Evaluation of Beam-Forming Algorithms for Automotive OFDM Signal Based Radar

Christian Sturm, Lars Reichardt, Thomas Zwick, and Werner Wiesbeck

Institut für Hochfrequenztechnik und Elektronik (IHE), University of Karlsruhe
Kaiserstr. 12, 76131 Karlsruhe, Germany
`christian.sturm@ihe.uka.de`

Abstract— **In this paper the applicability of beam-forming algorithms in radar systems operating with OFDM signals is investigated. It is shown that beam-forming techniques can be directly applied to the output of an OFDM radar processor in order to calculate two-dimensional radar images in distance and azimuth. With a dedicated system model including a realistic road scenario propagation simulator, the performance of different algorithms in typical automotive radar scenarios is analyzed for 24 GHz ISM applications.**

I. INTRODUCTION

Even though the idea of using orthogonal frequency division multiplexing (OFDM) signals in radar systems has existed for several years, radar systems based on OFDM signals have never become popular. While for classical radar applications, e.g. in remote sensing, OFDM signals do not provide a real benefit, in the area of automotive radar systems several interesting advantages result from their application. First, OFDM signals are reported to be advantageous regarding Doppler shift [1]. Besides providing high tolerance against Doppler shift they also do not experience range-Doppler coupling, which allows for independent and unambiguous range and Doppler processing. Second, due to their origin from digital communications, OFDM signals are designed to carry information, which allows for simultaneous information transmission in parallel to radar sensing [2]. This feature is in particular interesting regarding the development of future intelligent transportation networks, where vehicles equipped with a joint radar and communication system may interact and exchange status information in ad-hoc sensor networks. The feasibility of an OFDM system design adapted to automotive applications that allows for simultaneous operation of radar sensing and data communication without any performance limitations has already been discussed in a previous work of the authors [3]. Furthermore, a novel processing approach for OFDM radar has been proposed in [4] that allows for superior implementation of OFDM radar range processing regarding both resulting sidelobe levels and computational effort.

However, for automotive applications the simple calculation of a radar range profile is not sufficient. Instead, a two-dimensional environment sensing is required, that detects the position of objects in both distance and azimuth angle. This can be accomplished by applying multiple antenna processing techniques, which exploit the phase differences between the signals received at different spatial positions in order to determine the direction of arrival of the received signal. For that purpose numerous algorithms exist, that are based on different mathematical approaches. The aim of the work presented here is to investigate the possibility of efficiently applying such techniques in combination with OFDM signals in order to perform two-dimensional radar sensing with a signal that can transmit information in parallel. Also, it is intended to evaluate the performance of these algorithms when applied to OFDM signals in terms of object separability, which is accomplished by employing a deterministic propagation simulator based on ray-tracing.

The sections of the paper are organized as follows. First, the OFDM radar concept including the applied waveforms and the range processing at the receiver is described. Then, two typical multiple antenna techniques are discussed. Finally, for an example system parameterization, simulation results for the performance of these two algorithms are presented.

II. OFDM RADAR

An OFDM signal is generated by multiplexing a series of complex modulation symbols onto multiple orthogonal subcarriers. The OFDM time domain signal of one OFDM symbol can be expressed as

$$x(t) = \sum_{n=0}^{N-1} I(n) \exp(j2\pi f_n t), \quad 0 \le t \le T \qquad (1)$$

with N denoting the number of orthogonal subcarriers, f_n being the individual subcarrier frequencies, T being the elementary OFDM symbol duration, and $\{I(n)\}$ representing an arbitrary information series consisting of complex modulation symbols obtained through a discrete phase modulation technique, e.g. phase shift keying (PSK). In order to avoid interference between the single subcarriers the subcarriers have to be orthogonal, which is fulfilled in case of $\Delta f = 1/T$, where Δf represents the frequency difference between two adjacent subcarriers.

The OFDM radar platform is supposed to be a monostatic system being equipped with one transmitter and one receiver. The radiated signal, which may also simultaneously transmit information to a distant receiver, will be scattered from objects in the neighbourhood of the platform. The receiver located on the same platform shares the transmitted information $\{I(n)\}$ and can use this information in order to carry out radar processing. It is assumed that the radar processing is performed with one single OFDM symbol described by (1), which is generated from an arbitrary information sequence $\{I(n)\}$ without any specific restrictions.

For the calculation of the radar range profile a novel approach is applied, which is described in detail in [4] and guarantees a high performance independent from the transmitted information. The basic idea of this approach consists in comparing the transmitted information $\{I(n)\}$ and the received information $\{I_r(n)\}$ in soft-state at the output of the OFDM de-multiplexer before the channel equalization and the decoding is performed. At this point the distortion from the channel is fully contained in the complex modulation symbols $\{I_r(n)\}$. Since all information symbols within one OFDM symbol are transmitted through the channel at different carrier frequencies separated by Δf, the received information symbols can be used to perform a channel sensing at discrete frequencies like in stepped frequency radar. The samples of the frequency domain channel transfer function can easily be obtained by simply calculating an element-wise complex division

$$I_{div}(n) = \frac{I_r(n)}{I(n)} \qquad (2)$$

The sampled channel impulse response, which corresponds to the radar range profile, is obtained as the inverse (discrete) Fourier transform of $\{I_{div}(n)\}$

$$\begin{aligned} h(k) &= \mathrm{IDFT}\left(\{I_{div}(n)\}\right) \\ &= \frac{1}{N}\sum_{n=0}^{N-1} I_{div}(n)\exp\left(j\frac{2\pi}{N}nk\right), \quad k = 0,\dots,N-1 \end{aligned} \qquad (3)$$

As a consequence of sampling the spectrum, the resulting radar range profile is periodic in distance. The dynamic range is only limited by the Fourier transform sidelobes, which can be reduced by applying windowing functions to an arbitrarily low level. The most interesting fact however is, that this approach is completely independent from the transmitted information, since it relates every received modulation symbol to a transmitted one. This fact guarantees a constant and reliable system performance independent from the transmitted information. Of particular importance concerning the applicability of multiple antenna techniques is the fact that the resulting radar range profile $h(k)$ is complex-valued and contains phase information for each range cell k.

III. MULTIPLE ANTENNA PROCESSING

For the intended application in automotive radar it is essential to provide the ability of measuring not only the distance but also the direction in azimuth of scattering objects. This can be achieved by using multiple receive antennas connected to individual receivers and then applying multiple antenna processing techniques. In principle, these processing algorithms can be directly applied to the received signals in the baseband. However, it is much more efficient to apply the processing directly to the radar range profiles $h_i(k)$ obtained from for the individual antennas after an individual pre-processing, since the amount of data that has to be processed is much lower with this procedure. Assuming the receiver is equipped an antenna array of P elements, each connected to an individual receiver and pre-processor for the calculation of the radar range profile, the pre-processor output signals $h_i(k)$ obtained from the processing described in (3) can be arranged in a vector

$$\vec{h}(k) = \begin{bmatrix} h_1(k) & h_2(k) & \dots & h_P(k) \end{bmatrix}^{\mathrm{T}} \qquad (4)$$

In the following the application of two widely used multiple antenna processing approaches will be regarded. In order to limit the complexity, a horizontally oriented linear antenna array with constant element spacing d will be regarded, which will then allow for determining the azimuth angle of arrival ψ. As a common basis both approaches share the definition of a beam-steering vector, which is a vector that describes the samples of the complex wave front at the receiving antenna positions, provided that one single plane wave is impinging on the array from the azimuth angle ψ

$$\vec{b}(\psi) = \begin{bmatrix} 1 & e^{j\sin(\psi)2\pi d/\lambda} & \dots & e^{j\sin(\psi)2\pi(P-1)d/\lambda} \end{bmatrix}^{\mathrm{T}} \qquad (5)$$

First, the classical Fourier transform based approach will be regarded, which consists in simply adding the elements of the pre-processor output vector with additional phase shifts. This corresponds to multiplying the array signal vector with the beam-steering vector. The Radar image intensity I for a given range cell k and azimuth direction ψ is obtained as

$$I(k,\psi) = \left|\vec{h}^{\mathrm{T}}(k)\cdot\vec{b}(\psi)\right|^2 \qquad (6)$$

Second, a multiple antenna processing approach will be discussed that allows for considerably higher angular resolution. This approach is named MUSIC (Multiple Signal Classification) and has first been described in [5]. It operates on the eigen-structure of the correlation matrix of the array signal vector.

For the determination of the angular positions of the scatterers a particular property of the sub-spaces spanned by the eigenvectors related to the large and the small eigenvalues of the autocorrelation matrix of the array signal vector is exploited. The beam-steering vectors virtually pointing towards the scatterers are linear combinations of the eigenvectors $\vec{e}_{s,i}$ related to the large eigenvalues. Hence they must be orthogonal to the sub-space spanned by the eigenvectors $\vec{e}_{n,i}$ related to the small eigenvalues in the autocorrelation matrix of the array signal vector. With this property in mind the following pseudo Radar image intensity can be defined.

$$I(k,\psi) = \frac{1}{\sum_{i=1}^{P-Q} \left| \vec{b}(\psi) \vec{e}_{n,i} \right|^2} \qquad (7)$$

In case the orthogonality condition is fulfilled this expression will show a strong peak since the denominator approaches zero.

IV. SIMULATIONS AND RESULTS

In order to evaluate the applicability and performance of the regarded multiple antenna techniques in combination with ODFM signals, a dedicated simulation model has been implemented in MatLab. With this model the performance of the algorithms can be investigated for both point scatterer scenarios as well as realistic road scenarios, which is accomplished by including a ray-tracing tool. The detailed configuration of the simulation model and the obtained results are reported in the following

A. Implementation of the Simulation Model

A complete system model including OFDM transmitter, wave propagation, OFDM receiver and radar processing algorithms has been implemented in MatLab. An overview on the system parameters applied for the OFDM signal generation is provided in Table 1.

TABLE I
OFDM SYSTEM PARAMETERS

Symbol	Quantity	Value
f_c	Carrier frequency	24 GHz
N	Number of subcarriers	1024
Δf	Subcarrier spacing	90.909 kHz
T	Elementary symbol duration	11 µs
T_P	Cyclic prefix length	1.375 µs
T_{sym}	Transmitted symbol duration	12.375 µs
B	Total signal bandwidth	93.1 MHz
Δr	Radar range resolution	1.61 m
d_{max}	Unambiguous range	1650 m

The transmitter generates an OFDM signal with the specified parameters from random binary information by applying 4-PSK subcarrier modulation, arranging the modulation symbols in the frequency domain, and then calculating the sampled time domain transmit signal through an IDFT. The sampled time domain signal is then converted into a quasi-continuous signal by oversampling with a sample-and-hold element with subsequent low-pass filtering. Finally, the signal is converted to the carrier frequency in a bandpass sub-sampling representation.

For modeling the wave propagation two different approaches are applied. The first one is a point scatterer model that simulates the scattering of the transmitted signal at an arbitrary number of point scatterers. For each scatterer, the time delay, the phase shift, and the attenuation are calculated individually. The attenuation is the product of the free space attenuation and the attenuation caused by the scatterer resulting from an individual radar cross section σ. Then, the signal components resulting from the different scatterers are superimposed. Since the primary aim is to verify the proposed processing approach, no particular assumptions on transmitted power and antenna gain are made.

The second propagation model that is applied is a deterministic propagation simulator based on ray-tracing, which also provides random generation of typical traffic scenarios according to stochastic traffic models [6]. With this tool it is possible to evaluate the applicability of the regarded algorithms under realistic conditions.

In order to keep the effort at a limit that would be acceptable for commercial applications, it is assumed that the receiver is equipped with only 4 receiving antennas separated by a distance of half a wavelength. Each antenna is connected to an individual receiver, which converts the signal back to the baseband and samples at the modulation symbol rate. Then a DFT processing is performed in order to recover the soft-state modulation symbols in the frequency domain. In an individual pre-processing for every antenna the received symbols with continuous phase values are fed to the radar processing algorithm described in Eq. (2) and (3). Then the calculated radar range profiles are arrange to vectors as described by Eq. (4). Finally, the different multiple antenna processing techniques in Eq. (6) and (7) are applied.

B. Simulation Results

First, the performance of the algorithms is investigated for the point scatterer scenario. The algorithms are tested with two point scatterers with identical radar cross section of $\sigma = 10\ \text{dBm}^2$ in the same distance and an angular separation of 5 degree (located at ±2.5 deg). Fig. 1 shows the 2D radar image obtained when processing the received OFDM signals with the classical Fourier based beam-forming approach from Eq. (6). The images of the scatterers completely overlap and cannot be separated.

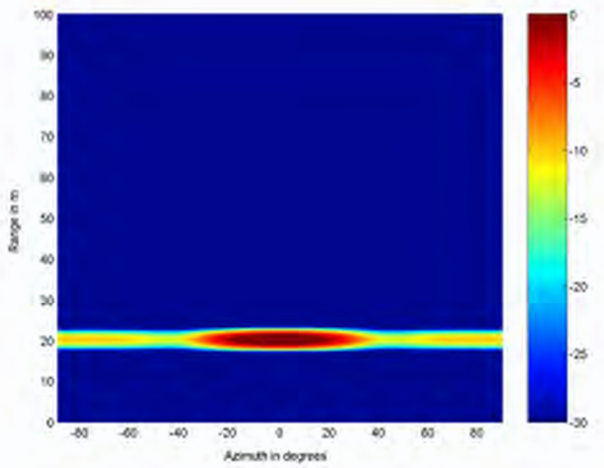

Fig. 1 2D radar image for 2 point scatterers separated 5 degree in azimuth calculated with Fourier based beam-forming

In Fig. 2 the result for the same scenario obtained when applying the MUSIC algorithm is shown. Here, only a limited range of the azimuth axis is plotted. The two scatterers appear with a very high resolution and are clearly separable.

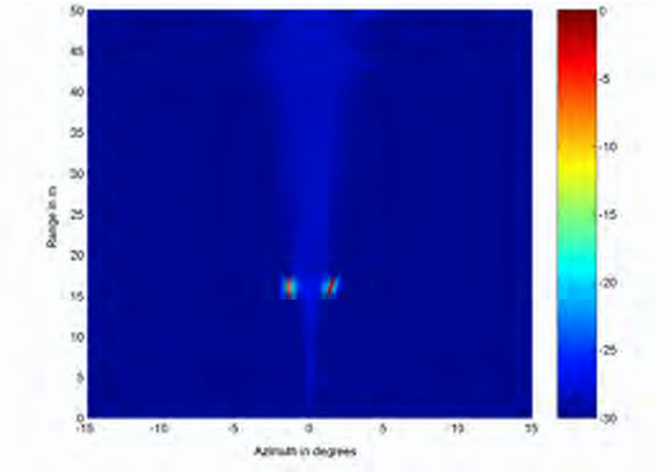

Fig. 2 2D radar image for 2 point scatterers separated 5 degree in azimuth calculated with the MUSIC algorithm

In order to verify the multiple antenna processing algorithms in a more realistic scenario the ray-tracing simulator is applied. Fig. 3 shows the road scenario that has been investigated. The yellow lines show the propagation paths that have been determined.

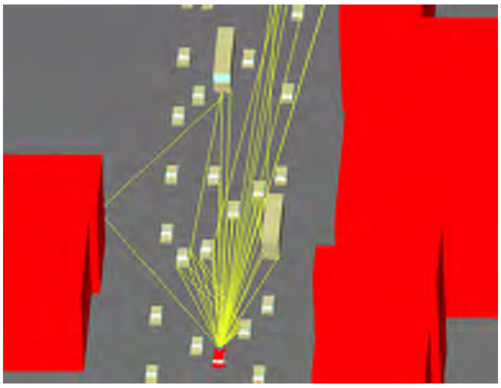

Fig. 3 Investigated road scenario in the ray-tracer

The radar image processed with the Fourier based beam-forming approach is shown in Fig. 4. The images have now been transformed to a cartesian coordinate system. Due to the low angular resolution a detection of different objects from the radar image is not possible. In Fig. 5 the simulation result obtained with the MUSIC algorithm is shown. With this processing technique the position of the cars that cause strong reflections of the OFDM signal can be clearly identified.

V. CONCLUSIONS

The presented results show that it is possible to apply standard beam-forming algorithms to the ouput signals of an OFDM radar distance processor. For the intended application in automotive systems, where it is desirable to need only a small number of receiving antennas, dedicated algorithms providing high resolution like MUSIC have to be used in order to have the ability of separating different objects in a typical street scenario.

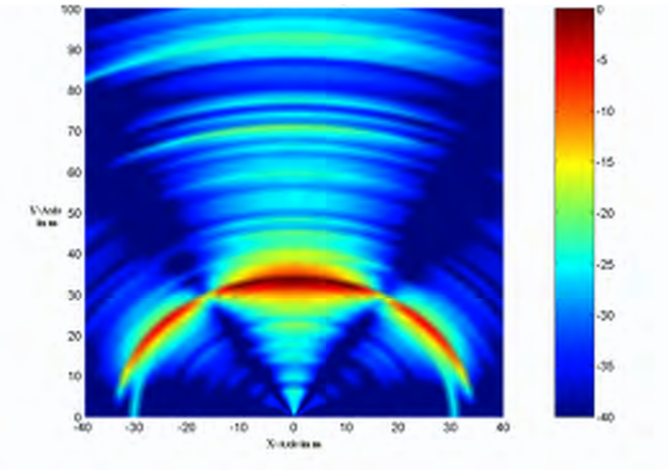

Fig. 4 2D radar image for the road scenario calculated with Fourier based beam-forming

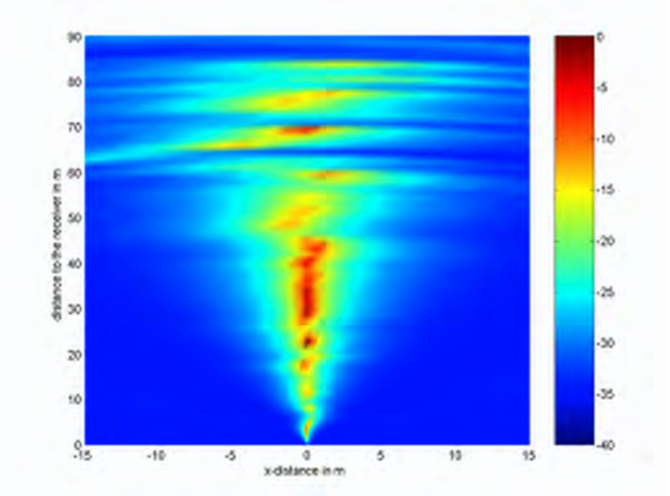

Fig. 5 2D radar image for the road scenario calculated with the MUSIC algorithm

REFERENCES

[1] G. E. A. Franken, H. Nikookar, P. van Genderen, "Doppler tolerance of OFDM coded Radar Signals," *Proc. 3rd European Radar Conference*, pp. 108 – 111, Manchester, Sept. 2006.

[2] A. Garmatyuk, J. Schuerger, Y. T. Morton, K. Binns, M. Durbin, J. Kimani, "Feasibility study of a multi-carrier dual-use imaging radar and communication system," *Proc. 37th European Microwave Conference*, pp. 1473 – 1476, Munich, Oct. 2007.

[3] C. Sturm, T. Zwick, W. Wiesbeck, "An OFDM System Concept for Joint Radar and Communications Operations," *IEEE 69th Vehicular Technology Conference*, Barcelona, April 2009.

[4] C. Sturm, E. Pancera, T. Zwick, W. Wiesbeck, "A Novel Approach to OFDM Radar Processing", *IEEE Radar Conference*, Pasadena, May 2009.

[5] R. O. Schmidt, "Multiple Emitter Location and Signal Parameter Estimation," *IEEE Transactions on Antennas and Propagation*, vol. 34, pp. 276-280, March 1986.

[6] T. Fügen, J. Maurer, T. Kayser, and W. Wiesbeck, "Capability of 3D Ray-Tracing for Defining Parameter Sets for the Specification of Future Mobile Communications Systems", *IEEE Transactions on Antennas and Propagation*, Special Issue on Wireless Communications, vol. 54, no. 11, pp. 3125-3137, October 2006.