Multi-sub-channels Spread Spectrum Anti-interference System and its Performance

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Abstract—Based on direct sequence spread spectrum, M-ary spread spectrum, multicarrier code division multiple access (CDMA), orthogonal frequency division multiplexing (OFDM) technology, etc., a new wireless communication anti-interference system, i.e. multi-sub-channels spread spectrum (MSCSS) system, has been proposed here. Transmitting end of the system processes spread spectrum twice using channel pseudo-random code and sub-channel pseudo-random code. Each bit of digital baseband signal was transmitted, through time-division manner, with 16 spread spectrum sub-channel signals. Pseudorandom codes of each spreading sub-channel are orthogonal to each other, so is the center frequency. Meanwhile, receiving end processes every bit of information in manner of parallel accumulation and adaptive threshold decision, to achieve receiving and processing of relevant multi-sub-channel spread spectrum signals, thereby improving noise immunity of communication system. Theoretical analysis and simulation results show that anti-interference capacity of the system is superior to traditional hybrid spread spectrum communication system. In detail, at the same information rate and the same bandwidth, its interference tolerance is higher than that of the hybrid DS/FH spread spectrum system by 5 dB.

Keywords-wireless communication; anti-interference; multi-sub-channel spread spectrum; orthogonal frequency division multiplexing; M-ary spread spectrum

I. INTRODUCTION

Electromagnetic environment has recently been increasingly complex and electronic information confrontation has been intensified, which require updating anti-interference capability of VHF communications, satellite communications and data links. Currently, the main technologies to improve data link anti-jamming capability are the follows: improving code rate of the DSSS signal, increasing code length, optimizing the properties of spreading code [1-3], accelerating hopping signal, increasing hopping points, optimizing hopping pattern [4-6], adaptive interference cancellation technique [7], hybrid spread spectrum [8-10], and so on. These techniques are based on the traditional spread spectrum technology to improve anti-jamming capability of the system, but they still cannot meet the higher requirements of certain anti-jamming system.

The combination of spread spectrum technology and OFDM technology could provide a more reliable SS-OFDM communication link [11-14]. Most of the related studies only directly apply spread spectrum methods to OFDM, which mainly embarks on how to improve the BER performance of transmission signal under multipath interference or other non-anthropogenic interferences, with the absence of anthropogenic interferences. In this paper, based on multi-band spread spectrum, direct sequence spread spectrum, orthogonal frequency division multiplexing and multi-carrier code division multiple access (MC-CDMA) technology, etc., we have developed a novel anti-interference wireless communication system, i.e. multi-sub-channels spread spectrum (Multi Sub-channels Spread Spectrum, MSCSS) anti-jamming system.

II. SYSTEM COMPOSITION

Fig. 1 shows the basal elements of system, in which elements of the MSCSS system consists of sending end and receiving end.

The sending end is composed of digital signal source, composite coding unit, electronic anti-interference (ECCM) transmitting unit, channel transmitter, antenna, clock control unit, power supply and other components. Where the composite coding unit contains modulus binary addition, 64-bit pseudo-random sequence generator, serial/parallel conversion, etc. ECCM transmission unit includes channel coding logic selector, 16 sub-channels generator, filter, combiner, etc.

The receiving end comprises antenna, channel receiver, ECCM receiving unit, composite decoding unit, synchronization unit, information sink, power supply, and so on. Where the ECCM receiving unit consists of splitter, 16 correlated processing sub-channels, 16 correlated peak detection and decision circuits, correlated processing sub-channel decoding logic controller, filters and other components.

Information output rate from the source is assumed to be 3.2 kb/s, the data at sending end are transmitted via the composite encoding unit and then the spectrum is spread using 64-bit pseudorandom sequence, to be converted into pseudo random signal. This serial signal is then converted into four parallel signals, which are subsequently sent to the ECCM transmitting unit. Hence, 16 spread-spectrum sub-channels signals are generated, to form IF (intermediate frequency) multi-sub-channels spread spectrum signals. They are sent to the channel transmitter unit and finally radiated by the antenna.

The antenna, at receiving end, converts the received signals, via channel receiving unit, into IF multi-sub-channels spreading signals. Then, these signals are received and processed by ECCM receiving unit. On one hand, according to the detection threshold of relevant peak, correlated peaks are extracted and sent to the synchronization unit to generate synchronization signals. On the other hand, the processing sub-channels decoding logic controller generates a decoded signal, through composite decoding unit, to obtain information at a rate of 3.2 kb/s which is sent to the information sink.

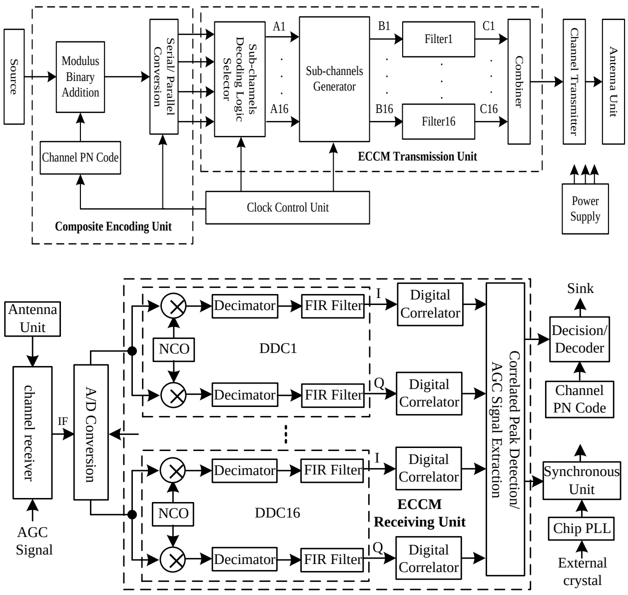

Figure 1. Basic composition of the system.

III. MATHEMATICAL MODEL OF THE SYSTEM

A. Mathematical model of the sending end

The mathematical model of the sending end is shown in Fig. 2. The input data at a rate of $1/T_s$ are multiplied by PN code of the channel with a higher rate, to accomplish composite encoding spread spectrum, so that the data rate becomes MK/T_s. And these data are divided and grouped by k bit, i.e., a data symbol of $M = 2^k$ number system. Each of the data symbol corresponds to M orthogonal spreading sub-channels which are formed by individual BPSK modulation of M orthogonal spreading sequences sub-channels belonging to orthogonal spread spectrum code set. Each symbol selects their own orthogonal spreading sub-channels according to the mapping coding principles, and then they are transmitted successively. Finally, RF unit transmits these symbols.

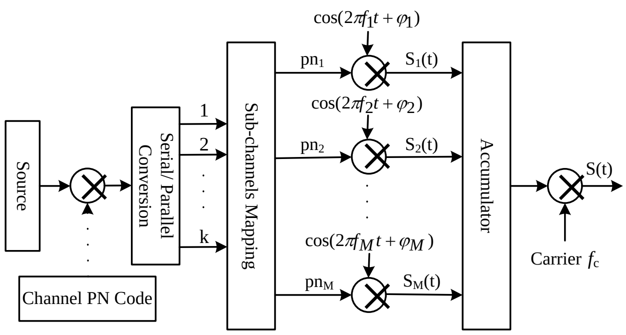

Figure 2. Mathematical model of the sending end.

It is assumed that symbol period of the digital signal source is T_s; the symbol magnitude of the q^{th} signal is A_q; the power $P_q = A_q^2/2$; code length of each orthogonal sequence in the orthogonal code set is N and the period is T_c; carrier frequencies $f_\lambda (\lambda = 1, 2, \ldots, M)$ of M modulators are an orthogonal frequency set. As a result, $T_c = T_s/MN$.

Assuming that waveform of a spreading code chip is a rectangular pulse p(t). Namely

$$p(t) = \begin{cases} 1, & 0 \le t \le T_c \\ 0, & others \end{cases} \tag{1}$$

The λ^{th} spreading sequence of the orthogonal code set is the follows

$$\boldsymbol{C}_\lambda = \{C(\lambda, i)\} \quad C(\lambda, i) \in [+1, -1] \tag{2}$$

where $\lambda = 1, 2, \ldots, M; i = 1, 2, \ldots, N$.

Thus, the output signal at sending end can be expressed as

$$\begin{aligned} \boldsymbol{S}(t) = \sum_{q=-\infty}^{+\infty} \sum_{\lambda=1}^{M} \sum_{i=1}^{N} \sqrt{2P_q} \cdot C(\lambda, i) \cdot \\ p(t - \frac{iT_s}{MN} - \frac{\lambda T_s}{M}) \cdot \cos 2\pi f_\lambda t \end{aligned} \tag{3}$$

B. Mathematical model of receiving end

Receiving end mathematical model is described in Figure 3. After the received signals are mixed, IF signals are thus formed, which are detected simultaneously using M non-coherent quadrature detectors. On the basis of orthogonality of spreading sub-channels and correlation of spreading codes, a correlated peak is detected within each timeslot of the spreading sub-channel. If the system can extract when 1 bit of information is transmitted, spreading sub-channels will be processed with inverse mapping operation based on the extracted correlated peaks. The results are sent into local channel PN code correlator, and thus one-bit of information will be recovered. As a result of the orthogonal detection method, the influence of each sub-channel carrier phase can be reduced, so it will be necessary to merely estimate and track the carrier frequency, rather than carrier phase, of sub-channels, thus reducing the operation difficulty of synchronization unit at receiving end.

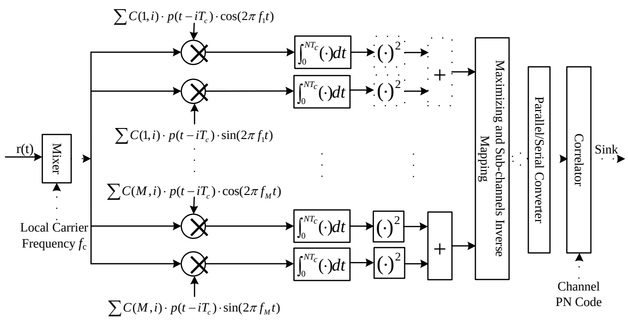

Figure 3. Mathematical model of the receiving end.

IV. ANTI-JAMMING PERFORMANCE ANALYSIS

At present, interference types towards communication system are broadband noise, partial band interference, continuous wave interference, pulse interference, etc. In the following part, broadband noise exemplifies the anti-interference performance of the multi-sub-channels spread spectrum anti-jamming system, and then compared with that of DS/FH system.

A. Anti-wideband-noise performance

Assuming that the system has been synchronized, the input signal at receiving end can be expressed as:

$$\boldsymbol{r}(t) = \boldsymbol{S}(t) + \boldsymbol{n}(t) \tag{4}$$

Where $n(t)$ stands for broadband noise, the above formula can be expressed as:

$$\boldsymbol{r}(t) = \boldsymbol{S}(t) + \sqrt{2}\boldsymbol{n}_I(t)\cos 2\pi ft - \sqrt{2}\boldsymbol{n}_Q(t)\sin 2\pi ft \tag{5}$$

Where $n_I(t)$ and $n_Q(t)$ are mutually independent normal low-pass noise, with a bilateral power spectral density of $N_0/2 + N_j/2$. N_0 is unilateral power spectral density of thermal noise, while N_j is unilateral power spectral density of interference signal.

$r(t)$ can be expressed as follows, according to the combination of equation 3 and 5:

$$\begin{aligned} r(t) = &\sum_{q=-\infty}^{+\infty}\sum_{\lambda=1}^{M}\sum_{n=1}^{N}\sqrt{2P_q}\cdot W_L(\lambda,n)\cdot p_c\left(t - \frac{nT_s}{MN} - \frac{\lambda T_s}{M}\right)\cdot \\ &\cdot\cos 2\pi f_\lambda t + \sqrt{2}n_I(t)\cos 2\pi ft - \sqrt{2}n_Q(t)\sin 2\pi ft \end{aligned} \tag{6}$$

Through calculations, the IF component is given as

$$\begin{aligned} x(t) = &\sum\sum\{\rho_i\left(t - \frac{iT_c}{M}\right)\cdot\cos[\omega_{IF}t + \theta_d(t)] \\ &+[\sqrt{2}n_I(t)\cos\omega_{ki}t - \sqrt{2}n_Q(t)\sin\omega_{ki}t] \\ &\cdot 2\cos[(\omega_i + \omega_{IF})t + \theta_s(t)]\} \end{aligned} \tag{7}$$

Where $\rho_i(\cdot)$ is autocorrelation function of the PN code of each sub-channel; $\theta_s(t)$ and $\theta_d(t)$ are random modulation phase.

At the receiver, output power spectrum of each sub-channel is expressed as follows:

$$\begin{aligned} S_{R\lambda}(f) = &\frac{2}{W_s}Sinc^2\left[\frac{2}{W_s}(f - f_{ki} - f_{IF})\right] \\ &+\frac{2}{W_s}Sinc^2\left[\frac{2}{W_s}(f + f_{ki} + f_{IF})\right] \end{aligned} \tag{8}$$

Where W_s is the spectrum width of the λ^{th} spreading sub-channel. The noise bilateral spectral density near $f = \pm f_{IF}$ is as follows:

$$\begin{aligned} &N(f) * S_R(f) \\ &= \frac{N_j + N_0}{W_s}\int_{f_{ki}-\frac{W_s}{2}}^{f_{ki}+\frac{W_s}{2}} Sinc^2\left[\frac{2}{W_s}(f - \lambda + f_{ki} + f_{IF})\right]d\lambda \\ &+\frac{N_j + N_0}{W_s}\int_{-f_{ki}-\frac{W_s}{2}}^{-f_{ki}+\frac{W_s}{2}} Sinc^2\left[\frac{2}{W_s}(f - \lambda - f_{ki} - f_{IF})\right]d\lambda \end{aligned} \tag{9}$$

Assuming that $\gamma' = f - \lambda + f_{ki} + f_{IF}$, $\gamma = f - \lambda - f_{ki} - f_{IF}$, the above equation can be expressed as

$$\begin{aligned} N(f) * S_R(f) \approx &\frac{N_0 + N_j}{W_s}\int_{f+f_{IF}-W_s/2}^{f+f_{IF}+W_s/2} Sinc^2\left(\frac{2\gamma'}{W_s}\right)d\gamma' \\ &+\frac{N_0 + N_j}{W_s}\int_{f-f_{IF}-W_s/2}^{f-f_{IF}+W_s/2} Sinc^2\left(\frac{2\gamma}{W_s}\right)d\gamma \end{aligned} \tag{10}$$

The convolution in eq10 is an even function of variable f, so either positive or negative frequency can be used to calculate. Assuming that $f_{IF} \gg W_s$, positive frequency component of the above equation is the following:

$$N(f) * S_R(f) \approx \frac{N_0 + N_j}{W_s}\int_{f+f_{IF}-W_s/2}^{f+f_{IF}+W_s/2} Sinc^2\left(\frac{2\gamma'}{W_s}\right)d\gamma' \tag{11}$$

In this system, the bandwidth of sub-channel is much greater than that of digital baseband signal and the matched filter also satisfy this condition. Therefore, adjacent to the point where $f = \pm f_{IF}$, noise bilateral spectral density can be described by the constant $N_n/2$ given in eq12:

$$\begin{aligned} &N_n/2 = N(f_{IF}) * S_R(f_{IF}) \\ &= \frac{N_0 + N_j}{W_s}\int_{-W_s/2}^{W_s/2} Sinc^2(2\gamma/W_s)d\gamma = \frac{k\cdot(N_0 + N_j)}{2} \end{aligned} \tag{12}$$

Where k is spread spectrum modulation function; integral of eq12 represents the area under the main lobe of $\mathrm{sinc}^2(2\gamma/W_s)$. On condition that $k = 1$, eq12 can be changed into

$$N_n/2 = \frac{N_0 + N_j}{2} \tag{13}$$

Digital model of the system shows that a bit of signal is composed of M sub-channels which function at different time slots, and each sub-channel occupies one time slot. Quasi-static method was used to calculate the output noise from near-IF matched filter. Namely, only one time slot was taken account of and, within each time slot, the bilateral spectral density of output noise from near-IF matched filter is $N_n/2$. Because we analyzed broadband noise, near IF, the spectral density of matched filter output noise is a constant regardless of time slot. Therefore, the output of band-pass filter, i.e., the input signal format of coherent detection unit, can be expressed as follows

$$y(t) = \sum_{\lambda=1}^{M}\rho_\lambda\left(t - \frac{\lambda T_s}{M}\right)\cdot\cos\left[\omega_{IF}t + \theta_d(t)\right] + n_n(t) \tag{14}$$

where $\rho_\lambda(\cdot)$ is the autocorrelation function of the λ^{th} sub-channel; $n_n(t)$ is band-limited white Gaussian noise with bilateral spectral density of $N_n/2$. At input end of the data demodulator, the broadband noise has the nature of receiver internal noise.

B. System bit-error performance analysis

Assuming the system receiving end has been synchronized, according to the receiving end model, the output of μ^{th} matched filter, i.e., symbol representing $1/M$ bit of information, could be given by

$$Z_\mu = \int_0^{NT_c}\boldsymbol{r}(t)\sum_{n=1}^{N}C(\mu,n)\cdot p(t - nT_c)\cdot\cos 2\pi f_\mu t dt \tag{15}$$

Simultaneous equations of 4 and 15 will give

$$Z_{\mu} = \begin{cases} NT_c\sqrt{2P_q} + Q(\lambda, r), \mu = \lambda \quad and \quad f_{\mu} = f_{\lambda} \\ Q(\mu, r), \mu \neq \lambda \quad or \quad f_{\mu} \neq f_{\lambda} \end{cases} \quad (16)$$

where $Q(\mu, r)$ is a Gaussian random variable with a mean of zero and variance of $NT_cN_0/4$.

The misjudgment probability of the j^{th} orthogonal code and orthogonal frequency is given as follows:

$$P_c(j) = [1 - P\{Z_j > (Z_1, \cdots Z_{j-1}, Z_{j+1}, \cdots, Z_M)/f_j\}] \cdot P(f_j) \quad (17)$$

where $P(f_j)$ is the misjudgment probability of the j^{th} frequency in orthogonal frequency set, i.e. $1/(M-1)$.

And

$$P\{Z_j > (Z_1, Z_2, \cdots Z_{j-1}, Z_{j+1}, \cdots, Z_M)/f_j\}$$
$$= \underbrace{\int_{-\infty}^{Z_j}\int_{-\infty}^{Z_j}\cdots\int_{-\infty}^{Z_j}}_{(M-1)} P\{Z/f_j\}dZ = [P\{Z_j > Z_x, x \neq j\}]^{M-1} \quad (18)$$

From eq16 and 18,

$$P_c(j) = \frac{1}{M-1} \cdot \{1 - [P\{Z_j > Z_x, x \neq j\}]^{M-1}\} \quad (19)$$

By the central limit theorem, when the orthogonal code length N is large enough, the distribution of Z can be approximated by a Gaussian process. And the variance and mean of $Z_j - Z_x$ is $\sigma^2 = NT_cN_0/4$ and $NT_c(P_q/2)^{1/2}$.

Thus,

$$P\{Z_j > Z_x, x \neq j\} = \int_0^{\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(y - NT_c\sqrt{P_q/2})^2}{2\sigma^2}} dy \quad (20)$$
$$= erf(\sqrt{E_b/N_0})$$

where erf (x) is the error function.

Simultaneous equations of 19 and 20 give

$$P_c(j) = \frac{1}{M-1} \cdot \{1 - [erf(\sqrt{E_b/N_0})]^{M-1}\} \quad (21)$$

Consequently, the misjudgment probability of the detection of M orthogonal codes and orthogonal frequencies can be expressed as

$$P_c = \frac{1}{M}\sum_{j=1}^{M} P_c(j) = P_c(j), j = 1, 2, \cdots, M \quad (22)$$

According to the system transmitter model, when M orthogonal codes and orthogonal frequencies are correctly detected, the system completes the transfer of one bit of information, and therefore error bit rate of the system under AWGN channel environment is the follows:

$$P_b = P_c = \frac{1}{M-1} \cdot \{1 - [erf(\sqrt{E_b/N_0})]^{M-1}\} \quad (23)$$

V. PERFORMANCE SIMULATION

From the above analysis, broadband noise has the nature of receiver internal noise, so it could be replaced by a Gaussian white noise signal controlled by variable gain for the simulation. Parameters of the variable gain can be regulated with channel environment. Meanwhile, in the simulation, the criterion that whether the correlated peaks can be recovered in the sub-channels of the receiving end of system is the prerequisite of judging whether the system functions normally. Interference tolerance limit values were determined to characterize anti-jamming capability of the system.

Systemview simulation platform was employed to simulate a multi-sub-channels spread spectrum system, and parameters are the following: source rate is 3.2 kb/s; channel PN code length is 64; PN code chip rate of composite encoding unit is 204.8kchip/s; the number of sub-channels (M) is 16; sub-channel PN code length is 32; sub-channel modulation method is BPSK; sub-channel PN code chip rate is 1638.4kchip/s; bandwidth of sub-channel is 3.2768 MHz; signal bandwidth of the system is 27.8528 MHz. Carrier frequencies of each sub-channel are

$$f_i = 29.4912 + 1.6384 \times i(MHz), i = 0, 1, ..., 15 \quad (24)$$

Center frequency of the system is assumed to be 41.7792 MHz. A/D and D/A parameters are as follows: 14 bit; sampling rate is 131.072 MSPS; amount of sampling points is 104859; the system runs for a cycle; channel environment accords with Rice channel model; channel parameter is set to the state that S/N = 0dB; the Rice factor is 11 dB; coherence time is 125 μs.

Fig. 4 and Fig. 5 are the time-domain waveform and frequency spectrum, respectively, of the input signal at receiving end in the presence of broadband noise. It is observed that MSCSS signals are buried in broadband noise.

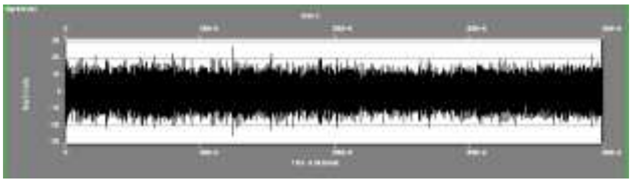

Figure 4. Received signal waveform when J/S=24 dB.

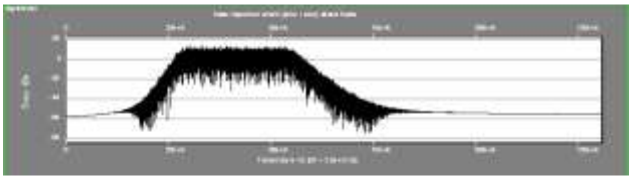

Figure 5. Received signal spectrum when J/S=24 dB.

For the sixth sub-channel, for example, as can be seen from Fig. 6, when jamming/signal ratio (J/S) is 24 dB, the receiving end can extract relevant peak of the sixth sub-channel. However, the relevant peak of the sixth sub-channel cannot be extracted when the J/S is 26 dB (Fig. 7). Analogous simulation results were observed for other sub-channels. Simulation results show that, under conditions of wideband noise interference and Rice channel environment, MSCSS system jamming tolerance is 24 dB.

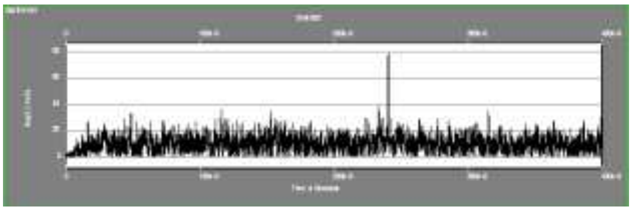

Figure 6. Correlated peak of the 6^{th} sub-channel when J/S = 24 dB.

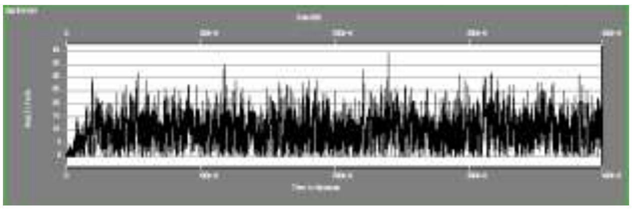

Figure 7. Correlated peak of the 6^{th} sub-channel when J/S = 26 dB.

Under the same conditions, the anti-jamming performance of DS/FH spread spectrum system was then simulated, and the output signal interfered with wideband noise is shown in Fig. 8. The extracted correlated peaks at two J/S ratios are exhibited in Fig. 9: when the J/S is 19 dB (left), correlated peaks at 16 hopping points can be correctly extracted; nevertheless, when J/S is 21 dB (right), relevant peaks cannot be extracted at 5 hopping points. To summarize, under conditions of wideband noise interference and Rice channel environment, DS/FH system jamming tolerance is 19 dB, lower than that of MSCSS system by 5 dB.

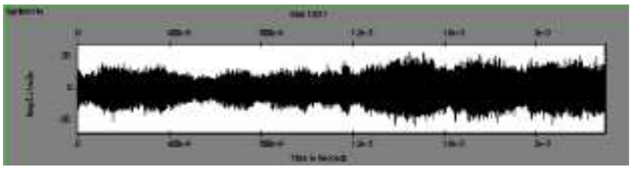

Figure 8. Output signal of DS/FH system under wideband noise.

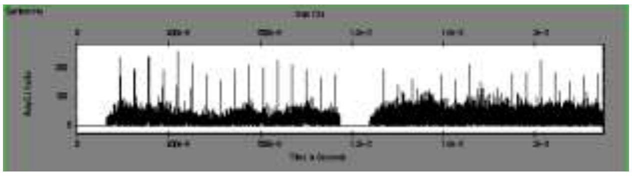

Figure 9. Correlated peaks of DS/FH system under wideband noise.

VI. CONCLUSIONS

On the basis of M-ary spread spectrum, direct sequence spread spectrum, orthogonal frequency division multiplexing, multi-carrier code division multiple access technology and so on, a novel wireless communication anti-interference system has been proposed, which was denoted by multi-sub-channels spread spectrum (MSCSS) system. The basic components and mathematical model of the system are illustrated. Furthermore, the anti-jamming performance and bit error performance of the system have been theoretically analyzed and simulated with computer.

Interestingly, under conditions of wideband noise and Rice channel environment, at the same information rate and the same bandwidth, jamming tolerance of the multi-sub-channels spread spectrum (MSCSS) system is higher than that of DS/FH spread spectrum system by 5 dB approximately.

ACKNOWLEDGMENT

The results discussed in this paper are part of the theses works of satellite communication system. This work is supported by Shaanxi Provincial Science & Technology Department (Program No. 2011K06-36) and the second batch of College Scientific Research Foundation in 2013 (Program No. XJ130225).

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