

École polytechnique de Louvain

Performance and Sustainability Analysis of 28GHz Switch Technologies

Author: **Hugo SCAILQUIN**

Supervisor: **Jean-Pierre RASKIN**

Readers: **Valeriya KILCHYTSKA , Martin RACK, Jose LUGO**

Academic year 2019–2020

Master [120] in Electrical Engineering

CONTENTS

List of Figures	v
List of Tables	vii
Abstract	ix
Acknowledgments	ix
1 Introduction	1
1.1 Context and Motivations	1
1.2 Outline	3
2 5G and mmWave Frequencies	5
2.1 Upcoming of 5G	5
2.2 The 28 GHz Frequency Band	8
2.2.1 Overcoming Limitations of 28GHz Frequency Band	9
2.2.2 MIMO and Beamforming	11
2.2.3 Small Cells 5G	13
3 RF Switch	15
3.1 RF Front-End Module	15
3.2 RF Components	17
3.2.1 Power Amplifier	17
3.2.2 Low Noise Amplifier	19
3.2.3 Other Components	20
3.3 RF Switch	22

3.3.1	RF Switches Types	22
3.3.2	RF Switch Parameters	27
3.3.3	Switch Topologies	33
3.3.4	Quarter Wavelength Section and Traveling-Wave Switch	35
4	Benchmark	37
4.1	Technologies Review	38
4.1.1	Bulk CMOS	38
4.1.2	GaAs	38
4.1.3	SOI	40
4.1.4	GaN	41
4.1.5	SiGe	42
4.1.6	PIN diode	42
4.2	Literature Review	42
4.2.1	Discrete RF Switches	42
4.2.2	Integrated RF switches	45
4.2.3	Existing Technologies	46
5	Sustainability Analysis	55
5.1	Sustainable Development	55
5.1.1	Semiconductor Industry and Sustainable Development	57
5.2	Holistic Approach	58
5.2.1	Economics	58
5.2.2	Society	59
5.2.3	Legislation	62
5.2.4	Energy	63
5.2.5	Materials	70
5.2.6	Environment	72
5.2.7	Synthesis	77
	Conclusion	81
	References	94

LIST OF FIGURES

1.1	Evolution of the peak data rate in cellular communication.	2
1.2	Elements from the periodic table present in the production of a phone.	3
2.1	Evolution of standards in mobile technology	5
2.2	Evolution of standards in mobile technology	6
2.3	Consumer expectations of 5G.	7
2.4	5G multi-layers approach.	8
2.5	Air attenuation as a function of the frequency.	10
2.6	Working principle of beamforming	12
2.7	MU-MIMO techniques.	13
2.8	Coverage of different cell types	14
3.1	Environment and components of a RFFE.	15
3.2	Estimate representation of the FEM for 4G/LTE applications, with 2 antennas. This not consider the Wi-Fi system.	16
3.3	Schematic of a RF PA	17
3.4	FoM's of RF PA. In red the power gain, in green the PAE and in blue the output power.	18
3.5	Matching networks for a PA.	19
3.6	BAW and SAW filters technologies	20
3.7	Antenna tuning techniques.	21

3.8	Different groups of RF switches	22
3.9	MEMS concepts	23
3.10	PIN diode structure and equivalent forward and reverse circuits	24
3.11	PIN diode resistance versus forward bias current.	24
3.12	Simple PIN series switch with the bias circuitry	26
3.13	I_D - V_G characteristic of FET transistors	26
3.14	Insertion Loss definition.	28
3.15	Output power vs input power	30
3.16	Input and output spectrum of non linear system.	30
3.17	Output power versus input power with intermodulation products.	31
3.18	Switching times definition.	32
3.19	Schematics of SPST and SPDTs	33
3.20	8x1 multiplexer from cascaded SPDT	33
3.21	Schematics of series and shunt SPDT's	34
3.22	Shunt Quarter-wave SPDT	34
3.23	Series-shunt SPDT	35
3.24	Simplified schema of the SPDT in transmitter and receive mode	35
3.25	ISO evolutions with different topologies	36
4.1	Adoption of SOI technology for the RF switch market	37
4.2	HEMT characteristics.	39
4.3	Evolution of SOI substrates	40
4.4	GaN HEMT	41
4.5	SiGe BICMOS cross section	42
4.6	Wire bonding BGA and Flip chip BGA	45
4.7	Drawbacks and benefits of CMOS.	46
4.8	Qualcomm Snapdragon X50 and QTM052.	47
4.9	Insertion Loss of analyzed switches at 28GHz	51
4.10	Isolation of analyzed switches at 28GHz	52
4.11	1dB Compression Point of analyzed switches at 28GHz	53

5.1	3 pillars of Sustainability	56
5.2	Evolution of the number of publications related to "Sustainable Development"	56
5.3	Caption	57
5.4	Annual revenue of semiconductor industry in billion \$	57
5.5	6 majors sectors generally involved in sustainable development.	58
5.6	Increase of power consumption with mmWaves deployment in base stations.	63
5.7	Global electricity demand of communication technology 2010–2030	64
5.8	Caption	65
5.9	Daily traffic load pattern of a BS for a residential cell in week-end day.	66
5.10	Precoders for mMIMO Systems (a) Digital precoder (b) Analog precoder (c) Fully-connected hybrid precoder (d) Partially-connected hybrid precoder.	67
5.11	Critical Raw Materials for EU.	71
5.12	2017 Economic importance and supply risk assessment of raw materials in EU in	73
5.13	Absorbed power for different insects at different frequencies.	74
5.14	Cycle materials system approach	76
5.15	Simplified recycling process.	76

LIST OF TABLES

2.1

Characteristics of different size cells

14

4.1

Electronic properties of semiconductors.

38

4.2

Bulk CMOS Ka-band switches

48

4.3

SOI based Ka-band switches

48

4.4

PIN diode based Ka-band switches

49

4.5

GaN based Ka-band switches

49

4.6

GaAs based Ka-band switches

49

4.7

SiGe based Ka-band switches

50

5.1

List of Critical Raw Materials for European Union

72

ABSTRACT

The fifth generation of mobile communications (5G) is becoming more and more a reality. Industries and network operators are constantly advertising the huge benefit in terms of data rate, health monitoring, connected devices and better quality of life in general. These improvements come at a certain cost regarding power and materials consumption and environmental impact in general. However, such negative drawbacks are rarely addressed when developing new technologies. This work tries to answer the technical part by reviewing the technologies for a RF switch applications at 28GHz but also the sustainable part by considering the impact of mmWaves deployment in legislative, economic, energetic, social, environmental and materials axes. This kind of analysis gives the opportunity to take a step and see the big picture. This work is mainly divided into two parts: the benchmark of RF switch technologies in the Ka-band and the sustainability analysis.

First, a review on the technical advantages and disadvantages of the 28GHz frequency band are considered. The proposed solutions and their implementation are discussed.

Second, theoretical background on the switch is given along with other RF components of the front-end modules. The main parameters of the switches are also presented.

Third, a review of the literature regarding different discrete technology to implement the 28GHz switch is analyzed. Integrated solutions are also considered. The work also addresses the different trade-offs which occur when designing a switch.

Fourth, the sustainability analysis is conducted based on six axis: legislation, economy, society, materials, environment and energy. At the end, the impact of the facts in the previous categories are classified and reported on the triple bottom line: people, planet, prosperity.

Finally, a conclusion about the work on the benchmark as well the sustainability analysis is made.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisor Professor Jean-Pierre Raskin for his valuable advice, support and guidelines throughout this work.

Special thanks to all the people present during the "sustainability" meetings between UCLouvain and Imec. These sessions really helped me to get more valuable information but also open my mind about certain problem in the electronic industry.

I would like to thank my girlfriend and my family for their ever lasting support as well as their encouragement and understanding during the writing of this report.

I am grateful to Jose Lugo for putting me in touch with people working in manufacturing process that could help me with my work.

I am also grateful to my friend Thomas for his proofreading and advice regarding my writing skills in English.

CHAPTER 1

INTRODUCTION

1.1 Context and Motivations

In today's world and mainly in the electronics sector, the research community and the industries are constantly looking for new, faster, better technologies to fulfill the relentless rise of consumer's needs. As one can see in figure 1.1 [1], for instance, the data rate of mobile communication has not stop growing since its beginning in the early 90's to offer more and more possibilities to the users. However, these new and boosted versions come at the cost of more complexity and more materials used, as visible in figure 1.2 [2], where we see the evolution of the number of elements present in a phone. The elements used are in yellow and critical materials are colored in red. One clearly sees here the striking example: a phone in the 50's was composed with 12 elements while the phone in today's life is composed with 53 elements which 21 are listed as critical raw materials. The same logic is applicable for most of the consumer electronics (see [2] for more examples). But as the word previously used "critical" suggests: Earth does not have infinite resources to provide, as proofed in the report "SCREEN" (Solutions for CRitical Raw materials - a European Expert Network). The purpose of this study is to list and map the critical raw materials in the European Union and propose possible substitutes [3]. Moreover, the world produces 50 million tons of electrical and electronic waste a year (called e-waste) [4, 5]. From this amount, only 20% will be recycled. The rest will end in a dump mainly in developing countries (especially Ghana and Nigeria [6]) with all the environmental and health problems that it implies. Electronic manufacturing processes also have an environmental burden through the extraction of the raw materials, the long and complicated manufacturing chain and the packaging. This idea is synthesized under the term embodied energy, which refers to the energy necessary to make the final product. These environmental impacts are rarely described since they are not clearly visible for in eye of the consumer. Still they are well present. The mentality of "produce, use and dispose" is strongly present in the

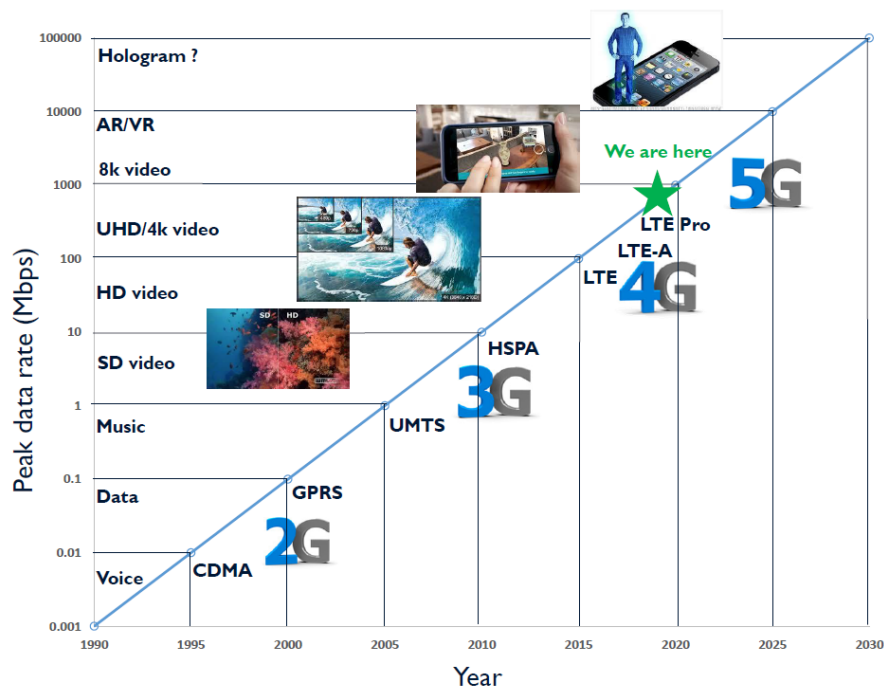


Figure 1.1: Evolution of the peak data rate in cellular communication.

electronic sector and also impact the other industries like automobile, health or entertaining since electronics are widely spread.

With these two problems in mind, the concept of sustainable development seems to be an interesting topic to develop to cope with the situation. This concept was first presented, in 1987, by the Brundtland's Commission as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs. [...] Thus the goals of economic and social development must be defined in terms of sustainability in all countries - developed or developing [...]" [7]. Two main ideas come through this paragraph: the needs for now and the future but also the needs for here and elsewhere in the world. Two points that are not fulfilled in the light of the above examples. As a future engineer it is a necessity to take a step and consider the big picture of the work. To address those, a shift in the mentality in the society is mandatory and engineers can help with it.

In this context, the fifth generation of telecommunication is at its first steps. There are still technical problems which need to be overcome and one of them is to choose the adequate technology for RF switches. Indeed, with higher frequencies for communications systems, especially the millimeter wave (mmWave) frequencies, stringent requirements lie on the RF components in general. The industry world would of course go for the best performer, as long as it does not mean a huge increase in cost. Because at the end, price stays the main driving force behind those choices.

This work tries to consider the two views not as opposite but rather as complementary. It is a first step in considering the impact of promising new technologies on not only the environment but also the social and economic implications. The classical analysis is not put aside. The goal here is not to completely reject the classical approach and analysis but rather add a

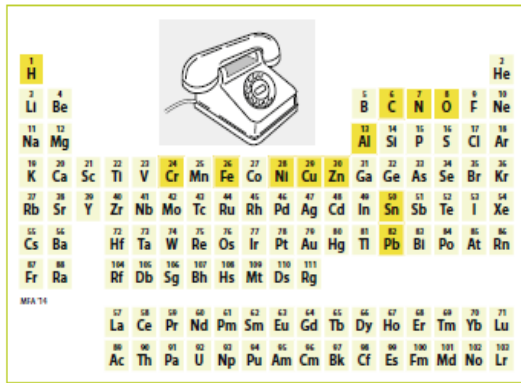


Figure 1.2(a) shows a periodic table with 12 elements highlighted in yellow, representing the elements used in the production of a 1950s rotary phone. The highlighted elements are: H, Li, Be, B, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn, Fr, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr.

(a) 12 elements for the phone of the 1950's

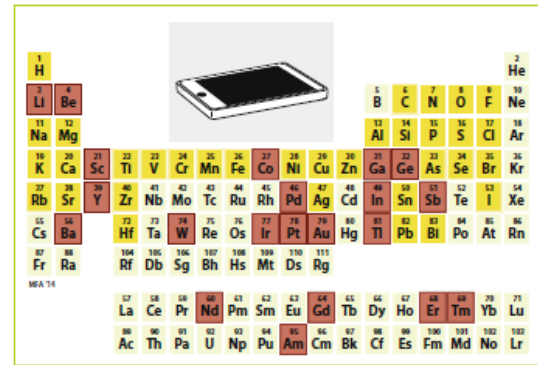


Figure 1.2(b) shows a periodic table with 53 elements highlighted in yellow, representing the elements used in the production of a present-day smartphone. The highlighted elements are: H, Li, Be, B, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn, Fr, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr.

(b) 53 elements which 21 are critical in a present-day phone

Figure 1.2: Elements from the periodic table present in the production of a phone.

new figure of merit to the benchmark and help in the decision making of future technologies. The RF switch possible technologies can be reviewed and at the same time the sustainable implications of the mmWave deployment can be described.

1.2 Outline

The second chapter focuses on the reasons of interest towards the mmWave frequencies for communications and especially the 28GHz band, in the context of the upcoming 5G. The main advantages of these frequencies are presented along with the main obstacles and solutions.

Chapter 3 covers the basic theory needed to understand the working principle of the RF switch. This includes a little bit of history, the possible technologies to implement such a component and the important parameters and Figures of Merit (FoMs) needed to characterize the device.

The literature review and benchmark of the existing technologies for 28GHz switches are given in Chapter 4. Graphs and tables resumed the important trends. The performances of the devices are compared regarding the 3 main parameters that were found in the literature: Insertion Loss, isolation and 1dB Compression Point.

In Chapter 5, an holistic analysis is made regarding the deployment of mmWave in the cellular network. The analysis is based on the Ashby method which considers 6 segments that are involved in most articulations of sustainable development: environment, society, economy, legislation, energy and materials.

The last chapter looks at the Life-Cycle Assessment of the production process the technologies considered in the benchmark. This chapter focuses on the energy and materials consumption, gases emission and general environmental impact due to the production of these semiconductor technologies.

Finally, a brief conclusion is made about this work.

CHAPTER 2

5G AND MMWAVE FREQUENCIES

2.1 Upcoming of 5G

In order to understand the meaning of this work, it is important to take a step back and look at the reasons, the changes and all the challenges that the fifth generation of communications (5G) implies. The first generation (1G) of communications was launched in 1979. Its unique objective was to transmit voices with analog technology. The second generation (2G) introduced digital signal treatment, SMS text messages and beginning of data exchanges. 3G brought high quality roaming and higher data rates. Finally, the fourth generation (4G) converged to very high data rate and much lower latency. The phone, that was simply designed to offer a vocal conversation, evolved into a much more complex data base device, with plenty of services and applications (games, Internet, video calls, ...). And with it, more and more complex circuitry linked o these versatile devices. In short, the mobile industry has gone through a huge transformation over the past past 20 years as visible in figure 2.1.

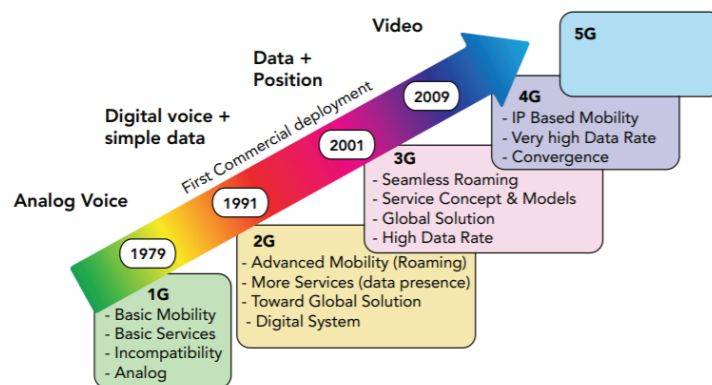


Figure 2.1: Evolution of standards in mobile technology

However, the current 4G cannot cope with the increasing demand of connected devices, the future Internet of Things (IoT) and data rates which keep growing at an estimated rate of 50% [8]. To address the problem, the communication industry wants to launch the fifth generation of telecommunication. This wireless technology is expected to revolutionize the people communicate and exchange information because of its implication in every field of the daily life. More concretely, most of the studies classify the impact of the 5G under 3 different axes, visible on figure 2.2 [9]: Enhanced Mobile Broadband (eMBB), Massive Machine type Communications (mMTC) and Ultra-Reliable and Low Latency Communications (URLLC). Concrete applications could be: Smart-City (Smart-grids, connected houses), e-Health, autonomous cars, smart monitoring, real time services, virtual reality services, Intelligent Transport Systems and of course entertainment. Other researchers also expect the use of Machine Learning and Artificial Intelligence to manage the complex interaction between all the devices in the network [10].

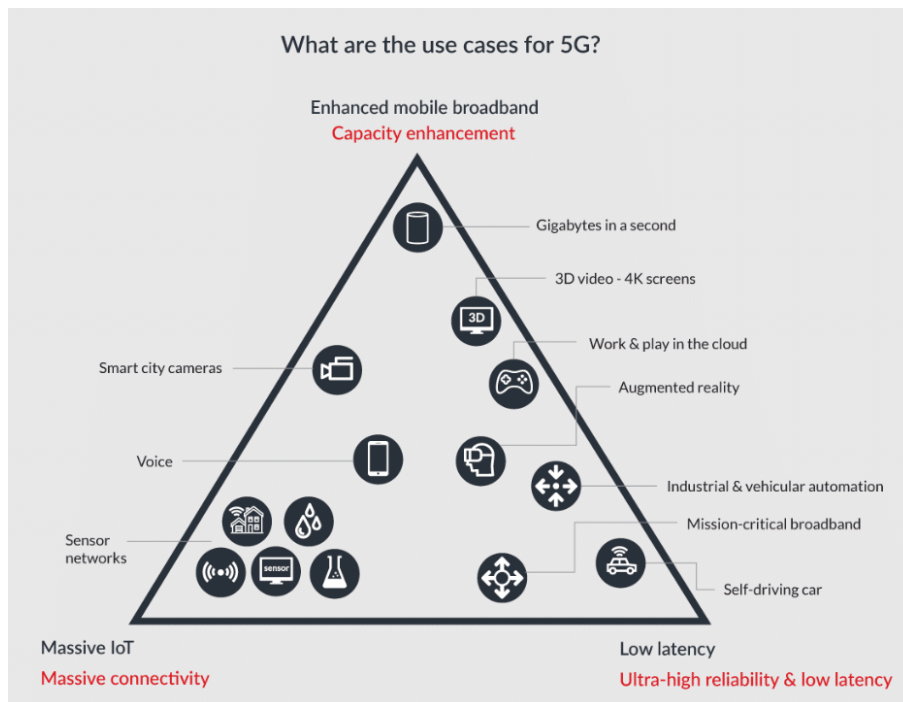


Figure 2.2: Evolution of standards in mobile technology

In terms of concrete performances for the wireless system, the goals and requirements are set to:

- **Low latency:** below $1ms$ RTT (Round Trip Time) which is the length of time it takes for a signal to be sent plus the length of time it takes for an acknowledgment that the signal has been well received. It is necessary for applications like control of the road traffic, e-health where people's life are at stake.
- **Multi-Gigabit-per-second (Gbps) data rates:** One of the main goal of the 5G is to give to the user the sensation of infinite capacity and this can only be achieved through

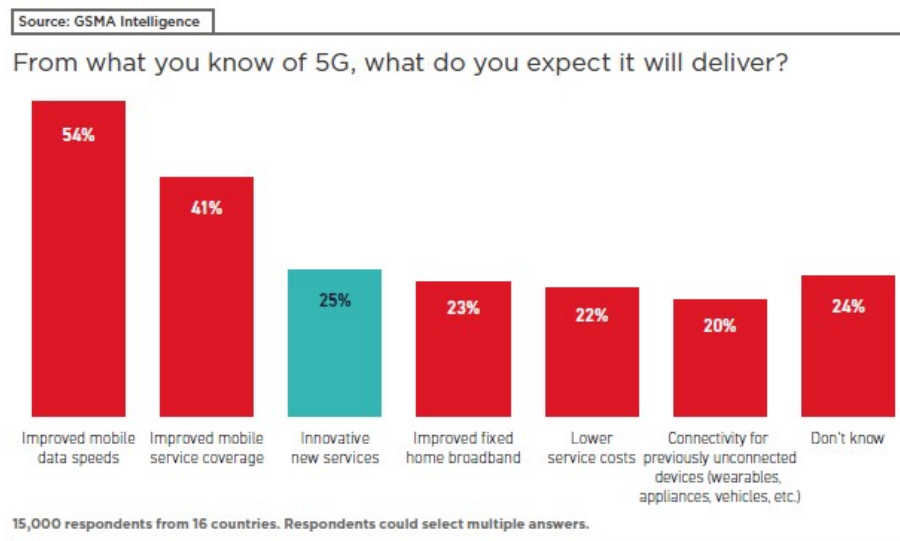


Figure 2.3: Consumer expectations of 5G.

higher data rates. And this higher data rates are the top one expectation for 5G when asked to consumer as one can see in figure 2.3 [11]. More concretely, 10 Gbps for a stationary user, 1 Gbps for a moving user and a minimum rate of 100 Mbps, even in the countryside. Today, the average value of download speeds lies between 20-40 Mbps on Europe. Of course the value for 5G are theoretical and will certainly be reduced in real applications.

- **Low Cost:** 5G is a real competition between all the major network operators and suppliers; who will be the most efficient with the lowest cost for the consumer?
- **Low power consumption:** years without charging for sensors for example but also limiting the impact on the environment with all the data base centers and numerous connected devices.
- **High reliability:** especially for critical use like autonomous cars, health sector.

In this idea, 3 main concepts, along with their challenges, have emerged to meet all this stringent requirements [12]

1. "Exploit unused and unlicensed spectrum": millimeter-wave (mmWave) frequencies and unlicensed spectrum in lower frequencies could be exploited in order to offer a better coverage and better data rates. This concept however raises challenges in the Tx and Rx branches design due to power-hungry signal processing and RF chains.
2. "Reduce the Tx/Rx distance and improve frequency reuse": massive communications between all the devices: device to devices communication (D2D) that comes with an ultra dense networks (UDNs). The challenges are found in the interference management because of the large number of devices and network cells that will lie next to each other.

3. "Enhance spectral efficiency": massive deployment of antennas and multiple-input multiple-output (MIMO). Problem with the signal processing and antenna cost, this problem will be deeper covered later in the work.

In this study, the focus is set on the first solution: exploiting new frequencies and especially those in the mmWave spectrum. This solution has received lots of attention in the past years and is particularly interesting regarding the implications at the hardware level, especially in the RF chain.

2.2 The 28 GHz Frequency Band

5G will extend the range of frequencies used for mobile communication, including above 6GHz frequency bands since the sub-3 GHz spectrum is overcrowded with existing technologies. More specifically, 5G is going towards multi-layers approach, visible in figure 2.4 [13] , with high, medium and low frequencies. Bands below 6 GHz will be used for scenarios in a wide-area. The 3300-4200 and 4400-5000 MHz frequency ranges are suitable to deliver the best compromise between wide-area coverage and good capacity. Low frequencies (below 2 GHz) will continue to be essential to extend the 5G mobile broadband experience to wide areas in the countryside [13].

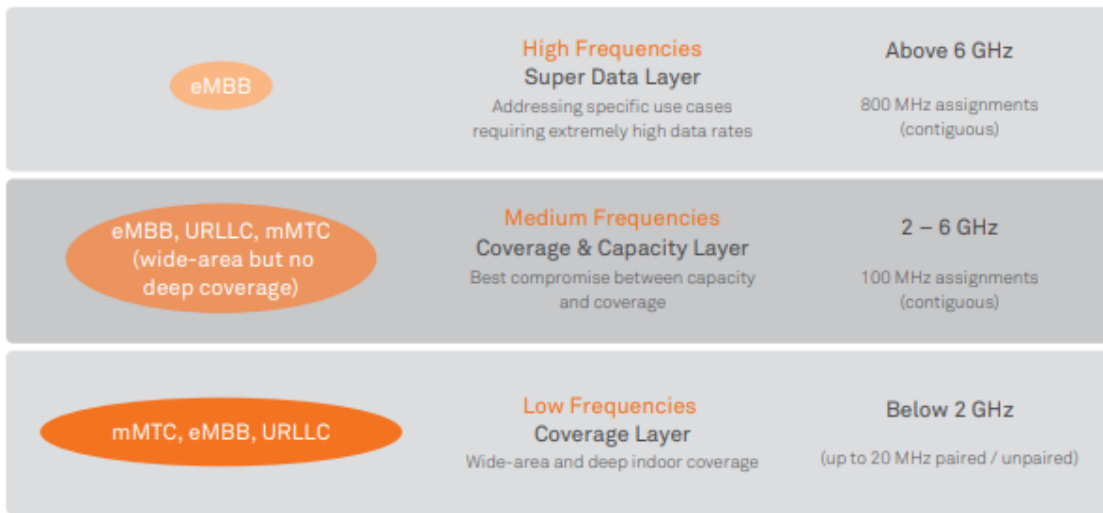


Figure 2.4: 5G multi-layers approach.

High frequencies (above 6 GHz) are here to provide additional capacity and higher data rates. The idea behind those frequencies is to serve as complement, in indoor systems or dense urban areas, to offer broadband spectrum with important data rates and meet the high capacity requirements. With this in mind, the research has started to investigate the millimeter wave bands (30-300 GHz) to look for potential bands for 5G applications in this large unlicensed and poorly utilized spectrum. The huge advantages of these higher frequencies is the bandwidth they can offer. As it is stated in the Shannon theorem in equation 2.1 with C the capacity of

the channel in *bits/s*, B the bandwidth in *Hz* and S/N the Signal to Noise Ratio (SNR) for a Gaussian Noise:

$$C = B \times \log_2\left(1 + \frac{S}{N}\right) \quad (2.1)$$

From today's bandwidth of 4-20 *MHz*, to 1.5*GHz* of bandwidth between 27.5-31.5 *GHz* as explained in [10], the gain in channel capacity is clear. However, this gain does not come for free, especially due to the higher attenuation of mmWave frequencies.

2.2.1 Overcoming Limitations of 28GHz Frequency Band

As one can see in equation 2.2, the Free Space Path Loss (FSPL) increases with the frequency. In this formula, no obstacle is considered, it is then called Line-of-Sight (LOS) operation.

$$\begin{aligned} FSPL[dB] &= 20\log\left(\frac{4\pi d}{\lambda}\right) \\ &= 92.45 + 20\log(f) + 20\log(d) \end{aligned} \quad (2.2)$$

Where d is the distance between the isotropic antennas or $\lambda/2$ dipoles, λ the wavelength of the signal and f the corresponding frequency. To give an example of this variation, for a given distance, compared to the free space path loss at 2.4 GHz, the FSPL is about 22dB larger for 28GHz and about 32dB larger for 100 GHz. A similar increase occurs if the frequency is fixed but the distance is increased. The previous computation only takes into account the attenuation due to propagation vacuum. In cellular network applications, the absorption due to water or other atmospheric gases can not be neglected. Signals interact with particles in the air and lose energy as they travel along the propagation path. The attenuation varies with different factors such as temperature, water density and pressure. Attenuation due to rain varies with the rain rate (in *mm/hr*) from drizzle (<0.25 *mm/hr*) to torrential rain (>50 *mm/hr*) [14]. The higher the rain rate, the more attenuated get the signal. An heavy rainfall (about 25 *mm/hr*) can cause around 5dB/*km* attenuation at 28GHz for a distance of 1*km*. Fog can also play a role in the attenuation of the signal. The precise models to simulate the effects of such phenomenon are listed by the International Telecommunication Union (ITU). For example, Recommendation ITU-R P.838-3(2005) focuses of the specific case of the rain. When there is no rain or no fog, signals still experience attenuation due to atmospheric gases. The losses are visible on figure 2.5 [15] and one can observe that the attenuation caused by atmospheric absorption is 0.012 dB over 200 m at 28 GHz. From all the different frequencies in the mmWave spectrum, frequencies around 30GHz suffer from less attenuation due to atmospheric gases like oxygen or water vapor. In [15], they also estimated that only 7 dB/km of attenuation is expected due to heavy rainfall rates of 25*mm/hr* for cellular propagation at 28 GHz, which translates to only 1.4 dB of attenuation over 200 m distance. This is why the 28 GHz frequency band (also called the *Ka*-band) is a very interesting band among the mmWave frequencies.

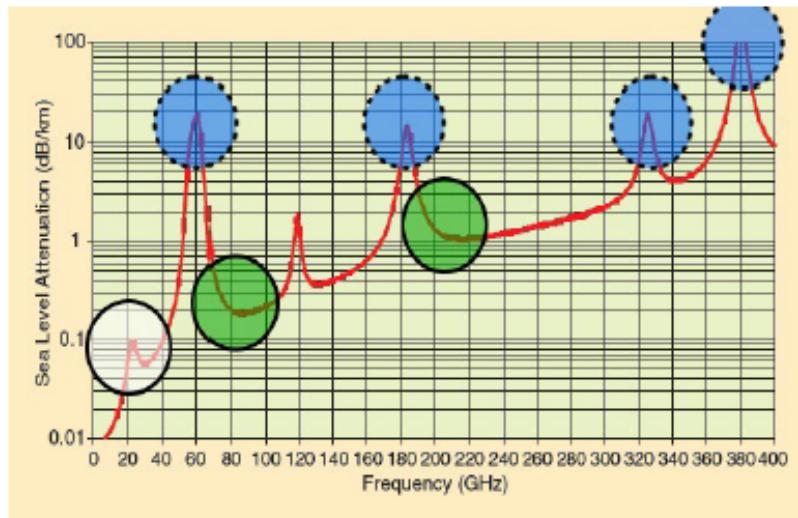


Figure 2.5: Air attenuation as a function of the frequency.

Still, there is a common belief that mmWave frequencies are not applicable for communication systems because of the high path loss associated to it and the need for Line of Sight operation (LOS). However if small cells are considered and with the fact that today's cell sizes in urban environments are on the order of 200 m, it becomes clear that mm-wave cellular can overcome these issues. Moreover, these drawbacks can become nearly nonexistent with highly directional steerable [16]. In fact, there is a misconception about this idea. It is true that the effective aperture of the antennas falls down with the frequency. And the antenna with the larger can capture more energy from the passing wave. But, with smaller wavelengths, more antennas can be packaged into the same area. Shorter wavelengths should not have a starting disadvantage, especially because with more antennas, beamforming with high gains is possible [17]. In 2015, Qualcomm showed with 64 antennas, mmWave technology in a dense urban environment and how directional beamforming can be used for LOS and Non Line of Sight (NLOS) communications [18]. This refers to the concept of MIMO and beamforming which will be later explained and that improves the energy transmission between the emitter and receiver. Another study [19] showed good indoor results with a throughput of up to 1.27 Gbps to 43m but also throughput up to 1 Gbps in outdoor circumstances (around 200m) with walking speed for the receiver. In [20] the authors showed very good results by using distributed MIMO, leading to throughput exceeding 10 Gbps in the downlink and 1.9 Gbps in the uplink achieved in the 28 GHz frequency band. The distances covered were also smaller, between 50-150m in a parking area. In [17] (2011), multi-Gigabit-per-second transfers over few kilometers at millimeter wave frequencies were already possible. However, the size, the power consumption make this impossible to adapt to mobile device. One can see here more a problem concerning the development and the maturity of the technology to be applicable to large electronic consumer.

28 GHz as communication band for mobile device is today a reality. Indeed, in the USA, the FCC (Federal Communications Commission) organized auctions in 2019 for the licenses in the 28-31 GHz spectrum. The total gross bids reached \$ 700 Million [21] and the spectrum was split between the big network operators such as Verizon, AT&T, ... In Asia this spectrum has

also raised interest: auctions were conducted in 2018 in South Korea to divide the mmWave frequency bands [22] and in Japan, in 2019 the government approved 5G spectrum allocations to the four main operators of the country [23]. Regarding Europe and the 28-31 GHz spectrum, UE is "lagging", or takes its time, since only 10 out of the 27 countries + UK adopted 5G services, all in the 1-6GHz ranges [24]. In April 2020, Italy was the only country that had auctioned 26 GHz frequency band. Just one other EU country, Finland, has scheduled mmWave auctions for 2020 [25]. It should be noted that even if the International Telecommunication Union (ITU) has declared the frequency bands between 24 GHz and 86 GHz as interesting and promising frequency bands for 5G, it has still not confirmed the 28 GHz band as a viable and applicable frequency. [26]

2.2.2 MIMO and Beamforming

MIMO is announced as a promising technology for mmWaves due to the smaller antenna size and bigger packaging possibilities. MIMO stands for Multiple-Input-Multiple-Output or in other words, the use of multiple antennas at transmitter (TX) and receiver (RX), also known in the literature as space-time wireless or multi-antennas communication. It has some important advantages against its single antenna counterpart due to its additional dimension: space [27] [28]. These are listed below. MU-MIMO (Multi-Users MIMO) refers to the particular case when the transmitter has indeed multiple antennas but the receiving side is made with multiple users, each one with one or more antenna(s).

1. **Diversity Gain:** diversity is used to tackle the problem of fading in wireless transmission. One can find 3 types of diversity: frequency, time and space diversities. The last one is interesting because it doesn't need extra bandwidth. By sending multiple versions of the same signal through space, the chance of avoiding obstacle fading is increased, resulting in better signal at the RX side. Indeed, the probability that all the independent emitted signals end up being too parasitized is smaller than the probability for 1 antenna. The same is applicable for the receiver side with multiple antennas: it receives the independent (supposed i.i.d. Rayleigh fading) faded versions of same original signal. The receiver can afterwards combine those signals to obtain an better (less faded and noisy) Rx signal than from only one signal. This of courses implies the knowledge of the channel. In MIMO, the order of diversity is characterized by the product of the number of Tx antennas and RX antennas.
2. **Spatial Multiplexing:** as diversity, the concept of multiplexing is applicable to time (Time Division Multiplexing), frequency (Frequency Division Multiplexing), space (Spatial Division Multiplexing) and even coding (Code Division Multiplexing). In general, the technique consists of dividing the signal into several parts called streams. Each stream is then transmitted via different (independent) channels. In a simple example with 2 emitting and receiving antenna, the bit sample can be demultiplexed into two half-rate streams. Each stream is transmitted in separated channels. If the receiver has the channel information, it can make the difference between the two channels, extract

the corresponding signals and recombine them to form the original bit sample. This leads to increased transmission rate. The idea could also be transposed to the case with a base station with multiple antennas and multiple users where the BS transmits two signals separated in space so that each user can decode the signals separately. The order of spatial multiplexing is defined by the minimum number of antennas between the Tx and Rx parts.

3. **Antenna Gain:** it is also referred as the beamforming gain. It is well understood that when antennas are aligned and emitting the same signal, constructive and destructive interference appear depending on the position of the receiver. If the user lies in a "dead" spot, the transmitter can figure out the time delays between the user and each antenna. By applying specific phase shifting to each antenna, one can make sure that all the different beams interfere constructively at the specific position and direction of the users. The main point of beamforming technique is the fact that you get a stronger beam in the specific direction(s) compared to an isotropic emitted signal. Indeed the power that disappear in certain direction finds its way into other directions, amplifying the signal power (generally by a factor corresponding to the number of antenna). The concept is visible on figure 2.6. Beamforming is closely linked to spatial multiplexing since the later requires spatially separated beams. Especially in the case of multiple users, where there is less interference because of the focused beams. 1D antennas array, also called Uniform Linear Array (ULA), leads to 2D beamforming while 2D antennas array lead to 3D.

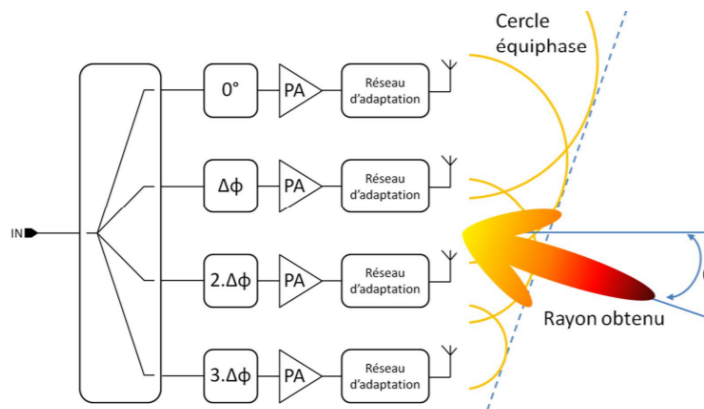


Figure 2.6: Working principle of beamforming

And this is precisely why beamforming techniques are so interesting for mmWaves applications. It can be used to compensate for the high propagation loss inherent with these higher frequencies. This is also due to fact reduction of the wavelength with increasing frequencies. Therefore, the antenna (generally $\lambda/2$) is significantly decreased which means that more antennas can be packed on a same area. It should be noted that such high computational complexity is only affordable at the base station, but is not suitable for battery-driven mobile devices. Indeed, proceeding to spatial multiplexing with multiple RF streams requires high complexity in signal processing and hardware and thus is power hungry. Therefore, phased

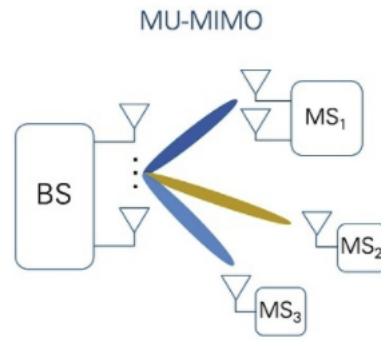


Figure 2.7: MU-MIMO techniques.

array antennas were first proposed for 5G mmWave handsets in [29]. This a more moderate technique and simpler to implement. An phased array would rather control the phase of all the antennas with the same RF stream, the same signal in order to control the direction of the antenna beam and get better power efficient. Some concrete example were showed in [30] where the antenna package consists of three sub arrays, and each sub-array covers part of the space. This gives the possibility to steer the beam in 3D and not only in one plane. The authors implement a switching circuit in the the antenna to select the desired area of coverage, while maintaining high gain beams. Due to the high signal attenuation at 28 GHz, the antenna must be placed in very close proximity to the 28 GHz front-end module. Implementing the antenna array directly on the printed circuit board (PCB) of the 5G cellular device will therefore keep the insertion loss between the antenna and RFIC to a minimum. The nuance here is to see the base station using MU-MIMO to cover different user while to user only exchange with one base station but because of the high loss at 28GHz, beam steering is necessary to ensure sufficient quality of transmission, as one can see in figure 2.7 [31].

2.2.3 Small Cells 5G

Two main reasons come for the large deployment of small cells. The first is to increase the capacity of the network: increasing the density of the network is needed as the small cells relieve the load on macro cells and therefore lead to an increased network capacity. Adding macro cells is also a possibility but it becomes increasingly difficult to find the place and expensive, especially in urban areas [32]. The second reason is due to the limitation of mmWave signals. As it was explained in chapter 2, mmWave do not propagates as far as microwave signals, so smaller distances between base station is required to keep a good coverage. The size of the cell is directly linked to the capacity of the base station (BS). So it is common to talk about macro BS and small BS. Such a deployment, with different sizes of cells is called an Heterogeneous Network (HetNet), unlike the homogeneous network with consistent cell size. In heterogeneous networks the cells of different sizes are referred to as macro, micro, pico and femto cells, listed in order of decreasing base station power.

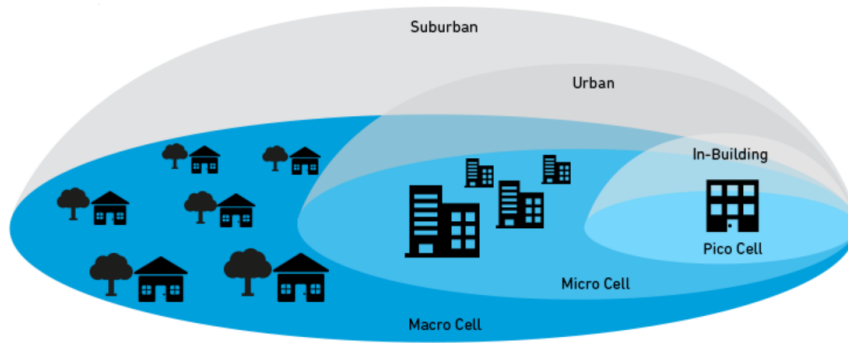


Figure 2.8: Coverage of different cell types

Macro BS have their communication range reaches up to 30 kilometers and they are usually installed in building rooftops. Micro and pico BSs cover small to medium areas with dense traffic (hotspots) such as shopping malls, residential areas, hotels, or train stations. The typical range of a micro/pico BS spans from a few hundred meters up to one kilometer. Femto cells are designed to serve smaller areas such as private homes or indoor spaces. The range of femto cells is typically only a few meters and they are generally wired to a private cable broadband connection. Small cells can be installed in street furniture like lampposts or traffic lights due to their small form factor [33]. The main characteristics are visible in table 2.1.

Cell Type	Output Power [W]	Cell Radius [km]	Users	Locations
Femto Cell	0.001 to 0.25	0.010 to 0.1	1 to 30	Indoor
Pico Cell	0.25 to 1	0.1 to 0.2	30 to 100	Indoor/Outdoor
Micro Cell	1 to 10	0.2 to 2.0	100 to 2000	Indoor/Outdoor
Macro Cell	10 to >50	8 to 30	>2000	Outdoor

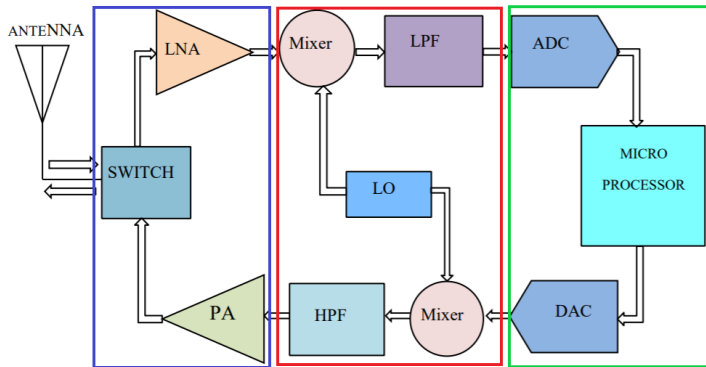
Table 2.1: Characteristics of different size cells

CHAPTER 3

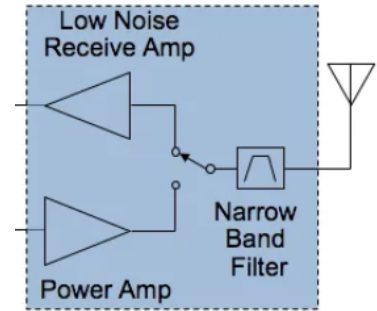
RF SWITCH

3.1 RF Front-End Module

The Radio Frequency Front-End (RFFE) modules or Front-End Modules (FEM) are defined as the part between the antenna and the RF Transceiver and the Modem, as visible in figure 3.1(a) [34].



(a) Schematic of a simplified RF Front-End in blue, RF transceiver in red and Modem in green



(b) Schematic of a simple RF FEM.

Figure 3.1: Environment and components of a RFFE.

The FEM is, in its simplest form, constituted with a Switch, a Low Noise Amplifier (LNA) and a Power Amplifiers (PA). A filter could also be added, like in figure 3.1(b) [35] between the antenna and the switch to make sure that the signal of interest gets no perturbation from the many frequency bands the antenna picks up. As indicated in the name, Front-End refers to the circuit near the antenna while Back-End refers to the circuits far from the antenna (modem in baseband, I and Q signals, ...). In receiver mode, the RF signal arrives through the antenna before reaching the FEM. The RF Transceiver will then convert the RF signal into IF signal

(with the help of mixers and local oscillators). This resulting signal arrives then in the modem (ADC, demodulator... in modern communication systems). The opposite direction can also be used to send the information through the antenna (= transmitter mode). Of course, this representation is greatly simplified. Today's FEM are way more complicated due to the high number of frequency bands that the phone need to cover. A 4G FEM would rather looks like something visible in figure 3.2 [36]. The RFFE has become more complex along with evolution of mobile communication generation. Indeed, from 4 frequency bands in 2G to more than 40 frequency bands in 4G, it is easy to understand the growing complexity and the stringent requirements on the different components of the FEM. Especially with the fact that 4G not only incorporates 4G bands, but also a number the 2G and 3G bands [35].

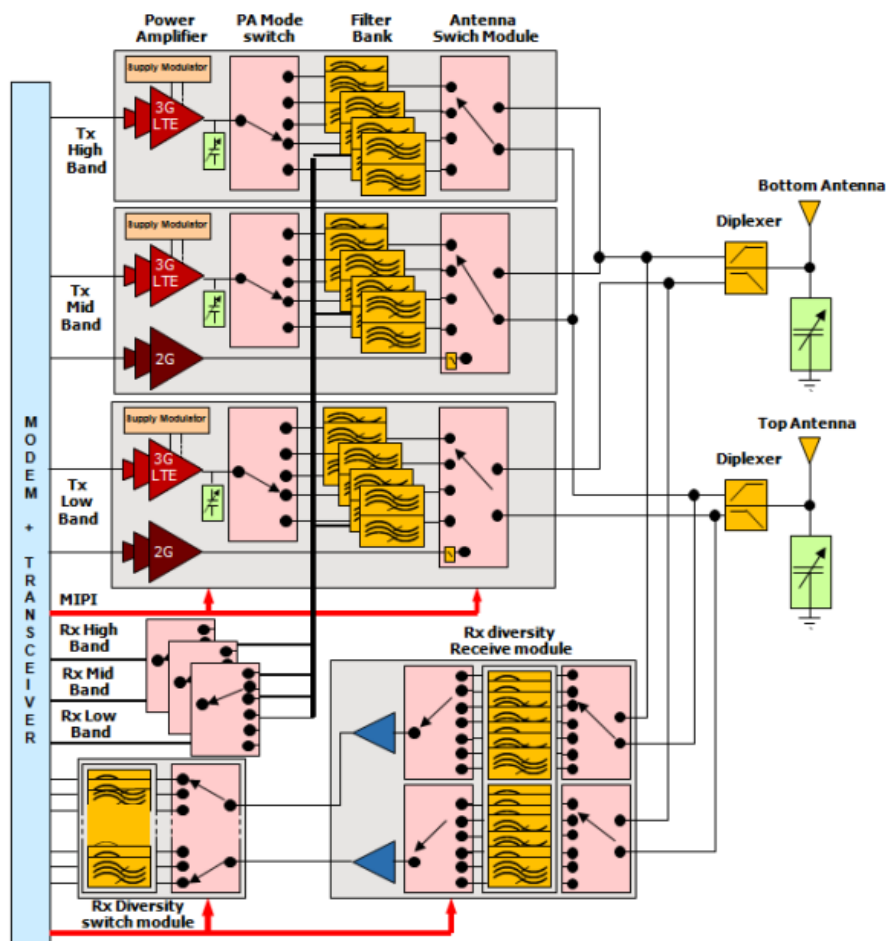


Figure 3.2: Estimate representation of the FEM for 4G/LTE applications, with 2 antennas. This not consider the Wi-Fi system.

From a quick look at figure 3.2, one can realize the importance of switches in such a system: they provide paths for shared PA's between low, mid and high bands and select filtering for that specific band. 4G/LTE also includes a diversity path linked to the 2 antennas. While the main path is used to transmit and receive, the diversity path is used only for receiving information. Therefore, it only needs to cover RX frequencies. The diversity path's job is to try to provide an independent sample of data from the signals in the surrounding environment

of the phone. The mobile phone's receiver then will typically do switched diversity (choose the received signal with the most energy) or combined diversity (sum the powers from the two receiving cellular antennas).

Front-End Modules have become important with the massive arrival of connected wireless devices since the beginning of the 2000's. The number of connected devices kept on growing since that, as one can see in CISCO [37] report where the number of connected devices is expected to reach 50 Billion in 2020 while it was 500 Million in 2003. This is explained by the huge growth of smartphones, tablets and PC's in the market. And the growth is not ready to stop as the experts from Yole Developments forecast an increase from \$ 15,087M in 2017 to \$ 35,167M in 2023 or an increase of 14% CAGR for the RF-FEM components market [1].

3.2 RF Components

In this section, the different components of the Front-End module are briefly analyzed. The goal here is not to give an exhaustive analysis of each component but rather give the global picture. The switch will be later explained since it is the center topic of the thesis.

3.2.1 Power Amplifier

The goal of the PA is to deliver to the antenna a signal with sufficient power such that the receiver can still correctly demodulates the signal after the distortion and attenuation of the transmission channel. The PA lies therefore in the transmitter (Tx) part and often dominates the overall performances of the Tx branch, see 3.3 for the schematic. The power can be anywhere from mW to hundreds or thousands of W . Generally, handset devices like smartphones require a power level $<3W$. The PA is not supposed to change the signal shape, simply amplifying it, but in practice non-idealities appear.

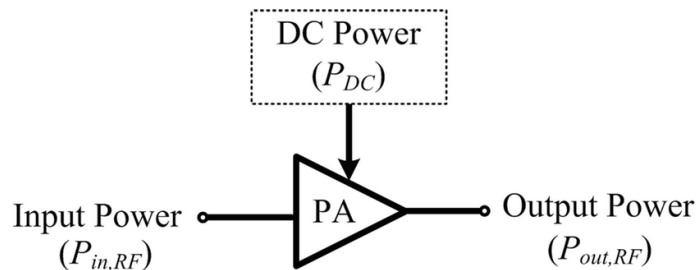


Figure 3.3: Schematic of a RF PA

The Output Power is not the only key parameter: other mainly used FoM's as gain, efficiency and linearity can be defined respectively with the following parameters, visible on figure 3.4. This list is not complete but gives the main parameters considered in the literature.

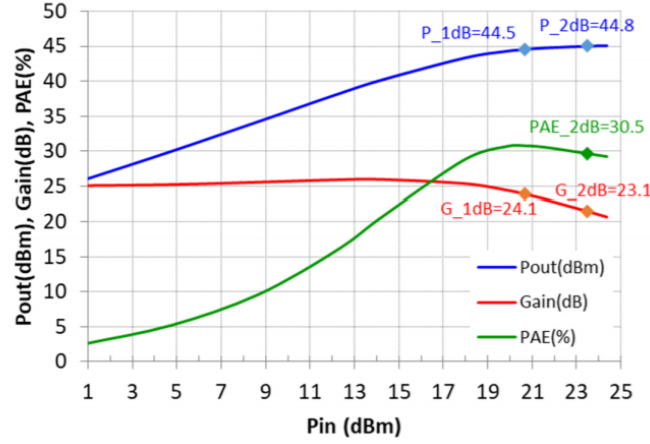


Figure 3.4: FoM's of RF PA. In red the power gain, in green the PAE and in blue the output power.

- **Power Gain:** gain is the main index to measure the amplification ability of amplifier. Gain is defined as the ratio of the power transmitted to the load by the amplifier to the power actually transmitted by the signal source to the amplifier, expressed in dB .

$$G = \frac{P_{in,RF}}{P_{out,RF}} \quad (3.1)$$

- **PAE:** Power Added Efficiency: this metric takes not only the classical definition of efficiency (also called drain efficiency), $\eta = 100 \times \frac{P_{out,RF}}{P_{DC}}$, into account but also RF power at the input. The inefficiency comes mainly from heat production in the device. PAE is, in short, a measure of the efficiency by which a device converts DC or RF input power to a higher RF output. It is calculated in percent as:

$$PAE = 100 * \frac{P_{out,RF} - P_{in,RF}}{P_{DC}} \quad (3.2)$$

- **1dB compression point (CP1dB):** : non linearity appears when the gain of the amplifier starts to decrease. When the difference between the ideal output power and the real output power is equal to 1dB, the input power is noted as the input power of 1dB compression point. At the same time, the gain also started to decrease. This is a indication of the linear region of the PA.

$$P_{out,RF}[dBm] = G[dB] + P_{in,RF}[dB] \quad (3.3)$$

- **Input/Output Matching:** The matching networks are capital for a good working amplifier. These are visible in figure 3.5. They determine a part of the losses, The output matching networks will for example defines how much power is delivered to the output and how much gain and noise are produced in the process. There is a trade-off between maximum output power, maximum gain and better efficiency linked to the output matching network.

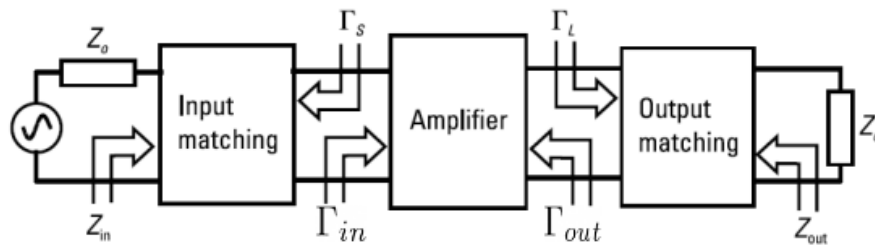


Figure 3.5: Matching networks for a PA.

The specifications of the PA depends strongly on the power level, the frequency, the modulated signal and all the requirements depending on the specific use. The power amplifiers are classified following their characteristics and performances into classes (A, AB, B, ...). Their precise description will not be addressed in this work. But there is a classical trade-off between efficiency and linearity for the PA'S following the class in which they operate, with class A PA being the most linear.

From [38] and [39], III-V semiconductors are still the most chosen technologies for the RF PA's due to their superior frequency response (higher electron mobility) and breakdown robustness. Silicon based technologies are more difficult to implement since their lower breakdown voltage limit the output power of the PA. In recent works, Gallium Arsenide (GaN) received most of the attention compared to its III-V counterpart Gallium Arsenide (GaAs) for its higher power density and better thermal dissipation [40, 41, 42]. Still, most of the commercial applications where the power level is $<5W$, are proposed in GaAs. At higher power levels, GaN becomes the semiconductor of choice. Some interest for RFSOI [43] and CMOS [44] also appears because of the integration possibilities for the complete RF FEM (filters, IF converters, Mixers,...) that are cheaper with silicon based technologies even if their output power is not as good as the III-V materials.

3.2.2 Low Noise Amplifier

The Low Noise Amplifier (LNA) appears right after the switch in the receiving branch (Rx). Its task is to amplify the received signal with adding the minimum possible noise to its output. It is an import function since the arriving wave comes with lots of distortion and defaults due to the transmission channel. The Rx performances of the FEM highly depends then on the LNA. As the classical PA, the gain and the linearity are important parameters for the PA but the change lies in the importance given to the noise figure. Because the maximum gain and the minimum noise figure can not be reached simultaneously, there is a trade-off between all the parameters. [45]

The noise factor F is calculated with:

$$F = \frac{P_{si}/P_{ni}}{P_{so}/P_{no}} = \frac{SNR_{in}}{SBR_{out}} \quad (3.4)$$

where P_{si} is the available signal power at the input, P_{so} is the available signal power at the output, P_{ni} is the input noise power and P_{no} the output noise power. The Signal-to-Noise Ratio

(SNR) is defined as the ratio between the signal power and noise power. The noise figure NF is obtained with:

$$NF[dB] = 10 * \log_{10}(F) \quad (3.5)$$

The NF is a challenging parameters, especially with system where transistors are cascaded to give more output power. Indeed, following Frii's Formula with F_i and G_i the noise factor and gain of stage i respectively (equation 3.6), it appears that the NF of the first stage of the receiver dominates the overall NF.

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \dots \quad (3.6)$$

The same schematic in figure 3.5, could be applied to the LNA matching networks, however their will be a large difference in output matching network compared to the PA because the objectives are not the same. In the LNA design, the noise can have as much importance as the gain. The optimization is made through the use of the Smith Chart.

3.2.3 Other Components

As one can see in figure 3.2, there are way more components than just switches, PA's and LNA's in the FEM. One of the most important components for RF transmission is the filter. Its objective is to "filter out", reject the undesirable frequency bands that may corrupt the signal. In the FEM, filters are grouped into a filter bank because of the large number of supported frequencies. They must be very sharp to adjust to channel bandwidth frequency bands. Most of today's filters, in phone applications, are using Bulk Acoustic Wave (BAW) and Surface Acoustic Wave (SAW) technologies.

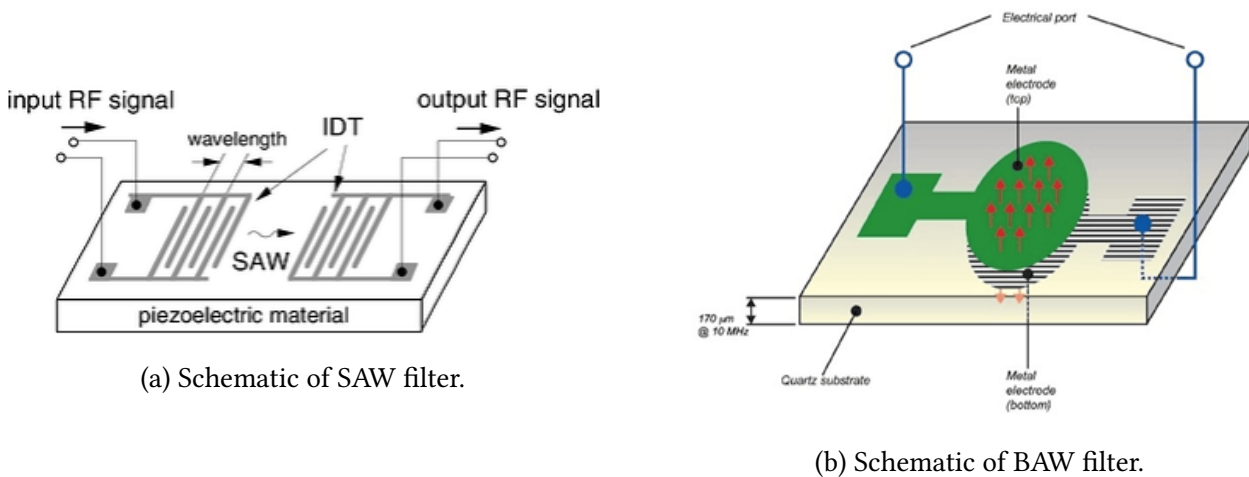


Figure 3.6: BAW and SAW filters technologies

The idea behind these concepts is based on two simple steps and interdigital transducers: 1) The input transducer creates acoustic waves from the electric signal and 2) The output transducer receives these acoustic waves and converts them back to electrical energy. This enables

signal processing in the acoustic, mechanic domain. Both technologies rely on piezoelectric materials and their unique properties. The difference between both is the direction of propagation of the acoustic wave. In a SAW component, acoustic waves travel across the surface of an elastic, piezoelectric material, with a amplitude that decays exponentially with the depth of the substrate, as visible in figure 3.6(a). The filtering effect comes from separation of the "fingers", spaced with 1 wavelength. This make sure that only a specific frequency can go through. In comparison, in BAW, the acoustic waves travel through the surface of the piezoelectric material and are stored in it and propagate vertically as shown in figure 3.6(b). Here, the adjustment of the filter is done with the thickness of the substrate [46]. The BAW technology is more recent than its SAW counterpart. It presents several advantages such as: higher working frequencies up to $10GHz$ while the SAW filter are limited to $2.7GHz$. They also are less sensitive to temperature changes, more sharp in their filtering but are more expensive. SAW devices are manufactured using anisotropic materials which include $LiNbO_3$ (lithium niobate), $LiTaO_5$ (lithium tantalate) and quartz [47]. The most common BAW material is aluminum-nitride (AlN).

Diplexers are also important components. It is a three-port network that splits incoming signals from a common port into two paths, dependent on frequency. This is done by frequency division using filters, either high-pass, low-pass, or band-pass filters. Hence, signals at two different frequencies could be sent and received from the same antenna. It is the same idea as the switch but rather that changing in time, the diplexer focuses on frequency. To function well, the quality and attenuation of the filters must scale with how close the signals are and at what power level they operate.

A final component which is worth noticing is the antenna tuner. Without tuning, the antenna performs well in a limited frequency range, but adding antenna tuning can optimize performance across a broader frequency range. Smartphones, for example, can use two approaches to antenna tuning – impedance tuning and aperture tuning. Aperture tuning changes the electrical length of an antenna to shift its resonance to the desired frequency band of operation. Antenna aperture tuners improve the total radiated power. Impedance tuning aims to match the impedance of the antenna with the impedance of the RF front-end, thus, optimizing the power transfer to the antenna. This is accomplished by switching various passive components to match the FEM output impedance and antenna impedance. Both techniques are visible in figure 3.7 [48]. The switch is therefore a very important components also for antenna tuning.

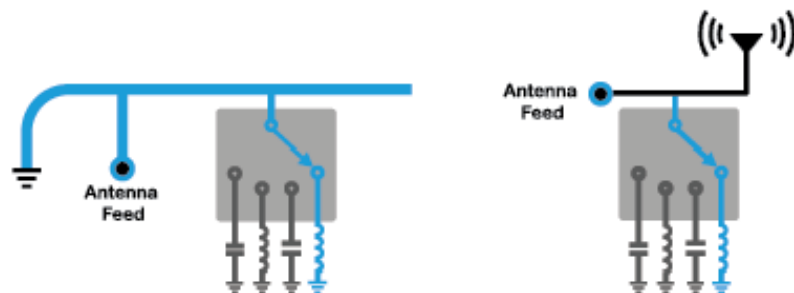


Figure 3.7: Antenna tuning techniques.

3.3 RF Switch

RF switches are used to selectively route the signal through different transmission paths. Those are widely present in the microwave test systems for routing the signal between instruments and devices under test (DUT). This allows to perform multiple tests with the same setup, without having to connect and disconnects frequently the instruments and devices. The idea for switches in RFFE's (RF Front-End) is similar: they provide access to shared resources, such as antennas and give the possibility of Time Division Duplex (TDD) where the antennas is alternately shared between the Tx and Rx branches during time slots. These time slots may be variable in length. This device must also isolate the two paths from each other very well because the switching must also prevent the high power pulses transmitted by the transmitter from damaging or destroying the circuits of the receiver, calibrated for the processing of very low power signals. They also could be used to switch between different frequency bands as it was shown in figure 3.2.

3.3.1 RF Switches Types

RF switches can be divided into two groups, as visible in figure 3.8: the electromechanical switches and the solid state switches.

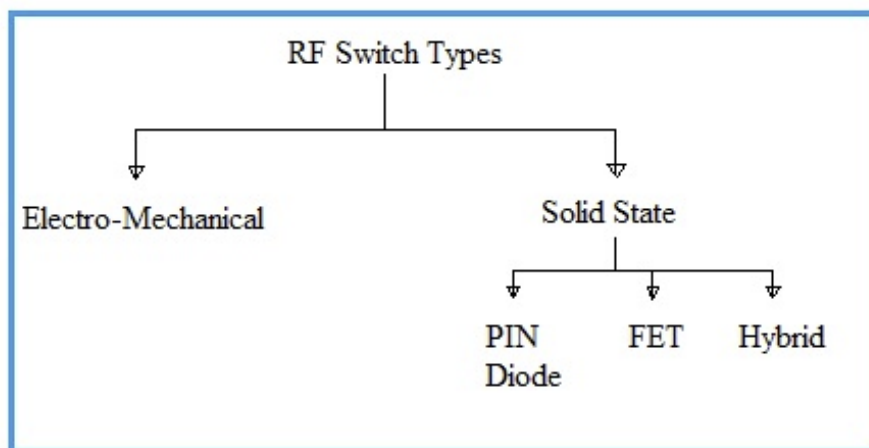


Figure 3.8: Different groups of RF switches

3.3.1.1 Electromechanical Switches

The first type uses mechanical contact to route the signal. Currently research looks more into Micro-Electromechanical Systems (MEMS). The working principle behind MEMS is to actuate a micro-scaled switching beam with electrostatic attraction or repulsion. Figure 3.9 shows a simplified model of a MEMS connected to a three terminals structure (Source, Gate, Drain). When no voltage is applied to the gate, the resistive spring pushes the switching beam away from the drain. The switch is in open mode, also called OFF state (case A in figure 3.9). When

DC voltage is applied on the gate, an electrostatic force appears. The beam is then pulled down towards the drain (the force must be sufficient to overcome the tension spring) and contacts the drain. the switch is in close mode or ON state (case B in figure 3.9). If the DC voltage is removed, the switching goes back to its initial position. The main drawback of large-scale MEMS production is the lack of reliability and consistency in large-scale manufacturing.

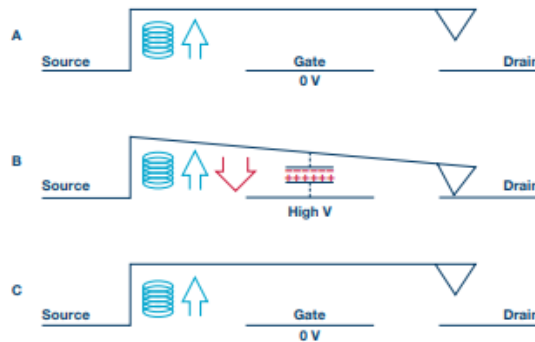


Figure 3.9: MEMS concepts

The term "solid-state" refers to electronic devices which contain neither vacuum tubes nor mechanical devices. Instead, electron flow through solid semiconductor materials. It was firstly introduced in the 1960's. Solid state switches show overall better reliability and longer life-time than MEMS due to their better wear and shock resistance. Moreover, the extreme repeatability of solid-state semiconductor processes is a real advantage in large scale production along with faster swathing time. However, the inherent higher ON resistance of the solid-state switches gives higher insertion loss than their electromechanical counterparts. Solid-state switches can also be divided into 3 main categories: PIN diode switches, Field-effect transistors (FET) switches and Hybrid (FET + PIN diode) switches.

3.3.1.2 PIN Diodes

The PIN diode acts as a variable resistor at RF frequencies. This resistance varies from $10\text{ k}\Omega$ (in OFF state) to few Ω (ON mode). Unlike a varactor which is voltage controlled, the PIN diode is a current controlled device: the forward DC current flowing through it determines the resistance. The switching aspect appears when the control current is alternatively injected in the diode. The structure of the PIN diode is constituted with 3 layers as shown in figure 3.10(a): an intrinsic (I) layer with high resistivity is inserted between two doped region: positively (P) charged and negatively (N) charged.

When the diode is forward biased, holes from the P region and electron from the N region are injected in the highly resistive I region (theoretical resistivity for I-region with silicon: $3000\Omega\text{-cm}$ at 300K). Because they don't recombine immediately, charges have a finite lifetime (τ) and charges lower the resistance of the intrinsic region. This is the situation in 3.10(b) where the equivalent circuit is just a resistance and a parasitic inductance, which depends on the geometrical properties the PIN diode.

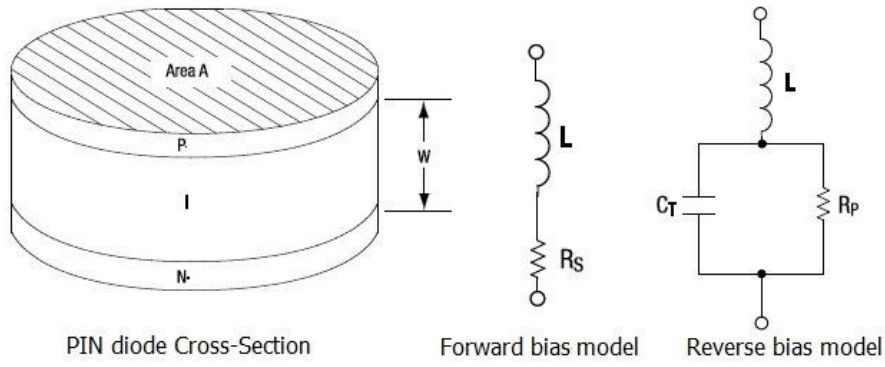


Figure 3.10: PIN diode structure and equivalent forward and reverse circuits

Since higher DC currents cause more charges to be injected into the I-region, the R_S resistance is inversely proportional to the injected DC forward current. Indeed, the quantity of stored charge Q depends on the recombination time τ and the forward current I_F and is given by:

$$Q = \tau I_F \quad [C] \quad (3.7)$$

The resistance of the I-region under forward bias, R_S , is inversely proportional to Q and is expressed with:

$$R_S = \rho \frac{W}{A} = \frac{W}{A} \frac{1}{qN(\mu_N + \mu_P)} = \frac{W}{A} \frac{AW}{Q(\mu_N + \mu_P)} = \frac{W^2}{(\mu_N + \mu_P)Q} \quad [\Omega] \quad (3.8)$$

When combining equations 3.7 and 3.8, the expression of R_S appears to be an inverse function of the current:

$$R_S = \frac{W^2}{(\mu_N + \mu_P)I_F\tau} \quad [\Omega] \quad (3.9)$$

where W is the intrinsic region thickness, μ_N and μ_P are respectively the electrons and holes mobility, I_F is the forward current, A is the PIN diode surface, ρ the resistivity of the I-region. The relationship between R_S and I_F is visible at figure 3.11.

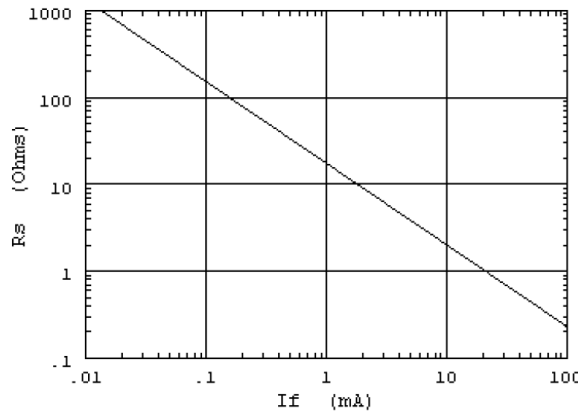


Figure 3.11: PIN diode resistance versus forward bias current.

Equation 3.9 only considers the resistance of the intrinsic region, in addition, effects like junction contact resistance and edge recombination have an impact on the real total resistance. Moreover, this equation is only correct for frequencies higher than the transit time frequency of the I-region, called f_T :

$$f_T = \frac{1033}{W^2} \quad [MHz] \quad (3.10)$$

Below this frequency, the period of the signal is above the transit time of the I region and the PIN diode behaves like a classic PN diode. It rectifies the signal and it is not suitable anymore for switch applications. A diode with a long transit time (W is large and therefore f_T is small) will have more tendency to retain the stored charge. But, a thicker PIN diode also means higher resistance. f_T generally lies in the kHz - MHz range.

When the diode is zero or reverse biased, charges are swept out from the two junction regions (P-I and N-I regions) as well as the I-region, causing the I-region to be fully depleted of charge and therefore acting as an insulating material. Because the two heavily doped regions are highly conductive, it appears as a simple parallel plate capacitor C_J . C_T represents the total PIN diode capacitance, R_P a shunt loss element and still the parasitic inductance L . The equivalent circuit is visible in figure 3.10(c). The C_T is the combination of the junction capacitance C_J and package capacitance C_P with

$$C_J = \frac{\epsilon_0 \epsilon_r A}{W} \quad (3.11)$$

which is valid for frequencies above the dielectric relaxation frequencies of the I region, expressed as:

$$f_d = \frac{1}{2\pi \rho \epsilon_0 \epsilon_r} \quad (3.12)$$

where ϵ is the dielectric constant of the I region material, A is the diode junction area, W is the intrinsic region thickness and ρ the resistivity the I region.

The main advantages of PIN diode is to control large RF signals with much smaller DC bias levels at the cost of some more complicated bias circuitry: RF choke inductors and DC-blocking capacitors are needed to make PIN diode switches work, as one can see in figure 3.12. The high switching speed and small size packaging make them choice candidate's for Rf switches even if the PIN diodes can not be used at lower frequencies.

3.3.1.3 Field-Effect Transistors

Field-effect transistors (FET) are one the most common semiconductor device in the electronics. If we consider a classical 3 terminals devices, the concept is to modify the conductivity

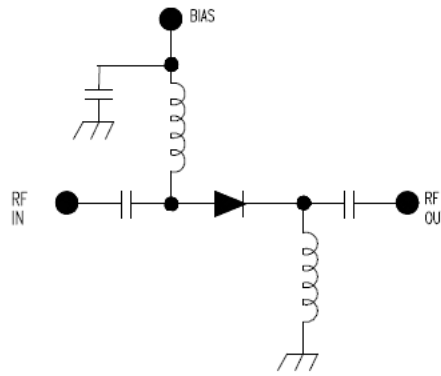


Figure 3.12: Simple PIN series switch with the bias circuitry

of the transistor by applying voltage on the gate such that the electric field shapes the channel between the drain and the source. The very good repeatability of the solid-state switches come from the good control of the processes and therefore, of the drain-to-source resistance. One major difference with the PIN diode switch is the possibility for FET switch to operate to lower frequencies (down to DC) because the low channel resistance is possible even on DC. It only depends on the voltage on the gate, see figure 3.13 where the two states are visible.

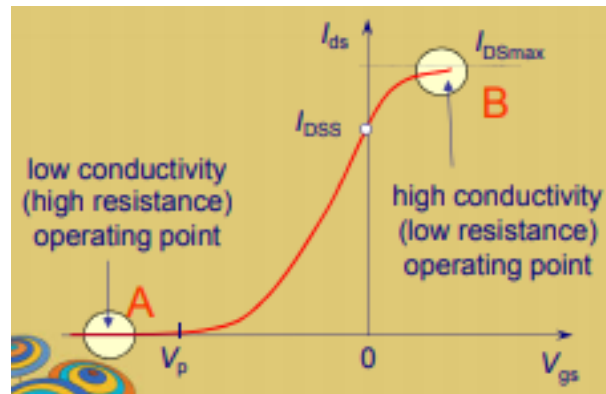


Figure 3.13: I_D - V_G characteristic of FET transistors

When the FET is biased ON, low resistance appears because a channel where the charges can flow exists between the drain and the source if a voltage difference is applied to the source. When it is reverse biased, there is a depletion region that appears such that there is no possible channel between the source and drain, this is the OFF mode. The resistivity of the channel is then very high. So solid state switches also provide high R_{OFF} at lower frequencies. The resistance is controlled by the gate voltage V_G . The isolation between the drain and the source in off mode degrades with increasing frequencies since the parasitic capacitance C_{GD} gets bigger. In short, the transistor switches from low Resistance (R_{DS-ON}) state to a low capacitor state (C_{DS-OFF}). For RF switches, transistor are intended to work as passive devices (no gain brought to the signal). The bias circuitry of the FET is much easier since the bias path (voltage control) is not directly connected to the RF paths. No need for large RF chokes, avoiding the insertion loss that comes with such complicated circuitry. However, the resistance of the

channel R_{DS} is larger than the resistance of the PIN Diode R_S leading to inferior insertion loss performances.

3.3.1.4 Hybrid

The idea is to combine the best of both worlds from PIN diodes and FET's. Using FET gives the possibility to work down to DC while PIN diodes exhibit in general better isolation. In practice, this is a type of RF switch rarely encountered in the literature.

3.3.2 RF Switch Parameters

In this next section, the key parameters used to benchmark the RF switches are detailed. As explained before, the main requirements for RF switches is to provide two states: ideally short and open for the ON and OFF state respectively. In reality, a perfect open and short circuits are not achievable, designers rather look to a low insertion-loss in the ON state and high isolation in the OFF state. That translates into the two main parameters of switches: R_{ON} and C_{OFF} . The goal is to minimize both parameters: low R_{ON} when routing the signal to provide low losses and a low C_{OFF} when blocking the path to avoid any capacitive coupling. A Figure of Merit (FoM) has then emerged for the RF switches:

$$FoM[Hz] = \frac{1}{2\pi R_{ON} C_{OFF}} \quad (3.13)$$

$$FoM[s] = R_{ON} C_{OFF} \quad (3.14)$$

Both definitions are used in the literature. The possible advantage of the first definition is that the FoM is assigned to a cut-off frequencies. The cut-off frequencies is generally 10 times larger the usable bandwidth of the switch [49]. R_{ON} is proportional to the device width and C_{OFF} is inversely proportional to the device width, making the FoM constant for a given technology or configuration.

3.3.2.1 Frequency Bandwidth

Highest and lowest authorized frequencies of operation, where the requirements and specifications of the switch are met. Narrow band applications are generally not interesting because it would mean higher resources and higher costs. There is willingness to propose broadband devices which keep good performances all along their working spectrum.

3.3.2.2 Insertion Loss (IL)

This is the measure of the power loss or signal attenuation after a specific device. Insertion loss are due to all the parasitic effects that comes with the RF components: finite resistances of series connected components, parasitic capacitors, transmission line loss due to interconnections, microstrip, ... An other way of viewing IL is to consider the the ratio between the power transmitted to a load before and after inserting a network between the source and the same load, as visible in figure 3.14 [50].

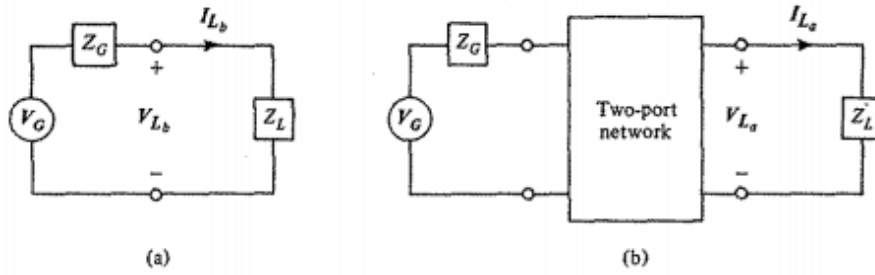


Figure 3.14: Insertion Loss definition.

It can be defined as a power loss:

$$IL = 10 \log_{10} \left(\frac{P_{L_b}}{P_{L_a}} \right) \quad [dB] \quad (3.15)$$

Or as voltage attenuation or current attenuation since both P_{L_a} and P_{L_b} are defined with respect to the same Z_L :

$$IL = 20 \log_{10} \left(\frac{V_{L_b}}{V_{L_a}} \right) = 20 \log_{10} \left(\frac{I_{L_b}}{I_{L_a}} \right) \quad [dB] \quad (3.16)$$

High insertion loss leads to reduce the dynamic range of the signal. Concretely, the IL can be expressed as the magnitude of the s_{21} scattering parameter in the ON state. In reality, it would be true if the load, generator and inserted two-port network are perfectly matched with the characteristic impedance Z_0 , which is never the case in practice and reflection happens. However, if all of this equipment is -20dB matched to Z_0 , the error of using S_{21} as IL would be of 1% or less [50].

$$IL = -20 \log |s_{21}| \quad [dB] \quad (3.17)$$

Depending if we consider a gain or not, one can find a plus sign. The important is more the absolute value of the insertion loss that need to be minimized.

3.3.2.3 Isolation (ISO)

The isolation is defined as the power ratio between the power level when the path is ON and the power level when the path is OFF. It characterizes how much can the switch suppress the signal. Isolation is crucial since it prevents unwanted signal from leaking into the other signal path(s). It can be thought as the IL of the open path, because it is not really an open circuit. ISO greater than 20dB is generally required. As for the IL, ISO can be measured with s_{21} when the path is OFF if all perfectly matched networks are considered. The main contributor factor is the capacitive coupling.

3.3.2.4 Return Loss (RL) and VSWR

For RF signals, the wavelength is comparable to the device which leads to wave transmission theory. Indeed if the wavelength is big compared to the transmission line or cable, the signal stays relatively constant through the object. At higher frequencies this is not the case anymore and it is import to take into account the reflection and transmission appearing while the wave is moving from a medium to another. The different media are here the interconnections between the different components which form the RF system. The Return Loss is a measurement of the Voltage Standing Wave Ratio (VSWR) that occurs when there is impedance mismatch between circuits. VSWR characterizes the reflected wave that will bounce back, maybe oscillates and generates heat. It is expressed as:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (3.18)$$

where Γ is the reflection coefficient. The return Loss can be seen as a subclass of insertion loss: the higher is RL, the higher IL because of the loss in the reflection. An other way to see RL is with the following expression in equation . In order to decrease the reflected power, the return losses must be the biggest possible.

$$RL = -10 * \log\left(\frac{P_{Reflected}}{P_{IN}}\right) \quad [dB] \quad (3.19)$$

S_{11} and S_{22} are equal to the reflection coefficient at the input and the output respectively. Return Loss can be computed in the ON and OFF states.

3.3.2.5 1dB Compression Point (CP1dB)

The 1dB compression point is a measure of the non-linearity of the device. While the device stays in the linear region, 1dB increase at the input results in 1dB increase at the output. The non-linearities appear when this equal increase is not happening anymore, the output starts to increase less than the input power. The CP1dB is defined as the input or output

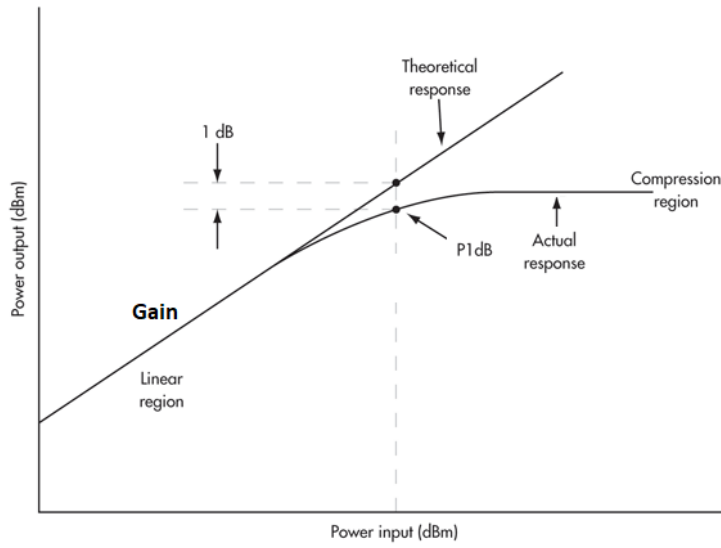


Figure 3.15: Output power vs input power

power (depending on the use) when the difference between the ideal and real output curve has reached a value of 1dB. The figure 3.15 shows the situation. Linearity is really important parameters for RF switch since designers really want to keep the signal as original as possible (Tx or Rx mode) and not corrupted by compression.

3.3.2.6 Third Order Intermodulation Intercept (IIP3)

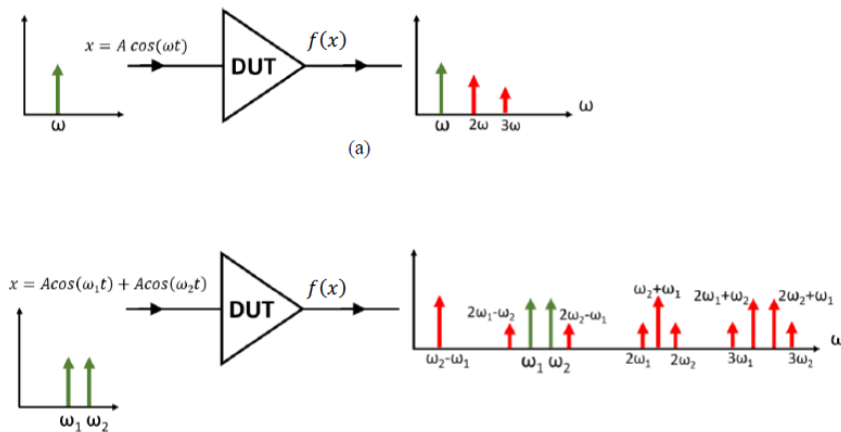


Figure 3.16: Input and output spectrum of non linear system.

Following the Taylor series expansion, around a small deviation, the large signal curve can be described by a polynomial:

$$s_o = a_1 s_i + a_2 s_i^2 + a_3 s_i^3 + \dots \quad (3.20)$$

If s_i is sinusoidal wave such as $S\cos(\omega t)$, s_o can be expressed as:

$$\begin{aligned}
 s_o &= a_1 S \cos(\omega t) + a_2 S^2 \cos^2(\omega t) + a_3 S^3 \cos^3(\omega t) \dots \\
 &= a_1 S \cos(\omega t) + \left(\frac{a_2 S^2}{2}\right)(1 + \cos(2\omega t)) + \left(\frac{a_3 S^3}{4}\right)(3\cos(\omega t) + \cos(3\omega t)) \dots \quad (3.21) \\
 &= \frac{a_2 S^2}{2} + \left(a_1 S + \frac{a_3 S^3}{4}\right)\cos(\omega t) + \frac{a_2 S^2}{2}\cos(2\omega t) + \frac{a_3 S^3}{4}\cos(3\omega t) \dots
 \end{aligned}$$

From equation 3.21, different frequency components appear in ω , 2ω , 3ω because the system is never completely linear. The output spectrum is visible in figure 3.16(a).

When multiple frequencies are injected into the input of a system, the output sees undesired output at other frequencies, linear combinations of the input frequencies. This is the principle of intermodulation distortion. Because the third-order intermodulation product ($2f_2 - f_1$ and $2f_1 - f_2$) are closest to the fundamental tone, they are difficult to remove with filters and their nonlinearities need to be considered 'see figure 3.16(b). The intermodulation signal will grow in power at a rate 3 times faster than the fundamental, causing the two curves (fundamental and third order distortion) to cross. The point is called the third-order intercept and the IIP3 is expressed in dBm generally, see figure 3.17

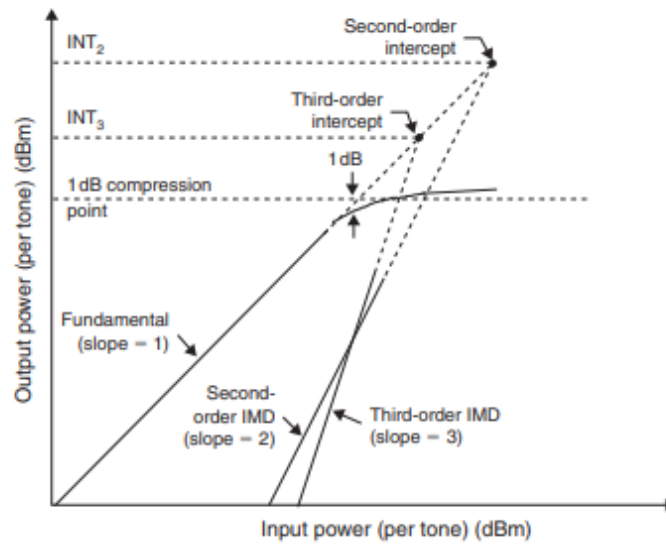


Figure 3.17: Output power versus input power with intermodulation products.

3.3.2.7 Switching Speed

Switching Speed refers to the time needed for a branch of a switch to move from ON state to OFF state and vice versa. Two definitions are possible: rise/fall time and ON/OFF time. The last definition takes into account the switch driver propagation delay. All of the following are visible on figure 3.18 [51].

- **Rise time:** time it takes for the output signal to move from 10% to 90% when going from OFF to ON state.
- **Fall time:** time it takes for the output signal to move from 10% to 90% when going from ON to OFF state).
- **ON time:** time it takes between 50% for the control signal to 90% for the output signal when going from OFF to ON state.
- **ON time:** time it takes between 50% for the control signal to 10% for the output signal when going from ON to OFF state.

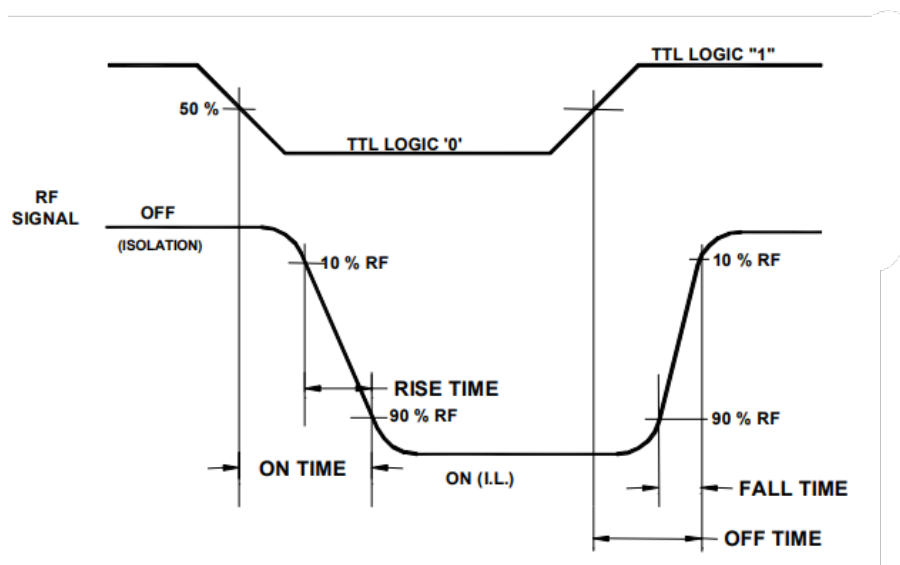


Figure 3.18: Switching times definition.

3.3.2.8 Reflective or Absorptive Switch

When the switch opens or switches the path, the impedance of the OFF branch jumps from generally $50\ \Omega$ (since source, load, transmission lines are generally matched to this value) to a very large impedance value. Two approaches are possible. Reflective design lets the unused port (OFF branch) unterminated, with no matching. The RF signal is then reflected back at the source because of the mismatch. This means very high VWSR. They generally have simpler design, lower costs and can handle higher power levels.

Absorptive switches provide a matched termination at the inactive port. The signal in this OFF branch is then absorbed and will not bounce back which implies that the power-handling would be less. These are a more complicated in their design. They also offer more protection towards the RF source. Absorptive switches can be used instead of reflective switches but the opposite is not true.

3.3.3 Switch Topologies

Poles are the number of switch contact sets and throws are the number of conducting positions. The most simple switch is a single-pole single-throw (SPST) where it has only one set of contact and only one position to route the signal, as one can see in figure 3.19(a). Its action is as simple as ON-OFF.

This work focuses on the single-pole double-throw configuration that which is a popular application for routing the signal between Tx and Rx paths, as shown in figure 3.19(b). This is very interesting in systems with Time Division Duplexing (TDD). The idea behind the SPDT is to reduce the number of hardware (i.e. antennas). SPDT are also used to ground the signal when the arriving signal must not be transmitted forward (figure 3.19 (c)). The SPDT switch is generally made from two SPST units.

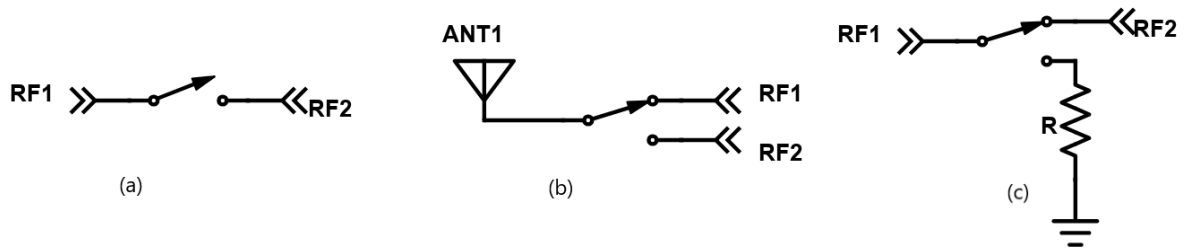


Figure 3.19: Schematics of SPST and SPDTs

More complicated multiplexer architectures are possible with still the one common port and N switched terminals (SPNT). Generally, for RF devices, the available multiplexers are in the 4x1 or 6x1 dimensions. Moreover, one can reach higher numbers of throws by cascading the simple ones. In figure 3.20 [52] for example, a SP8T is made from cascading SPDT on two layers until reaching the good number of throws. For this type of designs is important to be careful with the IL that increases with the number of layers [52]. The concept for higher number of throws is less routing between Tx and Rx but more choosing between different filters and frequency bands.

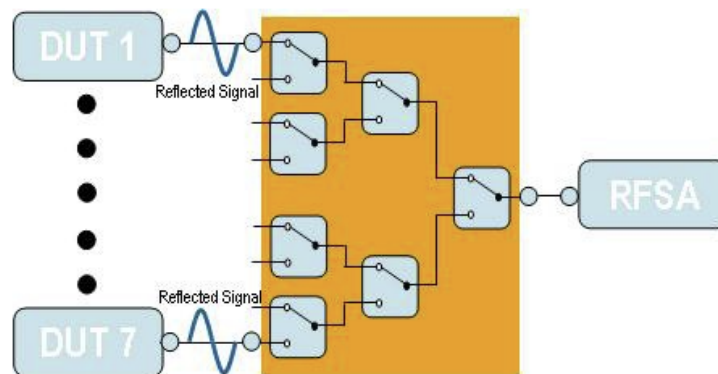


Figure 3.20: 8x1 multiplexer from cascaded SPDT

Once the number of ports is chosen, depending on the requirements, the switch can consist of series, shunt or series-shunt configurations. In the next examples, FET are used for the schematic but with PIN diodes would be the same except for the more complex bias circuitry. They are also represented as reflective SPDT's.

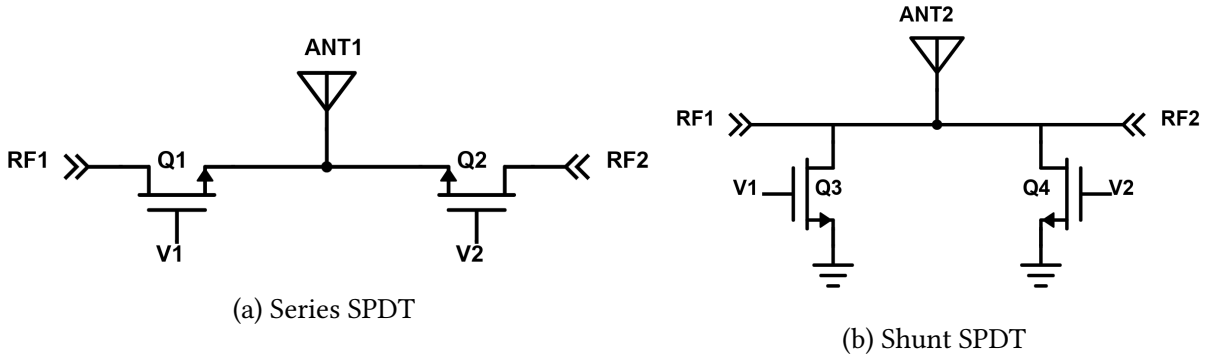


Figure 3.21: Schematics of series and shunt SPDT's

In figure 3.21(a), a series SPDT and a shunt SPDT are represented. Each topology has only one switching device in each branch. Both need to be controlled by complementary voltage V_1 and V_2 ($V_2 = \overline{V_1}$). These are the simplest SPDT but do not offer large ISO, especially for the series topology which can not offer a true open circuit because of the physical properties (parasitic capacitor $\frac{1}{j\omega C}$) that causes leakage especially at higher frequencies but offers instead a large bandwidth of use. The shunt topology seems more interesting because of better ISO and lower IL but also has its drawback: the created short circuit on the 'passing' arm finds its way in the other arm and also shorts it. Quarter-wave section is then needed between the antenna and each branch device to transform the short circuit from one branch into an open circuit in the other, see figure 3.22. Therefore, the RF signal sees a high impedance at the junction. This approach works well but limits the useful bandwidth of the SPDT.

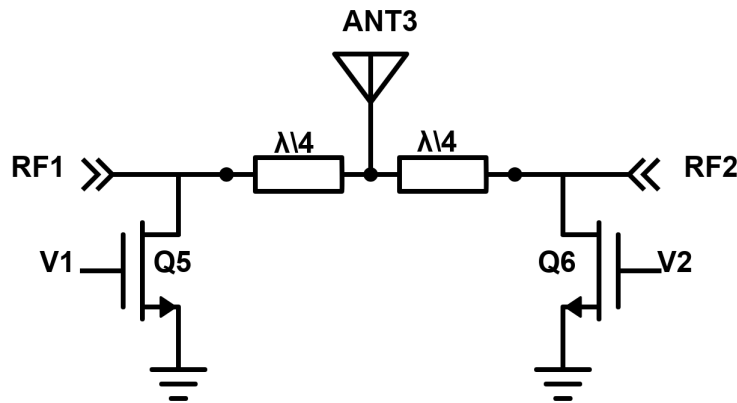


Figure 3.22: Shunt Quarter-wave SPDT

Often a combination of series and shunt devices are used to get the best of both worlds as shown in figure 3.23.

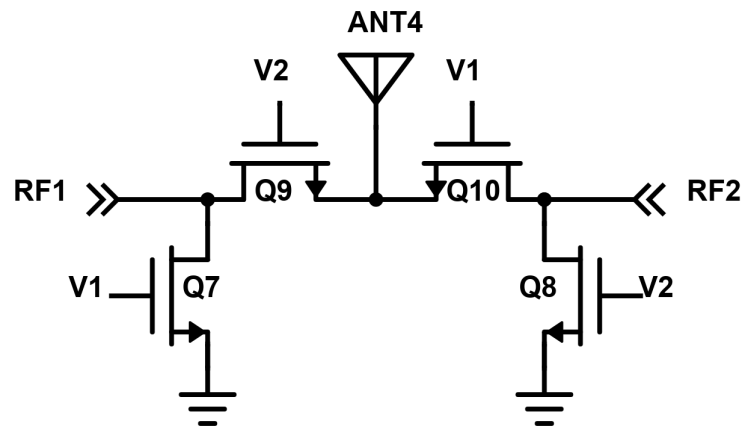


Figure 3.23: Series-shunt SPDT

This improves the isolation of the simple series designs at the cost of higher IL. They also work with complementary voltages V_1 and V_2 . When Q9/Q8 are ON and Q7/Q10 are in OFF state, the RF signal can flow between the port 1 and the antenna, this is the Tx mode. To get a connection between the port 2 and the antenna, Q10/Q7 must be ON and Q8/Q9 must be off, this is the Rx mode. Both modes are visible on figure 3.24 [53]. The shunt devices are here to ground the possible perturbations which may come from the unwanted branches and therefore, to increase the isolation of just the series devices. It should be noted that the Tx and Rx paths do not have to be identical. Following the requirements, designers can choose asymmetrical branches.

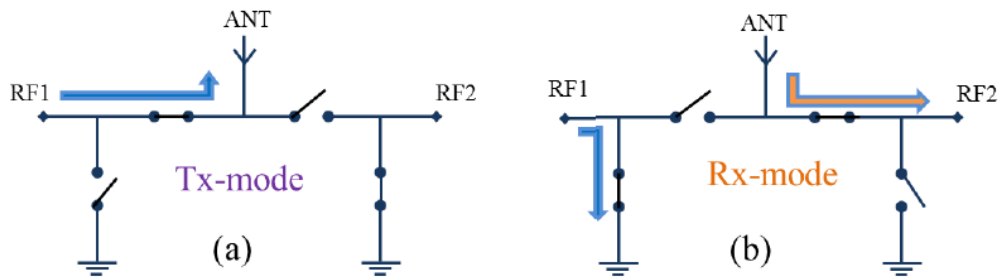


Figure 3.24: Simplified schema of the SPDT in transmitter and receive mode

3.3.4 Quarter Wavelength Section and Traveling-Wave Switch

As explained in the previous section, when using only shunt devices, designers have to also implement quarter-wave section to avoid shorting out the wrong branch. Indeed, the high impedance on the OFF side is shifted 180° in phase in the Smith Diagram, resulting into a low impedance at the other side. But this limits the frequency range of the SPDT since the quarter-wave section only corresponds to the Z_0 at a certain frequency. Outside this frequency, a

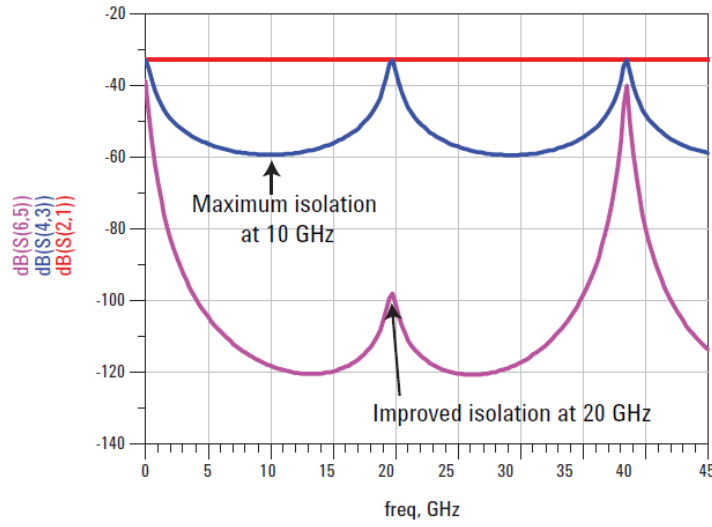


Figure 3.25: ISO evolutions with different topologies

mismatch appears. One way to solve this issue is to add different shunt devices in parallel along with $\lambda/4$ section to extend the working frequencies. This type of switch is called traveling-wave switch and exhibits some interesting broadband applications [**traveling-wave**]. The wavelength is given by:

$$\lambda = \frac{c}{f\sqrt{\epsilon_R}} \quad (3.22)$$

where c is the speed of light in vacuum, f the frequency and ϵ_R the relative permittivity of the material. So for example, a wave of frequency 10GHz in alumina substrate with $\epsilon_R = 6.466$ has a $\lambda/4 \approx 3\text{mm}$. As one can see in figure 3.25, the addition of a quarter-wave section between the two branches moves the ISO from red to blue line with a maximum isolation at 10GHz . If another quarter-wave section for 20GHz ($\approx 1.5\text{mm}$) with a PIN diode is added in each branch, the ISO moves from the blue to the purple line. This of course costs more in power consumption, there are more IL and the packaging becomes more complicated.

CHAPTER 4

BENCHMARK

The study focus on SPDT switch in Ka-band, especially at 28GHz. There is not a forced topology, instead the comparison between the different topologies is made regarding which one offers high ISO and low IL. It is time to look how the different technologies perform regarding the key parameters and FoM against each other. The following technologies will be briefly introduced: Bulk CMOS, RF SOI MOSFET, GaAs HEMT, GaN HEMT, SiGe BiCMOS and GaAs PIN diode. In a first time, the study focuses on separate board-level components and in a second time completely integrated RFFE's are analyzed.

Historically, GaAs and Silicon-on-Sapphire (SOS) were the main substrates used for RF switch before the arrival of RF-SOI as one can see in [54] from 1998 where GaAs MESFET were the state-of-the-art technology for RFFE's or in [55]. PIN diodes were also used in microwave switches but because of the large bias currents needed and DC power consumption, GaAs FET were preferred for mobile applications. Since 2012, SOI has never ceased to absorb the RF Switch handset market until reaching 85% in 2018, as visible in figure 4.1. Regarding the complete FEM, RF-SOI is also widely used, except for the PA's where GaAs still offers the best performances. Indeed, 4G's FEM are made up of various technologies that are fabricated and packaged separately and later assembled on the same carrier substrate.

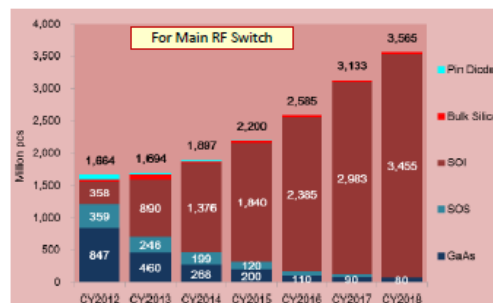


Figure 4.1: Adoption of SOI technology for the RF switch market

4.1 Technologies Review

Parameter	Si	GaAs	GaN	Ge
Band Gap [eV]	1.1	1.42	1.39	0.67
Electron Mobility [cm^2/Vs]	1350	8500	1200	3900
Dielectric Constant	11.8	13.1	9.0	16
Breakdown Electric Field [MV/cm]	0.3	0.4	3.3	0.1
Electron Saturation velocity [$10^7 cm/s$]	1.0	1.0	2.5	0.6
Thermal conductivity [W/cmK]	1.5	0.43	1.3	0.58
Lattice constant [$\text{\AA}$]	5.4	5.7	3.2	5.66

Table 4.1: Electronic properties of semiconductors.

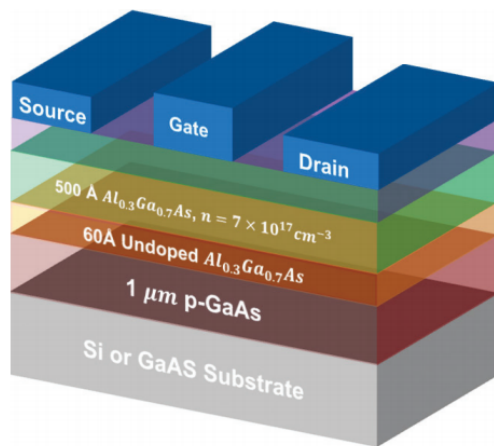
4.1.1 Bulk CMOS

CMOS was not originally developed for RF use and largely dominates the digital/baseband sector. The silicon MOSFET is the cheapest and most widely spread transistor mainly for two reasons: silicon can easily grow an high quality oxide SiO_2 and is the second most abundant element (27.7%) in the Earth's crust, after Oxygen [56]. However, it has always been considered inferior to its semiconducting counterparts for RF applications. Indeed, due to its electrical properties, visible at table 4.1: the modest band-gap linked to a low breakdown voltage and the poor electron mobility (in N-type) linked to a high on-resistance of the channel. Also silicon does not provide a good media for transmission lines since there is large coupling through the low-resistivity substrate (tens of Ωcm as nominal resistivity). This leads to non-linearities and increased IL. Therefore, it is also hard to make high quality passive components and the RF performances depends a lot on the passive components quality such as inductors, capacitors and interconnections [57]. However, research has for many years proceeded to "downscaling" of the silicon MOSFET, especially to increase the performances of digital MOSFET (and follow Moore's law). At the same time, it also improved the performance of RF MOSFET through better gate control on the channel, lower on-resistance for example. This leads to transition frequency up to $485GHz$ with 29nm gate length and specific strain technology [58]. An other advantage is the high integration possibilities with transceivers and baseband IC's on the same chip. And finally, its cost: since silicon is widely available and the processes are well mastered by the industries and very reliable for large scale market, the price of the 300mm wafer is low compared to other technologies.

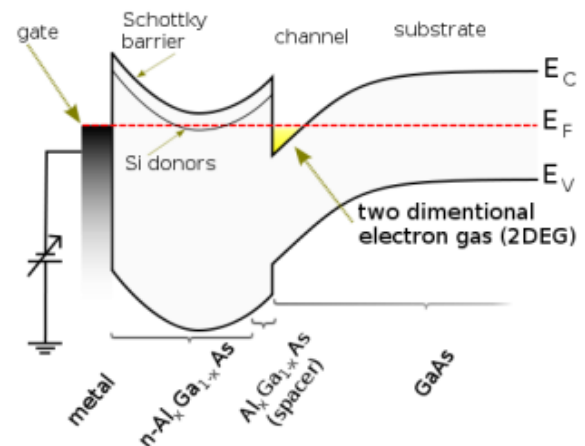
4.1.2 GaAs

Gallium Arsenide (GaAs) has always been a prime candidate regarding RF applications with its high electron mobility, see table 4.1 and low dielectric losses for high quality CPW or mi-

crostrips. A higher breakdown voltage and linearity make GaAs interesting for mmWave applications. The first GaAs Metal-Semiconductor Field-Effect Transistor (MESFET) was introduced in 1965 [59] and few years later MESFET with f_{max} of around 100 GHz was presented. High Electron-Mobility Transistors (HEMT) were introduced later. The structure of a HEMT is visible at figure 4.2 (a) [60]. The HEMT technology improved the performances of the MESFET by using the formation of a 2D Electron Gas (2DEG) at the AlGaAs/GaAs interface. The band structure is visible on figure 4.2(b). High mobility electrons are generated using the hetero junction of a heavily doped wide bandgap n-type donor (supply layer (example AlGaAs)) and an undoped narrow bandgap channel layer with no dopant impurities (example GaAs). The mobile electrons generated in the supply layer drop completely into the undoped channel layer which results in the depletion of AlGaAs donor layer. Because there are no donor atoms intentionally present in the undoped GaAs layer, electrons in the 2-DEG channel do not undergo impurity scattering and hence exhibit high mobility and velocity. Performances can even be improved by adding a layer of InGaAs as material for the 2DEG to improve confinement of carriers in the quantum well channel. This type of HEMT is called pseudomorphic HEMT (pHEMT). Metamorphic HEMT (mHEMT) use instead InAlAs as buffer layer, with the indium concentration graded so that it can match the lattice constant of both the GaAs substrate and the InGaAs channel. This technology lead to impressive RF performances: study on GaAs mHEMT shows f_t of 644 GHz [61].



(a) Series SPDT



(b) Band diagram in HEMT structure.

Figure 4.2: HEMT characteristics.

However, GaAs HEMTs suffer from integration problem regarding digital CMOS. Up to now, the problem was avoidable due to System-in-Package approach (SiP) where the best technology for each part of the FEM was used and assembled into a board. The PA's were still made from GaAs because other technologies can not cope with the output power and linearity of these. But with higher frequencies, the direction towards more integration on the same chip seems to dominate in order to reduce interconnection losses, costs, power consumption and weight [62]. However, if they can be made as discrete transistors, they can also be embedded into integrated circuits. The circuits are called Monolithic Microwave Integrated Circuit chips (MMICs) and are widely used for RF design applications.

4.1.3 SOI

In MOSFET on bulk silicon, the conduction channel is confined close to the gate oxide interface. Most part of the thickness of the silicon substrate is not used but it is subject to parasitic effects such as current leakage, latch-up. Placing an oxide (called BOX or buried oxide) between the active layer and the substrate makes sure that the conduction channel is isolated from the substrate, improving therefore the transistor characteristics.

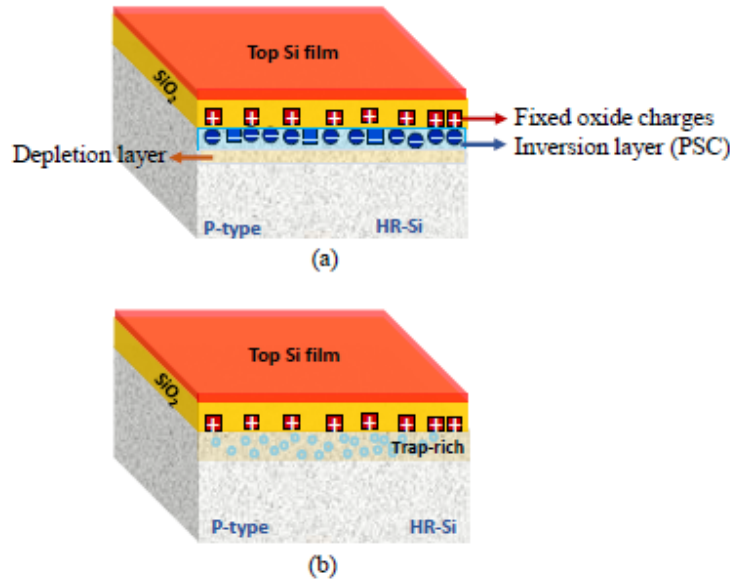


Figure 4.3: Evolution of SOI substrates

Since the 1970's, research have been made on Silicon-on-Insulator technology. The first SOI wafer was released in 1971 [53] [63]. Alumina (Al_2O_3) was used as an insulator. Those substrates provide very good performances and can also co-integrate digital and RF functions to produce the RF functionalities and high digital content needed to build highly programmable systems [64]. They provide the performances to make a RFFE with complete integration of the antenna, power amplifiers (not as good as other semiconductor), antenna tuning on a single chip. Sapphire was then commonly used for SOI, however, SOS is not cost effective and not applicable to larger scale production. The idea was then to adapt the insulator and in 1978, the first SOI with SiO_2 as insulator was investigated [65]. Since then, further improvements have been made on SOI substrates. First High-Resistivity (HR) substrates were developed to globally offer better RF performances. However, it has been recognized in [66] [67] that HR substrates suffer from Parasitic Surface Conduction (PSC), creating alternatively a depletion/inversion layer and reducing the RF performances by increasing losses and crosstalk. A solution to the problem consists of a trap-rich layer at the BOX/HR interface. This layer consists of polycrystalline silicon with a resistivity similar to the intrinsic silicon but presents higher density of traps in the bandgap. The charges are 'trapped' and interfere less with the RF signal. On figure 4.3, one can see the evolution from HR to Trap-Rich (TR) SOI substrates

4.1.4 GaN

Gallium Nitride is also a III-V material like GaAs. The first Gallium Nitride (GaN) MESFET was developed in 1993, quite late regarding the previous technologies and the first enhancement-mode n-channel GaN transistors were on the market around 2010 [59]. GaN is announced as the next semiconductor of choice regarding power applications due to its higher breakdown voltage, higher thermal conductivity and higher saturated drift velocity (especially for RF switching). This means higher output density than Si-based or GaAs devices and high operational voltage. Experts estimate that the market for GaN is supposed to increase from 380M\$ in 2017 to 1.3B\$ in 2023 as explained in [68]. In base stations, GaN has progressively replaced GaAs while in handset applications, GaAs is still widely used for RF power amplifiers. The structure of GaN HEMT is visible at figure 4.4 [69]. The concept of HEMT is the same as AlGaAs/GaAs HEMT but here, the two dimensional electron gas is much higher because of strong piezoelectric effects, polarization effects and large band offset [69], [70].

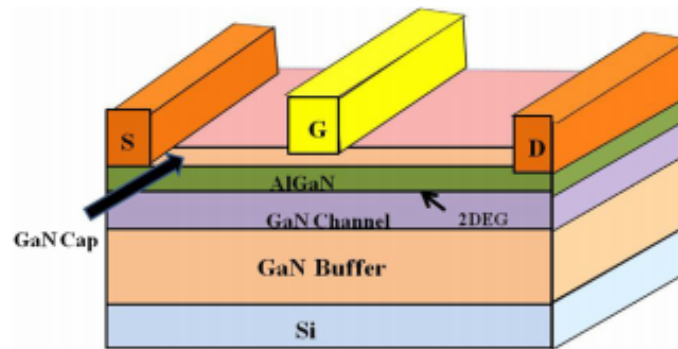


Fig. 1. Three dimensional schematic of AlGaIn/GaN HEMT.

Figure 4.4: GaN HEMT

Today GaN is grown on variety of substrate like sapphire, Si and SiC. Sapphire is the traditional substrate used commonly for white LEDs, but has a big disadvantage of small heat conductivity what makes constructing high power devices difficult. Silicon is much cheaper and available with large diameters wafers and also gives the possibility for higher levels of integration [71], however, the AlGaIn/GaN structures on Si contain large density defects. SiC would be the substrate of choice because very high heat conductivity and small lattice mismatch to GaN. Unfortunately, SiC substrates are still extremely expensive and large wafers are still produced in very small quantities.

It should be noted that GaN exists in three different crystalline structures, namely wurtzite, zinc blende and rock salt. The thermodynamically stable structure is wurtzite for bulk GaN. This the configuration used in table 4.1.

4.1.5 SiGe

Silicon Germanium was the first bandgap engineered Si-based substrate. The goal was to provide a material with competitive performances regarding III-V counterparts for RF applications while keeping the benefits of Si fabrication: enormous yield, cost and manufacturing. The first SiGe HBT was developed in 1987 [72] then in 1992, the BiCMOS technology achieved its first manufacturing qualification in 1996 [73]. A BiCMOS circuit consists of both bipolar junction transistors and MOS transistors on a single substrate, as shown in figure 4.5. The reason behind the hybridization is to combine the high-speed switching and high-output driving capabilities of the bipolar transistors and the low-power and high-density characteristics of the CMOS circuit. The real strength of SiGe lies in its ability to integrate analog, RF and digital on a single chip using existing CMOS fabs and this is why SiGe is commonly used in the RF transceiver circuits, integrated to the baseband circuits.

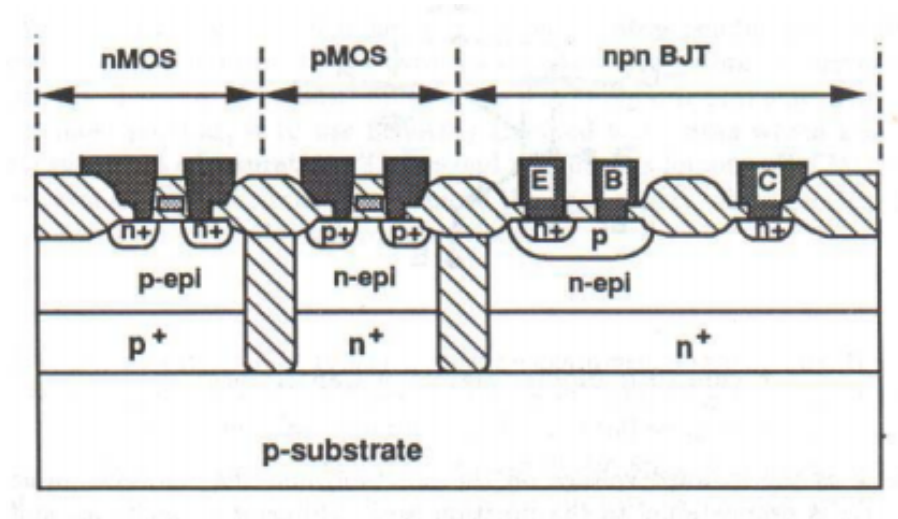


Figure 4.5: SiGe BiCMOS cross section

4.1.6 PIN diode

PIN diode can be made from Silicon [74], SOI [75], GaAs, GaN [76] or SiGe [77] [78] technology depending on the requirements, the use and the frequency. A lot has already been said about PIN diodes in previous section.

4.2 Literature Review

4.2.1 Discrete RF Switches

First, it should be noted that comparing switches based on the technology is not an easy task since there is always a trade-off between IL, ISO and power handling capability parameters and

these choices are made by the designers following their requirements. The tables 4.2, 4.3, 4.5, 4.6, 4.7, 4.4 summarize all the performances regarding bandwidth, IL, ISO, CP1dB and the size of the chip. The values in the table are the maximum (or minimum depending the parameters is IL, ISO or CP1dB) values all the way across the bandwidth. The size of the chip is sometimes including the RF pads for measurement and sometimes it is only the effective area, the core which is considered. Core is referred as ^c and with pads as ^p. One final note regarding the chosen parameters: in chapter 3, the measure of $R_{ON}C_{OFF}$ was introduced as an important FoM. However, in the literature review, there is just a few papers that clearly mention it or mention it but from calculations at frequency below 1GHz, which is not transposable to 28GHz. Some do not even mention R_{ON} and C_{OFF} . So this the reason why the FoM has not been considered in the comparison.

The first trade off that can be analyzed is the choice of the topology. In this case, it is interesting to look at the studies that propose different topology for the same technology node and substrate. As one can see in [79], they propose two different topologies: shunt and series-shunt. As expected, the shunt topology offers way lower insertion-loss due to absence of the channel resistance on the RF path of the series transistor. It is also interesting to observe that the shunt topology offers a much higher (50dB against 39dB) isolation. This was mostly due to the fact that designers use 3 shunted transistors for the shunt topology while there are only two shunted transistors for the series-shunt topology. One can clearly see here the impact of the number of shunted transistors which has an important impact of the isolation. One could ask why then to use series devices. The answer is that with series devices, switch circuits can operate on wider bandwidth since they don't need the $\lambda/4$ transmission line to adapt the impedance which is frequency dependent. The Series device plays the role of adjusting the right impedance (low or high) in the branch. Indeed, in this study, the bandwidth is 3 GHz, which is small compared to other papers. Another interesting example is the paper [80] where series and series-shunt topologies were analyzed. The series-shunt switch shows higher IL due to extra losses of the additional shunt transistors and also lower power handling capacity: this could be explained by the fact that the additional shunt transistors also add parasitic capacitance in the circuit, limiting the power. However the ISO are 2 times better when adding shunt transistors to ground the signal in the unwanted path. A final comparison of topologies is made in [81] between series-shunt, shunt shunt, series-shunt shunt and series-shunt cascaded. The first conclusion is the fact that the $\lambda/4$ transmission line between two shunt devices greatly reduces the bandwidth as expected. The 3 devices with multiple shunt transistors show larger isolation at the cost of higher IL. At the end, the authors choose the simple series-shunt that offers good compromise, especially regarding the bandwidth and the simpler design.

One other important trade-off, which is cited in every study reviewed is the size of the devices, especially the width of the transistor. Even for the PIN diodes, authors in [82], talk about design trade-off between the power consumption and IL since higher bias current would mean lower resistance of the device. But also the width of the device that increases the value of the OFF capacitance. Let's go back to transistor and take an example with a MOSFET. The equation

for the resistance in the on state of the channel is given by:

$$R_{DS} = R_{ON} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})} \quad (4.1)$$

Where μ_n is the transistor channel mobility, W and L are the channel width and length respectively, V_{GS} the gate source voltage and V_{th} the threshold voltage. So one can see that for certain technology, W is the only parameter that can be adjusted to reduce the losses. However, a wider transistor offers smaller R_{on} but comes with higher parasitic capacitor, increasing also C_{off} , limiting the bandwidth and decreasing the ISO. This why $R_{ON}C_{OFF}$ is a very interesting FoM since it does not depend on the width of the device. One interesting aspect brought in the discussion by [81], is the fact that the position of the transistor, whether in the series or shunt branch, also changes the impact of its width. A wider transistor in the shunt branch will result into higher isolation for example.

One final designer's choice that influences the IL and ISO is the stacking of transistors. Stacking is a technique commonly used to increase the voltage breakdown in devices [83], [84]. The high swinging voltage of the RF signal is spread along the stacked devices. So the switch can handle more power. Also the parasitic capacitor will be greatly reduced since stacked transistors are in series with each other. On the other hand, the resistance in the ON-state will be higher for the same reason. One way to compensate for it is to increase the width of the stacked transistors.

For all these reasons, comparing RF switches just based on the technology is quite complicated. Especially for IL and ISO that depend on the bandwidth, the power handling, the topology and design. But from the analyzed paers, it is possible to roughly extract trends regarding the 3 main parameters at 28GHz: Insertion Loss, Isolation and Compression Point. The figures 4.9, 4.10, 4.11 are respectively showing the parameters according to the technology at 28GHz.

For Insertion Loss, by looking at figure 4.9, the expected difference between CMOS and SOI is confirmed. Indeed, majority of the SOI based switches propose lower insertion loss than their bulk counterparts. This can has already been explained by the existing capacitive coupling through the low-resitivity substrate in Bulk technology. PIN diodes are also performing very well along with GaN based devices. One surprising result is the GaAs switches showing quite high IL. This could be explained by the fact that most of the topologies for GaAs were shunt [79], [85] or traveling-wave [86], [84] that also needs for passive elements. All of this could lead to higher losses in total. SiGe devices are performing similarly to GaAs devices.

When looking at the isolation in figure 4.10, the results are more dispersed but GaAs based switches are the switches offering the best performances for this parameter. As expected, regarding the previous comments on their specific topologies. The ISO are preferred at the expense of the IL referring the previous trades-off. SiGe and GaN are performing on the same level and SOI and Bulk also have similar ISO except for [87] with again the traveling-wave design.

Applications where power is the main concern should look for GaN based devices, as visible on figure 4.11, since they generally show the biggest CP1dB, no regard for the topology. It is

easy to understand the increasing popularity of GaN as technology for complete RF FEM since GaN based switches perform correctly for ISO and IL and are the best for linearity but also excellent for Power Amplifier design [88]. PIN diodes based on GaAs substrate also show very good power handling capability. For the other technologies, it is hard to conclude because of the difference frequencies at which the CP1dB was established.

In general, the PIN diodes are among the best for each parameter. However their more complicated circuitry and limited integration limits their use in handset RFFE. Moreover their non negligible DC power consumption (around 550mW) in [89] precludes their use in mobile applications where power consumption is a major problem.

SiGe based switches do not show any advantages compared to their counterparts and are quite underperforming. For III-V materials, Both GaN and GaAs seem to have their specificity: power handling and isolation respectively. Finally SOI and CMOS switches are performing similarly for ISO and CP1dB but not for IL where bulk devices are still lagging. These graphs could give a possible explanation for the wide use of SOI in today's RF switches and their possible use for mmWave applications. With simple Series-Shunt topology ([90], [91], [83], [92], [81], [93]) compared to other more complicated approach like Switched inductor [80], traveling-wave, Elevated series stub [94], diode connected HBTs [95], ... They offer a broadband operation with correct parameters. Due to the simple design, the size of the active are is also reduced compare to other structures which use transmission lines, adaption transform impedance. The series-shunt uses a minimal number of passive components (only matching networks and gate resistor) and these reduced losses are visible in the IL.

4.2.2 Integrated RF switches

Currently most of RFFE's are based on the SiP approach (System in Package) where the best technology for each components of the RF bloc is assembled onto an other board (flip chip mounted on BGA (Ball Grid Array) generally but not for the PA which is still wire mounted). The two ways are shown in figure 4.6 [96].

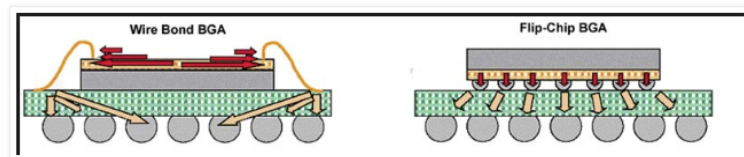


Figure 4.6: Wire bonding BGA and Flip chip BGA

But with higher frequencies the logical solution would be to look towards more integration to offer less interconnections loss that increase with frequency. But further integration can also help to reduce the cost, power consumption and weight which are critical parameters for mobile applications [53]. Such an integrated system is called a System-on-Chip (SoC) where all the RF components of the FEM are integrated on the same substrate. The next reports present complete FEMs and sometimes also the phased array antenna package which was

covered in chapter 2. In [97], authors are using two different chips: The GaAs chip is a low complexity design for the RFFE and the silicon core-chip, based on 45nm CMOS SOI, is a relatively high complexity chip for phase and gain control. These are flip chip mounted on a board. The switch presents an IL of 0.7dB at 28GHz. 45nm CMOS SOI is also used in [98] but to make the FEM this time. The bandwidth spans from 20 to 40GHz. The authors also give for information about the switch: it a series-shunt topology for broadband design. An asymmetric design is also used to handle the voltage waveform resulting from a transit power of 20 dBm. It shows less than 1dB IL and more than 25dB ISO in the bandwidth. the CP1dB is around 21 dBm. GaAs pHEMT is the choice in [99] to make the SPDT, PA and LNA. The $\lambda/4$ double shunt-FET structure is employed but also stacked shunt transistors to handle the high power output for 5G communications. Specific switch characteristics are not precised. 130nm SiGe BiCMOS is also used in [100] where the shunt nMOS topology is adopted for the SPDT switch design. Insertion loss of 2.7–3.7 dB and isolation of 33–51 dB are achieved from 30 to 45 GHz. CP1dB is around 8dBm at 35GHz. Even GaN technology is possible [101]. The goal here is not to list every single FEM that has been made but rather give the reader the global view. Most of the technology are viable, except PIN diodes, for handset devices.

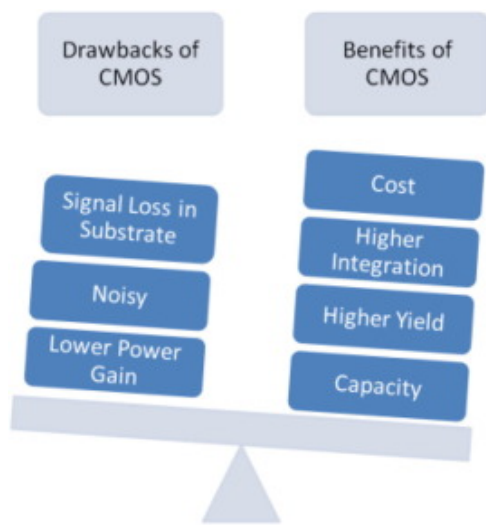


Figure 4.7: Drawbacks and benefits of CMOS.

However, it is true that silicon based technologies have received quite a lot of attention, especially for mobile applications where power level are not as important as in base station. The reasons for this interest are visible in figure 4.7. Even in the presence of better performing semiconductor III-V technologies, silicon technologies are going to remain in the forefront for designing of different mmWave circuits for 5G applications. Especially with technology like SOI that compete with the III-V material and offers better integration. RF performance of an integrated circuit will not only depend on the individual performances of the components, but also the quality of the back-end-of-line (BEOL). The constituted low-pass filters due

to parasitic resistances and inductances of metal lines and vias along the interconnections and capacitances between different layers limit the operational frequency of ICs [53].

4.2.3 Existing Technologies

To conclude this part about the mmWave switch and the mmWave FEM in general, the first commercial proposition is analyzed. In July 2018, Qualcomm released the first ever mmWave chipset. It consists in the Snapdragon X50 (5G modem), capable of simultaneously communicate with multiple QTM052 antenna modules. The QTM052 consists of 1 or multiple an-

tenna arrays but also includes first System on Chip integration of the front-end and power management. The QTM052 covers three 5G bands, handling up to 800 MHz aggregated carrier bandwidth in the 26.5 to 29.5 GHz band and covering the entire 27.5 to 28.35 GHz band and the entire 37 to 40 GHz band. It supports advanced beam forming, beam steering, and beam tracking technologies, drastically improving the range and reliability of mmWave signals. An other report [102] on it says that transceiver appears to contain the entire front end with LNA's and PAs in CMOS but also phase shifters, hybrid couplers. Power requirement at mmWave frequencies allow for PA's to be fabricated in CMOS which will allow integration into an SoC. There were no separate GaAs PA's.

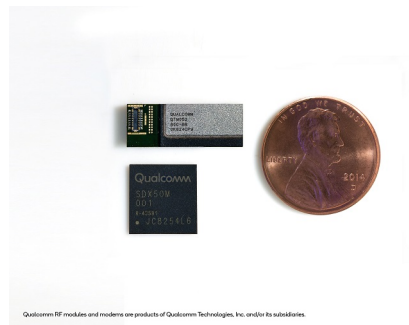


Figure 4.8: Qualcomm Snapdragon X50 and QTM052.

Since, they already reveal in 2019 the second version the chipset with the 5G modem Snapdragon x60 and the antenna modules QTM525

Device	Band [Ghz]	Technology	Topology	IL [dB]	ISO [dB]	CP1dB [dBm]	Size [mm^2]
[103] 2008	[10-28]	130nm CMOS triple-well	Series-Shunt	<2.6	>21	25.5 @ 28GHz	0.015 ^c
[87] 2010	[DC-60]	90nm CMOS	Series Traveling-Wave	<3	>48	17 @ 20GHz	0.5916 ^c
[94] 2011	[DC-70]	90nm CMOS	Series-Shunt Elevated series stubs	<3.5	>18	n.a.	0.07567 ^p
[104] 2013	[17-100]	65nm CMOS triple-well	Shunt Traveling-Wave	<2.8	>20	17 @ 35GHz	0.42 ^p
[105] 2014	[30-45]	130nm CMOS	Shunt with matching	2.7-3.7	33-50	8 @ 35GHz	0.0288 ^c
[80] 2018	[25-39.5]	65nm CMOS	Series Series-Shunt	<1.5 <1.9	>10 >20	12.55 @ 28GHz 7.25 @ 28 GHz	0.009 ^c 0.01 ^c
[106] 2019	[25-30]	65nm Triple- Well CMOS	Asymmetric	<1.16 <1.1	>16.4 >27	5.2 @ 28GHz 31.8 @ 28 GHz	0.043 ^c

Table 4.2: Bulk CMOS Ka-band switches

Device	Band [Ghz]	Technology	Topology	IL [dB]	ISO [dB]	CP1dB [dBm]	Size [mm^2]
[81] 2013	[DC-60]	45nm CMOS SOI	Series-Shunt with matching	<2.5	>23	7.1 @ 45GHz	0.04 ^c
[92] 2014	[DC-40]	180nm SOI HR ($\approx 1k\Omega cm$)	Series-Shunt with matching	<2	>15	11 @ 28GHz	0.0252 ^c
[90] 2015	[DC-50]	130nm SOI HR ($> 1k\Omega cm$)	Series-Shunt with matching	<1.9	>27	12 @ 30GHz	0.0399 ^c
[93] 2017	[DC-50]	40nm CMOS SOI	Asym. Tx Rx	<3.64 <3.2	>15.8 >10.1	20 @ 10GHz	0.462 ^p
[107] 2017	[DC-50]	130nm HR TR SOI	Series-Shunt with matching	<2.1	>27	>10.5	0.04066 ^c
[91] 2018	[DC-30]	45nm RFSOI TR	Series-Shunt	<1.2	>20	29.5 @ 14GHz	0.04 ^c
[83] 2020	[24-31]	65nm CMOS SOI	Series-Shunt	<1	>20	19.5 @ 28GHz	0.0024 ^c

Table 4.3: SOI based Ka-band switches

Device	Band [Ghz]	Technology	Topology	IL [dB]	ISO [dB]	CP1dB [dBm]	Size [mm^2]
[108] 2009	[30-40]	AlGaAs PIN Diode	Shunt $\lambda/4$ section	<0.8	>30	40	2.64 ^p
[82] 2016	[26-33]	AlGaAs PIN Diode	Series-Shunt	<1	>35	>31	2.95 ^p
[89] 2018	[0.01-70]	GaAs PIN Diode	Series-Shunt	<2	>10	25.2 @ 2GHz	0.4218 ^p

Table 4.4: PIN diode based Ka-band switches

Device	Band [Ghz]	Technology	Topology	IL [dB]	ISO [dB]	CP1dB [dBm]	Size [mm^2]
[109] 2013	[27-31]	GaN/SiC HEMT	Shunt with $\lambda/4$ section	<1.3	>25	49	1.539 ^p
[110] 2015	[30-40]	150nm GaN HEMT on SiC	Series-Shunt with matching	<2	>26	39 @ 35GHz	n.a.
[111] 2019	[33-39]	100nm pHEMT GaN/Si	Series with Inductors	<1.1	>22	39	4.5 ^p
[112] 2019	[28-51]	100nm GaN HEMT on SiC	Shunt with $\lambda/4$ section	1.4-2	23.5-27	>29 @ 75GHz	1.25 ^p

Table 4.5: GaN based Ka-band switches

Device	Band [Ghz]	Technology	Topology	IL [dB]	ISO [dB]	CP1dB [dBm]	Size [mm^2]
[113] 2015	[17-31]	GaAs from MACOM	n.a.	<1.6	>30	24 @ 24GHz	9
[84] 2017	[35-70]	100nm GaAs pHEMT	Traveling-wave	<2.9	>40	20.2 @ 31GHz	0.96 ^p
[79] 2017	[24-27]	70nm GaAs mHEMT	Shunt Series-Shunt	<1.5 <2	>50 >39	n.a.	3 ^p
[86] 2019	[36-38]	150nm GaAs HEMT	Traveling-wave	<3.2	>28	12 @ 37GHz	1.1 ^p
[85] 2020	[33-44]	150nm GaAs pHEMT	Shunt with radial stub	<2.5	>30	>24	2 ^p

Table 4.6: GaAs based Ka-band switches

Device	Band [Ghz]	Technology	Topology	IL [dB]	ISO [dB]	CP1dB [dBm]	Size [mm^2]
[114] 2012	[8-40]	200nm SiGe HBT	Series- Shunt	1.6-4.3	20.3-58	10 @ 10GHz	0.1968 ^c
[95] 2016	32	120nm SiGe HBT	Series LC resonant	3.3	21.8	16	0.2427 ^c
[115] 2016	[14-94]	55nm SiGe BiCMOS	Shunt $\lambda/4$ section	<2.6	>22	14 @ n.a.	0.28 ^c
[116] 2018	[20-32]	130nm SiGe BiCMOS	Shunt and Lumped	<2.7	>21	>17	0.1188 ^c
[117] 2020	[20-60]	130nm SiGe BiCMOS	Shunt $\lambda/4$ section	<3	>22.5	18 @ 32GHz	0.194 ^p

Table 4.7: SiGe based Ka-band switches

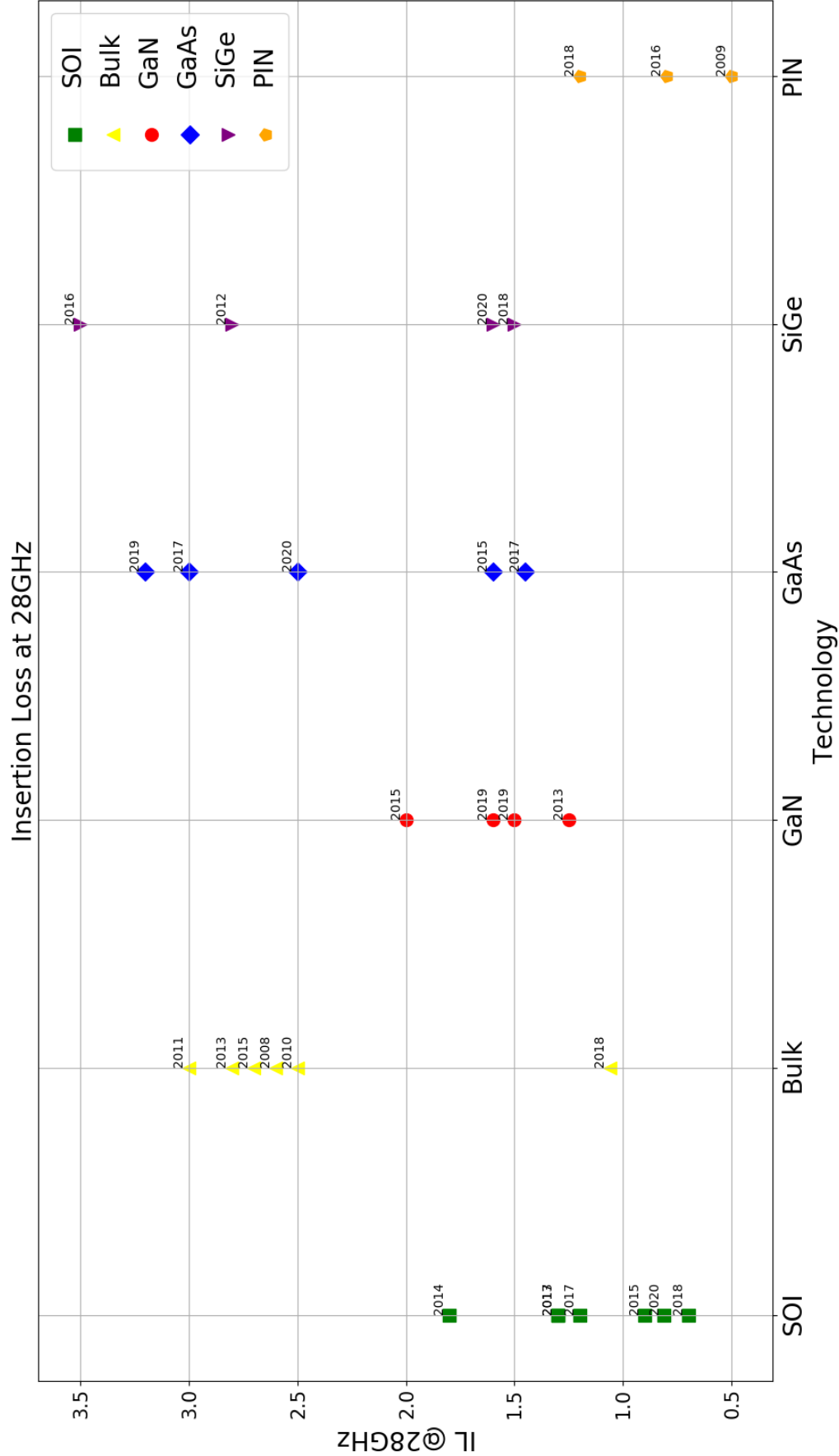


Figure 4.9: Insertion Loss of analyzed switches at 28GHz

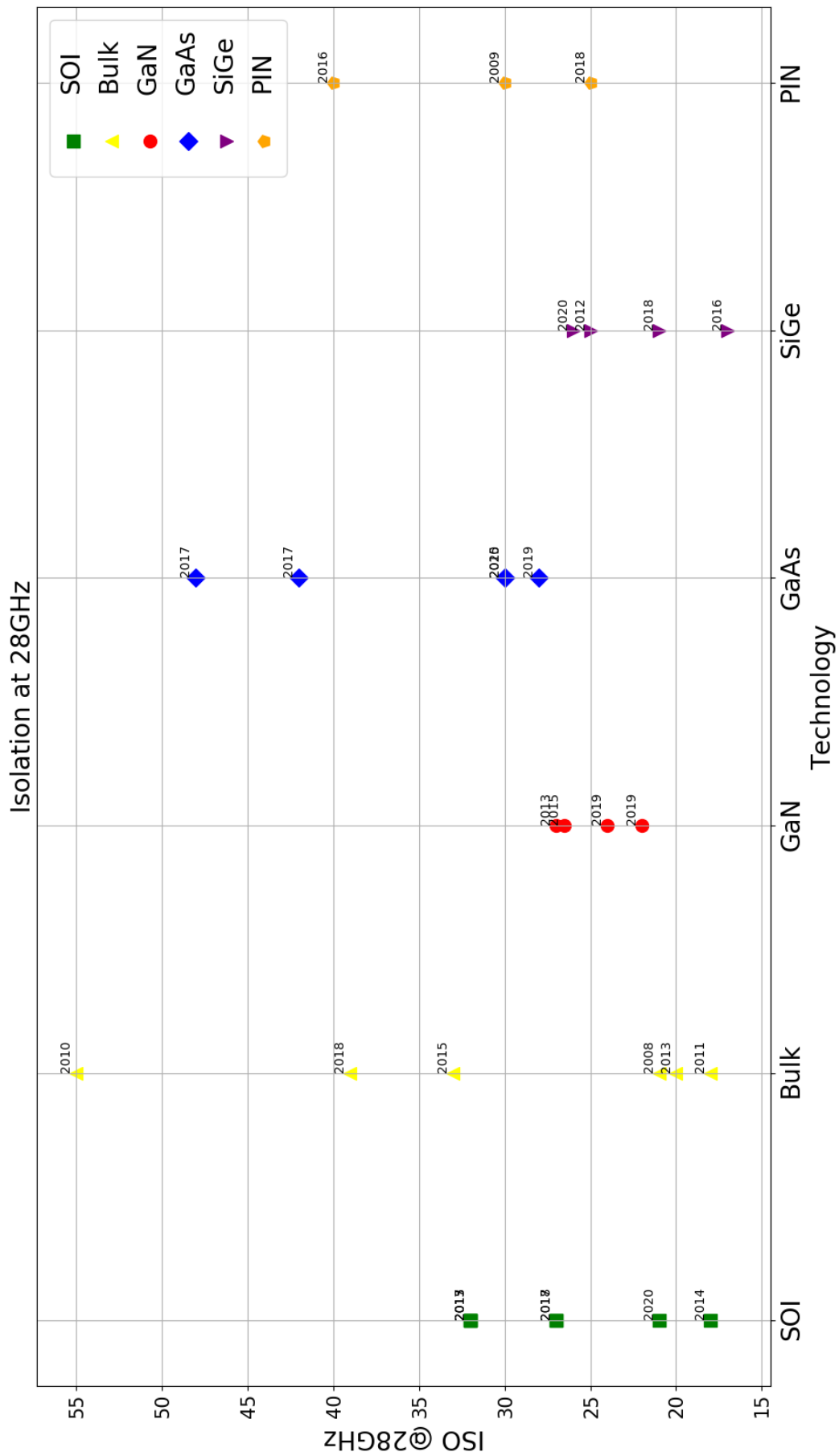


Figure 4.10: Isolation of analyzed switches at 28GHz

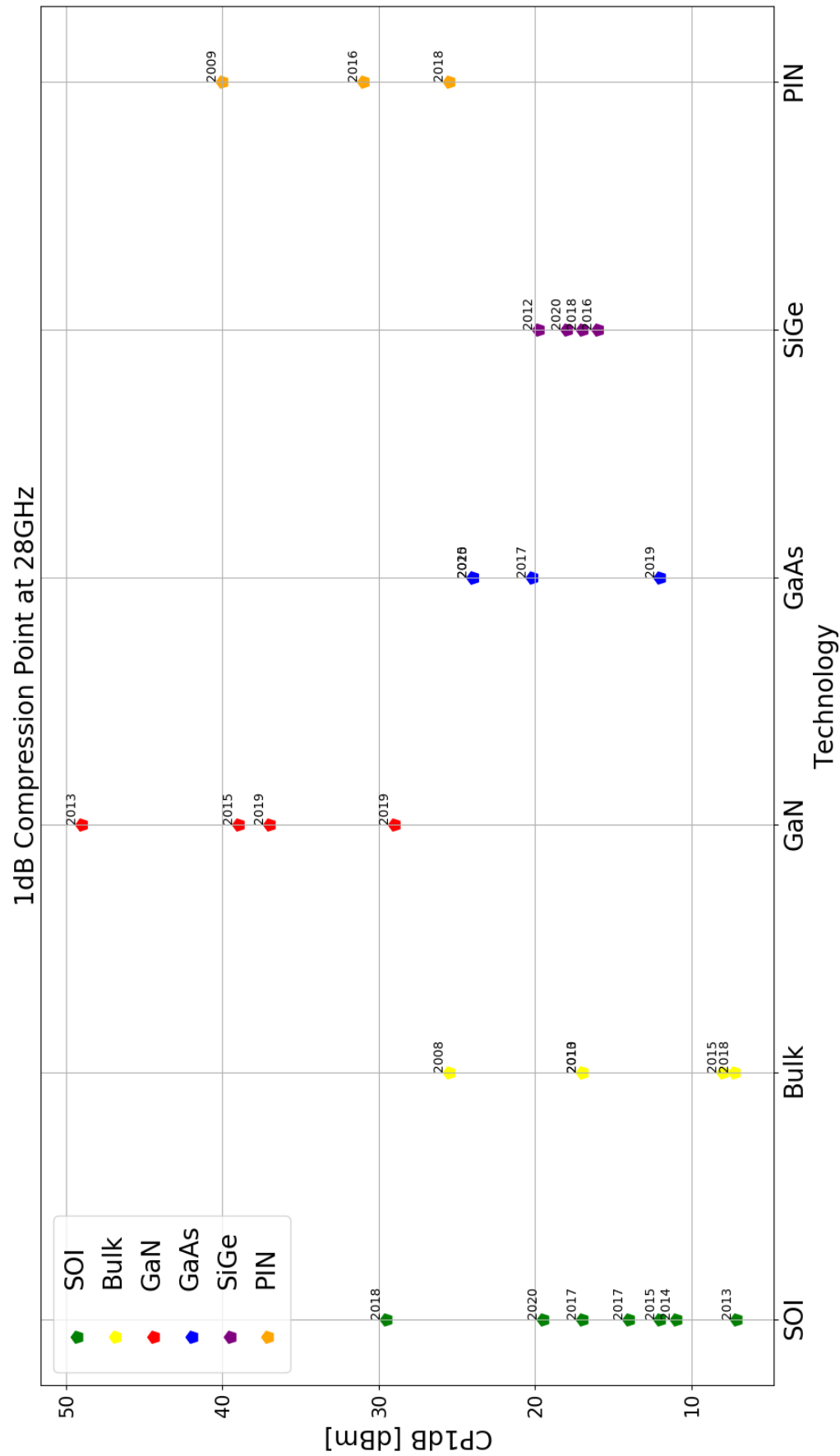


Figure 4.11: 1dB Compression Point of analyzed switches at 28GHz

CHAPTER 5

SUSTAINABILITY ANALYSIS

As explained in the introduction now that the classical benchmark with parameters as insertion loss, isolation and power handling capability has been made, it is time to take a step back from these 5G technologies to look at other FoMs, regarding the environment, the society and the economy. As the first part was mainly focused on mmWave applications, the same subject will be treated here. The chapter focuses on the impact of the deployment of mmWave systems and indirectly 5G in everyday life with a holistic approach based on different axes. The RF switch being an interesting topic but hardly transposable to all the different sectors coming.

5.1 Sustainable Development

As quoted in the introduction from the Brutland report, Sustainable Development is :

"[the] development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [7].

The goal of the report was to highlight and provide solutions regarding the danger of environmental degradation, economic instability and social inequality. However, the definition of Sustainable Development has been criticized for its vagueness and practical approaches [118]. To simplify the approach and clarify it, the concept of Sustainability has been broken down into the 3 axes, 3 pillars or triple bottom line: Prosperity (Economic), Planet (Environmental) and People (Social), visible at figure 5.1 [2]. Each category can be unpacked to be more specific:

- **Environmental pillar:** Atmosphere, land, fresh water, oceans, bio-sphere, material and energy resources.
- **Economic pillar:** Built environment, Industrial capacity, Financial health, GDP.

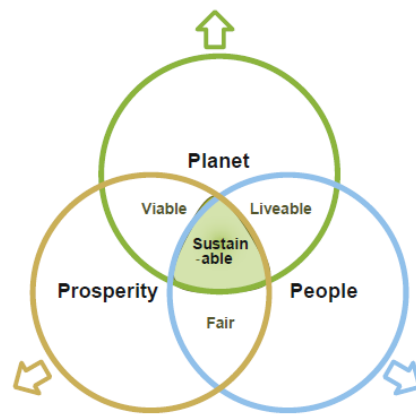


Figure 5.1: 3 pillars of Sustainability

- **Social pillar:** Education, health, skills, knowledge, happiness.

The 3 axes are of course interconnected and influence each other. Following this concept, a sustainable world would be a world where the 3 pillars are evenly considered in the decisions of any activities, organizations, technologies, However, even if the concept has received increasing attention over the past 20 years, see figure 5.2, the economical aspect always seems to dominate the debate to such an extent that social and environment concerns are often considered as secondary compared to the goal of a constant "growing" economy.

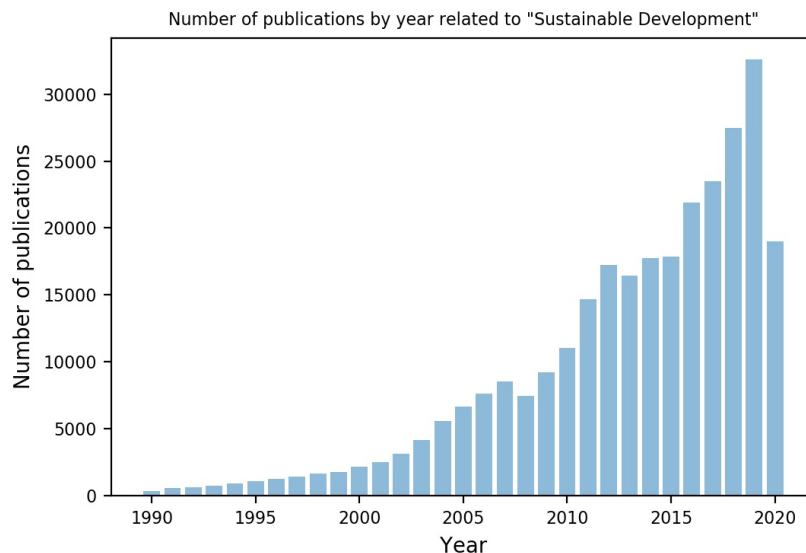


Figure 5.2: Evolution of the number of publications related to "Sustainable Development"

The current situation could be represented with the following diagram in figure 5.3 where the financial arguments overpower the social and environmental ones. However, objective of a sustainable development is the economic sustainability through making financial profit, social sustainability through reducing the negative effects of economic activities on people and environmental sustainability through decreasing pollution and green House Gases (GHG)

emissions. It is also possible to compensate for negative effects on the two last pillars by making actions that will have a positive impact on the people and the planet.



Figure 5.3: Caption

5.1.1 Semiconductor Industry and Sustainable Development

The Electronic industry is one of the main industry on the global market today. The Electronic sector is vast and diversified. One of the main driving forces behind it is the semiconductor industry which has never stop to evolve since its beginning in the 1960's.

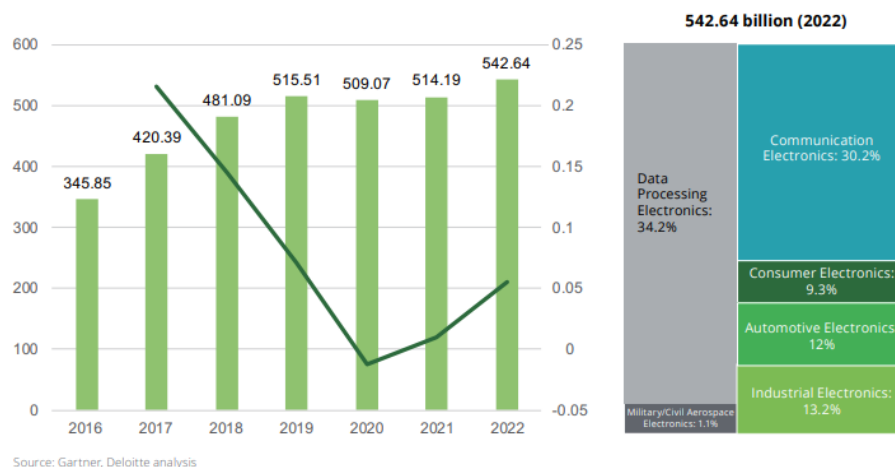


Figure 5.4: Annual revenue of semiconductor industry in billion \$

The performances of the semiconductor industry is globally nuanced. Indeed, on one hand, the economic of the semiconductor sector is thriving, as visible in figure 5.4 [119], with 5151.51 billion \$ of sales revenue in 2019 an offered around 6.6 million jobs around the world in 2012 [120], which can also be considered as a good performance on the social pillar. On the other hand, there are four main negative impacts of the semiconductor industry on the environment: pollution in manufacturing plants, depletion of raw materials, electricity consumption during use and accumulation of electronic waste (called e-waste). And also, to a lesser extent, the

little interest in quantifying the impact of all the process on the environment. However, it should be noted that the electricity consumption during use is way smaller compared to the energy used to make the final product, especially for small electronic devices. Let's take the example with the report of Apple on its carbon footprint to produce one Iphone 11. In [121], the company claims to that the production of one Iphone 11 has a carbon emission of 72kg, from which 79% Production, 3% Transport, 17% Use, <1% End-of-life processing.

5.2 Holistic Approach

This work is not going to follow each step in the Ashby's method [2], but step 3 of his method is quite interesting since it lays the foundations for the holistic approach with 6 specific axes. Those axis are visible on figure 5.5. Impact on legislative, economic, social, environmental, energetic and materials sectors will be reviewed. Each axes will not be developed as intensively as the energy, materials or environmental axes but they are also important since they participate to give the big picture of the problematic.

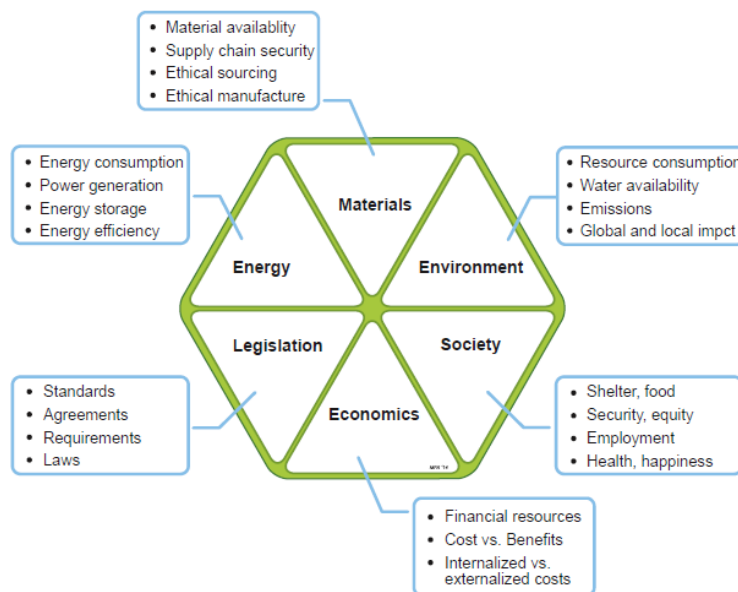


Figure 5.5: 6 majors sectors generally involved in sustainable development.

5.2.1 Economics

mmWave frequency means shorter ranges, as it was explained in chapter 2. This leads to a densification of the network. With 3G and 4G, the lower frequencies enable longer ranges: 2km (cities) up to 30km (rural) and therefore, "macro" cell is possible. With mmWave, the ranges are reduced, 20 to 200m is typical for indoor and outdoor use. In order to avoid the "not-spots" in cell, repetition of antenna every 20m should be installed. This equals 800 base stations per square kilometer in the worst case scenario. If antennas repeated every 200m, the number

of base stations per square kilometer drops to 8. Following [122], expecting a deployment between 100 and 350 small cells per square kilometer (indoors and outdoors) is a more plausible solution. It is then easy to understand the huge costs implied with the mmWave system because of this investment. A 2017 briefing from European Commission acknowledges the importance of 5G in world competitiveness and is ready to invest in public/private partnership with € 700 million EU capital, topped with 3.5 billion of private investment in 2025. The path to 5G, including all the technical specifications and standards, represents one of the most complex evolution that the mobile industry has undertaken to date [123]. Another study ran by the European Commission established that 500 billion in total to bring all 5G elements to life by 2025. The deployment of small cells to ensure the 1 Gbps for 100% coverage will be quite expensive, they estimate that the standalone cost of the modeled small cell deployment will be around € 119 billion. In the model, they precise that the estimation is correct if the following conditions are met:

1. The unit cost of a small cell fall to € 1000.
2. Around 50% of cells will be connected via a wireless connection and so, only half of small cells will need fiber connections (which increases the deployment cost).
3. Operators are able to share the small-cell infrastructure so only one network can be deployed and not one personal network for each telecom operator.
4. The radius of each small cell is at least 200 meters. Having a radius of only 100m could increase the cost by 98% from the current estimation.

But on the other hand, the gigabit society is expected to bring huge revenues. The investments triggered by the new framework could boost the EU's gross domestic product (GDP) by an additional € 910 billion and create 1.3 million new jobs by 2025 [124]. From 2025, benefits could also reach € 113.1 billion per year in four key sectors (automotive, health, transport and energy) since they are the first users of 5G connectivity. Other more optimistic studies [125] even estimate that 2.3 million jobs would be created by 2025 with 5G. One should also consider the fact that 58% of the EU's population live in rural areas whereas urban areas are better suited to the roll out of fast speed infrastructure, rural areas do not have the same infrastructure deployments and expected returns on investment given the relative lack of customers in such areas.

Regarding the technology, working with CMOS technology is the most cost effective choice. It is the most widely used technology, the more mature and because silicon is the second most abundant element in earth crust, there is little risk of supply chain problem. Price for wafer !!

5.2.2 Society

The positive sides like increased data rates, better coverage, connected devices and other benefits have already been cited in the first chapter of the work. Let's instead talk about the

controversial parts: the physiological and biological effects of electromagnetic waves on the human body and especially the mmWave frequencies.

Some citizens, students or PhD's have raised their voice against the deployment of 5G [126] in Belgium. They ask for more testing on health and environmental aspects.

A recent study of the National Institutes of Health called the National Toxicology Program (NTP) [127] showed the harmful effect from cell phone microwave radiation in general and not especially for mmWave frequencies. The study was undertaken over 2 years. The preliminary results show that exposure to RF radiation, at 900MHz, due to cell phone use was associated with: "Clear evidence of tumors in the hearts of male rats. [...] Some evidence of tumors in the brains of male rats. [...]. Some evidence of tumors in the adrenal glands of male rats. [...]". It was unclear if tumors observed in the studies were associated with exposure to RFR [Radio Frequency Radiation] in female rats (900 MHz) and male and female mice (1900MHz)". They also noted DNA damage significant increases in frontal cortex, the blood cells of female mice, and the hippocampus of the subjects animal. The NTP plans to conduct more studies around mmWave spectrum.

For higher frequencies, the wave does not penetrate as much as lower frequency wave. The effect to consider is more a heating effect of the skin and the dermal tissues. Indeed mmWave are well absorbed by water and heat the tissues around. In [128], it is precised that more than 90% of the transmitted power is absorbed by the epidermal and dermal layers. Because the depth is so superficial, higher heating occurs more quickly with less dissipation. It affects the skin surface, the surface of the eye or bacteria, plants and small life forms. Surface effects can be quite important on an organism as stimulation of skin receptors can affect nerve signaling causing a whole body response with physiological effects on heart rate and the immune system [129]. This absorption is characterized by the Specific Absorption Rate (SAR) in W/kg . The lower the SAR, the better because it means that the tissues receive less energy. Some authors, like in [130], try to consider this phenomenon when designing specific beamforming array antenna with reduced value of SAR. But, attention is not drawn to this parameter in general array antenna design. SAR metric depends on the type of tissue, the tissue orientation but also effects of other objects in the field near the exposed body.

Other study also shown the influence of mmWave on heart rate variability on anesthetized frogs [131] and [132] found certain frequencies from 53-78 GHz band (continuous wave signal) changed the natural heart rate variability in anesthetized rats. He showed that some frequencies had no effect (61 or 75 GHz) while other frequencies (55 and 73 GHz) caused pronounced arrhythmia. There was no change in skin or whole body temperature. The sensitivity to antibiotics was also questioned in [133]. Formation of cataracts in rat eyes was noted in [134] and [135], authors looked at gene expression in keratinocytes with 60GHz exposure at upper limit of current guidelines and concluded "In our experimental design, the high number of modified genes (665) shows that the ICNIRP current limit is probably too permissive to prevent biological response". The keratinocytes are the cell that represent 90% of the skin.

More recently, in 2018, authors in [136] reviewed articles on the biological and health effects of electromagnetic wave (EMW). After going through the different implications (cancer, re-

productive effects, metabolic effects, neurological effects and microbiological effects) of the electromagnetic waves in general, they do not focus especially on mmWaves but rather on their dense deployment. Because of high density networks of small cells, a proliferation of devices is expected. This will increase chance of human exposure to RF Electromagnetic Waves (RF-EMW). Moreover, mmWaves systems will operate in parallel with current mobile systems, at least at the beginning, with an unavoidable global increase in the exposure level. They conclude the review with "Evidences about the biological properties of RF-EMW are progressively accumulating and, although they are in some case still preliminary or controversial, clearly point to the existence of multi-level interactions between high-frequency EMF and biological systems". Also precisizing that further tests need to be conducted regarding mmWave to fully understand the health effects and underestimating the relevance of available results is not ethically acceptable. The precautionary principle is then applicable.

However other study [137] found that "There was no consistent relationship between power density, exposure duration, or frequency, and exposure effects. The available studies do not provide adequate and sufficient information for a meaningful safety assessment, or for the question about non-thermal effects.". On the contrary, they said that "higher power densities do not cause more frequent responses", considering a response rate of 70 % in general. It should be noted that the study was mainly founded by Deutsche Telekom.

At the end, there are a large number of data from laboratory and epidemiological studies showing that previous and present generations of wireless networking technology have significant negative health impacts (around 50% of conducted studies have shown health impacts according to [138]). Moreover, much of this data was obtained under conditions which do not reflect the real-life conditions such as including the carrier frequencies and other toxic stimuli in combination with the wireless radiation. When superimposing the causes, harmful effects associated with wireless radiation are increased substantially. Adding mmWaves radiation on an already crowded toxic wireless radiation environment will increase the adverse health effects which were already proved to exist.

With all results in mind, A 5G appeal was presented to the United Nations in 2015, and to the European Union from 2017, with an increasing number of scientists' signing (as of August 10, 2020, 398 scientists and medical doctors have signed the appeal.). The appeal recommends a slowdown on the deployment of 5G for telecommunications until potential hazards for human health and the environment have been fully investigated by scientists independent of industry. EU responded two times by saying their current exposure limits set by the European legislation remain valid but also that the recourse to the EU's Precautionary Principle to stop the distribution of 5G products appears too drastic a measure [139]. At the end, they precise that the protection of population from negative effects of RF-EMW remains with the Member States. In Belgium, the limitation of EMF exposure of the general population is a matter for the three regions. For example, Wallonia applies the EU limits and Flanders applies a stricter policy (10 % of the reference level in the EU recommendation).

5.2.3 Legislation

5.2.3.1 Radiation and Safety

The absorption of Electromagnetic Waves (EMW) is characterized by the Specific Absorption Rate (SAR) in W/kg . Between 100kHz and 10 GHz, the SAR is used as physical quantity to limit the exposure. However above 10 GHz, the power density in W/m^2 is used because at higher frequencies, energy absorption is increasingly confined to the surface layers of the skin, and it is difficult to define a meaningful volume for SAR evaluation [140]. However, evaluations based on the power density explain only the power traveling toward the tissue and do not explain the power absorption and field distribution in the tissues. So, power density is not considered useful to measure exposure in the near field at mmWaves, and SAR and temperature elevation techniques are used to study exposure at mmWaves frequencies in [141]. The ICNIRP is the International Commission on Non-Ionizing Radiation Protection and they specify basic restrictions on power density to be $10 W/m^2$ and $50 W/m^2$ for the general public, and the occupational group, respectively, for frequencies between 10 and 300 GHz. In Europe, the limit defined by the Commission is also of $10W/m^2$. These recommendations date from 1999.

5.2.3.2 European Proposals

In order to help with the 5G deployment, the European Commission has proposed three legislative proposals and one non-legislative measure to reform the actual regulatory framework of communications in EU:

- New European electronic communications code (ECC) that will review the current EU telecommunications framework dating back to 2009 so as to increase investments in infrastructure. It also includes simplified rules to make investing more attractive for companies.
- Wifi4EU, of which the goal is to increase the number of free public Wi-Fi internet access points for citizens, to help with reaching the new connectivity target.
- Updated regulation on the Body of European Regulators of Electronic Communications (BEREC). This would reinforce BEREC's role with national regulatory authorities.
- The non-legislative measure is a 5G action plan to give the main directive lines for all the member states.

5.2.3.3 Infrastructure Share

Due to the large densification of the network and proliferation of small cells, it would be impossible that each network operator possesses its own network. First for economic reasons established previously and second because of space restriction. With mmWaves, the competitors would share the same hardware resources but have their own "virtual networks". This

concept raise some concerns regarding the funding and maintenance costs. How will these costs be legally divided between the network operators? What will be the legal framework surrounding the shared use of the small cells, like property?

5.2.4 Energy

If 5G and mmWaves are deployed with the same energy tactic as previous generations, the energy consumption of mobile network will increase drastically along with the traffic demands. Indeed, the dense network and proliferation of small cells mean more devices to power up, more energy to provide. Energy consumption in a small cell is much lower than in a conventional cell but in the same time, they will be more frequently implemented. More frequency bands also need to be handled by the base station meaning more hardware components per base station. Power-hungry transceiver chains and complex signal processing techniques are required. Chinese giant Huawei has estimated an increase between 300 % to 350% when deploying 2.6GHz, 3.5GHz and mmWave bands as visible in 5.6 [142].

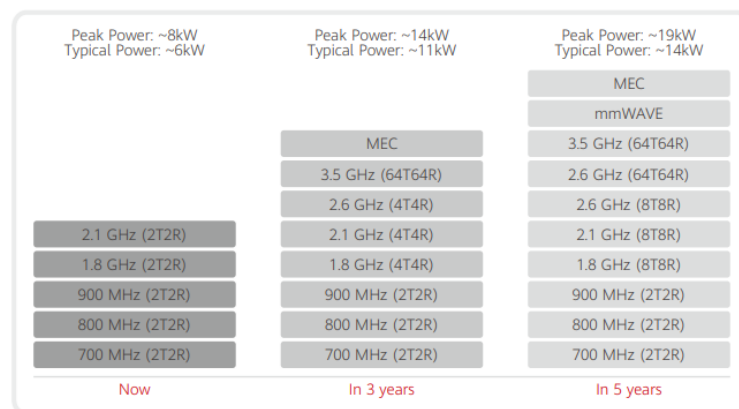


Figure 5.6: Increase of power consumption with mmWaves deployment in base stations.

An other paper [143] estimated that by 2030, the percentage of global electricity usage due to communication technology will increase from 10% in 2010 to 51% unless the electricity efficiency of wireless network and data center is sufficiently improved. This roughly equals an increase from 2500 TWh to 30000 TWh. In that specific worst case, ICT would be responsible for 23 % of the total carbon footprint by human activity. In figure 5.7, 3 different scenarios are considered. The difference here lays in the annual energy efficiency improvement, 30% (best), 22% (expected), 10% (worst).

In the light of this, designing energy-efficient 5G networks is critical and necessary and therefore, people start to investigate the field of "green communication" [144]. The goal is still to roll out 5G but also reducing the energy consumption. It means for the operator networks to use as little energy as possible while managing expected growth in data traffic. Another motivation is also the need to reduce energy cost and save money on OPERational EXpenditure

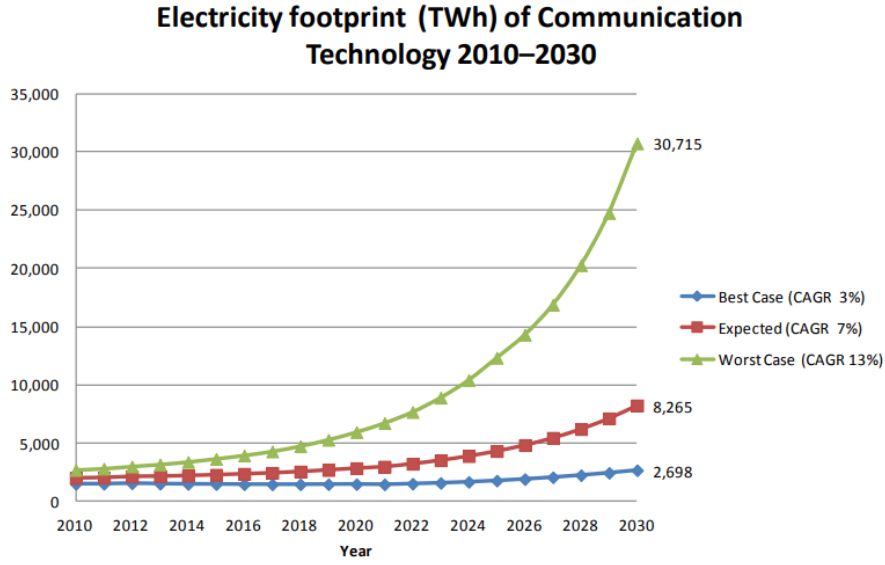


Figure 5.7: Global electricity demand of communication technology 2010–2030

(OPEX) for network operators. To quantify the performances of a communication system, two main parameters have been used: the Spectral Efficiency (SE) and it is defined as:

$$SE = K \times B \times N \times \log_2(1 + SINR(d)) \quad (5.1)$$

And the other important parameter for "green communications" which is the Energy Efficiency (EE) in bits/joule, defined as:

$$EE = \frac{K \times B \times N \times \log_2(1 + SINR(d))}{P_t + P_c} = \frac{SE}{P_t + P_c} \quad (5.2)$$

where K is the frequency reuse factor. This is the rate at which a group of radio channels or Frequency sub-bands can be re-allocated to a geographic area or a cell. To avoid cells interference, different sub-bands need to be used for adjacent cells. The higher the frequency reuse factor, the more efficient because the total band is not divided into too many sub-bands and thus higher capacity of the network. Sometimes K is also noted $1/K$, because one over K cells can have specific frequency sub-bands. B is the total bandwidth of the signal. N is the number of spatial beams (spatial multiplexing factor). d is the single link distance and $SINR$ is the signal-to-interference-plus-noise-ratio which is decreasing with d . P_t is the consumed transmit power and P_c is the power consumed by the circuit. The trade-off between SE and EE appears when one wants to increase the SE by, for example, increasing the SNR with higher output power level. This will raise the SE but decrease the EE due to the increased P_c of the circuit. There are various distinctive approaches to reduce/optimize energy consumption in a mobile cellular network. Approaches can be broadly classified into the following five categories according to [145] and [146]:

1. Improving energy efficiency of hardware components.

2. Turning off components selectively.
3. Optimizing the radio transmission process.
4. Planning and deploying heterogeneous cells.
5. Adopting renewable energy resources.

5.2.4.1 Hardware Solutions

The first approach goal is to optimize the power efficiency inside the hardware components. The biggest energy consumer of a cellular network is the base station with 57% of power consumed [147] and at the base station, the PA is the biggest energy-hungry component with between 50-80% of the total power consumption. This is visible at figure 5.8 [148]. This is logically the part where one wants to have the most efficient components. According to [148], the PA's efficiency has dropped for each generation due to higher Peak to Average Power Ratio (PAPR). Indeed, for each new generation, more complicated modulations have led to waveforms with higher PAPR. For these high PAPR signals, the power amplifier (PA) usually operates at a backed-off power level where the efficiency is degraded in order to avoid too high saturation when the peak levels come through [149].

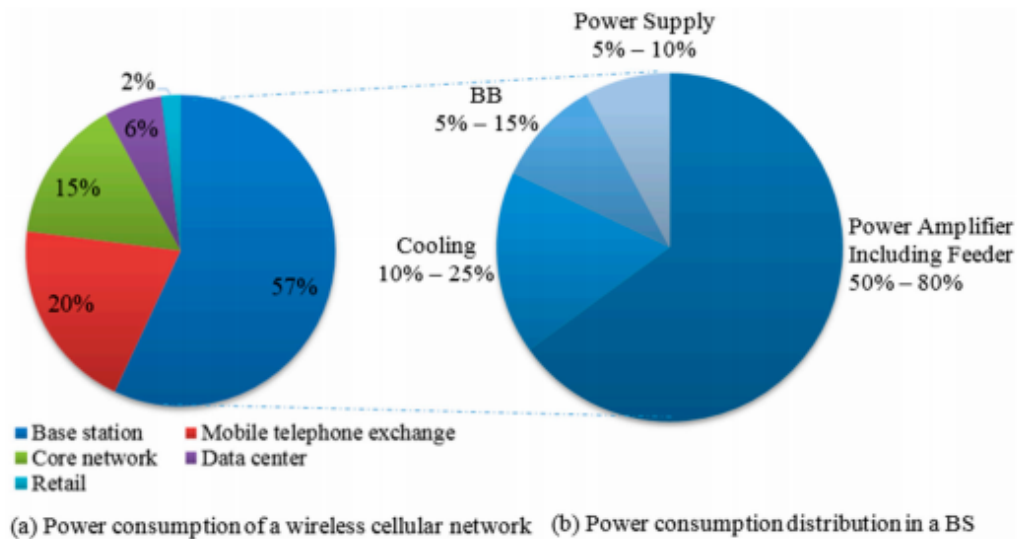


Figure 5.8: Caption

High power levels drive the PA in saturation mode where nonlinearity appears and nonlinearity introduces many undesirable effects such as harmonic distortion, gain compression, intermodulation distortion, phase distortion, adjacent channel interference [150]. So the PA needs to work at lower power level to prevent the non-linearities but this also means that the efficiency reduced. Developing high efficiency power amplifier while maintaining the linearity is the challenge. One can cite 3 largely used techniques to increase the PA efficiency: At the end-user's side, the radio module comes in second place (after the touchscreen) in the list

of functionalities that have the most impact on battery life [33]. This of course depends a lot on the operating mode (videos watching, phone calls, standby state, ...). For example, during a phone call the most energy draining component is the radio module, whereas, if a video is being played out, it is the display that consumes the most. It appears that the power consumption also depends a lot on the specific brand.

5.2.4.2 ON/OFF Solutions

The second approach consist of turning ON and OFF specific components of the transmission depending the data traffic demand. Figure 5.9 [151] shows the typical variation in data traffic load. We can see the large range of variations for the traffic load. It appears that cellular networks are designed to support traffic peaks (as for power amplifiers and the PAPR concern). The number of BS's and their capacity should be able to provide the require Quality of Service (i.e. good cover and high data rates) to the users even during the highest peaks of the data traffic. However, a non-negligible part of the day does not require high peak services, leading to an inefficient use of spectrum resources and to an excessive energy consumption. The idea is therefore to save energy by turning OFF (switching to sleep mode) and ON (active mode) certain parts of the network. This avoids the unnecessary energy consumption of underutilized components in the network. As BSs cannot serve any traffic when asleep, it is important to properly configure to switch between the modes to avoid service outage. This interesting approach cannot only be applied to PA's but also extended further in the network, to complete BS's cells for example [152]. This approach has received lots of interest because it uses the current network architecture and it is easier to test and implement.

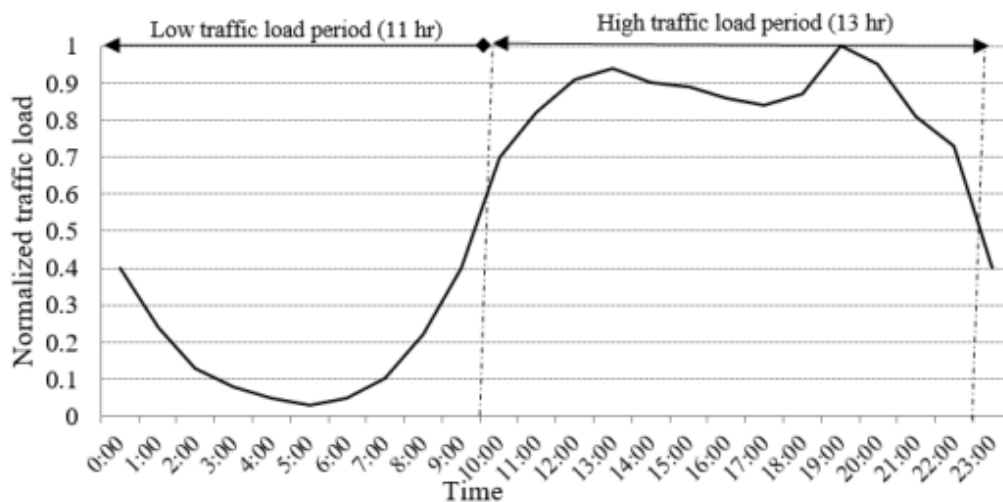


Figure 5.9: Daily traffic load pattern of a BS for a residential cell in week-end day.

Another idea is the concept of Cell Zooming. In this approach, a BS in HetNet can adaptively adjust its transmission power and consequently vary its cell size according to traffic fluctuations. The transmission power can be increased for cover more UE's in order to shut

down lightly loaded cells while maintaining coverage. One can also imagine a load balancing between highly to lightly congested BSs.

5.2.4.3 Optimization of Radio Transmission Process

The third concept aims to work on the radio transmission process. This refers to all the techniques, protocols used to transmit signal from one point to another without "collisions" between the users information. One of the main technique for mmWave is the MIMO techniques, that has already been introduced in the first chapter. Massive MIMO and beamforming are important factors in reducing the power consumption of base stations. Currently, the signals are emitted in all directions and therefore less efficient. With MIMO and beamforming, there is the channel efficiency, data rates, reduces interference and focuses radio energy directly at the client devices. This also reduces the minimum power required for operation and the power consumption for the base station as well for the user.

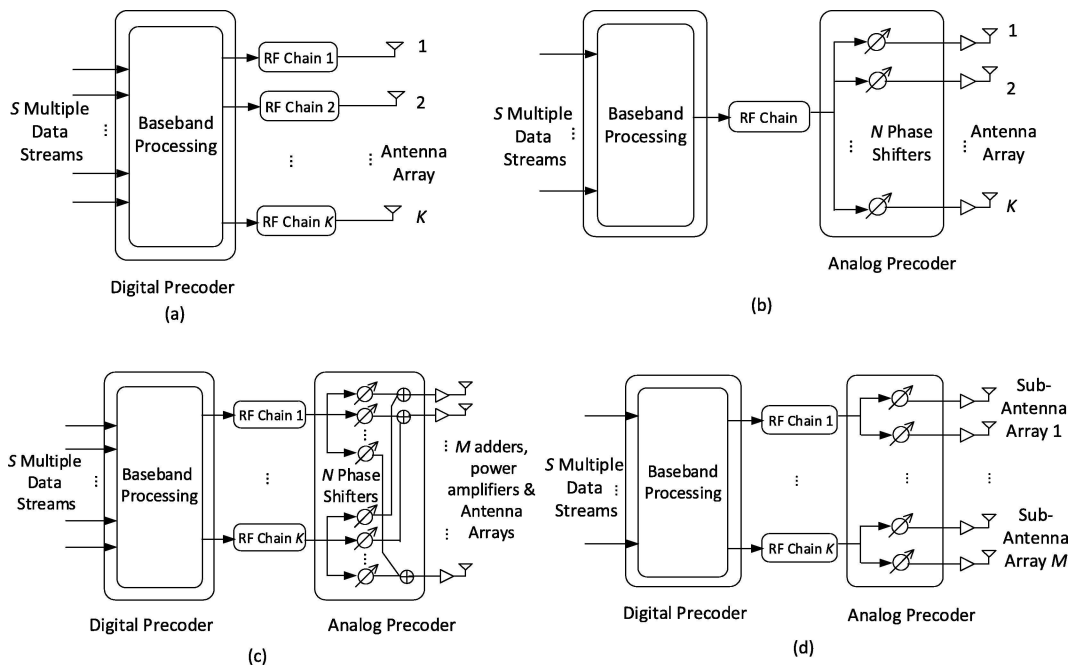


Figure 5.10: Precoders for mMIMO Systems (a) Digital precoder (b) Analog precoder (c) Fully-connected hybrid precoder (d) Partially-connected hybrid precoder.

Massive MIMO (mMIMO) is a scheme that took the concept of MU-MIMO to a next level by largely increasing the number of antennas (from 4, 8 antennas to tens or hundreds). Specifically, the number of Tx antennas largely exceeds the number of users (which is applicable mainly for small cells). This leads to very directive signals and low interference leakage. Because of the directivity of the beams, less power can also be utilized for transmission (not quite applicable for mmWave transmission). All of this leads to improvements in EE and SE [153]. For a practical implement of mMIMO it is important to consider the power consumption of the digital (computational) baseband units computation and the power of the RF unit. In [154], it is shown that both power consumptions increase with the number of antennas. Different

approaches are possible to implement beamforming: digital precoders, analog precoders and hybrid precoders (fully-connected and partially connected). These variants are visible in figure 5.10.

In digital precoders, each antenna is connected to a specific RF chain. This gives place to a full flexibility system where any signal can be sent to any antenna. This is the conventionnal MIMO architecture for frequencies below 6GHz [155] However, this technique is in practice hard to implement, especially for the mmWave frequencies. Firstly for space reasons: one RF chain by antenna means one PA's, LNA's, switches to be packed behind the antenna. Secondly, power consumption also limits this architecture: PA's and ADCs/DACs are power hungry components at mmWave frequencies and digital signal processing (digital conversion stage), with many parallel gigasamples per second data streams, also leads to excessive power consumption. In analog precoders, the beamforming is performed by using digitally controlled phase shifters. In this architecture, different antennas are connected via phase shifters to a single RF chain. Regarding size concerns, this is more feasible than the previous technique but one of the main drawbacks of this technique is limitation of single user and single stream transmission. It is not possible to benefit from the other benefits of MIMO. Plus phase shifters also occupy large areas. In hybrid precoders, the MIMO process is divided between analog and digital parts. In that case, S , the number of data streams is smaller than K , the number of RF chains also smaller than the number of antennas M . Two hybrid approaches are possible: fully connected where each RF chains is connected to each antenna and partially connected where each RF chain is connected to a subset of antennas. Having multiple subarrays reduces hardware complexity at the expense of less overall array flexibility. From [156], it appears that the first structure has a gain K bigger. However with practical $K = 4, 8$ the capacity loss is not significant and the structure complexity is much more lower for the partially-connected. The problem that the fully connected structure arises is also the power consumption with the large phase-shifting network. In [157], authors also analyse that fully-connected precoders lead to energy efficiency degradation as the PAs can not compensate for the power losses of the phase shifters. It also should be noted that alternatives to active phase shifting, with switches, were proposed in [155] to even further reducing the power consumption, at the cost of lower data throughput.

One last point to address is the good complementary between the small cells deployment and mMIMO. As small Cells suffer from backhauling problems and interference management. Intereference problem can be addressed with mMIMO though the high focused beams that cancel out the inter-small cell users. As backhaul refers to the portion of the network that makes the link between the core network and the small subnetworks, at the edge. Deploying wired backhaul in the context of dense small cells is complicated regarding the cost [158]. mMIMO could be a solution as wireless backhaul and serve the users at the same time.

5.2.4.4 Network Planning and Deployment

The fourth approach tackles the problem of energy by a deployment of small cells including micro, pico and femto cells, in the cellular network. The idea is to serve smaller antennas

with higher data rates. They serve as a complement for the macro base stations. Such a deployment is called a heterogeneous deployment or an Heterogeneous Network (HetNet). With the benefits of small cells such as low cost deployment, reduced load for macro BS's, improved indoor throughput, and low power consumption, also come the drawbacks such as increased complexity in network management and higher power consumption. Indeed, small cells consume less power, but since they will be more frequently deployed, if it is not carefully implemented, the consumption will certainly rise. And here for example, for small cells this is not the Power amplifier that is the most energy-hungry component but well the baseband and its going down the further the size and the range of the cell is decreased ...

5.2.4.5 Renewable Energy Harvesting and RF Energy Transfer

The last idea is to adopt renewable energy sources to provide power to the network. Compared to the actual main sources for electricity production such as which produce Green House Gases (GHG), wind and solar alternatives seem interesting regarding the environmental aspect. However these sources may not be sustainable since their production vary on climate conditions which can rapidly change over time and space. One practical method to avoid the inconsistency of renewable energies is to store the energy via fuel cells and batteries, but energy storage is quite costly to deploy and therefore the this approach is quite limited with BS's. Another solution to overcome this problem: the smart grid approach is considered. The distributed smart grid regroups different energy sources such as renewable and conventional energy which can be redistributed to the parts of the cellular network in need. The goal is really to continuously provide a QoS, no matter the availability of renewable energies. Another advantage of using renewable energy for the BS's in dense networks is the fact that the new BS's will not only compensate for the power consumption for themselves but also reduces the consumption in the power grid. In addition, a densified network also leads to more cooperation between the different BS's. For example, a BS sitting in a good spot (sunny or windy area), could either serve more users and extend its cell or transfer its superfluous energy to a BS situated in bad spot.

This concept of energy transfer raised some interests and in the same idea of getting the energy from different sources than conventional energy sources, the idea of Radio-frequency Energy Harvesting has emerged. This technique refers to harvesting energy from the radio signals over the air, thus enabling the recycling of energy that would otherwise be wasted. The different network components could share energy with one another. This seems to be a promising solution, especially regarding all the expected connected devices (IoT). One of the main advantages is of course the possible prolonged battery lifetime of components (for example the user's smartphone where the battery capacity is limited by the size, or small cells). In the literature, they are two main lines for exploiting the concept of Wireless Power Transfer (WPT). The first process is called Simultaneous Wireless Information and Power Transfer (SWIPT). It focuses on transmitting information and energy in the same signal, which of course raises problem regarding the cohabitation of information detection (ID) and energy harvesting (EH). Power splitting is reviewed in [159] as techniques to recover energy and information on the same signal. The power splitting technique divides the incoming RF signal into the classical

RF chain and the energy harvester. The main problem is the difference in power level between data communication power and power required for operating connected devices. In [160], the authors estimated that the first minimum power level is around 0dB and the second was just above the noise floor, above -120dB. In other words, this represents a 10^{12} power difference. The second process is called Wireless Powered Communication Networks (WPCNs) and consists of separating the energy harvesting and information over time. Specifically, the devices first received energy from a specific power station and then perform wireless information transmission with a classic BS with the harvested energy. This scheme needs careful optimization between the "energy" and "information" duration times.

An interesting point to consider is the "rebound effect". As mmWaves will bring higher data rates, people will consume more data. So at the end, the gain in energy efficiency is canceled by the consumer's behavior. In [161], they even say that "For every two steps forward we take with below-cost efficiency, rebound effects mean we take one or more steps backwards, sometimes enough to completely erode the initial gains made". The reasons behind this behavior are not well understood. One could think that because something costs less, people will start to use more intensively. Or perhaps doing something beneficial to the environment gives us "moral licence" to compensate with something less beneficial.

5.2.5 Materials

5.2.5.1 Need for critical raw materials

The problem was briefly introduced with the notion of European critical raw materials in the introduction. Let's clarify this concept now. The list, made by the European Commission, is updated approximately every 3 years (2011, 2014, 2017). Each time, the materials judged as economical and strategic important to the EU are added (some can also be removed) from the list. It is important to note that the definition only considers the economic aspect linked to the materials. More precisely, a raw material is determined as critical if [3]:

- They have a significant economic importance for key sectors in the European economy,
- They present a high supply-risk due to a large import dependence and/or the main extraction points are localized in particular countries,
- There is a lack of substitutes for the individual applications due to unique properties. The substitutes quality are characterized in terms of performance and cost.

These materials are of course closely linked to all the different types of industry: environmental technologies, consumer electronics, health, steel-making, defense, space exploration, and aviation. They are important to UE because they are involved in many supply chains and not only they participate to the high quality of life, through the growing number of materials used in today's consumer electronics but also because they are important for "clean" technologies as wind turbine, ...

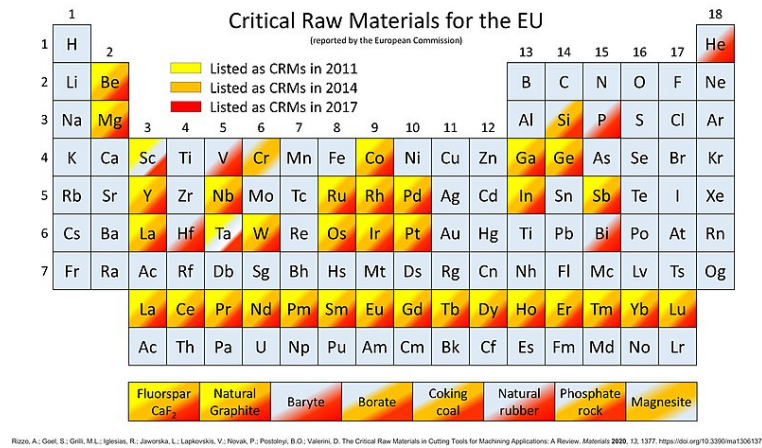


Figure 5.11: Critical Raw Materials for EU.

It is important to note that the materials are not only classified as critical because they are scarce but rather because they fulfill the previous criteria. The last list proposed 27 materials, visible in table 5.1 and figure 5.11 with HREEs=heavy rare earth elements, LREEs=light rare earth elements, PGMs=platinum group metals. The figure 5.12 gives more precision since one can see the supply risk and the economic importance of the materials. The economic importance is calculated from the valued added for the sector, the number of sector which need the resources and possible substitutions for the applications. The supply risk also depends on lots of factor as geo-political risks, legislative control risks, price volatility risk, ... But the Herfindahl-Hirschman Index (HHI) is a simple measure of the risk when the extraction, production of material is dominated by few nations, it shows the concentration of a product:

$$HHI = \sum_{i=1}^n f_i^2 \quad (5.3)$$

where f_i is the fraction of the worldwide quantity produced by a country i . The real supply risk in the report is of course more complicated by adding trading parameters, World Governance Index or recycling possibilities. The simpler HHI ranges from 0 to 1, 0 is the perfectly unconstrained supply and 1 is the value if only 1 country has all the production. Generally, a value above 0.25 shows a severe supply chain concentration. As we take the example of the Gallium in Europe and the database in [3], Gallium supply which is divide between China (36%), Germany (27%), United States (8%), Ukraine (6%), South Korea (5%), Hungary (5%), it gives:

$$HHI_{Ga} = \left(\frac{36}{87}\right)^2 + \left(\frac{27}{87}\right)^2 + \left(\frac{8}{87}\right)^2 + \left(\frac{6}{87}\right)^2 + \left(\frac{5}{87}\right)^2 + \left(\frac{5}{87}\right)^2 = 0.287 \quad (5.4)$$

which means a supply risk which needs to be considered [162].

It is important to note that the 3 of the main materials used to make RF switches, previously analyzed in the benchmark, are considered as CRMs. Precisely, from equation 5.3, the HHI_{Ge}

Antimony	Fluorspar	LREEs	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

Table 5.1: List of Critical Raw Materials for European Union

equals 0.37 and HHI_{Si} equals 0.2, which is consistent with figure 5.12 and the increasing supply risk assigned to Si, Ga and Ge progressively.

5.2.6 Environment

5.2.6.1 Impact on Wildlife

The impact on the human has been previously considered. In this part, the impact on the wildlife of mmWave is analyzed. Throughout the years, many studies were conducted to show the effects of EMF on the environment. A 2014 study [163] reviewed the literature for the frequency range from 10MHz to 3.6GHz. The analysis was divided into 5 groups: birds, insects, other vertebrates, other organisms, and plants. They found out that 50% of the animal studies and about 75% of the plant studies (about 2/3 of all the studies) were showing effects of EMF, both at high as well as at low dosages. No clear dose–effect relationship could be discerned. It is also precised that most of the studies were conducted in laboratory and not in a real ecosystems. From their work, the authors conclude that "The very low dosages are compatible with real field situations, and could be found under environmental conditions. However, a lack of standardisation and a limited number of observations limit the possibility of generalising results from an organism to an ecosystem level". An other study [164] investigated the impact of exposure of Insects to EMW from 2 to 10GHz. Humans and animals are similarly exposed to these fields, which are partially absorbed by their bodies. The absorbed dose depends on the frequency and as for the humans, the absorbed energy can lead to dielectric heating that may affect the insect behavior, physiology, and morphology. mmWaves have wavelengths comparable to the body size of insects means that the absorption of RF-EMws in insects is expected to increase. The researchers have numerically simulated the absorption of 4 types of insects: Australian Bee, European Bee, Locust and Beetle. The insects have different sizes, so they were first scanned and then 3D modelled. To quantify the difference in power absorption with frequency, authors first measure the average P_{abs} from frequencies below 6GHz. They then redo the measurement for frequencies above 6GHz. For the later frequencies, it is considered that 10% of the incident field is distributed over the frequencies above 6GHz. The intensity of the incident electrical field was 1 V/m. They found out that:

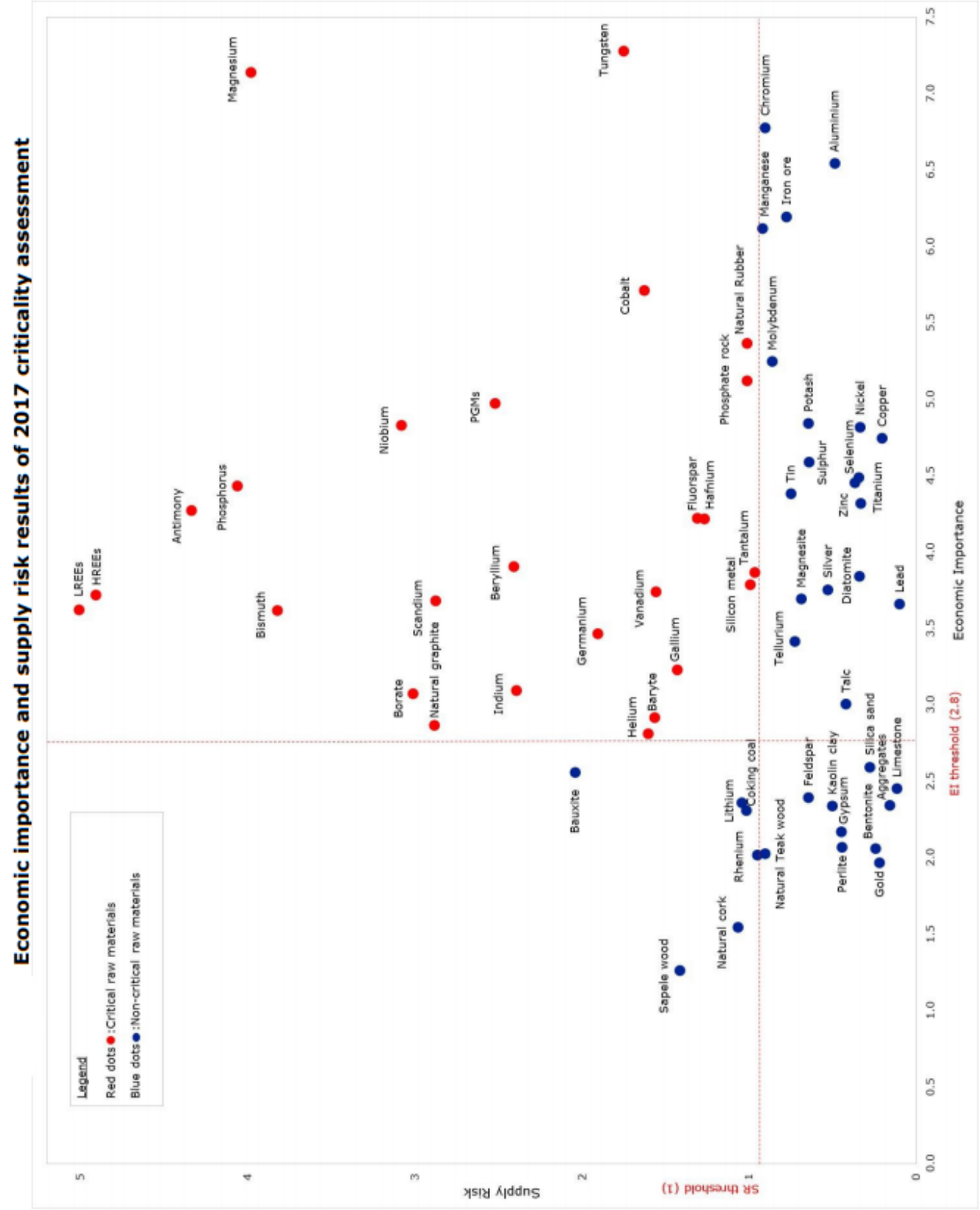


Figure 5.12: 2017 Economic importance and supply risk assessment of raw materials in EU in

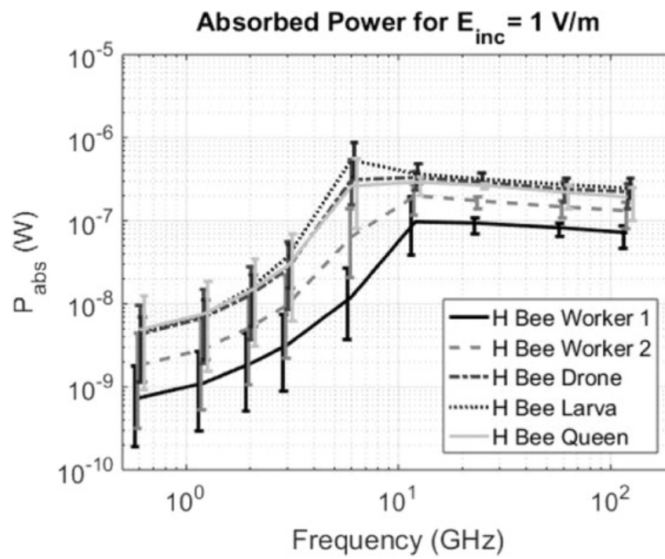


Figure 5.13: Absorbed power for different insects at different frequencies.

1. Australian Bee: 0.71 nW below 6GHz, 2.6nW above 6GHz or a increase of 370%.
2. Beetle: 2.6nW below 6GHz, 7.7nW above 6GHz or a increase 290%.
3. European Bee: 5.7nW below 6GHz, 14nW above 6GHz or a increase 240%.
4. Locust: 990nW below 6GHz, 1.0 μ W above 6GHz or a increase 3%.

The Locust, which was the biggest of the analyzed has an absorbed power which decreases slightly at the studied frequencies >6GHz, but remains higher than at 2 and 3GHz. This is due to its bigger body (55mm long) that resonates best with frequencies below 6GHz. The 3 other insects show maximum P_{abs} above 6GHz. This study clearly shows the negative effects due to higher absorption for insect even if the researches used a homogeneous dielectric simulation. A 2020 study [165] also investigated the impact of EMF from 0.6GHz to 120GHz and observed the same results (for different insects this time). The results are visible on figure 5.13 and one can easily observe the increase of absorbed power with the frequency. They also proposed measurements in real-life near beehives to get a realistic estimate of the exposure and absorbed power values. They observed that a relatively small shift of 10% of the incident RF field strength 0.06V/m from frequencies below 3GHz to higher frequencies will lead to a relative increase in absorbed power of a factor higher than 3.

Other studies show the impact on chicken eggs with higher mortality rate [166], the damages of EMF on trees [167] where burned or lesions were observed or the perturbations involved with the migratory birds' ability to orient themselves using the Earth's magnetic field.[168]. The previous works were exclusively conducted for frequencies below 6GHz and therefore not in the range of mmWave. Few studies have been conducted on the mmWave spectrum and its impact of ecosystems. But as for the humans, superimposing mmWave on the actual mobile spectrum will not reduce the actual proved impact of environment.

5.2.6.2 Electronic Waste

Electronic and computer industries are the historical customers of the microelectronic industry but lately, many new applications with electric and electronic devices have appeared and became common, like coffee machines, cars, medical applications, etc. integrate electronic functions. This leads to the increasing problem of electronic waste. E-waste is any electrical or electronic equipment that has been discarded due to replacement or defects. It is an important aspect to consider with the concept of sustainable development because of the negative environmental and social impact it has. In 2019, a record 53.6 Mt was generated worldwide (up 21% in 5 years) and the projection estimate 70Mt by 2030 mainly due to higher consumption rates of electric and electronic equipment, short life cycles, and few options for repair [169]. Worldwide, there is only 17.4% of the total e-waste recycled. The report from United Nations University estimates that these 53.6Mt represent 57billion \$ of raw material like copper, gold, aluminum but only 10billion \$ were documented, collected and properly recycled. Because of the European Legislation from 2003 that gives a legal framework for the handling of e-waste, the highest recycling rate is observed in Europe with 42.5% of its 12Mt recycled. The problem appears with the unrecycled rest, which is generally shipped to developing countries where the labor is cheap. Africa is the main destination for those e-waste along with some countries of Asia. According to [170], the e-waste end up in open dumpsites, notably in Ghana and Nigeria, where the problem is the most concerning. It is a very complicated task to monitor all the import of e-waste in Africa because reliable data statistic do not exist and there is also a important part of illegal import. [171] tried however to give an inventory of e-waste quantity in Nigeria, they estimate 60 000t/year were imported in the country (of which 46 000t comes from the EU and Belgium is the third biggest exporter with 5 700 t). The problem with these uncontrolled dumpsters is of course the pollution that arises from petrochemicals, glass, electrical and electronic components which are not biodegradable. In [172], the authors estimate the presence and the concentration of the heavy metals and other hazardous stuffs in such place. These are mostly endocrine disrupters, and most are neuro- and immune-toxic as well. A typical pathway of contamination can come from different sources: inhalation pathway due to burning stuffs in the area, dermal pathway due to direct contact with hazardous components, ingestion pathway due to food contamination of surrounding cattle or food sold nearby. Study showed the presence of e-waste components in human breast milk, urine, ... The situation is of course very problematic but opportunities could emerge from it. Indeed, under controlled and regulated collection on e-waste, a sustainable management can combat poverty and create jobs for the unemployed youth through collection, safer recycling and processing of e-waste, and this would also safeguard the environment and human health from the hazards posed by the toxic contaminants. An other advantage is the possible recovery and recycling for raw materials. It could be a secondary source for industry supply chain. The recycling process appears in the materials cycle after the end-of-line, as visible in figure 5.14. The idea here is to benefit from the "waste" of the users and of the manufacturers to reproduce raw materials.

Umicore, which is a global materials technology and recycling group dedicating most of its R&D efforts to clean mobility materials and recycling, has declared in one presentation the

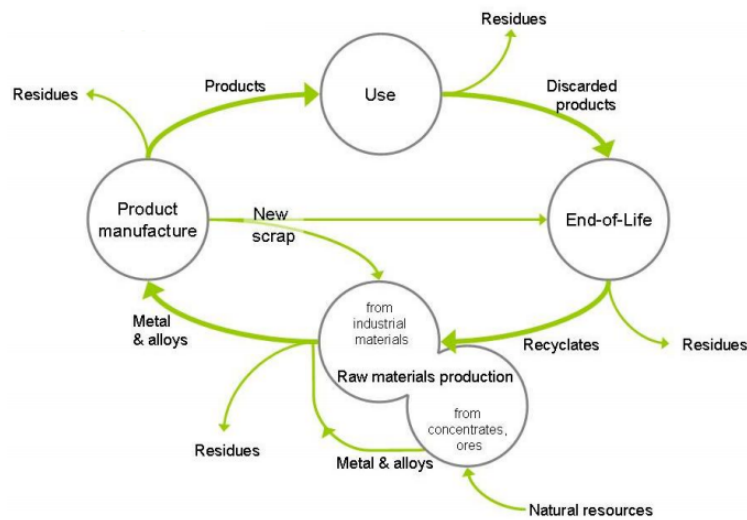


Figure 5.14: Cycle materials system approach



Figure 5.15: Simplified recycling process.

opportunities in e-waste recycling for Ghana. The idea with Ghana is to develop the manual dismantling and minimizing mechanical pre-processing to benefit from labor and fight against poverty. But let's take a look at the recycling process. The process is visible at figure 5.15 and the first step is logically the step of collection. An efficient recycling needs a large collection because no collection means no input in the recycling chain. It means no more illegal export and controlled, regulated "harvest". A second step is the inspection of the collected devices. If refurbishment is possible or not, separation of the devices. After that, the devices are dismantled, the components are separated and may also be inspected for possible reuse. The batteries are taken away to specific treatment flow. If we focus on PCB, they are shredded and then separated following their physical properties: ferrous materials are separated with magnetic system, plastic materials with eddy-current system.

The next step is metal refining and for this, metallurgy is at the core of recycling e-waste. At Umicore, they use Pb, Cu and Ni as collector materials to collect the pure metal, especially Cu for precious metal (like gold, silver, platinum, ...). The affinity between those 3 metals and other leads higher efficiency in recovery. They are using mainly two techniques: pyrometallurgy and hydrometallurgy.

The first one includes roasting, in which compounds are converted at temperatures just below their melting points, and smelting, which involves higher temperatures to completely melt the material which is then separated into two liquid layers, one of which contains the metals for further refining. Oxygen-enriched air may be injected into the molten bath to remove any volatile components present. An electric current can also be applied to separate further metal and non-metal components, where the metals will be deposited on the cathode. Thermal energy is used to melt down the inputs. This method is therefore quite energy intensive however, the required fossil fuel can be partially compensated by exploiting the plastic part of PCBs as fuel and reducing agent in the smelter [173]. While pyrometallurgical recycling processes are a cost-effective solution for electronic-waste recycling due to ability to deal with a broad range of scrap materials with minimal pre-processing, they carry a large environmental burden. Indeed, the PCB's used as fuel contain flame retardants that leads to the creation of volatile metals and give rise to environmental challenges. This type of recycling also displays poor selectivity for individual metals, meaning that multiple stages are required to recover metals in their pure elemental form.

Hydrometallurgy is used for further upgrading and purification of output streams from initial pyrometallurgy. The precious metals refining for example mostly uses this technique. It offers lower environment impact and greater scope for selective metal recovery which greatly simplifies the production of highly purity metal. The idea is to use acidic or alkaline solutions (with pressure/temperature effects) and chemical properties of substances to separate target from non-target substances. This step is mostly based on the concept of leaching which consists of treating the metal of interest with chemicals to transform it into soluble salt while the other non-target metals stay insoluble. It should be noted that copper is generally leached out firstly because of its high abundance in PCBs. The residue is then further refined for precious metal. For example, in gold refining, the reagent is cyanide (CN) which is cheap but highly toxic and offers very good leaching properties for gold. The chemical reaction behind this process are beyond the scope of this work. Drawbacks of leaching include its lower efficiency, the significant quantities of waste produced, which are usually either highly acidic or alkali as well as toxic and the nonexistent recovery for classical metals as Pb, Sn, Ni, ...

At the end, there is the need to handle all the "rest": cyanide solutions, toxic heavy metals. These are sorted and then stocked or sent to other competent structures.

5.2.7 Synthesis

In this last part, the facts found in the 6 sectors are compared with the 3 pillars of the sustainable development. At the end of each column, the most important fact are chosen. The final interpretation of this table is made in the conclusion.

Sector	Economic Pillar	Environmental Pillar
Economy	[-] Huge investment [+] Expected important return on investment.	
Society	[-] Fear that could limit the customer	
Legislation	[+] Simplified rules to attract more investors. [-] No exact laws for shared infrastructure.	[+/-] European law for e-waste recycling, maybe not strong enough.
Energy	[-] Important investment in energy efficiency	[-] Increased power consumption and carbon footprint. [-] Willingness towards clean energy for small cells. [-] Rebound effect
Materials	[-] Need for critical raw materials that are expensive	[-] Strong embodied energy for semiconductors
Environment	[+/-] E-waste recycling: recycling is expensive but possibility to get back raw materials.	[-] Important gas emission with manufacturing processes [-] Possible impact on wildlife and plants
Conclusion	[-] Important investment at the beginning for R&D, materials and infrastructure. [+] Important return on investment.	[+] E-waste recycling [-] Increase power consumption [-] Gas emission through processes

Sector	Social Pillar
Economy	[+] Jobs creation.
Society	[+] Better coverage and wireless experience [+] Better quality of life [+] Improved sensors and monitoring for health systems. [-] Precaution Principle not applied [-] Fear for human health consequences
Legislation	[+] Wifi4EU initiative [-] Need to adapt and standardize the laws regarding exposure to mmWaves
Energy	
Materials	[-] Bad work conditions for extraction
Environment	[-] E-waste harmful effects on health [-] Bad work condition in developing countries [+] Possibility for employment in developing countries but need for legal framework.
Conclusion	[+] Better overall experience with higher data rates? [+] Better quality of life and health systems. [-] Health concerns

CONCLUSION

In this work, the review of the technologies for a RF switch applications at 28GHz was conducted. After that the sustainability analysis of 5G and the mmWaves deployment was made.

The second chapter and third chapters were necessary to establish the background. This gives the reader the opportunity to understand the context of this thesis. The second chapter was mainly focused on the mmWaves and especially the 28GHz frequency band. The disadvantages such as higher attenuation and higher absorption were addressed as well as their possible solution. These consist of MIMO, beamforming but also small cells deployment. The main concepts of 5G were also cited. The third chapter gave the reader the theoretical basics needed to understand the benchmark of the technologies. One can cite the different types of RF switch, the different topologies but also the different parameters useful to compare the RF switches. Parameters such as $R_{ON}C_{OFF}$, insertion loss, isolation, 1dB compression point, ... were presented. In order to be complete, other components of the front-end module, along with their main parameters, were also presented. These are power amplifier, low-noise amplifier, filters, diplexers and antenna tuners. Main topologies like shunt, series, series-shunt were not forgotten.

In chapter 4, the comparison of different technologies was conducted. These technologies are Bulk CMOS, RF SOI MOSFET, GaAs HEMT, GaN HEMT, SiGe BiCMOS and GaAs PIN diode. Based on their insertion loss, SOI based switches performed the best. For isolation, GaAs based devices take a small lead. regarding 1dB compression point, the award goes to GaN based devices which largely outperform its counterparts. It is however important to note that trade offs are possible in the design of RF switches. These trade-offs (like topology, width of the transistors or stacking) impact largely the ISO, IL and CP1dB. The previous results regarding only the technology have to be considered with caution regarding this remark. PIN diodes are among the best performers for each parameter. From this analysis, it appeared that SOI based devices show the best compromise regarding IL, ISO with simpler design, mainly series-shunt topology which also participates to have broadband applications. After that, a rapid review of RF switches integrated into complete FEM SOC was conducted. The lower cost of Silicon technology offers a huge advantage for the industry. Si based technology such as SiGe and SOI are also very interesting regarding the integration possibilities with baseband circuits. In

the contrary, III-V materials have good performances but lack of integration capability. A final note on existing technology was also made.

In chapter 5, the sustainability analysis was performed. The impact of mmWave deployment on legislative, economic, social, environmental, energetic and materials axes were reviewed. After that, a synthesis was made where each fact in each sector was compared to the three pillars: society, environment and economy. From this table, it appeared that they are two main driving forces behind the deployment: an economic one with the important estimation of return on investment and also the job possibilities that it will create (quite linked to social pillar). The second main driving force is to enhance the quality of life of consumers in general. Better smartphone coverage, higher data rates to offer VR experiences, better monitoring and sensing for health applications, autonomous cars. On the other hand, the negative impacts find their place in each of the three pillars. In the economic pillar, biggest drawback is the investment necessary at the beginning. This investment is required for the deployment of small cells, R&D investment to improve technologies to perform correctly in mmWaves frequencies. The drawback for the environmental pillar is the increase in power consumption that will follow the deployment of small cells and dense networks. Indeed, these cells individually consumes less power but because they will be more frequently implemented, the total energy consumption should increase. The willingness of including clean energies in the system is an important subject of research that could decrease the carbon footprint but at the same times, the energies are not consistent and it is necessary to compensate for that. The social pillar is negatively impacted through the possible harmful effects of mmWaves. Indeed, adding new frequency band will increase the exposition of the population to electromagnetic waves. There are a large number of studies that show the impact of EMW on human health.

To conclude, I will speak for myself because the interpretation is personal and different for everyone. After the harvest of all the information regarding the deployment of 5G and mmWaves, I can easily understand the reluctance and concerns raised by some people. Indeed, I have the feeling that 5G is not a necessity for lots of people and that it is mostly pushed by the industries. I do not complain about the actual data rates and do find the purpose of Gbps data rates. mmWaves deployment also means a whole arrival of new equipment and with it, the environmental impact of extraction and manufacturing. At the same time, I understand the push towards new technologies. These are very interesting and complicated technical subjects. But I think that the energy and money invested in the 5G deployment could be invested in our actual technology to make it more sustainable. As an example, I had the idea at the beginning to compare each technology based on their environmental impact of the manufacturing process. But there are very few recent databases, papers that address the subject. Even in the industries, performances are the only goal and parameters such as electricity consumption, gases emission, toxicity are not considered. Of course harvesting such data requires time and money but this could be worth. Such data could lead to benchmark where not only IL, ISO and CP1dB but also the environmental impact (EI) are considered.

REFERENCES

- [1] Claire Troadec. *5G RF Front- End: Who has the most to win (and lose) ?* Yole Development, 2018.
- [2] Michael F. Ashby. *Materials and sustainable development*. Elsevier, 2015.
- [3] European Commission. *Critical raw materials*. URL: https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en. 2020.
- [4] The World Counts. *E-waste is a growing problem*. URL: <https://www.theworldcounts.com/challenges/planet-earth/waste/electronic-waste-facts>. 2020.
- [5] Communication Officer Shari Nijman. *UN report: Time to seize opportunity, tackle challenge of e-waste*. URL: <https://www.unenvironment.org/news-and-stories/press-release/un-report-time-seize-opportunity-tackle-challenge-e-waste#:~:text=The%20world%20produce%20as%20much,the%20GDP%20of%20most%20countries..> 2020.
- [6] Y. Amoyaw-Osei K. A. Asante and T. Agusa. *E-waste recycling in Africa: risks and opportunities*. Current Opinion in Green and Sustainable Chemistry, vol. 18, pp. 109–117, 2019.
- [7] G. Brundtland. *Report of the World Commission on Environment and Development: Our Common Future*. United Nations General Assembly document A/42/427, 1987.
- [8] Professor Theodore (Ted) Rappaport. *Spectrum Frontiers: The New World of Millimeter-Wave Mobile Communication*. NYU WIRELESS, 2016.
- [9] In: (). URL: <https://uk5g.org/5g-updates/read-articles/5g-the-state-of-play/>.
- [10] Benjamin H. Dickens-Jr. et Walker Townes Traduction de Henry Bakis et Michelle Rodet Edward M. Roche. “La prochaine génération de téléphonie mobile (5G) et ses implications (Infrastructure, Réglementation)”. In: *NETCOM* (2018).

- [11] In: (). URL: <https://www.5gworldpro.com/5g-knowledge/75-5g-s-great-expectations-do-consumers-see-anything-novel.html>.
- [12] Q. Wu et al. "An Overview of Sustainable Green 5G Networks". In: *IEEE Wireless Communications* 24.4 (2017), pp. 72–80.
- [13] Huawei. https://www-file.huawei.com/-/media/CORPORATE/PDF/public-policy/public_policy_position_5g_spectrum.pdf. 2017. URL: https://www-file.huawei.com/-/media/CORPORATE/PDF/public-policy/public_policy_position_5g_spectrum.pdf.
- [14] Pavithra Nagaraj. "Impact of atmospheric impairments on mmWave based outdoor communication". In: *PG Scholar, Digital Communication Engineering, Department of Electronics and Communication Engineering, BMS College of Engineering, India* (2018).
- [15] T. S. Rappaport et al. *Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!* IEEE Access, 2013.
- [16] Y. Azar et al. *28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City*. 2013 IEEE International Conference on Communications (2013 ICC), 2013.
- [17] Pi Zhouyue et al. *An introduction to millimeter-wave mobile broadband systems*. IEEE Commun. Mag., 2011.
- [18] Brown Daniel. *White Paper: Exploring the Potential of mmWave for 5G Mobile Access*. Qualcomm, 2016.
- [19] T. Obara et al. "Indoor and outdoor experimental trials in 28-GHz band for 5G wireless communication systems". In: *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. 2015, pp. 846–850.
- [20] D. Kurita et al. "Outdoor experiments on 5G radio access using distributed MIMO and beamforming in 28-GHz frequency band". In: *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. 2017, pp. 1–6.
- [21] URL: <https://www.fcc.gov/auction/101>. 2020.
- [22] Tom Leins. 2018. URL: <https://blog.telegeography.com/5g-spectrum-auctions-in-eastern-asia-china-japan-south-korea-taiwan-macau-hong-kong>.
- [23] MILAN MILANOVIĆ. *Inside Japan's Unique Approach to 5G*. 2020. URL: <https://www.speedtest.net/insights/blog/japan-launches-5g-2020/>.
- [24] URL: <http://5gobservatory.eu/market-developments/5g-services/>. 2020.
- [25] Martyn Roetter & Ricardo Tavares. *5G in Post-Quarantine Europe*. 2020. URL: <https://techpolis.com/5g-in-post-quarantine-europe/>.

- [26] *mmWave: The Battle of the Bands*. URL: <https://www.ni.com/fr-be/innovations/white-papers/16/mmwave--the-battle-of-the-bands.html>. 26 June 2020.
- [27] Arogyaswami Paulraj, Rohit Nabar, and Dhananjay Gore. *Introduction to Space-Time Wireless Communications*. 1st. USA: Cambridge University Press, 2008. ISBN: 0521065933.
- [28] *Three Benefits of Using Multiple Antenna in Communications [Video 2]*. Mar. 2019. URL: <https://www.youtube.com/watch?v=tw0yD65viVI> (visited on 08/04/2020).
- [29] W. Hong et al. "Study and prototyping of practically large-scale mmWave antenna systems for 5G cellular devices". In: *IEEE Communications Magazine* 52.9 (2014), pp. 63–69.
- [30] N. Ojaroudiparchin et al. "A Switchable 3-D-Coverage-Phased Array Antenna Package for 5G Mobile Terminals". In: *IEEE Antennas and Wireless Propagation Letters* 15 (2016), pp. 1747–1750.
- [31] everythingRF. *What is MU-MIMO?* URL: <https://www.everythingrf.com/community/what-is-mu-mimo>.
- [32] In: (). URL: <https://www.3gpp.org/technologies/keywords-acronyms/1576-hetnet>.
- [33] Nicola Piovesan et al. "Energy sustainable paradigms and methods for future mobile networks: A survey". In: *Computer Communications* 119 (2018), pp. 101–117.
- [34] RF wireless world. *What is RF Front end*. URL: <https://www.rfwireless-world.com/Terminology/what-is-RF-front-end.html>. 2020.
- [35] MARK LAPEDUS. *RF Device And Process Biz Heats Up*. 2017. URL: <https://semiengineering.com/rf-device-and-process-biz-heats-up/>.
- [36] Soitec Dr. Carlos Mazuré CTO. *Smart Cut™ Nano Technology*. 2018. URL: <http://www.eu-jp-tthelpdesk.eu/wp-content/uploads/2018/11/Soitec.pdf>.
- [37] Dave Evans. *The Internet of Things How the Next Evolution of the Internet Is Changing Everything*. CISCO, 2011.
- [38] D. Y. C. Lie et al. "A Review of 5G Power Amplifier Design at cm-Wave and mm-Wave Frequencies". In: *Wireless Communications and Mobile Computing*. 2020, pp. 1–16.
- [39] BILL SCHWEBER. *The RF power amplifier, Part 1: Functions*. 2020. URL: <https://www.analogictips.com/rf-power-amplifier-part-1-functions-faq/>.
- [40] Nicholas Estella et al. *High-Efficiency, Ka-band GaN Power Amplifiers*. IEEE, 2019.
- [41] M. Roberg et al. *40W Ka-Band Single and Dual Output GaN MMIC Power Amplifiers on SiC*. IEEE BCICT Sym., 2018.
- [42] A. Gasmi et al. *10W Power amplifier and 3W Transmit/Receive module with 3 dB NF in Ka band using a 100nm GaN/Si process*. IEEE CSICS, 2017.

- [43] P. Paliwoda et al. "Thermal Characterization and TCAD Modeling of a Power Amplifier in 45RFSOI for 5G mmWave Applications". In: *2020 IEEE International Reliability Physics Symposium (IRPS)*. 2020, pp. 1–5.
- [44] Y. Chang et al. "A Ka-Band Stacked Power Amplifier with 24.8-dBm Output Power and 24.3% PAE in 65-nm CMOS Technology". In: *2019 IEEE MTT-S International Microwave Symposium (IMS)*. 2019, pp. 316–319.
- [45] Merve. Yilmaz. "A TWO STAGE X-BAND LOW NOISE AMPLIFIER OPTIMIZED FOR MINIMUM NOISE APPLICATION". In: *bilkent university*. 2015.
- [46] Rob Rutkowski. *The Ultimate Guide to SAW Filters*. 2019. URL: <https://blog.bliley.com/the-ultimate-guide-to-saw-filters>.
- [47] 2018. URL: <https://www.rfwireless-world.com/Terminology/SAW-filter-vs-BAW-filter.html>.
- [48] QUORVO. *ANTENNA CONTROL SOLUTIONS*. URL: <https://www.qorvo.com/applications/mobile-products/antenna-control-solutions>.
- [49] URL: <https://www.microwaves101.com/encyclopedias/solid-state-switches>. 2020.
- [50] *Microwave Engineering: Passive Circuits*. Prentice-Hall Of India Pvt. Limited. ISBN: 9788120314610. URL: <https://books.google.be/books?id=Di-JtgAACAAJ>.
- [51] URL: <http://www.kratosmed.com/gmcatalog/microwave-switches/application-notes?r=gmc>. 2020.
- [52] National Instruments. *Présentation des spécifications essentielles en commutation RF*. 2020. URL: <https://www.ni.com/fr-be/support/documentation/supplemental/07/chapter-1--understanding-key-rf-switch-specifications.html>.
- [53] B. Kazemi Esfeh. "RF characterization of state-of-the-art technologies". In: *Prom. : Raskin, Jean-Pierre*. 2019.
- [54] L. E. Larson. "Integrated circuit technology options for RFIC's-present status and future directions". In: *Proceedings of CICC 97 - Custom Integrated Circuits Conference*. 1997, pp. 169–176.
- [55] ITRS. *INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS 2007 EDITION RADIO FREQUENCY AND ANALOG/MIXED-SIGNAL TECHNOLOGIES FOR WIRELESS COMMUNICATIONS*. 2007. URL: <https://www.semiconductors.org/wp-content/uploads/2018/08/2007Wireless.pdf>.
- [56] *UNIT 1 – MATERIALS ON THE EARTH*. URL: https://grupsderecerca.uab.cat/clilsi/sites/grupsderecerca.uab.cat.clilsi/files/Roser%20Canet_3r%20ESO_materials%20on%20the%20Earth%20crust.pdf.
- [57] P. Sarafis et al. "Advanced Si-based substrates for RF passive integration: Comparison between local porous Si layer technology and trap-rich high resistivity Si". In: *Solid-State Electronics* 87 (2013), pp. 27–33.

- [58] Vikram Passi and Jean-Pierre Raskin. "Review on analog/radio frequency performance of advanced silicon MOSFETs". In: *Semiconductor Science and Technology* 32.12 (2017), p. 123004.
- [59] M. Haque Bhuyan. "RF Semiconductor Devices Technology: History and Evolution, Prospects and Opportunities, Current and the Future". In: *SEU Journal of Science and Engineering*. Vol. 12. 2. 2018, pp. 29–39.
- [60] Muhammad Navid Anjum Aadit et al. "High Electron Mobility Transistors: Performance Analysis, Research Trend and Applications, Different Types of Field-Effect Transistors - Theory and Applications". In: *IntechOpen*. 2017.
- [61] J. Ajayan and D.Nirmal Ph.D. "22 nm In 0.75 Ga 0.25 As channel-based HEMTs on InP/GaAs substrates for future THz applications". In: *Journal of Semiconductors* 38 (May 2017). DOI: 10.1088/1674-4926/38/4/044001.
- [62] Imec. *Heterogeneous III-V/CMOS technologies for beyond-5G RF front-end modules*. 2020. URL: <https://www.imec-int.com/en/imec-magazine/imec-reading-room-january-2020/heterogeneous-iii-v-cmos-technologies-for-beyond-5g-rf-front-end-modules>.
- [63] S. Cristoloveanu. "Silicon films on sapphire". In: *Reports on Progress in Physics*. Vol. 50. 3. 1987, pp. 327–371.
- [64] S. Laurent and E. Desbionnets. "RF Substrate Technologies for Mobile Communication". In: *With the paper, Soitec*. 2011.
- [65] K. Izumi, M. Doken, and H. Ariyoshi. "C.M.O.S. devices fabricated on buried SiO₂ layers formed by oxygen implantation into silicon". In: *Electronics Letters* 14.18 (1978), pp. 593–594.
- [66] D. Lederer and J. -. Raskin. "Substrate loss mechanisms for microstrip and CPW transmission lines on lossy silicon wafers". In: *2002 IEEE MTT-S International Microwave Symposium Digest (Cat. No.02CH37278)*. Vol. 2. 2002, 685–688 vol.2.
- [67] Lederer et al. "High resistivity SOI substrates: how high should we go?" In: *2003 IEEE International Conference on SOI*. 2003, pp. 50–51.
- [68] semiconductorTODAY. "RF GaN market to grow at 22.9% CAGR over 2017–2023, boosted by 5G implementation". In: *Compounds&AdvancedSilicon*. Vol. 13. 2018.
- [69] K. Husna Hamza and D. Nirmal. "A review of GaN HEMT broadband power amplifiers". In: *AEU - International Journal of Electronics and Communications*. Vol. 116. 2020, p. 153040.
- [70] O. Ambacher et al. "Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGa_N/Ga_N heterostructures". In: *Journal of Applied Physics*. Vol. 85. 6. 1999, pp. 3222–3233.
- [71] Imec. *200mm GaN-on-silicon technology and GaN power devices*. Aug. 2019. URL: <https://www.imec-int.com/en/200mm-GaN-on-Si-technology>.
- [72] S. S. Iyer et al. "Silicon-germanium base heterojunction bipolar transistors by molecular beam epitaxy". In: *Tech. Dig. Int. Electron Device Meeting*. 1987, pp. 874–876.

- [73] J. N. Burghartz. "BiCMOS process integration and device optimization: Basic concepts and new trends". In: *Electrical Engineering* 79.5 (1996), pp. 313–327. ISSN: 1432-0487.
- [74] S. Jahdi et al. "Electrothermal modeling and characterization of SiC Schottky and silicon PiN diodes switching transients". In: *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2014, pp. 2817–2823.
- [75] F. Silva, R. Doria, and M. d. Souza. "Influence of the Intrinsic Length on the Behavior of PIN Diodes Fabricated on SOI Substrates Working as Solar Cells". In: *2018 33rd Symposium on Microelectronics Technology and Devices (SBMicro)*. 2018, pp. 1–4.
- [76] X. Zou et al. "Fully Vertical GaN p-i-n Diodes Using GaN-on-Si Epilayers". In: *IEEE Electron Device Letters* 37.5 (2016), pp. 636–639.
- [77] Y. Gong, J. W. Teng, and J. D. Cressler. "A Compact, High-Power, 60 GHz SPDT Switch Using Shunt-Series SiGe PIN Diodes". In: *2019 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*. 2019, pp. 15–18.
- [78] P. Song et al. "A high-power, low-loss W-band SPDT switch using SiGe PIN diodes". In: *2014 IEEE Radio Frequency Integrated Circuits Symposium*. 2014, pp. 195–198.
- [79] Liang Zhang et al. "Design of K/Ka-band passive HEMT SPDT switches with high isolation". In: *2017 China Semiconductor Technology International Conference (CSTIC)*. IEEE, 2017, pp. 1–3.
- [80] W. Lee and S. Hong. "Low-loss and Small-size 28 GHz CMOS SPDT Switches using Switched Inductor". In: *2018 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*. 2018, pp. 148–151.
- [81] Mehmet Parlak and James F. Buckwalter. "A Passive I/Q Millimeter-Wave Mixer and Switch in 45-nm CMOS SOI". In: *IEEE Transactions on Microwave Theory and Techniques* 61 (2013), pp. 1131–1139.
- [82] Andrzej Rozbicki and James J. Brogle. "EM analysis of Ka band multi-throw PIN diode MMIC switches". In: *2016 11th European Microwave Integrated Circuits Conference (EuMIC)*. IEEE, 2016, pp. 289–292.
- [83] Thibaut Despoisse et al. "Low-Loss Ka-band SPDT Switch Design Methodology for 5G Applications in 65 nm CMOS SOI Technology". In: *2020 IEEE 20th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems (SiRF)*. IEEE, Jan. 2020.
- [84] Li Zhao et al. "Compact 35–70 GHz SPDT Switch With High Isolation for High Power Application". In: *IEEE Microwave and Wireless Components Letters* 27.5 (2017), pp. 485–487.
- [85] Yi-Fan Tsao, Joachim Würfl, and Heng-Tung Hsu. "Bandwidth Improvement of MMIC Single-Pole-Double-Throw Passive HEMT Switches with Radial Stubs in Impedance-Transformation Networks". In: *Electronics* 9.2 (2020), p. 270.
- [86] Kim Tuyen Trinh et al. "A $\text{\$Ka\$}$ -Band GaAs MMIC Traveling-Wave Switch With Absorptive Characteristic". In: *IEEE Microwave and Wireless Components Letters* 29 (2019), pp. 394–396.

- [87] W. Lee and S. Hong. "Low-loss and Small-size 28 GHz CMOS SPDT Switches using Switched Inductor". In: *2018 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*. 2018, pp. 148–151.
- [88] M. Micovic et al. "High frequency GaN HEMTs for RF MMIC applications". In: *2016 IEEE International Electron Devices Meeting (IEDM)*. 2016, pp. 3.3.1–3.3.4.
- [89] H. Liu et al. "10-MHz-to-70-GHz Ultra-Wideband Low-Insertion-Loss SPST and SPDT Switches Using GaAs PIN Diode MMIC Process". In: *2018 Asia-Pacific Microwave Conference (APMC)*. 2018, pp. 1217–1219.
- [90] Bo Yu et al. "A DC-50 GHz SPDT switch with maximum insertion loss of 1.9 dB in a commercial 0.13-um SOI technology". In: *2015 International SoC Design Conference (ISOCC)*. IEEE, 2015, pp. 197–198.
- [91] Chaojiang Li et al. "< 0.8dB IL 46dBm OIP3 Ka band SPDT for 5G communication". In: *2018 IEEE 18th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems (SiRF)*. Anaheim, CA: IEEE, 2018, pp. 1–3.
- [92] Adilson S. Cardoso et al. "Low-loss, wideband SPDT switches and switched-line phase shifter in 180-nm RF CMOS on SOI technology". In: *2014 IEEE Radio and Wireless Symposium (RWS)*. IEEE, 2014, pp. 199–201.
- [93] C. Chen, X. Xu, and T. Yoshimasu. "A DC-50 GHz, low insertion loss and high P1dB SPDT switch IC in 40-nm SOI CMOS". In: *2017 IEEE Asia Pacific Microwave Conference (APMC)*. 2017, pp. 5–8.
- [94] K. Hettak et al. "DC to 70 GHz 90 nm 3D CMOS SPDT using elevated CPW and CPS series stubs". In: *2011 IEEE MTT-S International Microwave Symposium*. 2011, pp. 1–4.
- [95] Cuilin Chen et al. "A 30-GHz band low-insertion loss and high-isolation SPDT switch IC in 120-nm SiGe HBT". In: *2016 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*. IEEE, 2016, pp. 1–3.
- [96] Mantra. Jan. 1970. URL: <http://mantravlsi.blogspot.com/2014/10/flip-chip-and-wire-bonding.html>.
- [97] U. Kodak and G. M. Rebeiz. "Bi-directional flip-chip 28 GHz phased-array core-chip in 45nm CMOS SOI for high-efficiency high-linearity 5G systems". In: *2017 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*. 2017, pp. 61–64.
- [98] M. Lokhandwala, L. Gao, and G. M. Rebeiz. "A High-Power 24-40-GHz Transmit-Receive Front End for Phased Arrays in 45-nm CMOS SOI". In: *IEEE Transactions on Microwave Theory and Techniques* (2020), pp. 1–1.
- [99] Hyun Ahn et al. "28 GHz GaAs pHEMT MMICs and RF front-end module for 5G communication systems". In: *Microwave and Optical Technology Letters* 61 (Jan. 2019). DOI: 10.1002/mop.31669.
- [100] C. Liu et al. "A Ka-Band Single-Chip SiGe BiCMOS Phased-Array Transmit/Receive Front-End". In: *IEEE Transactions on Microwave Theory and Techniques* 64.11 (2016), pp. 3667–3677.

- [101] Mohammed Ayad et al. "Packaged High Power Front-End Module for Broadband 24GHz & 28GHz 5G solutions". In: July 2018, pp. 299–303. DOI: 10.1109/5GWF.2018.8517048.
- [102] Tech Insights. *Qualcomm QTM052 RF mmWave Antenna Module Analysis Product Brief* "World's first-announced, fully-integrated mmWave RF solution". 2019. URL: <https://osch.oss-cn-shanghai.aliyuncs.com/blogContentFile/1562306596954.pdf>.
- [103] Q. Li et al. "16.6- and 28-GHz Fully Integrated CMOS RF Switches With Improved Body Floating". In: *IEEE Transactions on Microwave Theory and Techniques* 56.2 (2008), pp. 339–345.
- [104] X. Tang et al. "A Traveling-Wave CMOS SPDT Using Slow-Wave Transmission Lines for Millimeter-Wave Application". In: *IEEE Electron Device Letters* 34.9 (2013), pp. 1094–1096.
- [105] C. Liu, Q. Li, and Y. Xiong. "A compact Ka-band SPDT switch with high isolation". In: *2014 International Symposium on Integrated Circuits (ISIC)*. 2014, pp. 304–307.
- [106] K. Lee, S. Choi, and C. Kim. "A 25–30-GHz Asymmetric SPDT Switch for 5G Applications in 65-nm Triple-Well CMOS". In: *IEEE Microwave and Wireless Components Letters* 29.6 (2019), pp. 391–393.
- [107] Bo Yu et al. "Ultra-Wideband Low-Loss Switch Design in High-Resistivity Trap-Rich SOI With Enhanced Channel Mobility". In: *IEEE Transactions on Microwave Theory and Techniques* 65.10 (2017), pp. 3937–3949.
- [108] Andrzej Rozbicki et al. "Ka band high power AlGaAs PIN diode switches". In: *2009 IEEE MTT-S International Microwave Symposium Digest*. IEEE, 2009, pp. 453–456.
- [109] Xiaosu Zheng et al. "Ka-Band High Power GaN SPDT Switch MMIC". In: *2013 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*. IEEE, 2013, pp. 1–5.
- [110] Dechun Guo et al. "Design of a Ka-band broadband SPDT switch MMIC based on GaN HEMTs". In: *2015 IEEE 16th International Conference on Communication Technology (ICCT)*. IEEE, 2015, pp. 241–243.
- [111] Giorgio Polli et al. "GaN/Si Ka-band SPDT for observation payloads". In: *2019 IEEE Asia-Pacific Microwave Conference (APMC)*. IEEE, 2019, pp. 288–290.
- [112] Fabian Thome et al. "Millimeter-Wave Single-Pole Double-Throw Switches Based on a 100-nm Gate-Length AlGaN/GaN-HEMT Technology". In: *2019 IEEE MTT-S International Microwave Symposium (IMS)*. IEEE, 2019, pp. 1403–1406.
- [113] https://cdn.macom.com/datasheets/MASW_011105.pdf.
- [114] Chung Hang John Poh et al. "An X-band to Ka-band SPDT switch using 200 nm SiGe HBTs". In: *2012 IEEE 12th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems*. IEEE, 2012, pp. 183–186.
- [115] V. Puyal et al. "A broad-band 55-nm BiCMOS T/R switch for mmW 5G small cell access point". In: *2016 14th IEEE International New Circuits and Systems Conference (NEWCAS)*. 2016, pp. 1–4.

- [116] Haoyi Dong et al. "A Compact Bi-directional K and Ka Band SPDT in 0.13um SiGe BiCMOS Process". In: (2018), p. 3.
- [117] Jubaid Abdul Qayyum et al. "A 20–60 GHz Ultra-Wideband SPDT Switch for Multi-Band Transceivers". In: *2020 IEEE 20th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems (SiRF)*. IEEE, 2020, pp. 16–18.
- [118] Tamara Tukhareli. "ANALYZING THE SUSTAINABILITY OF ELECTRONIC WASTE MANAGEMENT IN TORONTO, ONTARIO". In: *Thesis, Department of Geography Memorial University of Newfoundland* (2015).
- [119] Deloitte. *Semiconductors – the Next Wave Opportunities and winning strategies for semiconductor companies*. 2019. URL: <https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/technology-media-telecommunications/deloitte-cn-tmt-semiconductors-the-next-wave-en-190422.pdf>.
- [120] OXFORD ECONOMICS Global Semiconductor Alliance. *Enabling the Hyperconnected Age The role of semiconductors*. 2012. URL: http://www.semismatter.com/wp-content/uploads/2014/09/GSA_report_WEB.pdf.
- [121] Apple. *Product Environmental Report iPhone 11*. 2019. URL: https://www.apple.com/environment/pdf/products/iphone/iPhone_11_PER_sept2019.pdf.
- [122] Zahid Ghadialy. *Small Cells Densification for 4G & 5G*. 2017. URL: <https://smallcells.3g4g.co.uk/2017/12/small-cells-densification-for-4g-5g.html>.
- [123] European Parliament. "Towards a European gigabit society Connectivity targets and 5G". In: (2017).
- [124] European Commission. "State of the Union 2016: Commission paves the way for more and better internet connectivity for all citizens and businesses". In: (2016).
- [125] European Commission. "5G deployment could bring millions of jobs and billions of euros benefits, study finds". In: (2016). URL: <https://ec.europa.eu/digital-single-market/en/news/5g-deployment-could-bring-millions-jobs-and-billions-euros-benefits-study-finds>.
- [126] Louise Vanderkelen. *Le déploiement de la 5G doit être arrêté, l'appel de 100 étudiants biologistes et médecins*. 2020. URL: <https://www.lalibre.be/debats/opinions/le-deploiement-de-la-5g-doit-etre-arrete-l-appel-de-100-etudiants-biologistes-et-medecins-5eb26f7ad8ad580>.
- [127] national Toxicology Program. "Cellphone Radio Frequency Radiation Studies." In: (2018).
- [128] Cindy L. Russell. "5 G wireless telecommunications expansion: Public health and environmental implications". In: *Environmental Research* 165 (2018), pp. 484–495.
- [129] Andrei G. Pakhomov et al. "Current state and implications of research on biological effects of millimeter waves: A review of the literature". In: *Bioelectromagnetics* 19.7 (1998), pp. 393–413.

- [130] J. Bang and J. Choi. "A SAR Reduced mm-Wave Beam-Steerable Array Antenna With Dual-Mode Operation for Fully Metal-Covered 5G Cellular Handsets". In: *IEEE Antennas and Wireless Propagation Letters* 17.6 (2018), pp. 1118–1122.
- [131] Chernyakov GM et.al. "Reactions of biological systems of various complexity to the action of low-level EHF radiation". In: 1989, pp. 141–167.
- [132] IL Potekhina et al. "Effects of low-intensity electromagnetic radiation in the millimeter range on the cardio-vascular system of the white rat". In: vol. 78. 1992, pp. 35–41.
- [133] VG Bulgakova et al. "Effect of millimeter-band radiation of nonthermal intensity on the sensitivity of staphylococcus to various antibiotics". In: *Biofizika* 41 (1996), pp. 1289–1293.
- [134] M.Prost et al. "Badania doświadczalne nad wpływem promieniowania milimetrowego na transmisję światła przez soczewkę" [Experimental studies on the influence of millimeter radiation on light transmission through the lens]. In: *Klinika oczna* 96.257-9 (1994), pp. 8–9.
- [135] D.Habauzit et al. "Transcriptome analysis reveals the contribution of thermal and the specific effects in cellular response to millimeter wave exposure." In: *PLoS One* 9 (2014).
- [136] Agostino Di Ciaula. "Towards 5G communication systems: Are there health implications?" In: *International Journal of Hygiene and Environmental Health* 221.3 (2018), pp. 367–375.
- [137] Mattsson MO imkó M. "5G Wireless Communication and Health Effects-A Pragmatic Review Based on Available Studies Regarding 6 to 100 GHz". In: *Int J Environ Res Public Health* 16(18) (2019), p. 3406.
- [138] Ronald N. Kostoff et al. "Adverse health effects of 5G mobile networking technology under real-life conditions". In: *Toxicology Letters* 323 (2020), pp. 35–40.
- [139] 2017. URL: http://www.5gappeal.eu/wp-content/uploads/2018/06/reply_vinciunas.pdf.
- [140] C. M. Collins T. Wu T. S. Rappaport. "The Human Body and Millimeter-Wave Wireless Communication Systems: Interactions and Implications". In: *2015 IEEE International Conference on Communications (ICC)* (2015).
- [141] T. Hamed and M. Maqsood. "SAR Calculation & Temperature Response of Human Body Exposure to Electromagnetic Radiations at 28, 40 and 60 GHz mmWave Frequencies". In: *Progress In Electromagnetics Research M* 79 (2018), pp. 47–59.
- [142] Huwaei. "5G Telecom Power Target Network White Paper". In: s (2020).
- [143] T. Andrae A.S.G.; Edler. "On Global Electricity Usage of Communication Technology: Trends to 2030". In: *Challenges* 6 (2015), pp. 117–157.
- [144] Jaime Lloret, Sandra Sendra, and Elsa Macias-Lopez. "Editorial: Advances in Green Communications and Networking". In: *Mobile Networks and Applications* 24.2 (2019), pp. 653–656.

- [145] J. Wu et al. "Energy-Efficient Base-Stations Sleep-Mode Techniques in Green Cellular Networks: A Survey". In: *IEEE Communications Surveys Tutorials* 17.2 (2015), pp. 803–826.
- [146] Olumide Alamu et al. "Energy efficiency techniques in ultra-dense wireless heterogeneous networks: An overview and outlook". In: *Engineering Science and Technology, an International Journal* (2020).
- [147] In: (). URL: <https://connect.innovateuk.org/documents/2849135/3712563/DCKTN+energy+efficient+wireless+communications+positioning+paper+30Mar11.pdf>.
- [148] Mohammed Alsharif, Jeong Kim, and Jin Kim. "Green and Sustainable Cellular Base Stations: An Overview and Future Research Directions". In: *Energies* 10 (Apr. 2017), p. 587. DOI: 10.3390/en10050587.
- [149] J. J. Yan et al. "Effect of signal PAPR on efficiency of envelope tracking power amplifiers". In: *2013 Asia-Pacific Microwave Conference Proceedings (APMC)*. 2013, pp. 860–862.
- [150] S. P. Yadav and S. C. Bera. "Linearity improvement of microwave power amplifiers". In: *2016 IEEE Annual India Conference (INDICON)*. 2016, pp. 1–6.
- [151] "Energy Efficiency and Coverage Trade-Off in 5G for Eco-Friendly and Sustainable Cellular Networks". In: ().
- [152] Marco Ajmone Marsan et al. "On the effectiveness of single and multiple base station sleep modes in cellular networks". In: *Computer Networks* 57.17 (2013), pp. 3276–3290.
- [153] Shweta Rajoria, Aditya Trivedi, and W. Wilfred Godfrey. "A comprehensive survey: Small cell meets massive MIMO". In: *Physical Communication* 26 (2018), pp. 40–49.
- [154] X. Ge et al. "Energy Efficiency Challenges of 5G Small Cell Networks". In: *IEEE Communications Magazine* 55.5 (2017), pp. 184–191.
- [155] R. W. Heath et al. "An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems". In: *IEEE Journal of Selected Topics in Signal Processing* 10.3 (2016), pp. 436–453.
- [156] S. Han et al. "Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G". In: *IEEE Communications Magazine* 53.1 (2015), pp. 186–194.
- [157] L. N. Ribeiro et al. "Energy Efficiency of mmWave Massive MIMO Precoding With Low-Resolution DACs". In: *IEEE Journal of Selected Topics in Signal Processing* 12.2 (2018), pp. 298–312.
- [158] Md Maruf Ahamed and Saleh Faruque. "5G Backhaul: Requirements, Challenges, and Emerging Technologies, Broadband Communications Networks - Recent Advances and Lessons from Practice". In: *IntechOpen* (2018). URL: <https://www.intechopen.com/books/broadband-communications-networks-recent-advances-and-lessons-from-practice/5g-backhaul-requirements-challenges-and-emerging-technologies>.

- [159] X. Zhou, R. Zhang, and C. K. Ho. “Wireless Information and Power Transfer: Architecture Design and Rate-Energy Tradeoff”. In: *IEEE Transactions on Communications* 61.11 (2013), pp. 4754–4767.
- [160] K. W. Choi et al. “Simultaneous Wireless Information and Power Transfer (SWIPT) for Internet of Things: Novel Receiver Design and Experimental Validation”. In: *IEEE Internet of Things Journal* 7.4 (2020), pp. 2996–3012.
- [161] Breakthrough Institute. 2011. URL: http://thebreakthrough.org/blog/Energy_Emergence.pdf.
- [162] European Commission. “COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS”. In: (2017). URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0490>.
- [163] S. Cucurachi et al. “A review of the ecological effects of radiofrequency electromagnetic fields (RF-EMF)”. In: *Environment International* 51 (2013), pp. 116–140. URL: <http://www.sciencedirect.com/science/article/pii/S0160412012002334>.
- [164] Arno Thielens et al. “Exposure of Insects to Radio-Frequency Electromagnetic Fields from 2 to 120 GHz”. In: *Scientific Reports* 8.1 (2018), p. 3924.
- [165] Arno Thielens et al. “Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees”. In: *Scientific Reports* 10 (2020).
- [166] Florence Batellier et al. “Effects of exposing chicken eggs to a cell phone in “call” position over the entire incubation period”. In: *Theriogenology* 69 (2008), pp. 737–45.
- [167] Cornelia Waldmann-Selsam et al. “Radiofrequency radiation injures trees around mobile phone base stations”. In: *Science of The Total Environment* 572 (2016), pp. 554–569.
- [168] Joseph L. Kirschvink. “Radio waves zap the biomagnetic compass”. In: *Nature* 509.7500 (2014), pp. 296–297.
- [169] Vanessa Forti et al. *The Global E-waste Monitor 2020*. 2020. URL: <http://ewastemonitor.info/>.
- [170] Y. Amoyaw-Osei K. A. Asante and T. Agusa. “E-waste recycling in Africa: risks and opportunities”. In: *Current Opinion in Green and Sustainable Chemistry* 18 (2019), pp. 109–117.
- [171] O.K. Deubzer A.O. Odeyingbo I.C. Nnorom. “Used and waste electronics flows into Nigeria: Assessment of the quantities, types, sources, and functionality status”. In: *Science of The Total Environment* 666 (2019), pp. 103–113.
- [172] Orish Ebere Orisakwe et al. “Public Health Burden of E-waste in Africa”. In: *Journal of Health and Pollution* 9.22 (2019), p. 190610.
- [173] Mudila Dhanunjaya Rao et al. “Challenges and opportunities in the recovery of gold from electronic waste”. In: *RSC Adv.* 10 (8 2020), pp. 4300–4309.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain

Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/epl