A Synchronization Acquisition Method for the Dual-Sequence-Frequency-Hopping Communication System Based on Software Defined Radio at Low SNR

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Manuscript submitted January 10, 2021; accepted March 18, 2021.
doi: 10.17706/jsw.16.5.235-247

Abstract: The Dual-Sequence-Frequency-Hopping (DSFH) communication system based on software defined radio (SDR) system belongs to the field of information and communication security of software engineering. At very low signal-to-noise ratio (SNR), which is lower than -10dB, the DSFH fails to synchronize. Synchronization acquisition method via a combined multi-signal detection (SAMCMD) is proposed. The feature of a short sequence of frequency hopping (FH) frequency point is utilized to express the information of the time of date (TOD), and the time accumulation of several FH signals is used to extend the detection time. This method can not only be appropriate for DSFH but also greatly improve the synchronization performance at low SNR. Explain the principle and structure of the SAMCMD. And obtain the performance of this method of the SDR synchronization acquisition. The conclusions are as below: 1) the longer detection time is, the better the anti-jamming performance of SAMCMD is; 2) SAMCMD can gain about 22.5dB-24dB when the SNR is -20dB and the acquisition probability requirement is 96.31% due to the extension of the detection time, compared with the traditional FH synchronization acquisition method.

Key words: Dual sequence, frequency hopping, Low signal to noise ratio, synchronization acquisition, software defined.

1. Introduction

With the development of technology, the FH communication system is widely used in civil communications and military communications. FH communication system has advantages of remarkable anti-jamming ability, high confidentiality, and strong networking capability [1]-[3]. Recently SDR is widely utilized in almost all the wireless devices including the FH communication system [4],[5]. And most of the signal processing components in SDR are implemented digitally in software rather than in hardware, which makes the complex FH systems such as the DSFH realize more easily [6], [7]. With the development of informatization, the communication environment is getting worse and the worst communication environment is the Gaussian white noise environment [8]. In many cases, especially in the battlefield environment, we need to communicate at very low SNR but in the traditional FH communication system, the signal-to-noise ratio (SNR) is usually between 0dB and 20dB. To improve the anti-jamming ability especially anti - Gaussian white noise ability, the DSFH communication mode based on SDR system is proposed in emergency communication at low SNR (lower than -10dB) [9], [10]. DSFH uses “the medium is the message” [11] as a reference. It uses two channels to represent the message without modulating information on the carrier [12], [13]. And the smooth work of FH synchronization is an essential precondition for the normal work of DSFH. What is more, FH synchronization consists of two steps: synchronization acquisition and synchronization tracking, and the acquisition is the key to the synchronization process [14], [15]. Without a success of synchronization acquisition DSFH can not work. Then, whether there was a synchronization acquisition method that can match DSFH and can work under very low SNR becomes a key problem.

In the past, scholars paid more attention to how to shorten the synchronization acquisition time and neglected the anti-jamming ability of FH synchronization acquisition. Sun [16] proposed a synchronization acquisition method for dual-channel frequency hopping communication system. This method combined synchronization header method with parallel acquisition，used carrier frequency and modulated time information in synchronization process to determine frequency hopping time, and carried out parallel acquisition on two receiving channels to shorten synchronization time. Wang *et al*. [17] proposed a single-channel matched filtering method using a sub-synchronization header. This method greatly reduced the synchronization acquisition time but the system was complex and did not improve the anti-jamming performance. Zhao *et al*. [18] proposed a FH synchronization acquisition method based on the elimination decision introducing elimination parameters and increasing an exit judgment process. This method reduced the synchronization acquisition time while keeping the system simple. And these synchronization methods [16]-[18] needed to modulate TOD on the carrier to transmit synchronization information. It made these methods not be applied to DSFH. Zhao *et al.* [19] proposed a FH synchronization acquisition method based on sequence partial frequency point matching. This method used the characteristic of a short FH frequency point sequence to express TOD to improve the performance of anti-follower-jamming ability. But it could not work at very low SNR. Li *et al*. [20] proposed a different frequency hopping (DFH) synchronization method. This method used an improved sliding window synchronization algorithm to get better synchronization precision and less calculate time. Like Zhao *et al*. [19], this method also improved the performance of anti-follower-jamming ability but could not work at very low SNR. What is more, these methods [19], [20] could be applied to DSFH but could not work at extremely low SNR, which was lower than -10dB.

To solve the problem of synchronization of DSFH at very low SNR, this paper proposes synchronization acquisition method via a combined multi-signal detection (SAMCMD). The paper is organized as follows. The system models of DSFH and SAMCMD are introduced in Section 2. The detection performance and the performance of the SAMCMD method are analyzed in Section 3 and Section 4, respectively. Section 5 presents and discusses the simulation results to support the proposed method. The conclusions are drawn in Section 6.

2. System Model

2.1. Structure Models of the DSFH System

The structure of DSFH system transmission is shown as Fig. 1.

Channel 0 and channel 1 are carriers $f_{0,n}$ and $f_{1,n}$ respectively controlled by PN sequence FS_0 and FS_1. At time t, if code element 0 is sent, a sine carrier $s_0(t)$ with frequency $f_{0,n}$ is sent. If send code element 1, a sine carrier $s_1(t)$ with frequency $f_{1,n}$ is sent. The final transmitted signal $s(t)$ controlled by the channel switch is the combination of $s_0(t)$ and $s_1(t)$.

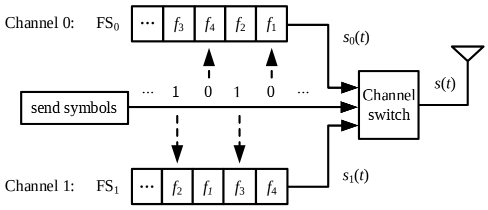

Fig. 1. Structure of DSFH system transmission.

Fig. 2 indicates the structure of DSFH system receiving.

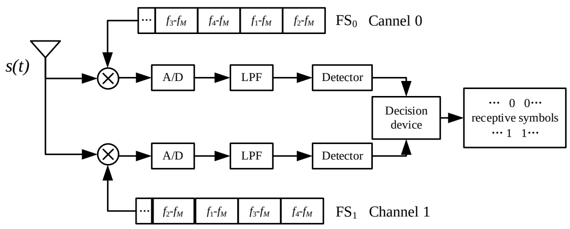

Fig. 2. Structure of DSFH system receiving.

The receiver receives the signal $s(t)$ under additive white Gaussian noise (AWGN), and then mixes the signal with super-heterodyne carrier controlled by FS_0 and FS_1. After passing the A/D convertor and low-pass filter (LPF), the signal consisting of sine wave with intermediate frequency (IF) and AWGN is detected by the detector. Assuming that the synchronization is completed, the receptive symbols are obtained after the signal passes the decision device.

2.2. The System Model of the SAMCMD

2.2.1. The principle of the SAMCMD

The principle of how the receiver obtains the transmitter's phase by matching two special sequences is described in Fig. 3.

Suppose that T_D minute difference is existed between the clock of the transmitter and receiver when they are turned on and the hopping rate is $\frac{1}{T_h}$ hops per second. The maximum phase difference between the transmitter and receiver is $Q = \frac{120T_D}{T_h}$ hops which constitutes a known sequence of R pulses at frequencies f_1, f_2,..., f_Q named sequence P. The receiver gets the sequence P by scanning $\frac{60T_D}{T_h}$ hops of the receiver's FH sequence before and after the current phase. The current phase of the transmitter is in sequence P. If the receiver gets a short local sequence P' from the transmitter which is at phase t_1, it would find the transmitter's phase by matching sequence P' and P. The sequence P' contains M special hops, and the frequencies are reference frequencies f_a and f_b selected at random from the frequency collection. The sequence P' is unique in sequence P when $M > 5$ [19]. Then the phase of the receiver is changed to $t_1 + \Delta t$ (where Δt is the data processing time). At the same time, the synchronization acquisition is completed.

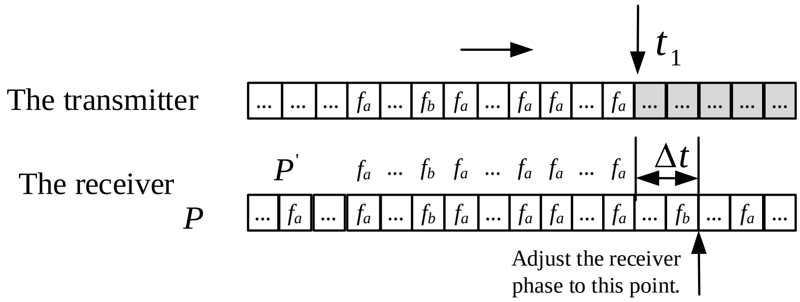

Fig. 3. Principle description of SAMCMD.

2.2.2. Structure models of the SAMCMD

The structure of SAMCMD is shown in Fig. 4.

Let us take the PN sequence FS_0 as synchronization sequence because the FH system can synchronize only one of the two PN sequences (FS_0, FS_1). The synchronization acquisition steps are as follows.

(1) The receiver obtains the local sequence P and marks the two reference frequencies from FS_0.

(2) The FH signal $s(t)$ received by the super-heterodyne receiver is submerged in the white Gaussian noise resulting in an extremely low SNR which is much less than 0dB. The two set reference frequencies control the super-heterodyne carriers. Then $s(t)$ is sampled N times by the A/D converter.

(3) Input the signal $s(t)$ into LPF. Since the frequencies of FH signals are high-frequency, only IF signal and the noise can get through the LPF.

(4) After the LPF, the signal $r(n)$ is inputted into the time-delay module (TDM) and the processed signal is stored into the register. The structure of TDM is shown in Fig. 5. In TDM, $r(n)$ is delayed by $0, \frac{1}{qf_m}, \ldots, \frac{q-1}{qf_m}$ (the step size is $\frac{2\pi}{q}$ and q is a preset positive integer) respectively. Then the q time-delay signals do cross-correlation calculation with $\cos(2\pi f_m n + \pi)$. The time-delay signal with the largest cross-correlation with $\cos(2\pi f_m n + \pi)$ is output into the register.

(5) As time goes by, the register gets a sequence. Then the detection of a combined multi-signal is performed.

(6) M reference signals containing the IF signals are obtained from the register by searching and matching the sequence and sequence P, as depicted in Fig. 6. The M reference signals are in turn to be delayed by 1, 2, …, $M-1$ hops duration time. Then sum them up. Now we get the combined multi-signal which exceedingly extends the detection time.

(7) The combined multi-signal is detected by the matched filter [9]. If the test statistic $T(x)$ is bigger than the threshold γ, the synchronization acquisition is completed and the sequence in the register is the sequence P'. Otherwise, the receiver will continue to receive the next FH signal and repeat the above steps.

According to the above, if the FH signals are sine-wave signals with frequencies of (…, f_6, f_3, f_7,…), the i th received FH signal after passing the AWGN channel is written as:

$$s_i(t) = A_i \cos(2\pi f_i t + \varphi_i) + \omega_i(t), \quad 0 < t \le T_h \tag{1}$$

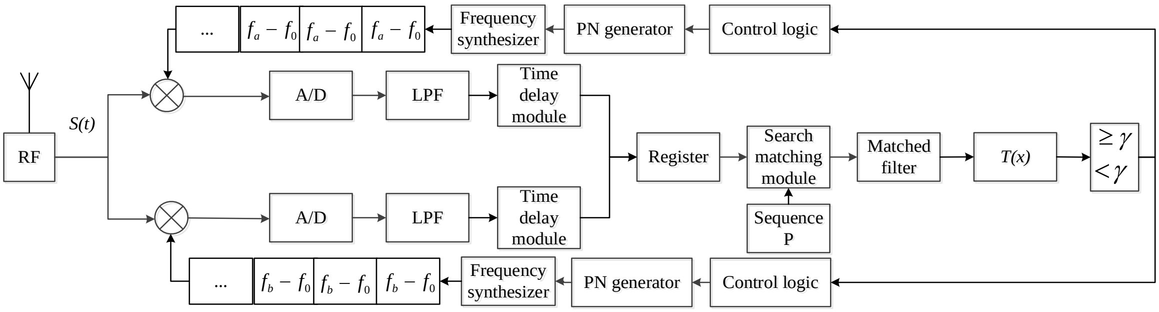

Fig. 4. Structure of the SAMCMD.

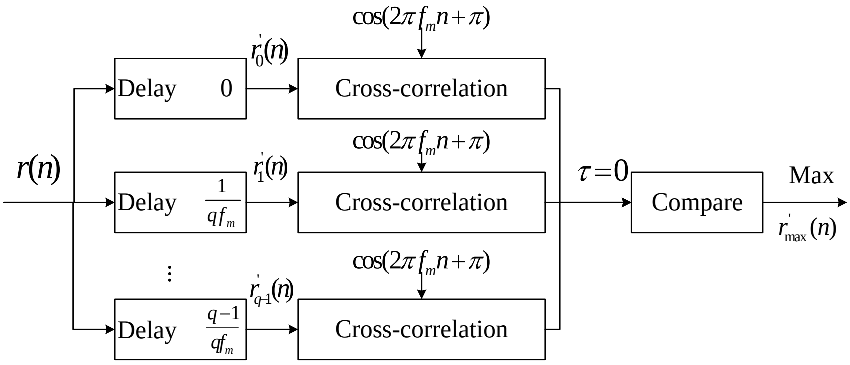

Fig. 5. Structure of the TDM.

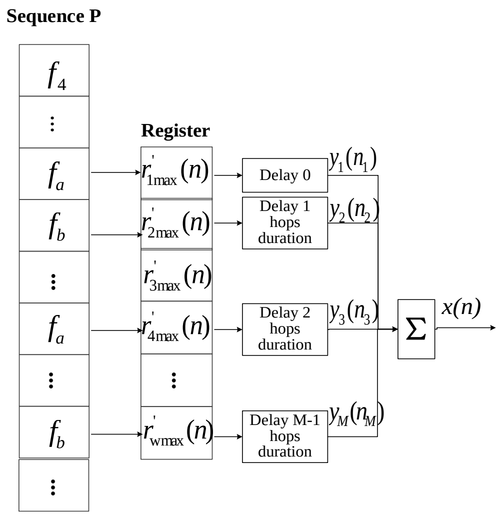

Fig. 6. Structure of search matching module.

where A_i, f_i, and φ_i are the amplitude, frequency, and phase of the i th FH signal, respectively. φ_i obeys the uniform distribution on $[0,2\pi]$. $\omega_i(t)$ is AWGN in the channel, whose expectation and variance are 0 and σ^2, respectively. T_h is the hop duration.

After the LPF, if $f_i = f_a$ or $f_i = f_b$, the signal can be formulated as

$$r_i(n_i) = A_i \cos(2\pi f_m n_i + \varphi_i) + \omega_i(n_i), n_i = 0,1,2...,N-1 \tag{2}$$

where f_m is the preset frequency of the IF signal. N is the sampling number. If $f_i \neq f_a$ and $f_i \neq f_b$, $r_i(n_i)$ only consists of $\omega_i(n_i)$.

After the TDM, the signal with f_m can be formulated as

$$r'_{i\max}(n_i) = A_i \cos[2\pi f_m (n_i - \frac{j_{\max}}{qf_m}) + \varphi_i] + \omega_i(n_i),\ j_{\max} = 0,1,2...,q-1 \tag{3}$$

$$y_i(n_i) = A_i \cos[2\pi f_m (n_i - \frac{j_{\max}}{qf_m}) + \varphi_i] + \omega_i(n_i),\ j_{\max} = 0,1,2...,q-1 \tag{4}$$

After the receiver receives w signals (the last signal is the Mth special signal with the reference frequency), the signal can be processed by the search matching module. Then the signal can be described as

$$x(n) = \sum_{i=1}^{M} y_i(n_i), n_1 = 0,1,...,N-1, n_2 = N, N+1,...,2N-1,..., n_M = (M-1)N, (M-1)N+1,..., MN-1 \tag{5}$$

where $x(n)$ is the combined multi-signal.

3. The Detection Performance

Performance of reliability and anti-jamming is an important measure of synchronization performance [21-23]. Performance of reliability refers to the speed of synchronization acquisition. Performance of anti-jamming refers to the acquisition probability, the error acquisition rate, and the missed acquisition rate [24],[25]. In order to calculate the acquisition time, the acquisition probability, the error acquisition rate, and the missed acquisition rate, we first need to obtain the detection performance of a combined multi-signal detection. And the detection performance is measured in terms of the detection probability and the false alarm probability [13]. The formulas for the detection probability and the false alarm probability are derived as follows.

For the i th received FH signal , assume that if $f_i = f_a$ or $f_i = f_b$, $c_i = 1$ and if $f_i \neq f_a$ and $f_i \neq f_b$, $c_i = 0$. Then the hypothesis testing problem is

$$\begin{cases} H_0 : x(n) = \sum_{i=1}^{M} y_i(n_i), c_1 = 0 \cup c_2 = 0 \cup ... \cup c_M = 0 \\ H_1 : x(n) = \sum_{i=1}^{M} y_i(n_i), c_1 = 1 \cap c_2 = 1 \cap ... \cap c_M = 1 \end{cases} \tag{6}$$

After the matched filter, the test statistic $T(\mathrm{x})$ is

$$\begin{aligned} T(\mathrm{x}) &= \frac{1}{MN}(\sum_{0}^{MN-1} x[n]\cos 2\pi f_m n)^2 + \frac{1}{MN}(\sum_{0}^{MN-1} x[n]\sin 2\pi f_m n)^2 \\ &\triangleq \xi_1^2 + \xi_2^2 \end{aligned} \tag{7}$$

where f_m is the preset frequency of the IF signal. N is the sampling number. And M is the number of combined signals.

If H_1, the expectation and variance of ξ_1 are

$$\begin{aligned} E(\xi_1) &= E\{\frac{1}{\sqrt{MN}}\{\sum_{i=1}^{M} \sum_{n_i=(i-1)N}^{iN-1} [A_i \cos(2\pi f_m n_i + \varphi_i - \frac{2\pi j_{\max}}{q}) + \omega_i(n_i)]\}\} \\ &= \sqrt{\frac{N}{M}} \sum_{i=1}^{M} E[A_i \cos(\pi + \Delta\varphi_i)] \\ &= -\frac{\hat{\mathrm{A}}\sqrt{MN} q \sin\frac{2\pi}{q}}{4\pi} \end{aligned} \tag{8}$$

$$D(\xi_1)=\frac{\sigma^2}{2}\,,\ \ H_1 \tag{9}$$

where $\Delta\varphi_i \sim \mathrm{U}[0,\frac{2\pi}{q}]$. $\frac{2\pi}{q}$ is the step size of TDM. $\hat{\mathrm{A}}$ is the signal amplitude expectation.

In the same way,

$$E(\xi_2)=\frac{\hat{\mathrm{A}}\sqrt{MN}q}{4\pi}(1-\cos\frac{2\pi}{q}) \tag{10}$$

$$D(\xi_2)=\frac{\sigma^2}{2} \tag{11}$$

Let k signals of the M signals only contain AWGN (that is H_0). The expectation and variance of ξ_1 and ξ_2 are

$$E(\xi_1)=-\frac{\hat{\mathrm{A}}(M-k)\sqrt{N}q\sin\frac{2\pi}{q}}{4\pi\sqrt{M}} \tag{12}$$

$$E(\xi_2)=\frac{\hat{\mathrm{A}}(M-k)\sqrt{N}q}{4\pi\sqrt{M}}(1-\cos\frac{2\pi}{q}) \tag{13}$$

$$D(\xi_1)=D(\xi_2)=\frac{\sigma^2}{2} \tag{14}$$

Since ξ_1 and ξ_2 are jointed Gaussian,

$$[\xi_1,\xi_2]^T \sim N(\begin{bmatrix} -\frac{\hat{\mathrm{A}}(M-k)\sqrt{N}q\sin\frac{2\pi}{q}}{4\pi\sqrt{M}} \\ \frac{\hat{\mathrm{A}}(M-k)\sqrt{N}q}{4\pi\sqrt{M}}(1-\cos\frac{2\pi}{q}) \end{bmatrix},\frac{\sigma^2}{2}\boldsymbol{I}),H_0 \tag{15}$$

$$[\xi_1,\xi_2]^T \sim N(\begin{bmatrix} -\frac{\hat{\mathrm{A}}\sqrt{MN}q\sin\frac{2\pi}{q}}{4\pi} \\ \frac{\hat{\mathrm{A}}\sqrt{MN}q}{4\pi}(1-\cos\frac{2\pi}{q}) \end{bmatrix},\frac{\sigma^2}{2}\boldsymbol{I}),H_1 \tag{16}$$

Normalization processing is made for $T(\mathrm{x})$. Then $T(\mathrm{x}) \sim \begin{cases} \chi_2^2(\lambda_{0k}), & H_0 \\ \chi_2^2(\lambda_1), & H_1 \end{cases}$, where $\lambda_{0k}=\frac{A^2N(M-k)^2q^2}{4\pi^2\sigma^2M}(1-\cos\frac{2\pi}{q})$, $\lambda_1=\frac{A^2NMq^2}{4\pi^2\sigma^2}(1-\cos\frac{2\pi}{q})$.

The detection probability P_D and false alarm probability P_f are

$$\begin{aligned} P_D &= P\{T(x)>\gamma;H_1\} \\ &= P\{\frac{T(x)}{\sigma^2/2}>\frac{\gamma}{\sigma^2/2};H_1\} \\ &= Q_{\chi_2^2(\lambda_1)}(\frac{2\gamma}{\sigma^2}) \end{aligned} \tag{17}$$

$$P_f = \sum_{i=1}^{M}[\frac{C_M^i}{2^M - 1} Q_{\chi_2^2(\lambda_{0k})}(\frac{2\gamma}{\sigma^2})] \tag{18}$$

where γ is the threshold value and $Q_{\chi_2^2(\lambda)}$ is the right tail probability of noncentral chi-square distribution. Based on the criterion of minimum error probability [26], γ is obtained from

$$\begin{aligned} P_e &= \frac{1}{2}(1 - P_D) + \frac{1}{2}P_f \\ &= \frac{1}{2}Q_{\chi_2^2(\lambda_1)}(\frac{2\gamma}{\sigma^2}) + \frac{1}{2}\sum_{i=1}^{M}[\frac{C_M^i}{2^M - 1}Q_{\chi_2^2(\lambda_{0k})}(\frac{2\gamma}{\sigma^2})] \end{aligned} \tag{19}$$

4. Performance of the SAMCMD

In this section, we analyze the performance of the SAMCMD which includes the performance of reliability and anti-jamming. According to the above, we use the expectation of acquisition time to measure the performance of reliability and the acquisition probability, the error acquisition rate, and the missed acquisition rate to measure the performance of anti-jamming. On the basis of Section 3, those formulas are obtained in this section.

4.1. Expectation of Acquisition Time

Since the P_D is nearly 1 and the P_f is nearly 0 for the available state, we suppose that P_D is 1 and P_f is 0. The time taken by the receiver to capture the sequence P is T_r and the time the receiver taking to process the data is T_p. Since T_p is mainly determined by hardware, we focus on T_r. The probability of the j th received FH signal being the M th reference signal is

$$P_{tj} = \frac{2^M C_{j-1}^{M-1} 2^L C_{Q-j}^L}{2^{M+L} C_Q^{L+M}} \tag{20}$$

where $L = [\frac{2}{B}Q - M]$. B is the number of frequency slots. Q is the number of hops of the sequence P. M has the same meaning as above. Then the expectation of the synchronization acquisition time is

$$E(t) = \sum_{i=M}^{Q-L}(i \cdot T_h \cdot P_{tj}) = \sum_{i=M}^{Q-L}(\frac{2^M C_{j-1}^{M-1} 2^L C_{Q-j}^L}{2^{M+L} C_Q^{L+M}} iT_h) \tag{21}$$

4.2. Anti-jamming Ability

The anti-jamming performance refers to the acquisition probability, the error acquisition rate, and the missed acquisition rate. If the interference is Gaussian white noise, from (21) and (22), we can know the acquisition probability, the missed acquisition probability P_M, and the false acquisition probability P_{FA} are

$$P_A = P_D = Q_{\chi_2^2(\lambda_1)}(\frac{2\gamma}{\sigma^2}) \tag{22}$$

$$P_{FA} = P_f = \sum_{i=1}^{M}[\frac{C_M^i}{2^M - 1}Q_{\chi_2^2(\lambda_{0k})}(\frac{2\gamma}{\sigma^2})] \tag{23}$$

$$P_M = 1 - P_A = 1 - P_D = Q_{\chi_2^2(\lambda_1)}(\frac{2\gamma}{\sigma^2}) \tag{24}$$

5. Simulation Results and Discussions

Simulink model simulates the synchronization acquisition method established in Section 3 and Section 4. According to GJB 2928A-2012, the Simulink parameters are as follows: the frequency of IF signal is 1kHz; the frequency slots number is 256; the frequency hopping band interval is 25kHz; the hopping rate is 200h/s; the channel interval is 25kHz; and the channel is a Gaussian white noise channel. The sample frequency is $f_m \cdot N / (f_m \cdot T_h)$=200$N$. To satisfy the Nyquist sampling theorem, $N > 10$.

Set $SNR = 20dB$. Then run the program 10000 times and take the average of them to obtain a simulation value of E(t) with a M. Fig. 7 shows the theoretical and simulation results of E(t) with different M of SAMCMD. E(t) increases with the increase of M, indicating that the synchronization acquisition time also increases with the increase of M. In practice, we should choose suitable M according to the requirements. The main purpose of this paper is to solve the problem of synchronization acquisition at very low SNR. And in DSFH communication mode which is proposed in emergency communication at low SNR, the performance of anti-jamming is more important. If SAMCMD can not work, the expectation of acquisition time will not make sense. We consider that the speed of synchronization acquisition can be appropriately sacrificed for the purpose.

We get a simulation value of P_A by running the program 100000 times. The theoretical and simulation results of the P_A of different M with $N = 500$ and different N with $M = 6$ are shown in Fig. 8 and Fig. 9, respectively. We can get the relationships of P_A, N, M, and SNR. When M and N remain the same, P_A increases to 1 with the increase of SNR. Because with the increase of SNR, the test statistic of the combined multi-signal in H_1 becomes larger. When SNR>10dB, the test statistic is large enough that P_A goes to 1. When SNR remains the same, P_A increases with the increase of M. Similarly, when SNR stays the same, P_A increases with the increase of N. Because M is the number of signals which make up the combined multi-signal. N is the sampling number of one hop signal. Increasing M or N will prolong the detection time of the combined multi-signal. If M increases by a and N increases by b, the detection time will increase $bM + aN + ab$. Ideally, prolonging the detection time can improve the detection probability.

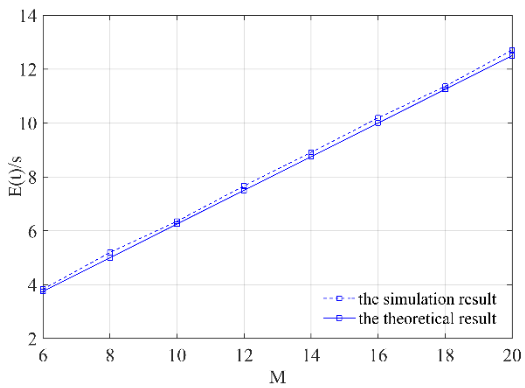

Fig. 7. The E(t) of different M of SAMCMD.

We get a simulation value of P_{FA} by running the program 100000 times. Fig. 10 and Fig.11 describe the theoretical and simulation results of the P_{FA} of different M with $N = 500$ and different N with $M = 6$, respectively. Firstly, P_{FA} decreases to 0 with SNR increasing when M and N remain the same. Because with the increase of SNR, the difference of the test statistic of the combined multi-signal in H_1

and H_0 becomes larger and the threshold becomes higher. Then it's very difficult for the test statistic in H_0 to exceed the threshold. When SNR>10dB, the difference is big enough that P_{FA} goes to 0. Secondly, suppose that N is a constant, P_{FA} decreases with M increasing. Thirdly, P_{FA} decreases as N increasing when M is a constant. Because with the increase of M and N , the detection time prolongs which makes the difference of the threshold and the test statistic in H_0 become larger. Then it becomes harder for the test statistic in H_0 to get bigger than the threshold. Finally, when the SNR is -20dB, P_{FA} can be 0.0818 which meets the requirement of GJB 2928A-2012.

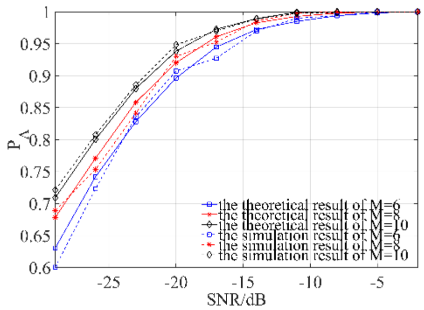

Fig. 8. The P_A of different M of SAMCMD.

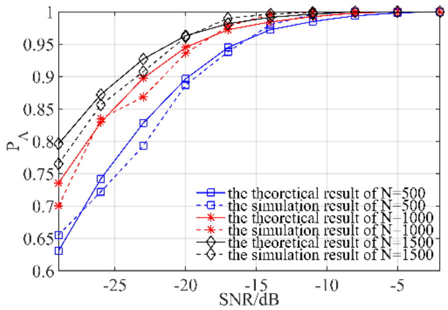

Fig. 9. The P_A of different N of SAMCMD.

The setting of M and N needs to comprehensively consider the acquisition time and the acquisition probability. In low SNR the first thing we need to do is make sure that we can synchronize. According to GJB 2928A-2012, P_A needs to be bigger than 95%. Then the acquisition time should be as short as possible. Fig. 9 shows that the first $P_A > 0.95$ occurs when SNR=-20dB and $N = 1500$. Fig. 7 shows that when $M = 6$ the acquisition time is the shortest. Then we set $M = 6$ and $N = 1500$. The P_A of several methods is shown in Fig. 12. It can be seen that the proposed method can achieve a larger P_A at low SNR, which indicates that the proposed method can achieve a better performance. The remarkable differences between SAMCMD and other methods is the order of signals accumulation and signal detection and the methods of signal detection. SAMCMD first accumulates the signals to the combined multi-signal and then detects the combined multi-signal. Some methods, such as method in [17] and method in [19], first detect the single signal and then accumulate the detect results. Others, such as the method in [20], only detect the special signal to complete synchronization. In low SNR, we can improve the detection performance of signal detection by prolonging detection time. But the existence of "SNR wall" makes the SNR no longer increase after N increases to a certain value $N_{\max}$ [27]. SAMCMD accumulates the detection time of M signals which raises $N_{\max}$ to $MN_{\max}$. This makes the detection performance have a big improvement. Besides, FH synchronization usually uses energy detection. SAMCMD uses matched filter with better performance [17]. The synchronization acquisition probability increases with the improvement of the detection performance. Therefore the methods in [17], [19], and [20] all have a smaller P_A at low SNR due to the low detection probability when detecting every signal frequency point to achieve synchronization acquisition. When the SNR is -20dB, the P_A of SAMCMD is 0.9631. When $P_A > 0.95$, the SNR of [17], [19], and [20] are 3dB, 2.5dB, and 4dB. Thus the proposed method has a performance gain of 22.5dB-24dB.

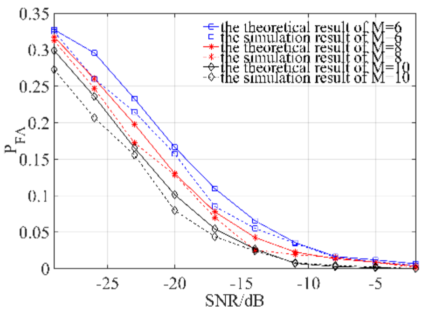

Fig. 10. The P_{FA} of different M of SAMCMD.

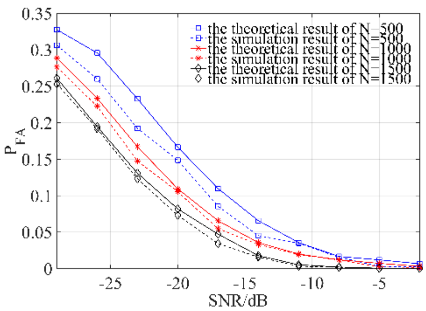

Fig. 11. The P_{FA} of different N of SAMCMD.

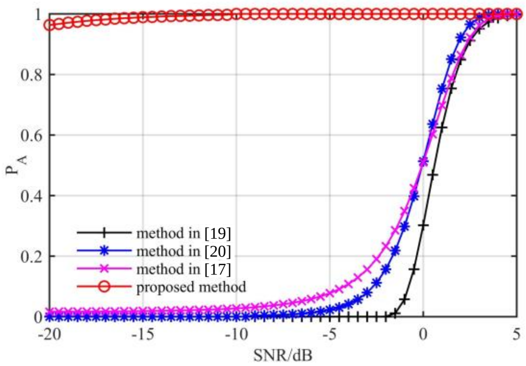

Fig. 12. The P_A of different methods.

6. Conclusions

A novel synchronization acquisition method is proposed for the DFSH mode based on SDR system at low SNR. Firstly, a short PN sequence is utilized to represent TOD and multi-FH signals are detected jointly to gain SNR. The formulas of mean acquisition time, acquisition probability, false acquisition probability, and missed acquisition probability are derived. Finally, the influences of parameters M and N on the synchronization acquisition performance are analyzed. By analyzing the simulation results, some conclusions are drawn: 1) the probability for synchronization acquisition success at $SNR = -20dB$ is 96.31%; 2) due to the extension of the detection time SAMCMD can gain about 22.5dB-24dB with $SNR = -20dB$ when the acquisition probability and false acquisition probability are required to be higher than 0.95 and lower than 10^{-1} compared with traditional FH synchronization acquisition method; 3) the larger the M and N are, the better the anti-jamming performance is. What is more, although the logic and data number of SAMCMD are complex and large. The SDR system can realize it easily. And using the feature of short sequence P' to express TOD instead of modulating the information on the carriers makes the proposed method be appropriate for the DSFH communication system and for the DFH communication system or other FH communication systems that only transmit carriers without modulation information. However, the proposed method sacrifices the performance of acquisition time to improve the acquisition probability at low SNR. It is necessary to consider how to reduce the acquisition time of the method in future research.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Houde Quan and Xiaolu Zhang conducted the research; Xiaolu Zhang and Huixian Sun analyzed the data;

Xiaolu Zhang and Guangkai Liu wrote the paper; Peizhang Cui modified the article; all authors had approved the final version.

Acknowledgment

This research was funded by The Natural Science Foundation of Hebei Province, grant number F201750600678.

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