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A Dynamic and Reconfigurable Satellite-to-ground Communication System Research Based on LoRa Technology

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Abstract. A dynamic and reconfigurable satellite-to-ground communication system research based on LoRa technology is proposed in this paper. Starting from the application background of the internet of things (IoT) on the low earth orbit (LEO) satellite, this paper proposes a modulation parameter dynamic and reconfigurable technology for the Long Range (LoRa) signal, so as to improve the reliability of the IoT used in the satellite-to-ground communication system. Then, a parameter reconstitution method is designed in detail according to the satellite-to-ground communication link budget, and this method has the advantages of low complexity and less resources. Meanwhile, in this communication system, a desired bit rate can be selected based on the parameter reconstitution method to support different application. Simulation results show that the dynamic and reconfigurable satellite-to-ground communication system can work as expected, and this research possesses a great guidance in making the space-based IoT.

Keywords: internet of things, satellite communication, LoRa, chirp spread spectrum

1 Introduction

Recently, the new application of the IoT have been widely used in the data acquisition, resource detection, emergency rescue, environmental monitoring and so on. With the characteristic of long-distance communication and low power consumption, the IoT is becoming the supplement of traditional mobile communication. In the fields of IoT, the LoRa technology as a typical representative has a lot of advantages such as high resistance of Doppler shift, high security and low complexity. In order to extend the communication coverage area of IoT, especially in the territory without traditional communication network, it is necessary to take advantage of the LEO satellites and retain the characteristic of low power consumption as well [1-2]. Meanwhile, with the development of antenna, LoRa communication link has become much more robustness [3].

Although the IoT based on LEO satellites is the trend of development and becoming the important supplement of the IoT on the ground, the current IoT with LoRa technology is not completely suitable for the satellite-to-ground communication system. Therefore, in this paper, an innovative low power consumption satellite-to-ground communication systems based on the LoRa technology is presented to propel the accelerate application of space-based IoT.

2 Preliminaries

The characteristic of LoRa technology is described in this part [4]. Then, these analysis results can be the design reference of the satellite-to-ground communication systems based on LoRa technology [5].

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2.1 LoRa and LoRaWAN

LoRa is a spread spectrum modulation technique derived from chirp spread spectrum (CSS) technology [6]. On this basis, LoRa devices are designed to provide compelling features for IoT applications such as low sensitivity, low power consumption, reliable and secure data transmission and so on [7]. The LORA technology can be used for public, private or hybrid networks, offering greater range than cellular networks. Meanwhile, it can be lightly plugged into existing public construction to support inexpensive, battery-powered IoT applications.

The LoRaWAN (LoRa Wide Area Network) open specification is a low power, wide area networking (LPWAN) protocol based on LoRa technology [8]. Designed to wirelessly connect battery operated things to the internet in regional, national or global networks, the LoRaWAN protocol utilizes the unlicensed radio spectrum in the Industrial, Scientific and Medical (ISM) band [9]. Meanwhile, the specification also defines device-to-infrastructure for LoRa physical layer parameters and the LoRaWAN protocol to provide seamless interoperability between devices.

As mentioned above, the LoRaWAN is a communication protocol for information transmission in the IoT, and the LoRa is a radio frequency modulation and demodulation mode. Therefore, the relationships between LoRa and LoRaWAN can be shown in Fig. 1.

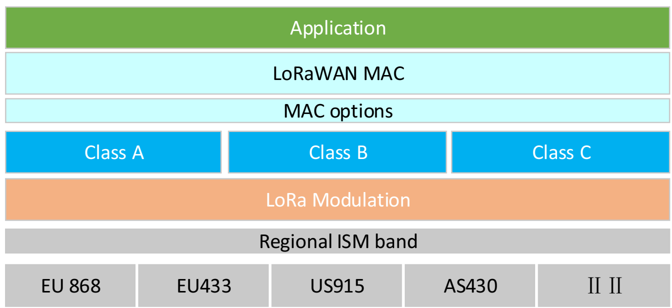

Fig. 1. Relationships between LoRa and LoRaWAN

Designed for the IoT communications, LoRa terminals and the LoRaWAN protocol enable the connection between remote point-of-use devices and LPWANs for delivery to analytic applications [10-11].

The typical architecture of IoT communication systems based on LoRa technology mainly includes devices, networks and applications, and it is shown in Fig. 2. In particular, devices in the IoT communication systems mainly include LoRa modulation, transceivers, end-nodes and gateways.

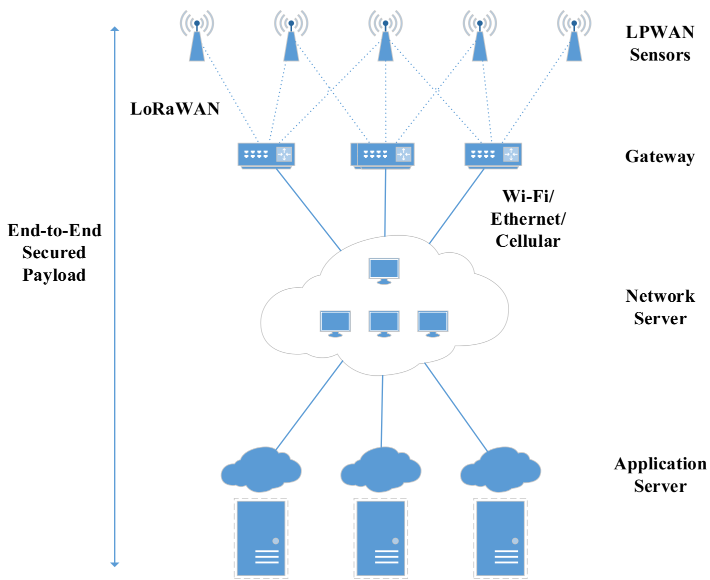

Fig. 2. The architecture of IoT communication systems

In the LoRaWAN, there are three operation modes, including Class A, Class B and Class C. For Class A mode, data on the LoRa terminals are collected and sent as needed, and two receiving windows are opened immediately after data have been sent. If there is no data to send, it will sleep at ordinary times. The data processing of Class A mode is shown in Fig. 3.

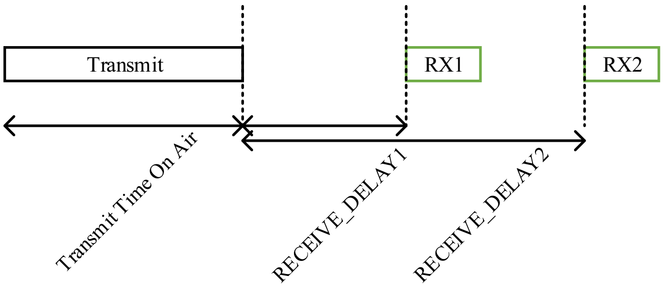

Fig. 3. Class A mode

The Class B mode is the most complex mode and the data processing of Class B mode is shown in Fig. 4. For the Class B mode, through the application of convention wake-up, periodically open beacon reception windows and ping time slots, different LoRa terminal can be based on a standard reference time to establish the communication link. Therefore, the LoRa terminals should depend on the beacon signal to proofread the time to ensure that the agreed time will not be misplaced.

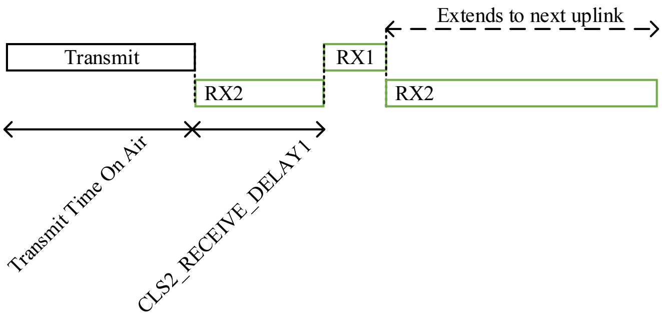

Fig. 4. Class B mode

According to these features, users or servers can discover LoRa terminal to achieve energy saving and fast wake up, by opening the reception functions in the foreseeable time. As a result, it is suitable for up-link (terminal transmit and satellite receive) data communication with the features of lower power consumption and low latency.

For Class C mode, the receiving window is closed only when sending data and the data processing of Class C mode is shown in Fig. 5. As a result, it is just suitable for down-link (terminal receive and satellite transmit) data communication with the features of ultra-low package loss.

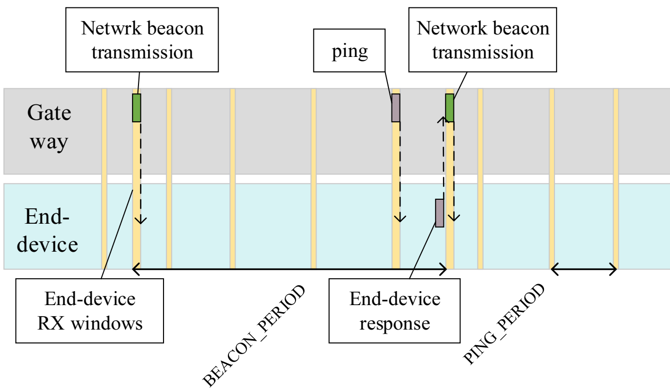

Fig. 5. Class C mode

2.2 Modulation Parameter

As mentioned above, the CSS is used for modulation, and the spreading factor (*SF*) can be denoted as below.

$$SF = \frac{R_{bit}}{R_{symbol}} \tag{1}$$

Where the R_{bit} is the bite rate, and the R_{symbol} is the symbol rate.

In a chip cycle, the bandwidth of the signal coverage can be denoted as below.

$$BW = \frac{1}{T_{chip}} \tag{2}$$

Where the BW is the signal bandwidth, and the T_{chip} is the chip cycle.

Therefore, the symbol cycle can be denoted as below.

$$T_{symbol} = 2^{SF} \times T_{chip} \tag{3}$$

According to the formula (1) ~ (3), the relationship between BW and SF can be denoted as below.

$$R_{bit} = \frac{SF \times BW}{2^{SF}} \tag{4}$$

Formula (4) means that in the case of constant communication bandwidth, the larger the spread spectrum factor will lead to the smaller the transmission bit rate.

According to the technical manuals of Semtech corporation [11], the receive sensitivity of LoRa terminal can be denoted as below.

$$S = (-1) \times ((SF - 7) \times 2.5 + (\log_2 \frac{500}{BW}) \times 3 + 118.5) \tag{5}$$

Where the S is the receive sensitivity.

To ensure the stability of the communication link, the dynamic and reconfigurable satellite-to-ground communication system should meet the receive sensitivity requirements of LoRa terminal.

3 Methodology

An innovative satellite-to-ground communication system based on LoRa technology is presented in this part. Then, link budge of the satellite-to-ground communication system is deduced and a modulation parameter dynamic reconfiguration method is presented.

3.1 System and Method

As presented above, the IoT on the LEO satellites can extend the signal coverage greatly. However, when compared with the IoT on the ground, the transmission distance of IoT is longer and the number of LoRa terminals is increased in the satellite-to-ground communication system. According to the existing research, the IoT on LEO satellites usually adopt a fixed network structure. The structure can be divided into space segment, ground segment and user segment. On the space segment, LEO satellite is responsible for forwarding the data uploaded by the LoRa terminals to the gateway station of the ground segment, and sending the interactive information returned by the ground segment to the LoRa terminals [12].

In addition, for the most applications of IoT on the LEO satellites, the LoRa terminals are usually distributed in various places, especially including inaccessible areas, and it is troublesome to maintain and charge these LoRa terminals regularly [13]. Therefore, it is important for the LoRa terminals work in the low power consumption condition. Meanwhile, the LoRa terminals should regularly collect data and send the local information to the LEO satellites with different data bandwidths. As a result, the communication up-link is very important for the LoRa terminals on the ground, and the Class C mode or Class A mode is not applicable. Furthermore, the LEO satellites move around the earth with a high speed, and the LoRa terminals have to depend on keeping time synchronization to communicate with them. From this point of view, the Class B is the most suitable mode for the LoRa terminals on the ground to communicate with the IoT systems on the LEO satellites.

Currently, the number of LEO satellites supporting LoRa technology is limited, so it is impossible to realize global networking and real-time interaction with the LoRa terminals on the ground. In this paper, through the method of time-division multiplexing and time synchronization, the point-to-point communication link between the LEO satellites and Lora terminals is established for information interactive, and the system can be shown in Fig. 6. In this system, satellite-ground link budget, information packet format, work mode and modulation parameter configuration are designed carefully which will lay a foundation for further application of this technology.

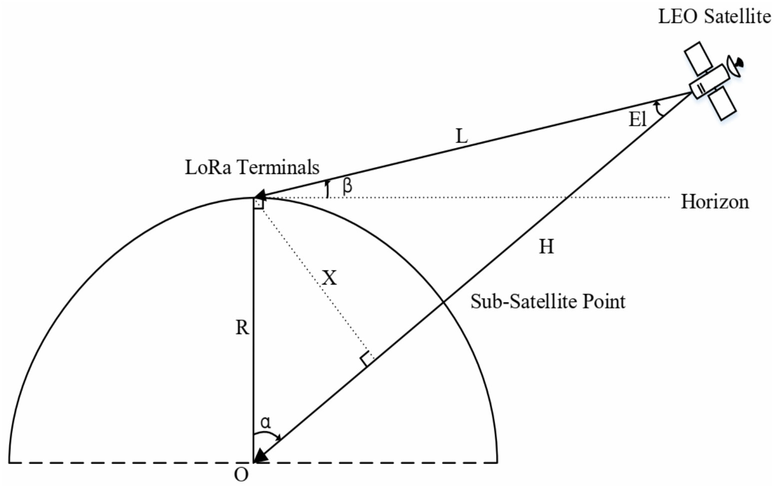

Fig. 6. Satellite-to-ground communication system

3.2 Link Budge

In order to build more robust communication links and improve the work efficiency of LoRa terminals, the reasonable *SF* and other modulation parameters should be reconfigured reasonably [14-15]. The parameters dynamic reconfiguration process can be shown in Fig. 7.

Firstly, the instantaneous elevation angle of satellite-earth communication link should be calculated. Based on the orbit information of the LEO satellite and the geographic location of the LoRa terminal on the ground, combining with the channel time slot, the elevation angle β can be denoted as below.

$$\beta = tg^{-1}\frac{\cos(\phi_2-\phi_1)\times\cos(\varphi)-0.15}{\sqrt{1-\left[\cos(\phi_2-\phi_1)\times\cos(\varphi)\right]^2}} \tag{6}$$

Where the ϕ_2 is the orbital longitude of the LEO satellite, the ϕ_1 is the longitude of the LoRa terminal on the ground, and the φ is the latitude of the LoRa terminal.

Secondly, the instantaneous distance of satellite-ground communication should be calculated. According to geometric knowledge, the relationship between elevation angle β and geocentric angle α can be denoted as below.

$$\alpha = \arccos\left[\frac{R\times\cos\beta}{R+H}\right]-\beta \tag{7}$$

Where the *R* is the radius of the earth, and the *H* is the altitude of the satellite above the earth.

According to law of cosines, the relationship between *R* and *H* can be denoted as below.

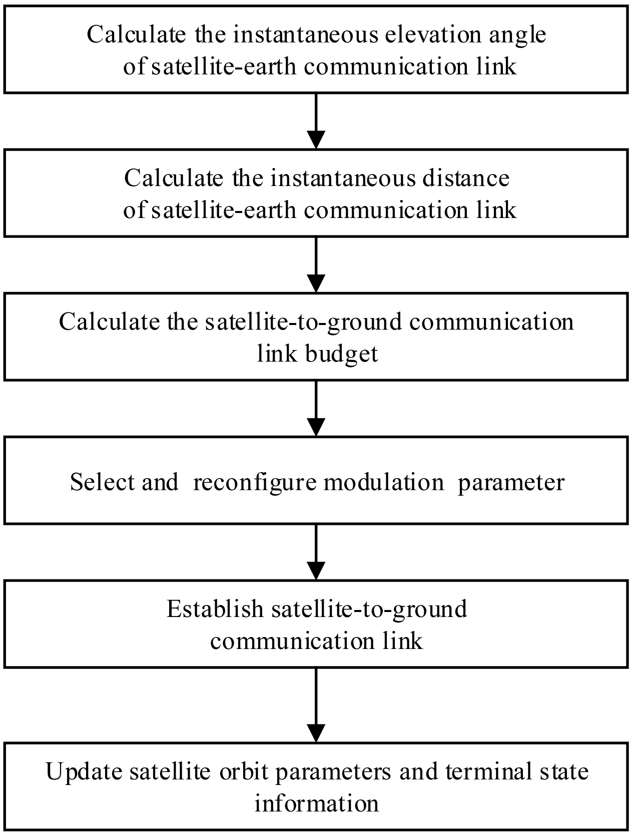

Fig. 7. Parameter dynamic reconfiguration process

$$\cos\alpha = \frac{R^2 + (R+H)^2 - L^2}{2\times R(R+H)} \quad \textbf{(8)}$$

Where the L is the distance of the satellite-to-ground communication link.

Then, calculate the satellite-to-ground communication link budget. The space propagation loss of radio signal can be denoted as below.

$$Ls = 32.44 + 20\log f + 20\lg L \quad \textbf{(9)}$$

Where the f is the communication frequency, and Ls is the space propagation loss.

The signal intensity received by the terminal using LoRa technology at the LEO satellite platforms can be denoted as below.

$$K = EIRP - Ls + Gr - Lp - Lo \quad \textbf{(10)}$$

Where the K is the signal intensity, the $EIRP$ is the equivalent isotropic radiated power of LoRa terminal on the ground, Gr is the LEO satellite antenna gain, Lp is the polarization loss, and Lo is the other loss.

The difference between K and S is the signal intensity allowance of the satellite-to-ground communication link, which can be denoted as below.

$$\Delta K = K - S \quad \textbf{(11)}$$

Therefore, according to the satellite orbit and data bandwidth requirements, the signal intensity allowance should be greater than 6dB by selecting the rational modulation parameters for maintaining link stability.

Finally, update satellite orbit parameters and terminal state information for the next communication task.

In addition, a large Doppler frequency offset between the LEO satellite and the LoRa terminals on the ground is always ever-present [17]. Therefore, it is necessary to overcome the influence of Doppler shift effecting on the reception sensitivity. The value of Doppler shift can be denoted as below.

$$f_d = f \times \frac{v_r}{c} = f \times \frac{v_r}{c} \cos\beta \tag{12}$$

Where the f_d is the value of Doppler shift, c is the speed of light and v_r is the speed of relative movement.

Actually, the LoRa technology has a certain frequency offset tolerance, according to Semtech's technical manuals, if the value of Doppler shift is within the range of a quarter of the BW, the reception sensitivity can be kept stable [16]. Therefore, in order to ensure the stability of the communication link, it is necessary to select a reasonable range of BW which makes the f_d is within the range, and the constraint can be denoted as below.

$$BW \le 4f_d \tag{13}$$

3.3 Packet Format

In a communication link, data is usually encapsulated and transmitted in a certain frame format, and the LoRa packet format used in this system can be shown in Fig. 8.

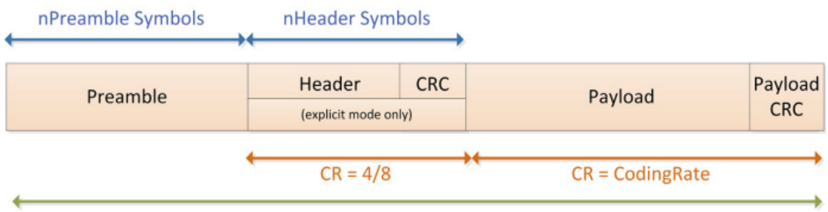

Fig. 8. LoRa packet format

As presented above, this system is based on time-division multiplexing. Therefore, in order to distribute the channel time slot, it is necessary to calculate the period for each transmission process [16]. Then, the LoRa terminal should finish its communication task in one or more periods, and a transmission period can be denoted as below.

$$T_{packet} = T_{preamble} + T_{payload} \tag{14}$$

Where the $T_{preamble}$ is the transmission period of preamble, and the $T_{payload}$ is the transmission period of payload.

The $T_{preamble}$ can be denoted as below.

$$T_{preamble} = (n_{preamble} + 4.25) \times T_{symbol} \tag{15}$$

Where the $n_{preamble}$ is the number of preambles.

Furthermore, the symbol number of payloads can be denoted as below.

$$n_{payload} = 8 + \max(ceil(\frac{2PL - SF + 11}{SF - 2})(CR + 4), 0) \tag{16}$$

Where the PL is the byte number of payloads, and CR is the code rate of payload.

Therefore, the $T_{payload}$ can be denoted as below.

$$T_{payload} = n_{payload} \times T_{symbol} \tag{17}$$

Referring to formula (14) ~ (17), the transmission period can be calculated finally.

4 Simulation

In this part, a series of simulations validate the feasibility of the modulation parameter dynamic reconfiguration method presented in this paper.

Firstly, the main parameters of the satellite-earth communication system should be confirmed for simulations and the relevant parameters are denoted in Table 1. According to formula (12), the *BW* can be set as 125 KHz.

Table 1. Main Parameters

Symbol	Quantity	Units
H	600	Km
R	6371	Km
$EIRP$	0	dBW
Gr	>-2	dBi
Lp	3	dB
Lo	0.5	dB
v_r	8	Km/s
c	300000	Km/s
f	433	MHz
CR	2	
PL	34	
$n_{preamble}$	16	

Secondly, according to the LEO satellite orbital information and the longitude and latitude of LoRa terminals, referring to formula (6), the β between LEO satellite and the LoRa terminals on the ground at different channel time slots is shown in Fig. 9. And the variation trends are different because each LoRa terminal has a different the geographical position.

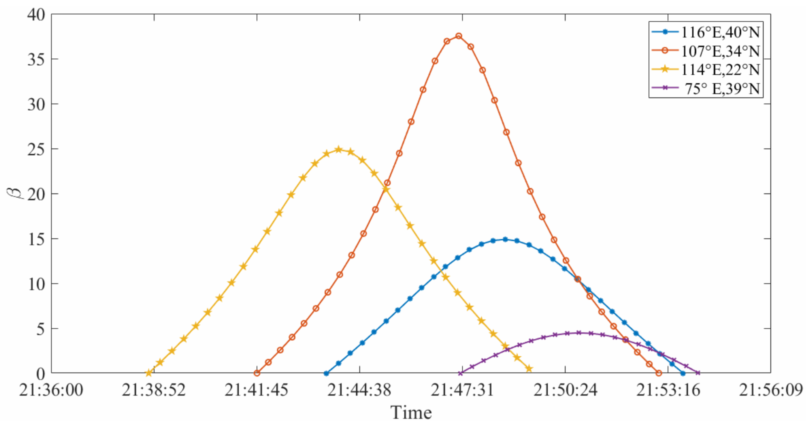

Fig. 9. The value of elevation angle at different channel time slots

Therefore, the LoRa terminals on the ground and the one on the LEO satellite should calculate the relative elevation angle with the distributional channel time slot in advance.

The signal intensity allowance of the satellite-to-ground communication system is the most important gist for the parameter dynamic reconfiguration of LoRa terminal on the ground. Referring to formula (9)~(11), the relationship between *SF*, β and ΔK can be shown in Fig. 10.

In Fig. 10, the red points mean the ΔK is less than 6dB and the blue ones mean the ΔK is lager then 6dB. According to the simulation result, on one hand, with the elevation increasing and the *SF* remaining constant, the signal intensity allowance is increasing. On the other hand, with the *SF* increasing and the elevation remaining constant, the signal intensity allowance is increasing as well.

As a result, in order to maintain the stability of communication link, the LoRa terminals on the ground should configure their modulation parameter based on the β, especially the *SF*.

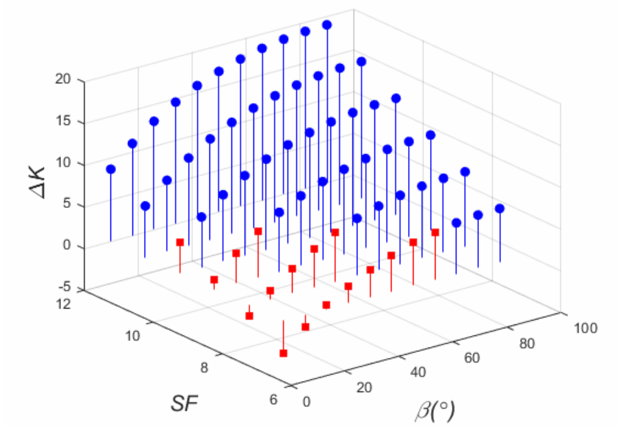

Fig. 10. The relationship of the main parameters

In addition, the R_{bit} and H are also major parameters which can affect the applications of the IoT based on LEO satellites. In the condition of communication link stability, with the larger H, LEO satellites can cover more LoRa terminals on the ground. And, with the larger R_{bit}, the LoRa terminals on the ground can transmit more application data. Therefore, the reasonable ΔK should be selected to ensure optimal performance of the communication system for different application.

The relationship between maximum R_{bit}, β and H can be shown in Fig. 11, and the unit of R_{bit} is kilo-bits per second (kbps). According to the simulation results, with the increase of H, the maximum R_{bit} is reducing. Meanwhile, with the increase of β, the maximum R_{bit} is reducing as well.

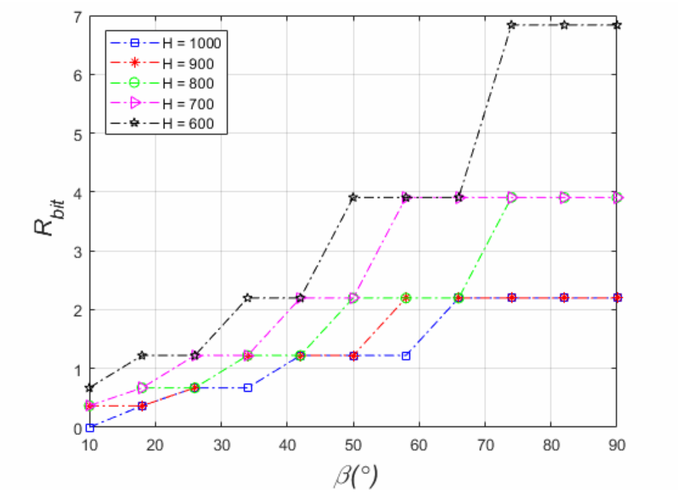

Fig. 11. The relationship of difference parameters

Finally, with the reasonable modulation parameter, the LoRa terminals on the ground can communicate with the LEO satellite as planned.

5 Conclusion

In this paper, an innovative low power consumption satellite-to-ground communication system based on LoRa technology is presented to establish the reliable application of the IoT on LEO satellites. Meanwhile, the constraint relation of each parameter is deduced in detail. Furthermore, a reference scheme of the bite rate limiting are presented for the systems of IoT on LEO satellites with lower power consumption. Simulation results show that the most suitable modulation parameters can be selected with the method presented in this paper to overcome the influence of the effect LEO satellites motion orbit.

References

[1] Z. Qu, G. Zhang, J. Xie, LEO Satellite Constellation for Internet of Things, IEEE Access (2017) 18391-18401.

[2] L. Fernandez, J.A. Ruiz-De-Azua, A. Calveras, A Camps. Evaluation of LoRa for Data Retrieval of Ocean Monitoring Sensors with LEO Satellites, in: Proc. IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium, 2020.

[3] M. Alibakhshikenari, B.S. Virdee, A. Ali, E. Limiti, Extended Aperture Miniature Antenna Based on CRLH Metamaterials for Wireless Communication Systems Operating Over UHF to C-Band, Radio Science 53(1-2)(2018) 154-165.

[4] T.-W. Wu, J. Xie, G. Zhang, Adaptability of LoRa modulation in LEO satellite internet of things, Video Engineering 42(9)(2018) 21-25+36..

[5] F. Li, K.-Y. Lam, Resource Optimization in Satellite-Based Internet of Things, in: Proc. 2020 International Conference on Artificial Intelligence in Information and Communication (ICAIIC), 2020.

[6] Y. Qian, L. Ma, X. Liang, The Performance of Chirp Signal Used in LEO Satellite Internet of Things, IEEE communications letters 23(8)(2019) 1319-1322.

[7] F.V.D. Abeele, J. Haxhibeqiri, I. Moerman, J. Hoebeke, Scalability analysis of large-scale LoRaWAN networks in ns-3, IEEE Internet of Things Journal (99)(2017)1-1.

[8] D. Bankov, E. Khorov, A. Lyakhov, Mathematical Model of LoRaWAN Channel Access with Capture Effect, in: Proc. 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), 2018.

[9] A.J. Wixted, P. Kinnaird, H. Larijani, A. Tait, N. Strachan, Evaluation of LoRa and LoRaWAN for wireless sensor networks, in: Proc. 2016 IEEE SENSORS, 2017.

[10] L. Li, J. Ren, Z. Qian, On the application of LoRa LPWAN technology in Sailing Monitoring System, in: Proc. 2017 13th Annual Conference on Wireless On-demand Network Systems and Services (WONS), 2017.

[11] U. Raza, P. Kulkarni, M. Sooriyabandara, Low Power Wide Area Networks: A Survey, IEEE Communications Surveys & Tutorials (2016) 1-1.

[12] I. Latachi, M. Karim, A. Hanafi, T. Rachidi, A. Khalayoun, N. Assem, S. Dahbi, S. Zouggar, Link budget analysis for a LEO cubesat communication subsystem, In: Proc. International Conference on Advanced Technologies for Signal & Image Processing, 2017.

[13] D. Zorbas, P. Maillé, B. O'Flynn, C. Douligeris, Fast and Reliable LoRa-based Data Transmissions, in: Proc. the 24th Symposium on Computers and Communications (ISCC), 2019.

[14] N. Benkahla, H. Tounsi, Y.Q. Song, M. Frikha, Enhanced ADR for LoRaWAN networks with mobility, in: Proc. 2019 15th International Wireless Communications and Mobile Computing Conference (IWCMC), 2019.

[15] K. Kousias, G. Caso, xd, zgü, Alay, F. Lemic, Empirical Analysis of LoRaWAN Adaptive Data Rate for Mobile Internet of Things Applications, in: Proc. 11th ACM Wireless of the Students, by the Students, and for the Students (S3) Workshop at 25th ACM Annual International Conference on Mobile Computing and Networking (MobiCom), 2019.

[16] Semtch, SX1272/3/6/7/8 LoRa modulation Design Guide, AN1200.13, Revision 1, July 2013.

[17] K.-F. Wang, Y. He, D.-J. Zhao, The Methods of Computing Doppler Shift in Satellite Communication, Gnss World of China 6(2006) 38-41.