Blind Doppler Tracking from OFDM Signals Transmitted by Broadband LEO Satellites

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***Abstract*—An algorithm for blind Doppler frequency estimation from orthogonal frequency division multiplexing (OFDM) signals transmitted by low Earth orbit (LEO) satellites is developed. A method for resolving the ambiguity in the Doppler estimate is also discussed. Two sets of experimental results are presented. The first demonstrates blind Doppler estimation from terrestrial fifth-generation (5G) signals on a mobile ground vehicle, achieving 14.5 Hz Doppler root mean-squared error (RMSE). The second demonstrates an unmanned aerial vehicle navigating using the proposed approach with emulated 5G signals from two Orbcomm LEO satellites for a period of 2 minutes, achieving 15.16 m position RMSE.**

***Index Terms*—OFDM, navigation, signals of opportunity, low Earth orbit satellites, blind Doppler tracking.**

I. Introduction

Recent studies have shown remarkable navigation performance with signals of opportunity (SOPs). On one hand, with terrestrial SOPs, meter-level accuracy [1]–[6] and sub-meter level accuracy [7], [8] have been demonstrated with cellular SOPs on ground and aerial vehicles, respectively. On the other hand, plans of private companies (e.g., OneWeb, SpaceX, and Boeing) to launch thousands of broadband Internet satellites into low Earth orbit (LEO) will trigger a renaissance of navigation with SOPs [9]. Several theoretical and experimental studies characterized broadband LEO satellite signals as potential reliable sources for navigation [9]–[12]. Among the most attractive attributes of LEO satellite signals are their abundance and diversity in geometry and frequency [11], [13]. However, the major underlying assumption in existing SOP navigation frameworks is that the structure of these SOPs is known at the receiver side. Many LEO broadband communication systems use proprietary protocols, to which barely any information about the signal structure is available. A natural question then arises: is it possible to still exploit the unknown signals transmitted by LEO satellites for navigation purposes? This paper aims at answering this question by investigating blind Doppler estimation from orthogonal frequency division multiplexing (OFDM) signals transmitted by LEO satellites.

OFDM is widely adopted in different communication generations, such as 4G long-term evolution (LTE) and 5G, and has attracted attention in the navigation literature [2], [3], [14]. However, in order to exploit navigation observables from OFDM-based SOPs, it is assumed that the receiver perfectly knows the synchronization sequences, such as the primary and secondary synchronization sequence (PSS) and (SSS), respectively. In the case where these sequences are unknown, which is the case of future broadband LEO satellite systems, acquiring and tracking these signals becomes impossible for a regular opportunistic navigation framework. As such, designing receivers that can blindly estimate these sequences is a crucial need for the future of opportunistic navigation.

The problem of blind OFDM symbol timing and carrier recovery has been considered in the signal processing literature [15]–[17]. The proposed approaches usually make assumptions that may not necessarily hold for LEO satellites, e.g., low frequency offset magnitude and stationarity of the channel between the source and the receiver. The received signals from LEO satellites usually suffer from high Doppler frequencies, which are typically greater than the subcarrier spacing of the transmitted OFDM symbols. As a result, it is almost impossible to coherently integrate the signal to accumulate enough power for reliably detecting the synchronization signals. While existing approaches rely on large and expensive high-gain antennas to accumulate enough power for a single snapshot [18]; this work, an extension of [19], aims at developing a framework for low-cost, online estimation of synchronization sequences in OFDM signals. The paper's main contributions are as follow. First, the effect of Doppler on OFDM signals from LEO satellites is studied. Second, a computationally efficient algorithm for blind Doppler estimation from OFDM signals transmitted by LEO satellites is proposed. Third, the paper presents two sets of experimental results. The first demonstrates blind Doppler estimation from real terrestrial fifth-generation (5G) signals for over 11 minutes on a mobile ground vehicle, achieving 14.5 Hz Doppler root mean-squared error (RMSE). The second demonstrates an unmanned aerial vehicle navigating using the proposed approach with emulated 5G signals from two Orbcomm LEO satellites for a period of 2 minutes, achieving 15.16 m position RMSE.

The rest of the paper is organized as follows. Section II presents the problem formulation and studies the effect of Doppler on LEO OFDM signals. Section III discusses the blind Doppler estimation algorithm. Section IV presents experimental. Concluding remarks are given in Section V.

II. Problem Formulation And System Models

A. Problem Formulation

SOP navigation receivers typically rely on correlating the received signal with the known beacon signal therein to acquire the SOP, track it, and produce navigation observables. The main challenge facing the blind opportunistic receiver is the partially known nature of the SOPs it aims to cognitively decipher, acquire, and track. *Cognitive deciphering* in the receiver refers to blindly detecting and tracking of the beacon signals, which in turn allows us to exploit the received signals for positioning and navigation purposes.

It is important to note that due to the properties of correlation receivers, the known beacon or pilot signals can still be detected reliably even at relatively low signal-to-noise ratios (SNRs). However, in the case of blind opportunistic navigation, the beacon is unknown to the receiver and the signal's SNR is typically too low for reliable blind detection. Consequently, coherent integration becomes crucial to increase the effective SNR of the received beacon signal. Unfortunately, the high Doppler shift in the received signal induced by the LEO satellites' high dynamics prohibits long integration periods. The Doppler shift (or Doppler frequency) for two Orbcomm LEO satellites is shown in Fig. 1.

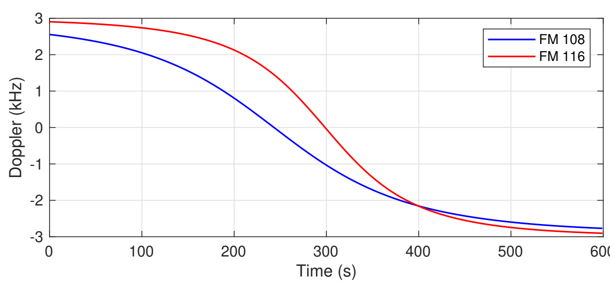

Fig. 1. Doppler frequency for two Orbcomm satellites (FM 108 and FM 116) obtained using two-line element (TLE) files and SGP4 software.

To this end, the Doppler frequency must be estimated first. Moreover, the Doppler frequency, from which the carrier phase can be calculated, is used as a navigation observable as well. This paper focuses solely on blind frequency recovery of OFDM signals transmitted by LEO satellites.

B. Received Baseband Signal Model

It can be shown that the transmitted OFDM signal can be written as

$$x(t) = \sum_{i=0}^{N_c-1} A_i \cos\left[2\pi(f_i + f_c)t + \phi_i\right], \qquad (1)$$

where f_c is the carrier frequency; N_c is the total number of subcarriers; and A_i,f_i, and ϕ_i are the amplitude, frequency, and phase of the ith subcarrier, respectively [20]. Due to the relative motion between the receiver and the LEO space vehicle (SV), a Doppler frequency f_D will be induced. The effect of the Doppler shift on the OFDM signal from LEO satellites is discussed next.

C. Effect of Doppler Shift on LEO Satellite OFDM Signals

Define the fractional Doppler frequency ξ as

$$\xi \triangleq \frac{f_D}{f_c}.$$

Note that for a given subcarrier spacing Δf, the i-th subcarrier is expressed as

$$f_i = i\Delta f.$$

The effect of f_D on the transmitted signal is hence given by

$$x'(t) = \sum_{i=0}^{N_c-1} A_i \cos\left[2\pi(1+\xi)(f_i + f_c)t + \phi_i\right]. \qquad (2)$$

From (2), the resulting Doppler frequency at the i-th subcarrier can be expressed as

$$f_{D_i} = \xi(f_i + f_c) = f_D + i\xi\Delta f. \qquad (3)$$

It can be seen from (3) that the Doppler frequency not only shifts the subcarriers but stretches the spacing between them as well, as illustrated in Fig. 2.

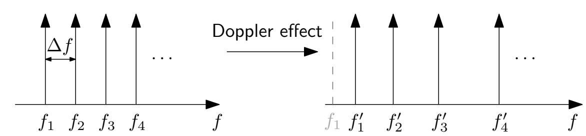

Fig. 2. Effect of Doppler on the subcarriers. Not only are the subcarriers shifted, but the subcarriers are spreading apart as well.

Fig. 3 shows $\xi_{\max} \triangleq \frac{f_{D_{\max}}}{f_c}$ as a function of the orbital altitude, where $f_{D_{\max}}$ is the maximum observed Doppler at the receiver. Current and future LEO constellations are also identified on Fig. 3 based on their orbital altitudes. It can be seen from Fig. 3 that $\xi_{\max}$ is small for the LEO constellations of interest. As such, if one also uses the lower subcarriers to track the Doppler shift, i.e., $i = 1$ or $i = 2$, then the observed Doppler shift at the i-th subcarrier can be approximated with

$$f_{D_i} \approx f_D.$$

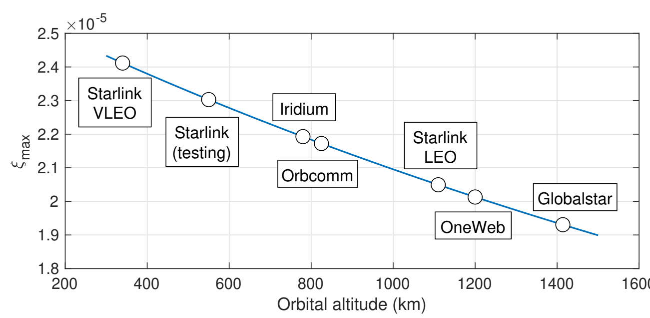

Fig. 3. Plot of $\xi_{\max}$ for current and future LEO constellations.

Therefore, at the receiver, after mixing to baseband and assuming an additive white Gaussian noise (AWGN) channel with noise power spectrum N_0, it can be shown that the received OFDM signal can be written as

$$y(t) = \sum_{i=0}^{N_c-1} A_i \cos\left[2\pi(f_i + \xi f_c)t + \phi_i\right] + n(t), \qquad (4)$$

where $n(t)$ is the zero-mean channel noise.

III. Blind Doppler Estimation for OFDM Signals from LEO Satellites

This section details the blind Doppler estimation framework.

A. Beacon Signal Model

The blind Doppler tracking algorithm relies on the existence of a beacon signal in the received data. A beacon is defined here as any periodic signal, whether a constant tone, a synchronization sequence, or any repeated pattern in the transmitted data. Let $s(t)$ denote the beacon signal with length Δt_b and period T_0. The Fourier transform of the repeated beacon signal modulated by a Doppler frequency f_D is given by

$$\mathcal{F}\left\{\sum_{l=-\infty}^{\infty} \exp\left(j2\pi f_D t\right) s(t-lT_0)\right\} = \sum_{l=-\infty}^{\infty} S\left(lf_0\right)\delta\left(f-f_D-lf_0\right), \quad (5)$$

where $S(f)=\mathcal{F}\{s(t)\}$ is the Fourier transform of $s(t)$ and $f_0=1/T_0$. Therefore, because of the periodicity of $s(t)$, impulses will appear in the Fourier transform of the received signal at $f=f_D+lf_0$. In practice, the Fourier transform can only be computed over a finite interval of the data, referred to as the coherent processing interval (CPI) and denoted I. The effect of I on the Fourier transform is discussed next.

B. Effect of the CPI on the Fourier Transform

The CPI can be thought of as a time-domain window multiplying the data. As such, the Fourier transform of a finite CPI will consist of shifted sinc functions with different weights. As the CPI approaches infinity, the sinc functions become narrower and narrower approaching the Dirac delta function at the limit, as apparent in (5). To visualize this, real 5G signals, which employs OFDM, were collected using a universal software radio peripheral (USRP) mounted on a ground vehicle. The discrete-time Fourier transform was computed using the FFT algorithm for different CPIs: 10, 20, and 200 ms. The results are shown in Fig. 4. For a CPI of 200 ms, the FFT was computed twice, 50 seconds apart, showing a shift in the peaks' locations due to the Doppler frequency induced by the relative motion between the vehicle and the 5G transmitter (i.e., gNB).

An important condition for the sinc functions to converge to delta functions is that the Doppler frequency should be varying slowly within the CPI, i.e., a fraction of the inverse of the CPI. This condition is satisfied for the case in Fig. 4 where the Doppler was almost constant at the times the FFTs were computed. However, in the case of LEO satellites, the Doppler frequency varies very quickly. As a result, increasing the CPI significantly introduces a chirp effect in the FFT instead of converging the sincs to deltas. To avoid such effects, the received signal is pre-processed to reduce the Doppler frequency before computing the FFT.

C. Initial Doppler Wipe-Off

It is assumed the receiver has a prior on its position. As such, one can predict the Doppler using the freely available TLE files and orbit determination software, e.g., SGP4. Let $\hat{f}_D$ denote the predicted Doppler from TLE. Next, the received signal is wiped-off with the predicted Doppler, yielding a small and slowly varying frequency offset. The prior on the receiver position does not need to be accurate. Fig. 5 shows the residual Doppler frequencies for four Orbcomm satellites after wipe-off with an error in the receiver position of more than 6.5 km.

The wipe-off operation on $x(t)$, after low-pass filtering, can be expressed as

$$\begin{aligned}\hat{y}(t) &\triangleq y(t)\cos(2\pi\hat{f}_D t)\\ &\approx \sum_{i=0}^{N_c-1} A_i\cos\left[2\pi(f_i+\tilde{\xi}f_c)t+\phi_i\right]+\hat{n}(t), \end{aligned}\quad (6)$$

where $\tilde{\xi}\triangleq\frac{\tilde{f}_D}{f_c}$, $\tilde{f}_D\triangleq f_D-\hat{f}_D$, and $\hat{n}(t)$ is the noise after wipe-off and filtering. However, the predicted Doppler will have errors due to ephemeris errors in the TLE, the initial error in the receiver position, and propagation errors. Subsequently, $\tilde{f}_D$ must be estimated, as discussed next.

D. Blind Residual Doppler Estimation

The blind Doppler estimator in the receiver processes CPI at a time. One can form the vector of samples of the discretized wiped-off signal $\hat{y}(t)$ as

$$\hat{\boldsymbol{y}}^k \triangleq \left[\hat{y}[kI],\hat{y}[kI+1],\ldots,\hat{y}[(k+1)I-1]\right]^{\mathsf{T}}, \quad (7)$$

where k denotes the CPI index. It can be seen from Fig. 5 that the residual Doppler, even in the most extreme cases, is small enough to consider it constant in reasonably long CPIs. Therefore, $\tilde{f}_D[n]=\tilde{f}_{D_k}$ in the kth CPI. As a result, the FFT of $\hat{\boldsymbol{y}}^k$ will have sharp peaks that are changing in frequency according to $\tilde{f}_{D_k}$. As such, a proper sliding band-pass filter is capable of tracking the Doppler frequency changes in different CPIs. The choice of which peak to track is done manually in this paper. However, it has to be as close as possible to the DC component in order to minimize the effect of the Doppler shift on higher subcarriers. As such, the effect of the subcarriers on the residual Doppler estimate is negligible.

Denote $\hat{\tilde{f}}_D$ as the estimated residual Doppler. Tracking the impulse trains of the periodic signals results in ambiguity that is an integer multiple of f_0 in the residual Doppler estimate and may be additionally offset due to the unknown indexes of the beacon's subcarriers. Let f_{offset} denote the frequency ambiguity. The final Doppler estimate can hence be formed as

$$\bar{f}_{D_{\text{amb}}} \triangleq \hat{f}_D+\hat{\tilde{f}}_D = f_D+f_{\text{offset}}+\epsilon_{f_D}, \quad (8)$$

where ϵ_{f_D} is the estimation error. A method for resolving f_{offset} is proposed next.

E. Doppler Ambiguity Resolution and Navigation Framework

In this work, the differential framework proposed in [13] is adopted (see Fig. 6). To this end, carrier phase measurements are obtained by integrating $\bar{f}_{D_{\text{amb}}}$, both for a reference receiver (base) and the navigating receiver (rover). Assuming both receivers have the same ambiguity, which can be achieved by coordinating which frequency component to track in the FFT, differencing the integrated Doppler frequencies cancels out the frequency ambiguity. Details of the carrier phase differential LEO (CD-LEO) framework are in [13].

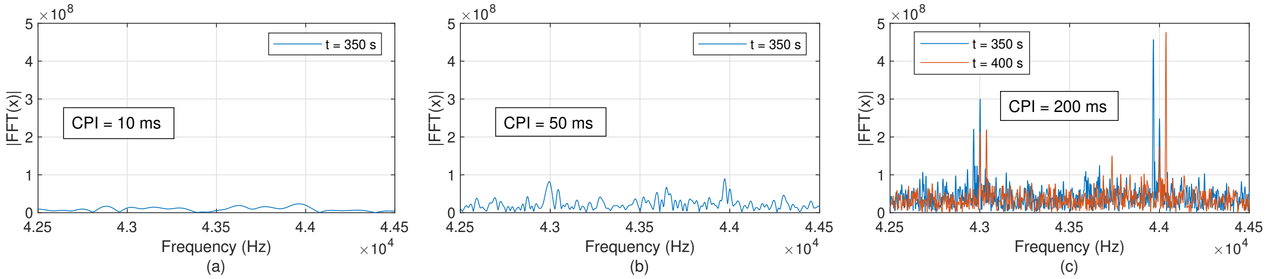

Fig. 4. (a) FFT of the received 5G signal for a 10 ms CPI at $t = 350$ s. (b) FFT of the received 5G signal for a 50 ms CPI at $t = 350$ s. (c) FFT of the received 5G signal for a 200 ms CPI at $t = 350$ s and $t = 400$ s.

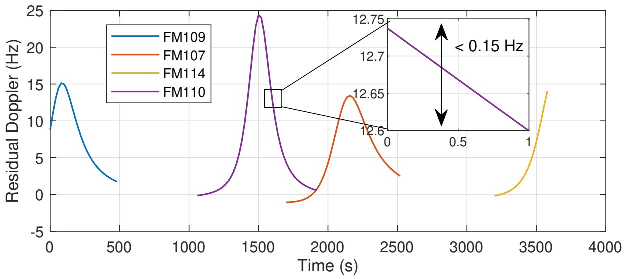

Fig. 5. Residual Doppler frequencies for four Orbcomm satellites after wipe-off with an error in the receiver position of more than 6.5 km. It can be seen that for such receiver position error, the residual Doppler varies by less than 0.15 Hz in 1 s. CPIs are typically chosen to be much less than 1 s, as seen in Fig. 4, which makes this residual Doppler variation even less significant.

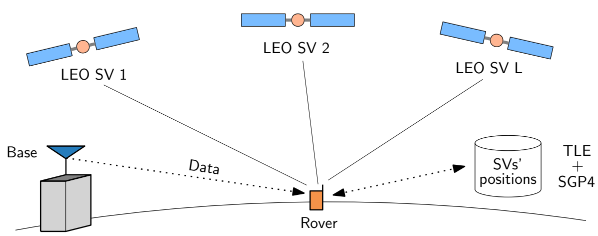

Fig. 6. CD-LEO framework used for blind opportunistic navigation.

IV. Experimental Results

To demonstrate the proposed Doppler estimation framework, 5G signals were collected on a ground vehicle to mimic residual Doppler after wiping-off the residual carrier of the received signal using the Doppler estimated from TLEs. Another blind opportunistic navigation experiment was conducted on a UAV with emulated LEO satellite 5G signals.

A. Experiment 1

1) Experimental Setup: In the first experiment, a USRP with a tri-band cellular antenna were equipped on ground vehicle to sample 5G signals at a sampling rate of 10 MSps. The sampled data were stored for post-processing. The receiver was listening to one 5G gNB, whose position was mapped prior to the experiment. The vehicle was equipped with a Septentrio AsteRx-i V integrated GNSS-inertial navigation system (INS) to provide a ground truth for position and velocity of the vehicle.

2) Experimental Results: The USRP sampled 5G signals over a period of about 700 seconds at a carrier frequency of 872 MHz. The proposed framework was used to track the Doppler throughout the trajectory. The estimated Doppler with ambiguity is shown in Fig. 7(a). The Doppler ambiguity was manually calculated to be 11.0025 kHz, and was subtracted from the estimated Doppler. The Doppler estimate without the ambiguity and the predicted Doppler from ground truth are shown in Fig. 7(b) for comparison. The RMSE between the final estimated Doppler and the predicted Doppler was calculated to be 14.5 Hz over the entire trajectory.

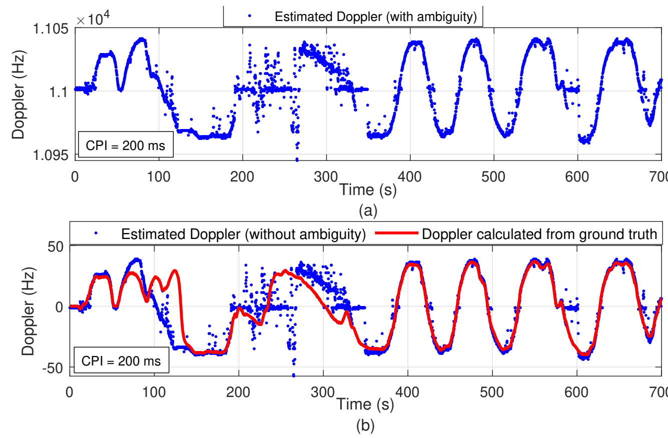

Fig. 7. (a) Estimated Doppler frequency with ambiguity. (b) Estimated Doppler frequency without ambiguity and predicted Doppler frequency from ground truth.

B. Experiment 2

1) Experimental Setup: In the second experiment, real 5G signals were mixed with Doppler measurements from Orbcomm LEO satellites to test the proposed approach with LEO-based 5G NR signals in a controlled fashion. To this end, a UAV was equipped with a USRP and a high-end VHF antenna. The base was a stationary receiver equipped with a USRP and a custom-made VHF antenna. The receivers were tuned to a 137 MHz carrier frequency with 2.4 MSps to sample the 137–138 MHz band allocated to Orbcomm SVs, which transmit symmetric differential quadrature shift-keying (SDQPSK) signals. Samples of the received signals were stored for off-line post-processing using the software-defined radio (SDR) developed in [21]. The LEO Doppler measurements were produced at a rate of 4.8 kHz and were downsampled to 10 Hz. Next, the real 5G signals from Experiment 1 were mixed with the Doppler frequencies measured by the SDR in [21], emulating 5G signals transmitted by LEO satellites. The base's position was surveyed on Google Earth, and the UAV trajectory was taken from its on-board navigation system, which uses a GNSS-INS. The UAV traversed a total trajectory of 1.036 km in 120 seconds.

Over the course of the experiment, the receivers on-board the base and the UAV were listening to 2 Orbcomm SVs, namely FM 108 and FM 116. The SV positions were estimated from TLE files and SGP4 software [22]. The satellites were simultaneously visible for 2 minutes.

2) Experimental Results: The proposed framework was used to track Doppler from emulated 5G signals throughout the trajectory. The estimated Doppler was used to form carrier phase observables, which were then processed in the CD-LEO framework to produce a navigation solution. Two navigation solutions were computed: (i) using the Doppler measured by the SDR in [21] and (ii) the Doppler estimates produced by the proposed blind tracking algorithm. The position RMSEs were calculated to be (i) 15.03 m and (ii) 15.16 m, respectively.

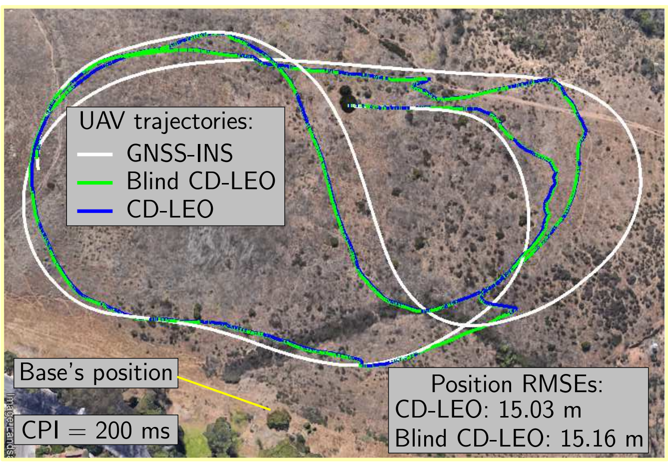

Fig. 8. Experimental results demonstrating a UAV navigating with emulated 5G signals from LEO satellites with the proposed framework.

V. Conclusion

This paper investigated blind Doppler estimation from OFDM signals transmitted by LEO satellites. The proposed framework uses TLE files to predict the Doppler, which is then used to perform initial wipe-off. Next, a blind Doppler tracking algorithm was discussed to track the residual Doppler. It was shown that the resulting Doppler estimate has a constant ambiguity, which can be resolved in a differential framework. Experimental results were presented showing the proposed receiver tracking real 5G signals from a mobile ground vehicle over a period of 700 seconds with a 14.5 Hz RMSE over the entire trajectory. Moreover, an experiment with emulated 5G signals from two LEO satellites showed a UAV navigating using the proposed approach for a period of 2 minutes with 15.16 m position RMSE.

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