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# Multitones' Performance for Ultra Wideband Software Defined Radar

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/60804>

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## Abstract

This chapter proposes and tests an approach for an unbiased study of radar waveforms' performances. Through an empirical performance analysis, the performances of Chirp and Multitones are compared with both simulations and measurements. An ultra wideband software defined radar prototype was designed and the prototype has performances comparable to the state of the art in software defined radar. The study looks at peak-to-mean-envelope power ratio, spectrum efficiency, and pulse compression as independent waveform criteria. The experimental results are consistent with the simulations. The study shows that a minimum of 10 bits resolution for the AD/DA converters is required to obtain near-optimum performances.

**Keywords:** Software Defined Radar, OFDM, Empirical Modelling, Chirp

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## 1. Introduction

In the past few decades, analogue circuits have been replaced by digital circuits. This evolution has permitted the use of purely digital waveforms (such as Multitones which have numerous commercial applications in the wireless communication industry – such as wireless LAN [1]) which present numerous advantages (i.e., increased data throughput, robustness against fading). To date, Multitones have seldom been implemented in operational radar.

Operational radar predominantly uses the linear frequency modulated pulse (also known as Chirp) and has been routinely used since the late 1940s [2]. The relatively slow adoption of Multitones in radar applications can be explained by a variety of factors. For example, it is

unlikely that a technology will advance to marketable applications unless there is demand for them. Lately, the use of a Unmanned Airborne Vehicles for military operations over urban areas are required to simultaneously perform radar sensing and remotely communicate data to a base station. This cannot be achieved with traditional Chirp. Consequently, there have been increased research efforts in integrating telecommunication waveforms such as Multitones into radar applications.

The constant developments in ADC/DAC, digital signal processors, signal synthesis/digitization, and component's instantaneous bandwidth allow digital platforms to process ultra wideband (UWB) signals. In radar applications, UWB signals enable finer slant range resolution for target identification and the implementation of waveform/spectrum diversity. Those recent technological developments constitute the foundation of software-defined radar, which can dynamically reconfigure its digital signal processing and adapt the frequency of converter. Such radar is inherently multifunction switching from operating mode to another (surveillance, tracking, imaging, and telecommunications).

Multitones will only be widely adopted when its capabilities match the specific task's requirements. The successful integration and subsequent widespread use in operational systems depends solely on that condition. In other words, without a viable commercial application, the development of a technology is unlikely to succeed.

Considering the capabilities of Multitones and/or OFDM signals with respect to classical radar waveforms, the second half of the introduction provides an overview of the literature on the subject.

Refs. [3-5] concern the communication aspect of multi-carriers in radar, leaving radar performances with multicarrier signals aside. A comparison of performances is found in terms of detection in Ref. [6]. The authors compared single carrier and multicarrier radar systems in simulations. They found that for target detection in radar based on multicarrier modulation, the required constant false alarm rate detection threshold is lower than for a single carrier radar system with polyphase codes.

In Ref. [2], it is shown that trains of diverse Multitone pulses coded in phase and amplitude yielded near thumbtack ambiguity functions. These ambiguity functions do not suffer from range-Doppler coupling as Chirp does. In Ref. [7], a near thumbtack ambiguity function is obtained using random spread tone agility. In both cases, this ambiguity function comes at the cost of a higher pedestal level.

Finally, new processing capabilities are emerging using the Multitones' structure such as Doppler resolution while using agility [7]. This particular feature cannot be performed with classic radar waveforms while using agility. In Ref. [8], the Doppler ambiguity is resolved over one pulse train.

For those reasons, Multitones are foreseen as a viable prospect for the future digital software defined radar. In order to improve power amplifier efficiency, Peak-to-Mean Envelope Power Ratio (PMEPR) reduction schemes (phase/amplitude modulation) are overlaid on Multitones. This signal can be a composite of independent bands for separate processing in multimode

scenarios [9]. Also in the presence of frequency selective fading, Multitones can still ensure successful detection of the target [10]. The waveform/spectrum agility is essential for stealthy operations to evade jamming and spectrum reuse with radar networks [11].

Based on these studies of the performances of Multitones compared to classic radar waveforms, Multitones show a great potential for new radar advances. However, it is important to note that most of these results come from simulations. For a real evaluation of the potential performances of Multitones for radar systems, experimental validations are required. Hence the simulations presented in section 4 will be compared to experimental results in section 5 based on an experimental setup that is described in part 3.5. Also Multitones need to be compared to a reference in radar applications: the linear frequency modulated (LFM) signal aka Chirp [2].

For this chapter, the focus will be on the performances of both Multitones and Chirp with respect to quantization. The underlying issue of implementation is the effect of the radio frequencies (RF) equipment on radar performances. The DAC and ADC converters determine the radar's dynamic range and thus contribute greatly to detection capabilities. On the subject of Multitones and quantification, the literature focuses on telecommunications [3, 12, 13], so there is no evaluation of radar performance. Note that to the best of the authors' knowledge, the literature is lacking on this particular subject for radar applications. The following section will review the state of the art for Multitones' performances in radar with an emphasis on the issue of quantization.

## 2. State of the art

In the radar community, one of the main goals is to improve detection to see further and with a higher sensitivity. The smallest received power depends on receiver sensitivity which is closely related to the ADC resolution: In Ref. [14], the rationale behind investigating various linearization techniques was to increase radar receiver dynamic ranges for the detection of small targets with a highly cluttered background. To determine the best ADC resolution for a given application, the effects of quantization on performances must be investigated. The novel approach adopted in this chapter is to study Multitones performance for radar applications only, using unbiased tools in simulation and experimentation. Multitones will also be compared to a signal of reference in the radar community. This will position the Multitones' performance with respect to reference known to the community. The quantization process will allow determination of the limits of utilization of a given hardware with respect to performance requirements.

In Ref. [12], the author conducted a survey of ADC performances ranging from the 1970s to present day and extracted possible trends in ADC evolution forward to 2020. It is reported that most recent designs benefit from scaled device geometries and higher bandwidth, but suffer in dynamic range and sampling linearity due to reduced supply voltages and available swing. The available swing is most likely the cause for ADC saturation noise floor around -160 dB observed in the survey. It also shows that for a given ENOB, the sampling rates are entering

or already are in a saturation phase and it is speculated that the improvement of state of the art sampling rates will be lower than 5 times by 2020. Now looking at the evolution of ENOB with respect to sampling frequencies, the projections show that ADCs with over 1 GS/s have not entered the saturation phase yet. The survey also shows that the main efforts in ADC research now focused more on power efficiency rather than SNDR/SNR to reduce the ADC Figure-of-Merit.

Practical use of ADCs are plagued by many physical limitations such as quantization in time and amplitude, aliasing, clock jitter aperture jitter, thermal noise, non-linear distortions (INL, DNL), etc. Some of the physical limitations can be partially compensated using oversampling. However with the high-end of wideband ADCs (e.g., Tekmicro announced a 2-channel digitizer with 5 GS/s and 10 bits resolution with 3 GHz of instantaneous bandwidth on the Proteus V6 [15] equipped with the EV10AQ190 [16] from E2V) oversampling is not an option and even if possible would be prohibitively expensive. Jitter (clock and jitter) is well known to severely reduce the achievable signal-to-noise ratio (SNR) [17].

Regarding the use of Multitones in telecommunications, common measures of spurious free dynamic range, total harmonic distortion, signal to noise and distortion and effective number of bits are defined for one tone or two tones only and the definitions used for some of the metrics are not unified. In the literature, clip correction post-processing allows the relaxation of ADC resolution constraints to improve packet error rate at the cost of an increased complexity in processing [3]. The second allows bit error rate improvements in the presence of narrowband interference [13]. In Ref. [18], the ADC resolution of multi-band and pulsed-OFDM ultra wideband systems (IEEE 802.15.3a) is derived using simulation results. They show that 4-bit resolution is enough to obtain a bit error rate with respect to SNR performances quasi-identical to the ideal case with infinite resolution.

Working on relaxing ADC requirements with digital post-processing, to compensate for the impairments of hardware ("Dirty RF") and to increase the performance of telecommunication, is a very active research field. Given the projections in Ref. [12], the ADCs' non-linearities are increasing with the reduction of voltage swing, maximum SNR capabilities for wideband digitizers are not improving or maybe will worsen, digital enhancements are going to be required especially in radar to maintain current levels of sensitivity and detection.

To the best of the authors' knowledge, the literature is mostly investigating performances for telecommunications and not for radar performances, also very few experimental results were found. Before trying to improve performances, these performances for radar have to be established and in this chapter the quantization process is investigated.

### 3. Empirical approach for the evaluation of the radar performances

In order to compare different waveforms on equal grounds, they have to be compared on waveform-independent criteria. Also to further this concept, the simulated processes and the experimental test bench should be identical to evaluate the performances without bias.

### 3.1. Waveform independent criteria

Several characteristics were chosen to determine the optimum operating point: power efficiency, peak to mean envelope power ratio (PMEPR), and pulse compression characteristics. The combination of both PMEPR and power efficiency gives information on the effective average power in the signal useful bandwidth. These criteria allow the evaluation of detection range at the radar system level. Besides, a high PMEPR may reduce the average transmitted power [6] thus reducing the detection range. At the ADC level, the maximum input power determines the maximum SNR after digitization. In Ref. [19], it was shown SNR decreases as the PMEPR increases, so the PMEPR will set to the maximum achievable SNR without clipping. In radar, the pulse compression is used to evaluate the radar detection capabilities [20]. The detection is realized using a matched filter. The characteristics of interest for this study are the spatial resolution and the contrast; these are measured with the characteristics of the main lobe and the side lobes.

These parameters will allow determining the respective performances of any waveforms. PMEPR, power efficiency, and pulse compression will allow determining the detection capabilities for each waveform. Others could be used to get a more accurate picture of the performances. Nonetheless, these criteria are sufficient for a first performance evaluation.

### 3.2. Simulated processes

For the study the data will be filtered to simulate a 1 GHz bandwidth to match the ADC's Nyquist band used for the experiment. The quantization process and the Nyquist band chosen for simulations are the same as the equipment employed for the experiment the Neptune VXS II digitizer [15]. The encoded value on  $n$  bits,  $n \in [2, 24]$ , is floored to the nearest signed integer. Thus the quantized values range from  $[-2^{n-1}; 2^{n-1} - 1]$ . The model adopted is perfect quantization.

The minimum number of useful bits required to reach near nominal theoretical values with respect to PMEPR, power efficiency, and pulse compression performances will be assessed in order to evaluate the ADC characteristics required to maximize the radar system detection capabilities.

The simulation process also matches the quantization schemes adopted for the experimental radar system which is presented in the following section.

### 3.3. Design approach for an unbiased experimental study

In order to unbiasedly compare different waveforms, it is essential that waveform-independent criteria are used. Further, to evaluate the performances without bias, the simulated processes and the experimental test bench should be identical. The maximum detection range and pulse compression in range profile can be used as a first step to evaluate radar waveform performances.

To compare the different waveforms, it is not sufficient to simply examine simulation results; and thus this comparison should be experimentally validated. It is therefore necessary to



develop a software defined radar prototype that can test the waveforms under study without any bias. The novel approach is to compare the studied waveforms on the same platform to remove any bias. In this paper, simulations and measurements are designed to provide the basis for an unbiased study of the radar waveforms.

It should be noted that the radar prototype should be designed prior to the simulations, this way the characteristics of the prototype can then be fed to the simulator for a subsequent and direct comparison between simulated and experimental results.

### 3.4. Experimental design

#### 3.4.1. Design of RF system

A few constraints were established for the test bench design. The first step was to optimize the instantaneous bandwidth to maximize the radar spatial resolution. To perform as well as state of the art radar prototypes [4, 19, 21], the bandwidth should be greater than 500 MHz. The radar should support any type of waveform with no changes to the RF frontend. These two requirements ensure an unbiased study of various waveforms on the same prototype. Also a reference channel is implemented to compensate for some of the circuit transfer function. This constraint is a special feature that is not normally implemented in operational radar systems but does allow refreshing the matched filter dynamically to compensate for any fluctuations in transfer function especially with power amplifiers.

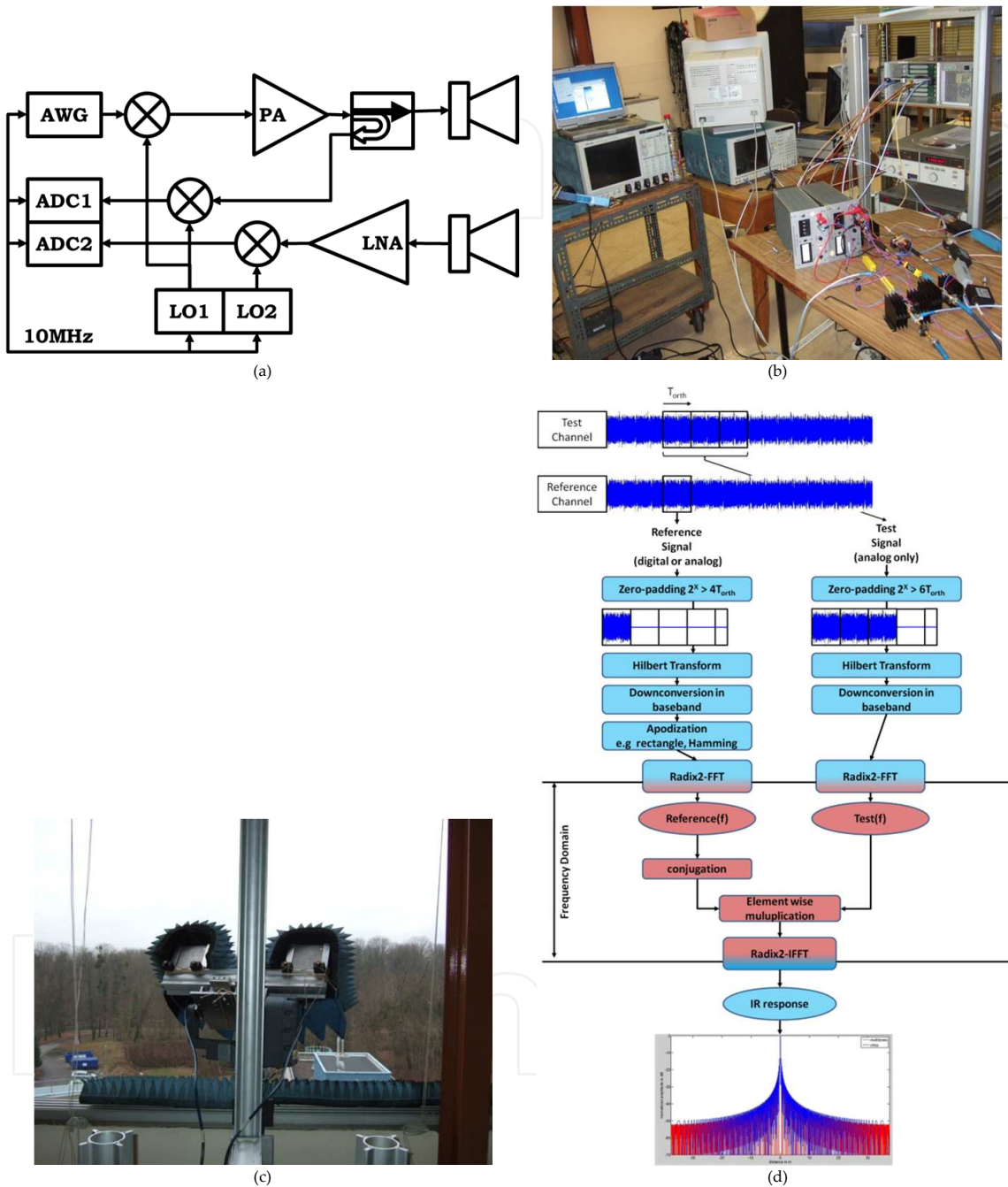
Due to spatial constraints on the experimental grounds, a maximum of 50 m in slant range is achievable. Consequently, the architecture must be bi-static and emit in continuous wave to allow for pulse compression gain greater than 20 dB.

Two architectures are proposed as candidates for the implementation: frequency-interleaved and parallel. The frequency-interleaved architecture is inspired from the prototype in Ref. [19]. It is investigated because it reduces the number of components and the number of ADC channels. The parallel architecture is derived from the frequency interleaved architecture. Although more components are required, it has a potential for more versatile usage.

### 3.5. Parallel architecture

A synoptic of the parallel architecture is shown in Figures 1.a, 1.b, and 1.c. The signal is directly synthesized in intermediate frequencies (IF) ranging from 1 to 2 GHz and a low pass filter removes the mirror image. The IF signal is up-converted in radio frequencies (RF) ranging from 9.9 to 10.9 GHz by FLO1 = 8.9 GHz, and a band pass filter removes the mirror image. For short-range applications, the signal can be amplified by a low noise amplifier; and for longer ranges, a power amplifier can be used. At the output of the amplifier stage, a 20dB directional coupler splits the signal: the coupled output feeds the signal to the reference channel and the direct path is connected to the transmitter antenna feed. The backscattered signal is received by the second antenna which is connected to the test channel. The received signal travels through a low noise amplifier and a band pass filter removes the mirror image before down-conversion by FLO1 = 8.9 GHz. The signal in the reference channel is attenuated and down-

converted by  $FLO2 = FLO1 = 8.9$  GHz. In both the reference and the test channels, the signals are band pass filtered to avoid aliasing and are then amplified prior to digitization.



**Figure 1.** (a): Schematic of parallel architecture. (b): Experimental test bench system overview. (c): Lab experimental test bench set-up. (d): Pulse compression algorithm radix-2 FFT for parallel architecture

A generic algorithm (Figure 1.d) was devised according to the architectures' characteristics, and with the objective to compare waveforms. The algorithm is implemented to process any kind of waveforms. This allows comparing two distinct signals on waveform-independ-



ent criteria. Radar systems use pulse compression in order to “see” the targets within the antenna beam. Matched filtering was chosen to process the data and the algorithm was modified to reduce the processing power required using radix-2 FFT.

This section presented the performance criteria, the simulation processes, and the radar system for an unbiased comparison of different waveforms. The next section will present the simulation results.

## 4. Waveform simulations

The radar emits in continuous wave and the waveforms will cover the bandwidths of 1 MHz, 10 MHz, 150 MHz, and 800 MHz, and pulse repetition period (PRP) of 500 ns, 5  $\mu$ s, 50  $\mu$ s, 500  $\mu$ s, and 1 ms. Each bandwidth value will be tested with every PRP values. It cannot be done in one case as 500 ns pulse already produces 2 MHz instantaneous bandwidth, thus the combination 1 MHz with 500 ns is not possible. The IF sampling frequency is 2 GS/s and the IF frequency range is centred on 1.5 GHz, the signal instantaneous bandwidth varies from 1 MHz to 800 MHz.

The studied signals are the Newman Phase Coded [22] Multitones and the linear Chirp. The latter is a reference in the radar community and will be used as reference to evaluate the performances of Multitones.

A multitude of phase codes exist to reduce PMEPR for Multitones such as Reed–Muller with complementary Golay codes, bi-phase codes, Newman phase codes, etc. For radar application, Doppler tolerance is important to detect moving targets and avoid the multiplication of filters to process the data, Newman phase-codes [22] were chosen because they are easy to implement, the PMEPR reduction is sufficient and it is Doppler tolerant. Furthermore this code is compatible with any vector size. Other codes – an overview of coding techniques can be found in [23] – may be more efficient but Newman phase-codes were chosen because they fit the requirements for radar applications; the aim is to evaluate the contribution of Multitones for radar, not to optimize the waveform phase code. Also note that Multitones need to respect constraints at the generation and digitization to avoid intermodulation interference.

### 4.1. Simulated results of the performance criteria

In this section, the simulated results for the PMEPR, the power efficiency, and the pulse compression will be presented. Note that the errors or differences express the variations between quantized with respect to perfect performance criteria.

#### 4.1.1. PMEPR

The effects of quantization on the nominal value of PMEPR are now evaluated through simulations for all bandwidth-time configurations of Chirps and Multitones under test. The Chirp’s PMEPR increases along with bandwidth, starting at 3.01dB @ 1MHz and going up to 4.22dB @ 800MHz. The increase in PMEPR for wideband Chirp (800 MHz) is explained by the

filter used to ensure a 1 GHz receiver bandwidth, cutting off the edges of the infinite Chirp spectrum. This effectively increases the Chirp's PMEPR by creating peaks in time domain. The PMEPR for Multitones is in the range 5.44 dB to 5.65 dB which matches the expected PMEPR reduction for Newman phase codes. Comparing both Chirp and Multitones, their difference in PMEPR reduces as bandwidth increases. The difference ranges from 1.5 dB @800 MHz to 2.5 dB @1 MHz. As the signal bandwidth reaches the order of the receiver bandwidth, the difference between PMEPR reduces. Using the radar equation, the maximum detection range for Chirp with respect to Multitones will be up to 15% greater in narrowband and up to 9% greater in wideband. The simulation results show that from 4 bits, the PMEPRs are at most 0.1 dB away from their nominal values which is negligible. Thus with respect to PMEPR, the minimum resolution required is 4 bits.

#### *4.1.2. Power efficiency*

The effects of the quantization process on the nominal value of power efficiency are now evaluated through simulations for all bandwidth-time configurations of Chirps and Multitones under test. The power efficiencies of both waveforms increase as the bandwidth-time product increases. The relative error on power efficiencies between both Chirp and Multitones decreases as the bandwidth-time product increases. Multitones have higher power efficiency than Chirp but the error is lower than 2% which is negligible. Thus both waveforms are equivalent regarding power efficiencies.

A minimum of 10 bits is necessary to get within 5% of the nominal power efficiencies for every signal configuration. With lower bit resolution, Chirp is more power efficient than Multitones. So in case of low bandwidth-time product and low bit-resolution, Chirp has a higher efficiency by up to 12%.

#### *4.1.3. Pulse compression*

If the bit resolution is not sufficient, the pedestal level of the pulse compression increases, although the characteristics of the main lobe and second side lobes are not affected. In order to dimension the digital radar DA/AD converters in single target scenarios, the highest bandwidth-time product should be set, in order to determine the required number of bits to obtain a pulse compression close to the nominal value. Considering a relative mean error of -40 dB and relative max error of -27.5 dB acceptable, the results showed that Chirp requires 14 bits resolution and Multitones 15 bits resolution to meet the acceptable error level for all signal configurations. Since the test bench only has up to 10 bits resolution, the quantization noise for any waveforms increases by 6 dB for every missing bit. The extra bit required for Multitones is related to PMEPR: The Multitones are hindered compared to constant envelope signals such as Chirp, explaining the need for an extra bit to reach the same relative mean error. Increasing the number of bits further than the minimum requirements reduces the noise on the curve; the distance compression pedestal remains unchanged. When using a measured reference, the noise floor will be raised by 6 dB if the minimum number of bits is not respected. However, the transfer function is corrected since the signal comes from the radar system.

## 4.2. Simulated system level performances

The average power in the useful bandwidth is determined by combining the results of PMEPR and power efficiency from the simulations at 10 bits for quantization. The difference in average power between Chirp and Multitones is in the range 1.18 dB to 2.55 dB. The difference in average power shows that Chirp will have 7% to 16% higher detection range compared to Multitones. In terms of consumption, the Chirp should be more efficient than Multitone signals at the amplifier and ADC level. Especially if the system has a low bit-resolution and is narrowband, Chirp should be favoured over Multitones. On the difference in average power between both waveforms, the result showed that as the signal bandwidth reached the order of the receiver bandwidth, the gap in power was reduced. Note that the simulations were realized with a constant receiver bandwidth of 1 GHz for all bandwidth configurations. On operational radar systems, the receiver bandwidth should be matched with the signal bandwidth to reduce noise power and avoid interferers to maximize the SNR. Extrapolating from the results at 800 MHz, with a receiver bandwidth matched to the signal bandwidth, the difference in average power would be around 1 dB between Chirp and Multitones, resulting in detection range difference around 7%.

Concerning pulse compression with respect to quantization and saturation, Multitones and Chirp have the same characteristics for main lobe and side lobes. Chirp displays a better contrast than Multitones, but the difference is of the order of a couple of dBs.

The analysis revealed that given 10 bit resolution, any waveform reached their nominal values in terms of PMEPR and power efficiencies. Manufacturers of state of the art converters announce DAC AWG7122C [24] at 12GS/s with 10 bit resolution and ADC Proteus V6 [15] at 5GS/s with 10 bit resolution or Calypso V6 [15] at 3.6 GS/s with 12 bit resolution. This means that direct synthesis of signals up to X band and digitization of signals up to S band and part of C band is possible with nominal values of PMEPR and power efficiencies.

The error on pulse compression depends on the bandwidth-time product. For a set error on compression, Multitones need an extra bit in resolution to reach the set value. Depending on the chosen emission band, requiring an extra bit resolution on state of the art AD/DA converters will either result in increased AD/DA converter consumption or in a reduced sampling frequency.

The simulations were indeed basic using perfect quantization process. The simulations were performed without any noise, jitter, or any complex models. This allowed determining a base for the experimental tests. If the experimental results are not satisfactory, then the simulations will go through more complex modelling to approach realistic conditions. However, simple simulations were chosen to reduce time to experiment and get a feel of the processes at work.

## 5. Experimental results

In this section, the experimental results extracted from the measurements on the radar system will be analysed and compared to the simulated results. The measurements were done on a

triangular corner reflector located 27 m away from the radar test bench. The results will be presented as for simulations starting with PMEPR, then power efficiency, and finally pulse compression.

### 5.1. PMEPR

From Figure 2, the measured PMEPR for Multitones and Chirp are consistent with simulations on the closed-loop DAC-filter-ADC experiment, with a difference between measured and simulated values ranging from -0.19 dB to 0.8 dB. The PMEPR for Multitones is in the range [5dB; 6dB]. As for Chirp, PMEPR increases as the signal bandwidth grows closer to the receiver instantaneous bandwidth. The differences in PMEPR between both waveforms are within the range [1.5dB; 2.5dB].

From simulation results, it was determined that 4 bits were sufficient to reach the nominal value of PMEPR. On this experiment, upgrading the resolution from 8 to 10 bits only affected the result on PMEPR by 0.15 dB, which is negligible. This confirms the hypothesis on bit resolution for PMEPR.

In this experiment, the anti-aliasing filter was wider than the first Nyquist band and some of the frequency contents from the first and third Nyquist band leak into the second Nyquist band, thus the recorded signals can be distorted. Also, the gain is not flat over the full bandwidth. This might have contributed to the PMEPR degradation. However, the simulated and measured results on PMEPR match, and this was not predictable a priori.

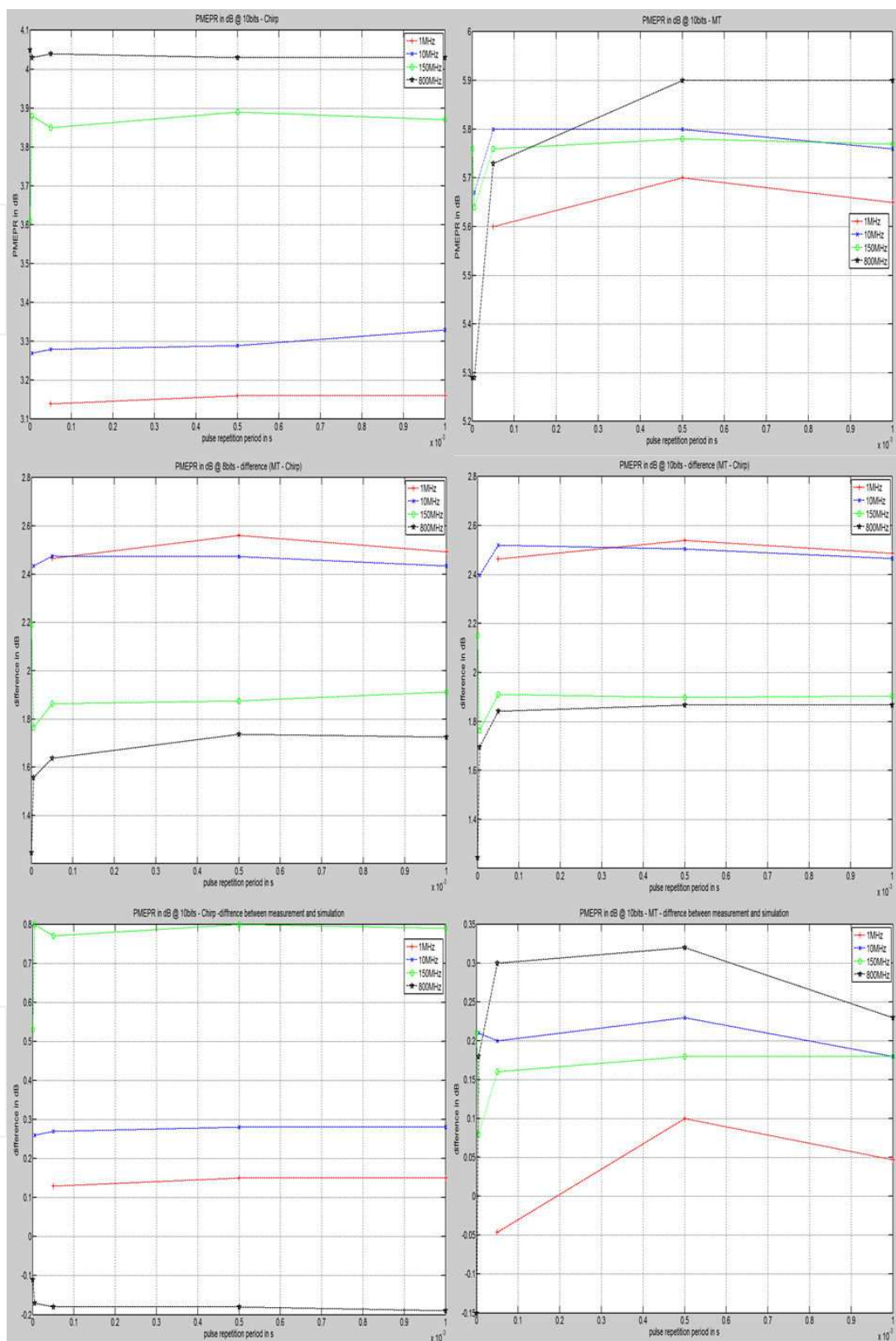
### 5.2. Power efficiency

The measured power efficiency is within 10% of the expected value and its general behaviour is consistent with simulations. Also, the difference between 8 and 10 bits resolutions is at most 0.62%, against 10% in simulation. So, this indicates that changing the DAC resolution from 8 to 10 bits for this experiment has little impact on this feature. This confirms the idea that 8 to 10 bit resolution is sufficient to get near nominal values for power efficiency.

Figure 3 displays the measured spectrum of Chirp and Multitones for 1 MHz and 800 MHz. It illustrates in the frequency domain the unevenness of the gain response of the closed loop DAC-filter-ADC experiment. Some unwanted signals are visible in the narrowband case, which reduces the power efficiency of the narrowband signals, explaining the error. However, these are also present in WB case, but since they are buried in the useful bandwidth, they do not affect power efficiency.

Since we are in closed loop, the unwanted signals come from the test bench. This means that with a radar platform with a receiver bandwidth adapted and a fine tuning to have a clean spectrum, the power efficiencies in narrowband would match the simulated values. Thus, extrapolating from the wideband case on this performance criterion, the measurement results are coherent with expected values, and this was not foreseeable before experimental testing.





**Figure 2.** Top: PMEPR @ 10 bits for Chirp and Multitones; middle: difference between Multitones and Chirp @ 8 and 10 bits; bottom: difference between measurement and simulation @ 10 bits for Chirp and Multitones



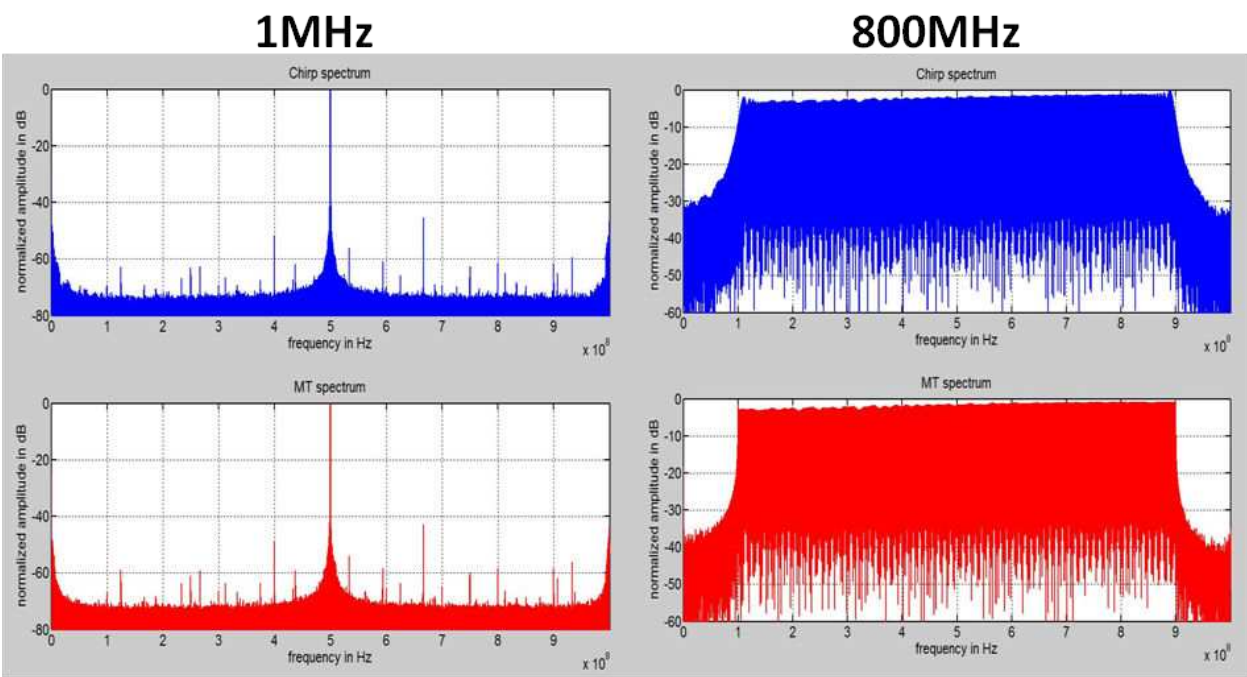


Figure 3. Measured spectrum of Chirp and Multitones at 1 MHz and 800 MHz

5.3. Pulse compression DAC-ADC measurements

The pulse compression was performed with a digital replica of the tested signals. The digital replica is a band-pass sampled version of the generated waveform. This generated waveform is sampled @ 10 GHz and the digital replica @ 2 GHz. The right hand side of the pulse compression presents reflections that are buried when the data is raw, but appear clearer when Hamming windowing is applied. The higher the bandwidth is, the more visible the circuit imperfections are, as shown in the figure. Indeed, problems with standing wave ratios cause uneven second side lobes @ 800 MHz, thus the second side lobes' characteristics will be exploited only for signal bandwidth, from 1 MHz to 150 MHz.

Tables 1 and 2 and Figure 4 show the measured impulse responses: main characteristics and differences/errors between measurements and simulations.

Bandwidth	1 MHz	10 MHz	150 MHz	800 MHz
Main lobe 3 dB width	133m	13.3m	0.9m	0.15/0.225m
Side lobe amplitudes	-13.3dB	-13.2dB	-13.3dB	-19.9dB/-10dB
Side lobe positions	±215m	±21.5m	±1.425m	±0.3m

Table 1. Main characteristics of the pulse compression with respect to bandwidth

In Table 2, the large errors for 3 dB main lobe width and side lobes positions at 800 MHz are caused by sample speck and perturbations induced by standing wave ratios in the circuit.

Otherwise, the other signals from 1 MHz to 150 MHz are within 3.1% of expected values, for 3 dB main lobe width and side lobe positions, and the difference in side lobes amplitudes are lower than 0.3 dB. Also both waveforms are equivalent on pulse compression. These results are really close to the expected values and the matching performances indicate good quality regarding the test bench.

Bandwidth	1 MHz	10 MHz	150 MHz	800 MHz
Main lobe 3 dB width error	<1.9%	<1.8%	<2.3%	<37%
Side lobe amplitudes difference	<0.3dB	<0.3dB	<0.3dB	-7dB / 3dB
Side lobe positions	<0.7%	<1.7%	<3.1%	<67%

Table 2. Relative error on main lobe width and side lobes’ characteristics between measurements and simulations

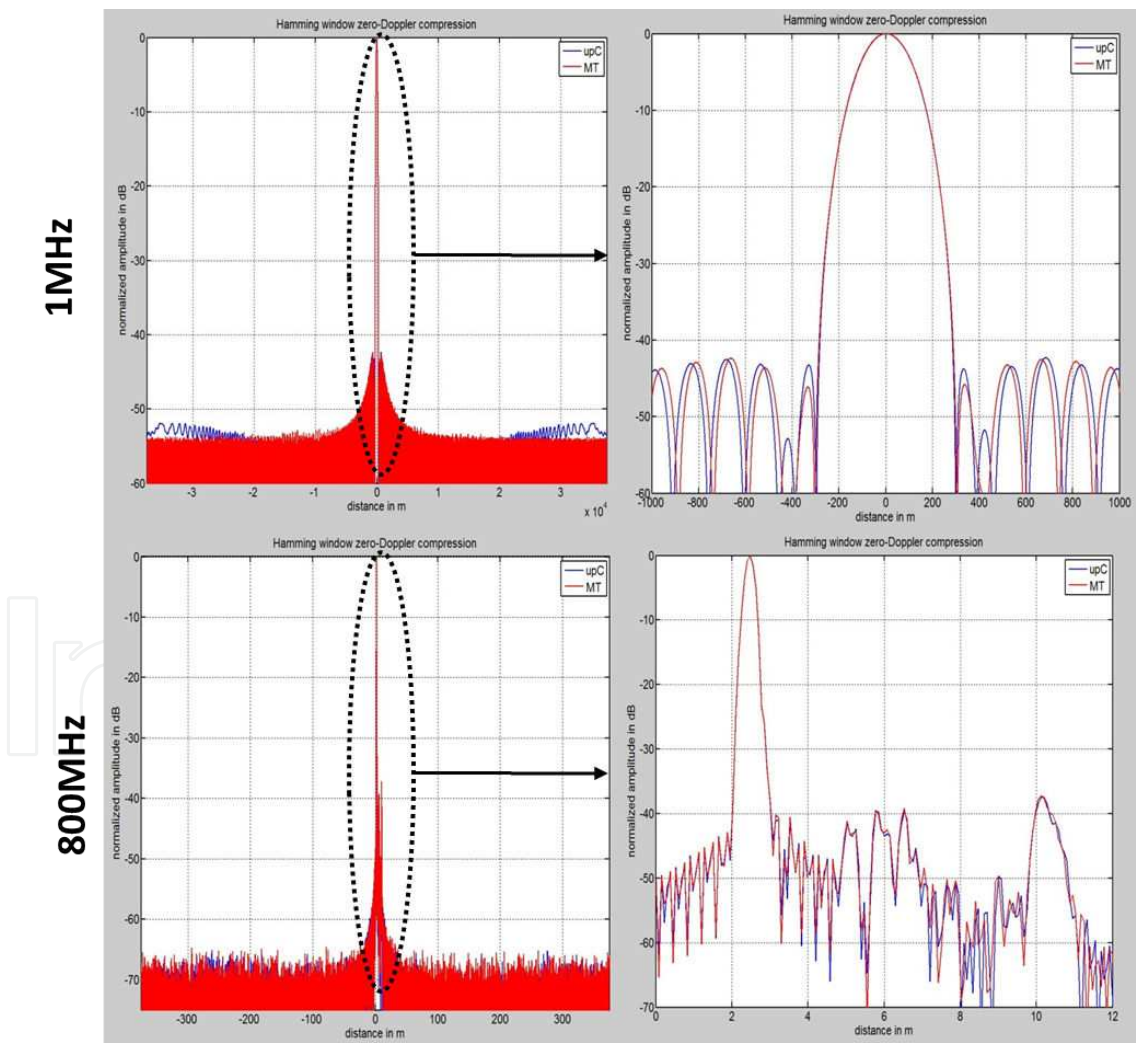


Figure 4. Compression in distance of Chirp and Multitones with (B 1 MHz, PRP 500 us) and (B 800 MHz, PRP 5 us) with Hamming window

The pulse compression displays large errors at 800 MHz caused by reflections in the circuit. From the results obtained for the other signals, reducing the standing wave ratios in the circuit would result in a good match between expected and measured performances at 800 MHz. In other words, imperfections in the circuit can be overlooked for narrowband systems as it only affects the pulse compression by fractions of dBs. As the bandwidth increases, the imperfections cause impairments and are visible in the distance compression. For radar systems, these reflection levels need to be reduced below target detection thresholds to avoid causing false alarms. Also, in the presence of two targets close from one another, one big target and one small, the reflection level may mask the smaller target, thus they should be kept below the desired contrast.

Furthermore, increasing the bandwidth allows locating smaller targets; however, a greater care has to be put to system reflections, as the sources of those reflections appear in the pulse compression. The upside is that with a high bandwidth, the sources of reflections can be more accurately located in the circuit.

Concerning Figure 4, the reflections in the circuit create secondary peaks that change the results on the error. Thus, this formula will not be experimentally validated.

## 5.4. Synthesis

The closed-loop DAC-filter-ADC measurements were remarkably close to the performance criteria's expected values. This allowed confirming the stability of PMEPR and power efficiency with bit resolution of 8 to 10 bits. This proves that the equipment used to perform the closed-loop experiment closely matches the simulation results obtained using perfect quantization process. These experiments showed that the digitizer technology was mature and that jitter is negligible. Thus simulation for high performance digitizers need not model the jitter. With state of the art digitizers, the expected performances in simulations will be the obtained performances in measurement.

### 5.4.1. Experiment on static targets: Stability measurements

This experiment used the whole radar system on a trihedral corner reflector located 27 m from the antennas and allowed determining the stability on the peak response of the compression in amplitude and phase over one pulse. The worst-case results are displayed in Table 3 and the evolution of stability over 16 ms. The measurements on stability were obtained using a digital replica and a measured replica. The difference in stability between the two methods is lower than 0.7 dB on the mean and minimum stability with respect to relative error, thus both methods are equivalent. Overall, the relative error in amplitude and phase is about -40dB in mean value and -30dB in minimum value. Both waveforms perform with equivalent performances with respect to stability. Thus, stability depends mostly on hardware rather than waveform.

This measurement of -40dB in stability shows the robustness of the system to clock drift. Note that stability measurements usually remain stable for a set period of time and then degrade with clock drift. Here two hypotheses can be considered: either the set time has not been

reached, or the clock is stable. The latter is actually the most plausible, as the sampling clock for the ADC was generated using the DAC, thus when the clock drifts in the DAC, it drifts accordingly in the ADC. Moreover the aperture jitters of the converters are lower than 200 fs, compared to a 500 ns sampling period which is excellent. Finally the mean value found in measurement is of the order of the predicted -42.3dB in RMS quantization noise floor, established for the Neptune VXS2 [15], with a sine wave @ 0 dBFS based on ENOB + losses.

Relative error		1 MHz	10 MHz	150 MHz	800 MHz
Raw	Mean	-41.6dB	-40.1dB	-38.6	-39
	Max	-32.11dB	-27dB	-28.8	-27.9

Table 3. Worst case relative error on stability with respect to bandwidth with digital replica

5.4.2. Synthesis

The experiments proved that the measurements matched the results obtained using perfect quantization. This indicates the degree of accuracy of the AD/DA converters (AWG7102 (86) and Neptune VXS 2 (74)) used in this experiment, which had aperture jitters lower than 200 fs. This accuracy is confirmed from the stability measurements, with a mean relative error on peak response subtraction of -40dB. With state of the art converters from 2006, the simple simulation results allowed accurate predictions of the PMEPR, power and efficiency, and compression performances. Future converters will have improved performances compared to that. This means that more complex modelling of jitter effect is unnecessary in that case. The requirements on bit resolution for radar systems could be dimensioned using this simple simulation process, rather than complex modelling.

In radar systems, the receiver bandwidth is matched to the signal bandwidth. This cuts off some of the Chirp spectrum, thus raising its PMEPR, and effectively reduces the gap in average power between both waveforms. Given unbound spectrum and linear properties, the average power difference between Chirp and Multitones is about 2.5 dB. When considering the receiver bandwidth matched to the signal bandwidth, this difference drops to about 1 dB. It is common in a radar system using Chirp to widen the receiver bandwidth to keep good signal properties and avoid spectrum clipping. Multitones could actually allow slightly reducing receiver bandwidth to slightly improve the SNR level, or use the full receiver bandwidth to slightly improve the spatial resolution. In any case, the conclusion of these measurements is that Chirp and Multitones have equivalent performances. The Chirp’s maximum detection range is extended by 7% with respect to Multitones’ maximum detection range. Also the maximum achievable SNR using the full ADC dynamic range would be about 1 dB higher for Chirp than for Multitones, thus improving a little detection performances and consumption at the ADC.

The outcome of the experiments is that Multitones are neck and neck with Chirp when the receiver bandwidth was equal to the signal bandwidth. The experiment on quantization allowed determining that the converter technology is reliable and accurate. This was demonstrated by the good agreement between measured and simulated results as well as the platform mean stability of -40dB.



## 6. Conclusions

In order to answer the issue on the contributions of Multitones to UWB software defined radar, an operational reconfigurable ultra wideband radar platform was developed. It supports any kind of waveforms and has 800 MHz instantaneous bandwidth on each ADC channel and 1.6 GHz tuning range. The mean stability is -40dB. The contribution of Multitones to UWB software defined radar is on performances, indeed Multitones displayed equivalent performances compared to Chirp. The detection range is at most 7% higher for Chirp than for Multitones. However Multitones allow more flexibility and thus enable the software defined radar development. Indeed with Multitones, it opens the path toward multifunction, spectrum insertion, sub-band independence, and signal diversity. On the effects of RF components on radar performances, it was demonstrated that simple simulations are sufficient to predict system performances. The AD/DA converters technology is now mature enough for radar applications. And for the performances criteria that were set a minimum of 10 bits resolution are necessary to get nominal performances. Higher resolution improves pedestal error on the impulse response.

## 7. Perspectives

The use of Multitones is mainly dealing with linearization [14] and performances for radio applications [4-5, 9-10, 12-13, 17-18, 23]. The results mostly come from simulations and were not experimentally validated. When looking into the impact of RF equipment on multicarrier signals, another key component stands out: the transmitter amplifier [5, 14]. The saturation effect will need to be studied to determine the best operating point to maximize radar detection capabilities. Concerning the spectrum insertion, the effect of notched spectrum on performances should be studied.

In the long term, a few technological limitations should be overcome before the implementation of a UWB software defined radar. Research must be pursued in digital architectures, truly adaptive RF components, and antenna arrays and digital beam forming.

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