Spectrum Extension Research of Radar-Communication Integrated Waveform

Ri-Qiang Huang, Xiao-Long Zhao, Qiang Zhang, Jiang Jia
Dept. of Information and Electronics, Beijing Institute of Technology
Beijing, China
e-mail: riqiang_huang@sina.com

***Abstract*—Integration of radar and communication is an important trend in the future development of radar technology. The combination of radar and communication allows them to give full play of their respective superiority while make up for their deficiencies. As a result, the detection radar becomes communication radar, a network platform for information giving, which will immensely enhance the force of battle group. The key of Radar-communication integration is the design of integrated waveform. A practicable waveform is to modulate Minimum Shift Keying (MSK) signal onto Linear Frequency Modulation (LFM) signal, but the problem is the likelihood of leading to the extension of the spectrum, which will seriously affect the performance of radar detection and communication. To solve the problem, this paper will elaborate from the following aspects: 1. Mathematical expression of the integrated waveform in order to deduce the reason of spectrum extension and propose solutions accordingly. 2. Application of MATLAB in the simulation of spectrum extension [1] and result of limiting spectrum extension using the algorithm proposed in this paper. 3. The practicability of the method proposed by in this paper by implementing integrated waveform and algorithm on FPGA using VHDL language.**

Keywords-radar-communication integration; MSK; LFM; spectrum extension

LFM-MSK

I. INTRODUCTION

Radar-communication integration will make the system not only can search, detect and track with hostile target but also can complete long-distance and two-way data communication with large-capacity and strong anti-interference. Integration of radar and communication is an important trend in the future development of radar technology. A lot of research on the design of waveform of integrated Radar and communication has been done in recent years, and many integration system models and signal processing algorithms have been proposed. Specifically, they can be divided into two types: 1) Multi-carrier [2-3] method, like OFDM [4]. 2) Single-carrier [5] method. The Single-carrier method is to improve the traditional radar waveform, such as *Linear Frequency Modulation* (LFM) [6] signal. The study of this paper is a novel and excellent Single-carrier method based on combination of Minimum Shift Keying (MSK)[7-8] with Linear Frequency Modulation (LFM). LFM signal has a high range resolution [9] and is not sensitive to Doppler shift[10], so LFM signal has been widely used in radar waveform design. 99 percent of the energy of MSK signal is limited to 1.5 times the rate of data transfer bandwidth [11], and signal envelope is constant [12], the system can use the cheap and efficient non-linear device. MSK signal is very attractive in wireless communication. So the combine of LFM and MSK signal is a good idea. On the one hand it allows the communication receiver to demodulate data from the integrated waveform; on the other hand it makes it possible for the radar receiver to receive the radar echo which contains exact target information.

Since the waveforms of radar and communication are the same, there is no need to distinguish which one is used for communication and which is for radar. As a result, the difficulty of signal processing is reduced. This paper focuses on the shortcomings of this method, and proposing solutions, as well as obtaining optimal results through simulation and actual measurement.

II. INTEGRATED WAVEFORM DESIGN

A. *Expressions in Time Domain*

Radar waveform is a chirp signal, refer to [13],which can be expressed as:

$$S_R(t) = A * rect(\frac{t}{T_p}) e^{j2\pi f_1 t + j\pi\mu t^2} \tag{1}$$

where,

$$rect(x) = \begin{cases} 0, else \\ 1, 0 \le x < 1 \end{cases} \tag{2}$$

A means the amplitude of the waveform, T_p means the pulse width, f_1 means the start frequency, and μ means the sweep slope.

According to Eq(1), the instantaneous frequency of radar waveform can be drawn from the following formula :

$$\begin{aligned} f_1(t) &= d\left[f_1 t + (\frac{1}{2\pi}) * \pi\mu t^2 \right] / dt \\ &= f_1 + \mu t \end{aligned} \tag{3}$$

Figure 1 shows the waveform of LFM signal in time domain. As can be seen from the Figure 1, the frequency changes linearly with time.

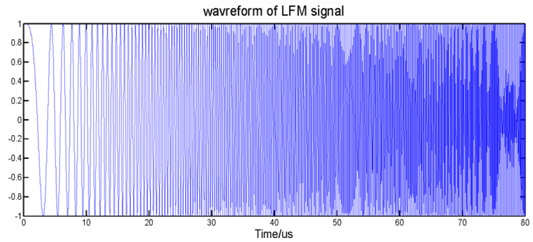

Figure 1. Wave form of radar signal.

The spectrum of LFM is shown in Figure 2. The bandwidth is 20M.

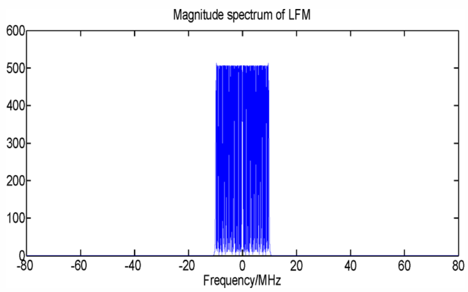

Figure 2. Spectrum of LFM.

Figure 3 shows the process of MSK modulation [14-15].

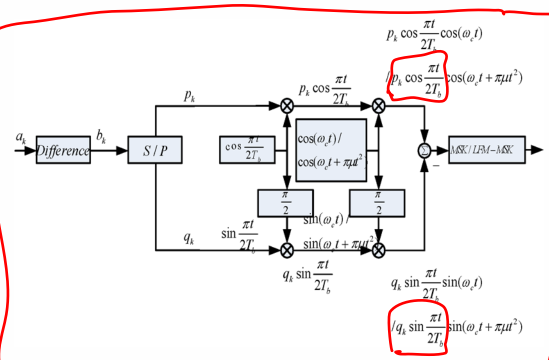

Figure 3. MSK and LFM-MSK modulation.

Figure 4 shows the msk signal.

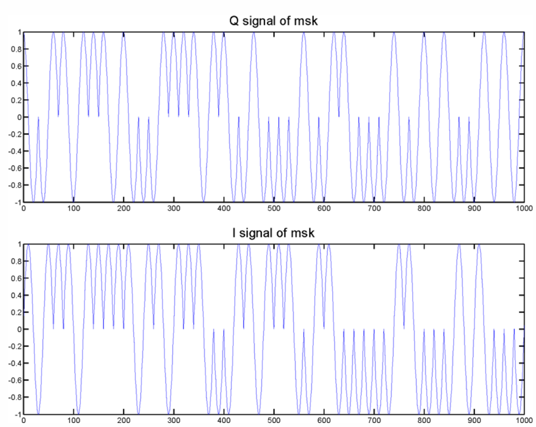

Figure 4. Waveform of msk signal.

If the carrier signal of MSK modulation is replaced by Linear Frequency Modulation (LFM), the integrated waveform based on LFM-MSK can be obtained [16], as shows in Figure.2.

The LFM-MSK signal can be expressed as:

$$
\begin{aligned}
s_k(t) &= p_k \cos(\frac{\pi t}{2T})\cos(2\pi f_1 t + \pi\mu t^2) \\
&\quad - q_k \sin(\frac{\pi t}{2T})\sin(2\pi f_1 t + \pi\mu t^2) \\
&= \cos(\pi\mu t^2 + p_k q_k \frac{\pi t}{2T} + \frac{1-p_k}{2}\pi)\cos(2\pi f_1 t) \\
&\quad - \sin(\pi\mu t^2 + p_k q_k \frac{\pi t}{2T} + \frac{1-p_k}{2}\pi)\sin(2\pi f_1 t)
\end{aligned} \tag{4}
$$

The LFM_MSK signal is shown in Figure 5.

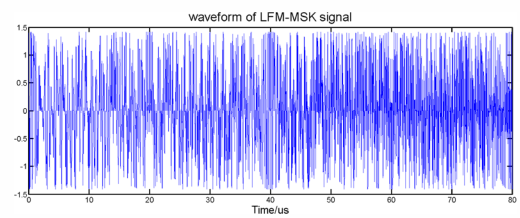

Figure 5. Wave form of Integration signal.

In the above formula, T means the cycle of code element, $p_{k,} q_k \in \{\pm 1\}$, is for carrying information. f_1 is the start frequency of LFM. Then the LFM-MSK signal with N bits data can be put in the plural form as:

复数形式

$$
\begin{aligned}
S_C(t) &= A * rect(\frac{t}{T_p}) \\
&\quad * e^{j2\pi f_1 t}\sum_{k=1}^{N} rect(\frac{t-(k-1)T}{T}) \\
&\quad * e^{j\pi(\mu t^2 + p_k q_k t + \frac{1-p_k}{2})}
\end{aligned} \tag{5}
$$

$T_p = NT$

$2T$

The same as Eq(1), A means the magnitude of signal, T_p means the pulse width. $T_p = NT$. Suppose that the bandwidth of radar signal is B, the bandwidth B can be expressed as:

$$
B = f_2 - f_1 = \mu T \tag{6}
$$

Then the bandwidth of integrated waveform is the same as that of radar detection waveform.

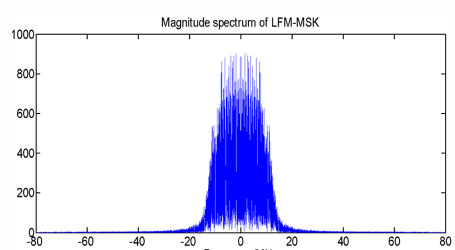

Figure 6. Spectrum of integrated waveform (LFM-MSK).

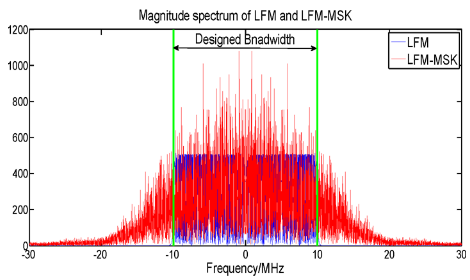

Figure 7. Spectrum of LFM-MSK and LFM.

In the above figures, Figure.6 illustrates the spectrum of integrated waveform (LFM-MSK). While Figure.7 presents collectively the spectrum of LFM-MSK and LFM, with the pulse width being 200us, and the sweep bandwidth being 20M, ranging from -10M to 10M.

III. Spectrum Extension and Solution

As Figure 6 shows, when the LFM signal is modulated with MSK, the bandwidth is no longer the designed one. In other words, the spectrum is extended and not meeting the system requirements.

Like Eq(3), the instantaneous frequency can be expressed as :

$$f_1(t) = d(f_1 t + \frac{1}{2}\mu t^2 + \frac{p_k q_k}{4T}t + \frac{1-p_k}{2})/dt$$

$$= f_1 + \mu t + \boxed{\frac{p_k q_k}{4T}} \qquad (7)$$

Among them, $p_k, q_k \in \{\pm 1\}$, so that $p_k q_k = \pm 1$. Compared with Eq(3), $\pm 1/4T$ is the extended section.

扩展的频段:

$$\boxed{\Delta f = \pm 1/4T = \pm \frac{N}{4T_p} = \pm \frac{R_b}{4}} \qquad (8)$$

As in Eq(8), R_b means bit rate. If the pulse width is determined, i.e. T_p is determined, the number of modulated code element is in direct proportion to the extension degree of the spectrum. That is to say, when the bit rate is higher, the spectrum extension is severer.

In an integrated system, if the extension of spectrum exceeds the designed value of bandwidth, the sidelobe will confront serious adjacent channel interference[17], which can cause great damage to the performance of the system. With that in mind, this paper proposes a method to limit the spectrum extension, rendering the spectrum of communication signals all kept within the designed value of LFM signal bandwidth. Specifically speaking, modulate the MSK signal onto the middle instead of the beginning or end section of carrier signal of LFM. And following is detailed derivation of the time horizon of not modulating MSK signal.

As Eq(3) shows, the instantaneous frequency of LFM signal is a linear function that varies linearly with time. Similarly, Eq(7) can be taken as two linear functions changing linearly with time. ① If $p_k q_k$ always equal to 1, then

$$\boxed{f_1(t) = f_1 + \mu t + \frac{1}{4T}} \qquad (9)$$

② If $p_k q_k$ always equal to -1, then

$$\boxed{f_1(t) = f_1 + \mu t - \frac{1}{4T}} \qquad (10)$$

Just as shown in Figure 8.

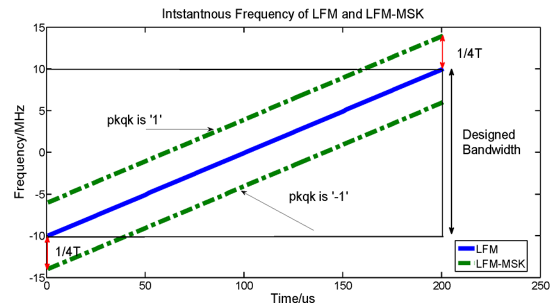

Figure 8. Instantaneous frequency of LFM-MSK and LFM.

Suppose that the time horizon of not modulating MSK signal is ΔT, then the critical condition that limits spectrum is as shown in Figure 9.

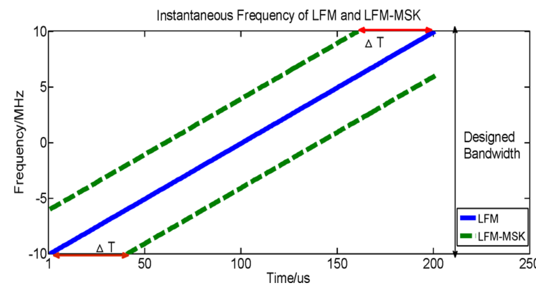

Figure 9. The critical situation of ΔT.

Through the basic approach of linear function, we know that ΔT needs to meet the following condition

$\mu \Delta T \geq \Delta f = \frac{N}{4T_p}$

$\mu = \frac{B}{T_p}$

$\Rightarrow$

$$\boxed{\Delta T \geq \frac{N}{4B}} \qquad (11)$$

Obviously, as LFM-MSK signals contain more than LFM signal, ΔT needs to meet another condition:

$$\boxed{2\Delta T \leq T_p} \qquad (12)$$

In the above figure, the pulse width is 200us, bit rate 16M, and the designed value of bandwidth ranges from -10M to 10M, accordingly, N=3200, $\boxed{\Delta T = 40\mu s}$

Thus the spectrum of LFM-MSK is well limited within the designed value of bandwidth.

$T_p - 2\Delta T = 120\mu s$

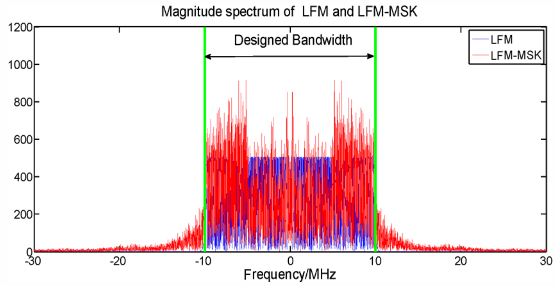

Figure 10. The spectrum of LFM and LFM-MSK.

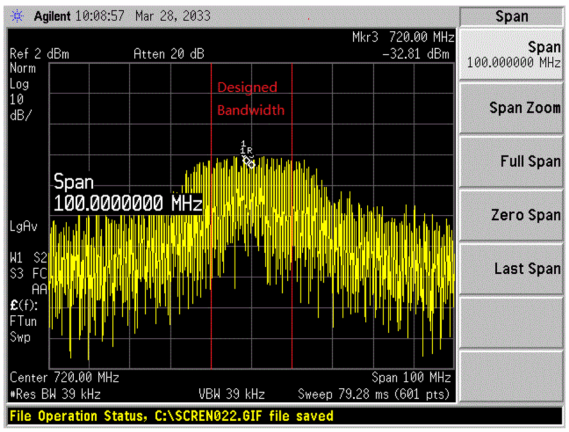

Figure 11. The actual spectrum LFM-MSK without spectrum limitation.

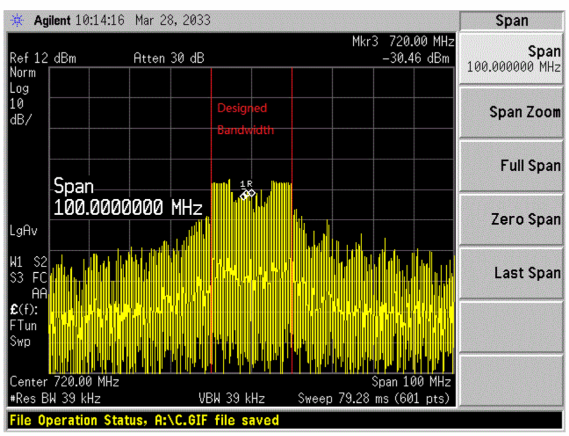

Figure 12. The actual spectrum LFM-MSK with spectrum limitation.

Figure.11 shows that the bandwidth of LFM-MSK signal without spectrum limitation has surpassed the designed bandwidth, while Figure.12 shows that the bandwidth of LFM-MSK signal with spectrum limitation is still within the range of designed bandwidth.

IV. CONCLUSIONS

LFM-MSK is a novel waveform that can be applied to Radar-communication integration. However, the spectrum extension is a serious drawback of this waveform. The problem has been confirmed through MATLAB simulation by this paper, and the extension value is found out to be nearly a quarter of bit rate. This paper proposes an algorithm that can perfectly solve the problem at issue. is The solution is to set a ΔT time of not modulating MSK signal in the beginning and the end section of carrier signal, then the spectrum extension will be reduced. Of course, ΔT should meet the conditions that $\Delta T \geq N/4B$, and $2\Delta T \leq T_p$ .The solution is proved, whether through matlab simulation or actual experiment, to be effective and has achieved good results in limiting the spectrum of integrated waveform to the designed bandwidth.

There are still many problems in the practical applications of Radar-communication integration waveform, which this paper hasn't done any research. . To name it, the rate of signal, or the Doppler sensitivity are also a matter of concern.

ACKNOWLEDGMENT

I want to take this chance to thanks to Yue Jiang. In the process of composing this paper, she gives me a lot of help in English writing.

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