A COST-BENEFIT ANALYSIS TO ACHIEVE COMMAND AND CONTROL (C2) LINK CONNECTIVITY FOR BEYOND VISUAL LINE OF SIGHT (BVLOS) OPERATIONS

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Abstract

Unmanned Aircraft Systems (UAS) operations are changing the way aviation and commerce are conducted today. Until recently, for civil aviation commercial operations, nearly all UAS operations are conducted within visual line of sight (VLOS). However, this severely limits the economic benefits that can be realized by the use of these unmanned, and someday, autonomous systems.

Beyond visual line of sight (BVLOS) operations require much more capabilities for the operator to rely on and for the general public to condone and be comfortable with. BVLOS operations rely on ground and platform technologies all with varying states of maturity. In this paper, we focus on the interaction between the UAS operator / Remote Pilot in Command (RPIC) to maintain a continuous Command & Control (C2) link with its unmanned aircraft. There must be a reliable, robust, infrastructure in place to enable operators to fly beyond visual range. In areas with sparse communications network coverage, various communication technologies such as LTE and satellite are expected to be utilized in combination to provide C2 connectivity. However, resources for communication links can be saturated, depending on the available spectrum and activity within each network (LTE, Satellite).

UAS Traffic Management (UTM) may ultimately be a pay-for-use service. UTM providers will certainly rely on commercial mobile networks for data communications services and guaranteeing quality of service. Use of communication services can be costly so they must consider implementing a cost-benefit analysis to determine service profitability based on number of service missions, mission type, distribution of missions over an area, and cost of use of each communication resource so that adequate price points can be set for its customers' service missions.

Using a combination of cost modeling and agent-based simulation, one can define many UTM operation scenarios with different parameters such as LTE service coverage area distributions that can be analyzed to determine when LTE communication channels are lost in order to switch to a secondary satellite link to re-establish a C2 connectivity. In this paper, we develop a cost model based on these parameters and a simulation methodology that is envisaged to help UAV fleet operators to manage and price their services while ensuring that BVLOS operations maintain C2 connectivity via a combination of communication technologies.

Introduction

Recently, BVLOS operations are increasingly being considered to extend UAS applications. To realize this, a reliable Command and Control (C2) link is fundamental for the safe operation of the Unmanned Aircraft. When relying on an LTE (or a future 5G) network to provide C2 communications for drone operations, the density of LTE ground base stations needs to be taken into account. In dense urban environments, the base stations will also be densely distributed. In rural environments, the density of base station may be sparser, and maintaining reliable connections may require the use of interference cancellation and antenna beam selection methods along [1]. The layout and configuration of cellular networks that have the capability to support C2 channels for UAV operations is analyzed in [2]. A more comprehensive review of UAS technology to enable BVLOS operations is provided in [3]. However, in most cellular communication network deployments, the distribution of the ground base stations is highly

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dependent on the population and/or economic activity in an area. In some rural areas, wireless carriers deploy a limited number of ground base stations trying to balance operating costs and viable user demand. In these areas, the sparse network connectivity can lead to degradation in the UAV's C2 communication reliability.

UAV operations in rural areas will likely need to employ a mix of cellular (LTE/5G) and satellite connectivity. Given the different charging and cost structures used in these networks, an analysis of the total communication cost for a UAV mission along with the related costs in infrastructure is needed to better understand the economic, reliability and profitability issues of conducting missions [4] [5][6].

This paper is structured as follows. First, the paper presents the cost analysis for data plans for cellular and satellite-supported UAV communications. Second, the paper describes the parameters used in an agent-based simulation platform (MATRUS) that was developed to simulate a predominantly rural environment where UAV missions are scheduled and executed. Afterwards, the paper provides an analysis of the cellular and satellite communication link resource usage obtained in the simulation. Following the aforementioned analyses, cost implications along with some recommendations on how to reduce those costs are analyzed. Finally, conclusions and perspectives for future work are described.

Costs of Cellular and Satellite Supported UAV Communications

Our analysis considers a UTM Operator that manages UAV missions in a predominantly rural environment where UAVs will need to use a cellular network infrastructure (e.g., cellular base stations) to maintain a C2 link; and when that link is not available, the Operator will rely on a satellite link which is considered to always be available when needed.

Cellular Data Plans for UAVs

Cellular-based communication services are expected to become available and grow as commercial applications of UAVs also grow. As pointed out in the report mentioned in [8], more than 10% of the world's UAVs are expected to support cellular connectivity by 2022.

Since 2016, several cellular service providers have announced their plans for supporting UAV communications, in particular in the USA. For example, T-Mobile outlined its use of the 600 MHz, 700 MHz band and 5G technology for UAV communications [9], and AT&T indicated its own plans [10]. Verizon Wireless even described that its UAV/drone data plans will start at $25 a month for 1 gigabyte of data and $80 for 10 gigabytes [11] [12]. These prices roughly align with what consumers pay now for data. It is worth noting that most cellular operators will also charge a one-time device activation fee for a device to start using services from the operator.

Cost of Satellite Data Transmissions

For our analysis we consider that UAVs can make use of a satellite-based communications link that is always available when a cellular link is not. Currently, there are several low-earth orbit (LEO) satellite constellations being deployed by different companies, where the intent of these satellites are to offer Internet access and related data services, and have the potential to serve UAVs, but no specific data plan costs have been detailed.

In contrast, Inmarsat, which is a geosynchronous orbit (GEO) satellite network operator, can currently provide data communication services to UAVs at data speeds up to 200Kbps [7]. With more satellite operators targeting UAV operations in the future, the choice of operators and satellite orbits, i.e., low-earth orbiting (LEO) or geosynchronous earth orbiting (GEO), will affect communication costs and latency directly. In this paper, we consider the use of a GEO satellite network for UAV communications.

In satellite-based data plans, charges can be mapped to the amount of data transmitted plus an additional one-time activation cost. Data plan charges can vary depending on the duration of time in which a commitment to use the service has been made (i.e. duration of service contract) and on allowed monthly data cap amounts. There are several companies that package access to Inmarsat data services. Some of the most illustrative/common pricing plans are mentioned below:

- Groundcontrol.com: Plans are offered with an average price of about $4.75 per Megabyte with High-priority routing. Consumer grade routing is also available but may impact achievable data speeds and latency ($0.53 – $1.66 per Megabyte) [13].
- AirSatOne: In most of their data plans the charge per Megabyte comes out to be in the range of $4.50 - $6.30 [14] .

Besides the charges for data services, there are also extra costs and operational considerations to take into account when making use of satellite communications for UAVs, such as:

- *Latency*: Communication via geosynchronous orbit satellite such as those of Inmarsat carries high latency which can reach a value of 0.5 seconds. In the case of LEO, the latency is in the range of 10 to 30 milliseconds [5].
- *Power*: The path loss via satellite links is relatively higher than that of cellular links. In order to maintain the same quality of service, a UAV will likely have to transmit at higher power levels to use a satellite link than when using a cellular link. Also, there are power implications in maintaining two transmission units (one for cellular, one for satellite) on a UAV even if one is in standby mode while the other one is operating.
- *Setup/activation fee*: There is a fixed one-time charge per UAV of $40 for Inmarsat satellite service.

Simulation-Based Analysis

The MATRUS Simulation Platform

In[15] and [16], we have presented a Multi-agent Air Traffic and Resource Usage Simulation (MATRUS) framework. The MATRUS platform is an integrated environment for air traffic simulation, communication resource estimation, data analysis, and traffic animation for Unmanned Aircraft Systems (UAS)/UAV applications. This simulation platform was developed to evaluate UAS air traffic management policies over metropolitan and rural areas. The modularized design of the platform takes into account the operational characteristics of each UAS and the base stations of the communications network in a given scenario. Thus, it provides an interface for us to plug-and-play different resource management policies and an opportunity to evaluate their performance.

As introduced in [15] and [16], the core functionality of the MATRUS' simulation engine, is developed over the REPAST (Recursive Porous Agent Simulation Toolkit) Simphony platform. Additionally, Google Earth APIs are used for location and traffic animation, and a Python based tool is used for data analysis. With these three components, agent-based modeling is being applied to model UAS behavior and air traffic phenomena as dynamical systems of interacting agents.

Taking advantage of the MATRUS platform, and for the purposes of this paper, we aim at simulating the C2 link connectivity in BVLOS operations with multiple UAVs and long-distance trajectories that may require the use of cellular and satellite link communication resources.

Assumptions and Scenario Description

Six UAV launching sites and six destinations are distributed across 5 counties in the state of Montana. In the selected area, the ground base stations are labeled as either "urban" or "rural" based on their location being near or far from population centers. Depending on this label, a specific propagation model for each base station is used. The service coverage area of the cellular base stations does not cover all of the selected study area, thus ensuring that satellite communications are required in parts of the area. For satellite communications, we assume the use of geostationary satellites and that there is always enough satellite communication network capacity for the UAVs in case any of them decides to use a satellite-based link. In our simulations, the carrier frequency for cellular communications is 750MHz, and the carrier frequency for satellite communications is 1620MHz. We assume channel and/or sub-channel assignments of enough bandwidth within each communication technology (LTE and Satellite) to satisfy the C2 data rate requirement, which is typically 100 to 200 kbps.

In the simulations, at every T seconds, each launching site will decide whether to launch a new

UAV with a predefined probability and select a destination with another probability distribution. Once the launch and destination locations are decided, the UAV will follow a point-to-point trajectory during its flight. The UAVs will connect to the available ground cellular base station that can provide the highest quality of service as evaluated by the value of the signal-to-interference-plus-noise ratio (SINR). To guarantee a minimum of C2 link connectivity quality, there is a predefined threshold for the SINR. Each UAV agent checks the SINR level periodically and decides whether to keep the current connection link active or not. In each period, the UAS agent will first check its current SINR. If the current C2 link can provide good service (i.e., the SINR is greater than the threshold), the UAV will continue using the current C2 link; otherwise, it will drop the link and establish a new one. When the UAV decides to establish a new link, it will first check all the channels of the nearest 3 ground cellular base stations to find the best link (i.e., the link that can provide the greatest SINR). If the best link can provide good service, a new C2 link will be established; otherwise, the UAV will switch to a satellite link and stay with the satellite connection for a period of time before it can switch back to the ground base station.

Propagation Model

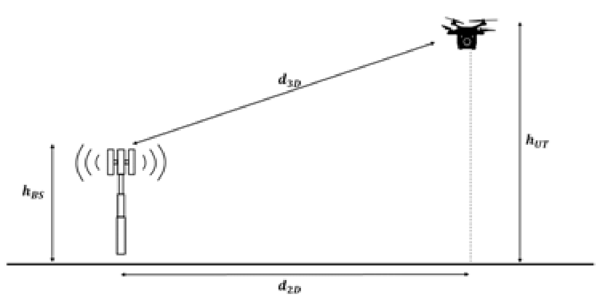

Figure 1. 2D and 3D Distance between the UAVs and Ground Base Station

In Figure 1, we show the definition of 2D distance d_{2D} and 3D distance d_{3D} for the UAVs. We assume that the UAVs are flying at a fixed height of $h_{UT} = 120m$. In this section, we use f_c to denote the carrier frequency. When it refers to cellular communications, the carrier frequency we use is $f_c = 750MHz$, and when it refers to the carrier frequency for satellite communication, we have $f_c = 1620MHz$ instead. We make use of standard guidelines from 3GPP on enhanced LTE support for aerial vehicles [17] to compute the path losses at each of the base stations in our scenarios.

For the rural macro base stations, the line of sight (LOS) probability is 1 for $40m < h_{UT} \leq 300m$. The path loss is given as:

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

for $10m < h_{UT} \leq 300m$ and $d_{2D} < 10km$.

For the urban macro base stations, the LOS probability is 1 for h_{UT} in the range of $100m < h_{UT} \leq 300m$. The corresponding path loss is given as:

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

For $22.5m < h_{UT} \leq 300m$ and $d_{2D} < 4km$.

As to the satellite communication, the free space propagation model is applied and the path loss is calculated as follows:

$$PL_{FS} = 20log_{10}(f_c) + 20log_{10}(d) - 147.55$$

Here, we should have $d = d_{3D}$, however, considering the heights of the GEO $h_{GEO} = 35{,}786$ Km, we find that $(h_{GEO} - h_{UT}) \gg d_{2D}$. Hence, we use $d = (h_{GEO} - h_{UT})$ instead of $d = d_{3D} = \sqrt{(h_{GEO} - h_{UT})^2 + {d_{2D}}^2}$.

Signal-to-Interference-Plus-Noise Ratio (SINR)

With the propagation model, the received power over the link can be determined. When we compute the SINR of one UAV and Ground Base Station (GBS) pair, we refer to the link between this pair as the main link, and all received power from other UAVs as part of the interference power. Then, with the path loss model introduced above, the received power over the main link and the interference power can be expressed, respectively, as

$$P_r = P_{TX}/PL_{\Phi}$$

$$I = \sum_i P_{TX,i}/PL_{\Phi}$$

where P_{TX} is the transmission power, i is the index of the interfering UAV, and the subscript $\Phi \in \{RMa -$

$AV - LOS,\ UMa - AV - LOS\}$ indicates the type of the path loss, i.e., either urban or rural. The SINR is given as

$$\text{SINR} = \frac{P_r}{I + \sigma^2}$$

where σ^2 is the additive white Gaussian noise variance.

Experimental Results & Analysis

Simulation setup

Since we want to study UAV operations in predominantly rural areas where UAVs will likely need to employ a mix of cellular based (LTE/5G) and satellite connectivity to maintain operations, we chose an area within the state of Montana for our simulations. Figure 2 and Figure 3 show the maps of the entire state of Montana and the selected 5 counties within the state, respectively. In the selected area of study, there are both urban and rural areas. In the two figures, the green markers are the locations of constructed antenna sites that can likely house antennas for cellular ground base stations. The locations were obtained from an FCC database [18]. According to the distribution of the base stations around urban and rural areas, 18 of the 45 base stations are labeled as "urban" base stations, and the remaining 27 base stations are labeled as "rural". The distance between the leftmost end to the rightmost end of the map is about 200 miles, and for most sections of the selected area, there is no cellular coverage, indicating that BVLOS UAV operations will likely need satellite connectivity during some portions of their flight.

The yellow and blue markers are the selected launching sites and destinations, respectively, and there is at least one launching site and one destination in each of the 5 counties. In the simulation, we avoid scheduling any mission that requires less than 30 minutes to complete to ensure that a mix of communication resources will be used in each mission.

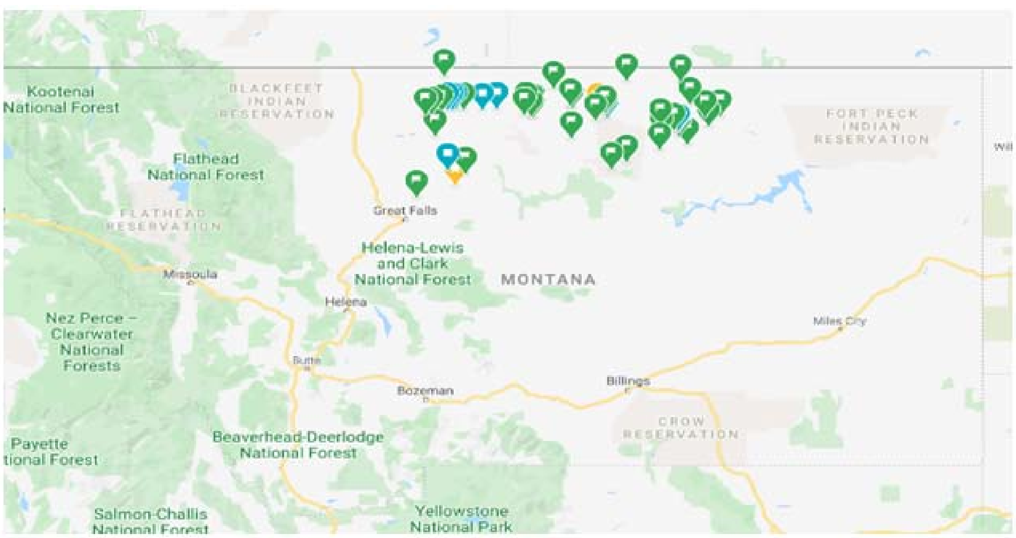

Figure 2. Map of Montana State

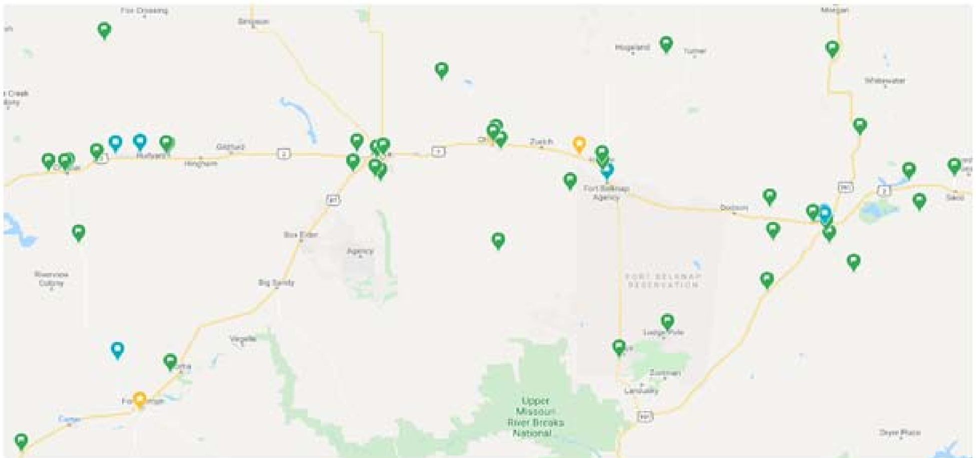

Figure 3. Map of the Selected Area Which Includes 5 Counties in Montana State: Liberty, Hill, Blaine, Philips and Chouteau

In Table 1, we list the parameters used in the simulation.

Table 1. Parameters for the Wireless Communication

Parameter	Value
Base Station Transmission power P_{TX}	45 dBm
Noise σ^2	-60dB
Flight altitude h_{UT}	120m
Flight Speed	45 m/s (100 mph)
Base Station Coverage Radius	4 km (urban) 10 km (rural)
SINR threshold	-6 dB
Generation rate (T)	Every 2 minutes
Satellite Minimum Connection Period	5 seconds
Simulation Time	3 hours

Simulation Results

In Figure 4, we plot a heatmap which reflects the intensity of the usage of satellite communications in different location. The areas with dark blue color are those at which higher numbers of UAVs are using satellite resources. The 2-D histograms provided at the top side and right side of the figure, separately indicate the intensity of use of satellite connectivity in the x and y coordinates of the map area. Additionally, we mark the areas where cellular based connectivity is used with green color points. We can observe that there are some base stations that are never used by the UAVs during the simulation. In Table 2, we provide the statistics on UAV communication link use based on 40 simulation runs. Each simulation run captures 3 hours of UAV flight activity. Each run simulates 3 hours of flight activity where only the steady state data of the last 2 hours of simulation data is used for our analysis (the first hour transient data is discarded).

Table 2. Statistics of UAV Connection

Measurement	Average	Standard Deviation
Flight time (minutes)	39.12	0.888
Cellular usage (minutes)	14.58	1.218
Satellite usage (minutes)	24.54	1.388
Percentage of flight time using cellular	41.03%	1.10
Percentage of flight time using satellite	58.97%	1.10

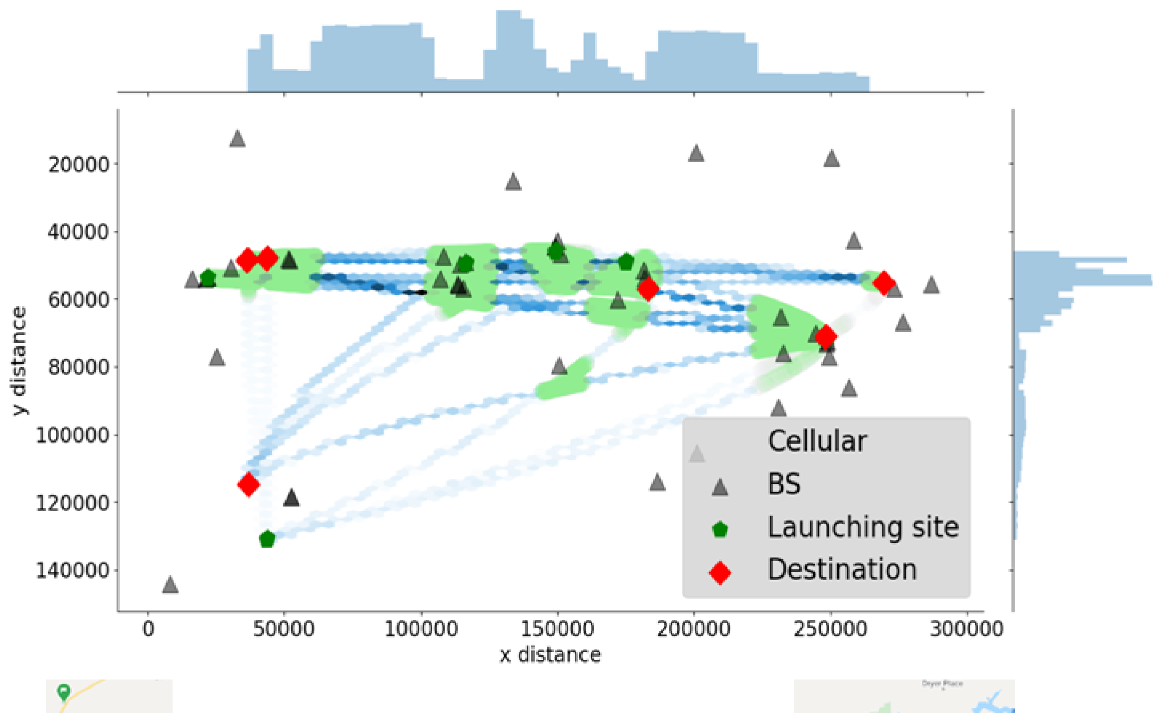

Figure 4. Heatmap of the Satellite Resource Usage Distribution (Distance Unit: meters)

In Figure 5, we show the average active time in minutes and the average number of UAVs served by each of the base stations during the last 2 hours of the simulation. The active time is measured in minutes, and in every active time slot, the base station serves at least one UAV. The average number of UAVs served by a base station depends on the number of UAVs that pass by its corresponding coverage area and indicates the usage level of the base station. A cost-based analysis of these results is provided in a following section in this paper.

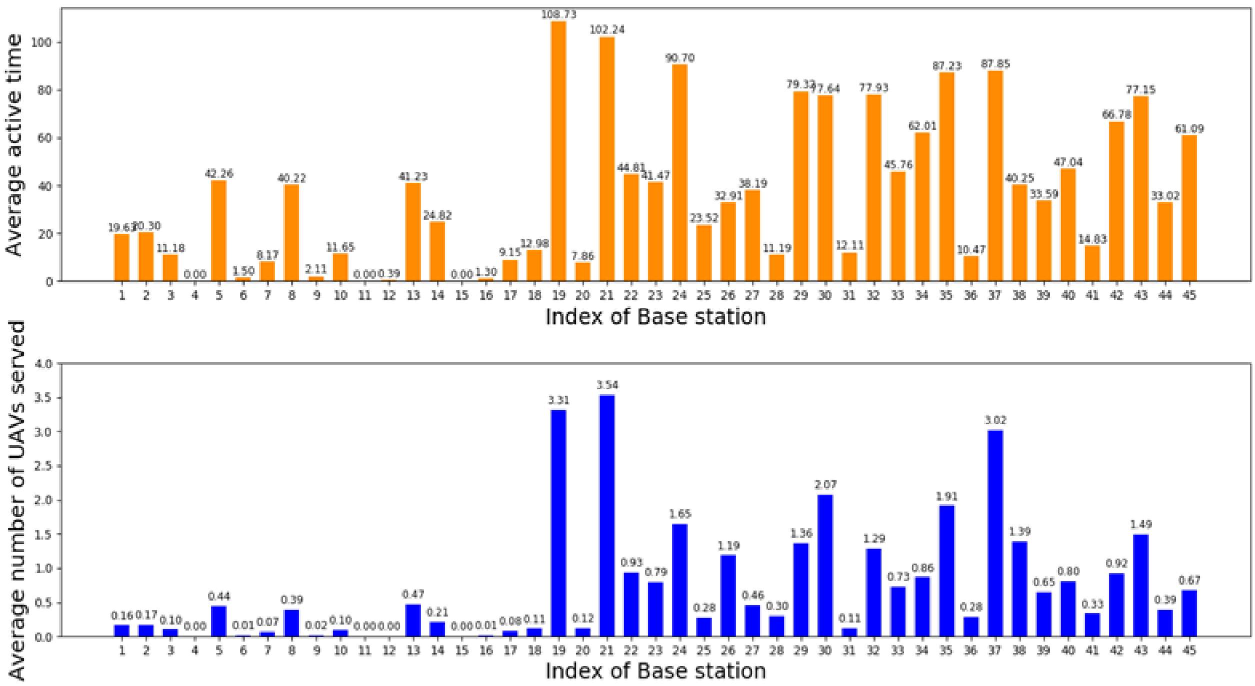

Figure 5. Average Active Time and Number of UAVs Served by Each Ground Base Station

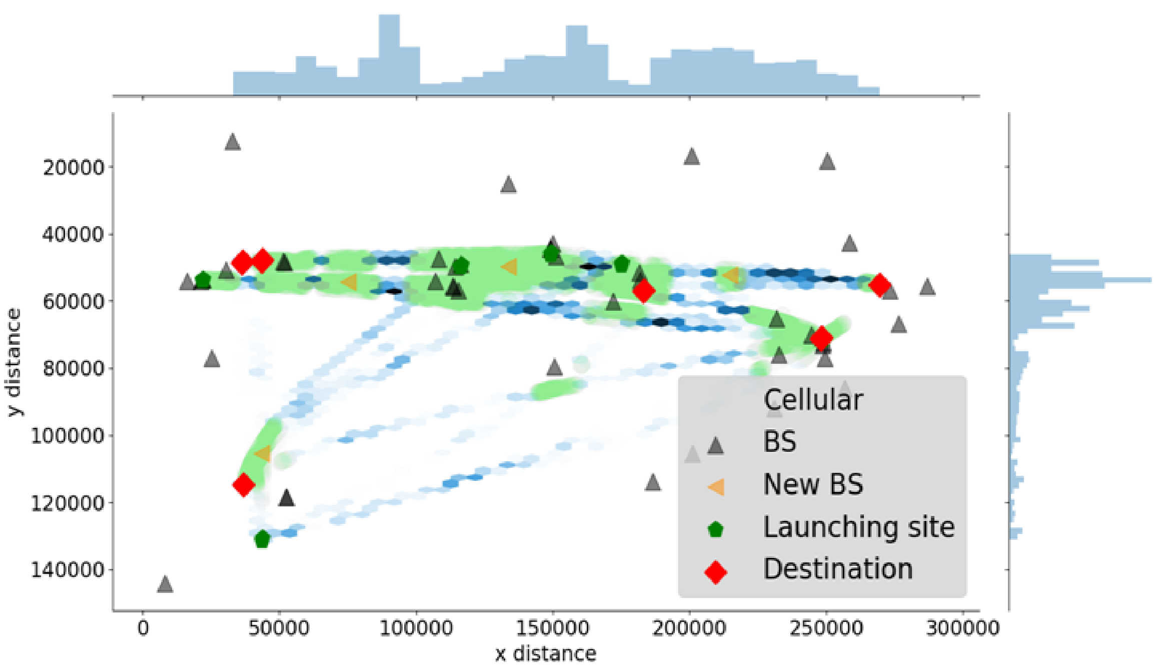

Figure 6. Heatmap of the Satellite Resource Usage Distribution, with New Base Stations Added (Distance Unit: meters)

After our initial results, we proceeded to add new base stations to the map with the aim of stations to the map with the aim of increasing the percentage of time the cellular links are utilized as their use is less costly than that of satellite links. As indicated in Figure 6, we have added 4 new base stations, locating them in positions where according to the histograms in Figure 4 there was a high use of satellite resources based on the UAV trajectories. With these newly added base stations, the UAVs get higher chances to have access to cellular resources in our study area. From the histograms over the x and y axes in Figure 6, it can be seen that the demand for satellite resource was reduced. In Table 3, we noticed that the percentage of flight time using cellular connectivity increased from about 41% to 47.3%. Moreover, the average number of cellular links used by UAVs that are in flight, shown in Table 4 rises from about 33.2 to about 42.2, almost as close to the number of satellite links being used by the remaining in-flight UAVs. In Figure 7, we again present the average active time and average number of UAVs served by the corresponding base station. Note that, in this figure, the newly added 4 base stations are indexed from 46 to 49. Comparing the average number of UAVs served by the base stations and average active time, we see that 3 of the 4 newly added base stations serve more than one UAV during their active time and that in addition to reducing the use of satellite links, they are relieving some of the cellular load from neighboring base stations.

Table 3. Statistics of UAV Connection with New Base Station Added to the Map

Measurement	**Average**	**Standard Deviation**
Flight time (minutes)	40.46	0.63
Cellular usage (minutes)	19.92	0.05
Satellite usage (minutes)	20.54	0.59
Percentage of flight time using cellular	47.31%	3.25
Percentage of flight time using satellite	52.69 %	3.25

Table 4. Comparison of Average Number of Links

	Scenarios With Original Base Stations	**Scenarios With New Base Stations**
(A) Average number of cellular links in use	33.21	42.18
Standard deviation of (A)	1.28	1.26
(B) Average number of satellite links in use	53.23	43.57
Standard deviation of (B)	1.48	1.20

Within our simulation framework it is assumed that only 8 UAVs are allowed to be served by each base station. This can be a rule imposed by a cellular network operator. Therefore, when the number of UAVs served by a base station is close to 8, we can consider that there is a potential traffic congestion in the area of the corresponding base station. We did not see any issues related to congestion in our simulations.

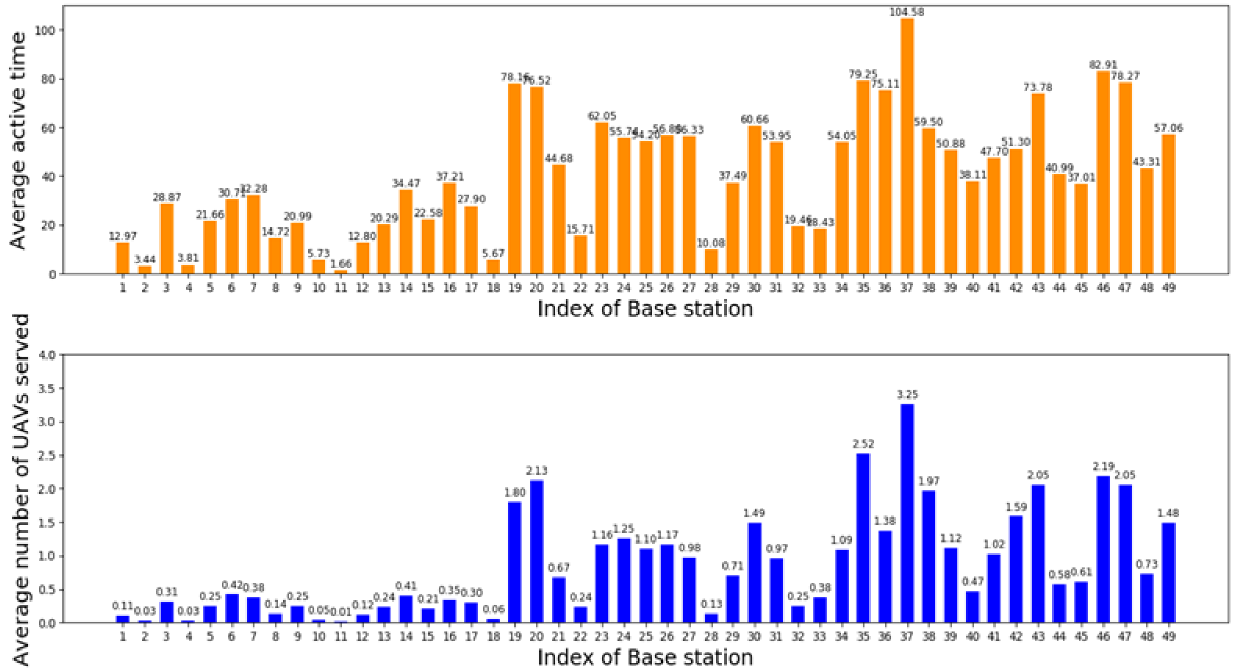

Figure 7. Average Active Time and Number of UAVs Served by Each Ground Base Station, with New Base Stations Added

Cost Analysis

Based on our simulation results and information on the cost of using cellular and satellite communication links for UAV C2 channels, we carry out a cost analysis to determine the overall cost of operating in a predominantly rural environment like the one used in our study and recommend strategies to bring costs under control.

Data Transmission Costs Model

To compute the data transmission costs per UAV we use the following parameters:

τ = average flight time per mission (in minutes)

R = UAV data rate in Mbps

N = average number of UAVs in flight

M_{DAY} = Number of hours in a mission-day

α = Charge per MByte by cellular operator

β = Charge per MByte by Satellite operator

k = Average percentage of flight time in which the cellular network was used

p_c = average percentage of UAVs in flight using the cellular network

F_s = UAV operator's fleet size

Note that M_{DAY} refers to the number of hours in a day in which flight missions were continuously scheduled (mission-day).

Based on these parameters, the average total amount of data transmitted per UAV mission in Mbytes, denoted as T_{UAV}, is:

$$T_{UAV} = \tau \times 60 \times \frac{R}{8}$$

The amount of data per UAV mission sent via the cellular network is:

$$k \times T_{UAV}$$

The amount of data per UAV mission sent via the cellular network is:

$$(1-k) \times T_{UAV}$$

The total data transmission cost per mission-day can be expressed as:

$$N \times M_{DAY} \times [(\alpha p_c k) + \beta(1-p_c)(1-k)] \times T_{UAV} = \alpha D_c + \beta D_s$$

where: D_c is the total data transmitted per UAV on a mission-day using the cellular network and D_s is the total data transmitted per UAV on a mission-day using the satellite network. However, the computation of cost still has to be adjusted to a monthly charging regime as used by many cellular and satellite operators.

We assume a 30-day month. If the operator's UAV fleet size is composed of F_s units, with adequate scheduling of the missions on each fleet unit we can assume that each unit was involved in transmitting an average of:

$$\frac{30D_c}{F_s} = D_{MCell}$$

units of data per month using the cellular network (D_{MCell}). If each day of the month has a similar scheduling pattern, we can express the total data transmission cost per month as:

$$C + 30\beta D_s$$

where:

$$C = \begin{cases} F_s C_1, & 0 < D_{MCell} \leq L \\ F_s(C_1 + \gamma(D_{MCell} - L)), & D_{MCell} > L \end{cases}$$

L = monthly data cap size

C_1 = Charge for the transmission of up to L Mbytes of data in a month

γ = penalty charge per MByte over L

In our total cost expression, we are using a cellular operator service charging model commonly employed where the operator charges a fixed amount C_1 if the monthly use of data by a device does not exceed a data cap size amount L. If the monthly use exceed the data cap, an additional charge per Mbyte above L will be charged, and we identify this charge as γ.

Cost Analysis Results and Recommendations

For our transmitted data amount computations, we will assume that a 1250 Byte message is sent every 100ms on the C2 channel thus requiring a 100 Kbps channel. This data transmission setup has been used by 3GPP and other reports [1]. For the scenarios where we considered 45 cellular base stations in our area of study (original scenario) and using the data reported in Tables 2 to 4 and the parameter values indicated in Table 5, we have the transmitted data amount results shown in Table 6 and the total transmission costs per month in Table 7.

Table 5. Parameters for Data Amounts and Cost Computations

Item	Size or Value
Hours in a mission-day (M_{DAY})	8 hours
Data Rate (R)	0.10 Mbps
Charge per Mbyte by satellite operator (β)	$ 4.80
Monthly charge by cellular operator (C_1)	$ 80.00
Monthly data cap size by cellular operator (L)	10000 Mbps
Average percentage of in-flight UAVs using the cellular network (p_c)	38.37%
Number of UAV in fleet (F_s)	150

Table 6. Transmitted Data Amounts

Item	Data Amount (Mbytes)
Total data transmitted per UAV	29.34
Data per UAV txm. via cellular network	12.04
Data per UAV txm. via satellite network	17.30
Total data txm. via cellular network per mission day	3178.09
Total data txm. via satellite network per mission day	7335.96
Total data txm. via cellular network per month	95342.56
Total data txm. via satellite network per month	220078.87

Table 7. Monthly Transmitted Data Costs

Item	Cost
Cellular data cost per month	$ 12,000.00
Satellite data cost per month	$ 1,056,378.58
Total cost of data transmission	$ 1,068,378.58

For the scenario where we added 4 additional cellular base stations in our area of study (enhanced scenario), the transmitted data amounts and monthly costs obtained are shown in Tables 8 and 9.

Comparing the costs shown in Tables 7 and 9, we can see that the addition of 4 base stations can produce a savings of almost $246,000 per month. In reality the savings would be larger as most satellite data service providers mainly offer data plans with a fixed monthly cost for a fixed monthly data cap. If the data cap is not reached by a device the UAV fleet operator still has to pay the monthly charge. The unused capacity is thus wasted and overall it leads to a higher price per Mbyte of satellite transmission.

Table 8. Transmitted Data Amounts in the Enhanced Scenario

Item	Data Amount (Mbytes)
Total data transmitted per UAV	30.35
Data per UAV txm. via cellular network	14.36
Data per UAV txm. via satellite network	15.99
Total data txm. via cellular network per mission day	4823.69
Total data txm. via satellite network per mission day	5628.05
Total data txm. via cellular network per month	144710.69
Total data txm. via satellite network per month	168841.52

Table 9. Monthly Transmitted Data Costs in the Enhanced Scenario

Item	Cost
Cellular data cost per month	$ 12,000.00
Satellite data cost per month	$ 810,439.31
Total cost of data transmission	$ 822,439.31

However, the costs to add the new base stations and their related operational infrastructure (e.g. backhaul connectivity) would need to be incurred either by a cellular network operator or a UAV fleet operator. If incurred by the fleet operator, the savings would not be as substantial but given their magnitude it could well be worth it.

An approach that a UAV fleet operator could use to expand the cellular network's (LTE) coverage on its own in rural areas is by deploying base stations that can operate under the Citizens Broadband Radio Service (CBRS) band and rules. CBRS base stations for LTE operate in the 3.5 GHz band and offer a great alternative in support of UAV communications. In addition, or as an alternative, to reduce the use of satellite connectivity, the UAV operator could implement trajectory routing mechanisms that steer the flight paths as much as possible through cellular coverage areas instead of just employing simple point-to-point routing. Our MATRUS simulation platform can support such routing but a detailed analysis of its cost implications is left for future work.

Conclusions

The provision of commercial UAV services in BVLOS conditions requires that adequate communication support for the UAV's command and control (C2) channel be provisioned in addition to any data payload service requirements. Relying on cellular and satellite based connectivity over a predominantly rural area of study (in Montana) we have used the capabilities of our MATRUS simulation platform (agent-based modeling supported) and a cost model to explore the technical and economic parameters impacting operations in rural areas with limited cellular communications infrastructure.

Overall, a detailed analysis of UAV trajectories, charging models by cellular and satellite operators, availability of cellular communications resources and operational factors of cellular and satellite devices (i.e. coverage range, path loss, SINR levels, frequencies used, etc.), we show that it is possible to adequately determine operational costs and elaborate recommendations for achieving reductions in those costs.

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