Deterministic Propagation Modeling for Joint Radar and Communication Systems

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***Abstract*—In this paper investigations on the performances of joint radar and communication systems in realistic traffic scenarios are presented. This is achieved by combining dedicated MatLab models for transmitter and receiver with a deterministic propagation simulator based on ray-tracing. Two different approaches towards a joint implementation of radar and communications with one common transmit signal are regarded. In the simulations in particular the direction of arrival estimation with the reflected signal has been investigated for different waveforms and beam-forming algorithms.**

I. INTRODUCTION

In recent years the idea of implementing joint radar and communication systems that provide both functions, based on only one common radio frequency platform architecture and even with a common waveform has attracted a lot of interest. These systems would be in particular suitable for applications in intelligent transportation systems, which require the ability for vehicle-to-vehicle communication as well as the need for reliable environment sensing. While first approaches toward a joint implementation of radar sensing and communications have been based on spread spectrum concepts [1], presently OFDM waveforms seem to be the most promising candidate for these applications [2].

In automotive radar applications not only distance measurements but also direction of arrival estimation are required in order to be able to distinguish between cars on different lanes. This can be accomplished by multiple antenna processing techniques, which exploit the phase differences between the signals, received at different spatial positions to determine the direction of arrival of the received signals. For that purpose numerous algorithms exist, based on different mathematical approaches.

In the presented investigations, a deterministic wave propagation simulator is applied to evaluate the performance of a joint radar and communication system with multiple antenna processing techniques in a realistic traffic scenario. In this context different multiple antenna processing techniques and different waveforms are considered. In the following sections first the ray-tracing simulator will be regarded, then, the implementation of different waveforms in the simulation tool will be discussed. In the following chapter the investigated multiple antenna processing techniques will be presented. Finally, simulation results will be shown and discussed.

II. TRAFFIC AND WAVE PROPAGATION MODEL

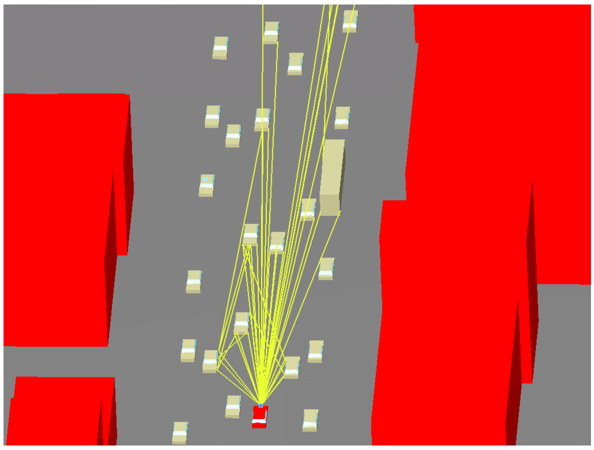

Fig. 1. Investigated traffic scenario

For the adequately modeling of the road-side scenario, including wave propagation and the scattering of the transmitted signal, a dedicated simulator is developed [3]. This software tool first creates a typical road environment from a stochastic traffic model. The result is a polygon object model of the scenario, in which each object (cars, trucks, buildings, etc.) is represented by a composition of several polygons. One car is equipped with the transmit antenna and one or multiple receive antennas for the radar and communication systems. The antennas can be assigned arbitrary gain patterns, or realistic patterns, computed with an EM simulator taking the vehicle into account. In a second step with ray-tracing algorithms all possible interactions of the transmit signal on its propagation to the receive antenna are determined. In order to consider the multiple antenna configuration at the receiver, the simulations are repeated for each receiving antenna position individually. The propagation path search also considers higher order reflections up to an order of 5. In Fig. 1 the randomly created scenario, used for the investigations presented in this paper, is shown. The car, equipped with the radar/communication system is colored in

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red. The yellow lines indicate the determined propagation paths from the transmit antenna to the receive antenna. For every determined propagation path the time shift, attenuation, and phase shift are individually calculated, taking into account the dielectric material properties of the reflecting objects and the antenna gain for the relevant direction. The antenna pattern has a cosine shape with 60° half power beamwidth in azimuth and 10° in elevation, respectively. Then, all propagation paths are coherently superposed to obtain the instantaneous channel impulse response. The absolute value of the channel impulse, resulting for the scenario in Fig. 1, is shown in Fig. 2.

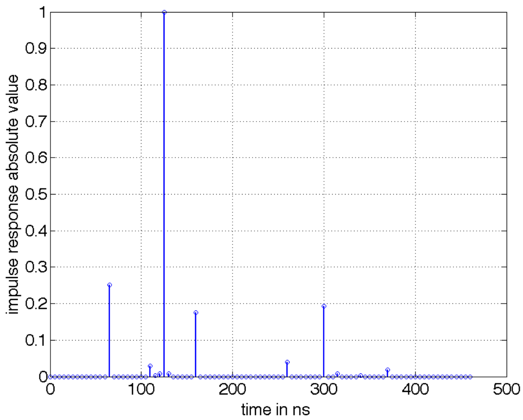

Fig. 2. Impulse response obtained for the scenario shown in Fig 1

III. Investigated Waveforms

For the simulation of the transmitter and the receiver MatLab models for the generation and demodulation of two types of waveforms that are suitable for joint radar and communications operations have been implemented. In the following the basic properties of these waveforms, the chosen system parameters and the applied processing algorithms in the receiver will be regarded.

A. Direct Sequence Spread Spectrum

The basic idea of the direct sequence spread spectrum approach is to use a pseudo random signal, to which only a small amount of user data is added so that it will still preserve its pseudo random characteristics. The radar processing will then be carried out, similar to any standard pseudo random radar.

In the implementation the starting point is an arbitrary binary data sequence that is regarded to be the payload data that has to be transferred to other receiving platforms. The data sequence is mapped to 2-PSK symbols and then spread with an M-sequence. The resulting code sequence with elements $c(i) \in \{1,-1\}$ is then band-limited by a transmit filter. The resulting transmit signal $x(t)$ in the baseband can be described by the following equation (1)

$$x(t) = \sum_{i=-\infty}^{\infty} c(i) g(t - iT)) \qquad (1)$$

with $g(t)$ being the impulse response of the transmit filter and T being the symbol duration. For one single scatterer the received signal can be expressed as

$$y(t) = A \sum_{i=-\infty}^{\infty} c(i) g(t - \frac{2r}{c_0} - iT)) \qquad (2)$$

with A being the amplitude and phase distortion and r the distance between the system platform and the scatterer. Since in the radar case transmitter and receiver are located on the same platform, the transmitted signal is known to the radar processor. The first step of the Radar processing, the range compression, is performed by correlating the transmitted signal with the received scattered signal. From this operation the following result is obtained:

$$\begin{aligned} R_{xy}(\tau) &= A \sum_{i=-\infty}^{\infty} c(i) c(i + \frac{2r}{c_0 T} + \frac{\tau}{T}) \\ &= A R_{cc}(i + \frac{1}{T}(\frac{2r}{c_0} + \tau)) \end{aligned} \qquad (3)$$

This means that a single point scatterer will appear in the correlation result with the shape of the auto-correlation function of the transmit signal R_{cc} shifted in time by $2r/c_0$. The intensity and the phase shift resulting from the scattering object contained in the factor A are fully preserved in the result of the correlation function. From this result two important conclusions can be drawn. First, the transmit signal must possess excellent auto-correlation properties in order to guarantee a high dynamic range of the radar processing. This can be achieved by applying high spreading factors and suitable spreading codes, e.g. M-Sequences. Second, since the full phase information from the scattering object is preserved, standard beam-forming techniques can be applied to the result. The system parameters used in the simulations are summarized in Table 1.

TABLE I
Direct Sequence Spread Spectrum System Parameters

Parameter	Value
PN code	M-sequence
Modulation	BPSK
Spreading factor	255
Chip rate	48 MChip/s
Transmit filter	Root raised cosine roll-off (r=1)
Transmit signal bandwidth	≈ 96 MHz
Transmit frame length	32 767 Chips (683 µs)
Carrier frequency	10 GHz

B. OFDM

The OFDM transmit signal is composed of a parallel stream of orthogonal sub-carriers, each modulated with transmit data. One OFDM symbol can be expressed as

$$x(t) = \sum_{n=0}^{N-1} d(n) \exp(j2\pi f_n t), \quad 0 \le t \le T \tag{4}$$

with N denoting the number of orthogonal subcarriers, f_n being the individual subcarrier frequency, T is the elementary OFDM symbol duration, and $\{d(n)\}$ 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 basic idea behind the OFDM radar processing approach developed by the authors [4] consists in comparing the transmitted information $\{d(n)\}$ and the received soft-state information $\{d_r(n)\}$ obtained in the receiver 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 $\{d_r(n)\}$. Since all information symbols in one OFDM symbol are transmitted through the channel at different carrier frequencies separated by Δf, the received information symbols can be used in order to perform 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 division

$$d_{div}(n) = \frac{d_r(n)}{d(n)} \tag{5}$$

The corresponding channel impulse response, which represents the radar range profile, is obtained as the inverse (discrete) Fourier transform of $\{d_{div}(n)\}$

$$\begin{aligned} h(k) &= \mathrm{IDFT}\big(\{d_{div}(n)\}\big) \\ &= \frac{1}{N}\sum_{n=0}^{N-1} d_{div}(n) \exp\left(j\frac{2\pi}{N}nk\right), k = 0,\ldots,N-1 \end{aligned} \tag{6}$$

With this approach the processing is completely independent from the transmitted information, since it relates every received modulation symbol to a transmitted one. No sidelobes except those caused by the Fourier transform will appear in the radar image. This fact promises a constant and reliable system performance and a very high dynamic range of the radar measurements. An overview on the system parameters applied in the simulation of the OFDM system is provided in Table 2.

TABLE II
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_p	Cyclic prefix length	1.375 µs
T_{sym}	Transmit OFDM symbol duration	12.375 µs
B	Total signal bandwidth	93.1 MHz
Δr	Radar range resolution	1.61 m

IV. Multiple Antenna Processing Techniques

With a multiple antenna configuration at the receiver it is possible to estimate the directions of arrival of the different signal components that are scattered from different objects. This allows for calculating two-dimensional radar images that show distance and azimuth or range and cross-range, respectively. In order to have the ability of carrying out the direction of arrival estimation by digital processing techniques, each receiving antenna must be equipped with an individual radio frequency frontend. In a typical automotive application the space as well as the costs for the frontends are limited, hence here a configuration with only four receiving antennas will be regarded. In order to avoid ambiguities an element spacing of half a wavelength is assumed.

In the following, two widely used multiple antenna processing approaches will be shortly discussed. 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

$$\vec{b}(\psi) = \left[1 \quad e^{j\sin(\psi)2\pi d/\lambda} \ldots e^{j\sin(\psi)2\pi(P-1)d/\lambda}\right]^{\mathrm{T}} \tag{7}$$

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

$$I(\tau,\psi) = \left|\vec{R}_{xy}^{\mathrm{T}}(\tau)\cdot \vec{b}(\psi)\right|^2. \tag{8}$$

Second, a multiple antenna processing approach will be applied 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. In this algorithm the (pseudo) Radar image intensity is defined as

$$I(\tau,\psi) = \frac{1}{\sum_{i=1}^{P-Q}\left|\vec{b}(\psi)\vec{e}_{n,i}\right|^2} \tag{9}$$

with $\vec{e}_{n,i}$ being the eigenvectors that are related to the eigenvalues of the correlation matrix $\mathbf{R}_{RR}$ of the array signal vector with values equal to the spectral noise density (P-Q is the number of these eigenvalues). (8) and (9) explicitly refer to the spread spectrum waveform. In case of OFDM signals the correlation R_{xy} must be replaced by the IFFT output $h(k)$.

V. Simulation Results

For verification simulation results are presented that are obtained by the combined simulator chain, composed of transmitter, propagation channel, receiver and multiple antenna processing. Both multiple antenna techniques that have been discussed and also the influence of different waveforms on the radar image will be regarded. In the propagation simulations the scenario shown in Figure 1 is modelled for a receiver with four antenna elements with a spacing of half a wavelength. In Figure 3 the two-dimensional radar image in distance and azimuth that results from an application of the Fourier based beamforming approach in combination with spread spectrum signals is shown. It can be seen that several cars appear in the image but the azimuth resolution is poor, which makes it impossible to precisely locate the reflecting cars.

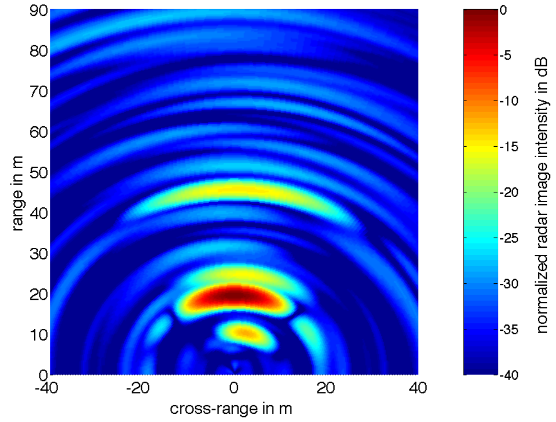

Fig. 3. Radar image with spread spectrum waveform and Fourier based digital beamforming

In Figure 4 a simulation result achieved with the same waveform but with the application of the MUSIC algorithm for the direction of arrival estimation is shown.

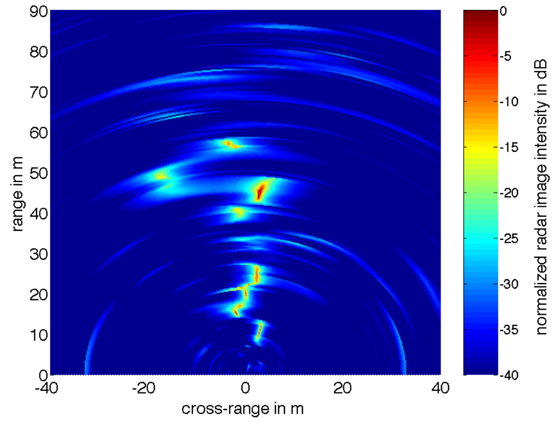

Fig. 4. Radar image with spread spectrum waveform and MUSIC algorithm

It can be seen that in this case the angular resolution is much higher and the position of all cars can be determined well.

Finally, in Figure 5 the result of a simulation with OFDM waveforms in combination with the MUSIC algorithm is shown. Also with this approach the angular resolution is high, however the background noise is distributed over the image in a different way compared to the case of spread spectrum signals.

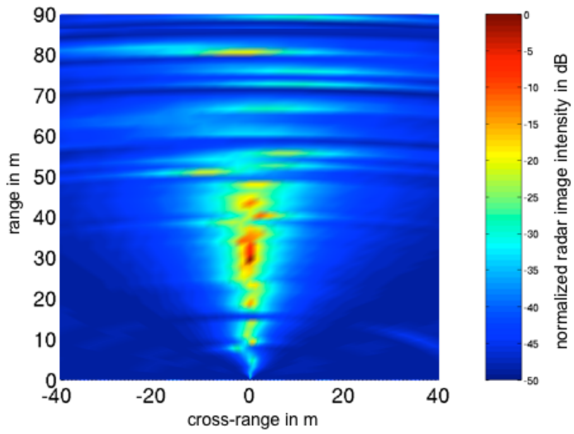

Fig. 5. Radar image with OFDM waveform and MUSIC algorithm

VI. Conclusions

In this paper a simulation tool has been presented, that allows for modeling the entire signal flow of a joint radar and communication system considering the wave propagation in a realistic street scenario. As an example simulation results regarding the performance of different multiple antenna processing techniques and different waveforms have been presented. It has been shown that with both regarded waveforms in combination with the MUSIC algorithm a radar imaging performance that is suitable for practical applications can be achieved.

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