Waveform Design and Analysis for Radar and Communication Integration System

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Abstract

Nowadays integration of electronic platforms has been a new research area, in which the radar and communication integration system is becoming a hot topic. Aiming to solve the incompatibility of signal design between the radar and communication applications, and followed by the principle of signal energy sharing, a radar and communication integration system based on random stepped frequency waveform is proposed. The transmission information is modulated on the carrier frequency, which accomplished the communication function without affecting the imaging radar performance. The radar imaging is mainly accomplished using Compressed Sensing theory. Simulations and analysis prove its feasibility.

1 Introduction

Along with the increasing threats to combat platform, the electromagnetic environment is becoming more and more complex. It is needed to equip more and more electronic devices for radar, communication, navigation and electronic warfare appliance. However, these devices take up the some effective space in of the combat platform, weakening the mobility, and the electromagnetic effects between among different systems may also affect their individual performance. To solve these problems, the traditional method is to optimize each system respectively, such as reducing the device's size, weight and power consumption. However, in many cases, the potential to optimize these indicators is limited. Therefore, it has becoming a new research area to constitute the integrated system combining different types of electronic equipment on the basis of advanced electronic technology.

Since 2005, Raytheon and Northrop Grumman from the United States have been using AN/APG77 airborne active phased array radar and radar-communication modem to achieve data transmission with 274 M bit/s high speed[1]. And accordingly, they put forward a new concept named as "radar communication data link", which is actually a proposed radar-communication integration solution based on Shared signal. The so-called Shared signal refers to a kind of signals with multiple functions, which can realize sharing transmitting energy of the integrated electronic warfare system and further improving the electronic system integration performance. For this type of radar-communication integration system, the main function is to make the integration signal accomplish target detection, radar imaging and efficient information transmission at the same time.

In the design of Shared signal, the method of superposition of radar signals and communication signals is a simple solution [2]. However, the implementation difficulty lies in the separation between radar signals and communication signals. In the literature [3] a communication system including encoder, encryption processor, modulation device, etc., is added at the transmitting end, and a group of radar & communication signal separator, communication signal processor and radar signal processor are added at the receiving end. Nijsure [4] adopts different pulse delay to represent different binary data realizing the effective information transmission. While Chirag [5] proposes to use different initial frequency of Chirp signals for data transmission. However a Chirp signal only represents 1 bit of binary data, where the data transmission rate is very low. Li Xiaobai [6] further proposes multi-carrier wave Chirp signal based on frequency modulation which improves the data transmission rate. Chen [7]extents the integration of radar communication concept to the radar-radio network, and introduces the existing cognitive wireless networks to accomplish feedback.

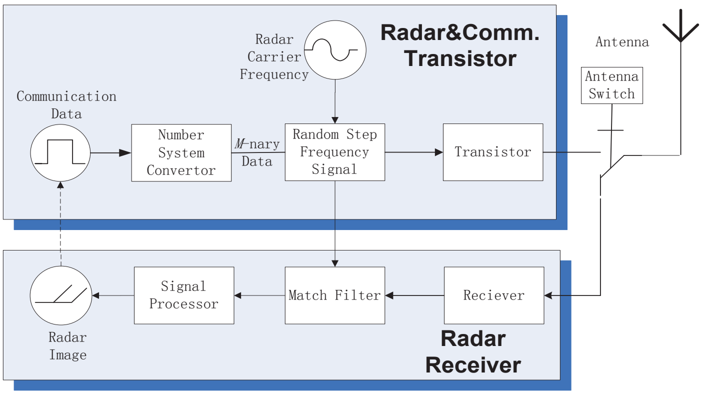
On the basis of the above literature, the paper designs a radar& communication integration solution based on random step frequency signal. In this scheme, the carrier frequency of radar signal is used for modulating communication information and realizing high-speed transmission, without influencing the performance of the high resolution radar imaging. At last, preliminary discussion on communication velocity and bit error rate for the integration system are provided.

2 Design of Radar and Communication Integration System

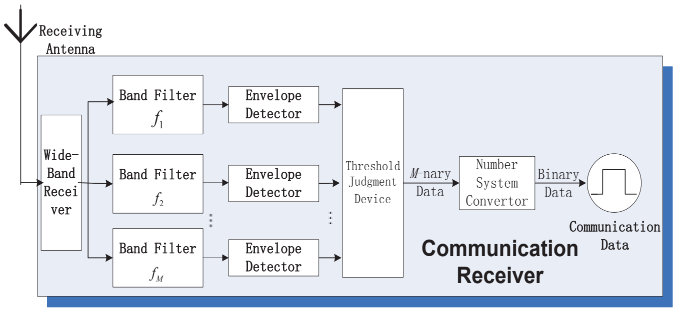
Radar communication integration system need to satisfy both radar and communication functions, and the analysis of radar and communication devices, functions and corresponding requirements should be conducted respectively. Therefore some basic principles are: firstly, the signal should satisfy the requirements such as easy to change the parameters, simple for wide band synthesis since the platform of the system is developed on the basis of traditional imaging radar; the second step is to modulate communication information on radar signals; finally, separation and respective processing of radar and communication signals should be achieved at the receiving ends to meet the radar and communication function respectively.

According to the above principles, the design in this paper is as follows: According to the demand of radar and communication task, choose proper independent information domain, and put the radar and communication information in different domain, forming one shared signal. The essence of this process is to find out possible information domain for information modulation, such as the signal's pulse delay, frequency hoops or phase. In this paper, frequency domain is chosen for information modulation domain, with wide band random step frequency signal as carrier, and radar communication integration system is finally designed.

As shown in Fig.1, the radar communication integration system based on Random Stepped-frequency waveforms (SFWs) can be divided into three parts, including radar&comm transmitter, radar receiver and communication receiver. The radar transmitter and receiver is located on the same platform (as A), and the communication receiver is located in another platform (as B). Platform A performs communication information modulation to integration signals when conducts radar detecting and imaging, and uses the same antenna to transmit the signals. Platform B receives integration signals and gets the communication information. In this way, the function of radar and communication integration is achieved respectively.



(a) Integration System Transistor and Radar Receiver



(b) Communication Receiver

Fig. 1. Radar and Communication Integration System based on Random Stepped Frequency Waveforms

The radar part is mainly designed on the basis of existing high resolution imaging radar, including radar signal generation, modulation signal generation and transmitter parts, as shown in Fig. 1(a). However, compared with existing radar transmitter, the difference lies in the modulation signal generation part where communication data is modulated on radar signal. The radar processing at the receiving end is similar to that of common radar, where the relevant processing of received signal and transmitting signal is performed and radar imaging is achieved. The radar imaging results can be used as communication data for transmitter input.

The scheme for communication receiver is inspired by the *M*-nary digital frequency modulation receiver, mainly including wide band receiving filter, band pass filter, envelope detector, threshold judgment, scale conversion and decoding unit, as shown in Fig. 1(b). The signals are received by wide band filter, detected by narrow band filter which is specially designed according to the presupposed frequency (consistent with the frequency of transmitter), and then compared to get the maximum as output in threshold judgment device. Since there is only one frequency of transmitted pulse each moment, which means there is only one maximum value in judgment each moment if ignore the problem of synchronization, the output of *M*-nary judgment device represents an *M*-nary data. Finally after conversion of number system and decoding the data can be obtained.

3 Random Stepped Frequency Waveforms and Imaging Method

3.1 Random Stepped Frequency Waveforms

Suppose that radar transmit random step frequency waveforms, i.e. every sub-pulse is random stepped frequency with time increment. It can be expressed as

$$S_m(t)=rect\left(\frac{t-mT_r}{T_p}\right)\exp\left(-j\pi\left(f_0+n_m\Delta f\right)t+\theta_m\right) \tag{1}$$

Where $rect(u)=\begin{cases}1, & |u|\le 1/2\\ 0, & |u|>1/2\end{cases}$. T_r, T_p, f_0 and Δf means pulse repetition period, pulse width, beginning frequency and stepped frequency respectively. $m=1,2,\ldots,M$ M is the number of a group pulses, and θ_m is the initial phase of the *m*th sub-pulse.

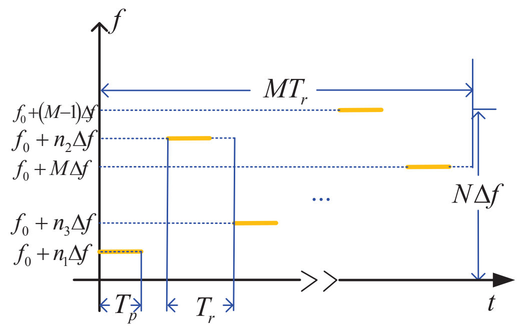


Fig. 2. Time-Frequency Plane of Random Stepped Frequency Waveforms

n_m is an element of a set $\{n_1,n_2,\ldots,n_m,\ldots,n_M\}$, which is constitute from the element random selected from the set $\mathbf{n}=\{1,2,...,N\}$, where N is pulse number for a group of pulses can be chosen. The bandwidth after synthesis will be smaller than $M\Delta f$ .Suppose that radar transmit random step frequency waveforms, then the echo received can be expressed in formula as

$$s_m(t,t_q)=\sum_{i=1}^{I}\sigma_i u\left(\frac{t-mT_r-2R_i(t_q)/c}{T_p}\right)\exp\left(j2\pi\left(f_0+n_m\Delta f\right)\left(t-2R_i(t_q)/c\right)+\theta_m\right) \quad (2)$$

where t represents fast time, t_q represents slow time, c denotes the speed of light, $R_i(t_q)$ denotes the distance between the i-th scatterer and radar at t_q time. From the in-synthetic aperture radar imaging model, we can get

$$R_i(t_q)=\sqrt{(vt_q-x_i)^2+h^2+y_i^2+x_i^2}=\sqrt{(vt_q-x_i)^2+R_i^2} \quad (3)$$

where Reference signal carrier frequency is $f_0+n_m\Delta f$, the distance is R_{ref}, then the reference signal can be expressed as

$$S_{ref}(t)=rect\left(\frac{t-mT_r-2R_i(t_q)/c}{T_{ref}}\right)\exp\left(-j\pi\left(f_0+n_m\Delta f\right)t+\theta_m\right) \quad (4)$$

Demodulate on received signal $s_m(t,t_q)$, and we get

$$\begin{aligned} s_{cm}(t,t_q)&=s_m(t,t_q)\cdot s_m^*(t)\\ &=\sum_{i=1}^{I}\sigma_i\, rect\left(\frac{t-mT_r-2R_i(t_q)/c}{T_p}\right)\exp\left(-j4\pi\left(f_0+n_m\Delta f\right)R_i(t_q)/c\right) \end{aligned} \quad (5)$$

where $s_{cm}(t,t_q)$ is the base frequency signals after demodulation. In order to reduce the sampling points, randomly sample one point in each sub-pulse echo signal, then all the needed information can be obtained. After the sampling the signal can be expressed as:

$$\begin{aligned} s_{cm}(t_q)&=\sum_{i=1}^{I}\sigma_i\exp\left(-j4\pi\left(f_0+n_m\Delta f\right)R_i(t_q)/c\right)\\ &=\sum_{i=1}^{I}\sigma_i\cdot\exp\left(-j4\pi n_m\Delta f\,R_i(t_q)/c\right)\cdot\exp\left(-j4\pi f_0\,R_i(t_q)/c\right) \end{aligned} \quad (6)$$

Notice that the phase of sampling signal $s_{cm}(t_q)$ consists of two parts, the first one keeps a linear relationship with n_m under a certain distance $R_i(t_q)$. And according to the literature [8], if the transmitted signals are step frequency modulation signal, i.e n_m is linear increased, and one-dimensional distance image of object can be obtained through inverse discrete Fourier transform where pulse compression is achieved. But if the transmitted signals are random step frequency modulated, namely n_m is randomly arranged, this method cannot be directly used. It's mainly because the synthesis bandwidth of random step frequency signal is not more than $M\Delta f$ ($< N\Delta f$). Further, considering the integration system uses frequency point to represent and identify communication information, the data may be unknown, but not necessarily satisfies a random distribution, which is very likely to be repeated. A large number of repeated radar signals of the same frequency can not only make radar bandwidth available for synthesis decreasing, which leading the resolution of distance decreasing, but also may cause imaging failure. To get the high resolution image , one radar imaging algorithm based on the the Compressed Sensing theory is proposed here.

3.2 Imaging Method based on Compressed Sensing Theory

In the last few years, the Compressed Sensing (CS) theory is introduced [8,9], which indicates that one can stably and accurately reconstruct nearly sparse signals from dramatically under-sampled data in an incoherent domain/ which indicates that reconstruction of approximately sparse signals from dramatically under-sampled data in an incoherent domain is available. With this prominent advantage, the CS theory has been widely used in many applications. Let $\mathrm{H}\in R^{N_1}$ denote a finite signal of interest. If there exists a basis matrix $\mathbf{\Psi}=\{\psi_1,\psi_2,...,\psi_{N_1}\}$ satisfying $\mathrm{H}=\mathbf{\Psi}\Theta$, where $\Theta=\{\theta_i\}$ is a K-sparse vector (namely, it can be approximated by its K largest coefficients or its coefficients following a power decay law with K strongest coefficients), then H can be reduced from N_1 -dimension to M_1 -dimension ($M_1\geq O(K\log(N_1))$), which is expressed as

$$\mathrm{U}^{M_1\times1}=\mathbf{\Phi}^{M_1\times N_1}\mathrm{H}^{N_1\times1}=\mathbf{\Phi}^{M_1\times N_1}\mathbf{\Psi}^{N_1\times N_1}\Theta^{N_1\times1} \quad (7)$$

where $\mathbf{\Phi}$ denotes a measurement matrix and U is the measurements vector of signal H. Generally, recovery of the signal H from the measurements U is an ill-posed problem because of $M_1 << N_1$. However, the CS theory tells us that when the matrix $\mathbf{\Phi\Psi}$ has the Restricted Isometry Property (RIP) [9], it is indeed possible to recover the K largest coefficients from the measurements U. The RIP is a significant consequence to ensure the convergence of the reconstruction algorithm, and a detail expression is given for it as follows:

$$1\text{-}\varepsilon_K\leq\frac{\|\mathbf{\Phi\Psi}\Theta\|_2}{\|\Theta\|_2}\leq1+\varepsilon_K, \qquad (\varepsilon_K>0) \quad (8)$$

When the RIP holds, the coefficients $\{\theta_i\}$ of the signal H can be reconstructed exactly from measurements U. It is difficult to validate if a measurement matrix satisfying the RIP constraints given in [10] directly, but fortunately, the RIP is closely related to an incoherency between $\mathbf{\Phi}$ and $\mathbf{\Psi}$, where the rows of $\mathbf{\Phi}$ do not provide a sparse representation of the columns of $\mathbf{\Psi}$ and vice versa. When $\mathbf{\Phi\Psi}$ satisfying the RIP constraints, the coefficients $\{\theta_i\}$ of the signal H can be reconstructed by solving the next optimization problem

$$\min\left\|\mathbf{\Psi}^{\mathrm{H}}\mathrm{H}\right\|_0 \quad \text{subject to} \quad \mathrm{U}=\mathbf{\Phi\Psi}\Theta \quad (9)$$

where $\|\cdot\|_0$ denotes l_0 norm, min(.) denotes the minimization. How to solve this optimization problem is an important aspect in CS theory. Because of the discontinuousness of the l_0 norm, it is difficult to solve (9) by gradient method. The smoothed l_0 (SL0) algorithm, which is using the continuous Gauss function to approach the l_0 norm, is proposed by [11]. This computational speed and computational accuracy is very high, so the SL0 algorithm is adopted to solve the above optimization problem. The computational speed and computational accuracy of the SL0 algorithm is very high, so it is adopted to solve the above optimization problem.

Assuming that the transmitted signal is the full-band SFW $s_n(t)$. The echo signal of $s_n(t)$ is processed by (5) and (6) in the aforementioned analysis, $s_{cn}(t_q)$ can be obtained, which is expressed as

$$s_{cn}(t_q) = \sum_{i=1}^{I} \sigma_i \exp\left(-j4\pi\left(f_0 + n\Delta f\right) R_i(t_q)/c\right) \tag{10}$$

We can perform IDFT for $s_{cn}(t_q)$ about n, the range profiles of the observed scene can be obtained

$$\begin{aligned} S_c(t_q) &= \underset{n}{\mathrm{IDFT}}[s_{cn}(t_q)] \\ &= \sum_{i=1}^{I} \delta\left[n - \frac{2N\Delta f R_i(t_q)}{c}\right] \cdot \exp\left(-\frac{j4\pi f_0 R_i(t_q)}{c}\right) \end{aligned} \tag{11}$$

where, $\mathrm{IDFT}(\cdot)$ denotes the IDFT function and $\delta(\cdot)$ is the impulse function in the discrete time domain. Let $\mathbf{X} = \left\{s_{c1}(t_q), s_{c2}(t_q), ..., s_{cN}(t_q)\right\}$, $\Theta = S_c(t_q)$. The above IDFT processing can be rewritten as matrix expression

$$\Theta = \mathbf{D}_N^{-1}\mathbf{X}^{\mathrm{H}} \tag{12}$$

where, $\mathbf{D}_N$ is a discrete Fourier transform (DFT) matrix, which can be expressed as

$$\mathbf{D}_N = \frac{1}{N}\begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & W_N^1 & W_N^2 & \cdots & W_N^{(N-1)} \\ 1 & W_N^2 & W_N^4 & \cdots & W_N^{2(N-1)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & W_N^{(N-1)} & W_N^{2(N-1)} & \cdots & W_N^{(N-1)^2} \end{bmatrix} \tag{13}$$

where, $W_N = \exp\left(-j2\pi/N\right)$. As to the echo signals of the sparse SFWs, let $\mathrm{Y} = \left\{s_{c1}(t_q), s_{c2}(t_q), ..., s_{cM}(t_q)\right\}$, From a CS theory point of view, the set Y can be viewed as a low-dimensional measurements of the set X, i.e.

$$\mathbf{Y}^{\mathrm{H}} = \mathbf{\Phi} \cdot \mathbf{X}^{\mathrm{H}} \tag{14}$$

where, $(\cdot)^{\mathrm{H}}$ denotes conjugate transposition, $\mathbf{\Phi} = \left\{\phi_{m,v}\right\}$ is a M-by-N random partial unit matrix. And

$$\phi_{m,v} = \begin{cases} 1, & m = 1,...,M, v = n_m \\ 0, & \text{others} \end{cases} \tag{15}$$

That is, the elements in each row vector of $\mathbf{\Phi}$ are 0, besides the n_mth element is 1. The physical meaning of $\mathbf{\Phi}$ is extracting the data from the full data. And the position of "1" is assigned according to the residual frequency points. As discussed in reference [12], the randomly selected partial Fourier matrix satisfies RIP. In this paper, the measurement matrix $\mathbf{\Phi}$ designed is a random partial unit matrix and the basis matrix $\mathbf{\Psi}$ is a DFT matrix. Thus their multiplication $\mathbf{\Phi\Psi}$, which is equal to the randomly selected partial DFT matrix satisfies RIP. Then we can obtain $\mathbf{\Theta}$ by solving the following expression

$$\min\left\|\Theta\right\|_0 \ \text{ s.t. } \mathbf{Y}^{\mathrm{H}} = \mathbf{\Phi} \cdot \mathbf{\Psi} \cdot \Theta \tag{16}$$

The above optimization problem is solved by the SL0 algorithm, and the range profiles of the observed scene can be obtained, which is expressed as

$$s_c(l, t_q) = \sum_{i=1}^{I} \sigma_i \delta\left(l - 2N\Delta f\, R_i(t_q)/c\right) \exp\left[-j4\pi f_0\, R_i(t_q)/c\right] \tag{17}$$

After this process, all the range profiles of the imaging scene can be observed. And the signal process in the azimuth direction is similar as conventional SAR imaging method [13].

4 Performance Analysis of Communication System

From the perspective of data transmission, the main performance indicators of communication system are the effectiveness and reliability of the system. The effectiveness of system usually refers to the transmission rate of data, represented by bit rate, while the reliability usually refers to the quality of transmission, represented by bit error rate. The radar communication integration system proposed in this paper adopt the radar signal frequency points as the carrier of communication data, which is different with the common communication system, therefore the performance indicators should be analyzed specially.

4.1 Transmitting Velocity

Generally the data transmission rate of communication systemcan be expressed in formula as:

$$S = \left(1/T\right)\log_2 N \tag{18}$$

where S denotes bit rate, T denotes pulse width, N denotes the number of states of a single pulse. From the theory of the integrated system, as can be concluded from Fig.1(b), the effective number of states which can be represented by a single pulse is the number of available frequency points M. The pulse repetition period is T_r, then the data transmission rate can be described as:

$$S = \left(1/T_r\right)\log_2 M \tag{19}$$

4.2 Bit Error Rate Estimation

When conducting analysis on the receiving data quality, it can be assumed that in the received random step frequency waveforms, there is only one path of M outputs of band-pass filter containing signal , other M-1 outputs only noise. It's also reasonable to assume that noise in all the paths are limited gauss noise independent of each other and their envelops subscribe to Rayleigh distribution. The probability that M

paths of noise are all small than a certain threshold level can be expressed as:

$$P(h)=[1-p(h)]^{M-1} \quad (20)$$

where $P(h)$ denotes the probability of noise of one path surpassing the threshold level h, subscribing to Rayleigh distribution, then we can get

$$p(h)=\int_h^{\infty}\frac{A}{\sigma_n^2}\mathrm{e}^{-A^2/2\sigma_n^2}dA=\mathrm{e}^{-h^2/2\sigma_n^2} \quad (21)$$

where A is noise envelope, σ_n^2 denotes the output noise power. Obviously, misjudgment will not occur if the noise level of M-1 paths are all small than threshold h; otherwise if one or more than one paths surpass the threshold h, misjudgment will occur .Therefore the probability of misjudgment is

$$\begin{aligned}P_e(h)&=1-[1-P(h)]^{M-1}=1-\left[1-\mathrm{e}^{-h^2/2\sigma_n^2}\right]^{M-1}\\&=\sum_{n=1}^{M-1}(-1)^{n-1}\binom{M-1}{n}\mathrm{e}^{-nh^2/2\sigma_n^2}\end{aligned} \quad (22)$$

where $\binom{M-1}{n}$ is the binomial coefficient, which is related to threshold value h.

From the relationship between bit error rate and error rate, the bit error rate can be further obtained:

$$P_b=\frac{2^{k-1}}{2^k-1}P_e=\frac{P_e}{2\left(1-(1/2)^k\right)} \quad (23)$$

It can be concluded from expression (12) that the bit error rate increases with k's incensement. In other words, the increase of communication channel number will bring the increase of bit error rate.

5 Simulations

5.1 Analysis of Radar Image

Suppose that the target is composed of 6 scatterers. The basic operation parameters of radar communication integration system are as shown in Tab.1. The settings consult the parameters of conventional step frequency radar.

Tab.1 Parameters of Radar& Communication Integration System

Carrier frequency	5 GHz
Sub-pulse frequency interval	3MHz
stepped Frequency number	64
Synthesis bandwidth	192MHz
Sub-pulse width T_p	1μs
Sub-pulse repetition interval T_r	50μs

To conduct comparison, two-dimensional SAR image of radar target containing all the frequency step signals under ideal conditions, namely complete bandwidth synthesis 192 MHz is shown in Fig.4.

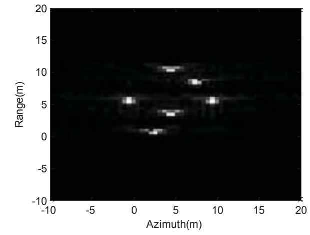
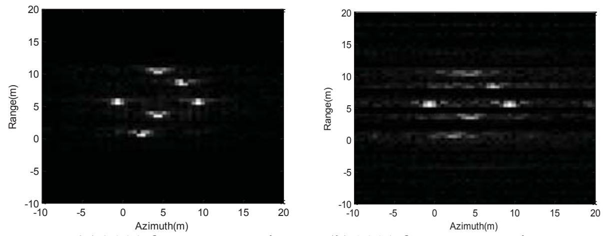


Fig. 3. Full Bandwidth Imaging Results

It can be seen from Fig.3, it can gain a high resolution in range and direction (about 1 meter) with the utilization of full bandwidth original step frequency waveforms.



(a)30% frequency points (b)10% frequency points

Fig. 4. Compressed Sensing Imaging Results

Fig.4(a) illustrates the compressed sensing imaging results of random step frequency waveforms designed in this paper, where only 30% frequency points are randomly utilized. It can be seen that about resolution in range and direction 1 meter can still be obtained. Therefore, we can conclude that when using compressed sensing technology in radar imaging, high quality SAR image can still be obtained even if the pulse number of frequency points is limited. However, when pulse number of frequency points is too few, the imaging process fails as is shown in Fig.4(b), where only 10% frequency points are available. Therefore, to guarantee the restoration of data, a floor level of frequency points should be set considering the sparse degree of scene.

5.2 Analysis of Communication Efficiency

In the valuation of communication system performance, the basic parameters are the same as Tab.1 of radar transmitter. The sub-pulse repetition period is 50 μs, and each sub-pulse can transmit k bit, and the transmission velocity is 20*k Kbit/s. If $k=\log_2 M$ and $M=64$, the transmission velocity will be 120 K bit/s.

From formula (12) and (13), the bit error rate of transmission system is related with the number of receiving channel, i.e., it is related with carrier frequency number M of radar system. When M is chosen as 2,16 and 64, and Monte Carlo simulation is done for transmitting a radar

SAR image with 300*200*8 bit, we get the bit error rate(BER) of with different *M*-nary system, as shown in Fig.8.

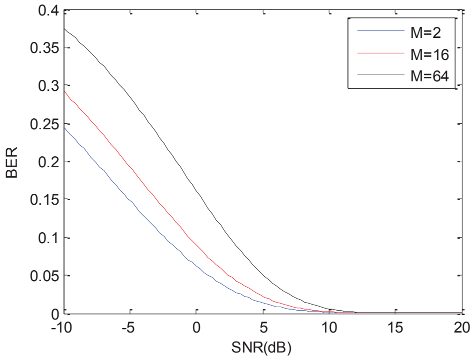


Fig. 5. BER of Communication Receiver at Different N-nary System

It is also shown in Fig.8 that followed with the increase of SNR, the BER of three systems is decreasing. Another influencing factor is *M*. The BER is smaller with a small *M*. For example, the BER of the receiver is about 1.4e-5 when *M*=2, and it is almost 1.7e-4 when M=64.

6 Conclusions

This paper designs a radar&communication integration system based on random step frequency waveforms. The thought of utilizing carrier frequency to modulate communication information without influence on the imaging performance of high resolution radar is put forward. The radar imaging function relies on random step frequency waveforms and utilization of Compression Sensing imaging method. In addition, the paper evaluates communication performance of integration system utilizing this kind of waveforms, estimated transmission rate and error bite rate. Simulations testify the good performance in completing radar and communication tasks.

Acknowledgement

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References

[1] Tavik G C, Hilterbrick C I,Evins J B, et al. The Advanced Multifunction RF Concept[J]. *IEEE Transaction on Microwave Theory and Techniques*, 2005, 53(3):1009-1020

[2] Shintiki Mannori. A dual-use system for radar and communication with complete complementary code[C].The 11th Radar Symposium (IRS), Japan,2010:1-4

[3] Mark Roberton, E. R. Brown. Integrated radar and communications based on chirped spread spectrum techniques[J]. *IEEE MTT S*, 2003:611-614

[4] Yogesh Nijsure, Yifan Chen, etc. Novel System Architecture and Waveform Design for Cognitive Radar Radio Networks[J]. *IEEE Transactions on Vehicular technology*, VOL.61, No.8, 2012: 3630-3641

[5] Chirag P, Prakshep M, et al. Chirp Based Multiple Access Technique using Fractional Fourier Transform[C]. IEEE Information, Communications& Signal Processing, 2007 6th International, 2007:1-4

[6] Li Xiaobai, Yang Ruijuan, Cheng Wei. Integrated Radar and Communication Based on Multicarrier Frequency Modulation Chirp Signal[J].*Journal of Electuonics&Information Technology(Chinese edition)*, 2013,35(2):406-412

[7] Y. Chen and P Rapjic. Ultra-wideband cognitive interrogator network: Adaptive illumination with active sensors for target localization[J]. *IET Commun*., vol. 4, no. 5, pp. 573-584, Mar. 2010

[8] Donoho D L. Compressed Sensing. *IEEE Trans. on Information Theory*, vol. 52, no. 4, pp. 1289-1306, Apr. 2006.

[9] Candes E., Romberg J., and Tao T.. Robust uncertainty principles: Exact signal reconstruction from highly incomplete frequency information. *IEEE Trans. Inform. Theory*, vol. 52, no. 2, pp. 489-509, Feb. 2006.

[10] Baraniuk R. A lecture on compressive sensing. *IEEE Signal Processing Magazine*, vol. 24, no. 4, pp. 118–121, Jul. 2007.

[11] Mohimani G. H., Babaie-Zadeh M and Jutten C. A fast approach for overcomplete sparse decomposition based on smoothed norm. *IEEE Trans. on Signal Processing*, vol. 57, no. 1, pp. 289-301, Jan. 2009.

[12] Candes E. and Tao T. Near optimal signal recovery from random projections: Universal encoding strategies. *IEEE Trans. on Information Theory*, vol. 52, no. 12, pp. 5406-5425, Dec. 2006.

[13] Yang J G, Huang X T, Jin T, et al. Synthetic aperture radar imaging using stepped frequency waveform [J]. *IEEE Trans. Geosci. Remote Sens.*, 2012,50,(5),pp. 2026-2036.

[14] Feng Z, Qun Z, Qiang L, Ying L. Reconstruction of Moving Target's HRRP Using Sparse Frequency-Stepped Chirp Signal[J]. *IEEE Sensor Journal*. 2011, 11(10): 2327-2334.