Inter-range-cell interference free compression algorithm: performance in operational conditions

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Abstract: The analysis of the performance of a novel algorithm found in the literature, the inter-range cell interference (IRCI) free compression algorithm, is presented in this paper. The algorithm presents a Dirac response in distance compression with a pedestal error at -350 dB. These performances would be very valuable for the radar field. The robustness of the performances for the IRCI free compression algorithm and matched filtering (MF) compression algorithm are explored first in simulations with point targets. Their sensitivity to bit resolution is also assessed. Both algorithms are then tested with measured signals from a wireless test performed using an ultra-wide band software defined radar platform with 800 MHz instantaneous bandwidth in X-band on a trihedral corner reflector. For an orthogonal frequency division multiplexing signal with *N* carriers, the results show that IRCI free compression algorithm offers an extra 2 dB in contrast for this measurement with an added processing cost of at least *4N* real multiplications when compared to MF compression algorithm.

Keywords: radar, inter-range-cell interference (IRCI), orthogonal frequency-division multiplexing (OFDM), zero side lobes, performance evaluation.

I. Introduction

In a series of papers [1-3], a novel inter-range-cell interference (IRCI) free compression algorithm with orthogonal frequency division multiplexing is proposed and is shown to display a Dirac response in range as opposed to the sinus cardinal (sinC) response that is presented by a conventional matched-filtering compression obtained with linear chirp. This paper documents the results from an exploration of the performance of the IRCI free algorithm and compares the results to those obtained when matched filtering (MF) [4] is applied on the same OFDM signal. A Dirac response in range is an ideal response and removes shadowing phenomenon of smaller targets by large targets' side lobes. This paper uses simulated and experimental results to assess the performance of both algorithms in operational conditions with limited bit resolution, band-pass signals, multiple targets and using an ultra wide band radar front end.

II. Signal Characteristics and conditions

A. OFDM signal

The OFDM signal used in simulations is defined in (1).

$$MT(m) = real\left(\sum_{n=0}^{N-1} e^{j2\pi\left((n_0+n)\frac{m}{M}+\phi_n\right)}\right) \quad (1)$$

where m is the sample number, n_o is the start frequency index, M is the number of samples per period, N is the number of carriers, and ϕ_n is a P3 phase code [4] as defined in (2).

$$\phi_n = \frac{\pi(n-1)^2}{N} \quad (2)$$

B. IRCI free compression algorithm

The algorithm described in [1-3] is inspired from communications systems and uses OFDM signals with a guard interval to achieve inter-range-cell interference (IRCI) free and ideally zero side lobes for range reconstruction. This algorithm was proposed to enhance SAR imaging range compression. It can be implemented as follows. A Fast Fourier Transform (FFT) is applied on the test and reference signals to convert the signal from the time domain to frequency domain. The test signal is composed of the backscattered signals form the targets in the observed scene. The reference signal can either be a digital replica of the transmitted signal or a measured reference used to compress the signal to form the distance response. The test signal is then divided element-wise by the reference signal. An inverse FFT (IFFT) is applied on the result to obtain the pulse compression. The signal requires a guard interval to allow the OFDM signal to have complete pulses returning from all the scatterers in the observed scene. This guard interval has to be discarded before compression.

C. Operational conditions

The IRCI free compression algorithm relies on two essential conditions to work as described in [1-3]. First, the reference cannot present any zeros; otherwise, the computation of the result is impossible. When zeros are present, they are replaced by a high value (e.g 10^{32}) to allow the computation of the result. The second condition is the key to the outstanding performances predicted in [1-2]. The signal must be "critically complex sampled" in order to present a Dirac response in range.

III. Simulations

Simulations are conducted using identical test ad reference signals to compare the performance of IRCI free compression algorithm with MF algorithm. The signal was first tested on two point targets. The pulse response is normalized to the peak response of target 1. The targets are located at 15.02 and 37.52 m, their radar cross sections (RCS) are -6 and 0 dBsqm, respectively in an ambiguous range of 75m. The simulations did not consider free space losses.

A. *Signal bandwidth is equal to the sampling frequency*

This case is ideal where the signal bandwidth B is equal to the sampling frequency Fs. The signal is thus "complex critically sampled". In those conditions, if the distance ambiguity is constituted of Ns samples, each range cell corresponds to the range resolution of the signal which is inversely proportional to the signal bandwidth. In this ideal case, a Dirac response is obtained for both algorithms considered. Figure 1 shows the compression of both targets when Fs equal 10 GHz, the signal pulse repetition period (PRP) is 500 ns, thus Ns = 5000. The IRCI free compression algorithm and the MF algorithm yield the same result – a Dirac response with a pedestal error and side lobes at about -350 dB. The side lobes are caused by numerical truncation errors as the calculations were performed with 64-bit precision. The Dirac response is obtained because the OFDM signal has a constant amplitude across all frequencies. Both algorithms remove the phase modulation, yielding a Dirac comb across all frequencies. The result using Fourier transform identities for an echo with zero delay is in the form of the Dirichlet kernel (3) [5] that converges to a Dirac delta in range after IFFT when all frequencies have equal amplitude.

$$X(m) = \frac{sin(\pi m)}{sin(\frac{\pi m}{Ns})} \tag{3}$$

The Dirac is obtained by critically sampling the kernel yielding a peak response at m equal zero and the zero-crossings occur at every m different from 0. The Dirac response in distance as shown in Figure 1 (a) for both targets for an ambiguity of 75m and expanded views of target 1 and 2 in Figure 1 (b) and (c) respectively is identical for both algorithms.

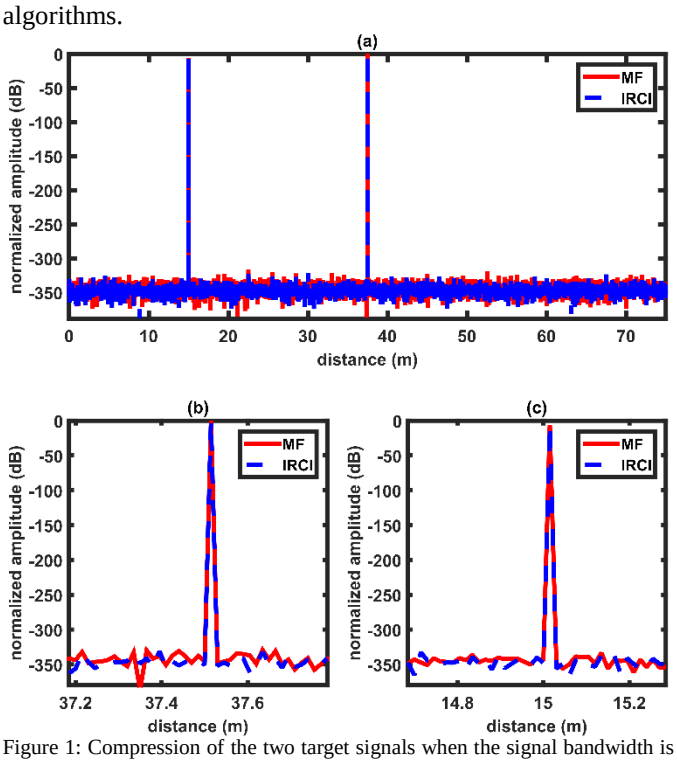

Figure 1: Compression of the two target signals when the signal bandwidth is equal to the sampling frequency for IRCI free compression algorithm and MF (a) full range ambiguity 75m with an expanded view around target 1 and target 2 shown in (b) and (c), respectively.

B. *Baseband signal, bandwidth is equal to 0.1Fs, the sampling frequency*

In this case the signal was baseband with a bandwidth equal to 0.1Fs. The signal was no longer critically sampled and presents a rectangular window in frequency domain. The compression displayed a Dirichlet kernel response as explained in II.A. The kernel was no longer sampled only at the zero-crossings. The pedestal error is about -50 dB, and the first side lobes are at -13dB below the peak responses.

The resulting outputs from the two algorithms are shown in Figure 2 (a) the contour of the compression for both targets for an ambiguity of 75m is shown for clarity because there are too many samples and two expanded views of target 1 and 2 in Figure 2 (b) and (c) respectively with all the samples. The performance is identical for both algorithms.

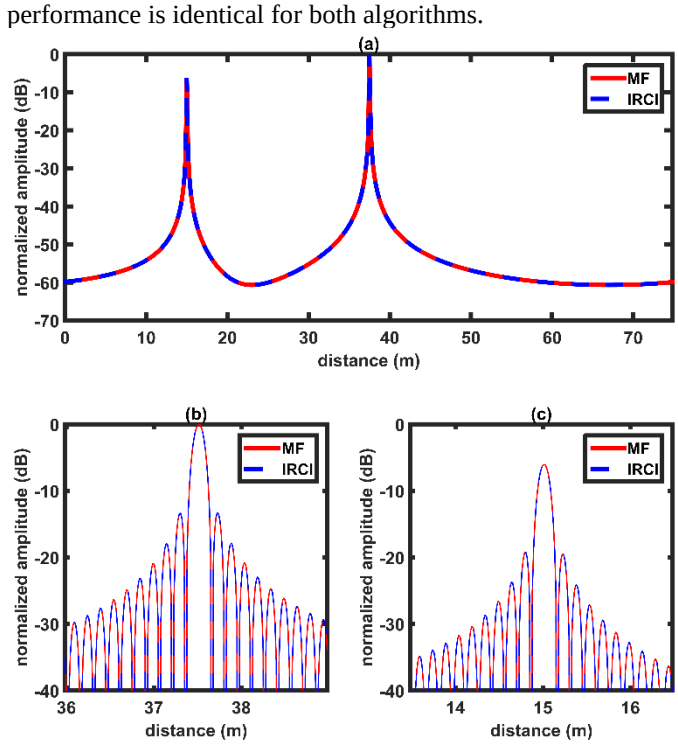

Figure 2: Compression of the two targets when the signal bandwidth is equal to one 10th of the sampling frequency for IRCI free compression algorithm and MF (a) the contour of a full range ambiguity 75m (for clarity) with an expanded view around target 1 and target 2 shown in (b) and (c), respectively.

C. *Real signal conditions*

The OFDM signal presented in II.A cannot be synthesized or digitized by converters and the precision of analogue-to-digital converters (ADC) for wideband receivers is limited e.g. 14 bits for the Tekmicro Charon V6 with a sampling frequency of 1.2 GHz [6]. Given that the two algorithms performed identically in the simulations shown in II.A and II.B, an evaluation of the IRCI free and MF algorithms under real signal conditions was carried out. The signal was set to have a bandwidth of 800 MHz, a start frequency at 1.1 GHz, and a signal period (PRP) of 500 ns. It was generated with a sampling frequency at 10 GHz and synthesized with a sampling frequency Fs1. The signal was tested for 3 different cases:

- A band-pass signal (when up on a carrier) with In-Phase and In-Quadrature (IQ) channels (Fs1 = 5 GHz)
- A band-pass signal with the real signal only and a Hilbert reconstruction of the complex part (Fs1 = 5 GHz)
- A band-pass signal with a real signal that is band pass sampled (Fs1 = 2 GHz) in the 2nd Nyquist band (sub-sampled frequencies but the sampling frequency is greater than twice the signal bandwidth therefore there is no loss of information) followed by a complex part reconstruction using a Hilbert transform.

The Dirac condition can be reproduced in all 3 cases as follows. In frequency domain, just before the IFFT, the OFDM signals are down converted to baseband and then the 400 in-band frequency coefficients of the OFDM signals are extracted and then used for compression, thus recreating the "critically complex sampled" conditions.

For the third case, the delay of the second target was changed to a fraction of range gate. The result is shown in Figure 3 for the third case with band-pass sampling. The first target is exactly at the range gate yielding a Dirac response. However the second target presents another sampling of the Dirichlet response, the peak value and the zeros are no longer hit but rather the envelope of the Dirichlet response: the well-known sinus Cardinal response. The backscattered signal from targets can never be predicted so expecting a perfect synchronization on all hits is unrealistic therefore the pedestal level will be directly affected by a single delay that is not perfectly matched to an integer number of range gates. An ideal response is superimposed on the first target to illustrate the difference in pedestal error. It can be observed that the two target peaks are recovered at the appropriate positions. The resolution, however, is reduced by a factor 12.5 since B is now 800 MHz against 10 GHz in section II.A. The performance is identical for both algorithms. Both algorithms yielded identical results.

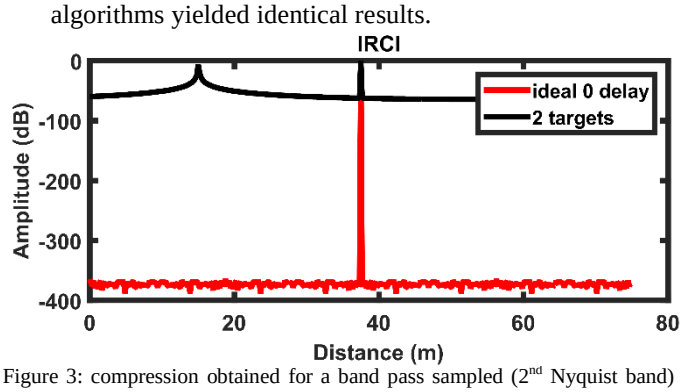

Figure 3: compression obtained for a band pass sampled (2nd Nyquist band) real signal with complex part reconstruction using Hilbert transform – for IRCI free compression algorithm for MF - full range ambiguity 75m

D. Sensitivity to converter bit resolution from 4 to 24 bits and additive white Gaussian noise (AWGN)

To further investigate the IRCI free algorithm, the signal as described in II.C is now quantized in amplitude from 4 to 24 bits, as shown in Figure 4, for an ideal point target of the reference and for the 2-target case. The dependence of the mean pedestal level to quantization is shown in Figure 5. As can be seen in Figure 4 and 5, the compression of an ideal point target using the IRCI free algorithm is not sensitive to quantization. In contrastthe compression of an ideal point target using the MF algorithm is sensitive to the converter bit resolution, as can be observed in Figure 5. For the 2-target case, the compressions obtained using both algorithms are equally sensitive to quantization and have same sensitivity to quantization as the ideal target case using the MF algorithm. In other words, as soon as there is more than one point target in the observed scene, both the MF and IRCI free compression algorithms have similar pedestal levels. The apparent advantage of IRCI free compression algorithm when compared to the MF algorithm using one ideal point target can be misleading.

The analysis of the sensitivity of both algorithms to AWGN yielded identical degradation in pedestal error with a decreasing signal-to-noise ratio.

Operationally, the presence of clutter and standing waves in the radar front end will be sufficient to destroy the advantages of the IRCI free algorithm when compared to the MF algorithm. When the results of the analysis of the sensitivity to quantization are analyzed further by applying a linear regression on the curves in Figure 5, a rate of change of the pedestal level to bit resolution is found to be about 6 dB/bit for the 2-target case for both algorithms as well the ideal target case for the MF algorithm. Considering (4) for the maximum achievable signal-to-noise ratio (SNR_{max}) for a sine wave with respect to the effective number of bits (ENOB), the rate of change is consistent with the expected sensitivity of 6.02 dB/bit for a digitized signal.

$$SNR_{max}(dB) = 6.02 \cdot ENOB + 1.76 \quad (4)$$

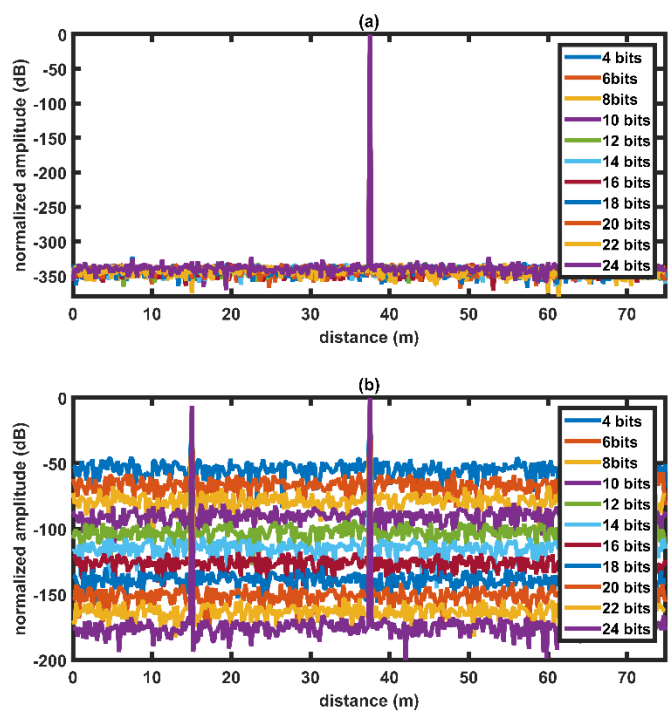

Figure 4: Sensitivity of IRCI free algorithm to converter bit resolution from 4 to 24bits for (a) the ideal point target case and (b) 2-target case

IV. Wireless Test

To determine the operational performance of both MF and IRCI free compression algorithms, a radar system (Figure 6) is used to measure the observed scene. Using the ultra-wide band software defined radar described in [7-8], the signal conditions as described in section II.C are reproduced experimentally. The raw OFDM signal measurements from the frontend are used to feed the algorithms. The main characteristics of the radar setup for the wireless test on a trihedral reflector at 27.5 m in line-of-sight of the radar antennae with an RCS of 30 dBsqm are given in Table I. Figure 7 shows the frequency coefficients extracted just before executing the IFFT operation on the data. It can be observed that the measured replica and measured signal from the wireless test have uneven spectra and standing waves are present.

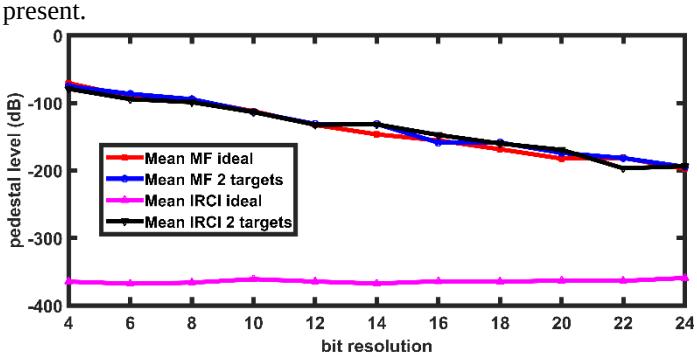

Figure 5: Sensitivity of MF and IRCI free algorithm mean pedestal level to converter bit resolution from 4 to 24 bits for the compression of the reference signal by itself (ideal) and the 2-target case taking the mean of the pedestal error.

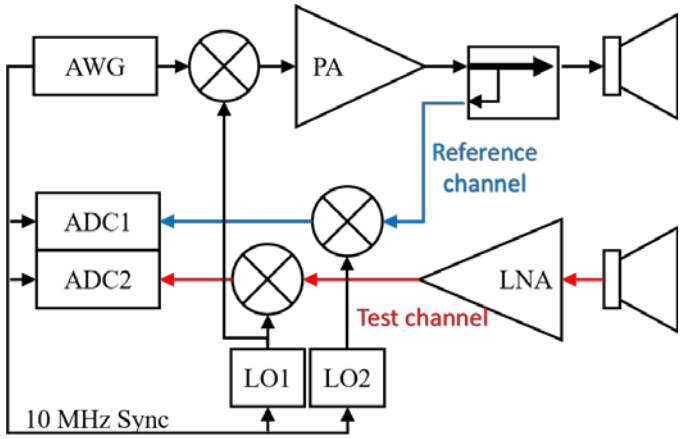

Figure 6: Radar synoptic of the experimental setup showing the reference and test channel

Figure 8 shows the compression of the measured replica with itself. The radar presents SWR in the measured reference signal below -30 dB compared to the main peak when performing the compression on itself. It can be seen in this case that the sensitivity of the IRCI to quantization is unaffected and has a pedestal level at approximately -350 dB. On the other hand, the MF algorithm shows a sensitivity to both the bit resolution and the unevenness in the band. The pedestal level for MF algorithm is about -65 dB. The result of the wireless test on a trihedral corner reflector for both algorithms are shown in Figure 9 (a) and (b) showing the full ambiguity and an expanded view around the trihedral corner reflector peak respectively. From this figure, the ISR is 1.4 dB better in the IRCI case and the PSR are quasi identical. On data points that have a value greater than -40 dB in amplitude, the compression obtained using the MF compression algorithm is about 1.9 dB higher in amplitude than the amplitude of the IRCI free compression on average which is not significantly better. In other words, the IRCI free compression will offer on average 1.9 dB better contrast than the MF algorithm on this measurement.

TABLE I
Main characteristics of experimental software defined platform

Parameter	Features
Intermediate Frequencies (IF)	1.1 – 1.9 GHz
Radio Frequencies	10 – 11.6 GHz
Instantaneous Bandwidth	Up to 800 MHz
Agility	Up to 1.6 GHz
Direct Synthesis	10 GS/s 1st Nyquist band 10-bit resolution
IF sampling	2 GS/s 2nd Nyquist band 10-bit resolution
Radar antenna setup	Bistatic 2 x Horn Antenna V-V Polarization 20 dB Gain

V. Implementation Considerations

The implementation of the MF algorithm and the IRCI free compression algorithms will vary only just before the IFFT stage. Two cases are considered; the first case is where the reference is fixed for compression and the second is when the reference is refreshed at the same rate as the measured signal to compensate for the front end transfer function.

When the reference fixed, the difference in number of operations between the two algorithms and, hence, the difference in run time happen just after the in-band coefficient extraction. The implementation of the MF algorithm requires the execution of an element-wise complex multiplication for each carrier coefficient while a complex division for each carrier is carried out in the IRCI free compression algorithm. A complex division requires first an inversion of the denominator and a complex multiplication, as shown in equation (4) [9].

$$\frac{a+ib}{c+id} = \frac{(a+ib)(c-id)}{(c+id)(c-id)} = (a+ib)\frac{c-id}{c^2+d^2} \quad (4)$$

The difference in processing between the algorithms for N carriers is then N real inversions, $4N$ real multiplications, and N real additions. When refreshing the reference continuously, the MF algorithms would need to calculate the complex conjugate of the extracted in-band coefficients. This requires a real inversion and a real addition by one. The difference in computation between the algorithms for N carriers would be reduced to $4N$ real multiplications. The run-time/computational overhead for the IRCI free compression algorithm is much higher than for the MF

algorithm in both cases, increasing the cost/reducing the speed at which this compression can be performed.

VI. Conclusion

The IRCI free compression algorithm relies on critical complex sampling to obtain the side lobe-free property observed in the compression and perfect synchronization. The compression of a signal by itself gives a Dirac response with -350 dB side lobes but the compression of a signal with multiple targets yields a pedestal level that is dependent on bit resolution of the converter, which theoretically is of -6.02 dB/bit and found to be -6.3 dB/bit experimentally. The pedestal level is also dependent on signal return delay. If it is not perfectly synchronized with the range gate then the sinus Cardinal function reappears because of the sampling of the Dirichlet function. Obtaining a Dirac every time would mean having an infinite number of range gates and thus an infinite bandwidth which is intractable. Since the target return delays are never known a priori and the signal bandwidth is limited, the range gates are limited and the signal is oversampled to obtain as much information as possible and be sure to capture as much energy as possible. Therefore unless windowing is used, the sinus Cardinal function will dictate the side lobe levels and pedestal level. Another aspect of this analysis is the limits of calculation in Matlab with double precision, the smallest increment is "eps = 2^{-52} or -313 dB", so any results under this value is hard to interpret. The performance on measurements shows that IRCI free compression algorithms offer approximately 2 dB more contrast than the MF algorithm for the chosen measurement and 1.4 dB on ISR for this measurement. This improvement in contrast comes at cost in implementation. For a fixed reference, compressing *N* carriers using the IRCI free algorithm requires *N* inversions, *4N* multiplications, and *N* additions more than MF algorithm and requires *4N* more multiplications when the reference is updated on every run. So operationally, this 2dB gain in contrast for compression is computationally costly and may be unfeasible when there are limitations on time , processing power, the number of available chip resources(area, slices,…) and/or on power consumption. This IRCI algorithm could be used in anechoic chambers for radar cross section measurements where precision is key and timing considerations are not as important.

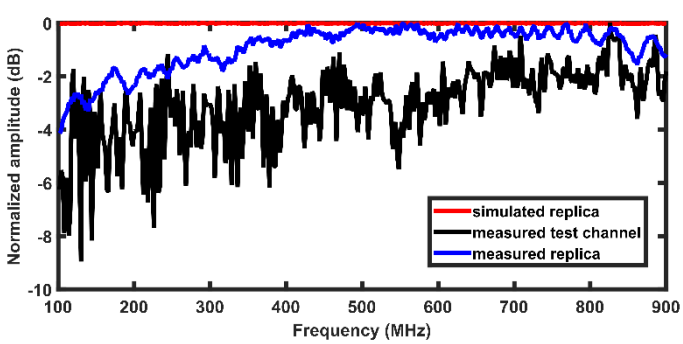

Figure 7: Extracted in-band frequency coefficients of the OFDM signal for the simulated replica/reference (red), measured replica/reference (blue), and the measured test signal.

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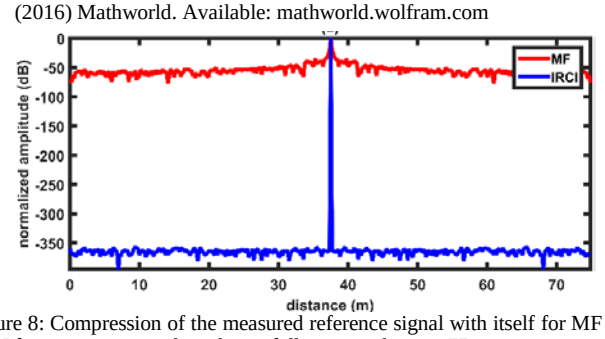

Figure 8: Compression of the measured reference signal with itself for MF and IRCI free compression algorithms - full range ambiguity 75m

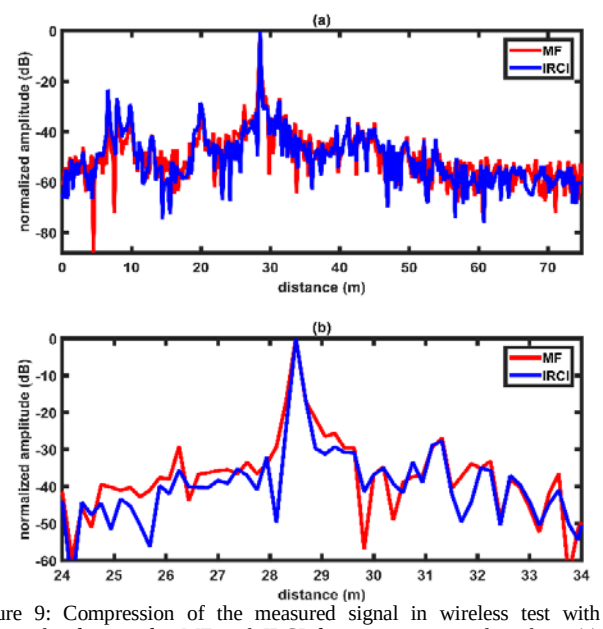

Figure 9: Compression of the measured signal in wireless test with the measured reference for MF and IRCI free compression algorithms (a) full ambiguity and (b) expanded view around the trihedral corner reflector peak.

Integrated sidelobe ratio on this measurement: ISR_{MF} = -10.77 dB ISR_{ICRI} = -12.24 dB, peak to sidelobe ratio: PSR_{MF} = -16.77 dB, PSR_{IRCI} = -16.6 dB.