalone)
- 4G: TD-LTE, FDD LTE
- 3G: UMTS
- 2G: GSM/EDGE/ GPRS

5G MULTI-BANDS:

5G needs spectrum across low, mid, and high spectrum ranges to deliver widespread coverage and support all use cases. All three band ranges have an important role to play:

- **Low bands** (e.g. sub-1 GHz) support widespread coverage across urban, suburban, and rural areas and help support Internet of Things (IoT) services.

- **Mid-High bands** typically offer a good mixture of coverage and capacity benefits. Bands which may be assigned to or refarmed by operators for 5G include 1800 MHz, 2.1GHz, 2.3 GHz, and 2.6 GHz. In the long term, more spectrum in this band is needed to maintain 5G quality of service and growing demand.

- **C bands** networks are relying on spectrum within the 3.3-3.8 GHz range. Other bands which may be assigned for 5G include 3.3-4.2GHz or 4.4-5GHz, which can support wider channel bandwidths.

- **mmW bands** are needed to meet the ultra-high broadband speeds envisioned for 5G. Currently, 26 GHz, 28 GHz and 40 GHz have the most international support and momentum.

The specific requirements for mmWave will be updated later according to the progress of global spectrum allocation and operators' deployment.

4.2.1 Standalone Requirements

A standalone NR deployment configuration would not require an associated LTE network. The NR-capable UE uses random access to directly establish a radio link connection with a gNB, and attach to the 5GC to establish service. This would require support for new sets of interfaces and core network as compared to most initial non-standalone deployments. This subsection would provide key UE requirements to be supported in Standalone mode:

5G NR SA Bands:

Based on globally auctioned spectrum, operator's refarming plans, and GTI survey response, GTI has identified the lists of overall 5G NR bands as shown in Table 4-4 below.

# of Operators	NR Band	TDD/FDD	Band name	DL Freq	UL Freq
4	n77	TDD	3700	3300-4200	
4	n78	TDD	3500	3300-3800	
3	n41	TDD	2600	2496-2690	
3	n1	FDD	2100	2110-270	1920-1980
3	n3	FDD	1800	1805-1880	1710-1785
3	n28	FDD	700	758-803	703-748
2	n66	FDD	AWS-3	2110-2200	1710-1780
2	n40	TDD	2300	2300-2400	
2	n79	TDD	4700	4400-5000	
2	n8	FDD	900	925-960	880-915
2	n71	FDD	600	617-652	663-698
1	n25	FDD	1900+	1930-1995	1850-1915
1	n38	TDD	2600	2570-2620	
1	n70	FDD	AWS-4	1995-2020	1695-1710
1	n74	FDD	L- Band	1475-1518	1427-1470

Table 4-4 NR Bands - GTI operator survey

A total of 15 NR bands have been requested by GTI operators for the 5G Global device.

In addition, GTI operators have also recognize some potential SUL bands as well for the 5G global device: n80 (UL Freq 1710 MHz – 1785 MHz) and n84 (UL Freq 1920 MHz – 1980 MHz).

SCS and CBW:

The maximum transmission bandwidth configuration N_{RB} for each UE channel bandwidth and subcarrier spacing is specified in Table 4-5.

Devices need to support 15 KHz SCS for NR FDD bands, and 30KHz SCS for NR TDD Bands.

SCS (kHz)	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	30 MHz	40 MHz	50 MHz	60 MHz	70 MHz	80 MHz	90 MHz	100 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
15	25	52	79	106	133	160	216	270	N/A	N/A	N/A	N/A	N/A
30	11	24	38	51	65	78	106	133	162	189	217	245	273
60	N/A	11	18	24	31	38	51	65	79	93	107	121	135

Table 4-5 Maximum transmission bandwidth configuration N_{RB}

MCS:

The 5G UE should support QPSK, 16QAM, 64QAM and 256QAM on Downlink and Uplink across various supported bands.

The device shall also support π/2-BPSK MCS on uplink.

OTHER REQUIREMENTS:

Device shall support 3GPP Release 15 specification.

Device shall support CP-OFDM and DFT-S-OFDM waveforms on Uplink.

Device shall support data compression techniques such as RoHC. Support UDC (Rel 17) when available.

4.2.2 EN-DC / Multi-Mode Requirements

NSA / EN-DC is 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 was used to combine the coverage advantage of existing LTE networks with the throughput and latency advantages of NR. However, EN-DC requires more complex UE implementations to allow simultaneous connections with both LTE and NR networks, potentially increasing the cost of UEs. In order to support uninterrupted 5G services, GTI would like to define core EN-DC combos for global roaming as well as local services:

EN-DC configuration	Uplink EN-DC configuration (NOTE 1)	Single UL allowed
DC_1A_n78A	DC_1A_n78A	No
DC_3A_n41A	DC_3A_n41A	DC_3_n41
DC_39A_n41A	DC_39A_n41A	No
DC_3A_n78A	DC_3A_n78A	DC_3_n78
DC_3A_n79A	DC_3A_n79A	No
DC_5A_n78A	DC_5A_n78A	No
DC_8A_n78A	DC_8A_n78A	No
DC_39A_n79A	DC_39A_n79A	No
DC_2A_n41A	DC_2A_n41A	No
DC_66A_n41A	DC_66A_n41A	No
DC_66A_n25A	DC_66A_n25A	No
DC_2A_n66A	DC_2A_n66A	No
DC_2A_n71A	DC_2A_n71A	No
DC_66A_n71A	DC_66A_n71A	No
DC_1A_n28A	DC_1A_n28A	No
DC_1C_n40A	DC_1C_n40A	No
DC_1C_n78A	DC_1C_n78A	No
DC_1A_n77A	DC_1A_n77A	DC_1_n77
DC_2A_n78A	DC_2A_n78A	DC_2_n78
DC_1A_n40A	DC_1A_n40A	No
DC_3A_n1A	DC_3A_n1A	DC_3_n1
DC_3C_n1A	DC_3C_n1A	
DC_3A_n28A	DC_3A_n28A	No
DC_3C_n28A	DC_3C_n28A	
DC_3A_n38A	DC_3A_n38A	No
DC_3C_n38A		
DC_3C_n41A	DC_3C_n41A	DC_3_n41
DC_3C_n78A	DC_3C_n78A	No
DC_3C_n40A	DC_3C_n40A	No
DC_39C_n41A	DC_39C_n41A	No
DC_3A_n77A	DC_3A_n77A	DC_3_n77
DC_3C_n78A	DC_3A_n78A	DC_3_n78
DC_3A_n79C	DC_3A_n79A	No
DC_3C_n79A	DC_3C_n79A	
DC_3A_n40A	DC_3A_n40A	No
DC_4A_n78A	DC_4A_n78A	No

DC_5A_n66A	DC_5A_n66A	DC_5_n66
DC_5B_n66A		
DC_7A_n1A	DC_7A_n1A	No
DC_7C_n1A	DC_7C_n1A	
DC_7A_n28A	DC_7A_n28A	No
DC_7C_n28A	DC_7C_n28A	
DC_7C_n40A	DC_7C_n40A	No
DC_7A_n77A	DC_7A_n77A	No
DC_7A_n78A	DC_7A_n78A	No
DC_7C_n78A	DC_7C_n78A	
DC_8A_n1A	DC_8A_n1A	No
DC_8A_n77A	DC_8A_n77A	No
DC_8A_n78A	DC_8A_n78A	No
DC_20A_n1A	DC_20A_n1A	No
DC_20A_n38A	DC_20A_n38A	No
DC_20A_n41A	DC_20A_n41A	DC_20_n41
DC_20A_n77A	DC_20A_n77A	No
DC_20A_n78A	DC_20A_n78A	No
DC_40A_n41A	DC_40A_n41A	No
DC_40C_n41A		
DC_40A_n77A	DC_40A_n77A	No
DC_40A_n78A	DC_40A_n78A	No
DC_40C_n78A	DC_40C_n78A	
DC_40A_n79A	DC_40A_n79A	No
DC_40C_n79A		
DC_71A_n41A	DC_71A_n41A	No
DC_41C_n71A	DC_41C_n71A	No
DC_41A_n77A	DC_41A_n77A	No
DC_41C_n77A	DC_41C_n77A	
DC_41A_n78A	DC_41A_n78A	No
DC_41C_n78A	DC_41C_n78A	
DC_41A_n79A	DC_41A_n79A	No
DC_41C_n79A	DC_41C_n79A	
DC_28C_n78A	DC_28C_n78A	No
DC_28C_n40A	DC_28C_n40A	No

Table 4-6 GTI EN-DC Combos

This EN-DC combo list is expected to be evolving and ever growing.

4.3 Voice Support

Voice service is a key application for most operators across the world. Despite the recent growth of mobile broadband and smartphones, a good portion of cellular industry revenues still come from voice applications. Irrespective of the rapidly rising volumes of data traffic and the need for more capacity and speed, it is clearly important for operators to retain the ability to deliver a good voice experience, on any radio network deployment intended for a broad audience.

The voice services provided over Public Land Mobile Networks (PLMNs) are featured with global interoperability and accessibility across different mobile networks, using different radio technologies, and different fixed networks, and employing either IP based packet switch technology or circuit switched technology. Subscribers enjoy unified user interfaces to make call from the terminal devices and obtain the similar user experience worldwide.

Such worldwide usable voice services over one single subscription is achieved not only because of the interconnected telecommunication infrastructures, well established technical standards and well-coordinated roaming agreements among MNOs, but also rely heavily on multimode-multiband terminal devices which play an extremely important role to enable the global interoperated voice services.

For 5G MMMB devices, depending on the RAT/CN technology and the device infrastructure capabilities, there would be different voice solutions for the device. At a very high-level, these voice solutions can be divided into two groups.

- Making/receiving a voice call over the RAT/CN on which the MMMB device is monitoring.
  - Voice over 2G (GSM)
  - Voice over 3G (WCDMA)
  - VoLTE over 4G (LTE)
  - VoNR over 5G (NR)
- Making / receiving a voice call with fallback/handover to another RAT/CN other than the band on which the device is monitoring.
  - CS Fallback
  - EPS Fallback

In the following sub-sections, the possible voice solutions for a MMMB device are described in groups according to the RAT technology the MMMB device is using for standby.

4.3.1 2G / 3G Voice Technology Support

5G MMMB devices should be capable of supporting several types of RAT/CN technologies.

Network technology deployments around the world do not occur at the same pace, with some regions still supporting only 2G/3G network infrastructure. Thus, 5G NR capable devices would need to rely on 2G/3G networks to get mobile services in these specific regions.

Over 2G/3G, voice is provided through circuit switched voice call (CS Call). Voice frames from the device are routed to MSC and switched/transmitted to the peer via a previously set up path as illustrated example in Figure 4-3.

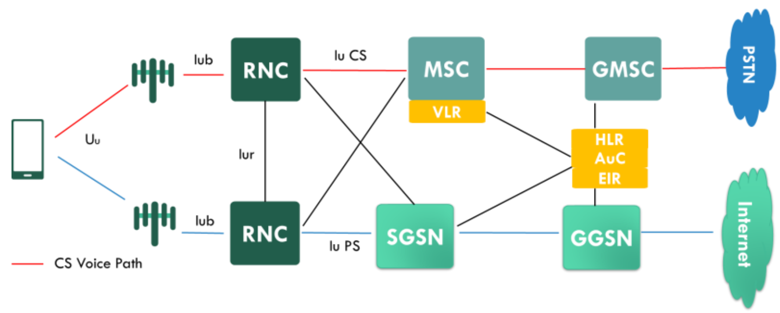

Figure 4-3 3GPP Release 99 Circuit Switched Voice (CS example)

The GTI 5G UE should support CS voice call for 2G (GSM) and 3G (WCDMA) radio access technologies.

4.3.2 4G Voice Technology Support (VoLTE, CSFB, SRVCC)

4G is designed as an all-IP network. The IMS sub-system is standardized for providing IP based voice services over 4G. Depending on IMS sub-system readiness, the optimization of 4G EUTRA/LTE for supporting voice, as well as the additional 4G network features to support voice service, a 5G capable MMMB device which standby on 4G network can adopt the following solutions to get voice service.

VoLTE

The Voice over LTE (VoLTE) scheme was designed as the standardized solution for transferring voice packets over EPC/LTE network. It is based on the IP Multimedia Subsystem (IMS) network which adopts SIP/SDP to set up the call and RTP/RTCP to transfer the voice stream, where the voice service is being delivered as data flows within the radio and EPS data bearer.

The aim for VoLTE is to utilize the low latency and QoS features available within LTE to ensure that the voice service offers an improvement over the standards available on the 2G and 3G networks. Introduction of HD voice and video codecs can significantly improve call quality. VoLTE would offer certain advantages over other schemes, such as:

1) Flexible design due to all IP implementation.

2) Call setup time of VoLTE will be shortened if it is well optimized.

3) HD voice and video codecs, if adopted, can improve call/voice quality.

CSFB

CSFB (Circuit Switched FallBack) was introduced in 3GPP Rel-8 (TS 23.272) to allow a 4G standby device to return to CS domain for voice services. CSFB specifies the method for a UE to switch its radio from EUTRAN to other RAT (e.g. GERAN/UTRAN/1xRTT access) that can support CS domain services. With CSFB, the device camps on LTE/EPC and is served by LTE/EPC for data services and when a voice call is triggered, it will fall back to the CS domain and set up the call.

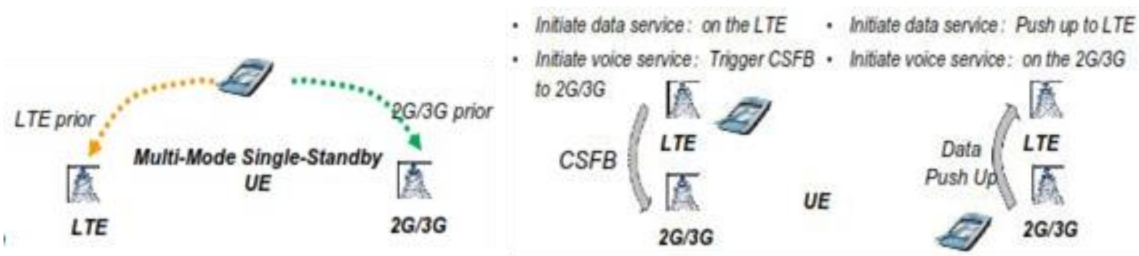

Figure 4-4 4G CSFB Modes Transition

CSFB mechanism has little implication on device side, particularly for hardware, and leads to lower power consumption when compared to some other schemes. However, the call set-up time may be longer than expected in certain cases.

SRVCC

SRVCC offers voice service when the device moves out of the LTE coverage area. Thus, when the VoIP subscriber moves out of LTE coverage, SRVCC ensures smooth handoff of voice from the LTE to the CS network, keeping the impact minimum on the user experience.

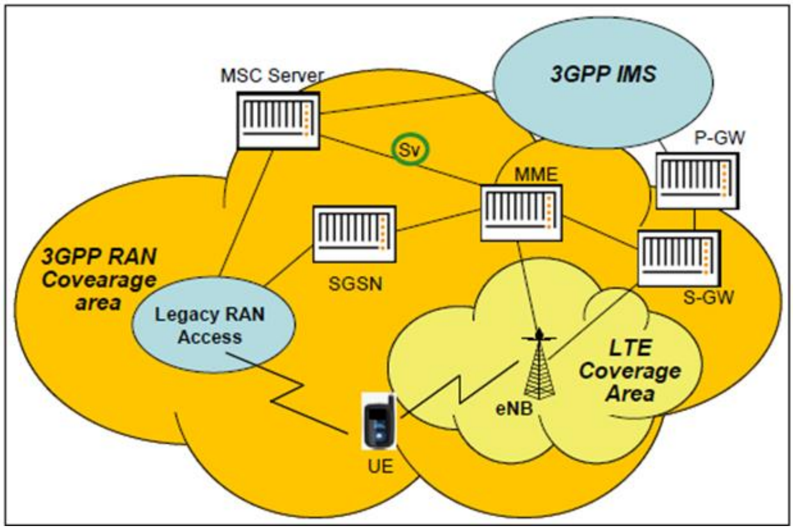

Figure 4-5 SRVCC network architecture

With SRVCC approach, the SRVCC-capable UE's engaged in a voice call determines that it is moving away from LTE coverage, it notifies the LTE network. The LTE network determines that the voice call needs to be moved to the legacy circuit domain. It notifies the MSC server of the need to switch the voice call from the packet to the circuit domain and initiates a handover of the LTE voice bearer to the circuit network. The MSC server establishes a bearer path for the mobile in the legacy network and notifies the IMS core that the mobile's call leg is moving from the packet to the circuit domain. The circuit-packet function in the IMS core then performs the necessary inter-working functions. When the mobile arrives on-channel in the legacy network, it switches its internal voice processing from VoIP to legacy-circuit voice, and the call continues.

4.3.3 5G Voice Technology Support (VoNR, EPS Fallback)

3GPP introduced several network deployment options when standardizing New Radio (NR) technology for 5G. These options provide flexibility for RAN and CN to evolve separately when MNOs migrate their networks from 4G to 5G.

Some of the migration options maintain much of the Evolved Packet Core (EPC) infrastructure, allowing preservation of the existing IMS core and continuation of packet voice using VoLTE. SBA based 5GC, which can work with legacy IMS with some necessary updates, allows the implementation of core components into the 5G Service Based Architecture (SBA), as studied in 3GPP TR 23.794 and related normative work in 3GPP. Depending on the different network deployment options, there are different voice solutions. This white paper discusses Option 3 and Option 2.

For Option 3, network works in NSA mode with eNB as the master node. UE always camps on LTE and the voice solution is the same as for LTE MMMB terminals, CSFB or VoLTE/SRVCC as discussed in section 错误!未找到引用源。. For network deployment Option 2, there are two solutions available, VoNR and EPS fallback.

VoNR

VoNR (Voice over NR) refers to making/receiving voice calls over NR-5GC-IMS. As illustrated in Figure 4-6, the voice packets are carried by 5G NR and 5GC, then over to the IMS subsystem.

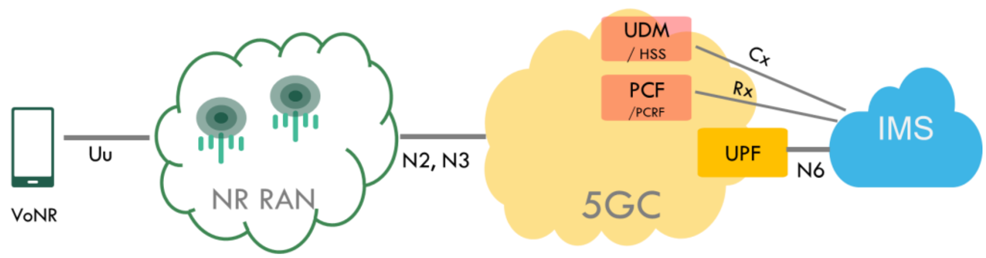

Figure 4-6 VoNR High-level Architecture

To deploy VoNR, the IMS network need some upgrades, such as adding access type and location information parameters to the pertinent interfaces. Or updates to eIMS in future to enable SBA based interfaces for Cx and Rx, so that the IMS sub-system can employ all 5GC functions for voice services.

However, network deployment occurs in stages, and initial NR coverage may not be as good as LTE. Thus for seamless voice service, inter-system handover from VoNR to VoLTE will benefit user experience.

EPS Fallback VoLTE

EPS fallback refers to a feature where a 5GC connected device fallback to LTE (VoLTE) for voice calls. When a voice call is triggered on a 5G SA UE, the UE shall establish a VoLTE call over EUTRAN-EPC-IMS, i.e. “fallback” to LTE, using VoLTE for voice call as shown in Figure 4-7. Such feature can be used when VoNR is not ready.

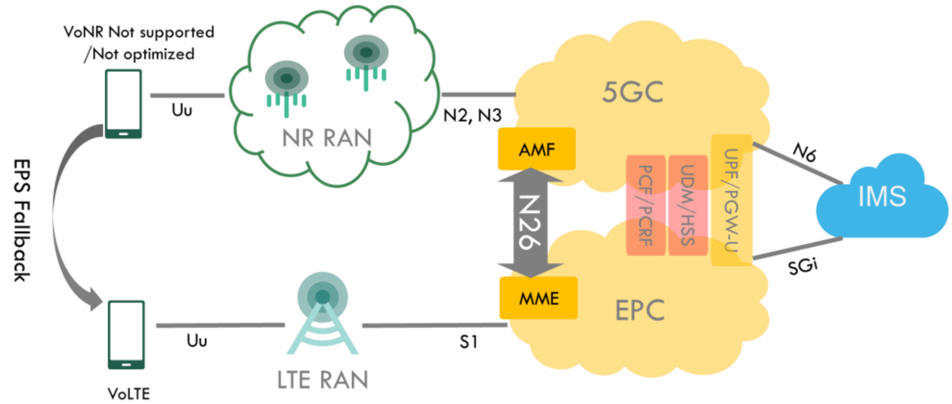

Figure 4-7 EPS Fallback Architecture

4.4 2G / 3G Data Support

The vast majority of global networks support 4G, with many also supporting 5G. However, as seen from the requirements in other sub-sections, the 5G MMMB devices should be capable of supporting the older RAT/CN technologies 2G, 3G. This helps global device operation since the network deployment pace is not the same across the globe and some networks will still operate in 3G and 2G modes. Also, there might be specific agreements between international operators for roaming purposes, limiting the users to 2G / 3G access. Thus, the 5G NR capable devices may need to rely on 2G/3G networks to get mobile services in some regions. The following sub-sections would provide some key requirements for 2G and 3G data operation.

4.4.1 2G Capabilities

The 5G Global device should support GSM / GPRS / EDGE operation for data when 5G, 4G and 3G access technologies are not available for use.

The 5G device should support GSM band 2, 3 and 8. GSM band 5 is optional.

The device shall also support mobility between access technologies (2G and 3G) as directed by the operating access network.

4.4.2 3G Capabilities

The 5G Global device should support 3G UMTS operation for data when 5G and 4G access technologies are not available for use.

The 5G device should support UMTS band 1, 2, 4, 5 and 8.

The device shall also support mobility between access technologies (2G, 3G and 4G) as directed by the operating access network.

4.5 MIMO Support and Antenna Specifications

MIMO (Multiple Input Multiple Output) technology helps LTE/5G NR achieve ambitious throughput and spectral efficiency targets, which are essential for supporting broadband data services over wireless links. Various forms of MIMO exist in the E-UTRAN specifications from LTE Rel-8 onwards, with further enhancements in Rel-9 through Rel-14. The benefits that MIMO provides include improved signal quality at cell edge and higher throughput through parallel transmission of multiple data streams. 5G NR supports 4Rx as the default for most 5G bands.

Massive MIMO is one of the main enabling technologies in 5G wireless communications, where a large number of antenna elements at the base station bring extra degrees of freedom for increasing the throughput and considerable beamforming gains for improving the coverage. Beamforming is the ability to direct radio energy through the radio channel toward a specific receiver. By adjusting the phase and amplitude of the transmitted signals, a constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput.

Compared to LTE, 5G has taken a giant leap in support/implementation of massive MIMO and control/data channel beamforming both in the existing bands and in the new mmWave bands, with the help of high-resolution channel state information acquisition and beam management using Reference signals in SSB, CSI-RS, CSI-IM and TRS (DL/UL).

This section will focus on the requirements pertaining to MIMO and antenna configurations for the GTI 5G global device based on GTI operator survey.

4.5.1 Antenna Requirements

For NR Bands, the UE is required to be equipped with a minimum of two Rx antenna ports in all operating bands except for the bands n38, n41, n77, n78, n79, n25 and n66 where the UE is required to be equipped with a minimum of four Rx antenna ports. This requirement applies when the band is used as a standalone band or as part of a band combination.

Table 4-7 shows the general Antenna requirements for both LTE and NR bands.

Bands	Antenna Requirement	MIMO Support
n77	4	4*4
n78	4	4*4
n41	4	4*4
n1[1]	2	2*2
n3[1]	2	2*2
n28	2	2*2
n66	4	4*4
n40[1]	2	2*2
n79	4	4*4
n8	2	2*2
n71	2	2*2
n25	4	4*4
n38	4	4*4
n70	2	2*2
n74	2	2*2

Table 4-7 Antenna requirements for Devices bands

Note 1: It is recommended to support 4 Rx antenna ports and 4*4 MIMO, for a better performance and user experience.

4.5.2 MIMO Configuration

5G UE should support following downlink MIMO layer configuration:

Receive Antenna Num.	Downlink Layer Num.
4	1,2,3,4
2	1,2

Table 4-8 Downlink MIMO Configurations

For SA, UE should support following uplink MIMO layer configuration:

Transmit Antenna Num.	Uplink Layer Num.

2	1,2
1	1

Table 4-9 Uplink MIMO Configurations

In order to support multi-layer (up to 4 layers) non-codebook precoding in downlink on TDD bands, UE should be able to send antenna-switch sounding reference signal (AS-SRS). The AS capability can be 2T4R (4 antennas are divided into 2 groups with 2 antennas each, and SRS is emitted at each group alternatively) or 1T4R (SRS is emitted at each of the 4 antennas sequentially).

4.5.3 Transmission Modes and Channel Estimation Requirements

In 5G, the transmission mode is unified for the downlink control and traffic channels, which relies on downlink demodulation reference signal (DM-RS). No matter how many antennas the gNB employs, the UE only sees the DM-RS ports and receives the number of port (rank) layers of data. It then estimates the downlink equivalent channel, consisting of air-interface channel and the precoder from DM-RS which is used for coherent detection. The precoder is applied by the gNB to transmit the rank-layer of data over its antennas. The gNB derives the precoder either by computing the non-codebook beamformer from its AS-SRS estimation, or by directly applying the UE-feedback codebook-based PMI (Precoding Matrix Indicator). For the later scheme, the UE selects PMI based on the estimation of Channel State Information RS (CSI-RS).

For 5G uplink, there are two codebook-based MIMO schemes (for the UE and bands that support 2 transmit antennas). Both schemes rely on the codebook SRS (CB-SRS) that is sent by UE. gNB estimates the uplink channel from CB-SRS and chooses one wide-band precoder from the codebook.

The code-book based precoding includes both non-coherent (one antenna port) and coherent (two antenna port) precoder definitions, which can be selected dynamically by the eNB/gNB based on the CB-SRS. For coherent UL-MIMO, the precoder aims at the data stream being coherently combined at the gNB. However, coherent UL-MIMO imposes extra requirement on UE’s radio-frequency (RF) channel, which includes the amplitude/phase between RF channels not changing drastically within each CB-SRS measurement and lower delays, to guarantee the correctness and gains of the precoder selection.

2-antenna UL precoder codebook for single layer transmission is as follows:

Index	0	1	2	3	4	5

Precoder	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}0\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$
Type	Non-coherent		Coherent			

Table 4-10 2-antenna single-layer UL Precoder Codebook

5G UE should support the estimation of following downlink reference signals:

- Downlink DM-RS: channel estimation of DM-RS is used for downlink control/traffic channel coherent demodulation.
- Channel State Information RS (CSI-RS): channel estimation of CSI-RS is used for 3I (PMI, CQI, RI) measurement. For massive-MIMO, the CSI-RS is beamformed by gNB, but the beamformer is transparent to UE.

Tracking RS (TRS): TRS is used for fine time and frequency tracking as well as path delay spread and Doppler spread estimation. The results are used by improving the channel estimation performance of DM-RS. TRS is particularly critical for UE supporting mmWave bands.

For downlink LTE, the UE shall support TM (transmission modes) 3, 4, 7, 8, 9 and 10.

4.6 Device Configuration Requirements to Support Roaming Scenarios

Roaming on traditional mobile networks is based on authentication against public land mobile network (PLMN) IDs (sometimes known as Operator IDs). A PLMN ID is unique to each operator and is a concatenation of the Mobile Country Code (MCC) and the Mobile Network Code (MNC).

The UE normally operates on its home PLMN (HPLMN) or equivalent home PLMN (EHPLMN). However, a visited PLMN (VPLMN) may be selected, e.g., if the MS loses its home network connection. In this case, there are two modes for PLMN selection:

1. Automatic mode: This mode utilizes a list of PLMNs in priority order. The highest priority PLMN which is available and allowable, is selected.
2. Manual mode: Here the MS indicates to the user which PLMNs are available. Only when the user makes a manual selection does the MS try to obtain normal service on the VPLMN.

There are two cases for roaming boundaries:

- International Roaming: This is where the MS receives service on a PLMN of a different country than that of the HPLMN.
- National Roaming: This is where the MS receives service from a PLMN of the same country as that of the HPLMN, either anywhere or on a regional basis. The MS makes a periodic search for the HPLMN while national roaming.

GTI has been working on establishing a suitable roaming arrangement between members. To this end, device USIMs could potentially be configured to facilitate preferred or prioritized roaming to a GTI partner before alternative networks. That is, PLMN-IDs for GTI members could be preconfigured with higher priority on the USIM based on business arrangements.

4.7 Interoperation Requirements

As mentioned in Section 4.1, a 5G global device should support NR SA/EN-DC/LTE/3G/2G access technologies. Inter-RAT mobility shall be supported to allow users to move among different operators' networks or different access networks belonging to the same operator.

This subsection summarizes requirements for mobility among 2G, 3G, and 4G, mobility between 4G and 5G SA, and mobility between SA and EN-DC.

4.7.1 Interoperation among 2G, 3G and 4G

Interoperation / mobility becomes critical when the device supports multiple access technology modes so as to provide seamless user experience across various networks. Below are key mobility requirements to support interoperation between 2G, 3G, and 4G modes:

When working under LTE/WCDMA/GSM (GPRS) modes, the device shall support:

- Cell Reselection/ Redirection/Handover between TD-LTE and FDD LTE
- Cell Reselection/Redirection between FDD LTE and WCDMA
- Cell Reselection between LTE and GSM, Redirection from LTE to GSM, NC0 Reselection from GSM to LTE
- Cell Reselection/Redirection between TD-LTE/WCDMA is optional.

4.7.2 Interoperation between 4G and 5G

In order to support service continuity between EPS and 5GS, the architecture in Figure 4-8 was introduced for non-roaming scenario.

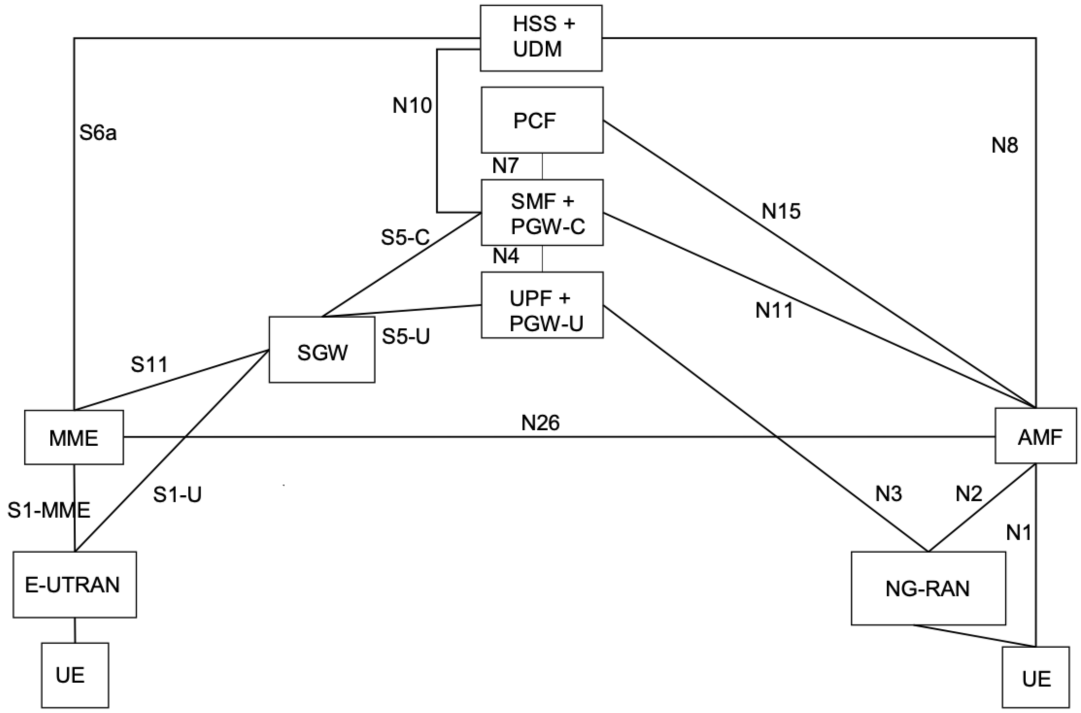

Figure 4-8 Non-roaming architecture for interworking between 5GS and EPC/E-UTRAN, source: 3GPP 23.501

SMF+PGW-C (for control plane) and UPF+PGW-U (for user plane) are dedicated to support interworking between EPC and 5GC. N26 interface, which implements a subset of S10 functionalities, enables the network to handover a UE from 4G access network to 5G access network or vice versa. With this architecture, user plane shall anchor in 5GC for a UE with 5G subscription.

While UE moving from 4G to 5G, the established PDN connections have to be transferred to PDU sessions. In order to correlate a PDN connection and a PDU session, the UE sends a PDU session ID to the network via PCO IE during PDN connection establishment in the EPC. Then, the SMF+PGW-C can send the UE an associated S-NSSAI and other 5QoS parameters via PCO IE. Similarly, AMF allocate an EBI associated with a PDU session to a UE when the UE request a PDU session establishment.

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

- For idle mode mobility from 5GS to EPS, the UE performs either TAU or Attach procedure with EPS GUTI mapped from 5G-GUTI sent as old Native GUTI, and indicates that it is moving from 5GC. The UE includes in the RRC message a GUMMEI, mapped from the 5G-

GUTI and indicates it as a native GUMMEI and should in addition indicate it as "Mapped from 5G-GUTI". The MME retrieves the UE's MM and SM context from 5GC.

- For connected mode mobility from 5GS to EPS, either inter-system handover or RRC Connection Release with Redirection to E-UTRAN is performed. During the TAU or Attach procedure, the HSS+UDM cancels any AMF registration associated with the 3GPP access.
- For idle mode mobility from EPC to 5GC, the UE performs mobility Registration procedure with the 5G GUTI mapped from EPS GUTI and indicates that it is moving from EPC. The UE derives GUAMI from the native 5G-GUTI and includes GUAMI in the RRC message to enable RAN to route to the corresponding AMF (if available). If the UE holds no native 5G-GUTI, then the UE provides in the RRC message a GUAMI, mapped from the EPS GUTI and indicates it as "Mapped from EPS". The AMF and SMF retrieve the UE's MM and SM context from EPC.
- For connected mode mobility from EPC to 5GC, either inter-system handover or RRC Connection Release with Redirection to NG-RAN is performed. During the Registration procedure, the HSS+UDM cancels any MME registration.

When the UE supports single-registration mode and network supports interworking procedure without N26 interface:

- For mobility from 5GC to EPC, the UE with at least one PDU Session established in 5GC may either:
  - If supported and if it has received the network indication that interworking without N26 is supported, perform Attach in EPC with a native EPS GUTI, if available, otherwise with IMSI with Request type "Handover" in PDN CONNECTIVITY Request message and indicating that the UE is moving from 5GC and subsequently moves all its other PDU Session using the UE requested PDN connectivity establishment procedure with Request Type "handover" flag.

  Or:

  - Perform TAU with 4G-GUTI mapped from 5G-GUTI sent as old Native GUTI indicating that it is moving from 5GC, in which case the MME instructs the UE to re-attach. IP address preservation is not provided in this case.
- For mobility from 5GC to EPC, the UE with no PDU Session established in 5GC:
  - Perform Attach in EPC (TS 23.401 [26], clause 5.3.2.1) indicating that the UE is moving from 5GC.
- For mobility from EPC to 5GC, the UE performs Mobility Registration Update in 5GC with 5G-GUTI mapped from EPS GUTI and a native 5G-GUTI, if available, as additional GUTI and indicating that the UE is moving from EPC. In this case, the AMF determines that old node is

an MME, but proceeds as if the Registration is of type "initial registration". The UE may either:

- if supported and if it has received the network indication "interworking without N26 supported", move all its PDN connections from EPC using the UE initiated PDU Session Establishment procedure with "Existing PDU Sessions" flag,

Or:

- Re-establish PDU Sessions corresponding to the PDN connections that it had in EPS. IP address preservation is not provided in this case.

As a summary in Table 4-11, several mechanisms are available to support mobility between 4G and 5G SA:

1) Redirection and cell re-selection mobility mechanism between 4G and 5G SA should be mandatorily supported by the UE.

2) Inter-RAT handover is a mandatory feature with capability signaling, which is used to indicate whether the feature has been successfully tested.

Thanks to seamless service continuity via connected mode handover, users enjoy better QoS for delay sensitive services such as un-buffered streaming media and VoIP/VoNR/EPS Fallback.

Some GTI operators are going to launch 5G SA commercial service in near future this year. Depending on different strategies, a network can introduce EPS Fallback for voice service initially and then VoNR for a better user experience.

Because it takes time to deploy nation-wide 5G coverage, voice call service continuity should be supported by the interworking between 4G and 5G access network for both EPS Fallback and VoNR. It is suggested that the operators should implement N26 interface between MME and AMF to support handover that can have seamless service continuity while the UE performs an inter-system change. With the EPS Fallback deployed scenario, once voice service is initiated, the UE connected in 5GC will fallback to 4G. It is a praiseworthy way to try Fast Return to 5G SA after voice service end and with no other data service ongoing, by the network using RRC Connection Release with Redirection procedure.

Direction	Mechanism	Network with N26	Network without N26	UE requirement
LTE to 5G	Inter-RAT handover	supported	not	Mandatory with capability

SA			supported	signaling(diff for LTE FDD/TDD, diff for NR FR1/FR2, NR FDD/TDD)
	RRC Connection Release with Redirection procedure	supported	supported	Mandatory without capability signaling
	Cell Re-Selection from EUTRA RRC_IDLE to NR RRC_IDLE	supported	supported	Mandatory without capability signaling
5G SA to LTE	Inter-RAT handover	supported	not supported	Mandatory with capability signaling(diff for NR FR1/FR2, NR FDD/TDD)
	RRC Release with Redirection procedure	supported	supported	Mandatory without capability signaling
	Cell Re-Selection from NR RRC_INACTIVE/RRC_IDLE to EUTRA RRC_IDLE	supported	supported	Mandatory without capability signaling

Table 4-11 4G to 5G SA and vice-versa mobility mechanism

The Table 4-11 above summarizes the mobility / interoperation mechanisms between 4G and 5G SA, along with UE requirements necessary to support these mechanisms.

4.7.3 Interoperation between SA and NSA

5G network deployment option 3 (NSA/EN-DC), uses 4G EPC as the Core Network and a single C-plane connection between the eNB and the EPC. The requirements in section 4.7.2 are also applicable to interoperation between SA and NSA except below.

The 3GPP has agreed that the inter-RAT handover from SA to EN-DC shall not be supported in Rel-15, but the inter-RAT handover from E-UTRA with EN-DC configuration to SA is supported.

4.8 Co-Existence Requirements between WiFi and 5G

The multi-band multi-standard support on the 5G NR terminals plays important role with current 5G deployment. All the modern 5G mobile phones support cellular (3GPP) and non-cellular wireless communications standards at the same time. 3GPP cellular wireless communication standards (e.g. 2G, 3G, LTE and 5G) operate in the 3GPP defined frequency bands with up to 100MHz bandwidth in FR1 and up to 400MHz in FR2. IEEE802.11 wireless LAN standards (Wi-Fi) are also important standards for mobile phones, besides other non-3GPP standards like Bluetooth, UWB or NFC. Wi-Fi standards operate in unlicensed ISM (industrial, science and medical) bands with bandwidths up to 160MHz (802.11ax) so far. Also, to achieve high throughput, higher order modulation is used by 5G NR as well as Wi-Fi. With these above facts, the signal quality of transmission and reception channels are very important.

RF inference from the signal emissions of those standards, can be more significant in some frequency ranges than in others. This section will analyze the coexistence issues with focus on two frequency ranges:

n40/41 and 2.4GHz ISM band

n79 and 5GHz ISM band

4.8.1 Co-Existence between n40/n41 and WiFi 2.4GHz

3GPP has defined 2 NR bands in 2.4GHz range as seen in Table 4-12

n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD

Table 4-12 n40/n41 3GPP Band

According the ITU Radio Regulations, 2.4GHz ISM band is allocated at (2400MHz – 2483MHz). Individual countries' use of the bands designated in these sections may differ due to variations in national radio regulations.

The Figure 4-9 shows the frequency allocation with n40/41 and 2.4GHz ISM band.

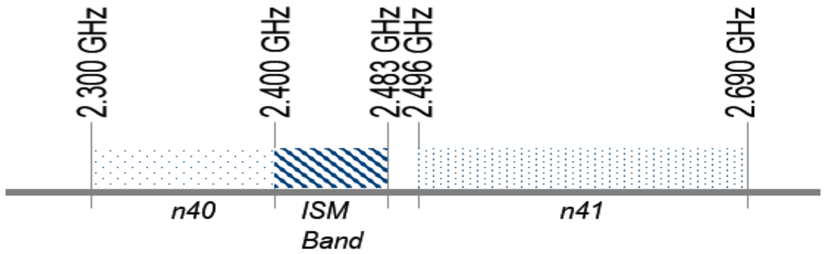

Figure 4-9 frequency allocation with n40/n41 and 2.4GHz ISM band

The adjacent edge areas around 2.4GHz and (2.483GHz-2.496GHz) are the most challenging. Any RF leakage from poor quality device can cause interference to other communication channels. To avoid interference from occurring, both 3GPP and IEEE standards have defined measurement methods and requirements.

In 3GPP TS38.521, chapter 6.5 Output RF spectrum emissions, several test cases are defined. Under chapter 6.5.2, two test cases on spectrum emission mask and adjacent channel leakage power ratio limits are specified for unwanted emissions immediately outside the assigned channel bandwidth, resulting from the modulation process and non-linearity in the transmitter. For devices, which support n40 or n41, these test cases verify that the device does not interfere other devices in ISM band. The Figure 4-10 is an example of spectrum emission mask measurement.

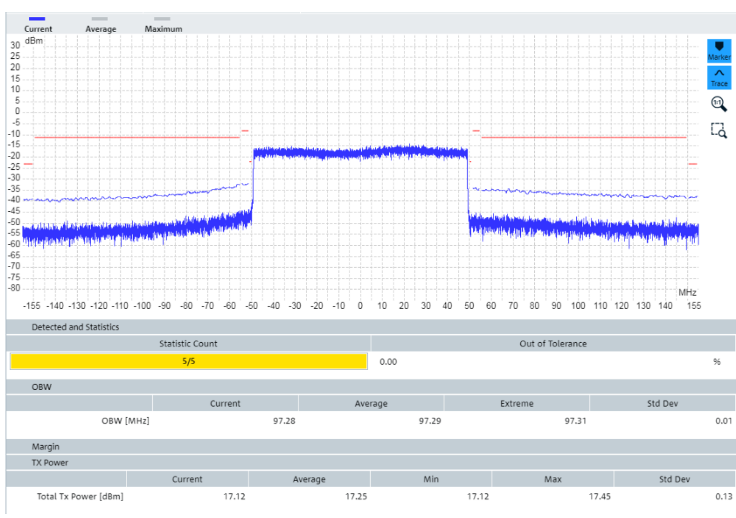

Figure 4-10 3GPP UE spectrum emission mask

In the IEEE Std 802.11-2016, similar spectrum emission mask test cases are defined to secure that the device does not interfere to other devices close to ISM band RF channels, n40/n41 this case.

The Figure 4-11 is an example with 802.11g. The 11g device must meet the spectral mask given in the 11g amendment and any applicable regulatory requirements.

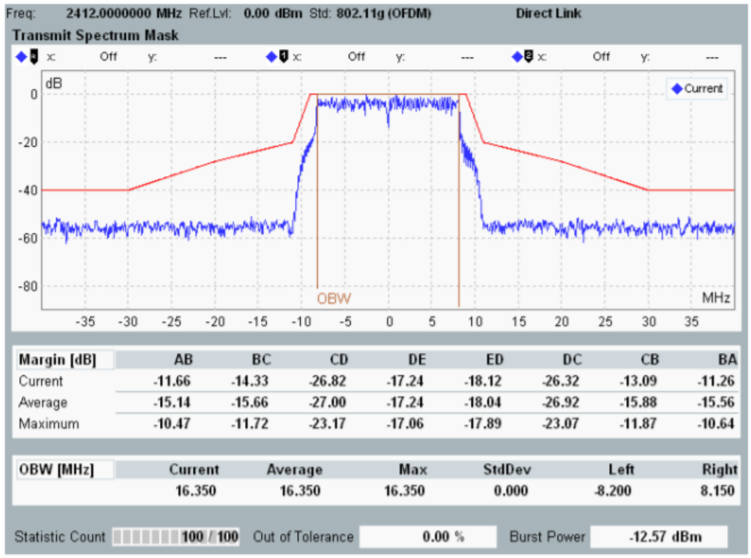

Figure 4-11 spectrum emission mask (802.11g UE)

Compared to TX requirements, the RX requirements are not as emphasized by both 3GPP and IEEE using dedicated Rx test cases. But in practice, RX is more challenging from a co-existence perspective and can be measured using a kind of dedicated packet error rate measurement, called “desensitization”. Desensitization is the reduction of RX sensitivity due to a powerful interferer signal, especially from in-device coexistent transmitters on an adjacent RF channel.

The design of 5G mobile phones tends to be more elegant and more compact. With MIMO technology in both LTE/5G NR and Wi-Fi, multiple antennas are mandatory on compact design of modern 5G mobile phones. The required number of antennas are still increasing because of multi-band and multi-mode support and the distance between in-device antennas tends to decrease. It can be generally assumed that a LTE/5G NR antennas and a Wi-Fi antennas are mounted within 5cm in-device. The coupling between the affected antennas (antenna isolation) is approximately equal to free-field attenuation ‘a’ dB. That is, for example, approximately 15 dB with a separation of 5 cm at 2.4 GHz and approximately 20 dB at 5.5 GHz.

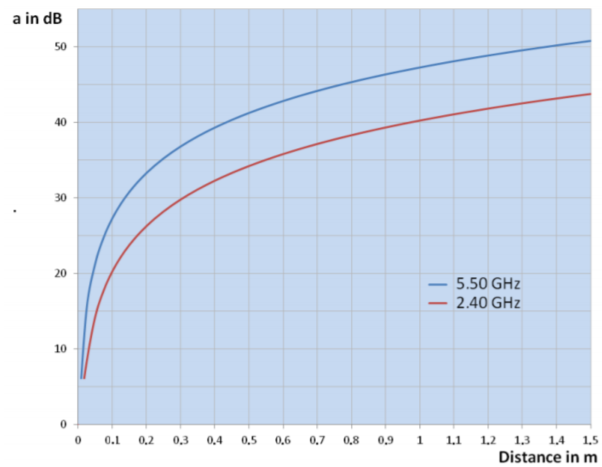

Figure 4-12 Free-field attenuation a between two antennas at 2.4 GHz and 5.5 GHz

The primary problem of any in-device coexistence situation is that the emissions from one system's antenna have a strong presence on the other. The TX signal of one radio system (interferer) directly interfere the receiver of another. The packet error rate on that receiver channel increases significantly, when the device/antenna design does not protect such interference.

Based on the standard sensitivity test, a desensitization test is proposed and illustrated here. The packet error rate measurements can be adopted as a figure of merit. The Packet error rate (PER) in this case is measured for WLAN. The blue curve in Figure 4-13 shows the typical WLAN PER progression without interferer influence. As soon as the RX signal falls below a minimum input level, packet error rate increase significantly.

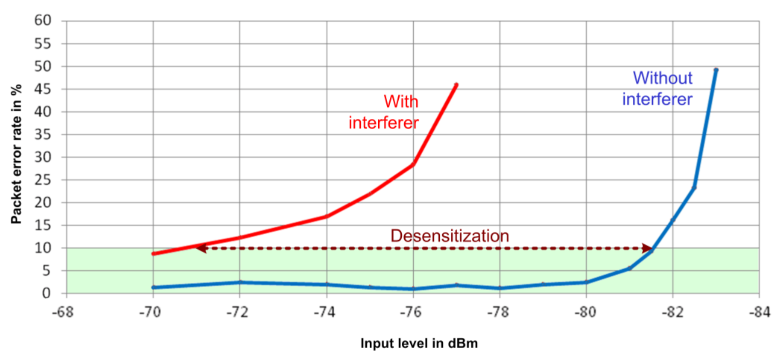

Figure 4-13 desensitization test case

Now, adding an interferer signal (e.g. a cellular interferer), shifts the blue curve to the left. The WLAN PER progression with interference is shown in red.

Thus, to determine the degradation of the RX sensitivity, a first measurement determines the RX input level for 10 % PER (without interferer). This level is referred to as the "receiver sensitivity" or the "intermediate sensitivity level". It is an individual value which can differ between different DUTs by several dB's.

To achieve a PER of 10 % in presence of an interferer, a much higher receiver input level is required. This value is called the "effective intermediate sensitivity level" EIS.

The desensitization is calculated from the difference:

"10% PER level" with interferer (EIS) – "10% PER level" without interferer or effective intermediate sensitivity level, even when the transmit power of the interferer is reduced. The desensitization measurements must begin with very low interferer signals.

Thus, in the Figure 4-13 above, for example, without interferer, an input signal of -81.5 dBm is required for PER = 10 %. With a certain interferer applied, the wanted signal - in the example - has to be -71 dBm for PER = 10 %.

The desensitization is calculated to -71 dBm + 81.5 dBm = 10.5 dB.

The similar test can also be done for 5G NR receiver sensitivity testing under the interference of in-device Wi-Fi signal.

4.8.2 Co-Existence between n79 and WiFi 5GHz

3GPP has defined one band in 5GHz range as seen in Table 4-13

n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD

Table 4-13 3GPP Band n79

According the ITU Radio Regulations, 5GHz ISM band is allocated at (5170MHz – 5835MHz). Individual countries' use of the band may differ due to variations in national radio regulations.

The figure shows the frequency allocation with n79 and 5GHz ISM band.

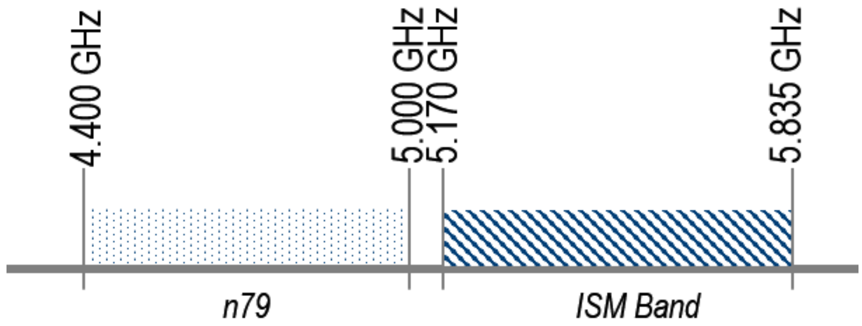

Figure 4-14 frequency allocation with n79 and 5GHz ISM band

The 3GPP test cases, spectrum emission mask and adjacent channel leakage power ratio, are valid for n79. The IEEE Std 802.11-2016 also has defined test case on spectrum emission mask, for 5GHz ISM Band.

The proposed test scenario about desensitization is also highly recommended, due to multiple antennas and less isolation in-between due to compact size of modern 5G terminals.

4.9 SRS Requirements

SRS is an uplink sounding reference signal, and base station receives the SRS signal from the UEs to calculate exact uplink channel response by channel estimation, and measure the quality of the uplink channel, and appropriately selects the physical resource and the corresponding MCS according to the measurement result etc. A more important use of uplink SRS channel response is to calibrate downlink channel response and calculate exact downlink beam weight and direction for SU and MU scenarios. The downlink beam weights calculated by SRS are much more accurate than CSI and PMI information which is feedback by UE for TDD systems, as downlink channel response is reciprocal to that of uplink, using the same carrier. Moreover, additional SRS antenna switching feature can further improve network performance and user experience for 5G TDD systems.

For 5G UEs that do not support SRS antenna switching, only partial antennas' channel response can be measured. Thus, the calculation of accurate downlink beam weights and the overall performance gains may be lower as all the antennas' channel responses are not available.

4.9.1 SRS Antenna Switching

It is typical for 5G UE to be deployed with 4 receiving antennas and 1 or 2 uplink transmitting antennas. Just as defined in 3GPP TS 38.214 and showed as Figure 4-15, it is recommended that

5G UE should support 1T4R SRS antenna switching or 2T4R SRS antenna switching. In case of 2T4R, 4 antennas are divided into 2 groups with 2 antennas each, and SRS is emitted at each group alternatively. In case of 1T4R, SRS is emitted using each of the 4 antennas sequentially.

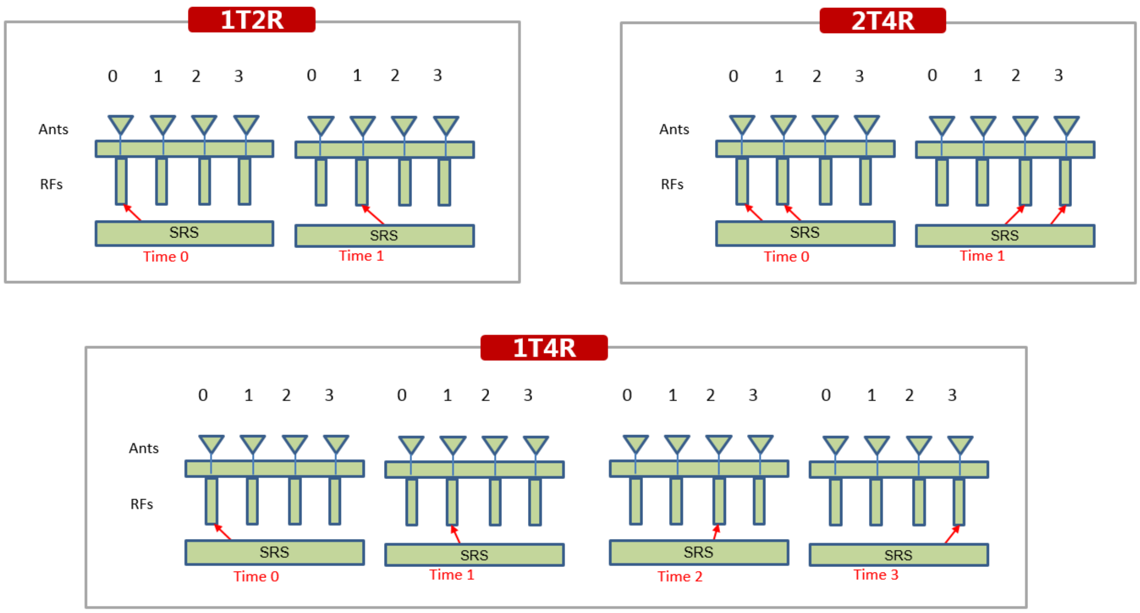

Figure 4-15 Illustration for 1T2R, 1T4R, 2T4R SRS Configuration

4.9.2 Field Test Performance Comparison

For performance comparison, the downlink beam weights with SRS antenna switching and downlink beam weight with PMI were tested, under same environment conditions and terminals. When SRS antenna switching was deactivated, the downlink beam weight with Type I PMI was used. The CSI-RS configuration for PMI/CQI/RI feedback stayed the same for fair comparison.

As defined in "3GPP R1-1907862", Type I PMI codebook 2/4/8 port support is mandatory without capability signaling for FR1 UE. Type II PMI is a UE optional feature, which provides beams combination, better performance than Type I PMI, and aims to approach the performance of SRS antenna switching. However, it may cause hundreds of payload bits (overhead) for CSI information feedback, and needs commercial terminals to support this optional capability and warrants validation of its actual performance.

SRS antenna switching can provide 30% gain for SU experience for static point test and drive test. The Cell capacity can be boosted. Approximately 50~150% capacity gain can be expected with user number growing.

With the UE supporting optional features and capabilities, like more CSI-RS ports for Type I PMI measurement and even Type II PMI, the SRS antenna switching gain may be different because of PMI performance would be different depending on CSI-RS ports configuration and UE capabilities.

- **Average SU Static Experience Improved By ~30%**

Figure 4-16 SU Static Trial Scenario for SRS Antenna Switching

Four test points were selected in Hangzhou, Point A, Point B, Point C and Point D. Test terminal was a commercial smartphone supporting 1T4R SRS antenna switching. In order to compare performance, SRS antenna switching was de-activated and then later activated. Under same test points and same conditions, an average of ~30% downlink user throughput gain was observed.

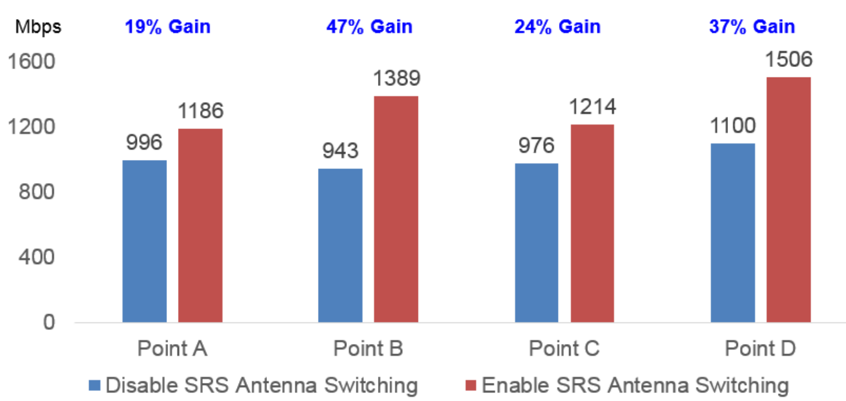

Figure 4-17 DL Throughput Gain for SRS Antenna Switching, SU Static Scenario

- **Average SU Drive Test Experience Improved By ~30%**

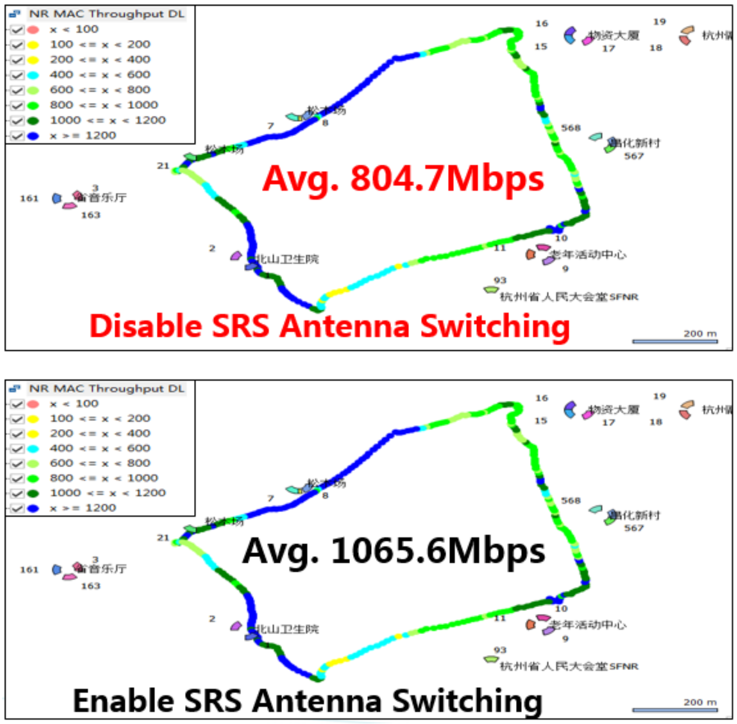

Figure 4-18 DL Throughput Gain for SRS Antenna Switching, SU Drive Test Scenario

With same drive route in Hangzhou and same commercial smartphone supporting 1T4R SRS antenna switching, the downlink throughput was tested by disabling and then later enabling SRS antenna switching. As showed in Figure 4-18 average 32% downlink throughput gain was observed.

- **MU Reaches 50%~150% Cell Capacity Gain**

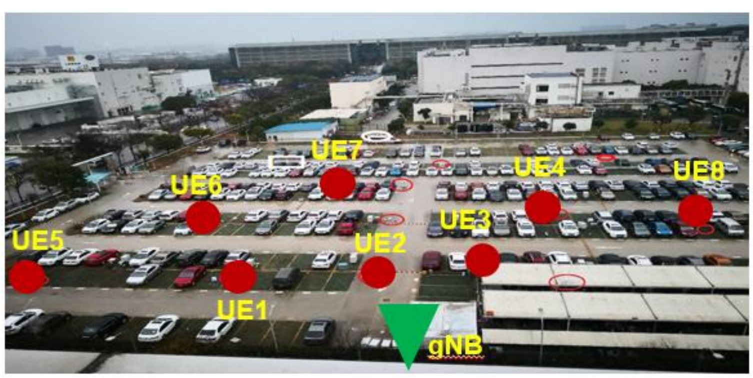

Figure 4-19 MU Trial Scenario for SRS Antenna Switching

8 terminals were distributed in a car parking lot in Shanghai. These terminals were commercial smartphones supporting 1T4R SRS antenna switching. The Downlink cell throughput was measured by disabling and then later enabling SRS antenna switching, and adding terminals one by one. Under same user number at same points and same conditions, 50~150% downlink cell capacity gain was observed.

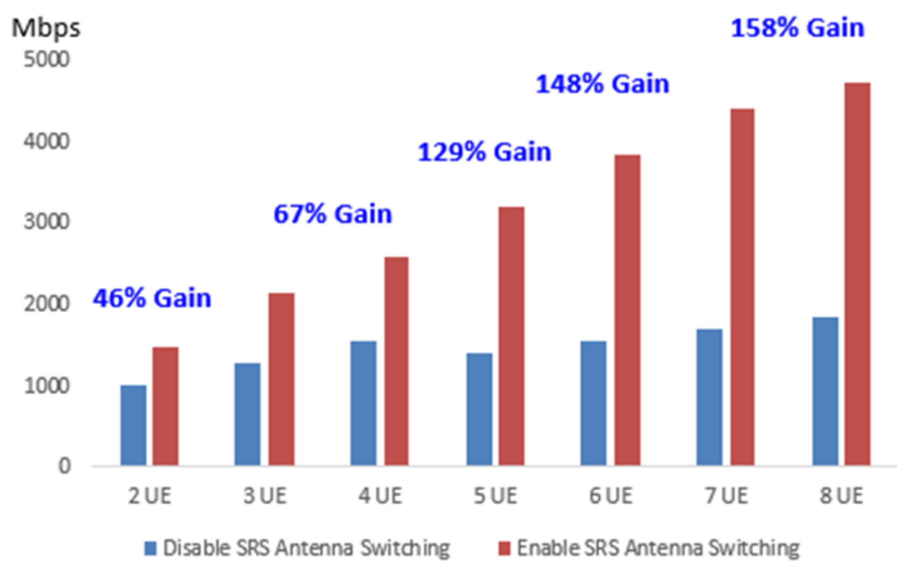

Figure 4-20 DL Cell Capacity Gain for SRS Antenna Switching, MU-MIMO

The principles for UE SRS transmission and DL beam calculation were the same for '1T4R' and '2T4R' terminals. However, for terminals that supported '2T4R' SRS Antenna switching capabilities, the time delay for gNB to receive all the wireless channel response was reduced by half as it needs 4 SRS transmissions for '1T4R' terminals, and only 2 SRS transmission for '2T4R' terminals. In typical scenarios, 5%~10% performance gain can be expected from 2T4R's shortening time delay.

4.10 OTA Requirements

Embedded antennas will perform differently from device-to-device, depending on various design factors. Due to this difference, OTA (Over the Air) testing is the key method to evaluate the antenna performance and radiated performance of wireless devices. Without a rigorous testing stage, a device can perform poorly or fail to work.

Unlike traditional devices, 5G devices will come in various sizes, shapes, materials and work in different environments. This presents lots of challenges for OTA testing of 5G devices.

Given the fast development of the 5G industry, the importance of OTA measurements and the existing standardization status, the industry is developing the specification of OTA Testing of 5G devices, which includes test set-up, test method, test procedures and performance requirements.

4.10.1 FR1 5G Device OTA Test Requirements

In general, there are two categories of test requirements apply to FR1 5G devices.

RF PARAMETRIC TEST:

TRP and TIS are most popular test cases used in OTA RF test.

The Total Radiated Power (TRP) is a measure of how much power is radiated by an antenna. The measurement is taken isotopically, i.e the antennas total received power is calculated and summed up over all possible directions.

TIS Testing: The receiver performance of a cellular device is determined by measuring the effective receiver sensitivity of the device (utilizing Bit Error Rate (BER), Frame Error Rate (FER), or other error criteria) at incremental locations surrounding the device. A three-dimensional pattern characterization of the receiver performance of the device is assembled by analyzing the data from the spatially distributed measurements.

The TRP and TIS can be tested in anechoic chamber or reverb chamber.

OTA PERFORMANCE TEST:

OTA performance test is designed to measure MIMO OTA testing basically measures the changes in data throughput and signal strength of the device when it is moved further from the closest base station. High accuracy MIMO OTA testing during the product R&D phase helps you to avoid very expensive product modifications at the final phase of the product development. The MIMO OTA test was required for 4G device, which was mainly focused on 2x2 MIMO. But in 5G 4x4 MIMO is required for FR1, and the test solution should be updated.

The OTA performance test had been required by CTIA earlier, and there are three solutions that could be used

A. *Multiple-Probe Anechoic Chamber (MPAC) Method:*

The MPAC method utilizes a large anechoic chamber equipped with a ring of probe antennas, each connected to a channel emulator output port. The required number of antennas depends on three main aspects: the channel model, DUT size, and polarization. The DUT is at the center, and the antennas are in a circle around the DUT with uniform spacing (e.g., 45° with 16 elements arranged in 8 positions, where each position contains a vertically and horizontally polarized antenna pair). The number of antenna positions limits the maximum allowed distance between the phase centers of the DUT antenna.

In the MPAC method, the angular spread for the transmit side and the desired XPR are generated in the channel emulator, while the angular spread for the receive side is emulated by sending the signals for a cluster to several antennas located on the 2D circle. By controlling the power for each antenna, the system can emulate the multipath spatial distribution around the DUT.

B. Radiated Two-Stage (RTS) Method:

The RTS method utilizes a traditional SISO anechoic chamber but divides the MIMO OTA test into two stages. In the first stage, the device antenna pattern is measured. In the second stage, a channel emulator is used to convolve the measured antenna pattern with the desired channel model to provide the stimulus for a conducted or radiated throughput test on the DUT. An assumption of the RTS method is that the antenna patterns of the DUT, measured in the far field, can fully capture the mutual coupling of the antennas and be used to measure radiated performance. To accurately measure the antenna patterns of the device, it is necessary for the DUT to support amplitude and relative phase measurements of the antennas. Other methods for measuring the antennas are intrusive, requiring physical device modification and use of cables, and are not considered suitable for conformance testing although they have uses in device development.

In the RTS method multipath fading, the angular spread for the transmit and receive sides and the XPR are all generated in the channel emulator, enabling a simple two-probe SISO anechoic chamber to emulate arbitrarily complex 2D or 3D channels. Further details of the RTS method will be provided later in this paper.

C. Reverberation Chamber Methods:

Unlike the anechoic chamber methods which create Line Of Sight (LOS) propagation environments, the reverberation chamber methods utilize mechanical stirrers to emulate a statistically isotropic multipath environment. The reverberation chamber by itself has a limited range of channel modeling capabilities. For example, the power delay profile is limited to a continuous exponential decay, the Doppler spectrum and the relatively slow motion of the stirrers' limits maximum Doppler speed, and the specific correlation cannot be controlled. However, a reverberation chamber with a MIMO channel emulator can overcome these limitations to some extent. The channel emulator can configure the desired PDP, Doppler, and correlation properties. The resulting overall channel property is the convolution of the channel emulator with that of the reverberation chamber.

The significant difference between the reverberation methods and the anechoic MPAC and RTS methods is that the angular spread in the reverberation chamber is not controllable and can only produce statistically isotropic 3D distribution. The reverberation chamber also cannot control signal polarization. These limitations mean that the emulated channel in the reverberation chamber cannot exactly match the spatial channel models in the anechoic methods. Another difference between methods is that the RC, RC + CE, and RTS methods are not suitable for use with devices that have receive antennas that can adapt their patterns according to the instantaneous channel conditions.

4.11 Uplink Data Compression Requirements

The use cases for cellular networks have been ever evolving. Primary applications on LTE were mostly downlink intensive. However with 5G, new types of use cases have exploded. Many requires improved uplink performance, which is particularly critical for TDD bands where the DL: UL splits is unequal. 3GPP has been supporting various RoHC profiles for many years, however, RoHC is used for Header compression and does not support compression of data payload packets which may also carry repetitive information. UDC supports both, the header as well as data payload compression in PDCP layer, independent of Application layer. The Figure 4-21 below illustrates the basic operation of UDC feature.

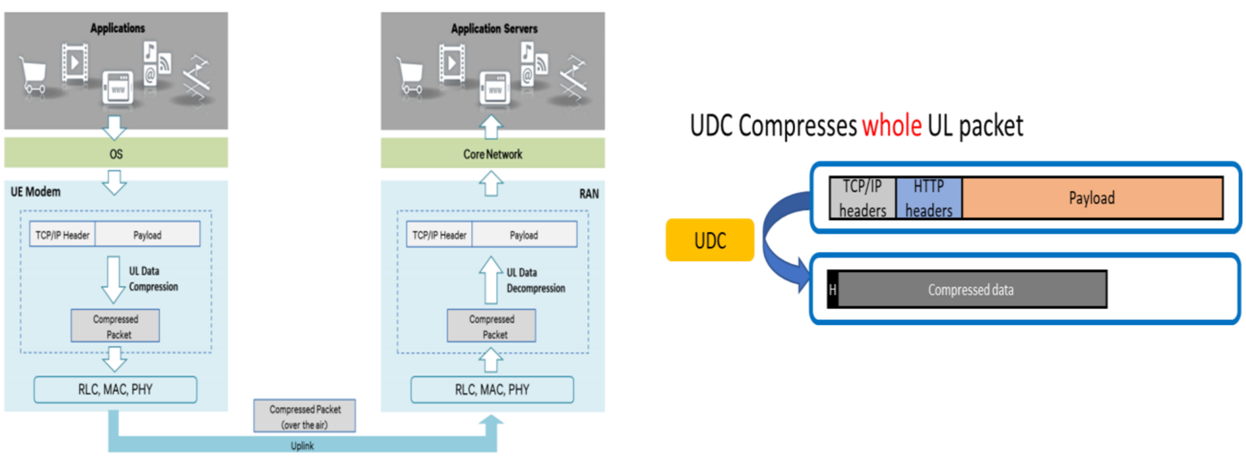

Figure 4-21 UDC basic operation

Some of the benefits of UDC are:

- Increased UL capacity – Compression at higher layer results in lower PRB utilization.
- Increased coverage – Lowers cell edge throughput requirements.

- Improved user experience – Shorter response time and possibly supporting higher relative throughput
- Possibly reduce cell edge interference and UE Battery life improvement– Shorter transmission time and potentially overall lower Tx power.

3GPP Rel 15 (LTE) has included support for DEFLATE based UDC (RFC1951, May 1996). However, no UDC support is available currently for NR in Rel 15 and Rel 16. 3GPP will address UDC as Rel-17 work item.

The 5G global device should support RoHC and UDC for both LTE and NR when available as it is an important tool for improving UL performance, particularly needed for TDD bands.

5 Product Requirements

This section provides some high-level guidelines on the product requirement. The initial GTI Global 5G product is expected to be a smartphone form factor and hence these requirements pertains to it. This section shall be updated in subsequent versions of this whitepaper based on additional needs of GTI operators.

5.1 Wi-Fi Requirements

The support for Wi-Fi has been integral part of any device form-factor. Based on response from some GTI operators, the GTI 5G global device shall support following IEEE Wi-Fi Specifications.

Wi-Fi Client	Support Required?
802.11ax (Wi-Fi 6)	YES
802.11ac (Wi-Fi 5)	YES
802.11 a/b/g/n	YES

Table 5-1 Wi-Fi Support

Wi-Fi 6 (802.11ax) is a recent version of IEEE Wi-Fi specification operating on 2.4GHz and 5GHz unlicensed band. Other Wi-Fi versions to be supported by this GTI 5G Global device are traditional 802.11a/b/g/n/ac.

5.2 Display Requirements

Display requirements are key in providing enhanced user experience. This is particularly important in supporting applications touted by 5G such as gaming / enhanced eMBB video experience. Based on some survey response from GTI operators, the GTI 5G global device shall support display resolution of up to 3168*1440 with a refresh rate of 120Hz using OLED display. The recommended screen size is 6.5” – 6.8”.

5.3 Battery Requirements

Battery is another key component of a portable device. The need for improved battery capacity has been every increasing, given the enhancements in camera, video/display technology, smartphone applications/use cases supporting high throughput as well as supporting multiple wireless technologies. Based on initial survey from operators, below are some of the guidelines on determining battery capacity:

- The battery capacity shall be greater than 4000mAh.
- In standby mode, the current shall not exceed 10 mA;
- In connection mode without data service, the current shall not exceed 120 mA (enable C-DRX both 4G and 5G);
- In downlink data services mode (Data rate: 1 Gbps, Transmission power: 0dBm), the current shall not exceed 1000 mA;
- In uplink data services mode (Data rate: 70 Mbps, Transmission power: 0dBm), the current shall not exceed 700 mA.

The above guidelines shall help determining it overall operation and capacity.

6 Testing Requirements

Cellular communications systems have been developed and operated through multiple generations from the early days of GSM (2G). It is essential the device operates according to the 3GPP standards as well as regulatory specifications. This ensures interoperability, optimal performance and meeting important regulatory requirements. This section will provide more details on testing aspects for a global 5G device.

6.1 3GPP Spec Conformance requirements

The 3GPP conformance tests are designed to ensure a mobile device would operate correctly and safely with the network.

3GPP RAN5 introduced a work item for 5G UE Conformance Tests for Release 15 in May-2017. This work item required to produce a number specifications as shown in the diagram below:-

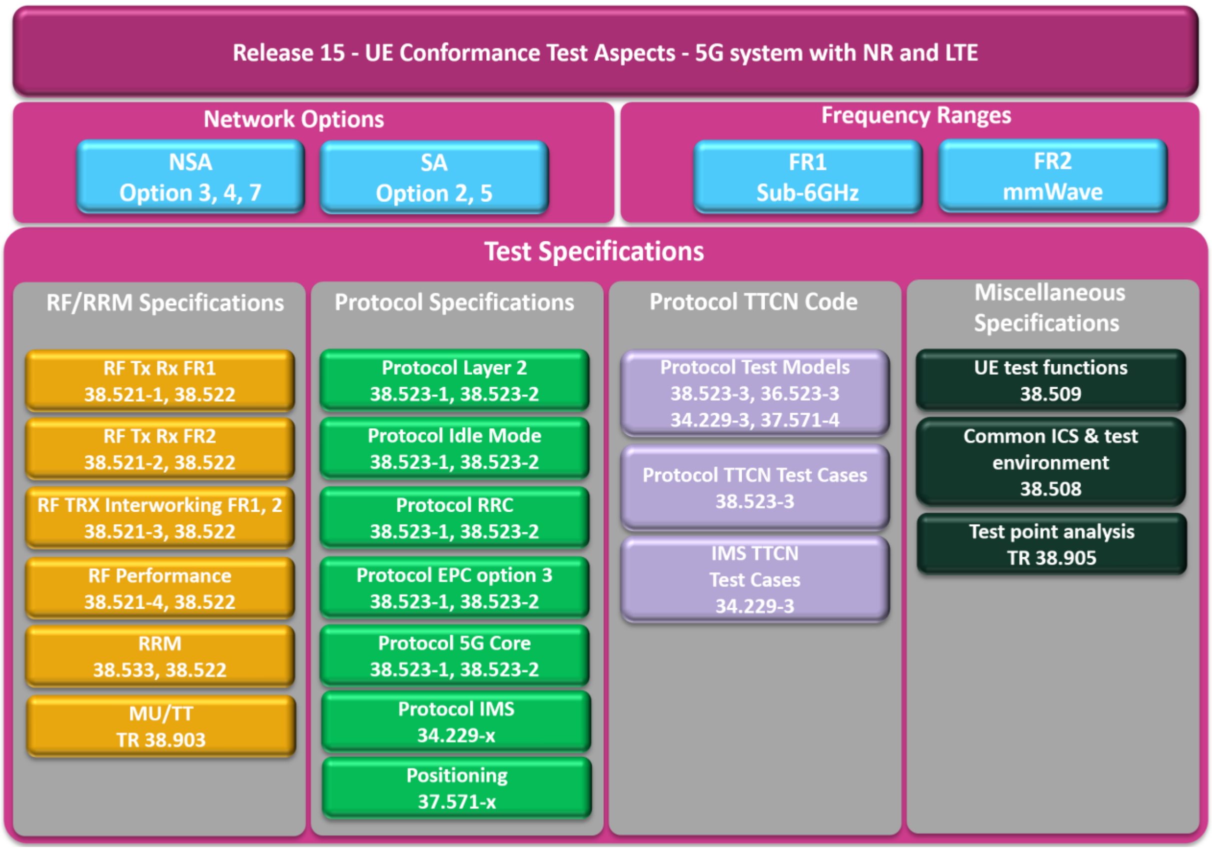

Figure 6-1 Rel 15 UE Conformance Tests

Since the introduction of the 5G UE conformance test item, the group have been designing test cases initially focusing on FR1 and FR2 in NSA option 3 and SA Option 2. The latest progress was reported at the RAN5#86 meeting (R5-200490) in February 2020. It was as shown follows:-

	FR1		FR2		FR1+FR2	
Test area	**SA Option 2**	**NSA Option 3**	**SA Option 2**	**NSA Option 3**	**SA Option 2**	**NSA Option 3**
Positioning	21	21	21	21	17	8
RF Rx/Tx	99	73	7	7		
Demod/CSI reporting	50	50	0	0	0	0
RRM	51	38	0	0	0	0
Protocol Idle Mode	54		15			
Protocol Layer 2	72	68	72	67		
Protocol RRC	58	42	24	35		
Protocol EPC option 3		3		3		
Protocol 5GC	59		59			

Multilayer and Services	14		14			
Overall number of test cases	**478**	**295**	**212**	**133**	**17**	**8**

Table 6-1 RAN5#86 Progress report

These test cases are designed to be executed in the different bands in FR1 and FR2 as defined by 3GPP technical specification 38.101.

The design of the conformance tests in RAN5 was done over a number of phases since the beginning, in order to prioritize the test areas and test cases to meet the industry requirements. Below is table showing the phases and progress (extracted from R5-200490) by RAN5 to-date:

		SA								
	Option:	Option 2								
	Phase:	1	2	3	4	5	6	7	8	9
	Target date:									
Area	TS/TR	RAN5#81 (Nov-18)	RAN5#82 (Feb-19)	RAN5#83 (May-19)	RAN5#84 (Aug-19)	RAN5#85 (Nov-19)	RAN5#86 (Feb-20)	RAN5#87 (May-20)	RAN5#88 (Aug-20)	RAN5#89 (Nov-20)
Completion of sub-areas		**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**40%**	**17%**	**0%**
WP sub-areas	TS/TR									
UE test functions	38.509	100%		100%	100%					
Common ICS	38.508-2	100%								
Common test environment	38.508-1	100%	100%	100%	100%			28%		
RF Tx Rx FR1	38.521-1	100%	100%	100%	100%	100%	100%	38%		
RF Tx Rx FR2	38.521-2		100%	100%	100%	100%	100%	46%	19%	
RF Tx Rx Interworking FR1, FR2 and other radio	38.521-3 38.522				100%			45%		
RF performance	38.521-4			100%	100%	100%	100%	56%	35%	
RRM	38.533			100%	100%	100%	100%	22%	55%	0%
MU/TT Rx Tx	TR 38.903			100%		100%		42%	0%	
MU/TT Demod	TR 38.903							0%	0%	
MU/TT RRM	TR 38.903							27%	10%	
Protocol Layer 2	38.523-1	100%	100%		100%	100%	100%	14%		
Protocol Idle Mode	38.523-1		100%		100%	100%	100%	81%		
Protocol RRC	38.523-1	100%	100%	100%	100%	100%	100%	69%		
Protocol EPC Option 3	38.523-1,									
Protocol 5GC	38.523-1	100%	100%	100%	100%	100%	100%	0%		0%
Multilayer & Services	38.523-1			100%	100%	100%	100%	19%		
Positioning	37.571-x			100%	100%	100%		90%		
Protocol IMS	34.229-x				100%			4%		
Protocol Test Models	38.523-3	100%	100%	100%	100%	100%	100%			

Table 6-2 NR SA (Option 2) completion versus work plan sub-areas and delivery phases

	Option:	NSA									
		Option 3									
	Phase:	1	1.5	2	3	4	5	6	7	8	9
Area	TS/TR Target date:	RAN5#79 (May-18)	RAN5#80 (Aug-18)	RAN5#81 (Nov-18)	RAN5#82 (Feb-19)	RAN5#83 (May-19)	RAN5#84 (Aug-19)	RAN5#85 (Nov-19)	RAN5#86 (Feb-20)	RAN5#87 (May-20)	RAN5#88 (Aug-20)
Completion of sub-areas		100%	100%	100%	100%	100%	100%	100%	100%	39%	41%
WP sub-areas	TS/TR										
UE test functions	38.509	100%		100%		100%					
Common ICS	38.508-2	100%									
Common test environment	38.508-1	100%	100%	100%	100%		100%	100%		15%	
RF Tx Rx FR1	38.521-1										
RF Tx Rx FR2	38.521-2										
RF Tx Rx Interworking FR1, FR2 and other radio	38.521-3 38.522			100%	100%	100%	100%	100%	100%	53%	34%
RF performance	38.521-4					100%	100%	100%	100%	57%	
RRM	38.533				100%	100%	100%	100%	100%	27%	66%
MU/TT Rx Tx	TR 38.903										
MU/TT Demod	TR 38.903										
MU/TT RRM	TR 38.903										
Protocol Layer 2	38.523-1	100%		100%					100%	7%	
Protocol Idle Mode	38.523-1										
Protocol RRC	38.523-1	100%		100%	100%	100%		100%	100%	82%	
Protocol EPC Option 3	38.523-1,	100%									
Protocol 5GC	38.523-1										
Multilayer & Services	38.523-1										
Positioning	37.571-x			100%			100%	100%		90%	
Protocol IMS	34.229-x										
Protocol Test Models	38.523-3	100%		100%	100%	100%	100%				

Table 6-3 EN-DC (Option 3) completion versus work plan sub-areas and delivery phases

In general, the early phases cover the functional test aspect of the 5G devices. This is to ensure the safe and correct operation of these devices in the network. The test cases in the test specifications were mostly completed by mid-2019. Since then, the emphasis moved onto addressing performance in the RF and RRM areas. For protocol in SA, the work moved onto the testing of the multilayer and services in order to get ready for new 5G features such as Network Slicing.

6.2 Device Certification

For conformance testing, the operators around the world participate in various certification forums such as GCF, PTCRB, GTI, etc. One key function for the operators is to specify work items for the bands and the list of test cases for their specific test requirements.

The test industry (test equipment vendors and test laboratories) are responsible to provide test platforms and validated test cases for the operators globally to use as part of their 5G device acceptance testing. At this time, test cases in many of bands in NSA and SA mentioned in this documents are ready and available in multiple test platforms for the operators to perform device certification as part of the overall 5G device acceptance testing.

6.3 Regulatory Requirements

Regulatory requirements are written/updated on a regional basis, by the regional legal regulatory bodies. Although there can be many different requirements or procedures to follow, the technical aspects of the testing are usually related to 3GPP radio requirements (transmitter and receiver testing) and mostly these specifications are referenced. Most regulations are focused onto the emissions coming from the device, both the intended ‘in band’ emissions and the unintended ‘out of band’ emissions. Also, the sensitivity and susceptibility of the device to suffer from emissions coming into the receiver band are often tested.

Typical tests that are performed are:

- Transmitter (in-band): Output Power, EVM, Frequency Error, Occupied Bandwidth, Spectrum Emission Mask, Adjacent Channel Leakage Ratio.
- Transmitter (out of band): Tx Spurious Emissions Mask, Rx Spurious Emissions Mask.
- Receiver: Transmit Inter-Modulation, Blocking, Adjacent Channel Sensitivity, Rx Sensitivity.

For this reason, the actual test equipment and measurement methods are usually very similar to equivalent GCF/PTCRB RF Conformance Test systems, as they are designed to make very similar types of measurement. The overall aim to ensure that the radio in the device will perform correctly in the expected radio environment (i.e. expected level of external signals coming into the receiver), and that the radio will not cause interference to other radio devices by having excessive levels of radio emissions either in or out of band. This will ensure compatibility of the cellular network devices with other radio devices that may be in the nearby area. For this reason, regional specific requirements may be added, depending on regional licensing and spectrum usage. This is to ensure clean spectrum occupancy without affecting adjacent bands that may have specific sensitivity requirements. In some regions, the neighbor frequency bands may be used by high power systems such radar systems or may have highly sensitive receiver systems such as satellite communications links, and these existing users of neighbor frequency bands must be accommodated with regional specific extra requirements.

There are different approval processes across different regions. These vary in terms of ‘who is approved/able to perform the testing and certification’, and the ‘availability of test specifications and procedures to be followed’. They are roughly grouped into four categories and summarised below.

Self-Declaration:

In this type of regime, the manufacturer is responsible to follow the required test procedures and to ensure compliance. There is no requirement for an external or independent (approved) test laboratory to test or certify the product, and no specific certificate is issued. The manufacturer will be able to directly claim compliance based on their own measurements. However, the manufacturer is responsible to ensure the correct specifications and requirements have been followed, and that the testing has been done correctly. The manufacturer should also have a suitable quality system in place to ensure the procedures are correctly followed. One of the key markets that has 'Self declaration' is the EU and European Free Trade Area (EFTA), which follows the EU Radio Equipment Directive (RED, 2014/53/EU)

Approved Laboratory Testing:

In this type of regime, there is sometimes a requirement for independent test laboratories to be certified (approved) to perform the required testing. Such approval will normally cover both the technical capabilities and the quality procedures of the test facility. A manufacturer will normally then be required to submit a test results and documentation to a national regulator or approved private certification body, to then be issued with the required regulatory certificates. Depending on specific regions, this may either require test results to come from an approved laboratory or may accept the use manufacturers own test results. In either case, a formal certificate will finally be issued by the authority. Examples of this type of scheme are USA (FCC), Canada (ISED), China (RTA, NAL, CCC), Japan (ARIB/TRCC).

Specific local approval schemes:

In these types of regime, the regulatory testing is normally performed by specific local testing laboratories, using specific local procedures and requirements coming from local certification bodies. In these cases, the exact local procedures and processes must be followed, and usually requires a local presence to manage the process.

Unregulated market regions:

For some markets, there are currently no declared regulatory testing schemes. For these markets, there are often specific administrative procedures to be followed to achieve certification.

In addition to the above 'spectrum and radio compatibility' requirements, some regions also have safety related requirements specifically relating to the 'Specific Absorption Rate' (SAR) testing. SAR is a measure of the magnitude and distribution of the absorbed electro-magnetic energy that is absorbed by a biological body (e.g. human) when exposed to electro-magnetic fields radiating from a transmitter. SAR is measured in Watts/Kg, and is averaged over a specific volume of 'body' and averaged over a specific length of time.

The SAR requirement extends the testing beyond 3GPP, to include body absorption effects, so a 'Phantom' body is used to absorb radiation from the device, and the level of absorption is measured using probes which are placed within the phantom body. To test this, the radio device (e.g. mobile phone) is put into a controlled environment (shielded chamber) and then configured to transmit at a specified level (e.g. max power), the absorbed energy levels are then measured using probes in the Phantom. This Phantom is made of material with similar absorption properties as the body and comes in different form factors to represent different body parts and the associated 'use case'. Examples are 'head' for mobile phone when talking, 'arms' for laptop/tablet, 'torso' for mobile phone when using 'hands free' and device is in pocket. The test set-up consists of an OTA test chamber, phantom to create body effects and probes to measure absorption, and a network simulator to establish a call and put device into correct transmission/reception mode.

6.4 National / Operator Specific Requirements

Since 2G (GSM) era, public mobile operators around the world have been adopting global standard technology for their mobile service. Although many of the core services offered would be the same, but the configuration from operators could be somewhat different as later standard technologies (3G, 4G and 5G) consist of many optional features. This leads to operators in different regions having different test requirements for some of the following reasons:-

- Network architecture (eg. SA, NSA)
- Operating bands
- Specific network services offered
- Network sharing between operators in the same geographical area
- Roaming
- Operating environment (eg. High Speed Train, very densely populated urban, etc.)

For these reasons, whilst operators would mostly utilize standard industry tests such as conformance, they would introduce additional operator-specific tests. This is sometimes referred to as Carrier Acceptance Tests, CAT.

Generally they will comprise of:-

- Subset of 3GPP conformance tests
- Lab tests using

  - Network simulators for Inter-Operability Tests (NS-IOT) to provide high degree of control and configurability of the test environment
  - Real network elements (eg. gNode-B) for IOT to allow testing of real-life scenario in a 'controlled' environment.
  - OTA
- Field trial
- Mobile Drive Tests

Operators around the world would generally perform the above as part of the device acceptance, but the detail content would be different and some may choose to take different elements of the above.

It is known that some operators in USA, China, Korea, Japan would include all of these elements in their device acceptance tests. For the NS-IOT part, operators in these countries would define their own specific test specification to define the test areas and test cases.

For 5G device testing, GTI have defined 5G Device Function and Performance Test Specification which is available for the GTI operators to use for their NS-IOT part of testing. To-date this test specification consists of the following test areas:-

- Basic Function
- Mobility
- Service
- Roaming
- Power Consumption
- Data Throughput
- Latency
- High Speed Train
- Beam Management
- Data Throughput with CA

These are designed to cover areas that are not addressed by 3GPP conformance tests. More test areas are expected to be added to the specification in the coming months.

The test industry are invited by the operators to develop test platforms and test cases for these tests. This is typically done in partnership with operators and chipset/device vendors.

In Europe, it is quite common that operators would skip the NS-IOT part and rely on the other elements for the device acceptance tests. This has been the case since the 2G era.

7 Device Architecure Recomendations

As seen from section 3, various operators use different LTE / NR bands, the number of which is constantly increasing. Furthermore, any global roaming LTE/5G device would also require support for, at least, a set of core LTE/5G bands in order to facilitate roaming. It is only through the re-use of the same hardware device architectures and electronic components that will benefit, when economies of scale will kick in and lower cost global smartphones may become available to a larger pool of customers.

All these multi-mode multi-band requirements along with technology features such as increased channel bandwidth, MIMO, multi carrier aggregation, dual/multiconnectivity, support for simultaneous voice and data support in different forms, undoubtedly imposes significant challenges in terms of device architectures, size, power consumption, processing power, and software complexity related to inter-RAT selection and mobility.

To that effect, this section will focus on global device implementation challenges and architecture recommendations that would facilitate and enhance Global 5G device ecosystem and address the device requirements as specified in the previous sections.

7.1 Multi-Mode Multi-Band Device Challenges

With the global deployment of 5G well under way, mobile device manufacturers face a growing list of new challenges. While network operators push for more universal device definition and higher levels of performance in order to commercially leverage the strengths of the 5G standard, device manufacturers struggle with increasingly complex RF systems, higher order interference problems, more crowded and functionally dense product requirements and always-present cost challenges. As the 5G standard matures and networks expand, significant backward compatibility with established prior standards remains critical while new demands are being introduced to 5G devices. As previously outlined, a 5G UE should support:

- 5G/NR
- LTE FDD
- TD-LTE
- WCDMA/HSPA
- GSM/EDGE/GPRS

Layered on top of these modes of operation, are the significant number of frequency bands required to enable local and roaming connectivity. These bands continue to expand as more spectrum is identified for re-farming from prior standards to 5G NR, while continuing to maintain continuity to past standards. Compounding the mix of modes and bands, rapid and cost-effective global network implementation, drives the need for simultaneous operation across standards as in the case of non-standalone 5G. All of these factors are rapidly changing as new devices are continuously developed.

Prior chapter had identified the benefit/need for multi-mode multiband integrated RF front-end modules in solving many of the global operator problems. These modules are the backbone of complex 5G applications, providing high functional density and proven performance for fast time-to-market and robust supply. With new requirements ahead, these modules will continue to be key building blocks of 5G terminal devices, but manufacturers will to now need to consider the impact of these new requirements on the complexity and performance of these solutions. A few examples serve to illustrate the growing challenges faced by multi-mode multiband solutions.

Challenge 1: Increasing RF complexity impacts the system budget leading to a number of important considerations.

As global 5G devices are defined with higher levels of RF content to enable necessary regional bands, carrier aggregation or EN-DC combinations, the manufacturer must manage a more complex RF architecture. New frequencies expand the required antenna bandwidth and features such as SRS or DR-DSDS quickly increase the number of needed antenna elements. In a compact industrial design, antenna elements can be affected by area or volume limitations and radiated efficiency can be reduced. Complex filter combinations and switch elements will be necessary to support CA and EN-DC. Such simultaneous Tx or Rx capability requires excellent selectivity, isolation and linearity to realize the system's full potential for high data throughput. These system requirements drive higher in-line insertion losses that compound the already challenged antenna limitations previously mentioned and illustrated by comparison of a simple MMMB architecture (Figure 7-1) with the required complex architecture (Figure 7-2). With losses mounting and efficiency reduced, demands for higher transmit power and better receive sensitivity become a focus in development.

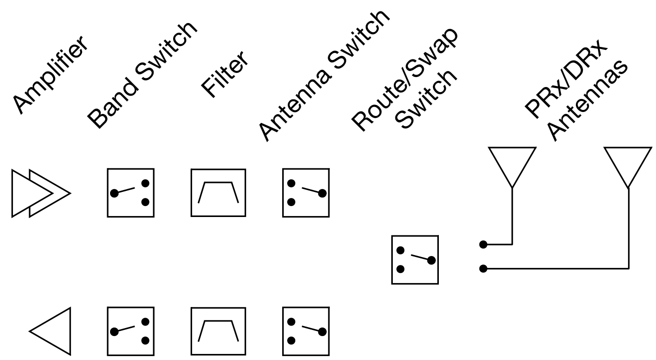

Figure 7-1 Simple MMMB Architecture

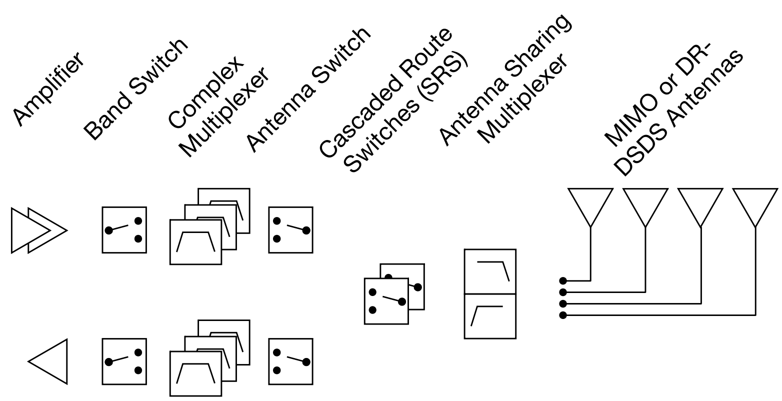

Figure 7-2 Complex 5G MMMB Architecture

Each new generation of multi-mode multiband RF module is asked to provide higher transmit power to overcome increased system losses. Design for higher transmit power requires a careful balance of trade-offs. Higher power is desired to achieve better connectivity and throughput. However, strong throughput using the high order modulation also relies on maintaining excellent linearity for signal integrity. Driving power higher to overcome system inefficiencies pushes the amplifier operating point toward more non-linear operation in order to maintain reasonable power dissipation. In addition to linearity impacts, high power also brings more opportunity for cross-circuit coupling and interference, degraded harmonic or spurious effects and increased thermal dissipation. Such increases in thermal may, in fact, exceed the capability of poorly selected filters or other circuit elements.

These effects can be managed effectively by careful selection of filter, switch and amplifier technology and proper specification can allow for a productive balance of engineering trade-offs. High levels of module integration can provide pre-validated solutions that directly optimize these complex functions, minimize unintended losses and reduce implementation risk in the final application.

Challenge 2: Reduced PCB area, increased circuit density and more complex frequency aggregation highlights new application risks.

While 5G mobile devices now need to implement more combinations of bands and modes and new spectrum is being considered, the available area for RF circuitry remains the same or is often reduced to accommodate new product features. This situation forces the RF front-end content to continue to shrink in size and consolidate into fewer module placements. This higher density of RF directly conflicts with an increasing need for isolation and rejection to achieve robust performance in simultaneous operation modes like CA or EN-DC. New modules place transmit and receive functions in close proximity and reduce isolation between key frequency bands.

To achieve the best possible system optimization, extensive EM modeling becomes more important. Such modeling should be utilized at circuit, module and PCB levels. Even with excellent modeling, non-ideal or unintended interaction is possible. Unexpected parasitic effects may arise in the end application that can cause shifts in key areas of RF operation. Mechanical housings may degrade antenna structures or metal shield cans, added late in development, may de-tune important resonant circuits causing significant impact to receive sensitivity, cross-circuit isolation or transmit harmonics as illustrated in Figure 7-3. While these effects are not always obvious in simple modes of operation, they may be present in more obscure modes or frequency aggregation combinations.

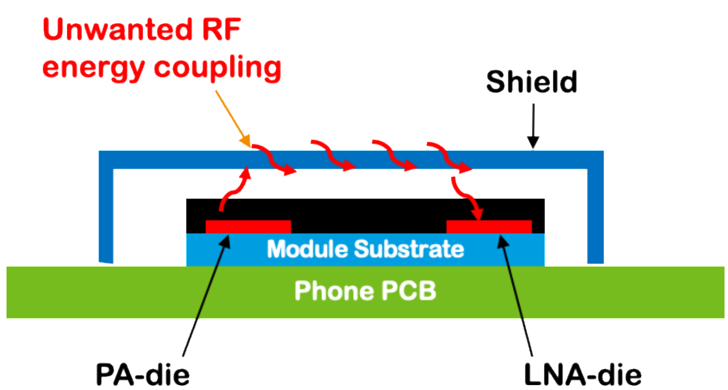

Figure 7-3 Example of Unwanted Tx to Rx Coupling Caused by Metal Mechanical Shield Can

While these effects are challenging to manage and often present risk late in a UE development stage, such risk can be mitigated through careful specification of RF module solutions and through key features such as integrated module shielding. Integrated module shielding decreases module sensitivity to parasitic RF effects that may arise late in development despite careful modeling and planning.

<u>Challenge 3: Global UE definition with multi-regional CA or EN-DC combinations compounds device complexity.</u>

Desire to reach a broad global market and support multiple operators and regions, either directly or through roaming, greatly affects frequency selection architecture. Across regions, different operators support widely varying frequency bands and aggregate these bands to meet their coverage and usage needs. Some overlap of common bands exists, and support of these common bands, along with their unique aggregation combinations, drives very difficult system requirements. Often a particular band may need to be combined with several other bands depending on the region of current operation. This problem generates a matrix of possible use cases that must be carefully optimized in the multi-mode multiband solution. The following list highlights some of these overlaps:

B39 + n41

B3 + n41

B3 + n40

B1 + n40

B2/25 + n41

B2/25 + B66 + n41

Note in this example that B41 must be combined effectively with B39, B3, B2/25 and B66. Other bands face similar requirements. Additionally, bands like B41 and B40 must support HPUE and operate at higher power.

To support all of these different combinations, multi-mode multiband solutions must optimize shared multiplexed filter paths to provide low losses in-band and carefully tuned out-of-band rejection. Each additional case that must be optimized raises the complexity of the matching and tuning problem and forces careful management of the additive loading effects. Poor technology selection or inadequate design leads to higher system losses or to poor isolation. As previously highlighted, these system factors lead to more demand for higher transmit power or concerns about reduced receive sensitivity ultimately degrading connectivity, throughput or thermal dissipation and power consumption.

As in earlier examples, careful selection of technology and specification of the solution can mitigate these challenges and provide acceptable 5G performance.

7.2 Device Architectures

The focus of this paper is on global 5G devices, which mainly encompasses smartphone devices. However, there are indications that other types of devices may have a global or regional appeal, particularly serving various 5G use cases. There is a growing interest on tablets and hotspot personal router devices to provide support for multi-band configurations, so that those devices could be used for national, regional, and in some cases global purposes as well.

As each of those device categories could have different type of requirements in terms of multi-mode multi-band support and type of applications (i.e. data only-vs-voice and data), it is understandable that different device hardware architecture would be applicable for each specific type of device. However, as the level of functionality integration using a single/integrated chipset is constantly increasing, there is a lot of commonality between chipsets and RF electronic components that can be reused irrespective of device type. This should be considered a positive development as it would help reduce device cost due to economies of scale factor.

A block diagram of a typical device architecture is shown in Figure 7-4. The applicability of various functions such as audio, touch, graphic, camera and AI depends on the type of the device. Typically, smartphone and tablet form factors require support for all of these building blocks. Hotspot or other form factor may not require all of these blocks associated with the AP. However, other blocks such as BP, RFIC, RFFE, Antenna are expected to be similar across various form factors.

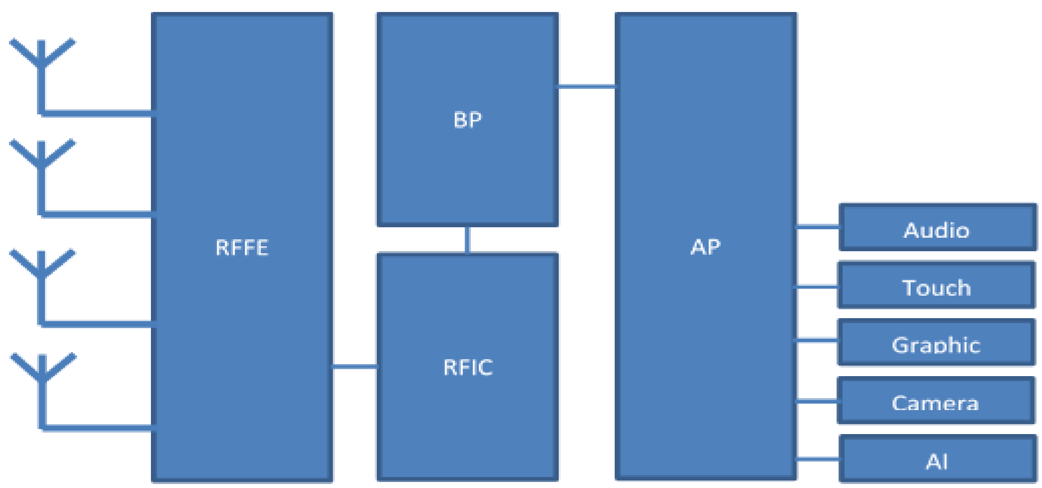

Figure 7-4 Block diagram of device architecture

This sub-section describes some of the main architectures considerations and recommendations to implement GTI MM-MB requirements.

7.2.1 Global Device Architectures considerations for SMARTPHONES

Figure 7-5 below illustrate a device architecture for a multi-mode multi band global smartphone.

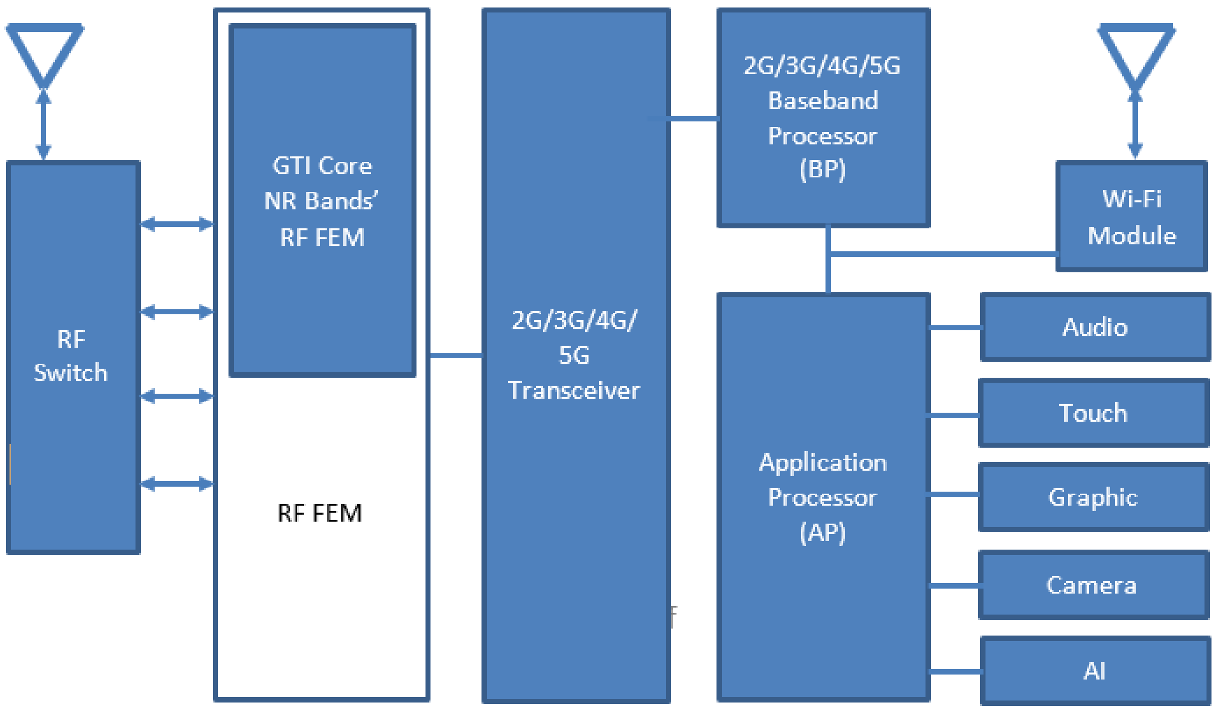

Figure 7-5 Device architecture for global smartphone

The device architectures for 5G smartphones is similar to 4G smartphones. The baseband processor and transceiver supports multi-mode (2G / 3G / 4G / 5G) operation. The RF front-end module design and implementation of the GTI global 5G device is expected to be very complex due to the need of supporting various bands ranging from frequency 600MHz to 5GHz. The antennas could be shared across various bands in a specific frequency range but may need additional antenna subsystem for other frequency bands. Wi-Fi could be supported using the same baseband / transceiver or using a dedicated module.

As the 5G introduces new frequency band, wider bandwidth, more transmit and receive antennas, SRS switching for TDD band, HPUE, uplink CP-OFDM waveform, co-existence of 5G and Wi-Fi and device self-interference in NSA, there is a need to develop new solutions for antenna, RFFE, RF transceiver and BP.

These 5G characteristics / features have an impact to RF key components and design including transceiver, PA, filter and switches. These impact considerations are illustrated below:

Multi-band / Multi-Antenna: New frequency band, wider channel bandwidth and more transmit and receive antennas increase the number of RF components and the design complexity. The RFFE and RF transceiver in Figure 7-5 need to support frequencies from 600-5000MHz in order to support all GTI required bands. Also, a minimum of two Rx antenna ports in many operating bands, while some bands such as n7, n38, n41, n77, n78, n79, n25, n66 where the UE is required to be equipped with a minimum of four Rx antenna ports, with one or two Tx antenna ports. SRS switching increase the complexity of RF design and requires the RF components with less loss. RFFE in Figure 7-5 should supports 2T4R or 1T4R SRS switching. Thus, more transmit and receive antennas leads to ever increasing number of total antenna support.

Other 5G considerations: The higher PAPR associated with NR CP-OFDM waveform leads to tough Tx linearity vs. efficiency tradeoff. Use of HPUE requires stronger durability of Tx-chain. The need for Latency re-check for timing capability of key components (switch, tuner, PA, PMIC, etc), with NR ON-OFF timing 20 uS (vs. LTE 10 uS).

Co-existence: 5G smartphones are multi-mode multi-band device and the BP should support 2G/3G/4G/5G features to ensure the user experience. The Co-existence of 5G and Wi-Fi as well as device self-interference in NSA mode causes interference issues. The isolation of most RF component cannot meet the requirement for co-existence of n40/n41 and Wi-Fi 2.4GHz and the n79 and Wi-Fi 5GHz. These issues of co-existence of 5G and Wi-Fi as well as device self-interference in NSA can be solved using software solution in BP.

Application processor: With the rapid commercialization of 5G network, the applications of 5G service might increase rapidly as well. This leads to the higher requirements of function and performance for AP, as well as the enhancement of the units of audio, touch, graphic, camera and AI.

Battery: Based on GTI 5G Device Power Consumption White Paper, the power consumption of the components that have the greatest impact on terminal power consumption includes the RFFE (such as PA, AD/DA, filter), RF transceiver, BP, AP and screen parts. Analyzing the 5G features that have impact on the smartphone power consumption, such as bandwidth, UL-MIMO and HPUE, the 5G smartphone power consumption might increase. However, there are 5G features that can be used for power saving as well, such as DRX, BWP, cross-slot scheduling and periodic PDCCH monitoring. On the other hand, as the applications of 5G service increases rapidly, the usage time of 5G smartphone might be higher. Thus, the capacity of the battery should be increased to meet the above requirements as well as maintain the size and the weight of the battery at the same time.

Dual Standby: The majority of the dual-standby smartphones in the global market supports 2G/3G/4G/5G + 2G/3G/4G. The RFFE and RF transceiver for each SIM card should support all GTI required bands. The BP should support the functionality of dual-standby mode.

Overall, the functional integration of RF components and RF path co-banding should be used to reduce the size and the cost of the smartphones. Minimization of RF components loss and interference and increase of RF components efficiency should be used to improve the radio performance of the smartphones and extend the battery usage time. Use of specific software implementation in BP to account for co-existence.

7.2.2 DATA ONLY Device Architectures

The data only device could be supported in various forms such as hotspot, tablet, module for various 5G vertical use cases. There may be specific requirements for each of these device types, particularly related to AP functionality support. However, it is expected that the BP, RF transceiver, RFFE and Antenna requirements would be similar to the ones for the smartphone form factor, though many device type may not have stringent space constraints as a smartphone. This allows for better implementation and performance.

8 Conclusion

Having surveyed GTI member companies on their 5G multi-band, multi-mode device design requirements to address immediate network deployment needs as well as longer range deployment plans, the Global 5G device task force identified a common set of frequency bands across 5G NR, LTE and 2G/3G technologies as well as other capabilities that should be supported in initial 5G global device designs to meet the near-term requirements of the majority of GTI member companies.

The recommended smart phone design includes 20 LTE bands and 15 NR sub-6GHz bands, to support global needs. Along with the combination of FDD / TDD LTE and 5G NR, the device shall also WCDMA and 2G GSM technologies. The Global 5G device task force also recommends that the device design include support for inter-RAT mobility for voice and data, support MIMO operation as well as co-existence with ISM bands. Additionally, data-centric device designs should leverage the RF front end development work for smart phones to maximize efficiencies and expedite the development process.

Below is the summary of key requirements for the Global 5G device:

- A 5G UE shall support both standalone and non-standalone 5G operations.

- Device shall support 2G (GSM/GPRS/EDGE) and 3G UMTS, along with LTE and 5G access technologies.
- Device shall support GSM bands 2, 3, 8 and UMTS bands 1, 2, 4, 5, 8.
- Device shall support mobility between RATs for voice and data.
- Device shall support VoLTE, VoNR, CS Voice, CSFB, SRVCC and EPS fallback for voice.
- Device shall support 5G NR bands: n77, n78, n41, n1, n3, n28, n66, n40, n79, n8, n71, n25, n38, n70 and n74.
- Device shall support 4G LTE bands: B3, B1, B8, B40, B7, B41, B2, B39, B42, B28, B71, B34, B5, B25, B66, B20, B38, B43, B70 and B11.
- Device shall support 15 KHz SCS for NR FDD bands, and 30KHz SCS for NR TDD Bands.
- The 5G UE shall support QPSK, 16QAM, 64QAM and 256QAM on Downlink and Uplink across various supported bands. Also, support π/2-BPSK MCS on uplink.
- Device shall support 3GPP Release 15 specification.
- Device shall support 3GPP defined Channel BWs for the supported NR bands.
- Device shall support CP-OFDM and DFT-S-OFDM waveforms on Uplink.
- Device shall support data compression techniques such as RoHC. Support UDC (Rel 17) when available.
- Device shall support up to 4 Rx for most bands and 2Tx for most TDD bands.
- Device shall support SRS antenna switching (2T4R or 1T/4R) for TDD bands as well as codebook based SRS for UL MIMO.
- Device shall support estimation of DL reference signals (DMRS and CSI-RS).
- Redirection and cell re-selection mobility mechanism between 4G and 5G SA shall be supported by the UE
- Inter-RAT handover support shall be a mandatory feature with capability signaling.
- Device shall support co-existence between n40/n41 and 2.4GHz ISM band and between n79 and 5GHz ISM band in terms of Spectrum mask, ACLR and Receiver desense.
- Device shall support Wi-Fi specifications such as IEEE 801.11a/b/g/n/ac/ax.

With this set of common requirements identified, GTI will commence working closely with OEM and other ecosystem partners to bring devices incorporating these design criteria to market as expeditiously as possible.

9 References

[1] .

10 Appendix - I