AN INTEGRATED SIMULATION PLATFORM FOR THE ANALYSIS OF UAS BVLOS OPERATIONS SUPPORTED BY 4G/5G COMMUNICATIONS

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Abstract

Secure and stable command and control (C2) data links can be established over cellular networks for various types of UAS missions. The planning of UAS traffic and the provision of cellular communication resources are cross-coupled decisions and should be analyzed together. The key to effective planning is the accurate estimation of communication link quality and resource usage for a given air traffic requirement. In this work, a simulation and modelling framework is developed that integrates two open-source simulation platforms, Repast Simphony and ns-3, to generate UAS missions over different geographical areas and simulate the provision of 4G/5G cellular network connectivity to support their C2 and mission data links. To the best of our knowledge, this is the first simulator that co-simulates air traffic and cellular network communications for UAS while leveraging standardized 3GPP propagation models and incorporating detailed management of communication channels (i.e., resource blocks) at the cellular base stations. We use three examples to showcase how the simulator can be used to provide guidelines in communication resource allocation, air traffic management, and mission safety management in beyond visual line of sight (BVLOS) operations.

Introduction

The introduction of unmanned aircraft systems (UAS) into urban and rural airspace environments is of great interest to many industries that can leverage their capabilities to provide new services. The air traffic demands from new entrants in low-altitude airspace will need to be supported by a reliable and secure communication infrastructure that can establish secure and stable command and control (C2) data links over cellular networks for various types of commercial UAS missions (e.g., package delivery, bridge inspection, etc.). In this work, a simulation and modeling framework is developed that integrates two open-source simulation platforms, Repast Simphony [1] and ns-3 [2], to generate UAS missions over different geographical areas and simulate the provision of 4G/5G cellular network connectivity to support their C2 and mission data links. Various scenarios have been run in the integrated simulation platform which leverages standardized 3GPP propagation models and detailed management of the communication channels (i.e., resource blocks) at the cellular base stations to identify the impacts of UAS-to-base station distance, UAS mission scheduling, mission requirements, and RF interference on the viability of using the cellular network infrastructure to support different UAS air traffic demands.

Beyond visual line of sight (BVLOS) operations are increasingly being considered to extend the use of UAS in civilian applications. To achieve this, a reliable C2 link is critical for the safe operation of unmanned aircrafts. To ensure the safety of the UAS, constant communication between the UAS and their ground control center must be maintained. Therefore, it is important that the C2 link can guarantee a minimum throughput at all times in flight during the mission. In addition to the C2 link, a communication link to relay data related to specific missions that each unmanned aircraft will conduct is also necessary. However, the transmission of mission related data has little impact on flight safety and its timing is more flexible compared to the C2 data. The mission link may not need to be active in every segment of the aircraft's trajectory, but only when data related to the mission needs to be transmitted (e.g., during picture and/or video transmission when aiming to complete an infrastructure inspection mission once the infrastructure site has been reached). Hence, in this work, we focus on the C2 link communication quality.

LTE/5G networks could be used to provide C2 communication links and mission data links for UAS operations. To leverage these networks, several factors such as the location of LTE/5G ground base stations, effective communication coverage areas and interference, among others need to be considered [3]. The availability of the communication resources will impact the decisions related to UAS traffic management. There is a strong interplay between the air traffic density that can be supported in a region and the amount and quality of communication resources available in the same region. Thus, effective air traffic management that is aware of the state of the communication network will eventually determine the scale of UAS applications/services that can be supported in a particular air space and within the capabilities of existing communications infrastructure.

Our results provide guidelines for how 4G/5G cellular networks can support UAS based services. In particular, how capacity and coverage should be managed to provide a secure and feasible operational environment. We aim to develop a framework that also provides guidelines on the design and use of cellular network infrastructure to guarantee that the quality of cellular network communications can achieve the levels necessary to support UAS BVLOS operations.

This paper is organized as follows: First, we present a brief overview of previous work related to using cellular networks to support UAS operations. Second, we provide a description of the characteristics of 4G/5G networks that need to be taken into account to evaluate their feasibility to support BVLOS UAS operations. Afterwards, we describe our co-simulation approach and the developed software platform. Additionally, we provide the experimental results for three scenarios we simulated, which illustrate the key capabilities of our platform and provide insights on the inter-relationship between air traffic density and communication resource usage. Finally, conclusions and perspectives for future work are provided.

Background and Motivation

In the past, Wi-Fi based wireless local networks (WLANs) were typically used to provide connectivity between a UAS and its ground control station (GCS) [11]. As the interests and potential commercial applications for UAS expand to activities where operation beyond visual line of sight (BVLOS) is needed, a Wi-Fi connection is no longer sufficient. A wireless communications infrastructure with long range coverage and sufficient spectral resources is needed to support the transmission of the C2 messages between the GCS and the UAV. Additionally, the same communications infrastructure may also support the transmission of the data payloads relevant to the UAV's service or mission. In recent years, cellular networks have been proposed to support UAS communication needs [4][5]. The existing LTE/5G infrastructure is ready to provide low latency and high data rates, and both characteristics are highly desirable in UAS commercial applications [6][7][8][9][10]. In this work, we focus our analysis on LTE and 5G based approaches to support BVLOS operations.

Recent studies on cellular UAV communications typically measure the quality of communication by the signal-to-noise ratio (SNR) of the link between the UAS and the GCS. In [12], a UAS trajectory optimization algorithm is presented, and for a single UAS, the most energy efficient trajectory is sought while making sure that the SNR of the UAS-to-base station connection is above a given threshold. The authors in [13] perform simulations to find the communication quality based on a specific propagation model. Only SNR is considered in the model. However, SNR is not sufficient in measuring the quality of the wireless channel. A more accurate metric is the signal-to-interference-plus-noise ratio (SINR). Secondly, as we will discuss in the next section, the achievable throughput of cellular communication is determined by two factors, the SINR of the channel, and the amount of available communication resources, i.e., resource blocks. If a connection has low SINR, then more resource blocks must be allocated to achieve the desired communication throughput. The decrease in the communication throughput is directly caused by the lack of resource blocks, which can be mitigated by either increasing the SINR or allocating more resource blocks. The relationships among the SINR, resource blocks and communication throughput are highly complicated especially in a dynamic environment with multiple UAS and GCS. No simple analytical model is currently available. Furthermore, the SINR of the channel in cellular networks highly depends on the distance between the user and base station and the local environment of the user. Hence, to determine the communication quality for UAS air traffic, we need a simulator that (1) has a full-fledged propagation model, (2) can accurately simulate the spectrum resource management performed by the base stations, and (3) can track the trajectories of each UAS at every time step.

To the best of our knowledge, there has not been a simulator that jointly simulates the UAS air traffic and the status of their communication within the cellular network. The only related studies are communication simulations for autonomous vehicles [16] [19]. These simulators cannot directly be used for UAS systems. First of all, the traffic simulators for autonomous vehicles are based on predefined road networks, which may not be applicable to UAS traffic. Furthermore, these simulators emphasize on vehicle-to-vehicle (V2V) communication [15], which is based on dedicated short-range connections. The UAS trajectory is more flexible than that of ground vehicles, and the relative positions among UASs are more fluid during flight. Therefore, V2V communication is not a focus in our simulations.

Using LTE/5G Networks to Support UAS BVLOS Operations

In our work, to determine the viability of LTE/5G networks to support commercial UAV operations in urban and rural environments, we focus on the key elements of the physical layer of the network. In LTE networks, the mobile terminal is referred to as the UE (User Equipment) and the base station that terminates the wireless interface protocol and is the first point of contact for the UE is referred to as the eNode-B (eNB). Other components of the LTE architecture are not directly monitored in our simulations but their operation is taken into account as each LTE capable wireless interface in the UAS is a UE that participates in the LTE network within the area under study (rural or urban).

An LTE network operator will configure each eNB to provide wireless services over a given channel bandwidth. That bandwidth is managed as a set of resource blocks which, when assigned to UEs, allow the UEs to communicate. The resource block is the basic element of radio resource assignment in LTE networks (and similarly in 5G networks with several differences). In LTE, one resource block (RB) contains 12 sub-carriers of 15KHz each, making the total bandwidth of one RB equal to 180 KHz. The mapping between eNB transmission bandwidth and RBs is shown in Table 1.

Table 1 Transmission bandwidth configuration

Transmission Bandwidth (MHz)	1.4	3	5	10	15	20
Max. number of Resource Blocks	6	15	25	50	75	100

Table 2 SINR and CQI mapping [21]

SINR [dB]	**CQI code**	**Modulation**	**Code Rate**	**Spectral efficiency**
-6.7	1	QPSK	0.076	0.15
-4.7	2	QPSK	0.12	0.23
-2.3	3	QPSK	0.19	0.38
0.2	4	QPSK	0.3	0.6
2.4	5	QPSK	0.44	0.88
4.3	6	QPSK	0.59	1.18
5.9	7	16QAM	0.37	1.48
8.1	8	16QAM	0.48	1.91
10.3	9	16QAM	0.6	2.41
11.7	10	64QAM	0.45	2.73
14.1	11	64QAM	0.55	3.32
16.3	12	64QAM	0.65	3.9
18.7	13	64QAM	0.75	4.52
21	14	64QAM	0.85	5.12
22.7	15	64QAM	0.93	5.55

Depending on noise and interference conditions, a Channel Quality Indicator (CQI) value is determined for operations within the eNB’s bandwidth. The CQI is a 4-bit integer value and is based on the observed SINR at the UE. The UE and eNB interact to determine the CQI value and based on it the eNB selects an optimum Modulation and Coding Scheme (MCS) for transmission that will be used over the set of RBs that will carry the UE’s payload at a given point in time. Overall, the CQI reported values are used by the eNB for downlink scheduling and link adaptation in LTE. The relationship between SINR, CQI and other LTE performance parameters is shown in Table 2.

The relationship between SINR to CQI to Resource Block assignments from an eNB to a UE plays an important factor in enabling effective and reliable communications to UAVs using a 4G/5G network. When relying on an LTE/5G network to provide C2 communications for UAV operations, the density of LTE ground base stations needs to be taken into account. In urban environments, the base stations will be densely distributed while in rural environments, the density of base stations may be sparser. In both cases, maintaining reliable connections may require the use of interference cancellation and antenna beam selection methods [22] [23].

Possible network congestion or outages will lower airspace capacity by limiting the amount of UAV data (for C2 and mission links) that can be handled by a specific eNB or a collection of them, which in turn limits the number of UAVs that can be in flight. Due to the inter-relationship between UAV air traffic density and communication resources in the network, traffic management policies will be required to dynamically take into account the capabilities and capacity of the network infrastructure [14]. These policies should take into account the planning of UAV trajectories based on the measured and predicted status of communication resources to avoid congestion and scenarios where a C2 link might become unreliable and/or where a mission cannot be executed.

Air Traffic and Cellular Communication Co-simulation

Overall architecture

Our air traffic and communication co-simulator consists of two components as shown in Figure 1. On the left-hand side is the UAS traffic simulator that leverages the Multi-Agent Air Traffic and Resource Usage Simulation (MATRUS) framework developed in our previous work [14]. MATRUS is built on top of the Repast agent-based simulation platform. It simulates UAS air traffic and collects UAS mobility information. On the right-hand side is the communication simulator developed on top of the network simulator ns-3 and its LTE module. Message passing between these two components is established using a socket interface to exchange information such as UAS mobility and communication status.

The co-simulation framework allows users to model different scenarios by changing various parameters such as base station locations, number of base stations, number of resource blocks per base station, urban vs. rural propagation models, no-fly zone definitions, mission profile, among many others. The integrated simulator can produce reports that include information such as Channel Quality Indicator (CQI), Reference Signal Received Power (RSRP), Signal-to-Interference-plus-Noise Ratio (SINR), resource block (RB) usage, occurrence of handover events, etc., for each UAS at different time resolutions. The data can be mapped to the spatial temporal domain to demonstrate the change and impact of the communication environment on UAS operations. The details of the traffic simulator MATRUS can be found in [14]. We will focus on the communication simulator and the message passing interface in this paper.

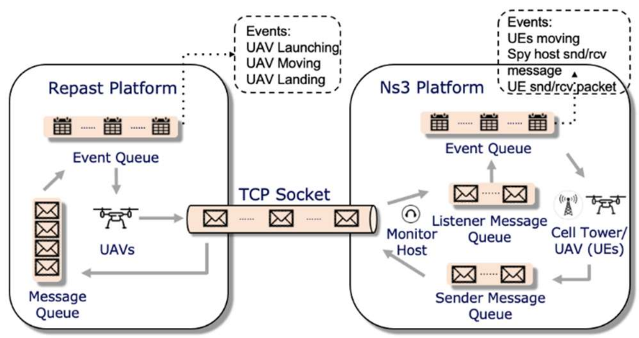

Figure 1 Integrated Simulation Platform

Communication Simulator

Ns-3 is a network simulator that models a communication network using four key abstractions: nodes, applications, channels, and net devices. The nodes represent the basic computing devices. In the LTE module, they represent the UEs and the eNBs. The applications are the basic abstractions for a user program that generates activities to be simulated. The channels model the basic communication links. And the net devices are abstracts for the software driver and the hardware that enable communications through channels. In the LTE module, the net device containers are used to install the LTE protocol stack on the eNBs and UEs respectively.

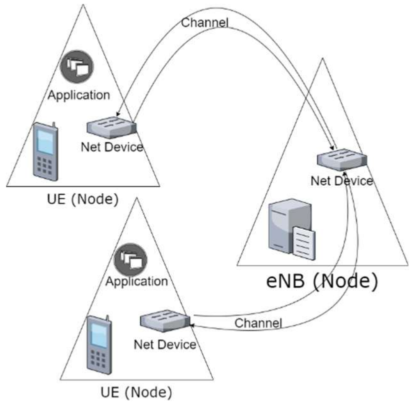

Figure 2 Basic abstractions of ns-3

In ns-3, the key communication quality metrics that we follow are SINR, RB usage, receiver/transmitter throughput (Rx/Tx throughput) and the CQI. The communication status indicators that we follow are the connection status and the handovers. We determine whether a connection exists or not from the states of the UE Radio Resource Control (RRC) module in ns-3.

The above information is queried via the event tracing mechanism supported by ns-3. The tracing mechanism provides an event triggered way to update network status. It consists of two parts: the trace source, which is the generator of data, and the trace sink, which is the consumer of provided data. The trace source provides access to the values of underlying variables of the simulator when an event of interest happens to a list of connected trace sources. The trace sink will be invoked by the trace source. It processes and moves the data from the connected trace source to the output.

In addition to the detailed but focused event tracing, to enhance the realistic nature of the simulations, a propagation model defined by 3GPP is used [24]. To apply the model, we define the 2D distance d_{2D} as the distance between the location of the eNB and the projection of the UAV on the ground, the 3D distance d_{3D}- as the real point-to-point distance between the eNB and the UAV considering their heights above a terrain height reference. We use f_c to denote the carrier frequency and h_{UT} to denote the height of the UAV. According to the guidelines from 3GPP on enhanced LTE support for aerial vehicles[24], we modified the propagation models in ns-3 as described below.

The line of sight (LOS) probability, for a rural macro (RMa) base station, is 1 for a UAV flying at a height between 40 meters and 300 meters. The path loss model is as follows:

$$PL_{RMa-AV-LOS} = \max(23.9 - 1.8\log_{10}(h_{UT}), 20)\log_{10}(d_{3D}) + 20\log_{10}\left(\frac{40\pi f_c}{3}\right).$$

The LOS probability, for an urban macro (UMa) base station, is 1 for a UAV flying at a height between 100 meters and 300 meters. The path loss model is given as

$$PL_{UMa-AV-LOS} = 28.0 + 22\log_{10}(d_{3D}) + 20\log_{10}(f_c).$$

Inter-component information exchange

The traffic and communication simulator exchange information through a TCP socket interface. The traffic simulator component will send UAV status updates such as launching, landing, and flight based movement to ns-3 and also issue commands to query communication link status. These messages and commands are sent periodically or in an event-driven manner through the TCP socket. A message monitoring service periodically fetches and processes those messages and commands from the message queue.

Instead of dynamically creating and destroying UEs during a simulation, a pool of UEs is created at the beginning of the simulation and maintained dynamically so that each one is active in the airspace only when needed. The number of UEs in the pool is decided by the maximum number of UASs that could simultaneously be in the air. The launching message contains UAS ID, coordinates of its launching location, and the ID of the cell tower that it will connect to at launch time. Upon receiving the launch message, the communication simulator moves a UE from the pool to the airspace, marks its status as busy, places it at the desired location and attaches a UAS ID to it. Connection between this UE and the targeted cell tower is established. The UE (representing a UAV) will fly to a destination based on its mission and may need to execute one or more handovers to connect to different base stations during its flight path. Once the UAV completes its mission, a landing message is sent to the communication simulator, which consists of only the UAS ID. The corresponding UE is removed from the airspace, goes back to the UE pool and its status is marked as idle. All cellular connections to this UE are disconnected.

A movement message consists of a UAS ID and its new location. It will be sent periodically for any moving UAS. It creates a mobility event in ns-3 to move the UE/UAS to the desired location. Upon receiving a query command, the communication simulator will respond with a message that consists of the communication status of the target UE, such as its SINR, CQI and Rx/Tx throughput, etc. The traffic simulator can query the status of both UAS and cellular stations and maintains an overall picture of the software agents (i.e UEs, eNBs, etc) involved in a simulation scenario.

Experimental Results and Analysis

Three experiments were set up to showcase how the simulator can be utilized in UAS traffic planning and cellular network resource provisioning. In the first experiment, we demonstrate how traffic density will affect the Rx/Tx communication throughput, and how increasing the number of RBs in the base station can help to improve the throughput to meet the requirements of the C2 link. In the second experiment, we show how simulations can be used to discover communication hotspots and prompt a new traffic pattern design by changing the location of a launching area. To show different traffic scenarios, point-to-point trajectory and Manhattan trajectory are considered in these two experiments. The last experiment considers the rural scenario, where the simulation predicts the possible lost connections in the C2 link due to low link quality (low SINR).

In the first two experiments, we consider an urban setting near Watford City, ND. A map of this area is given in Figure 3. There are two launch areas and one landing area as shown in the figure. This corresponds to a hypothetical UAS-based package delivery system where items from two warehouses are delivered to a workshop. There are 4 base stations in this area, and they are located at the center of the green circles. The information of the base stations is obtained from [25]. The third experiment considers the rural area 30 miles northeast to the Watford City.

All UASs fly at an altitude of 100 meters at about 50 mph when they are in the air. We assume that the C2 link sends and receives 10 packets every second and each packet has a size of 500 bytes. This corresponds to a data rate of 40kbps. The transmission powers of the base station and UAS are 46dBm and 15dBm, respectively. We use the 3GPP urban model as the propagation model.

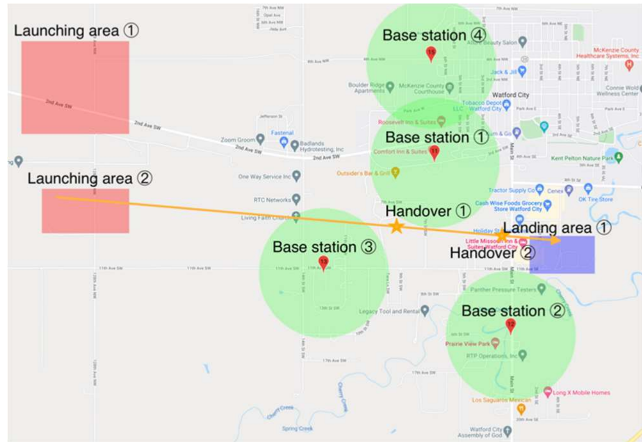

Figure 3 Environment information

All simulations collect the following cellular communication information for each UAS to eNB link: SINR, CQI, Rx/Tx throughput, connection status, and hand-over events.

Experiment 1: cellular resource provision

In this experiment, point-to-point UAS trajectories are used. First, we vary the traffic density to stress test the communication network. The departure of UASs from each launching area follows a Poisson process. The average time interval between two departures varies from 2 to 32 seconds. They correspond to high, medium and low traffic densities. The average flight time of the UASs is 221 seconds. Depending on the launch rate, the maximum number of UAS that are in the air simulatenously at any point in time varies from 26 to 203. We assume that 8 resource blocks (RBs) are dedicated in each base station to serve the UAS C2 communications.

First of all, we noticed that the SINR and CQI are not affected by the traffic density. They are determined by the position of the UAS relative to a base station. The farther away the UAS is from the base station, the lower SINR and CQI it will have. Figure 4 and Figure 5 show the SINR and CQI over the trajectory of the UAS. In both figures, the X and Y axis represents the longitude and latitude. The red

"Y" shaped marks represent the location of the base station. Each colored dot represents a possible spatial location of a UAS during the simulation, and the color represents the SINR or CQI level. As we can see, because the trajectories are relatively close to the base stations, the SINR and CQI are generally quite high. Because the CQI is directly proportional to the SINR, we can see that the color pattern of SINR and CQI distributions are very similar.

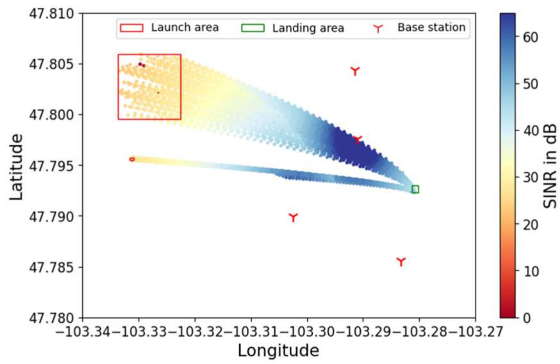

Figure 4 Heat Map for SINR distribution

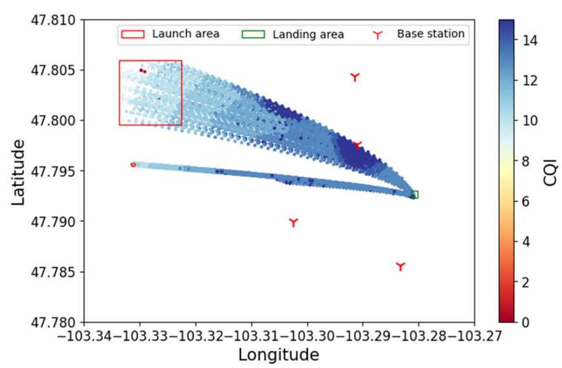

Figure 5 Heat Map for CQI distribution

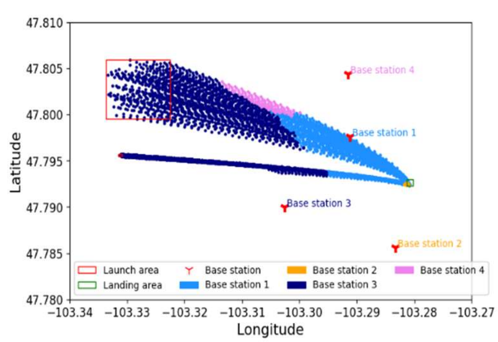

Figure 6 UAS-Base Station Connectivity

Figure 6 shows the general coverage area of each base station. In this figure, each base station is color coded. At a specific spatial location, if a UAS is connecting to a base station, that location will be marked using the color of the base station. There is no exact boundary between the coverage of two base stations. When a UAS moves away from one base station and approaches another, its connection switches from one to the other. This process is referred to as a handover. The handover is triggered by the change in the RSRQ (Reference Signal Received Quality) value. When the following three conditions hold, the UAS will disconnect from the "serving" base station and connect to the "neighbor" base station.

$$\begin{cases} RSRQ_{neighbor} - RSRQ_{serving} \geq RSRQ_{offset} \\ RSRQ_{neighbor} \geq RSRQ_{threshold} \\ RSRQ_{serving} < RSRQ_{threshold} \end{cases},$$

where $RSRQ_{neighbor}$ and $RSRQ_{serving}$ are the RSRQ level of the "neighbor" base station that the UAS is considering to switch to, and the "serving" base station that the UAS is currently connecting with. In the simulation, we set $RSRQ_{threshold}$ to be 30 and $RSRQ_{offset}$ to be 1.

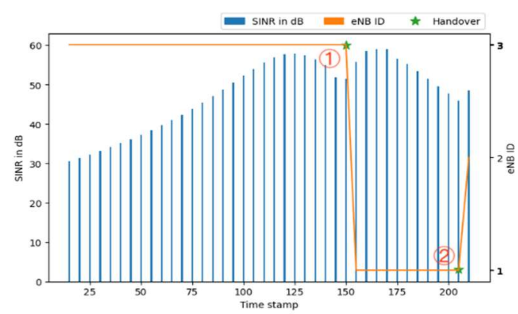

Figure 7 Handover Events and SINR Value

Figure 7 shows how the SINR changes during the handover. We picked a UAS that travels along the orange line shown in Figure 3 and recorded its SINR over time. The X-axis gives the time, and the Y-axis gives the SINR level of the UAS's cellular connection. As we can see, the SINR first increases then decreases. This is because the UAS first flies towards the base station number 3, then flies away from it. We can see that the SINR grows again, and this is when the handover occurs and the UAS switches from base station 3 to 1. This is the first handover event in the trip. Towards the end of this trip, there is another handover event, where the UAS switches from base station 1 to base station 2. The two events are labeled in Figure 3 and Figure 7 using orange circled 1 and 2. Associated with both handover events, an decrease and increase of the SINR level was observed.

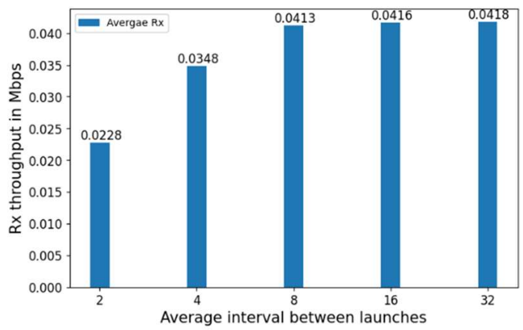

Figure 8 Average Rx/Tx throughput

We varied the average launching interval from 2 to 32 seconds, and recorded the average Rx/Tx throughput of the UASs. They are compared in Figure 8**.** The number of RBs dedicated for the C2 link in each base station is 8. As we can see, the average data communication is 22.8kbps and 34.8 kbps when the launching intervals are 2 and 4 seconds, which correspond to high traffic density. When the launching interval is 8 seconds or above, the average data communication throughput is above 41kbps. Considering that the C2 link data rate is 40kpbs, we conclude that the network can well tolerate the communication load for medium or low density traffic where the average launching interval is 8 seconds or above. The network is capable enouth to handle high density air traffic where the launching interval is 4 seconds or below.

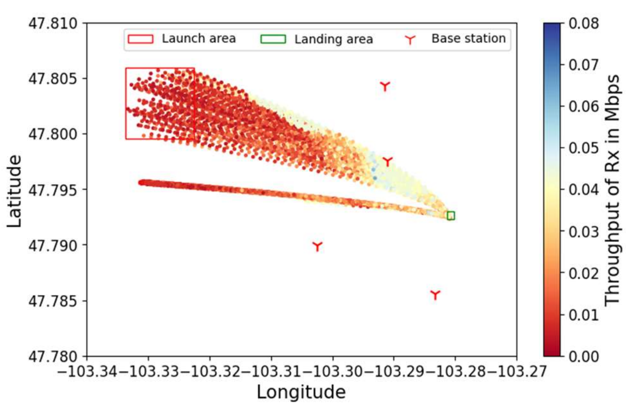

Figure 9 Rx Throughput of 8 Resource Blocks

Figure 9 plots how the Rx/Tx throughput at different locations along the UAS trajectories changes when the average launching interval is 4 seconds. We observed that the pattern of Rx/Tx hotspots does not exactly follow the pattern of SINR in Figure 4. Although they are loosely correlated, a higher SINR does not necessarily lead to higher Rx/Tx throughput.

By provisioning more resources to the base station, high density traffic can be supported. For example, when we increase the number of RBs at each eNB from 8 to 16, for heavy traffic with average launching interval equal to 4 seconds, the average Rx/Tx throughput increases to 41kbps. Figure 10 shows the Rx/Tx spatial distribution when we increased the number of RBs to 16. We can see that the hotspots are significantly reduced. Thus, using our simulator, we can find out how much RB resources need to be reserved for the C2 link.

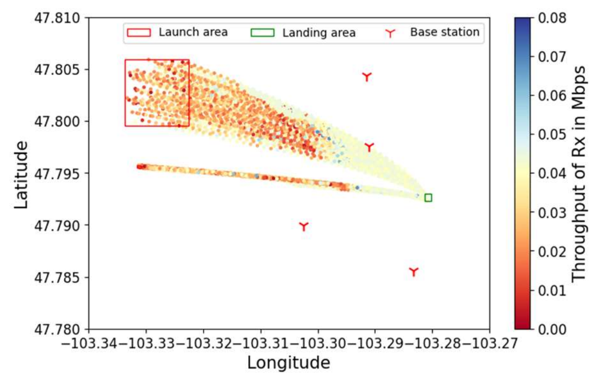

Figure 10 Rx Throughput of 16 Resource Blocks

Experiment 2: UAS trajectory planning

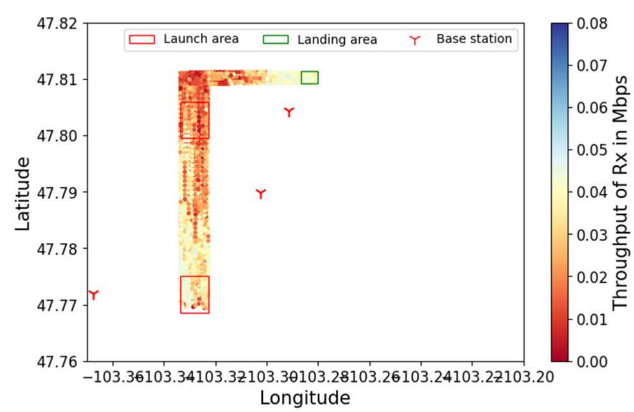

Figure 11 Rx Throughput Along UAS Trajectory

In the second experiment, again two launching areas and one landing area are considered, and Manhattan style trajectory is assumed. All UASs fly south-north until they reach the destination latitude and then fly east-west to the destination. Figure 11 shows the Rx throughput along the trajectory of the UASs. As we can see, there are large amount of hotspots. The average Rx/Tx throughput is 32.1 kbps.

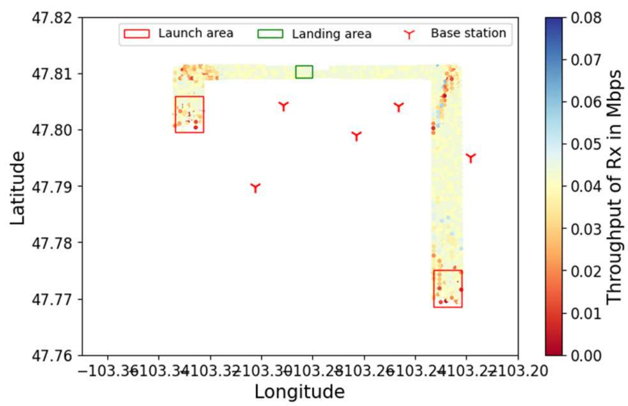

Figure 12 Rx Throughput for Modified Trajectory

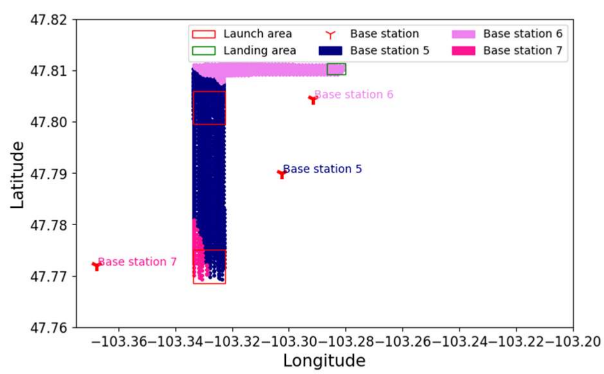

Figure 13 UAS-Base Station Connectivity for Original Trajectory

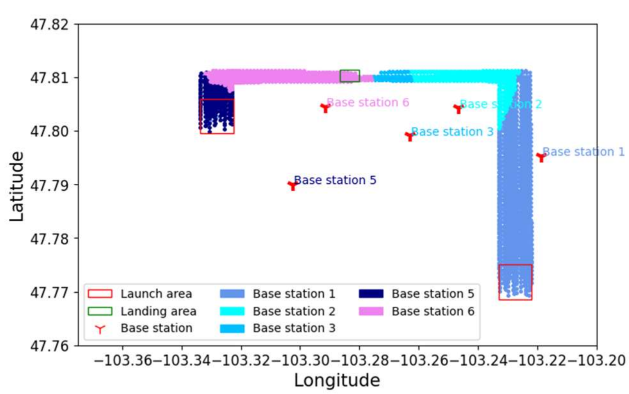

Figure 14 UAS-Base Station Connectivity for Modified Trajectory

We change the trajectory of the UASs departing from launching area 2 by moving the launching area to the right side as shown in Figure 12. This change does not change the flight distance, but significantly improves the quality of C2 communications. The average Rx/Tx throughput is now 41 kbps. Figure 13 and Figure 14 shows the connectivity between UAS and base stations. As we can see, the new traffic pattern distributes the communiation load to more base stations compared to the original one (base stations 1, 2, and 3, which original were not utilized, are not utilized), hence it can achieve a higher throughput.

Experiment 3: UAS communication in rural area

In the third experiment, we consider a rural area scenario, where a sigle UAS flies along route 10 (in North Dakota). There two base stations in this area, their locations are labeled using the red marks in Figure 15. 16 RBs are reserved for the UAS C2 link in each base station. The blue line gives the UAS trajectory. The distances from base stations to the UAS departure location labeled in the figure. During the entire trip the UAS connects only to base station 1 since it is closer. In the rest of the paper, we will drop the base station 2 from the plot and zoom into the area of UAS trajectory.

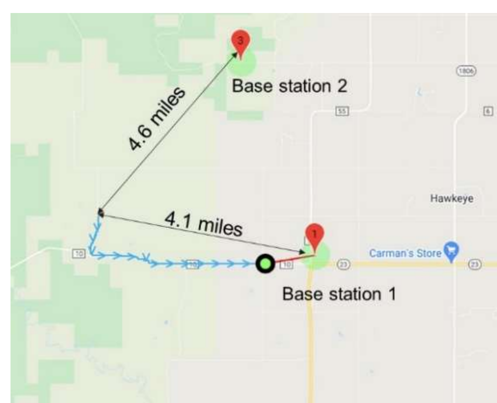

Figure 15 Map of the Rural Area

Figure 16 to Figure 18 give the SINR, CQI and Rx/Tx throughput values experienced by this UAS. Figure 19 shows the location where the UAS is not connected to any base stations. As we can see, the

SINR, CQI, and Rx/Tx rate drops as the UAS and base station distance increases. However, the Rx/Tx throughput maintains at an acceptable level. Actually, the average Rx/Tx throughput is 43kbps. This is because, despite low SINR and CQI, the base station reserves sufficient number of RBs to sustain the UAS communication requirement. However, as shown in Figure 19, very low SINR (SINR≤0) can cause disconnection between UAS and the base station, which cannot be remediated by adding more RBs. This critical information must be considered by the air traffic control during mission scheduling.

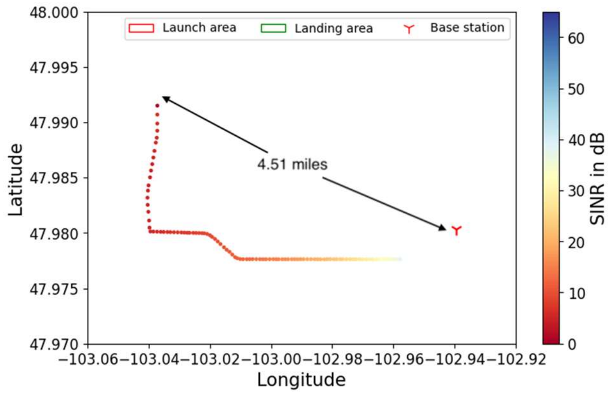

Figure 16 SINR of UAS in rural area

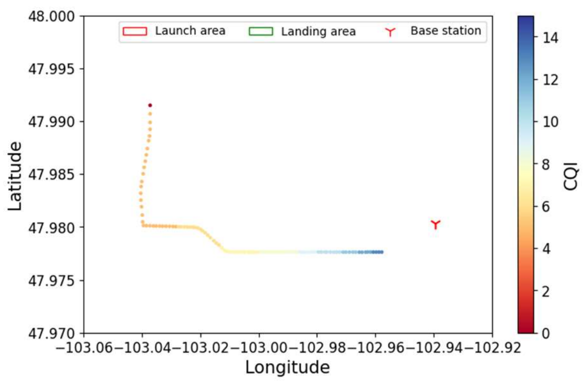

Figure 17 CQI of UAS in Rural Area

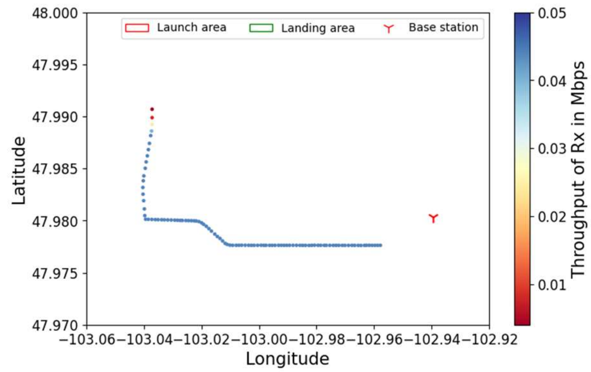

Figure 18 Rx/Tx Throughput of UAS in Rural Area

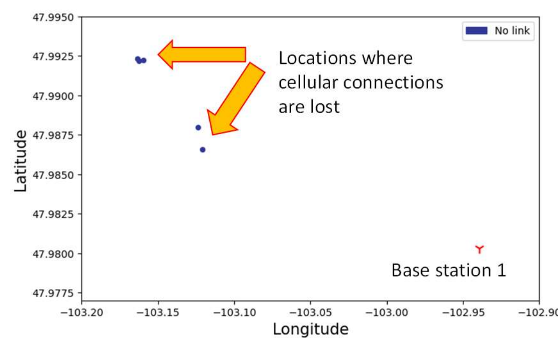

Figure 19 Locations Where Cellular Connection is Unavailable

Conclusions and Future Work

We presented an air traffic and cellular communication co-simulation framework that analyzes the data communication of UAS with a focus on the C2 link. The simulator leverages our previous UAS traffic simulator MATRUS and the ns-3 network simulator to provide a detailed analysis of how variables such as SINR, CQI, Rx/Tx throughput vary and interact with the movement and density of the UAS. The simulator also reports events such as disconnection and handover between UAS and the base stations. The simulator can help assess the viability of using the cellular network to support reliable BVLOS operations in a given geographical location by incorporating base station density, availability of spectrum resources (resource blocks), air traffic density and scheduling and flight trayectory planning. With these capabilities, research on intelligent trajectory planning or UAV scheduling for commercial BVLOS UAS operations can be carried out on this simulation platform.

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