Replies to Editorial Board

Thanks a lot for the help. We are grateful to the editors and reviewers for their treasure time, great efforts and useful comments towards making this paper better in quality and readability. Now, after a careful revision, we present a point-by-point response to the comments and suggestions of the reviewers along with the new paper and hope it meets the requirement of publication. Below are the replies to the comments.

Replies to Comments by Reviewers

In the subsequent correspondence, “Comments from reviewers” are copied herein again in blue color while the “Replies” are written in black color. All the changes in the new paper are marked in red color.

Comments from Reviewer 2:

Overall, this paper represents an interesting contribution to MIMO-OFDM radar waveform design. However, before publication, it is my opinion that the authors should address the following major comments:

1. The abstract should be rephrased so as to provide a gentler introduction to the considered problem.

Replies: Thanks a lot for your comment. The abstract has been rephrased in the new paper for gentler introduction as:

Abstract: There are some special merits for the orthogonal frequency division multiplexing (OFDM) chirp waveform as multiple input multiple output (MIMO) signals. This signal has high range resolution, good Doppler tolerance and constant modulus superiority, since it exploits a full bandwidth and bases on chirp signals. The correlation sidelobe peaks level are critical for the detection requirement of MIMO radar signals, however, conventional OFDM chirp signals will produce high autocorrelation sidelobe peaks (ASP) and cross-correlation peaks (CP), which reduces the detection performance. In this paper, we explore the structure of OFDM chirp signals’ autocorrelation function and proposed a scheme to reduce the ASP of designed signal by designing
suitable range of subchirp bandwidth and a segmented transmit-receive mode. Next, we explore a suitable range of interval between the chirp rates of each two signals to reduce the CP. The simulation of designed signals verifies the effectiveness of proposed methods in reduction of ASP and CP and the correlation performance are compared with recent relate studies. In addition, the multiple signals detection and one-dimensional range image simulation show the good detection performance of designed signal in MIMO radar detection.

2. The following related works, dealing with radar waveform design, should be discussed for completeness:


Replies: Thanks a lot for your significant suggestions. The related works above have been discussed and referenced in the Sec. I and Reference Section of new paper as follow, which makes the introduction more complete.

A time & code OFDM algorithm was proposed to solve the large residual carrier errors existing in complex indoor environments [3]. Literature [4] designed a mutual-information OFDM waveform based on MIMO radar for low-grazing angle tracking and it achieved performance improvements verified by realistic physical modeling due to adaptive OFDM waveform design. During different environments, there are many different spectrum sensing methods for OFDM signals proposed in [5]-[8], which improved the detection application of OFDM signals. Based on the orthogonality of it, OFDM signal was revised to complete micro-doppler estimation and the detection in frequency-selective fading channels [9] [10]. In the application of passive radar signal processing, OFDM waveforms were chosen for being easily decoded to acquire the noise-free signal [11]. Moreover,
OFDM signal was used to raise the resolution for its high range resolution and was investigated for range ambiguity suppression for its diversity superiority in synthetic aperture radar (SAR) image [12] [13]. In addition, [14]-[16] completed the simulation and implementation of it in SAR.

Based on intrapulse radar-embedded communications, new waveforms were designed for covert and multiple target optimization, where the design criterion of constrained maximization of the signal-to-interference ratio and constrained minimization of a suitable correlation index improve the signal detection performance well [17] [18]. And better robust was designed based on polarimetric radar considering the worst case signal-to-interference plus noise ratio [19]. Thus, in order to obtain a better Doppler tolerance and constant modulus, a new OFDM signal combined with chirp signals was proposed, called OFDM chirp signals, which had great potential in radar application.


3. Additionally, the discussion of related works should be rewritten to better highlight the current limitations of the existing works.

Replies: We really appreciate you for your significant suggestions.

1) The discussion of related works has been rewritten in Sec. I.

Multiple input multiple output (MIMO) radar is the radar which can transmit multiple orthogonal signals and then receive them together to get multi-dimensional information. In order to obtain the properties of high range resolution and weak target detection, the corresponding waveform should be
designed with wider bandwidth and lower ASP than before. In addition, the CP between each two waveforms need to be reduced to satisfy the orthogonality of the MIMO radar signals.

Traditionally, multiple subbandwidth approaches were divided to obtain the orthogonality among signals, which left limited bandwidth and insufficient bandwidth for each signal. The OFDM signal was first proposed in the radar system to fully utilize the bandwidth for high range resolution [1]. The OFDM signal suggests low mutual interference between nearby radar instruments which is verified by ambiguity function. For the advantage and widespread use of OFDM signals, many new techniques were generated. Under uniform circular array (UCA) and near-field conditions, the OFDM signal was combined to design a closed-form algorithm for localization [2]. A time & code OFDM algorithm was proposed to solve the large residual carrier errors existing in complex indoor environments [3]. Literature [4] designed a mutual-information OFDM waveform based on MIMO radar for low-grazing angle tracking and it achieved performance improvements verified by realistic physical modeling due to adaptive OFDM waveform design. During different environments, there are many different spectrum sensing methods for OFDM signals proposed in [5]-[8], which improved the detection application of OFDM signals. Based on the orthogonality of it, OFDM signal was revised to complete micro-doppler estimation and the detection in frequency-selective fading channels [9] [10]. In the application of passive radar signal processing, OFDM waveforms were chosen for being easily decoded to acquire the noise-free signal [11]. Moreover, OFDM signal was used to rise the resolution for its high range resolution and was investigated for range ambiguity suppression for its diversity superiority in synthetic aperture radar (SAR) image [12] [13]. In addition, [14]-[16] completed the simulation and implementation of it in SAR.

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of fully using of a bandwidth of OFDM chirp signal made it better to be simultaneously used for information transmission and radar sensing. OFDM chirp signals based on MIMO radar was simulated in a low grazing angle target detection for its superiority of low peak-to-average-power ratio level and larger time–bandwidth product [22]. However, there were still some embedded problems left for OFDM chirp waveform. It’s high ASP in central region for basing chirp signal and high CP for fully using of a bandwidth. About OFDM chirp signal, many improvement measures has been proposed. A Spread Spectrum-Coded OFDM chirp waveform was proposed in [23]. By examining the ambiguity function and correlation function, the designed waveform can stay orthogonal on the receiver and have large time-bandwidth product for separating closely spaced targets. In addition, based on random matrix modulation, a new OFDM chirp signal with low peak–average ratio and low frequency-shift correlation peaks was designed in [24]. Which was also an effective way to reduce the high CP. Considering the high CP was caused by same chirp rate of OFDM chirp waveform, reference [25] raised to various the sub-chirp durations or sub-chirp bandwidths specially. However, the above methods only consider the case of CP’s reduction, they leave high ASP unsolved, since the spectrum structure of signal keeps unchanged. Moreover, we find the method for reducing ASP may restrict the reduction of CP and a model should be proposed to reduce both the ASP and CP for better detection.

2) And the limitation of conventional OFDM signal and existing relate works have been discussed in line 140-147 in the end of Sec. II and in the line 356-372 of Sec. V. These numerical results show high correlation influence exists in conventional OFDM signals, which will reduce its detection properties. As the signals’ number adds, such as 4 signals in the Section 5 simulation, the cross-correlation influence will be more serious. Moreover, in the one-dimensional range image, multiple point targets echo’s correlation sidelobes will overlap and become higher, which may cover up the weak targets and cause false detection. Thus, it’s necessary to reduce the ASP and CP of conventional OFDM signal and evaluate the multiple signals detection performance and one-dimensional imaging detection level of designed signal. In addition, some recent study results should be compared with the simulation results of designed signals. (line 140-147)

Next, for further comparisons of detection performance, the ASP and CP values of conventional OFDM signal, Li’s OFDM signal [25], PNLFM signal [26] and designed segmented transmitting OFDM (STOFDM) signal are listed in Table 4. Where STOFDM signal has its superiority of the lowest sidelobes in both ASP and CP. (line 356-372)
<table>
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<th>Waveforms (B=400M)</th>
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<td>PNLFM</td>
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<td>-23.1</td>
</tr>
<tr>
<td>STOFDM</td>
<td>-30.2</td>
<td>-40.5</td>
</tr>
</tbody>
</table>

4. Please rephrase the sentence “…dimensional information. To obtain its superiorities in range resolution and detection, the corresponding waveform should be designed with large enough bandwidth and low ASP. And the CP between each two waveforms need to…” aiming at improved readability.

**Replies:** We are very sorry for our negligence in the original paper and are really thankful for your reminding. The sentence has been rephased as follow, in line 29-33 of Sec. 1 in the new paper.

In order to obtain the properties of high range resolution and weak target detection, the corresponding waveform should be designed with wider bandwidth and lower ASP than before. In addition, the CP between each two waveforms need to be reduced to satisfy the orthogonality of the MIMO radar signals.

5. Please avoid beginning sentences with “And….”, as well as contracted/informal writing, e.g. “What’s more”.

**Replies:** Thanks a lot for your significant suggestions. The “And” and “What’s more” at the beginning of sentences in the new paper has been revised as “Moreover” or “In addition” in the new paper.

6. Please add a notation paragraph at the end of Sec. I.

**Replies:** We really appreciate you for your significant suggestions. A notation paragraph has been added at the end of Sec. I in the new paper as:

**Notation:** In the rest of the paper, boldface characters denote vectors. We use the upper indices to denote the type of variable, and lower indices are used to denote the order. The upper indices ‘suba’, ‘subc’ and ‘center’ denote sub-autocorrelation, sub-cross-correlation, center range around main lobe and designed one which is distinguish from the conventional one. \( \varepsilon(\cdot) \) denotes jump function.
7. It would be useful for the generic reader adding a figure in Sec. II depicting the considered system model. Additionally, Sec. II mostly lacks a clear statement of the considered problem.

**Replies:** We really appreciate you for your significant suggestions.

1) In this paper, we mainly try to designed an improved OFDM chirp signal and we think the OFDM chirp signal model, contained signal formula structure, time-frequency structure and correlation structure, is the necessary depiction of considered system, which is revised in Sec. II in new paper. And it would give a good model basics to the generic reader for understanding of proposed signals.

2) We are very sorry for the unclear statement in the original paper and are really thankful for your reminding. A discussion of the conventional OFDM chirp signal’s properties and application problems have been added in the end of Sec. II based on the simulation results of Sec. II, which can be echoed by the simulation of Sec. V.

As show in Figure 2 (a), it can be found conventional OFDM signal’s ASP is up to -13.4dB. In addition, the ASP appears in the central region near the main lobe, called ACSP, while the autocorrelation side peaks in the edge region are low enough. On the other hand, Figure 2 (b) shows signal’s CP value as -25 dB and there are many high cross-correlation peaks in it.

These numerical results show high correlation influence exists in conventional OFDM signals, which will reduce its detection properties. As the signals’ number adds, such as 4 signals in the Section 5 simulation, the cross-correlation influence will be more serious. Moreover, in the one-dimensional range image, multiple point targets echo’s correlation sidelobes will overlap and become higher, which may cover up the weak targets and cause false detection. Thus, it’s necessary to reduce the ASP and CP of conventional OFDM signal and evaluate the multiple signals detection performance and one-dimensional imaging detection level of designed signal. In addition, some recent study results should be compared with the simulation results of designed signals.

8. Please double-check the whole paper so as to avoid any kind of typo, e.g. “auto-corelation” and “cross-corelation” within some of the figures.

**Replies:** We are very sorry for our negligence in the original paper and are really thankful for your reminding. All the figures have been checked and revised in the new paper.
9. Secs. 3 and 4 are a little bit hard to follow. In my opinion, they should be rephrased so as to provide a more streamlined and structured exposition.

**Replies:** We really appreciate you for your significant suggestions. Sec. 3 and Sec. 4 have been checked and revised with a more streamlined and structured exposition.

10. In Sec. 5, the authors compare their waveform proposal only with simple LFM. At least a few waveform design baselines should be considered to provide a more solid comparative analysis.

**Replies:** Thanks a lot for your significant suggestions. In Sec. 5, a necessary revision has been made in the new paper.

1) We compare the proposal signal with same coded conventional OFDM chirp signal in aspects of self-ambiguity function, time-frequency structure, correlation function and one-dimensional image application for better understand of the designed signals’ Doppler performance and correlation property, which emphasis the improvement basing on the conventional OFDM chirp signals.

2) Next, several related recent waveform design works have been referenced and compared in lines 368-372 and lines 398-400 of Sec. 5 and corresponding analyzing of autocorrelation and cross-
correlation properties has been discussed and concluded.

Next, for further comparisons of detection performance, the ASP and CP values of conventional OFDM signal, Li’s OFDM signal [25], PNLFM signal [26] and designed segmented transmitting OFDM (STOFDM) signal are listed in Table 4. Where STOFDM signal has its superiority of the lowest sidelobes in both ASP and CP. (lines 368-372)

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<td>-40.5</td>
</tr>
</tbody>
</table>

The RPSLRs of each signal are showed in Table 6. (lines 398-400)

<table>
<thead>
<tr>
<th>Radar model</th>
<th>Waveforms</th>
<th>RPSLR/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>SISO</td>
<td>COFDM($s_i$)</td>
<td>-13.4</td>
</tr>
<tr>
<td></td>
<td>Li’s OFDM</td>
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</tr>
<tr>
<td></td>
<td>PNLFM(B=400M)</td>
<td>-25.2</td>
</tr>
<tr>
<td></td>
<td>STOFDM($s_i$)</td>
<td>-30.5</td>
</tr>
<tr>
<td>MIMO</td>
<td>STOFDM($s_i$ and $s_j$)</td>
<td>-28.7</td>
</tr>
<tr>
<td></td>
<td>STOFDM($s_i$ and $s_j+s_k$)</td>
<td>-28.5</td>
</tr>
<tr>
<td></td>
<td>STOFDM($s_i$ and $s_j+s_k+s_m$)</td>
<td>-27.3</td>
</tr>
</tbody>
</table>

3) Moreover, multiple signals detection simulation has also been made and analyzed considering as MIMO radar signals.

11. Conclusions should be enriched with what the authors consider to be further avenues of research.

**Replies:** We really appreciate you for your significant suggestions. The conclusions have been enriched with our considers to be further avenues of research in the new paper as:

In future work, we intend to further optimize the multiple signals detection model, reduce the impact among transmitted signals. On the other hand, the targets RCS property will be combined to analyze the signal detection performance in specific changes and targets. Thus, the application of designed signals can be improved.
Again, we would like to show our gratitude to the editors and reviewers for their treasure time, great efforts and good comments. We hope the revised paper can meet the requirement of publication.

Thank you!

Replied by Xiang Lan, Min Zhang, Jinxing Li.
OFDM Chirp Waveform Design Based on Subchirp Bandwidth Overlap and Segmented Transmitting for Low Correlation Interference in MIMO Radar

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Received: date; Accepted: date; Published: date

Abstract: There are some special merits for the orthogonal frequency division multiplexing (OFDM) chirp waveform as multiple input multiple output (MIMO) signals. This signal has high range resolution, good Doppler tolerance and constant modulus superiority, since it exploits a full bandwidth and bases on chirp signals. The correlation sidelobe peaks level are critical for the detection requirement of MIMO radar signals, however, conventional OFDM chirp signals will produce high autocorrelation sidelobe peaks (ASP) and cross-correlation peaks (CP), which reduces the detection performance. In this paper, we explore the structure of OFDM chirp signals’ autocorrelation function and proposed a scheme to reduce the ASP of designed signal by designing suitable range of subchirp bandwidth and a segmented transmit-receive mode. Next, we explore a suitable range of interval between the chirp rates of each two signals to reduce the CP. The simulation of designed signals verifies the effectiveness of proposed methods in reduction of ASP and CP and the correlation performance are compared with recent relate studies. In addition, the multiple signals detection and one-dimensional range image simulation show the good detection performance of designed signal in MIMO radar detection.

Keywords: time-frequency structure; autocorrelation sidelobe interference; cross-correlation interference; orthogonal frequency-division multiplexing (OFDM) chirp waveform; multiple-input multiple-output (MIMO) radar.

1. Introduction

Multiple input multiple output (MIMO) radar is the radar which can transmit multiple orthogonal signals and then receive them together to get multi-dimensional information. In order to obtain the properties of high range resolution and weak target detection, the corresponding waveform should be designed with wider bandwidth and lower ASP than before. In addition, the CP between each two waveforms need to be reduced to satisfy the orthogonality of the MIMO radar signals.

Traditionally, multiple subbandwidth approaches were divided to obtain the orthogonality among signals, which left limited bandwidth and insufficient bandwidth for each signal. The OFDM signal was first proposed in the radar system to fully utilize the bandwidth for high range resolution [1]. The OFDM signal suggests low mutual interference between nearby radar instruments which is verified by ambiguity function. For the advantage and widespread use of OFDM signals, many new techniques were generated. Under uniform circular array (UCA) and near-field conditions, the OFDM signal was combined to design a closed-form algorithm for localization [2]. A time & code
OFDM algorithm was proposed to solve the large residual carrier errors existing in complex indoor environments [3]. Literature [4] designed a mutual-information OFDM waveform based on MIMO radar for low-grazing angle tracking and it achieved performance improvements verified by realistic physical modeling due to adaptive OFDM waveform design. During different environments, there are many different spectrum sensing methods for OFDM signals proposed in [5]-[8], which improved the detection application of OFDM signals. Based on the orthogonality of it, OFDM signal was revised to complete micro-doppler estimation and the detection in frequency-selective fading channels [9] [10]. In the application of passive radar signal processing, OFDM waveforms were chosen for being easily decoded to acquire the noise-free signal [11]. Moreover, OFDM signal was used to rise the resolution for its high range resolution and was investigated for range ambiguity suppression for its diversity superiority in synthetic aperture radar (SAR) image [12] [13]. In addition, [14]-[16] completed the simulation and implementation of it in SAR.

Based on intrapulse radar-embedded communications, new waveforms were designed for covert and multiple target optimization, where the design criterion of constrained maximization of the signal-to-interference ratio and constrained minimization of a suitable correlation index improve the signal detection performance well [17] [18]. And better robust was designed based on polarimetric radar considering the worst case signal-to-interference plus noise ratio [19]. Thus, in order to obtain a better Doppler tolerance and constant modulus, a new OFDM signal combined with chirp signals was proposed, called OFDM chirp signals, which had great potential in radar application. For exploiting the full bandwidth for each waveform to improve the resolution in SAR, a novel OFDM chirp waveform was raised for multiple transmitters [20]. In the study of [21], the authors designed communication-embedded OFDM chirp waveforms for delay-Doppler radar applications. The benefit of fully using of a bandwidth of OFDM chirp signal made it better to be simultaneously used for information transmission and radar sensing. OFDM chirp signals based on MIMO radar was simulated in a low grazing angle target detection for its superiority of low peak-to-average-power ratio level and larger time–bandwidth product [22]. However, there were still some embedded problems left for OFDM chirp waveform. It’s high ASP in central region for basing chirp signal and high CP for fully using of a bandwidth. About OFDM chirp signal, many improvement measures has been proposed. A Spread Spectrum-Coded OFDM chirp waveform was proposed in [23]. By examining the ambiguity function and correlation function, the designed waveform can stay orthogonal on the receiver and have large time-bandwidth product for separating closely spaced targets. In addition, based on random matrix modulation, a new OFDM chirp signal with low peak–average ratio and low frequency-shift correlation peaks was designed in [24]. Which was also an effective way to reduce the high CP. Considering the high CP was caused by same chirp rate of OFDM chirp waveform, reference [25] raised to various the sub-chirp durations or sub-chirp bandwidths specially. However, the above methods only consider the case of CP’s reduction, they leave high ASP unsolved, since the spectrum structure of signal keeps unchanged. Moreover, we find the method for reducing ASP may restrict the reduction of CP and a model should be proposed to reduce both the ASP and CP for better detection.

In this paper, a series of methods are introduced to reduce the ASP and CP of the conventional OFDM chirp waveforms. At first, we derive and analyze the autocorrelation function formula and explored the suitable range of subchirp bandwidth to find the lowest autocorrelation
central sidelobe peaks (ACSP). To remove the multiple sub-cross-correlation peaks (MSCP), which
will produce high peaks in ASP as subchirp bandwidth adds, we propose a transmit-receive mode of
transmitting the subchirp durations one by one and superimposing each matched filtering output at
receiver during time domain. Next, the suitable interval is designed between the chirp rates of two
signals to reduce the CP. At last, the designed signals’ properties are evaluated by simulation of self-
ambiguity function, correlation function and one-dimensional range image, which shows remarkable
improvement in range side lobe property and orthogonality as suitable MIMO radar signals. In
addition, correlation function peaks value has been compared with other recent studies, which proves
the designed signal has a better correlation performance.

The rest of the sections of this paper are organized as follows. Section 2 introduces the signal
model and correlation function of the conventional OFDM chirp waveform. The autocorrelation
function is explored and a new OFDM chirp waveform with lower ASP than conventional one is
proposed in Section 3. And in Section 4, we explore the cross-correlation function and designed a
suitable range of interval between the chirp rates of two relative signals. The examples and
corresponding simulation results are provided in Section 5. Finally, this paper is concluded in Section
6.

Notation: In the rest of the paper, boldface characters denote vectors. We use the upper indices
to denote the type of variable, and lower indices are used to denote the order. The upper indices s, sub, c,
and d denote sub-autocorrelation, sub-cross-correlation, center range around main lobe
and designed one which is distinguish from the conventional one. $\epsilon(\cdot)$ denotes jump function.

2. Conventional OFDM Chirp Signal Model

A conventional OFDM chirp signal is made up of several subchirps, which are in different
subcarrier frequencies. Each subchirp has the same subchirp bandwidth and subchirp duration for
simpler modulation. In addition, each waveform has a unique code sequence of the subcarrier
frequencies for orthogonality to the waveforms of the other antennas. The nth conventional OFDM
chirp signal with M subchirps can be expressed as:

$$s_n(t) = \sum_{m=0}^{M-1} s_m(t),$$

$$s_m(t) = (\epsilon(t - mT_d) - \epsilon(t - mT_d - T_c)) \cdot \exp[j2\pi(f_m(t - mT_d) + k_n(t - mT_d)^2 / 2)]$$

(1)

where, $s_n(t)$, $n=1, 2, \ldots, N$ is the nth transmitting signal and $N$ is the number of transmitting signals.
$s_m(t)$ is the mth subchirp signal of $s_n(t)$. $T = MT_d$ denotes the total duration, $T_d$ is the subchirp
duration and $M$ is the number of subchirp. The $\epsilon$ where $0 \leq t \leq T$, represents the time samples of the
signal. In addition, $\epsilon(t) = 1, \ t \geq 0$ is the jump function. $B = (M-1)B_n^t + B_n^f$ represents the
bandwidth of the signal, $B_n^f$ denotes the subchirp bandwidth of nth transmitting signal and $B_n^t$
denotes the minimum interval between two subcarrier frequencies of nth transmitting signal. $f_m$ is
subcarrier frequency, which is the starting frequency of nth subchirp of nth signal. $f_m = C_mB_n^t$, $C_m$
is subcarrier frequency code. Lastly, we define $k = B_n^f / T_d$ as chirp rate of the nth transmitting signal
since all subchirp rates are the same during an OFDM chirp signal.

According to the signal model in (1), conventional OFDM chirp waveforms with 16 subchirps
are designed [24]. Without loss of generality, the conventional OFDM chirp signals $s_i(t)$ and $s_j(t)$
are chosen to explore the correlation property. We define the parameter as: $B = 400M$, $T = 8\mu s$, $M$
The subcarrier frequency code sequences are given as: \( C_1 = \{6, 2, 11, 5, 10, 4, 9, 7, 14, 8, 15, 16, 1, 3, 13, 12\} \) and \( C_2 = \{6, 10, 4, 13, 2, 7, 1, 12, 14, 9, 8, 5, 16, 15, 11, 3\} \). In order to do a comparison with designed signals below, we set signal \( s_1 \) with plus subchirp rates and \( s_2 \) with minus subchirp rates. Signals’ time-frequency structures diagram are shown in Figure 1.

![Figure 1](image)

Figure 1. Time-frequency structure of conventional OFDM chirp waveform, \( M=16 \). (a) \( s_1(t) \); (b) \( s_2(t) \).

By fully using of the bandwidth based on subchirp signal, the conventional OFDM chirp signals have high resolution while have no range-Doppler coupling. To better evaluate the property of conventional OFDM chirp signals, the correlation function [25] of the two waveforms is defined as:

\[
c_{pq}(\tau) = \begin{cases} 
\int_{0}^{T} s_p(t) s_q^*(t-\tau) dt, & 0 < \tau < T \\
\int_{-T}^{T} s_p(t) s_q^*(t-\tau) dt, & -T < \tau \leq 0 
\end{cases}
\]

where \( \tau \) is the time delay, \( c_{pq}(\tau) \) is the cross-correlation function under \( p \neq q \), and it represents autocorrelation function after \( p = q \). The autocorrelation function of \( s_1(t) \) and cross-correlation function between \( s_1(t) \) and \( s_2(t) \) calculated by (2) is obtained in Figure 2.

As show in Figure 2 (a), it can be found conventional OFDM signal’s ASP is up to -13.4dB. In addition, the ASP appears in the central region near the main lobe, called ACSP, while the autocorrelation side peaks in the edge region are low enough. On the other hand, Figure 2 (b) shows signal’s CP value as -25 dB and there are many high cross-correlation peaks in it.

These numerical results show high correlation influence exists in conventional OFDM signals, which will reduce its detection properties. As the signals’ number adds, such as 4 signals in the Section 5 simulation, the cross-correlation influence will be more serious. Moreover, in the one-dimensional range image, multiple point targets echo’s correlation sidelobes will overlap and become higher, which may cover up the weak targets and cause false detection. Thus, it’s necessary to reduce the ASP and CP of conventional OFDM signal and evaluate the multiple signals detection performance and one-dimensional imaging detection level of designed signal. In addition, some
recent study results should be compared with the simulation results of designed signals.

![Figure 2](image_url)  
**Figure 2.** Correlation curve of conventional OFDM chirp signals. (a) Correlation curve of \( s_p \) and \( s_q \) during \(-0.06 \mu s \sim 0.06 \mu s\). (b) Correlation curve of \( s_p \) and \( s_q \) during \(-8 \mu s \sim 8 \mu s\).

3. Subchirp Bandwidth and Transmitting Structure Design for Reducing ASP

In this Section, we begin with the derivation and analysis of the autocorrelation function of conventional OFDM signals. Next, we separate the function into several parts and evaluate each part’s influence to the ASP. Lastly, we propose the designed signal structure and show corresponding autocorrelation performance evaluated by transmit-receive structure diagram, time-frequency structure figure and ASP curve.

Under the situation of \( p=q=n \), (2) is the auto-correlation function of the signals. Since the function is probably symmetric by \( \tau=0 \), which is sufficient to study the peak value in \( 0 \leq \tau < T \), (2) can be written as:

\[
c_m(\tau) = \int_{-T}^{T} s_n(\tau) s_n^*(t-\tau) dt, \quad 0 < \tau < T ,
\]

(3)

We assume \( l \cdot T_d \leq \tau < (l+1)T_d \), where \( l \) is an integer with \( l \geq 0 \), and set the signal parameters as the one in Figure 1. Based on (1) and (3), the signal’s autocorrelation function structure diagram is obtained in Figure 3. Next, based on different integral function as showing in Figure 3, the region is divided into \( 2M-2l-1 \) regions and the (3) can be expanded as:

\[
c_m(\tau) = \sum_{m=0}^{M} \int_{-T}^{T} s_n(m,-(l+i)T_d-mT_d) s_n^*(m,t-\tau-mT_d) dt + \sum_{m=0}^{M} \int_{-T}^{T} s_n(m,-(l+i+1)T_d-mT_d) s_n^*(m,t-\tau-mT_d) dt ,
\]

(4)

where \( c_1(\tau) \) and \( c_2(\tau) \) are the first and second part of \( c_m(\tau) \).
AF is MSAF, which is the first part of (4), and it can be expressed as:

\[ c_{\text{ms}}^{\text{sub}}(\tau_1) = c_1(\tau_1), \quad 0 \leq \tau_1 < T_d, \quad (5) \]

the one in \( T_d + mT_d \sim \tau_1 + (m+1)T_d \) is MSCF which is the second part of (4), and it can be expressed as:

\[ c_{\text{ms}}^{\text{sub}}(\tau_1) = c_2(\tau_1), \quad 0 \leq \tau_1 < T_d, \quad (6) \]

Under \( t = \tau_2 \), AF is made up of MSCF only, and it can be expressed as:

\[ c_{\text{ms}}^{\text{sub}}(\tau_1) = c_1(\tau_2) + c_2(\tau_2), \tau_2 \geq T_d, \quad (7) \]

In order to reduce the ASP of the signals, the auto-correlation curve structure can be adjusted by changing its spectral structure. Its subchirp bandwidth \( B'_{\text{sub}} \) has been changed to find the suitable low ASP value. We define:

\[ p_1 = \max(c_{\text{ms}}^{\text{sub}}(\tau), 0 < \tau \leq T), \quad (8) \]

\[ p_2 = \max(c_{\text{ms}}^{\text{sub}}(\tau), 0 < \tau \leq T)), \quad (9) \]

\[ p_3 = \max(c_{\text{ms}}^{\text{sub}}(\tau), 0 < \tau \leq T)). \quad (10) \]

Where \( p_1 \) is autocorrelation sidelobe peak (ASP), \( p_2 \) is multiple sub-autocorrelation sidelobe peak (MSASP) and \( p_3 \) is multiple sub-cross-correlation peak (MSCP), where \( p_1 = \max(p_2, p_3) \). According to (4)-(7), their curves changing with \( B'_{\text{sub}} \) are shown in Figure 4. Where the MSASP has two minimal values when \( B'_{\text{sub}} / (B/16) \) is near 6.97 or 9.62, and the MSCP and ASP have high value in these points.
According to Figure 2 (a), the high ASP appears in the central region near the main lobe. We explore the $1/200T_d$ region centered on main lobe, where $\tau$ is smaller than $1/200T_d$ and the second part of (4) is about -46dB in value of the first one. So, the AF in central region can be obtained without the second part in (4) as:

$$c_{\text{center}}^{\text{center}}(\tau) \approx c_{l=0}(0/16l) \quad 0 \leq \tau < T_d, \quad (11)$$

Comparing (11) with (5), it shows $c_{\text{center}}^{\text{center}}(\tau) \approx c_{\text{sub}}(\tau)$ during $0 \leq \tau < T_d$. Thus, as the MSASP curve obtained in Figure 4, it can be concluded the central ASP can reduce to about -30 dB when $B'_n / (B/16)$ takes suitable value. However, the MSCP curve will appear high peaks when $B'_n / (B/16) > 1$ which will cause new high ASP out of the central region of main lobe.

Next, the reason of high MSCP according to the (6), (7) is qualitatively analyzed. We expand the multiple sub-cross-correlation function $c_{\text{sub}}^{\text{sub}}(\tau)$ during $\tau > T_d$ as:

$$c_{\text{sub}}^{\text{sub}}(\tau) = \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\tau} n(m,T_d) s_n(m,t-lT_d) s_n(m,t-\tau-mT_d)dt$$

$$+ \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\tau(l+1)T_d} n(m,T_d) s_n(m,t-(l+1)T_d-mT_d) s_n(m,t-\tau-mT_d)dt$$

$$= \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\tau} n(m,T_d) \exp(2\pi j((2n(l+1)+f_m)+k(\tau-I_T_d))t) \cdot \exp(2\pi j(\varphi_m))dt$$

$$+ \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\tau(l+1)T_d} n(m,T_d) \exp(2\pi j((2n(l+1)+f_m)+k(\tau-(l+1)T_d))t) \cdot \exp(2\pi j(\varphi_m))dt. \quad (12)$$

$\tau > T_d$

$$\varphi = -f_n(l+m)(l+mT_d) + f_m(mT_d + \tau) + 1/2k(((l+m)T_d)^2 - (mT_d + \tau)^2)$$

$$\varphi = -f_n(l+m+1)(l+m+1T_d) + f_m(mT_d + \tau) + 1/2k(((l+m+1)T_d)^2 - (mT_d + \tau)^2)$$

Where $|f_{n(l+1)} - f_m| \geq B'_n$. When $B'_n \leq B'_n$, $|k(\tau-(l+1)T_d)| \neq |f_{n(l+1)} - f_m|$ and

$|k(\tau-I_T_d)| \neq |f_{n(l+1)} - f_m|$, MSCF will not produces high peaks. But when $B'_n > B'_n$, $|k(\tau-(l+1)T_d)| = |f_{n(l+1)} - f_m|$ or $|k(\tau-I_T_d)| = |f_{n(l+1)} - f_m|$ may happen while MSCP will produces the
Thus, it can be concluded suitable value of $B'_s$ can reduce the ASP in the central range of main lobe in AF. However, the MSCP will keep high value as the $B'_s$ increases to more than $B'_s$, which cause new edge high ASP values. A designed transmit-receive structure need to be proposed to remove the MSCF part from the AF.

The autocorrelation function of $n$th subchirp signal can be written as:

$$c_m^{sub}(m, \tau) = \int_{t = mT}^{t = (m+1)T} s'_{n}(m, t) \cdot s'^*_{n}(m, t-\tau) dt$$

$$0 \leq \tau < T_d$$, (13)

and (3) can be expanded and rewritten as:

$$c_m^{sub}(\tau) = \sum_{n=0}^{M-1} c_m^{sub}(m, \tau) \quad 0 \leq \tau < T_d$$, (14)

where MSAF is the sum of $M$ subchirp autocorrelation functions. Inspired by (14), designed signals can be designed for removing the MSCF part by a new transmit-receive mode based on OFDM chirp signal as Figure 5 compared with conventional signal.

1) In Figure 5 (a), all subchirps are continuously transmitted in a pulse with each subchirp duration $T_d = T / M$ in the transmitting of conventional OFDM signal. However, in the transmitting of designed signal, each subchirp duration is $T_d = T$ and is transmitted in different pulses according to the code order. Where $T_p$ is the pulse duration and we set the $M=2$ to simplify the autocorrelation structure.

2) In Figure 5 (b), same matched filter output is obtained in a pulse in conventional OFDM signal processing. However, in the designed signal processing, $M$ different matched filter outputs are produced among $M$ pulses of time domain in the order of the transmitting subchirps.

3) After matched filtering, $M$ pulse durations outputs are accumulated at receive. In which both signals will improve the SNR, and the designed one can also get a low ASP.

As mentioned above, designed signal can be formulated as:

$$s'_{n}(t) = \sum_{n=0}^{M-1} s'_{n}(m, t)$$

$$s'_{n}(m, t) = (c(t - mT_p) - c(t - mT_p \cdot T_p))$$ \cdot \exp[j2\pi(f_{m}(t - mT_p) + k_{s}(t - mT_p^2) / 2)]$$

where $s'_{n}(t)$, $n=1, 2, ..., N$ is the $n$th designed OFDM chirp transmitting signals. The pulse duration is $T_p$ and the subchirp duration is $T$, where $T < T_p$. The range of $t$ is $0 \leq t \leq M \cdot T_p$. In addition, $B'_s$ will be chosen during the suitable range to reduce the ASP.
To explore the autocorrelation property of designed signals, we set the parameters as: $B = 400M$, $T = 8\mu s$, $M = 16$, $N = 1$ and $B_n' = 6.97B / M$, according to the conclusion in Figure 4. In addition, the subchirp carrier frequency code sequences are same as the conventional OFDM chirp signal in Figure 1. The time-frequency structure of designed waveform is plotted in Figure 6. Where Figure 6 (a) is the first part of Figure 6 (b) during $0\sim T_p$, which shows each subchirp duration of designed waveform exists in a unique pulse. Moreover, the Figure 6 (b) plot the whole time-frequency structure of designed signal during $0\sim MT_p$. It shows each subchirp rate is the same and they overlap in the frequency dimension since $B_n' = 6.97B / M$. 

**Figure 5.** transmitting and processing structure of designed signals; (a) Transmitting structures of two signals; (b) Matched filtering output structures of two signals
Compared with (2), the correlation function of designed OFDM chirp signals can be defined as $c_{pq}(\tau)$. Since the subchirp signals of the designed signals are transmitted according to the pulse one by one and the $M$ outputs are superimposed at time domain without delay, $c_{pq}(\tau)$ can be written as:

$$c_{pq}(\tau) = \sum_{m=0}^{M-1} c_{pq}^m(m, \tau),$$

$$c_{pq}^m(m, \tau) = \begin{cases} \int_{T-mT_p}^{(m+1)T_p} s_p^*(m,t)s_q^*(m,t-\tau)dt & 0 \leq \tau \leq T, \\ \int_{(m-1)T_p}^{mT_p} s_p^*(m,t)s_q^*(m,t-\tau)dt & -T \leq \tau < 0. \end{cases}$$

The autocorrelation function of designed signals can be expressed as:

$$c_{nn}(\tau) = \sum_{m=0}^{M-1} c_{nn}^m(m, \tau),$$

its ASP can be defined as:

$$p_4 = \max(c_{nn}^m(\tau), 0 < \tau \leq T),$$

According to (15)-(18), the designed signal’s ASP curve with $B'_\omega$ is plotted in Figure 7 compared with the MSASP of conventional signal.
In Figure 7, since the ASP of designed signal is equal to the MSASP of conventional one, the ASP of designed signals can be suppressed effectively when taking a specific $B'_c$ value. The suitable range of $B'_c$ when designed signal’s ASP is under -30 dB can be obtained, which is shown in Table 1.

Table 1. ASP values with $B'_c$

| $|ASP - ASP'_{B/B(16)/c}|$ (dB) | $ASP$ (dB) | $B'_c$ (B/M) |
|---------------------------------|-----------------|-----------------|
| 0                              | -13.4           | 1               |
| $>$16.6                        | $<-30$          | $6.77 - 7.25, 9.37 - 9.77$ |

4. Chirp Rates Interval Design for Reducing CP

Considering the correlation function of designed signal, (16) can be written under $p \neq q$ as:

$$
c'_{pq}(\tau) = \sum_{m=0}^{M-1} c'_{pq}(m, \tau)
$$

$$
c'_{pq}(m, \tau) = \begin{cases} 
\int_{\tau+\alpha T}\int_{\alpha T} s_n^*(m, t) s_n^*(m, t-\tau) dt & 0 < \tau < T \\
\int_{\alpha T} s_n^*(m, t) s_n^*(m, t-\tau) dt & -T < \tau < 0 
\end{cases}
$$

where $c'_{pq}(\tau)$ is the cross-correlation function between $s_p^*(t)$ and $s_q^*(t)$, and $c'_{pq}(m, \tau)$ is the $m$th pulse of it. We expand $c'_{pq}(\tau)$ as:

$$
c'_{pq}(\tau) = \sum_{m=0}^{M-1} \int_{\tau+\alpha T} \int_{\alpha T} \exp(2\pi j((f_p m - f_q m) + k_p - k_q)(1/2T^2 + mT^2)) dt \cdot \exp(2\pi j(\varphi_0))
$$

$$
\varphi_0 = -f_p m T + f_q m T + 1/2(k_p - k_q)\sqrt{(1/2T^2 + mT^2)}
$$

$$
c'_{pq}(\tau) = \sum_{m=0}^{M-1} \int_{\alpha T} \int_{\alpha T} \exp(2\pi j((f_p m - f_q m) + k_p - k_q)(1/2T^2 + mT^2)) dt \cdot \exp(2\pi j(\varphi_0))
$$

$$
\varphi_0 = -f_p m T + f_q m T + 1/2(k_p - k_q)\sqrt{(1/2T^2 + mT^2)}
$$
where owing to $0 \leq |k_0| \leq B$, and $-B \leq f_m - f_q \leq B$, $(f_m - f_q + k_g \tau)=0$ will happen during $-T \leq \tau \leq T$. Furthermore, under $k_p = k_q$, if $(f_m - f_q + k_g \tau)=0$, function $co'_{pq}(m, \tau)$ would have a maximum value, which causes high CP. So, when the time-frequency structure in Section 2 is unchanged, $k_p \neq k_q$ should be established to avoid high CP. We define $\Delta k$ as:

$$\Delta k = k_p - k_q,$$

(22)

and define the CP between $s_p'(t)$ and $s_q'(t)$ as:

$$p_{5} = \max (co'_{pq}(\tau), -T \leq \tau < T).$$

(23)

Next, the relation between the CP and $\Delta k$ is explored. We set $k_q = 8\left(\frac{B}{MT}\right)$, and keep $k_p$ changing during $0 \leq k_p \leq 16 \left(\frac{B}{MT}\right)$. Moreover, the subcarrier frequency code sequences are set the same as the one of the conventional OFDM chirp signal in Figure 1. Lastly, the CP curve of the designed signals $s_p'(t)$ and $s_q'(t)$ with chirp rate difference $\Delta k$ is plotted basing (20)-(23) in Figure 8.

![Figure 8. CP curve with $\Delta k$ when $k_q = 8\left(\frac{B}{MT}\right)$](image)

Table 2. CP values with $\Delta k$

| $|CP - CP_{\Delta k=0}|$ / dB | CP / dB | $|\Delta k| / (B / MT)$ |
|---------------------|---------|----------------|
| 0                   | -19.5   | 1               |
| > 10.5              | < -30   | $\geq 0.165$    |

In Figure 8, the CP shows a remarkable reduction with $\Delta k$’s increase. The range of interval between the chirp rates of two designed signals for reducing their CP under -30 dB is shown in Table 2. When $\Delta k=0$, the CP is -19.5 dB, which will reduce to -30 dB while $\Delta k$ is taken as $0.165\left(\frac{B}{MT}\right)$. Thus, low CP can be obtained with a suitable interval between the chirp rates of two designed signals.
5. Design Examples and Simulation Results

In this Section, we will give some designed examples and corresponding simulation results to evaluate the effectiveness of the proposed OFDM chirp waveform methods.

Figure 9. Self-ambiguity functions and their zero-delay and zero-Doppler “cuts.” (a) Conventional OFDM waveform; (b) Zero-delay cut; (c) Zero-Doppler cut; (d) Designed OFDM chirp waveforms; (e) Zero-delay cut; (f) Zero-Doppler cut;

To explore the designed signals’ Doppler performance, Figure 9 (a)-(f) gives the self-ambiguity function response of conventional OFDM signal and designed signal with its $B' = 6.8/16B$, and their parameters are $B = 40M$ and $T = 8\mu s$. As shown in Figure 9 (b) and (e), designed signal has the same doppler resolution performance as conventional OFDM chirp signal. Furthermore, in Figure 9 (c) and (f), designed signal has lower range sidelobes than conventional ones.

Table 3. Parameters of simulation signals

<table>
<thead>
<tr>
<th></th>
<th>$B = 400$ MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subchirp bandwidth</strong></td>
<td></td>
</tr>
<tr>
<td>$s_1'$</td>
<td>$B_1' = 6.8/16B$</td>
</tr>
<tr>
<td>$s_2'$</td>
<td>$B_2' = 7.09/16B$</td>
</tr>
<tr>
<td>$s_3'$</td>
<td>$B_3' = 9.4/16B$</td>
</tr>
<tr>
<td>$s_4'$</td>
<td>$B_4' = 9.77/16B$</td>
</tr>
<tr>
<td><strong>Minimal interval of the chirp rates</strong></td>
<td>$\Delta k_{\text{min}} = 0.29 \left( \frac{B}{MT} \right)$</td>
</tr>
</tbody>
</table>
In order to evaluate the time-frequency structure and correlation performance of designed signals, four signals $s_1', s_2', s_3', s_4'$ are simulated. According to the conclusion in Table 1, there are two ranges for $B'$ to obtain low ASP. So, we designed two groups of four signals with each two taking the $B'$ value during each range respectively for the simulation. In addition, as the conclusion in Table 2, the interval of the chirp rates between two simulation signals will be more than -0.165 $(\frac{B}{MT})$. The designed parameters are shown in Table 3.

After subchirps sequences coding and subchirp rate plus and minus (PM) coding for reducing the designed signals’ CP, the time-frequency structures of designed four OFDM chirp signals are plotted in Figure 10 (a)-(d). Where $s_1'$ and $s_2'$ are coded as the sequences of $s_1$ and $s_2$ for comparison. In Figure 10, each subchirp duration is $T$, and in a signal, each subchirp bandwidth is $B_n'$, where $n$ is 1, 2, 3, 4. Since the PM coding will not influence the ASP of designed signals for each subchirp being transmitted separately, we set signals $s_1'$ and $s_1'$ with all plus subchirp rates and signals $s_2'$ and $s_2'$ with all minus subchirp rates to further reduce the CP.

Figure 10. Time-frequency structure of four simulation designed OFDM chirp signals, $M=16$. (a) $x_1'$, $B_1'^{+}$ =6.8/16B; (b) $x_2'$, $B_2'^{+}$ =7.09/16B; (c) $x_3'$, $B_3'^{+}$ =9.4/16B; (d) $x_4'$, $B_4'^{+}$ =9.77/16B.

Figure 11 plot the correlation functions of signals $s_1'$ and $s_2'$. Comparing the results in Figure 11 (a) with that in Figure 2 (a), it shows that the autocorrelation of conventional OFDM waveforms
and designed waveforms are different. Figure 2 (a) shows high sidelobes near the main lobe, which also influences the resolution among multiple close targets or in continuous targets and easily causes false detection. The reason is the inappropriate subchirp bandwidth causes high peaks in multiple-subchirp autocorrelation function. Since the suitable subchirp bandwidths are taken and designed transmitting mode is adopted which removes the MSCF from AF, the designed waveforms’ ASP obtains an effective suppression near the main lobe, as obtained in Figure 11.

![Figure 11](image)

**Figure 11.** Correlation curve of designed OFDM chirp signals $s_1'$ and $s_2'$. (a) Correlation curve of $s_1'$ and $s_2'$ during $-0.06\mu s < t < 0.06\mu s$. (b) Correlation curve of $s_1'$ and $s_2'$ during $-8\mu s < t < 8\mu s$.

Then comparing the results in Figure 11 (b) with that in Figure 2 (b), it shows that the cross-correlation functions of the conventional waveforms and designed waveforms are also diverse. The cross-correlation functions of the conventional waveforms in Figure 2 (b) have some high grating sidelobes, which are easily judged as weak targets especially when multiple sidelobes of several close targets overlap and causes false detection. The reason is the subchirps with same carrier frequency and same chirp rate of two signals exists in same subchirp duration simultaneously. Since the chirp rates of two signals have kept enough interval as the proposed methods, the sidelobes in cross-correlation function of designed waveforms reduce dramatically in Figure 11 (b), and the sidelobe levels are more stable than that of the conventional waveforms.

For evaluation of the resolution property, the autocorrelation curves comparison has been made in Figure 12. Since there exists difference among the frequency spectrums of three signals, they have different autocorrelation function structures. Where, the NLFM signal has widest main lobe 4.05ns and the lowest sidelobes -52.7dB and the conventional OFDM signal has the narrowest main lobe 2.16ns but the highest sidelobes -13.4dB. Designed signal takes the middle properties with the main lobe width 3ns and sidelobe height -30.2dB, which obtains a balance between resolution and detection. So, the resolution property of designed signal reduces for the improvement of detection, which is 0.52m compared with 0.375m of conventional one.
Figure 12. Autocorrelation curve comparison among designed OFDM chirp signals $s_1$, conventional signal $s_1$ and NLFM signal during $0 < t < 0.06 \mu s$.

Next, for further comparisons of detection performance, the ASP and CP values of conventional OFDM signal, Li’s OFDM signal [25], PNLFM signal [26] and designed segmented transmitting OFDM (STOFDM) signal are listed in Table 4. Where STOFDM signal has its superiority of the lowest sidelobes in both ASP and CP.

Table 4. ASP and CP of previous and designed signals

<table>
<thead>
<tr>
<th>Waveforms (B=400M)</th>
<th>ASP/dB</th>
<th>CP/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>COFDM</td>
<td>-13.4</td>
<td>-25</td>
</tr>
<tr>
<td>Li’s OFDM</td>
<td>-13.4</td>
<td>-26.3</td>
</tr>
<tr>
<td>PNLFM</td>
<td>-25.0</td>
<td>-23.1</td>
</tr>
<tr>
<td>STOFDM</td>
<td>-30.2</td>
<td>-40.5</td>
</tr>
</tbody>
</table>

To better evaluate the multiple signals detection performance, the different combinations of four designed signals are simulated with their ASP and CP values listed in Table 5. The autocorrelation of signal $s_1 + s_2$ and cross-correlation between signal $s_1 + s_2$ and $s_1 + s_4$ are shown in Figure 13. In addition, the autocorrelation of signal $s_1$ and cross-correlation between signal $s_1$ and $s_3 + s_4$ are shown in Figure 14. Where the average correlation sidelobes among four designed signals $s_1 - s_4$ are stable and all lower than -30 dB since the number of transmitting signals adds to 4, which proves the good sidelobe properties of STOFDM signals as MIMO radar signals.
Figure 13. Correlation curve of designed OFDM chirp signals $s_1' + s_2'$ and $s_1' + s_3'$. during $-8 \mu s < t < 8 \mu s$.

Figure 14. Correlation curve of designed OFDM chirp signals $s_1'$ and $s_2' + s_3' + s_4'$. during $-8 \mu s < t < 8 \mu s$.

Table 5. ASP and CP of STOFDM signals with different number of signals

<table>
<thead>
<tr>
<th>Waveforms(B=400M)</th>
<th>ASP/dB</th>
<th>CP/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>STOFDM($s_1'$)</td>
<td>-30.2</td>
<td>\</td>
</tr>
<tr>
<td>STOFDM($s_1'$ and $s_2'$)</td>
<td>-30.2</td>
<td>-40.5</td>
</tr>
<tr>
<td>STOFDM($s_1'$ and $s_1' + s_2'$)</td>
<td>-30.2</td>
<td>-35</td>
</tr>
<tr>
<td>STOFDM($s_1'$ and $s_2' + s_3' + s_4'$)</td>
<td>-30.2</td>
<td>-33.3</td>
</tr>
<tr>
<td>STOFDM($s_1' + s_2'$ and $s_3' + s_4'$)</td>
<td>-31.3</td>
<td>-37.1</td>
</tr>
</tbody>
</table>

Finally, we simulate the proposed OFDM chirp waveforms in MIMO radar one-dimensional range imaging application. Without loss of generality, we consider a four-antenna MIMO radar using the waveforms $s_1' - s_3'$ illustrated in Figure 10. Other parameters are assumed as: $B = 100M$, $T = 20 \mu s$. In one-dimensional range image, we decomposed a ship target, which is 172m long and 16m wide, into 152 point targets. Figure 15 (a) is the one-dimensional RCS range images and Figure 15 (b) shows the one of four matched filters output of $s_1'$. For a comparison, the imaging result for a conventional SISO SAR using a conventional OFDM chirp signal with equal system parameters is
also shown in Figure 15 (c). Compared with Figure 15 (a), there are some high amplitude false target points in Figure 15 (c), for the high range peak sidelobe ratios (RPSLR) of conventional chirp signal. But in Figure 15 (b), those false targets are suppressed and real target points are compatible with Figure 15 (a) even after adding cross-correlation interferences with $s_i-ss$'. The RPSLRs of each signal are showed in Table 6.

### Table 6. RPSLR of previous and designed STOFDM signals in SISO and MIMO radar

<table>
<thead>
<tr>
<th>Radar model</th>
<th>Waveforms</th>
<th>RPSLR/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>SISO</td>
<td>COFDM($s_i'$)</td>
<td>-13.4</td>
</tr>
<tr>
<td></td>
<td>Li’s OFDM</td>
<td>-13.4</td>
</tr>
<tr>
<td></td>
<td>PNLFM(B=400M)</td>
<td>-25.2</td>
</tr>
<tr>
<td></td>
<td>STOFDM($s_i'$)</td>
<td>-30.5</td>
</tr>
<tr>
<td>MIMO</td>
<td>STOFDM($s_i'$ and $s_i'$)</td>
<td>-28.7</td>
</tr>
<tr>
<td></td>
<td>STOFDM($s_i'$ and $s_i'$+$s_i'$)</td>
<td>-28.5</td>
</tr>
<tr>
<td></td>
<td>STOFDM($s_i'$ and $s_i'$+$s_i'$+$s_i'$)</td>
<td>-27.3</td>
</tr>
</tbody>
</table>

### 6. Conclusion

The OFDM chirp waveform is widely applied in MIMO radar, because of its high range resolution and good Doppler tolerance. However, some high lobes exist in the signals' cross-correlation function for multiplexing of bandwidth and since the signal is based on chirp signal, high sidelobes also exists in its autocorrelation function. These two imperfections may influence the weak target detection. To solve the problem, the proposed method includes two design steps: signal autocorrelation construct design and orthogonality design between signals. Where a range of subchirp bandwidths and a corresponding transmit-receive mode are designed for reduction of ASP, and a range of suitable intervals between the chirp rates of two relative signals are proposed for reduction of CP. The self-ambiguity functions and correlation function verifies the good Doppler tolerance, low ASP and CP properties and a little main lobe broadening of designed signal. Moreover, the multiple signals detection and one-dimensional range image simulation proves the improvement of multiple signals detection performance in MIMO radar especially for weak targets detection and low range peak sidelobe superiority of designed signals.

In future work, we intend to further optimize the multiple signals detection model, reduce the mutual impact among transmitted signals. On the other hand, the targets RCS property will be combined to analyze the signal detection performance in specific changes and targets. Thus, the application of designed signals can be improved.
Figure 15. One-dimensional range image. (a) One-dimensional RCS range images; (b) Designed signal $s_1$ during total signal $s_1+s_2+s_3+s_4$ in MIMO; (c) Conventional OFDM signal in SISO;

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Reference


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