The influence of LEO satellite Doppler effect on LoRa modulation and its solution

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Abstract. In order to explore the adaptability of LoRa technology in low Earth orbit satellite communications, this paper studies the influence of the Doppler effect on LoRa modulation in satellite-to-Earth radio channel, and finds that the larger the LoRa modulation spreading factor, the more vulnerable to the Doppler-Rate. The LoRa technology did not estimate and compensate the Doppler-Rate when it was designed. Therefore, this paper proposes a Doppler-Rate estimation algorithm that can better adapt the LoRa technology to low Earth orbit satellite communications.

1. Introduction
In recent years, Internet of things (IoT) is developing at an impressive speed, and the range of applications of IoT is becoming wider. In remote areas and ocean areas that are difficult to cover by ground base stations, to realize IoT communication, IoT base stations need to be built on LEO satellites. LoRa technology is currently one of the most promising terrestrial low-power wide area network technologies. It has mature technology, low cost, a complete network protocol and mature modules. Therefore, LoRa technology has become popular candidate technology for IoT satellites.

In order to study the adaptability of LoRa technology in LEO satellites, [1] analyses the adaptability of LoRa protocol including LoRa network architecture, activation mode, access mechanism, bandwidth, and the mode of work. And some suggestions for improving inapplicable characteristics is given. [2] performs a set of tests to assess the robustness of the LoRa modulation when it is affected by ionospheric scintillation. [3] presents the results of laboratory testing and outdoor experiments conducted to determine the feasibility of the LoRa modulation in LEO satellites communication. It points that Doppler-Rate leads to the destruction of the satellite-to-Earth radio channel when the satellite is flying directly above the ground station using high values of spreading factor (SF). [4] proposes a folded chirp-rate shift keying (FCrSK) modulation with strong immunity to doppler effect, but FCrSK is a little worse than LoRa in robustness to noise and spectral efficiency.

Based on the above research, this article first introduces the characteristics of the LEO satellite Doppler effect, analyzes and simulates the impact of the LEO satellite dynamic Doppler effect on the LoRa modulation, and finally proposes a method that can estimate the Doppler-Rate.

2. Doppler Effect of LEO Satellite
Since the high speed of relative motion between the satellite and the user terminal, the Doppler frequency shift changes rapidly with time. When the satellite's orbital height is H and the terminal is in the satellite's orbital plane, the expression of Doppler frequency offset $f_d$ is
\[ f_d = f_c \cdot \frac{v}{c} = f_c \cdot \frac{gR}{c} \cdot \frac{\sin(\psi)}{\sqrt{\left(1 + \frac{H}{R}\right)^2 - 2 \cdot \left(1 + \frac{H}{R}\right) \cdot \cos(\psi) + 1}} \]  

(1)

where

\[ \psi = \frac{\sqrt{g / R}}{(1 + \frac{H}{R})^{3/2}} \cdot t \]  

(2)

Here \( f_c \) is the carrier frequency, \( c \) is the speed of light in vacuum, \( v \) is the projection of the satellite’s speed on the connection between the satellite and the terminal, \( R \) is the radius of the earth, and \( g \) is the acceleration of gravity on the surface. It shows that the Doppler effect is mainly related to the signal carrier frequency and the satellite orbit height. When the carrier frequency is larger, the satellite orbit height is lower, and the Doppler effect is more serious.

For LoRa-LEO satellite communication system, the maximum carrier frequency is 928MHz, and the satellite orbit height is 600km. The curve of Doppler-Shift and Doppler-Rate when the Doppler effect is severe is shown in Figure 1. It can be obtained that the maximum Doppler-Shift of LoRa signal is about \( \pm 22kHz \), and the maximum Doppler frequency deviation is about \( \pm 270Hz/s \).

![Figure 1. simulation curve of Doppler-Shift and Doppler-Rate](image)

3. The influence of Doppler effect on LoRa modulation

The essence of LoRa modulation is to cyclically shift the Chirp signal [6], the Chirp signal is a complex cosine signal with frequency changes linearly with time, and its expression is

\[ s_0(nT) = \exp \left[ j2\pi \left( \frac{nT}{2} \right)^2 \cdot \frac{B}{T_s} \right] \]  

(3)

Where \( B \) is the signal bandwidth, \( T = 1/B \) is the sampling interval of the signal, \( n = 0, 1, 2, \ldots, 2^{SF} - 1 \) represents a total of \( 2^{SF} \) sampling points, SF is the spreading factor of the signal, and there are \( 2^{SF} \) sampling points in each symbol interval \( T_s = 2^{SF} \cdot T \). So \( s_0(nT) \) can be simplified to

\[ s_0(n) = \exp \left[ j2\pi \frac{n^2}{2^{SF+1}} \right] \]  

(4)

Different cyclic shift values \( K \) represents different modulation information. There are \( 2^{SF} \) sampling points in total, so \( K = 0, 1, \ldots, 2^{SF} - 1 \). The LoRa signal with modulation value \( K \) is

\[ s_K(n) = \exp \left[ j2\pi \left( \frac{(n + K) \mod 2^{SF}}{2^{SF+1}} \right)^2 \right] \]  

(5)
The demodulation of the LoRa signal has to go through two steps, the first is to multiply the conjugate of unmodulated signal to get

$$ s_{rx}^*(n) = s_k(n) s_0^*(n) = \exp\left(j 2\pi \frac{nk}{2^SF}\right) \tag{6} $$

Then perform DFT

$$ DFT\left[s_{rx}^*(n)\right] = \sum_{n=0}^{2^SF-1} e^{j(2\pi \frac{nK}{2^SF})} e^{-j(2\pi \frac{nK}{2^SF})} = \sum_{n=0}^{2^SF-1} e^{j(2\pi \frac{nK + \Delta f \cdot 2^SF}{2^SF})} $$

$$ = \begin{cases} 2^SF, & k = K \\ 0, & k = else \end{cases} \tag{7} $$

The DFT output has a peak value at the modulation value $K$, the peak value is $2^SF$, and the other positions are all 0, so that the information can be demodulated.

Ignore the Doppler-Rate first and only consider the presence of Doppler-Shift. Set the Doppler frequency offset to $\Delta f$ and the received signal is

$$ s_k'(n) = s_k(n) \exp\left(j 2\pi \Delta f \frac{nB}{2^SF}\right) \tag{8} $$

To demodulate the signal, first multiply it with the local conjugate signal to get

$$ s_{rx}'(n) = s_k'(n) s_0^*(n) = \exp\left(j 2\pi n \frac{K + \Delta f \cdot 2^SF}{2^SF} / B\right) \tag{9} $$

After DFT

$$ DFT\left[s_{rx}'(n)\right] = \sum_{n=0}^{2^SF-1} e^{j(2\pi \frac{nK + \Delta f \cdot 2^SF}{2^SF} / B)} e^{-j(2\pi \frac{nK + \Delta f \cdot 2^SF}{2^SF} / B)} = \sum_{n=0}^{2^SF-1} e^{j(2\pi \frac{nK + \Delta f \cdot 2^SF}{2^SF} / B)} \tag{10} $$

It can be seen that when there is a Doppler-Shift $\Delta f$, the position of the DFT output peak changes from $K$ to

$$ \left[K + \Delta f \cdot \frac{2^SF}{B}\right] \tag{11} $$

$[\ ]$ is rounding operation.

Next, the influence of the Doppler-Rate is considered. Taking SF=12, B=125kHz, when the Doppler-Rate is 270Hz/s, the symbol period is $T_s = \frac{2^SF}{B} \approx 0.0328s$, the frequency deviation caused by the Doppler-Rate between adjacent symbols is 8.8Hz. From equation (11), it can be seen that when the frequency offset reaches $B / 2^{SF+1} \approx 30.5Hz$, the demodulation result will shift, so the fourth symbol and subsequent demodulation results will be wrong. The following table shows that when B=125kHz and Doppler-Rate =270Hz/s, LoRa signals with different SF are affected by the Doppler-Rate.

| Table 1. the influence of Doppler-Rate |
|---------------------------------------|
| symbol interval (ms) | Frequency deviation between adjacent symbols (Hz) | Frequency deviation tolerance (Hz) | The first symbol with error |
| SF=7 | 1 | 0.28 | 976.6 | 3532 |
| SF=8 | 2 | 0.55 | 488.3 | 883 |
| SF=9 | 4 | 1.1 | 244 | 221 |
| SF=10 | 8.2 | 2.2 | 122 | 55 |
| SF=11 | 16 | 4.4 | 61 | 14 |
| SF=12 | 33 | 8.8 | 30.5 | 4 |
It can be seen that the larger the SF, the longer the symbol period, the larger the frequency offset between adjacent symbols, and the smaller the tolerance of the demodulation result to the frequency offset. Therefore, the LoRa modulation with bigger SF is more affected by the Doppler-Rate. In order to better adapt the LoRa modulation to LEO satellite communications, it is necessary to estimate and compensate the Doppler-Rate.

4. Doppler-Rate estimation

The beginning of the LoRa data packet is composed of a continuous unmodulated LoRa signal, which can be used to estimate the Doppler-Rate. We assume linear digital data modulation affected by additive white Gaussian noise (AWGN). Timing recovery is ideal but the received signal is affected by time-varying Doppler distortion. So, the received signal is

$$z(k) = s_0(k)e^{j(\theta + 2\pi f_dfTk+\pi f_d'r^2)} + n(k)$$  \hspace{1cm} (12)

Where $\theta$ is the carrier initial phase uniformly distributed in $[-\pi, \pi]$. $f_d$ is Doppler-Shift, $f'_d$ is Doppler-Rate. $T$ is the sampling interval of the signal. $n(k)$ is independent and identically distributed complex Gaussian random variables with zero mean.

Multiply the signal at the header of the received LoRa data packet with its conjugate signal to get

$$r(k) = z(k) \cdot s_0^*(k) = e^{j\phi} + w(k)$$  \hspace{1cm} (13)

$w(k) = n(k)e^{j\phi}$ is statistically equivalent to $n(k)$. Next, use the maximum likelihood criterion [7] to estimate the phases of the 4 points in $r(k)$, which are

$$\hat{\phi}_1 = \arg\left\{ \sum_{k=0}^{N/4-1} r(k) \right\}, \quad \hat{\phi}_2 = \arg\left\{ \sum_{k=N/4}^{N/2-1} r(k) \right\},$$  
$$\hat{\phi}_3 = \arg\left\{ \sum_{k=N/2}^{3N/4-1} r(k) \right\}, \quad \hat{\phi}_4 = \arg\left\{ \sum_{k=3N/4}^{N-1} r(k) \right\}$$  \hspace{1cm} (14)

$\arg\{\}$ denotes the phase of the complex-valued argument. $N$ is the total length of the signal, $\hat{\phi}_i, i = 1, 2, 3, 4$ are the above mentioned ML phase estimates, and $N/8, 3N/8, 5N/8, 7N/8$ are the four times instants that we conventionally associate to the four estimates. The above four points all satisfy the following second-order polynomial

$$\varphi_p(n) = \pi f_d'T \left(n - \frac{N}{8}\right)^2 + 2\pi f_d'T^2 \left(n - \frac{N}{8}\right) + c$$  \hspace{1cm} (15)

the MSE is written as

$$\varepsilon(f_d, f'_d, c) = \frac{1}{4} \sum_{i=1}^{4} \left[ \varphi_p(n_i) - \hat{\phi}_i \right]^2$$  \hspace{1cm} (16)

Equating to zero the derivatives of $\varepsilon(f_d, f'_d, c)$ with respect to a, b and c, we obtain

$$\frac{\partial\varepsilon}{\partial f_d} = 0$$  
$$\frac{\partial\varepsilon}{\partial f'_d} = 0$$  
$$\frac{\partial\varepsilon}{\partial c} = 0$$  \hspace{1cm} (17)
Solving the above equations, we can get the estimation of $f_d$ and $f'_d$ respectively as

$$f_d = \frac{\hat{\theta}_2 + \hat{\theta}_4 - \left(\hat{\theta}_1 + \hat{\theta}_3\right)}{2\pi NT}$$

(18)

$$f'_d = \frac{\hat{\theta}_4 - \hat{\theta}_1 - \left(\hat{\theta}_2 - \hat{\theta}_3\right)}{\pi\left(N/2\right)^2 T^2}$$

(19)

5. Numerical and Simulation Results

First, simulate the estimated range of the Doppler-rate. Set $SF=12$, $B=125\text{kHz}$, $N = 2^SF$ and assume ideal time synchronization and ideal frequency offset compensation, order $Eb/No=6\text{dB}$ on the AWGN channel, and repeat the estimation for each point 1000 times to obtain the estimated mean value and present of the Doppler-rate. The relationship between the values is shown in Figure 2. It can be seen that within the estimated range, the algorithm can accurately estimate the present Doppler-rate, and the estimated range is greater than the maximum Doppler-rate encountered in actual LEO satellite communications. Next, the Doppler-rate estimation algorithm is simulated under different signal-to-noise ratios. As shown in Figure 3, when $Eb/No$ is greater than 4dB, the curve of normalized RMSEE converges, indicating that the estimated Doppler-rate is valid.

6. Summary

This work simulates the Doppler effect of LoRa communication in LEO satellites, and obtains that the maximum Doppler-Shift is about 22kHz and the maximum Doppler-Rate is about 270Hz/s. Secondly, the influence of the LEO satellite Doppler effect on the LoRa modulation is analysed, and the LoRa packet error rate under the influence of the Doppler-Rate is simulated. It is found that when the spreading factor is greater than 9, within the range of the maximum Doppler-Rate, the packet error rate will reach 100% as the Doppler-rate increases. Finally, a Doppler-Rate estimation algorithm is proposed, and the simulation analysis of this algorithm can effectively and accurately estimate the Doppler-Rate when $Eb/No$ is greater than 4dB.

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