The OFDM Joint Radar-Communication System: An Overview

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***Abstract*—This paper presents an overview of the OFDM joint radar and communication system concept which has been developed for automotive radar applications. Using an OFDM-based signal, the range and Doppler estimation algorithm are independent of the payload data and overcomes the typical drawbacks of correlation-based processing. The derivation of parameters for the operation at 24 GHz suited for automotive applications are then shown. The system concept is then verified with MATLAB simulation and measurement. A brief description of the on-going work to adapt this system to a realistic multipath-multiuser environment along with simulation results are also presented.**

***Keywords*—Doppler processing; interference cancellation; orthogonal frequency division multiplexing; radar; ray-tracing**

I. Introduction

The idea of combining a radar and a communication system on a single platform has long been proposed [1] but a relevant system concept has never been developed till now. Initially the major hurdle was that communication and radar systems utilize very different frequency ranges but as more and more radio frequency front-end architectures are replaced by processing in the digital domain nowadays, the gap between the hardware requirements for the radar and communication systems becomes narrower and the devices more similar.

A popular choice for the common radar and communication signal is the orthogonal frequency division multiplexing (OFDM) signals in combination with phase-shift keying (PSK) as OFDM offers advantages such as robustness against multipath fading and relatively simple synchronization. OFDM-like signals has been shown to be suitable for radar applications [2] and the feasibility of integrating communication functions in radar networks [3], [4] have also been explored. For the case of the radar function, it has also been been pointed out in another study [5] that OFDM-coded radar signals are comparable with linear frequency modulation (LFM) signals and furthermore, experiences no range-Doppler coupling. Hence the merging of the two platforms becomes a possibility and would lead to a significant cost-efficient measure in targeted application areas such as in the intelligent transportation networks which require the ability of inter-vehicle communication as well as reliable environment sensing.

The concept of the Orthogonal Frequency Division Multiplex joint radar and communication (RadCom) [6], [7] is presented here. The system uses OFDM communication signals as radar signals leading towards its dual role in object sensing and communication between systems. Unlike conventional radar processing approaches that use correlation-based processing [8], the ranging algorithm presented utilizes only Fourier transformations. Such a method not only allows for a relatively faster procesing speed but also reduces the sidelobe levels (as compared to [9]) while being independent of the transmitted data.

The OFDM RadCom concept as well as the range and Doppler processing schemes are presented in Section II. The requirements for its operation in the 24 GHz ISM band is discussed in Section III followed by the system concept verification with Matlab and measurement results in Section IV. Finally, the current on-going work to extend the RadCom for use in a multipath-multiuser scenario is presented in Section V.

II. OFDM RadCom Concept

The OFDM transmit signal consist of parallel orthogonal subcarriers, each modulated with a data. The resulting time domain signal is expressed by

$$x(t) = \sum_{\mu=0}^{M-1} \sum_{n=0}^{N-1} D\left(\mu N + n\right) \exp\left(j 2\pi f_n t\right), \qquad 0 \leq t \leq T \tag{1}$$

with N denoting the number of subcarriers used, M, the number of consecutive symbols evaluated, f_n, the individual subcarrier frequency, T, the OFDM symbol duration, and $\{D(n)\}$, called the 'complex modulation symbol', is the arbitrary data modulated with a discrete phase modulation technique e.g., phase-shift keying (PSK). Interference between individual subcarriers is avoided based on the condition of orthogonality given by

$$f_n = n\Delta f = \frac{n}{T}, \qquad n = 0, ..., N-1 \tag{2}$$

In the presence of a reflecting object at the distance R from the RadCom with the relative velocity of v_{rel}, which results in the Doppler frequency of f_D, the received OFDM symbol in time domain becomes

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$$y(t) = \sum_{\mu=0}^{M-1} \sum_{n=0}^{N-1} D_r(\mu, n) \exp(j2\pi f_n t) \quad (3)$$

where

$$D_r(\mu, n) = D(\mu, n) \exp\left(-j2\pi f_n \frac{2R}{c_0}\right) \exp(j2\pi f_D t) \quad (4)$$

Based on (4), it can be seen that the distortions due to the channel is fully contained in the received complex modulation symbol $\{D_r(n)\}$, which is obtained at the receiver at the output of the OFDM demultiplexer prior to channel equalization and decoding. Thus comparing the transmitted signal $\{D(n)\}$ with the soft-side received signal $\{D_r(n)\}$ would yield the frequency domain channel transfer function. This is computed by simply performing an element-wise division

$$I_{div}(\mu, n) = \frac{D_r(\mu, n)}{D(\mu, n)} \quad (5)$$

In this manner, the acquisition of the range and Doppler profiles will be independent of the payload data.

A. Range Processing

For an object at the distance R from the radar, all subcarriers within the same reflected OFDM symbol will experience a linear amount of phase shift equivalent to two times the time length taken to travel the distance R. Assuming that the object is stationary, the corresponding channel transfer function is

$$I_{div}(n) = \exp\left(-j2\pi n \Delta f \frac{2R}{c_0}\right) \quad (6)$$

The channel impulse response containing the range profile of the object can then be determined by taking an inverse discrete Fourier transform (IDFT) of $\{I_{div}(n)\}$

$$\begin{aligned} h(p) &= \text{IDFT}(\{I_{div}(n)\}) \\ &= \frac{1}{N} \sum_{n=0}^{N-1} I_{div}(n) \exp\left(j2\pi \frac{n}{N} p\right), \qquad p = 0, ..., N-1 \end{aligned} \quad (7)$$

B. Doppler Processing

Unlike with communication signals, the reflected radar signal of an object moving with a relative velocity of v_{rel} will experience twice the amount of Doppler shift according to

$$f_D = \frac{2\, v_{rel}}{\lambda} \quad (8)$$

where $\lambda = c_0/f_c$, with c_0 being the speed of light and f_c, the carrier frequency.

This causes a phase shift of $2\pi\mu f_D T_{sym}$ on every subcarrier of the μ-th OFDM symbol, where T_{sym} is the transmit OFDM symbol duration. It can be assumed that the Doppler affects all subcarriers by the same amount since the system bandwidth is much smaller than the carrier frequency. Thus for an object having a non-zero relative velocity to the radar, the corresponding time-varying channel transfer function (due to the Doppler only) is

$$I_{div}(\mu) = \exp(j2\pi f_D \mu T_{sym}), \qquad 0 \leq \mu \leq M-1 \quad (9)$$

By taking the discrete Fourier transform (DFT) through the time axis the Doppler term can be estimated.

$$\begin{aligned} h(q) &= \text{DFT}(\{I_{div}(\mu)\}) \\ &= \frac{1}{N} \sum_{\mu=0}^{M-1} I_{div}(\mu) \exp\left(-j2\pi \frac{\mu}{M} q\right), \quad q = 0, ..., M-1 \end{aligned} \quad (10)$$

III. SYSTEM PARAMETERIZATION

The system parameterization presented here is oriented towards automotive applications since one of the intended application area for such a system is in the intelligent transportation systems. The operation at the frequency of 24 GHz ISM band which is suitable for both the radar and communication operations has been chosen.

A. Common constraints

There exist two major constraints pertaining the joint operation of the RadCom; the first is the subcarrier spacing and the second is the cyclic prefix (CP) length. The subcarrier spacing is limited by the Doppler frequency which has the potential to shift the alignment of the subcarriers thus destroying their orthogonality. Assuming a maximum relative velocity for typical traffic scenarios to be v_{rel} = 200 km/h = 55.6 m/s, according to (8) this would result in the maximum Doppler shift of $f_{D,max}$ = 8.9 kHz for f_c = 24 GHz. Following a rule-of-thumb, it can be assumed that the subcarrier spacing of $\Delta f > 10\, f_{D,max}$ will ensure that the orthogonality remains.

To avoid inter-symbol interference (ISI), each elementary OFDM symbol is prepended with a prefix containing a repetition of some of its last values (thus rendering the time domain symbol 'cyclic'). This CP duration T_{CP} is governed by the *maximum excess delay* which is the maximum time difference between the arrival of the first and last propagation path in a multipath environment. Assuming that due to the high attenuation of the scattering process the maximum detectable distance is 200 m and taking into account that the reflected signal to the radar has to travel twice the distance, we obtain a time duration of 1.33 μs which corresponds to the maximum delay difference between the propagation path of 400 m. Hence, setting $T_{CP} > 1.33$ μs would ensure that ISI is avoided.

As such, in order to obtain round numbers, the elementary symbol length of $T = 11$ μs was chosen which is equivalent to Δf = 90.909 kHz. The CP length is chosen to be T_{CP} =

$1/8\,T = 1.375\ \mu$s, resulting in the total transmitted OFDM symbol duration of $T_{sym} = T + T_{CP} = 12.375\ \mu$s.

B. Range resolution

The maximum unambiguous range of the radar is given by

$$r_{max} = \frac{c_0}{2\Delta f} = \frac{Tc_0}{2} \quad (11)$$

It can be seen that the unambiguity of the radar range profile is highly dependent on the elementary OFDM symbol duration. Hence for a good radar range profile, T must be chosen to be as large as possible. This also coincides with the need to obtain a sufficiently high signal-to-noise ratio. For practical applications where the transmit power is limited, the integration time of the processor must be chosen to be as long as possible to obtain a higher processing gain. Therefore T must be chosen to be as long as possible without violating the constraints due to the Doppler effect.

One of the key performance parameters of a radar is its range resolution, Δr. It is only dependent on the total bandwidth occupied by the transmit signal and the relation is given as

$$\Delta r = \frac{c_0}{2B} = \frac{c_0}{2N\Delta f} \quad (12)$$

For the intended automotive application, a range resolution of between 1 m to 2 m is sufficient. Typically a power of 2 number is chosen for the number of subcarrier N, as this allows for an efficient implementation of the necessary DFT and IDFT processing. Within the required context, $N = 1024$ is chosen. With the chosen values, $r_{max} = 1650$ m and $\Delta r = 1.61$ m. This corresponds to a total signal bandwidth of 93.1 MHz which is compliant with the regulations of the 24 GHz ISM band.

C. Doppler resolution

The unambiguous Doppler frequency is related to the symbol duration T_{sym} and can be expressed by

$$v_{max} = \frac{\lambda}{2T_{sym}} \quad (13)$$

Substituting the parameter values, $v_{max} = 505$ m/s is obtained. Since Doppler can be both positive and negative, it should rather be expressed as $v_{max} = \pm 252.5$ m/s. This then corresponds to around ± 910 km/h which is more than required for an automotive application.

The Doppler resolution is dependent on the number of evaluated symbols M, and amounts to

$$\Delta f_D = \frac{1}{MT_{sym}} \quad (14)$$

or in terms of velocity resolution, taking into account that twice the Doppler of the relative velocity occurs for a reflected wave

TABLE I
OFDM SYSTEM PARAMETERS

Symbol	Parameter	Value
f_c	Carrier frequency	24 GHz
N	Number of subcarriers	1024
Δf	Subcarrier spacing	90.909 kHz
T	Elementary OFDM symbol duration	11 μs
T_{CP}	Cyclic prefix duration	1.375 μs
T_{sym}	Transmit OFDM symbol duration	12.375 μs
B	Total signal bandwidth	93.1 MHz
Δr	Range resolution	1.61 m
r_{max}	Maximum unambiguous range	1650 m
v_{max}	Maximum unambiguous velocity	$\pm$252.5 m/s
M	Number of evaluated symbols	256
Δv	Velocity resolution	1.97 m/s

$$\Delta v = \frac{\lambda}{2MT_{sym}} \quad (15)$$

In principle, evaluating a greater number of OFDM symbols would give a finer velocity resolution. This is however impractical as moving objects must remain within one range resolution cell during the evaluation. Hence, by evaluating over $M = 256$, with the duration of 3.17 ms, an object traveling at the maximum unambiguous velocity would have traveled only 0.8 m, which is still within the resolution cell size of 1.61 m. With this, the velocity resolution becomes $\Delta v = 1.97$ m/s or 7.1 km/h, guaranteeing an appropriate performance for practical automotive applications. All system parameters are summarized in Table I.

IV. SIMULATION & MEASUREMENT RESULTS

For the verification of the range and Doppler processing presented in Section II, a simulation of two point-scatterers has been implemented in MATLAB. The simulation model comprises a transmitter, receiver and a point-scatterer channel model utilizing the parameters in Table I. The point-scatterer channel model computes the distance, velocity, phase and attenuation for every pre-defined point scatterers and is able to support an arbitrary number of them. At the receiver, the received baseband signal is processed with the algorithm as described in (6) and (9) without prior channel equalization and decision.

Two identical point scatterers placed at $R = 20$ m from the radar with the respective relative velocities of $v_1 = 0$ m/s and $v_2 = 7$ m/s were set in the simulation. At the FFT processing, a Hamming window is applied to minimize the sidelobes. The resulting radar image is as shown in Fig. 1. The two objects are clearly separable in range and Doppler and the sidelobes only occur due to the FFT processing.

In verifying the simulation results, a measurement emulating the simulation scenario has also been done. The measurement setup is as shown in Fig. 2. A stationary corner reflector with the radar cross section (RCS) of $\sigma = 16.3$ dBm^2 and a car moving at 25 km/h (7 m/s) are located 20 m away from the

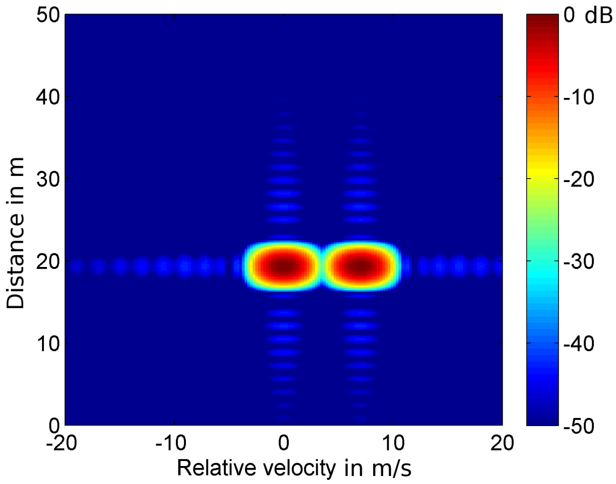

Fig. 1. Simulation of 2 point scatterers

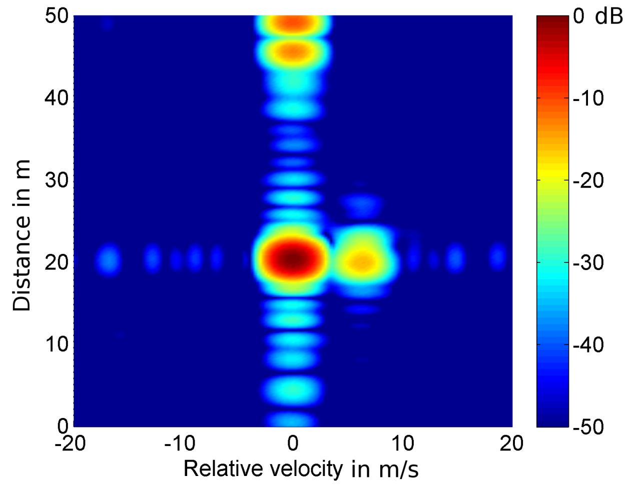

Fig. 3. Measurement result of the setup in Fig. 2

Fig. 2. Measurement scenario

radar at the time of measurement. The resulting radar image is as shown in Fig. 3.

Thus it can be seen that the measured result corresponds highly with the simulated result. Although the reflection from the car is approximately 15 dB weaker than the reflection of the corner reflector, it is nevertheless sufficient to be distinguished in the radar image. Also seen in the figure are other reflecting objects which are the result of the metal road signs behind the car and reflections from the ground. Hence this demonstrates the capability of the processing algorithm in resolving multiple reflecting objects. The measurement setup for performance verification can be found in [10].

V. Current work

The current work focuses on extending the OFDM RadCom to cope in a realistic road environment i.e. in multipath and multiuser scenarios. The following sections outlines the work undertaken and its outcome.

A. Multipath scenario

Within a multipath environment, a certain transmitted signal will not only arrive at the receiver over the Line-of-Sight (LOS) path but also over Non-Line-of-Sight (NLOS) paths which interact in a complex manner with the objects (e.g. buildings, vehicles, persons, trees) within the propagation vicinity. These NLOS signals experience reflection, diffraction and scattering, resulting in their different attenuations, time delays, phase shifts and even polarizations. It is precisely due to the superposition of these NLOS signals that give rise to the frequency-selective, time-variant and direction-selective behavior of the mobile radio channel. As such, an accurate description of these multipath waves propagation in a given scenario is necessary to produce realistic time series of the Channel Impulse Response (CIR).

For modeling the wave propagation in a multipath scenario, a three-dimensional fully polarimetric Ray-tracing algorithm developed by [12], [13], [14] is used. This channel model is based on Geometrical-Optics (GO) and describes the asymptotic behavior of the electromagnetic fields at high frequencies with the assumption that the wavelength is very small compared to the dimensions of the modeled objects in the simulation scenario. Each propagation path is represented by a ray which may experience several different propagation phenomena.

The 3D scenario for modeling the deterministic channel model is as shown in Fig.4. This urban scenario comprises two lanes and four cars (one moving in the same direction and two moving towards the radar) with buildings and vegetation on both sides of the street. The green 'rays' depict the path traveled by the electromagnetic waves.

B. Multiuser scenario

In a multiuser scenario, the reflected OFDM signal at the receiver contains not only the effect of the channel, but also communication signals from interferers and noise. We consider here another user of the same OFDM RadCom system which is also transmitting a message-radar signal, denoted henceforth as the *interferer*. The analysis is made from the view point of the first RadCom system, denoted as the *radar*.

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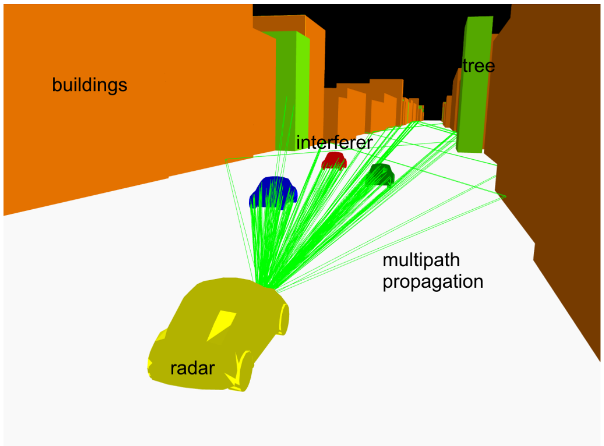

Fig. 4. Ray-tracing scenario

The Signal-to-Interferer ratio (SIR) at the radar can be estimated by taking the ratio of the receive power due to the reflecting objects in the radar's surrounding (radar equation) and the receive power due to the interferer (Friis equation), which gives:

$$SIR = \frac{R_{int}^2\,\sigma}{(4\pi)^2\,R_{obj}^4} \tag{16}$$

where R_{int} and R_{obj} are the distance of the interferer to the radar, and the reflecting object to the radar respectively, and σ is the RCS of the reflecting object. A reflecting object with $10\ \mathrm{dBm}^2$ RCS located at 10 m, and the interferer at 50 m respectively from the radar would give an SIR of -18 dB. That is to say, the interferer signal is almost always higher than the reflected radar signal (even though the reflecting object is located nearer the radar) and hence appears as noise in the radar image, impairing the dynamic range.

From the ray-tracing results, the SIR is -48.2 dB and the strongest multipath component of the interferer is 11.7 dB weaker than its LOS. The resulting radar image for the scenario of Fig. 4 is as shown in Fig. 5 where the mean noise floor is at -20.2 dB while the dynamic range (peak-to-sidelobe level) is a mere 8.46 dB. Consequently no distinguishable object reflection is visible in the radar image.

C. *Interference cancellation*

As can be seen in Fig. 5, the communication signals end up as noise on the radar image. Since the radar also has access to the communication data, with a *near-precise reconstruction* of the interfering signal as received, this signal can then be subtracted from the radar signal.

In order to obtain an adequate reconstruction of the interfering signal, good time and frequency synchronization as well as channel estimation are necessary. The severity of erroneous frequency offset estimation on the reconstruction of the interferer signal is such that the difference of a mere 20 Hz residue from the real frequency offset will cause a degradation of more than 20 dB to the dynamic range, as can be seen in Fig. 6.

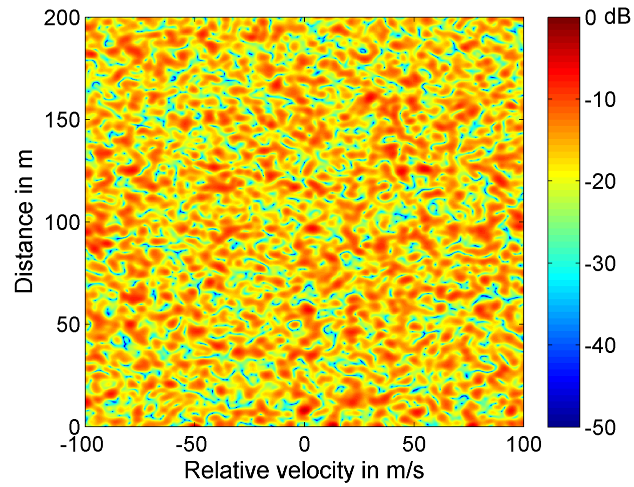

Fig. 5. Radar image of the ray-tracing scenario, before interference cancellation

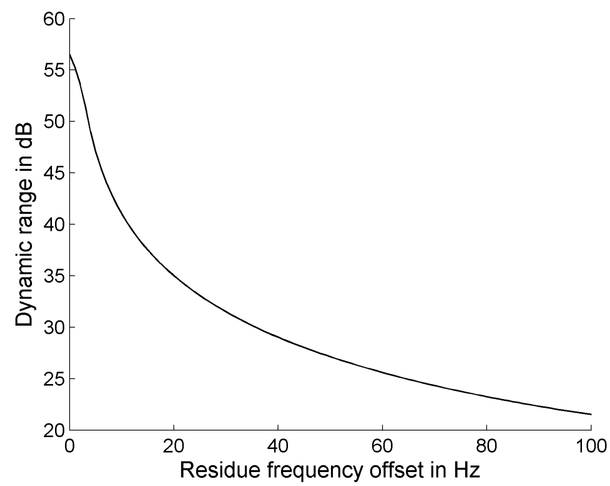

Fig. 6. Dynamic range (after interference cancellation) vs. residue frequency offset

For the purpose of time and frequency synchronization, the Schmidl and Cox algorithm (SCA) [15] has been implemented. The OFDM frame is thus extended by the length of two symbols which does not cause any impairment to the radar's ranging capabilities. The channel estimation is done by having regularly distributed pilot symbols within the OFDM frame [11].

It has been observed however that in a multipath-multiuser environment that when the LOS or strongest signal is less than 15 dB in difference with other NLOS and reflected signals, the SCA is incapable of correctly estimating the frequency shift. This frequency shift occurs largely due to the Doppler of the reflecting objects and also the possibility of local oscillator mismatch between the transmitter and the receiver. Thus a fine frequency offset estimator has been developed [11], which

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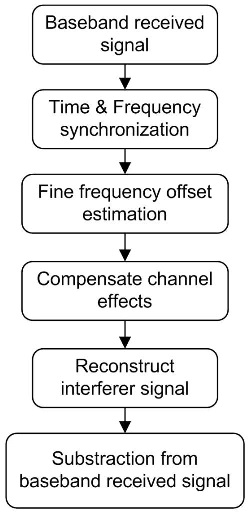

Fig. 7. Flow diagram of the interference cancellation

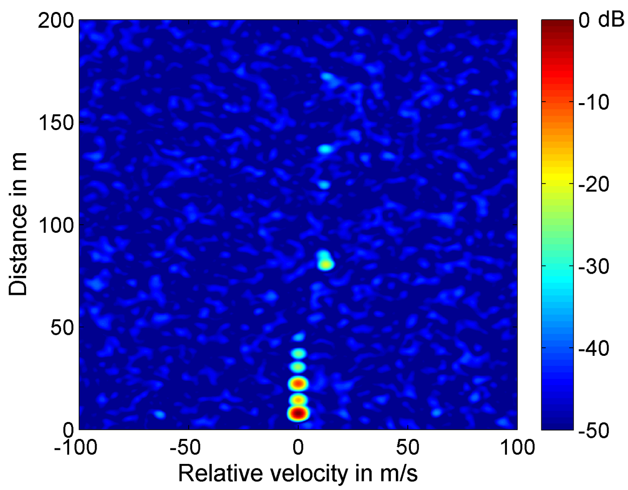

Fig. 8. Radar image after interferer's LOS component cancellation

when used with the SCA is capable of estimating the frequency offset to the accuracy of 2.5 Hz and below.

The flow of the interference cancellation scheme is as shown in Fig. 7. Interference cancellation is done based on the 'reliability' of the received signal. A signal is 'reliable' if the the SCA synchronization is able to 'identify' a signal through correlation. Shown in Fig. 8 is the resulting radar image after interference cancellation of the interferer's LOS path, where the residue frequency offset amounts to only 1.2 Hz and the mean noise floor is now at -51.8 dB along with 35.2 dB of dynamic range (peak-to-sidelobe ratio). With this, all reflecting objects in the path of the rays are visible.

VI. Conclusion

An OFDM system which is able to support both communication and radar applications on a single platform has been presented whereby the processing scheme is independent of the payload data, and is capable of resolving multiple objects. The parameterization for automotive radar applications has also been derived and its implementation feasibility verified by simulations and measurements. In the subsequent step for extending the RadCom to function in a multipath-multiuser environment, the challenges of the realistic multipath scenario setup and the implication of another user in the radar's vicinity have been discussed. It has also been shown that the interfering signal severely corrupts the radar's dynamic range. Hence an interference cancellation scheme using the availability of the receive communication signal to the radar has implemented and the performance of the radar has been seen to improve by 33.3 dB after the cancellation of the strongest (LOS) path of the interferer.

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