UBSpot: A Universal Broadband Flying Hotspot Experimental Testbed Toward Programmable Aerial-Ground Wireless Networks

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***Abstract*— UAV-assisted wireless networking has been envisioned as a key technology to provide pervasive, elastic and spectrally-efficient network services in 5G-Beyond and Wireless Internet of Things (W-IoT). To enable rapid and repeatable experimentations for UAV-assisted wireless networking, in this article we propose UBSpot, a universal broadband flying hotspot for software-defined aerial-ground wireless networking in the microwave and mmWave frequency bands. The major components of UBSpot are described, including *Data Plane*, *Mobility Plane*, and *Control Plane*. A software-defined prototype of UBSpot is also presented.**

***Index Terms*— Programmable Networks, Internet of Things (IoT), Unmanned Aerial Vehicle (UAV), mmWave Band Communication.**

I. Introduction

Unmanned aerial vehicles (UAVs, or drones) have been envisioned as an enabling technology for pervasive, elastic and spectrally-efficient network applications in 5G-Beyond and Wireless Internet of Things (W-IoT) [1], [2], [3]. Examples of these applications include, as illustrated in Fig. 1, i) UAV-enabled blockage-aware communications in the mmWave band, ii) flying hotspot assisted spectrum coexistence in heterogeneous wireless networks, and iii) emergency IoT with fast-deployable flying wireless infrastructure, among others.

While UAV-assisted wireless networking can certainly enable a wide range of new applications, existing research in this area has been primarily focusing on theoretical modeling, analysis and simulation-based performance evaluation [3], [4], [5], with the system challenges largely unexplored except several recent efforts [6], [7]. One of the main reasons is that, as of today, there are still no publicly available, software-defined and open-source-based experimentation platforms that allow researchers to verify their theoretical results in UAV-assisted wireless networking by rigorous testbed experiments.

In this article, we take an initial step toward filling this gap by proposing UBSpot, a universal broadband flying hotspot experimental testbed for programmable aerial-ground wireless networking. UBSpot features broadband communication capabilities in microwave and mmWave frequency bands, MIMO communications, and programmable protocol stack. To the best of our knowledge, UBSpot is the first open, software-defined experimental platform for integrated aerial-ground wireless networking. Next we first describe the architecture and major components of UBSpot, and then discuss the new experiments that can be enabled with UBSpot.

II. Related Work

Wireless UAV networking has recently received a significant attention in the scientific literature [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. For example, an aerial LTE base station facilitating broadband communications in emergency scenarios is studied in [9]. In [10], Zhu et al. use a chain of UAV repeaters to improve the link capacity for mobile ground nodes. A testbed for aerial drone applications is discussed in [11]. Mastronarde et al. propose UB-ANC, an emulator for aerial communications and networking [12]. Please refer to [13], [14], [15] and references therein for an excellent survey of the main results in this area. These works are either simulation- or emulation-based, or are based on testbeds with *limited or no* communication and networking capabilities. As of today, a fully programmable wideband experimental platform for integrated aerial-ground wireless networking is still missing.

III. UBSpot Design

The architecture of UBSpot is illustrated in Fig. 2, where there are three major components, i.e., *Data Plane*,

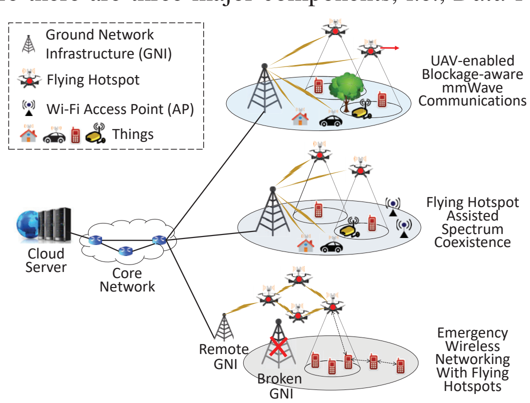


Fig. 1. Applications of UAV-assisted wireless networking.

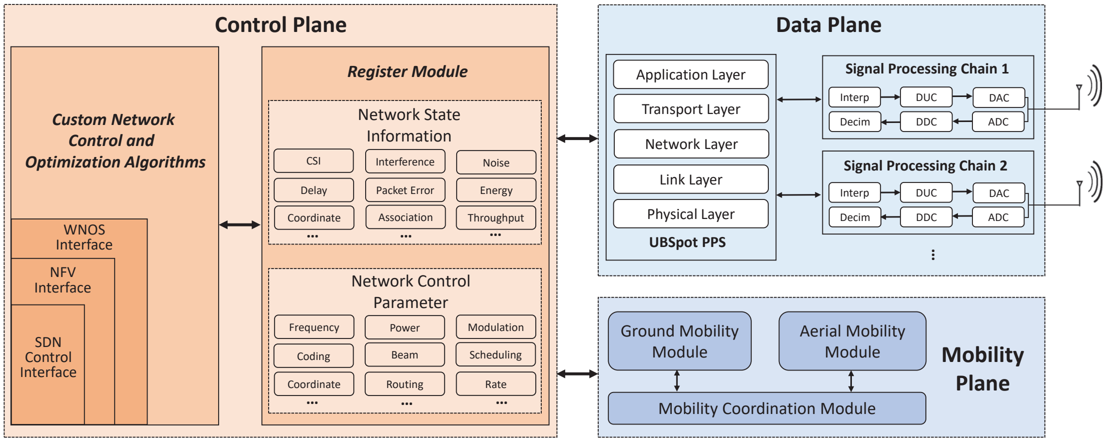


Fig. 2. Architecture of UBSpot: A universal broadband flying hotspot for software-defined aerial-ground wireless networking.

Mobility Plane, and *Control Plane*. The *Data Plane* implements the communication and networking functionalities, including the UBSpot programmable protocol stack (UBSpot PPS) and the signal processing chains; the *Mobility Plane* enables autonomous taking off, flight and landing of the drones as well as the movement synchronization between the drone and the ground robot; the *Control Plane* determines the optimal networking and movement parameters for the drone based on custom network control and optimization parameters, and feeds the optimized parameters to the *Data Plane* and *Mobility Plane*.

Data Plane. As illustrated in Fig. 2, this plane consists of UBSpot PPS, which spans from the physical layer up to the application layer, and a set of signal processing chains. The network state information at each protocol layer is sent to and stored in *Control Plane*, which further determines the optimal network operating parameters with the received network state information. The physical layer of the UBSpot PPS supports communications in two frequency bands: microwave and mmWave bands.

• *Microwave Band:* In the microwave band two different types of software-defined radio (SDR) front-ends are supported, with frequency range of 1.2 GHz - 6 GHz for USRP N210 and 70 MHz - 6 GHz for USRP B210. In addition to custom physical layer protocols, several widely adopted open source libraries have also been integrated, including OpenAirInterface (OAI) and srsLTE. For example, based on a combination of OAI and USRP B210 SDR, a softwarized LTE testbed with an eNodeB and an Evolved Packet Core (EPC) has been implemented and tested in the *Data Plane*.

• *Millimeter Wave Band.* The mmWave band radio interface has been designed based on NI mmWave 2 GHz reconfigurable SDR, consisting of a populated NI PXIe-1085 PXI Express chassis for baseband signal processing and SiBeam 60 GHz upconverter with phased array antenna (24 elements, 12 each for Tx and Rx). The mmWave band radio interface is compatible with X60 [16], which features a fully programmable MAC/PHY layers with multi-Gbps rates and a user-configurable 12-element phased antenna array.

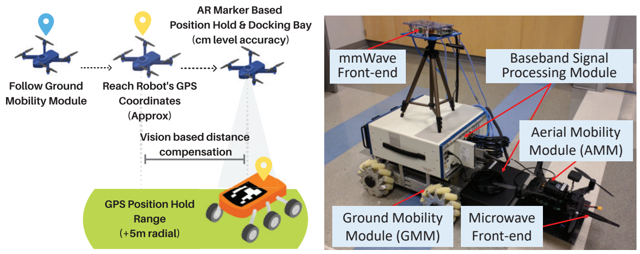
The upper layers of the UBSpot PPS are designed with different optimizable parameters at each layer. For example, the transport layer implements segmentation, flow control, congestion control as well as addressing, with programmable parameters including transmission rate, sliding window size and packet size, among others.

Mobility Plane. The job of this plane is to enable autonomous flight of the drone and synchronized movements of the drone and the ground mobile platform.[1] This is accomplished by three modules: ground mobility module, aerial mobility module, and mobility coordination module.

• *Aerial Mobility Module (AMM).* The AMM is a drone SDR endowed with antennas. In UBSpot, an Intel Aero Ready-to-Fly (RtF) drone is adopted, which is fully programmable and is pre-assembled with GPS, Wi-Fi, propellers and camera controlled by Intel Atom Processors. The GPS data is collected from AMM and transferred to host computer connected with the *Ground Mobility Module (GMM)* (which will be described later). The latest Intel Aero Image installation on AMM brings up the on-board computer with the BIOS for peripherals and flight controller, while Ubuntu is adopted as the on-board computer OS running MAVLink protocol streams.

• *Ground Mobility Module (GMM).* The GMM is a mobile ground platform carrying all the bulky baseband computing equipment. In UBSpot, the mobile platform is a 4-wheel-driven all terrain heavy duty robot (SuperDroid robot IG32 SB, powered by two car batteries, with maximum payload of 200 lbs), with motors controlled by Arduino micro controller. The GMM is equipped with a GPS module based on Ublox NEO 6M connected with

[1]Because of the limited payload of the drones and to protect the expensive baseband signal processing equipment in the case of drone crashes, only front-end antennas are amounted on the drone, while the baseband signal processing equipment is carried on the ground mobility platform and connected to the front-end antenna using extension cables.



(a) (b)

Fig. 3. (a) Synchronization of the aerial and ground mobility modules; (b) Prototype of UBSpot.

Arduino to provide the required location information for the GMM.

• *Mobility Coordination Module (MCM)*. This module is in charge of synchronizing the movements of AMM and GMM. The basic principle behind this is to provide the AMM with the GPS coordinates of the GMM, enabling the AMM to follow the GMM autonomously. To this end, the GMM's coordinates are periodically updated and fed to the AMM for path planning and autonomous navigation. It is worth pointing out that the accuracy of the available commercial off-the-shelf (COTS) GPS units is approximately within 5m. This can cause an inevitable drift during the movement synchronization. To compensate for the drift, as illustrated in Fig. 3(a), a vision based position hold method is adopted in UBSpot by letting the drone track the Aruco tag on the GMM to hold the AMM in position with centimeter-level precision.

Control Plane. This plane controls the network operating parameters of *Data Plane* and *Mobility Plane*. To this end, *Control Plane* receives network state information from *Data Plane* and stores the information in the register module. These information includes channel state information (CSI), interference level of the links, packet error rate, coordinates of the nodes, the set of associated users, among others. With the received information, the network operating parameters are optimized at network run time by a set of local custom network optimization algorithms or a remote software-defined networking (SDN) controller via the built-in SDN control interface, as illustrated in Fig. 2.

A unique feature of UBSpot is that the *Control Plane* is enabled with network function virtualization (NFV) [17] and wireless network operating system (WNOS) [18] capabilities. For example, based on WNOS network operators are provided with an abstraction of the wireless network, hiding the lower-level details of the wireless protocol stack and the distributed nature of the network operations. Network operators are allowed to define different network control programs in a centralized manner using high level APIs, while the distributed cross-layer control programs can be automatically generated based on distributed decomposition and optimization theories.

IV. Enabled New Experiments

UBSpot has been prototyped in the Wireless Intelligent Networking and Security (WINGS) Laboratory at University at Buffalo. With UBSpot, testbed experiments can be enabled for a wide set of new research topics, including spectrum optimization in drone-cell networks (SPOT-OPT), spectrum coexistence in heterogeneous wireless networks (SPOT-COX), and emergency networking with networked flying hotspots (SPOT-NET), among others.

SPOT-OPT. As illustrated in the top scenario of Fig. 1, in collaborative network environments where cellular wireless networks are deployed and operated by single service provider, there are strong incentives for the mobile hotspots to collaborate with each other in favor of a social network management objective under certain fairness policy.

SPOT-COX. In UAV-enabled 5G-Beyond and IoT, wireless systems may be operated by different service providers (SPs), who do not have strong incentives to collaborate with each other, as in the middle scenario of Fig. 1. The network management objective in this scenario is to enable fair and spectrally-efficient coexistence between the co-located wireless networks, e.g., by dynamically adapting the deployment of the drone hotspots.

SPOT-NET. In emergency environments, the ground network infrastructure could be partially or completely destroyed in certain areas. The objective of network management in this scenario is to enable elastic wireless networking through networked mobile hotspots. This can be achieved by allowing a swarm of drone hotspots to form a multi-hop or mesh network to extend network coverage, as shown in the bottom scenario of Fig. 1.

Fig. 4. Experimental setup for synchronized movement of aerial and ground mobility modules.

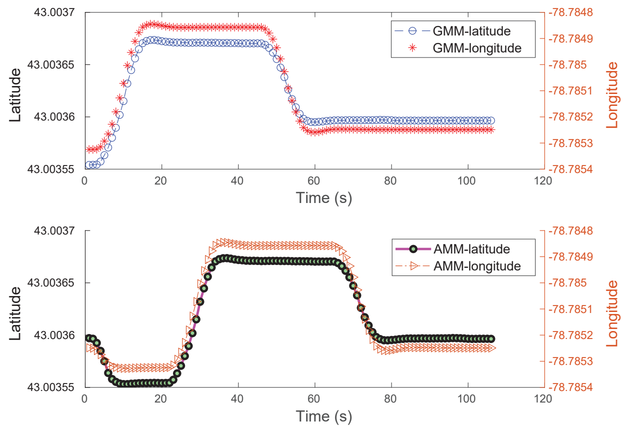


Fig. 5. Location vs Time Plot of GMM and AMM.

V. Experimental Evaluation

The objective of the experiments is to test the capability of autonomous movement synchronization of AMM (i.e., the drone) and GMM (i.e., the ground robot). To this end, the ground robot first initiates an autonomous ground based mission, followed by the drone taking off after a predefined delay. The GPS coordinates of GMM are sent to AMM periodically using MAVLink Protocol during the experiments. The experimental setup is shown in Fig. 4.

In Fig. 5, the top figure plots the trajectory (including latitude and longitude coordinates) of the GMM against time, while the bottom figure plots the path followed by the AMM. In this experiment, the GMM completes its mission and becomes stationary after 60 seconds. The AMM takes off, reaches a predefined altitude and then holds its position until it receives the GPS coordinates from the GMM. Once the coordinates are received, the go-to command is triggered to signal the AMM to move towards the next waypoint, i.e., the location of the GMM. Upon reaching the target waypoint, the AMM enters LAND mode and becomes stationary again. Comparing the two figures, it can be observed that the AMM almost has the same trajectory as that of the GMM, meaning that synchronized movements have been achieved.

VI. Conclusions

In this article we discussed the architecture of UBSpot, a universal broadband flying hotspot for software-defined aerial-ground wireless Internet of Things (IoT) in the microwave and mmWave frequency bands. The major components of UBSpot are described, including *Data Plane*, *Mobility Plane*, and *Control Plane*. In future work, we will experimentally test the effectiveness of UBSpot by considering specific network control problems, and open UBSpot to the community by designing a *GUI Plane* to allow researchers to access and operate UBSpot remotely through the Internet.

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