A Novel Integrated Radar and Communication Waveform based on LFM Signal

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Abstract—**The design of integrated waveform that can simultaneously perform radar and communication function is a key technology in radar and communication integration. This paper proposes a novel integrated radar and communication waveform based on linear frequency modulated (LFM) signal, which performs radar function. Communication data of different channels as well as adjusting data are multiplied with corresponding orthogonal sequences and added together to form communication baseband signal which then modulates the LFM signal. The whole modulating process refers to technologies including 2PSK and CDMA. Theoretical analysis and simulation results demonstrate this novel integrated waveform performs well and meets practical requirements.**

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Keywords-multifunction RF system; integrated waveform; radar and communication integration; LFM signal

I. Introduction

To meet the need of modern information warfare, quantity and complexity of electronic equipment on weapon platforms are constantly increasing. Under this background, concept of multifunction RF system is proposed in [1]-[2]. Related researches mainly focus on the integration of radar and communication because of its high feasibility. Radar and communication system have many similar hardware configurations such as antenna, transmitter, receiver and signal processor. Due to the development of software-defined radar in [3] and VSLI technology, signal processor now can be programmed flexibly to process integrated waveform. Such an integration technology can decrease equipment's quantity and complexity, enhance platform's mobility and reduce electromagnetic interference.

Existing researches about integration mainly focus on the design of waveform which can simultaneously perform radar and communication function. References [4]-[5] propose an integrated system using linear frequency modulated (LFM) signals of opposite chirp slopes as radar and communication signal respectively. Such two kinds of LFM signals are quasi-orthogonal 准正交的 other than completely orthogonal, which will inevitably induce systematic error in demodulated signals and further damage the system performance. In [6], the initial phase of LFM signals is modulated by communication data to transport information. The data rate is relatively low considering the large pulse width of radar waveform. In [7]-[10], technology similar with CDMA is applied. Radar and communication waveform are modulated by orthogonal sequences. In [11]-[13], an integration technology based on OFDM is proposed. Radar and communication waveforms are carried to channels of different frequencies, making them orthogonal. Both the technologies mentioned above including CDMA and OFDM confront a problem that the envelope of integrated waveform is non-constant 不恒定. The transmitted waveform is distorted when the power amplifier works on nonlinear area. In [14]-[15], the carrier waveform of conventional MSK technology is replaced by LFM signal, which meanwhile perform radar function. Graphics of the ambiguity function indicate that such an integrated waveform has better resolution. However, in some cases, the ambiguity function of such a waveform can't be deduced.

This paper proposes a novel integrated radar and communication waveform based on LFM signal. Communication data of different channels as well as adjusting data are multiplied with corresponding orthogonal sequences and added together to form the communication baseband signal, which then modulates the LFM signal. The whole modulating process refers to technologies including 2PSK and CDMA.

This integrated waveform has properties shown as following: (1) Envelope of the integrated waveform is constant, avoiding nonlinear distortion caused by power amplifier. (2) Communication information is disguised 掩盖，伪装 by adding signals of different channels. (3) Carrier signal can be obtained from received signal even if influenced by Doppler frequency. (4) CDMA technology realizes multiplexing of three channels.

The rest structure of this paper is shown as following: ① Section 2 describes the system architecture and the function of each module in it. ② Section 3 discusses the selection of symbol period and the mathematical expression of integrated signal. ③ Section 4 analyzes three key properties including bit rate, bandwidth and bit error rate under an ideal condition. ④ And the impact of Doppler frequency on symbol period is discussed in Section 5. ⑤ Section 6 obtains the method to calculate adjusting data with communication data and shows mathematical demonstration of this method. ⑥ Simulations are implemented in Section 7, whose results are consistent with theoretical analysis. Since signal that just transports one-channel data looks the same with the integrated signal, we replace the integrated signal with this sub-signal in Section 3-5 to simplify the discussion.

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II. ARCHITECTURE OF INTEGRATED SYSTEM

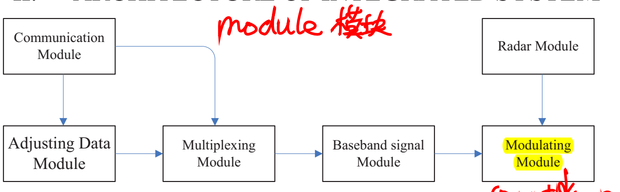

Figure 1. Transmitting Terminal

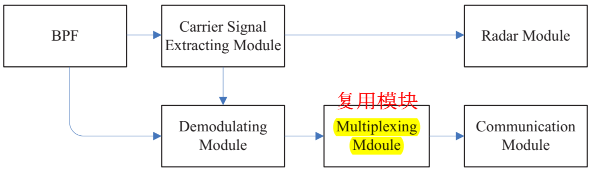

Figure 2. Receiving Terminal

The architectures of transmitting and receiving terminal in integrated radar and communication system are respectively shown in Fig.1 and Fig.2.

In transmitting terminal, communication data of three channels from communication module are inputted to adjusting data module to obtain adjusting data of the fourth channel. Data of these four channels enters into multiplexing module and multiplies with corresponding sequences which are mutually orthogonal. Communication baseband signal is formed in baseband signal module. Modulating module outputs integrated signal.

In receiving terminal, integrated signal, filtered by a band-pass filter, enters into carrier signal extracting module. The output of this module can perform as radar signal, when entering into radar module, and carrier signal, when entering into coherent demodulating module to demodulate the received signal. Multiplexing module receives the demodulated signal and separates it into signals of the four channels.

III. SYMBOL PERIOD & EXPRESSION OF INTEGRATED SIGNAL

In traditional 2PSK communication system, modulating the phase of carrier signal is equivalent to 等价于 modulating its amplitude. Inspired by this, we propose a novel method which uses LFM signal other than single-frequency signal as carrier signal. Different from single-frequency signal, LFM signal has a changing period. To ensure that amplitude of integrated signal, formed by multiplying LFM signal and communication baseband signal, is continuous, the period of symbol in baseband signal should be carefully selected. It need meet the requirement: in integer multiples of it, values of LFM signal are zero.

f_i, μ, T_0, B are parameters of LFM signal, where f_i represents initial frequency, μ represents frequency modulation slope, T_0 represents pulse duration period, B represents bandwidth. The expression of LFM signal is

$$s(t) = \sin(\omega_i t + \pi\mu t^2). \tag{1}$$

The expression of its phase is

$$\emptyset(t) = \omega_i t + \pi\mu t^2. \tag{2}$$

Let T_d represent symbol period, and it can be expressed as

$$T_d = T_0/M, \tag{3}$$

where M is a positive integer, representing the number of symbols in a pulse duration period. To ensure that amplitude 振幅 of integrated signal is continuous, values of LFM signal function should be zero in edges of each symbol period, i.e. $\emptyset(mT_d) = n\pi$, where m and n are integers. According to (2) and (3), we know

$\mu = \frac{B}{T_0}$

$$\boxed{\begin{aligned} n &= \mu {T_d}^2 m^2 + 2f_i T_d m = \mu {T_0}^2 m^2/M^2 + 2f_i T_0 m/M \\ &= (m^2 + 2Mf_i m/B)BT_0/M^2. \end{aligned}} \tag{4}$$

Let $Mf_i/B = A_1$, $BT_0/M^2 = A_2$, where A_1 and A_2 are integers, (4) can be expressed as

$$n = (m^2 + 2A_1 m)A_2. \tag{5}$$

Obviously, n is an integer when m is any positive integer. From (3), we can conclude that the selecting of T_d is equivalent to that of M. Now, we have got constraint conditions of the integer M: Td的选择 等价于 M的选择

M的约束条件

$$Mf_i/B = A_1, \tag{6}$$

$$BT_0/M^2 = A_2. \tag{7}$$

The mathematical expression of integrated signal is

LFM 基带信号

$$e(t) = \sin(\omega_i t + \pi\mu t^2)\sum d_m g(t - mT_d), \tag{8}$$

where $d_m = \begin{cases} 1, & P = 0.5 \\ -1, & P = 0.5 \end{cases}$, $g(t) = \begin{cases} 1, & 0 \le t \le T_d \\ 0, & \text{else} \end{cases}$.

IV. PROPERTIES

A. Bit Rate

From (7), we know

$\frac{M}{T_0/F} = F \cdot \frac{M}{T_0}$

$$M \le \sqrt{BT_0}. \tag{9}$$

$\le F\sqrt{\frac{B}{T_0}} = F\sqrt{\mu}$

This means the maximum number of symbols in a single pulse duration period is related to the product of the signal's pulse width and bandwidth. We let F represent pulse duty cycle, 占空比 R_b represent bit rate, then $R_b = \frac{M}{T_0/F} = F\cdot\frac{M}{T_0} \le F\sqrt{\frac{B}{T_0}} = F\sqrt{\mu}$

$$R_b \le F\sqrt{B/T_0} = F\sqrt{\mu}. \tag{10}$$

From (10), we know maximum value of bit rate R_b is related to frequency modulation slope μ, when pulse duty cycle F is determined. The larger the μ is, the larger the R_b is.

In order to obtain high range and velocity resolution, modern radar generally uses LFM signal with large pulse width as well as large bandwidth. Such a fact ensures a relatively high bit rate of the integrated waveform in this paper. If $f_i = 1100\text{Mhz}$, $\mu = 10^6\text{Mzh/s}$, $T_0 = 100\mu\text{s}$, $B = 100\text{Mhz}$, $F = 0.5$, then we can get the result that $M = 100$, $R_b = 0.5\text{M}$.

B. Bandwidth

We let B_d represent bandwidth of communication baseband, B_a represent that of integrated signal. According to convolution property, we can know

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$$\boxed{B_a \approx B + B_d = B(1 + \eta),} \tag{11}$$

where $\eta = B_d/B = 2M/BT_0$. When M equals the maximum value $\sqrt{BT_0}$, $\eta = 2/\sqrt{BT_0}$. Considering the fact that LFM signal in modern radar generally has large pulse width and bandwidth, we can know that $B_a \approx B$. If $B = 100\text{Mhz}$, $T_0 = 100\mu\text{s}$, the maximum value of M is 100. Under this situation, $\eta = 0.02$, $B_a = 1.02B$.

C. *Bit Error Rate* BER

$s_m(t)$, $x_m(t)$, $n(t)$, $c_m(t)$, $y_m(t)$ respectively represent integrated signal, received signal, received noise, carrier signal for coherent demodulation, output signal after modulation in the mth symbol period. $n(t) \sim N(0, \sigma^2)$, f_c represents carrier frequency, $f_c = \mu M T_d/2$.

In the mth symbol period, $n\pi$ is corresponding phase of LFM signal. In the following, we let M and n are even. 偶数 Then

$$x_m(t) = s_m(t) + n(t) = d_m \sin[2\pi(f_i + \mu m T_d)t + \pi\mu t^2]$$
$$+[n_c(t)\cos(\omega_c t) - n_s(t)\sin(\omega_c t)], \tag{12}$$

$$c_m(t) = \sin[2\pi(f_i + \mu m T_d)t + \pi\mu t^2]$$
$$= \sin[2\pi(f_c + \mu \Delta m T_d)t + \pi\mu t^2], \tag{13}$$

where $m - M/2 = \Delta m$. After demodulation,

$$y_m(t) = d_m + [n_{cs}(t) - n_{sc}(t)], \tag{14}$$

where $n_{cs}(t) = n_c(t)\sin(2\pi\Delta f t + \pi\mu t^2)$, $n_{sc}(t) = \cos(2\pi\Delta f t + \pi\mu t^2)$, $\Delta f = \mu \Delta m T_d$. The results can be applied beyond the limitation that M and n are even.

Obviously, $n_{cs}(t) \sim N(0, \sigma^2 \sin(2\pi\Delta f t + \pi\mu t^2)^2)$, $n_{sc}(t) \sim N(0, \sigma^2 \cos(2\pi\Delta f t + \pi\mu t^2)^2)$. So $[n_{cs}(t) - n_{sc}(t)] \sim N(0, \sigma^2)$. That means the additive noise of output signal after demodulation is Gaussian noise which has mean value and variance the same with received noise. So the bit error rate after coherent modulation should be equal to that in 2PSK system.

V. IMPACT OF DOPPLER FREQUENCY ON SYMBOL PERIOD

有相对运动时，才会多普勒频移

The integrated waveform may be influenced by Doppler phenomenon when ① reflected by moving target, ② transmitted or received by moving platforms. In these situations, symbol period of communication baseband signal after demodulation will change. In the following we will analyze the impact of Doppler frequency on the symbol period.

State of received signal at the moment t is corresponding with that of transmitted signal at the moment $t - \tau(t)$, where $\tau(t)$ means the delay time. We can know $\tau(t) = 2(R_0 - vt)/(c - v)$, where R_0 is the distance between platform and target at the moment 0, v is radial velocity of target, c is velocity of light. In time domain, the difference between initial moment of received signal and transmitted signal is $\tau_0 = 2R_0/(c + v)$. If we set initial moment of the received signal as moment 0, then a new expression of received signal can be expressed as

$$r(t) = s[t + \tau_0 - \tau(t + \tau_0)]$$
$$= \sin\{\omega_i[t + \tau_0 - \tau(t + \tau_0)] + \pi\mu[t + \tau_0 - \tau(t + \tau_0)]^2\}$$
$$= \sin(K\omega_i t + \pi K^2 \mu t^2), \tag{15}$$

where $K = 1 + 2v/(c - v)$. Expression of the phase is

$$\theta(t) = \omega_i' t + \pi\mu' t^2. \tag{16}$$

where $\omega_i' = K\omega_i$, $\mu' = K^2\mu$.

We introduce a variable t_m and let $\emptyset(mT_d) = \theta(t_m)$, then $t_m = mT_d/K = mT_d[1 - 2v/(c + v)]$. We let T_d' represent symbol period influenced by Doppler phenomenon, ΔT represent the difference between T_d and T_d', then

$$T_d' = T_d[1 - 2v/(c + v)], \tag{17}$$

$$\Delta T = T_d - T_d' = T_d 2v/(c + v). \tag{18}$$

Though the symbol period changes when influenced by Doppler phenomenon, the changed period is still a constant. Given the relatively low speed of moving target or platforms, extracting of synchronous clock will not be influenced.

VI. MULTIPLEXING OF THREE CHANNELS

Integrated signal realizes multiplexing of three channels with orthogonal sequences, which can better disguise data. To ensure that envelope of the integrated waveform is constant, which is important to avoiding nonlinear distorting in power amplifier and extracting carrier wave, this paper introduce a concept of adjusting data transported through the fourth channel.

The orthogonal sequence set consists of four sequences and each of them has four elements. The matrix of this orthogonal sequence set is shown as

$$\mathbf{W} = \begin{bmatrix} \boldsymbol{\alpha}_1 \\ \boldsymbol{\alpha}_2 \\ \boldsymbol{\alpha}_3 \\ \boldsymbol{\alpha}_4 \end{bmatrix} = [\boldsymbol{\beta}_1{}^T \quad \boldsymbol{\beta}_2{}^T \quad \boldsymbol{\beta}_3{}^T \quad \boldsymbol{\beta}_4{}^T]$$
$$= \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix}. \tag{19}$$

These four sequences including $\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$, $\boldsymbol{\alpha}_3$, $\boldsymbol{\alpha}_4$ respectively belong to the four data channels. Among them, Channel 4 is used to transport adjusting data to adjust envelope. We let $\boldsymbol{h}$ represent data vector and it can be expressed as $[h_1 \quad h_2 \quad h_3 \quad h_4]$. h_1, h_2, h_3 are communication data of three channels, whose value are 1 or —1. h_4 is adjusting data of the fourth channel, whose value is an integer. The integrated waveform is formed by adding together the waveforms from four channels. Since its envelope is constant, we can know $|\boldsymbol{W} \cdot \boldsymbol{h}| = \boldsymbol{A}$, i.e.

$$\begin{aligned} |h_1 a_{11} + h_2 a_{21} + h_3 a_{31} + h_4 a_{41}| &= A \\ |h_1 a_{12} + h_2 a_{22} + h_3 a_{32} + h_4 a_{42}| &= A \\ |h_1 a_{13} + h_2 a_{23} + h_3 a_{33} + h_4 a_{43}| &= A \\ |h_1 a_{14} + h_2 a_{24} + h_3 a_{34} + h_4 a_{44}| &= A, \end{aligned} \tag{20}$$

where A represents value of the constant envelope. We let $\boldsymbol{\gamma}_1 = [a_{11} \quad a_{21} \quad a_{31}]$, $\boldsymbol{\gamma}_2 = [a_{12} \quad a_{22} \quad a_{32}]$, $\boldsymbol{\gamma}_3 = [a_{13} \quad a_{23} \quad a_{33}]$, $\boldsymbol{\gamma}_4 = [a_{14} \quad a_{24} \quad a_{34}]$, $\boldsymbol{p} = [h_1 \quad h_2 \quad h_3]$. Equation (20) can be developed into

$$|\boldsymbol{p}\cdot\boldsymbol{\gamma}_1{}^T + h_4 a_{41}| = A$$
$$|\boldsymbol{p}\cdot\boldsymbol{\gamma}_2{}^T + h_4 a_{42}| = A$$
$$|\boldsymbol{p}\cdot\boldsymbol{\gamma}_3{}^T + h_4 a_{43}| = A$$
$$|\boldsymbol{p}\cdot\boldsymbol{\gamma}_4{}^T + h_4 a_{44}| = A. \qquad (21)$$

From (19), we know $\boldsymbol{\beta}_1, \boldsymbol{\beta}_2, \boldsymbol{\beta}_3, \boldsymbol{\beta}_4$ are mutually orthogonal, and

$$\boldsymbol{\beta}_i\cdot\boldsymbol{\beta}_i{}^T = \boldsymbol{\gamma}_i\cdot\boldsymbol{\gamma}_i{}^T + a_{4i}{}^2 = 4, \qquad (22)$$

$$\boldsymbol{\beta}_j\cdot\boldsymbol{\beta}_i{}^T = \boldsymbol{\gamma}_j\cdot\boldsymbol{\gamma}_i{}^T + a_{4j}a_{4i} = 0, \qquad (23)$$

where $i \neq j$. According to (19),

$$a_{4j} = \begin{cases} a_{4i} & \text{both } i,j \text{ are even or odd} \\ -a_{4i} & \text{one of } i,j \text{ is even, the other is odd} \end{cases}.$$

From (22) and (23), we know

$$\boldsymbol{\gamma}_i\cdot\boldsymbol{\gamma}_i{}^T = 3, \qquad (24)$$

$$\boldsymbol{\gamma}_i\cdot\boldsymbol{\gamma}_j{}^T = \begin{cases} -1 & \text{both } i,j \text{ are even or odd} \\ 1 & \text{one of } i,j \text{ is even, the other is odd} \end{cases}. \qquad (25)$$

Obviously, $\boldsymbol{p} \in \{\boldsymbol{\gamma}_i, -\boldsymbol{\gamma}_i\}$. If $\boldsymbol{p} = \boldsymbol{\gamma}_i$, according to (23)- (25), (21) can be developed into

$$\begin{cases} |3 + h_4| = A \\ |-1 + h_4| = A \end{cases} \quad i \text{ is odd},$$

$$\begin{cases} |3 - h_4| = A \\ |-1 - h_4| = A \end{cases} \quad i \text{ is even}. \qquad (26)$$

Because the formula set has two formulas as well as two unknown variables, there must be solutions to it. Solutions are

$$\begin{cases} h_4 = -1 \\ A = 2 \end{cases} \quad i \text{ is odd},$$

$$\begin{cases} h_4 = 1 \\ A = 2 \end{cases} \quad i \text{ is even}. \qquad (27)$$

If $\boldsymbol{p} = -\boldsymbol{\gamma}_i$, similarly, solutions are

$$\begin{cases} h_4 = 1 \\ A = 2 \end{cases} \quad i \text{ is odd},$$

$$\begin{cases} h_4 = -1 \\ A = 2 \end{cases} \quad i \text{ is even}. \qquad (28)$$

TABLE I. ADJUSTING DATA LOOK-UP TABLE

Communication Data			**Adjusting Data**
Channel 1	Channel 2	Channel 3	Channel 4
—1	—1	—1	1
—1	—1	1	—1
—1	1	—1	—1
—1	1	1	1
1	—1	—1	—1
1	—1	1	1
1	1	—1	1
1	1	1	—1

To sum up, two steps are needed to calculate adjusting data: (1) confirming $\boldsymbol{p} \in \{\boldsymbol{\gamma}_i\}$ or $\boldsymbol{p} \in \{-\boldsymbol{\gamma}_i\}$. (2) confirming i is even or odd. Mathematical deduction above demonstrates the existence of adjusting data and offers us theoretical foundation to calculate it. Considering the limited number of communication data groups, we create a look-up table, shown in Table 1, to "calculate" adjusting data.

VII. SIMULATION

We let $f_i = 1100\text{Mhz}$, $\mu = 10^6\text{Mhz/s}$, $T_0 = 100\mu\text{s}$, $B = 100\text{Mhz}$.

A. Bandwidth

Fig.3 to Fig.6 show spectrum graphs of the integrated signals. Signal in Fig.3 is radar LFM Signal. Integrated signal in Fig.4 to Fig.6 respectively have 20, 50, 100 symbols in a pulse duration period. According to (11), their corresponding bandwidths are approximately $1.004B$, $1.01B$, $1.02B$. Compared with original LFM signal, integrated signal after modulation almost has a same bandwidth.

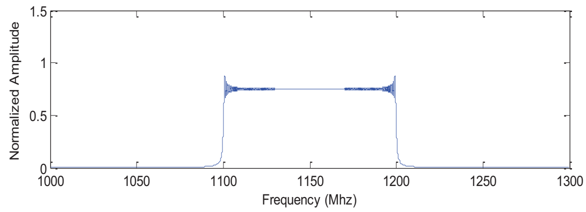

Figure 3. Radar LFM Signal

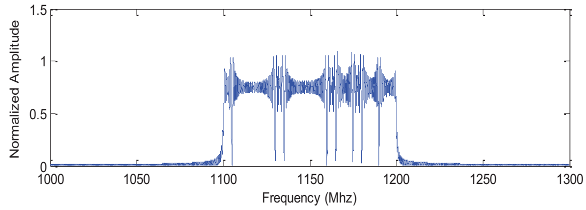

Figure 4. Integrated Signal, M=20

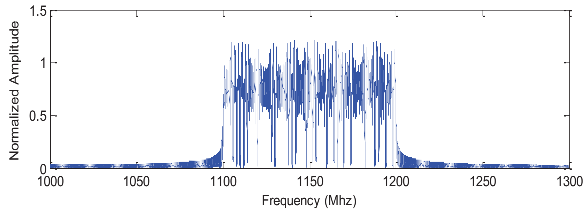

Figure 5. Integrated Signal, M=50

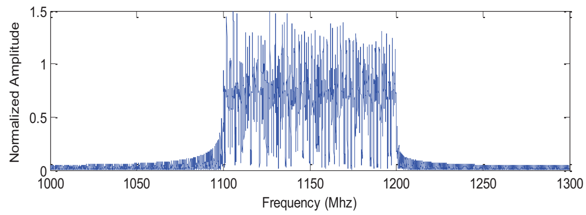

Figure 6. Integrated Signal, M=100

B. Symbol Period & Impact of Doppler Phenomenon on It

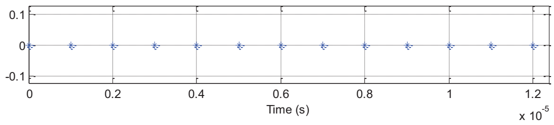

Figure 7. Integrated signal without Doppler frequency

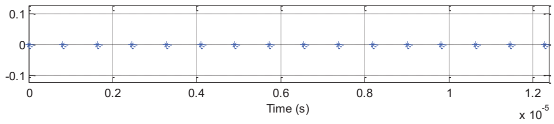

Figure 8. Integrated signal with Doppler frequency

Fig.7 and Fig.8 show points' values at the edges of each symbol period in integrated signals without and with Doppler frequency. We set $M = 100, v = 3 \times 10^7 \mathrm{m/s}$. According to (17), corresponding $T_d{}'$ is $9/11\mu s$.

C. Bit Error Rate

BER

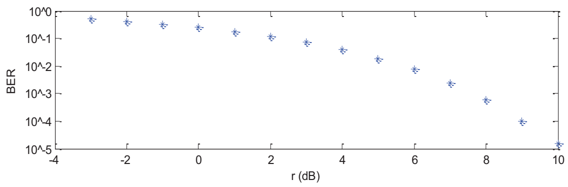

Figure 9. BER

Fig.9 shows curve of the integrated system's BER which is calculated with 1×10^8 symbols. The simulation result shows that the integrated system is able to perform communication function with an acceptable BER.

D. Adjusting Data

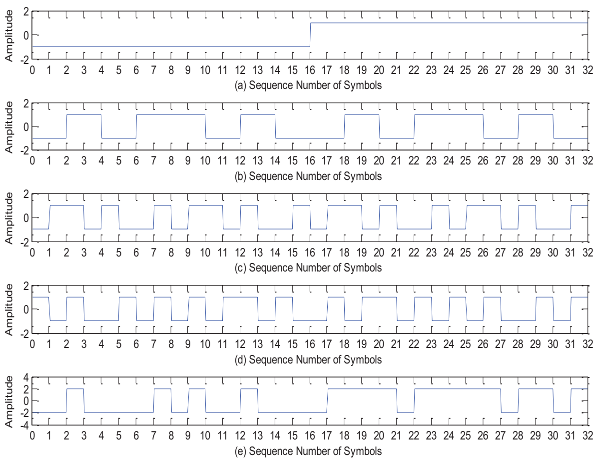

Figure 10. Baseband waveform

Fig.10 (a)-(d) show the baseband waveform of the four channels. Fig.10 (e) shows the baseband waveform after combination. In the simulation, we consider all the possible communication data groups. Data in Channel 1-3 are set as [—1 —1 —1 —1 1 1 1 1], [—1 —1 1 1 —1 —1 1 1], [—1 1 —1 1 —1 1 —1 1]. According to (26) and (27), adjusting data in the fourth channel is [—1 1 1 —1 1 —1 —1 1]. The simulation confirms the validity of adjusting data.

VIII. CONCLUSION

推断

Constraint conditions to select symbol period are deduced from the mathematic expression of LFM signal. Key properties of this integration waveform are analyzed and simulated with specific parameters. Basic communication requirements including bit rate and bit error rate can be met by this integrated waveform, the spectrum width of which is nearly equal to that of LFM signal. Symbol period changes and keeps equal to each symbol when influenced by Doppler frequency. And multiplexing technology and adjusting data disguise the communication data since there is no difference between the integrated waveform transporting communication data of three channels and its sub-signal.

通信: ① Bit Rate
② BER (Bit Error Rate)

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