Universal Receiver Architecture for Blind Navigation with Partially Known Terrestrial and Extraterrestrial Signals of Opportunity

Joe Khalife, M. Neinavaie, and Zaher M. Kassas
University of California, Irvine

BIOGRAPHIES

Joe Khalife is a postdoctoral fellow at the University of California, Irvine and member of the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory. He received a B.E. in Electrical Engineering, an M.S. in Computer Engineering from the Lebanese American University and a Ph.D. in Electrical Engineering and Computer Science from the University of California, Irvine. From 2012 to 2015, he was a research assistant at LAU, and has been a member of the ASPIN Laboratory since 2015. He is a recipient of the 2016 IEEE/ION Position, Location, and Navigation Symposium (PLANS) Best Student Paper Award and the 2018 IEEE Walter Fried Award. His research interests include opportunistic navigation, autonomous vehicles, and software-defined radio.

Mohammad Neinavaie is a Ph.D. student at the University of California, Irvine and member of the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory. He received a B.E. in electrical engineering and an M.S. in digital communication systems from Shiraz University. His research interests include opportunistic navigation, blind opportunistic navigation, cognitive radio, wireless communication systems and software-defined radio.

Zaher (Zak) M. Kassas is an associate professor at the University of California, Irvine and director of the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory. He is also director of the U.S. Department of Transportation Center: CARMEN (Center for Automated Vehicle Research with Multimodal AssurEd Navigation), focusing on navigation resiliency and security of highly automated transportation systems. He received a B.E. in Electrical Engineering from the Lebanese American University, an M.S. in Electrical and Computer Engineering from The Ohio State University, and an M.S.E. in Aerospace Engineering and a Ph.D. in Electrical and Computer Engineering from The University of Texas at Austin. He is a recipient of the 2018 National Science Foundation (NSF) Faculty Early Career Development Program (CAREER) award, 2019 Office of Naval Research (ONR) Young Investigator Program (YIP) award, 2018 IEEE Walter Fried Award, 2018 Institute of Navigation (ION) Samuel Burka Award, and 2019 ION Col. Thomas Thurlow Award. His research interests include cyber-physical systems, estimation theory, navigation systems, autonomous vehicles, and intelligent transportation systems.

ABSTRACT

A universal receiver architecture that is capable of exploiting partially known signals of opportunity (SOPs) for navigation is presented. A partially known signal refers to a signal to which only the center frequency and bandwidth are known to the receiver. Assuming that the SOP follows a standard modulation scheme, e.g., phase shift keying (PSK) or quadrature amplitude modulation (QAM), and a standard multiplexing scheme, e.g., code-division multiple access (CDMA) or orthogonal frequency-division multiplexing (OFDM), the proposed receiver architecture can blindly acquire and track the SOP to provide a navigation solution. Experimental results are presented showing the proposed receiver successfully producing meter-level-accurate navigation solutions from different types of terrestrial and space signals: GPS, cellular 4G long-term evolution (LTE) and 5G, and Starlink LEO satellites, under the aforementioned partially known assumption.

I. INTRODUCTION

Meter-level accurate ground and aerial vehicular navigation with terrestrial signals of opportunity (SOPs) have been demonstrated in the recent years [1–9]. In addition to the demonstrated remarkable potential of SOPs as complement or alternative to global navigation satellite systems (GNSS), especially in challenging environments, plans of private companies such as OneWeb, SpaceX, and Boeing to launch thousands of broadband Internet satellites into low Earth orbit (LEO) will trigger a renaissance in navigation with SOPs [10, 11]. Several theoretical and experimental studies characterized broadband LEO satellite signals as potential reliable sources for navigation [12–18]. Much like cellular signals, the most attractive attributes of LEO satellite signals are mainly their abundance and diversity in geometry and frequency [19–21]. This diversity increases the availability of a navigation system and provides immunity against interference, jamming, and spoofing. However, one must emphasize that the major underlying assumption in existing SOP navigation frameworks is that the structure of these SOPs is known at the receiver side [22]. Many of the LEO broadband communication systems are using proprietary protocols and have made barely any information about their signal structure available. Similarly, there are several reference signals in 4G long-term evolution (LTE) and 5G new radio (NR) systems that are not exploited by current opportunistic receivers, as these typically high-bandwidth references signals are either unknown to these opportunistic receivers or are only transmitted on demand [23, 24]. A natural question arises from the unknown nature of the upcoming LEO broadband and some of the cellular reference signals: is it possible to still exploit these unknown signals for navigation purposes? This paper aims at answering this question by proposing a computationally-efficient universal receiver architecture that can extract navigation observables from any partially known signal with a periodic beacon.

A partially known signal here refers to a signal to which only the center frequency and bandwidth are known to the receiver, and a periodic beacon refers to a sequence of any kind that is periodically transmitted for synchronization, channel estimation, or positioning purposes [25]. Assuming that the SOP follows a standard modulation scheme, e.g., phase shift keying (PSK) or quadrature amplitude modulation (QAM), and a standard multiplexing scheme, e.g., code-division multiple access (CDMA) or orthogonal frequency-division multiplexing (OFDM), the proposed receiver architecture can blindly acquire and track the signal to provide a navigation solution. Most communication systems employ a synchronization beacon for receiver timing and carrier recovery. For example, in cellular CDMA, pseudorandom noise (PN) sequences are used on the forward-link pilot channel for synchronization proposes [26]. Other examples of such beacons are the primary synchronization signal (PSS) and secondary synchronization signal (SSS) in 4G LTE and 5G NR systems. Even though different broadband providers may use known modulation schemes, their underlying configuration and parameters can be different. For instance, the Globalstar satellite system uses similar protocol to the IS-95 cellular CDMA system but with different PN sequences [26, 27]. Without knowing these PN sequences, a standard opportunistic receiver cannot draw navigation observables from these signals. As such, a crucial stage in the architecture of the proposed universal receiver is to blindly estimate the unknown beacon sequence of the SOP on-the-fly.

The problem of discovering the unknown signal characteristics has been considered in both communications and navigation literature for CDMA and OFDM signals, e.g., see [28–37]. The algorithms for blindly detecting synchronization sequences proposed in the communications literature rely on coherently integrating samples of the transmitted signals [28, 29, 31–34]. However, such approaches do not account for the time-varying Doppler shifts and delays, especially for LEO-based signals, which make it impossible to accumulate enough signal power to detect the beacon signal. Alternative approaches make use of high-gain antennas to accumulate enough signal power for PN sequence detection [31]. In contrast with these approaches, the proposed receiver has the flexibility of *cognitively* detecting the unknown beacon of any broadband signal using a particular communication standard, e.g. CDMA or OFDM. Therefore, unlike [31], which concentrates on deciphering one particular system, the proposed receiver is universal and capable of cognitively deciphering beacons of partially known SOPs in a computationally-efficient way and in turn produce Doppler and pseudorange measurements.

The two main factors defining the proposed receiver architecture are (i) the periodicity and (ii) the correlation properties of the beacon sequence. Exploiting the "desirable" correlation properties of the beacon sequence allows the proposed receiver to track the beacon's Doppler and phase as it is repeated over time. While this may seem intuitive for CDMA signals, it applies to a larger family of signals as well, including OFDM signals. OFDM is widely adopted in different communication generations such as 4G LTE and 5G NR communication systems and attracted a lot of attention in opportunistic navigation systems. It is also anticipated that OFDM will be used in future LEO megaconstellations such as SpaceX's Starlink constellation [20]. 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. A traditional LTE or NR opportunistic receiver would use a local replica of the known PSS and SSS to correlate with the received signals and recover timing and the frame structure. In the case where these sequences are unknown, as in the case of future broadband LEO satellite systems or some of the on-demand reference signals in 5G NR signals, acquiring and tracking of these SOPs becomes impossible unless the receiver blindly and adaptively estimates these sequences. As such, the often forgotten time-domain orthogonality of OFDM signals is exploited to jointly estimate all the reference signals contained within the received OFDM signal, without the need to reconstruct the frame. This shortcut alleviates a significant computational burden. A similar approach is used for other types of signals, e.g., CDMA. Another important part of the proposed receiver are traditional phase-locked loops (PLLs) and delay-locked loops (DLLs) to track the carrier and code phases of the estimated beacon sequence. However, it will be shown that the estimated Doppler will have an ambiguity that is an integer multiple of some fundamental frequency inherent to the signal. This ambiguity needs to be resolved to perform proper carrier tracking and aiding.

This paper extends the work in [38] and [39] through the following contributions. First, a universal signal model for blind Doppler and code phase tracking is derived from standard signal models, namely CDMA and OFDM. Second, a receiver architecture capable of estimating the unknown beacon sequences and produce Doppler and pseudorange measurements from the universal signal model is proposed. Third, extensive experimental results are presented showing successful tracking and navigation solution production from multiple sources using the proposed receiver for different types of signals: GPS, cellular 4G LTE and 5G, and Starlink LEO satellites, under the aforementioned partially known assumption.

The remainder of the paper is organized as follows. Section II presents the signal model. Section III overviews the proposed blind universal receiver architecture. Section IV characterizes and demonstrates the proposed receiver in producing a navigation solution with GPS, cellular 4G LTE and 5G signals, and Starlink LEO satellite signals. Section V gives concluding remarks.

II. SIGNAL MODEL

Let $x(t)$ be the unknown signal transmitted by a navigation source. The proposed framework does not assume any particular modulation or multiplexing scheme. The only assumptions are the following:

1. The transmitted signal $x(t)$ comprises M periodic synchronization signals $\{s_m(t)\}_{m=1}^{M}$, with the m-th signal having a period T_m. The total number of periodic signals M may be unknown. Furthermore, these periodic signals may be multiplexed in time, frequency, and/or code.
2. The periodic signals $\{s_m(t)\}_{m=1}^{M}$ have "nice" autocorrelation and cross-correlation properties, i.e.,

$$R_{s_m s_m}(\tau) \triangleq \int_{-\frac{T_m}{2}}^{\frac{T_m}{2}} s_m(t+\tau)s_m^*(t)dt = \begin{cases} g_{\text{bell}_\text{m}}(\tau), & |\tau| \leq \gamma_m T_m, \\ g_{\text{tail}_\text{m}}(\tau), & \text{otherwise}, \end{cases} \tag{1}$$

where g_{bell_m} is a bell-shaped function, γ is a positive real number close to one, and $g_{\text{tail}_\text{m}}(\tau)$ is the tail of the autocorrelation function such as $|g_{\text{tail}_\text{m}}(\tau)| < \epsilon$ for all $|\tau| > \gamma_m T_m$, where ϵ is a small, positive real number; and

$$R_{s_m s_{m'}}(\tau) \triangleq \int_{-\frac{T_m+T_{m'}}{2}}^{\frac{T_m+T_{m'}}{2}} s_m(t+\tau)s_{m'}^*(t)dt, \quad m' \neq m, \tag{2}$$

where $\left|R_{s_m s_{m'}}(\tau)\right| < \epsilon$, $\forall\, \tau$.

As such, $x(t)$ is modeled as,

$$x(t) = \sum_{n=-\infty}^{\infty} \sum_{m=1}^{M} s_m(t - nT_m) + y(t), \tag{3}$$

where $y(t)$ denotes the remaining, non-periodic signals in the original transmitted signal $x(t)$. Let T_0 denotes the least common multiplier of $\{T_m\}_{m=1}^{M}$. Subsequently, one can define a periodic signal $s(t)$ with period T_0 as

$$s(t) = \sum_{m=1}^{M} s_m(t). \tag{4}$$

The transmitted signal can now be expressed as

$$x(t) = \sum_{n=-\infty}^{\infty} s(t - nT_0) + y(t), \tag{5}$$

where $s(t)$ encompasses *all* periodic signals contained in $x(t)$.

Fig. 1 shows examples of synchronization sequences with correlation properties that satisfy (1) and (1): (a) the primary and secondary synchronization sequences (PSS and SSS, respectively) in 5G signals as well as the demodulation reference signal (DM-RS) and (b) a GPS L1 C/A pseudorandom noise (PRN) sequence as well as the downlink pseudo-noise (PN) sequence in cdma2000.

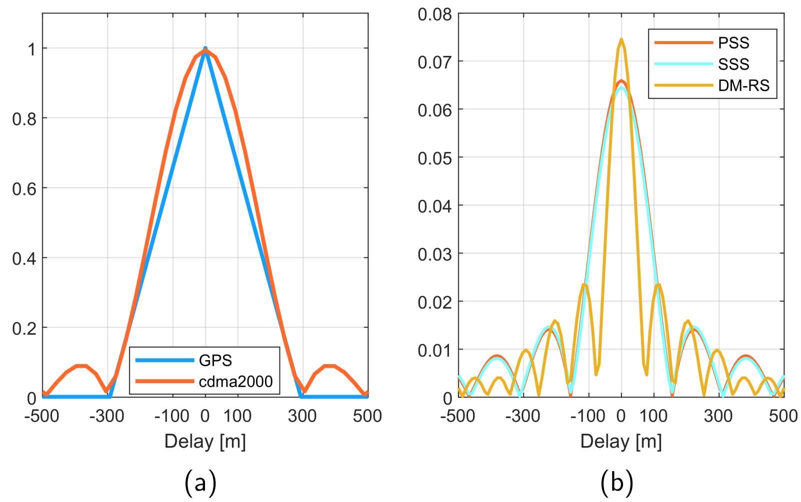

Fig. 1. Correlation function of (a) GPS C/A PRN and cellular cdma2000 PN and (b) cellular LTE/5G PSS and SSS and cellular 5G DM-RS.

III. Blind Universal Receiver Architecture

Fig. 2 shows a block diagram of the proposed universal receiver architecture. Similar to correlation-based receivers, the universal receiver consists of a phase-locked loop (PLL) and a delay-locked loop (DLL) to track the carrier and code phase of the synchronization sequence present in the received signal. The proposed receiver has two additional blocks: (i) a block that refines the estimate of the unknown synchronization sequence [38] and (ii) a block that resolves ambiguities in the estimated Doppler before switching to carrier aiding.

The receiver is initialized with a Doppler estimate that can be obtained in one of two ways: (i) using the maximum likelihood approach described in [24] or (ii) from the phase of the inner product of two consecutive received frames. Either way, the initial Doppler will have an ambiguity of $\frac{N}{T_0}$, where N is an integer. The initial Doppler estimate $\hat{f}_{D_0}$ can be expressed as follows:

$$\hat{f}_{D_0} = f_{D_0} + \frac{N}{T_0} + \epsilon_0,$$

where f_{D_0} is the true initial Doppler and ϵ_0 is the initial error due to noise. The Doppler estimate produced by the tracking loops will have the aforementioned ambiguity. To use the Doppler estimate for carrier aiding, the ambiguity must be resolved. This can be performed by comparing the Doppler constructed by the delay estimate to the Doppler produced by the tracking loops. Once the Doppler ambiguity is resolved, the receiver can switch to carrier aiding to produce smooth code phase estimates.

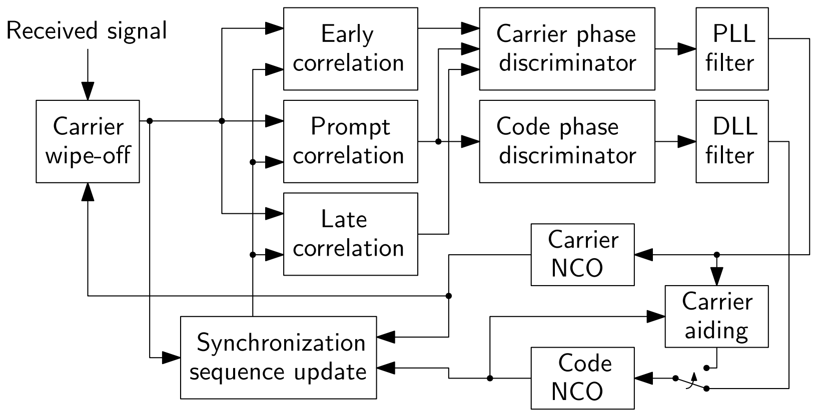

Fig. 2. Blind universal receiver architecture.

The above receiver is first tested to track a simulated Globalstar-like signal. The inner-product approach was used to initialize the Doppler. Fig. 3 summarizes the simulation results, which show that the Doppler and delay estimates converge to the true ones at varying carrier-to-noise ratios (CNRs). Fig 3 also shows the norm squared of the estimated sequence, $|S|^2$ which converges to its maximum at steady-state. Fig. 4 shows a scatterplot of the estimate sequence at varying CNRs.

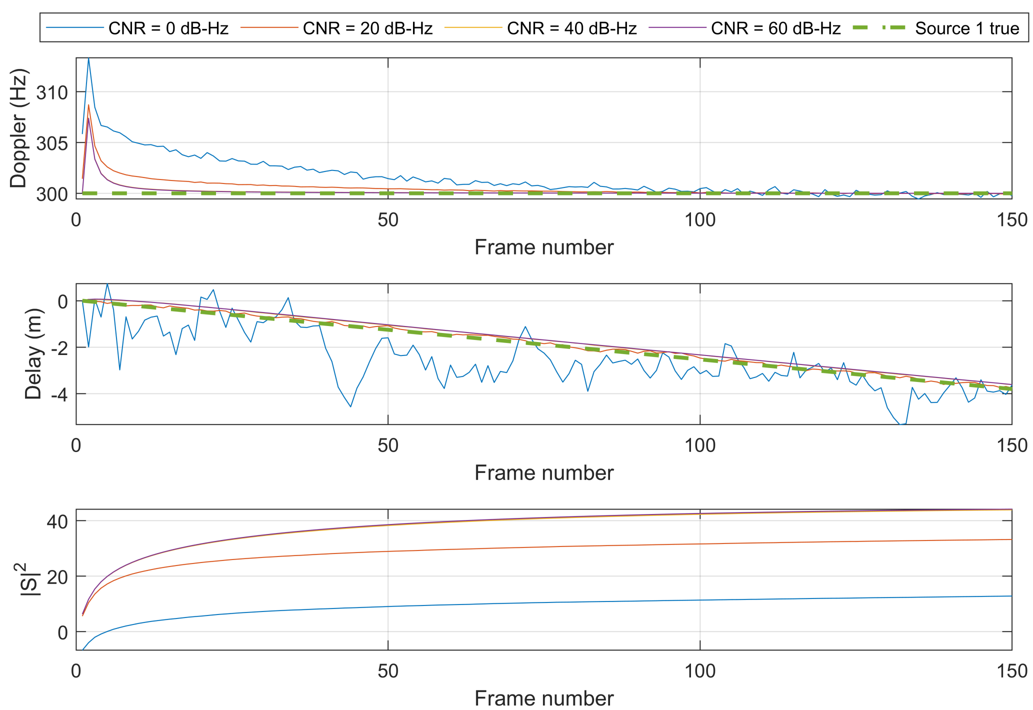

Fig. 3. Simulation results showing the Doppler and delay estimates converging to the true ones at varying CNRs. The figure also shows the norm squared of the estimated sequence, $|S|^2$ which converges to its maximum at steady-state.

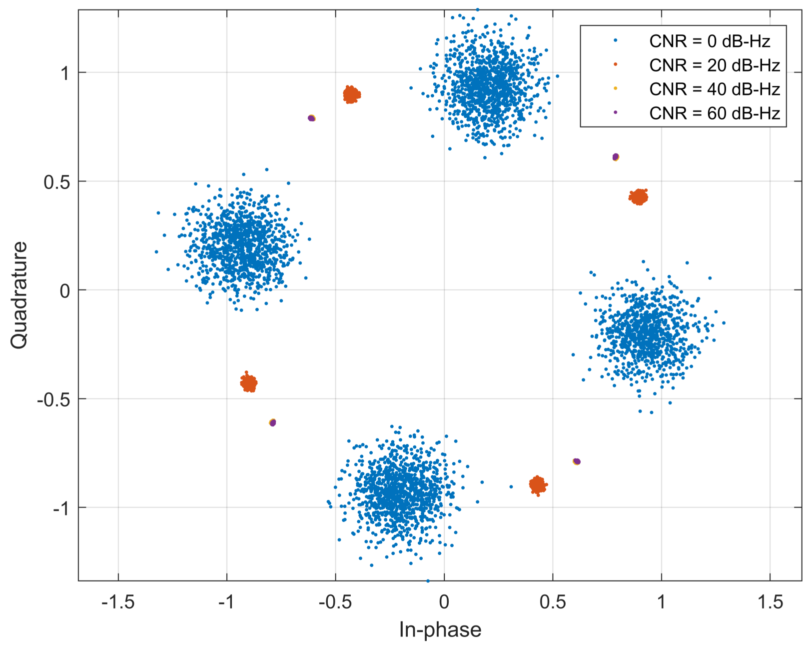

Fig. 4. Simulation results showing the estimated synchronization sequence at varying CNRs.

IV. EXPERIMENTAL RESULTS

This section shows experimental application of the blind universal cognitive receiver in producing a navigation solution with GPS L1 C/A signals, cellular 4G LTE and 5G signals, and Starlink LEO satellite signals.

A. GPS Signals

In order to test the proposed receiver with GPS L1 C/A signals, a GPS antenna which was mounted on the roof of the Winston Chung Hall at the University of California, Riverside, USA. The GPS signals were down-mixed and sampled via a National Instruments universal software radio peripheral (USRP), driven by a GPS-disciplined oscillator (GPSDO). The samples of the received signals were stored for off-line post-processing. The GPS L1 C/A signals contain PRN codes at 1.023 Mega chips per second (Mcps), modulated by binary PSK (BPSK) ($M = 2$) navigation bits at 50 bits per second (bps). Multiple GPS satellites transmit simultaneously in the same channel using CDMA. As such, the maximum likelihood approach in [24] was used to initialize the Doppler of four GPS satellites. The correlation function between the estimated and true PRNs of the 4 GPS satellites are shown in Fig. 5. The decoded PRNs are then used in an SDR to produce pseudorange measurements on GPS satellites and in turn solve for a stationary receiver's position. The acquisition and tracking results of PRN 21 are shown in Fig. 6. Note that the GPS signals were used opportunistically; hence, no clock corrections were performed and the satellites' positions were obtained by propagating the two-line element (TLE) files available for the visible satellites [38]. The final position error was found to be 54.5 m. The experimental layout and the true and estimated receiver positions are shown in Fig. 7.

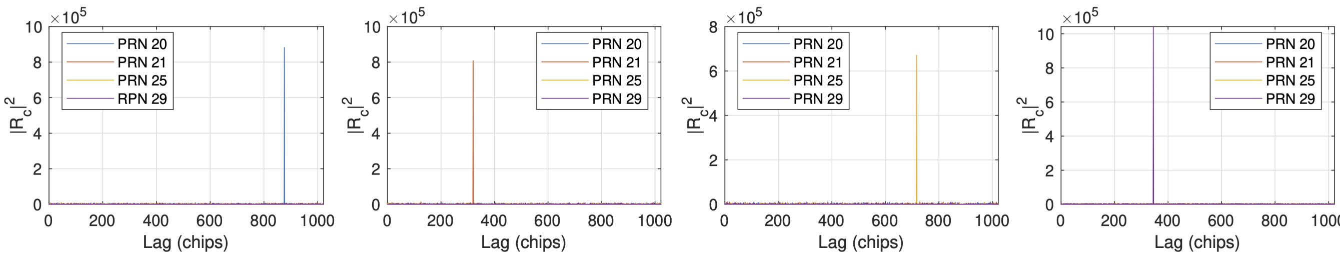

Fig. 5. Correlations between the decoded PRN of each GPS satellite and the true PRNs

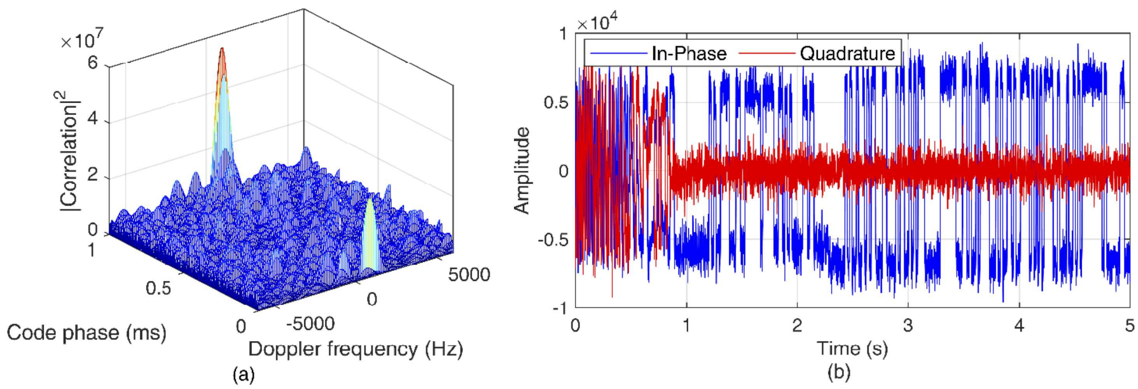

Fig. 6. GPS signal acquisition for PRN 21 using the decoded beacon. (b) Signal tracking of PRN 21 over a period of 5 seconds.

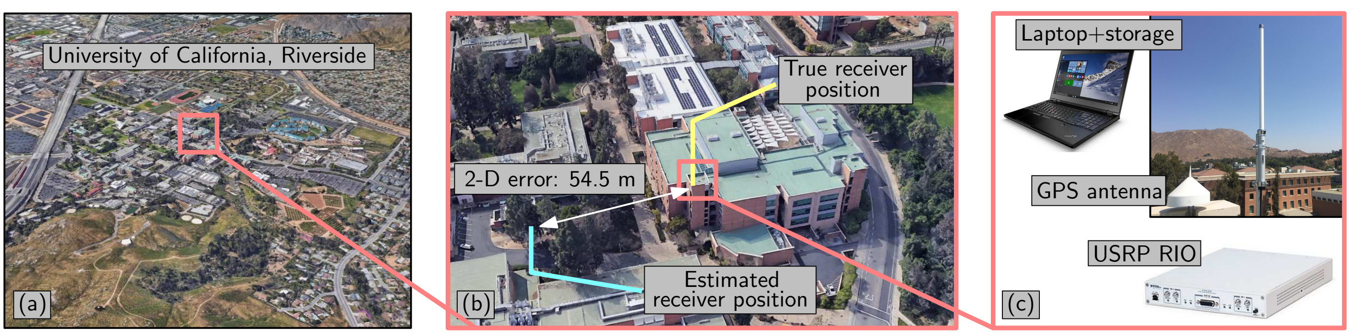

Fig. 7. (a) Experimental environment for GPS L1 C/A signals. (b) True and estimated receiver positions. (c) Experimental hardware setup.

B. Cellular 4G LTE Signals

In this experiment with LTE signals, a DJI Matrice 600 UAV was equipped with an NI USRP-2955 and four consumer grade 800/1900 MHz cellular antennas to sample LTE signals near Aliso Viejo, California, USA. The channels of the USRP were tuned to 1955, 2145, 2125, and 739 MHz carrier frequencies, respectively, which are 4G LTE frequencies allocated to the U.S. cellular providers AT&T, T-Mobile, and Verizon. The sampling rate for each channel was set to 10 MSps and the sampled LTE signals were stored on a laptop for post-processing. The UAV was equipped with a Septentrio GNSS-aided INS for ground-truth. The UAV traversed a trajectory of 609 m. Fig. 8 shows the environment layout and the UAV trajectory. The blind receiver was used to produce pseudorange and carrier phase measurements and estimate the UAV trajectory [24]. The position RMSE from both the blind receiver and a conventional receiver was found to be 2.07 m. Fig. 9 shows the true and estimated UAV trajectories.

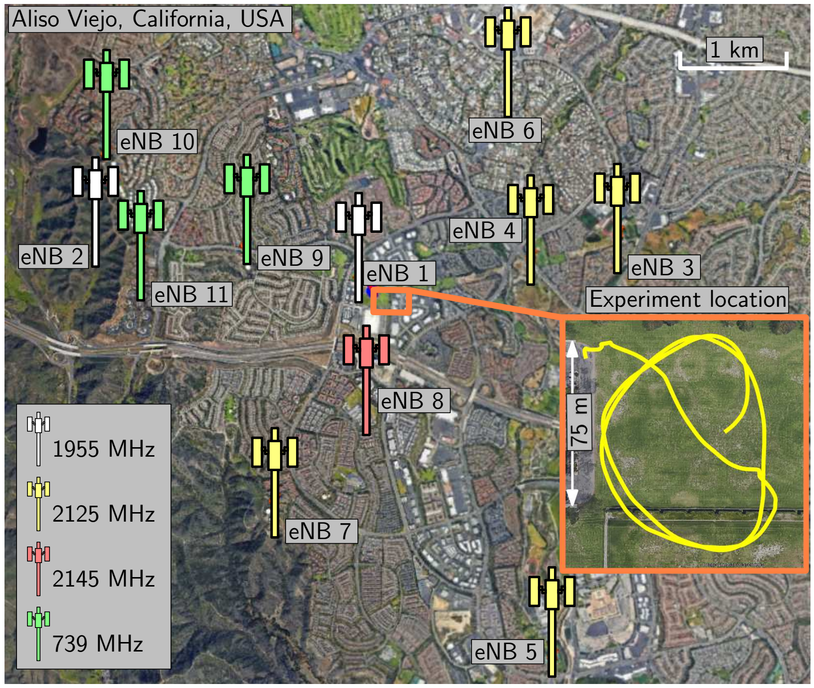

Fig. 8. LTE eNodeB layout.

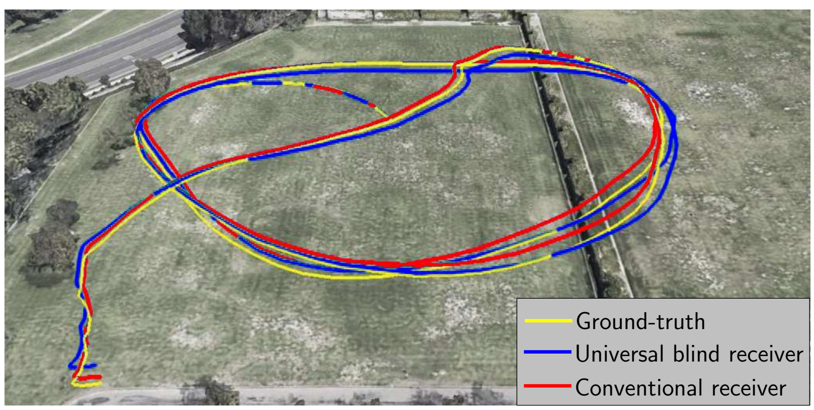

Fig. 9. Navigation results. Total traversed trajectory was 609 m and Position RMSE: 2.07 m (Universal blind and conventiona receiverss

C. Cellular 5G Signals

In this experiment with 5G signals, an Autel Robotics X-Star Premium UAV equipped with a single-channel Ettus 312 USRP connected to a consumer-grade 800/1900 MHz cellular antenna and a small consumer-grade GPS antenna to discipline the on-board oscillator. The cellular receivers were tuned to the cellular carrier frequency 632.55 MHz, which is a 5G NR frequency allocated to the U.S. cellular provider T-Mobile. Samples of the received signals were stored for off-line post-processing. The ground-truth reference trajectory was taken from the on-board Ettus 312 USRP GPS solution. The UAV traversed a trajectory of 416 m. Fig. 10 shows the environment layout and the vehicle trajectory. The blind receiver was used to produce pseudorange and carrier phase measurements and estimate the UAV trajectory [24]. The position RMSE was found to be 4.35 m. Fig. 11 shows the true and estimated UAV trajectories.

Fig. 10. 5G gNB layout.

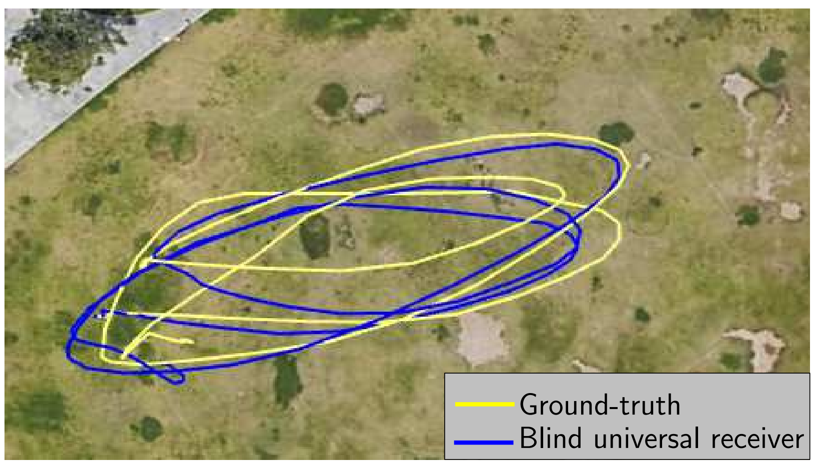

Fig. 11. 5G Navigation results. Total traversed trajectory was 416 m and position RMSE was 4.35 m.

D. Starlink LEO Signals

In this experiment with Starlink signals, a stationary NI USRP-2945R was equipped with a consumer-grade Ku antenna and low-noise block downconverter (LNB) to receive Starlink signals in the Ku-band. The sampling bandwidth was set to 2.5 MHz and the carrier frequency was set to 11.325 GHz, which is one of the Starlink downlink frequencies. The samples of the Ku signal were stored for off-line processing. The USRP was set to record Ku signals over a period of 800 seconds. During this period, a total of six Starlink space vehicles (SVs) transmitting at 11.325 GHz passed over the receiver, one at a time. The universal receiver was adapted to acquire and track the signals from these satellites using the Starlink signal model discussed in [40]. The final 3–D position error was found to be 33.5 m, while the 2–D position error was 25.9 m. Upon equipping the receiver with an altimeter (to know its altitude), the 2–D position error goes down to 7.7 m. A skyplot of the Starlink SVs, the environment layout, and the positioning results are shown in Fig. 12.

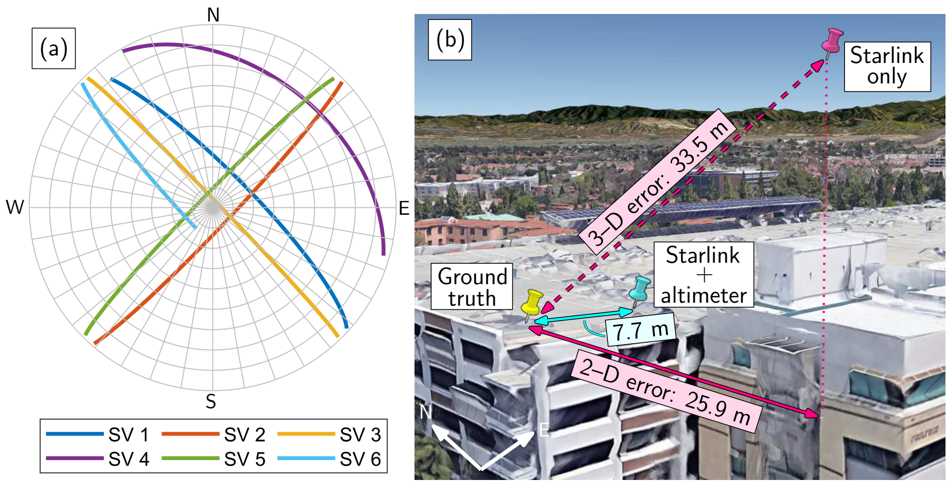

Fig. 12. Positioning results with Starlink LEO satellites.

V. CONCLUSION

This paper presented a universal receiver architecture for blindly exploiting terrestrial and space SOPs for navigation. The only assumption the receiver makes is knowledge of the center frequency and bandwidth of the SOP. Experimental results were presented showing the proposed receiver successfully producing meter-level-accurate navigation solutions from different types of terrestrial and space signals: GPS, cellular 4G LTE and 5G, and Starlink LEO satellites, under the aforementioned partially known assumption.

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