HiPER-V: A High Precision Radio Frequency Vehicle for Aerial Measurements

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***Abstract*—There is a growing interest towards enabling practical, dynamic and agile wireless applications by systems of independent or cooperative mobile agents such as Unmanned Aerial Vehicles (UAVs). Such mobile UAVs are often constrained on resources like storage, power and radio capabilities and require accurate position information to facilitate many of these wireless applications. In this paper, we introduce `HiPER-V`, which is a generalized UAV prototype platform to enable a broad range of applications in wireless communications using a single UAV or can be extended to a swarm of UAVs. We implement `HiPER-V` by using an UAV, equipped with resource constrained radio devices, and high precision position information available via RTK-GPS modules, achieving a median position accuracy of 3.8 cm. The details of implementation of `HiPER-V` and its applicability to a wide variety of applications in wireless communications are presented in this paper. With minimal payload and simple software modification, our solution can be ported to any UAV platform and extended to multiple UAV testbeds that enable an array of research in wireless applications using UAVs.**

***Keywords*—UAV testbed, UAV positioning, aerial wireless communications.**

I. Introduction

In this work we introduce a generic, outdoor and mobile prototype platform (namely, 'HiPER-V') for wireless communication applications, using a radio-resource constrained UAV with accurate position information. This prototype platform can be extended to larger, multiple UAV based testbeds as required by the specific application. Compared to conventional ground communication nodes, the advantage of using UAVs as flying communication/ monitoring nodes, lie in their ability to adjust altitude, avoid obstacles, and enhance the possibility of establishing line-of-sight communication and broader sensing [1]. Often, accurate position information of the UAVs are assumed to be available. Especially, applications that employ swarms of UAVs [2], [3] have more stringent requirement on the availability of accurate position information of the UAVs. Thus, the goal of HiPER-V is to provide a prototype platform with radio enabled UAV with accurate position information, that can be used to implement a variety of UAV testbeds to validate applications in wireless communications. Hence, the UAV is mounted with a radio module (software defined radio (SDR) equipment) to facilitate communication or wireless signal acquisition along with high-precision positioning to enable precise position estimation of the UAV. The system diagram of HiPER-V is shown in figure 1. UAVs may be con-

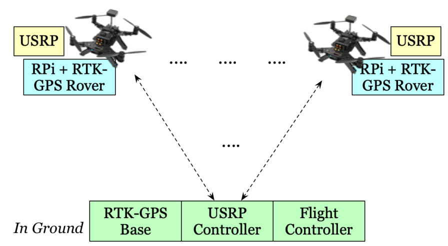
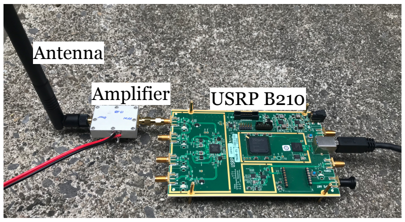


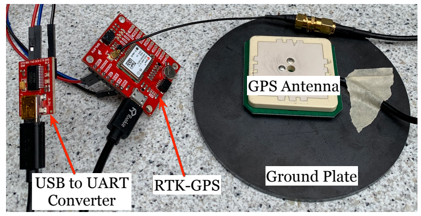
Fig. 1: HiPER-V prototype - UAV is equipped with USRP B205-mini SDR and a high-precision positioning module. A ground station is used for ground flight control, SDR control and high precision positioning using RTK-GPS.

trolled in an independent or collaborative manner depending on the requirement, while each UAV might follow a planned or random trajectory. In HiPER-V, automated flight control of the UAV and automated data acquisition from the radio on the UAV is achieved via a ground controller (typically a laptop with a wifi link to the on-board computer of the UAV) which acts as both the flight controller and the SDR controller (detailed in §II). However this platform, is generic, as the design and the software can be easily ported to various types of UAVs with minimal modification.

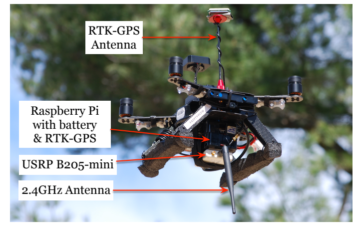
Generic platform: HiPER-V makes no assumptions on the make and the model of the UAV, the SDR, or the specific RTK-GPS board used. The prototype platform is implemented and verified for the Intel Aero Ready-to-Fly Drone [6], mounted with a USRP B205 mini SDR [4], and a sparkfun RTK-GPS module [5]. However, all the software for control and position acquisition is developed using open source software, which can be ported to most make and model of UAV. Precise motion and control of the UAV is achieved via autonomous flight missions, programmable via Dronekit [7]. This allows manual or automatic configuration of the flight path of the UAV from a ground controller. Dronekit is used to develop apps that run on the UAV's on-board computer to control the UAV, and augment the autopilot by performing tasks that are computationally intensive. DroneKit is compatible with vehicles that communicate using the MAVLink (Micro Air Vehicle Link [8]) protocol which is supported by a majority of the UAV community. The choice of the SDR platform is based on the trade-off between performance (noise floor, bandwidth, sample rate, etc.) and available resources (storage and power constraints). While, we verified the platform with a small form factor, USRP B205 mini [4], larger UAVs can



(a) Ground Node with an USRP B210 [4] and 10dBi antenna.



(b) RTK Base setup with RTK-GPS [5] and GPS Antenna on ground plate.



(c) Intel Aero Ready-to-Fly Drone [6] equipped with an USRP B205 mini [4] and a single antenna as the receiver.

Fig. 2: Implementation details of `HiPER-V` prototype, (a) the ground communication node, (b) the RTK-GPS base, and (c) the UAV mounted with the SDR and the RTK-GPS rover.

support more powerful USRP radios to improve the fidelity of wireless communications, support higher frequencies and bandwidth with MIMO applications. RTKlib [9] serves as an open source program package for precise positioning with GNSS (global navigation satellite system) and can be used in conjunction with any RTK-GPS board, to achieve high precision positioning of the UAV.

UAV-based and Swarm-based applications: The `HiPER-V` platform facilitates the implementation of a variety of testbeds for a range of applications in wireless communications, but is especially lucrative for applications that demand high precision positioning of the UAV. The platform also enables practical validation of theoretical and simulation based research on wireless communication applications with UAVs, using over-the-air measurements. It can also be used to enable single UAV based applications as in: a) the efficient placement of an aerial base station [10] in order to maximize the number of covered users in a given area, b) trajectory optimization of a single UAV serving one ground user or a wireless sensor network, for energy efficiency [11]. Designing cruising aerial base stations, requires autonomous mobility control algorithms that rely on accurate positioning of UAVs, to be able to continuously adjust the direction or heading of the base station for optimum system performance [1]. Although a single UAV can perform a multitude of tasks, multiple UAVs may form a cooperative group to achieve an objective more efficiently, and increase the chance of successful task operation. Robustness of the communications can be increased by deploying cooperative UAVs, where maintaining the connectivity and controlling the distance between multiple UAVs is a key challenge [3]. Maximizing the coverage area [12], searching and localizing a target [13] are among the various tasks that are facilitated by multiple UAVs.

Thus, `HiPER-V` serves as a generic prototype platform for application of UAVs in wireless communications, that can be used for various waveforms and bandwidths and can be ported to any system of UAVs, SDRs and RTK-GPS boards. The rest of the paper is organized as follows: §II outlines the implementation details followed by application scenarios in §III. §IV discusses the existing testbeds, and the concluding remarks are presented in §V.

II. System Design and Implementation

In this section, we describe the `HiPER-V` prototype platform, which has the following functionalities: a) Flight control, b) RF signal transmission and reception, and c) Precise positioning. The hardware used in the prototype is shown in figure 2. The navigation and communication from multiple UAVs is an extension of a single UAV system. Thus, `HiPER-V` can be used to implement multi-UAV testbeds as well. For testbed based on multiple UAVs, it is crucial that the swarm of UAVs collaborate to perform the provided mission using the wireless communication. In this paper, we focus on a single UAV and ground control system.

A. UAV flight control

The automated flight control of the UAV is achieved by configuring the required flight trajectory of each UAV or the path-planning algorithm [14] from the ground flight controller (typically a laptop) over a wifi link. To facilitate a variety of navigation requirements for applications in wireless communications, we implemented two modes (types) of flight control of the UAV as outlined below.

i. Precision Flight Control: Actuation of the UAV is only as good as the sensors available. We exploit the high-precision position estimation of the UAVs to facilitate precise flight control of the UAVs. Several wireless applications, based on single UAV or a swarm of UAVs require precise placement and navigation. The precise flight control is outlined below.

Precise flight control, refers to the navigation of the UAV such that there is minimal (sub-meter-level) error between the actual and desired positions of the UAV. This fine navigation of the UAV is achieved by manipulating the torques provided to each rotor. The UAV used in the current implementation, consists of four rotors placed equidistant from the center of mass of the UAV. The torque provided to all rotors are used to move the UAV in roll, pitch and yaw directions. These torques along with the high-precision position feedback from the RTK-GPS module are used for precise flight control of the UAV using conventional PID (proportional integral derivative) controllers, which is implemented within the UAV. It should be noted here that each UAV is initially calibrated to tune the PID parameters to achieve the best performance in navigation.

```
$ ./drone_fine_navigate
-- Connecting to vehicle on: tcp:127.0.0.1:5760
-- >>> APM:Copter V3.5.7 (d2c78176)
-- >>> PX4: b535f974 NuttX: 1bcae90b
-- >>> Frame: QUAD
-- >>> AEROFCv1 004D001F 33355118 39343335
-- Basic pre-arm checks
-- Waiting on vehicle to initialize...
-- Arming motors
-- Taking off
-- Setting Yaw Angle of 5 degrees
-- Setting Yaw Angle of 0 degrees
-- Landing
```

Listing 1: Precise Flight Control of the UAV.

A sample output of the precise flight control code (implemented using 'dronekit') is shown in Listing 1. This shows the TCP connection established between the onboard computer of the UAV and the flight controller. The pre-arm checks are used to ensure that certain conditions (visibility of GPS satellites and remaining battery-life) are met before arming the UAV. Once the pre-arm checks are completed, the motors are armed and the UAV takes off. The UAV takes off, makes a fine movement (depending on the intended displacement) in a certain direction (determined by the yaw angle). Once the movement is complete, the UAV lands and the program finishes executing. This technique can be extended to facilitate more complicated automated flight trajectories and path planning algorithms.

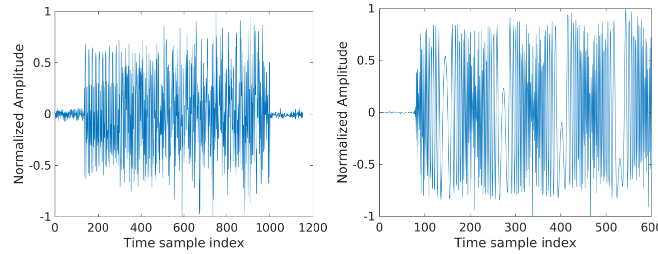
ii. Random Flight/Hovering/Loitering: We may also choose to loiter or hover in a position as it will drift due to wind. This type of motion is conducive for applications which do not require precise navigation of the drone. For instance, to facilitate distributed beamforming [15] using a swarm of UAVs (further detailed in §III), it is only required that the position of the UAVs are accurately known, and there is no requirement for precise placement or navigation of the UAVs. Hence, we can allow the UAVs to navigate independently and randomly or hover around a specific position for such applications.

In our implementation of the system, we use an Intel Aero drone [6] running version 16.04 of Ubuntu, equipped with the Intel Aero flight controller flashed with version 3.5.7 of Arducopter controller firmware [16].

B. RF module of the UAV

We use an Intel Aero drone [6] as the main element of `HiPER-V`, with Ubuntu. `HiPER-V` may consist of many such elements depending on the testbed required for the application of interest. We have chosen a USRP B205 mini [4] equipped with a single isotropic antenna as the radio and mounted it on the UAV as shown in Figure 2c. The orientation of the antenna (pointing downwards), ensures that the communication or monitoring from the radio of the UAV is independent of the orientation of the UAV around its vertical axis (yaw).

We are able to stream digital complex samples at 5, 10 and 20 MHz using USB 3.0 connection and RAM disk. We would also like to *highlight* here that we have chosen the USRP B205 mini for its small form factor at the cost of its receiver sensitivity. It has 12-bit ADC and higher noise floor ($\approx 8dB$), compared to other off-the-shelf receiver cards or Wi-Fi Access Points, which vary between $2 - 4dB$. We can also use other more capable USRP radios, that enable higher fidelity communication over higher bandwidths and support MIMO, at the cost of a larger footprint and higher power consumption (feasible to be mounted on heavy-weight drones). We use USRP B210 [4] with a $10dB$ RF amplifier and $10dBi$ antenna as the ground communication node as shown in figure 2a. This node is not part of the UAV or the ground control, but is used to transmit or receive test wireless signals, which are used to be received by or transmitted from the UAV. Multiple UAVs and multiple ground wireless transceiver nodes enable the implementation of various applications in wireless communications involving UAVs. These include aerial adhoc networks, maximal coverage to ground nodes from aerial base stations and spectrum monitoring.



(a) Received Wi-Fi (b) Received LoRa

Fig. 3: The time-domain representation of received waveforms.

The communication from the USRP radio on the drone is controlled via radio (USRP) controller (implemented on the ground controller) as shown in figure 1. This ground control of the radio communication is used to trigger the type of communication demanded by the wireless application of interest. a) For instance, applications that require spectrum monitoring or signal reception from the UAV (e.g., DoA estimation or localization), can be achieved by setting the radio on the drone to continuously or intermittently monitor or capture radio signals over time. b) On the other hand, to test the fidelity of communication links among the UAVs, packet transmission and reception can be triggered randomly among different pairs of UAVs. For the illustration of the communication link and the performance of the platform, we have chosen to transmit Wi-Fi preamble, from the ground node as shown in figure 2a, and receive it from the radio on the UAV as shown in figure 2c. We use one of the unused Wi-Fi bands as the transmission frequency to avoid interference with other Wi-Fi networks in the area. The amplifier is used to boost the signal emanated from the B210, which can only transmit up to $100mW$. With the $10dB$ amplifier and $10dBi$ antenna, the maximum power output of our transmitter is $30dBm$, which is still much lower than any commercially available Wi-Fi Access Points and FCC's recommendation of Equivalent Isotropically Radiated Power (EIRP) of $36dBm$ ($4W$) in $2.4GHz$ unlicensed spectrum. Figure 2a shows our experimental setup of the ground node, which is periodically transmitting a 802.11 [17] packet. The received Wi-Fi OFDM

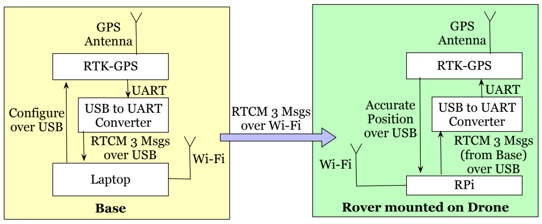


Fig. 4: RTK Setup Block Diagram.

packet from the drone is shown in figure 3a. The use of a software defined radio allows us to communicate at a broad range of frequencies (the USRP B205 mini operates over a wide frequency range, i.e, 70 MHz to 6 GHz). An example signal capture of a LoRa transmission from the UAV at 915 MHz is shown in figure 3b. LoRa communication is of interest in long range, low power UAV communication.

C. Positioning of the UAV

Conventional GPS based positioning can only achieve about 3 meter accuracy [18], which is not sufficient to support applications that rely on precise positioning of UAVs. We rely on Real-time kinematic (RTK) positioning to realize the position of the UAV. RTK achieves enhanced precision of position data by depending on information from satellite-based positioning systems (Global Navigation Satellite Systems (GNSS)) including GPS, GLONASS, Galileo, and BeiDou. The ability of RTK systems to yield up to centimetre-level accuracy is contingent upon the availabity of a) Measurements of the phase of the signal's carrier wave in addition to the information content of the signal, and b) real-time correction streaming from a reference station. RTK has been used for land surveys, automatic ground vehicle and UAVs for high precision applications. With the advent of many low cost GPS-RTK receivers in the market (CUAV C-RTK GPS, Drotek XL RTK GPS, Here+ RTK GPS, Trimble MB-Two) and support by open source UAV development community [19], it has become an essential part of UAVs for precise navigation. Although many off-the-shelf available modules exist for developers, we chose SparkFun GPS-RTK Board [5], based on u-blox NEO-M8P-2 [20] module, for its small form factor and ease of use. This unit is supposed to report GPS location with a precision of 1cm and accuracy of 2.5cm, but may vary significantly.

Figure 4 shows the block diagram of the base and the rover units in our setup. The base is the static unit, which transmits phase correction stream over Wi-Fi connection to the mobile unit, namely rover, mounted on the UAV. The base unit is first configured to enable RTCM (Radio Technical Commission for Maritime Services) v3 messages, which is transmitted over Wi-Fi to the mobile rover unit in the UAV. We specifically used the RTCM messages: 1005, 1077, 1087 and 1230. Once the rover receives these correction messages from the base, it forwards that to the RTK-GPS unit, which then can calculate its position accurately.

We used a laptop for the base and a Raspberry Pi as the rover due to its small size and powered it with a separate

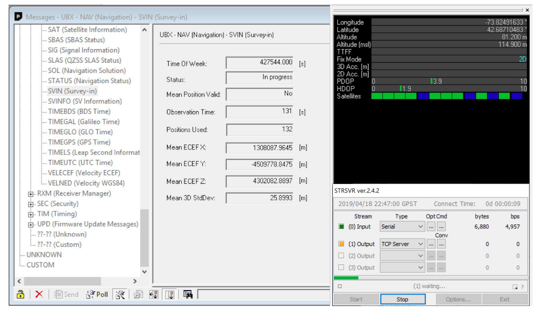


Fig. 5: RTK GPS base GUI.

battery. The Raspberry Pi is set up as a Wi-Fi hotspot that the base laptop connects to it, in order to stream the RTCM messages. Once both the base and rover are on the same network, a TCP connection between them is established using RTKLIB. The base is set up as a TCP server that takes in the RTCM data from the RTK-GPS through the USB to UART converter as its input and outputs it to the IP address corresponding to the rover. The rover is set up as a TCP client and takes the RTCM data as an input and outputs it to the RTK-GPS through the USB to UART converter. Once the RTK-GPS receives the RTCM data, it calculates its position. The Raspberry Pi stores the accurate location and the GPS time as a tuple during the flight. This information serves as the timestamped position of each UAV which is crucial to drive the variety of online or offline wireless communication tasks.

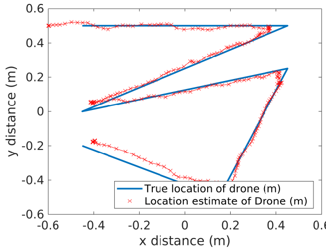
A snapshot of the RTK-GPS base GUI is shown in figure 5. A sample output of the RTK-GPS base and rover codes are shown in Listings 2. The base listing shows the message being sent to the base RTK-GPS, indicating that the base should obtain positional data until a minimum of 300 seconds has passed and an accuracy of 1.5 meters is obtained. The messages after that show the current status of the base RTK-GPS while it is obtaining the positional data. The rover listing shows the RTK-GPS accuracy constantly being outputted. The RTK fix is achieved, when the accuracy of the position estimate at the rover drops below 2.5 cm.

Accuracy of Positioning: In this section we investigate the impact of the position errors of the UAV on precise navigation. Accurate knowledge of the UAV is required to facilitate a

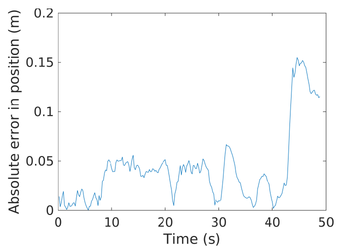
```
$ ./run_rtk_base
-- Required Accuracy: 1.5 meters
-- Observation Time: 300 seconds
-- Sending Message
-- Status:  In progress
-- Observation Time Passed: 14 seconds
-- Accuracy: 3.2925 meters
...
-- Status:  Successfully Finished
-- Observation Time Passed: 303 seconds
-- Accuracy: 1.49277 meters
```

```
$ ./run_rtk_rover
--GPS Accuracy: 3.92 cm
--GPS Accuracy: 3.40 cm
...
--GPS Accuracy: 2.59 cm
--RTK Fix Achieved (below 2.5 cm accuracy)
--GPS Accuracy: 2.38 cm
```

Listing 2: RTK-GPS Base and Rover messages.



(a) Random array trajectory



(b) Drift in accuracy over time

Fig. 6: The accuracy of the position of the UAV during signal capture using RTK-GPS and its drift over time, achieving a median position accuracy of 3.8 cm.

variety of swarm UAV based wireless communication applications. The UAV's position is measured using the RTK-GPS. Any error in the measured position of the UAV, affects the performance of the wireless communication task (detailed in §III). The position estimate of each UAV at any time may be slightly impaired due to the limitations in RTK-GPS position estimates: The RTK-GPS [21] position estimates have a centimeter-level accuracy and precision. Figure 6a shows the measured positions of the UAV (vs. the true positions) for a particular trajectory. It is evident that the measured positions deviate from the true positions (with cm-level error). The error we noticed is often higher than the claimed accuracy of 2.5cm. Figure 6b portrays the position error over time. Unlike INS based positioning systems there is insignificant drift over time, which encourages the use of RTK-GPS based positioning and navigation in position sensitive UAV based applications in wireless communications.

III. UAVs for Wireless Communications

A variety of UAV enabled wireless communication applications rely on accurate positioning of the UAV for optimal placement, for optimal navigation and for lucrative cooperation or collaboration in distributed settings. While many of prior research are presented in theoretical settings, we provide a prototype platform capable of achieving the high precision positioning required to both facilitate and validate the performance of such work in practical settings. Optimal placement and optimal trajectory of an UAV or a system of UAVs (serving as aerial base stations) is essential to provide maximal coverage and connectivity to ground nodes [10], [11]. These require reasonably-precise position estimation of the UAV and precise navigation based on these position estimates as facilitated by `HiPER-V`. [14] presents a paradigm for localization of violations using autonomous agents (e.g., UAVs), which again requires precise positioning and navigation of the UAVs.

However, applications in wireless communications that rely on swarms of collaborative or distributed UAVs are more sensitive to position estimation errors of the UAV. The true benefit of `HiPER-V` can be reaped in such settings. This is elaborated using an example on collaborative beamforming below: The effective use of multiple UAVs, emulates a distributed aerial antenna array, where each element is a UAV with a single isotropic antenna. Such an emulated distributed antenna system (DAS), facilitates a range of tasks (e.g., distributed MIMO, collaborative beamforming, joint provision of wireless service/connectivity). This distributed antenna array emulated by multiple UAVs can be used for transmission or reception beamforming by applying the concepts in [15], provided the locations of the UAVs are accurately known. The direction of the beam, in distributed beamforming is very sensitive to any errors in the position estimation of the UAVs. As such, the centimeter-level accurate positioning of UAVs achieved in `HiPER-V`, minimizes the impact on the direction of the beam and thereby, practically enables a swarm of UAVs to be applicable for distributed beamforming. This in turn, practically enables tasks like accurate Direction of Arrival (DoA) estimation and localization of RF transmitters (for search and rescue operations) or improving the throughput to ground nodes using a swarm of UAVs. [2] proposes the theoretical optimal control of a swarm of distributed UAVs to maximize the wireless service (minimizing the service time) to ground users. Achieving these precise actuation or navigation of UAVs require the precise position estimation and precise navigation of UAVs facilitated by `HiPER-V`. These examples demonstrate the wide applicability of `HiPER-V`, especially for collaboarative communications and sensing.

IV. Existing Testbeds

UAVs have been the subject of recent wireless research [1] due to their autonomy, mobility, and broad range of application domains. However, a bulk of this research in the domain of wireless communications, has been in theory and simulation with some limited attempts in implementing and verifying via real testbeds [1]. These simulations often assume that UAVs can move in any direction at any time without specific constraints of obstacles or any hardware restrictions, and hence may be far from realistic for many specific scenarios. Table I enlists the features of the most relevant of these testbeds.

UAV Testbeds for wireless communications: In [22], a realization of a low-cost testbed is introduced to validate the possibility of creating a flying ad-hoc network. [23] implements a UAV testbed on which one can run and test ad-hoc routing protocol implementation. An autonomous helicopter is used in [24] to investigate the accuracy of a navigation system, and achieves a 3 meter accuracy in a pre-planned trajectory with the actual flight path by the helicopter. In [25], authors present a single portable helicopter based localization system, and uses the received signal strength of the signals captured at various points along a trajectory for localization. Authors in [27], have exploited UAVs for direction of arrival (DoA) estimation and localization of RF sources. Most of these testbeds rely on conventional GNSS (Global Navigation Satellite System) or INS (Inertial Navigation Systems) or a combination of both for position estimation and achieve at best meter-level positioning of UAVs. However none of these testbeds, achieve the positioning accuracy conducive for position sensitive applications in wireless communications, such as distributed beamforming and distributed MIMO.

TABLE I: Comparing HiPER-V with existing wireless testbeds

Testbed	Task	Equipment	Positioning
[22]	Adhoc network among multiple UAVs	Raspberry pi, Parrot Ar. Drone	GPS based GNSS
[23]		Custom telemaster based plane	
[24]	Accuracy of the navigation system	AirRobot quadrotor simulation	GPS-INS
[25]	Aerial localization	Draganflyer X6, Nokia N900	GPS based GNSS
[26]	Controlling the UAV path to improve link quality between mobile nodes	NexSTAR unmanned aircraft	GPS based GNSS
HiPER-V	A wide range of wireless communication applications	Can be ported to any system of UAVs, SDRs and RTK-GPS modules	high precision RTK-GPS based

Localizing The UAV: Localizing a flying UAV is of interest to the research community for various applications. The information from the UAV's gyroscope, magnetometer and accelerometer (Inertial Measuring Unit (IMU)), could be used to sense the accelerations and rotations of the UAV, and over time, estimate the position and orientation of the UAV (INS). An INS can estimate the location of the UAV without the need of external references (such as GNSS). However, the error in the estimation grows over time and becomes very inaccurate after 10 seconds or more [28]. Sensor fusion (typically using Kalman filtering) between INS and GNSS, while improving the localization accuracy, only achieves meter-level position accuracy [29]. However, using high precision RTK-GPS information alone, we achieve centimeter-level positioning accuracy, which is crucial to facilitation position sensitive RF tasks.

To the best of our knowledge, HiPER-V is the first platform of its kind to facilitate practical wireless communications that require precise positioning of the UAV in resource constrained UAVs, due to the availability of accurate positioning (centimeter-level) information of the UAVs.

V. Conclusion

We presented HiPER-V, an outdoor UAV prototype platform to enable various wireless communication applications, which uses resource constrained devices. We use high precision RTK-GPS for accurate positioning to enable emerging UAV-based applications. Our platform is based on commodity hardware and modifications in open-source software, which makes it portable to any other UAV or USRP models.

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