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COMPASS: Communication-aware Trajectory Planning for UAV-based Rescue Missions via Non-Terrestrial Networks

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***Abstract*—Satellite-based connectivity is on the rise. More and more large companies worldwide announce the development of their own satellite constellation for commercial and private internet access. Hence, these orbital platforms are emerging as considerable broadband alternatives to terrestrial internet access. Besides the straightforward use as broadband for private users, particularly in remote locations, satellite networks offer considerable potential for providing fast and ubiquitous connectivity during disaster response and critical search and rescue missions. Especially in the latter category of scenarios, the use of semi-autonomous systems becomes increasingly important. To enable the reliable teleoperation and monitoring of these systems, robust connectivity is critical. As conventional survey trajectory planning focuses on maximum survey coverage and does not consider the geometry from the antenna to the satellite, continuous connectivity is sacrificed. In this paper, we propose the novel COMPASS algorithm, which leverages a digital twin-based communication-aware trajectory planning and steering, based on a self-conducted satellite connectivity campaign, including measurements for a geostationary and a low earth orbit system. Compared to the generic trajectory planning and more naive approaches, COMPASS improves the minimum SNR by 9 dB while still achieving 100 % survey coverage.**

I. INTRODUCTION

Unmanned Aerial Vehicle (UAV)-based support for search and rescue missions is becoming increasingly crucial in the current era. These semi-autonomous systems still mostly rely on teleoperation, so reliable and robust communication is critical. While terrestrial networks can provide reliable communication in regions with the necessary infrastructure, in maritime scenarios, only a certain distance from the coast can be covered, as terrestrial base stations are only installed on land. Promising alternatives to terrestrial networks are satellite-enabled Non-Terrestrial Networks (NTNs), especially with the upcoming Low Earth Orbit (LEO) mega-constellations. Depending on the satellite constellation, almost global coverage is offered with acceptable latencies and data rates while being very dependent on suitable Line-of-Sight (LOS) conditions. This paper focuses on two NTNs, the LEO-based Starlink, and the geostationary Inmarsat. The orbits of geostationary satellites are synchronized to the Earth's rotation and hover consistently above the equator. Due to the considerable distance between these communication satellites and the user terminals on Earth, a single satellite can cover a large area; thus, only a few satellites are needed to achieve full global coverage. On the other hand, multiple LEO mega-constellations are currently being deployed. However, in LEOs, satellites must have a higher speed than their geostationary counterparts to maintain their orbit, circling Earth several times daily. Due to their relatively small distance to Earth, significantly more satellites are needed to achieve global coverage, causing frequent handover procedures. Nonetheless, these LEO systems allow significantly higher data rates and lower latencies. Considering not only satellite mobility but also the mobility of the user terminal and, especially in the case of UAVs, the antenna's orientation to the serving satellite, there are geometric situations in which a LOS connection is impossible as shown in Fig. 1. In these cases, the UAV's trajectory and turn behavior must be adapted to the NTN era to allow reliable connectivity. We propose the novel COMPASS approach, consisting of two components. First, a real-time digital twin-enabled analysis of the UAV with a live steering adjustment depending on the satellite's location, and second, a pre-planned mission adjustment for communication-aware u-turns.

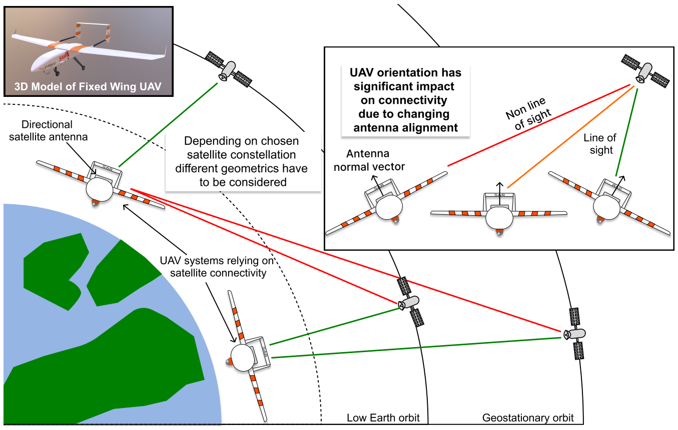


Fig. 1. Visualization of UAV-to-Satellite geometry, influencing radio propagation by generating NLOS channel conditions through roll maneuvers.

The remainder of this paper is structured as follows. After discussing the related work in Sec. II, we perform an in-depth measurement campaign of the geostationary Inmarsat and the Starlink LEO system in Sec. III, from which we derive the set of parameters for COMPASS. Sec. IV focuses on key components of the implemented digital twin together with the proposed COMPASS approach for satellite connectivity-aware trajectory planning. A comparison between COMPASS and non-optimized trajectory planning is conducted in Sec. V. Finally, a conclusion and an outlook is given in Sec. VI.

II. RELATED WORK

UAV Path Planning is already a widely discussed subject. Apart from general survey area planning[1], a field of communication-aware planning research is summarized by [2]. Still, most work focuses on terrestrial network connectivity. In [3] the authors plan an optimal UAV path based on a cellular coverage map, the drone's battery level, and possible winds. The authors use QGroundControl (QGC) [4] to test their algorithms and maximize worst-case as well as average throughput. [5] focuses on trajectory planning, communication awareness, and urban factors like housing and potential collisions. There are also machine learning-based approaches to communication-aware path planning like [6] and [7]. Further, the optimization of network communication aspects using mobility information is studied in [8]. For this, a Q-learning algorithm is employed to dynamically optimize handover decisions to provide efficient ground-to-air connectivity. The authors of [9] confirm that airframe shadowing for UAV channel characterization is still largely unexplored, while [10] provide such a study for air-to-ground connections. The influence of tilt angles for UAV to UAV communications is explored in [11], which optimizes the trajectory to increase data transmission and minimum bit rate. In [12], UAVs serve as relays for geostationary satellites and ground User Equipments (UEs), showing that satellite links provide better Signal to Noise Ratio (SNR) for terrestrial links with Rician characteristics. The term connectivity-aware mission planning is already employed within the topic of Search and Rescue (SAR) to divide search areas according to the efficiency of individual agents and to ensure their communication with each other [13]. Survey area coverage, as studied in this work, is addressed by [14] under the term *coverage path planning*. Yet, constraints focus on crosswinds instead of roll angles, which is a challenge few current planning and autopilot software solutions tackle. Other works combining satellite networks and UAVs like [15] and [16] focus on the benefit of enhancing satellite networks rather than adapting UAVs or path planning.

III. SATELLITE MEASUREMENT CAMPAIGN

This section details a measurement campaign for two satellite constellations. These include two mobility user terminals from the geostationary Inmarsat system and the LEO-based Starlink. Due to the different natures of both systems in use cases and the dimensions of the user terminals, we focus more on deriving their characteristics instead of directly comparing their Key Performance Indicators (KPIs). In the case of Inmarsat, we can measure both active KPIs such as data rate and Round Trip Time (RTT), as well as passive KPIs like the SNR/Hz, following just called SNR. For the Starlink system, such passive KPIs were recently removed from the user terminals Application Programmable Interface (API), only allowing datarate and RTT measurements. This work focuses on uplink throughput and RTT for both systems for the use of a video stream from the SAR UAV. For the measurements, we selected 31 different user terminal orientations, covering eight cardinal directions and four tilt angles, as displayed in Fig. 2. Between these measured points, all KPIs are interpolated. In addition, measurable KPIs vary between both systems. For the geostationary system's SNR in Fig. 3, the used coordinate system is azimuth-wise normed to the satellite's position. The SNR characteristics show good reception when it has a physically possible LOS to the satellite hovering over the equator at 25° azimuth. Although slight variations exist from 270° to 90° over the tilt angles, the

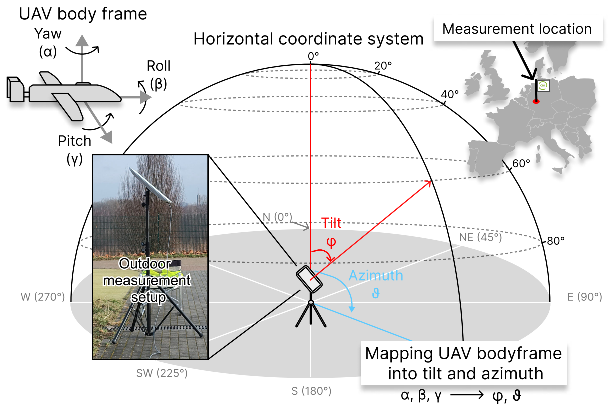


Fig. 2. Satellite measurement campaign set-up and coordinate definition for the UAV body frame α, β, γ, as well as tilt φ and azimuth θ.

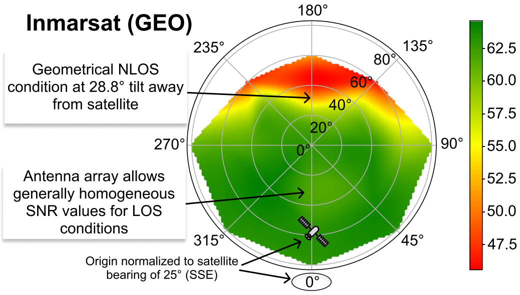


Fig. 3. Empirical downlink SNR measurements of a geostationary satellite constellation. The serving satellite is located at 0 degrees. Measurement positions are located on the grid nodes with interpolation in-between.

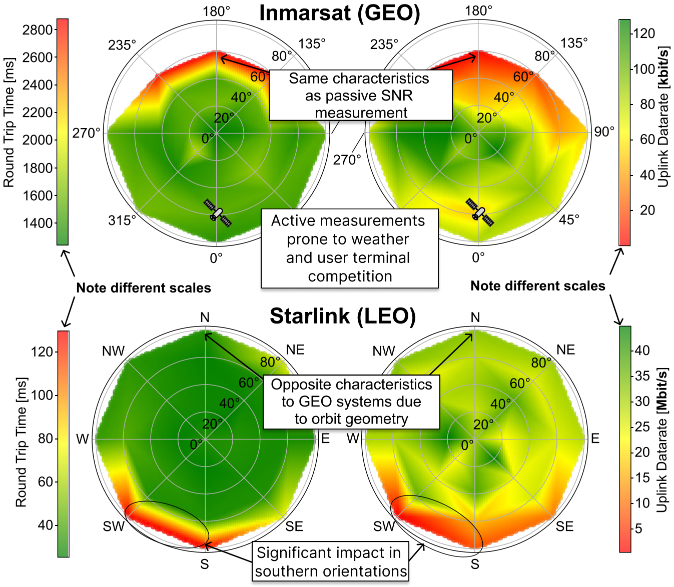


Fig. 4. Empirical uplink RTT and data rate measurements of Inmarsat and Starlink (note different scales) showing opposite tilt characteristics. Measurement positions are located on the grid nodes with interpolation in-between.

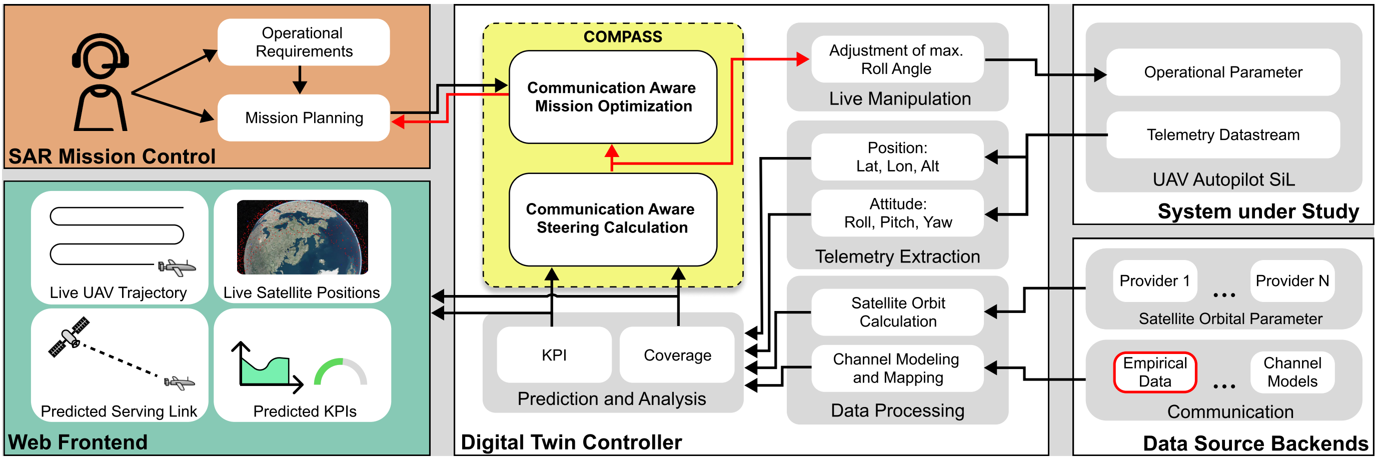


Fig. 5. The architecture of the proposed digital twin enables COMPASS by considering empirical measurement data and a satellite constellation. Furthermore, the digital twin allows the visualization of KPI, allowing in-depth analysis of the UAV's communication conditions.

SNR is mostly homogeneous. However, when aligned to an opposite-facing azimuth, the antenna quickly loses its LOS, reflected in the significant reduction in SNR. Therefore, when rotating the antenna over the opposite-facing azimuth (e.g., in a turn of the UAV), the tilt angle must be seriously reduced to maintain a good SNR. Furthermore, Fig. 4 shows the measured data rates and RTT for both the Inmarsat and Starlink systems. Note that the scale differs drastically between both systems (e.g., kbit/s vs Mbit/s). In general, Inmarsat's active KPIs shows the same tilt and azimuth-depending characteristics as the SNR. However, it has to be noted that for the active measurements, potential weather and competition with other user terminals result in more inhomogeneous measurements. As expected, Starlink outperforms the already aged Inmarst drastically in data rate and RTT. SpaceX generally instructs their stationary antennas to be orientated to the north and their mobility antennas (used in this work) with eight-degree elevation for best connectivity. This is also reflected in the measurements, with high data rates and low RTT in the northern region. The Starlink system also performs excellently up to a 40° tilt angle when facing south. This can be explained by the orbit geometry with longer LOS paths to the satellites, and according to [17], there is a potential user terminal shut-off due to possible interference with a geostationary satellites. Concluding from this comprehensive measurement campaign, it can be derived that the antenna's orientation and, therefore, the UAV's orientation can significantly impact communication performance and thereby motivate communication-aware trajectory planning and steering.

IV. IMPLEMENTATION OF A COVERAGE PREDICTING DIGITAL TWIN

For communication-aware mission planning and live steering, a tool must first be created to map the communication conditions and mobility between the UAV and the satellites. Therefor, we designed and implemented a digital twin which combines channel prediction and mobility mapping. The Architecture of the digital twin is shown in Fig. 5. In the following paragraphs, we discuss the implementation of this digital twin and describe its functionality, starting with the underlying visualization framework. This is followed by an overview of the corresponding satellite mobility prediction, the UAV's trajectory and orientation aspects and ends with our novel communication-aware planning COMPASS.

A. Visualization Framework

For the digital twin, visualization is one of the essential components allowing the mission control to asses the communication conditions at any time. Focusing on drone and satellite mobility, both micro and macro-scale visualization is critical. At the same time, communication-related KPIs like channel predictions and signal mapping must be displayed. A well-established 3D geo-visualization library is used to render the entire globe with the ability to overlay satellite imagery and terrain information, as illustrated by Fig. 6. Moreover, it allows a smooth transition between different zoom levels.

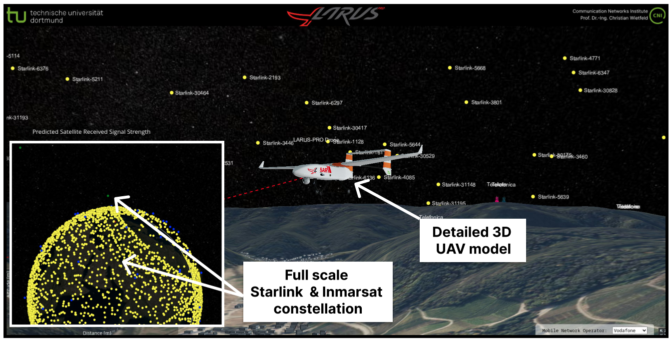


Fig. 6. Impressions of the digital twin's visualization framework, presenting two major satellite constellations and the detailed 3D model of the UAV.

B. Mobility Modelling

The prediction of a satellite position can be performed very accurately due to the fixed orbits, which can be described relative to a reference plane with the Keplerian elements [18]. These Kepler elements are publicly available for most satellite constellations. In this work, we only focus on the Starlink and Inmarsat systems, but due to the designed modularity, different constellations can also be integrated. Regarding the UAVs mobility, the digital twin connects to the telemetry stream of the autopilot in both Software-in-the-Loop (SiL) simulations and real systems. Processing the telemetry stream enables the extraction of the UAV's live position in latitude, longitude, and altitude, as well as its roll, pitch, and yaw attitude.

C. Communication-aware Mission Planning COMPASS

In this section, we focus on the novel communication-aware mission planning COMPASS. Standard planning tools like QGC [4] can create boustrophedon paths for a drawn survey area, where the spacing of the parallel paths corresponds to the width of the image taken with the onboard camera. In most cases, however, these tools only plan the waypoints, not the actual flown trajectory. The shortest and, therefore, most direct path for the autopilot results in two 90° turns that fixed-wing UAVs cannot fly. In addition based on the experiments in Sec. III, we can estimate that the connection to, e.g., the geostationary satellite remains unchanged during a roll movement towards the satellite but deteriorates and ultimately breaks off during a high angular roll movement away from the satellite.

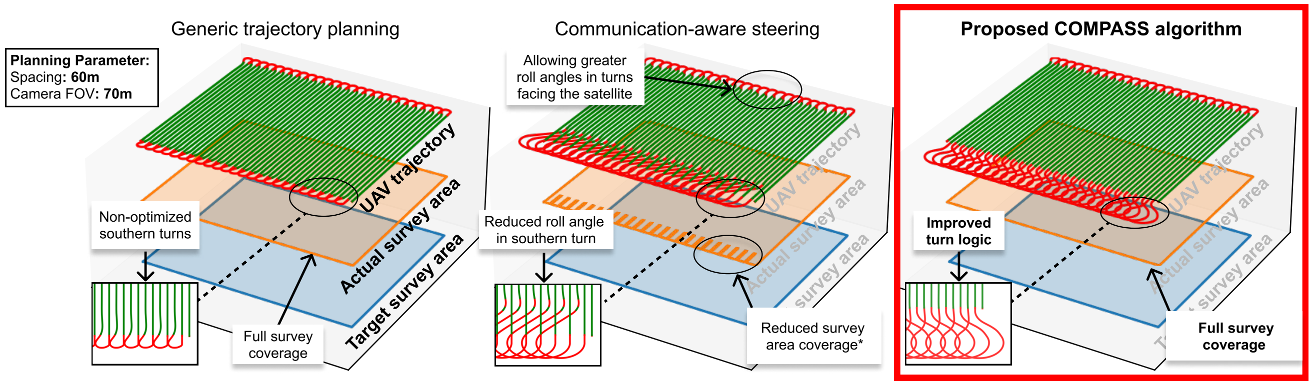
Therefor, as the first part of COMPASS, communication-aware steering is implemented, which live updates the autopilot maximum roll angle used in turn maneuvers; based on the current cardinal heading, and the heading of the next waypoint to determine the curve to be flown. This curve is compared with the satellite's position and evaluated to decide whether or not it is an advantageous or disadvantageous turn. The maximum roll angle is then set accordingly. The second variant can be generated in preprocessing, as the angles with which the curves are planned are saved during planning. Each waypoint is given a maximum roll angle based on the method mentioned earlier and applied between itself and the next waypoint. The UAV thus receives its next waypoint and the maximum roll angle simultaneously without having to calculate the roll angle first. As the steering alone only focuses on connectivity, the overflown survey area is not respected, resulting in wider turns and reduced survey coverage.

In a second step, a communication-aware mission adaptation is proposed considering the flight characteristics of fixed-wing UAVs requiring circular turn planing. Based on the communication-aware maximum angle ϑ, the true airspeed v and the gravitational force g, the necessary turn radius can be derived. The true airspeed is assumed to be 22 m/s, corresponding to the drone's speed in the used SiL simulation. An adjusted turn radius is calculated based on the UAV's rotation and orientation and the communication-aware roll angle. The lower limit of the turn radius is set to the minimum of either half the distance of two neighboring trajectories or the radius of the calculated max roll angle curve. To allow the turn to happen outside the survey area, additional waypoints are planned to map the expected curve behavior, thereby constructing a semicircle leading tangentially into the subsequent trajectory.

V. DIGITAL TWIN DRIVEN EVALUATION OF COMPASS

In the following, COMPASS is evaluated in a SiL scenario. In this evaluation, we focus on the flown distance, the actual survey coverage, and predicted SNR for an Inmarsat-based trajectory planning. The behavior is expected to be similar to the Starlink system, with just a cardinal direction change. Fig. 7 shows the resulting flown trajectories of the different Approaches. The general planning is done with a spacing of 60 m and an assumed camera Field of View (FOV) of 70 m. Furthermore, only trajectories with a roll angle below 20° are considered for the survey coverage to mimic a realistic survey with a video operator.

First, generic trajectory planning using QGC is considered. It can be seen in Fig. 7 and Fig. 8 that complete survey area coverage is possible with a low distance overhead of 12 %. However, a delta of almost 12.5 dB exists between the mean and minimum SNR. Next, a COMPASS sub-component, the communication-aware steering, is considered. By flying more extensive south turns, the overhead distance is increased by approx. 14 %. In addition, the planning does not account for the extensive turn, resulting in greater roll angles than 20° within the survey area, thus not fulfilling the survey area requirement. Note that this decrease in the covered survey area depends highly on the survey size and the ratio of turn to survey distance. On the other hand, the mean of the SNR remains the same, but the minimum values are drastically improved by 9 dB. Last, the combination of communication-aware steering with communication-aware trajectory planning in COMPASS is considered. For this scenario, the minimum SNR keeps the same as the solo steering scenario but fulfills the survey requirements. Only the flown distance remains increased compared to the non-optimized scenario. Following, we focus in-depth on the impact of the maximum allowed roll angle in COMPASS. In Fig. 9 the trade-off between flown distance, maximum permitted roll angle, and SNR is shown. The expected behavior of the minimum SNR deteriorating as the permitted roll angle increases can be observed. Furthermore, the overhead of the flown distance is reduced with higher roll



*Trajectories are only considered as survey area, when the roll angle is smaller than 20°

Fig. 7. Comparison between three SiL-simulations with focus on target survey coverage, flown trajectory and actual coverage.

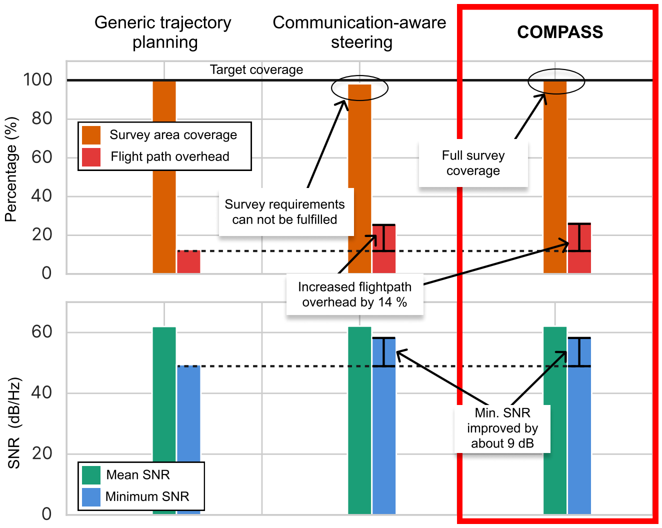


Fig. 8. Comparison between survey area coverage, flight overhead, and communication availability for different trajectory planning approaches.

angles. The highest decrease in connectivity of around 8 dB is seen from 20° to 30°. While the flown distance overhead from 40° to 60° keeps on decreasing to 13 %, the signal strength stagnates at around 46 dB.

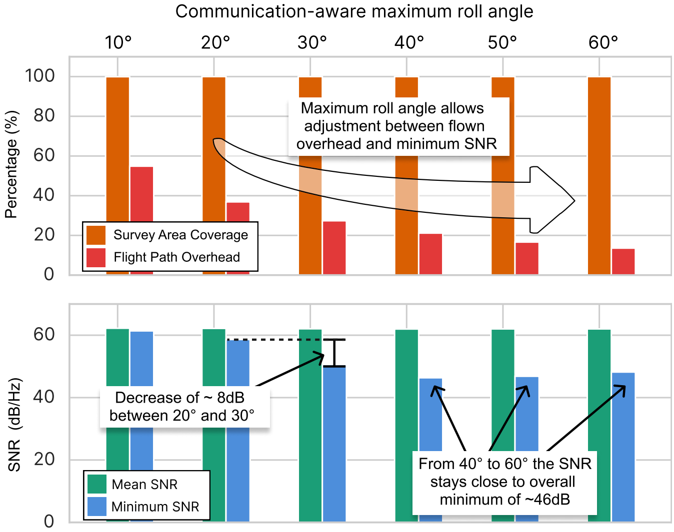


Fig. 9. Comparing the impact of different maximum roll angles on COMPASS regarding survey coverage, flight distance overhead, and downlink SNR.

VI. Conclusion and Outlook

This paper presents the novel communication-aware trajectory planning and steering approach COMPASS. Based on an empirical satellite measurement campaign and powered by a novel digital twin, COMPASS improves the SNR in the shown scenarios by up to 9 dB while maintaining the operator's survey area requirement. Further, it is shown that the trade-off between connectivity and flown distance overhead can be adjusted by fine-tuning the considered parameters. In future work, the digital twin-based approach can extend COMPASS to live UAV systems. In addition, more in-depth information of the satellite constellations could be considered to further improve COMPASS. We also plan to apply communication-aware trajectory planning for UAVs in terrestrial networks, based on UAV-specific channel models as in [19].

Acknowledgment

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