

Modeling and Simulation for Reliable LTE-based Communications in the National Airspace System

A UAS C2 Use Case

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Abstract—The need for high-data-rate wireless communications to, from, and among users of the National Airspace System (NAS) in the United States is increasing. There are also large numbers of new and upcoming users requesting access to the NAS, including unmanned aircraft systems (UAS) and urban air mobility vehicles. This paper describes a modeling and simulation framework and an initial capability to support research and technical analyses on the potential use of the fourth-generation (4G) Long Term Evolution (LTE) wireless network architecture and its fifth-generation (5G) progression for aviation communications. The research presented in this paper is focused on developing the means to analyze an initial problem, namely how the performance of LTE-based networks, developed for terrestrial use, will be affected by the potential introduction of small UAS (sUAS) as additional users. More and more sUAS are requesting access to the NAS for complex operations beyond the visual line of sight (VLOS) of the remote pilot in command. To safely support such beyond-VLOS (BVLOS) operations, a reliable UAS command and control (C2) solution is necessary. This paper describes initial scenarios, analysis methodologies, and simulation results of using LTE to support a UAS C2 use case. The analyzed scenarios developed for this use case are in a rural environment with small unmanned aircraft (sUA) and terrestrial users sharing the resources of an LTE-based network.

Keywords - *unmanned aircraft systems, LTE, modeling and simulation, RF link performance, UAS C2*

I. INTRODUCTION

There is an ever-increasing need for high-data-rate wireless communications to, from, and among users in the National Airspace System (NAS) in the United States. There are also large numbers of new and upcoming users requesting access to the NAS, including unmanned aircraft systems (UAS) and urban air mobility vehicles. Reliable, scalable, and flexible communication link solutions are needed for the aeronautical environment to support the increasing communications needs of existing and upcoming users in the NAS.

This paper describes a modeling and simulation (M&S) framework and an initial capability to support research and technical analyses on the potential use of the fourth-generation (4G) Long Term Evolution (LTE) wireless network architecture and its fifth-generation (5G) evolution for aviation communications.

The focus of the research presented in this paper is on developing the means to analyze an initial problem, namely, to understand how the performance of LTE-based networks,

developed for terrestrial use, will be affected by the introduction of small Unmanned Aircraft (UA). The potential integration of small UA (sUA) and terrestrial users within the same network may be challenging because of their different needs and characteristics.

More and more UAS, especially small UAS (sUAS), are requesting access to the NAS for complex operations beyond the visual line of sight (VLOS) of the remote pilot in command. To safely support such beyond-VLOS (BVLOS) operations, a reliable UAS command and control (C2) solution is necessary. However, no widespread commercial UAS C2 solution that is flexible, scalable, and robust exists for sUAS.

4G LTE and 5G wireless technologies are under consideration within the sUAS community and the wireless industry for enabling BVLOS sUAS communications. Standardization efforts taking place in the Third Generation Partnership Project (3GPP) are considering support for sUAS as a goal [1], [2]. When addressing topics related to support for sUA in terrestrial networks, 3GPP documents use the term “aerial vehicles” to refer to sUA.

For this paper, the terms “aerial vehicles”, “sUA”, and “drones” are used interchangeably. The term sUAS is used to describe the sUA, its ground control station (GCS), and the communication link between them.

In this paper, we analyze UAS C2 link performance in scenarios with sUA and terrestrial users sharing the resources of an LTE-based network. M&S activities are an integral part of this research effort. We used the developed M&S framework and initial capability to perform the described studies.

The developed M&S framework, analysis methodologies, and scenarios will also enable future studies of expanding complexity. Such analyses are envisioned to explore sUAS scenarios in urban environments, and to assess measured data from sUAS flights in various operational scenarios.

M&S results will also determine whether gaps exist that need to be addressed by technology evolution through standardization activities and/or by future network implementations.

In the longer term, such an M&S framework and capability can be evolved to expand the research to larger UAS and to other NAS users (e.g., general aviation aircraft and future urban air mobility users).

II. M&S FRAMEWORK

The M&S framework developed as part of this research effort is shown in Figure 1. It identifies three focus areas where modeling and simulations are needed to comprehensively analyze sUAS BVLOS scenarios using wireless terrestrial networks for their communications needs. These areas are:

1. LTE physical layer performance analyses that explore the impact of sUA speed, sUA altitude, and frequency band on link performance
2. Discrete Event Simulation (DES) studies that explore link performance for both sUA and terrestrial users in terms of latencies and data throughput
3. Radio frequency (RF) network performance analyses that evaluate network performance over a wide geographical area with terrestrial users and sUA sharing network resources

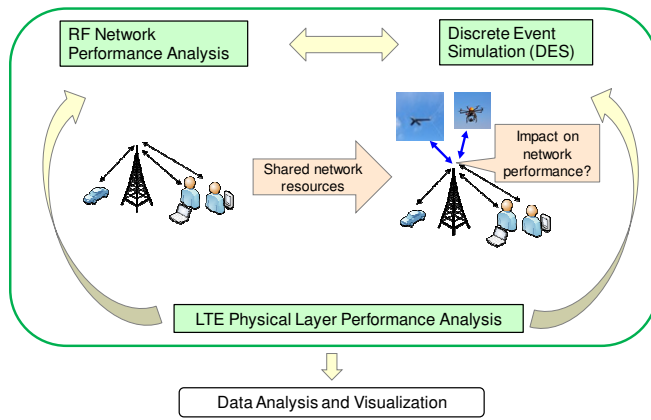


Figure 1. M&S Framework.

The framework also identifies data analysis and visualization as other important elements. In this paper we describe physical layer performance analyses and RF network performance studies.

Table 1 presents a common set of assumptions and RF parameters used for all analyses described in this paper. These parameters are derived based on Annex A.1 of [1] and are recommended for system-level performance evaluations for LTE-based networks in a rural macrocell environment with aerial vehicles (i.e., sUA). Such a rural environment is denoted as RMa-AV in [1].

TABLE I. COMMON ASSUMPTIONS AND RF PARAMETERS

Assumptions and RF Parameters	Values
UAS operational environment	Rural
Base station antenna height	35 meters (m)
Frequency band	700 megahertz (MHz)
Channel Bandwidth	10 MHz
Duplexing mode	Frequency division duplex

Assumptions and RF Parameters	Values
Modulation schemes	QPSK, 16-QAM, 64-QAM
Transmission scheme	Transmit diversity
Propagation channel model	As described in [1] Annex B
Antenna gain for terrestrial users and sUA	0 dBi

Notes:

QPSK = quadrature phase shift keying

QAM = quadrature amplitude modulation

III. SUAS INFORMATION FLOW

To enable the development of analysis scenarios from a UAS communications perspective, we identified an initial sUAS information flow that potentially could be supported using a terrestrial wireless network. This is presented in Figure 2.

In this figure, and for the remainder of this document, transmissions to sUA are denoted as forward link (FL) transmissions and transmissions from the sUA to the ground are denoted as reverse link (RL) transmissions.

This flow includes UAS C2 message exchanges between each sUA and its corresponding GCS where the remote pilot in command is located. It could also include message exchanges from sUA to a UAS traffic management service supplier's (USS) server [3]. Such exchanges could potentially support remote identification (Remote ID) functionality.

Figure 2 also shows that additional messages could be exchanged between a USS server and ground control stations, for example to support functionality informing sUAS pilots of potential weather changes in their areas of operation.

The network consists of a radio access (wireless) part supporting the communication to and from users and ground transceivers (cell towers), and a "core" (wireline) part that provides access to other systems (e.g., USS server). The "core" network consists of gateways, routers, switches, and other network infrastructure elements. It supports the user data transmission and the signaling that is required for the network to function.

Figure 2 also illustrates how various sUAS operations could be enabled by a terrestrial wireless network.

- A BVLOS operation is shown between a remote pilot in command located at GCS₁ and its sUA denoted as sUA₁. The pilot at GCS₁ is communicating wirelessly to a cell tower nearby, and the sUA₁, operating farther away, is communicating to a different cell tower.
- An extended VLOS (EVLOS) operation is also shown. In this example, a pilot in command at GCS₃ and its corresponding sUA₃ are within the coverage area of the same cell tower, and therefore use the same cell tower for connectivity. However, the remote pilot in command would not be close enough to the sUA to be able to see it.

- An additional BVLOS scenario could be envisioned as GCS₂ could potentially communicate to more than one sUA (shown in the figure as sUA₂ and sUA₄). In this example, GCS₂ is shown as connected to the “core” part

of the network. Both sUA₂ and sUA₄ would be beyond the visual line of sight of the remote pilot in command located at GCS₂.

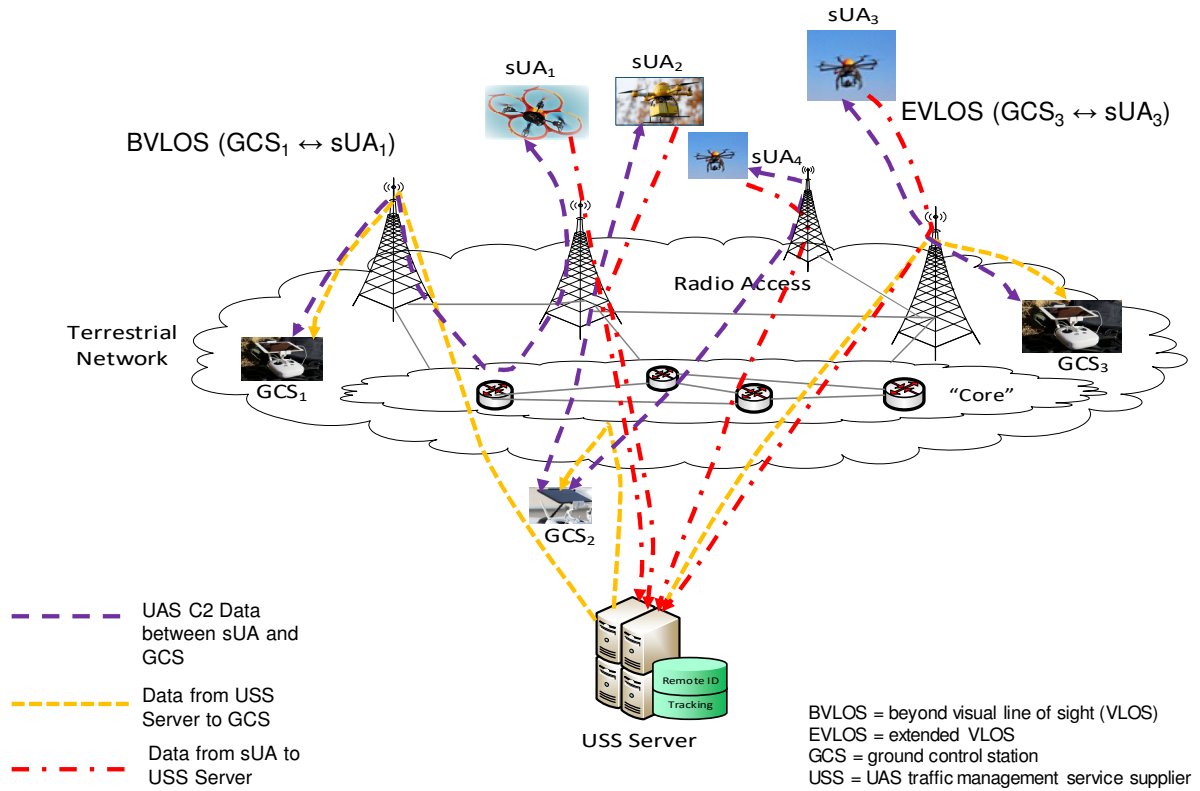


Figure 2. Potential sUAS Information Flow

IV. PHYSICAL LAYER PERFORMANCE ANALYSIS IN A UAS CONTEXT

The performance of LTE-based terrestrial networks in the context of supporting the communications needs of sUAS is a topic of research and evaluation through M&S efforts and field trials. In this section we document physical layer performance studies using the MATLAB LTE Toolbox [4] and its 5G library add-on [5]. The goal of our studies is to explore the LTE link performance impact of each of the following factors:

- sUA speed
- RF operational environment
- sUA altitude

In these studies, the LTE link performance is expressed in terms of the block error rate (BLER) [6]. In the future, BLER results may be further used for DES and RF network performance studies [7], [8].

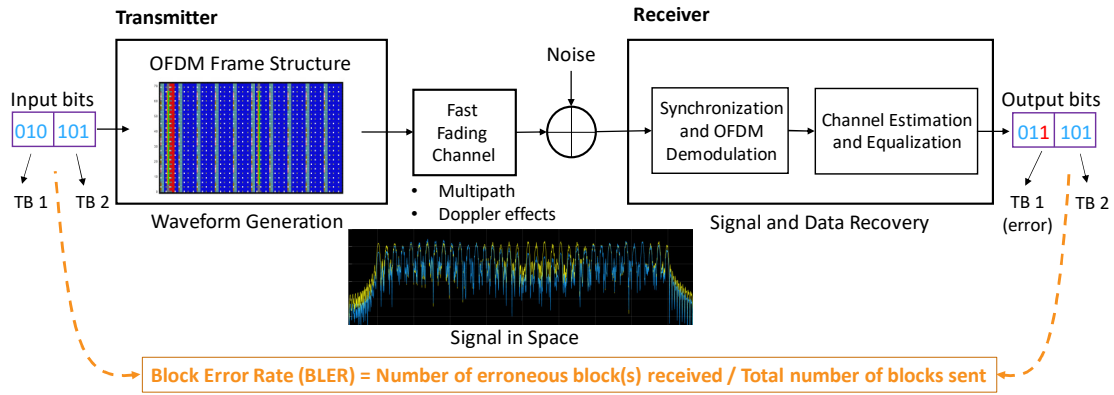
A. Simulation Setup

We performed simulations by developing scenarios that would characterize an LTE link in a sUAS environment. The

toolbox provides functionality for physical layer modeling [9], while the 5G library allows us to perform simulations with a three-dimensional (3D) channel model as defined by 3GPP [10], [11]. Such 3D channel models are expected to be extensively used in 5G, especially as advanced antenna systems get widely implemented.

Figure 3 illustrates the block diagram of our LTE end-to-end simulation setup [12]. In this setup we implemented the RF parameters recommended for data transmissions from LTE base stations (BSs) to aerial vehicles (i.e., sUA). Table 1 described the set of common parameters in more detail.

The LTE waveform, generated in accordance with these parameters, propagates through a noisy fast fading channel model [1], [13]. Multipath effects contribute to signal attenuation due to reflections and diffractions in the RF environment between the LTE BS and an airborne sUA being served by that BS. Doppler effects, due to sUA speed, cause signal distortions in the frequency domain. Additive white gaussian noise is incorporated to model noise effects through the channel.



Notes:
 OFDM = Orthogonal Frequency Division Multiplexing
 TB = Transport Block

Figure 3. End-to-End LTE Physical Layer Simulation Setup

After propagating through the channel, the signal is received at the sUA. Channel estimation is performed at the sUA to help reduce the impact of the propagation conditions on the received signal [14]. After demodulating and decoding the received signal, the BLER metric is calculated. BLER, the ratio of incorrectly received blocks to the total number of transmitted blocks, is a measure of signal quality in an LTE network.

Table 1 defines a common set of assumptions and RF parameters used for all analyses described in this paper. All analyzed scenarios consider a rural environment with an LTE-based network supporting both terrestrial users and sUA.

Table 2 presents additional assumptions and RF parameters used for the physical layer analyses performed using the MATLAB LTE toolbox. These parameters, identified in Annex A.1 of [1], are recommended for system-level performance evaluations in a rural macrocell environment with aerial vehicles (RMA-AV).

TABLE II. SPECIFIC ASSUMPTIONS AND RF PARAMETERS FOR PHYSICAL LAYER STUDIES

Assumptions and RF Parameters	Values
Allocated RF resources for data traffic	50%
BS transmitter antenna configuration	2 antennas, cross-polarized
BS antenna pattern	As described in [10]
Simulation duration	100 frames
sUA receiver antenna configuration	2 antennas, cross-polarized
sUA mobility	{20, 80} kilometers per hour (km/hr.)
sUA altitudes	{100,200,300,400} feet (ft)

It should also be noted that the physical layer simulations performed with the MATLAB LTE toolbox assume a perfect channel estimator at the receiver to minimize the ambiguity of

the channel-estimation algorithm implemented by hardware vendors [7], [15].

B. Simulation Scenario and Results

A scenario with terrestrial users and sUA in a rural environment is shown in Figure 4. Typically, in a rural environment, the height of the BS or cell tower is higher than that of surrounding buildings. In rural areas, it is often assumed that for sUA flying at least 40 meters (m) (i.e., 130 ft) above ground level (AGL), the RF operational environment can be characterized as line of sight (LOS) [1]. For sUA flying at altitudes below 40 m AGL, the sUA can experience either an RF LOS condition or an RF non-line-of-sight (NLOS) condition.

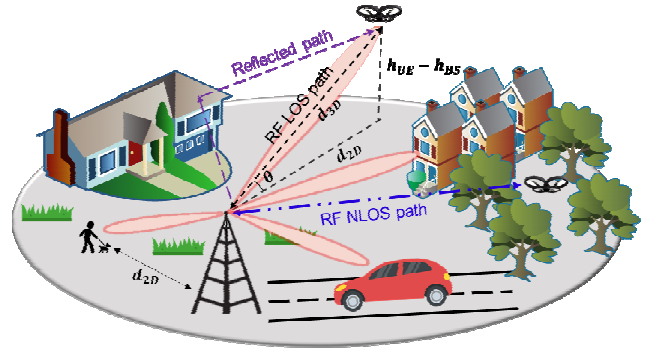


Figure 4. sUAS Scenario in a Rural Environment

C. Impact of sUA Speed and RF Operational Environment on LTE Link Performance

We performed simulations with sUA flying at 100 ft AGL in both LOS and NLOS conditions. BLER results for two sUA speeds and for both LOS and NLOS conditions are shown in Figure 5.

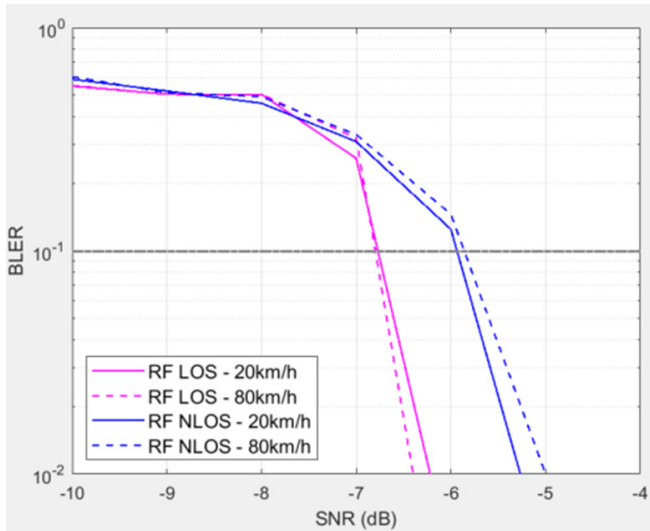


Figure 5. BLER Results for sUA at 100 ft AGL in a Rural Environment

The two sUA speeds are 20 km/hr and 80 km/hr. We observe that for these modest sUA speeds, which are typical for sUA operations, and using a frequency band of 700 MHz, the impact of the actual sUA speed on LTE link performance is not significant in either LOS or NLOS conditions.

A target BLER of 10% (or 10^{-1}) is typically considered acceptable in LTE-based terrestrial networks [8], [16].

A signal-to-noise ratio (SNR) of about 1 decibel (dB) lower is needed to achieve a BLER of 10^{-1} in a scenario with the sUA experiencing an RF LOS condition (shown in magenta) than in a scenario with the sUA experiencing a NLOS situation (shown in blue). This means a lower signal quality can be tolerated if RF LOS exists between the BS and the sUA. For example, the sUA could be farther away from a BS if a RF LOS situation exists, and the sUA could still experience acceptable link performance.

D. sUA Altitude Impact on LTE Link Performance

Figure 6 illustrates a sample scenario in which the sUA is in the horizontal main beam of the BS antenna at various altitudes. This means the RF link between the BS and the sUA will experience a specific BS antenna gain that depends only on the sUA's elevation angle as seen from the BS [10].

Figure 7 shows the BLER performance results for sUA altitudes ranging from 100 to 400 ft in a rural environment with sUA in RF LOS conditions. Results are shown for three modulation schemes, and for a coding rate of 1/2. The modulation schemes are: QPSK, 16-QAM, and 64-QAM, as described in Table 1.

The BLER performance results for a terrestrial user are also shown as a baseline for comparison in each of the three figures. It should also be noted that for the terrestrial link's BLER simulations we used the corresponding 3GPP channel model for terrestrial users in a rural environment [10], [12].

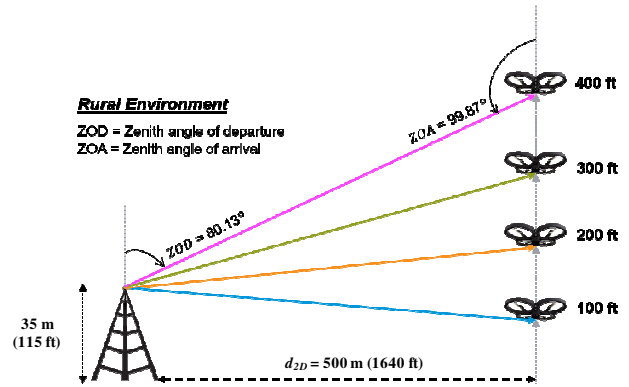


Figure 6. Sample Scenario with sUA at Different Altitudes

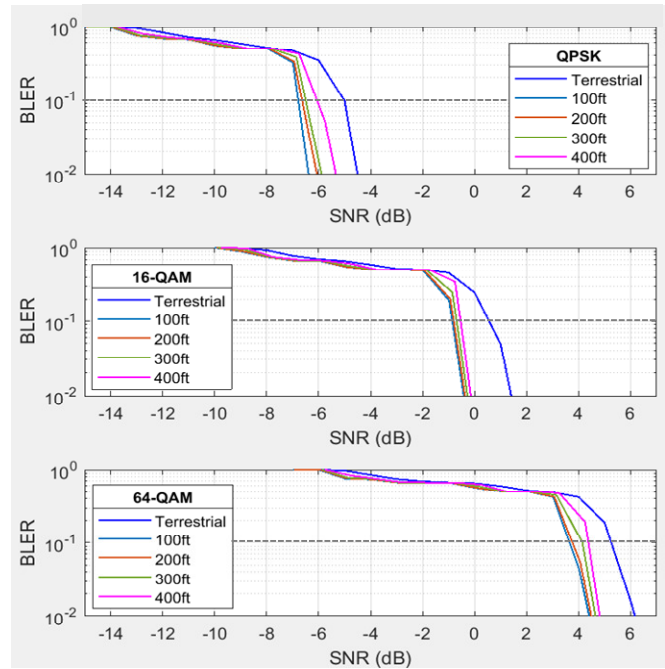


Figure 7. Physical Layer Link Performance Results in LOS Conditions in a Rural Environment

At the target BLER of 10^{-1} , the simulation results in Figure 7 show that sUA BLER outperforms the terrestrial BLER for each of the three analyzed modulation schemes. Results also indicate that sUA BLER performance degrades slightly as the sUA altitude increases.

It can also be observed that lower SNR values are needed to achieve a given BLER if the lowest modulation order (i.e., QPSK) is used. However, QPSK has a lower spectral efficiency than the higher modulation orders such as 16-QAM and 64-QAM. On the other hand, 64-QAM offers a higher spectral efficiency than QPSK, but requires better signal quality (i.e., a higher SNR) to support it.

E. Summary of Findings from Physical Layer Analyses for sUAS

Our current findings for the physical layer analyses focused in a rural environment can be summarized as follows:

- BLER is lower if the sUA encounters an RF LOS condition to its serving BS than if it encounters an RF NLOS condition.
- For the analyzed sUA speed ranges and frequency bands, the sUA speed had a fairly modest impact on link performance. This is because we used relatively low UA speeds, which are typical for sUAS operations, and also frequency bands at or below 2.5 gigahertz (GHz). Use of higher frequency bands, if needed, should be further studied.
- For all four analyzed sUA altitudes, link performance is better for a sUA than for a terrestrial user.
- For a sUA in the horizontal main beam of its serving base station antenna but at varying altitudes in the 100 ft to 400 ft range, the BLER performance gets worse as the sUA altitude increases.

Our next steps include performing simulations in an urban environment. Propagation channel characteristics are quite different between rural and urban areas. In an urban area, the sUA would encounter a rich multipath environment and a lower probability of staying within the RF LOS of an LTE base station [1] than in a rural area. The aerial fast fading channel model defined for urban scenarios will be used for sUA in urban-area simulations [1].

V. RF NETWORK PERFORMANCE ANALYSIS

The main focus of the studies described in this section is to evaluate the performance of an LTE network over a wide geographical area in a rural environment. For these studies, we assume that terrestrial users and sUAS share the network resources. Envisioned sUAS operations in this area could include agricultural operations (e.g., crop monitoring) and linear infrastructure inspections.

A. Wide Geographical Area Scenario and Operational Environment Data

In order to build the wide-area analysis scenario, we used Atoll, a network design and optimization software tool [18]. The rural environment, comprising of both terrestrial users and sUAS, is depicted in Figure 8.

We selected a rural area, approximately 35 km by 35 km, near Richmond, Virginia for our studies. Within that area, we assumed a set of thirty-seven BSs spaced about 5 km apart in a hexagonal grid layout, as described in [1] for a rural environment. Each BS is equipped with three directional antennas, spaced 120° apart in azimuth.

We used digitized terrain and land-use (clutter) data for all studies described in this section. This allows us to better characterize the geographical environment that sUA would encounter when operating within the analysis area.

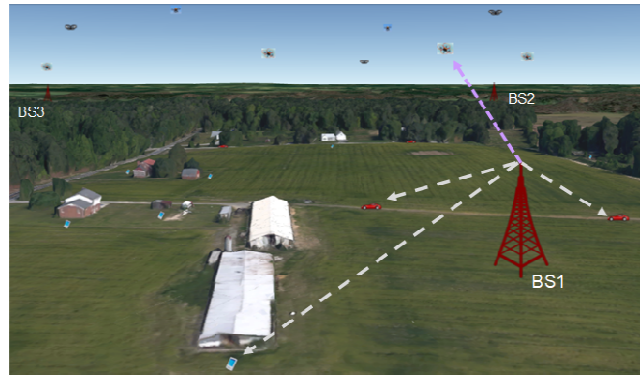


Figure 8. Wireless Network Serving sUAS and Terrestrial Users in a Rural Area

Figure 9 shows the terrain elevation in the area of interest. The spatial resolution of this data is 10 meters (about 1/3 arcsecond in latitude and longitude) [19]. Digital terrain elevation information shows elevations at or below 400 ft above mean sea level for most of the analysis area.

Land-use (clutter) data, represented through clutter classes, is shown in Figure 10. The analysis area is rural, with many locations characterized as either forest or agricultural [19].

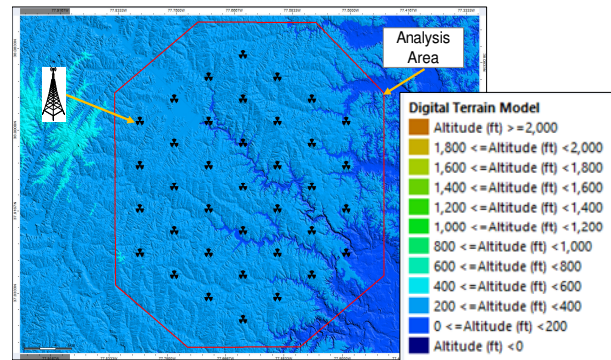


Figure 9. Terrain Data for Analysis

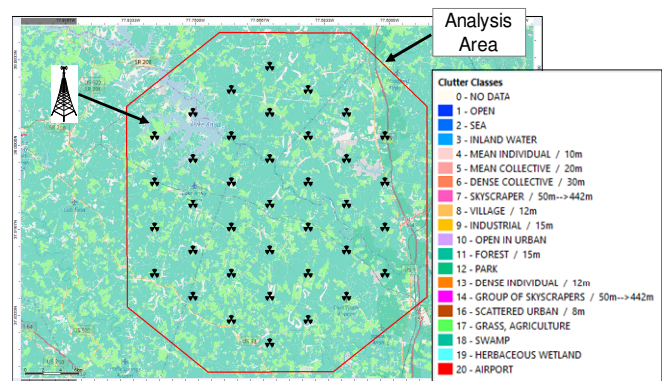


Figure 10. Land-Use Data for Analysis

Any additional link losses that occur because of terrain or clutter obstructions are automatically incorporated in the

analysis [18]. Such losses are included for all link performance studies presented in this section.

Within the analyzed scenario, we used RF propagation models for typical terrestrial users and for sUAS. The model for terrestrial users is based on [10], and the model for sUAS is as specified in [1].

We implemented the path loss equations for sUA in a rural environment for various altitudes as described below.

For sUA in RF LOS conditions the path loss expressed in dB is:

$$PL_{LOS} = \max(23.9 - 1.8 \log_{10}(h_{UA}), 20) \log_{10}(d_{3D}) + 20 \log_{10}(40 \pi f_c / 3) \quad (1)$$

where:

$$\begin{aligned} h_{UA} &= \text{sUA height AGL (m); } 10 \text{ m} < h_{UA} < 300 \text{ m} \\ d_{3D} &= \text{slant range between BS antenna and the sUA (m),} \\ f_c &= \text{frequency in GHz} \end{aligned}$$

Similarly, for sUA in RF NLOS conditions the path loss expressed in dB is:

$$PL_{NLOS} = \max(PL_{LOS}, -12 + (35 - 5.3 \log_{10}(h_{UA})) \log_{10}(d_{3D}) + 20 \log_{10}(40 \pi f_c / 3)) \quad (2)$$

where the parameters are as described for (1).

We have also included the impact of shadow fading for both sUA [1] and terrestrial users [10].

B. Link Performance Studies

In this section we present our link performance results for two typical LTE performance metrics, namely, Reference Signal Received Power (RSRP), and Reference Signal Received Quality (RSRQ). For each metric, we show results for sUA at 100 ft and 400 ft AGL and results for terrestrial users.

1) RSRP Results

RSRP is a forward link metric describing the power of the reference signal as received by each user. RSRP is used by the network for cell selection, cell reselection, and base station handover [16]. It is also used for power control algorithms.

Figures 11 and 12 show RSRP results for sUA at 100 ft and 400 ft AGL, respectively. The results identify average RSRP signals in the analysis area. Generally, strong RSRP levels are observed for sUA at both 100 ft and 400 ft AGL. Results in Figure 11 show that for sUA at 100 ft, there are locations at the edges of the analysis area where lower RSRP values are observed, which are due to terrain effects.

Comparing results in Figures 11 and 12, it can be observed that, generally, RSRP decreases as the sUA altitude increases. Larger areas are shown in lighter orange in Figure 12 than in Figure 11, corresponding to lower average RSRP values. This is because of the longer path between a higher-altitude sUA and its serving BS, and because of decreased BS antenna gain in the direction of a higher-altitude sUA.

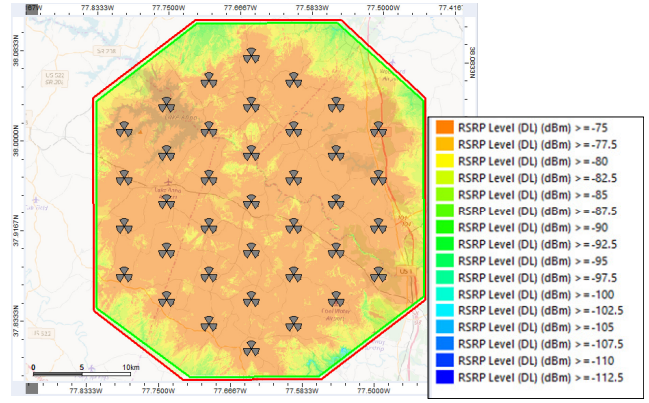


Figure 11. RSRP Results for sUA at 100 ft AGL

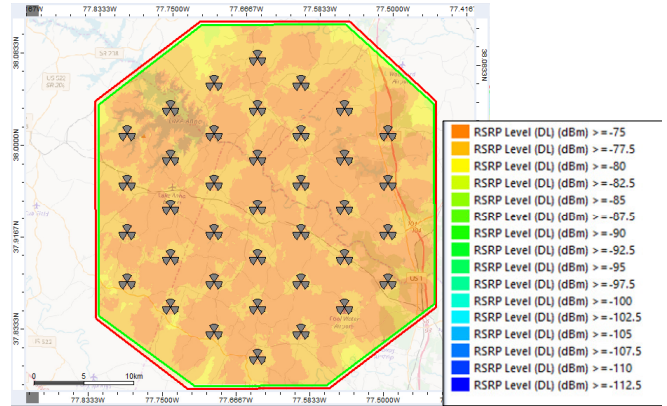


Figure 12. RSRP Results for sUA at 400 ft AGL

Figure 13 shows RSRP results for terrestrial users. Comparing results from Figures 11, 12, and 13, the RSRP values for terrestrial users are significantly lower than those for sUA at altitude.

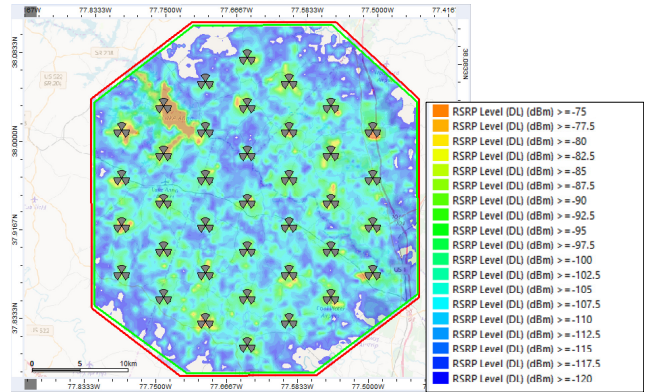


Figure 13. RSRP Results for Terrestrial Users

This is because the path losses encountered by terrestrial users are considerably higher than those encountered by sUA, even in a rural environment. It would be expected that the difference in path losses encountered by sUA and terrestrial

users would be even more pronounced in suburban or urban areas where buildings are much denser.

It can also be seen that terrain effects at the edges of the analysis area are also more pronounced for terrestrial users than for sUA, resulting in even lower RSRP values at those locations, or coverage gaps.

2) RSRQ Results

RSRQ is a network-related forward link metric describing the quality of the reference signal information as received by each user. The RSRQ metric is used for cell selection, cell reselection, and BS handover.

Figures 14 and 15 show RSRQ results for sUA at 100 ft and 400 ft AGL, respectively. The results identify average RSRQ values in the analysis area.

Comparing results in Figures 14 and 15, we note the same trend in the RSRQ variation with sUA altitude as for RSRP, (i.e., RSRQ values decrease as sUA altitude increases). Larger areas are shown in cyan or light blue in Figure 15 than in Figure 14. Those areas correspond to lower RSRQ values.

This is due to a decrease in received reference signal level with sUA altitude and because of an increase in intra-system interference with sUA altitude. As the sUA altitude increases, more BSs can be “seen” within the radio line of sight (RLOS) of the sUA, thereby contributing to an increase in RF interference at the sUA.

Even at the lower RSRQ levels, the signal quality should suffice, given the relatively modest data rate requirements assumed to be needed by a UAS C2 link (i.e., 100 kilobits per second [1]).

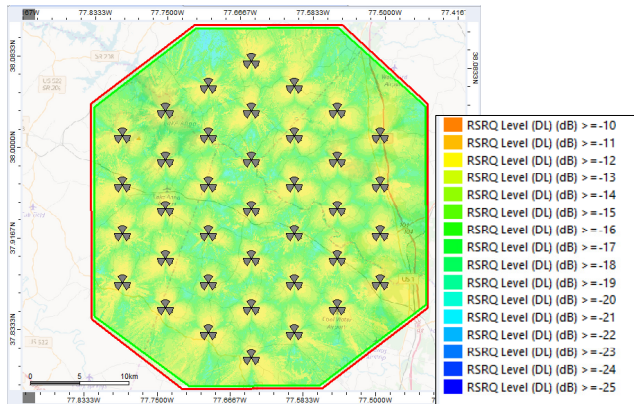


Figure 14. RSRQ Results for sUA at 100 ft AGL

Figure 16 shows RSRQ results for terrestrial users. As with RSRP results, the effects of the terrain and clutter make it more challenging to provide good signal quality towards the edges of the analysis area.

Comparing the results in Figure 16 with those in Figure 15, we observe that better RSRQ values are experienced by terrestrial users than by sUA at 400 ft AGL, in the areas where terrestrial users experience relatively good coverage. This is because the intra-network RF interference is much less at

ground level. A terrestrial user can “see” and “be seen by” far fewer BSs than a sUA at altitude, and so its RSRQ value is better.

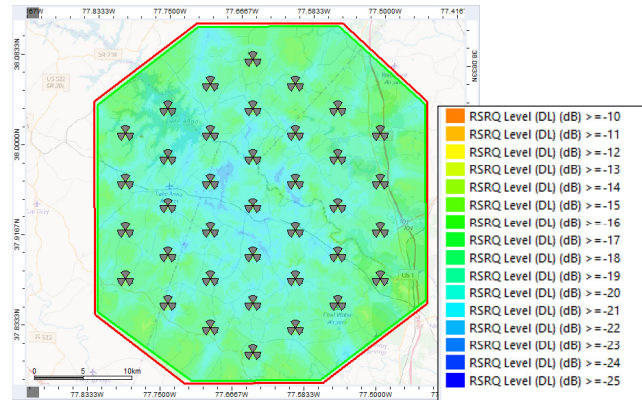


Figure 15. RSRQ Results for sUA at 400 ft AGL

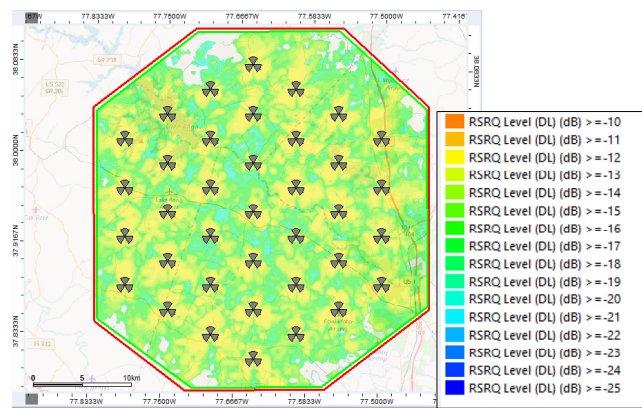


Figure 16. RSRQ Results for Terrestrial Users

We should also note that the assumed distribution of base stations in our analysis is fairly sparse, even for a rural environment, with base stations about 5 km apart. A denser distribution would further increase the number of BSs that could be “seen” by sUA at altitude, resulting in even lower RSRQ values. This is an area of further investigation, as methods to mitigate this interference are being researched and developed [17].

Besides the wide-area studies for sUA and terrestrial users, we also performed initial data traffic simulations. In these simulations, the available network resources are shared between sUA and terrestrial users. The effect of potential intra-network interference between the two user types is considered. We distributed five sUA and ten terrestrial users in each BS sector and performed Monte Carlo simulations.

Our initial results indicate a larger increase in mutual interference between the two types of users when loading for each user-type exceeded 25%. This effect had also been documented in other analyses, such as [20]. Therefore, we are allowing a maximum of 25% of network resources to be available for each user type in our data traffic simulations.

We also observed that sUA transmissions (on the reverse link) have a larger impact on the link performance experienced by terrestrial users when compared to the impact of terrestrial users' transmissions on the link performance experienced by sUA.

Although performed in different geographical areas, and evaluating different scenarios, our analyses indicated performance trends similar to those published in [21], [22].

VI. CONCLUSIONS

In this paper we have described an M&S framework developed to identify focus areas where M&S are needed to analyze comprehensively the potential use of wireless terrestrial networks for aviation communications.

We are developing an initial M&S capability to analyze an initial problem, namely how the performance of LTE-based networks, developed for terrestrial use, will be affected by the potential introduction of sUA as additional users in such networks. We are also analyzing the impact of sUA altitude and speed on the link performance it would experience from an LTE network.

We started by analyzing BVLOS sUAS scenarios in a rural environment, with sUA operating at or below 400 ft AGL. Our findings are as follows:

- For our physical-layer studies, we analyzed the impact of sUA altitude on link performance for four sUA altitudes: 100, 200, 300, and 400 ft AGL.
 - For all four altitudes, the sUA link performance was better than that of terrestrial users.
 - As the sUA altitude increased from 100 to 400 ft, the link performance for sUA degraded slightly.
- For our physical-layer studies we also analyzed the impact of sUA speed ranges (up to 80 km/hr) and frequency bands (up to 2.5 GHz) on link performance. We observed that the sUA speed had a modest impact on link performance in the analyzed frequency bands.

Next steps include modeling and simulations of physical layer link performance in urban environments.

In this paper we also described and analyzed a wide-area scenario in a rural area near Richmond, Virginia. This is a mostly rural environment, with open areas and fairly flat terrain. Envisioned UA operations in this area could include agricultural operations (e.g., crop monitoring) and linear infrastructure inspections. Our findings are as follows:

- Received signal levels at the sUA from its serving BS decrease with increasing UA altitude.
- Received signal levels for sUA at 100 ft and 400 ft are better than those experienced by terrestrial users within the analysis area.
- Received signal quality at sUA also decreases as the sUA altitude increases. This is due to a decrease in received signal level with altitude and because of an increase in intra-system interference with altitude. As

the sUA altitude increases, the sUA can "see" and "be seen" by more BSs.

- The impact of terrain was observed primarily at the low(er) sUA altitude (e.g., 100 ft).
- A larger increase in mutual interference between the two types of users (i.e., terrestrial users and sUA) was observed when the network loading for each user type exceeded 25%. Therefore, in our data traffic simulations we are allowing a maximum of 25% of network resources to be available for each user type.

Results for the wide-area studies indicate that, for the considered LTE network configuration in a rural environment, good signal levels and good signal quality could be achieved for sUAS at low altitudes. However, as the UA altitude increases, a decrease in signal quality can be observed. This result needs to be further investigated, especially for network configurations with denser distributions of base stations.

Next steps include continuing the data traffic simulations in rural areas, and then scenario development and analyses in urban environments.

NOTICE

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ABBREVIATIONS

Term	Definition
3D	Three Dimensional
3GPP	3 rd Generation Partnership Project
4G	Fourth-generation
5G	Fifth-generation
AGL	Above Ground Level
BLER	Block Error Rate
BS	Base Station
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
dB	Decibel
dB _i	Decibel with respect to isotropic
DES	Discrete Event Simulation
DL	Downlink
EVLOS	Extended Visual Line of Sight
FL	Forward Link
ft	Feet
GCS	Ground Control Station
GHz	Gigahertz
km/hr	kilometers per hour
LOS	Line of Sight
LTE	Long Term Evolution
m	meter
M&S	Modeling and Simulation
MHz	Megahertz

Term	Definition
NAS	National Airspace System
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RL	Reverse Link
RLOS	Radio Line of Sight
RMA-AV	Rural Macrocell Environment with Aerial Vehicles
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
SNR	Signal to Noise Ratio
sUA	small Unmanned Aircraft
sUAS	small Unmanned Aircraft System
TB	Transport Block
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
USS	UTM Service Supplier
UTM	UAS Traffic Management
VLOS	Visual Line of Sight

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