Waveform Design Principles for Automotive Radar Systems

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***Abstract*—This paper presents a high performance 77GHz FMCW radar sensor for automotive applications. Powerful automotive radar systems are currently under development for various applications. Radar sensor based comfort systems like Adaptive Cruise Control (ACC) are already available on the market. The main objective from a radar sensor point of view is to detect all targets inside the observation area and estimate target range and relative velocity simultaneously with a high update rate.**

FMCW radar sensors have the advantages of very high range resolution but a serious task occurs in multiple target situations to suppress so-called ghost targets. In classical FMCW waveforms this has been solved in using multiple chirp signals with different slope. But in this case a long measurement time (approximately 50ms) is needed which is a contradiction to a high update rate. Therefore, in this paper a new waveform design is presented which has all advantages of FMCW radars but needs an extremely low measurement time (10ms) in a radar sensor with 3 different antenna beams.

***Index Terms*—Automotive radar, waveform design, FMCW**

I. INTRODUCTION

77 GHz radars are already on the market as Adaptive Cruise Control (ACC) systems for high performance automotive applications. The most important requirement for these radars is the simultaneous target range and velocity measurement with high resolution and accuracy even in multi-target situations. The well-known waveforms need a relatively long measurement time (50-100ms). Future developments will be more concentrated on safety applications like Collision Avoidance (CA) or Autonomous Driving (AD). In this case the requirements for reliability (extreme low false alarm rate) and reaction time (extreme short measurement time) are much higher compared with ACC systems. To give a general idea of the most important requirements for automotive radar systems the maximum range for automotive radars is 200m, the range resolution is 1m and the velocity resolution is 2.5km/h, respectively.

To meet all these system requirements specific waveform design techniques must be considered. For ACC systems both radar types of classical pulse waveform with ultra short pulse length (10 ns) or alternatively continuous wave (CW) transmit signal with a bandwidth of 150 MHz are considered. The main advantage of CW radar systems in comparison with classical pulse waveforms is the low measurement time and low computation complexity for a fixed high range resolution system requirement. Two classes of CW waveforms are well known in literature: The linear frequency modulated (LFM) and the frequency shift keying (FSK) CW waveform types. FSK uses at least two different discrete transmit frequencies (see Fig. 1).

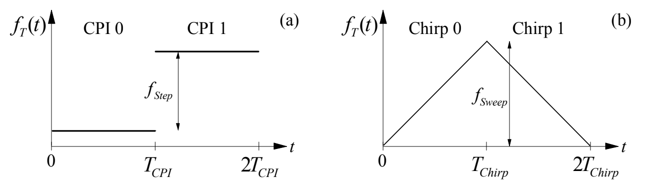

Fig. 1. Two CW waveform principles: (a) FSK modulation, (b) LFM modulation.

This paper describes a new waveform design for automotive applications based on CW transmit signals which lead to an extreme short measurement time. The main idea of this new waveform is based on a combination between LFM and FSK CW waveforms in an intertwined technique. Unambiguous range and velocity measurement with high resolution and accuracy can be required in this case even in multi-target situations. After an introduction into FSK and LFM waveform design techniques in section II and III the combined and intertwined waveform will be described in detail in section IV.

II. PURE FSK MODULATION PRINCIPLE

Pure FSK modulation as shown in Fig. 1 (a) uses two discrete frequencies f_A and f_B (so-called two frequency measurement) [1] in the transmit signal. Each frequency is transmitted inside a so-called coherent processing interval (CPI) of length T_{CPI} (e. g. $T_{CPI} = 5\text{ ms}$). Using a homodyne receiver the echo signal is down converted by the instantaneous frequency into base band and sampled N times. The frequency step $f_{Step} = f_B - f_A$ is small and will be chosen in dependence of the maximum unambiguous target range. The time-discrete receive signal is Fourier transformed in each CPI of length T_{CPI} and targets will be detected by an amplitude threshold (CFAR). Due to the small frequency step in the transmit signal a single target will be detected at the same Doppler frequency position in the adjacent CPI's but with different phase information on the two spectral peaks. The phase difference $\Delta\varphi = \varphi_B - \varphi_A$ in the complex spectra is the basis for the target range R estimation. The relation between the target distance and phase difference is given by the following equation

$$R = -\frac{c \cdot \Delta\varphi}{4\pi \cdot f_{Step}}. \tag{1}$$

To achieve an unambiguous maximum range measurement of 150 m a frequency step of $f_{Step} = 1\,\mathrm{MHz}$ is necessary. In this case the target resolution only depends on the CPI length T_{CPI}. The technically simple VCO modulation is an additional advantage of this waveform. But this FSK waveform does not allow any target resolution in the range direction, which is an important disadvantage of this measurement technique. Especially in automotive traffic environment more than a single fixed target will occur simultaneously inside an antenna beam. These fixed targets can not be resolved by a FSK waveform.

III. PURE LINEAR FREQUENCY MODULATION PRINCIPLE

Radars which apply pure linear frequency modulation technique (LFM) modulate the transmit frequency with a triangular waveform [STO92]. The oscillator sweep is given by f_{Sweep}. A typical value for the bandwidth is $f_{Sweep} = 150\,\mathrm{MHz}$ to achieve a range resolution of $\Delta R = \frac{c}{2 \cdot f_{Sweep}} = 1\,\mathrm{m}$. In general, a single sweep of the LFM waveform gives an ambiguous measurement in range *R* and relative velocity *v*. The down converted receive signal is sampled and Fourier transformed inside a single CPI. If a spectral peak is detected in the Fourier spectrum at index κ (normalized integer frequency) the ambiguities in target range and velocity can be described in a R-v-diagram by the following equation

$$\kappa = \frac{v}{\Delta v} - \frac{R}{\Delta R} \quad \Leftrightarrow \quad \frac{v}{\Delta v} = \frac{R}{\Delta R} + \kappa, \tag{2}$$

where Δv describes the velocity resolution resulting from the CPI duration T_{Chirp} ($\Delta v = \frac{\lambda}{2 \cdot T_{Chirp}} = 0.8\,\mathrm{m/s}$, λ is the wavelength of 4 mm @ 77 GHz and $T_{Chirp} = 2.5\,\mathrm{ms}$).

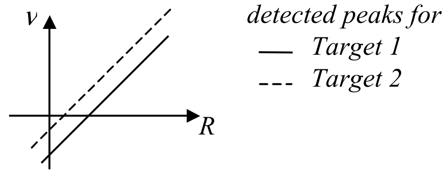

Fig. 2. : example *R*-*v*-diagram for two targets measured with up chirp.

Fig. 2 shows an example inside the R-v-diagram for a two target situation measured with a single chirp. Each line drawn in Fig. 2 corresponds to a measured spectral line at index κ indicating all solutions for equation 2 and all possible combinations of target Range *R* and velocity .

For reason of resulting range-velocity ambiguities further measurements with different chirp gradients in the waveform are necessary to achieve an unambiguous range-velocity measurement even in multi-target situations. The well known up-/ down-chirp principle as it is depicted in Fig. 1 (b) is described in detail in [6]. LFM waveforms can be used even in multi-target environments, but the extended measurement time is an important drawback of this LFM technique.

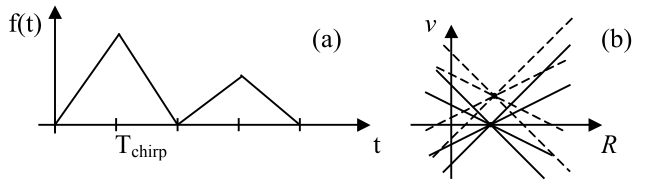

Fig. 3. : (a) waveform for use in multi target situations and (b) corresponding example *R*-*v* -diagram for a two target situation and the related intersection points

In multi target situations a waveform as shown in Fig. 3 (a) is used which consists of 4 different chirp signals. In general, the frequencies modulation will be different in each of the 4 chirps. In each chirp signal all targets are detected which still fulfil equation (2). The detected spectral lines from all 4 chirp signals can be drawn in a single R-v-diagram (Fig 3 (b)) where the gradient of a single line is dependent on the chirp sweep rate. In multiple target situations many intersections between lines of different and adjacent chirps appear as the example in Fig 3 (b) shows. If such an intersection point occurs which has no physical representation of a reflection object it is called a ghost target. A real target is represented by an intersection point between all considered 4 lines.

IV. CONCEPT OF COMBINED FSK AND LFM WAVEFORMS

The combination of FSK and LFM waveform design principle offers the possibility of an unambiguous target range and velocity measurement simultaneously. The transmit waveform consist in this case of two linear frequency modulated up-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. The combined and intertwined waveform concept is depicted in Fig. 4.

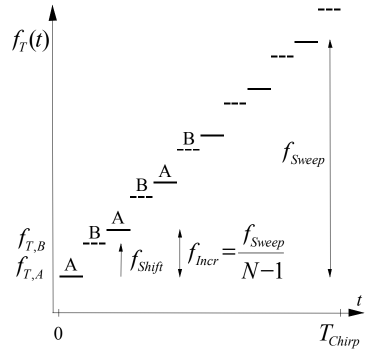

Fig. 4. Combined FSK-LFMCW waveform principle.

Each signal sequence A or B will be processed separately by using the Fourier transform and CFAR target detection techniques. A single target with specific range and velocity will be detected in both sequences at the same integer index $\kappa = \kappa_A = \kappa_B$ in the FFT-output signal of the two processed spectra. In each signal sequence A or B the same target range and velocity ambiguities will occur as described in Equation 2. But the measured phases φ_A and φ_B of the two (complex) spectral peaks are different and include the fine target range and velocity information which can be used for ambiguity resolution. Due to the coherent measurement technique in sequence A and B the phase difference $\Delta\varphi = \varphi_B - \varphi_A$ can be evaluated for target range and velocity estimation. The measured phase difference $\Delta\varphi$ can be described analytically by the following equation:

$$\Delta\varphi = \frac{\pi}{N-1} \cdot \frac{v}{\Delta v} - 4\pi \cdot R \cdot \frac{f_{Shift}}{c}, \tag{3}$$

where N is the number of frequency steps (or receive signal samples) in each transmit signal sequence A and B. In this first step $\Delta\varphi$ is ambiguous but it is possible to resolve these ambiguities by combining the two measurement results of Equation 2 and 3. The intersection point of the two measurement results is shown in Fig. 5 in a graphical way. The analysis leads to an unambiguous target range R_0 and relative velocity v_0:

$$R_0 = \frac{c \cdot \Delta R}{\pi} \cdot \frac{(N-1) \cdot \Delta\varphi - \pi \cdot \kappa}{c - 4 \cdot (N-1) \cdot f_{Shift} \cdot \Delta R} \tag{4}$$

$$v_0 = \frac{(N-1) \cdot \Delta v}{\pi} \cdot \frac{c \cdot \Delta\varphi - 4\pi \cdot f_{Shift} \cdot \Delta R \cdot \kappa}{c - 4 \cdot (N-1) \cdot f_{Shift} \cdot \Delta R} \tag{5}$$

This new intertwined waveform shows that unambiguous target range and velocity measurements are possible even in multi-target environment. An important advantage is the short measurement and processing time.

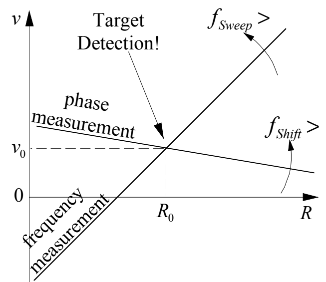

Fig. 5. Graphical resolution principle of ambiguous frequency and phase measurements.

V. SYSTEM EXAMPLE

In this section a waveform design based on the new intertwined signal is developed as an example for automotive applications. The signal bandwidth is $f_{Sweep} = 150$ MHz to fulfill the range resolution requirement of 1 m. The stepwise frequency modulation is split into $N = 256$ separate bursts of $f_{Incr} = \frac{150\ \text{MHz}}{255} = 588\ \text{kHz}$ each. The measurement time inside a single burst A or B is assumed to be 5 µs resulting in a chirp duration of the intertwined signal of $T_{Chirp} = 2.56$ ms which results in a velocity resolution of $\Delta v = \frac{\lambda}{2 \cdot T_{Chirp}} = 2.7$ km/h.

The important waveform parameter f_{Shift} is optimized on the basis of high range and velocity accuracy. The highest accuracy occurs if the intersection point in the R-v-diagram results from two orthogonal lines as it is depicted in Fig. 7. For this reason the frequency shift between the signal sequences A and B is $f_{Shift} = -\frac{1}{2} \cdot f_{Incr} = -294\ \text{kHz}$ (the related waveform is shown in Fig. 6). In this specific case Equation 4 and 5 turn into

$$\frac{R_0}{\Delta R} = \frac{N-1}{2\pi} \cdot \Delta\varphi - \frac{\kappa}{2}, \qquad (6)$$

$$\frac{v_0}{\Delta v} = \frac{N-1}{2\pi} \cdot \Delta\varphi + \frac{\kappa}{2}. \qquad (7)$$

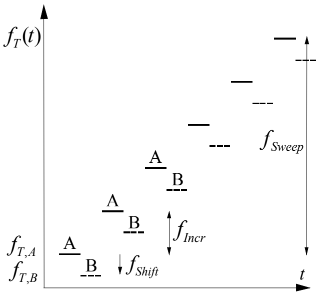

Fig. 6. Combined FSK-LFM waveform with optimized frequency shift.

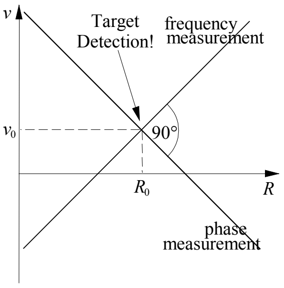

Fig. 7. R - v -diagram for the combined waveform with optimized frequency shift.

VI. EXPERIMENTAL CAR

The new waveform has been tested in our experimental car in realistic street situations. The following picture shows the test car which is equipped with a 77 GHz radar sensor, a smart brake buster and a throttle control system for automatic driving. The radar sensor detects all targets inside the observation area and measures target range and velocity simultaneously. The relevant target is selected by signal processing and the car control system is activated by this information. In this case the car follows the detected relevant object with controlled distance.

The experimental car was used for radar tests in more than 40000 km on public streets. Many important experiences have been gained since this time. The implemented sensor is a 77 GHz FMCW radar with a separated transmit and receive antenna. The target azimuth angle is measured by the receive signal in 3 adjacent and overlapping beams. The new radar waveform shows very good results and especially extreme short measurement time.

Fig. 8. Experimental car of the Technical University Hamburg Harburg equipped with a 77GHz far range radar sensor.

VII. CONCLUSION

The proposed intertwined CW waveforms show high performance in range and velocity measurement accuracy. The main advantage is the short measurement time in comparison to classical LFM waveforms while the resolution and accuracy performance is unchanged. Compared with a pure FSK waveform the intertwined waveform allows resolution in velocity and range simultaneously. The properties of the new intertwined CW waveform technique are quite promising. This concept is a good basis for high performance automotive radar systems with different safety applications (e.g. pre crash) which require ultra short measurement and processing time.

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