A Two-Step Time Delay Difference Estimation Method for Initial Random Access in Satellite LTE System

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Abstract—**In initial random access, base station (BS) estimates the distance between the user equipment (UE) and BS. In the mobile satellite system (MSS), however, the characteristics of large transmission delay makes the estimation method used in the terrestrial system not applicable in the MSS. To solve this problem, a two-step time delay difference estimation scheme is proposed for orthogonal frequency division multiple access (OFDMA) multi-beam satellite system. We first divide a beam cell into some layered small sub-areas according to the different delay difference values. Then, two types of Physical Random Access Channel (PRACH) preamble burst format are performed: the first one is for the fractional delay difference value measurement and the second one is for the integer part. Further, complete criteria for the designation of PRACH parameters are proposed and closed-form expressions of the system performance are also derived, including the false alarm probability and the missed detection probability. Finally, according to the numerical analysis, the method shows good performance.**

Keywords—**PRACH, LTE, satellite, random access, doppler shift**

I. INTRODUCTION

Recent years, researchers have paid more and more attentions on LTE, Therefore, terrestrial-satellite convergent system based on LTE becomes the current research hotpot [1][2]. Corresponding researches are given on whether the key technologies for LTE, OFDM technology and MIMO, are suitable to be applied in satellite communications. Among the technologies, random access, as the initial step of the user access network, is crucial for the establishment of the entire communication process, among which, the time delay estimation is the core technology

In the mobile satellite system (MSS), however, the characteristics of large transmission delay leads to large time difference when each terminal's preamble sequence reaches the satellite. This makes the method used in the terrestrial system not satisfy the requirement in the MSS, and has been a tough problem for satellite LTE (S-LTE) system. In [3], the impact of the satellite delay and Doppler are taken into account, and they state that the preamble sequence needs to be redesigned, and give the conclusion of not to use the cyclic shift sequence. But the detailed criterions are not actually given. Anyhow, a mature delay estimation method for random access in S-LTE system has not been given in existing works.

This paper proposes a two-step time delay difference estimation method for S-LTE system. The influence of Doppler shift and large time delay in the transmitting process is considered, and thus we can correctly estimate the time delay. Meanwhile, this method is compatible with terrestrial LTE system very well. We divide the cell into several sub-areas according to the time delay difference. The fractional part of the delay difference is measured in first step, and of which the UE is informed. Then, UE send the preamble in advance, thus the gate way station (GWS) will decide the specific sub-area which the UE belongs to.

The rest of this paper is outlined as follows. In section II, the model for S-LTE system is described. In section III, we propose a two-step delay difference estimation method, as well as the detailed criteria for parameters designation. In section IV, the performance of our method is estimated and numerical analysis and simulations for above method are given, and in section V we conclude this paper.

II. SYSTEM MODEL

In multi-beam satellite communication systems, a number of spot beams are formed by beam-forming technology, and the coverage of adjacent beams are partially overlapped just like the overlay structure of terrestrial cellular systems. There are two patterns used by the GEO satellite system in China, one with 109 spot beams and a beam radius of 200 km, and the other with 218 spot beams and a beam radius of 150 km.

GEO satellite is synchronous to the earth's surface. Thus there is a certain elevation angle in China ranging from 20° to 60°, which causes different propagation delays of users at different positions in a same beam. As shown in Figure 1, the delay difference between the longest and shortest propagation delay in a beam is defined as $\Delta T_{\max}$.

$$\Delta T_{\max} = \frac{d_{far} - d_{near}}{c} \tag{1}$$

with d_{far} and d_{near} the farthest and nearest distance from the points in the beam cell to the satellite, and c represents the propagation speed for the electromagnetic wave.

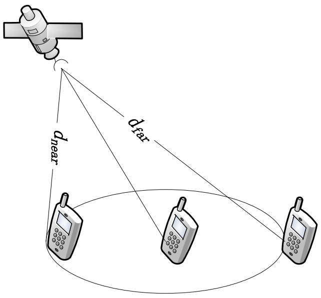

Figure 1. The difference for transmission delay in one Beam

From the calculation of the regions in China, the largest maximum differential propagation delay is in Mohe [4]:

$$\max\left(\Delta T_{\max}\right)=\begin{cases}1.2407\text{ms}, & 109\text{ spot}\\ 0.9306\text{ms}, & 218\text{ spot}\end{cases} \tag{2}$$

When the UE is moving, the Doppler shift is written as

$$f_d = f\frac{v}{c}\cos\theta \tag{3}$$

where θ is the angle between the UE's forward velocity and the incident wave，v is the velocity of the UE, f is the carrier frequency, and f_d is the Doppler shift. As for the GEO satellite systems, the satellite can be seen as stationary and the Doppler shift is caused entirely by the UE's movement.

Calculation model for Doppler shift is shown in [5], consider the case f = 2GHz and v = 350km/h, the maximum Doppler shift of typical areas in China are shown in [5].

Table I. THE MAXIMUM DOPPLER SHIFT OF TYPICAL AREAS IN CHINA

City	Kashgar	Mohe	Sanya	Beijing
Doppler Shift(Hz)	567	569	247	468

III.PROPOSED METHOD AND PERFORMANCE ANALYSIS

A. *Proposed method*

Due to good zero autocorrelation and cross-correlation performance, Zadoff-Chu (ZC) sequence is generally used in many systems [6]. However, a drawback of ZC sequence is that it is difficult to judge whether the delay difference is caused by Doppler shift or by the transmit delay difference. A false peak can be caused by Doppler shift. With large Doppler shift, false peak can be greater than the true peak, leading to a mistake in the detection. Considering the large delay and Doppler shift, we propose a two-step random access method.

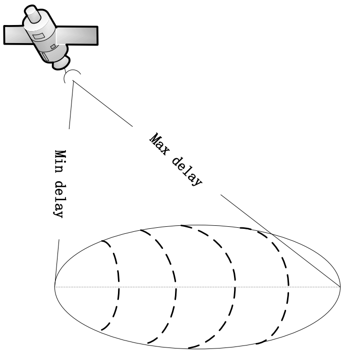

Figure 2. Beam within the sub-area

As shown in Figure 2. We divide the cell into several small sub-areas according to the principles shows in Eq.(5). In the Figure 3, the Z-axis directs to North Pole and the Y-axis is determined by point O at earth's core and the subpoint of satellite at equator (S). The distance between satellite and earth surface is H and earth radius is R, the coordinate of satellite in this coordinate system is (0, H+R, 0). A is the point nearest to the satellite in the beam, and the distance between A and satellite is d_{min}. B is the point in the beam randomly and the distance between B and satellite is d.

The first sub-area is formed by the area in which the differential propagation delays are limited by $0<d - d_{min}\leq d_{SEQ}$, where $d_{SEQ} = c*T_{SEQ}$, T_{SEQ} represents observation interval. In the nth sub-area, the difference between propagation delays is in the scope $(n-1)d_{SEQ} <d - d_{near}\leq nd_{SEQ}$.

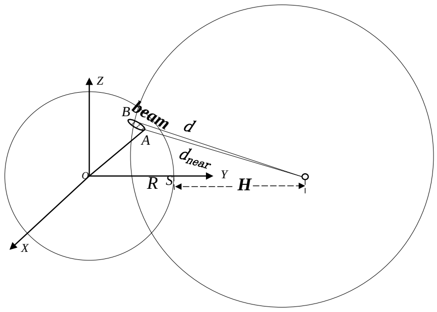

Figure 3. Propagation delay difference calculation

The coordinate of points(x,y,z) in the nth sub-area satisfies

$$\begin{cases}x^2+y^2+z^2=R^2\\ (n-1)\cdot d_{SEQ}<\sqrt{x^2+\left(y-(H+R)\right)^2+z^2}-d_{near}\leq n\cdot d_{SEQ}\end{cases} \tag{4}$$

1) *Step 1 PRACH burst format*

$$\begin{cases}T_{CP}=\max(RTDD_{satellite})+\max(Delay\ spread_{satellite})\\ T_{GT}=\max(RTDD_{satellite})\\ T_{SEQ}=\left\lfloor\frac{1/(2f_{off})}{T_{OFDM}}\right\rfloor\cdot T_{OFDM}\end{cases} \tag{5}$$

T_{OFDM} represents the OFDM symbol duration. Where $f_{off} = 2f_d = 2fv\cos\theta/c$. RTDD means the round trip delay difference. Doppler shift is calculated twice in GWS. There is no cyclic shift for ZC sequence, and only one receiver is needed, with the observation interval T_{SEQ}. Part of the UE delay difference τ can be measured to be $\tau_{frac} = \tau \bmod T_{SEQ}$. GWS notifies the UE τ_{frac}. If these two sequences conflict with each other, the received sequence should be abandoned. If Doppler shift causes the presence of false peak, the measured peaks apper in pairs, and false peak can be considered to be the smaller one.

Table II. STEP 1 PRACH BURST FORMAT

Beam mode	109	218
T_{CP}/μs	2481.65	1861.45
T_{CP}/T_s	76236	57184
T_{GT}/μs	2481.4	1861.2
T_{GT}/T_s	76228	57176
T_{SEQ}/μs	400	400
T_{SEQ}/T_s	12288	12288
$\Delta f_{RA,satellite}$ / Hz	2500	2500

For GEO satellite, the maximum Doppler shift to a velocity of 350km/h is f_d=569Hz, and f_{off}=1138Hz in GWS, as shown in Table I. max(*Delay spread*$_{satellite}$)=250ns for ITU-R M. 1225 model. All parameters must be designed as integral multiples of the sample period T_s=1/30.72us. The parameters in Eq.(5) are listed in Table II

2) Step2 PRACH burst format

$$\begin{cases} T_{CP} = \max(Delay\ spread_{satellite}) \\ T_{GT} = \left\lfloor \dfrac{\max(RTDD_{satellite})}{T_{SEQ}} - 1 \right\rfloor \cdot T_{SEQ} \\ T_{SEQ} = \left\lfloor \dfrac{1/(2f_{off})}{T_{OFDM}} \right\rfloor \cdot T_{OFDM} \end{cases} \tag{6}$$

T_{CP} is used to ensure that each UE's preamble sequence is completely received. UE transmits the sequence with an advance τ_{frac}. and we have $\tau_{\text{int}} = \lfloor \tau / T_{SEQ} \rfloor \cdot T_{SEQ}$.

Combining the results of the above two steps, the difference of time delay should be

$$\tau = \tau_{frac} + \tau_{\text{int}} \tag{7}$$

The parameters in Eq.(6) are listed in Table III

Table III. STEP2 PRACH BURST FORMAT

Beam mode	109	218
T_{CP}/μs	0.25	0.25
T_{CP}/T_s	8	8
T_{GT}/μs	2000	1200
T_{GT}/T_s	61440	36864
T_{SEQ}/μs	400	400
T_{SEQ}/T_s	12288	12288
$\Delta f_{RA,satellite}$ / Hz	2500	2500
Number of rake receiver	7	5

B. Performance Analysis

1) False Alarm Probability:

The false alarm probability refers to the probability that when the input is pure noise, signals are detected [7][8]. Generally this probability should be less than 0.1%, from which we can determine the detection threshold. We set the detection variable to be the ratio between the peak and the average value. If the input contains no signal, the received signal is Gaussian noise.

$$z(l) = \sum_{m=1}^{N_{ZC}} n(m)x^*(m+l) \tag{8}$$

where x is ZC sequence, n is the noise., $z(m)$and $z(m \pm 1)$ are irrelevant and independent with each other.By normalizing $z(l)$ to be a standard normal distribution $z'(l)$, PDP is

$$PDP = \left[\left(\frac{z_r(l)}{\sqrt{N}\sigma} \right)^2 + \left(\frac{z_i(l)}{\sqrt{N}\sigma} \right)^2 \right] N\sigma^2 \tag{9}$$

Where $z_r'(l)$~$N(0,1)$, $z_i'(l)$~$N(0,1)$,($z'(l)$)^{2}is the central chi-squared distribution with a k = 2 degree of freedom and k the expectation value. Considering the sample size is large enough, the average value of the random variable can be estimated by expectation value, the false alarm probability is

$$P_{fa} = P(\max |z'(l)|^2 > th_{re} \overline{|z'(l)|^2}) = 1 - p_{th}{}^N \tag{10}$$

p_{th} is the probability when $|z'(l)|^2 < th_{re} \overline{|z'(l)|^2}$ for l=0,1⋯N_{zc}, th_{re} is the false alarm detection threshold, and p_{th} is the cumulative probability at 2th_{re}, that is

$$p_{th} = \gamma(\frac{k}{2}, \frac{2th_{re}}{2}) / \Gamma(\frac{k}{2}) \tag{11}$$

$\gamma(a,b)$ the incomplete Gama function, $\Gamma(x)$ the Gama function.

2) Missed Detection Probability:

The missed detection probability is defined as the probability that the transmitter sends the preamble sequence, while the receiver does not detect it.The correlation function is

$$\begin{aligned} z(l) &= \sum_{m=1}^{N_{ZC}} \left[x'(m) + n(m) \right] x^*(m+l) \\ &= N'\delta(l) + \sum_{m=1}^{N_{ZC}} \left[n(m)x^*(m+l) \right] \end{aligned} \tag{12}$$

where x' is the sequence influenced by Doppler shift. With $N'$the height for the true peak. The second part on the right of Eq.(12) is the same as Eq.(8), and normalizing $z(l)$ to $z'(l)$, we get the PDP to be

$$PDP = \left[\left(\frac{z_r(l)}{\sqrt{N}\sigma} \right)^2 + \left(\frac{z_i(l)}{\sqrt{N}\sigma} \right)^2 \right] N\sigma^2 \tag{13}$$

$(z'(l))^2$ satisfies a non-central chi-squared distribution with non-centrality parameter $\lambda = \sum_{i=1}^{k} (\frac{\mu_i}{\sigma_i})^2 = \frac{N'^2}{N\sigma^2}$ and k=2 degree of freedom, and the missed detection probability is

$$\begin{aligned} P_{ms} &= P(|z'(l)|^2 < th_{re}{}^* \overline{|z'(l)|^2}) = F(2th_{re}{}^*) \\ &= 1 - Q_{k/2}(\sqrt{\lambda}, 2th_{re}{}^*) \end{aligned} \tag{14}$$

where $th_{re}{}^*$ is the missed detection threshold, and $Q_M(a,b)$ the Marcum Q-function.

IV. SIMULATION RESULTS

A. False alarm probability

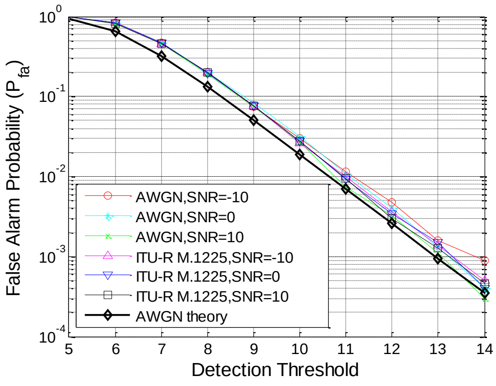

Figure 4. False alarm probability with detection threshold for different SNR

We give a performance of the false alarm probability. In this case, the peak and mean value are both independent with the noise. However, in practical systems, the length of the sequence is finite, and the false alarm probability may be dependent on the noise. For a long sequence, the average value can be well approximated by its expectation value.

Figure 4 illustrates the false alarm probability in AWGN and ITU-R M.1225 channel versus detection threshold for different SNR. We simply set SEQ length to be 419. We can see that when the detection threshold is greater than 13, false alarm probability is less than 0.1%. The SNR has little effect on the false alarm probability, which coincides well with our theoretical analysis. We can see that the theoretical curve is close to simulation in Figure 4.

B. Missed detection probability

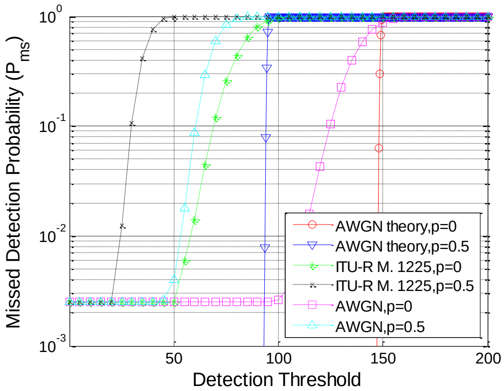

Figure 5. Missed detection probability for different Doppler frequency shift

We theoretically analyse the missed detection probability, where the practical average value is still approximated by the expectation value, and we only consider the true PDP peak affected by Doppler shift. The designed PRACH parameters ensure $p = f_{off} / \Delta f_{RA} \le 0.5$, that is $p \leqslant 0.5$. Therefore, our simulation only focuses on this range of Doppler shift.

Figure 5 illustrates the missed detection probability in AWGN and ITU-R M.1225 versus detection threshold for different Doppler shift with SNR=0dB. Here *p* is ratio of the Doppler shift to the sub-carrier spacing. When *p* is less than 0.5, by setting the detection threshold to be less than 20, the missed detection probability is less than 1%. Figure 5 shows that the performance in the AWGN is better than in the ITU-R M. 1225 channel. The theoretical performance is better than the simulation results as well. Because we have simplify the process of transmit and receive. Thus the false detection theoretical performance is better than simulation performance. In simulation, AWGN channel only take the noise into consideration, while ITU-R M.1225 channel model including the effect of multipath and noise. So ITU-R M.1225 channel model has larger impact on the performance.

V. CONCLUSIONS

In this paper we focus on the time delay estimation of terrestrial-satellite convergent system based on LTE. A time delay difference estimation method is proposed, which divides the beam into several sub-areas. The fractional part of the delay difference is measured in first step, and of which the UE is informed. In the second step, UE send the preamble in advance, thus GWS will decide the specific sub-area which the UE belongs to. Then based on the proposed method, we give the detail parameters of the burst format. Meanwhile, we give the closed-form expressions of the system performance. Furthermore, calculation of false alarm probability and missed detection probability are given based on AWGN and ITU-R M. 1225 model. According to the good performance, the results verify the proposed method is applicable to S-LTE.

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