Remote and Rural Connectivity via Multi-tier Systems through SDN-Managed Drone Networks

Alvaro del Aguila Jonathan Valdez Mendoza Sai Bhargav Mandavilli Janise McNair
Dept. of Electrical & Computer Engineering, University of Florida; Gainesville, FL 32611
delaguila.alvaro@hotmail.com, vjonathan5037@gmail.com, smandavilli@ufl.edu, mcnair@ece.ufl.edu

***Abstract*—Rapid technological advancements in wireless networks have promised reliable and fast Internet connectivity across the globe. However, a challenging barrier to global connectivity is the lack of connections in rural, remote or damaged locations due to lack of cellular infrastructure. This paper proposes the use of drones, managed by software-defined network control, to provide wireless networking capabilities to such areas. Software-defined networks (SDN) can provide management of routing tables, protocols and algorithms for the purposes of path selection, energy preservation, quality of service, or security. We provide a selection of hardware that can be used to develop a suitable experimental communications-based drone network. Simulations were conducted using Mininet-WiFi and the ONOS controller to gauge the performance for a varying number of drones. Using our controller, we can achieve a less than 25% packet loss for WiFi connectivity delivered using 20 low cost, low power drones as access points.**

I. Introduction

Unmanned air vehicles in the form of drones are one of the most disruptive technologies created in the last decade. They have enabled users to create and deploy airborne sensors, e.g., video, image, audio, heat, and other data collection equipment, to out-of-reach and/or dangerous places for surveillance and monitoring, and to deliver and retrieve packages from shopping to medical deliveries. However, research is ongoing to achieve advances in the use of drones for telecommunication [1], [2], [3], [4]. In [5], an experimental drone-based Wi-Fi network is presented. The network uses a session border controller (SBC) and mini PCIe slots that allowed them to use standard mPCIe modules for Wi-Fi and Bluetooth, as well as SIM card adapters. Their project consisted of deploying the aerial network with both access point-based (AP) infrastructure modes and ad hoc modes. They were able to successfully create an internet access point through a drone which was at a height of 10 to 20 meters above the ground. Project Loon [6] was a project by Google that aimed to deliver wireless internet to under served areas and disaster areas using telecommunications equipment on high altitude balloons. These types of balloons can also be attached to drones to (1) extend drone battery life and/or to (2) increase the mobility of balloons. [7] studies the use of a controllable helium-based kite to quickly set up broadband networks for US Army deployments in Afghanistan. Radio antenna mounted on the kite communicated with a geostationary satellite and achieved upstream and downstream flows on the order of 5 and 20 Mbps respectively.

Researchers have also investigated the integration of the "airborne tier", e.g., drones, unmanned air vehicles (uav), and high altitude balloons, with the "space tier" satellite systems to supplement the terrestrial cellular system [8]. Terrestrial systems are located in population centers with substantial physical infrastructure and do not reach remote and rural areas. While the satellite system provides global access, it is limited by long propagation delays and high cost. The "airborne tier" can provide base stations and relays to extend either satellite or terrestrial wireless services to locations that lack a strong telecommunications infrastructure [9], [10], [11], [12], [13], [14], [15].

A major barrier to providing airborne wireless service has been the need for rapid, adaptive network coordination and management. This paper promotes the use of software defined networks (SDN) to fulfill this role. SDN is a routing and networking concept that separates the control plane from the data plane, and provides a network controller, consisting of the software built with applications written on a high level code. SDN provides management of routing tables, protocols and algorithms in the path selection of the control plane, leaving the data plane capabilities to the access points and base stations of the network, decreasing the use of hardware reconfiguration in a network. Furthermore, low battery capacity often limits the flight time of many drones. To tackle these shortcomings, energy efficient designs and operations, such as reducing processing power consumption, reducing payload and body weight etc. are needed for maximum usage. The use of SDNs can reduce energy consumption in the network by avoiding bottlenecks, managing the ports used, and implementing dynamic load balancing algorithms [16].

This paper aims to combine these two impacting technologies and their benefits to bring connectivity and networking capabilities to hard-to-reach regions, including geographically remote regions, rural areas; disaster areas; or tactically deployed areas, where the cellular infrastructure may be absent, damaged or destroyed. Using a central station as the SDN controller, and drones as mobile access points (APs), controlled by the central station, we show that creating a dynamic mobile mesh network is feasible. Section II presents the system architecture, as well as considerations for hardware implementation, and Section III presents the Mininet simulation and performance evaluation, and Section IV concludes the paper.

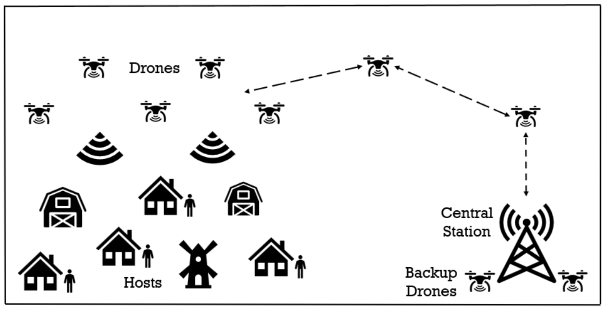

Fig. 1. Coneptual Topology for Network Service Delivery. An SDN controller at a Central Station deploys connected drones (Mobile Access Points)

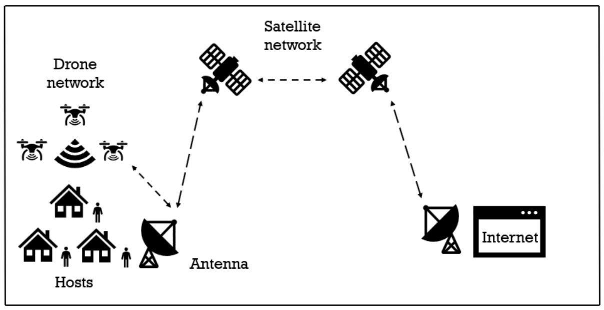

Fig. 2. Conceptual Topology for Internet Access. Satellite SDN controller and satellite network integrated with the drone network.

II. System Architecture Considerations

An conceptual illustration of an architecture for an airborne drone telecommunications network is provided in Figure 1, in which the SDN controller guides the drones to position themselves over the desired area. The drones act as mobile access points delivering the network services from the central station to the target area. Backup drones are positioned at or near the central station for fault tolerance/ redundancy.

Using a cloud SDN controller instead of the central station controller would not add more hardware to the system. Integrating the drone network with a small satellite system in a central location would also enable drones to be used as Access Points to expand satellite network access to all users in the region. Figure 2 shows the conceptual satellite topology. One candidate satellite system is the Starlink project which aims to bring Internet access all around the world at a reduced price, especially in places where internet access was not available before [17]. Ground stations on the Earth broadcast the signals to satellites in orbit, which can then relay the data back to users on Earth, with an original download internet speed of 1Gbps, and a latency around 30ms. To use a Starlink device as a controller, the topology would replace the central station with Starlink kit ground hardware with a clear view of the sky, an antenna (satellite dish) to send/receive 5G signals, a Wi-Fi router, power supply, cables and a mounting tripod.

We have discussed conceptual representations of the architecture. Next, we present technical information about drone and hardware considerations, including system requirements, power constraints and connection capabilities, as well as candidate devices to meet these constraints.

A. Drones

The number of drones needed to be deployed to provide Wi-Fi services in a given area depends on the desired coverage for the area of interest and the connection capability of the selected Wi-Fi technology. Typical Wi-Fi technology can have a range of around 300 feet. Connectivity must be maintained long enough to achieve a satisfactory data exchange. Typical flight time for most high-quality drones is about 20 minutes which is not a very long time to maintain connectivity. The following drones were selected as candidates due to their size, flight times, and power consumption.

1) ARRIS M900 4 axis Quadcopter [18]: This drone provides capabilities for long flight times at about 60 minutes with 6.7Kg takeoff weight and 30 minutes with 9.7Kg takeoff weight. This is compatible with 6S 22.2v 12000mah to 25000mah.

2) ZD550 Pro 550mm 4 Axis [19]: This drone is a carbon fiber umbrella folding quadcopter combo with motorized propellers. It has a flying time of 20 minutes with a 4s 10000mah battery.

3) ARRIS M700 Umbrella [20]: This is another foldable carbon fiber hexcopter frame kit that is compatible with the aspects of the ZD550.

4) Tarot Peeper Long Flight Quadcopter Super Combo TL750S1 [21]: This drone can fly for approximately 47 minutes with a 6S 10000mah Lipo battery.

For continuous power, drones can be equipped with power cord tethers, which connect the drone to a ground-based generator. The tethers can be made of 18 gauge wire and capable of carrying 400V DC current. Tethers enable drones to stay in the air for an extended period of time, even in rough weather conditions. If the tether is disconnected for some reason, the drones can be programmed to switch to a backup battery.

For tetherless drones, the onboard computer must be small enough to be carried by the drone and must not consume energy at a rate that requires a significant portion of the battery power.

B. On-board Computer

To provide control, we propose single board computers. A single-board computer (SBC) is a complete computer built on a single circuit board, with microprocessor(s), memory, input/output (I/O) and other features required of a functional computer. It has a small form factor, low power consumption, open specifications and hardware information for maker-friendly expansions, and open software support. Another, less powerful options is to use launchpads, inexpensive Texas Instruments (TI) prototyping tools that provide on-board emulation for programming and debugging. LaunchPads are included because they perform better than SBC with respect to power consumption.

1) SimpleLink Wi-Fi CC3235S dual band Launchpad [22]: This is a single chip security and wireless microcontroller which integrates a user application dedicated ARM cortex MCU and a network processor that runs 2.4GHz and 5GHz Wi-Fi internet, and security protocols. It is very popular to implement IOT projects and mesh networks. Wi-Fi TX power is 2.4 GHz 16dBm at 1 DSSS, 5GHz 15.1 dBm at 6 OFMD. Wi-Fi RX sensitivity is 2.4 GHz -94.5 dBm at 1 DSSS, 5GHz -89 dBm at 6 OFMD.

2) TI CC3100MODBOOST [23]: This board integrates protocols for Wi-Fi and internet which greatly minimize host software requirements. TXpower is 17dBm at 1 DSSS, 17.25 dBm at 11CCK and 13.5dBm at 54 OFDM. The RX sensitivity is -94.7dBm at 1 DSSS, -87 dBm at CCK and, -73 dBm at 54 OFDM.

C. Session Border Controllers

In the interest of energy efficiency, more power may be required to drive the Wi-Fi network. In this case, we consider the use of session board controllers. Raspberry pi 4 provides Wi-Fi cards that can be added. It allows for a PCIE 2x1 socket which enables broader use of stronger antennas such as the EDUP PCIe Wi-Fi 6 card 2x 6dBi high-gain antennas. However, these are likely to limit the drone choice and increase the energy consumption. Instead, a few competitors were selected which have the required functionality.

1) Rock Pi X B4E32 [24]: This one can run windows 10, is a compact size, 85mm x 54mm (Raspberry Pi form factor) and includes both 802.11 ac Wi-Fi and Bluetooth 4.2 with an onboard antenna and external support. This board also provides a gigabit Ethernet (GbE) LAN with power over the Ethernet (PoE) support.

2) Rock PI 4 model C [25]: This one has similar dimensions, 85mm x 54 mm, and provides 802.11ac Wi-Fi and Bluetooth 5.0, an on board antenna, and GbE LAN with PoE support.

D. Software-Defined Network Management

As mentioned previously, SDN is becoming established as a networking infrastructure that supports the dynamic nature functions of future networks with simplified hardware and adaptation of network behavior through software. It's many benefits, such as lower costs, adaptability, and downloadable network reconfiguration is found to be suitable for drones mobile access point networks [26].

As shown in Figure 3, the main characteristics that differentiate SDN other network layer architectures are:

- Differentiation and separation of the control plane and the data plane of the switching hardware.
- Using software for the control plane functions, reducing hardware usage and requirements. That software is known as a controller, which is centralized and has a complete view of the network.
- Open interfaces between the controllers and the devices located in the data plane, which in this case will be the drones.

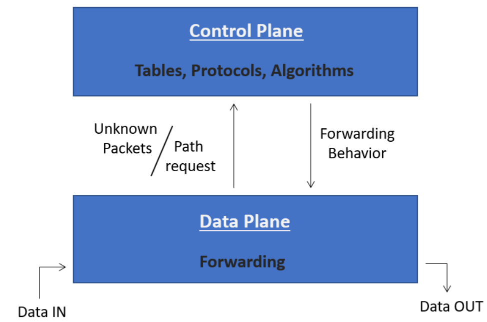

Fig. 3. SDN Separation of Control Plane and Data Plane

- Customization of the controller through applications that can be programmed by any external source or user, which will be essential when adapting the controller to the drone network.

The traditional SDN is deployed in a centralized architecture with a single controller entity that organizes and manages the entire network. This allows for all information to be gathered in a single location to form a critical global view describing the performance of each device within the network and the network performance as a whole. In this architecture permission must be granted by the controller for the source node to communicate with the destination node. The network can operate with a a duplicated controller architecture in which multiple controllers manage the same switching device(s). This redundant architecture sacrifices some of the network performance in order to guarantee fault tolerance, if one of the controllers fail, with no additional controller failover latency included. In distributed and decentralized SDN architectures, the cluster of controllers share a distributed data storage. The distributed architecture differs when it comes to granting controllers access to information in the shared storage and evenly load balancing the workload between the controllers. Implementing a distributed architecture requires distributed operations between controllers with node localization and resource management, reactive or proactive path planning, and developing network protocols for security and scalability [27].

A centralized controller communicates with every node in the network. This approach puts a heavy load on the device and compromises the entire system when under attack. Alternatively, an SDN architecture with distributed controllers offers better scalability and security. [28] demonstrates that distributed controllers also decrease the time required for processing LLDP packets by half in large network topologies. Also, SDN control enables AI-enhanced autonomous decision-making, and an implementation Blockchain would provide highly secure communication in large-scale and distributed networks, making these technologies highly beneficial for managing drone fleets [29].

1) Ericsson: An Ericsson, or similar, cloud based SDN controllers has the benefit of configuring the controller apps and accessing all the information in real time from anywhere

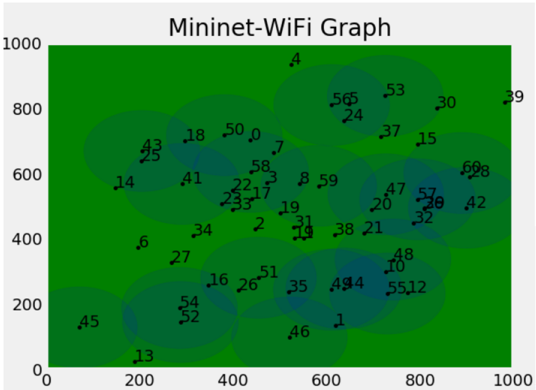

Fig. 4. Example of a dynamic topology run in Mininet-WiFi, with 40 hosts and 20 drones (APs).

with a connection. The negative side is the cost of accessing the Ericsson services, being dependent on the external connectivity control, and losing the control of the network topology when there is no connection.

2) ONOS [30]: An ONOS controller, which will be discussed in more detail in a later section, is an open source controller, which has no cost to its implementation. The downside is that to implement this system the designer must physically and manually install it and its applications, and must monitor the controller and the network.

III. Simulations to capture network performance

For this project, we simulated wireless static hosts in the rural area with the mobile drones as APs, using Mininet WiFi to build the network illustrated in Figure 1. Mininet is a SDN network emulator that simulates virtual hosts, switches, links and controllers, that run Linux network software [31]. Mininet-WiFi is an extension that adds WiFi stations and Access Points (AP) based on wireless Linux drivers, which perfectly suits the wireless dynamic SDN network needs that are demanded for the simulations of this proposal, using mobile APs as drones. It supports OpenFlow, and it can connect to the ONOS controller selected for this project. Mininet-WiFi runs Python scripts, which gives freedom to create different topologies for different tests. Mininet-WiFi enables the creation of a custom dynamic SDN network, adding hosts and APs as needed, with user-defined ranges, speeds and paths, which enables the user to test various scenarios for connectivity and conflict.

The Mininet WiFi simulation, as shown in Figure 4, covers a 1km x 1km area with 40 hosts, and a varying number of drones (APs), with a reliability of 120 meters, according to the previously discussed real hardware that would be used when building this project. The path loss model will be $L_p(d) = L_o + 10\alpha\log(d) + X$, where L_p is the loss in propagated signal at distance d, L_o is a constant related to antenna properties, α is the path loss constant with $\alpha = 2$ representing free space, and X is the fading factor.

The mobility model used is Random Way Point (RWP) [32]. RWP provides random changes in location, velocity and

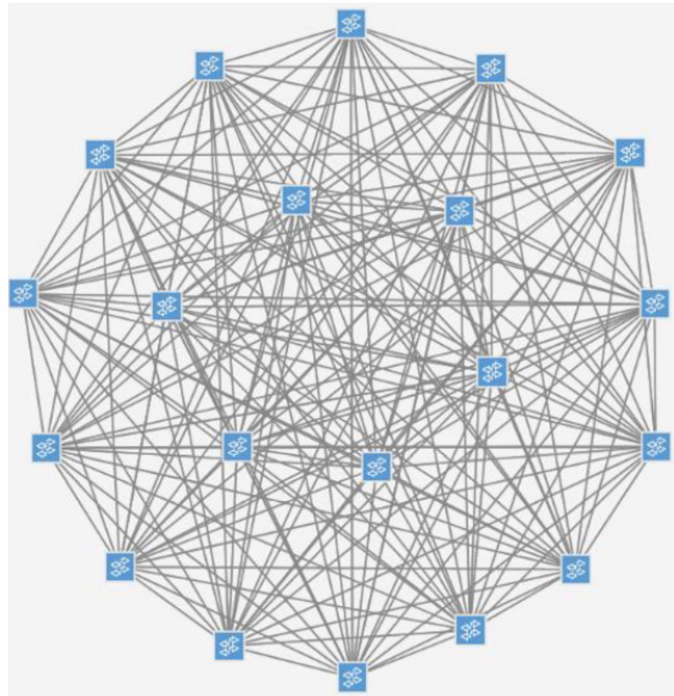

Fig. 5. Representation of a dynamic mobile mesh network of 20 drones (APs) from the ONOS GUI

acceleration of the network nodes over time. The destination, speed and direction are all chosen randomly and independently of other nodes in the successive iterations. Specficially, the parameters associated with this model are as follows:

– Speed = $[V_{min}, V_{max}]$
– Destination = [Random X, Random Y]
– Pause Time ≥ 0

Each node begins by pausing for a fixed number of seconds. The node then selects a random destination, [Random X, Random Y], in the simulation area and a random speed between minimum Speed (V_{min}) and maximum Speed (V_{max}). The node moves to this destination and again pauses for a fixed period before selecting another random location and speed. This behavior is repeated for the entire length of the simulation. RWP is not the most realistic mobility model. However, it is the most commonly used mobility model, and is useful as a reference for comparisons. Our study uses a minimum velocity of 1m/s and a maximum velocity of 14m/s. The handover association mechanism (ac_method) is least loaded first (llf).

The controller used for the Mininet WiFi simulations is the Open Network Operating System (ONOS) [30]. OpenFlow protocol is used to give access to the forwarding plane of the network switch or router, and allows the controller to determine the route of the packets across the drone network. It is layered on top of the Transmission Control Protocol (TCP) and establishes the use of the Transport Layer Security (TLS). Other ONOS applications, such as SDN IP, SDN Reactive Routing, Reactive Forwarding, Path Visualization and Segment Routing were tested and compared using dynamic mobile mesh network, as shown Figure 5. The Reactive Forwarding application provided a simpler controller while also providing most efficiency in terms of the number of packets sent and received, which allows for a longer battery life. the Reactive Forwarding application installs forwarding entries on-demand to the network switches, after a sender starts transmitting packets. When a packet is sent, the application handles the packet and configures it according to policy.

The Reactive Forwarding application works by choosing the first available path from the sender to the receiver and gives priority to the time to build the path. In this project, the application was modified to choose the best paths based on the shortest paths in terms of the number of hops, or the hop count, indicating the use of the least drones possible, using the shortest path algorithm. Based on the related work section, the application was also modified to not use the same path more than once, to avoid wearing out the network by routing through only on a few drones repeatedly. This technique is demonstrated as software code shown in Listing 1.

```
/*
    private Path pickForwardPathIfPossible(Set<Path>
     paths, PortNumber notToPort) {
        for (Path path : paths) {
            if (!path.src().port().equals(notToPort)
    ) {
                return path;
            }
        }
        return null;
    }
*/


    private Path pickForwardPathIfPossible(Set<Path>
     paths, PortNumber notToPort) {
        Path bestPath = null;
  for (Path path : paths) { //goes through all the
    paths
            if (!path.src().port().equals(notToPort)
    ) {
    if((bestPath == null) || (path.cost()<=bestPath.
    cost()) && ((path!=oldPath) || (oldPath == null)
    )){
      bestPath=path;
    }else if((bestPath == null) || (path.cost()<
    bestPath.cost()))
      bestPath=path;
            }
  }
  return bestPath;
    }
```

Listing 1. Original Java code in the commented upper part vs modified code in the lower section

A. Experimental Analysis

We tested various scenarios to determine the performance of the drone network with respect to path establishment delay, i.e., the longest time to create a routing path between the source and destination, and the packet loss for several sets of drones. Obviously, in the best case scenario simulated, the drones and the hosts would be static and they would all be able to connect to each other. All packets would be received. However, that is not a realistic approach, since the drones and the hosts will be moving around the area of the network. We simulated the other extreme, where every element of the network is constantly moving.

# of drones	Longest time to create a path	% of packages lost
9	1 ms	-
14	3 ms	+21%
20	41 ms	+23%

Fig. 6. Comparison of path establishment delay and packet loss

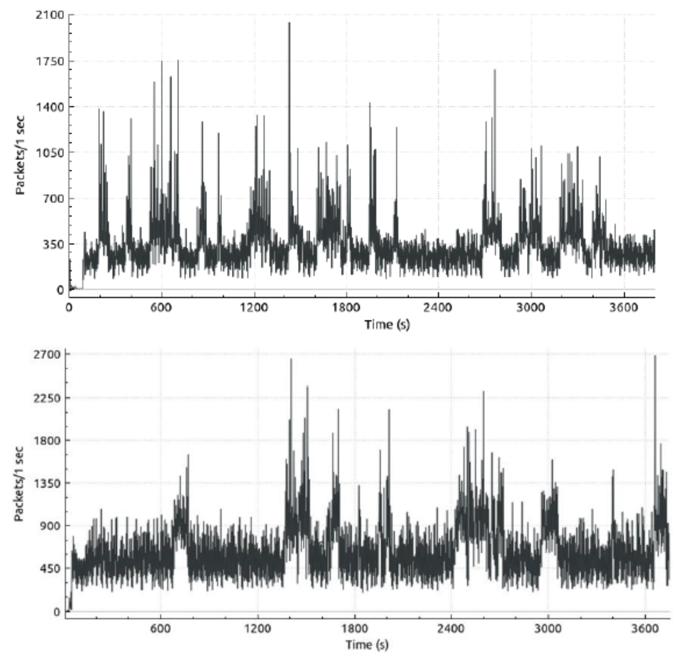

Fig. 7. Packet flow in the drone network. On top is a network with 9 drones and the bottom graph is a network with 14 drones.

The table in Figure 6, shows the impact of the number of drones. The more there are mobile drones in the network, the longer the time for the controller to create a path from source to destination. Because of the lack of stable paths, the number of packets lost increases.

The packet flow, in packets per second, can be seen in Figure 7. The Wireshark tool was used to observe packet exchanges in a drone network with 9 drones and a drone network with 14 drones. Moment by moment the affect of the controller having to deal with more APs can be observed. The larger peaks in the graphs show the impact of the information exchanges with the controller to modify the routing paths. The smaller peaks are related to sending information from host to host. On the other hand, on the upper graph, since there are fewer APs, less information is exchanged for AP path reconfiguration and there are more low peaks for host-to-host information exchange. The controller can get saturated with too many mobile APs, but with too few mobile APs, some packets may not find their destination. A study of the network, its area, topology and user behavior has to be implemented so that the optimal number of drones can be deployed to have the best possible performance of the network.

IV. Conclusion

In this paper, possibilities and scenarios to give connectivity using drones were discussed, and networking capabilities using software defined networking as a controlling system were examined. A detailed study of available hardware has been provided, with a selection of hardware configurations that could be most successfully combined. Simulation studies have shown that as the number of drones (APs) increase in the network, the more saturated the controller becomes with repeatedly updated and selecting shortest path routes. There is a need to study the mobile topology in the areas where networks will be deployed, to launch an adequate number of drones that will provide proper connectivity to rural areas. Furthermore, the shortest path algorithm process may create too many delays and needs to be replaced with a fast, adaptive approach, that preserves energy while determine a good path through the network. Further modification of the ONOS applications can be implemented as well, to make the operation of the SDN controller more energy efficient, giving a longer battery life for the drones that will act as the access points in the network.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant Number 2030122.

References

[1] M. Gharib, S. Nandadapu, and F. Afghah, "An exhaustive study of using commercial lte network for uav communication in rural areas," in *IEEE International Conference on Communications Workshops*, 2021, pp. 1–6.

[2] H. C. Nguyen, R. Amorim, J. Wigard, I. Z. Kovacs *et al.*, "Using lte networks for uav command and control link: A rural-area coverage analysis," in *IEEE Vehicular Technology Conference*, 2017, pp. 1–6.

[3] H. C. Nguyen, R. Amorim, J. Wigard, I. Z. Kovács, T. B. Sørensen, and P. E. Mogensen, "How to ensure reliable connectivity for aerial vehicles over cellular networks," *Ieee Access*, vol. 6, pp. 12 304–12 317, 2018.

[4] G. Faraci, A. Raciti, S. Rizzo, and G. Schembra, "A 5g platform for unmanned aerial monitoring in rural areas: Design and performance issues," in *IEEE Conference on Network Softwarization and Workshops (NetSoft)*, 2018, pp. 237–241.

[5] A. Guillen-Perez, R. Sanchez-Iborra, M.-D. Cano, J. Sanchez-Aarnoutse, and J. others Garcia-Haro, "Wifi networks on drones," in *ITU Kaleidoscope: ICTs for a Sustainable World (ITU WT)*, 2016, pp. 1–8.

[6] L. Nagpal and K. Samdani, "Project loon: Innovating the connectivity worldwide," in *IEEE International Conference on Recent Trends in Electronics, Information and Communication Technology (RTEICT)*, 2017, pp. 1778–1784.

[7] I. Bucaille, S. Héthuin, A. Munari, R. Hermenier *et al.*, "Rapidly deployable network for tactical applications: Aerial base station with opportunistic links for unattended and temporary events absolute example," in *IEEE Military Communications Conference*, 2013, pp. 1116–1120.

[8] G. Giambene, E. O. Addo, and S. Kota, "5g aerial component for iot support in remote rural areas," in *IEEE 2nd 5G World Forum (5GWF)*, 2019, pp. 572–577.

[9] G. Geraci, A. Garcia-Rodriguez, M. M. Azari, A. Lozano, M. Mezzavilla, S. Chatzinotas, Y. Chen, S. Rangan, and M. Di Renzo, "What will the future of uav cellular communications be? a flight from 5g to 6g," *IEEE Communications Surveys Tutorials*, pp. 1–1, 2022.

[10] J. Li, S. Alian, M. S. A. T. Zadeh, B. Maharjan, and Y. Bai, "Drone-assisted fog-cloud iot content service platform for rural communities," in *IEEE International Conference on Mobile Cloud Computing, Services, and Engineering (MobileCloud)*, 2020, pp. 39–46.

[11] V. Hassija, V. Saxena, and V. Chamola, "A blockchain-based framework for drone-mounted base stations in tactile internet environment," in *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2020, pp. 261–266.

[12] Y. Zhang, T. Arakawa, J. V. Krogmeier, C. R. Anderson, D. J. Love, and D. R. Buckmaster, "Large-scale cellular coverage analyses for uav data relay via channel modeling," in *IEEE International Conference on Communications (ICC)*, 2020, pp. 1–6.

[13] M. Gapeyenko, I. Bor-Yaliniz, S. Andreev, H. Yanikomeroglu, and Y. Koucheryavy, "Effects of blockage in deploying mmwave drone base stations for 5g networks and beyond," in *IEEE International Conference on Communications Workshops (ICC WKSHPS)*, 2018, pp. 1–6.

[14] I. Bor-Yaliniz and H. Yanikomeroglu, "The new frontier in ran heterogeneity: Multi-tier drone-cells," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 48–55, 2016.

[15] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Drone small cells in the clouds: Design, deployment and performance analysis," in *IEEE Global Communications Conference (GLOBECOM)*, 2015, pp. 1–6.

[16] P. Fondo-Ferreiro, M. Rodríguez-Pérez, and M. Fernández-Veiga, "Implementing energy saving algorithms for ethernet link aggregates with onos," in *International Conference on Software Defined Systems (SDS)*. IEEE Spain, 2018, pp. 118–125.

[17] J. Callaham, "What is starlink? elon musk's satellite internet service explained," https://www.androidauthority.com/what-is-starlink-1134426/ Last accessed April 5, 2022., November 2021.

[18] Arris Hobby, "Arris m900 4 axis quadcopter frame kit good for long flight time drone with motor/esc/propeller (unassembled)," https://arrishobby.com/products/arris-m900-4-axis-quadcopter-frame-kit-good-for-long-flight-time-drone-with-motor-esc-propeller-unassembled?VariantsId=13522 Accessed October 2022.

[19] ——, "Zd550 pro 550mm 4 axis carbon fiber umbrella folding quadcopter combo with motor esc propeller," https://arrishobby.com/products/zd550-pro-550mm-4-axis-carbon-fiber-umbrella-folding-quadcopter-combo-with-motor-esc-propeller Accessed October 2022.

[20] ——, "Arris m700 umbrella foldable carbon fiber hexacopter frame," https://arrishobby.com/products/arris-m700-umbrella-foldable-carbon-fiber-hexacopter-frame Accessed October 2022.

[21] RCWing, "Tarot peeper long flight quadcopter super combo tl750s1," https://www.rc-wing.com/tarot-reeper-quad-combo.html Last accessed October 2022.

[22] Texas Instruments, "Simplelink wi-fi cc3235s dual band launchpad development kit," https://www.ti.com/tool/LAUNCHXL-CC3235S Last accessed April 5, 2022.

[23] ——, "Simplelink™ wi-fi® cc3100 wireless network processor boosterpack™ plug-in module," https://www.ti.com/tool/CC3100BOOST Accessed October 2022.

[24] Radxa, "Rock pi x," https://wiki.radxa.com/RockpiX Accessed October 2022.

[25] Adafruit, "Raspberry pi the compute module 4 io board," https://www.adafruit.com/product/4787 Accessed October 2022.

[26] S. Sezer, S. Scott-Hayward, P. K. Chouhan, B. Fraser, D. Lake, J. Finnegan, N. Viljoen, M. Miller, and N. Rao, "Are we ready for sdn? implementation challenges for software-defined networks," *IEEE Communications magazine*, vol. 51, no. 7, pp. 36–43, 2013.

[27] A. C. Starke, "Development of sdn architectures for management and security of wireless and mobile systems," Ph.D. dissertation, University of Florida, 2020.

[28] A. Starke and J. McNair, "Load balanced controller association in wireless distributed sdns," in *IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, 2020, pp. 1–2.

[29] R. Gupta, A. Kumari, and S. Tanwar, "Fusion of blockchain and artificial intelligence for secure drone networking underlying 5g communications," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 1, p. e4176, 2021.

[30] Onos, "Open network operating system (onos)," https://wiki.onosproject.org/display/ONOS/ Accessed April 5, 2022.

[31] Mininet, "Mininet," http://mininet.org/ Last accessed April 5, 2022.

[32] C. Bettstetter, G. Resta, and P. Santi, "The node distribution of the random waypoint mobility model for wireless ad hoc networks," *IEEE Transactions on mobile computing*, vol. 2, no. 3, pp. 257–269, 2003.