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EMPIRICAL PERFORMANCE ANALYSIS OF LINEAR FREQUECY MODULATED PULSE AND MULTITONES ON UWB SOFTWARE DEFINED RADAR PROTOTYPE

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Abstract

In this study, we apply a protocol for an unbiased analysis of radar signals' performances. Using an experimental UWB software-defined radar, range profile, Doppler profile and detection range are evaluated for both Liner Frequency Modulated pulse and Multitones. The radar was prototyped and is comparable in overall performance to software defined radar test-beds found in the literature. The measured performances are in agreement with the simulations.

Keywords: Radar, Multitones, P3 phase-code, UWB, Software Defined Radio/Radar.

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In the past few decades, analogue circuits have been replaced by digital circuits.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 prominently uses the linear frequency modulated pulse (also known as Chirp) and has been routinely used since the late 40s [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 need for them. Lately, the use of a Unmanned Airborne Vehicles for military operations on urban terrain are required to simultaneously perform radar sensing and remotely communicate data to a base station. This cannot be achieved with just Chirp. Consequently, there has been an increased number of research efforts in integrating telecommunication waveforms such as Multitones in radar applications.

The constant developments in AD/DA converters, digital signal processors, signal synthesis & digitization and component's instantaneous bandwidth allow digital platforms to process ultrawideband (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 hardware, converters, and digital signal processors. 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.

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 [3]. Also in the presence of frequency selective fading, Multitones can still ensure successful detection of the target [4]. The waveform/spectrum agility is essential for stealthy operations to evade jamming and spectrum reuse with radar networks [5]. As a result, our research question is how do Multitones signals compare to Chirp signals in multifunction radar applications?

This background and literature review is provided next, part II examines the current knowledge of Multitones radar performances and the practical implementations of reconfigurable radar. Part III depicts the radar prototype implementation as well a the experimental setup. Finally, in part IV, the performances of the tested signals are analyzed using a direct comparison of simulations with experimental results from the implemented radar.

2 Literature Review

Recent studies report on the telecommunication capabilities of Multitones in SAR systems has been addressed without considering radar performances [c.f. 6]. Moreover, the relative performance of Multitones were investigated in a radar context [7][8][9]. In [7], the results showed that a higher level of precision was achieved using Multitones rather than poly-phase single carrier signals.

Using trains of diverse amplitude/phase-coded Multitones [2][8][9], they achieved near thumbtack ambiguity functions.

As opposed to Chirp, the resulting ambiguity function does not present range-Doppler coupling [2], adversely the pedestal level is higher.

New radar advances using the inherent structure of Multitones are appearing such as target velocity resolution while using frequency hopping [8] and target velocity ambiguity resolution [9].

It should be noted that much of the results in this area have been obtained through simulation. To the best knowledge of the authors, the fundamental radar performances of Multitones are not adequately quantified and the comparison of Multitones to a viable radar waveform would complement the studies found in the literature. The most commonly employed signal in operational radar is the linear frequency modulated (LFM) pulse [2] and its performances will set a reference to evaluate the performances of Multitones.

Regarding reconfigurable radar implementations, only a handful of papers dealing with laboratory experimental radar implementing Multitones signals have been found [6][10][11][12]. Design rules were drawn (details in [13]) from this study and used for the design of prototype.

The development of software-defined radar technology is still in its infancy. Its reconfigurability is bound in terms of degrees of freedom (waveform generation, bandwidth, frontend architecture). Increased flexibility of the radar system often means increased hardware complexity or increased interferences in the receiver.

3 Conception of software defined radar

This section describes a protocol that can be applied for radar signals unbiased comparison, the implementation of the prototype and the experimental set up.

3.1 Design protocol for unbiasedly studying radar signal performances in practice

To perform a comparison of various signals without bias, it is important that waveform-independent criteria are selected. Furthermore, the simulation model and experimental platform should be identical. The range/Doppler profiles and the maximum detection range are chosen at first to assess radar signals.

In this study, MATLAB models for simulations and the radar test-bed for measurements were devised to set the ground for an unbiased comparison of the radar signals and to allow a direct comparison between simulations and measurements.

3.2 Experimental Design

Design rules were drawn from the study of existing software defined radars [6][10][11]. First, the instantaneous bandwidth should be in excess of 500 MHz to at least match reviewed radar test-beds [6][10][11] and to obtain finer spatial resolution for imaging. The architecture has to be devised in order to support any signal without modifying the hardware. Following these design rules will permit an unbiased comparison of various signals on the same platform. Also a special feature was added (not present in commercialized radar), a fraction of the transmitted signal is recorded as reference to improve match filtering and consequently pulse compression performances by partially compensating for fluctuations in circuit frequency response (especially when high power amplifiers are used).

The experiment took place in a 12m deep anechoic chamber. Therefore, a bistatic set up is required as well as continuous wave signal emission to allow for at least 20dB gain after pulse compression.

A general view of the experimental radar test-bed is presented in Figure I and its characteristics are shown in table I. A detailed description is available in [13]. The only variation is the ADC Tektronix DSA71254 [14].

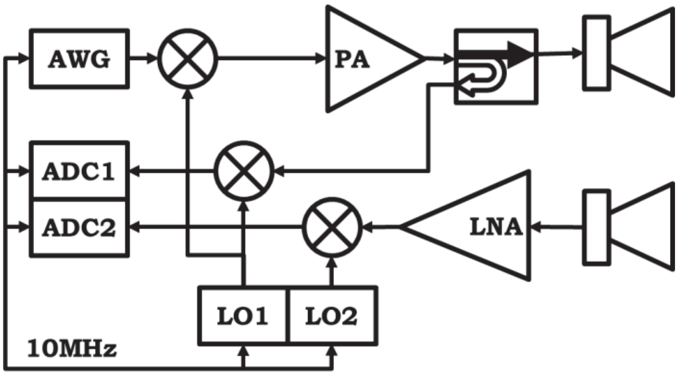

Figure I: synoptic of experimental radar test-bed

Intermediate / Radio frequencies	1.1-1.9 GHz / 10-11.6 GHz
Instantaneous Bandwidth/ Agility	Up to 800MHz / 1.6 GHz
Direct synthesis sampling frequency	10GS/s / 1st Nyquist band / 10bits
Direct sampling frequency	6.25GS/s / 2nd Nyquist band / 8bits
Mode / Antenna / Gain / Polarization	Bistatic / Horns / 20dB / VV
Doppler sampling	configurable
Pulse repetition period / waveform	configurable / configurable

Table I: software defined radar prortoype characteristics

The signal processing algorithm was devised to be waveform-independent for unbiased analysis of various radar signals. Radar systems commonly implement match-filtering for target detection, this technique optimizes signal-to-noise ratio in presence of white noise.

The proposed range-Doppler imaging algorithm is depicted in Figure II & III and the only parameter that varies in the proposed algorithm is the acquired number of samples to match the tested signal configurations.

In Figure II, the algorithm constructs the range profiles using matched filtering and is described in details in [13]. Figure III describes the method used to obtain the Doppler-profiles.

The phase modulation caused by target motion is sampled over a fixed period $T_{Doppler\_sampling}$ (e.g. 5µs) which dictates the Doppler ambiguity $\Delta\upsilon$. N range profiles are accumulated over time for Doppler resolution $\delta\upsilon = \Delta\upsilon/N$. A Hamming window is applied in the time direction to improve the peak-to-sidelobe ratio. Zero-padding is then applied up to the next power of two $2^X \geq 2N$ before a radix-2 inverse FFT is used to form the range-Doppler image.

The parameters of the Tektronix DSA71254 [14] ADC (which is part of the test-bed) are fed to the simulator to estimate the processing power requirements for the proposed algorithm. The A2D converter has an 8-bit resolution and thus requires one byte per sample. With a set sampling frequency of 6.25 GS/s, the data stream is 6.25 GB/s per A2D converter when recording continuously.

The required processing power in number of real multiply/accumulate operations per seconds (MACS), to form a range-Doppler image in real-time with the proposed architecture is given in equations (1) [13] for range profile and (2) for Doppler profile. Results are shown in Figure IV in comparison to state of the art FPGAs from Xilinx and Altera.

$$\left(6M + 35 \cdot 2^Y n(Y+1)\right) \cdot f_{IR} \tag{1}$$

$$M\left(6N + 5 \cdot 2^{Z-1}(Z-1)\right) \cdot f_{IR}/N \tag{2}$$

Where n is the number of channels, M is the vector length and X and Y are integers so that $4M \leq 2^Y$, $2N \leq 2^X$ and f_{IR} is the frequency at which range profiles are formed.

The estimated required processing power is in the range 3.5 to 10 TMACS (TeraMACS). However this is close to the announced performances of the new FPGA chipsets (Altera Stratix V [15] ≤ 2.5 TMACS and Xilinx Virtex 7 [16] ≤ 5.314 TMACS). The practical implementation of the proposed algorithm on an FPGA platform for various vector sizes still has to be developed. Based on the estimated processing power requirements and the capabilities of the new FPGAs, real-time processing with two A2D converters with 6.25 GS/s sampling frequency and an 8-bit resolution is feasible. Optimizations in terms of processing power would be required by implementing e.g pulse bursts, decimation, polyphase filters for coherent integration.

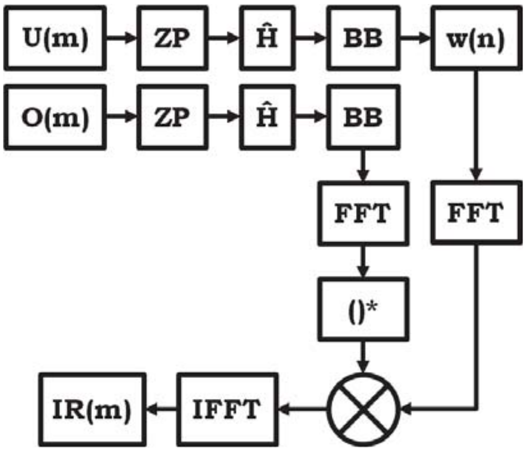

Figure II: Range-profile radix-2 FFT algorithm[1]

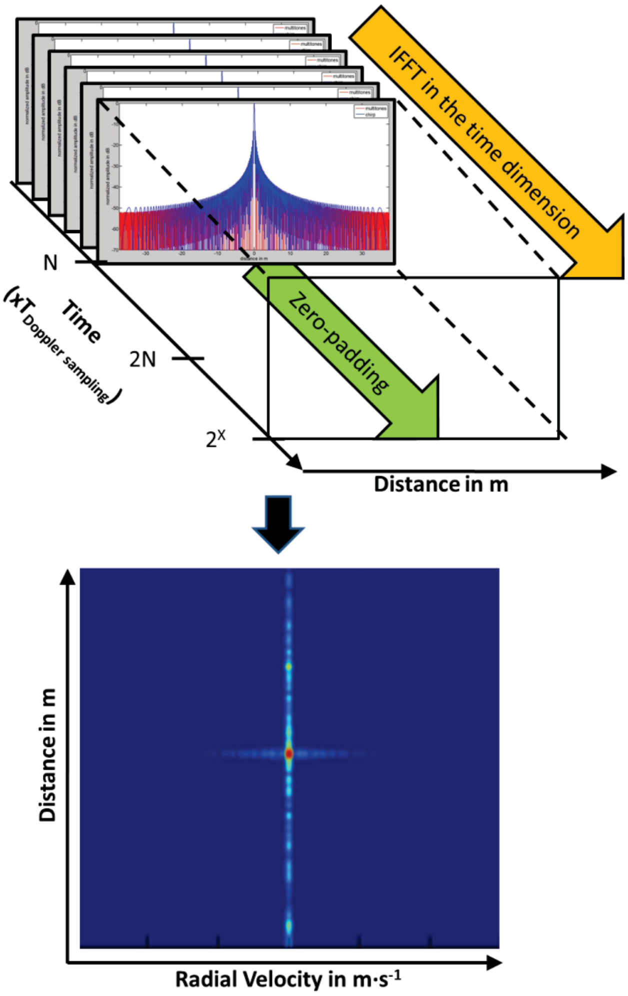

Figure III: Doppler-profile radix-2 FFT algorithm[2]

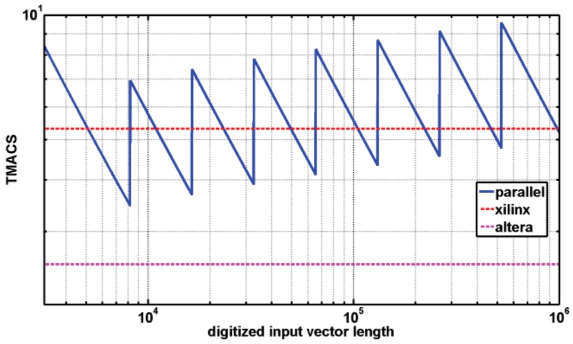

Figure IV: processing power requirements for the experimental radar test-bed in TeraMACS for various input vector sizes – sampling frequency 6.25GS/s, Doppler resolution $\delta\upsilon = \Delta\upsilon/N$ $(N = 1000)$ and a word length of 8bits

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[1] U(m): test signal samples, O(m) reference signal samples, ZP: zero-padding, Ĥ: Hilbert transform, BB: baseband, w(n): window function, FFT: radix-2 FFT, ()*: complex conjugate, IFFT: inverse FFT, IR(m): range profile

[2] U(m): test signal samples, O(m) reference signal samples, ZP: zero-padding, Ĥ: Hilbert transform, BB: baseband, w(n): window function, FFT: radix-2 FFT, ()*: complex conjugate, IFFT: inverse FFT, IR(m): range profile

3.3 Implementation of the Software defined radar test-bed2.1 Figures and tables

The radar setup is depicted in Figure V and the details of the implementation can be found in [13][17]. Its performances (see Table I) are comparable in performances with state of the art platforms [13]. This reconfigurable radar test-bed can digitally configure the signal/frequency agility without any changes in the RF frontend.

In Figure VI, the target is an active transponder in an anechoic chamber. The active transponder emulates Doppler by applying a square modulation on the signal. As a result, this target produces two fixed echoes and a Doppler shifted echo as illustrated in Figure VII. Consequently, this set-up allows for reproducible experiments since the fixed echoes are static and the modulation is unchanged. The data is saved on a computer to be later processed by MATLAB.

The hardware setup should be carefully devised to perform reproducible experiments constitute and form the foundation of an unbiased signal comparison.

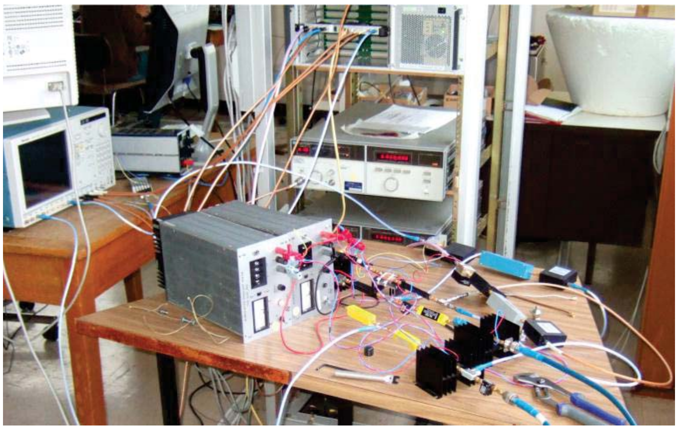

Figure V: software defined radar prototype

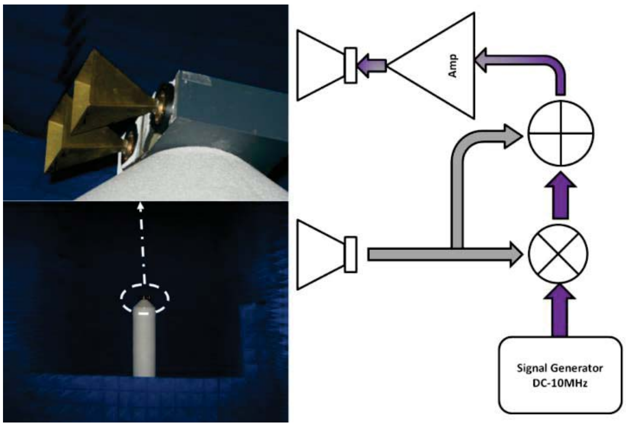

Figure VI: active transponder (left) experimental setup (right) synoptic

4 Simulated vs measured results comparison of radar signals' performances

4.1 Tested radar signals

The software defined radar operates in CW mode and the signal configurations will include the bandwidths (B) of 1 MHz, 10 MHz, 150 MHz and 800 MHz, and signal period (T) of 500 ns, 5 µs, 50 µs, 500 µs and 1 ms. All the tested configurations have a bandwidth-time product greater than 75.

The tested waveforms are the P3 phase-coded [2] Multitones and the linear frequency modulated pulse. The LFM pulse is used widely in operational radar and will therefore set a viable reference to evaluate the performances of Multitones against it.

The equations of Chirp (3) and Multitones (4) are as follows.

$$upC(t) = real\left(exp\left(i2\pi\left(f_0 + \frac{B}{2T}t\right)t\right)\right) \quad (3)$$

$$MT(t) = real\left(\sum_{n=0}^{N-1} exp\left(i2\pi\left(\delta f\left(n_0 + n\right)t + \phi_n\right)\right)\right) \quad (4)$$

where $\Phi_n = N^{-1}\pi(n-1)^2$ is the P3 phase modulation and *t* is in the range *[0;T[*, T is the pulse repetition period, $B = N\delta f$ is the signals' bandwidth, N is an integer and the number of frequencies in the Multitones, $\delta f = T^{-1}$ is the Multitones' frequency spacing. $f_0 = n_0\delta f$ is the signals' lower frequency.

Better results will be obtained in pulse compression for Multitones if the orthogonality is maintained (constraints for signal synthesis and acquisition to avoid inter-modulation distortion). Note that better linearity is achieved for Chirp than for Multitones with fewer constraints.

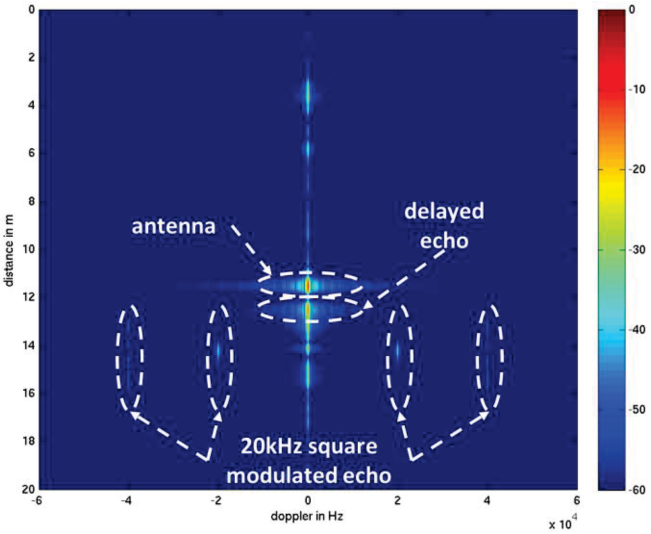

Figure VII: range-Doppler image of the active transponder

4.2 Range profile results: Simulations and Measurements

For range profiles, the study conducted in [13] established (see Table II) that waveforms are < 3.1 % of the expected values, for spatial resolution and sidelobe distance, and the difference in sidelobe ratios are < 0.3 dB (large differences with 800 MHz bandwidth are due to sample speck and the presence of reflections in the test-bed). The performances of LFM pulse and Multitones are equivalent in range profile.

Bandwidth	1 MHz	10 MHz	150 MHz	800 MHz
Spatial resolution (relative error)	133 m <1.9 %	13.3 m <1.8 %	0.9 m <2.3 %	0.225 m <37 %
Sidelobe ratio (difference)	-13.27 dB <0.3 dB	-13.27 dB <0.3 dB	-13.27 dB <0.3 dB	-13.27 dB [-7;3 dB]
Sidelobe distance (relative error)	±214.8 m <0.7 %	±21.4 m <1.7 %	±1.425 m < 3.1 %	±0.3 m <67 %

Table II: comparison of measured results with respect to simulated results [13]

4.3 Doppler profile results: Simulations and Measurements

For Doppler profiles, the active transponder modulates the incoming signal with a 700Hz square wave. With this modulation, the narrowband approximation used for the Doppler processing introduces an integrand error [18]. Considering an error of smaller than 5% is acceptable, this algorithm is valid for signal configurations with Bandwidth-Time products between 75 and 100k. From Figure VII, a section of the 2D image is taken along the Doppler axis where the peak response of the modulation is detected as shown in Figure VIII.

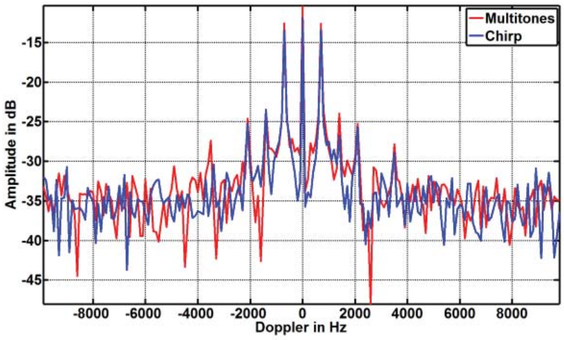

Figure VIII: distance cut of the range-Doppler image – modulation 700Hz – signal bandwidth 150MHz, period 50µs

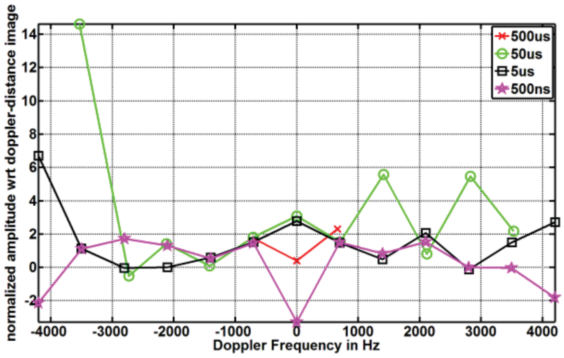

Figure IX: difference (Multitones - Chirp) of the amplitude of the Doppler peaks detection in the distance cut for signals with 150MHz bandwidth.

The overall results for the tested configurations show that Multitones perform better with modulation than Chirp on average between 0.5dB and 3dB. This differs from simulations, where both waveforms performed identically with respect to modulation. The hypothesis is that Multitones perform better when measuring time-varying target imaging. In [11], Multitones are used in a radar cross-section measurement system to improve imaging in presence of micro-Doppler. Further investigations in the simulation model and experimental analysis are necessary to confirm the results on Doppler.

4.4 Maximum slant range detection results: Simulations and Measurements

In [13], it was demonstrated empirically that Chirp provides an extra 15 % in slant range detection with respect to compared to P3 phase-modulated Multitones.

5 Conclusion

This paper applied a protocol for an unbiased comparison of signals for radar applications. The implemented radar test-bed allows a direct comparison of simulations and measurements without bias. The software-defined radar performances matches the platform presented in section II. The data processing was conducted using MATLAB.

Based on simulated and measured data, the LFM pulse and P3 phase-modulated Multitones present the same detection performances in distance. However the LFM pulse can sense the same target 15 % further than Multitones. Also preliminary results show that Multitones perform better than LFM pulse when imaging time-varying targets. Further investigations are required to confirm this trend.

Multitones has an added-value for radar applications with wireless communications capabilities. Implementing Multitones in radar implies 15% loss minimum in detection range (for PMEPR reduction schemes comparable to P3). Other classic radar signals may outperform Multitones when looking at individual radar performance criteria (PMEPR, ambiguity function, telecommunications), however they outperform any other in a multifunction scenario. As such, Multitones can be thought of as the decathlete of waveforms – not be the best in any individual discipline but the best overall [13]. Furthermore the emergence of new processing capabilities with Multitones (such as target velocity resolution while using frequency hopping [8] and target velocity ambiguity resolution [9] which cannot be implemented with LFM pulse) should compensate for Multitones' shortcomings. LFM pulse will probably remain the prominent signal for long range applications (e.g transhorizon radar). Multitones is likely to become the prominent waveform for short to mid-range applications – and is very likely to succeed to LFM pulse in the future.

This study showed that the required processing power is greater than what can be achieved by the latest FPGA chipsets using state of the art ADC. Based on the prototype presented in this paper, the required processing power is in the range of the latest Virtex 7 [16] capabilities. the algorithm still has to be programmed on FPGA and real-time processing will demand several FPGAs, pipelining, pre-processing and decimation to reach this goal. Real-time applications are also affected by bus communication speed and writing speed for storage. UWB software defined prototypes will probably need to operate in bursts and store rather than continuous operation, and then process the data offline.

6 Perspectives

An improvement of the proposed architecture can be achieved by time-interleaving the channels. It will require fewer components and reduce the required TMACS while retaining these prototypes advantages. Switches would bypass the antennas to acquire a reference, consequently disrupting detection. Moreover, added constraints on synchronization and signal coherence are required to reduce the calibration-cycle frequency. The development of new radar concepts (hardware+digital signal processing) will continuingly improve on processing power requirement and data throughputs, which are the major contributors in hindering real-time processing.

The algorithm proposed in this work is only a building block of the radar detection system. Current trends show that single-chip signal processors are preferred and with increasing data throughputs, the intra-chip interconnections to sustain such throughput are becoming problematic.

For this study, the algorithm assumed narrowband approximation for Doppler processing and the tested Doppler were within those bounds. However Doppler spread will affect the orthogonality of Multitones and thus results may differ for different phase-modulations. A balance will need to be found between wireless communications and radar depending on the implemented phase-codes. Software defined radar use signal/frequency agility and notched spectra hence performances will be affected, further investigations will be necessary to evaluate the impact of these factors on radar/telecommunications.

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