A 24 GHz ACC Radar Sensor

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Abstract
The paper introduces a 24GHz radar sensor, which is applicable for the Advanced Driver Assistance Systems (ADAS) function ACC (Adaptive Cruise Control) on automobiles. Running an FMCW narrow-band operational mode, it complies with most existing frequency regulations in the ISM band. Concept, technical and performance data are given and difficulties and technical solutions of the particular application are described.

I Application Requirements

77GHz automotive sensors are in production since 1998. Today, they have found their way into a number of high-class models. Although being extremely valuable regarding the reduction of the number of road accidents, and allowing for a relaxed driving, the percentage of vehicles originally equipped with ACC is remarkably low. There is one main reason for this: cost.

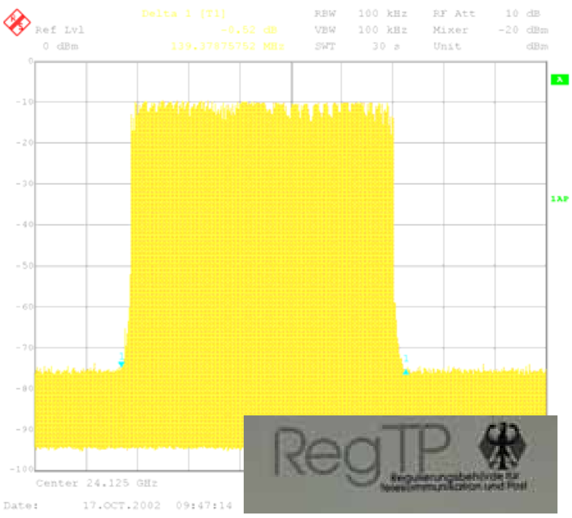
So at the beginning there was the question: would it be feasible to build a 24GHz radar having a sufficient performance to be applicable as an ACC sensor? If it was possible to reduce the cost to less than 50% of the cost of a 77GHz device, certain performance restrictions can be accepted, and the chance for higher takes rates increases significantly.

During the development phase, requirements were collected from a number of OEMs. Most requirements can be met. A list of the achieved technical performance data is given in a table below. The most difficult thing was to find an optimum antenna design providing the narrowest possible beam using the smallest possible aperture.

II. Frequency Regulations

Any device operating in the 24GHz ISM band must meet the existing regulations, which are given (for Europe) by the harmonized standards ETSI EN 300440-1 and –2 (and others).

For the UMRR sensor, operating in FMCW narrow-band mode, the frequency approval for many (including automotive) purposes was granted already in 2002 by the German Frequency Allocation Authority, RegTP. By today, the sensor has been approved in a large number of countries, including France, UK, US and Canada. The spectrum of the device's transmit waveform is depicted on the right.



The UMRR sensor is not subject to the SARA restrictions for 24 GHz UWB radars. Hence the radar can be produced beyond 2013, there are no limitations for the percentage of equipped vehicles. The compatibility between UMRR and traffic enforcement devices (police radars) was demonstrated. Due to the narrow band input amplifiers, the susceptibility to mutual interference is quite low.

III Technology

The sensor consists of 2 modules: RF module and DSP module [1].

RF Module Hardware

The RF module contains a VCO, transmit and receive amplifiers, mixers, and is made all planar of discrete components. There are also means provided for the waveform generation as well as for the control of in-band emissions and waveform linearity. A monopulse principle, patch antenna type is applied.

DSP Module Hardware

A low cost fixed point DSP is the heart of the sensor. An optimized software was created for this device to exploit the performance in the best way. The chip already has A/D converters, a CAN module, Flash and some RAM memory on board and requires just a small number of additional components.

Software Technology: Waveform and Target Detection

The narrowband FMCW waveform is created by software. As an example, an FMSK signal (see [2] –[4]) is depicted. This combination of FSK and LFM waveform design principle offers the possibility of an unambiguous and simultaneous target range and velocity measurement. The transmit waveform consists in this case of at least two linear frequency modulated up-chirp or down-chirp signals (the intertwined signal sequences are called A and B). The two chirp signals will be transmitted in an intertwined sequence (ABABAB...), where the stepwise frequency modulated sequence A is used as a reference signal while the second up-chirp signal is shifted in frequency with f_{Shift}. The received signal is down converted into base band and directly sampled at the end of each frequency step.

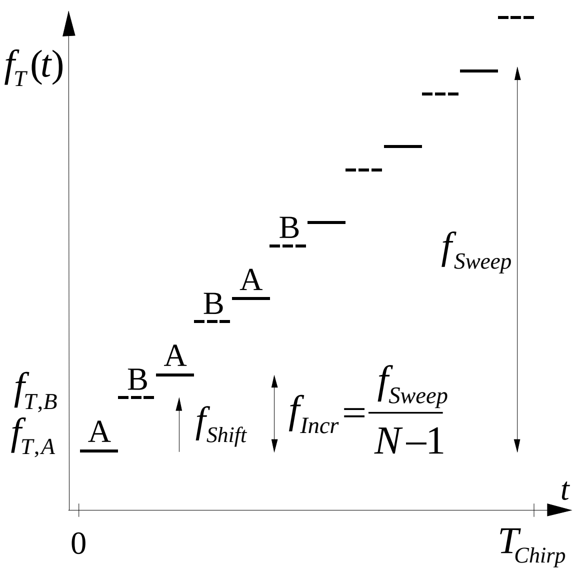


Figure 2: FMSK-2 Transmit Waveform

Measurement parameters are:

Upchirp: $f_{diff.up} = f_{dop} - \frac{2R}{c}\frac{f_{sweep}}{T_{Chirp}}, \Delta\varphi_{up,AB}\Big|_{f_{diff,up}} = 2\pi\frac{2R}{c} f_{Shift} - 2\pi \cdot f_{dop} \cdot N \cdot T_{Chirp}$,

$$f_{dop} = -\frac{2v_{rel}}{c} f_T$$

Downchirp: $f_{diff.down} = f_{dop} + \frac{2R}{c}\frac{f_{sweep}}{T_{Chirp}}, \; \Delta\varphi_{down,AB}\Big|_{f_{diff,down}} = -2\pi\frac{2R}{c} f_{Shift} - 2\pi \cdot f_{dop} \cdot N \cdot T_{Chirp}$

The target calculation in both chirps uses $f_{diff.up}$, $f_{diff,down}$, the difference phases $\Delta\varphi_{up,AB}$, $\Delta\varphi_{down,AB}$ for a calculation of R, v_{rel} for each individual target

One measurement cycle has a duration of 39ms. Only one chirp (up- or downchirp) is run per cycle. A direct and simultaneous measurement of range, velocity and angle in that single measurement cycle is performed.

By using the same modulation scheme in inverse order, i.e. transmitting the FMSK signal alternating as an upchirp and a downchirp, different spectral characteristics of the received echo can be observed. This leads to a higher detection probability of a target, because target masking probability is reduced. Further on, if a target is detected in both chirps (upchirp and downchirp), the measurement accuracy can be improved. This is due to the higher measurement accuracy of frequency compared to the combined accuracy of phase and frequency measurement, which is used for the range-velocity calculation in a single chirp. While the target measurement accuracy of a single FMSK up- or downchirp has roughly the required measurement accuracy for ACC applications, the combined accuracy is more than sufficient. In contrast to simple LFM waveforms the FMSK waveform yield no ghost targets due to the fact, that a single measurement is unambiguous. The speed of targets has no influence on the maximum range.

By using so called HiRes-algorithm it is even possible to get a rough estimation of the radial length of a target. Therefore it is possible to distinguish between point targets like traffic signs, bicycles (small targets) and van or transporters (very big targets, target radial length > 10m).

The 3db angular field of view of +-7.5° is more than sufficient for ACC. But the detection field in the near range up to 20m is much broader, approximately around +-18°. The UMRR monopulse antenna concept is able, to measure the target angle up to +-30°, so it can take full advantage of the higher near fiield detection range and can resolve cut-in situationtions easily.

Target Tracking

A traditional approach to radar based target tracking is to assume that a single point measurement corresponds to a real world target at each time step. This approximation is adequate for targets in the far field of a radar sensor. The UMRR has a high resolution and is able to resolve a number of features for extended objects especially in the near field. If these measurements can be adequately interpreted, they provide valuable information about the target motion and the body orientation, which could be exploited by a tracking filter.

Models are used for extended vehicle objects to describe the expected observations (reflection signatures) and the dynamic behavior of the vehicles. The reflection of electromagnetic waves caused by a vehicle is hard to predict. A vehicle can be seen as a collection of several different scattering centres. Each one of these centers depending on the aspect angle and the range to the sensor contributes to the echo the receiving antenna picks up. Moving targets also yield fluctuations of the radar cross section. Here a multi-modal distribution is used to model the reflection signatures. With this model statistical distances are calculated for the association step, where the unmarked measurements from the sensor are associated with vehicle objects. Clutter measurements that arise due to multi-path effects, other objects in the sensor range or noise complicates the data association.

To model the evolution of the vehicle state with respect to time we use a coordinated turn model, where the object is supposed to follow straight line segments and circle segments. This is a reasonable model of roads and usual driver maneuvers. Transitions between straight lines and circles are modeled as state noise.

The ego-motion of the host vehicle is calculated by a linear single track model from the vehicle dynamic data available on the vehicle bus, such as the yaw rate, the steering angle and the speed. Ego-motion is compensated by the tracking filter. For ACC it is necessary to decide whether a preceding vehicle is in the same lane or not, therefore a path prediction of the host-vehicle with high accuracy is needed. The path prediction algorithm analyses the vehicle dynamics, the motion of vehicles ahead and if existing as well the shape of the guardrail.

Technical Data

In the table, a list of technical data is provided.

Parameter	Value
Model	UMRR-P-0704
Operation Principle	FMSK
3dB Bandwidth	< 100MHz
Minimum Range	1.5m, below 1.5m: Presence Detection Available
Maximum Range	240m
Cycle Time	39ms
Velocity Interval	-69.4...+69.4m/s
Carrier Frequency	24.125GHz
Maximum Transmit Power	20dBm
Antenna Type	Patch Antenna
Field of View (Example)	15° (3dB Azimut) x 10° (3dB Elevation)
Supply/Interface	9V-36V / CAN, RS232, USB, Flexray, SPI

Table 1: Technical Data

Typical accuracy data are:

Range: Typical < 0.5m (under 10m, 10m...max. range: better than +- 1.25%).
Velocity: Typical < 0.25km/h.
Angle: Typical < 0.5 degree.

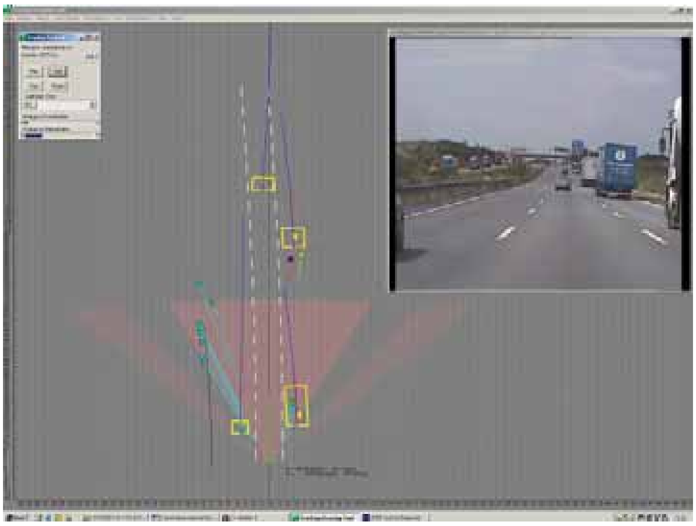
The radar is able to resolve (separate), handle and track multiple objects. To be separately detectable, two objects of identical reflectivity must be different in at least one of the following parameters:

Range Difference >= 1.8m
Speed Difference >= 0.8km/h.

A separation in angle with one single sensor is not possible with the actual monopulse antenna.

The main question for the feasibility of the ACC function concerned the max. ranges, typically achieved on representative targets. The typ. max. range on pedestrians is 40m, on bicycles 80m and on passenger cars above 120m-150m.

IV. Special ACC Application Issues



While target detection and tracking is done for targets up to 150m range, unambiguous target measurement is done up to ranges of 600m. This is due to high sensitivity of the sensor, targets having a high radar cross section, like trucks, can be detected up to 350m-400m.

The field of view is of course much wider than for a 77GHz sensor using the same aperture. This leads to excellent cut-in situation handling, because at short ranges the detection angle is typically +-18°. The higher the range, the narrower the angle interval becomes, but is is still quite large. This leads to a high clutter level and an enormous number of reflectors that need to be handled in the software. Other issues are: indirect reflections over guard rails or the like and the detection and classifications of brigdes etc. On the other hand, road borders can be well detected, which is helpful for the path prediction algorithms.

V Outlook

The ACC-Sensor can also be run in an narrowband pulse mode. This mode has not the high detection range and sensitivity of the narrowband FMSK-mode, but is advantageous in classical STOP&Go situations, with many targets with low relative velocity in near range. If such a situation is ahead, the sensor will automatically switch in the pulse mode with a higher range resolution. If such a dense traffic situation is resolved and the ego velocity goes up, the sensor changes back into the FMSK mode with its high detection range.

The possibility to switch the mode makes it possible to use the ACC sensor even in dense urban environments and the minimum activation velocity for ACC-systems can likely be reduced to zero.

It was shown that it is feasible to produce an ACC sensor operating at 24GHz. It certainly does not have the full performance of its 77GHz counterpart, but the 24GHz ACC function is robust enough in practice on test cars. The potential of that new sensor is high, as it allows a significant cost reduction. Two tier one automotive supplies have already licensed the technology.

References:

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[3 Hermann Rohling, Marc-Michael Meinecke.Waveform Design Principles for Automotive Radar Systems, CIE International Conference on Radar, Beijing, China, October 2001

[4] M. M. Meinecke; H. Rohling: Combination of FSK and LFMCW Modulation Principles for Automotive Radars. German Radar Symposium GRS2000, Berlin,11.-12.10.2000