Blind Doppler Estimation from LEO Satellite Signals: A Case Study with Real 5G Signals

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BIOGRAPHIES

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ABSTRACT

A computationally-efficient algorithm for blind Doppler frequency estimation from orthogonal frequency division multiplexing (OFDM) signals is proposed. The objective of this algorithm is to estimate the Doppler frequency of received low Earth orbit (LEO) satellite OFDM signals, which are planned for massive future deployment. A method for resolving the ambiguity in the resulting Doppler estimate is discussed. To demonstrate the efficacy of the proposed algorithm, and knowing that the considered LEO satellite constellations are not fully deployed yet, experiments are conducted with real terrestrial fifth-generation (5G) New Radio (NR) signals. The experimental results show a ground vehicle traversing a 6.5 km trajectory in 700 seconds, while blindly estimating the Doppler frequency of received 5G signals, achieving a Doppler root mean squared-error (RMSE) of 6.45 Hz.

I. INTRODUCTION

The potential of signals of opportunity (SOPs) as a reliable navigation source has been undoubtedly uncovered in the past decade. Meter-level accurate ground vehicle navigation [1–4] and sub-meter level accurate unmanned aerial vehicle (UAV) navigation [5,6] with cellular SOPs were experimentally demonstrated. Moreover, several theoretical and experimental studies characterized broadband low Earth orbit (LEO) satellite signals as possible reliable sources.
for navigation [7–14]. While such results bring hope to solving the problem of reliable navigation in global navigation satellite system (GNSS)-challenged environments, one must emphasize that the major underlying assumption therein is that the structure of these SOPs is known. For example, the cellular third-, fourth-, and fifth-generation (3G, 4G, and 5G, respectively) standards are open, and they are published and maintained by the 3GPP [15–17]. However, private companies, such as OneWeb, SpaceX, Boeing, and others are planning to launch thousands of broadband Internet satellites into LEO, yet very little is known about their transmitted signal structure. A natural question then arises: Can one still exploit the unknown signals transmitted by LEO satellites for navigation? This paper investigates blind Doppler detection from orthogonal frequency division multiplexing (OFDM) signals as one step towards blind navigation with OFDM signals transmitted by LEO satellites.

LEO satellites possess desirable attributes for positioning in GNSS-challenged environments: 1) they are around twenty times closer to the Earth compared to GNSS satellites, which reside in medium Earth orbit (MEO), making their received signal power between 24 to 34 dBs higher than GNSS signals; 2) they will become abundant as thousands of broadband Internet satellites are expected to be deployed into LEO [8]; and 3) each broadband provider will deploy broadband Internet satellites into unique constellations, transmitting at different frequency bands, making LEO satellite signals diverse in frequency and direction [18]. Figure 1 depicts some of the existing and future broadband LEO constellations.

Moreover, the Keplerian elements parameterizing the orbits of these LEO satellites are made publicly available by the North American Aerospace Defense Command (NORAD) and are updated daily in the two-line element (TLE) files. Using TLEs and orbit determination algorithms (e.g., SGP 4), the positions and velocities of these satellites can be known, albeit not precisely. In addition, some of these broadband LEO satellites, such as Orbcomm satellites, are equipped with GPS receivers and broadcast their GPS solution to the terrestrial receivers. However, there are several challenges to overcome to navigate exclusively with LEO satellite signals, mainly the absence of: (1) publicly available receivers that can extract navigation observables from LEO satellite signals, (2) source of error characterization for designing LEO satellite navigation frameworks, and (3) performance analyses tools to evaluate these frameworks. These challenges have been partially addressed for Orbcomm satellite signals [12–14, 19, 20]. Experimental results of a carrier phase differential LEO (CD-LEO) framework showed an unmanned aerial vehicle (UAV) navigating with signals from 2 Orbcomm LEO satellites over 1.03 km traversed in two minutes with a position root mean-squared error (RMSE) of 15 m. However, the proposed frameworks so far rely on the knowledge of the structure of the signals transmitted by the Orbcomm satellites [21]. There is still little information about the signal structure of future constellations that will bring thousands of satellites into LEO. Yet, one can be fairly certain that OFDM will be at the core of the transmission protocol of these broadband LEO satellites.

OFDM is already at the heart of the standards for 4G long-term evolution (LTE) and 5G new radio (NR) communication systems. Its multiple-input multiple-output (MIMO) capabilities allow for higher data rates to be achieved compared to other multiplexing techniques. In addition to the high bandwidths, beamforming and spatial diversity have enabled high-rate reliable communication in such systems. Subsequently, it is safe to assume that OFDM will play an important role to the future of broadband LEO satellite communication. In OFDM systems, data symbols
are mapped onto multiple carrier frequencies called subcarriers. The serial data symbols are first parallelized in groups. Then, each group is zero-padded to make the data vector length an even power of two, and an inverse fast Fourier transform (IFFT) is taken. The zero-padding provides a guard band in the frequency-domain. Finally, to protect the data from multipath effects, the last few symbols are repeated at the beginning of the data, which are called the cyclic prefix (CP). The transmitted symbols can be obtained at the receiver by executing these steps in reverse order. To do so, an OFDM receiver must first acquire symbol timing. That is why OFDM systems employ synchronization signals. For example, a primary and secondary synchronization sequence (PSS) and (SSS), respectively, are transmitted in LTE and NR systems for symbol timing recovery. Such sequences can be exploited for opportunistic navigation purposes [4, 22, 23]. However, in such cases, it is assumed that the receiver perfectly knows the synchronization sequences and can correlate local replicas of these sequences with the received signals. In the case where these sequences are unknown, as in the case of future broadband LEO satellite systems, acquiring and tracking of these satellite signals becomes impossible for a regular opportunistic receiver. As such, designing receivers that can blindly and adaptively estimate these sequences is a crucial need for the future of opportunistic navigation.

The problem of blind OFDM symbol timing recovery has been considered in the wireless communications and cognitive radio literature [24–26]. The proposed approaches make assumptions that do not hold for the case of LEO satellite transmitters, mainly the low magnitude of the frequency offset and stationarity of the channel. Unfortunately, Doppler frequencies of 240 kHz or more could be observed for LEO satellites transmitting in the Ku band. Such frequencies are most likely greater than the subcarrier spacing of the transmitted OFDM symbols. As a result of the high dynamics of LEO satellites, it is virtually impossible to coherently integrate the signal to accumulate enough power for reliably detecting the synchronization signals. While other approaches rely on large and expensive high-gain antennas to accumulate enough power for a single snapshot [27], this work aims at developing a framework for low-cost, online estimation of synchronization sequences in OFDM signals.

This paper’s main contributions are as follow. First, a computationally-efficient algorithm for blind Doppler estimation from OFDM signals, where the resulting Doppler estimate will have an ambiguity. Second, the paper proposes a way to resolve the ambiguity in the Doppler estimate. Third, to demonstrate the efficacy of the proposed algorithm, and knowing that the considered LEO satellite constellations are not fully deployed yet, experiments are conducted with real terrestrial 5G NR signals. The experimental results show a ground vehicle traversing a 6.5 km trajectory in 700 seconds, while blindly estimating the Doppler frequency of received 5G signals, achieving a Doppler root mean squared-error (RMSE) of 6.45 Hz. It is worth noting that while 5G NR signals have been studied for navigation purposes, the literature have been confined to theoretical analyses, simulations, or laboratory-emulated 5G signals [28–33]. This work, in contrast, presents experimental results with real 5G signals.

The rest of the paper is organized as follows. Section II formulates the problem and introduces the signal model. Section III discusses the blind Doppler estimation algorithm. Section IV presents experimental results showing blind Doppler tracking of real 5G NR signals. Concluding remarks are given in Section V.

II. PROBLEM FORMULATION AND SIGNAL MODEL

A. Problem Formulation

The main challenge facing the 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 the beacon signals, which in turn allows for the exploitation of the received signals for positioning and navigation purposes. Beacon signal detection requires estimating a number of unknown parameters from the observations and the partially known information about the SOP. Given the scenarios considered in this paper, it is reasonable to assume that only the bandwidth of the transmitted signal is known to the receiver. However, the Doppler frequency, the modulation type, and the length and symbols of the beacon signal are unknown. Modulation classification and unknown signal length estimation are widely investigated in the literature, e.g., see [34].

It should be pointed out that, by definition, a beacon or pilot signal is a signal known by the receiver and is used for timing and carrier synchronization, e.g., the pseudo-random noise (PN) sequence in 3G cdma2000 systems or the CP, SSS, or PSS in 4G LTE and 5G NR systems. Correlation-based receivers are typically used to detect the presence of beacon or pilot signals and synchronize to them. Due to the properties of correlation-based receivers,
the known beacon or pilot signals can still be detected reliably even at relatively low signal-to-noise ratios (SNRs). However, the beacon is unknown to a blind 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. To be able to coherently integrate successive transmissions of the beacon signal, the Doppler shift (or Doppler frequency) must be estimated. 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

\[ x(t) = \sum_{i=1}^{N_c-1} A_i \cos([\omega_i + \omega_c]t + \phi_i), \]  

(1)

where \( \omega_c \) is the carrier angular frequency; \( N_c \) is the total number of subcarriers; and \( A_i, \omega_i, \) and \( \phi_i \) are the amplitude, angular frequency, and phase of the \( i \)th subcarrier [35]. Due to the relative motion between the receiver and the LEO space vehicle (SV), a Doppler frequency \( f_D \) will be induced. Define

\[ \xi \triangleq \frac{f_D}{f_c}, \]

as the fractional Doppler frequency, where \( f_c \) is the carrier frequency. The effect of \( f_D \) on the transmitted signal is given by

\[ x'(t) = \sum_{i=1}^{N_c-1} A_i \cos((1 + \xi)\omega_i t + \xi \omega_c t + \phi_i). \]  

(2)

It can be seen from (2) that the Doppler frequency not only shifts the subcarriers, but it also stretches the spacing between them. 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

\[ y(t) = \sum_{i=1}^{N_c-1} A_i \cos((1 + \xi)\omega_i t + \xi \omega_c t + \phi_i) + n(t), \]  

(3)

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

III. BLIND DOPPLER ESTIMATION OF OFDM SIGNALS FROM LEO SATELLITES

This section details the blind Doppler estimation framework. In what follows, the receiver is assumed to be stationary.

A. Initial Doppler Wipe-Off

The Doppler frequency observed from LEO SVs is significantly large and must be accounted for. Since TLE files are available for free, one can predict the Doppler using TLE and orbit determination software, e.g., SGP4, and a prior on the receiver position, which can be off by kilometers. Fig. 2(a) shows the predicted Doppler of two Orbcomm LEO SVs using TLE and SGP4 software. Let \( \hat{f}_D \) denote the predicted Doppler from TLE files. The wipe-off operation on \( x(t) \), after low-pass filtering, can be expressed as

\[ \hat{y}(t) \triangleq y(t) \cos(2\pi \hat{f}_D t) \approx \sum_{i=1}^{N_c-1} A_i \cos\left((1 + \xi)\omega_i t + \xi \omega_c t + \phi_i\right) + \hat{n}(t), \]  

(4)

where \( \xi \triangleq \frac{\hat{f}_D}{f_c} \), \( \hat{f}_D \triangleq f_D - \hat{f}_D \), 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, \( \hat{f}_D \) must be estimated. Fig. 2(b) shows Doppler residuals for 2 Orbcomm LEO SVs. The true Doppler was measured using the receiver developed in [19].
B. Blind Residual Doppler Estimation

The blind Doppler estimator in the receiver processes one integration period at a time, known as coherent processing interval (CPI), to estimate the Doppler for that particular CPI. Denoting the length of the $k$th CPI by $I$, one can form the vector of samples of the discretized wiped-off signal $\hat{y}(t)$ as

$$\hat{y}^k \triangleq [\hat{y}[kI], \hat{y}[kI+1], \ldots, \hat{y}[(k+1)I-1]]^T.$$ (5)

To accumulate enough energy, $I$ has to be large enough to include a sufficient number of complete cycles of beacon and synchronization signals. The periodicity of such signals in the data will show up as an impulse in the frequency domain. For systems that operate at a low SNR regime, $I$ should be chosen to be large enough to accumulate energy and compensate for the low SNR. It can be seen from Fig. 2(b) that the residual Doppler is small enough to consider it constant in reasonably long CPIs. Therefore, $\hat{f}_D[n] = \hat{f}_{Dk}$ in the $k$th CPI. As mentioned earlier, the Fourier transform of the signal part of the observations including a periodic beacon $s(t)$ of length $T_0$ can be written as an impulse train with period $f_0 = \frac{1}{T_0}$. More precisely,

$$\mathcal{F}\left\{\sum_{i=-\infty}^{\infty} \exp\left(j2\pi \hat{f}_D t\right) s(t-iT_0)\right\} = \sum_{i=-\infty}^{\infty} S(i f_0) \delta\left(f - \hat{f}_D - i f_0\right),$$ (6)

where $S(f) = \mathcal{F}\{s(t)\}$ is the Fourier transform of the beacon signal $s(t)$. As such, a proper sliding band-pass filter is capable of tracking the change of Doppler frequency at different CPIs. The choice of which peak to track is performed manually in this paper. However, it has to be as close as possible to the direct current (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. To see the effect of CPI, 5G data were collected and processed for different values of $I$. The experimental setup is described in Section IV. The signals were collected on a mobile ground vehicle, so the Doppler was time-varying. Fig. 3 shows how the impulse train becomes visible once the CPI is increased. Moreover, Fig. 3(c) shows that the FFT peaks can be tracked over time.

Let $\hat{f}_D$ denote 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, assuming the beacon subcarriers are centered at the DC component. Both $f_0$ and the integer ambiguity $m$ are unknown to the receiver. The total Doppler estimate can hence be formed as

$$\hat{f}_{D_{amb}} \triangleq \hat{f}_D + \hat{f}_D = f_D + mf_0 + \epsilon_{f_D},$$ (7)

where $\epsilon_{f_D}$ is the estimation error. A method for resolving $mf_0$ is proposed next.

C. Doppler Ambiguity Resolution

As shown in Fig. 2(a), the Doppler profile of a LEO SV and a stationary receiver will have an inflection point at $f_D = 0$. Subsequently, the inflection point is calculated from the time history of $\hat{f}_{D_{amb}}$ using polynomial curve fitting
around the inflection point. Let $\bar{f}_{D,amb,0}$ denote the Doppler frequency at the inflection point. Subsequently, a final Doppler estimate is formed according to

$$\bar{f}_D \triangleq \bar{f}_{D,amb} - \bar{f}_{D,amb,0}. \quad (8)$$

IV. EXPERIMENTAL RESULTS

To demonstrate the proposed Doppler estimation framework, 5G NR signals were collected on a mobile ground vehicle to mimic the residual Doppler after wiping-off received OFDM signals from LEO SVs using the Doppler estimated from TLEs.

A. Experimental Setup

The experiment was performed in Costa Mesa, California, USA. A National Instrument (NI) universal software radio peripheral (USRP)-2955 with a tri-band Laird cellular antenna were equipped on a moving ground vehicle to sample 5G NR 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 Astex-i V integrated GNSS-inertial navigation system (GNSS-INS) to provide a ground truth for position and velocity of the vehicle. The Astex-i V is equipped with a dual-antenna multi-frequency GNSS receiver and a VectorNav VN-100 micro-electromechanical system (MEMS) inertial measurement unit (IMU). The ground truth obtained from the GNSS-INS system, along with the known gNB position, was used to calculate the Doppler frequency due to the motion of the car. The experimental setup is shown in Fig. 4.

B. 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 blindly track the Doppler throughout the 6.5 km trajectory. The estimated Doppler with ambiguity is shown in Fig. 5(a). The Doppler ambiguity was calculated by averaging the location of the inflection points and was found to be 11.0025 kHz. It was then subtracted from the estimated Doppler. The Doppler estimate without the ambiguity and the predicted Doppler from ground truth are shown in Fig. 5(b). The RMSE between the final estimated Doppler and the predicted Doppler was calculated to be 14.5 Hz over the entire trajectory, and 6.45 Hz over the second half of the trajectory. While the vehicle is all the way down on Fairview Rd., buildings are obstructing the line-of-sight more often as the vehicle is closer to the gNB. This explains the poor Doppler tracking performance between seconds 60 and 140, during which the vehicle was closest to the gNB. Next, as the vehicle travels west of the gNB, it switches from one sector to another. Since the beacon signals differ between gNB sectors [36], the impulse trains from (6) will shift between the sectors, causing the blind algorithm to lose track of the Doppler between seconds 180 to 320. At 320 seconds, the vehicles enters back the sector where it started initially, and remains in that sector for the rest of the trajectory. This explains why the Doppler tracking algorithm performs overall better in the second half of the trajectory.
Fig. 4. Experimental layout and hardware setup.

Fig. 5. (a) Estimated Doppler frequency with ambiguity. (b) Estimated Doppler frequency without ambiguity and predicted Doppler frequency from ground truth.

V. CONCLUSION

This paper investigated blind Doppler estimation from OFDM signals transmitted by LEO satellites. The proposed framework uses the TLE to predict the Doppler and performs initial wipe-off with the latter. 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, and a method for resolving this ambiguity was proposed. Experimental results were presented showing the proposed receiver tracking real 5G NR signals from a mobile ground vehicle over a trajectory of 6.5 km traversed in 700 seconds, achieving a Doppler RMSE of 14.5 Hz for the entire trajectory, and 6.45 Hz for the second half of the trajectory.
ACKNOWLEDGMENTS

This work was supported in part by the Office of Naval Research (ONR) under Grant N00014-19-1-2511 and Grant N00014-19-1-2613. The authors would like to thank Ali Abdallah for his help with data collection and the preparation of the paper.

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