Radar Waveform for Automotive Radar Systems and Applications

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Abstract—**This paper describes three different continuous wave (CW) radar waveforms which are applied in automotive radar sensors. The radar sensor should be able to detect all objects inside the observation area and to estimate range, radial velocity and azimuth angle simultaneously even in multi target situations.**

A classical Linear Frequency Modulation (LFM) waveform provides a very high range and velocity resolution. But in multiple target situations so-called ghost targets will occur. Alternatively, a Frequency Shift Keying (FSK) waveform delivers a very high velocity resolution and avoids any ghost target situation but will not resolve targets in range direction. Finally, a combination between LFM and FSK provides simultaneously a high range and velocity resolution, extremely short measurement time and avoids any ghost target situation. It combines the advantages of both FSK and LFM waveforms. In all three cases the azimuth angle estimation is based on two receive antennas and the monopulse technique.

Index Terms— **Radar Waveforms, Automotive Radar, CW, FMCW, FSK, Monopulse Technique**

I. Introduction

High performance automotive radar systems are currently under development for various applications. Comfort systems like Adaptive Cruise Control (ACC) are already available on the market as 24 GHz and 77 GHz radar sensors. Target range, azimuth angle and radial velocity are measured in this case simultaneously with high resolution and accuracy even in multi target situations. Future radar sensor developments will be more concentrated on safety applications like Collision Avoidance (CA), Pre Crash (PC) or even Autonomous Driving (AD). In this case the system requirements for target detection reliability (extreme low false alarm rate), measurement accuracy and reaction time (extreme short measurement time) will be much stronger and much more important compared with today ACC systems.

To meet all these system requirements in automotive applications, very specific waveform design techniques should be considered. For ACC systems both radar types of a classical pulse waveform with ultra short pulse lengths (30 ns) or alternatively continuous wave (CW) and LFM waveform with a bandwidth of 150 MHz (and a resulting range resolution of 1m) have been proposed and developed.

In this paper three different radar waveforms are considered for a more general system requirement, to measure target range, radial velocity and azimuth angle simultaneously and unambiguously. The paper is focused on CW based radar systems due to some important advantages in short measurement time and low computation complexity compared with classical pulse radars. It is characteristic for all automotive radar applications that almost always multiple targets will be observed. Therefore, the target resolution properties of the different waveforms play an important role in the system analysis.

II. Pure Linear Frequency Modulation CW Principle

The LFM transmit signal is a classical and well known waveform [7] for many different radar applications. In this case the oscillator sweep and the system bandwidth is described by f_{Sweep}, the chirp duration is called a coherent processing interval (CPI) and is described by $\mathbf{T}_{\text{CPI}}$.

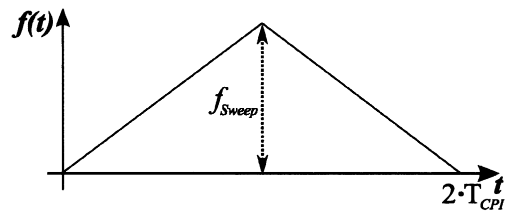

Figure 1 – LFM CW waveform principle

The target range R and the radial velocity v_r both cause a frequency shift in the down converted signal denoted as:

$$f_\tau = 2\frac{f_{Sweep}}{c\cdot T_{CPI}}R \tag{1}$$

$$f_D = -2\frac{v_r}{\lambda} \tag{2}$$

where λ is the wavelength of the carrier-frequency. The range resolution ΔR depends in the LFM case directly on the signal bandwidth f_{Sweep} and the resolution in radial velocity Δv depends on the observation time $\mathbf{T}_{\text{CPI}}$.

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$$\Delta R = \frac{c}{2 \cdot f_{Sweep}} \quad (3)$$

$$\Delta v = \frac{\lambda}{2 \cdot T_{CPI}} \quad (4)$$

The radar echo signal is directly down converted by the instantaneous carrier frequency and the base band signal is analysed to measure target range R and radial velocity v_r. The down converted receive signal is sampled and Fourier transformed inside the time interval $\mathbf{T_{CPI}}$. For target detection an ordered statistic (OS) constant false alarm rate (CFAR) procedure with an adaptive amplitude threshold is applied due to the expected multi target situations [8].

In a moving target situation, a single LFM sweep gives an ambiguous measurement in range and radial velocity. If a target is detected, the spectral peak position Δf in the Fourier spectrum depends on the radial velocity v_r or the Doppler frequency f_D and the target range R:

$$\Delta f = f_D - f_\tau = -\frac{2}{\lambda} v_r - 2\frac{f_{Sweep}}{c \cdot T_{CPI}} R. \quad (5)$$

Equation 5 describes the ambiguities in target range R and radial velocity v_r. If the measured difference frequency Δf in the base band signal is normalized by the measurement time TCPI the measured frequency position $\kappa = T_{CPI} \cdot \Delta f \in [0,N)$ covers the entire interval from 0 to N, where N describes the number of samples. Equation 5 turns in this case into

$$\kappa = -\frac{1}{\Delta v} v_r - \frac{1}{\Delta R} R \quad (6)$$

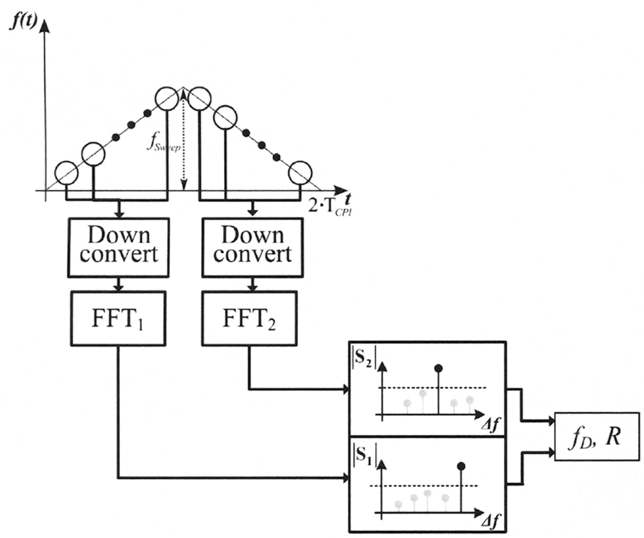

Figure 2 – LFM CW signal processing

To resolve these measurement ambiguities a second chirp signal will be transmitted but as a down chirp signal, as shown in Figure 1. The up- and the down chirp signals are processed separately in two FFTs as shown in Figure 2. After each FFT processing a spectral peak will be detected in the Fourier spectrum at two different frequencies Δf_1 in the up chirp case and Δf_2 in the down chirp case:

$$\begin{aligned} \Delta f_1 &= f_D - f_\tau \\ \Delta f_2 &= f_D + f_\tau \end{aligned} \quad (7)$$

This measurement principle and the ambiguity resolution of equation 7 can be applied perfectly in a single target situation [5]. But in multiple target situations ghost targets will occur which can be removed only by extending the waveform with a third and fourth chirp signal [5]. The extended measurement time by a factor of four is in this case an important drawback of this LFM waveform technique.

III. Pure FSK CW Signal Modulation Principle

The LFM waveform has some strong limitations in multiple target situations due to the technically complicated association step. After target detection procedure for the up- and down chirp case it is in multiple target situations indeed ambiguous, which spectral lines from the two chirp echo signals should be associated to find the target range and radial velocity for a certain target. Therefore the pure FSK CW modulation scheme has been invented as shown in Figure 3. In this case two discrete carrier frequencies f_A and f_B [1] are used in the narrowband transmit signal in an alternated or intertwined form. The FSK waveform is a narrowband transmit signal.

For each carrier frequency a time interval of length $\mathbf{T_{CPI}}$ will be considered in the digital signal processing part. The radar echo signal is again down converted by the instantaneous carrier frequency into base band and sampled N times inside the CPI. The frequency step $f_{Step} = f_B - f_A$ is small and will be chosen in dependence of the required maximum unambiguous target range measurement. The time-discrete receive signal is Fourier transformed separately for the upper and the lower frequency inside the time frame $\mathbf{T_{CPI}}$ and targets will be detected by an amplitude threshold (CFAR). Due to the small frequency step between f_A and f_B and the intertwined transmit signal a single target echo signal will be detected by nearly the same amplitude and at the exact same Doppler frequency position in the two resulting frequency spectra

$$f_D = -2\frac{v_r}{\lambda} \quad (8)$$

$$\kappa = -\frac{v_r}{\Delta v} \quad (9)$$

but with different phase information on the two spectral peaks. The signal processing block diagram is shown in Figure 4. The Doppler frequency is measured in this case in an unambiguous way and due to the long observation time with a high velocity resolution. All radar objects with a slightly different radial velocity can be separated by this FSK radar waveform. If a single radar object is observed on this Doppler line the related target range R can be measured in this case by a phase difference measurement.

The phase difference $\Delta\varphi = \varphi_B - \varphi_A$ of the complex valued Doppler spectra is the basis for the target range R estimation.

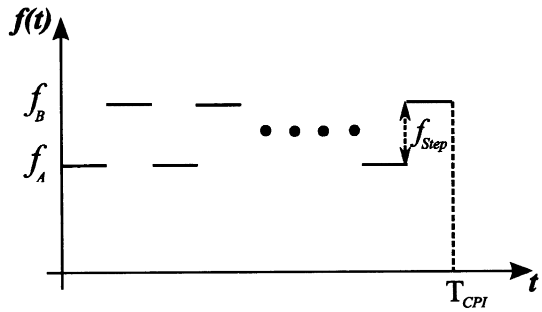

Figure 3 – FSK CW waveform principle

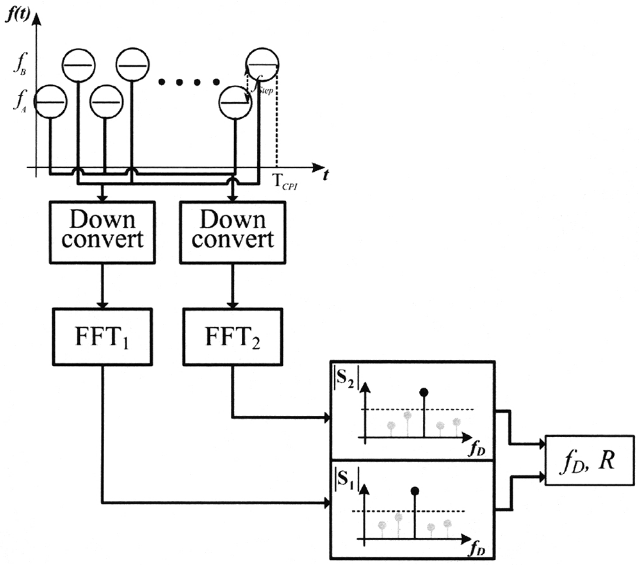

Figure 4 –FSK CW signal processing

The relation between the target range and measured phase difference is given by the following equation

$$\mathbf{R} = -\frac{\mathbf{c} \cdot \Delta\boldsymbol{\varphi}}{4\boldsymbol{\pi} \cdot \mathbf{f}_{\mathbf{Step}}}. \tag{10}$$

In this case the target radial velocity resolution depends on the time interval length $\mathbf{T_{CPI}}$ like in the LFM case. But this FSK waveform does not resolve two or more targets with the same radial velocity in range direction, which is characteristic for this FSK measurement technique.

IV. Concept of Combined FSK and LFM Waveforms

A fruitful combination between an FSK and an LFM waveform design principle offers the possibility of an unambiguous target range and radial velocity measurement simultaneously. The transmit waveform is in this case a stepwise frequency modulated signal which consists of two linear frequency modulated up-chirp signals which are transmitted in an intertwined way. The two chirp signals have an identical slope and bandwidth. They just differ by a small frequency shift f_{Step} as shown in Figure 5.

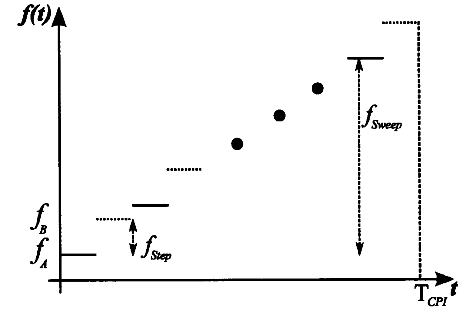

Figure 5 – Combined FSK-LFM-CW waveform principle

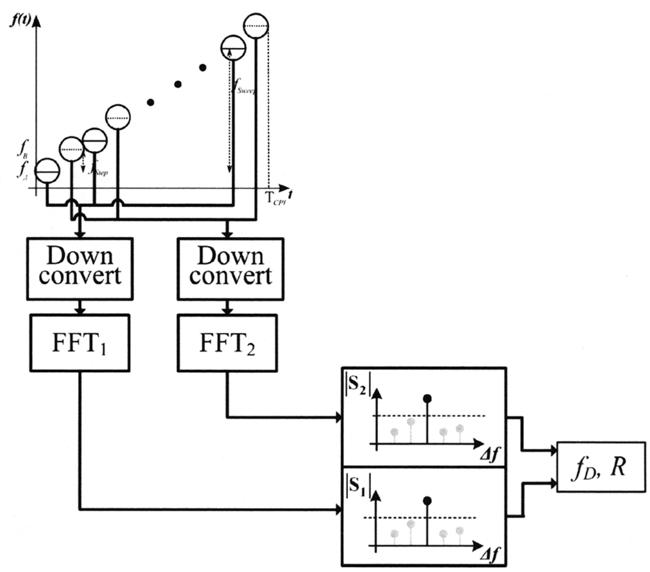

Figure 6 – Combined FSK-LFM-CW signal processing

The received signal is again down converted into base band and directly sampled at the end of each frequency step. Each of the two intertwined chirp signals will be processed separately by using the Fourier transform and CFAR target detection techniques, as shown in Figure 6. A single target with range R and radial velocity v_r will be detected in both chirp sequences at the same difference frequency position

$$\Delta f_A = \Delta f_B = f_D - f_\tau \tag{11}$$

In a normalized frequency axis and based on the measurement Δf at the output of the two FFT spectra the frequency position $\kappa = \kappa_A = \kappa_B$ becomes

$$\kappa = -\frac{1}{\Delta \mathbf{v}} v_r - \frac{1}{\Delta \mathbf{R}} \mathbf{R} \tag{12}$$

In both of the two intertwined chirp signal sequences the same frequency position κ will be measured in case of a single target. This frequency position depends on target range R and radial velocity v_r in a linear equation, as shown in equation 12.

But the measured phases φ_A and φ_B of the two (complex valued) spectral peaks at frequency position κ will show different measurement results due to target range R and radial velocity v_r. The resulting phase difference $\Delta\varphi = \varphi_B - \varphi_A$ can be described analytically by the following linear equation:

$$\Delta\varphi = \frac{\pi}{N \cdot \Delta v} v_r - \frac{4\pi \cdot f_{Step}}{c} R \tag{13}$$

where N is the number of frequency steps (or receive signal samples) in each transmit chirp signal sequence.

From the measured frequency position κ and the phase difference $\Delta\varphi$ the target range R and radial velocity v_r can be calculated by solving the two related linear equations 12 and 13. This new intertwined waveform shows that unambiguous target range and velocity measurements are possible even in a multi target environment. An important advantage is the short measurement time.

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 ΔR = 1m. The stepwise frequency modulation is split into N = 1024 separate bursts with a difference of 146 kHz between two adjacent transmit frequencies.

The measurement time inside a single burst is assumed to be 5 µs resulting in a total chirp duration of the intertwined signal of $\mathbf{T_{CPI} \approx 10}$ **ms** which results in a velocity resolution of Δv = 0.7 km/h with a wavelength of 4 mm at a carrier frequency of 77 GHz. The frequency step f_{Step} between the two intertwined chirp signals is chosen to f_{Step} = 73 kHz.

VI. Monopulse Technique

After a simultaneous and unambiguous range and radial velocity measurement the azimuth angle should be measured also. In all three discussed waveforms a monopulse antenna technique will be applied.

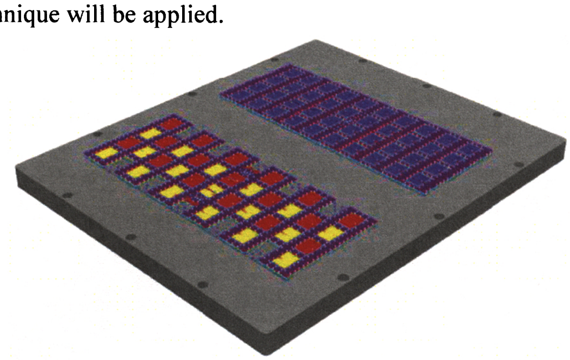

Figure 7 –Intertwined patch antenna for monopulse technique

Figure 7 shows a new patch antenna with large aperture but low distance of phase centre and large unambiguous interval in the azimuth measurement field. The received signal at the output of the two antennas is processed separately. The signal processing is shown exemplary for the FSK waveform in Figure 8.

If a target has been detected and the frequency position κ has been calculated the amplitude and/or the phase of the two received signals at the frequency position κ will be used for the azimuth angle estimation. Even the lateral velocity of an extended car can be measured with this FSK waveform combined with a monopulse antenna as shown in [6].

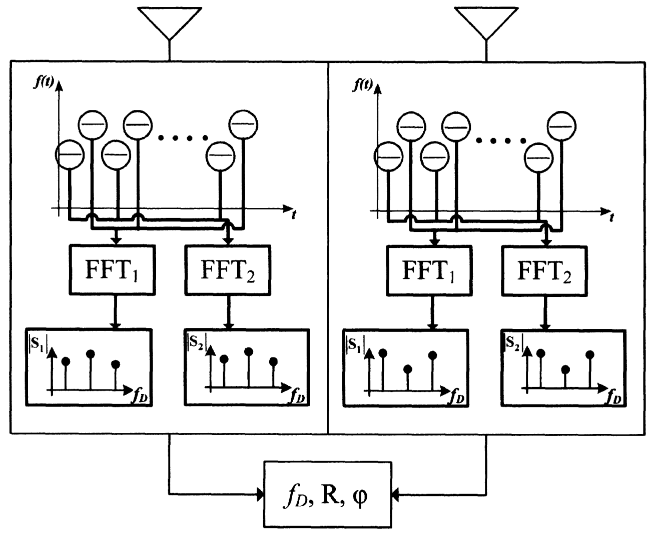

Figure 8 –Monopulse signal processing for an FSK CW waveform

VII. Conclusion

The proposed CW waveforms show high performance figures in target range and velocity measurement. The classical LFM waveform has severe limitations in multiple target situations. The pure FSK waveform resolves target signals in the radial velocity direction only, while the intertwined LFM-FSK waveform allows resolution in velocity and range direction simultaneously. The properties of the new intertwined waveform technique are quite promising.

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