New Chirp Sequence Radar Waveform

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The general requirement in the automotive radar application is to measure the target range R and radial velocity v_r simultaneously and unambiguously with high accuracy and resolution even in multitarget situations, which is a matter of the appropriate waveform design. Based on a single continuous wave chirp transmit signal, target range R and radial velocity v_r cannot be measured in an unambiguous way. Therefore a so-called multiple frequency shift keying (MFSK) transmit signal was developed, which is applied to measure target range and radial velocity separately and simultaneously. In this case the radar measurement is based on a frequency and additionally on a phase measurement, which suffers from a lower estimation accuracy compared with a pure frequency measurement. This MFSK waveform can therefore be improved and outperformed by a chirp sequences waveform. Each chirp signal has in this case very short time duration T_{chirp}. Therefore the measured beat frequency f_B is dominated by target range R and is less influenced by the radial velocity v_r. The range and radial velocity estimation is based on two separate frequency measurements with high accuracy in both cases. Classical chirp sequence waveforms suffer from possible ambiguities in the velocity measurement. It is the objective of this paper to modify the classical chirp sequence to get an unambiguous velocity measurement even in multitarget situations.

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I. INTRODUCTION

Radar systems are based on a suitable technique to meet the high performance requirements for automotive radar sensors. Target range R and radial velocity v_r are estimated unambiguously and simultaneously with high accuracy and resolution. However these features are subject to the radar waveform design. There are several interesting continuous waveform (CW) proposals which have been developed in the last years for new radar systems to measure range and radial velocity simultaneously [1–10].

Automotive radar sensors apply frequency modulated (FM) CW signals with a signal bandwidth f_{sw} of 150 MHz, which guaranties a range resolution of 1 m [8].

There are several FMCW transmit signals proposed for automotive applications with totally different performance and resulting computation complexity. The block diagram of an FMCW radar system with a single transmit and two receive inphase and quadrature channels is shown in Fig. 1. In case of any CW radar it is a characteristic first step in signal processing that the receive echo signal is down-converted into baseband by the instantaneous transmit frequency. Therefore the bandwidth of the baseband signal is much smaller than the bandwidth of the transmit signal.

The resulting difference frequency between transmit and receive signal is called beat frequency f_B, which is measured directly by a fast Fourier transform (FFT) procedure with high accuracy and resolution. The system parameters affecting the beat frequency are the chirp duration T_{chirp}, the sweep bandwidth f_{sw}, and the carrier frequency f_0. The carrier frequency f_0 and the sweep bandwidth f_{sw} are assumed to be unchanged in the following. For a long chirp duration the beat frequency f_B is small and vice versa. In general the beat frequency f_B can be positive or negative. Therefore a two channel receiver with I- and Q-channel is necessary. However it is important to notice that the beat frequency f_B is influenced simultaneously by the target range R and radial velocity v_r in an unresolvable way.

In this paper a new class of FMCW signals is described, which consists of FMCW modulated chirp sequences where each individual chirp signal has a very short duration T_{chirp}, which increases the baseband signal bandwidth. In this case the target range is measured by an FFT procedure, which is applied to each single and individual chirp signal. The Doppler frequency is also measured by a second FFT applied to the chirp sequence. The estimation accuracy will be improved in this case.

II. SINGLE CHIRP SIGNAL

For the simultaneous measurement of target range R and radial velocity v_r a linear FMCW transmit signal is considered as depicted in Fig. 2. The receive signal (blue line) is directly down-converted by the instantaneous transmit frequency (red line). Therefore the resulting baseband beat frequency f_B describes the difference

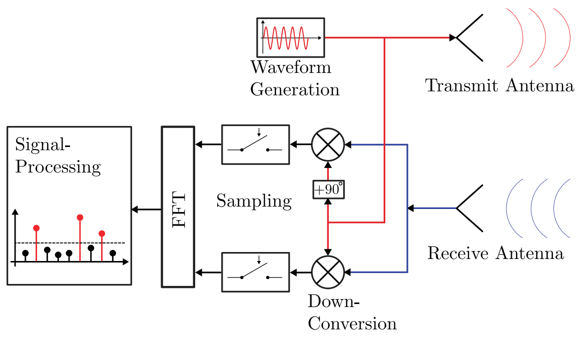

Fig. 1. Transmitter and dual channel (I/Q) receiver.

between the instantaneous transmit and receive frequency. In a measurement situation without any moving targets and due to the linear frequency modulation, the propagation delay τ of the signal from the transmitter to the reflecting object and back to the radar receiver causes a frequency shift f_R. In this static case the beat frequency f_B is influenced by the target range R only.

However in a moving target situation the beat frequency f_B consists additionally of the Doppler frequency f_D in the following quantitative way:

$$f_B = f_R - f_D = -\frac{f_{sw}}{T_{chirp}} \frac{2}{c} R + \frac{2}{\lambda} v_r. \tag{1}$$

The ideal time continuous baseband receive signal (without any noise components) is described by the beat frequency f_B and the phase ϕ in the following equation:

$$s(t) = \exp\left(j2\pi\left(f_B \cdot t + \phi\right)\right). \tag{2}$$

For a single chirp signal, (1) shows that the measured beat frequency f_B contains the information about the target range f_R and radial velocity v_r in an unresolvable way. In order to measure target range R and radial velocity v_r separately several extended waveforms have been developed for automotive applications, e.g. an up- and down-chirp scheme [2].

III. MULTIPLE FREQUENCY SHIFT KEYING WAVEFORM

The limitations of a single chirp signal can be totally overcome by a so-called multiple frequency shift keying (MFSK) transmit signal. In this case two linear FM signals with the same frequency modulation and an additional frequency shift are combined in the transmit signal. The MFSK transmit scheme is depicted in Fig. 3. The two FM signals are developed in an intertwined way.

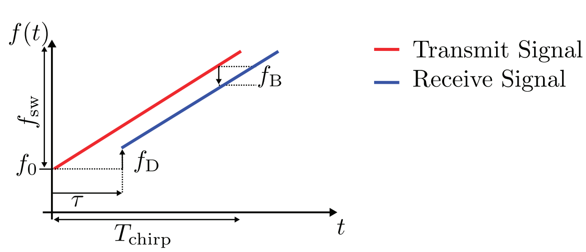

Fig. 2. FMCW transmit and receive signal.

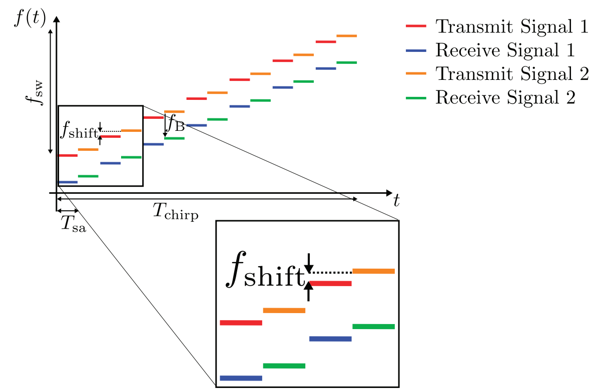

Fig. 3. MFSK transmit and receive signals.

The echo signals are down-converted by the corresponding instantaneous transmit frequency. This results in the two intertwined baseband signals $s_1(t)$ and $s_2(t)$:

$$s_1(t) = \exp\left(j2\pi\left(f_B \cdot t + \phi_1\right)\right), \tag{3a}$$

$$s_2(t) = \exp\left(j2\pi\left(f_B \cdot t + \phi_2\right)\right). \tag{3b}$$

The frequency difference f_{shift} of the two intertwined signals is very small compared with the carrier frequency, so that the baseband frequency f_B will be the same for both intertwined receive signals. However the difference in the constant phase terms ϕ_1 and ϕ_2 is very important. In order to determine the beat frequency f_B and the two phase terms ϕ_1 and ϕ_2, the baseband signals $s_1(t)$ and $s_2(t)$ are sampled separately by the sampling interval T_{sa}, one sample per frequency step, and transformed to the frequency domain by two separate FFT procedures:

$$S_1(m) = \sum_{k=0}^{K-1} s_1(k) \cdot \exp\left(-j2\pi \frac{k \cdot m}{K}\right), \tag{4a}$$

$$S_2(m) = \sum_{k=0}^{K-1} s_2(k) \cdot \exp\left(-j2\pi \frac{k \cdot m}{K}\right), \tag{4b}$$

where k is the sample index of the time discrete baseband signal and m the beat frequency index. Both discrete spectra consist of K complex values indicating the amplitude and the phase of the signal at a given beat frequency. The beat frequencies caused by one target are identical in both spectra. However the phase terms at this specific beat frequency:

$$\phi_1(m) = \arg(S_1(m)), \tag{5a}$$

$$\phi_2(m) = \arg(S_2(m)) \tag{5b}$$

show a certain difference that depends on target range and Doppler frequency:

$$\begin{aligned} \Delta\phi(m) &= \phi_2(m) - \phi_1(m) \\ &= 2\pi\left(f_{shift}\frac{2}{c} \cdot R + f_D \cdot T_{sa}\right). \end{aligned} \tag{6}$$

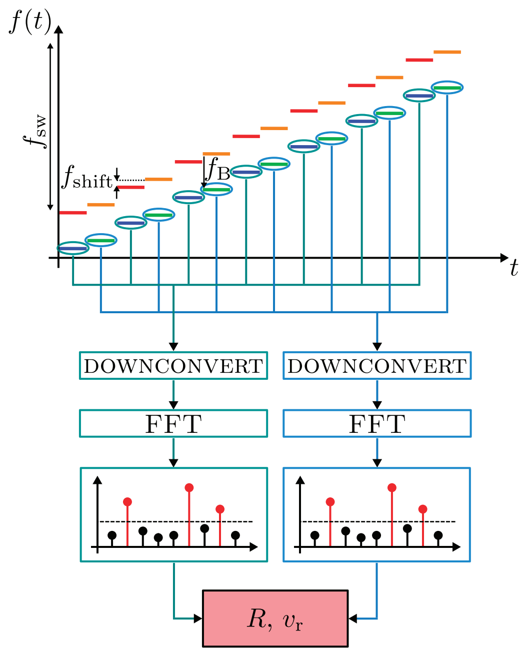

Fig. 4. MFSK waveform with signal processing scheme.

The phase correction term $f_D \cdot T_{sa}$ is necessary due to the time shift T_{sa} between the two signals $s_1(t)$ and $s_2(t)$.

With the measured beat frequency f_B [see (1)] and the measured phase difference $\Delta\phi(m)$ [see (6)] there are two equations that can be used to determine target range R and Doppler frequency f_D simultaneously based on two measurement results. The complete signal processing procedure is illustrated in Fig. 4.

The MFSK waveform gives the opportunity to measure and to resolve targets in range and Doppler frequency simultaneously and unambiguously even in multitarget situations. However this technique suffers from low estimation accuracy due to the phase measurement.

IV. CHIRP SEQUENCE WAVEFORM

Another important class of radar waveforms is described by chirp sequences [9]. Fig. 5 shows such a chirp sequence with L coherently transmitted chirp signals with identical frequency modulation where each single chirp has a very small chirp duration T_{chirp}.

Due to the small chirp duration the received time continuous baseband signal of a single chirp has a large signal bandwidth. The beat frequency f_B is calculated for

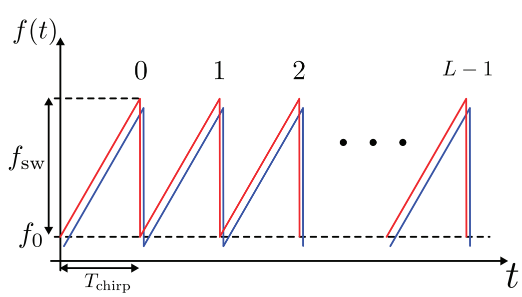

Fig. 5. Chirp signal sequence.

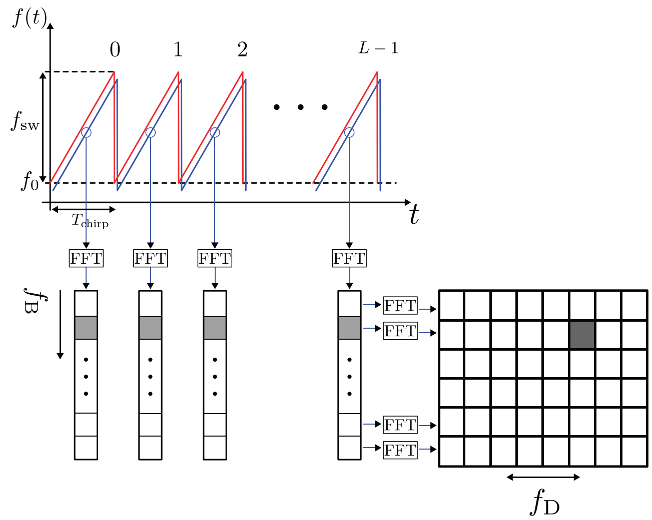

Fig. 6. Two-dimensional beat and Doppler frequency matrix.

each individual chirp signal by an FFT and contains again both the target range f_R and Doppler frequency f_D in an unsolvable way [see (1)].

The received and down-converted echo signal of the chirp sequence contains the beat f_B and the Doppler frequency f_D as well as the phase information ϕ. The time continuous baseband signal is analytically described by the following equation:

$$s(t, l) = \exp\left(j2\pi\left(f_B \cdot t - f_D \cdot lT_{chirp} + \phi\right)\right). \quad (7)$$

This baseband signal is sampled and FFT processed for each individual chirp signal, which splits the echo signal into K adjacent range gates:

$$S(m, l) = \sum_{k=0}^{K-1} s(k, l) \cdot \exp\left(-j2\pi \frac{k \cdot m}{K}\right), \quad (8)$$

where k is the sample index of the time discrete baseband signal and m is the beat frequency index. The echo signal of each individual chirp signal contains the beat frequency f_B. This procedure is repeated for each chirp signal and in total L FFTs are processed. The resulting spectra are stored column-wise in a two-dimensional matrix.

In a second step the Doppler frequency f_D is measured by applying a second FFT inside each single range gate. The FFT length in this case is L:

$$Q(m, n) = \sum_{l=0}^{L-1} S(m, l) \cdot \exp\left(-j2\pi \frac{l \cdot n}{L}\right), \quad (9)$$

where n describes the discrete Doppler frequency index.

In this case the FFT is applied to each row (range gate) of the above mentioned two-dimensional signal matrix. The described signal processing procedure is illustrated in Fig. 6.

For each detected target within the derived matrix the following linear system of equations is given

$$f_B = f_R - f_D = -\frac{f_{sw}}{T_{chirp}} \frac{2}{c} \cdot R + 2\frac{v_r}{\lambda}, \quad (10a)$$

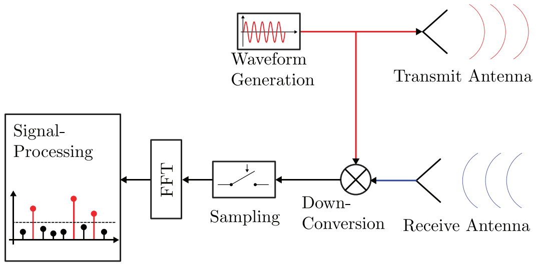

Fig. 7. Radar system with single receive channel.

$$f_D = -2\frac{v_r}{\lambda}. \tag{10b}$$

Due to these two different measurements of beat frequency f_B and Doppler frequency f_D the target range R and radial velocity v_r can be calculated for each detected target as follows:

$$R = -(f_B + f_D) \cdot \frac{T_{chirp}}{f_{sw}} \frac{c}{2}, \tag{11a}$$

$$v_r = -f_D \frac{\lambda}{2}. \tag{11b}$$

Based on this chirp sequence waveform radar targets are resolved in range and in radial velocity separately. This feature is important for multiple target situations, which occur almost always in automotive applications.

Two targets can be distinguished and resolved if they are separated in range by

$$\Delta R = \frac{c}{2 f_{sw}}. \tag{12}$$

Two moving targets can be resolved by their different radial velocities v_r if they are separated at least by

$$\Delta v_r = \Delta f_D \cdot \frac{\lambda}{2} = \frac{1}{L \cdot T_{chirp}} \cdot \frac{\lambda}{2}. \tag{13}$$

In case of a very short chirp duration T_{chirp} the measured beat frequency f_B is in any case negative and will never be positive. In this case the radar receiver can be developed by a single receive channel (inphase component) only. This property of a single receive channel reduces the hardware complexity and improves the estimation accuracy. This is an important advantage for chirp signals with very short chirp duration T_{chirp}. Any channel calibration procedures can be avoided in this case. Fig. 7 shows the structure of the radar system by a block diagram and a single channel receiver.

V. AMBIGUITIES IN DOPPLER FREQUENCY

In case of a chirp sequence waveform and the resulting signal processing based on FFT processing for each chirp signal and additionally by FFT within each range gate, some ambiguities can occur in the Doppler frequency f_D domain. The Doppler frequency is determined by

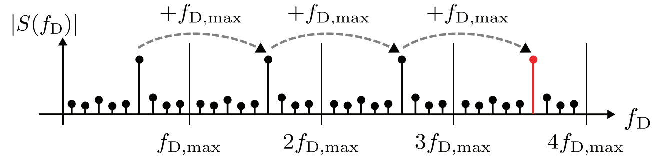

Fig. 8. Ambiguous Doppler frequency measurement.

TABLE I
System Design Example I

System Parameter	Symbol	Value
Carrier Frequency	f_0	24 GHz
Chirp Duration	T_{chirp}	1 ms
Maximum Radial Velocity	$v_{r,max}$	6.25 m/s
Time on Target	$T_{oT} = L \times T_{chirp}$	64 ms
Velocity Resolution	Δv_r	0.1 m/s
Sweep Bandwidth	f_{sw}	150 MHz
Range Resolution	ΔR	1 m

evaluating the baseband signal described in (7) from one chirp to the next. Therefore the maximum unambiguous Doppler frequency is defined by the chirp duration T_{chirp} and is denoted by

$$f_{D,max} = \frac{1}{T_{chirp}}. \tag{14}$$

The unambiguous Doppler frequency $f_{D,unamb}$ can be obtained by adding a multiple q of the chirp repetition frequency $\frac{1}{T_{chirp}}$ to the ambiguously estimated Doppler frequency $f_{D,amb}$:

$$f_{D,unamb} = f_{D,amb} + q \cdot f_{D,max}, \qquad q \in \mathbb{Z}. \tag{15}$$

The unknown factor of q represents the ambiguity of the Doppler frequency measurement, as depicted in Fig. 8. If q can be determined, the measured ambiguities are resolved.

The system parameters of such an automotive radar system based on a chirp sequence waveform with $L = 64$ adjacent chirp signals are given in Table I. The described 24 GHz radar sensor has a target range resolution of 1 m due to the sweep bandwidth of 150 MHz. The radial velocity resolution is 0.1 m/s due to the 64 ms time on target.

The unambiguous radial velocity, which can be measured by this waveform depends on the single chirp duration T_{chirp} and results in 6.25 m/s = 22.5 km/h, which is clearly too small for automotive applications.

These Doppler frequency ambiguities show a strong disadvantage of chirp sequence waveforms compared with the MFSK waveform.

VI. NEW CHIRP SEQUENCE WAVEFORM

The main idea of this section and this new waveform is to design a chirp sequence waveform, which can avoid the discussed ambiguities in the Doppler frequency domain. This waveform will finally fulfill all requirements of an automotive application. It will be a combination of the classical chirp sequence and an additional frequency shift keying or frequency modulation component. The

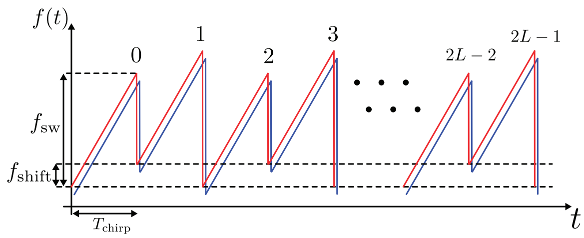

Fig. 9. New chirp sequence waveform.

waveform design principle can be compared with the MFSK waveform of Section III.

The new chirp sequence waveform consists of two sequences, which are intertwined to each other. The length of the two intertwined waveforms is $2L \cdot T_{\text{chirp}}$. Each chirp signal has the same frequency modulation, the same bandwidth, and the same chirp duration. However there is a frequency shift between two adjacent chirp signals.

The new waveform with two intertwined chirp sequences is down-converted to the baseband domain in the classical way. The two resulting baseband real valued signals are denoted by $s_1(t)$ and $s_2(t)$. The new waveform is shown in Fig. 9.

The signal $s_1(t)$ consists of all even chirp numbers ($2l = 0; 2; 4 \ldots (2L-2)$), while the signal $s_2(t)$ consists of all odd chirp numbers ($(2l + 1) = 1; 3; 5 \ldots (2L-1)$). The two resulting time continuous signals are described by

$$s_1(t,l) = \cos(j2\pi(f_{\text{B}} \cdot t - f_{\text{D,amb}} \cdot 2l \cdot T_{\text{chirp}} + \phi_1)),$$
$$s_2(t,l) = \cos(j2\pi(f_{\text{B}} \cdot t - f_{\text{D,amb}} \cdot (2l+1) \cdot T_{\text{chirp}} + \phi_2)). \tag{16}$$

These two time continuous and intertwined real valued baseband signals with beat frequency f_{B} and ambiguous Doppler frequency $f_{\text{D,amb}}$ are sampled individually. Since in this case every second chirp is included in the FFT procedure, the maximum unambiguous Doppler frequency corresponds to twice the chirp duration:

$$f_{\text{D,max}} = \frac{1}{2 \cdot T_{\text{chirp}}}. \tag{17}$$

The two time discrete signals are processed by a first FFT to calculate the beat frequency f_{B} and by a second range gate specific FFT to measure the ambiguous Doppler frequency $f_{\text{D,amb}}$. After these FFT processing steps two different two-dimensional signal matrices are obtained as shown in Fig. 10.

The frequency shift f_{shift} is chosen so small that the beat frequency measurement and ambiguous Doppler frequency measurement are not influenced by this frequency shift waveform parameter. That means in case of this new chirp sequence waveform the beat frequency f_{B} and the ambiguous Doppler frequency $f_{\text{D,amb}}$ are measured for each target twice. Targets will be resolved by these two frequency measurements in range R and in ambiguous Doppler frequency $f_{\text{D,amb}}$ separately. This is shown in the two-dimensional matrix of Fig. 10.

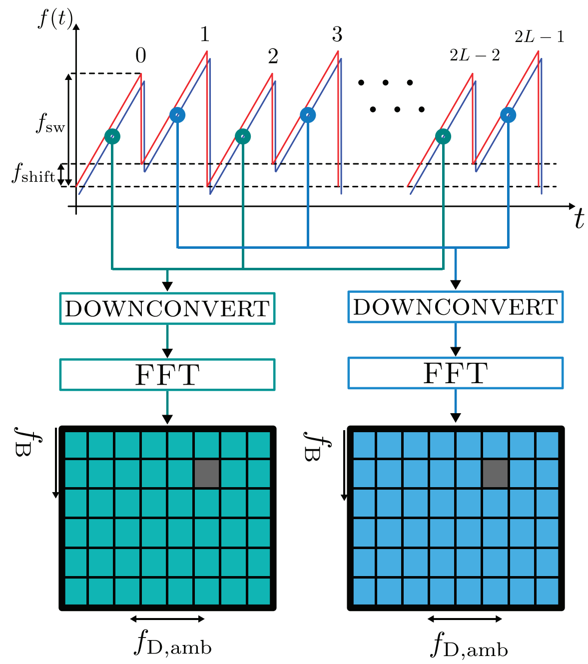

Fig. 10. Two-dimensional signal matrices.

Each point inside the matrix is a complex value consisting of amplitude and phase ($Q_1(m, n)$ and $Q_2(m, n)$). The signal phase depends on the target range R information only and is described analytically as follows:

$$\phi_1(m,n) = \arg(Q_1(m,n)), \tag{18a}$$

$$\phi_2(m,n) = \arg(Q_2(m,n)). \tag{18b}$$

This additional phase information will now be used for a resolution of ambiguities in the Doppler frequency domain.

The calculated phase difference $\Delta\phi(m, n)$, which depends on the target range R and on the known frequency shift f_{shift}, can be calculated as follows:

$$\begin{aligned}\Delta\phi(m,n) &= \phi_2(m,n) - \phi_1(m,n)\\ &= 2\pi\left(f_{\text{shift}}\frac{2}{c} \cdot R + f_{\text{D,amb}} \cdot T_{\text{chirp}}\right).\end{aligned} \tag{19}$$

The phase correction term $f_{\text{D,amb}} \cdot T_{\text{chirp}}$ [see (6)] is again necessary due to the time shift T_{chirp} between the receive signals $s_1(t, l)$ and $s_2(t, l)$.

The maximum unambiguous target range R_{max} in terms of the phase measurement can be adjusted by the frequency shift:

$$R_{\text{max}} = \frac{c}{2}\frac{1}{f_{\text{shift}}}, \tag{20}$$

which results e.g., into 300 m in case of a frequency shift of 500 kHz.

The signal processing and parameter estimation procedure to calculate an unambiguous Doppler frequency starts with an unambiguous range $\hat{R}$ measurement based

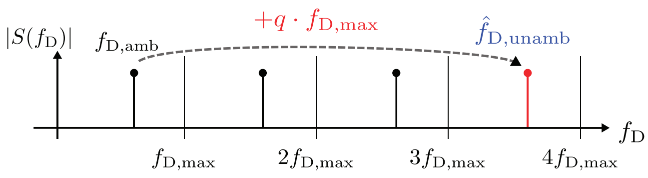

Fig. 11. Resolution of ambiguities in Doppler frequency measurement.

on the measured phase difference $\Delta\phi(m, n)$:

$$\hat{R} = \left(\frac{\Delta\phi(m, n)}{2\pi} - f_{\mathrm{D,amb}} \cdot T_{\mathrm{chirp}}\right) \frac{1}{f_{\mathrm{shift}}} \frac{c}{2}. \quad (21)$$

Due to the phase measurement this first range estimation step has a limited accuracy. The target range R contribution to the beat frequency is $f_{\hat{\mathrm{R}}}$:

$$f_{\hat{\mathrm{R}}} = -\frac{f_{\mathrm{sw}}}{T_{\mathrm{chirp}}} \frac{2}{c} \cdot \hat{R}. \quad (22)$$

Based on the measured range information the unambiguous Doppler frequency $\hat{f}_{\mathrm{D,unamb}}$ can therefore be obtained from the measured beat frequency f_{B} and the estimated target range dependent frequency $f_{\hat{\mathrm{R}}}$:

$$\hat{f}_{\mathrm{D,unamb}} = f_{\mathrm{B}} - f_{\hat{\mathrm{R}}}. \quad (23)$$

With this information the Doppler frequency measurement $\hat{f}_{\mathrm{D,unamb}}$ is now unambiguous but due to the phase measurement is of low estimation accuracy. At this point the two ambiguous Doppler frequency measurements $f_{\mathrm{D,amb}}$ come into play. The ambiguous Doppler frequencies $f_{\mathrm{D,amb}}$ are measured by FFT processing and have therefore a high estimation accuracy.

To resolve the ambiguities the unambiguous Doppler frequency $f_{\mathrm{D,unamb}}$ can be represented by the ambiguous Doppler frequency $f_{\mathrm{D,amb}}$ and a parameter q as shown in (15):

$$f_{\mathrm{D,unamb}} = f_{\mathrm{D,amb}} + q \cdot f_{\mathrm{D,max}}. \quad (24)$$

The parameter q is calculated by the comparison of (24) and the unambiguously but inaccurately measured Doppler frequency $\hat{f}_{\mathrm{D,unamb}}$ of (23). This procedure is illustrated in Fig. 11.

From a signal processing point of view the parameter q is the nearest integer value obtained from (24) with the unambiguous Doppler frequency $\hat{f}_{\mathrm{D,unamb}}$ obtained from the phase measurement:

$$q = \mathrm{round}\left\{\frac{\hat{f}_{\mathrm{D,unamb}} - f_{\mathrm{D,amb}}}{f_{\mathrm{D,max}}}\right\}. \quad (25)$$

Finally target range R can be determined by the unambiguous and high accuracy Doppler frequency $f_{\mathrm{D,unamb}}$ measurement:

$$R = -(f_{\mathrm{B}} - f_{\mathrm{D,unamb}}) \cdot \frac{T_{\mathrm{chirp}}}{f_{\mathrm{sw}}} \frac{c}{2}. \quad (26)$$

The first Doppler frequency measurement is very accurate, however ambiguous. The second Doppler frequency measurement is unambiguous, however not accurate due to the phase measurement. The combination of the two independent Doppler frequency estimation procedures gives finally the desired result.

VII. DISCUSSION OF THE PROPOSED WAVEFORM

In automotive radar as in many other applications a simultaneous, accurate, and unambiguous measurement of target range and radial velocity is required even in multitarget situations.

The considered MFSK waveform and the related signal processing scheme of the received signal is based on a simultaneous frequency and phase measurement. In additive noise situations the signal phase measurement is limited in accuracy. Therefore the target range and radial velocity measurements result in some accuracy limitations as well.

The classical chirp sequence waveform has a high target range and radial velocity measurement accuracy because it is based on two frequency measurements with high accuracy each. Table I shows a system design example. Due to the chirp duration of $T_{\mathrm{chirp}} = 1$ ms and the carrier frequency of 24 GHz, the maximum unambiguous radial velocity is $v_{\mathrm{r,max}} = 6.25$ m/s, corresponding to 22.5 km/h, which is not sufficient in almost all radar applications. Therefore, the new chirp sequence waveform has been designed to avoid the ambiguities of the radial velocity measurement. The target range and radial velocity measurement accuracy is unchanged compared with the classical chirp sequence. Therefore, the new chirp sequence fulfills all requirements of a simultaneous, highly accurate, and unambiguous measurement of target range and radial velocity even in multitarget situations.

VIII. CONCLUSION

Automotive radar sensors require accurate, simultaneous, and unambiguous measurements of target range R and radial velocity v_{r}. Both target parameters contribute to the beat frequency f_{B} of each single chirp signal simultaneously but in an unresolvable way. The new chirp sequence waveform fulfills all these requirements of unambiguous measurements even in multitarget environments.

The list of system parameters given in Table I can be updated for the new waveform. The new chirp sequence waveform measures the Doppler frequency f_{D} unambiguously. Therefore, no maximum unambiguous radial velocity parameter $v_{\mathrm{r,max}}$ is given. However, the maximum radial velocity will be limited by the phase measurement accuracy or simply by the signal-to-noise ratio (SNR). Table II shows the system parameters and performance features for the new waveform.

In contrast to the classic chirp sequence waveform, the new scheme makes use of a phase measurement, which is unambiguous within a certain maximum target range interval R_{max} as defined in (20). For completeness this system parameter is added in Table II. With a frequency shift $f_{\mathrm{shift}} = 500$ kHz the maximum unambiguous target

TABLE II
System Design Example II

System Parameter	Symbol	Value
Carrier Frequency	f_0	24 GHz
Chirp Duration	T_{chirp}	1 ms
Time on Target	$T_{\text{oT}} = 2\,L \times T_{\text{chirp}}$	128 ms
Velocity Resolution	Δv_{r}	0.05 m/s
Sweep Bandwidth	f_{sw}	150 MHz
Range Resolution	$\Delta\, R$	1 m
Frequency Shift	f_{shift}	500 kHz
Maximum Range	R_{max}	300 m

range of $R_{\text{max}} = 300$ m is achieved, which is sufficient for all automotive applications.

The signal processing of the new waveform is based on two different ways to measure an unambiguous Doppler frequency $f_{\text{D,unamb}}$. The first measurement is unambiguous, however of low estimation accuracy due to the phase measurement. The second estimation of the unambiguous Doppler frequency $f_{\text{D,unamb}}$ is based on an accurate, however ambiguous, frequency measurement. The combination of these two measurements gives the desired result.

The two-dimensional resolution of targets in range R and in Doppler frequency f_{D} direction and the unambiguous measurements show strong advantages for the new chirp sequence waveform.

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