OFDM Chirp Waveform Diversity For Co-Designed Radar-Communication System

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Abstract: *Co-designed radar-communication is becoming necessary, but there is a challenge to design suitable waveforms that can be simultaneously employed for information transmission and radar applications. This paper introduces the orthogonal frequency division multiplexing (OFDM) chirp radar waveform by embedding communication codes for co-designed radar-communication system from a top-level system description. Several implementation issues are also discussed. The object is to call for more investigations on this topic in wireless communication community.*

1. Introduction

Co-designed wireless communications and radar detection is becoming increasingly necessary owing to their similar structures and greater demand on bandwidth against strictly finite radio frequency (RF) spectrum resource [1, 2]. By using a joint waveform, the occupied spectrum would be used efficiently and both applications could be operated simultaneously. Such a co-designed radar-communication system has been reported in multiple papers [3]. An early example of co-designed radar-communication system is the NASA Space Shuttle Orbiter [4]. Another example is the intelligent transportation system, which requires the intelligent vehicles to autonomously sense the driving environment and cooperatively exchange information data. Furthermore, the proposals for integrating cognitive radar and cognitive radio for efficient spectrum sharing are also suggested.

The main challenge in co-designed radar-communication implementation lies in finding suitable waveforms that can be simultaneously employed for information transmission and radar sensing. Classical radar waveform design aims at creating the waveforms with optimum autocorrelation properties. The most popular example fulfilling this requirement is the chirp waveform, also called "linearly frequency modulated (LFM) signal". An intuitive approach for designing a joint radar-communication waveform is to use chirp modulation to encode the data, but it achieves low communication symbol rate corresponding to the chirp rate only [3]. In [5], different Oppermann sequences are employed for radar and communication applications, respectively. These

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two waveforms have to be separated first in the receiver before subsequent signal processing. In [6], another radar-communication waveform by modulating frequency modulated continuous-wave waveform with amplitude shift keying (ASK) is adopted, but it has poor peak-to-average power ratio (PAPR) performance due to the employment of amplitude modulation. In order to achieve better communication performance in term of symbol rate, continuous transmit signals should be employed [1]. A typical communication waveform with good autocorrelation properties is the spread spectrum signal, but it is not suitable for radar applications due to its limited time-bandwidth product and low frequency efficiency [7].

Orthogonal frequency division multiplexing (OFDM) is a popular choice for joint radar and communication signal because it offers many advantages such as robustness against multipath fading and relative simple synchronization [8, 9, 10]. Time and frequency synchronization is crucial in OFDM communications to preserve subcarrier orthogonality. For radar, however, sensitivity to synchronization is beneficial since radar uses a stored version of the transmitted signal and measures the time-delay and frequency offsets between the transmitted signal and received echo to estimate the range and closing velocity of a target [11]. Moreover, traditional OFDM communication signals usually have high PAPR, which brings design difficulties for subsequent RF hardware implementation. As chirp waveform has been widely used in practical radar systems due to its attractive properties in large time-bandwidth product and constant envelope [12], we designed the OFDM chirp waveforms [13, 14, 15, 16], which considers only radar applications. It was shown that OFDM chirp waveform is comparable with classic chirp signals and furthermore experiences no range-Doppler coupling problem.

In this paper, we extend the OFDM chirp waveform [14] by embedding communication codes for co-designed radar-communication system from a top-level system description, with an aim to call for more publications and investigations on this promising topic. Note that the difference between the proposed OFDM chirp and existing standard OFDM waveforms [1] lies in that the former uses chirp-frequency subcarriers, instead of single-frequency subcarriers as the latter, to improve the PAPR performance of the transmitted signals.

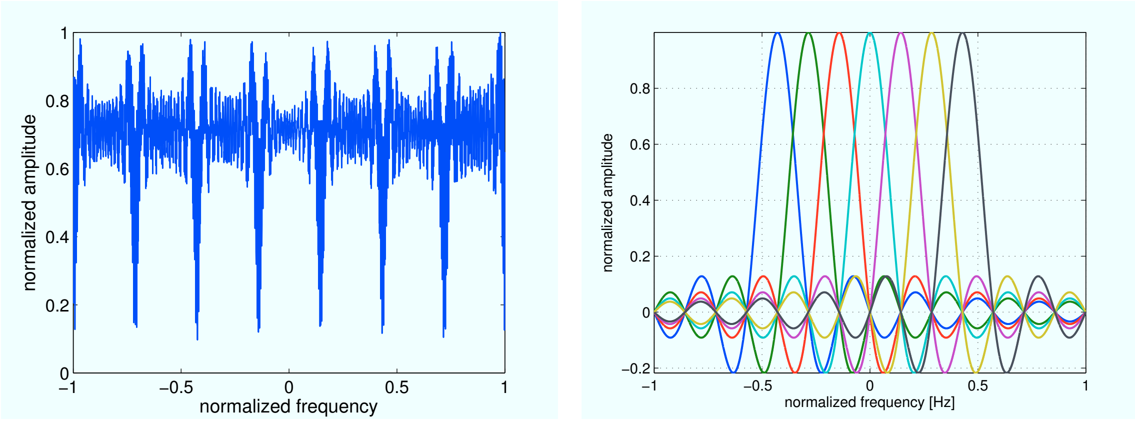
2. Communication-Embedded OFDM Chirp Waveform

2.1. OFDM Chirp Waveform

As OFDM chirp waveform can be regarded as a parallel stream of multiple chirp signals with orthogonal carriers, each modulated with different transmit data. Analogous to a standard OFDM waveform [1], which can be expressed as

$$x(t) = \sum_{k=0}^{N_s-1} \sum_{n=0}^{N_c-1} c_{k,n} e^{j\left(2\pi f_n t + \pi k_r t^2\right)} \mathrm{rect}\left(\frac{t - kT_w}{T_w}\right) \tag{1}$$

where N_s is the number of modulation symbols, N_c is the total amount of subcarriers, $c_{k,n}$ is the information data modulated on the kth symbol and the nth subcarrier, f_n is the individual subcarrier starting frequency, k_r is the subcarrier chirp rate, T_w denotes the total OFDM chirp



(a) OFDM chirp waveform spectra.

(b) Standard OFDM waveform spectra.

Figure 1: Illustrative spectra comparisons between OFDM chirp waveform and standard OFDM waveform.

symbol duration including an elementary symbol duration T and a guard interval duration T_g, and rect (t/T_w) describes a rectangular window with duration T_w. Specially, when $k_r = 0$, the OFDM chirp waveform $x(t)$ simplifies to a standard OFDM signal.

In order to avoid coupling interference between individual subcarriers, f_n should hold as $f_n = \frac{n}{T} = n\Delta f, n = 0, 1, \ldots, N_c - 1$, with Δf being the frequency separation. Accordingly, the spectrum of each subcarrier signal is different from the standard OFDM subcarrier signal spectra, namely, $T\mathrm{sinc}\,(fT - n)$. Since sinc $(fT - n)$ has the first null at an inverse of the signal duration T, the spectra of the subcarriers will be overlapped in time-domain, but the subcarrier signals are mutually orthogonal.

Suppose $n = 1$, Figure 1 compares the spectra of the OFDM chirp waveform and standard OFDM waveform, where the number of subcarriers (7 subcarriers) is used for illustration purpose only. It can be noticed that the OFDM chirp basis has lower PAPR, which is desired for RF hardware transmitter and an almost constant modulus like a standard chirp waveform. Therefore, it is expected that the OFDM chirp waveform provides a potential solution to waveform diversity for co-designed radar-communication system.

2.2. Co-Designed Radar-Communication Scheme

Similar to OFDM communications, cyclic prefix with a length longer than the desired maximum radar return time delay should be adopted. For instance, if D range cell paths are superposed together in the returned signal, the guard interval length T_g in the analog transmission signal should be $T_g = (D-1)T_s$, with T_s being the sampling interval at the receiver. Then the total OFDM chirp symbol duration should be $T_w = T + T_g$. A partial cyclic repetition of the time domain signal of the duration T_g can be used for the cyclic prefix, which is typically at the beginning of the symbol, occupying the interval $[0, T_g)$ within the total symbol duration T_w. In standard OFDM radar applications, the transmitted signals and returned signals are usually separated in time due to the fact that in monostatic case the transmitter and receiver share the

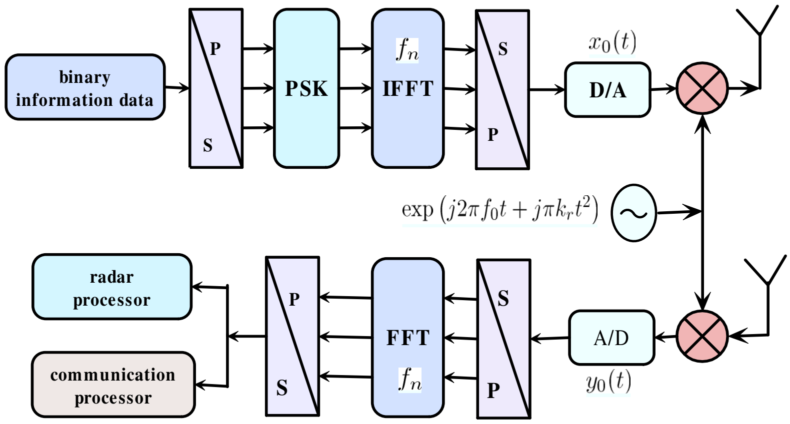


Figure 2: Block scheme of co-designed radar-communication system.

same antenna and cannot transmit and receive simultaneously. This implies that a reasonable receive window is needed between two consecutive pulses. In order to achieve high transmission throughput for the communications, the communication-embedded OFDM chirp pulses are transmitted consecutively.

Figure 2 illustrates the block scheme of the co-designed radar-communication system. First, the binary communication data is divided into parallel streams, and mapped onto complex-valued phase-shift keyed (PSK) symbols. Next, the standard OFDM waveform $x_o(t)$ can be obtained by an inverse fast Fourier transform (IFFT) and subsequent parallel-to-serial and digital-to-analog (D/A) conversions. Finally, after being mixed with a local oscillator (LO) signal $\exp\left(j2\pi f_0 t + j\pi k_r t^2\right)$ with a carrier frequency f_0, the generated OFDM chirp signal is radiated towards the desired region. Note that the main implementation difference between our OFDM chirp waveform and standard OFDM signal in this system scheme is that the former uses $\exp\left(j2\pi f_0 t + j\pi k_r t^2\right)$ as the LO signal to achieve lower PAPR to facilitate subsequent RF amplifier design, whereas the latter uses $\exp\left(j2\pi f_0 t\right)$ as the LO signal. This implies that the proposed waveforms can be early implemented as the traditional OFDM signal.

The returned signals from a reflecting object at the distance R can be expressed as

$$y(t) = \sum_{k=0}^{N_s-1} \sum_{n=0}^{N_c-1} c_{k,n} \exp\left(j2\pi f_n \left(t - \frac{2R}{c_0}\right) + j\pi k_r \left(t - \frac{2R}{c_0}\right)^2\right) \times e^{j2\pi f_d t} \text{rect}\left(\frac{t - kT_w - \frac{2R}{c_0}}{T_w}\right) \tag{2}$$

where f_d is the Doppler shift and c_0 is the speed of light. Note that, here, we consider only the baseband signal and ignore the carrier frequency associated terms, which will be canceled out by the RF mixer and corresponding phase compensation algorithm. The subsequent receiver processing steps are then carried out in an inverse order of the transmitter's processing steps.

The radar functionality can be achieved by exploiting the baseband signals $x(t)$ and $y(t)$ with matched filtering. A similar realization approach has been investigated in [17], which calculates the radar range profile by correlating the received time-domain signal $y(t)$ with the transmitted time-domain signal $x(t)$, namely, $z(\tau) = \int y(t)x(t-\tau)\mathrm{d}\tau$, where τ is just the time variable of the range profile to be measured. But this approach may result in high sidelobe levels in the radar range profile due to unperfect waveform auto-correlation. The novel OFDM radar processing approach proposed in [1] can be employed to circumvent this disadvantage. The basic idea is to use the transmitted information and the received information at the output of the OFDM de-multiplexer before the channel equalation and decoding. In doing so, the distortion from the channel is fully contained in the complex modulation symbols. Since all information symbols in one OFDM symbol are transmitted through the channel at different carrier frequencies separated by Δf, the received information symbols can be used to perform channel sensing at discrete frequencies like that in stepped frequency radar. The details can be found in [1].

In the same time, the receiver recovers the individual modulation symbols for the communication functionality by observing the received signal for only the elementary OFDM chirp symbol duration T. This implies that, when the guard interval duration T_g is properly designed, we can cut the observed samples and accordingly the time shift of the $\mathrm{rect}(\cdot)$ in (2) can be neglected. In this case, after canceling or compensating the chirp rate k_r associated terms in the dechirp-on-receive operation [18], the matched filtering signal is equal to the received signal in the standard OFDM communication system and thus, the transmitted information can be simply recovered by classic OFDM communication algorithms.

3. Waveform Performance Analysis in Radar-Communication System

Radar performance emphasizes detection, resolution and localization capability, while communication performance focus on data rate, error probability and coding efficiency. These performances have a direct relation with the signal-to-noise ratio (SNR). It is easily understood that OFDM chirp waveform and standard OFDM waveform have equal output SNR under the same condition.

If waveform diversity is required for the system, the impacts of undesired mutual interferences between distinct waveforms can be equivalently evaluated by the cross-ambiguity function between any two waveforms $y_1(t)$ and $y_2(t)$, namely, $\chi(\tau, f_d) = \int y_1(t)y_2^*(t-\tau)e^{j2\pi f_d t}\mathrm{d}t$, with * being the conjugate operator. Specifically, when $y_1(t) = y_2(t)$, it simplifies to the auto-ambiguity function.

An effective metric to evaluate the waveform ambiguity function is the empirical cumulative distribution function (ECDF), which represents the percentage of samples of $|\chi(\tau, f_d)|$ lower than a given magnitude. Suppose the following parameters that are same to [19]: $M = 4$, $Q = 10$, $K = 15$ and $k_r = 273$, Figure 3 compares the ECDFs between OFDM chirp waveform and standard OFDM signal, in which the result of classic chirp waveform is also provided for the comparison. It means that the OFDM chirp waveform yields smaller sidelobe energy among the three waveforms.

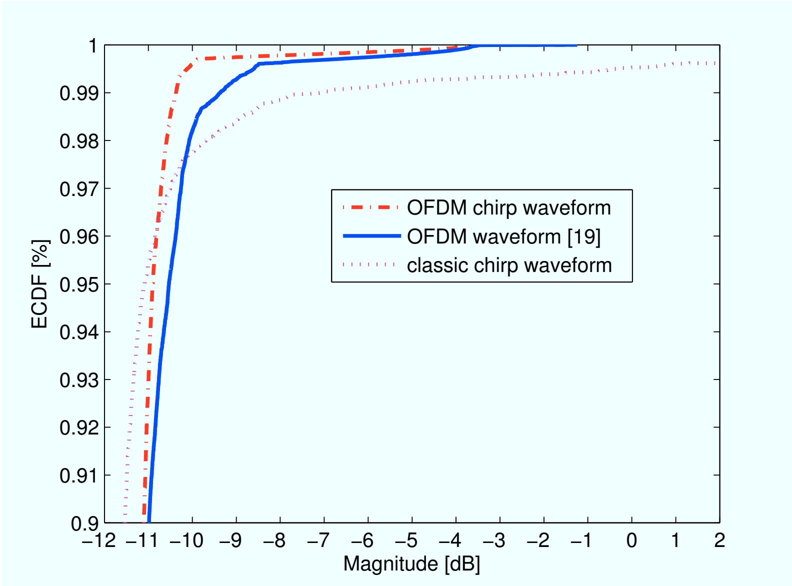


Figure 3: Comparisons of ECDF results.

Another radar performance metric is the achievable range resolution. It depends on neither the employed waveform nor the particular system parameterization but only the total bandwidth occupied by the transmitted signal, namely, $c_0/2N_c\Delta f$. In typical radar applications, the range resolution should be in the order of 1 to 2 m and the required total banwidth is over 100 MHz. This is compliant with the regulations for the 24 GHz industrial scientific medical (ISM) band [1].

In communication aspects, the BER is determined by $P = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$, where $Q(\cdot)$ is the complementary Gaussian error function and E_b/N_0 is the SNR per bit with E_b and N_0 denoting the signal and noise, respectively. It is obvious that the BER of the OFDM chirp waveform is the same as that of a standard OFDM waveform.

4. Implementation Issues and Discussions

4.1. Doppler Frequency Shift

Doppler frequency shift is an important radar feature for target velocity estimation, but little attention has been paid in the literature. It is noticed from the comparisons of leaked energy versus Doppler shift given in Figure 4 that, the proposed OFDM chirp waveform has a smaller ratio of leaked energy than the conventional OFDM signal. This implies that the proposed waveforms are less sensitive to the Doppler shift. That is, Doppler sensitivity means that the range of the target is sensitive to the speed of the target and different speeds can result in different range data for an identical target, namely, the designed waveforms are less sensitive to Doppler effects, which is an advantage for high-resolution radar imaging.

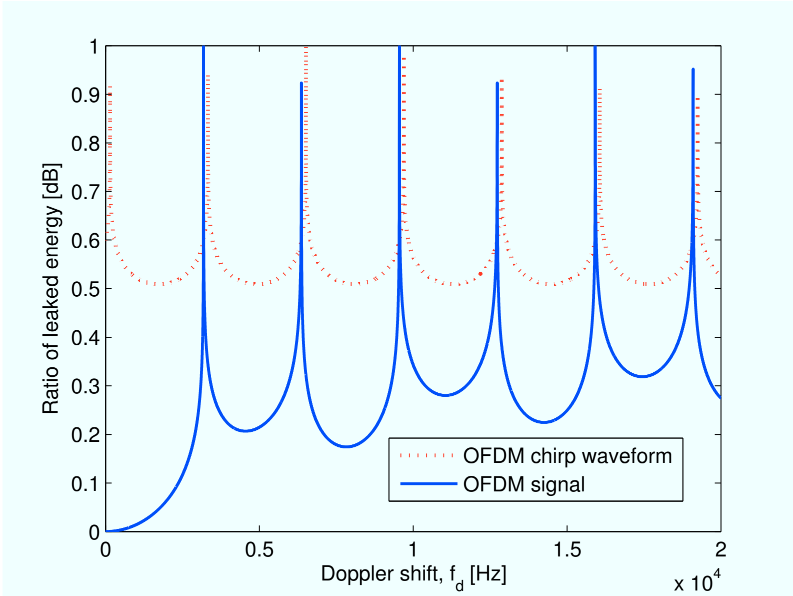


Figure 4: Comparisons of leaked energy for Doppler tolerance analysis.

Nevertheless, a method to compute the Doppler shift from OFDM signals, independent of the applied multi-carrier coding, has been presented in [20]. Since this correlation-based method has the drawback of high computing complexity and Doppler ambiguities, another Doppler processing scheme regardless of the transmitted signal information and coding is proposed in [21]. This scheme operates by processing the symbols that compose the OFDM symbols directly instead of processing the baseband signals. In doing so, it can be applied in combination with the transmission of arbitrary user data and is able to resolve multiple reflecting targets with a high dynamic range and low sidelobe levels.

However, for a fixed OFDM chirp symbol index, the Doppler frequency shift has no individual influence on the different modulation symbols within the same OFDM chirp symbol because it brings an identical phase shift on every subcarrier. Although both the distance to the reflecting target and Doppler shift introduce a linear phase shift in the returned OFDM chirp signals, they have completely orthogonal influence on the OFDM modulation symbols [1]. Therefore, the target Doppler and range can be independently estimated with suitable signal processing algorithms.

4.2. Multipath Propagation Effect

Another implementation issue is multi-path propagation. Like in standard OFDM communications, the OFDM chirp symbols must be extended by adding a cyclic prefix at the beginning to avoid inter-symbol interference between adjacent symbols. Its duration T_g should be the maximum expected signal travel time between platform and scatterer instead of only the time difference as for pure communication links, to allow for fully compensating the multipath propagation effects.

On the other hand, in order to obtain a sufficiently high SNR for the received signals, the symbol duration T should be chosen as long as possible. However, the guard interval duration T_g and symbol duration T are limited by the maximum unambiguous velocity measurement $v_{\max}$, namely, $v_{\max} = \frac{c_0}{(T+T_g)f_0}$. Hence, a trade-off should be made in the system design.

5. Conclusion

Co-designed radar-communication is a promising technique, but waveform diversity design is a bottleneck problem. This paper extended the OFDM chirp waveform used in radar imaging by embedding communication codes for co-designed radar-communication system from a top-level system description, with an aim to call for more investigations on this topic. It is shown that OFDM chirp waveform indeed provides promising potentials for future co-designed radar-communication systems, although more further work about waveform diversity design and corresponding signal processing algorithms should be carried out.

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