Novel Automotive Radar Applications

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***Abstract*-The first commercial automotive radars are designed for blind-spot detection, collision warning, and automatic cruise control. These radars, however, could be used for other applications as well, such as road condition classification, vulnerable road user detection, and data transfer from ubiquitous sensors or tags. This paper discusses automotive radar for road condition classification at 24 GHz and shows results of semi-passive and active radar transponders at 77 GHz that could be used as ubiquitous sensors or tags in traffic applications.**

I. INTRODUCTION

The first commercial automotive radars are used for blind spot detection, automatic cruise control, and collision warning. Some car manufacturers, such as Volvo, are also offering radars that automatically brake when they detect a pedestrian in a risk of a forthcoming collision. Blind spot detection systems typically operate at the 24 GHz band in Europe [1] and facilitate driving detecting objects hidden in blind spots for example during a lane change. Forward looking automatic cruise control radars adjust the vehicle speed according to the preceding vehicle and operate currently at 77 GHz in Europe [2]. An additional band, 77 – 81 GHz, is being allocated by European Telecommunications Standards Institute (ETSI) for short range (30 m) collision warning automotive radars [3].

The automotive radars are proposed for other traffic applications as well, such as detecting lowered road friction due to water, rime, ice, or snow on road surface. Currently road surface conditions are monitored with infrared optical systems that are too expensive for ordinary passenger cars and whose detection range is very limited. Multipurpose radar sensors could offer cost benefits and also longer range as compared to optical systems. Several monostatic [4], bistatic [5] – [9] and passive radiometric [10] systems have been reported for road condition classification. In this paper, we review selected monostatic results at 24 GHz for road condition classification originally presented in [4].

Automotive radar could also be used to read out tags and sensors based on the backscattering communication principle. Such tags could be used with radar to detect vulnerable road users (i.e. road users possessing a high risk to be seriously injured in a traffic accident), such as pedestrians, bicyclists, and motorcyclists, which typically present a small radar cross section, and are hence hard to see with a radar. Traffic signs could also be equipped with such transponders such that their information is automatically read by the radar. This could facilitate driving especially during bad optical visibility and, depending on the level of automation, could warn the driver when detects a traffic rule offense.

This paper presents preliminary results on 77 GHz semi-passive and active transponders based on backscattering communication principle. Millimeter wave transponders, or tags, have been earlier presented e.g. in [11]. In addition to automotive radar applications, such tags could be used for high-speed communication with future millimeter wave radio systems [12],[13].

II. ROAD CONDITION CLASSIFICATION

A. *Test Setup*

We have studied 24 GHz dual-polarized automotive radar for road condition classification in two measurement campaigns, one in winter and the other in summer. The studied road conditions in the winter campaign were dry, snowy, and icy asphalt. Test tracks with different conditions were prepared on a cast-off runway of Ivalo airport, Finland. Test tracks with different road conditions were at least 50 meters long and 4 meters wide. The test tracks with close-ups of different road surfaces are shown in photographs presented in Figure 1.

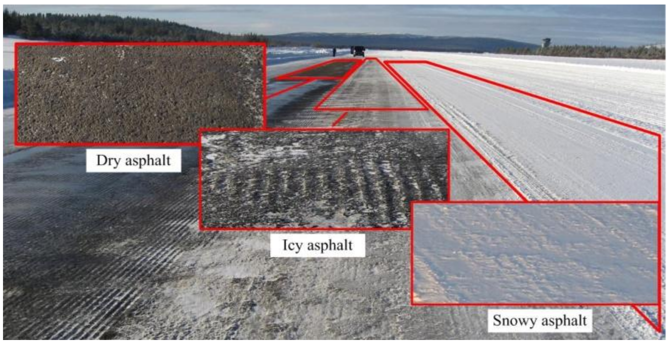

Fig. 1. The test tracks with different road conditions. From left to right: dry asphalt, icy asphalt, and snowy asphalt.

Summer tests were performed at a test track located in Nokia, Finland, and the studied road conditions were dry and wet asphalt.

A vector network analyzer (HP 8510) was used as a radar in the measurements, and the equipment was placed on a boot space of a van. The power required was generated with an aggregate and the measurement antennas were aligned to point to the track from the opened back door of the van. The test van with the measurement equipment is shown in Figure 2.

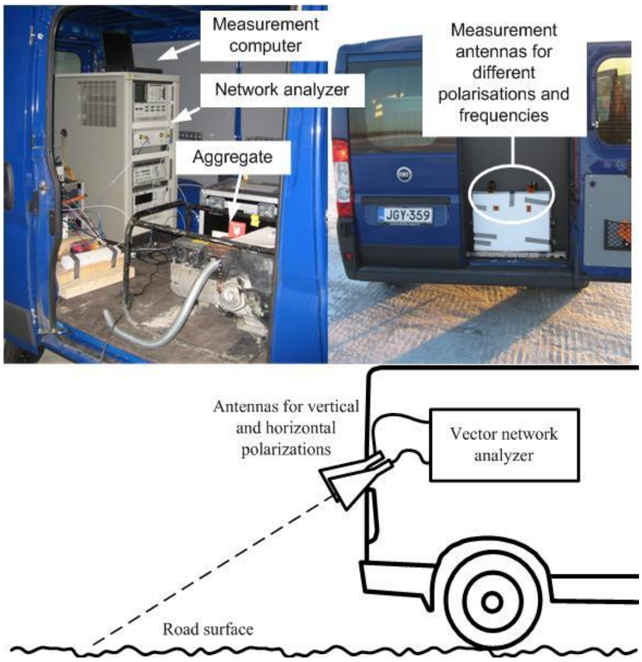

Fig. 2. The test van equipped with measurement equipment.

The measurement antennas were located 1 m above the road surface and their main beams were tilted 65^{o} respective to the normal of the road surface. Several measurements on each road conditions were measured such that results could be averaged.

B. *Results*

Different methods are presented for classifying the road conditions from a measured backscattering response. When a phase-coherent data are not available for different polarizations, a simple approach is to compare the amplitudes of backscattered signals at different polarizations. Using such relative quantity enables to mitigate the effect of several unknown parameters, such as target distance and weather conditions, which could affect absolute amplitude measurements.

Figure 3 shows the ratio between the backscattering coefficients at *vv*- and at *hh*-polarizations (the first letter stands for the polarization of the transmitted signal and the second for that of the received signal) for different road conditions. The markers represent single measurements and solid lines are average values for respective road condition and polarization.

Figure 3 shows that the ratio between backscattering coefficients changes in absolute value with road conditions. The average value on wet road is 6 dB higher than that on dry asphalt. Compared to dry asphalt, ice lowers the value more than 1 dB and snow further lowers it approximately 2 dB. Therefore, average values can be used to classify road conditions although variation between adjacent measurements is so large that averaging is required to obtain the road condition reliably.

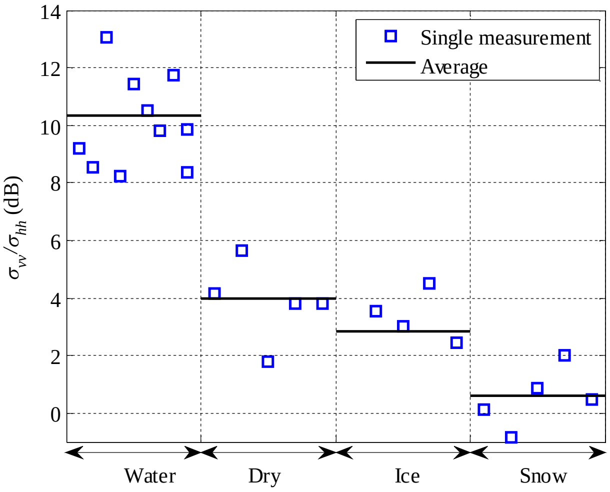

Fig. 3. Measured ratio between backscattering coefficients at *vv*- and *hh*-polarizations for different road surfaces. Markers represent single measurements and solid lines are averaged values over respective road condition.

Same measurements were performed also at 77 GHz. Similar behavior with different road conditions were observed also at that frequency, although the changes in backscattered signals were somewhat smaller than at 24 GHz.

According to this study, it seems possible to classify road conditions using a modified automotive radar. However, because the radar illuminated the road surface at a few meters distance from the vehicle and because several measurements need to be averaged for a reliable classification, the system may not suit for pre-warning the driver as such. Instead, the road friction information could be exploited for example to automatically adjust the suspension to prevailing friction conditions.

III. SEMI-PASSIVE AND ACTIVE TRANSPONDERS

A. *Range estimation*

Radar transponders, or tags, are based on the backscattering modulation principle. This principle is in extensive use e.g. in RFID systems at UHF frequency. Backscattering modulation does not require a local oscillator in the transponder, but only the incoming millimeter wave radiation is modulated by load or gain modulation. A simplest radar tag consists of an antenna and a diode, whose bias is modulated to achieve low- and high-impedance states. The change in the antenna load impedance is seen as a change in the scattered millimeter wave field of the antenna. This reflection is then detected by the radar. The modulation can carry information about the tagged object, e.g. type of target (pedestrian, cyclist, traffic sign etc.) and additional information, such as speed limit. The operation principle, shown in Figure 4, is compatible with the hardware of modern FMCW automotive radars.

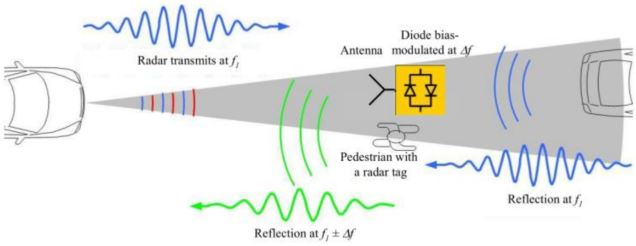

Fig. 4. Operation principle of radar tags. The tag antenna is load modulated at *Δf*, resulting in reflection of the radar signal at $f_1 \pm \Delta f$, which is easily separated from normal target reflections and clutter at f_1.

The detection range of the radar tags can be estimated from using the modulated radar cross section σ_m. For a square wave modulation, the radar cross section presenting the power in single-sideband at the modulation frequency Δf becomes [14]

$$\sigma_m = \frac{\lambda^2 G_{tag}^2}{4\pi}\frac{1}{\pi^2}\left|\Gamma_1 - \Gamma_2\right|^2 = \frac{\lambda^2 G_{tag}^2}{4\pi} m, \qquad (1)$$

where Γ_1 and Γ_2 are the reflection coefficients related to the impedance states 1 and 2 of the tag, G_{tag} is the tag antenna gain, and m is the modulation index. The definition of the modulation index limits its maximum value to -3.9 dB. Now we can use radar equation for range estimation

$$r = \frac{\lambda}{4\pi}\sqrt[4]{\frac{G_{rx} G_{tx} G_{tag}^{2} P_{tx} m}{P_{rx}^{0}}}, \qquad (2)$$

where G_{tx} and G_{rx} are the transmit and receive gains, respectively, P_{tx} is the transmit power and $P_{rx,0}$ the noise floor of the receiver.

B. Transponder designs and measurement results

Two semipassive and an active radar transponder were designed to demonstrate the feasibility of the proposed radar communication system at 77 GHz. All the tags have a 4×4 element antenna array [15], but they have different millimeter wave components and substrates (see Figure 5). The least expensive of the designs was a semipassive tag composed of a Schottky diode (UMS DBES105a99F [1]) on a 100-µm LCP substrate (Rogers Ultralam 3000 [2]). A semipassive tag with MEMS switches on a glass substrate was manufactured with VTT RF MEMS process [16]. The active tag included an amplifier (Triquint TGA4705-FC[3]) on the LCP substrate.

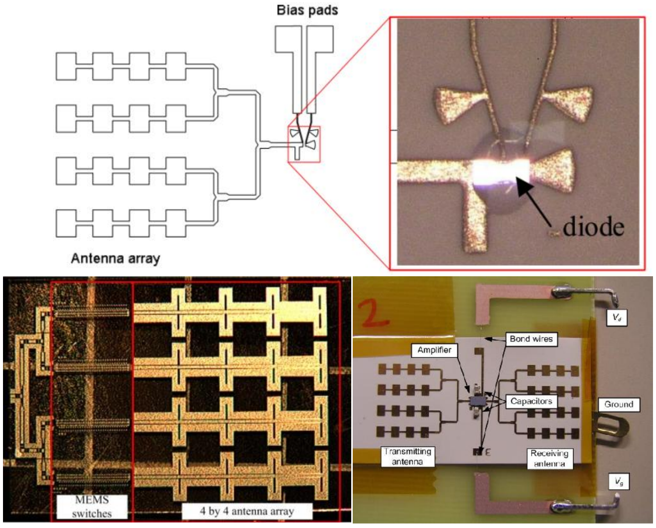

Fig. 5. Radar tag designs: A semipasssive tag with a Schottky-diode on a LCP substrate (above), a semipassive tag with a MEMS switches on a glass substrate (below left), and an active tag with an amplifier on a LCP substrate (below right).

The modulation index was measured on a probing station with tag samples equipped with 50-ohm probe pads instead of antennas. In semipassive tags, the Schottky diode or the MEMS switch was driven with a low-frequency signal *Δf* from a battery powered circuitry. The diode provides the simplest bias circuit, as it requires a voltage of about 1 V and a current of 10 µA. Hence a small coin cell battery of 100 mAh is enough to feed the circuitry for a year. The MEMS switch enables higher modulation index, but requires a more complex bias circuit due to excitation voltages exceeding 10 V. The switches are capacitive, and hence the current remains minuscule. In the active tag, the gain of the amplifier was modulated at *Δf*. The power consumption of the active tag is 74 mW, but it provides almost 30 dB higher modulation index.

The radar cross section of the tags was measured with a similar waveguide-based measurement setup, where the probes were replaced by a horn antenna. A metal plate was used as a reference target. The radar cross section of the Schottky and amplifier based tags are shown in Figs. 6 and 7. The measured σ_m of the semipassive tag is high compared to the modulation index, indicating a problem in absolute value calibration.

The detection range of the proposed tag designs were calculated using (2) at 77 GHz. The transmit power was estimated to be 30 dBm EIRP, all antenna gains 14 dB, and the noise floor to be -120 dBm. These values present a state-of-the-art automotive radar at 77 GHz. The operation of the semipassive tags is limited to about 10 meters, but the active tag provides a range exceeding40 meters, making it feasible for e.g. tagging traffic signs even in highway environments. The measured results and calculated range estimations are collected in Table I.

Table I. Comparison of the transponder designs.

Design	m (dB)	σ_m (cm^2)	r (m)
Schottky	-14	3	8.7
MEMS	-11	–	10
Amplifier	+14	130	43

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[1] http://www.ums-gaas.com/

[2] http://www.rogerscorp.com/

[3] http://www.triquint.com/

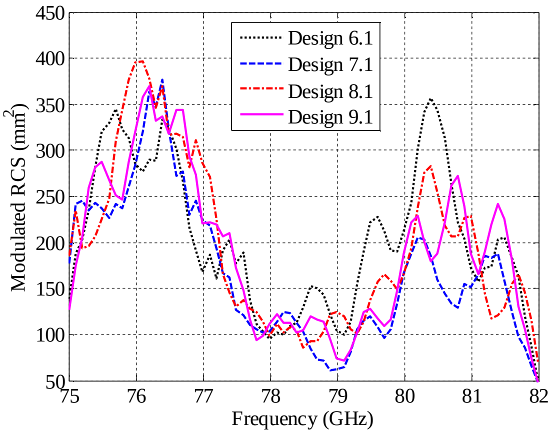

Fig. 6. Measured modulated σ_m (RCS) of semi-passive diode-based transponders samples.

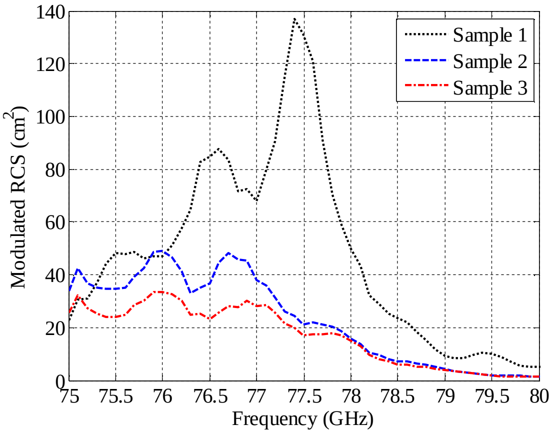

Fig. 7. Measured modulated σ_m (RCS) of active transponder samples.

IV. CONCLUSIONS

The paper presented advanced automotive radar applications for road condition classification and backscattering communication using radar tags. It was shown that the road condition (ice, snow, dry, water) can be classified by comparing vertical and horizontal scattered signals at 24 GHz. Three designs of radar tags were introduced, and their modulated radar cross sections measured at 77 GHz. The semipassive tags enable communication to about 10 m, but the active tag up to 40 m.

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