Joint Radar Sensing and Communications based on OFDM Signals for Intelligent Transportation Networks

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***Abstract*—In this paper the possibility of designing an OFDM system for simultaneous radar and communications operations is discussed. Requirements for both applications are analyzed. A suitable processing concept and system parameterization for operation at 24 GHz will be introduced and verified with MatLab simulations.**

***Index Terms*—OFDM, Radar, Communications**

I. INTRODUCTION

Even though the idea of combining radar and communications in one single system platform has been existing for a long time [1], there has never been introduced any relevant implementation of such concept. A joint radar and communications system would constitute a unique cost-efficient platform for future intelligent transportation systems, for which both environment sensing and the allocation of ad-hoc communication links are essential tasks. The most important reason for not having introduced such systems might be that traditional radar platforms and signals have been too much different from their communications counterparts. Nowadays, when the baseband processing can be easily performed in the digital domain, these restrictions do not apply any longer. Also as a result of this progress, in recent years orthogonal frequency division multiplexing (OFDM) in combination with frequency shift keying (PSK) has become a popular modulation technique in new communications standards. OFDM offers several advantages like robustness against multi-path fading, easy synchronization and equalization, and a high flexibility in system design, which allows for easily adapting the system parameters to the given channel characteristics. Furthermore, it has been shown that OFDM-like signals are also suitable for radar applications [2]. Also, it has already been proposed in literature to implement radar networks with integrated communications functions based on OFDM signals [3].

In this paper the feasibility of the design of an OFDM system that even simultaneously allows for performing radar and communications operations will be investigated. First, the OFDM signal structure will be regarded and a novel approach to OFDM radar processing will be proposed. Finally, simulation results for the novel processing approach from a MatLab model will be presented.

II. OFDM RADAR

Strictly speaking OFDM is not a modulation technique but a multiplexing technique, which allows for multiplexing the transmission of symbols over orthogonal subcarriers. These subcarriers are defined by base functions

$$\psi_n(t) = \exp(j2\pi f_n t)\frac{1}{\sqrt{T}}\operatorname{rect}\left(\frac{t}{T}\right), \quad n = 0,\ldots,N-1 \qquad (1)$$

with f_n representing the individual subcarrier frequencies, T denoting the OFDM symbol duration, and N being the number of subcarriers. These base functions are orthogonal in case of

$$\Delta f = \frac{1}{T} \qquad (2)$$

hence, we have to choose this spacing in order to avoid inter-carrier interference. With this choice we obtain for the individual subcarrier frequencies

$$f_n = f_{\min} + n\Delta f, \quad n = 0,\ldots,N-1 \qquad (3)$$

with f_{min} being an arbitrary frequency. An arbitrary information series $\{I(n)\}$ consisting of complex modulation symbols obtained through discrete phase modulation (e.g. PSK) is converted to an OFDM signal by projecting the modulation symbols onto the orthogonal base functions. The resulting time domain signal can be expressed as

$$x(t) = \sum_{\mu=-\infty}^{\infty}\sum_{n=0}^{N-1} I(\mu N + n)\,\psi_n(t-\mu T) \qquad (4)$$

From this result one single OFDM-symbol can be extracted by regarding only μ=0, which results in

$$x(t) = \sum_{n=0}^{N-1} I(n)\exp(j2\pi f_n t), \quad 0 \le t \le T \tag{5}$$

In the frequency domain this corresponds to

$$X(f) = \sum_{n=0}^{N-1} I(n)\sqrt{T}\,\frac{\sin(\pi(f-f_n)T)}{(\pi(f-f_n)T)} \tag{6}$$

Hence, the resulting spectrum is the sum of N *sinc*-functions, each shifted with constant spacing Δf on the frequency axis.

The OFDM radar platform is supposed to be equipped with one transmitter and one receiver. The radiated signal, which is intended to transmit information to a distant receiver, will at the same time be scattered from objects in the neighborhood of the platform and also the receiver that is co-located to the transmitter will receive these scattered waves. The co-located receiver shares the transmitted information $\{I(n)\}$ and can use this information for the radar processing. It is assumed that the radar processing is based on one transmitted OFDM symbol described by (5) and (6) which is generated from an arbitrary information sequence $\{I(n)\}$ without any specific restrictions.

The basic idea of the proposed processing approach consists in evaluating directly the transmitted information $\{I(n)\}$ and the received information $\{I_r(n)\}$ 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 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 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 division

$$I_{div}(n) = \frac{I_r(n)}{I(n)} \tag{7}$$

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

$$\begin{aligned} h(k) &= \mathrm{IDFT}\left(\{I_{div}(n)\}\right) \\ &= \frac{1}{N}\sum_{n=0}^{N-1} I_{div}(n)\exp\left(j\frac{2\pi}{N}nk\right), \quad k = 0,\ldots,N-1 \end{aligned} \tag{8}$$

With this processing approach the dynamic range is only limited by the Fourier transform sidelobes, which do not cause a significant reduction of performance and can even be reduced by applying windowing functions. Also the novel processing 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. The only minor disadvantage is the periodicity of the radar range profile, which can cause ambiguities in an improper system parameter configuration.

III. VERIFICATION SIMULATIONS

An overview on the chosen system parameters is provided in Table 1.

TABLE I
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

In order to verify the operability and the performance of the proposed parameterization and processing concept a complete system model including OFDM transmitter, wave propagation, OFDM receiver and radar processing algorithms has been implemented in MatLab. In particular the intention has been to investigate the available dynamic range and resolution that is obtained when processing real OFDM signals and to assure the system operability in the presence of Doppler shift.

The processor has first been tested with one single point scatterer with radar cross section $\sigma = 10\ \mathrm{dBm}^2$ and relative velocity $v_{rel} = 0$ at a distance of $d = 30$ m. The radar range profile calculated from the received signal is shown in Fig. 1. The scatterer is sharply depicted at a distance of 30 m. The only sidelobes that are occurring are those resulting from the Fourier transform.

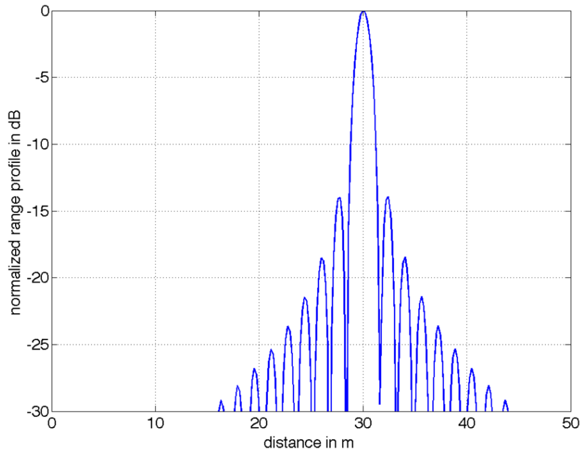

Fig. 1. Radar range profile for one single scatterer with $\sigma = 10\ \mathrm{dBm}^2$, $v_{rel} = 0$, at $d = 30$ m

In order to assess the capability of the proposed algorithm concerning the achievable resolution in terms of separability of adjacent scatterers, a similar simulation but with two scatterers at distances d = 30 m and d = 31.9 m (again with σ = 10 dBm^2 and v_{rel} = 0 for both objects) has been performed. The relevant area of the radar range profile is shown in Fig. 2.

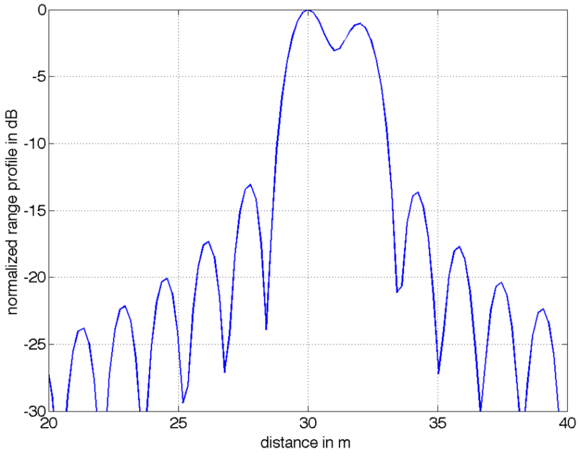

Fig. 2. Radar range profile for two scatterers with σ = 10 dBm^2, v_{rel} = 0, at d = 30 m and d = 31.9 m

The drop in the radar range profile between the two scatterers amounts approximately 3 dB. Hence, under ideal conditions two scatterers in a distance of Δr = 1.9 m are seperable, which corresponds to the usual assumption that in practical application the separation of two targets is approximately possible at twice the resolution distance of Δr = 1.61 m. Also it has to be remarked that this simulation result proofs that the proposed processing approach is capable of imaging multiple objects.

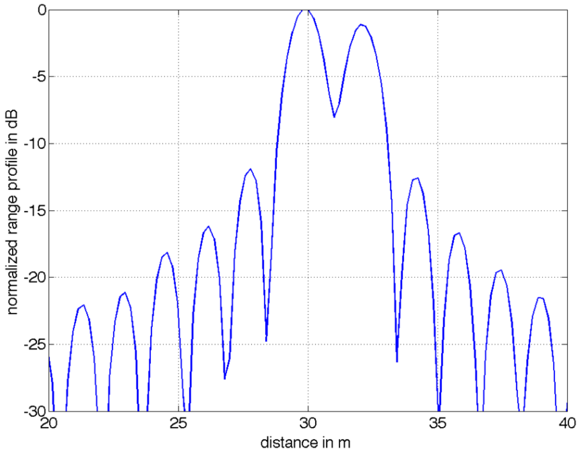

Fig. 3. Radar range profile for two scatterers with σ = 10 dBm^2, one with v_{rel} = 0 at d = 30 m and the 2nd with v_{rel} = 100 m/s at d = 31.9 m

Finally, which is a crucial requirement for automotive applications, the resistance of the concept and the chosen parameter set against Doppler shift has been investigated. For that purpose again the same two point scatterers have been simulated, but the second one has now been assigned a relative velocity of v_{rel} = 100 m/s = 360 km/h. The relevant area of the calculated radar range profile is shown in Fig. 3.

Again, the full operability of the processing algorithm is available. Both objects are fully depicted and even better separable, only the dynamic range has slightly decreased. Hence, the Doppler shift has no influence on the distance processing.

IV. System Demonstrator Setup

The system setup that has been developed can be operated in two different configurations. The system consists of three main hardware components, which are a Rohde&Schwarz (R&S) SMJ100A vector signal generator, a R&S FSQ26 signal analyzer, and optionally a R&S SMR40 microwave signal generator. The SMJ100A is limited to a maximum carrier frequency of 6 GHz but offers higher output power than the SMR40. Therefore it has been decided to set up two different configurations, one with the SMJ100A only in order to achieve high output power at 6 GHz and another one with both SMJ100A and SMR40 in order to generate a signal at the intended carrier frequency of 24 GHz but with reduced transmit power. All instruments are connected through an Ethernet link and controlled from a computer via the MatLab Instrument Control Toolbox. All signals are generated and processed in MatLab.

The first configuration of the system setup is shown in Fig. 4. The transmit signal is generated in MatLab, transferred to the signal generator, converted to the carrier frequency and radiated. The signal analyzer is synchronized in phase through a 10 MHz reference signal and in time through a trigger signal. The signal analyzer samples the I and Q components of the received signal after conversion to the baseband and transfers them back to the computer. The signal generator provides a maximum carrier frequency of 6 GHz and a maximum peak power of 20 dBm. Since with the chosen parameters the OFDM signal shows a relatively stable peak-to-average power ratio (PAPR) of approx. 10 dB, a maximum mean transmit power of 10 dBm is available. The employed horn antennas at the transmitter and at the receiver have a gain of 18.5 dBi each.

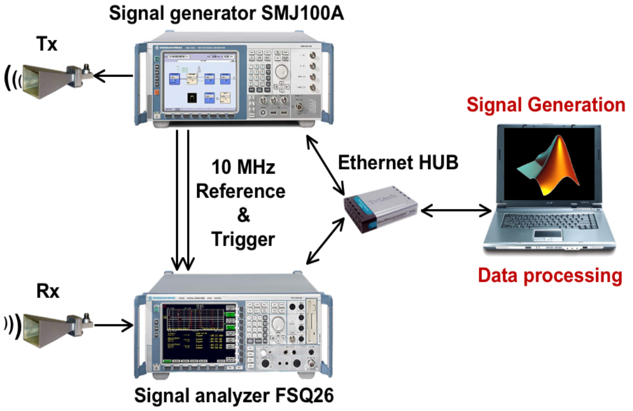

Fig. 4. First configuration of the system setup with maximum carrier frequency of 6 GHz

In order to carry out measurements with a carrier frequency of 24 GHz an additional mixer is required. In that case a slightly different second setup is used, in which the output signal of the SMJ100A signal generator is fed to the external modulation signal input of the SMR40 signal generator. Since the SMR40 does not support I/Q-signals, its output signal shows two sidebands. With an intermediate frequency of 200 MHz at the input of the SMR40 and a local oscillator frequency of 23.85 GHz, the center frequencies of the two sidebands occur at 23.65 GHz and 24.05 GHz, respectively. The receiver is tuned to the upper sideband, which spans from 24.0 GHz to 24.1 GHz. The radiation of the lower sideband is only a side effect of the immature setup and will not occur when using an I/Q mixing stage in future systems. The external modulation input of the SMR40 does not allow for output power control. When driving the SMR40 with an average input signal power of 0 dBm, a total average output power of -9 dBm has been measured with a thermal sensor, hence the desired sideband has a transmit power of only -12 dBm. Also in this setup horn antennas are employed, which have a gain of 22 dBi each.

In order to verify the dynamic range a scenario with objects distributed over a wide range is required. Therefore it has been decided to carry out the measurements from the rooftop of our institute building, which has several other high buildings in its vicinity that will act as clearly identifiable targets. A photo of the measurement setup and the background in the viewing direction of the radar platform is shown in Fig. 5. For all large objects the approximate distance is given. The closest metal object is a large satellite dish that is lying on the roof in a distance of 10 m. The most distant large building is located approximately 380 m away.

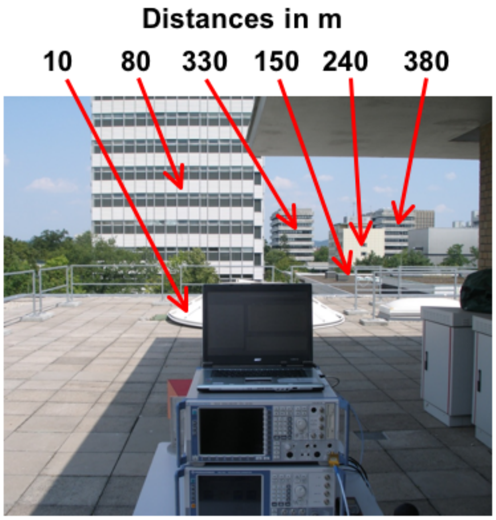

Fig. 5. Radar measurement for the verification of the dynamic range

The OFDM radar system is operated at a carrier frequency of 6 GHz with the maximum output power of 10 dBm. The transmit signal is modulated with random data and QPSK sub-carrier modulation. The normalized radar image obtained with the novel symbol-based processing approach, Hamming windowing and coherent integration over 256 subsequent OFDM symbols is shown in Fig. 6. It can be seen that reflections from all objects appear in the radar image. Moreover, reflections from the inner structures of the buildings, e.g. for a distance of 95 m, are visible. No sidelobes due to random correlation effects occur. The dynamic range between the strongest and the weakest reflection is 49.5 dB. The relative average noise level in the radar image compared to the strongest peak has been evaluated for distances larger than 400 m (where no reflections are present) and amounts -70.3 dB.

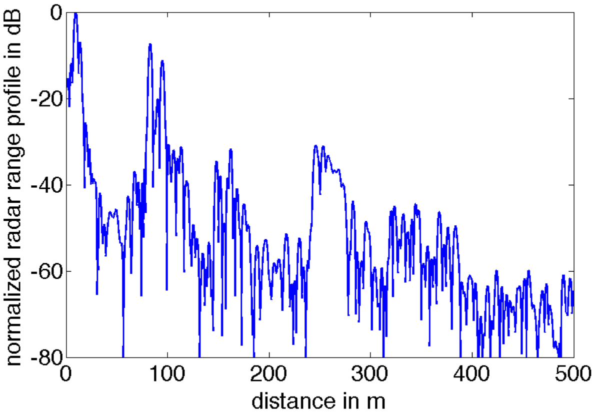

Fig. 6. Calculated radar range profile for the scenario shown in Fig. 5

V. CONCLUSIONS

In this paper a detailed system concept for a joint radar and communications system based on OFDM signals has been presented. A novel OFDM radar processing approach has been proposed, that directly operates on the modulation symbols instead of the baseband signal and overcomes the drawbacks of classic correlation based processing. A suitable system parameterization for the 24 GHz ISM band has been derived. With MatLab simulations and a dedicated measurement setup the operability of the proposed concept and its superior performance concerning dynamic range and resolution have been proven.

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