Survey on Doppler Characterization and Compensation Schemes in LEO Satellite Communication Systems

Byungha You and Haejoon Jung
Department of Electronics and Information Convergence Engineering
Kyung Hee University
Yongin-si, 17104, South Korea
{syeon2513, haejoonjung}@khu.ac.kr

In-Ho Lee
School of Electronic and Electrical Engineering
Hankyong National University
Anseong 17579, South Korea
ihlee@hknu.ac.kr

***Abstract*—To achieve a global coverage and enhance throughput, low Earth orbit (LEO) satellites have been adopted in B5G and 6G communications, because they can provide lower latency and higher service density compared to those with higher orbital altitude. However, in the LEO satellite networks, ground users may observe significant Doppler, which should be estimated and compensated for reliable communications. Thus, in this paper, we provide a comprehensive review of the existing studies on Doppler characterization and compensation.**

***Index Terms*—Low Earth orbit satellite, Doppler characterization, Doppler compensation.**

I. INTRODUCTION

Due to its capability to provide connectivity to the area that terrestrial base stations cannot cover or be deployed, satellite constellations consisting of a massive number of low Earth orbit (LEO) satellites have attracted considerable research attention. In particular, when it comes to beyond 5G (B5G) and 6G, the deployment of LEO satellites will be more desirable compared to satellites with higher orbit, because of the lower delay and higher service density resulting from the lower orbital altitude [1]. While integrating terrestrial (TN) and non-terrestrial networks (NTN) is expected to be a key solution to meet the exploding data traffic in B5G and 6G, the high mobility of the LEO satellites may pose a technical challenge of the Doppler effect in the link [2]. Significant Doppler frequency shift, which is subject to the orbit and the relative velocity of the satellite with respect to the user terminal, is observed at mobile users or base stations on Earth and leads to a phase twist in every symbol period [3], [4]. Therefore, it is imperative to estimate and compensate Doppler for reliable communications. Motivated by its significance, in this paper, the review of state-of-the-art research on the characterization and compensation of Doppler in the LEO satellite networks is provided.

II. DOPPLER CHARACTERIZATION

Characterization of various global navigation satellite system (GNSS) receivers was studied in [5]. Doppler frequency and Doppler frequency rate were analyzed as functions of an effective range of angle of a satellite at a terrestrial terminal, assuming the GNSS receivers are moving at different speeds and altitudes. The simulation results showed that Doppler shift decreases linearly with the orbital altitude of the LEO receiver.

Statistical characterization of Doppler shift was studied in [6], exploiting stochastic geometry instead of delving into the deterministic network topology of ground users. Grouping the stationary users served by LEO satellites into non-overlapped clusters with Matern cluster process (MCP) and assuming the users' locations are on a plane, the distribution of Doppler in a cluster for a time instance was derived. The analytical and simulation results showed that the Doppler shift is inversely proportional to the cluster size. In addition, the cumulative distribution function (CDF) curve of the magnitude of Doppler shift degrades with a lower altitude of the satellite or further distance between the cluster center and the satellite.

A maximum a posteriori (MAP) estimator of the Doppler frequency is proposed in [7], where the Doppler shift is characterized as a function of maximum elevation angles and time. Assuming an orthogonal frequency division multiplexing (OFDM)-based broadband mobile links with LEO satellite, Doppler was accurately estimated for moving terrestrial terminals using the proposed estimator. The simulation results suggested that the proposed algorithm always performs better in both additive white Gaussian noise and satellite channels and achieves higher estimation accuracy for varying terminal velocity, as compared to the conventional estimators. An algebraic solution for the satellite Doppler positioning was considered in [8], where the measured Doppler frequency is used to calculate an initial point enabling convergence in iterative algorithms. An analysis of downlink non-orthogonal multiple access (NOMA) was provided in [9], where the Doppler shift is characterized for analyzing the performance of the proposed symmetrical coding (SC) scheme. A resource allocation algorithm aiming to decrease the high differential Doppler values, which result in deterioration of system performance, was proposed in [10].

III. DOPPLER COMPENSATION

A method of fast-tracking Doppler compensation which is achieved within one OFDM frame was proposed in [11], to overcome the issue that OFDM signals are susceptible to high Doppler channels. The simulation results showed enhancement in system performance and aggravation in system overhead with increasing pilots. Two methods of suppressing very high Doppler frequency, which are pilot method and phase locked loop (PLL) method, were proposed in [12]. Through simulation results, it was shown that the Doppler frequency estimation error for the PLL method is higher than that for the pilot method in lower signal-to-noise ratio (SNR) environments, while it turns low in higher SNR. Despite the expense of data rate, the pilot method showed better performance in terms of the estimation accuracy in the range of low SNR.

A method of estimation and compensation of Doppler shift was proposed in [13]. The used estimator has two stages, which are the time-varying Burg spectral analyzer and alpha-beta filter. The former performs the role of estimating the Doppler shift in each sample, and the latter is introduced to fulfill the role of smoothing and tracking the result acquired in the previous stage. Through the simulation results, the proposed scheme proved effective to track the fast-changing Doppler shift with high precision, when the SNR is low.

A method of tracking satellite signals and estimating the Doppler stretch was proposed in [14], considering Globalstar LEO satellite. Utilizing the relationship between Doppler and the chipping rate offset (CRO) and between CRO and the apparent sample number of the pseudo-noise (PN) sequence, a Doppler estimator provides the compensated Doppler whose effect is included in an estimate of Doppler stretch. Because Doppler compensation occurs based on the center of each spot beam, the original Doppler frequency needs to be recovered, and this Doppler stretch estimation technique can track Globalstar satellite signals, followed by estimating the pseudo range of one of Globalstar satellites. The experimental results demonstrated Globalstar LEO satellites, which employ a code-division multiple access (CDMA) system, in order to draw a parallel between the delay tracking scheme and the delay estimated by two-line element (TLE) files, where the results showed great accordance.

A method of estimation and compensation of the Doppler carrier offset using the pilot signal was proposed in [15]. The peak value of the correlation at the receiver is reduced by the carrier offset, and the correlation peak value after the incoherent accumulation algorithm arises due to the PN code offset. Based on the compensation principle of Doppler offset and PN code offset between the satellite and the terminal, both of which are caused by the high-speed moving LEO satellite, the algorithm of terminal signal processing was provided, which consists of pilot signal acquisition, uplink transmission, and downlink acquisition. With a hardware platform of terminal, the algorithm enables the satellite and the terminal to consume less resource and power, which was demonstrated with various system parameters through hardware tests.

IV. CONCLUSION

The ongoing development of B5G and 6G communications has enhanced the feasibility of integrating the TN and NTN. As the key pre-requisite of the corresponding performance enhancement through the seamless integration of the two, the mitigation of dynamic Doppler shifts should be properly addressed. For this reason, in this paper, we have reviewed the existing studies on the LEO satellite communication system with the emphasis on the Doppler characterization and Doppler compensation.

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