

Research on the Propagation Delay Characteristic of Multi-beam GEO Satellite Communications System¹

Xi Luan*, Jianjun Wu², Xiaoyan Xu*, Shubo Ren*, Haige Xiang*

*Satellite and Wireless Communications Lab., EECS, Peking University, China

luanxi@pku.edu.cn, just@pku.edu.cn, g.ericaxu@gmail.com, renshubo@pku.edu.cn, xianghg@pku.edu.cn

Abstract— The plan of constructing satellite communications system has been implementing in China since the miserable Wenchuan Earthquake in 2008. Several radio transmission technologies of terrestrial cellular systems are investigated to adapt to the satellite communications environment. In order to study the feasibility of TDD or HFDD satellite communications system compatible with TD-SCDMA standard, an analytical expression of the propagation delay within GEO satellite spot beams is derived based on the space geometry model. Meanwhile, the differential propagation delays in several typical beams are calculated, according to a possible multi-beam coverage pattern of China. The results show that satellite communications system compatible with TD-SCDMA is preliminarily feasible even in the worst case.

Keywords—Multi-beam satellite system, geosynchronous satellite, propagation delay, Time Division Duplex

I. INTRODUCTION

Constructing satellite communication system is not only the important method for realizing seamless coverage of wireless communication, but also significant guarantee for economic development and social stability. With the worldwide application of 3rd Generation (3G) networks, several satellite communication systems based on 3G standard have been constructed, such as Inmarsat BGAN. Though the literatures about 3G satellite system is emerging quickly, most of them are based on Frequency Division Duplex (FDD) mode. For example, the compatibility of WCDMA and satellite communications system from aspects of air interface, random access, network architecture is analyzed in [1][2].

Apart from FDD, however, TDD is also an important option of 3GPP UMTS, such as TD-SCDMA. But so far, only Iridium system is TDD satellite communications system, which is LEO satellite system and can not provide a reference for public satellite communications system because of its expensive cost and complicated constellation. In contrast with the shortcomings of LEO satellite system, GEO system is more achievable.

However, the propagation delay in GEO satellite system is quite large (approximately 270ms for a round trip), and the differential propagation delays within spot beams also can't

be neglected. It is a crucial step to resolve frame synchronization problem caused by propagation delay characteristic in order to apply TDD mode to satellite system. The physical frame design method given by [4] is suitable for GEO system based on TDD. The key idea of which is setting guard slot in normal radio frame with length of $2X$. The value of X is decided by the signal differential propagation delay between user's current position and the geographical midpoint of its belonging satellite beam. Nevertheless, there is no specific analysis of propagation delay characteristic in Multi-beam satellite system in [4].

A central contribution of our work is providing space geometry model for calculating differential propagation delays in areas covered by multi-beam satellite system and analysing the feasibility of TDD or HFDD satellite communications system. The results shows that satellite communications system compatible with TD-SCDMA is preliminarily feasible even in the worst case.

The paper is organized as follows: Section II gives an introduction of propagation delay characteristic, key parameters and typical beam coverage patterns in China; Section III describes the space geometry model of differential propagation delays in detail; Based on this model, the results of actual cases in China has been calculated and analyzed in Section IV; The conclusion is given in Section V.

II. SYSTEM DESCRIPTION

In multi-beam satellite communications system, a number of spot beams can be formed by beamforming technology in the focused areas, and the coverage of adjacent beams are partially overlapped just like the overlay structure of terrestrial cellular systems, as shown in Fig.1. The beam coverage patterns vary with different satellite systems and networking solutions. There are two patterns in China used by GEO satellite system: 109 spot beams pattern (beam radius: 200km); 218 spot beams pattern (beam radius: 150km).

Since the system we concentrated is GEO satellite system, the satellite orbit position (longitude) is one of the crucial parameters. The available positions in China are 115.5°E, 125°E, 87.5°E and 110.5°E, which all have been authorized.

GEO satellite remains stationary relative to the earth's surface and lies over the equator. Thus there is a certain elevation angle in China ranging from 20° to 60°, which causes different propagation delays of users even at different positions in a same beam. In Fig.2, the difference value of the

¹ This work is supported by the National Science Foundation of China (Grant No. NFSC #61071083).

² Corresponding author is Jianjun Wu (e-mail: just@pku.edu.cn).

longest and shortest propagation delay in a beam is defined as maximum differential propagation delay. In order to solve the problems caused by this parameter — synchronization problem—an efficient way is to set guard slot in normal radio frames to realize synchronization of all users within a beam on satellite. The maximum length of this guard slot should not be shorter than the maximum differential propagation delay of its belonging beam [4]. On the purpose of analyzing propagation delay characteristic, we will set up an analytical model of satellite spot beams based on space geometry in the next section.

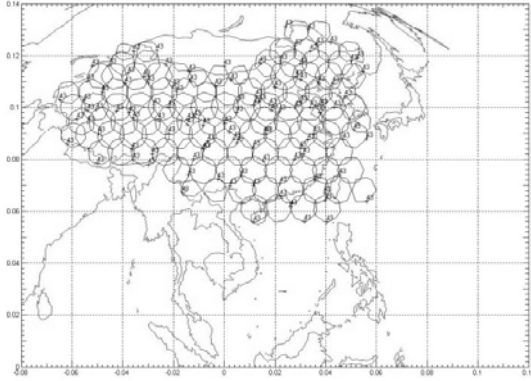


Figure 1. Typical coverage pattern of satellite spot beams in China

III. MODELING OF PROPAGATION DELAY CHARACTERISTIC

We define an orthogonal coordinate system, with 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), as shown in Fig.3. If the distance between satellite and earth surface is H and earth radius is R , the coordinate of satellite in this coordinate system is $(0, H+R, 0)$.

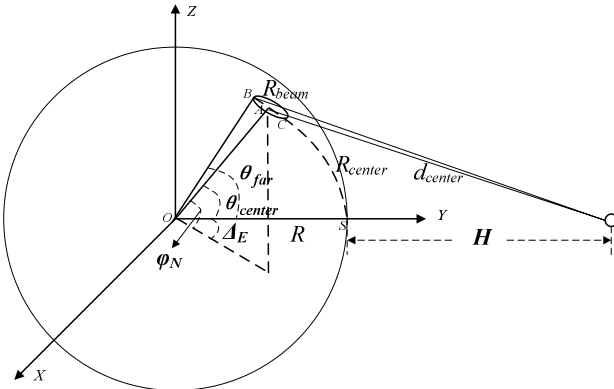


Figure 2. Coordinate system used for propagation delay calculation

We choose a satellite spot beam randomly, the longitude and latitude of whose geographical midpoint A are θ_E and φ_N . Therefore, the differential longitude between point A and the

satellite is ΔE , in other words, the angle between subpoint of point A at X-Y plane and Y-axis is ΔE .

According to conversion formula between spherical coordinate and orthogonal coordinate, we can obtain the coordinates of point A is

$$x_{center} = R * \cos(\varphi_N) * \sin(\Delta_E) \quad (1)$$

$$y_{center} = R * \cos(\varphi_N) * \cos(\Delta_E) \quad (2)$$

$$z_{center} = R * \sin(\varphi_N) \quad (3)$$

Thus, the distance between satellite and geographical midpoint A of the selected spot beam is given by

$$d_{center} = \sqrt{(x_{center} - x_{sat})^2 + (y_{center} - y_{sat})^2 + (z_{center} - z_{sat})^2} \quad (4)$$

If we define the angle between Y-axis and the line determined by point O and point A is θ_{center} , this angle is calculated as

$$\theta_{center} = \arccos\left(\frac{y_{center}}{R}\right) \quad (5)$$

The arc length between point A and point S is

$$R_{center} = R * \theta_{center} \quad (6)$$

According to point A and point S, we define a circle surrounding earth surface with its center being the same as point O. There are two crossing points—point B and point C—of this circle with the selected spot beam. Point B is farther from equator, so the propagation delay is longer; On the contrary, point C has shorter propagation delay.

Now, we can calculate the longest propagation delay at first. Point A, B and S is on the same circle, as shown in Fig.4. If the radius of a beam is R_{beam} , arc length between point B and point S is

$$R_{far} = R_{center} + R_{beam} \quad (7)$$

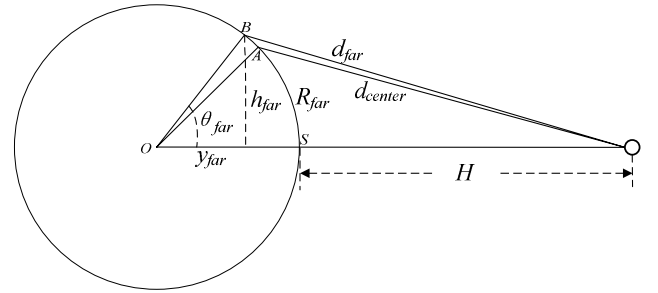


Figure 3. calculate the longest propagation delay in a spot beam

The angle between Y-axis and the line determined by point O and point B is

$$\theta_{far} = \frac{R_{far}}{R} \quad (8)$$

Y coordinate of point B and the distance between point B and X-Y plane (equatorial plane) can be calculated by (9) and (10)

$$y_{far} = R * \cos(\theta_{far}) \quad (9)$$

$$h_{far} = R * \sin(\theta_{far}) \quad (10)$$

Therefore, the distance between satellite and the furthest point B in the selected beam is expressed as

$$d_{far} = \sqrt{h_{far}^2 + (H + R - y_{far})^2} \quad (11)$$

In a similar way, the distance between satellite and the nearest point C can be calculated. Then we obtain the maximum differential propagation delay in a spot beam

$$\Delta T_{max} = \frac{d_{far} - d_{near}}{C} \quad (12)$$

Meanwhile, the propagation delay of geographical midpoint of this spot beam is

$$T_{center} = \frac{d_{center}}{C} \quad (13)$$

The latitudes and longitudes are different from one spot beam to another. Therefore, propagation delay characteristics may be different in different beams. For example, there is 62 degrees difference of longitude from east to west (about 5500 kilometers) and 49 degrees difference of latitude from north to south (about 5000 kilometers) in China. We will calculate and analyze the propagation delay characteristic in section IV based on the actual situation of China.

IV. RESULT AND ANALYSIS

A general model has been proposed in section III, and we will analyze actual cases in China in this section.

It can be seen that the beams which have the maximum or minimum ΔT_{max} (maximum differential propagation delay) are more likely to be the beams near territorial boundaries. Therefore, calculating and analyzing this parameter of these beams will be more significant than other ones. The latitudes and longitudes of several typical areas in China are presented in Table 1.

TABLE 1. LATITUDES AND LONGITUDES OF TYPICAL AREAS IN CHINA

Areas	longitude	Latitude
Kashi (west side of the mainland)	76.0 °E	39.5 °N
Altay (northwest side of the mainland)	88.1 °E	47.8 °N
Mohe (north side of the mainland)	122.5 °E	53.5 °N
Sanya (south side of the mainland)	109.5 °E	18.2 °N
Nansha (south side of seas)	116.8 °E	11.0 °N
Shanghai (east side of the mainland)	121.5 °E	31.2 °N
Donghai (east side of seas)	124.7 °E	21.3 °N
Beijing	116.5 °E	39.9 °N
Hong Kong	114.1 °E	22.3 °N

Apart from latitude, longitude and parameters discussed in Section II, some other physical constants are necessary, such as earth radius (6371.3 km) and altitude of GEO satellite (35786.3 km).

According to the method proposed in Section III, we can calculate the maximum differential propagation delay in some typical beams based on two different beam coverage patterns——109 spot beams and 218 spot beams——and four different GEO satellite orbit positions——115.5°E, 125°E, 87.5 °E and 110.5°E. The results are shown in Table 2 and Tabel 3.

Since the beam radius of 109 spot beams pattern is larger, the maximum differential propagation delay in the same area is larger in general. From the results exhibited in Table 1, we can see that there is differential propagation delay in every beam which can't be ignored if compared with chip durations of 3G spread spectrum systems. Moreover, the maximum differential propagation delays are different in different beams——values are between 0.49 and 1.24ms in mainland beams and smaller in seas.

Consider the discussion in [4], radio frame should be design according to differential propagation delays in order to apply TDD mode in satellite communications system. That is to say, in TDD multi-beam satellite system, we should set guard slot for each spot beam with its length being slightly larger than the maximum differential propagation delay in that beam. Thus, all users can realize synchronization on the side of satellite.

Consider the frame structure of TD-SCDMA defined by 3GPP, downlink and uplink transmissions are organized into radio frames with 10ms duration and each radio frame can be divided into two subframes of length 5ms each. More specifically, each subframe consists of 7 slots reserved for downlink and uplink transmissions and a special subframe with the three fields. A normal downlink or uplink slot of length 0.675ms consists of 864 chips. Comparing the standard lengths of subframe and slot with differential propagation delays obtained above, it can be seen that if the maximum differential propagation delay is only about 0.49ms——the spot beams near Sanya——only one slot should be reserved as guard slot; If this parameter is 1.29ms as opposed to small values——the spot beams near Mohe——two slots are enough.

A better case is 218 spot beams pattern because the length requirement of guard slot can be smaller. Therefore, apart from the inevitable slots cost for synchronization, the major part of the radio frame can still be used for downlink and uplink transmissions and the remaining issue which should be considered in future is how to make full use of the guard slots in order to enhance transmission efficiency.

Moreover, we can also calculate the propagation delay of different areas and further find out the differential values of between the north and south side or the west and east side of China. From Table 4 we can see that the differential propagation delay from south to north is 7.5~9.1ms for different satellite orbit positions, and there is 4.8~8.2ms difference from east to west. According to these results, we

can do some compensation in the process of frame timing synchronization quantitatively.

TABLE 2. MAXIMUM DIFFERENTIAL PROPAGATION DELAYS IN TYPICAL BEAMS (109 BEAMS PATTERN) (UNIT: MS)

	Altay	Kashi	Mohe	Sanya	Nansha	Shanghai	Donghai	Beijing	Hong Kong
115.5°E	1.1657	1.1666	1.1649	0.5088	0.3005	0.8008	0.6064	1.0218	0.6233
125 °E	1.2121	1.2327	1.1615	0.6211	0.3694	0.7936	0.5625	1.036	0.6829
87.5 °E	1.0907	0.9788	1.2407	0.7256	0.7883	1.0453	0.9999	1.1581	0.9035
110.5 °E	1.1433	1.1288	1.1724	0.4861	0.3423	0.8256	0.6607	1.0285	0.6293

TABLE 3. MAXIMUM DIFFERENTIAL PROPAGATION DELAYS IN TYPICAL BEAMS (218 BEAMS PATTERN) (UNIT: MS)

	Altay	Kashi	Mohe	Sanya	Nansha	Shanghai	Donghai	Beijing	Hong Kong
115.5°E	0.8744	0.8750	0.8738	0.3816	0.2254	0.6007	0.4548	0.7226	0.4409
125 °E	0.9092	0.9246	0.8712	0.4659	0.2771	0.5953	0.4219	0.7327	0.4830
87.5 °E	0.8181	0.7342	0.9306	0.5443	0.5913	0.7841	0.7500	0.8190	0.6390
110.5 °E	0.8576	0.8467	0.8793	0.3646	0.2568	0.6193	0.4956	0.7273	0.4451

TABLE 4. PROPAGATION DELAY OF TYPICAL AREAS IN CHINA (UNIT: MS)

	Altay	Kashi	Mohe	Sanya	Nansha	Shanghai	Donghai	Beijing	Hong Kong
115.5°E	128.99	129.01	128.97	120.66	119.75	122.97	121.28	125.01	121.15
125 °E	130.35	131.06	128.88	121.39	120	122.89	120.98	125.21	121.55
87.5 °E	127.24	125.24	131.36	122.23	122.84	126.36	125.57	127.26	123.53
110.5 °E	128.42	128.07	129.17	120.54	119.89	123.23	121.68	125.1	121.19

Therefore, we can say that TD-SCDMA can be generally compatible with satellite system on the level of radio frame design. Fortunately, TD-LTE has the similar radio frame structure with TD-SCDMA: frame of length 10ms, special subframes and downlink and uplink slots. Consequently, the similar analysis can be made for TD-LTE and the method of frame design for the former can provide a reference for TD-LTE with the purpose of being compatible with satellite communications systems.

V. CONCLUSIONS

The differential propagation delays within and among spot beams are important parameters in multi-beam satellite communications systems. In this paper, we set up a calculating model to analyze propagation delay characteristic in multi-beam satellite communications system by using space geometry method. According to the actual parameters, several specific results in China have been obtained. The results show that satellite communications system compatible with TD-SCDMA is preliminarily feasible even in the worst case. It is essential study for the satellite communications system based on TDD mode because it plays a significance role in dealing with some important issues such as radio frame design and

synchronization algorithm. Analysis of propagation delay characteristic can provide theoretical preparation for the further development of TDD multi-beam satellite communications system.

REFERENCES

- [1] Béatrice MARTIN, N. Chuberre, H.J. Lee, "IMT-2000 Satellite Radio Interface for UMTS Communications over Mobile Satellite Systems[J]", HAdvanced Satellite Mobile Systems, 2008. ASMS 2008. 4thH, Sep. 2008, Page(s): 167 - 172.
- [2] A. U. Quddus, R. Tafazolli, B. G. Evans, "Time Diversity in WCDMA FDD Downlink for Multimedia Broadcast/Multicast Services using Chip Block Interleaving[J]", HPersonal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium onH, Volume 1, July 2006, Page(s): 311 – 315.
- [3] Emmons Jr., Thomas Peter, Robert Anthony, "System and method for providing dual satellite communications coverage [P]," US Patent 6,411,609 B1, Jun. 25, 2002.
- [4] Arif Ansari, Santanu Dutta, Michael Tseytlin, "S-WiMAX: adaptation of IEEE 802.16e for mobile satellite services [C]", IEEE Communications Magazine, Volume 47, HIssue 6H, Jun. 2009, page(s): 150-155,
- [5] 3GPP TS 25.221 V4.8.0, "Physical channels and mapping of transport channels onto physical channels (TDD) [S]", 2005.
- [6] 3GPP TS 36.211 V8.8.0, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation[S]", 2009.