Waveform Design for Joint Radar-Communication with Nonideal Power Amplifier and Outband Interference

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***Abstract*—The joint radar-communication system is a good way to meet the intelligent transportation systems' need of detecting the cars and barriers around and exchanging information from each other at the same time. Among various schemes, the joint system with integrated waveform attracts general interest because the interference between the radar and communication subsystems will be fundamentally avoided. For all kinds of integrated waveforms, the spectrum must be limited within B_0, the original working band of the radar, in order to avoid the performance loss brought by the attenuation of the power amplifier (PA) and the interference from other devices out of band, which is inevitable in actual devices and environment. In this paper, the time-frequency characteristics of an integrated waveform based on Linear Frequency Modulation (LFM) and Continuous Phase Modulation (CPM) is studied in detail with the Short Time Fourier Transform (STFT). Based on the theoretical analysis, a modified three-section waveform with a limit of the mapping codebook of communication symbols is proposed. Simulation results show that the bandwidth of the modified waveform is limited within B_0 and the bit error rate (BER) performance with a band-limited PA and out-band interference is almost the same as the BER with ideal PA and no interference.**

I. INTRODUCTION

The idea of a joint radar-communication system is first proposed as a concept of "multifunction RF" in [1], and attracts general interest in the area of intelligent transportation systems [2], [3]. The joint system has various advantages of making efficient use of the spectrum, reducing interference between the two systems, and transmitting data at high speed and far distance thanks to the large bandwidth and high-power amplifier of the radar. A simple way of joint design is transmitting radar and communication signals at different time slots, frequency channels, sub-arrays, respectively [4]. However, the interference between the two subsystems can hardly be avoided. Further work of the joint system is based on integrated waveform. The Orthogonal Frequency Division Multiplexing (OFDM) waveform is studied because of its wide bandwidth and widely application in communication [5]. However, with high Peak to Average Power Ratio (PAPR), the OFDM waveform can't make full use of the radar's power amplifier (PA) at the saturation region and therefore the working distance of the joint system is limited.

Another way of designing the integrated waveform is to load the communication symbols on the radar waveform [6], [7]. As we all know, radar systems with the linear frequency modulation (LFM) [8] is widely equipped and a large amount of signal processing schemes have been proposed and applied. So an integrated waveform based on LFM is easy to be implemented in the existing devices. Meanwhile, to hold the radar's working distance and avoid distortion caused by the nonlinearity of PA, the loaded communication symbols must be with constant modulus, among which the continuous phase modulation (CPM) waveform could be considered [9]. As a result, an integrated waveform based on LFM and CPM is fit for the joint system and worth studying.

There have been various research of detecting and tracking, modulation and demodulation, equalization and synchronization based on similar integrated waveforms [6], [7]. However, few work takes into consideration the broadening of the spectrum of the integrated waveform. In fact, the PA in a certain radar device is specially designed for its working band and the out-band attenuation is considerable [10]. At the same time, as spectral resources become more and more tense, the adjacent bands of B_0, the original working band of the subsystem of radar, may have been assigned to other systems. The signal power of other systems may be so great to cause strong interference even after a significant attenuation of the PA. So a study of limiting the spectrum of the integrated waveform within B_0 is in great need.

The joint time-frequency analysis is widely applied for non-stationary signal processing [11], and is necessary for the integrated waveform with random communication symbols. There are various tools for joint time-frequency analysis, and we choose the Short-Time Fourier Transform (STFT) in this paper to make it easier for analysis with analytic expression of elementary functions as well as flexible resolution with different window functions. Based on the analysis, modification can be implemented for the integrated LFM-CPM waveform.

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The rest of the paper is organized as follows. In Section II, a general description of the integrated LFM-CPM waveform and a joint system model considering bandlimited PA and out-band interference is presented. In Section III, STFT is applied for joint time-frequency analysis of the waveform and therefore a modified three-section waveform with limited bandwidth is proposed by halving the codebook of communication symbols in the head and tail end. Transmission efficiency of the proposed waveform is also analyzed. In Section IV, simulation result is showed. Power spectrum of the modified waveform is limited within B_0, and the BER performance considering bandlimited PA and out-band interference is almost the same as the one with ideal PA and no interference. With same communication efficiency, the BER of the unmodified waveform is much higher than the modified one. Therefore the modification is valid and worthwhile. The ambiguity function of the modified waveform is also showed in this section, and proves that the waveform is fit for the radar subsystem.

II. SYSTEM MODEL

A. Integrated Waveform for Joint Radar-Communication System

The integrated waveform for joint radar-communication system can accomplish data transmission and detection at the same time, therefore interference between the radar and communication subsystems will be totally avoided. So the integrated waveform should maintain the properties of both the two subsystems. One intuitive way is to load the communication systems on the radar waveform and therefore a compound waveform will be obtained, which is,

$$S\left(t\right) = \mathrm{rect}\left[\frac{t-T}{T}\right] \exp\left(j2\pi f_{\mathrm{c}} t\right) S_{\mathrm{r}}\left(t\right) S_{\mathrm{c}}\left(t\right) \qquad (1)$$

where $S_{\mathrm{r}}\left(t\right)$ is the baseband signal of radar, $S_{\mathrm{c}}\left(t\right)$ is the baseband signal of communication, T is the pulse width, $\mathrm{rect}\left[x\right] = \begin{cases} 1, & 0 < x < 1 \\ 0, & else \end{cases}$.

For integrated waveform obtained in this way, there have been some research of signal processing schemes from both the view of radar and communication [6]. For the sub-system of radar, the fixed matching filter at the receiver should be changed to parameter-variable matching filter according to the communication symbols sent in each pulse. The change is not hard to be implemented because the transmitter and receiver of the radar is at the same end and the capability of digital signal processing is developing fast nowadays. While for the sub-system of communication, if only we get the baseband communication signal, the signal processing goes back to traditional communication. Since the baseband signal of radar is known, it can be processed as a part of carrier. So the baseband signal of communication can be obtained by conjugate multiplication.

In this paper, we choose LFM waveform for the radar subsystem [8]. That is,

$$S_{\mathrm{r}}\left(t\right) = A \cdot \mathrm{rect}\left[\frac{t-T}{T}\right] \exp\left(j\pi\mu t^2\right) \qquad (2)$$

where, A is the amplitude, μ is the chirp rate of LFM. To simplify the discussion, we assume that $A = 1$, $\mu > 0$. If $\mu < 0$, similar analysis can be done and symmetric conclusion will be derived. The bandwidth of LFM is defined as,

$$B_0 = \mu T \qquad (3)$$

As for the sub-system of communication, CPM is considered with its advantage of constant envelope, continuous phase change, rapid roll-off of the spectrum out of band [9]. In one pulse, the number of communication symbols is N, that is, $a = [a_0, a_1, ..., a_{\mathrm{N}-1}]$, where,$a_{\mathrm{i}} \in \{-(M-1), -(M-3), ..., (M-3), (M-1)\}$ is a bipolar amplitude modulation sequence, M is the modulation order. So the modulated sequence is,

$$S_{\mathrm{c}}\left(t, a\right) = A \sum_{k=0}^{N-1} \mathrm{rect}\left(\frac{t-kT_0}{T_0}\right) \exp\left(j\phi\left(t, a\right)\right) \qquad (4)$$

where $T_0 = T/N$ is the period of a communication symbol, h is the modulation index, $\phi\left(t, a\right)$ is the continuous phase coding sequence, and $q(t)$ is decided by the integral of the shaping pulse $g(t)$,

$$\phi\left(t, a\right) = 2\pi h \sum_{i=-\infty}^{+\infty} a_{\mathrm{i}} q(t - iT) \qquad (5)$$

$$q(t) = \int_{-\infty}^{t} g(\tau) d\tau \qquad (6)$$

The pulse width of $g(t)$ is LT_0, that is $g(t)$ is non zero only when $0 < t < LT_0$. $L \in \mathbb{N}$ is the correlation length. At the same time, the integration of $g(t)$ in the whole real field is 1/2. so $q(t)$ can be expressed as,

$$q(t) = \begin{cases} 0 & t < 0 \\ \int_0^t g(\tau) d\tau & 0 \le t \le LT \\ 1/2 & t > LT \end{cases} \qquad (7)$$

Usually, the shaping pulse can be rectangular (L-REC), raised cosine (L-RC), Gaussian, and so on. L represents the pulse width. Similarly, let $A = 1$ in equation (4) for convenience in the following discussion.

Now we get the expression of the integrated waveform loaded onto the carrier with center frequency of f_{c} in detail,

$$\begin{aligned} S(t) &= \sum_{k=0}^{N-1} \mathrm{rect}\left(\tfrac{t-kT_0}{T_0}\right) \exp\left(j2\pi\left(f_{\mathrm{c}} t + \tfrac{\mu}{2} t^2\right)\right) \cdot \\ &\quad \exp\left(j2\pi h \left(\sum_{i=k-L+1}^{k} a_{\mathrm{i}} q\left(t - iT\right) + \tfrac{1}{2} \sum_{i=0}^{k-L} a_{\mathrm{i}}\right)\right) \end{aligned} \qquad (8)$$

B. Transmitting and Receiving Model with PA and Interference

In this paper, we take the actual PA and interference into consideration. The amplification factor of the PA in the saturation area almost holds a constant within the working band and attenuates quickly out of band. We use $S_{\mathrm{P}}(f)$ to represent the relationship between the amplification factor and

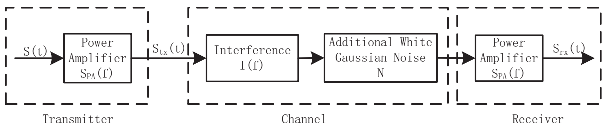

Fig. 1. A diagram of signal transmitting and receiving considering power amplifier and interference.

the frequency. The transmitted signal is first amplified at the transmitter, then interference and noise is added, finally the received signal is amplified for the second time at the receiver. We assume additional white Gaussian noise and interference $I(f)$ represented in frequency domain. so the received signal $S_{\mathrm{rx}}(t)$ is,

$$
\begin{aligned}
S_{\mathrm{rx}}(t) &= \mathcal{F}^{-1}\left\{\left(S_{\mathrm{tx_f}}(f)+I(f)+N\right)\sqrt{S_{\mathrm{P}}(f)}\right\} && (9)\\
S_{\mathrm{tx_f}}(f) &= \mathcal{F}\left\{S_{\mathrm{tx}}(t)\right\}\sqrt{S_{\mathrm{P}}(f)} && (10)
\end{aligned}
$$

where $\mathcal{F}\{\cdot\}$ and $\mathcal{F}^{-1}\{\cdot\}$ is the Fourier and inverse Fourier transform. A diagram of transmitting and receiving is showed in Fig. 1.

III. Modified Integration Waveform

A. Spectrum Analysis

Since the communication symbols are in random, a time-frequency analysis is necessary to know the exchange of spectrum as the communication symbols changes at a time slot of T_0. Among various tools for time-frequency analysis, the short-time Fourier transform (STFT) is applied for analysis in this paper [11]. In the following analysis, we'll see the advantage of STFT for this problem. The definition of STFT is,

$$
\mathrm{STFT}(t,f)=\int_{-\infty}^{+\infty} S(\tau) g_{\mathrm{w}}^{*}(\tau-t)\exp(-j2\pi f\tau)d\tau \qquad (11)
$$

where $g_{\mathrm{w}}(t)$ is the window function which intercepts the signal into pieces. We can get different time and frequency resolution with different window functions. In this paper, Gaussian function is used.

$$
g_{\mathrm{w}}(t)=\exp\left(-\frac{t^2}{2\sigma^2}\right) \qquad (12)
$$

Among the LFM-CPM waveforms with various shaping pulses, only the STFT result of rectangular shaped waveform can be expressed analytically. So the following analysis is based on the LFM-CPM waveforms with rectangular shaping pulse, and in the following section of simulation, we'll show that the conclusion is fit for waveforms with other shaping pulse.

$$
\begin{aligned}
\mathrm{STFT}(t,f)= \;& \sigma\sqrt{\beta/\pi}\exp\left(j\Phi_{\mathrm{N}}(t,f)\right)\cdot\\
& \sum_{k=0}^{N-1}\mathrm{rect}\left(\tfrac{t-kT_0}{T_0}\right)A_{\mathrm{k}}(t,f)\exp\left(j\Phi_{\mathrm{k}}(t,f)\right)
\end{aligned} \qquad (13)
$$

where $\Phi_{\mathrm{N}}(t,f)$ and $\Phi_{\mathrm{k}}(t,f)$ are real functions with t and f, and,

$$
\begin{aligned}
\beta &= \frac{(2\pi\sigma)^2}{\left(2\pi\mu\sigma^2\right)^2+1} && (14)\\
A_{\mathrm{k}}(t,f) &= \exp\left[-\frac{\beta}{2}\left(f-f_{\mathrm{k}}(t)\right)^2\right] && (15)\\
f_{\mathrm{k}}(t) &= f_{\mathrm{c}}+\mu t+\frac{h}{2LT_0}\sum_{i=k-L+1}^{k}a_{\mathrm{i}} && (16)
\end{aligned}
$$

And we can define the power spectrum as,

$$
\begin{aligned}
S_{\mathrm{P}}(t,f) = &\;|\mathrm{STFT}(t,f)|^2\\
= &\left|\sum_{k=0}^{N-1}\mathrm{rect}\left(\tfrac{t-kT_0}{T_0}\right)A_{\mathrm{k}}(t,f)\right|^2\tfrac{\sigma^2\beta}{\pi}
\end{aligned} \qquad (17)
$$

Further more, $\mathrm{rect}\left(\frac{t-kT_0}{T_0}\right)\neq 0$ holds only when $kT_0 < t < (k+1)T_0$, so S_P can be simplified as,

$$
S_{\mathrm{P}}(t,f)=\frac{\sigma^2\beta}{\pi}\exp\left[-\beta(f-f_0(t))^2\right] \qquad (18)
$$

where,

$$
f_0(t)=f_{\mathrm{c}}+\mu t+\frac{h}{2LT_0}\sum_{k=0}^{N-1}\mathrm{rect}\left(\frac{t-kT_0}{T_0}\right)\sum_{i=k-L+1}^{k}a_{\mathrm{i}} \qquad (19)
$$

Equation (18) states that the power spectrum has a maximum at $f_0(t)$, and declines exponentially as f goes away from $f_0(t)$ on both side. So the maximum point $f_0(t)$ can be regarded as the major component of the spectrum of the integrated waveform.

B. Modified Three-Section Integrated Waveform

The aim of the modification of the waveform is to restrain the spectrum within $[f_{\mathrm{c}}, f_{\mathrm{c}}+B_0]$, which means that for any $k\in[0,1,...,N-1]$, $f_{\mathrm{c}}\le f_0(t)\le f_{\mathrm{c}}+B_0$ should always hold. Considering symmetry, we first discuss how to keep $f_0(t)\ge f_{\mathrm{c}}$, which equals,

$$
\mu kT_0+\frac{h}{2LT_0}\sum_{i=k-L+1}^{k}a_{\mathrm{i}}\ge 0 \qquad (20)
$$

Since the communication symbols are in random, the worst case, $a_{\mathrm{i}}=-(M-1)$, should be considered (note that $\mu>0$ is assumed in Section II),

$$
\mu kT_0-\frac{h}{2LT_0}L(M-1)\ge 0 \qquad (21)
$$

We get,

$$
k\ge\frac{h}{2\mu{T_0}^2}(M-1)=\frac{h(M-1)}{2}\frac{N}{B_0T}N \qquad (22)
$$

Define $k_0=\left\lceil\frac{h}{2\mu{T_0}^2}(M-1)\right\rceil$, where $\lceil x\rceil$ means the minimum integer that is equal to or greater than x. Equation (22) states that equation (20) will always hold when $k\ge k_0$, while when $k<k_0$, there must be $a_{\mathrm{i}}>0$, which means only the

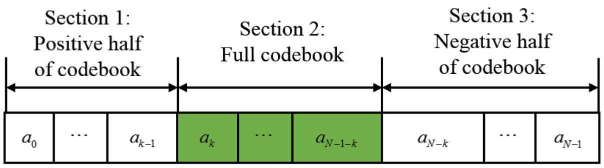

Fig. 2. A diagram of the modified three-section waveform ($k = k_0$ or $k = k_1$).

positive half of the codebook $\{1, 3, ..., (M-3), (M-1)\}$ can be used.

Symmetrically analysis reveals that when $k \geq N - k_0$, $a_{\rm i}$ should be limited within the negative half of the codebook, which is, $\{-(M-1), -(M-3), ..., -1\}$.

Now a simple three-section waveform is obtained. But the analysis above is very intuitive and the characteristics of memory is not considered, which is an important property for CPM with partial response (correlation length $L > 1$). The following discussions declares that k_0 can be narrowed down to $k_1 = k_0 - L + 1$ in some conditions, and as a result the communication efficiency can be promoted.

To reduce k_0 to k_1, there should be $f_0(t) \geq 0$ for $(k_0 - x)T \leq t < (k_0 - x + 1)T$, $1 \leq x \leq L-1$, and $x \in \mathbb{N}$. The key point is $\sum\limits_{i=k-L+1}^{k} a_{\rm i}$. For each x, there are x symbols in section 1 and is guaranteed positive. The worst case of them is +1. The other $L-x$ symbols are in section 2, and take values in $\{-(M-1), -(M-3), ..., (M-3), (M-1)\}$. The worst case is $-(M-1)$. That is,

$$\mu(k_0 - x)T + \frac{h}{2LT}(1 \cdot x - (M-1)(L-x)) \geq 0 \quad (23)$$

for any $1 \leq x \leq L-1$, $x \in \mathbb{N}$.

So that,

$$\frac{h}{2L}\frac{N}{B_0 T}N \geq 1 \quad (24)$$

Symmetrically, $f_0(t) \leq B_0$ also holds in this condition.

Further more, if k_0 is narrowed down to $k_2 < k_0 - L + 1$, then for $(k_0 - 1)T \leq t < k_0 T$, all the symbols in $\sum\limits_{i=k-L+1}^{k} a_{\rm i}$ are in section 2, which means the worst case will be $a_{\rm i} = -(M-1)$ for any $k_0 - L \leq i \leq k_0 - 1$. From equation (19) we know that $f_0(t) < 0$, so the spectrum will exceed the lower border $f_{\rm c}$. So $k_1 = k_0 - L + 1$ is the lower bound of the length of modification.

A schematic diagram of our modified three-section waveform is showed in Fig. 2. In one pulse with communication symbols of N and $\frac{h}{2L}\frac{N}{B_0 T}N \geq 1$, when $k_1 \leq k \leq N-1-k_1$, the whole codebook can be used for symbol mapping, while when $k \leq k_1 - 1$ or $k \geq N - k_1$, only the positive half or the negative half of the codebook can be used. In addition, when $\frac{h}{2L}\frac{N}{B_0 T}N < 1$, k_1 should be extended to k_0.

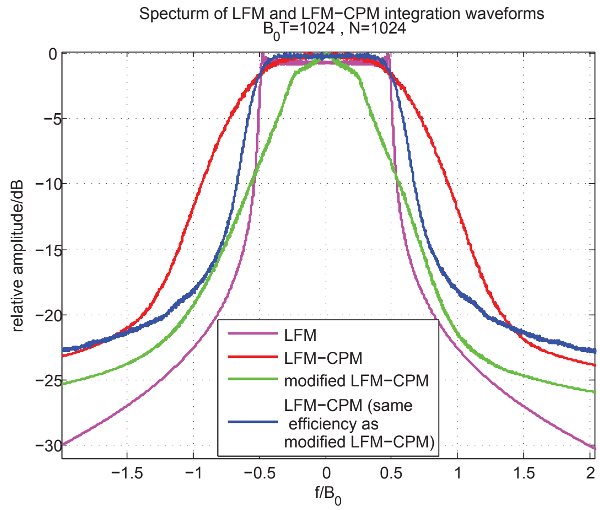

Fig. 3. The spectrum of LFM and the integrated waveforms.

C. Transmission Efficiency Analysis

Transmission efficiency of the modified waveform is lowered because of the limit of codebook. Before the modification, the number of bits transmitted by one pulse is,

$$N_{\rm b} = N \log_2 M \quad (25)$$

And after the modification,

$$\begin{aligned} N_{\rm bk} &= (N-2k)\log_2 M + 2k(\log_2 M)/2 \\ &= (N-k)\log_2 M \end{aligned} \quad (26)$$

where k can be k_0 or k_1 according to parameters of the waveform.

Therefore the ratio of the sacrificed efficiency of the communication is,

$$r_{\rm bk} = \frac{N_{\rm b} - N_{\rm bk}}{N_{\rm b}} = \frac{k}{N} \quad (27)$$

In the following session of simulation, we'll show that considering the actual PA and out-band interference, the BER of the unmodified waveform is much higher than the modified waveform with same efficiency, so that the sacrifice of transmission efficiency is necessary and the modification is valid.

IV. Simulation And Analysis

Firstly, the power spectrum of the modified and unmodified waveform is studied. In table I, there are three sets of parameters of LFM-CPM and the proportion of the power spectrum within B_0, and correspondingly, Fig. 3 shows the distribution of power spectrum of LFM and the integrated LFM-CPM with parameter set 1 in Table I. Both the numerical result and the figure show clearly that the power spectrum of the modified waveform is mostly limited in B_0 while the unmodified one always below 90% inside B_0.

An ideal PA holds the magnification in the whole frequency domain, which is, $S_{\rm PA,ideal} = 1$. While considering the actual PA with limited working band, a normalized piecewise model is used in numerical simulation. The model considers the

TABLE I
THREE SETS OF PARAMETERS IN SIMULATION.

Parameter	set 1	set 2	set 3
Number of communication symbols in one pulse	N=1024		
CPM modulation order M	M=4		
CPM modulation index h	h=1/4	h=1/5	h=2/9
CPM shaping pulse	Rectangular	Raised Cosine	Gaussian
correlation length L	L=4	L=3	L=5
the proportion of the Power Spectrum of the modified LFM-CPM limited in B_0	99.8%	99.3%	99.1%
the proportion of the Power Spectrum of the unmodified LFM-CPM limited in B_0	89.1%	87.7%	85.7%
the length of the modified section k	k=381	k=305	k=338
k/N	37.2%	29.8%	33.0%
Bandwidth of LFM B_0	B_0=1MHz		
Bandwidth-delay product	$B_0 \cdot T$=1024		
interference strength	-3dB		
bandwidth of the interference	$[0.01B_0, 0.5B_0]$		
starting frequency of the interference	$[f_c + 1.05B_0, f_c + 2.05B_0]$ $[f_c - 1.05B_0, f_c - 0.05B_0]$		

saturation region of the PA. Within the working band, the power magnification is constant, and outside is exponentially decaying until a very small constant, that is,

$$S_{\mathrm{PA}}(f) = \begin{cases} 1 & -0.1B_0 \le f - f_c \le 1.1B_0 \\ 10^{-4f_1} & -1.1B_0 < f - f_c < -0.1B_0 \\ 10^{-4f_2} & 1.1B_0 < f - f_c < 2.1B_0 \\ 10^{-4} & else \end{cases} \quad (28)$$

$$f_1 = \frac{f_c - 0.1B_0 - f}{B_0} \quad (29)$$

$$f_2 = \frac{f - (f_c + 1.1B_0)}{B_0} \quad (30)$$

The channel in simulation is additional white Gaussian noise (AWGN) channel added with a random strong interference. The interference also obeys Gaussian distribution in frequency domain. Its average power spectral density is -3dB of the maximum of the power spectral density of the integrated waveform. Its bandwidth is evenly distributed over $[0.01B_0, 0.5B_0]$, and the starting frequency is evenly distributed over $[f_c + 1.05B_0, f_c + 2.05B_0]$ and $[f_c - 1.05B_0, f_c - 0.05B_0]$.

With the model described above and the parameters listed in table I, BER performance is studied in the following circumstances,

(a) The unmodified LFM-CPM with the PA model described in equation (28).
(b) The unmodified LFM-CPM with an ideal PA model and random interference
(c) The modified LFM-CPM with the PA model described in equation (28) and random interference
(d) The unmodified LFM-CPM whose transmission efficiency is equal to the modified LFM-CPM, with the PA model described in equation (28) and random interference
(e) The modified LFM-CPM with an ideal PA and no interference.

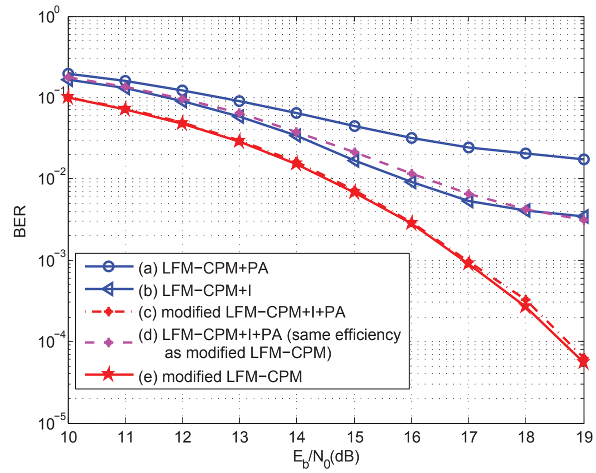

Fig. 4. BER performance of the integrated LFM-CPM waveforms with and without modification with parameter set 1.

The BER performance of parameter set 1 in table I is showed in Fig. 4. For the unmodified waveform, with only the actual PA model or random interference, the BER remains above 10^{-3} even at high SNR, meaning that the unmodified waveform can hardly accomplish the transmission task. While for the modified waveform with the actual PA model and random interference, the BER is almost the same as the one with ideal PA and no interference. The BER performance of the unmodified LFM-CPM with the same transmission efficiency in one pulse as the modified waveform is also showed in Fig. 4. It is clear that even with the same efficiency, the BER performance of the modified waveform is still much better than the unmodified one. In a word,the modification is effective and worthwhile considering the bandlimited PA and out-band interference.

In Fig. 5, the BER performance of (c)(e) with parameter set 2 (Gaussian shaping pulse) and set 3 (raised cosine shaping pulse) is showed. From Fig. 4 and Fig. 5 we can see the modified waveforms with various shaping pulse and other parameters maintain good BER performance with bandlimited PA model and random out-band interference. The simulation result declares the extensive and universal validity of the modification.

At last, the fitness of the modified waveform for radar subsystem is studied. The ambiguity function (AF) is a basic and important measurement of the performance of radar. The 2-dimensional AF is,

$$A(\tau; f_{\mathrm{d}}) = \left| \int_{-\infty}^{\infty} S(x) e^{j2\pi f_{\mathrm{d}} x} S^*(x - \tau)\, \mathrm{d}x \right| \quad (31)$$

where f_{d} is the doppler offset and τ is the time delay of the received signal of the subsystem of radar.

An ideal AF should be unimodal both in the distance and velocity domain. In Fig. 6, the distance and velocity AF of the LFM waveform and the modified LFM-CPM waveform with parameter set 1 is showed. The velocity AF of the

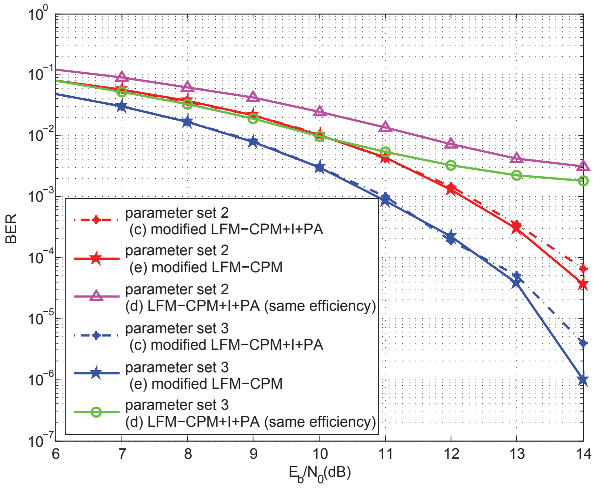

Fig. 5. BER performance of the modified integrated LFM-CPM waveforms and the unmodified waveform at same transmission rate with parameter set 2 and parameter set3.

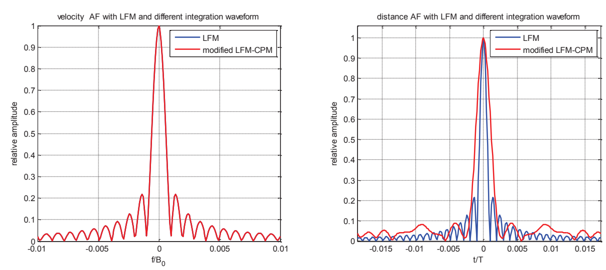

Fig. 6. (a). The velocity ambiguity function of LFM and the integrated LFM-CPM waveforms. (b). The distance ambiguity function of LFM and the integrated LFM-CPM waveforms.

modified LFM-CPM is almost the same with the LFM, while the distance AF of the modified LFM-CPM has a slightly broadened main lobe and slightly fluctuated side lobes. In a word, the AF of the modified LFM-CPM holds the basic properties of LFM and is fit for the radar sub-system.

V. Conclusion

To meet the need for transmitting and detection at the same time in intelligent transportation systems, an integrated waveform fit for the joint radar-communication system is studied in detail in this paper. Considering the attenuation of PA and random interferences outside working band in practical application, the integrated waveform should be limited within B_0. Based on the time-frequency analysis with STFT, a three-section modified waveform is proposed. The mapping codebook of the communication symbols at the head and tail with a length of $k_1 = \left\lceil \frac{h}{2\mu T_0^2}(M-1) \right\rceil - L + 1$ (when $\frac{h}{2L}\frac{N}{B_0 T}N \geq 1$), or at most $k_0 = \left\lceil \frac{h}{2\mu T_0^2}(M-1) \right\rceil$, is limited to the positive and negative half of the original codebook, respectively. Simulation results show that the spectrum of the modified waveform is mostly limited within B_0. The BER performance with bandlimited PA model, random out-band interference and ideal band-stop filtering, is almost the same as the one with ideal PA and no interference, and is far superior to the unmodified waveform with the same transmission efficiency in one pulse. The ambiguity function of the modified waveform holds the basic property of a single peak in both the velocity and distance domain, and therefore it is fit for the radar subsystem.In a word, the proposed three-section LFM-CPM waveform is fit for the joint radar-communication system considering bandlimited PA and random out-band interference. As a result, it can be used in actual intelligent transportation systems.

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References

[1] G. C. Tavik, C. L. Hilterbrick, J. B. Evins, J. J. Alter, J. G. Crnkovich, J. W. de Graaf, W. Habicht, G. P. Hrin, S. A. Lessin, D. C. Wu *et al.*, "The advanced multifunction rf concept," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 3, pp. 1009–1020, 2005.

[2] C. Sturm and W. Wiesbeck, "Waveform design and signal processing aspects for fusion of wireless communications and radar sensing," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1236–1259, 2011.

[3] C. Sturm, T. Zwick, and W. Wiesbeck, "An ofdm system concept for joint radar and communications operations," in *VTC Spring 2009 - IEEE 69th Vehicular Technology Conference*, April 2009, pp. 1–5.

[4] Z. Wu, Y. Zhang, and Z. Hang, "A burst sc-fde scheme for high-speed communication based on radar," in *MILCOM 2013 - 2013 IEEE Military Communications Conference*, Nov 2013, pp. 1541–1546.

[5] D. Garmatyuk, J. Schuerger, K. Kauffman, and S. Spalding, "Wideband ofdm system for radar and communications," in *2009 IEEE Radar Conference*, May 2009, pp. 1–6.

[6] X. Chen, X. Wang, S. Xu, and J. Zhang, "A novel radar waveform compatible with communication," in *Computational Problem-Solving (ICCP), 2011 International Conference on*, Oct 2011, pp. 177–181.

[7] Z. Liu, X. Chen, X. Wang, S. Xu, and Y. Feng, "Communication analysis of integrated waveform based on lfm and msk," in *IET International Radar Conference 2015*, Oct 2015, pp. 1–5.

[8] M. A. Richards, "Fundamentals of radar signal processing," *McGraw-Hill Professional*, 2005.

[9] C.-E. Sundberg, "Continuous phase modulation," *IEEE Communications Magazine*, vol. 24, no. 4, pp. 25–38, 1986.

[10] H. M. Nemati, C. Fager, and H. Zirath, "High efficiency ldmos current mode class-d power amplifier at 1 ghz," in *2006 European Microwave Conference*. IEEE, Sept 2006, pp. 176–179.

[11] H.-J. Zepernick and A. Finger, *Pseudo Random Signal Processing: Theory and Application*. John Wiley & Sons, 2013.