A Survey on Doppler Mitigation Approaches in Satellite Communications

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***Abstract*—Satellite communication has attracted considerable attention as a future communication technology due to its advantages such as wide coverage, which is expected to bring new opportunities to improve various services in the Internet of Things (IoT). Low Earth orbit (LEO) satellites have been adopted as a core technology for next-generation communications, beyond 5G (B5G) and 6G, due to their low latency and high service density. However, there exist problems that arise because of technical differences with existing IoT services and Doppler shift caused by fast movement. In this paper, we review the existing studies on innovative approaches to solve the problems in satellite communication.**

***Index Terms*—Satellite communication, Internet of Things, Low Earth orbit satellite, Doppler.**

I. Introduction

Satellite communication services offer wide coverage, low latency, and high service density, making them attractive for providing connectivity in areas beyond terrestrial base stations. However, the existing satellite and terrestrial Internet of Thing (IoT) protocols alone cannot fully meet the requirements of IoT services [1]. Thus, the use of low Earth orbit (LEO) satellites is preferred to high orbit satellites for improved service density and low latency in beyond 5G (B5G) applications [2].

In the context of B5G and 6G, integrating terrestrial networks (TN) and non-terrestrial networks (NTN) is seen as a crucial solution for handling the growing data traffic. However, the mobility of LEO satellites poses technical challenges, particularly related to the Doppler shift in the communication link [3]. Doppler shift causes frequency shifts, which are subject to the satellite's orbit and relative velocity, leading to phase distortion during each symbol period for mobile users and Earth-based base stations [4], [5]. To ensure reliable transmissions, it is essential to address the challenges, including the Doppler shift, in satellite communications. For this reason, in this paper, we review recent innovative studies and approaches that aim to tackle these issues.

II. Innovative Approaches to Satellite IoT

Satellites can be better exploited in the 5G systems for IoT services [6]. In this section, we present cutting-edge approaches or technologies in satellite IoT networks. We divide such technologies into narrowband IoT (NB-IoT), physical layer (PHY) design, medium access, orthogonal frequency division multiplexing (OFDM), and orthogonal time-frequency space (OTFS) and treat them in the following subsections respectively.

A. NB-IoT

NB-IoT is low power wide area network (LPWAN) technology that can be used in satellite networks. When it comes to satellite links, LPWAN technology can be named low power global area network (LPGAN). The main focus of the ongoing NB-IoT research is to improve the air interface to support satellite communications. For example, NB-IoT is set up for detection algorithm to minimize the disadvantage of Doppler shift on demodulation performance [7], and LEO satellite-based uplink scheduling techniques to tolerate differential Doppler without increasing complexity [8].

B. PHY Design

A method for improving the performance of the PHY layer with the introduction of symmetry chirp signal (SCS) is proposed in [9], where detailed descriptions of SCS is introduced in [10]. Further, [11] introduces a novel chirp signal variation, namely the asymmetric chirp signal (ACS), for satellite IoT transmission. The ACS is derived from the approach presented in [9] with certain modifications. Notably, it effectively resolves the issue of high peaks in spectral cross-correlation when confronted with substantial satellite Doppler shift. The investigation conducted in [12] focuses on chirp spread spectrum (CSS) modulation for satellite IoT. The authors propose an innovative method called monopole coding to enable efficient randomized multiple access for multiple transmitting devices. However, an associated concern in CSS modulation pertains to its susceptibility to Doppler shifts. This concern is particularly pertinent to LEO satellites, which exhibit significant Doppler shifts that may severely impede link performances. In response to this challenge, [13] presents a novel modulation scheme known as folded chirp-rate shift keying. This scheme is distinguished by its remarkable capability to withstand Doppler shifts and unforeseen frequency drifts.

C. Medium Access

In [14], the authors present a distributed method in satellite IoT systems that adjusts the transmission probability of each machine-type device (MTD) based on the current traffic load of the service, with the objective of ensuring bidirectional communication. In [15], an analysis is conducted to assess the applicability of direct-sequence spread spectrum Aloha (DSSS-Aloha) in satellite IoT systems operating in LEO. In [16], a protocol named irregular repetition slotted Aloha (IRSA) is introduced for random access in a power-constrained scenario. Lastly, [17] puts forward solutions compliant with indirect-to-satellite communication to optimize the energy consumption of the data collection process.

D. OFDM and OTFS

OTFS modulations are known to be robust against Doppler shift [18]. In LEO satellite communications, significant Doppler shifts can induce time-selective fast fading and result in performance degradation. For disadvantages, various techniques exist to estimate and compensate for Doppler shift, such as single-carrier modulation or OFDM. Poor performance of OFDM can be decreased by increasing the space of subcarriers, or by increasing the length of the pilot sequence. However, the methods are not proper for high-speed LEO satellite communication because of reduced spectral efficiency.

Unlike OFDM, OTFS [19] operates in the delay-Doppler domain, which offers advantages for transmitting signals in time-varying wireless propagation channels affected by Doppler shift. Therefore, OTFS is more robust compared to OFDM against Doppler shifts. In contrast, vector OFDM (VOFDM) in [20] is a common form of OFDM and single-carrier systems that uses a single transmit antenna with high robustness to time-varying channels. On the transmitter side, the discrete and continuous forms of signals in VOFDM align with OTFS. Therefore, VOFDM and OTFS have the same BER performance. The joint demodulation of vector information symbols in VOFDM facilitates the achievement of multipath and signal space diversity at the receiver, enabling the system to combat wireless fading and mitigate time-selective fading caused by Doppler shift.

III. Conclusion

With the explosive growth of demand for terrestrial IoT services, satellite is envisaged to be integrated into existing TN. In this paper, we have categorized the technical limitations, which are emerged when NTN is adopted to enhance IoT services. Furthermore, we have reviewed novel methods and techniques for alleviating severe Doppler shifts, by which the potential for integration of TN and NTN in next-generation communications would be enhanced.

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