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

A UAS C2 Use Case

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Outline

- Research motivation and goals
- Modeling and simulation (M&S) framework
- Potential small unmanned aircraft system (sUAS) information flow
- Physical layer performance analysis in a sUAS context
- Radio frequency (RF) network performance analysis for wide-area scenario with terrestrial users and sUAS
- Summary of our findings
- Conclusions and next steps
Research Motivation

- Ever-increasing need for wireless connectivity among existing National Airspace System (NAS) users

- Large numbers of new NAS users, including UAS and urban air mobility (UAM) vehicles who will also need wireless connectivity

- Reliable, scalable, and flexible communications link solutions will be key enablers of future large-scale operations
  - Initial Research Use Case: 4G LTE and 5G communications for sUAS to enable BVLOS operations in the NAS

Notes:
- LTE = Long Term Evolution
- BVLOS = Beyond Visual Line of Sight
Overarching Research Goals

- Develop an M&S capability to enable analyses on the command and control (C2) link performance in the context of ensuring the safety of UAS operations
  - Consider the potential use of 4G LTE and 5G for sUAS connectivity
  - Consider potential sharing of network resources among sUAS and terrestrial users

- Provide independent data-driven inputs to FAA for decision making
  - On related oversight and guidance
  - Regarding industry standards recommendations
M&S Framework

RF Network Performance Analysis

Discrete Event Simulation (DES)

LTE Physical Layer Performance Analysis

4G / 5G = 4th / 5th generation wireless technology;
LTE = Long Term Evolution;

Impact on network performance?

Shared network resources

Data Analysis and Visualization

Source: graphics from Pixabay
Potential sUAS Information Flow

BVLOS (CGS₁ ↔ sUA₁)

EVLOS (CGS₃ ↔ sUA₃)

UAS C2 Data between sUA and GCS

Source: graphics from Pixabay

BVLOS = beyond visual line of sight (VLOS)
EVLOS = extended VLOS
GCS = ground control station
Potential sUAS Information Flow (cont.)

BVLOS (CGS₁ ↔ sUA₁)

EVLOS (CGS₃ ↔ sUA₃)

Data from USS Server to GCS

Source: graphics from Pixabay

BVLOS = beyond visual line of sight (VLOS)
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Physical Layer Performance Analysis in a sUAS Context

- **Goal:** evaluate LTE link performance impact of:
  - sUAS speed
  - RF operational environment
  - sUAS altitude

- **Simulation setup:**
  - MATLAB LTE Toolbox
  - 5G Library add-on

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Block Error Rate (BLER) = Number of erroneous block(s) received / Total number of blocks sent

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

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sUAS Simulation Scenario

Main Assumptions and Parameters

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<th>Values</th>
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<td>UAS operational environment</td>
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<td>Frequency band</td>
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<tr>
<td>Channel Bandwidth</td>
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<td>Propagation channel model for sUAS</td>
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<td>Allocated RF resources for data traffic</td>
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<td>sUA mobility</td>
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<tr>
<td>sUA altitudes</td>
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</tbody>
</table>

Notes:
3GPP = 3rd Generation Partnership Project
3GPP develops communications standards for cellular networks
Sample Physical Layer Results

Results for sUA at 100 ft AGL in a Rural Environment

Results in RF LOS conditions in a Rural Environment

Notes:
RF LOS = radio frequency line of sight
RF NLOS = radio frequency non-line of sight
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Summary of Findings from Physical Layer Analyses

- Better performance (lower BLER) if sUA encounters an RF LOS condition to its serving base station (BS) than an RF NLOS condition.

- For our analyzed speeds and frequency bands (at or below 2.5 GHz), sUA speeds have a fairly modest impact on link performance.

- For all 4 analyzed sUA altitudes, better link performance was observed for a sUA than for a terrestrial user.

- However, physical layer performance degrades as the sUA altitude increases.
Wide Geographical Area Scenario and Operational Environment Data

- **Analysis in a rural area near Richmond, VA**
  - 35 km by 35 km

- **Assumed 37 BSs spaced about 5 km apart**
  - Hexagonal grid as described in 3GPP TR 36.777

- **Incorporated digitized terrain and land-use (clutter) data**

Source: background image from Google Earth
Wide Geographical Area Scenario and Operational Environment Data (cont.)

- **Implemented RF propagation models for terrestrial users and for sUA**
  - as described in 3GPP documents
    - TR 38.901 (for terrestrial users)
    - TR 36.777 (for sUA)
  - Included the impact of shadow fading

- **For sUA, the path loss is expressed as:**

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

  - where:
    - \( h_{UA} \) = sUA height AGL (m); \( 10m < h_{UA} < 300 \) m
    - \( d_{3D} \) = slant range between BS antenna and the sUA
    - \( f_c \) = center frequency in Gigahertz (GHz)

  \[
  PL_{NLOS} = \max(PL_{LOS}, -12 + (35 - 5.3 \log_{10}(h_{UA})) \log_{10}(d_{3D}) + 20 \log_{10}(40 \pi f_c / 3))
  \]
Signal Level Results for sUA at 100 ft

- Performance Metric: Reference Signal Received Power (RSRP)
Signal Level Results for sUA at 400 ft

- Performance Metric: RSRP
Signal Level Results for Terrestrial Users

- Performance Metric: RSRP
Signal Quality Results for sUA at 100 ft

- Performance Metric: Reference Signal Received Quality (RSRQ)
Signal Quality Results for sUA at 400 ft

- Performance Metric: RSRQ
Signal Quality Results for Terrestrial Users

- Performance Metric: RSRQ
Summary of Findings from RF Network Performance Studies

- Analysis was performed over a wide geographical area near Richmond, VA

- As the sUA altitude increases, the received signal levels at the sUA decrease in areas with no terrain effects
  - Terrain blockage was not a main factor at the analyzed sUA altitudes
  - However, some terrain effects were observed primarily at the lower sUA altitude (100 ft), at the edge of the coverage area

- Received signal levels for sUA at 100 ft and at 400 ft AGL were better than those experienced by terrestrial users

- Received signal quality at sUA decreased as the sUA altitude increases
  - Primarily because of an increase in intra-system interference at the sUA
    - As the sUA altitude increases, the sUA “can see” and “be seen” by more BSs
Conclusions and Next Steps

- Developed a M&S framework and an initial M&S capability
- Analyzed an initial scenario in a rural environment with sUA and terrestrial users sharing network resources

Initial results showed that good signal levels and good signal quality could be achieved for sUAS at low altitudes
- However, as the sUA altitude increases, a decrease in signal quality is observed
- Further analysis is needed, especially for network configurations with denser distributions of BSs

Next steps include:
- Enhancing the M&S capability
- Scenario development & analyses in urban environments
Thank you!

Questions
## Abbreviations

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>3D</td>
<td>Three-Dimensional</td>
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<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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<tr>
<td>4G</td>
<td>Fourth-generation</td>
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<td>5G</td>
<td>Fifth-generation</td>
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<td>AGL</td>
<td>Above Ground Level</td>
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<td>BLER</td>
<td>Block Error Rate</td>
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<td>BS</td>
<td>Base Station</td>
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<td>BVLOS</td>
<td>Beyond Visual Line of Sight</td>
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<td>C2</td>
<td>Command and Control</td>
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<tr>
<td>dB</td>
<td>Decibel</td>
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<tr>
<td>dBi</td>
<td>Decibel with respect to isotropic</td>
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<td>DES</td>
<td>Discrete Event Simulation</td>
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<tr>
<td>DL</td>
<td>Downlink</td>
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<td>EVLOS</td>
<td>Extended Visual Line of Sight</td>
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<td>FL</td>
<td>Forward Link</td>
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<tr>
<td>ft</td>
<td>Feet</td>
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<tr>
<td>GCS</td>
<td>Ground Control Station</td>
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<tr>
<td>GHz</td>
<td>Gigahertz</td>
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<tr>
<td>km/hr</td>
<td>kilometers per hour</td>
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<tr>
<td>LOS</td>
<td>Line of sight</td>
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<thead>
<tr>
<th>Term</th>
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<tbody>
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<td>LTE</td>
<td>Long Term Evolution</td>
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<tr>
<td>m</td>
<td>meters</td>
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<tr>
<td>M&amp;S</td>
<td>Modeling and Simulation</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>NAS</td>
<td>National Airspace System</td>
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<tr>
<td>NLOS</td>
<td>Non-Line of Sight</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RL</td>
<td>Reverse Link</td>
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<tr>
<td>RLOS</td>
<td>Radio Line of Sight</td>
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<tr>
<td>RMa-AV</td>
<td>Rural Macrocell Environment with Aerial Vehicles</td>
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<tr>
<td>RSRP</td>
<td>Reference Signal Received Power</td>
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<tr>
<td>RSRQ</td>
<td>Reference Signal Received Quality</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>sUA</td>
<td>small Unmanned Aircraft</td>
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<tr>
<td>sUAS</td>
<td>small Unmanned Aircraft System</td>
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<tr>
<td>TB</td>
<td>Transport Block</td>
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<td>USS</td>
<td>UAS Service Supplier</td>
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