HIGH FIGURE OF MERIT (FOM) VERSATILE 5G C BAND NEW RADIO IQ RECEIVER SYSTEM

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by

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LIST OF SYMBOLS

Φ	Conduction angle
γ	Channel thermal noise coefficient
ω	Frequency in rad/s
ω_C	Center Frequency in rad/s
ω_{IF}	IF angular frequency
£	Leeson Phase noise
ξ	Riemann zeta function
ω_{LO}	LO angular frequency.
Ω	Ohm
1/f	Flicker Noise
C_{gs}	Gate-Source Parasitic Capacitance
C_{gd}	Gate-Drain Parasitic Capacitance
C_{ox}	Gate Oxide Capacitance
C_p	Parasitic Capacitance
f	Frequency in Hz
f_{IF}, ω_{IF}	Frequency of Intermediate Frequency Signal
f_{LO}, ω_{LO}	Frequency of Local Oscillator Signal
f_{RF}, ω_{RF}	Frequency of Radio Frequency Signal
ft	Transit Frequency
g_m	Transconductance
k	Boltzmann's constant
NF_{LNA}	Noise figure of the LNA
Lg	Gate Inductor
L	Gate length of Transistor

P_{IF}	IF output power
P_{RF}	RF input power
P_{LO}	LO input power
ro	Output resistance of the transistor
S	jω
T	Absolute Temperature
V_{DD}	Supply voltage
V_{TH}	Threshold Voltage of Transistor
W	Width of Transistor

LIST OF ABBREVIATIONS

4G	4th Generation
5G	5th Generation
AC	Alternating Current
AGC	Automatic Gain Control
AM	Amplitude Modulation
AM-AM	Amplitude Modulation to Amplitude Modulation
AM-PM	Amplitude Modulation to Phase Modulation
APD	Analogue Pre-Distorter
BC	Barkhausen Criterion
CCO	Current-controlled oscillator
CG	Common Gate
CG	Conversion Gain
CMO	Current- Mode Oscillator
CMOS	Complementary Metal Oxide Semiconductor
CS	Common Source
CSD	Capacitive Source Degeneration
CS	Capacitive Switching
DBM	Double Balanced Mixer
dB	Decibel
dBm	Decibel with respect to 1mW
DC	Direct Current
DM	Differential Mode
DRC	Design Rule Check
DSP	Digital Signal Processing
DUT	Device Under Test
EDA	Electronic Design Automation
F	Noise Factor
FS	Frequency Synthesizer
FM	Frequency Modulation
FRO	Free Running Oscillator
FT	Fourier Transform

GaAs	Gallium Arsenide
GBP	Gain Bandwidth Product
GC	Grounded -capacitor
GFSK	Gaussian Frequency Shift Keying
GPSK	Gaussian Phase Shift Keying
GND	Ground
GSGSG	Ground-Signal-Ground-Signal-Ground
GSO	Gate-Source Overdrive
HB	Harmonic Balance
HBAC	Harmonic Balance AC analysis
HO	Harmonic Oscillator
Hz	Hertz
IC	Integrated Circuit
IF	Intermediate Frequency
IM	Intermodulation
IMD3	3rd Order Intermodulation Distortion
IMN	Input Matching Network
IoE	Internet of Everything
IoT	Internet of Things
IIP3	Input -referred Third-Order Intercept Point
IP3	Third -order Intercept Point
IQ	In-Phase, Quadrature-Phase
IR	Image Rejection
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
Kf	Stability
Kp	Process Parameter
LMV	LNA+Mixer+VCO
LNA	Low Noise Amplifier
LO	Local Oscillator
LP	Low Power
LTE	Long Term Evaluation
LVS	Layout Vs Schematic
MIM	Metal-Insulated-Metal

MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MC	Monte Carlo
NEF	Noise Excess Factor
NF	Noise Figure
NFA	Noise-Figure Analyzer
nMOS	N-Channel Mosfet
NR	New Radio
OIP3	Output-referred Third-Order Intercept Point
OMN	Output Matching Network
P1dB	1dB Compression Point
PM	Phase Modulation
pMOS	P-Channel Mosfet
PN	Phase Noise
PVT	Process, Voltage and Temperature
Qf	Quality Factor
QLNA	Quadrature Low Noise Amplifier
QVCO	Quadrature Voltage Controlled Oscillator
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RMS	Root Mean Square
SBM	Single Balanced Mixer
S-Par	Scattering Parameter
SA	Spectrum Analyzer
SAW	Surface Acoustic Wave
Si	Silicon
SoC	System on Chip
SiGe	Silicon Germanium
SOI	Silicon on Insulator
SNR	Signal-To-Noise Ratio
SRF	Self – Resonance Frequency
SSA	Signal Source Analyzer
TIA	Trans-impedance Amplifier
UWB	Ultra-Wide Bandwidth
VCO	Voltage Controlled Oscillator

VG	Voltage Gain
VNA	Vector Network Analyzer
WPAN	Wireless Private Area Network

LIST OF APPENDICES

SISTEM PENERIMA PELBAGAI GUNA 5G JALUR FREKUENSI C IQ RADIO BAHARU DENGAN TAHAP MERIT (FOM) YANG TINGGI

ABSTRAK

Evolusi teknologi 5G untuk generasi seterusnya dalam aplikasi berkelajuan tinggi memerlukan dorongan inovasi yang ketara bagi membangunkan sistem komunikasi tanpa wayar. Disertasi ini bertujuan untuk menangani cabaran berkaitan kelajuan tinggi serta mengatasi tarik-ulur bagi meningkatkan prestasi liputan bagi penerima 5G New Radio jalur C. Kajian ini memperkenalkan sistem penerima jalur lebar 5G New Radio dengan Tahap Merit (FoM) yang tinggi, direka khas untuk aplikasi jalur C sub-6 GHz dan dilaksanakan melalui proses CMOS Silterra 130 nm. Sistem penerima ini menggabungkan konfigurasi Penguat Hingar Rendah (LNA) dua peringkat untuk mencapai gandaan yang tinggi dalam lebar jalur sasaran 3 hingga 5 GHz, tanpa mengorbankan kelinearan, angka hingar (NF), dan kestabilan. LNA ini diintegrasikan dengan litar penjana IQ inovatif bagi memastikan penjanaan RF quadrature pada empat fasa: 0°, 180°, 90°, dan 270°. Pencampur keseimbangan berganda, yang diintegrasikan dengan litar penjana IQ, disokong oleh 3 hingga 5 GHz VCO hibrid untuk membentuk isyarat perantaraan (IF) I dan Q dalam julat 100-200 MHz, yang seterusnya dipertingkatkan dengan peringkat Penguat Transimpedance (TIA) bertindan. Hasilnya, sistem penerima mencapai parameter utama dengan gandaan 35.6 dB, kelinearan 16.1 dBm, dan angka hingar (NF) 4.2 dB pada penggunaan kuasa hanya 12 mW. Prestasi VCO menunjukkan tahap hingar -120 dBc/Hz isyarat keluaran sehingga 8 dBm. Oleh itu, sistem penerima yang dicadangkan mencapai tahap merit (FoM) tinggi sekitar 94 dB, serta menunjukkan kepelbagaian dan kebolehpercayaan yang tinggi untuk sistem 5G New Radio.

HIGH FIGURE OF MERIT (FOM) VERSATILE 5G C BAND NEW RADIO IQ RECEIVER SYSTEM

ABSTRACT

The evolution of 5G technology for the upcoming generation of high-speed applications demands a substantial drive for innovation to develop a more extensive wireless communication system. This dissertation aims to address the challenges associated with high speeds and overcome trade-offs to enhance coverage performance for the 5G New Radio C Band receiver. It introduces a high Figure of Merit (FoM) 5G New Radio wideband receiver system, designed for sub-6 GHz C band applications and implemented using the 130 nm CMOS Silterra process. The receiver system incorporates a dual-stage Low Noise Amplifier (LNA) configuration to achieve a high and consistent gain across the target bandwidth of 3 to 5 GHz, without sacrificing linearity, noise figure, and stability. The LNAs are integrated with an innovative IQ generator circuit to ensure RF quadrature generation at four phases: 0°, 180°, 90°, and 270°. The double balance mixer, integrated with the IQ generator circuit, is supported by 3 to 5 GHz free-running tailless hybrid VCOs to form I and Q Intermediate Frequency (IF) of 100-200MHz, further enhanced with stacked Transimpedance Amplifier (TIA) stages. Consequently, the entire proposed receiver system achieves key parameters of 35.6 dB gain, linearity of 16.1 dBm, and a noise figure (NF) of 4.2 dB under 12mW power consumption. The VCO's phase noise reaches -120 dBc/Hz with output signal power up to 8 dBm. Therefore, the proposed receiver system offers a promising solution for achieving a high FoM around 94 dB, demonstrating high versatility and reliability for the 5G New Radio system.

CHAPTER 1

INTRODUCTION

1.1 Research Background

5G embodies the breadth and enormous depth of innovative and comprehensive mobile wireless communications technology. The future of 5G is audacious [1]. It is far more than the next generation of the mobile networks. The trend of the technology such as cloud computing, artificial intelligence (AI) and machine learning (ML) augmented reality (AR) , virtual reality (VR) and billions of connected devices are heading towards higher and newer heights [2]. The 5G interconnected network technology shown in Figure 1.1 assure faster, more reliable and near –instant connections that connecting people and things everywhere. The enhancement of the 5G accommodates everyone to feel a real time live events and video streaming, thus enhancing communication especially in some urban areas.

Figure 1.1 5G interconnected network [1]

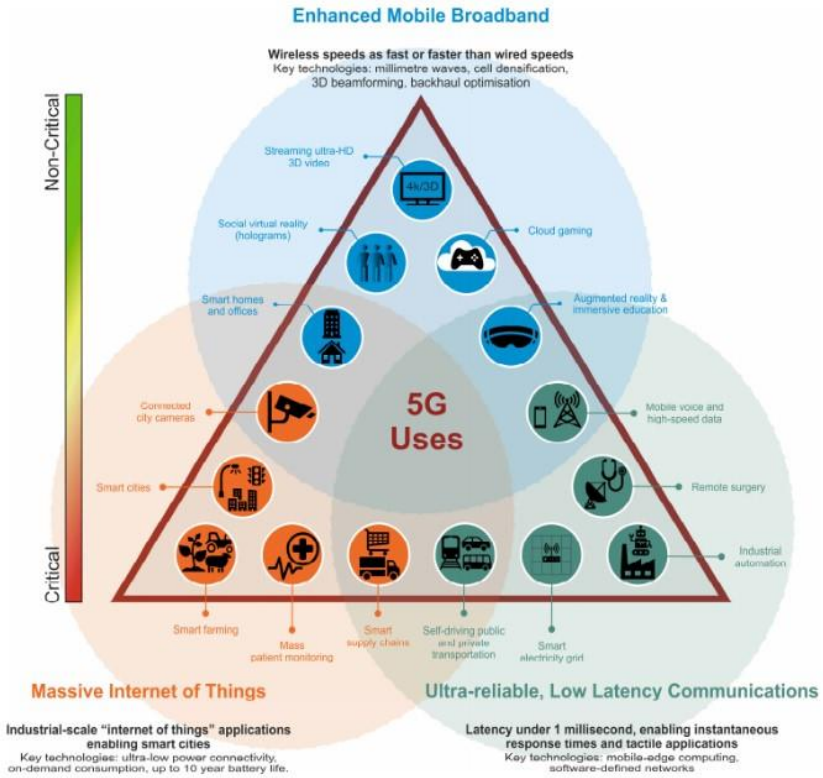

Figure 1.2 5G cases landscape [3]

The smart devices with AI feature create more customised and personalised environment for everyone. There would be three cases for the 5G functionality as shown in Figure 1.2 firstly would be an enhanced mobile broadband (eMBB). This refers to the target of the 5G peak and average data rates, capacity and coverage as compared to the conventional type of the mobile broadband. The eMBB specifies a 5G design capable of supporting up to 20 gigabits per second (Gbps) in the downlink (DL) and 10 Gbps in the uplink (UL). Secondly, would be a massive machine type communications (mMTC) which supports the 5G IoT use cases with billions of connected devices and sensors. It covers both low-data rate or low bandwidth devices with infrequent bursts of data requiring long battery life as well as very high bandwidth and high data rate devices. Thirdly would be an ultra-reliable and low latency communication (URLLC) which focuses on the applications that require fail-safe, real-time communications

example as autonomous vehicles, the industrial internet, smart grids, infrastructure protection and intelligent transportation system. This would be a paramount consideration whereby it can accommodate low facilities in a highly populated area, thus transforming into a truly connected world [4].

As the advancement with time, the fourth generation (4G) technology shows intrinsic limits and no longer sufficient to support the requirement and the need of emerging technology which require lower latency and higher traffic capacity [5]. Thus, this leads the Third Generation Partnership Project (3GPP) to set and develop a new standard for the communication need since 2015. The 3rd Generation Partnership Project (3GPP) is an industry consortium responsible for developing the standards for mobile telecommunications including the protocols, architectures, system requirements and so on. Release 15 a.k.a Rel -15 of the 5G NR specification is the first implementable standard for the 5G and it established a flexible foundation to facilitate the future release of 5G features [2] –[6]. This next big thing is known as New Radio (NR). NR is the new standard for wireless communication and foundation for the 5th generation of mobile networks. It is expected that 5G network will be the predominant option for communication industry in 2020 and following decade. NR are design to meet the criteria and performance laid down by International Telecommunication Union (ITU) for International Mobile Telecommunications for 2020 (IMT-2020) [7].

The potential of 5G is significantly greater than that of its forerunners where some of the new applications enabled would be multi-gigabit wireless mobile broadband, fixed broadband wireless access, augmented reality (AR) and virtually reality (VR), autonomous vehicles, vehicle to everything (V2X) communications, the mobile internet of things (IoT) and wireless industrial IoT(IIoT). The Long-Term Evolution (LTE) is to 4G as NR is to 5G. The 5G NR standard is still being developed to support the increased

dependability, more flexible networks, faster data rates, better coverage, and lower latency [1].

1.2 Receiver for 5 G Applications

The state-of-the-art 5G technology is a rapidly evolving landscape, with advancements in network infrastructure, edge computing, and integration into various platforms. There are many semiconductors' companies moving towards the development and the deployment of 5G solutions [8]. Narrowing the scope in the 5G platform, which is the receiver for 5G applications symbolizes one of the critical components in the 5G network infrastructure. They operate across the frequency bands inclusive of sub 6 GHz and mmWave and are typically integrated into smartphone, IoT devices and 5G base stations [9] - [10]. There are essential key components and technologies indulged in which are through an antenna array of massive MIMO to increase the signal quality and alleviate the interferences. Next, the front end of RF blocks involved would be LNA, filters, mixers and duplexers which are responsible to process the signal to ensure sufficient output signal. These signals need to be processed in the baseband processing to perform decoding and signal reconstruction tasks to be further managed by the power management systems.

1.3 Receiver for 5 G C Band applications and design specs

The 5G C Band typically refers to the mid band frequency in the range of 3.3 GHz to 4.2 GHz spectrum whereby it is crucial for 5G networks. This band is used for 5G networks, providing a good balance between coverage and capacity [11]. The modulation schemes which are commonly used are QPSK, 16QAM, 64 QAM and 256 QAM and besides the channel bandwidth is up to 100MHz per channel with the possibility of carrier aggregation to achieve higher bandwidths. Furthermore, the

estimation receiver's noise figure should be below 6 dB and the gain should be higher than 20 dB . The general application which emulates the specification of the 5G C band receiver is mobile devices, base station, smart cities, industrial IoT(IIoT) and many more. This band is particularly significant for 5G deployments as it offers a good mix of speed and range making it useful for the wide range of use cases[12]. The eMBB is one of the primary use cases for 5G C band which able to provide high -speed internet access supporting streaming HD and 4K videos, Virtual Reality (VR) and Augmented Reality (AR) experiences. Besides that, the demand for the 5G C Band is high especially during the Covid-19 pandemic as it helps to facilitate high speed internet to homes and businesses where fibre optic infrastructures are not feasible such as broadband internet services, remote work and education. Moreover, 5G C band also supports the smart homes in smart cities [13].

1.3.1 The challenges in Meeting 5G C Band

As the demand becomes higher in terms of performance, bandwidth and efficiency to meet the standards of 5G C Band systems, it also introduces technical challenges to meet the high data rates, low latency and reliable connections as shown in Figure 1.3. Firstly, the primary challenges in designing a 5G C Band receiver is supporting for the wide channel bandwidths up to 100 MHz per carrier with multiple carriers. This demands high linearity, low noise figures and efficient signal processing to handle wideband signals without signal distortion. As the C Band spectrum is densely packed, the receivers must ensure better sharp and high-quality filter system to filter out the interferences from the neighboring channels and coexisting systems ensuring minimal insertion loss especially under the high frequencies and wide bandwidth

platform. Next challenge is the power efficiency and cost to support the receiver system with the minimal usage of battery power and with a cheaper cost of manufacturing. Furthermore, under larger bandwidth in 5G C Band, it is difficult to maintain signal consistency that could also lead to an increase in phase noise and causes fast signal variation in the time domain and higher variation in the power domain. Besides that, the modern 5G C Band receivers face difficulty during integration while meeting performance specifications, especially dealing with the risk of parasitic, interference and heat dissipation issues. Therefore, meeting the 5G C Band receivers [14] demand, involves the performance balancing, power efficiency, size and cost while addressing interference, bandwidth and regulatory constraints. Besides the technological advancements in materials, integration and digital processing, creative mitigation techniques are also crucial in overcoming these challenges and to achieving better standards required for the 5 G C Band receiver networks.

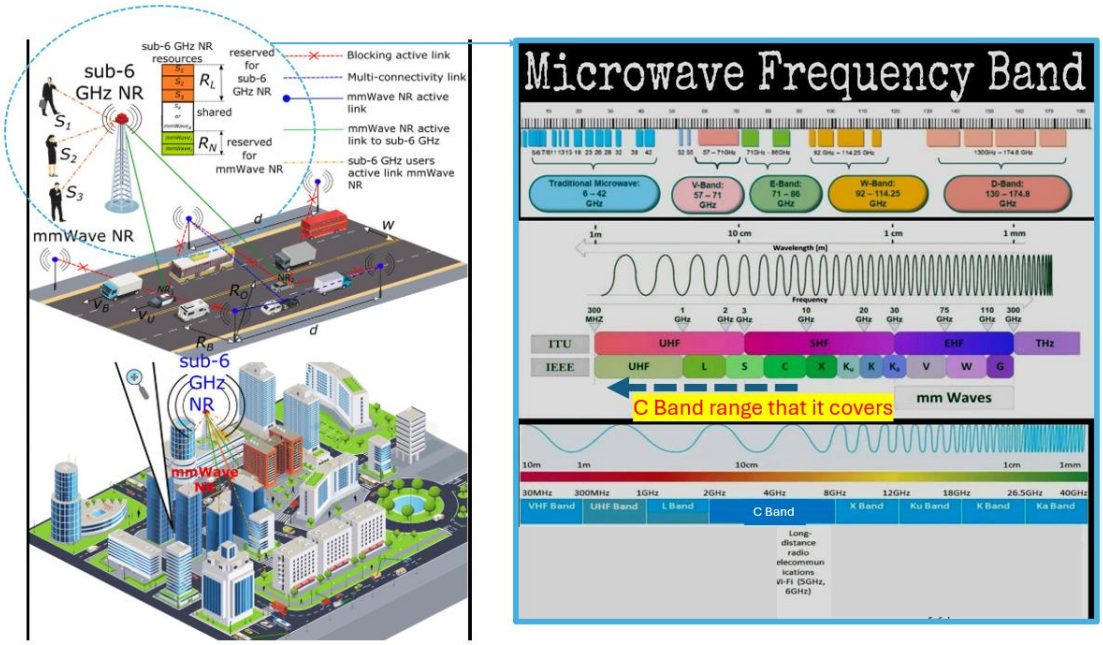

Figure 1.3 Sub 6 GHz NR Receiver for C Band range [14]

1.3.2 The challenges in 5G Band, which narrows towards sub 6 GHz New Radio GHz.

While 5G offers exciting possibilities, it also faces several challenges in mmWave that influence the focus towards sub 6 GHz frequencies. Firstly, limited coverage, where mmWave signals possess shorter wavelengths, which result in a reduced coverage area and a higher susceptibility to being obstructed by physical barriers such as buildings, foliage, and precipitation. These characteristics necessitate a more densely deployed network infrastructure, which can lead to increased costs [4]. Millimeter-wave (mmWave) frequencies are typically defined as those within the 30 GHz to 300 GHz range, which corresponds to wavelengths between 10 millimeters (1 centimeter) and 1 millimeter [9]. Due to their shorter wavelengths, mmWave signals do not travel as far as lower-frequency signals before they attenuate or weaken. Additionally, these signals have a harder time penetrating materials, making them more prone to absorption and reflection by obstacles encountered in urban and natural environments [15]- [20]. The higher frequency of mmWave signals also means that they can carry more data, which is beneficial for high-bandwidth applications [21].

However, the trade-off is that to maintain a robust and reliable mmWave network, service providers need to install more base stations or small cells at closer intervals compared to networks operating at lower frequencies. This denser network infrastructure is necessary to ensure that the signal can reach users without significant degradation, especially in areas with many physical obstructions. The requirement for a denser deployment translates into higher costs for network providers. More base stations mean more equipment, more installation labor, and potentially more site rentals, which all contribute to the overall expense of building and maintaining a mmWave network. In summary, while mmWave technology offers the potential for high-speed

wireless communications, its deployment is a challenged by the physical limitations of the signal propagation and the economic implications of constructing a dense network infrastructure.

Moreover, the devices that incorporate mmWave technology typically necessitate specialized antennas and components, which at present, result in higher costs when compared to devices that operate on sub-6 GHz frequencies [22]. Furthermore, higher device cost of the devices acts as a barrier to their widespread use, which in turn affects the entire network ecosystem and the potential benefits. In a nutshell, the sub -6 GHz NR receiver system would be the suitable band application compared to mmWave especially due to the lower cost. It is an essential application to meet with 5G coverage, due to its mobility and efficiency, to be able to balance speed and range. It serves as the foundation of widespread 5G deployment, ensuring reliable connectivity while handling interference, multi-user scenarios and spectrum sharing.

1.3.2(a) The advantages of Sub 6 GHz.

There are important advantages of Sub 6 GHz which is, they have the capability to cover wider areas and penetrate obstacles more effectively. This results in more extensive network coverage, which is particularly beneficial in regions that are not densely populated, such as rural and non-urban areas. Lower frequency signals, such as those in the sub-6 GHz range, have longer wavelengths [23]-[24]. These longer wavelengths are less susceptible to attenuation caused by obstacles like buildings and trees. Consequently, they can travel greater distances without significant loss of signal strength and this characteristic makes sub-6 GHz bands well-suited for providing coverage over large geographic areas, which is why they are often used for cellular networks that need to serve both urban and rural locations. In contrast, higher frequency signals, such as those used in millimeter-wave (mmWave) bands, have shorter

wavelengths and are more prone to attenuation. While they can offer higher data rates due to their larger bandwidth, their range is much shorter, and they struggle with penetrating materials, making them more suitable for dense urban environments where small cells can be deployed closely together [25].

Next is deploying sub-6 GHz technology can be more cost-effective than establishing entirely new millimeter-wave (mmWave) networks because it allows for the use of existing infrastructure and technologies. This approach can reduce the need for significant capital investment in new hardware and facilities, as sub-6 GHz deployments can often utilize current cellular towers, backhaul connections, and other network components [26].

Sub-6 GHz frequencies have been a backbone of wireless communication for many years, and the equipment supporting these frequencies is widely deployed. This existing network infrastructure can be upgraded or augmented to support new sub-6 GHz services, such as 5G, without the need for a complete overhaul [27]. In contrast, mmWave networks operate at much higher frequencies and require a denser network of cell sites due to their shorter range and poorer penetration through obstacles. Building out a new mmWave network would involve significant investment in new cell sites, backhaul infrastructure, and other network elements, which can be costly and time-consuming [4]. Moreover, sub-6 GHz networks can cover larger geographic areas with fewer cell sites compared to mmWave networks, leading to more efficient use of resources and potentially faster deployment times. This efficiency is particularly beneficial in rural or suburban areas where the deployment of a dense network of mmWave cell sites may not be economically feasible.

Next, is faster adoption where lower-cost sub-6 GHz devices facilitate broader adoption among users, which in turn contributes to an expanded user base and

accelerates the expansion of the 5G network ecosystem. In summary, leveraging existing infrastructure for sub-6 GHz deployments can lead to cost savings, quicker deployment, and a more efficient use of resources compared to the construction of new mmWave networks.

1.3.2(b) The approach towards Sub 6 GHz.

The difficulties encountered have prompted a strategic pivot towards prioritizing sub-6 GHz frequencies shown in Figure 1.4 resemblance the initial deployment of 5G networks in numerous areas. Although millimeter-wave (mmWave) technology delivers exceptional speed and capacity for specific scenarios such as densely populated urban centers, the broader coverage, reduced costs, and quicker implementation possibilities of sub-6 GHz frequencies render it a more practical option for widespread 5G network adoption. Firstly, balance approach where numerous service providers are adopting a dual-pronged strategy, leveraging sub 6 GHz frequencies to achieve broad coverage and milimeter-wave (mmWave) technology for high-speed applications in specific areas. Secondly, the priority of Sub 6 GHz which allows broader 5G access initially and then gradual integration of mmWave as technology matures and costs decreases. Globally, the sub-6 GHz spectrum is the primary frequency band utilized for the deployment of 5G networks. This band offers extensive coverage and the capacity to serve many users. On the other hand, mmWave deployments are less common but are expanding in certain areas and for specific applications. Continuous research and development efforts are focused on enhancing both sub-6 GHz and mmWave technologies to achieve broader coverage, increased data transmission speeds, and improved cost-effectiveness.

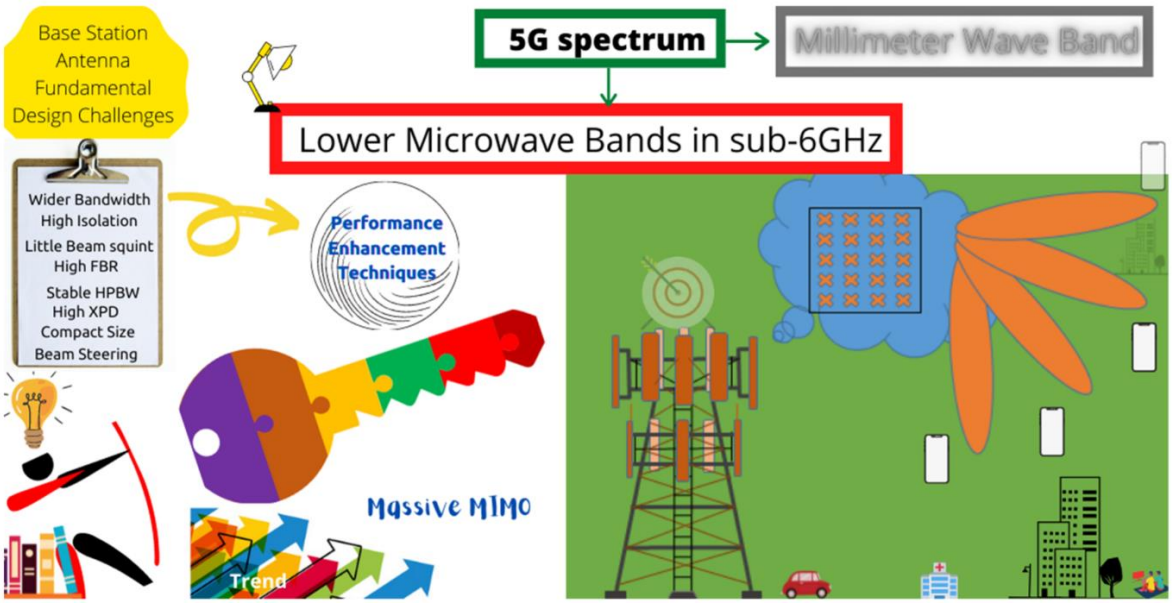

Figure 1.4 The feature towards enhancing sub 6 GHz [16]

Real 5G is combination of sub 6 and millimeter wave happening is a global scale. Higher frequency signals can transmit more data, which translates to more bandwidth and rapid network speeds as shown in Figure 1.5. Therefore, at a certain extent, mmWave 5G devices can facilitate maximum speeds of around 4-5Gbps, even though the customer speeds are often lower. MmWave can be faster than the most wired fiber broadband connections, by comparison, the best sub-6GHz network can hit a few hundred Mbps, even though tens of Mbps is more realistic. However, the drawback of the mmWave signals is that they are more susceptible to losses when passing through obstacles. There are only few hundred megabits per second are visible unless a direct line of sight with the mmWave cell tower. In such where the lower frequency of 5G bands come into the picture and these lie in the range of 1 to 6 GHz and referred to as sub-6 GHz 5G.

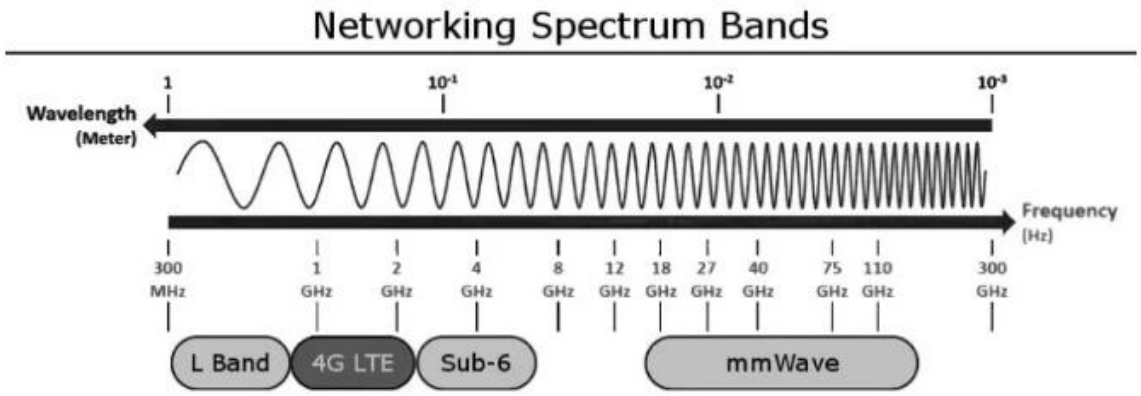

Figure 1.5 Network Spectrum Bands of 5G

The sub-6 GHz 5G bands cover similar frequency ranges as the previous generations and not as departure as mmWave 5G, which offer slight improvement in terms of the speed over LTE , more bandwidth and faster user speeds. This includes the ability to penetrate obstacles. The sub-6GHz spectrum is known to be as a backbone of the global 5G deployments.

Therefore, the mobile communications in the 5G deployments supports only sub-6GHz even though it consists of millimeter wave spectrum and the fastest way to get the devices wanted is through the sub-6Hz only. The support towards the sub-6GHz is extensive due to the higher cost bearing required in the millimeter wave. Therefore, the ABI Research forecast that approximately 90 percent of 5G cell sites emerging markets will be operating with the support for a combination of the sub-6GHz bands by the year 2026.

The sub6 GHz band provide the optimum coverage and it is faster that the 4G which has a longer range and more affordable for carriers to implement. While millimeter wave (mmWave) with its large amount of bandwidth able to meet at a very high-capacity demand. However, its poor propagation and cost of deployment shift it in disadvantage condition to sub -6GHz for 5G deployment. The sub 6 Ghz able to meet

the sufficient capacity and its higher propagation over a wide distance and not attenuated by the rain.

Furthermore, most of the handset vendors focused on the emerging technology of the sub6-GHz bands where it gives an additional benefit of keeping the bill of the material cost down. The 5G handset shipments supporting the sub-6Ghz band will be expected to expand to nearly 600 million by 2026 at a Compound Annual Growth Rate (CAGR) of 22.7 percent from 2020 [28]. It is deemed an importance towards sub-6GHz in supporting the key applications such as the Internet of Things (IoT) as well as the Fixed Wireless Access (FWA). However, these applications require very robust propagation characteristics and sufficient capacity capability which can be supported and provided by the sub-6Ghz bands. Therefore, for applications such as LTE and sub 6 GHz technologies the performance especially on the low power receivers are critical. The specifications ensure that the receivers can handle the required frequency ranges within gain balance, interference tolerance and minimum pulse width response, among other factors.

1.3.3 Low Power Receiver

Past few years, it would be changing 1 billion of batteries per day to maintain the network of devices. Due to the higher impact of the battery disposal at higher scale, nobody seems to take care of the battery maintenance issue whereby it limits the mass adoption of 5G solutions [29]. Thanks to the 5G solutions today, most devices in the world today, operates on a battery that provides longevity for an average of three years. It seems very generous considering of today's technology that have batteries with shorter lives. There are few specifications for the receiver performance needed to consider which the power, sensitivity, data rate is and signal to interference ratio (SIR)

and the adjacent channel rejection. Generally, there has been trade-off among one another, however figure of merits captures its relative impact across all types of receiver's frequencies, modulations and so on.

Several receiver architectures especially, the ultra-low power receiver supports the variation of a passive envelope detection radio frequency (RF) front end, reducing the power-hungry RF blocks such as the low noise amplifiers (LNAs) and RF local oscillators (LOs). There are some architectures are not considered as ULP, like hybrid architectures added back the LNA block for the sensitivity improvement with the integration of the passive mixer incorporating some RF blocks. These architectures somehow dissipate power > 20uW and >100uW as well [30]-[31].

On the other hand, passive transformers and matching networks integrated at the front of the envelope detector (ED) to eliminate the noise bandwidth and improve the sensitivity up to 20dB, thus extending the wireless range. This passive voltage booster performs better with its higher RF ED input impedance which would be easier to achieve especially at the lower frequencies < 10nW receivers which tend to be sub gigahertz. However, the passive envelop detector that is used for the down conversion posses with a wide bandwidth but encounter higher noise which limits the sensitivity at around -50dB referenced to 1mW. The baseband gain and filtering stage operate in the sub threshold with a minimum bandwidth to lower the power typically achieving a minimum voltage in 1-10mW range. The data rates of these receivers are less than 1kb/s however limited by its speed and bandwidth of the subthreshold analog and digital baseband circuits [32].

1.4 Challenges and Trade-Offs in the Sub 6 GHz Receiver system

The sub 6 GHz frequency bands are widely used for various communication systems, including mobile networks and are critical for 4G/LTE and 5G technologies [30]. A receiver system operating in the sub 6 GHz range faces the gain imbalance were ensuring that the gain imbalance is less than 1 dB which is crucial and important to maintain the signal integrity [31].

Next would be the antenna design which must be optimized for the sub 6 GHz spectrum to ensure efficient signal reception. The dimensions and specifications of the antenna play a crucial role in the receiver's performance.

Thirdly, noise figure where at low noise figures are necessary to minimize the signal degradation and improve the receiver sensitivity.

Fourthly, in terms of the linearity, the receiver must maintain the linearity over the operating frequency to avoid distortion of the signals received.

Next, Sub 6 GHz bands congested with various signals from WiFi, LTE and other sources [32]. Designing selective filters to extract the desired signal while suppressing unwanted ones is crucial. Balancing sensitivity, filtering, and processing power with limited batter life in mobile devices is a constant challenge [33]. Due to mobility and environmental factors, sub 6 GHz channels experience rapid changes, requiring the receiver to continuously estimate and adapt to maintain optimal performance. Even small timing errors can significantly impact data recovery. Achieving accurate synchronization in the presence of multipath and interference is crucial.

1.5 Problem Statement

With the advancement of the Sub 6 GHz receiver, there are recent problems and several challenges that are continuously being addressed. The Sub-6 GHz frequency bands are densely populated with a variety of signals from technologies such as LTE, Wi-Fi, and other forms of wireless communication. This congestion necessitates that receivers in the Sub 6 GHz band encounter a stringent requirement to satisfy and improve the efficiency of the system. Firstly, the challenges would be compromising the performances by mitigating the tradeoffs of gain, linearity, noise figure (NF) and power consumption of the receiver system especially for the respective blocks of Low Noise Amplifier (LNA), Mixer and Voltage Controlled Oscillator (VCO) [5]-[13], [34]-[43].

Firstly, as the LNA which is the front-end stage of the receiver, adopted multiple techniques to ensure the essential performances are met. Despite many proposed techniques applied e.g. as forward-body bias technique applied in [41] which can reduce power consumption and improve the noise factor of the LNA, but the linearity tends to degrade. Another topology of folded cascoded LNA proposed to ensure high gain but exists a tradeoff between power consumption and gain [42]. The approach towards a higher bandwidth with low power consumption is challenging, which limits the signal amplitude and quality and affects the SNR with low gain and high noise. [33]. In addition, in certain cases, especially dealing with multiple levels of interferences, especially under the wideband implementation which affects the signal in the sub-6 GHz frequencies, and it tends to diminish more over time and distance which is difficult to detect weaker signal in particularly at the areas under limited coverage or within challenging environments [36]. All these customized architectures and methods focus on improving and satisfying a specific parameter, indirectly impacting the other critical

performances and introduces more difficult tradeoff to solve which is linearity, noise and gain tradeoffs under especially with the requirement of low power and wide bandwidth.

This is followed by the next stage of the LNA's building block which is the down-conversion mixer. In recent works, the IQ down conversion mixer encounter I and Q mismatches that result in poor image – rejection ratio vulnerable to the system. Poor image rejection is known to be sensitive and that would cause mismatches in the receiver path [13]. Some complex IF mixer in the receiver relies on through calibration mechanism but it is difficult to maintain the I and Q in sub 6 GHz bandwidth. Furthermore, additional effort on design may impact on additional complexity and it is not recommended for area reduction plan and adding extra cost. On the other hand, intermodulation and unwanted harmonics are significant especially dealing with complex mixer with mixed signal simulation. These harmonics introduce into the mixer degrade the signal integrity which results in poor signal-to-noise ratio (SNR). In fact, with poor isolation between these ports lead to signal and power leakage and crosstalk which limits the signal quality and affects the entire mixer functionality [17]-[18], [37] – [43].

Consequently, during the mixer's operation, the carrier signal needed to down convert the signal in the mixer with the help from the signal from VCO which actively providing the carrier signal. Therefore, maintaining purity and quality is utmost important. In many reported works, ensuring the low phase noise with high output signal power under low power consumption has been a tough challenge. Work in [15] able to achieve a very low phase noise performance at 1MHz offset but with the expense of additional power needed. Phase noise and low power has been an inevitable trade off and adjusting the power consumption which is not a preferable method just to realize a

low phase noise performance [15]. Besides that, another challenging design trend for CMOS VCO is to achieve a low phase noise across a wide frequency range. To tackle the bandwidth limitation of the VCO, the most commonly are used switched capacitor banks for frequency tuning, and in fact some works [18] used a digitally controlled varactor arrays, but however it contributed to major portion of resistance parasitics to the oscillation resonant tank which eventually degrades the phase noise and tuning range. In conjunction to tuning range, it is hard to achieve a high figure of merit as well, which resulted in high power consumption that can be even up to 200mW [43]. In some cases, the stability in tuning frequency is not linear for the VCO wideband tuning. Therefore, to achieve a stable and accurate oscillation frequency over process, voltage and temperature variation (PVT) is taxing which requires an additional circuit to control the loop and with several compensation mechanisms [43]. Moreover, in the IQ receiver system, the area of the VCO especially in generating for a wideband range requires high passive tank contributor and thus this would increase the cost as well for the entire receiver size [44].

The receiver in the integrated system directly impacts on the entire system power consumption, system linearity, entire noise, gain and stability performance. In the IQ receiver system, many researchers developed the IQ imbalance compensation methodology using an IQ demodulator which is then filtered and amplified [13]. Besides that, works using digital implementations, the direct analog frequency down conversion encounter two side effects that can be observed in the spectrum of received signal which is the DC offsets, and the sideband image effects. The DC offsets limit the dynamic range of the receiver and cause interferences that affect the fundamental signal quality [45]. Considering all important criteria, the significant concern of the system performance is the figure of merit of the system performance. The figure of merit which

resembles a performance measurement that quantifies the efficiency and effectiveness of the receiver system which includes the sensitivity, noise figure, gain and other paramount performance metrics. The longevity of the receiver is also dependable to the versatility of a receiver to be suitable and efficient.

The sustainability and efficiency of the entire receiver to operate for a long-term run can be only achieved when the solution to mitigate all these challenges are critically addressed and executed with techniques. This is a significant concern because excessive degradation of the sub blocks performance in the integrated system may also affects the power usage which not only shortens the battery life of the devices but also impacts the sustainability of the entire network infrastructure [40]. It is also imperative to focus on optimizing the design of receivers to enhance their energy efficiency. By doing so, it can extend the battery life of mobile devices, which is a critical factor for users who rely on their devices throughout the day [41] – [46]. Therefore, the focus on this research is to achieve, solve and mitigate the trade-offs of the standalone performance of the LNA , mixer and VCO with better performance across the sub 6 GHz bandwidth which is from 3 to 5 GHz range. Moreover, the ultimate target to ensure an overall high figure of merit (FoM) of the receiver system with enhanced performance of these front-end blocks, managed to solve all the trade-offs and acquire a versatile receiver architecture that meets the sub 6 GHz receiver requirements and target specifications

1.6 Research Objectives

By understanding and addressing these challenges and problems of the sub 6 GHz, ideas evolved to mitigate all challenges through various advancements to optimize the receiver design. The research objectives are as follows:

I. Design the standalone LNA, mixer and VCO and integrated them together as CMOS receiver achieving an overall low power less than 20mW, low noise figure, NF with higher port to port isolation and with minimum I and Q quadrature phase error at the receiver's output to be less than 4 dB.

II. Design and verify the results of the pre-layout, post-layout and measured results of the proposed 5G Sub 6 GHz receiver until target specification are met.

III. Validate the fabricated receiver's functionality to meet the sub 6 GHz standard and owned its versatility as an efficient and reliable high FoM receiver of above 90 dB.

1.7 Thesis Scope

The scope of this project elaborates on the design of the high figure of merit (FoM) versatile Sub 6 GHz C band receiver in low cost 130nm Silterra CMOS technology. The construction of the receiver is built in stages starting from the prelayout, postlayout and towards the measurement which is done in detail for the architecture of the receiver starting from the front end wideband low noise amplifier (LNA) followed by the development of the I and Q quadrature generation integrated with the mixer and next with the hybrid structure of the VCO. The design build up is fulfilled with the aid of the software tools which is the Electronic Design Automation (EDA) tool in the Cadence. This tool is the most significant in the semiconductor integrated circuit (IC) design to ensure reliability and to test the design correctness under varying conditions. In this platform, Cadence Virtuoso facilitates the design development and simulation using Cadence Spectre from the top to down approach of

the schematic to post layout and able to accelerate the whole design process verification with extensive optimisation of the receiver design until reaching the target specification. The fabrication process would be conducted and completed by the semiconductor Silterra foundry using the EDA tools where the final top level of the receiver integration with the Silterra generated metal filling and is streamed out from the Cadence as GDSII file and sent to the foundry to start for the fabrication process. Once the chip has arrived, the measurement process would be carried out in the Collaborative Microelectronic Design Excellence Center (CEDEC) lab at the USains, USM to ensure, validate and verify the entire receiver performances on wafer. The on-wafer measurement using probe station equipped with Vector Network Analyzer (VNA), Spectrum Analyzer (SA), Noise Figure Analyzer (NFA), Signal Generator to measure the S-parameters, Output powers, Noise Figures, 3^{rd} order Intercept Point (OIP3) respectively for the receiver and whereas the Parameter Analyzer to supply the DC voltage and ground supply. The Signal Source Analyzer (SSA) is used to measure the phase noise of the VCO and oscilloscope to measure the signal quality, output and input power of the proposed receiver. Therefore, the whole plan to build up the whole receiver architecture is applied to certify the novel proposed receiver as a versatile 5G Sub 6 GHz C Band receiver that can meet the standard needed.

1.8 Thesis Organization

The thesis is divided into 5 Chapters which are organized as follows:

Chapter 2 introduces the literature reviews and general background on the detailed works on different types of on various latest published work and techniques adopted on each LNA, Mixers, VCOs and entire Receivers. Furthermore, table of comparison of each block and entire receiver was included and concluded.

Chapter 3 introduces the design methodology of the proposed Receiver, explaining with the detailed mathematical analysis for each subsequent blocks of the LNA, Mixer and VCO and as whole Receiver system and testbench setup used for each of the blocks and entire receiver for pre-lay, post-lay and measurement.

Chapter 4 presents the results of pre-schematic simulation, to post layouts and finally to measurement results. In addition, the comparison between each of the results were included with the comparison of recent reported works and the proposed design with its fabricated chip micrograph are described as well.

Finally, Chapter 5, shows the discussion and conclusion of the proposed research along with its improvements and possibilities that would be suggested for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In some communication system, data transmission only occurs in one direction. Simplex transmission is one of the signal direction systems which performs data transmission in one direction only. But Simplex transmission is not often used as the receiver which is unable to feedback any errors or control signals to the transmit end. In modern communication systems, system transmission must carry in two -way interchangeable data and information transfer. Both ends of the radio channel need to integrate the transmitting and receiving capabilities to achieve two-way communication system. The function of a wireless transmitter is to transmit a frequency waveform encoded with information signals while wireless receiver is to detect and receive incoming modulated signals. A device comprising both transmitter and receiver which combines and shares common circuitry is known as transceiver.

The quality of wireless transmission performance is influenced by more than just the channel through which it propagates, and it is also contingent upon the capabilities of the transmitting and receiving equipment. Therefore, the architecture selected for the implementation reveals in an important notation of performance such as power dissipation, complexity, and production cost. Additionally, selectivity and sensitivity requirements are equally important in RF front-end receiver [14]. Receiver sensitivity refers to the lowest strength of an incoming signal that a receiver can detect to achieve a specified signal-to-noise ratio (SNR) at its output. This is a critical parameter as it determines the minimum signal level at which the receiver can operate effectively.

Receiver selectivity, on the other hand, is the ability of a receiver to discern and process the desired signal while ignoring other signals that are close in frequency. This characteristic is essential for the receiver to function properly in an environment where multiple signals may be present. Wi-Fi or LTE can be affected by noise from platform components, which can lead to a degraded SNR at the radio receiver's input. This degradation can impact data throughput and the range of the wireless link. Generally, there are unwanted interferes present close to the spectrum of the desired signal that will corrupt the demodulation in the receiver system. Therefore, filters are required to eliminate the effects of these interference. The overview of LNA, Mixer and VCO that develop the Sub 6 GHz would be briefly explained in this chapter.

2.2 LNA Overview

Section 2.2 focuses on LNA introduction, and its analysing and interpreting existing knowledge that is pertinent to this work. It establishes the foundation for this study, which is the primary focus of this thesis's investigation. The parameters used to analyse the performance of an LNA is discussed in Section 2.2.1. Then, in Section 2.2.2 explains on the various cascoded LNA and wideband LNA topologies which will be discussed, along with their related work summary shown in section 2.2.3. The literature review is necessary to demonstrate the significance of this research compared to previous studies.

2.2.1 LNA Performance Parameters

This segment discusses critical performance parameters for determining the effectiveness of an LNA. The performance of an LNA is measured by its gain, noise figure, power consumption, input impedance matching, and linearity. A trade-off between these parameters must be made to get the optimum result.