A Multiple Target Doppler Estimation Algorithm for OFDM based Intelligent Radar Systems

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Abstract— **In this paper an approach will be presented that allows for estimating the velocity of multiple reflecting objects with standard OFDM communication signals. The proposed technique does not require any specific coding of the transmit signal and provides high dynamic range and low sidelobe levels. This allows for an efficient acquisition of velocity information in joint communication and radar systems. The paper discusses the developed algorithm and a possible OFDM system concept for automotive applications. Measurement results are provided that prove the operability in practical scenarios.**

I. Introduction

In the current technological development the radio frequency frontend architectures used in radar and digital communication technology are becoming more and more similar. In both applications more and more functions that have traditionally been accomplished by hardware components are now being replaced by digital signal processing algorithms. Moreover, today's digital communication systems use frequencies in the microwave regime for transmission, which are close to the frequency ranges traditionally used for radar applications. This technological advancement opens the possibility for the implementation of joint radar and communication systems, that are able to support both applications with one single platform and even with a common transmit signal. A typical application area for such systems would be intelligent transportation networks, which require the ability for inter-vehicle communications as well as the need for reliable environment sensing.

First concepts of joint radar and communication systems have been primarily based on spread spectrum techniques [1]. Recently, OFDM signals have gained a lot of attraction for this purpose. This is motivated by two facts. First, most currently released communications standards, e.g. IEEE 802.11.p, employ OFDM signals [2]. Second, in the radar community recently OFDM signal have attracted general interest and their suitability for radar applications has been proven [3]. Hence, currently OFDM signals seem to be the ideal basis for joint radar and communication implementations.

In OFDM radar typically the signals are processed with a correlation of the transmitted and received baseband signals as for any pulsed radar system. The authors have proposed a novel processing scheme for OFDM radar that offers a superior dynamic range independent from the transmitted information [4]. This is achieved by processing directly the information symbols that compose the OFDM signal instead of processing the baseband signals. However, not only the range measurement but also the capability of Doppler measurement is an important feature of radar systems. In particular, regarding vehicular applications the availability of velocity information is an essential requirement. In the investigation of OFDM radar concepts up to now only little attention has been paid to Doppler estimation. In [5] a concept for Doppler estimation is presented, however the results show ambiguities with a relatively high level.

In this paper the novel processing approach that has been introduced by the authors for OFDM radar range processing is extended to a similar concept for Doppler processing. The algorithm can be applied in combination with a transmission of arbitrary user data and is able to resolve multiple reflecting objects with a high dynamic range and very low sidelobe levels.

The remainder of the paper is organized as follows: In chapter II the mathematical description of the OFDM signal and the range processing based on the modulation symbols will be discussed. In chapter III, these considerations will be extended to a series of subsequent OFDM symbols and the symbol based approach will be adapted to Doppler processing. In chapter IV a suitable system parameterisation for the 24 GHz ISM band will be derived. The operability of the developed Doppler estimation algorithm will be verified with simulations. In chapter V a system setup will be presented and measurement results will be shown.

II. Symbol-Based OFDM Radar Processing

The OFDM transmit signal represents a parallel stream of orthogonal subcarriers, each modulated with transmit data. One OFDM symbol can be expressed as

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

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 basic idea behind the information-based processing approach consists in comparing the transmitted information $\{I(n)\}$ and the received soft-state information $\{I_r(n)\}$ 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 $\{I_r(n)\}$. 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 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

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

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

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

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.

III. Proposed Algorithm for Doppler Processing

The idea of the symbol based processing can also be applied in order to estimate the Doppler shift, that is introduced by the reflection of the signal at a target moving with different velocity. For estimating the Doppler, instead of the symbols on the different subcarriers within one single OFDM symbol, now the subsequent symbols on one single subcarrier have to be regarded. The complete OFDM signal can be written as follows

$$x(t) = \sum_{\mu=-\infty}^{\infty}\sum_{n=0}^{N-1} I(\mu N + n)\exp(j2\pi f_n t). \qquad (4)$$

It can be assumed that the system bandwidth is very small compared to the carrier frequency and hence on all subcarriers the same Doppler shift f_D will appear. In the presence of one reflecting object the received signal will be

$$x(t) = \sum_{\mu=-\infty}^{\infty}\sum_{n=0}^{N-1} I(\mu N + n)\exp(j2\pi f_n t)\exp(j2\pi f_D t). \qquad (5)$$

The Doppler shift will cause a phase shift of $\mu f_D T$ on the μ-th symbol on every subcarrier. Every consecutive symbol on one subcarrier will show a phase shift of $f_D T$ compared to the previous one. Hence the Doppler shift and thus the velocity of the reflecting object can easily be determined by evaluating the change of the phase shift between the transmitted and the received symbol. For that purpose analogously to (2) the received symbols have to be normalized to their transmitted counterparts, now along the time axis with different μ -index resulting in $\{I_{div}(\mu)\}$. Then the Doppler spectrum $d(l)$ can be calculated as the discrete Fourier transform of the sequence $\{I_{div}(\mu)\}$

$$\begin{aligned} d(l) &= \mathrm{DFT}\left(\{I_{div}(\mu)\}\right) \\ &= \sum_{\mu=0}^{M-1} I_{div}(\mu)\exp\left(-j\frac{2\pi}{M}\mu l\right), \quad l = 0,\ldots,M-1 \end{aligned} \qquad (6)$$

where M denotes the number of consecutive OFDM symbols that are evaluated for the Doppler estimation. Also here the processing based on the modulation symbols guarantees that the information transmitted with the OFDM signal does not affect the Doppler estimation and a constant performance is ensured. Moreover, the dynamic range is only limited by the sidelobes of the Fourier transform. Due to the sampling of the symbols, the Doppler spectrum $d(l)$ is periodic with the subcarrier distance Δf or the inverse of the OFDM symbol duration, respectively. The Doppler resolution depends on the number of evaluated symbols M and amounts

$$\Delta f_d = \frac{\Delta f}{M} = \frac{1}{MT} \qquad (7)$$

or in terms of velocity resolution taking into account that for a reflection twice the Doppler of the relative speed occurs

$$\Delta v = \frac{\lambda \Delta f}{2M} = \frac{\lambda}{2MT}. \qquad (8)$$

IV. System Parameterization and Simulations

Before detailed simulations can be conducted a suitable parameterization of the OFDM system has to be found. For that purpose a parameterization that has already been evaluated in a theoretical study of the authors [6] has been adapted. The system parameters have been derived and optimized for an application in the 24 GHz ISM band. An overview on these system parameters is provided in Table I. It has been shown that with these parameters there does not occur any adverse impact on the radar performance from Doppler and multi-path propagation in typical road scenarios. The limitation of the unambiguous range is a result of the sampling of the spectrum in the symbol-based processing. However, for the intended application in automotive systems this limitation should not cause any disadvantages.

In the original parameter study only the robustness of the signal against Doppler was considered, however, the explicit estimation of Doppler and the suitability of the parameters for that purpose have not yet been investigated. Hence, the original considerations have to be reviewed in the context of Doppler ambiguity and Doppler resolution. Since the proposed processing concept samples with the OFDM symbol rate along the time axis, the estimation of the Doppler frequency is ambiguous. The unambiguous Doppler frequency corresponds to the subcarrier distance Δf, which gives

$$v_{\max} = \frac{\lambda \Delta f}{2} = \frac{\lambda}{2T}. \qquad (9)$$

With the regarded parameters $v_{\max}$ = 568 m/s is obtained. However, it must be considered that in contrast to the range measurement, where only positive distances can be measured, in the Doppler estimation both positive and negative values for the Doppler will occur. Hence the available unambiguous Doppler should rather be expressed as $v_{\max}$ = ± 284 m/s. Nevertheless, this value corresponds to roughly ± 1000 km/h, which is more than required for any automotive application.

TABLE I.
OFDM SYSTEM PARAMETERIZATION

OFDM Radar System Parameters		
Symbol	***Quantity***	***Value***
f_c	Carrier frequency	24 GHz
N_c	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
d_{max}	Unambiguous range	1650 m
v_{max}	Unambiguous velocity	± 284 m/s
M	Number of evaluated symbols	256
Δv	Velocity resolution	2.22 m/s

The Doppler resolution (8) does not only depend on the subcarrier distance but also on the number of consecutive OFDM symbols M that are evaluated. In principle, the number of evaluated OFDM symbols should be chosen as large as possible in order to obtain optimum Doppler resolution. However, in practical applications the observation duration is limited since all objects must stay within one resolution cell during the measurement. With an evalution over M = 256 OFDM symbols, which takes 3.17 ms in total, an object with the maximum unambiguous velocity would travel a distance of around 0.9 m. This is still less than the resolution cell size of 1.61 m and hence M = 256 should guarantee that no performance degradation will occur. With this choice the velocity resolution results in Δv = 2.22 m/s or 7.99 km/h respectively, which should guarantee an appropriate performance for practical automotive applications.

In a first approach the performance of the proposed Doppler estimation algorithm in combination with the derived parameter set has been investigated with MatLab simulations. The simulation model comprises an OFDM transmitter, a point scatterer model that supports an arbitrary amount of scatterers with individual distance, attenuation, phase and Doppler, and an OFDM receiver. The transmitter and receiver operate with the system parameters shown in Table I. The received OFDM symbols are processed with the Doppler estimation algorithm in (6) without performing any previous channel equalization or decision. The result of a simulation, in which two point scatterers with indentical radar cross section have been placed in an identical distance of R = 35 m to the radar but have been assigned different relative velocities of v_1 = 10 m/s and v_2 = 14 m/s is shown in Figure 1. In the FFT processing a Hamming window has been applied. It can be observed, that the relative velocities are estimated correctly and both objects can be clearly separated in the radar image. The image has a high dynamic range and the sidelobes are well suppressed.

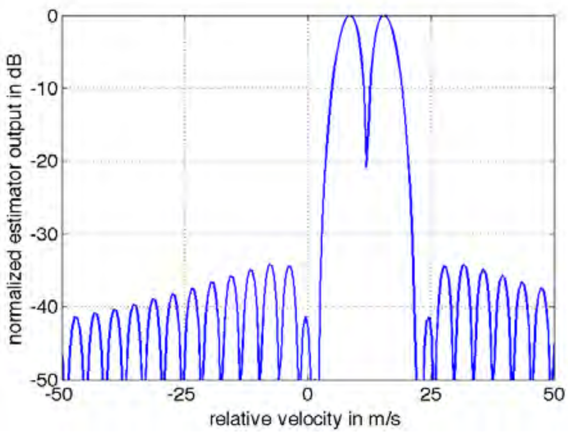

Fig. 1 Simulation result 2 point scatterers with v_1 = 10 m/s and v_2 = 14 m/s

V. MEASUREMENT SETUP AND RESULTS

In order to verify the algorithm in a realistic scenario an OFDM transmission system based on commercial measurement equipment has been set up. The setup consists of three main hardware components, which are a Rohde&Schwarz (R&S) SMJ100A vector signal generator, a R&S FSQ26 signal analyzer, and a R&S SMR40 microwave signal generator. The OFDM signal is generated with the SMJ100A at an intermediate frequency of 200 MHz and then upconverted to 24 GHz through 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 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. With an additional amplifier the available transmit power amounts approximately 9 dBm. The signal analyzer receives the reflected signal and performs a direct down-conversion to the baseband and the sampling of the I/Q components. At both transmitter and receiver horn antennas with a gain of 22 dBi each are used. All instruments are connected through an Ethernet link and fully controlled from a computer via the MatLab Instrument Control Toolbox. All signals are generated and processed in MatLab.

Fig. 2 Scenario for measurement (car approaching with 25 km/h)

With this setup a measurement of the scenario shown in Figure 2 has been taken. The scenario consists of a corner reflector with a radar cross section of σ = 16.3 dBm^2 at 24 GHz and a car moving towards the radar with a velocity of approximately 25 km/h. The measurement was taken at the instant when the car was at the same distance of R = 20 m as the reflector. The result obtained from the Doppler estimation algorithm is shown in Figure 3. Again, in the FFT processing a Hamming window has been applied. It can be observed that both a high peak from the reflector at zero velocity and an additional velocity component of approximately 7 m/s corresponding to the speed of the car appear in the image. The reflection from the car is around 15 dB weaker than the signal scattered from the reflector. Nevertheless the dynamic range of the estimator is more than sufficient in order to image and separate the two objects. Hence, it has been shown that also in a practical application the proposed algorithm is able to resolve multiple reflecting objects with different Doppler, even if they are located in the same distance. The performance corresponds to the simulation results, the dynamic range is only limited by the sidelobes of the Fourier transform.

VI. Conclusions

In this paper an algorithm has been presented and discussed, that allows for estimating the velocities of multiple reflecting objects with a standard OFDM communication signal. The algorithm does not require any specific coding of the signal. A typical application area would be an additional implementation of radar sensing functions into car-to-car communication system hardware.

The approach discussed here directly operates on the modulation symbols that compose the OFDM signal. It has been shown that with this approach the performance of the estimator is completely independent from the transmitted user data and a high dynamic range is achieved, which is only limited by the sidelobes of the Fourier transform. A theoretical parameter study has shown, that with a suitable OFDM system parameterization the proposed concept can be applied even for extremely high velocities. The operability of the developed algorithm has been successfully verified by both simulations and measurements in a realistic scenario.

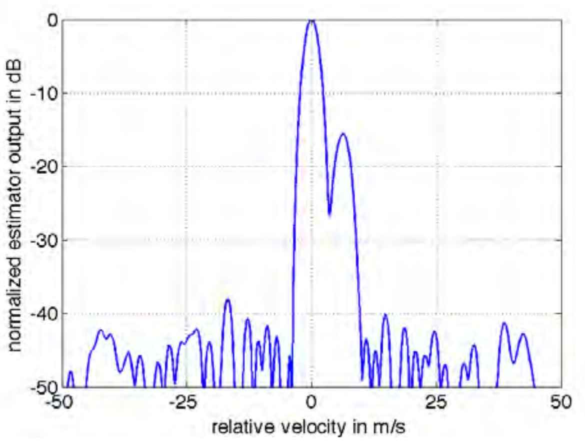

Fig. 3 Doppler estimation result for the real scenario shown in Fig. 2

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