

HYBRID DS/FH TWO-LEVEL CODE ACQUISITION OF FREQUENCY HOPPING RADIO IN RAYLEIGH FADING CHANNEL*

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Abstract. A method for very long pseudonoise (PN) code acquisition of frequency hopping (FH) radio is presented and analyzed. This method is realized through two-levels: (1) acquisition of preamble, which consists of several short PN codes (sync prefixes) modulated by using direct sequence (DS) technique, and (2) long PN code synchronization of FH signal checking out. This scheme at the receiving side uses a set of passive correlators and a bank of active correlators. Some numerical results of acquisition performance measures in Rayleigh fading channel are presented.

Key words: radio communication, spread spectrum communication, synchronization, Rayleigh channels

1. INTRODUCTION

Spread spectrum techniques [1, 2] have been widely used in modern radio communications for a variety of reasons, including: low detectability, interference rejection, anti-eavesdrop protection, code division multiplexing and high-resolution ranging. Two of the most prevalent forms of spread spectrum techniques are: frequency hopping and direct sequence, both of which utilize long pseudonoise codes for spreading the spectrum. Aiming to despread the spectrum at the receiving side, it is necessary to generate a local replica of the long PN code in the receiver and to synchronize it to the one superimposed on the received waveform. In general, the code synchronization process is accomplished in two steps: initial synchronization (acquisition), which is a coarse alignment process bringing the two long PN codes within one chip interval, and tracking, which is a fine tuning and synchronization maintaining process. In the technical literature several methods of long PN code acquisition in FH radio are proposed and analyzed [3-8]. A possible approach for very long PN code acquisition, so-called two-level acquisition [5, 6], is

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based on serial search and using a preamble. Although the authors' claim that schemes are intended for spread spectrum radio, both preamble and long PN code are in FH format.

The principal shortcomings of the previously reported schemes with preamble are: (1) processing gain during emitting preamble is limited by the number of FH frequencies used, and (2) FH signal is exposed to surveillance during emitting preamble.

In order to overcome these shortcomings, in this paper we propose a hybrid DS/FH two-level code acquisition of frequency hopping radio. Another advantage of the proposed method is that the initial synchronization is acquired more precisely.

In hybrid DS/FH two-level code acquisition, preamble consists of a certain number of sync prefixes (short PN codes) in DS format, while long PN code is in FH format. In the first level, the set of passive correlators is supposed to detect at least one sync prefix. The high signal level at the output of the first level activates a bank of active correlators, which is intended in second level to check up whether the long PN code synchronization is or is not acquired. The effect of two most important synchronization parameters (number of passive correlators and number of active correlators) on acquisition performance measures in the presence of noise, wideband interference and Rayleigh fading is analyzed.

2. MODEL OF HYBRID DS/FH TWO-LEVEL CODE ACQUISITION

At the beginning of the communication between two users, the calling station starts transmission by emitting a message transmission leader, shown in Figure 1.

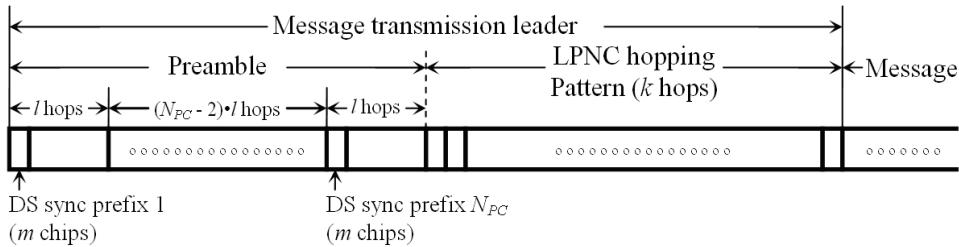


Fig. 1 Structure of message transmission leader

The message transmission leader consists of two parts (levels): (1) preamble and (2) the long PN code (LPNC) hopping pattern for synchronization checking out.

Preamble consists of N_{PC} sync prefixes in DS format. Each of them is m chips long, emitted within one hop interval, while the separation between the starting times of successive prefixes is l hops. So, the preamble duration is $T_1 = N_{PC} l T_h$, where T_h is a hop duration. In the previously reported schemes with preamble [5, 6], processing gain is limited to preamble length $L = N_{PC} l$. In hybrid scheme the prefixes are spread m times by using DS and hence the processing gain is improved to $N_{PC} l m$. Besides, initial synchronization is acquired m times more precisely.

Long PN code has been emitted after the preamble being transmitted. Synchronization checking out has been done within k hops of the long PN code. When the emitting of message transmission leader has been finished, transmitter starts message transmission.

Receiver consists of two basic parts: a set of N_{PC} passive correlators and a bank of N_{AC} active correlators, as is shown in Figure 2. The set of passive correlators is used to detect the preamble. Each passive correlator ($1, 2, \dots, N_{PC}$) is matched to the respective sync prefix ($1, 2, \dots, N_{PC}$).

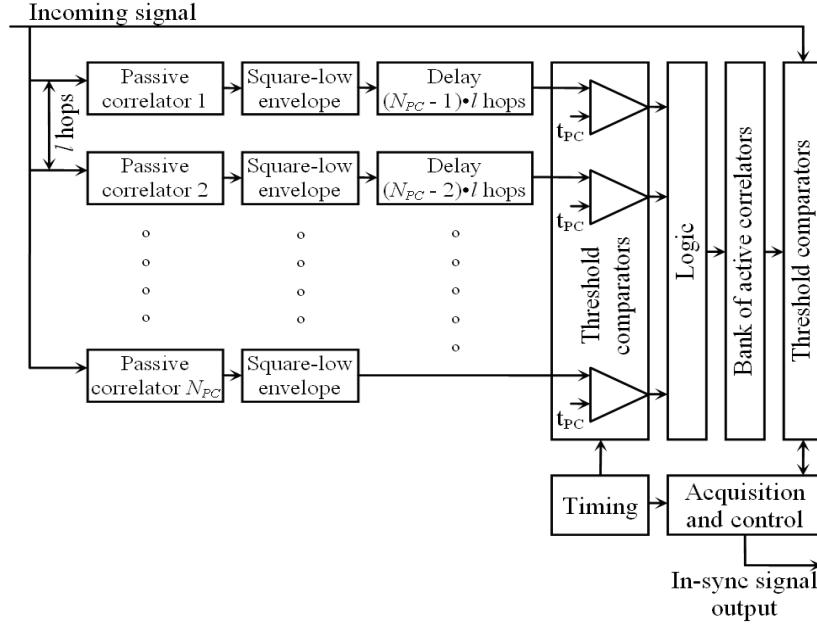


Fig. 2 Receiving side of code synchronization scheme

Passive correlators integrate over sliding windows of mT_c width, where T_c denotes PN code chip duration. Square-law envelope detector and a threshold comparator follow each of passive correlators. We assume that decision making rate indicating the presence or absence of a sync prefix is $f_c = 1 / T_c$.

Since the incoming signal after square-law envelope detector is passed through an appropriate delay, all sync prefixes arrive at the respective threshold comparator simultaneously.

If at least one sync prefix is detected, the receiver starts an active k -hop correlator from the bank, which is supposed to check up whether the long PN code synchronization is or is not acquired. At the end of correlation interval of long PN code, the output of the active correlator is compared to threshold t_{AC} .

Accordingly, the code synchronization is acquired if receiver detects at least one sync prefix, a start signal of long PN code generator finds at least one active correlator idle and the result of checking out confirms that the long PN code synchronization is acquired.

Decision whether the synchronization (either of sync prefix or of long PN code) is acquired is based on the outlet of comparison of signal level at the correlator output (either passive or active) to appropriate threshold. Outlet of comparison of the signal level at the correlator output (either passive or active) to threshold can be characterized in probabilistic sense by: probability of detection P_d and probability of false alarm P_{fa} , which can be defined as follows:

(a) Probability of detection represents the probability that correlator correctly detects an in-sync condition when it is present,

(b) Probability of false alarm represents the probability that the correlator falsely detects an in-sync condition when in fact it is not present.

Let $P_{d1}(i)$ and $P_{fa1}(i)$ be the probability of detection and probability of false alarm at the outputs of i^{th} passive correlator, respectively. Probability of detection and probability of false alarm at the output of active correlator we denote with P_{d2} and P_{fa2} , respectively.

Let E_c denote the received signal energy per chip and η denote the effective one-sided (noise + wideband interference) power spectral density.

The probability of detection at the i^{th} passive correlator is [9]:

$$P_{d1}(i) = Q\left(\sqrt{2m \frac{E_c}{\eta}}, \sqrt{t_{pC}^*}\right) \quad (1)$$

where Q is Marcum's Q function and t_{pC}^* is the normalized detection threshold

$$t_{pC}^* = \sqrt{\frac{2t_{pC}^2}{\eta m T_c}}, \text{ where } t_{pC} \text{ denotes voltage threshold. It has to be noted that } mE_c = E_h,$$

where E_h denotes the received signal energy per hop.

The probability of false alarm at the i_{th} passive correlator is:

$$P_{fa1}(i) = Q\left(0, \sqrt{t_{pC}^*}\right). \quad (2)$$

In order to improve the decision reliability, active correlator correlates over k hops.

If the channel condition changes slowly, so that the state of the channel remains the same for duration of all of the k hops of long PN code, the probability of detection at the active correlator is:

$$P_{d2}(i) = Q\left(\sqrt{2k \frac{E_h}{\eta}}, \sqrt{t_{AC}^*}\right), \quad (3)$$

$$\text{where } t_{AC}^* \text{ is the normalized detection threshold } t_{AC}^* = \sqrt{\frac{2t_{AC}^2}{\eta k T_h}}, \text{ where } t_{AC} \text{ denotes voltage}$$

threshold. The probability of false alarm at the output of active correlator can be described by:

$$P_{fa2} = Q\left(0, \sqrt{t_{AC}^*}\right). \quad (4)$$

At the first level of acquisition, when no sync preamble is present, the signals that falsely indicate preamble synchronization at the output of the set of passive correlators are generated at an average rate of:

$$\lambda = \frac{1}{T_c} \left\{ 1 - \prod_{i=1}^{N_{PC}} [1 - P_{fa1}(i)] \right\}. \quad (5)$$

At any moment of decision, a message demodulator can be activated and a false start signal of the long PN code generator can be generated if at least one of N_{PC} passive correlators generates false alarm.

At the second level, the active long PN code generator is activated for seconds during whom the synchronization is checked out.

Assuming that the false long PN code start signals arrive approximately according to a Poisson point process with an arrival rate λ , using queuing theory, the activity of the bank of active correlators can be modeled as a queuing system [10] with a finite number of servers - active correlators N_{AC} , fixed holding time kT_h and no room for waiting. In that case, the offered load to the bank of active correlators is:

$$\alpha = \lambda k T_h. \quad (6)$$

Owing to more than one consecutive false decision at the output of the passive correlators, it is possible to have more than one active correlators simultaneously integrating over the k -hop sequence of the long PN code. Start signal of the long PN code, which finds all active correlators engaged, is ignored. The probability that the long PN code start signal finds the all active correlators from the bank engaged (blocked) is the blocking probability $B(N_{AC}, \alpha)$.

Modeling the bank of active correlators on that way, the blocking probability is given by the Erlang-B formula [10]:

$$B(N_{AC}, \alpha) = \frac{\left(\frac{\alpha N_{AC}}{N_{AC}!}\right)}{\sum_{j=0}^{N_{AC}} \left(\frac{\alpha^j}{k!}\right)} \quad (7).$$

3. RAYLEIGH FADING CHANNEL

Energies of one chip and one hop in the absence of fading are respectively:

$$E_c = \frac{R^2 T_c}{2} \text{ and } E_h = \frac{R^2 T_h}{2}, \text{ where } R \text{ denotes received signal amplitude.}$$

For a fading channel, R is a random variable r with some probability density function. We assume that the fading is constant across the total spread spectrum bandwidth and varies slowly in time, so as the fading is constant during time interval of k hops. Although our analysis allows for arbitrary fade statistics, in further text we assume the commonly used Rayleigh fading amplitude statistics which describes the case where the received signal consists of multiple reflected rays and the amplitude of the direct component approaches zero.

The slow frequency non-selective Rayleigh fading is characterized by the probability density function:

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \quad r \geq 0, \quad (8)$$

where r is the envelope amplitude of the received signal and $2\sigma^2$ is the predetection mean power of the multipath signal [11].

The overall probability of detection is obtained by averaging over (8). When slow frequency non-selective Rayleigh fading affect received signal, the probability of detection at i^{th} passive correlator $P_{d1}^f(i)$ is:

$$P_{d1}^f(i) = \int_0^\infty Q\left(\sqrt{2m \frac{rT_c}{\eta}}, \sqrt{t_{PC}^*}\right) \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \quad r \geq 0. \quad (9)$$

Similarly, under assumption that the state of the channel remains the same for duration of k hops of the long PN code, the probability of detection at the active correlator P_{d2}^f in the presence of slow frequency-nonselective Rayleigh fading is:

$$P_{d2}^f = \int_0^\infty Q\left(\sqrt{2k \frac{rT_h}{\eta}}, \sqrt{t_{AC}^*}\right) \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \quad r \geq 0. \quad (10)$$

4. PERFORMANCE MEASURES

We use false lock probability, miss probability and acquisition time as performance measures. False lock is the situation when the acquisition control unit indicates that code synchronization is acquired, but in fact, it does not happen. That occurs if all of the following three events consecutively occur:

- (a) at the output of at least one of N_{PC} passive correlators the false alarm occurs, leading to generation of a long PN code start signal,
- (b) at least one of N_{AC} active correlators is idle, so as the long PN code start signal is not blocked,
- (c) the idle active correlator, which was engaged by the long PN code start signal, produces a false alarm.

Therefore, for the long PN code start signals, the probability of false lock P_{fl} can be described by:

$$P_{fl} = \left\{ 1 - \prod_{i=1}^{N_{PC}} [1 - P_{fa1}(i)] \right\} [1 - B(N_{AC}, a)] P_{fa2}. \quad (11)$$

Miss is the situation when the acquisition control unit indicates that code synchronization is not acquired, but in fact it happens. In-sync condition is missed (not detected) if any of the following three mutually exclusive events occurs:

- (a) none of N_{PC} passive correlators detects sync prefix,
- (b) at least one of N_{PC} passive correlators detects sync prefix, but all the active correlators are busy and hence the long PN code start signal is ignored,
- (c) at least one of N_{PC} passive correlators detects preamble synchronization, at least one of the active correlators is idle, but signal level at the output of active correlator does not exceed the threshold t_{AC} .

Probability of missing the in-sync condition P_{miss} can be described by:

$$\begin{aligned} P_{miss} = & \prod_{i=1}^{N_{PC}} [1 - P_{d1}(i)] + \left\{ 1 - \prod_{i=1}^{N_{PC}} [1 - P_{d1}(i)] \right\} B(N_{AC}, a) + \\ & + \left\{ 1 - \prod_{i=1}^{N_{PC}} [1 - P_{d1}(i)] \right\} [1 - B(N_{AC}, a)] (1 - P_{d2}). \end{aligned} \quad (12)$$

In the hybrid two-level code synchronization scheme, just prior to data transmission, the transmitter sends a message transmission leader. Thus, the length of the leader represents the maximum time that the receiver has for code synchronization. It is supposed that, within duration of message transmission leader, the receiver acquire the synchronization with high probability.

So, the acquisition time can be described using the following relation:

$$T_A = (L + k)T_h \quad (13)$$

For the following set of acquisition parameters ($L = 160$, $k = 512$) and hopping rate of 100 hops/s, i.e. $T_h = 0.01s$, acquisition time is $T_A \approx 0.67s$.

5. NUMERICAL RESULTS AND CONCLUSIONS

The false lock probability and the miss probability are functions of the passive and active correlators' thresholds, the system parameter (N_{PC} , m , L , N_{AC} , k), received signal energy per hop E_h and effective noise power spectral density η . For a given set of system parameters and channel characteristics, relations (11) – (12) depend only upon thresholds.

Thresholds optimization will be done so as to minimize the miss probability under constraint that the false lock probability is specified. Mathematically, the problem is to find thresholds t_{PC}^* and t_{AC}^* , so as to minimize the probability P_{miss} under the constraint $P_{fl} \leq 10^{-p}$, where $p > 0$ (typically $p = 8$).

Numerical calculations in this paper are done for the following set of acquisition parameters: number of passive correlators $N_{PC} = 16$, sync prefix length $m = 64$ chips, preamble length $L = 160$ hops, number of active correlators $N_{AC} = 1$, and length of active correlators $k = 128$ hops. These values are called “standard values of acquisition parameters”.

Figure 3 presents the miss probability with respect to the normalized detection threshold, in Rayleigh fading environment, for standard values of acquisition parameters and signal-to-noise ratio $E_h / \eta = 10 \text{ dB}$, while false lock probability is kept $P_{fl} \leq 10^{-8}$. Envelope amplitude of the received signal is $r = 0.5 \text{ V}$ and predetection mean power $2\sigma^2 = 0.98$ ($\sigma = 0.7$), which are called “standard Rayleigh fading parameters”. Minimum miss probability for standard values of acquisition parameters in standard Rayleigh fading environment is $1.3 \cdot 10^{-2}$.

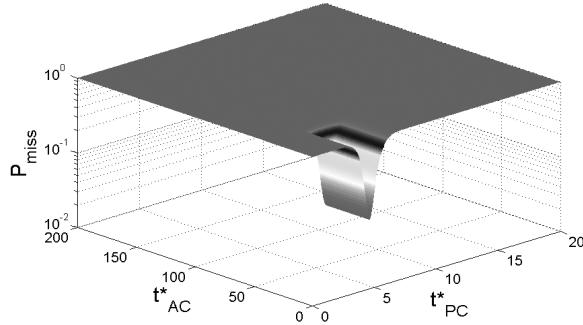


Fig. 3 Miss probability versus normalized detection thresholds in the presence of Rayleigh fading ($P_{fl} \leq 10^{-8}$, $N_{PC} = 16$, $m = 64$, $L = 160$, $N_{AC} = 1$, $k = 128$, $E_h / \eta = 10 \text{ dB}$, $r = 0.5 \text{ V}$, $\sigma = 0.7$)

Figure 4 and Figure 5 present the minimum miss probability with respect to E_h / η in the fading environment, where N_{PC} and N_{AC} are being parameters, respectively, and $P_{fl} \leq 10^{-8}$.

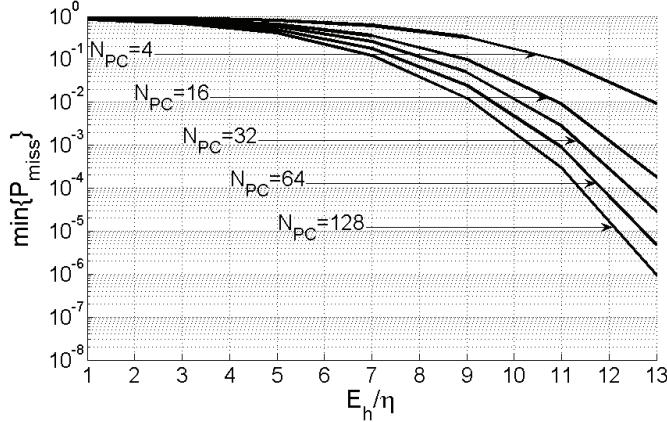


Fig. 4 Minimum miss probability versus signal-to-noise ratio E_h / η in the presence of Rayleigh fading, where number of passive correlators N_{PC} is parameter ($P_{fl} \leq 10^{-8}$, $N_{PC} = 16$, $m = 64$, $L = 160$, $N_{AC} = 1$, $k = 128$, $r = 0.5$ V, $\sigma = 0.7$)

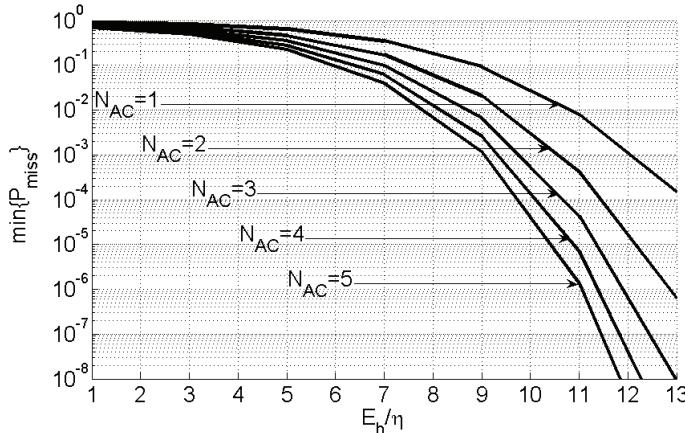


Fig. 5 Minimum miss probability versus signal-to-noise ratio E_h / η in the presence of Rayleigh fading, where number of active correlators N_{AC} is parameter ($P_{fl} \leq 10^{-8}$, $N_{PC} = 16$, $m = 64$, $L = 160$, $k = 128$, $r = 0.5$ V, $\sigma = 0.7$)

As a general conclusion, we can say that hybrid DS/FH two-level code acquisition method is a promising algorithm for very long PN code acquisition of FH radio. The principal advantage of the proposed hybrid scheme with DS preamble in comparison to standard scheme with FH preamble is that the processing gain during emitting preamble is improved. Besides, the initial synchronization is acquired more precisely.

The choice of the suitable acquisition parameters is closely related to the complexity of hybrid DS/FH radio system. Minimum miss probability can be significantly reduced by

increasing the number of passive and active correlators. For a simple and cheap system, we suggest using eight passive and one active correlator, while in a system of moderate complexity an optimal compromise is to use sixteen passive and two active correlators. For an expensive system, sixty-four passive and five active correlators may be used.

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