Design of TOD Self-Synchronization Method in Frequency Hopping System*

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***Abstract*—One of the main questions of frequency hopping (FH) is Frequency-hopping synchronization. In this paper, a TOD (time of day) self-synchronization based method of frequency hopping synchronization is proposed to archive the rapid and reliable synchronization in a high speed hoping system. This method designed a new structure of the synchronization information, which used special rules sending the synchronization information at the transmitter side and applied the slow scanning combined with the maximum likelihood (ML) algorithm to track the FH sequence at the receiver side. We established a simulation platform of frequency-hopping system to simulate the principle and processes of proposed method. The simulation results represented the advantages we archived at the high acquisition probability, the low false alarm rate, and the long synchronization keeping time. And also we discussed the relationship between the transmission BER and the acquisition probability.**

Keywords-component;FH sequence;FH synchronization ;TOD; acquisition ;tracking

I. INTRODUCTION

Frequency-hopping communication has an important and irreplaceable position in the field of wireless communications. It will minimize the unauthorized interception or jamming of telecommunications, and it has the applications of anti-multipath fading, multiple access networks. The higher hopping rate and faster data transfer rate are the inevitable trend of development of the frequency hopping communication, which means frequency hopping synchronization requires more reliability and needs to be faster. FH synchronization has become a major problem restricting the development of frequency hopping systems. FH synchronization includes frequency hopping pattern synchronization, carrier synchronization, frame synchronization and bit synchronization. Frequency hopping pattern synchronization is unique and critical. It is the focus of this paper, the synchronization following text refers to only means pattern synchronization.

Currently, there are three hopping synchronization methods, namely the reference clock method, self-synchronization method and the independent channel method. The independent channel method requires a separate channel for the information of synchronization, and then the channel resource is wasted, the ability of interference immunity is poor, confidentiality is not strong.

The reference clock method requires an accurate reference clock, which is difficult and expensive to design. Since the time of the initial synchronization is too long self-synchronization method is only applicable to systems, which use simple hopping sequence. The three methods have their advantages and disadvantages. TOD self-synchronization method designed in the paper is a combination of these three methods.

There are two stages into the synchronization of FH system, acquisition and tracking. The former completes the coarse synchronization on the half of the frequency slot. The latter completes the further meticulous synchronization and the real-time tracking. Performance of acquisition determines the anti-jamming performance, the overhead and the speed to get synchronization. Performance of tracking determines the time of synchronization maintenance and reliability of the system. In this paper, the system uses a slow-scan multiple serial capture threshold, while ML maximum likelihood criterion with jitter phase-locked loop tracking algorithm is used either.

II. TOD SELF-SYNCHRONIZATION METHOD

Because the design of the synchronization information is closely connected with the parameter such as the data rate, the FH time period and the number of bit transmitted in each hop, the paper introduces the parameters of the system first：

TABLE I. PARAMETERS OF THE SYSTEM

Channel Spacing	1KHz
Frequency Collection	512（select from 1024）
Hopping Rate	1000Hops/s
Hopping Cycle	1ms
Number of Bit Per Hop	64
Modulation Type	DBPSK
FH Band width	5MHz

A. The Structure of Synchronization Information

Synchronization information is the key to be synchronized between the RX and TX, and the most important part of the synchronization information is TOD. TOD is the communication between the two sides which is actually the real time information of them, including date, day, hour, minute, second, millisecond, nanoseconds, provided by the high-precision clock source. Because both sides use the same hopping code sequences and hopping frequency table, the only difference is TOD. The two sides can complete synchronization when they have same TOD. Under specified conditions, the difference of TOD between two sides is only low bit, and the high should be same, such as at least the two sides have the

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same date(day, month, year), and it allows that the bits of point and second could be different. So when transmitter sends the initial synchronization information, it only needs send the low bits of TOD. The structure of synchronization information is shown as:

Coarse synchronization	Frame synchronization	TODL (low bit of TOD)	Empty hop

Figure 1.Structure of synchronization information

- Coarse synchronization: sequences having good correlation properties, m sequence, 64 bit, because the system sends 64 bit in each hop
- Frame synchronization: a special set of sequences, tells the RX that TODL will be transmitted next hop
- TOD: the key to achieving time synchronization, the paper uses a nonlinear TOD notation. TOD is divided into two parts, the high and low, provided by the local real-time clock. The length of high part is 32 bit, means year, month, day, hour and minute. The length of the low is 16 bit, using each hop time epoch as timing interval, when it comes to one minute, the high part plus one.
- Empty hop: buffer, leaves free time to correct the TODL, calculates the hopping pattern.

B. The Generation of Synchronization Frequency

Synchronization information is also sent by frequency hopping signal, and the synchronization frequency (the frequency that synchronization information is sent on) designed to six frequencies is generated from TODH using a simple method.

The key to generating synchronization frequency:

$$\text{TODH} \longrightarrow F_0$$
$$\text{TODH-1} \longrightarrow F_1$$
$$\text{TODH-2} \longrightarrow F_2$$
$$\text{TODH-3} \longrightarrow F_3$$
$$\text{TODH-4} \longrightarrow F_4$$
$$\text{TODH-5} \longrightarrow F_5$$

I.e. TODH corresponds to a synchronization frequency, then a new TODH which is one minute later than the real one corresponds to another synchronization frequency and there are six frequencies altogether. The receiver generates six frequencies according to its own TODH in the same way. That means as long as the error of TODH less than 5 minutes (fast or slow), there is at least one synchronization frequency is the same with the synchronization frequency created in transmitter.

The method for generating a synchronization frequency is that, making AND operation with TODH and each column of a random matrix which has 32 lines and n columns, then we can have a new matrix that has 32 lines and n columns. Count the number of 1 in each column, if it is an odd number, we mark it as 1, else 0. So we obtain a n-bit binary number, turn it to a decimal number and use it to select the frequency in frequency hopping table as the synchronization frequency. After generating all the six synchronization frequencies, test that if the six frequencies satisfy the wide interval that means each interval between the numbers of any two frequencies is greater than 64, if not satisfied, the random matrix should be changed to generate the synchronization frequency once more. The synchronization frequency generated by such method not only meets the requirements for wide interval between hopping frequencies, but also have another advantage, that the system will produce a new synchronization frequency every minute, all synchronization frequencies will be replaced in six minutes, increasing the ability of anti-jamming. Synchronization frequency generation process is shown in the following figure.

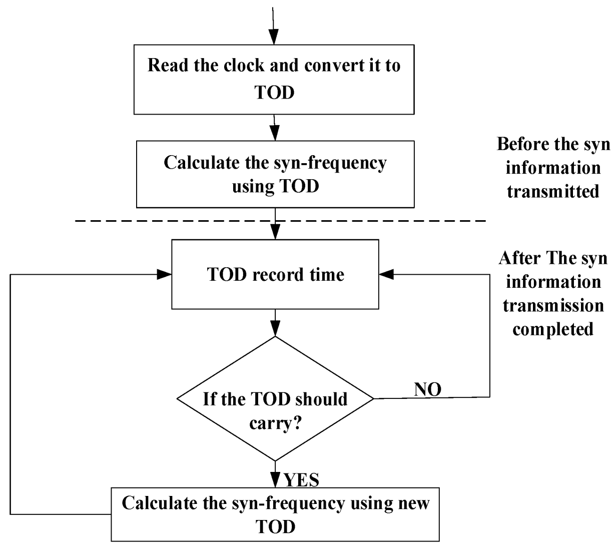

Figure 2.Synchronization frequency generation process

C. The Transmittion of The Synchronization Information

According to the international standards, the synchronization time should be less than 0.6s, so the system sends synchronization information in 600 hops. When sending coarse synchronization information, in order to enable the receiver to correct TODH after receiving a synchronizing frequency correctly, the transmitter distributes a m-sequence to each synchronization frequency, so that the receiver can determine the number of synchronization frequency they receive through the m-sequence, then the receiver compares the number with their own to get the error of the two TODH, which can be used to correct the TODH of receiver. The transmitter sends coarse synchronization in a group of six synchronization frequencies, 79 groups, 474 hops totally.

Frame synchronization information is a m-sequence which is sent 6 times by 6 synchronization frequencies, when the RX receives the frame synchronization information, it prepares to receive TOD information. The frame synchronization information is sent only one group, 6 hops.

TODL is a 16-bit binary number which is divided into four parts, TOD1, TOD2, TOD3, TOD4, each part 4 bit, using spread spectrum modulation techniques, spread over 15: 1, that means each bit baseband information becomes 16bit chip information, so that TODL can be guaranteed correct. The transmission form is still hopping on the synchronous frequency, which sending a total of 116 hops including four empty hops at the end.

Seven leader sequences used in this design, as well as the spreading code used to send TODL information, are m-sequences which have different primitive polynomial and buffers. The generation method of m-sequence is simple, and Hamming correlation resistance is also very good. The m-sequence can be captured, and tracked easily.

III. ACQUISITION AND TRACKING

Acquisition is the action that the FH system automatically searches of indefinite areas to obtain the time of the receiver frequency hopping sequence, so that the time error of the transmitter hopping sequence is less than the allowable value. Acquisition is the base of synchronization, and the time of it limits the time synchronization established, the interference immunity of acquisition directly affects the performance of the whole system, so the design of a suitable acquisition scheme is very important.

Tracking is the process that after acquisition is completed, further reduces the error of the receiver and transmitter's hopping sequence beginning time until the error is small enough and the synchronization can be maintained. The common method of tracking is to use phase-locked loop to adjust the local clock. Due to changes in channel transmission delay, the drift of the clock's frequency, the noise in receiver and other reasons, the take off time of hopping sequence will fluctuate. In order to make FH system accurate and reliable, the error rate is low, the hopping sequence synchronization should be accuracy and keep long time which requires tracking loop to achieve.

A. The Acquisition of The Synchronization Information

The receiver of the system uses a method of slow-scan multiple serial capture threshold. When the receiver just begins to work, it calculates sync frequencies with their own system clock, and slow scan on the six sync frequencies, the time of scan is 7 times than the time of transmission, so that it can increase the probability of acquisition.

The specific method is to capture the signal carrier frequency firstly, and then complete the capture of the signal according to the relevant characteristics of the leader sequence. Scan slowly at the receiver, if the scanning frequency and the carrier frequency are identical, we can multiply them and let the result through the band-pass filter, then the baseband modulated signal is got. If the scanning frequency and the carrier frequency is different, the energy of the signal which is out from the band-pass filter is very small. It can be determined by the energy detection whether the carrier frequency is captured successfully, as shown in Fig 3.

After the acquisition of carrier frequency, we obtain a baseband signal, and then to capture the preamble sequence, the acquisition results are shown in Fig 4.

A scanning period of the receiver is 42 hops. The scan lasts some periods, and records the number that each synchronization frequency is captured successfully, after the scan is finished, select the frequency which is captured the most frequently, and reside on the synchronization frequency, receive the preamble sequence to determine the number of the synchronization frequency, then calculate the difference between the two TODH and correct it, recalculate synchronization frequency with the correct TODH. After the receiver captures successfully once more, begin to jump in normal frequency (1000hop/s) with the next synchronization frequency hopping until accepting the frame synchronization information which is the preparation for the transmission of TODL, after accepting TODL successfully, there will be free jumps as a buffer in which the receiver can correct its TODL, then calculate the hopping pattern, begin to transmit information.

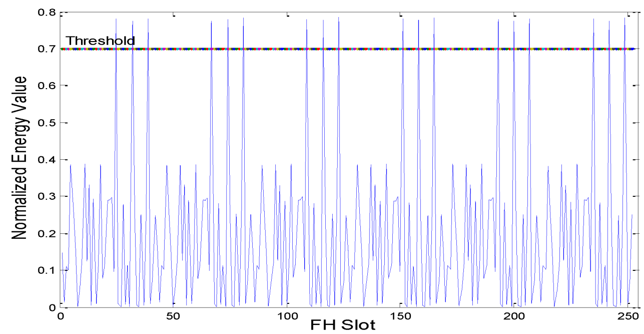

Figure 3.The acquisition of carrier

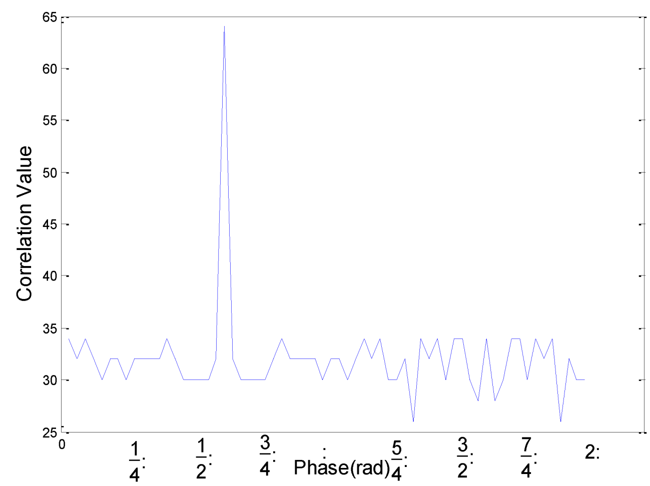

Figure 4.The acquisition of preamble sequence

B. Tracking Durning The Communication

The design uses the maximum likelihood criterion (ML) algorithm to track. This is a phase-locked loop dithering algorithm based on maximum likelihood criterion. The algorithm is effective and feasible, whose feature is there will be long time to unlock. Algorithm is described below.

First predict the arrival time of hopping signal and use bisection method at forecasting location. A hopping cycle is divided into two parts, the forward and the later. Calculate their spectral energy value individually. When hopping signals accurately synchronize, it means the signals' arrival time is same with the predicted time. In a hopping cycle, the output signal of filter is constant envelope signal, the difference between the forward part and the later is equal to zero. When the received signal is ahead of the local signal, the forward part of the output signal of filter has more energy than the later. When the local signal lags behind, the results contrast. As shown in Fig 5, the shaded part is a hopping cycle.

Therefore, the spectral energy difference between two parts constitutes a linear function of timing error, as shown in Fig 6. In order to achieve time synchronization tracking, estimate time error based on the ML algorithm constructs a loop to make sure the energy difference between the two parts is zero.

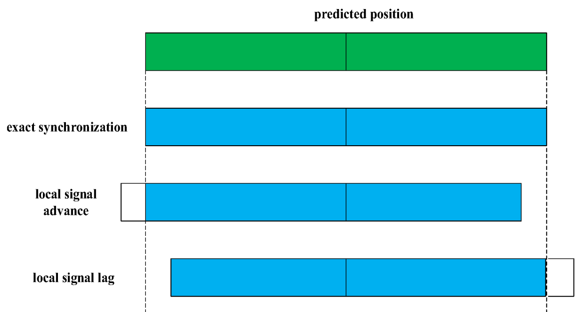

Figure 5.ML algorithm

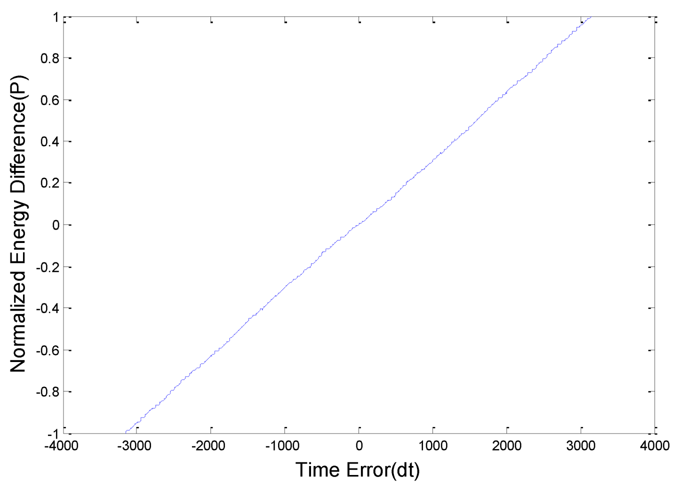

Figure 6.Linear relationship between time error and energy difference

IV. Simulation Results And Performance Analysis

This paper uses Matlab to build a simulation platform, assuming local receiver demodulation carrier ideally has been tracked in the transmitted carrier, and the frame synchronization, bit synchronization have been completed, set the channel for AWGN.

Information rate is 64kbps, the duration of each hop is 0.001s, that means each hop transmits 64bit, modulation scheme of baseband signal is DBPSK, bandwidth is 128KHz, modulated carrier frequency is 64KHz. Hopping bandwidth is 512KHz, intermediate frequency is 0.64MHz, signal sampling rate is set to 6400000 times/s, so each data bit simulation sampling for 100 points, each hop sampling for 6400 points. Use wide interval hopping sequences which is done to dual-band method as hopping sequence. The frequency spectrum of output signal of the synchronization information transmitted by hopping is shown in Fig 7.

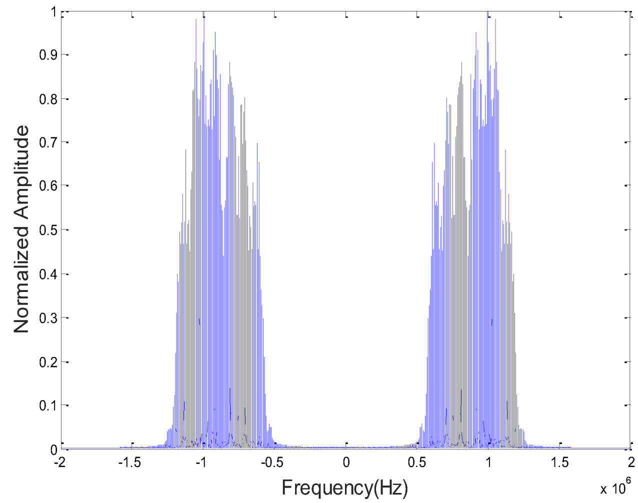

Figure 7.Spectrum of IF Signal

A. Synchronization Time

Synchronization time is the duration to complete the synchronization, which defines the time when the synchronous head is transmitted in initial synchronization, namely:

$$t_s = 600 \times 1 = 600ms \tag{4-1}$$

According to international practice, synchronization time should be less than 0.6s, so the design meets the requirements.

B. Maximum Time Allowed for the Initial Synchronization

Synchronization can be completed when one of the transmitter and the receiver's synchronization frequencies are same at least, then five sync frequencies can be replaced in six all frequencies, and the system changes a synchronization frequency every minute, therefore the maximum time allowed for the initial synchronization is:

$$\Delta t_{\max} = 5 \times 1 = 5\min \tag{4-2}$$

This maximum time may be ahead or delayed, as long as the time error is less than 5 minutes, synchronization can be completed. Almost all clocks in general can meet this requirement.

C. Synchronization Holding Time

Synchronization holding time is the maximum time interval that synchronization can be completed next time by the synchronous head after the initial synchronization, the formula is expressed as:

$$t_h = \frac{(6-1) \times T_w}{2\rho} \tag{4-3}$$

In the formula ρ ———— clock precision;

T_w ———— frequency conversion time;

$\rho = 10^{-6}$, T_w = 60s, it means the system replaces a synchronization frequency in one minute. The denominator is 2 because of considering the clock drift of the transmitter and receiver. So after the clock drift, the clock time difference between the transmitter and receiver coming to 5min needs 1736 days, namely synchronization holding time.

D. Acquisition Performance Analysis

1) detection probability for correlation code

During the scanning process, as long as the system received the preamble whose length is N for K times continuously, acquisition can be completed. Store the demodulated baseband signal in the N-stage shift register, and use it to do correlation calculation with the local code. Then use large numbers decision, if exceeds the threshold value, it is considered successful acquisition. Preamble of this program is 64-bit m-sequence.

Suppose the bit error rate of restored baseband signal is P_b, the length of preamble is N, the detection threshold is n, the correct detection probability for preamble P_t and error detection probability for preamble P_f, respectively:

$$P_t = \sum_{i=n}^{N} C_N^i \left(1-P_b\right)^i P_b^{N-i} \tag{4-4}$$

$$P_f = \sum_{i=n}^{N} C_N^i \left(1-P_b\right)^{N-i} P_b^i \tag{4-5}$$

In the formula, C_N^i is the binomial coefficient，Fig 8 is the relation graph of P_t with P_b and n when N is 64，Fig 9 is the relation graph of P_f with P_b and n when N is 64.

As shown in Fig 9, when the error rate is going decrease, the correct detection probability for preamble increases, and the error detection probability decreases.

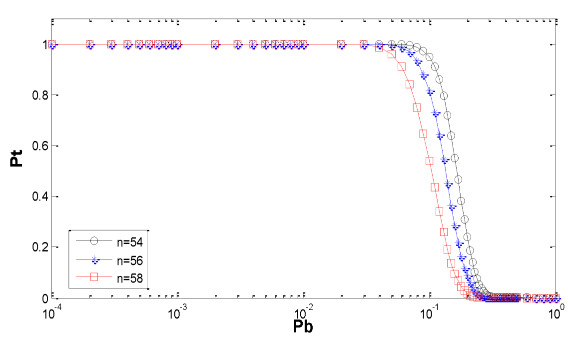

Fig 8.The relationship between P_t and P_b

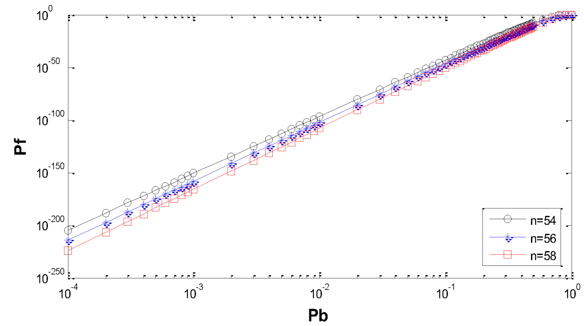

Fig 9.The relationship between P_f and P_b

2) Acquisition probability and false alarm probability

In the scheme, there are total of 462 jumps in the leader sequence, in which 210 jumps are used to capture the preamble. Assume when the receiver starts to slowly scan the signal, the transmitter starts to send sequence at the same time, at the maximum opportunity 210/6 = 35 times, the correct detection probability for signal and the error detection probability for signal, respectively is:

$$P_c = \sum_{i=1}^{35} C_N^i \left(1-P_t\right)^{i-1} P_t \tag{4-6}$$

$$P_e = \sum_{i=1}^{35} C_N^i \left(1-P_f\right)^{i-1} P_f \tag{4-7}$$

Use large number decision to verify tracking, the probability of success and failure are:

$$P_s = \sum_{i=3}^{6} C_6^i \left(1-P_t\right)^{6-i} P_t^i \tag{4-8}$$

$$P_u = \sum_{i=3}^{6} C_6^i \left(1-P_f\right)^{6-i} P_f^i \tag{4-9}$$

Because of probability independence, the probability of acquisition is:

$$P_m = P_c \times P_s \tag{4-10}$$

False alarm probability is:

$$P_n = P_e \times P_u \tag{4-11}$$

Fig 10 is the relation graph of P_m with P_n and n when N is 64 and Fig 11 is the relation graph of P_n with P_b and n when N is 64. The two figures show that with the decrease of the error rate, the acquisition probability increases and false alarm probability decreases. In the case of the same error rate, the higher the threshold value of n, the smaller the false alarm probability, but also the acquisition probability decreases. Therefore, the acquisition probability and the false alarm probability should be both taken into account when determining the optimal detection threshold value. Fig 12 is the BER graph of the system compared with the theoretical value, the BER of FH is a little larger than the theoretical and they both decrease with the increase of E_b/N_0.

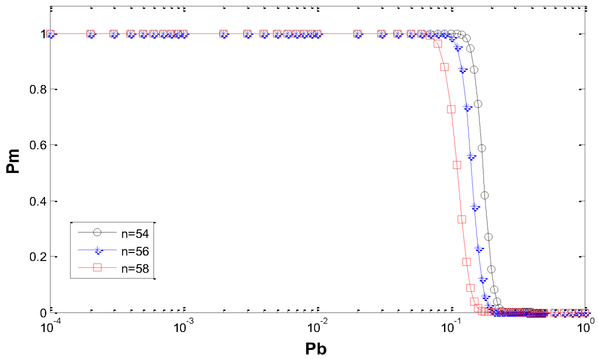

Figure 10.The relationship between P_m and P_b

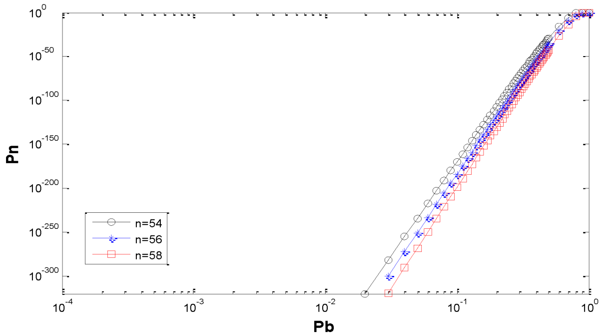

Figure11.The relationship between P_n and P_b

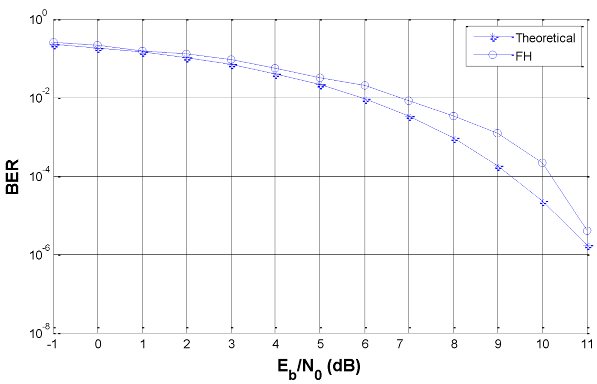

Fig 12.BER

V. Conclusion

The performance analysis shows the TOD synchronization method designed in the paper is easy to realize followed by short synchronization time, better security performance, high reliability and long holding time. Its synchronization time is only 600ms, which meets the requirements of the international practice. And its holding time is as long as 1736 days. Because of the length of the preamble, the correct detection probability is close to 1,when the error rate less than 0.01. In conclusion, it is a kind of optimal synchronization scheme for high speed FH radio.

Acknowledgment

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