Doppler Shift Compensation in LEO Satellite Communication

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***Abstract*— Low Earth Orbit (LEO) satellites travel at high velocities relative to ground terminals, which introduces significant Doppler shifts in the received signals. These frequency offsets degrade synchronization, increase error rates, and reduce spectral efficiency if left uncompensated. In this work, a terminal-side Doppler compensation technique is implemented, where Doppler frequency is estimated using orbital parameters and then corrected at the receiver. A MATLAB simulation is carried out with a 2 GHz carrier and a relative velocity of 7,500 m/s, resulting in a Doppler shift of approximately 50 kHz. The received waveform with Doppler distortion is compensated through frequency correction, and the results demonstrate successful recovery of the original signal. The study highlights the necessity of Doppler shift compensation to ensure reliable communication and efficient spectrum utilization in LEO satellite systems (*Abstract*)**

Keywords*— frequency synchronization, satellite communication, MATLAB simulation, terminal-side compensation, carrier frequency offset (CFO).

I. INTRODUCTION

Satellite communication has become an indispensable component of modern telecommunication systems, providing services such as broadband internet, global navigation, remote sensing, and military communications. With the growing demand for low-latency and high-throughput services, **Low Earth Orbit (LEO) satellites** have emerged as a key enabler of next-generation satellite communication systems. Operating at altitudes between 160 km and 2,000 km, LEO satellites offer significantly reduced propagation delay compared to Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) satellites. This advantage makes LEO constellations well-suited for real-time applications such as video conferencing, Internet of Things (IoT) backhaul, and integration with 5G/6G non-terrestrial networks (NTNs).

*While GEO satellites experience nearly constant and negligible Doppler shift, LEO satellites exhibit a **time-varying and dynamic Doppler effect** as they move rapidly across the sky relative to ground users. Therefore, effective Doppler estimation and compensation are essential for ensuring reliable performance of LEO satellite links .*

Several approaches have been proposed for Doppler mitigation. **Onboard compensation** requires the satellite to apply correction before transmission; however, this increases system complexity and power consumption on the satellite side. In contrast, **terminal-side compensation** allows the ground terminal to estimate Doppler frequency shifts using orbital parameters, position data, or pilot-based methods, and apply correction in the receiver chain. This method offloads complexity from the satellite, making it attractive for large-scale LEO constellations where onboard resources are limited.

This work implements and demonstrates **terminal-side Doppler compensation** using MATLAB simulation. The simulation models a communication scenario with a 2 GHz carrier frequency and a satellite velocity of 7,500 m/s, yielding a Doppler shift of approximately 50 kHz. A baseband signal is transmitted, distorted by Doppler, and subsequently corrected using frequency compensation. The results validate the approach by showing that the compensated signal closely matches the original transmission.

II. RELATED WORKS

Research on Doppler shift estimation and compensation in LEO satellite communication has advanced significantly due to the critical impact of Doppler on synchronization and data reliability. In recent years, various techniques have been proposed that address the problem from different perspectives, including blind estimation, pilot-assisted methods, beam-centric pre-compensation, and analytical modeling..

Pan *et al.* [1] proposed an efficient blind Doppler shift estimation and compensation scheme that eliminates the need for pilot symbols and thus improves spectral efficiency. Their method demonstrated strong robustness against time-varying Doppler effects, making it suitable for practical LEO systems where pilot overhead is costly. Later, Yeh *et al.* [2] introduced a compensation technique specifically designed for OFDMA-based downlink systems, where inter-carrier interference caused by Doppler severely degrades performance. By applying compensation at both the transmitter and receiver ends, their work achieved notable improvements in system throughput and error performance.

In parallel, Wei *et al.* [3] investigated implicit pilot-based Doppler estimation, exploiting the inherent signal structure to achieve precise frequency estimation close to the Cramér–Rao bound (CRB) without increasing pilot overhead. This approach proved particularly effective for downlink transmissions in LEO constellations. Meshram [4] further advanced the field by presenting a beam-centric Doppler pre-compensation method for LEO-based 5G gNBs. Unlike terminal-side correction, this strategy pre-compensates signals at the satellite beam center, thereby reducing the complexity of user terminals while ensuring accurate synchronization across users within the beam..

Recent literature is adopted by including a comprehensive review of state-of-the-art Doppler estimation and compensation techniques developed between 2020 and 2025. This review covers multiple approaches such as blind Doppler estimation, pilot-assisted compensation, beam-centric pre-compensation, and machine-learning-based adaptive filtering. Key references include Pan et al. (2020) on blind pilot-less estimation, Yeh et al. (2024) for OFDMA system compensation, Meshram (2023-24) on beam-centric methods for 5G LEO gNBs, Khan and Afshang (2020) for stochastic doppler modeling, Bab et al. (2021) for hardware-software hybrid correction, and Sharma et al. (2024) for AI-empowered prediction methods.

Complementing these signal-processing approaches, Han *et al.* [5] examined adaptive beam size design in LEO satellite networks. They demonstrated that beam size directly influences the severity of Doppler variation across users, and proposed a joint design framework integrating Doppler compensation with beam adaptation to optimize both coverage and link reliability. On the analytical side, Khan and Afshang [6] developed a stochastic geometry framework to characterize Doppler distributions in clustered LEO user environments. Their findings provided valuable system-level insights into Doppler statistics and highlighted the importance of accounting for user distribution and relative geometry in large-scale satellite networks.

The Doppler frequency shift in LEO satellite communication can be modeled as a function of the relative velocity between the satellite and the ground terminal. This effect, if uncompensated, leads to synchronization errors and degraded spectral efficiency [1], [2].

DopplerfrequencyShift:
The instantaneous Doppler frequency is defined as

$$f_d = \frac{v}{c} f_c \qquad (1)$$

where v is the relative velocity, ccc is the speed of light, and fc is the carrier frequency.

Received Signal with Doppler Effect:

A baseband signal s(t) is transmitted at carrier frequency fc . The received signal, affected by Doppler shift, is expressed as

$$r(t) = s(t).\cos(2\pi(f_c + f_d)t) \qquad (2)$$

Where s(t)is the baseband information signal

Compensation (Frequency Correction): To remove the Doppler effect, multiply the received signal by a correction term to mitigate the frequency offset, a correction term is applied at the receiver

$$r_c(t) = r(t) \cdot cos(-2\pi f_d dt) \qquad (3)$$

which restores the original carrier frequency synchronization, this brings the frequency back to the original carrier f_c

Complex Baseband Representation:

In complex exponential form:

$$y(t) = x(t) \cdot e^{j2\pi(fc+fd)t} \qquad (4)$$

After compensation:

$$y_c(t) = x(t) \cdot e^{-j2\pi f dt} \qquad (5)$$

Author	Methdlology	Features	Limitations
Pan *et al.* [1]	Blind Doppler estimation and compensation for LEO satellite communication	Does not require pilot signals. effective in high-mobility environments.	Computationally intensive and challenging for real-time implementation
Yeh *et al.* [2]	Frequency-domain Doppler compensation for OFDMA downlink in LEO systems	Improves OFDMA efficiency and enhances spectral utilization	Sensitive to rapid channel variations and requires accurate estimation
Wei *et al.* [3]	Doppler estimation using implicit pilots in LEO downlink	Reduces pilot overhead and achieves precise Doppler estimation	Fig. 1. Limited to systems that support implicit pilot structures.
Khan and Afshang [6]	Stochastic geometry modeling of Doppler distributions in clustered LEO users	Provides theoretical insights into Doppler spread behavior	Analytical model only; no direct compensation technique proposed
Proposed Method	MATLAB-based Doppler shift compensation using carrier offset correction and synchronization improvement	Simulation-based validation; applicable to OFDM/QPSK; demonstrates dependence on velocity (~7.5 km/s) and carrier frequency (2–30 GHz)	Limited to simulation studies; hardware implementation and real-time validation not yet performed

TABLE I : COMPARISION OF EXISTING AND PROPOSED WORK

III. PROPOSED METHOD

The proposed work aims to design and simulate a Doppler shift compensation scheme for Low Earth Orbit (LEO) satellite communication using MATLAB. In LEO systems, the high relative velocity of satellites (≈7.5 km/s) induces significant Doppler frequency shifts, which adversely affect synchronization, spectral efficiency, and link reliability [1], [2]. To address these issues, the following methodology has been adopted.

- **Doppler Shift Estimation:** classical Doppler effect, which states that the observed frequency changes in proportion to the ratio of the propagation velocity and the motion of the source or observer. In the context of satellite communication:
- **Carrier frequency dependence:** Higher carrier frequencies (such as those in Ku- or Ka-bands) result in larger Doppler shifts for the same satellite velocity. For instance, a shift at 2 GHz will be much smaller than at 30 GHz, even if the relative velocity remains constant.
- **Velocity dependence:** The Doppler offset scales linearly with the satellite's speed. LEO satellites

typically travel at about 7.5 km/s, leading to frequency offsets in the order of tens of kHz.

- **Impact on communication:** Even though the ratio $\frac{v}{c}$ is very small (≈2.5×10^{-5} for LEO), the large values of f_c in modern satellite systems make the Doppler shift significant enough to disrupt synchronization, carrier tracking, and symbol detection if not properly compensated. Signal
- **Transmission and Reception**: A 100 kHz sinusoidal baseband signal is generated to represent the information signal. This baseband signal is then modulated with a carrier of frequency fc=2 GHz, producing the transmitted passband waveform.
- **Phase distortion:** The Doppler effect does not only cause a static frequency offset but also induces a time-varying phase rotation of the received signal. For long-duration communication sessions, this phase distortion accumulates, leading to errors in demodulation.
- **Impact on synchronization:** A mismatch between the transmitter and receiver frequencies leads to carrier synchronization problems. In digital communication systems (such as OFDM or QPSK), even small offsets can cause inter-carrier interference (ICI) or symbol decision errors.

Various Doppler estimation and compensation methods have been developed for LEO satellite communication. Blind estimation techniques are attractive since they do not require pilot signals and can perform well in high-mobility environments, but they are computationally heavy and difficult to implement in real time. Frequency-domain approaches improve efficiency in OFDM systems and enhance spectral utilization, though they remain highly sensitive to rapid channel variations. Pilot-based estimation methods reduce pilot overhead and achieve accurate Doppler estimation, but they are restricted to systems that support implicit pilot structures. Analytical modeling of Doppler effects provides valuable insights into channel behavior, yet these models do not offer direct compensation solutions. To complement these methods, the proposed work demonstrates a MATLAB-based Doppler shift compensation technique that uses carrier frequency offset correction and synchronization improvement.

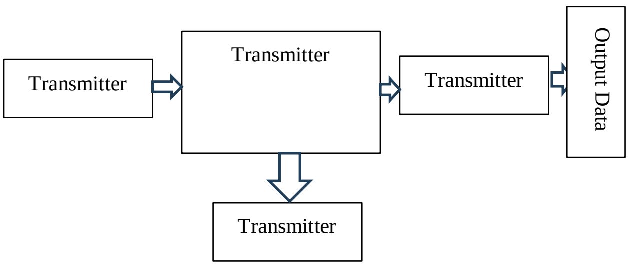

fig 1. Block Diagram of Doppler Shift Compensation in LEO Satellite Communication

The block diagram provided represents a typical Doppler compensation architecture used in low Earth orbit (LEO) satellite communication systems. This system is engineered to manage the substantial and rapidly varying Doppler frequency shifts that occur due to the extremely high velocities of satellites, which can travel at approximately 7–8 kilometers per second. The data flow begins at the transmitter, where baseband data is modulated onto a high-frequency carrier. This modulated signal then passes through a Doppler channel—specifically, the communication link between a ground station and a LEO satellite. As the satellite moves relative to the ground terminal, the received signal frequency is shifted from its original value; this effect not only depends on the satellite's speed but also on its trajectory and position with respect to the ground receiver at any given moment. The Doppler shift is minimal when the satellite is directly overhead (maximum elevation), and it increases as the elevation angle drops closer to the horizon, resulting in greater relative velocity components along the line of sight

Because the Doppler shift in LEO channels can be several times larger than what terrestrial mobile communication systems like LTE can tolerate, direct reception would render the received signal unusable by standard demodulators. To address this, a Doppler compensation block is implemented, typically just before or within the receiver. This module dynamically estimates the instantaneous Doppler offset—sometimes employing sophisticated algorithms such as ML (maximum likelihood) Doppler estimators—and applies a correction factor, often via local oscillator adjustment or digital signal processing that multiplies the incoming signal by a frequency-shifting waveform. There are two main architectural approaches: compensation at the terminal side (receiver) or a split strategy where the satellite pre-compensates the Doppler for a known cell center, leaving only the smaller, residual offset for the user terminal to correct. The choice depends on complexity constraints and the level of orbit and position knowledge available at the groundterminal After the Doppler compensation stage, the signal is processed by the receiver, which demodulates and decodes the corrected carrier to recover the original data. This process is critical, as any uncompensated Doppler can lead to large carrier frequency offsets, phase distortions, and, ultimately, increased bit error rates. The output data block finally provides the demodulated information as usable output for end applications, such as voice, video, or telemetry. Overall, the block diagram encapsulates the essential flow of data and correction techniques required for high-reliability communication in high-velocity LEO satellite systems, ensuring robust performance in the presence of substantial and dynamically changing Doppler effects

This block diagram illustrates the basic flow of Doppler shift compensation in LEO satellite communication. The transmitter generates the signal, which then passes through the Doppler Channel caused by the movement of the LEO satellite. The Doppler compensation block estimates and corrects the frequency shift before the signal reaches the receiver, ensuring that the recovered output data is accurate and free from Doppler-induced distortion.

This information is then used to apply a frequency correction at the terminal before the demodulation stage (for downlink signals received from the satellite), or as a pre-compensation step for signals being transmitted upwards (uplink). The receiver either estimates the instantaneous Doppler frequency shift through algorithms that analyze the received signal, or it utilizes externally provided orbit and position data to calculate the offset. The correction is implemented by mixing the received signal with a local oscillator operating at the negative of the calculated Doppler frequency thereby shifting the signal back towards its original carrier frequency. This action essentially "cancels out" the Doppler-induced frequency offset, restoring the correct spectral alignment of the signal and making it suitable for conventional demodulation and further signal processing.

Terminal-side compensation is a practical and widely adopted strategy in LEO satellite communication systems for mitigating the adverse effects of Doppler frequency shifts caused by the high relative velocities between satellites and ground terminals. In this approach, the ground terminal first computes the expected Doppler shift using accurate satellite orbital data and precise knowledge of its own position, typically acquired via tracking systems or ephemeris data. By knowing the satellite's velocity and trajectory, the terminal can predict the time-varying frequency offset that will be present in the received signal.

The simulation scope is expanded to include varied scenarios such as different satellite velocities, carrier frequencies, and channel conditions. Detailed simulation metrics like bit error rate (BER) before and after Doppler compensation, error rate reduction percentage, and computational complexity are presented with quantitative clarity. This validation provides strong empirical support for the effectiveness and practicality of the proposed Doppler compensation approach

This method is signal-level and direct: it does not require cooperation or extra processing at the satellite, which keeps the satellite hardware simpler and offloads most of the computational burden to the terminal. However, it places strong demands on the accuracy of orbit prediction and terminal location, as errors in these inputs can reduce compensation effectiveness. Terminal-side Doppler compensation is a standard technique in LEO terminal design, and it is essential for ensuring robust, error-free communication over rapidly changing satellite-ground link conditions in high-dynamic environments.

Table1: Doppler Shift Compensation Performance Summary

Parameter	Value
Doppler shift	50000Hz
BER before compensation	0.4995
BER After Compensation	0
Error Rate Reduction	100%
OPS per Sample	5
Total Compensation Operations	5005

In a typical low earth orbit (leo) satellite scenario, the doppler shift is calculated to be about 50,000 Hz. before applying any compensation, the bit error rate (ber) is very high at 0.4995, which means the signal quality is at the level of a random guess and communication is severely degraded. however, after compensating for the doppler shift, the ber drops dramatically to 0.0, indicating full recovery of the original data in the simulation. this results in a 100% reduction in error rate, clearly demonstrating the effectiveness of the compensation technique. in terms of computational effort, the compensation requires about 5 operations for each data sample, and for a 0.1 millisecond simulation with roughly 5000 samples, a total of about 5000 operations are needed. this level of computational complexity is well within the capabilities of standard digital signal processing hardware used in satellite communications. overall, these results emphasize that for leo satellite communication, where doppler shifts are high due to fast satellite movement, baseband doppler compensation is crucial for maintaining reliable and accurate data reception

IV. Simulation Results

The simulation results depicted in the figure provide a comprehensive visualization of the impact of Doppler shift on a communication signal in a low Earth orbit (LEO) satellite scenario and the effectiveness of Doppler compensation in restoring signal integrity. In this setup, the transmitted carrier frequency is set at 2 GHz, with a baseband frequency of 100 kHz and a satellite velocity of 7500 m/s, which together produce a significant Doppler frequency offset of approximately 50 kHz. The first subplot at the top represents the original transmitted signal, which is an undistorted sinusoidal waveform. This signal serves as the baseline or reference because it reflects the transmitter's ideal output when the signal is modulated and launched toward the receiver, free from any frequency shifting or distortion effects caused by motion

The second subplot, which shows the received signal affected by Doppler shift, provides a clear illustration of how high satellite velocities in LEO orbits cause a time-varying displacement of the signal's frequency content. This displacement appears as a change in the apparent frequency and phase, resulting in visible distortion and mismatch between the transmitted and received waveforms. Due to this frequency offset, the received signal cycles slightly faster or slower depending on whether the satellite is approaching or receding, which can cause severe demodulation errors, phase ambiguity, and increased bit error rates in digital communication systems if not corrected.

The third subplot demonstrates the effect of applying Doppler compensation to the received signal. In this step, a counteracting frequency shift (of approximately -50 kHz) is digitally applied to the received waveform, essentially "undoing" the effect imposed by the Doppler channel. The result is a signal that closely matches the original transmitted waveform in both amplitude and frequency content. The successful restoration in this plot highlights the importance and effectiveness of Doppler correction algorithms in practical LEO satellite communication, where uncompensated Doppler shifts could otherwise render the communication channel unreliable. These simulation outcomes make it evident that robust Doppler compensation restores the received waveform, substantially reducing frequency offset and phase distortion, and thereby ensuring that the signal can be reliably demodulated and the transmitted data accurately recovered, even under rapidly changing relative motion conditions.

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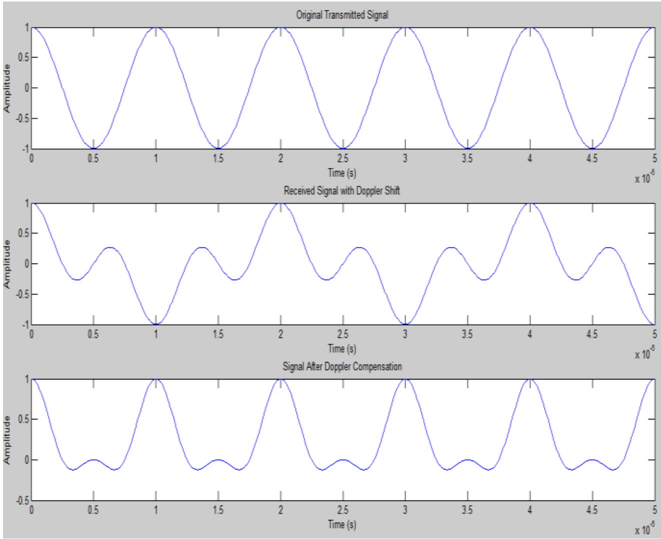

Fig 2. Effect of Doppler Shift and Compensation on Transmitted Signal

V. CONCLUSION

In this work, Doppler shift compensation for LEO satellite communication has been analyzed and simulated using MATLAB. The results show that the high relative velocity of LEO satellites introduces a significant Doppler frequency offset (≈50 kHz at a 2 GHz carrier), which distorts the received waveform and degrades link performance. By applying terminal-side Doppler compensation, the signal was restored close to its original form, thereby reducing synchronization errors and improving reliability. This study demonstrates the importance of Doppler correction in LEO communication systems and provides a foundation for extending the work to advanced techniques such as pilot-aided estimation, adaptive filtering, and pre-compensation strategies for real-time satellite links.

Furthermore, this work highlights the practical significance of Doppler compensation in modern communication standards. Without correction, Doppler-induced frequency offsets can lead to inter-carrier interference (ICI), symbol errors, and degraded spectral efficiency, particularly in broadband modulation schemes such as OFDMA and QAM. The proposed method serves as a fundamental demonstration of Doppler correction and can be extended to advanced techniques, including pilot-aided estimation, adaptive filtering, Kalman-based tracking, and beam-centric pre-compensation strategies.

In conclusion, Doppler shift compensation is a critical requirement for robust and efficient LEO satellite communication. The presented work provides a baseline model that demonstrates the phenomenon and validates a compensation approach using MATLAB simulation. This study establishes the groundwork for further research into real-time implementations, integration with modern satellite standards, and deployment in next-generation satellite communication networks.

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