Harmonic Automotive Radar for VRU Classification

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***Abstract*—A harmonic radar and set of passive transponders are used for detection and identification of vulnerable road users (VRUs) in automotive applications. The radar system transmits a signal consisting of two distinct frequency components in the 76-81 GHz band. A small transponder is carried by the VRU. The antenna and the electric circuitry of the transponder are printed on flexible film and it can therefore be integrated in clothes. In the transponder the two frequency components are mixed together and a harmonic product, offset from all other reflections, is transmitted back to the radar. By synthesizing this harmonic frequency the radar system can unambiguously identify and localize VRUs**

Keywords- automotive radar; harmonic radar; transponder;

I. INTRODUCTION

Automotive radars are becoming standard equipment in premium cars and they are expected to become common also in medium and lower class cars. Currently the commercially available systems are used for blind spot detection (BSD) and automatic cruise control (ACC). BSD systems ease certain maneuvering, such as lane changing, whereas ACC systems adjust the vehicle speed according to the preceding vehicle. These radars, however, can not easily identify vulnerable road users (VRUs), such as pedestrians, cyclists and motorcyclists from other road users and obstacles such as cars and traffic signs.

The current paper investigates the use of a harmonic automotive radar system, consisting of a harmonic radar unit and a set of passive transponders to provide an unambiguous classification and localization of VRUs.

The harmonic radar transmits a signal that consists of two distinct frequency components (f_1 and f_2), see Fig. 1. In the transponder the two frequency components are mixed together and a harmonic product is transmitted back to the radar. To comply with the designated band for automotive radars the f_2 lies close to f_1 and thus also the third order harmonic, $2f_1$-f_2, generated in the transponder, lies close to f_1 and f_2

The generation of harmonic return frequency at $2f_1$-f_2 in the transponder occurs in a non linear element (ferroelectric varactor, diode or MEMS resonator). The transponder is passive, i.e. it uses only the energy of the received electromagnetic waves.

The radar system processes the reflections from conventional targets by using a replica of the transmitted signal at f_1 (or f_2). The transponder return is processed by synthesizing the transponder frequency based on the two transmitted frequency components. This way the radar can have two main outputs where one output is related to the conventional reflections and the other unambiguously related VRUs carrying transponders.

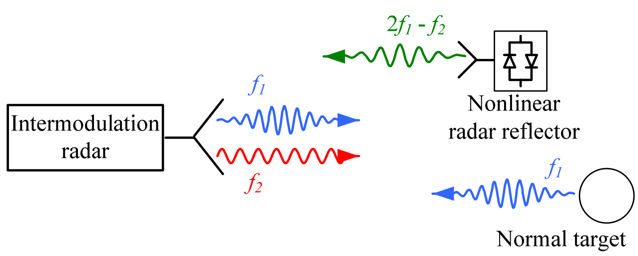

Figure 1. The overall concept of harmonic radar and transponders

The development of the Automotive Harmonic radar and transponders are done within the ADOSE-project (Reliable Application Specific Detection of Road Users with Vehicle On-Board Sensors) [1], funded by the European Union under seventh framework program, information and communication technologies. ADOSE aims at increasing the road safety by developing reliable obstacle detection and classification with on-board sensors. The sensor technologies developed in addition harmonic radar are far-infrared sensor, multifunctional CMOS vision sensor, 3D camera and silicon retina sensor.

II. Harmonic radar band usage

The harmonic automotive radar system has to be compliant with the upcoming ETSI (The European Telecommunications Standards Institute) regulations [2]-[4]. The definitions of the bands for SRR and LRR (short and long range radar, respectively) are shown in Table I.

In addition it is desirable that the harmonic radar is based on similar waveforms as will be seen in future automotive radar systems. In the following we focus on a system where the first frequency component, f_1, is a linear frequency modulated sweep (LFM).

A third order harmonic system fits well within the ETSI regulations. The time varying transponder return frequency is found as

$$f_T = 2f_1 - f_2 ,$$

where f_1 and f_2 are the transmitted time-varying frequencies. As an example, if the harmonic radar transmits signals at 79 GHz and at 80 GHz, the transponder returns a signal 78 GHz.

The actual resolution of the radar system, Δr, both for the conventional returns (the reflections at f_1 and f_2) and for the transponder returns is related to the received bandwidth, BW, through

$$\Delta r = \frac{c}{2BW} ,$$

where c is the speed of light.

For the conventional targets the received bandwidth is for all practical purposes the same as the transmitted bandwidth, which is not necessarily true for the transponder return. Depending on the waveforms used the bandwidth of the transponder return can be either be wider, narrower or the same as that of f_1 or f_2.

For example, 0.25 m radial resolution requires a bandwidth of 600 MHz regardless whether the bandwidth is limited by the radar or the transponder.

III. Radar waveforms and transponder returns

Several different waveforms can be used for the second frequency to generate a transponder return of sufficient bandwidth in a typical pulsed LFM or frequency modulated continuous wave (FMCW) system. Four examples are briefly discussed in the following list and displayed in Fig. 2.Figure 2.

TABLE I. ETSI Band Definition ([2]-[4]).

	SRR	Present LRR	
		FMCW	**Pulsed**
Frequency	77 GHz to 81 GHz	76 GHz to 77 GHz	
Worst Case Mean EIRP Spectral Density @ 79 GHz	<-15 dBm/MHz to -3 dBm/MHz		
Mean Power	18 dBm to 30 dBm	50 dBm	23,5 dBm
Worst Case Peak EIRP @ 79 GHz	46,2 dBm to 55 dBm	55 dBm	55 dBm
Operating Distance	30 m	150 m	150 m

a) A linear frequency sweep of the same rate as the first signal. In this case the reflected harmonic is negative offset with the frequency difference between the first and second base signals.

b) Sweeping with another rate. The transponder return sweeps with a rate unequal to the rate of the other signals.

c) Fixed frequency. This will result in a harmonic reflection with that sweeps with a double compared to the first base signal.

d) Frequency coding. A coded frequency transmission would improve the interference rejection.

The waveforms can be received either in separate channels or in a common channel.

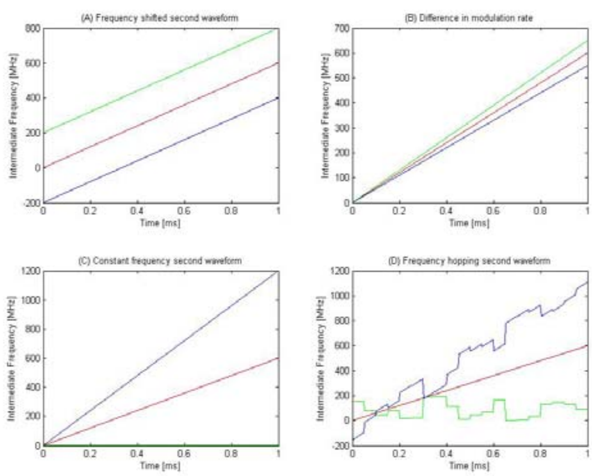

Figure 2. Different harmonic waveforms (in the intermediate frequency band). Base signal 1 and 2 are in red and green respectively. The transponder return signal is in blue.

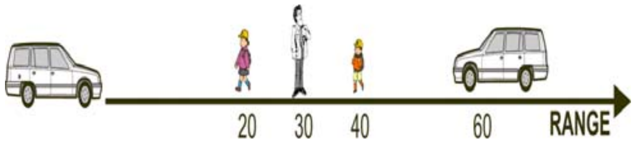

Figure 3. Targets used in simulation. The children at 20 and 40 meters are wearing passive tags.

A. Separate channels

The instant frequency difference between the two base signals is greater than the channel bandwidth of the receiver. In this case the reflected transponder signal is out of the frequency band of the first base channel. This method would offer a higher dynamic range compared with a common channel scheme. In addition, the transponder return would not mix with Doppler-shifted reflections from conventional targets. The channel bandwidth can be rather narrow. However, the radar system would need at least two receive channels that are separated in frequency. This leads to a complementary set of mixers and signal generators to realize the second transmit signal and the transponder receive channel.

The separate channel approach is studied in a simulation using the targets as seen in Fig. 3. The two children at 20 and 40 meters are wearing passive tags. Results from the simulation are presented in Fig. 4.

Fig. 4 shows that all targets are present in the two base channels. However, only the two children are present in the transponder channel. Note that the dynamic range is limited by the skirts of the targets and not by the noise level (which in typical similar applications is could be as low as – 130 dBm). The skirts arises in the Fourier Transform and can be somewhat reduced at the expense of radial resolution by applying windowing.

B. Common channel

In the common channel architecture, the instant frequency difference between the two transmitted signals is small such that transponder return and the base returns are in the same frequency channel. In this case the transponder signal may mix with the Doppler-shifted reflections form conventional targets

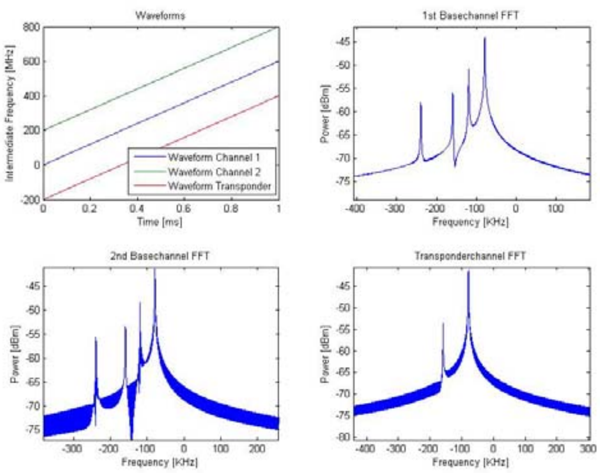

Figure 4. Simulation results of separathe-channel radar architecture

and there will appear inter-modulation products between the two base frequencies in the band which might degrade the

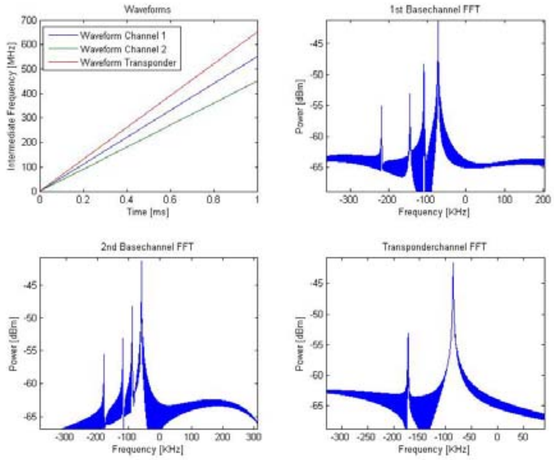

Figure 5. Simulation results of common channel radar architecture.

dynamic range of the system. System wise this method gives a minimum of hardware modifications to a conventional system.

The common channel approach is studied by the same simulation as the separate channels approach. The simulation results are shown in Fig. 5. The targets and the other parameters are as the previous case. The transponders are easily identified in the transponder channel in this approach as well.

IV. THE PRELIMINARY PROTOTYPE

The harmonic automotive radar is desired to operate both in SRR- and LRR-mode. The system is aimed to achieve 10 Hz update rate and a 2-degree angular resolution covering 120 degrees in front of the vehicle with a radial resolution of 0.25 m in SRR-mode.

The first harmonic radar prototype is under development and results from experiments are expected to be available during the beginning of 2009.

The design of this prototype is based on voltage controlled oscillators under computer control. A complete transmit-receive subsystem for the first waveform enables operation of the system as a conventional automotive radar. Harmonic operation is achieved by adding transmitting circuitry for the parallel waveform and a subsystem for receiving the transponder return.

The desired performance parameters of the first prototype radar are:

- FM pulses 1 ms to 100 ms
- At least 600 MHz bandwidth
- Ramp and triangular FM modulation
- Synchronous transmission of two parallel channels

- Reception of at least one channel and the transponder channel
- Transmit level in accordance with ETSI (55 dBm EIRP)

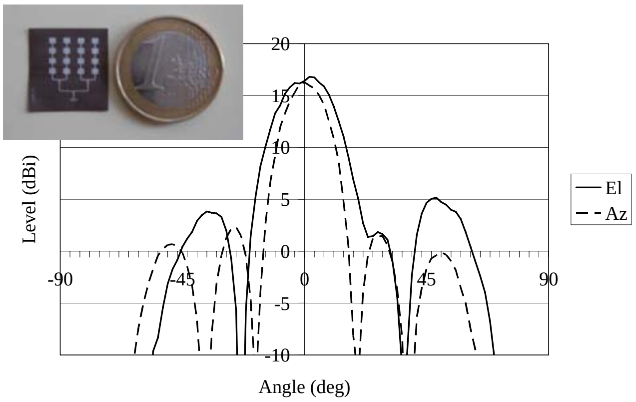

Figure 6. Measured elevation and azimuth cuts of the radiation patternof fixed-beam high-gain tag antenna.

Baseband signal processing and system control are performed by a conventional lap-top computer which enables flexibility and a possibility to exploit a number of different waveforms (both for SRR and LRR mode) in the first rounds of experiments.

V. Wearable Radar Reflectors

One objective of the current project is to develop low-cost transponders small enough to be integrated in clothing. The passive transponder does not have a battery and is basically a mixing element (diode, ferroelectric varactor or a MEMS resonator) directly matched to the antenna.

The mixing loss of the non-linear elements is inversely proportional to the input power squared. Therefore, in order to maximize the detection range, the tag antennas should have a reasonable directivity providing sufficient power to the mixing element.

The body-worn tags should preferably be integrated in jackets or coats. For durability and comfort to the user, they should be built on thin flexible substrates. In the current design Rogers Liquid crystal polymer (LCP) Ultralam 3000 [5],[6], with 9 μm Cu metallization is used. A microstrip patch array antenna is designed (Fig. 6) with 16 dBi gain having 21º beamwidth in elevation, 16º beamwidth in azimuth and a bandwidth of 2.5 GHz.

The achievable detection range of the system havily depends on the mixing element used in the transponder. The achievable detection ranges using a Schottky-diode, ferroelectric varactor and MEMS resonator as the mixing element are studied in [7] by simulations using the link-budget parameters shown in Table II and the transponder antenna presented above. The simulations concluded with a detection range of 22 m using a Schottky-diode, 39 m using a ferroelectric varactor and 74 m using a MEMS resonator as nonlinear element in the transponder.

TABLE II. The Estimated Parameters Used for Link Budget Calculations.

Transmitted power	$P_t = 16$ dBm
Gain of the radar antenna	$G_{radar} = 40$ dBi
Gain of the tag antenna	$G_{tag} = 15$ dBi
Wavelength	$\lambda = 3.9$ mm ($f = 77$ GHz)
Antenna temperature	$T_A = 270$ K
Receiver noise figure	$NF = 7$ dB
Noise bandwidth	$B = 200$ kHz
Noise power	$P_n = -114$ dBm

VI. ConclusionS

An harmonic radar and a set of passive transponders has been presented as a tool to unambiguously identify and localize VRUs.

The general concept overview, harmonic waveform and transponder antenna specifications are presented. Results from simulations show that a VRU detection range between 22 m and 74 m depending on the choice of nonlinear element in the transponder could be achieved.

An experimental harmonic radar system is under construction and results from experiments are expected in the beginning of 2009.

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