Waveform Design For Joint Radar-Communication System With Multi-User Based On MIMO Radar

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***Abstract*—The joint radar-communication system integrates the function of detection and data transmission to reduce interference and improve the overall spectrum efficiency, as well as to reduce total volume of devices in vehicles, which is widely used in the intelligent transportation systems. Among these joint systems, a MIMO radar based system has significant advantage for multi users with orthogonal waveforms transmitted by each antenna. In order to realize high speed transmission, a quasi-orthogonal multi-carrier LFM-CPM waveform is proposed for the joint system. This waveform preserves the characteristics of LFM with constant envelope and continuous phase, so that the distortion caused by the nonlinearity of the high power amplifier and the reduction of effective working distance can be avoided. The spectral efficiency of the proposed waveform is much higher than the 1-bit multi-carrier LFM waveform and simulation of bit error rate (BER) performance is close to that of single-carrier LFM-CPM with no interference. The simulation of ambiguity function shows that the random communication symbols has little influence on the radar subsystem. In a word, the shared waveform based on multi-carrier LFM-CPM and MIMO radar can meet the need of the detection and multi-user transmission at the same time, and is suitable for the intelligent transportation systems.**

I. Introduction

The intelligent transportation system has great significance of managing the huge traffic, and one of the key technologies is to exchange and share information among the users [1]. The topology of the system and the surroundings are time-variant, so each user needs real-time target detection and tracking based on the radar system. At the same time, a short delay, high speed, low interference data transmission network is in urgent need among multi users. However, the separation of the radar and communication systems is a waste of the similar hardware such as antennas, amplifiers and digital signal processing chips, and makes it hard to avoid the interference of the two systems. Besides, traditionally, the two systems need separate spectrum resources, and thus cannot make full use of the spectrum. To solve the problems above, the concept of a joint radar-communication system is proposed in 1996 [2] and has been developed rapidly in recent years.

The joint radar-communication system enables the two subsystems work collaboratively in one single device. So the interference of each other can be reduced and the spectrum efficiency of the whole system can be promoted. Furthermore, to meet the need of communication with multi users and reduce the multi-user interference, the joint system based on MIMO radar has received extensive attention. In MIMO radars [3], each antenna sends orthogonal waveform to avoid interference from each other, so that it is easy to be separated at the receiver, which is significant both for the radar and communication subsystems.

Compared with the joint system of just sharing hardware [4], a joint system based on a shared waveform is a deep integration of the two systems. The functions of the radar and communication subsystems will be accomplished with one waveform so that the interference of the two subsystems can be totally avoided. The research of the shared waveform started from widely used communication waveforms, such as the Orthogonal Frequency Division Multiplexing (OFDM) waveform [5]. However, the peak-to-average power ratio (PAPR) is so high that the distortion of the transmitted waveform is unavoidable and the power of the transmitted waveform, meaning the effective working distance, is reduced seriously [6].

To avoid the problems brought by high PAPR, a new way for waveform design based on traditional radar waveforms, such as linear frequency modulation (LFM) waveform, is proposed. They have been studied for tens of years, and there are plenty of solutions for signal processing of the radar subsystem [7]. In [8], a shared waveform based on multi-carrier LFM is proposed. The subcarriers are quasi-orthogonal with large time-delay bandwidth, and is fit for multi-user transmission, that is, one subcarrier is corresponding to one user. However, information can only be transmitted through the initial phase (with 0 or π corresponding to +1 or -1) of each subcarrier in one pulse, which means only one bit. It is obviously that the low capacity can't meet the need for high-speed transmission in practical systems.

To achieve high-speed transmission, we suggest communication symbols modulated into continuous phase modulation (CPM) baseband waveform and loaded on the corresponding LFM subcarrier. In this way, a much larger number of communication symbols will be transmitted in one pulse, so that high-speed data transmission is realized. At the same time, each subcarrier of the shared waveform transmitted by each antenna of the MIMO radar is constant enveloped, so the distortion brought by the nonlinearity of the amplifier can be totally avoided, and a long effective working distance can be achieved.

In the following of this paper, firstly the waveform design based on MIMO radar is showed in section II, which is the

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shared multi-carrier LFM-CPM waveform. In section III, a brief idea of signal processing for the radar and communication subsystems is showed and the operating mode of the whole joint system based on the proposed waveform for multi users is described. In section IV, simulation and analysis is showed. The spectrum efficiency of the proposed multi-carrier LFM-CPM is much higher than the 1-bit multi-carrier LFM waveform, and the bit error rate (BER) performance is close to the single-carrier LFM-CPM, with a loss of only around 0.5dB, which means the interference of the adjacent users is weak enough to be ignored. As for the radar subsystem, the velocity and distance ambiguity function is showed. The ambiguity function holds the basic property of LFM with a single peak and low side lobes. So the shared waveform can well accomplish the assignment of the radar subsystem.

II. Waveform Design

In the intelligent transportation system, the users are widely distributed with high mobility. So the topology of the whole system is always changing and real-time and wide-range detection is needed. MIMO radar [3] is a new technology in recent years with multi-antennas sending orthogonal waveforms. As a result, the beams sent by a MIMO radar is much more wide, which means the MIMO radar is suitable for wide-range detection.

For a certain user (user 0), the number of users that user 0 need to communicate with is N_t, marked as $\{$user 1,...,user $N_t\}$. The communication links from user 0 to other users are corresponding to $\{$antenna 1,...,antenna $N_t\}$ of the MIMO radar, and the waveform sent by antenna n_t is $S_{n_t}(t)$. So the transmitted waveform of the whole MIMO radar is,

$$S(t) = \sum_{n_t=1}^{N_t} S_{n_t}(t) = \sum_{n_t=1}^{N_t} S_{c,n_t}(t) S_{r,n_t}(t) \tag{1}$$

where $S_{c,n_t}(t)$ is the baseband waveform of communication with user n_t, and $S_{r,n_t}(t)$ is the radar carrier.

The radar carrier is quasi-orthogonal LFM pulse. Each LFM pulse sent by each subarray occupies adjacent frequency bands, and the other parameters of them are the same, such as the time-delay bandwidth product D, pulse width T, frequency modulation rate (FM rate) μ, bandwidth B_0, and so on [7].

$$S_{r,n_t}(t) = \exp(j2\pi(f_0 + n_t\Delta f + \mu/2 \cdot t)t) \tag{2}$$

$$D = B_0 T \tag{3}$$

To keep the quasi-orthogonality of each subcarrier,

$$\Delta f = B_0 = \mu T \tag{4}$$

Constant enveloped continuous phase modulation (CP-M) [9] is used for communication symbols, which ensures that the shared waveform sent by each sub-array remains constant envelope and continuous phase. So a maximum effective working distance is maintained and distortion due to the non-linearity of the power amplifier is avoided.

The CPM modulation first converts the bit sequence into a bipolar amplitude modulated sequence. Note that within a pulse, the sequence of symbols to be sent to user n_t is,

$$a_{n_t} = [a_{n_t,0}, a_{n_t,1}, a_{n_t,2}, \ldots, a_{n_t,N_s-1}] \tag{5}$$

where $a_{n_t,i} \in \{-(M-1), -(M-3), ..., (M-3), (M-1)\}$, M is the modulation order, and N_s is the number of symbols transmitted in one pulse on each subcarrier.

Then phase modulation is applied,

$$\phi_{n_t}(t, a) = 2\pi h \sum_{i=0}^{+\infty} a_{n_t,i} q(t - iT) \tag{6}$$

$q(t)$ is decided by the integral of the shaping pulse $g(t)$,

$$q(t) = \int_{-\infty}^{t} g(\tau) d\tau \tag{7}$$

There are various$g(t)$ used for CPM, for example, the rectangular shaping pulse, the raised cosine shaping pulse, the Gaussian shaping pulse, and so on.

So the baseband waveform sent to user n_t is,

$$S_{c,n_t}(t, a_{n_t}) = A \cdot exp(j\phi_{n_t}(t, a_{n_t})) \tag{8}$$

And the shared waveform in equation (1) now is described in detail,

$$S(t) = \sum_{n_t=1}^{N_t} \exp(j2\pi(f_0 + n_t\Delta f + \mu/2 \cdot t)t + j\phi_{n_t}(t, a)) \tag{9}$$

III. Signal Processing And Operating Model

For the communication subsystem, due to the prior agreement of the communication protocol, the receiver knows the relevant parameters of the radar carrier. We assume the channel as the additional white Gaussian noise (AWGN) channel, because for multi-path channels, channel equalization can be implemented so that it can be equal to AWGN situation. So the received RF signal is,

$$y_0(t) = S(t) + n(t) \tag{10}$$

where $n(t)$ is the white Gaussian noise.

In this research, we assume that the synchronization of $y_0(t)$ has been perfectly down. So that we can firstly multiply the received signal by the conjugate of the corresponding radar subcarrier k and obtain a multi-carrier baseband signal,

$$y_{\text{base,k}}(t) = y_0(t) S^*_{\text{r,k}}(t) \tag{11}$$

Then low pass filtering is applied to get the communication signal on subcarrier k.

$$y_{\text{cpm,k}}(t) = \exp(j\phi_k(t, a_k)) + P_k(t) \tag{12}$$

where $P_k(t)$ represents the left noise and interference. To ensure that the power of $P_k(t)$ is much lower than $\exp(j\phi_k(t, a_k))$,

$$R_s <= B_0 \tag{13}$$

$$R_s = N_s/T = N_s/D * B_0 \tag{14}$$

where R_s is the rate of communication symbols of each subcarrier.

Combine equations (3)(4)(13)(14)

$$N_s <= D \tag{15}$$

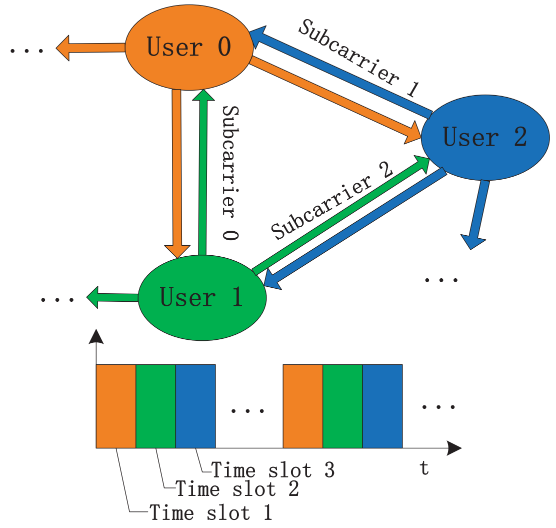

Fig. 1. A diagram of the operating model of the joint system.

Finally, CPM demodulation and decoding is implemented and the communication symbols will be get. There are various methods for CPM demodulation and decoding, for example, Viterbi, state reduction, and so on.

For the radar subsystem, since the transmitter and the receiver are at the same end, the transmitted communication symbols are already known. So for subcarrier k, the information carried on it is first removed by multiplying the conjugate of the baseband communication waveform of user k,

$$y_{\mathrm{r,k}}(t) = S(t) * S_{c,k}^{*}(t) \tag{16}$$

So the ambiguity function for subcarrier k is,

$$A_{\mathrm{k}}(t; F_{\mathrm{D}}) = \left| \int_{-\infty}^{\infty} y_{\mathrm{r,k}}(x) e^{j2\pi F_D x} S_k^{*}(x-t)\, dx \right| \tag{17}$$

Further signal processing can be implemented on $y_{\mathrm{r,k}}(t)$ according to the modulated communication symbols in each pulse to get better performance of the radar subsystem.

Now we can summarize the operating mode of the joint system as follows. Each user node in the system can be a central node (user 0) and transmit the shared pulse $S(t)$ in a fixed time slot. $S(t)$ is composed of radar carriers and the information to be transmitted to each peripheral user, namely $S_{c,n_t}(t)$. Each user, from user 1 to user N_t, occupies one subcarrier. At the same time, user 0 can detect and track the surrounding targets by echo. In the whole system, the time slots and subcarriers occupied by each user to transmit the shared pulse needs to be pre-allocated or adaptive coordinated. Similarly, pre-allocation or adaptive adjustment is also needed to ensure that the FM rate of the subcarriers sent by each pair of users is of opposite sign, so that matched filtering can be used to distinguish the echo and the shared waveform sent by other users. A diagram of the joint system is in Fig. 1.

IV. Simulation And Analysis

In this section, we evaluate the performance of the radar and communication subsystem respectively. The parameters of the shared waveform and the channel model used in the simulation are shown in TABLE I.

TABLE I. The parameters of the multi-carrier LFM-CPM waveform in simulation

Parameter	Value
Number of subcarrier	N_f = 8
Bandwidth of each subcarrier	B_0 = 0.1MHz
Bandwidth-delay product	D = 256
Number of communication symbols of each subcarrier in one pulse	M = 256
Strength of multipath	$h0$ = [0,-8,-15]dB
Time delay of multipath	$T_d = [0,3,7] * \tau/D$
$E_b/N_0 = [6:1:20]$	$E_b/N_0 = [6:1:20]$
Modulation of the communication symbols	CPM
CPM modulation order M	M=4
CPM modulation index h	h=1/4
CPM shaping pulse	Raised cosine
Rolloff factor	a = 0.2
CPM Correlation length	L=2

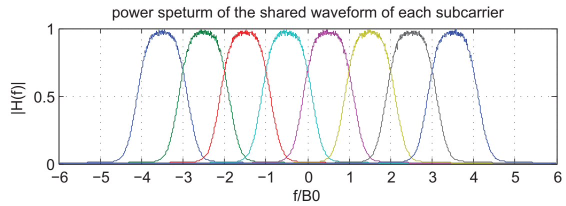

Fig. 2. Power spectrum of the shared waveform of each subcarrier.

Firstly, we analyze the spectral efficiency of the proposed multi-carriers LFM-CPM. The power spectral density of each subcarrier is shown in Fig. 2. The subcarriers overlap with each other. Each subcarrier occupies the bandwidth of $B0 + R_s(1+\alpha)$, α is the roll-off coefficient. The number of bits transmitted on each subcarrier in one pulse is N_s, and the number of subcarriers is N_t. So spectrum efficiency is,

$$R_{multi} = \frac{N_t N_s log_2 M}{B_0 N_t + R_s(1+\alpha)} = \frac{N_s log_2 M}{B_0 \left(1 + \frac{N_s(1+\alpha)}{D N_t}\right)} \tag{18}$$

And R_{multi} gets the maximum value at $N_s = D$,

$$R_{multi,max} = \frac{1}{B_0} \frac{D\log_2 M}{(1 + (1+\alpha)/N_t)} \tag{19}$$

While for the 1-bit multi-carrier LFM waveform in [8], the spectrum efficiency is,

$$R_{1bit} = N_t/(B_0 N_t) = 1/B_0 \tag{20}$$

In a word, the spectrum efficiency of the proposed multi-carrier LFM-CPM waveform is almost $D\log_2 M$ times higher than the 1-bit multi-carrier LFM waveform.

BER performance is shown in Fig. 3. Compared with single carrier LFM-CPM with no interference and distortion, the BER performance of the proposed multi-carrier waveform is slightly worse, at about 0.5dB, both in the AWGN channel and the multi-path channel, because of the interference brought by the adjacent channel. Luckily, the loss is not huge enough because a SNR loss in equalization may be as large as 1dB or even higher. So that the proposed joint system can well accomplish the communication between users with a relatively good performance.

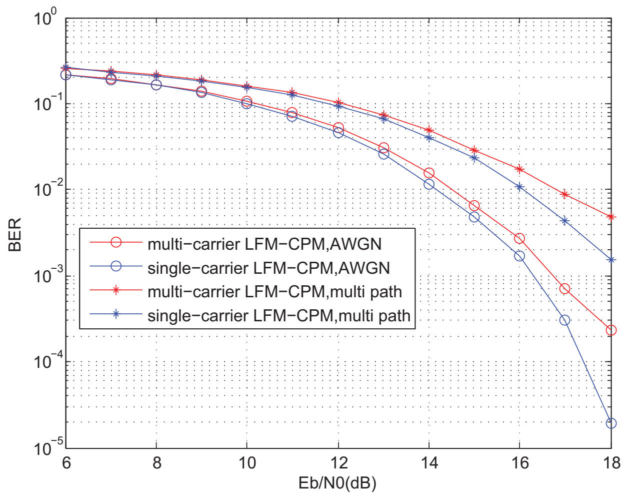

Fig. 3. BER performance of the multi-carrier LFM-CPM and single-carrier LFM-CPM.

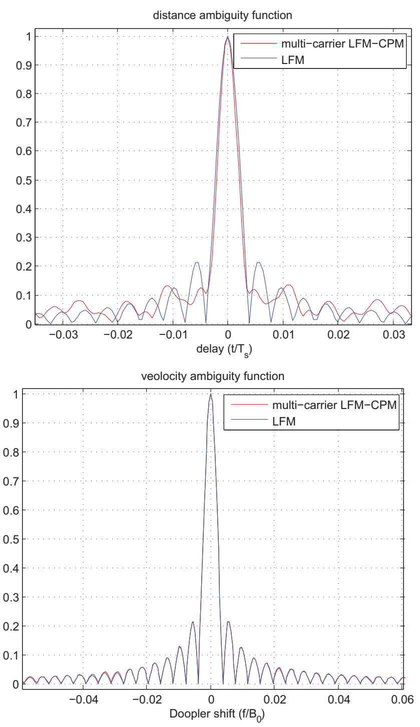

Fig. 4. Ambiguity function of the shared multi-carrier LFM-CPM and LFM waveform.

In total, the proposed waveform highly promotes the spectrum efficiency and can accomplish the multi-user communication with quite good BER performance.

For the radar subsystem, the ambiguity function of each subcarrier is shown in Fig. 4. The velocity ambiguity function of the shared waveform is almost the same with the LFM waveform. As for the distance ambiguity function, the side lobes fluctuate slightly, but the basic property of single-peak and low side-lobes is hold so that the shared waveform can well accomplish the assignment of detection.

V. Conclusion

In the intelligent transportation systems, there is a need of detecting the surroundings and exchanging information simultaneously. In this paper, a multi-carrier quasi-orthogonal LFM-CPM waveform based on mimo radar is proposed, and the operating mode of the joint system is described for multi-users. Each subcarrier sent by one antenna of the MIMO radar is constant enveloped so that a long effective working distance with no waveform distortion is achieved. The spectral efficiency of the proposed multi-carrier waveform is almost $D\log_2 M$ times higher than the 1-bit multi-carrier LFM waveform, and the BER performance of the shared waveform is close to that of the ideal single-carrier LFM-CPM without adjacent channel interference. The simulation of velocity and distance ambiguity function shows that the shared waveform preserves the basic properties of LFM and can be applied to radar detection. In summary, the proposed quasi-orthogonal multi-carrier LFM-CPM waveform can be applied to the joint radar-communication system with multi-users, which is of great significance for the development of intelligent transportation systems.

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