An Improved Preamble Detection Method for LTE PRACH in High-Speed Railway Scenario

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***Abstract*—In high-speed railway scenario, Doppler frequency shift influences the performance of preamble detection by inducing pseudo correlation peaks at the receiver side of Physical Random Access Channel (PRACH). To solve this problem, an improved preamble detection method which is carried out by two steps with combined detection thresholds is proposed in this paper. The first step is to detect the correlation peaks by each root Zadoff-Chu (ZC) sequence and the second step is to detect the exact number of random access users by search window. The superiority of the proposed method over the traditional method is verified in performance and flexibility to various propagation channels. Under the condition of different preamble formats, simulation results show that the performance of detection probability of the proposed method is at least 3dB better than the protocol requirement.**

Keywords-preamble detection; high-speed railway; frequency offset; detection threshold

I. INTRODUCTION

Nowadays Long Term Evolution (LTE) systems have been the mainstream mobile communication system in the world. In LTE, the initial uplink communication is established by Physical Random Access Channel (PRACH), including the initial access and uplink time synchronization. According to the LTE standard, Zadoff-Chu (ZC) sequence with a unique cyclic shift is used by UE as the preamble for random access (RA) procedure [1]. The sequence is provided with ideal auto-correlation and cross-correlation properties [2]. There are 64 random access (RA) preambles available in each cell. Additional preamble sequences, in case 64 preambles cannot be generated from a single root ZC sequence, are obtained from the root sequences with the consecutive logical indexes until all the 64 sequences are found [1]. A UE transmits the RA preamble through PRACH if it requests accessing the LTE network. The RA preamble detector of BS is able to detect the presence of RA preamble, estimate the exact user ID of RA preamble and calculate the propagation delay between UE and BS.

Some previous works have analyzed the methods of preamble detection in low-speed scenario. In [3], a preamble detection method that can work usefully in a large propagation delay environment is proposed. The authors in [4] propose a modified method of PRACH detection threshold setting in LTE system. In [5], the authors mainly research on the performance of preamble detection when channels become more time dispersive.

However, these schemes are just suitable for detection in low-speed scenario. With the development of high-speed railway and public growing demand on data traffic, the performance of preamble detection in high-speed railway scenario becomes important. Literatures [6] and [7] focus on analysis and modeling for LTE systems in high-speed railway scenario. Different from low-speed scenario, larger Doppler frequency shift is caused by high speed movement. In [8], the frequency offset effects on random access signals are described. A frequency offset estimation algorithm based on PRACH preambles is proposed in [9]. From these literatures, it is known that Doppler frequency shift results in the formation of pseudo correlation peaks. Therefore Doppler frequency shift will affect the performance in terms of both the detection probability and the false alarm probability. Considering this problem, an improved preamble detection method is proposed for high-speed scenario in this paper. The proposed method is implemented by two steps with combined detection thresholds. The first step is to detect the correlation peaks by each root ZC sequence and the exact number of random access users is detected by search window in the second step. Compared with the traditional single step method in which the preamble sequence is detected just by search window, the proposed method can perform better in various propagation channels with each preamble format stipulated in the LTE standard for PRACH.

The remainder of this paper is organized as follows. Section II describes the system model of the whole PRACH receiving process and the features in high-speed railway scenario. Detection methods including a traditional preamble detection method and the proposed preamble detection method for high-speed railway scenario are described in Section III. Simulation results are presented in Section IV, and Section V concludes the paper.

II. SYSTEM MODEL AND FEATURES IN HIGH-SPEED RAILWAY SCENARIO

A. Random Access Preamble Sequence

The LTE system adopts ZC sequence as a random access preamble. The definition of ZC sequence is

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$$x_u(n) = e^{-j\frac{\pi un(n+1)}{N_{ZC}}}, \quad 0 \le n \le N_{ZC}-1. \tag{1}$$

where N_{ZC} is the length of the ZC sequence.

The random access preambles with zero correlation zones based on the uth root ZC sequence with length of $N_{CS}-1$ are defined by cyclic shifts according to

$$x_{u,v}(n) = x_u((n+C_v) \bmod N_{ZC}). \tag{2}$$

where C_v is the cyclic shift and the value of N_{CS} is given in [1].

B. Hybrid Time-Frequency Domain Process

A hybrid time-frequency domain receiving model is shown in Fig. 1.

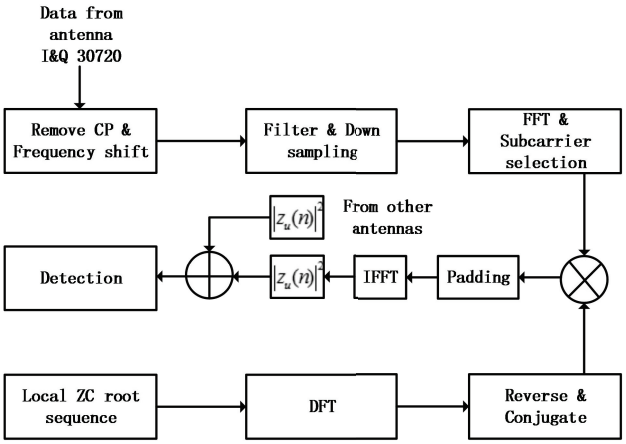

Figure 1. Hybrid time-frequency domain receiving process in LTE

The hybrid time-frequency domain process removes CP and implements the frequency shift first. With the process of anti-aliasing filtering and down-sampling, the subcarrier signal of PRACH can be extracted after a small size FFT. The anti-aliasing filter is to filter out interferences from uplink data and uplink controlling. Then multiply the frequency domain signal with local root ZC sequences. The result pads with zeros in order to adjust the required IFFT size. The data after IFFT is modulus square to get the power delay profile (PDP). And the presence of RA preamble is detected through using the PDP.

The detection process with FFT/IFFT is of low complexity and easier to be implemented [11]. The sampling rate of the system is 30.72MHz corresponding to 20MHz system bandwidth, whereas the PRACH sequence only occupies 1.08MHz including guard band of 31.25kHz at two side of PRACH signal in frequency domain. Therefore, the down sampling could reduce the complexity by realizing a small-size FFT block at receiver because the preamble sequence length is only 839 for format 0-3 or 139 for format 4. The format 4 is only applied to low-speed scenario for preamble detection. Thus, in this paper, the performance of the proposed method in preamble format 0-3 is mainly discussed. In practice, we choose 2048 as the size of FFT and IFFT.

C. Features in High-Speed Railway Scenario

In high-speed railway scenario, we mainly analyze the frequency offset effects on random access preamble detection. $x_u(n)$ denotes the original preamble sequence and $\Delta\omega$ denotes the phase to frequency offset Δf. The received preamble with frequency offset $y(n)$ is given by

$$y(n) = x_u(n)e^{-j\Delta\omega n} + w(n) = x_u(n)e^{-j2\pi n\frac{\Delta f}{f_s}} + w(n) \tag{3}$$

where $w(n)$ is a complex Additive White Gaussian Noise (AWGN) with the power of σ_n^2 ,that is, $w(n) \sim CN(0,\sigma_n^2)$. f_s is equal to $1/T_{samp}$ and T_{samp} is the time sample interval. Therefore, $y(n)$ can be expressed as

$$y(n) = x_u(n)e^{-j2\pi\Delta fT_{samp}n} + w(n) = x_u(n)e^{-j\frac{2\pi\Delta fT_{SEQ}n}{N_{ZC}}} + w(n) \tag{4}$$

where T_{SEQ} denotes the time length of preamble sequence. The variable $\Delta f_{RA} = 1/T_{SEQ}$ is the subcarrier spacing for the random access preamble. For LTE preamble format 0-3, Δf_{RA} is 1250Hz. PDP is the power distribution derived from the cross correlation between received preamble sequence and the cyclic shift of original ZC sequence. It can be expressed as

$$PDP(l) = \left|\sum_{n=0}^{N_{ZC}-1} y(n)x_u^*\left[(n+l) \bmod N_{ZC}\right]\right|^2, l = 0,...,N_{ZC}-1 \tag{5}$$

With (1), (4) and (5), the peak power of the PDP at $l=0$ is given by

$$\begin{aligned} PDP_{l=0}(\Delta f) &= \left|\sum_{n=0}^{N_{ZC}-1}[x_u(n)e^{-j2\pi\Delta fT_{samp}n} + w(n)]x_u^*(n)\right|^2 \\ &= \left|\sum_{n=0}^{N_{ZC}-1}\left(e^{-j\frac{2\pi n\Delta fT_{SEQ}}{N_{ZC}}} + x_u^*(n)w(n)\right)\right|^2 \end{aligned} \tag{6}$$

If the effect of noise is ignored, (6) can be simplified as

$$\begin{aligned} PDP_{l=0}(\Delta f) &= \left|\sum_{n=0}^{N_{ZC}-1} e^{-j\frac{2\pi n\Delta fT_{SEQ}}{N_{ZC}}}\right|^2 = \left|\frac{1-e^{-j2\pi\Delta fT_{SEQ}}}{1-e^{-j\frac{2\pi\Delta fT_{SEQ}}{N_{ZC}}}}\right|^2 \\ &= \left|\frac{\sin(\pi\Delta fT_{SEQ})e^{-j\pi\Delta fT_{SEQ}\frac{N_{ZC}-1}{N_{ZC}}}}{\sin\frac{\pi\Delta fT_{SEQ}}{N_{ZC}}}\right|^2 = \left|\frac{\sin(\pi\Delta fT_{SEQ})}{\sin\frac{\pi\Delta fT_{SEQ}}{N_{ZC}}}\right|^2 \end{aligned} \tag{7}$$

According to [12], the frequency offset will result in pseudo correlation peaks at $(C_v \pm n \cdot d_u) \bmod N_{ZC}$. The variable d_u is the cyclic shift corresponding to a Doppler shift of magnitude $1/T_{\mathrm{SEQ}}$ and is given by

$$d_u = \begin{cases} p & 0 \le p < N_{\mathrm{ZC}}/2 \\ N_{\mathrm{ZC}} - p & \text{otherwise} \end{cases} \tag{8}$$

where p is the smallest non-negative integer that fulfills $(pu) \bmod N_{ZC} = 1$ [1]. The peak power of the PDP at $l = d_u$ is given by

$$\begin{aligned} PDP_{l=d_u}(\Delta f) &= \left| \sum_{n=0}^{N_{ZC}-1} e^{-j\frac{2\pi n \Delta f T_{SEQ}}{N_{ZC}}} e^{j\pi u \frac{\left(d_u^2 + 2nd_u + d_u\right)}{N_{ZC}}} \right|^2 \\ &= \left| \frac{\sin\left(\pi\left(\Delta f T_{SEQ} - 1\right)\right)}{\sin\left(\frac{\pi}{N_{ZC}}\left(\Delta f T_{SEQ} - 1\right)\right)} \right|^2 \end{aligned} \tag{9}$$

Similarly, the peak power of the PDP at $l = -d_u$ is given by:

$$PDP_{l=-d_u}(\Delta f) = \left| \frac{\sin\left(\pi\left(\Delta f T_{SEQ} + 1\right)\right)}{\sin\left(\frac{\pi}{N_{ZC}}\left(\Delta f T_{SEQ} + 1\right)\right)} \right|^2 \tag{10}$$

The curves of $PDP_{l=0}(\Delta f)$, $PDP_{l=d_u}(\Delta f)$ and $PDP_{l=-d_u}(\Delta f)$ are shown in Fig. 2. When $0 \le abs(\Delta f) \le \Delta f_{RA}$, $PDP_{l=0}(\Delta f)$ decreases with the increasing of the absolute value of the frequency offset. Specially, when $\Delta f = \pm \Delta f_{RA}$, $PDP_{l=0}(\Delta f)$ decreases to zero. $PDP_{l=-d_u}(\Delta f)$ and $PDP_{l=d_u}(\Delta f)$ which reach to the maximum value when $\Delta f = -\Delta f_{RA}$ and $\Delta f = \Delta f_{RA}$ respectively are the left and right curves of $PDP_{l=0}(\Delta f)$.

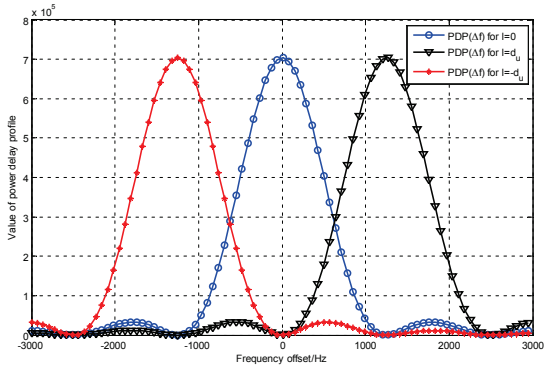

Figure 2. Curves of $PDP_{l=-d_u}(\Delta f)$, $PDP_{l=0}(\Delta f)$ and $PDP_{l=d_u}(\Delta f)$

Based on the above analysis, we can see the changed trend of the correlation peaks in high-speed railway scenario. The speed of high-speed train is up to 370km per hour. Thus, depend on the center frequency, Doppler frequency shift is generally no more than 1500Hz. So we just need to consider the effects of pseudo correlation peaks at $(C_v \pm d_u) \bmod N_{ZC}$ on the process of preamble detection.

III. DETECTION METHOD

A. Traditional Preamble Detection Method

The traditional detection principle of random access preamble is to judge the correlation peak value between different cyclic shift of the root sequence and received preamble. In low-speed scenario, constructing a searching window with the length of N_{CS}, the detection succeeds if correlated value exceeds the pre-set detection threshold. And according to the time sampling point of the correlation peak value, we can calculate the propagation delay between UE and BS. But the noise is assumed if the correlation peak value doesn't exceed detection threshold. The detection threshold is commonly set based on the noise power estimation [3] [4].

In high-speed railway scenario, two additional detection ranges besides the main search range are required to deal with pseudo correlation peaks, as shown in Fig. 3. Each search range is divided into multiple search windows with the length of N_{CS}. And synthetic detection of three correlated windows needs to be carried out, such as CS_{-1}, CS, CS_{+1}.

The traditional method sets three threshold factors respectively for the three search ranges. Separately search the maximum power value in each of the three correlated windows and judge whether it's greater than the threshold factor multiplied by the value of noise power estimation. If any of the three correlated windows has the peak value satisfying detection threshold, the detection is successful or else the noise is assumed.

To evaluate the preamble detection method, the performance of false alarm probability and correct detection probability needs to be considered in various channel conditions with each of the preamble formats, such as AWGN and Extended Typical Urban (ETU) channels. However, the traditional method has its disadvantages in practice. For example, the performance of the traditional method will be instable in various channels.

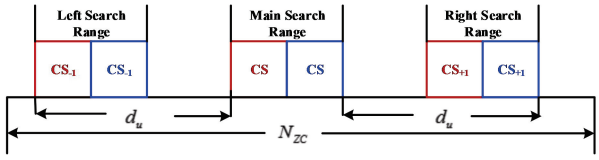

Figure 3. Random access detection in high-speed scenario

B. Proposed Preamble Detection Method

In order to solve the problems of the traditional method, besides the frequency offset effects, the effects of channel conditions on preamble detection in high-speed railway scenario should also be considered. ETU model is shown in TABLE I [10]. The maximum time delay is 5000ns and the

system sampling rate is 30.72MHz. And the size of FFT and IFFT is 2048. So the theoretical length of the PDP that including all of the correlation peak power in ETU channel is $5000\times10^{-9}\times30.72\times10^{6}/12=12.8$.

TABLE I. EXTENDED TYPICAL URBAN MODEL

Excess tap delay [ns]	Relative power [dB]
0	-1.0
50	-1.0
120	-1.0
200	0.0
230	0.0
500	0.0
1600	-3.0
2300	-5.0
5000	-7.0

For preamble format 0-3, the length of the preamble sequence is 839 and after the zero padding the size of IFFT is 2048. Therefore, without the effects of frequency offset the theoretical power of correlation peak will be allocated into two or three consecutive points of the PDP in AWGN channel. From what has been discussed above, considering the features in high-speed railway scenario, we propose a two-step preamble detection method.

1) Detect the correlation peaks by each root sequence

Assume that 64 preambles are generated from M Zadoff-Chu root sequences and each root sequence will generate a group of PDP sequence of N_{IFFT} points according to the system model mentioned in Section II. In order to facilitate describing the method, the PDP sequences are expressed as $PDP^{(q)}(n),\ 0\le q\le M-1,\ 0\le n\le N_{IFFT}-1$. Find the maximum value of each group of PDP sequences, which is denoted by $MaxValue^{(q)}$. And $MaxValuePos^{(q)}$ denotes the position of $MaxValue^{(q)}$. If $MaxValuePos^{(q)}$ is in the main search range as shown in Fig. 3, $MaxDuValue^{(q)}$ denotes the bigger value between $PDP^{(q)}((MaxValuePos+D)\bmod N_{IFFT})$ and $PDP^{(q)}((MaxValuePos-D)\bmod N_{IFFT})$ where $D=d_u\cdot N_{IFFT}/N_{ZC}$. If $MaxValuePos^{(q)}$ is in the left or right search range, the value of the corresponding position in the main search range is $MaxDuValue^{(q)}$. $SumWinA^{(q)}$ is given by

$$SumWinA^{(q)}=MaxValue^{(q)}+MaxDuValue^{(q)} \quad (11)$$

$SumWinB^{(q)}$ is given by

$$SumWinB^{(q)}=MaxValue^{(q)}+SMaxValue^{(q)} \quad (12)$$

where $SMaxValue^{(q)}$ denotes the bigger value between $PDP^{(q)}(MaxValuePos+1)$ and $PDP^{(q)}(MaxValuePos-1)$. Considering the effects of ETU channel, we also need to use the window length of 14 sample points to slide in $PDP^{(q)}$ and add the values of 14 points. $SumWinC^{(q)}$ denotes the maximum sum of 14 points. $MeanValue$ is given by

$$MeanValue=\sum_{n=0}^{N_{IFFT}-1}PDP^{(q)}(n)\Big/N_{IFFT} \quad (13)$$

where the value of q has no effect on calculating the mean value of each PDP sequence because of energy conservation. Based on $MeanValue$, the $ThresholdA$, $ThresholdB$ and $ThresholdC$ are given by

$$ThresholdA=K_A\cdot MeanValue \quad (14)$$

$$ThresholdB=K_B\cdot MeanValue \quad (15)$$

$$ThresholdC=K_C\cdot MeanValue \quad (16)$$

where K_A, K_B and K_C are adjustment factors derived from simulations. If $SumWinA^{(q)}>ThresholdA$ or $SumWinB^{(q)}>ThresholdB$ or $SumWinC^{(q)}>ThresholdC$, go on to implement the second step. Otherwise, it means there is no random access user and detecting by search window is unnecessary in this group of PDP sequence. Thus the time overhead is saved through this step. Then continue to detect the next group of PDP sequence.

2) Detect the exact number of random access users by search window

$MaxValue^{(q)}$ of the first step is used to help us detect the exact number of random access users by search window in this group of PDP sequence. The length of search window is expressed as

$$W=N_{CS}\cdot N_{IFFT}/N_{ZC} \quad (17)$$

Each random access user should be synthetic detected by three correlated search windows, as shown in Fig. 3. The starting positions of three correlated windows are $((C_v-d_u)\cdot N_{IFFT}/N_{ZC})\bmod N_{IFFT}$, $C_v\cdot N_{IFFT}/N_{ZC}$ and $((C_v+d_u)\cdot N_{IFFT}/N_{ZC})\bmod N_{IFFT}$. The maximum value of the three correlated search windows is denoted by $MaxWinValue^{(q)}(v)$ that the range of v is stipulated in the LTE standard for PRACH [1]. $SumWinD^{(q)}(v)$ is given by

$$\begin{aligned}SumWinD^{(q)}(v)=&PDP^{(q)}(SPos_l{}^{(q)}(v)+MaxWPos^{(q)}(v))\\&+PDP^{(q)}(SPos_m{}^{(q)}(v)+MaxWPos^{(q)}(v))\\&+PDP^{(q)}(SPos_r{}^{(q)}(v)+MaxWPos^{(q)}(v))\end{aligned} \quad (18)$$

where $SPos_l{}^{(q)}(v)$, $SPos_m{}^{(q)}(v)$ and $SPos_r{}^{(q)}(v)$ denote the starting positions of three correlated windows respectively, $MaxWPos^{(q)}(v)$ denotes the position of $MaxWinValue^{(q)}(v)$ relative to the starting position of the search window. Then the noise power of the three correlated windows is estimated as follows

$$NoisePower^{(q)}(v) = (SumThreeWin^{(q)}(v) - SumWinD^{(q)}(v))/(3 \cdot W - 3) \quad (19)$$

where $SumThreeWin^{(q)}(v)$ denotes the total value of three correlated search windows. Based on $NoisePower^{(q)}(v)$ and $MaxValue^{(q)}$, the $ThresholdD$ and $ThresholdE$ are given by

$$ThresholdD^{(q)}(v) = K_D \cdot NoisePower^{(q)}(v) \quad (20)$$

$$ThresholdE^{(q)} = K_E \cdot MaxValue^{(q)}, 0 < K_E < 1 \quad (21)$$

where K_D and K_E are adjustment factors derived from simulations. If $SumWinD^{(q)}(v) > ThresholdD^{(q)}(v)$ and $MaxWinValue^{(q)}(v) > ThresholdE^{(q)}$, it means there is a random access user and $MaxWPos^{(q)}(v)$ is used to calculate the propagation delay between UE and BS. Or else, the noise is assumed in this group of search windows, and then continue to synthetic detect the next group of three correlated search windows.

IV. SIMULATIONS

The performance of the preamble detection in LTE is measured by false alarm probability and detection probability. According to the protocol requirements of [10], the false alarm probability shall be less than or equal to 0.1%. The probability of detection shall be equal to or exceed 99% for the SNR levels listed in the TABLE II. Thus the missed detection probability should not be more than 1%. The LTE PRACH parameters used in simulation are listed in TABLE III.

TABLE II. PRACH MISSED DETECTION REQUIREMENTS FOR HIGH SPEED MODE

Propagation conditions	**Frequency offset**	**SNR[dB]**			
		Format 0	***Format 1***	***Format 2***	***Format 3***
AWGN	0	-14.1	-14.2	-16.3	-16.6
ETU70	270Hz	-7.4	-7.3	-9.3	-9.5
AWGN	625Hz	-12.4	-12.3	-14.4	-14.4
AWGN	1340Hz	-13.4	-13.5	-15.5	-15.7

TABLE III. SIMULATION PARAMETERS

Parameters	**Specification**
Bandwidth	20MHz
Sample frequency	30.72MHz
Subcarrier spacing	1.25KHz
Preamble format	Format 0-3
Logical sequence index	384
N_{ZC}	839
Number of TX antennas	1
Number of RX antennas	2
Channel models	AWGN, ETU70

In the proposed method, there are five threshold factors in all. The settings of K_A, K_B and K_C require a large number of simulations, which can ensure that the false alarm probability less than 0.1%. The suggestive values of K_A, K_B and K_C are listed in TABLE IV. The settings of K_D and K_E are relatively flexible based on the variable number of random access users. For instance, if there is only one random access user in the cell, the assignment for K_D and K_E can be 13 and 0.9 respectively with preamble format 0.

TABLE IV. SUGGESTIVE VALUES OF THRESHOLD FACTORS

Preamble format	**Threshold factors**		
	K_A	K_B	K_C
Format 0	12	18	46
Format 1	14	20	50
Format 2	9	12	36
Format 3	10	13	39

To evaluate the performance of the proposed preamble detection method, the traditional method is adopted in the simulation as well. The simulation results are shown in Fig. 4-7.

Fig. 4-7 demonstrate that the proposed preamble detection method has overwhelming advantages over the traditional method in AWGN and ETU channels with each of the preamble formats stipulated in the LTE standard for PRACH. Also it is necessary to compare the performance of the proposed method with the protocol requirements. For example, under the condition of the missed detection probability is equal to 1%, the SNR of the proposed method is about -17.3dB with preamble format 0 when the channel condition is AWGN and the frequency offset is 0Hz. The SNR of the protocol requirement is just -14.1dB in this case as shown in TABLE II. So the detection probability performance is 3.2dB better than the protocol requirement in this scenario. In a similar way, we can draw a conclusion that the detection probability performance of the proposed method is at least 3dB better than the protocol requirements in high-speed railway scenario.

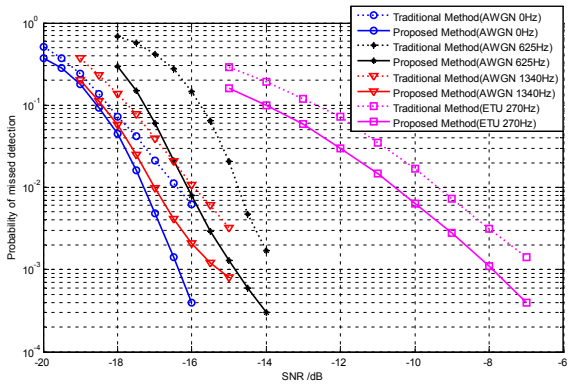

Figure 4. Performance of different methods with preamble format 0

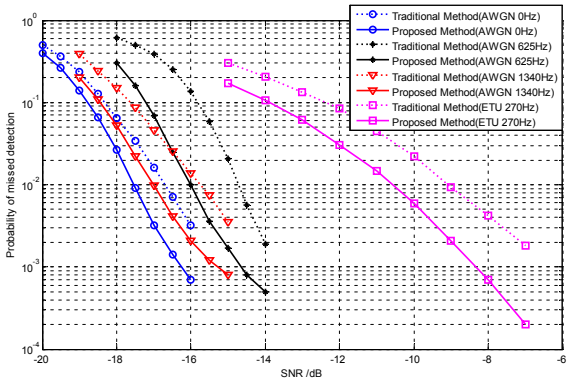

Figure 5. Performance of different methods with preamble format 1

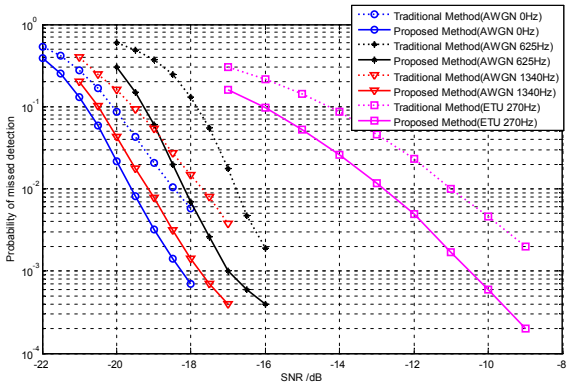

Figure 6. Performance of different methods with preamble format 2

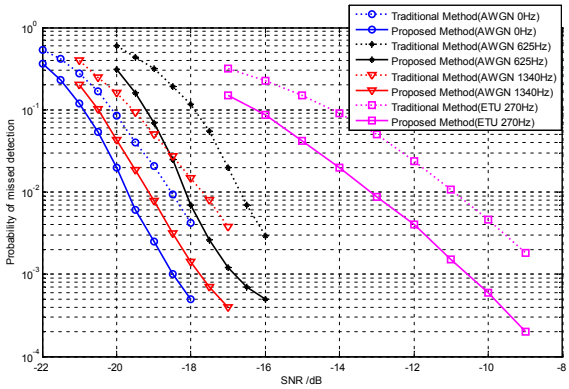

Figure 7. Performance of different methods with preamble format 3

V. CONCLUSIONS

In this paper, an improved preamble detection method is proposed for LTE PRACH in high-speed railway scenario. The method is carried out by two steps with combined detection thresholds. The correlation peaks is detected by each root ZC sequence in the first step. And then the second step is to detect the exact number of random access users by search window. The proposed method shows better performance than the traditional single step method. The simulation results also indicate the outstanding detection probability performance of the proposed method compared with the protocol requirements. In addition, this improved preamble detection method can be applied to various channels with different preamble formats, and has promising value in engineering.

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