Regression based Pilot Design for Doppler Effect Estimation and Compensation in LEO Satellite Communication with LoRa

Jinho Kang†, Gyeongrae Im‡, Dong-Hyun Jung‡, Sooyeob Jung‡, Jung-Bin Kim‡, Pansoo Kim‡, and Joon Gyu Ryu‡
†Department of Electronic Engineering, Gyeongsang National University (GNU), Jinju-si, Gyeongsangnam-do, Korea
‡Satellite Wide-Area Infra Research Section, Radio & Satellite Research Division,
Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea
Email: jinhokang@gnu.ac.kr, {imgrae, dhjung, jung2816, jbkim777, pskim, jgryurt}@etri.re.kr

***Abstract*—Low-earth orbit (LEO) satellites based low-power Internet of Things (IoT) service has attracted attention to provide the hyper-space communication networks in 6G communication. In this paper, we study the regression based pilot design for estimation and compensation of the Doppler effect caused by the high-speed mobility of the LEO satellite.**

***Index Terms*—LEO satellites, LoRa, Doppler effect, Estimation, Compensation**

I. INTRODUCTION

Recently, satellite communications have great attention for next-generation communication systems to realize the hyper-space communication networks [1], [2]. Besides, efficient transmission scheme is essential for low-power Internet of Things (IoT) service in 6G networks [3]. To harvest this end, low-earth orbit (LEO) satellites based communication is considered to provide ubiquitous coverage with massive connectivity [2]. In this paper, we study the LEO satellite communicatoin with LoRa to provide the low-power service in 6G networks. In order to alleviate the performance degradation from the Doppler effect caused by the high-speed mobility of the LEO satellite, we study the regression based pilot design for Doppler effect estimation and compensation.

II. SYSTEM MODEL

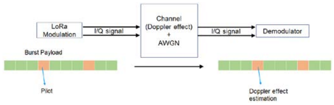

Fig. 1. System model.

In this paper, we consider the commercial LoRa signal as the transmitted signal [2], [4], [5]. For the modulation, LoRa exploits the chirp spread spectrum (CSS) based on a linear chirp as a transmitted symbol denoted by s, which has the spreading factor of sf where $\mathrm{sf} \in \{7, ..., 12\}$ [2], [4], [5]. For the demodulation, the discrete Fresnel transform (DFnT) based detector is widely adopted to detect a symbol with the advantage of low complexity [2], [5]. With the spreading factor of SF where $\mathrm{SF} = 2^{\mathrm{sf}}$, the (m, n)-th element of the DFnT matrix, denoted as $\mathbf{\Psi} \in \mathbb{C}^{\mathrm{SF}\times\mathrm{SF}}$, is given by [5]

$$\mathbf{\Psi}(m, n) = \frac{\exp(-j\frac{\pi}{4})}{\sqrt{\mathrm{SF}}} \exp\left[j\frac{\pi}{\mathrm{SF}}(m-n)^2\right], \tag{1}$$

where $\forall m, n \in \{1, ..., \mathrm{SF}\}$ and $\mathbf{\Psi}$ is the orthonormal matrix. Then, at the receiver, a demodulated symbol is obtained by

$$\hat{s} = \underset{s\in\{1,...,\mathrm{SF}\}}{\arg\max} |\mathbf{\Psi}_s^{\dagger}\mathbf{s}|^2, \tag{2}$$

where $\mathbf{\Psi}_s$ denotes the s-th column of $\mathbf{\Psi}$ and † represents the conjugate transpose operator. We notice that the DFnT based detector has a frequency resolution of $\frac{1}{\mathrm{SF}}$. In this paper, we adopt the DFnT matrix $\mathbf{\Psi}$ to estimate Doppler shift and variation rate for low complexity according to (2). Here, the DFnT based estimator estimates the effective frequency shift affected by both Doppler shift and variation rate with a frequency resolution of $\frac{1}{\mathrm{SF}}$. However, it yields an quantization error [6], i.e., an estimation error.

III. REGRESSION BASED PILOT DESIGN FOR DOPPLER ESTIMATION AND COMPENSATION

The Doppler effect caused by the LEO satellite results in the performance degradation because the carrier frequency of the transmitted signal is distorted [2]. To overcome this difficulty, we study the Doppler effect estimation and compensation method at the receiver, by designing the pilots in the payload.

The receiver estimates the Doppler shift and variation rate based on the known pilots, and then compensate the

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Jinho Kang was with the Satellite Wide-Area Infra Research Section, Radio & Satellite Research Division, ETRI, Daejeon, Korea. He is now with the Department of Electronic Engineering, GNU, Korea.

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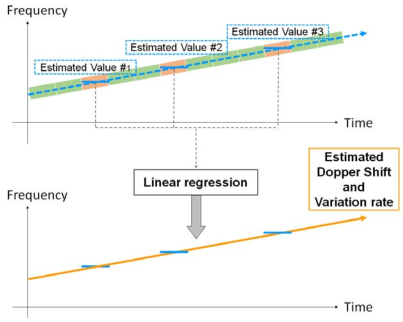

Fig. 2. Regression based pilot design.

distorted shift and rate. The receiver obtains the estimated values, which are affected by both Doppler shift and variation rate, at the certain position of the pilots. Here, the DFnT based estimator is only able to estimate a frequency with the resolution of $\frac{1}{\mathrm{SF}}$ and not able to estimate a frequency variation rate. But, we notice that the Doppler shift as well as the Doppler variation rate with time are reflected in each estimated value. Also, the quantization error, i.e., the estimation error, of the DFnT estimator includes not only the error of the Doppler shift, but also the error of the Doppler variation rate.

In order to obtain the Doppler shift and variation rate from the estimated values each of which has an unknown quantization error, we exploit the regression method as follows. Since the Doppler shift and variation rate have a linear relationship on the time-frequency axis, as shown in the Fig. 2, we adopt the linear regression such that $f = c_{\text{rate}}t + c_{\text{shift}}$ where t and f denote the time and frequency, respectively, and c_{shift} and c_{rate} are the unknown regression coefficients which are obtained from the observed values, i.e., the estimated values at the receiver. In this way, c_{shift} and c_{rate} mean the estimated Doppler shift and the estimated Doppler variation rate, respectively.

Based on the estimated c_{shift} and c_{rate}, we compensate the Doppler shift and variation rate, which are caused by the mobility of the LEO satellite, in the payload at the receiver. The estimated Doppler shift and variation rate based on the linear regression by exploiting the DFnT estimator, i.e., c_{shift} and c_{rate}, are affected by the number of pilots and their positions according to the actual Doppler effect from the LEO satellite mobility. Accordingly, we design the pilots by controlling the number of pilots and corresponding positions according to the length of the payload, the SF, and the Doppler effect caused by the LEO satellite mobility, in order to improve the performance of the estimation and compensation.

IV. NUMERICAL RESULTS

Fig. 3 shows the bit error rate (BER) of the proposed scheme versus Eb/No (dB). For the LoRa payload, the length of the payload is 30 symbols with the carrier frequency of 1 GHz, the bandwidth of 125 kHz, and the spreading factor of 12, i.e., sf = 12, respectively. For comparison, we consider the BER of the AWGN channel environment without the Doppler effect. To evaluate our proposed scheme in the various Doppler effect environments in LEO satellite, we consider the Doppler shift and variation rate with $[10\ \text{ppm}, 200\ \text{Hz/s}]$ and $[0\ \text{ppm}, 300\ \text{Hz/s}]$, respectively, by referring the altitude and orbit of the LEO satellite [1]. We design the pilots such that one pilot is placed for every 3 payload symbols, thus the total length of the payload symbols including the pilots becomes 40 symbols. Fig. 3 demonstrates that our proposed scheme is comparable to the AWGN channel environment without the Doppler effect with a marginal gap of 2 dB for both $[10\ \text{ppm}, 200\ \text{Hz/s}]$ and $[0\ \text{ppm}, 300\ \text{Hz/s}]$. This result verifies that our proposed scheme enables to estimate and compensate the Doppler effect caused by the mobility of the LEO satellite. However, efficient wireless energy transfer [3] and channel quantization [6] for low-power IoT service in the LEO satellite communication remains as our future work.

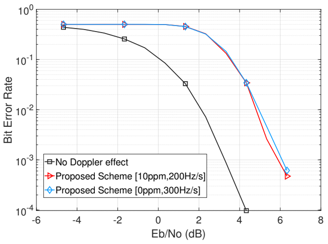

Fig. 3. Bit error rate (BER) of the proposed scheme.

V. CONCLUSION

This paper studied the regression based pilot design for Doppler effect estimation and compensation in LEO satellite communicatoin with LoRa and verifed that the Doppler effect caused by the mobility of the LEO satellite enables to be suppressed.

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