Spatial-Time Complementary Coding Signal Design for RadCom System

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Abstract—Sharing signal design is an important challenge in radar communication integrated (RadCom) system. In this paper, a spatial-time complementary coding signal design method is proposed. Coding signal generation, radar receive processing and communication receive processing are presented sequentially. Numerical simulation results show that the proposed method achieves better sidelobe reduction than ordinary random coding signals.

1. INTRODUCTION

Radar and communication devices are two completely different electronic systems though both based on similar electromagnetic principles[1][2][3]. In recent years, due to the rise of multi-function concept, the development of software definition technology, and the advancement of electronic technology, more and more attentions[4][5][6] have been paid to the integration of radar and communication into an integrated system (RadCom system).

One of the key technologies of RadCom system is sharing signal design, which can both satisfy radar and communication application at the same time. Existing main methods can be concluded and classified into three classes: one is using communication signal directly as the sharing signal, such as OFDM, MCPC signals[7][8][9]; the other is adding radar signal and communication signal to form integrated signals[10][11]; the third is considering integrated signal design as an optimization problem, which using mathematic computation method including one or multiple targets function to obtain the best signal codes[12][13][14][15][16].

It can be noticed that the above methods have validate the feasibility of the integrated signal design to some extent. However, things are not perfectly come over in these aspects such as coding security, comprehensive loss in signal degree, falling performance for sole system, especially signal scene difficult adaptation for separated radar targets and communication objects, etc.17

Based on these, a new integrated signal encoding and transmission method is proposed, which takes into account the differences between radar and communication system. It can effectively solve the secure communication and maximize the RadCom system detection and communication performance.

2. SPATIAL-TIME COMPLEMENTARY CODING SIGNAL GENERATION

In practical application scenarios, electronic systems may play different roles depending on the need for use. Based on this, an integrated system can be divided into three roles[18][19]: an integrated array, a radar array, and a communication station, as shown in Fig. 1, where $f_0, f_1, ..., f_{N-4}$ represents the carrier frequencies transmitted by each element.
According to the above three different roles, different combinations are formed, such as communication and detection corporation between one RadCom system with another RadCom system, communication corporation and detection by itself or corporate with another radar, etc., which greatly enhances the flexibility and applicability of the system implementation.

![Fig. 1. System scenario](image)

Based on the flexibility of system implementation and the best possible performance of radar detection and communication transmission, a transmitting flow structure of space-time complementary signal encoding is presented, as shown in Fig. 2.

![Fig. 2. Transmitting flow structure](image)

The signal transmission architecture is first analyzed. Radar signals mainly consist of a baseband signal modulated by complementary code $A_j$. The communication content is firstly information encoded, then correlated with complementary code $A_i$ for a round of encryption, then secondary encryption with random chaotic sequence to get a randomized communication codes. Through channel coding, processes such as code modulation and transmitting are carried out.

It should be noted that this design architecture does not require a one-to-one correspondence between radar and communication elements. Instead, the corresponding signals can be arranged according to the actual needs. RadCom system can thus fully share signals, that is, by simply radiating communication signal, it can satisfy the communication function and distinguish the detection of radar target from the communication radiation coverage by beam control or time-sharing operation at the same time.

To further analysis the design mechanism, it can be obtained as follows:

For radar part, a complementary coded signal is emitted. Taking two sequences $A_i$ and $A_j$ with equal length $N$ as an example, the ideal complementary coded signal satisfies the aperiodic autocorrelation function like
where \( C_A(\tau) \) and \( C_{A_b}(\tau) \) represent the aperiodic autocorrelation function of the sequence signal \( A \) and \( A_b \) respectively.

Referring to the design idea of complementary encoding\(^{[20]}\), considering that there is both autocorrelation overlay of matched filters and cross correlation of radiated signals from other antenna elements when actually receiving radar, it may be advisable to assume the number of radar elements is \( I \) in a RadCom system, each signal sequence is expressed as \( A_i \), the length of each sequence is \( N \), then single channel correlation processing is satisfied

\[
C_A(\tau) + C_{A_b}(\tau) = \begin{cases} 2N, & \tau = 0 \\ 0, & \tau \neq 0 \end{cases}
\]  

(1)

where \( AR(\tau) \) and \( AR_{ij}(\tau) \) are the cross-correlation of \( A_i \) and \( A_j \). Unlike the principal peak enhancement and sidelobe cancellation effects of ideal complementary coding, the sidelobe of both autocorrelation and cross-correlation is cancelled while the mainlobe remains in single channel. Considering channel fusion processing, the conditions can be relaxed to that like

\[
\sum_{j=1}^{I} AR(\tau) + \sum_{j=1, j \neq i} AR_{ij}(\tau) = \begin{cases} IN, & \tau = 0 \\ 0, & \tau \neq 0 \end{cases}
\]  

(2)

Furthermore, complementary sequences are applied to time pulse accumulation, radiating a complementary code sequence that meets the requirements between element pulses to construct a space-time complementary signal sequence, as shown in Fig.3. It may be advisable to assume that the number of pulses accumulated per element is \( K \), then there is

\[
\sum_{k=1}^{K} \sum_{j=1}^{I} AR_{ik}(\tau) + \sum_{j=1, j \neq i} AR_{ik,ij}(\tau) = \begin{cases} KIN, & \tau = 0 \\ 0, & \tau \neq 0 \end{cases}
\]  

(3)

where \( AR_{ik}(\tau) \) represents the autocorrelation of spatial signal \( A_{ik} \) in time dimension, and \( AR_{ik,ij}(\tau) \) is the cross-correlation.

The design of space-time complementary sequence based on the above construction ensures the best signal-to-noise ratio for radar signal receiving, thus ensuring the maximum detection distance.

Formula (4) is as an ideal case. In general, we define

\[
RR(m) = \left| \sum_{k=1}^{K} \sum_{j=1}^{I} AR_{ik}(m) + \sum_{j=1, j \neq i} AR_{ik,ij}(m) \right|
\]  

(5)

where \( m \) represents the discrete sequence shift amount.

With the definition of peak sidelobe ratio PSL and integrated sidelobe ratio ISL\(^{[21]}[22]\) as optimization criteria, the problem is transformed into optimization problem. We also define PLR (Peak Level Ratio) criteria to evaluate the cross-correlation effect as

\[
PLR = 20 \times \log_{10} \left( \frac{\max(\text{abs}(CR))}{\max(\text{abs}(AR))} \right)
\]  

(6)

where \( CR \) represents cross-correlation series and \( AR \) is autocorrelation series. Then optimization algorithms are applied to obtain the optimal sequence library for radar space-time signal modulation.
In communication part, after two rounds of complementary coding and chaotic random operation with communication content sequence, two rounds of encryption operation are actually performed. Noted that the chaotic sequence is generated by a deterministic system, while the sequence behavior is random and sensitive to an initial value. In theory, an infinite length key can be generated without transmission after the key has been agreed upon, which effectively ensures communication tightness.

According to the Shannon Theorem, signal satisfying random distribution of white noise has the maximum theoretical communication capacity. Therefore, a chaotic system close to satisfying the random distribution of white noise can be chosen to generate random sequence, which can use to white noise the sequence of communication codes.

In general, it satisfies

$$AR_{\delta,i,j}(m) \approx \begin{cases} N, & m = 0 \& i = j \\ 0, & \text{others} \end{cases}$$

(7)

To a certain extent, it has good complementary space-time pulse signal characteristics, and is also conducive to signal accumulation, anti-multipath interference, multi-address communication and so on. Moreover, in the self-receiving system, it is also convenient to use as radar signal directly.

3. Spatial-Time Complementary Coding Signal Receiving

Because radar and communication are different functional mechanisms, the signal processing flow should be separated in the receiver whether integrated or not, so the radar receiving processing and communication receiving processing under the design mechanism should be discussed separately.

3.1 Radar receiving processing

The radar receiving processing flow is shown in Fig. 4. After receiving the echo from the antenna of each receiving channel of array radar, the radar target information can be obtained directly through signal processing of receiver de-carrier, single channel processing and multi-channel fusion processing. The general RadCom system architecture for radar receiving processing method requires processing the communication signal in advance, and the radar matching filtering can only be carried out after the communication decoding. It is different that the proposed method has no specific requirements for this. As described above, it is enough to simply process multi-channel radar signal in the general sense, greatly simplifying the radar receiving and processing flow of the RadCom system, thereby reducing the receiver cost. At the same time, it also extends the flexibility of the system, such as supporting the detection connection relationship between the RadCom system and the simple radar system in Fig. 1.

The mathematical description is as follows
where $ABR_{\alpha,\beta}(m)$ represents the cross-correlation function of radar signal $A_{\alpha}$ and communication signal $B_{\beta}$, and $BR_{\alpha,\beta}(m)$ is the cross-correlation function of communication signal $B_{\alpha}$ and $B_{\beta}$, which holds for any signal set. In the generation of communication coding signal, based on the correlation characteristics of random sequence, the fully randomized communication coding signal and the deterministic random coding radar complementary code signal are close to orthogonal, that is, the cross-correlation is near to zero level. Moreover, the spatio-temporal coded signal mechanism ensures the maximum accumulated gain in the spatiotemporal two-dimensional direction. Therefore, pure matching filtering based on known radar signals can achieve high peak sidelobe gain. The total received signal $RRC(m)$ can be expressed as

$$
RRC(m) = \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{m=1}^{M} \left[ AR_{\alpha,\beta}(m) + \sum_{n=1, n \neq j}^{J} AR_{\alpha,\beta}(m) + ABR_{\alpha,\beta}(m) \right]
$$

To optimize (5), (7) and (8), formula (9) can obtain the effective gain of radar reception processing.
radar signal and communication signal are orthogonal in form, and two different pulse communication signals are also orthogonal, which greatly reduces the crosstalk between signals, thus enhancing the communication robustness.

3.3 Beneficial effects
The proposed RadCom system adopts array mechanism: the integrated transmitter, integrated receiver, radar receiver and communication receiver can be deployed separately or integrated, which greatly enhances the flexibility of the system and widens the adaptability of the system.

Space-time complementary coding signal design is effective: Transmitting complementary coding signal in time dimension and space dimension to maximize radar and Communication capability.

The communication content code is encrypted by the complementary code and the chaotic random code sequence, so the communication security can be guaranteed without passing a key.

The quasi orthogonality of radar and communication coding signal in time and space dimensions ensures the signal processing gain, and the best RadCom performance can be optimized.

Radar receiver is simplified: Unlike classical integrated systems relies on pre-communication coding and demodulation, the proposed design scheme can be directly applied to the general radar signal processing to reduce requirements of the RadCom receiver, thus reducing cost.

4. NUMERICAL SIMULATION AND ANALYSIS
Based on the Bernoulli chaotic system, four-phases coded MCPC signals are generated for numerical simulation. The simulated annealing algorithm is used to generate corresponding complementary coded signal, and the correlation function performance is then compared with four pulses in time and half array element used for radar half for communication in space, as shown in Fig.6, Fig.7 and Fig.8.
Fig. 6. Comparison of total correlation functions between MCPC signals and space-time complementary coded signals

Fig. 7. Comparison of autocorrelation performance between MCPC signals and space-time complementary coded signals

Fig. 8. Comparison of cross-correlation performance between MCPC signals and space-time complementary coded signals
From the above numerical simulation, it can be seen that the performance of signal correlation function including auto-correlation and cross-correlation is much better for space-time complementary coding signals, where shows smaller sidelobe level in Fig.6. Moreover, PSL and ISL ratios are calculated with auto-correlation and cross-correlation respectively, as presented in Fig.7 and Fig.8. It can be found out that the improvement amplitude is more than 5dB, even near 10dB, which shows great potential for the proposed RadCom signal coding method for real application.

5. CONCLUSION

A design method of space-time complementary coding signal is proposed for application in RadCom system, where part of array elements transmit space-time complementary coding signal and part transmits chaotic based MCPC signal. The proposed mechanism shows better performance in communication security and radar detection, greater flexibility for system structure, which is verified by numerical simulation and analysis. The proposed method reveals well potential for RadCom system application.

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