Verification of an OFDM-based Range and Doppler Estimation Algorithm with Ray-Tracing

Yoke Leen Sit, Christian Sturm, Lars Reichardt, Werner Wiesbeck, Thomas Zwick
Institut für Hochfrequenztechnik und Elektronik
Karlsruhe Institute of Technology
Karlsruhe, Germany
{leen.sit|christian.sturm|lars.reichardt|werner.wiesbeck|thomas.zwick}@kit.edu

***Abstract*—In this paper, a simulation and validation method using ray-tracing for an OFDM joint radar and communication system is presented. The motivation is to verify the range and Doppler estimation algorithm and to observe the behaviour of the OFDM radar system in a real scenario where there are multipath and multiusers in its environment. The OFDM radar system has only been performance verified for a single user and since Doppler measurement is not easily repeatable, it is thus unreliable to use measurement verification for performance observation purposes of a real scenario. Hence a ray-tracing technique based on geometrical-optics is used where the wave propagation, material parameters and traffic are modeled according to realistic environments. The ray-tracing results are then exported into the OFDM radar system's model on MATLAB and the result is observed from the radar image where the set distance and velocity are compared to those processed with the novel range and Doppler estimation algorithm.**

I. Introduction

An orthogonal frequency division multiplex (OFDM) joint radar and communication (RadCom) system concept based on the operation at 24 GHz has been proposed in [1]. The system uses OFDM communication signals as radar signals leading towards its dual role in object sensing and communication between systems. The novel radar processing method proposed is simple and completely independent of the transmitted information. Performance verification has also been done in [2] which made the concept feasible to be implemented in real systems. A typical application area for such systems would be in the intelligent transportation networks which require the ability of inter-vehicle communication as well as reliable environment sensing.

In this paper, a new verification method for the RadCom system is explored. In implementing the RadCom for use in a realistic scenario where multipath propagation and multiusers exist, there comes a need for a realistic channel modeling to simulate and validate the RadCom's performance in terms of range and Doppler measurement. In modeling the wave propagation, it is natural to resort to the well-known Maxwell equations. In practical applications however, the analytical solutions using the Maxwell equations is not possible due to the large computational effort. Several other numerical approximation methods such as the Parabolic Equation Method (PEM) and the Finite Difference Time Domain Method (FDTD) were also considered but were found to be computationally inefficient for the modeling of objects/scenarios that are larger than several wavelengths of the operating frequency.

Geometric-optical (GO) models on the other hand were found to achieve accurate results with substantially less complexity and computing time. This model is based on iterative approaches using the boundary conditions of electromagnetic fields at high frequencies, simplifying the description of the wave propagation. The modern GO takes into account the wave characteristics such as phase, interference and polarization and does not depend on the frequency alone.

Section II outlines basis of the RadCom's range and Doppler estimation algorithm. The wave propagation modeling and the conditions for usage is explained in Section III. Section IV then describes the modeling of the scenario and provides the simulation results.

II. OFDM RadCom Concept

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

$$x(t) = \sum_{\mu=0}^{M-1} \sum_{n=0}^{N-1} D\left(\mu N + n\right) \exp\left(j2\pi f_n t\right) \operatorname{rect}\left(\frac{t-\mu T}{T}\right) \tag{1}$$

where N is the number of subcarriers used, M, the number of consecutive symbols evaluated, f_n, the individual subcarrier frequency, T, the elementary OFDM symbol duration, and $D(\mu, n)$, 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 $f_n = n\Delta f = \frac{n}{T}, \quad n = 0, ..., N-1$.

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

$$y(t) = \sum_{\mu=0}^{M-1} \sum_{n=0}^{N-1} D_r(\mu, n) \exp\left(j2\pi f_n t\right) \operatorname{rect}\left(\frac{t-\mu T}{T}\right) \tag{2}$$

where

$$D_r(\mu,n) = D(\mu,n)\exp\left(-j2\pi n\Delta f\frac{2R}{c_0}\right)\exp\left(j2\pi\frac{2v_{rel}}{\lambda}T_{tot}\right) \tag{3}$$

and T_{tot} is the total transmit OFDM frame duration including the cyclic prefix. Based on (3), it can be seen that the distortions due to the channel are fully contained in the received complex modulation symbol $D_r(\mu,n)$, which is obtained at the receiver at the output of the OFDM demultiplexer prior to channel equalization and decoding. Thus comparing the transmitted signal $D(\mu,n)$ with the soft-side received signal $D_r(\mu,n)$ would yield the time-variant frequency domain channel transfer function. This is computed by an element-wise division

$$I_{div}(\mu,n) = \frac{D_r(\mu,n)}{D(\mu,n)} \tag{4}$$

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

A. Range estimation

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

$$I_{div}(n) = \exp\left(-j2\pi n\Delta f\frac{2R}{c_0}\right), \qquad n = 0,...,N-1 \tag{5}$$

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

$$\begin{aligned} h(p) &= \text{IDFT}\left(\{I_{div}(n)\}\right) \\ &= \frac{1}{N}\sum_{n=0}^{N-1} I_{div}(n)\exp\left(j2\pi\frac{n}{N}p\right), \qquad p = 0,...,N-1 \end{aligned} \tag{6}$$

B. Doppler estimation

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 $f_D = 2\,v_{rel}/\lambda$, 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 $2\pi f_D \mu T_{sym}$ on every subcarrier of the μ-th OFDM symbol, where T_{sym} is the OFDM symbol duration with its CP. 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-variant channel transfer function (due to the Doppler only) is

$$I_{div}(\mu) = \exp\left(j2\pi f_D \mu T_{sym}\right), \qquad \mu = 0,...,M-1 \tag{7}$$

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

$$\begin{aligned} h(q) &= \text{DFT}\left(\{I_{div}(\mu)\}\right) \\ &= \sum_{\mu=0}^{M-1} I_{div}(\mu)\exp\left(-j2\pi\frac{\mu}{M}q\right), \qquad q = 0,...,M-1 \end{aligned} \tag{8}$$

Details of the system parameterization is summarized in Table I.

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

III. Multipath wave propagation modeling

In a real environment, a transmitted signal will arrive at the receiver not only over the line-of-sight (LOS) path but also over non-line-of-sight (NLOS) paths. Before arriving at the receiver, the NLOS signal will also interact with the propagation vicinity (e.g. buildings, objects, persons, vehicles) in terms of being reflected, diffracted and scattered. This in turn will result in every NLOS signal experiencing different time delays, attenuations, phase rotations, Doppler and even polarizations.

Upon the arrival at the receiver, the transmitted LOS and NLOS signals will be superimposed and this results in the frequency selective and time-variant behavior of the mobile radio channel. Therefore an accurate description of this multipath wave propagation bahavior is required to produce the realistic observation of the channel.

For modeling the wave propagation in a multipath environment, a three-dimensional fully polarimetric ray-tracing algorithm developed by [3], [4], [5] is used. This channel model is based on geometrical-optics and describes the asymptotic behavior of the electromagnetic fields at high frequencies. The two main conditions for its use are (1) the wavelength must be very small compared to the dimensions of the modeled objects in the simulation scenario, and (2) the material properties must be constant within one wavelength. These conditions are fulfilled with good approximation for operating frequencies above 1 GHz.

To model reflection, the modified Fresnel coefficients, which account for slightly rough surfaces are used. Diffraction is described by the Uniform Theory of Diffraction (UTD) and the corresponding coefficients for wedge diffraction. To describe scattering i.e. from trees, the surface of scattering objects is subdivided into small squared tiles. Depending on the energy, which is incident to the surface of the objects, each tile forms a Lambertian scattering source.

The 3D model of the deterministic scenario is as shown in Fig.1. Each multipath is represented by a green ray which can consecutively experience several different propagation phenomena. The ray-tracing algorithm takes into account reflections of up to five times, diffraction up to three times and a single scattering.

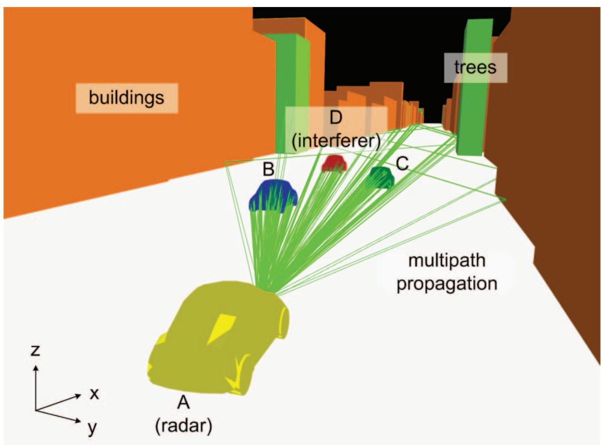

Fig. 1. Ray-tracing scenario

Electrical parameters such as permittivity ϵ_r, permiability μ_r, and the standard deviation of the surface roughness σ are assigned to the objects in the scenario. The parameters used for this simulation are as shown in Table II. Furthermore, each object can be assigned with an arbitrary velocity. To simulate the behavior of the channel, objects can be equiped with a transmitter and a receiver. The position of the antennas and as well as the corresponding antenna radiation pattern and orientation can also be set.

TABLE II
MATERIAL PARAMETERS FOR RAY-TRACING SIMULATION

Material	ϵ_r	μ_r	σ**[mm]**
concrete (building)	$5 - j0.1$	1	1
concrete (road)	$5 - j0.1$	1	0.4
metal	inf	1	0
trees	$10 - j6$	1	-

IV. Realistic Environment Modeling

As depicted in Fig. 1 the investigated urban scenario comprises two lanes and four cars with buildings and vegetation on both sides of the street. Car A is performing the radar sensing and is thus denoted as the *radar*. Cars A and C are moving at the same direction with the set velocity v_{set}, of 12.9 m/s while B and D are moving in the opposite direction with the velocities of -13.3 m/s and -14.5 m/s respectively. The distances R, calculated from the center point of the cars of B, C and D from A are 16.4 m, 26 m, and 34.6 m respectively.

The 3D model of the cars as shown in Fig. 2 is made up of around 700 triangles, each at least 25 cm^2, guaranteeing a large size relative to the wavelengths at 24 GHz which fulfill the requirements for using the ray-tracing algorithm. The model of the car is 3.8 m in length, 1.85 m in width and 1.7 m in height, with all perfect electrical conducting surfaces.

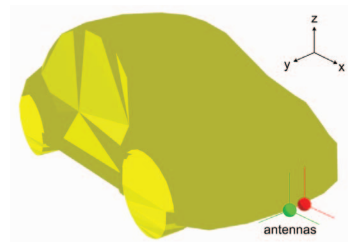

Fig. 2. 3D car model

Two antennas (depicted in red and green), one transmit and one receive, are affixed on the bumper of car A and both have the characteristics of covering 90° in the azimuth and 180° in elevation (to take into consideration the reflections from the ground). With all the settings as described, one 'snapshot' is taken from the scenario. This snapshot file contains all the paths of the rays including the amplitude, phase, Doppler and time delay.

This snapshot file is then exported to the RadCom channel simulation in MATLAB. Each of the rays are mapped onto the transmit signal by multiplying the time domain transmit signal with the amplitude attenuation, phase rotation and Doppler shift and shifted according to the time delay of the ray. After that, all the time delayed transmit signal are superimposed on each other by means of simple element-wise addition in MATLAB. The end result of this superimposition is the channel-distorted received signal.The received signal is then processed using the algorithm discussed in Section II for the range and Doppler estimation. The resulting radar image is as shown in Fig. 3.

The detected range and relative velocities are as summarized in Table III. It can be seen that the simulated and set values have a slight difference. This is due to the fact that the reflective centers of the cars are not exactly at their center. Therefore a detection difference of within ± 1.9 m (equivalent to half the length of the car) is considered as an accurate localization of the moving car. The object images at above 60 m are reflections from buildings along the road, and they depict the velocity at which the radar is traveling. Any objects other than the ones mentioned are the multiple reflections that bounced off the car and the ground. By adjusting the antenna elevation characteristics, the detection of these reflections can be reduced.

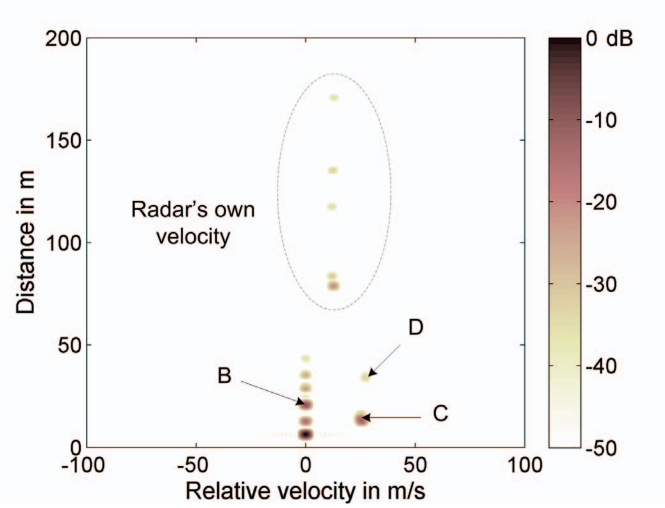

Fig. 3. Radar image car A, single user

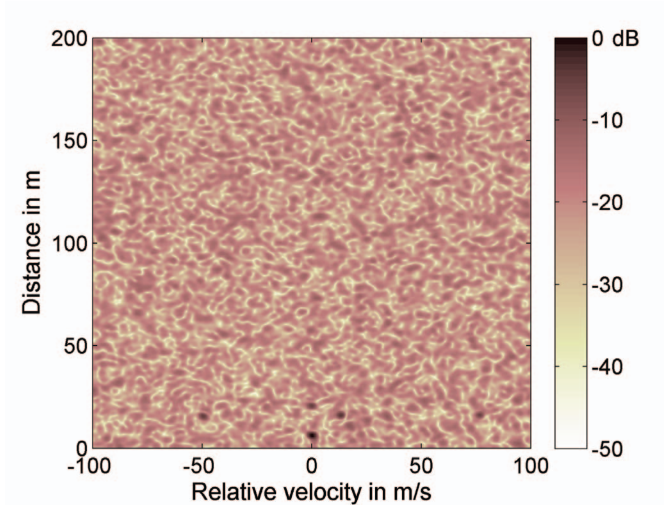

Fig. 4. Radar image of car A with car D as the interferer

TABLE III
RAY-TRACING SIMULATION DATA

Object	Settings			Simulation	
	R [m]	v_{set} [m/s]	v_{rel} [m/s]	R [m]	v_{rel} [m/s]
A	0	12.9	0	-	-
B	16.4	-13.3	26.2	16.1	25.7
C	26	12.9	0	25.2	0
D	34.6	-14.5	27.4	34.4	27.4

Multiuser scenario

In the case of a multiuser scenario, car D is equipped with the same radar system as car A (as depicted in Fig. 1) and the impact of introducing another user in the environment can be simulated. The ray-tracing program will calculate four channels in this case and these files record the influence of cars A and D on each other, namely the channels A-A, A-D, D-D and D-A. The resulting radar image for car A with the superimposition of the interfering transmit signal from car D is as shown in Fig. 4.

The effect of a multiuser environment and the details about the handling of the interference can be found in [6]. An interference cancellation algorithm has also been developed and presented. After the removal of the interference, the resulting radar image of car A is as depicted in Fig. 5.

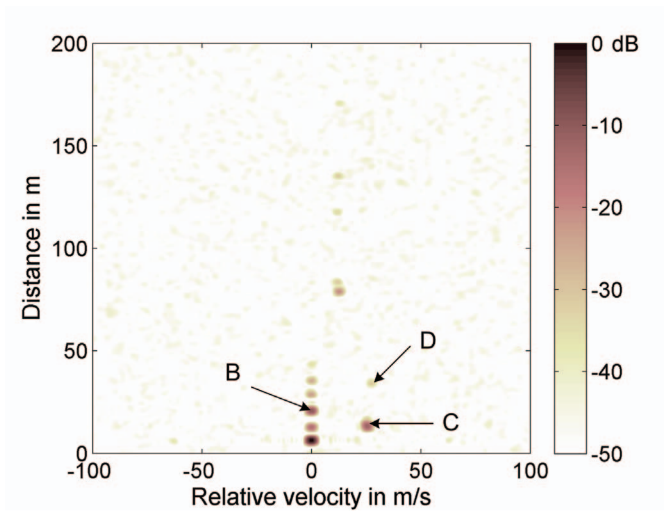

Fig. 5. Radar image of car A after the cancellation of car D's influence

V. CONCLUSION

A geometrical-optics based ray-tracing simulator for modeling the wave propagation in a realistic multipath-multiuser scenario has been discussed. In modeling the realistic environment, all propagation phenomena e.g. reflection, diffraction, scattering, and material parameters have been taken into account. Based on the comparison of the set values in the ray-tracing software the novel range and Doppler estimation algorithm of the OFDM RadCom are validated. With this verification, the ray-tracing algorithm can then be extended for use in the investigation of a multiuser scenario for the RadCom.

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