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COMBINATION OF LFMCW AND FSK MODULATION PRINCIPLES FOR AUTOMOTIVE RADAR SYSTEMS

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1. 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 77 GHz radars. Target range and velocity are measured simultaneously with high resolution and accuracy even in multi-target situations but the measurement and processing time to detect the relevant object is approximately 100 ms. 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 delay) are much higher compared with ACC systems.

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 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 Figure 1).

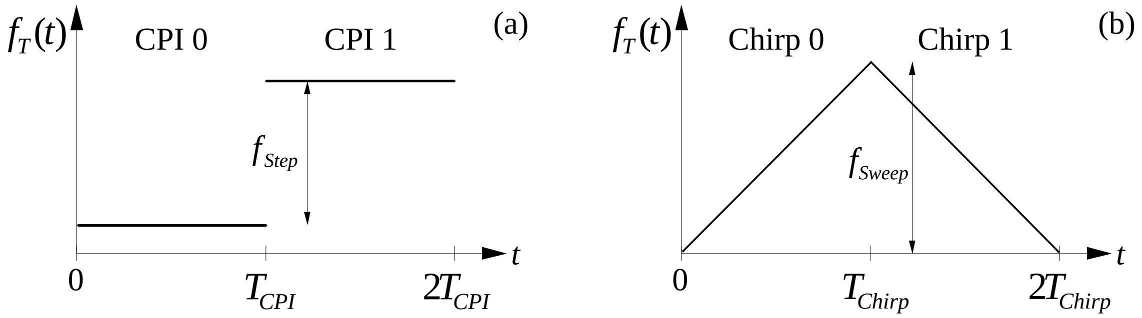

Figure 1. Two CW waveform principles: (a) FSK modulation, (b) linear frequency modulation (LFM).

This paper describes a new waveform design for automotive applications based on CW transmit signals which lead to an extreme short measurement time. The basic idea is a combination of 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 chapters 2 and 3 the combined and intertwined waveform will be described in detail in chapter 4.

2. PURE FSK MODULATION PRINCIPLE

Pure FSK modulation (as shown in Figure 1 (a)) uses two discrete frequencies f_A and f_B (so-called two frequency measurement) [ART99] in the transmit signal. Each frequency is transmitted inside a so-called coherent processing interval (CPI) of length T_{CPI} (e. g. $T_{CPI} = 5\,\mathrm{ms}$). 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 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 $\Delta j = j_B - j_A$ 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

$$R = -\frac{c \cdot \Delta j}{4p \cdot f_{Step}} .$$

Equation 1

To achieve an unambiguous maximum range measurement of $150\,\mathrm{m}$ 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.

3. 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 and relative velocity. 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 k (normalized integer frequency) the ambiguities in target range and velocity can be described in a R-v-diagram by the following equation

$$k = \frac{v}{\Delta v} - \frac{R}{\Delta R} \quad \Leftrightarrow \quad \frac{v}{\Delta v} = \frac{R}{\Delta R} + k \ ,$$

Equation 2

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

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 Figure 1 (b) is described in detail in [ROH98a]. LFM waveforms can be used even in multi-target environments, but the extended measurement time is an important drawback of this LFM technique.

4. 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 Figure 2.

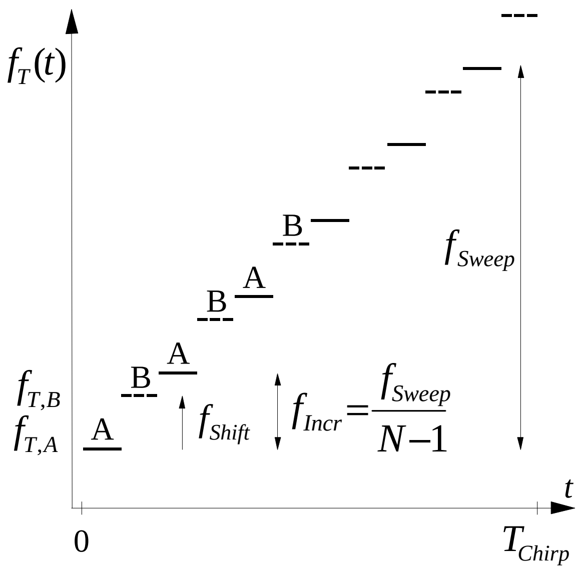

Figure 2. Combined FSK-LFMCW waveform principle.

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 $k = k_A = k_B$ 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 j_A and j_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 $\Delta j = j_B - j_A$ can be evaluated for target range and velocity estimation. The measured phase difference Δj can be described analytically by the following equation:

$$\Delta j = \frac{p}{N-1} \cdot \frac{v}{\Delta v} - 4p \cdot R \cdot \frac{f_{Shift}}{c},$$

Equation 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 Δj is ambiguous but it is possible to resolve these ambiguities by combining the two measurement results of Equation 2 an 3. The intersection point of the two measurement results is shown in Figure 3 in a graphical way. The analysis leads to an unambiguous target range R_0 and relative velocity v_0:

$$R_0 = \frac{c \cdot \Delta R}{p} \cdot \frac{(N-1) \cdot \Delta j - p \cdot k}{c - 4 \cdot (N-1) \cdot f_{Shift} \cdot \Delta R},$$

Equation 4

$$v_0 = \frac{(N-1) \cdot \Delta v}{p} \cdot \frac{c \cdot \Delta j - 4p \cdot f_{Shift} \cdot \Delta R \cdot k}{c - 4 \cdot (N-1) \cdot f_{Shift} \cdot \Delta R}.$$

Equation 5

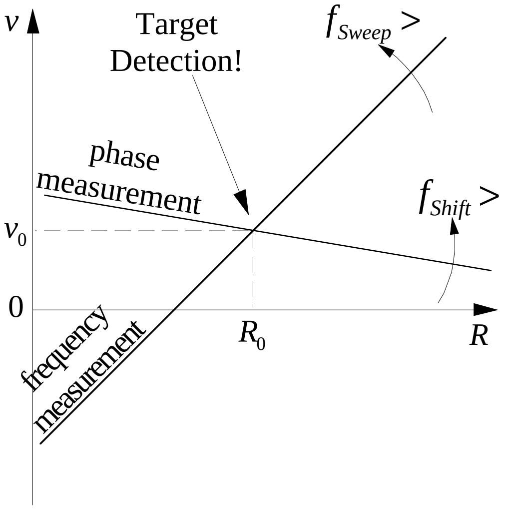

Figure 3. Graphical resolution principle of ambiguous frequency and phase measurements.

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.

5. 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 $f_{Sweep} = 150\,\text{MHz}$ to fulfil 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 $T_{Chirp} = 2.56\,\text{ms}$ which results in a velocity resolution of $\Delta v = \frac{l}{2 \cdot T_{Chirp}} = 2.7\,\text{km/h}$.

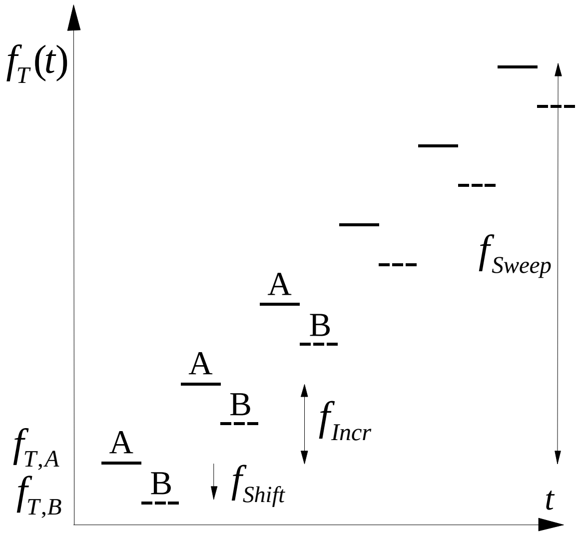

Figure 4. Combined FSK-LFM waveform with optimised frequency shift.

The important waveform parameter f_{Shift} is optimised 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 Figure 5. 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 Figure 4). In this specific case Equation 4 and 5 turn into

$$\frac{R_0}{\Delta R} = \frac{N-1}{2\pi} \cdot \Delta\varphi - \frac{k}{2},$$

Equation 6

$$\frac{v_0}{\Delta v} = \frac{N-1}{2\pi} \cdot \Delta\varphi + \frac{k}{2}.$$

Equation 7

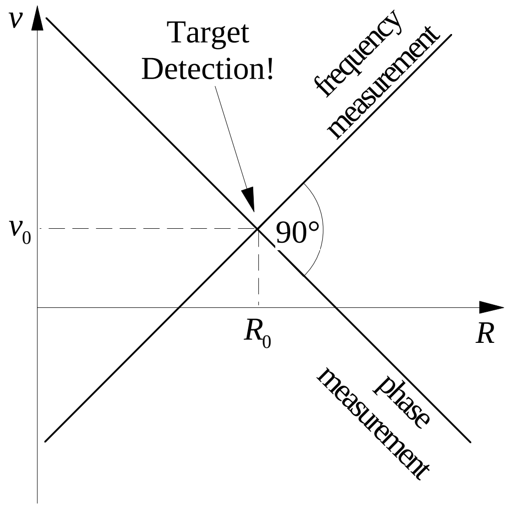

Figure 5. R-v-diagram for the combined waveform with optimised frequency shift.

6. 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.

7. REFERENCES

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