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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 (VRU) 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 VRU.**

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 (VRU), 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 radar unit and a set of passive transponders to provide an unambiguous classification and localization of VRU.

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 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 the 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 one of the transmitted frequency components, f_1 (or f_2), directly. 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 to VRU carrying 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 the 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. Other sensor technologies developed in ADOSE 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.

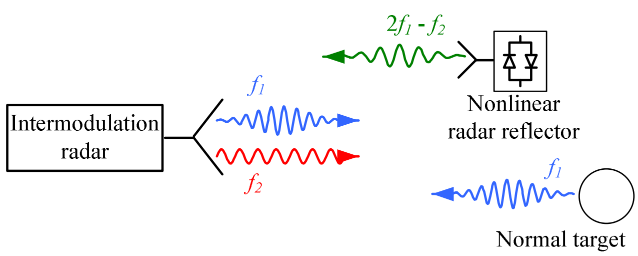

Figure 1. The overall concept of harmonic radar and transponders.

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2011 under *grant agreement* n° 216049

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

To ease the integration with conventional automotive radar 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

$$f_T = 2f_1 - f_2 , \quad (1)$$

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

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

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

Different waveforms can be used for the second frequency, f_2, 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.

- A linear frequency sweep of the same rate as the first frequency. In this case the reflected harmonic is negative offset with the frequency difference between the first and second base signal.
- Sweeping with another rate. The transponder return sweeps with a rate unequal to the rate of the other signals.
- Fixed frequency. This will result in a harmonic reflection that sweeps with twice the rate of that of the first base signal.
- Frequency coding. A coded frequency transmission would improve the rejection of interference.

If the waveforms are close in frequency they can all be received using single channel architecture. However, if their separation in frequency is large dual channel architecture is used with one channel for transponder returns and one for conventional return at f_1 (or f_2).

Simulations for these two approaches are performed using the targets seen in Fig 3. The results from the simulations are seen in Fig. 4 and Fig. 5.

A. Dual channel reception

A large frequency separation between the transmitted signals results in a frequency separation between the transponder returns and the conventional returns that exceeds the bandwidth of a typical reception channel. A separate channel (in hardware) will then perform the reception of the transponder returns. This method would offer a higher dynamic range compared with a single channel solution as one can use

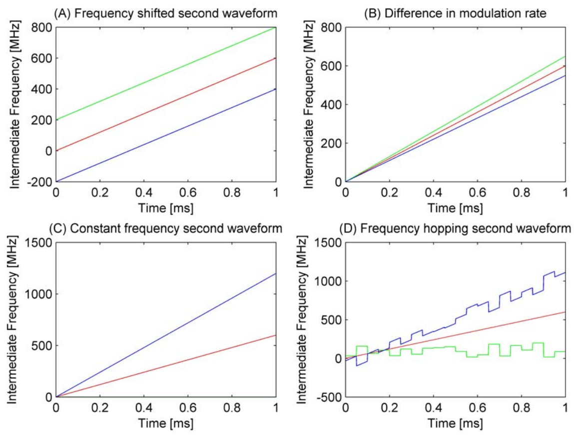

Figure 2. Different harmonic waveforms (in the intermediate frequency band). Base signal 1 and 2 are in red and green respectively. The transponder return signal is in blue.

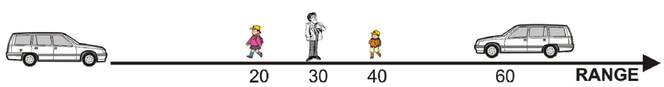

Figure 3. Targets used in simulations. The children at 20 and 40 meters are wearing tags.

narrow band processing. Also, due to the large separation of the signals in frequency, the transponder return would not mix with Doppler-shifted reflections from conventional targets. However, the dual channel radar system would need a

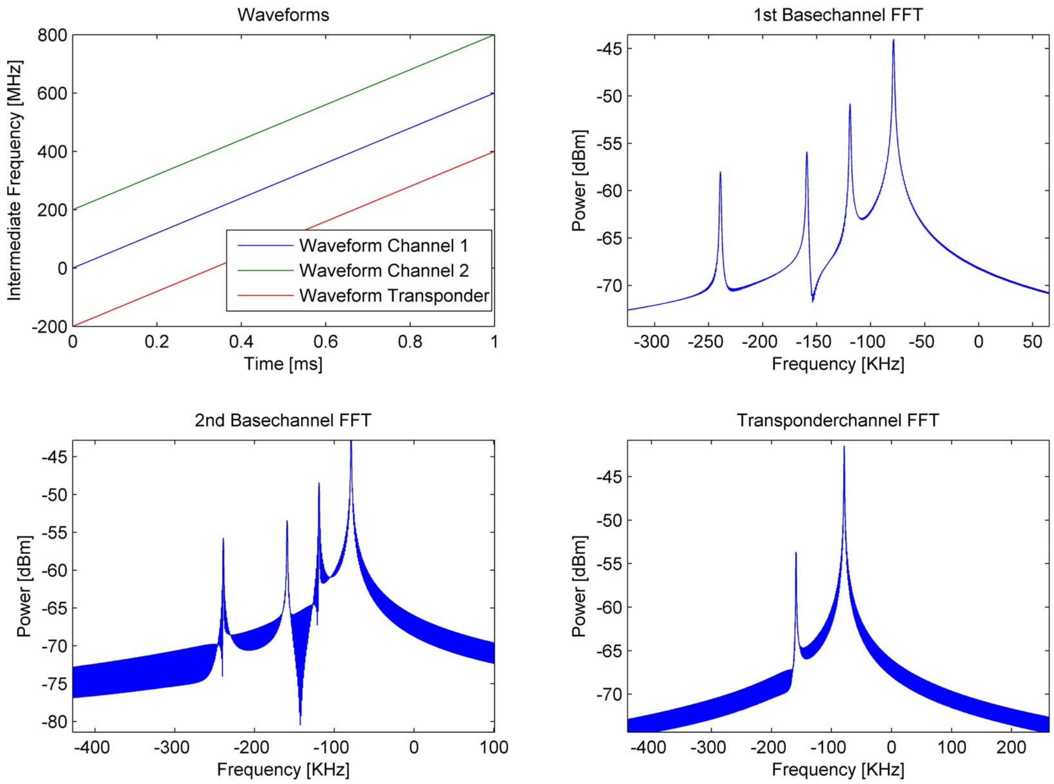

Figure 4. Simulation results of dual channel radar arcithecture.

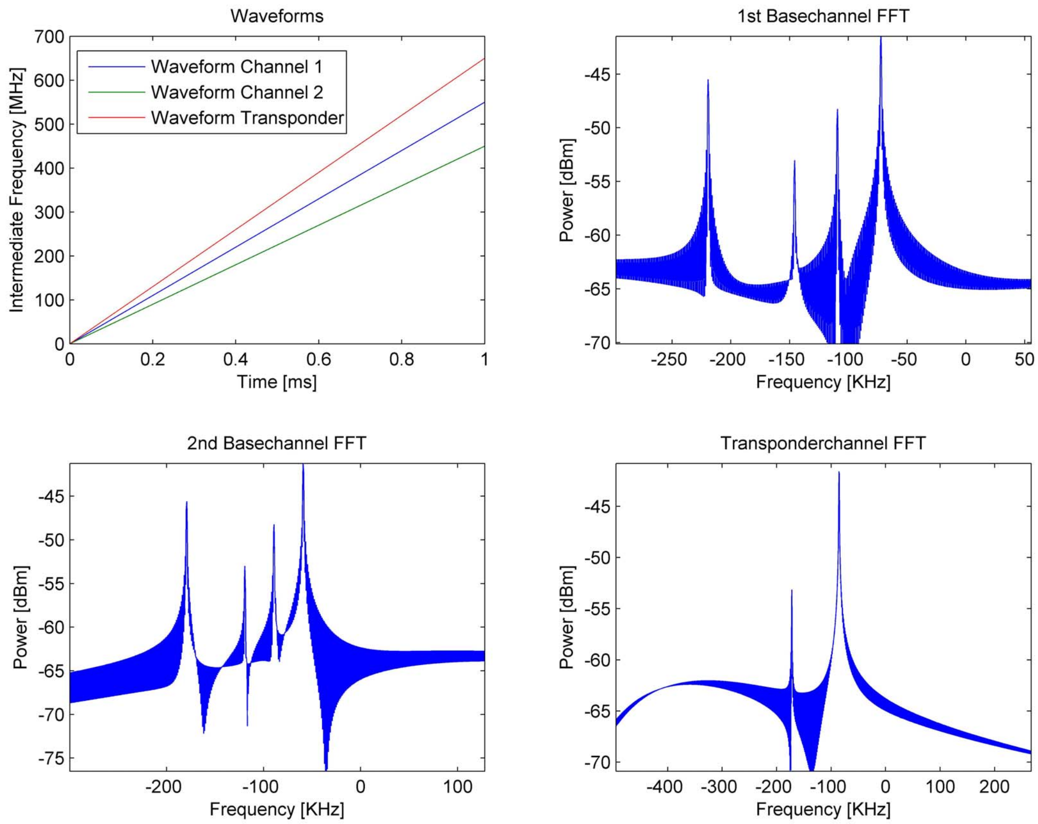

Figure 5. Simulation results of the single channel radar architecture.

complementary set of mixers and signal generators to realize the second transmit signal and the transponder receive channel.

As for the simulations one can se in Fig. 4 that all targets are present in the two base channels. This is as expected as the VRU wearing tags also reflects the base signals as any other targets. However, only the reflections from the tags worn by 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. Single channel

In the single 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 and there will appear inter-modulation products between the two base frequencies in the band which might degrade the dynamic range of the system. System wise this method gives a minimum of hardware modifications to a conventional system.

The single channel approach is studied by the same simulation as the dual channel 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 towards the end 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)

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 heavily 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.

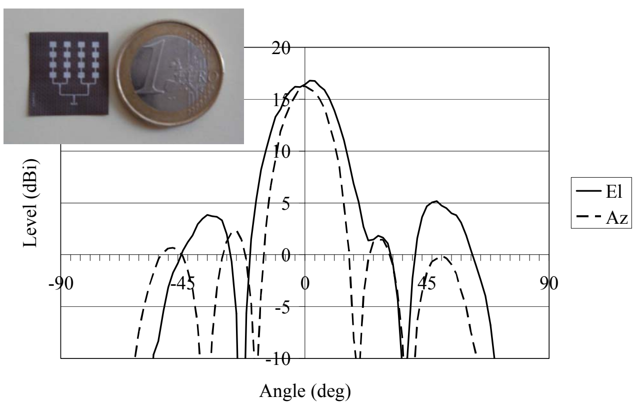

Figure 6. Measured elevation and azimuth cuts of the radiation pattern of fixed-beam high-gain tag antenna.

TABLE II. THE ESTIMATED PARAMETERS USED FOR LINK BUDGET CALCULATIONS.

Transmitted power	$P_t = 15$ 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

A harmonic radar and a set of passive transponders has been presented as a tool to unambiguously identify and localize vulnerable road users.

The general concept has been presented and different harmonic waveforms have been discussed. The transponder consists of a nonlinear element and an antenna on flexible substrate. A microstrip patch array antenna with 16 dBi gain has been designed. Results from simulations show that a detection range between 22 m and 74 m depending on the choice of nonlinear element in the transponder can be achieved.

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

REFERENCES

[1] http://www.adose-eu.org/

[2] "Electromagnetic compatibility and Radio spectrum Matters (ERM); Radio equipment to be used in 24 GHz band; System Reference Document for automotive collision warning Short Range Radar," ETSI TR 101 982 V1.2.1, July 2002.

[3] "Electromagnetic compatibility and Radio spectrum Matters (ERM); Road Transport and Traffic Telematics (RTTT); Radar equipment operating in the 76 GHz to 77 GHz range; Part 1: Technical characteristics and test methods for radar equipment operating in the 76 GHz to 77 GHz range;" ETSI EN 301 091-1 V1.3.3, Nov. 2006.

[4] "Electromagnetic compatibility and Radio spectrum Matters (ERM); Road Transport and Traffic Telematics (RTTT); Radio equipment to be used in the 77 GHz to 81 GHz band; System Reference Document for automotive collision warning Short Range Radar," ETSI TR 102 263 V1.1.2, Feb. 2004.

[5] www.rogerscorporation.com, Rogers Corporation, Ultralam 3000 Data Sheet.

[6] S. L. Smith and V. Dyadyuk, "Measurement of the Dielectric Properties of Rogers R/flex 3850 Liquid Crystalline Polymer Substrate in V and W Band," *Proceedings of the International Symposium of IEEE Antennas ad Propagation Society*, Vol. 4B, July 2005, pp. 435-438.

[7] V. Viikari, J. Saebboe, S. Cheng, M. Kantanen, M Al-Nuaimi, T. Varpula, A. Lamminen, P. Hallbjörner and A. Rydberg " utomotive Intermodulation Radar for Detecting VRUs," *Proceedings of the 69th Vehicular Technology Conference*, Apr. 2009