UAS in the NAS Project - Large-scale Communication Architecture Simulations with NASA GRC Gen5 Radio Model

System Description and Performance Report February 29, 2016

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Introduction

The large-scale, communication architecture simulation system has been developed for research and performance analysis of NAS operations using proposed communication architecture concepts to manage and control unmanned aircraft flying alongside piloted aircraft in the NAS, with the focus of its implementation on using CNPC, Flight Test radios and their associated infrastructure developed at NASA GRC. The development effort for this simulation capability has produced two large-scale architecture concept models, one Relay architecture model - where ATC messaging is relayed through the UA over the CNPC radio link to/from UA controllers, and one Non-relay architecture model – where ATC messaging is conveyed over ground networks, both for LOS and BLOS operations.

This report provides a description and performance characterization of the large-scale, Relay architecture, UAS communications simulation capability developed for the NASA GRC, UAS in the NAS Project. The system uses a validated model of the GRC Gen5 CNPC, Flight-Test Radio model. Contained in the report is a description of the simulation system and its model components, recent changes made to the system to improve performance, descriptions and objectives of sample simulations used for test and verification, and a sampling and observations of results and performance data.

The simulated architectures use the NASA ACES application as the baseline architecture application to provide air traffic for the simulations and the platform for the ground communication system infrastructure. Integrated into the architectures is the Gen5 CNPC data-link radio system, developed in Opnet Modeler, which provides a continuous uplink and downlink of UA command and control, navaid and surveillance data throughout the duration of a simulated UA flight, and for the relay of ATC Voice and CPDLC messaging data traffic services for Air Traffic Management.

Scope

* The system description and results in this report are for simulations using the UA, Relay communication system architecture model. The system has been developed also with a non-Relay option that will use an end-to-end network model for messaging, however a complete definition of the model still needs to be developed and integrated. * The architecture model uses the NASA GRC, Gen5 version of the CNPC Flight-Test radio model for UA CNPC datalink operations with IP protocol for moving data/messaging between the UA CNPC Radio and the UA controller supported by a networked ground station infrastructure. * For simulations run for this report, UA and Piloted flight traffic scenarios are defined primarily in ZAU Center due to a high level of NAS sector detail we have available for evaluation and analysis in ZAU at this time. * In most of the simulations, configuration settings for several of the architecture delay contributing components in the ground subsystem models in the ground components were set for fixed delays wherever the models did not inherently generate dynamic delay contributions. However, also available as configurable settings, are variable ranges for these models and programmable configuration options. Recent work to define a model for the ATC ground architecture network operations was completed and is demonstrated in one simulation covered in this report. * For messages used in the simulations, the current communication description files contain baseline message sets for communication dialog. These message-sets provide messaging that occurs in departure and arrival TRACON airspace, for 1st Center entry and Center and Sector crossings for each aircraft in a simulation. * Service classification designations and data rates used in simulations for C2, TLM/Navaid data, surveillance and weather data are derived based on a radio capacity sizing analysis that was done at NASA GRC.

System Description

Relay Architecture Simulation Concept

The large-scale, communication Relay architecture concept that the system design is based on was initially defined in RTCA Issue Paper SC005 several years ago, which presented several options on communication architectures for Unmanned Aircraft operation in the NAS. After an internal evaluation of those options, and selection of a candidate Relay architecture, the selected configuration from SC005 was translated into a working architecture diagram (shown in Figure 1). The selection of this architecture was based on an assessment process where the concept, and the one used for our Non-relay architecture, were determined to provide a high level of functional compatibility with the UAS-in-the-NAS integration plan as it was currently understood, and a high level of flexibility for communications operations.

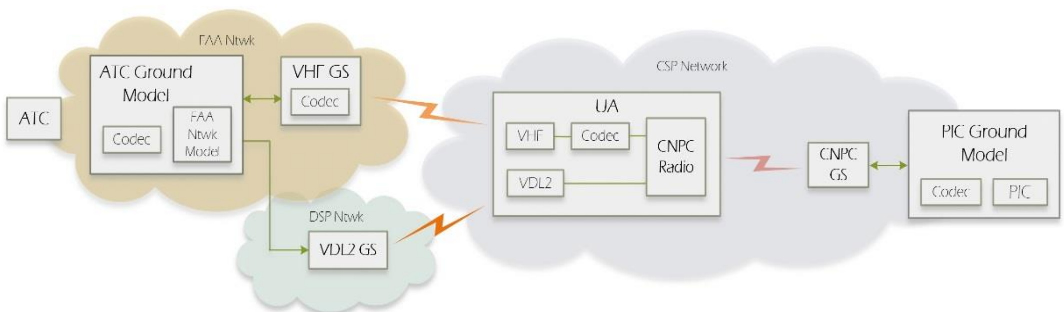


Figure 1: Relay Architecture Concept Diagram

ACES - Relay Architecture Model Implementation

After selection of the architecture, the concept from Figure 1 was translated to the working architecture model shown in Figure 2. The diagram shows the component models and interconnectivity via an ACES communication service channel. The transition to this system model carried the key components and subsystems of the architecture concept and included major delay contributing, functional elements to implement the concept in the system model. In simulations, modifications to settings for the operation of these components is selectable based on configuration options or via code changes that can be made to each of the component models. For the CNPC radios, a common framework for interaction with the end-to-end architectures was established that allows us to swap the radio models by version or type without modifying the simulation environment to simplify reconfiguration.

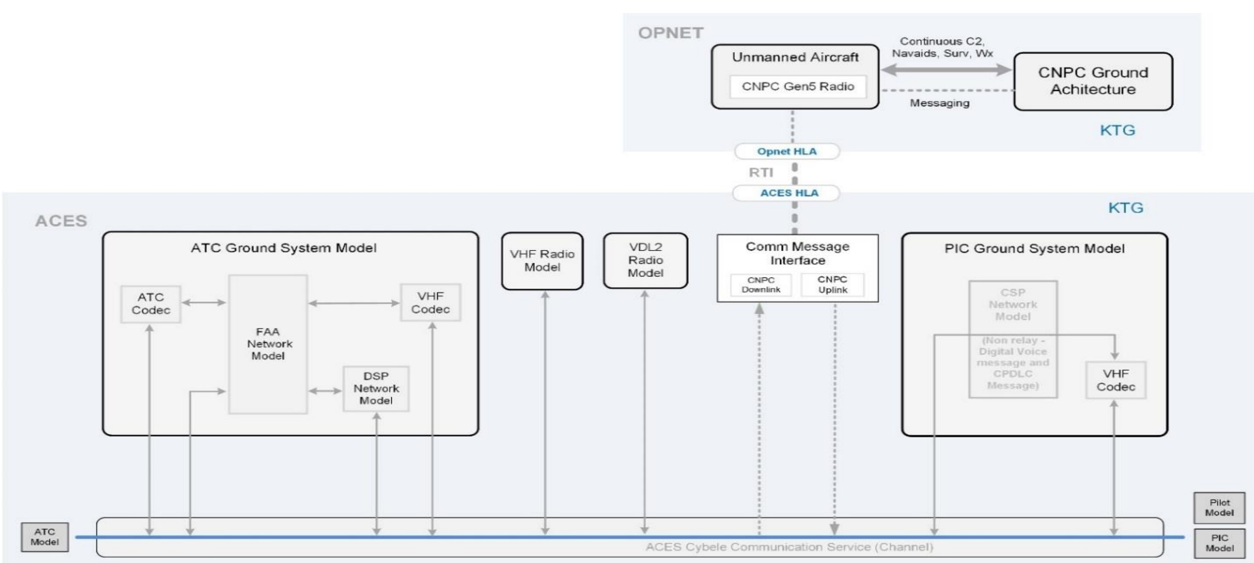


Figure 2: Relay Architecture Model Implementation Diagram

Simulated Architecture Operation

The end-to-end architecture uses the Airspace Concept Evaluation System (ACES) and Opnet Modeler applications interactively. ACES, developed by NASA for airspace concept studies, provides the simulated aircraft flights and flight operations, NAS architecture models and rules that govern NAS aircraft flights. ACES has been updated for communication simulations to provide the ground based components of our communication system architecture. The Opnet Modeler application (where the CNPC radio models have also been developed in our work for independent study) provides the CNPC radio models and the CPNC ground infrastructure operating independently within the Opnet environment, and interactively within the end-to-end architecture of the large-scale simulations.

For a simulation, the two applications startup and are synchronized in time using a common Run Time Infrastructure (RTI). The RTI provides precise timing coordination between the applications, the timing and transfer of interactions meant to synchronize the UA flight dynamics and the means by which operations and messaging instances are transferred between the applications. In both ACES and Opnet, a common wheels-up to wheels-down Kinematic Trajectory Generator (KTG) has been integrated that provides state data (e.g. latitude, longitude, altitude, airspeed, etc…) for piloted flights and UA on the ACES side, and for UA flights flown in a simulation on the Opnet side. This process allows the flight operations that ACES provides inherently, and also places the CNPC Radio Model on-board the UA moving at the same rate as the UA, at the same position as the UA and at the same altitude for the duration of the flight. For simulation runs, configuration of user selectable simulation details occurs in ACES for ACES component model settings, communication system settings and Flight Data Sets that define UA and Piloted aircraft traffic scenarios. Both applications are synchronized in time at start up, and all communication activity is simulated gate-to-gate for piloted flight routes and from wheels-up to wheels-down for UA.

On the Opnet side of the simulation, as UA are initiated in the simulation, each UA is provided an indication from ACES just before wheels-up to recognize when it will attain wheels-up status to begin the CNPC connections for C2, TLM/Navaid, surveillance, and weather data as appropriate to a each UAs Service Class. At that time, the CNPC Model for each UA begins sourcing and sinking the data streams associated with each of these applications through the model. These data stream rates are application service dependent and provided in the radio design, and the radios will continue to move those data throughout the duration of the UA flight, through CNPC Ground Station transitions until the UA attains wheels-down status. Also, for each service class, Opnet will automatically vary the data rates carried over the link for these services depending on TRACON vs. Enroute airspace requirements as appropriate to each UA service class.

For UA Service Classes 2-4 and for Piloted aircraft that require ATC message traffic, Voice or CPDLC messages are initiated by the ATC or Pilot or PIC models in ACES. ACES uses the dedicated Communication Service Channel and an publish-subscribe relationship established in each of the modeled components to move the message to each, next responsible model after the current model has acted on the message after its delay contribution is applied. For operations to hand messages off to Opnet, the architecture uses a Comm Message Interface component that passes the message type and information about the message that Opnet requires over the RTI via specific interaction types for each message. The CNPC radio model processes the message and conveys it over either its uplink or downlink (as appropriate) and then provides ACES with a message success indication that directs ACES to continue the message on to the next model component in the architecture until the message is received by its target recipient.

All of the operations that occur as described above are handled independently per-UA or per-airspace as the air traffic load and distribution of flights in the CONUS dictate. ACES and Opnet both provide instantiations of models for the components of the architecture and for the radio models respectively, as required to service each UA or Piloted flight as needed. Mapping and operations for interconnectivity with VHF and VDL2 ground stations are provided on the ACES side of the simulation and CNPC GS infrastructure is provided in Opnet.

The following is a summary of the Comm Architecture capabilities applied in the relay architecture.

ACES Infrastructure - Architecture Model Capabilities

End-to-end ATM-Pilot to/from PIC, messaging interactive with Opnet UA Gen5 CNPC Communication system infrastructure model. RTI synchronizes timing ACES-Opnet.

- ATC Ground System Model
  - Networked, ATC VHF Ground Stations
  - Networked VDL2 Ground Stations within a Datalink Service Provider network model.
  - Codec model components as key contributors to end-to-end message latency.
  - ATC Ground System Model is a distributed Model – Instantiated in simulations as required at A/C Departure/Arrival sites.
  - Configurable FAA and DSP network/model delay capabilities (Fixed, Random-within-range, and Programmable)
- VHF Voice Comm Model
  - Instantiated for each current airspace where an aircraft is flying (within CONUS).
  - Physical layer propagation model with VHF message human factor management
  - NAS mapping to best available sectorization (one Freq per sector) and generalized for Airport/TRACON frequencies.
- VDL2 Comm Model
  - Instantiated for current airspace where an aircraft is flying.
  - Generic GS grid mapping – default in ACES for VDL2 Operation
  - Physical and upper layer protocol model
- UA PIC Ground System Model
  - Codec delay for incoming and outgoing PIC Voice messages.
- Synchronization of UA Flights in Opnet environment with ACES architecture.
  - Common Trajectory Generator running in ACES/Opnet (UA State data in ACES = UA State data in Opnet)
- Baseline ATC Communication Messaging scenario

Opnet CNPC Radio System – Model Capabilities

Gen5 CNPC Radio models and CNPC GS mapping/network operations running independently in Opnet Modeler. Runs interactively with ACES architecture model. RTI synchronizes timing ACES-Opnet.

- Distributed CNPC Radio Models
  - Instances of the GRC Gen5 CPNC radio model are created, associated with, and flown onboard any UA flown in the simulation.
- Networked CNPC Ground Station infrastructure/mapping.
  - Derived per GRC/Rockwell Collins specifications for the Gen5 model design and IPv6.
  - Provides CPNC datalink ground station distribution and connectivity/handoff capability for wheels-up to wheels-down UA CNPC link operations.
- Synchronization of UA Flights in Opnet environment with ACES architecture.
  - Common Trajectory Generator running in Opnet/ACES. (UA State data in Opnet = UA State data in ACES)
- UA Command & Control, Navaid and Surveillance data streams provided continuously to/from a UA for the duration of a flight via the CNPC uplink/downlink.
  - Generated/sinked in Opnet Modeler environment.
- Receives/processes ATM messages from ACES.
  - Voice messages provided as msg duration to UA conversion/processing - transmitted over the CNPC down link. Message processing includes encoding/decoding + uplink/downlink processing delay + uplink/downlink link delays.
  - CPDLC messages to UA provided as bit length – transmitted over CNPC down link.
- Distributes VHF situation awareness messages to all UA’s in similar airspace for additional CNPC radio loading.

Kinematic Trajectory Generator (KTG)

The Kinematic Trajectory Generator (KTG) is a medium fidelity wheels off to wheels on, 4D flight trajectory generator that is used for modeling and simulation-based validation of trajectory-based operational concepts. KTG calculates the motion of each aircraft in the simulation using kinematic aircraft data, which is defined by Eurocontrol's Base of Aircraft Data (BADA) data file derived from nominal aircraft performance.

The KTG software is integrated into NASA's Airspace Concept Evaluation System (ACES) using the Swappable Trajectory Generator (STG) bridge. The ACES STG bridge allows for the substitution of different trajectory generators within ACES. The Trajectory Generator Interface (TGI) provides an interface to the KTG for trajectory generator creation and initialization, flight trajectory generation, querying for current flight state, and applying maneuvers.

KTG also supports a standalone mode of trajectory generation. The OPNET software, running the Gen 2 Radio Model, makes use of this mode by providing flight plans and initial flight states received from ACES to initialize the standalone KTG that is directly under its control. Once the standalone KTG is initialized, the OPNET software model makes use of calls to the standalone KTG, via a Java Native Interface (JNI), that allow the software to advance the time and obtain current flight states from the standalone KTG under the OPNET model's control. This design methodology was chosen so that in large scale simulations, detailed flight state information did not need to be sent frequently across the RTI connection, thereby minimizing network communication bottlenecks. Because the ACES KTG and the OPNET KTG are both time-controlled in a unified manner by the RTI clock, the resulting aircraft state calculations are accurately synchronized with one another.

ACES/Opnet Interoperability – HLA/RTI (Run-Time Infrastructure)

The High Level Architecture (HLA) was developed by the U.S. Department of Defense (DOD) to provide a means for many different types of simulation software to interoperate. The MAK Run-Time Infrastructure (RTI) is software that implements the HLA interface specification by providing a set of software services to coordinate timing and data exchange between applications (called federates) within a federation (a managed grouping of federates). In the large-scale implementation, the ACES is considered a one federate, and OPNET, executing the Gen5 Radio Model Software, is another federate.

Key software services that the MAK RTI provides are the creation of the federation, allowing federates to join or resign from the federation, establishing synchronization points, and controlling the publication of, and subscription to, objects and interactions exchanged by individual federates. One of the more important services provided by the RTI for ACES and OPNET Gen5 Radio Modeling simulation applications is the coordination of the advancement of individual federates along a unified time axis. Time management is beneficial for simulation applications that must maintain a timestamp ordering to the interaction and object messages exchanged between federates.

In the UAS Project Large-scale simulation, the primary operations provided by the MAK RTI are: 1) General timing for simulations, 2) Providing synchronization between the ACES and Opnet instances of the Kinematic Trajectory Generator to allow synchronization of aircraft state data, and 3) For the synchronized transfer of interactions that carry Voice or VDL2 message information between the applications and provide Opnet message Uplink or Downlink success indications.

CNPC - Opnet Radio Models Implementation in Large-Scale Simulation Architecture

Gen5 Radio - Model Description

The Gen5 radio model version used in these simulations reflects the as-validated, radio characteristics and capabilities of the Gen5, Flight Test radio currently in use at NASA GRC. The radio waveform provides a Time Division Duplex with TDMA uplink and FDMA downlink with the radio able to support multiple data link connections with priority, bi-directional link health assessments and operations for multiple aircraft / multiple tower handoffs as an enhancement for large-scale simulations. Networking capabilities are integrated into this radio model version using IPv6 with mobility support and header compression.

Various UA have different requirements for data traffic. As such, several different waveform modes are provided in order to efficiently support the different UA. These are designated as Mode A through Mode D, and are summarized in the table below. The varied modes are used within service class assignments for the unmanned aircraft.

	Bandwidth (kHz)	Max Throughput (kbps)
Mode A	30	6.24
Mode B	60	15.2
Mode C	90	24.8
Mode D	120	33.8

Gen5 Architecture/Infrastructure in LS Simulations

In the large-scale simulations, each UA (as it is initiated in a simulation at wheels-up) is equipped with an instance of the Gen5 Radio and associated RF system components on the OPNET Modeler side of the simulation architecture. The OPNET Modeler simulation also provides the ground architecture in the form of distributed Ground Stations (GS) in a configuration the Gen 5 radio is designed for to be supported by.

In the simulations, the CNPC GSs are networked together. GS locations were selected at airport locations to provide coverage along all flight paths and to the ground at airports used by UAs in the simulation, while also attempting to utilize a hexagonal grid spacing with 69NM cell radius, Figure 3 shows the ARTCC boundary in white and the locations of the GSs with their respective coverage areas.

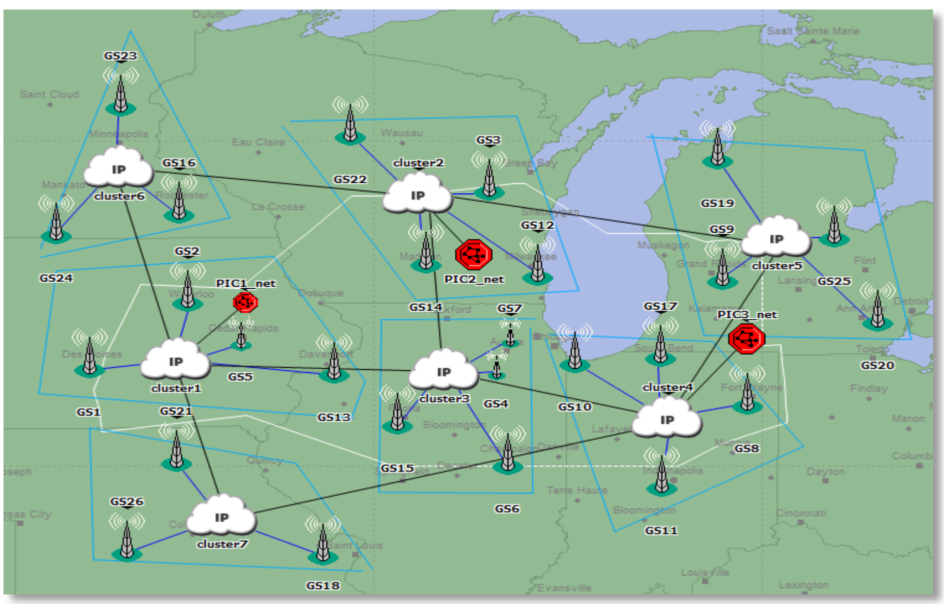


Figure 3. ZAU ARTCC Boundary and Ground Station Coverage Areas

The GSs are configured for the UL24 mode, in which the uplink time is divided into 24 TDMA slots. The GS can transmit to a different UA in each of these slots, allowing a single GS to communicate with up to 24 UA in a single frame. The different waveform modes are implemented via utilizing multiple slots for a UA, with a single slot for Mode A, two slots for B and three for C (Mode D is not required for any UA in the uplink). Therefore, the actual number of UA supported by a GS with 24 slots is dependent upon their traffic requirements.

For the downlink, each GS is configured with 10 Mode A links, 4 Mode B links, and 8 Mode D links to support several different types of UA. These were selected to support the maximum number of UAs of each type expected to be encountered by any tower.

Nearby GSs are connected to an IPv6 router represented by the 'clouds' in the diagram. The links between the GSs and the router are modeled at DS1 speeds (1.544 Mbps) which is sufficient to support the max expected UA uncompressed traffic rates.

The IPv6 router 'clouds' are interconnected forming the backbone of the CNPC ground network. Since the links between these routers will contain traffic aggregated from multiple GSs, these links are modeled at the DS3 speed of 45 Mbps. Three separate PIC networks, which house the PIC and associated systems (including the home agent for Mobile IPv6), are attached to the backbone network also at the DS3 link speed.

Data Traffic/Applications

There are currently 5 different applications that send data over the radio:

- ATC Voice: In the large-scale simulations this application traffic is provided as per the VHF Voice message sequencing that occurs - generated by the ACES simulation.
- ATS Data (CPDLC): In the large-scale simulations this application traffic is provided as per the configuration of the use of CPDLC and message traffic and as per the Voice message sequencing that occurs - generated by the ACES simulation.
- Command & Control (C2): Continuous uplink and downlink between the PIC and each UA flown in a simulation - wheels-up to wheels-down
- Navaids: Continuous uplink/downlink between the PIC and each UA flown in a simulation - wheels-up to wheels-down
- Surveillance data: Continuous downlink between the UA and PIC for each UA flown in a simulation - wheels-up to wheels-down
- Weather data: Continuous downlink between the UA and PIC – wheels up to wheels down

Each of these data traffic types is defined as a separate service flow to the CNPC radio, which is identified by the radio via the use of the IPv6 traffic class settings. By classifying the traffic this way, the CNPC radio can prioritize the traffic to provide the most critical data the lowest delays. In these simulations, the C2 and navaids traffic are the highest priority, followed by voice traffic, surveillance, ATS data, and finally weather.

The characteristics of these data applications depends upon the phase of flight of the UA, with separate profiles defined for the departure phase, en route phase, and arrival phase. The departure phase begins when the UA is instantiated and lasts until the UA is 5 NM away from the departure airport. At that time it switches to the en route phase, which in general generates less traffic than the departure phase. The UAS switches to the arrival phase when the UA is 5 NM from the arrival airport. In this phase the data traffic is generally higher than the other two phases.

To adapt to the changing data requirements for the different phases of flight, the CNPC radio will adjust its link settings with the GS. In the departure and arrival phases, for instance, the radios will operate in a 20 Hz mode, utilizing 20 transmissions per second between the UA and its connected GS. While in the en route phase, with the less demanding traffic profile, the UA will operate in a 15 Hz mode with its connected GS. That leaves 5 frames per second available, which the CNPC radio uses to scan nearby towers enabling handoffs.

The table below summarizes the data application profiles (identified by 4 Service Class designations) available to be assigned to UA using the Gen5 Model. These are assigned on a per A/C type basis in large scale simulations.

Service Class	Transmit Power	Phase	Downlink Mode	Downlink Rate (Hz)	Uplink Quanta[1]	Uplink Rate (Hz)
SC1	1	Departure	DL-B	20	2	20
		En-route	DL-A	15	1	15
		Arrival	DL-B	20	2	20
SC2	10	Departure	DL-C	20	3	20
		En-route	DL-C	15	3	15
		Arrival	DL-C	20	3	20
SC3	10	Departure	DL-D	20	3	20
		En-route	DL-D	15	3	15
		Arrival	DL-D	20	3	20
SC4	10	Departure	DL-D	20	3	20
		En-route	DL-D	15	3	15
		Arrival	DL-D	20	3	20

CNPC Message/Link Delays

Every message transmitted across the CNPC link will experience delays with contributions from several sources. These components are explained using simple example is shown in Figure 4, which uses a small message represented by the thin blue arrow and a large message represented by the thick green arrow. In the center of the graphic is a depiction of the 50ms CNPC frames. In these simulations, each UA is configured to use 15 out of 20 frames every second (for a rate of 15Hz) for the en route phase and 20 out of 20 frames (20Hz) for departure and arrival phases. The frames utilized by the example UA are shaded, and have a red arrow indicating the transmission opportunities. For a GS CNPC radio, this arrow represents the beginning of the slot assigned to the UA in the uplink sub-frame. For a UA CNPC radio, the arrow represents the beginning of the downlink sub-frame.

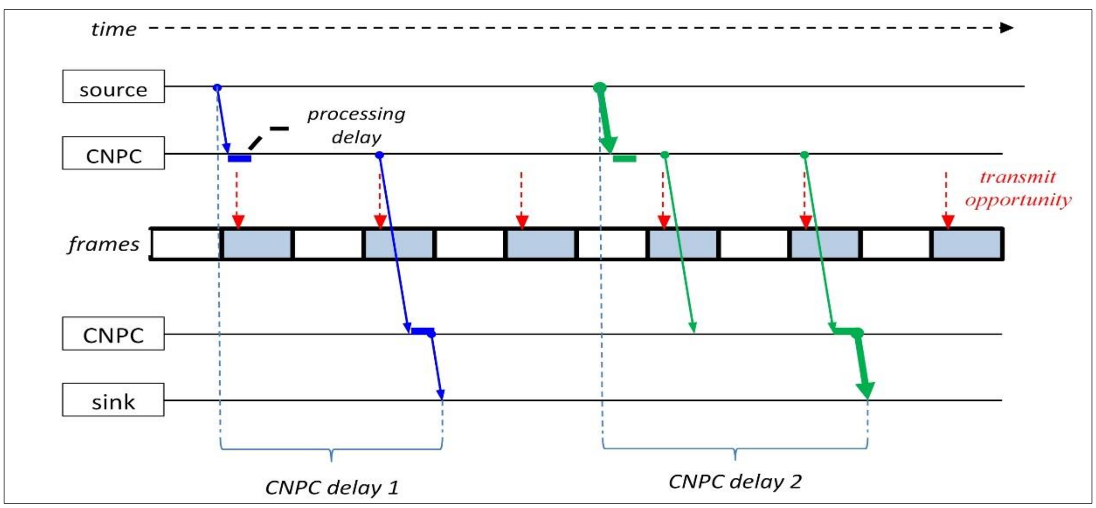


Figure 4. CNPC delay components example

When a CNPC radio receives a message for transmission, there is a small delay representing the hardware processing required to prepare the message for transmission. This delay is represented by the small blue box on the CNPC radio line. In the case of the small message, by the time the processing is completed the nearest transmission opportunity has been missed and the radio must wait until the next opportunity. When the next opportunity arises, the message is transmitted across the link, taking a full slot to transmit (0.96-2.88ms uplink

[1] "Uplink Quanta" it is the number of consecutive slots used. Each uplink frame has 24 uplink slots, which in theory can support 24 different UAs. However for larger service classes they need multiple consecutive slots, so looking at the SC3 and SC4, a tower can only support 8 at a time since each one needs 3

or 23 ms downlink) and incurring a slight propagation delay. When the message is received by the peer CNPC radio another processing delay is incurred, after which the message is sent to the sink.

The green arrow in the example represents a message that is too large to fit into a single CNPC frame. When this message is received by the CNPC radio, it incurs the processing delay. Since the processing is completed shortly before the transmit opportunity, the message begins transmission in the upcoming opportunity with a shorter overall wait than the earlier blue message. Due to its size, only part of the message is transmitted on this opportunity; the rest is transmitted 50 ms later in the next opportunity. Once both fragments are received by the peer radio, there is another receive processing delay after which the message is sent to the sink.

One additional delay source not discussed in the example is a queuing delay on the transmit side. When traffic is received by a CNPC radio for transmission (and after the processing), the data is placed into one of several priority queues. On every transmit opportunity, the CNPC radio looks first in the highest priority queue for traffic. After serving any data in that queue, if there is still room in the frame for more traffic, the radio obtains data from the next priority queue, and so on, until no more data fits into the frame or all queues have been serviced. Therefore, traffic sent over the radio may be delayed based on its priority relative to other traffic.

In summary, the overall CNPC delay is based on the following components:

- Transmit-side processing delay (10 ms)
- Queuing delay (variable based on other traffic, priority)
- Delay until start of next transmit opportunity (0-100ms, based on arrival time of message)
- Transmission length delay (0.96-2.88 ms uplink, 23ms downlink)
- Propagation delay (variable based on distance, 0.4 ms at 69 NM)
- Fragmentation delay (50-100 ms per additional fragment)
- Receive processing delay (10 ms)

Ground Network Delays

The ground network delays are based on the number of hops between the UA's current ground station and the PIC, along with the network load at each of those hops. On average, there are 4.5 hops between a CNPC GS and a PIC home agent, and 1 hop between the home agent and the PIC. The network load is dynamic and will vary based on factors such as the number of UA's in the simulation, the phase of flight of the UA's, and the UA locations relative to their PICs. Aside from the UA traffic, the network also carries a small amount of routing protocol traffic to maintain the network links.

Voice Codec Delays

The ATC voice relay traffic has additional delays imposed upon it by the voice encoding / decoding procedure. The encoding process is represented in
Figure 5. First, the analog voice is split into smaller samples. At the end of every sample, the encoding process incurs a delay (for some codecs, information from sample N+1 is required to complete encoding of sample N resulting in longer delays). This step results in a stream of encoded samples. Not every encoded sample is individually transmitted, rather several samples are packetized together and transmitted as a single unit. The overall encoding delay is thus measure from the beginning of the first sample until the packet is completed at the end of the last encoded sample in that packet.

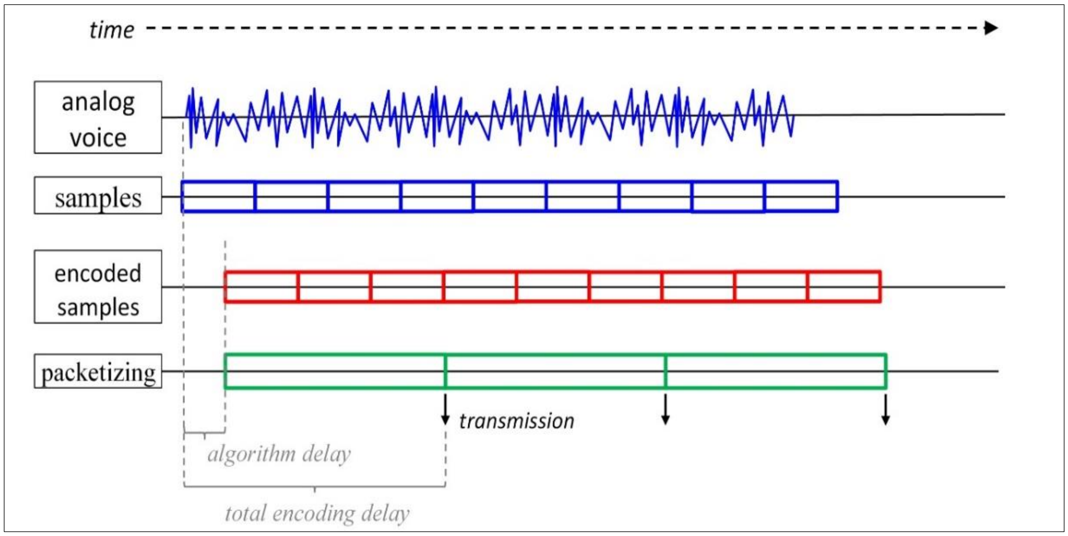


Figure 5: Voice Encoding Process

The decoding process is an inverse of the encoding procedure. Encoded samples are removed from the received packets and placed into a buffer. The samples are held in the buffer for a short amount of time to help compensate for jitter experienced during transmission over the network and CNPC link. It is intended to ensure that data is continuously available to decode and reproduce an unbroken analog stream. After the buffering delay, the encoded samples are decoded which imparts another delay. The decoded sample is then played back as analog audio.

Specific information for the various delays has not been found for the proposed AMBE-ATC-10 voice codec. For these simulations, representative numbers have been used based on other technologies, with the intent to refine these in the future.

The overall voice codec delay components are:

- Voice sample size (20 ms)
- Algorithm delay (65 ms)
- Packetization delay (5 samples, 100 ms)
- Buffering delay (50 ms)
- Decoding delay (7.5 ms)

CNPC Ground Station Link Management Methods

The Gen5 CNPC model is required to perform several important link management functions during the course of a UA flight. These are:

- Scanning for GSs
- Establishment of a link to a GS
- Hand off from one GS to another
- Management of the link settings to adapt to data requirements for each phase of flight
- Lost link recovery

The mechanisms built into the model are based on the approaches used for the prototype Gen5 radio but have been extended as necessary to provide all the functionality required for the LS simulations. These mechanisms are described below in the context of the phases of a typical flight.

Pre-Flight

When a UA is first instantiated in the simulation at the departure airport (90s before takeoff), the CNPC model starts in an uninitialized state with no links established. At this time there is no application traffic, so the UA requires only a small amount of CNPC resources to prepare for the flight. The UA must scan for a GS to connect with. The UA CNPC model consults a pre-defined onboard database of GSs to find the closest ones (based on the UA's location) and obtains a set of uplink modes and frequencies to use in scanning. The UA CNPC model then begins to listen for broadcasts from the GSs (one at a time) using all 20 CNPC frames. After going through the list, the UA CNPC model chooses the GS with the best uni-directional health and begins the link establishment process.

Link establishment begins with the UA sending a connection request message to the GS using the access channel advertised in the GS broadcast. Upon receiving this request message, the GS checks the link requirements provided by the UA against the GS's available resources and replies with connection response message indicating either the resources granted to the UA or an indication that no resources are available. Once resources are granted, dedicated link streams are created for the UA and GS to communicate along with a set of primary and secondary management connections. At this point the UA must perform authentication with the GS.

Authentication consists of an authorization request and response message exchange initiated by the UA. This exchange is a modified version of the 802.16 PKMv2 mutual authentication procedure. The 802.16 procedure requires the exchange of both parties X.509 certificates (signed by a higher level CA) using the request and response messages. These certificates may be relatively large compared to the CNPC throughput capabilities and require several seconds of time to transfer. As an optimization, the model allows for the certificates to be omitted (via an assumption GS certificates can be pre-loaded on the UA as part of UA flight planning procedures, and UA certificates can be registered with the CNPC service provider and obtained via ground links for GS) for a percentage of the authentications (including always and never).

Failures may occur at several points in this process. Timers and retransmissions are used to recover from message losses during the connection and authentication processes. If too many retransmissions occur, or the GS responds that it does not have the resources to support the UA, then the UA may attempt to connect to the next best GS (if one is available) or return to scanning.

Departure

The UA transitions to the departure phase 10s before takeoff. At this point the currently configured CNPC link streams do not have enough capacity to support the departure data traffic. The UA CNPC model begins the waveform change procedure to obtain the resources necessary for this phase of flight.

The waveform change is initiated via the UA sending a change request to the GS with its new link requirements. Upon receiving this request, the GS checks the requirements against its available resources and responds with either granting the new parameters or an indication that resources are not available. Once the new resources are granted, both the UA and GS will switch the link stream settings at a prearranged time. The UA and GS create connections for each of the UA's service flows to allow data transfer to begin.

Failures may occur in this process. Timers and retransmissions are utilized to recover from a lost request. To recover from a lost response (which causes the GS to switch settings but not the UA), or a failure of the new link parameters, both the UA and GS will monitor the performance of the new link. If the new link is not sufficient within a small amount of time, both the UA and GS will revert back to the prior settings. At this point the UA may re-attempt the change.

En Route

Once the UA is airborne and 5NM from the departure airport, the application traffic lessens. The UA initiates another waveform change to reduce the number of CNPC frames used. The now-free frames are used by the UA CNPC model to scan for nearby GS. When another GS is found with sufficient uni-directional health, the UA will perform the connection process with it as a standby secondary GS using minimal CNPC resources. This connection process is the same as for the primary GS, with the exception that the UA indicates that the new link can only operate in frames not used by the primary GS. Some resources must remain free to continue the scanning process.

The UA CNPC model continually compares the uni-directional health of the secondary GS with results from the scans. When the health from another GS is deemed greater than that of the secondary GS, the UA will disconnect from that GS (via sending a detach notification) and connect to the new GS as secondary.

The UA also continually compares the bi-directional health of the secondary GS with that of the primary GS. When the secondary GS is providing a better link than the primary, the UA begins the handoff process. This is implemented as a pair of waveform change exchanges. The first is between the UA and the secondary (soon to be primary) GS to modify the link to support the data requirements and create connections for the service flows. Once granted, the UA initiates a second change exchange to the current primary GS to reduce its resources and destroy the service flow connections.

Failures may occur during the handoff process. The secondary GS may not have the resources to support the data transfer requirements of the UA, in which case the UA maintains the link to the primary and may search for another secondary GS. If the waveform change occurs but the new primary link turns out to be insufficient, the UA will revert back to the original GS using the prior settings. It is also possible that the handoff succeeds but the old GS cannot support the secondary link (due to not having resources available in frames not used by the new GS), or the new secondary link may fail. This is not deemed as failure of the handoff, rather the old GS link is disconnected and the UA searches for another GS to use as secondary.

Arrival

Just prior to the arrival phase, the UA must ensure that it is connected to a GS that has coverage at the arrival airport, as the UA may have a good connection with a particular GS at altitude but lose that connection as it descends due to line of sight. This is accomplished in the models by providing preference to the arrival airport GS when considering handoffs. At the beginning of the arrival phase, the UA will drop connections to the secondary GS and perform a waveform change to the primary GS to obtain the resources required for the arrival data traffic.

Post-Flight

After completion of the arrival phase, the UA CNPC model performs a waveform change to the primary tower to destroy the service flow connections and reduce the resource utilization at the GS. After 90s, the UA CNPC model is disabled. The GS will detect the loss of signal from the UA shortly after and free all resources assigned to it.

CNPC Lost Link

A lost link is primarily defined as non-reception of health messages from a GS for more than 5 sec, but equivalently can be interpreted as any failure of the connection, handoff, or waveform change processes (for example by too many retransmissions of a management message).

At any point in the flight, the UA may lose the link to its primary GS. If a secondary link has been established, the UA immediately attempts a handoff to the GS. If that handoff fails or there is no secondary GS, then UA will attempt to establish a link to the best scanned GS as a new primary GS. If the UA has no candidate GS to attach to, it will scan until one is found.

After any link failure, the UA will not attempt to re-attach to the failed GS for at least 1 minute. This prevents the UA repeatedly attempting to attach to a GS that has shown it cannot maintain a reliable link to the UA, and providing enough time for conditions to change that the subsequent attempt may be successful. This delay however can cause long term lost link conditions if, for example, lost link occurs during the arrival or departure phases (where only 1 GS may be able to provide service to the UA at low altitudes). These outages, if they occur, should be identified in the simulation results as an implementation issue due to model limitations and not necessarily attributed to an availability issue of the CNPC system.

Simulated Architecture Implementation for ATC/ATM Operations

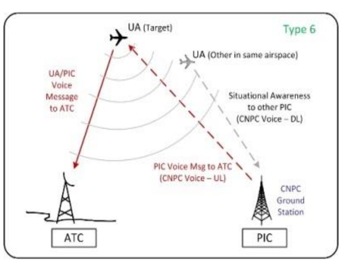
Operational Assumptions

The following is a listing of current operational assumptions for UAS-in-the-NAS that are made in our large-scale communication architecture simulations. These assumptions are reflected in the type of aircraft flown in the simulations for this evaluation and in messaging/messaging results from simulations.

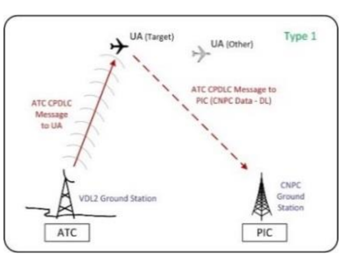
- UAS are managed in the NAS the same as piloted aircraft.
- UAS Service Classes are assigned based on the UAS aircraft class. All UAS flown in our simulations are of a classification high enough to require controlled airspace, ATC communications.
- All UA that operate in the Relay communication architecture use legacy VHF voice and/or may use mixed mode operation with Voice and CPDLC (over VDL2).
- All UA are equipped with a supporting compliment of communication equipment including VHF or VDL2 and datalink CNPC. (Comm service types may vary)
- All flights in a simulation are managed by ATM. (if they depart/arrive at managed or unmanaged airports, they will fly in managed en-route airspace for some duration of their flight)
- UA that depart/arrive from untowered airports follow the same procedures as piloted flights for entering/departing managed airspace.
- All UA process Piloted flight voice message traffic as situation awareness information when operating in common, controlled airspace.
- UA process other UA voice message traffic as situation awareness information when operating in common, controlled airspace.

ACES - Message Types Description

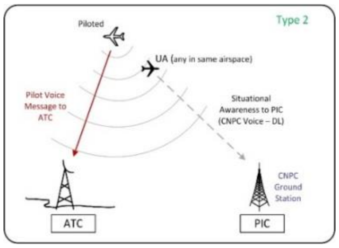
Air traffic management in the simulations is provided by replicating dialog that typically occurs between ATC and Piloted aircraft, with that dialog extended to the UA Controllers who pilot the UA. The communication that occurs is tailored to dialog common in today's airspace operations, with dialog sequences initiated by both ATC and aircraft operators (pilots or PICs). Dialog used is defined by message sets that occur based on airspace events, such as information typically transferred for initiating frequency changes at airspace crossings and contact dialog once an aircraft enters new airspace. For the simulation of these conversations, each message of a message set requires specific movement through the system architecture, dictated by who hears a message and who needs to respond to a message, which once UA are introduced becomes more complex. To address the message transfer requirements, the following 6 message types have been defined, and are used in simulations. The message types are described below with emphasis on the implications of each type to UA Comm operation:



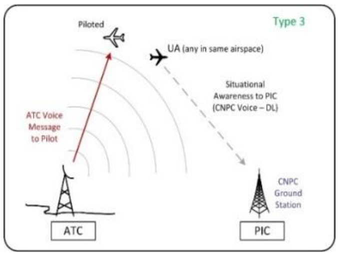
Type 6 - UA/PIC-to-ATC Voice message – Sent by PIC. Received by ATC as target recipient. Also received by any other UA operating in the same airspace for situation awareness.



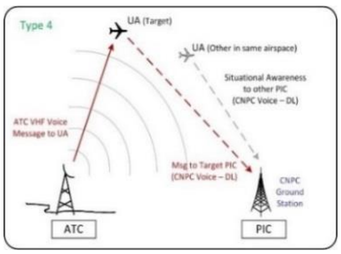
Type 1 - ATC-to-UA/PIC CPDLC message – Sent by ATC. Received by UA Controller (PIC) as target recipient. Directed only to a specific PIC.



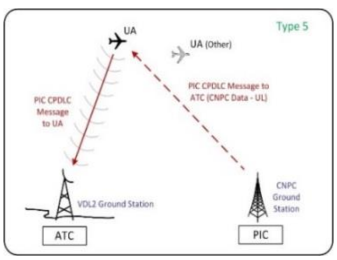
Type 2 - Pilot-to-ATC Voice message – Sent by piloted flight. Received by ATC as target recipient. Also received by any UA/PIC operating in same airspace for situation awareness.



Type 3 - ATC-to-Pilot Voice message – Sent by ATC. Received by piloted aircraft as target recipient. Also received by any UA/PIC operating in the same airspace for situation awareness.



Type 4 - ATC-to-PIC/UA Voice message – Sent by ATC. Received by UA Controller (PIC) as target recipient. Also received by any other UA operating in the same airspace for situation awareness.



Type 5 - PIC/UA-to-ATC (CPDLC) message – Sent by PIC. Received by ATC Directed only to ATC as sole recipient.

Message Collision Detection and Back-off (Voice Model)

The voice model initially developed in ACES was intended for use in a system that only included ATC/Pilot communication where the model simulated the transmission of voice messages between air traffic controllers and pilots. As a management function for simulations, the model also was used to provide human factor decisions where if a message channel was in use, a new message over that channel would be delayed since ATC and pilots would be hearing the ongoing message and wait to begin speaking. Since the VHF link adds minimal delay before messages are audible to the target, the management function in the model for message collisions was able to quickly detect ongoing messages on a channel in either direction, wait for it to end, add a slight back-off delay, and then process a next message once the channel was clear. In this situation, there were very few instances where messages incurred step-on or which had collisions with one message sent on top of another.

However with the use of this model in the comm architectures for UAS, where network and other component delays within the architecture now effectively hide the initiation of messages spoken by ATC, Pilots and UA Controllers , the management and detection of collisions at the voice model posed new scenarios that needed to be evaluated to continue to detect messages sent on top of each other, detect real step-on occurrences, reduce false collision detection and to change the human factor operations for situations where the recipient of a message had already begun to hear a message and would likely back-off on talking to allow an ongoing message to be completed.

To address this, timing diagrams were created for each of our message types[2] that generalized the delay contributor's role along the message path from the time it is initiated to the time where the message becomes audible at the recipient site. The timing diagrams (example shown in Figures 6) defined the movement of each message type along its primary path and for its path as a situation awareness message to other recipients if appropriate to the type of message. Once the general movement of each message was defined, conditions were evaluated for each of the other possible message initiators for times that they might intend-to-send (ITS) a message while the message type is currently en-route. These are indicated in the diagrams at the ITS_{xxxx} arrows for each of the timing conditions where they were deemed applicable.

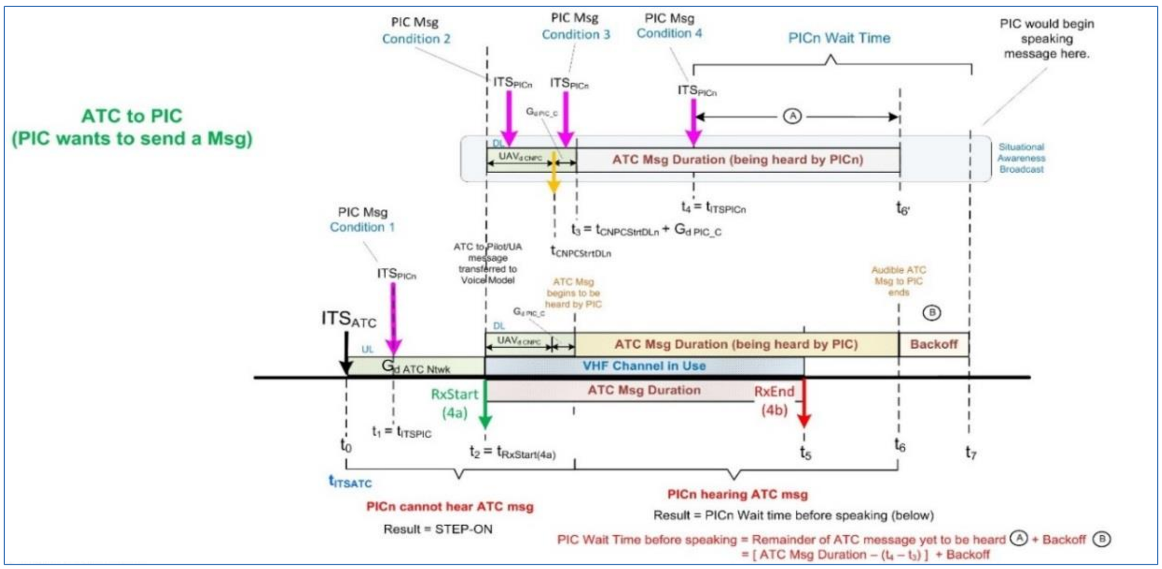


Figure 6: ATC-to-PIC (PIC ITS) – Message collision/backoff timing diagram

After the assessment was completed we were left with responses to each of the conditions that were integrated into the Voice model, and the ITS indicators and other timing indicators from the simulation needed to make the decisions were added to the system for voice model message management operations. A sample of the type of ITS conditions with a brief description of what occurred, and the resulting response in the system are provided below for the ATC-to-PIC Message (other PIC ITS) scenario shown above.

Conditions / Description / Results (ATC-to-PIC, PIC ITS)**:**

Condition 1: VM receives any ITS_{PICn} after t_0 (t_{ITSATC}) but before the VM generates RxStart(4a)
Description: PIC begins to speak while ATC Msg is delayed by ATC Gnd Ntwk or CNPC Downlink delay or PIC Gnd Ntwk delay.
Result: Message Step-on occurs. Message will be resent

Condition 2: VM receives ITS_{PICn} after t_2 ($t_{RxStart(4a)}$) but before the VM receives $t_{CNPCStrtDLn}$ indication.
Description: ATC to PIC message is delayed in UA to PIC CNPC downlink of that PIC and is not yet audible to PICn.
Result: Message Step-on occurs. Message will be resent

Condition 3: VM receives an ITS_{PICn} between $t_{CNPCStrtDLn}$ and ($t_{CNPCStrtDLn}$ + $G_{d\ PIC\_C}$)
Description: PIC message is delayed in UA to PIC CNPC downlink and is not yet audible to other PICs (i.e. PIC2)
Result: Message Step-on occurs. Message will be resent

[2] Included Relay architecture and Non-relay architecture voice message evaluations.

Condition 4: VM receives ITS_{PICn} between t_3 ($t_{CNPCStrtDLn}$ + $G_{d\ PIC\_C}$) and $t_{6'}$ ($t_{CNPCStrtDLn}$ + $G_{d\ PIC\_C}$ + ATC Msg Duration). PICn Msg delayed by [ATC Msg Duration – ($t_{ITSPICn}$ – ($t_{CNPCStrtDLn}$ + $G_{d\ PIC\_C}$)] + Backoff

Description: PIC began to hear message

Result: PIC waited until message ended. Wait time extended through completion of related message sequence associated with this message (see note 1 below)

Message scenario scripts are comprised of groups of associated Air-to-Ground and Ground-to-Air messages (2-3 messages per group) that are initiated at specific airspace situations (e.g. maneuver message groups in the TRACON, message groups prior to and after Sector crossings, etc…). These groups are subsets of the full ATM dialog simulated during a flight. Since the intent here was to create a more realistic human factor scenario, this back-off concept was later extended to include a wait time through the end of the ongoing message group (ongoing dialog) for any message that had to wait to be transmitted. This allows the ongoing ATM dialog to complete, which we felt was a realistic process to include to allow dialog for the current activity to end. After the complete message group is transmitted, the message that waited, and its message group are allowed to continue.

Note: This capability does not attempt to solve messaging issues in these architecture but is only intended to detect and respond to the operational characteristics presented by the architecture and provide more realistic operations and responses in these simulations. Prior to this change many erroneous message failures were being reported (due to the out of date voice model management function) and were resolved with this new management scenario.

Forced Message Operation for CNPC Lost-link (Voice Model)

Of the changes that we found with the use of the Gen5 radio system in the large-scale simulations, the one area that impacts simulations the most is the sensitivity of the CNPC link on the Opnet side to lost link, and the impact of lost link occurrences on the end-to-end operations for messaging[3]. The simulated architecture moves messages though the architecture and relies on the successful delivery of a message to the target recipient to complete its route and for the progression of each message group associated with the aircraft airspace event that is being serviced by the current ATM communication. When a lost CNPC link event occurs, and a message that is en-route is disrupted, the message that needs to be moved to the recipient does not arrive. This causes the process to generate a message retransmission with the hope that the CNPC link recovered and the message will be delivered, or in what we encountered as a worst case situation (without a work around), for the simulation to freeze if the link for that CNPC connection does not come back up.

To provide a fallback to this worst case scenario, an evaluation was done to assess the timing of messages and message group progression through the CNPC Radio model. The assessment was done to determine which timing indicators we could use from the system to help us make the decision that the radio model is not responding properly in these cases, and the current situation of the message progression, to allow us to generate forced messages that would replace the undelivered messages (samples shown in Figure 7).

Since our system can absorb failed message delivery and will retransmit a message not responded to in a timely manner, the system is able to overcome some short duration lost link. However, for longer lost link situations, we set a timer to look for one of two RTI Interactions that should be present in a message up or downlink success within a widow of time after handoff of the message to the radio. If neither of these indications occur, the ACES system determines that the CNPC link is not available, automatically generates the end result message to the recipient, identifies that a lost link has occurred in an output file and the simulation is able to progress.

[3] The previous version of the radio system model (i.e. Gen2 - prototype) provided a more ideal link handoff method that did not allow lost link. See lost link description above.

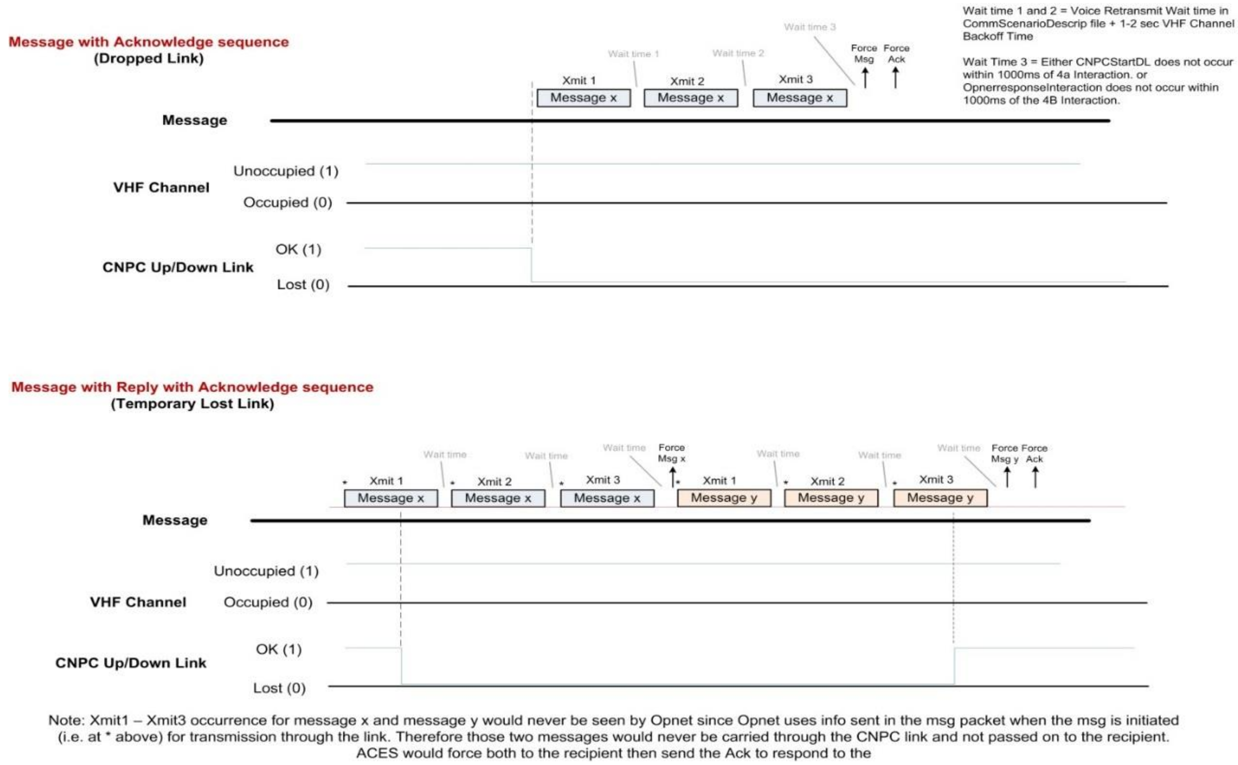


Figure 7: Lost Link / Forced message timing scenario (samples)

The end result of this workaround was verified while the testing and integration of the Gen5 radio model was still in the process of defining GS locations and working handoff scenarios using the newly added IP networking, for our planned simulations in ZAU airspace. Since its inclusion, simulations have successfully completed in a scenario also with the Gen5 Radio model turned off (where all messages were forced) and the simulation completed successfully.

Simulations Output Descriptions

ACES Outputs – Results Data

The ACES local data collection service saves data for every ATM message sent to and from all piloted and all UA flights in a simulation. ACES also saves interactions data and message delivery timing/success indications used in the simulation architecture to facilitate the interoperability between ACES and Opnet. The information is all stored with independent, epoch timestamps for simulation time-of-occurrence to the millisecond level. When a simulation is competed the database tables are used to reconstruct the end-to-end message sequences that occurred for every flight, for every Voice or CDPLC message that occurs. The information is evaluated to provide delay data for the CNPC radio link delays of the individual messages (using indicator interactions transferred over the RTI) and for end-to-end, through-the-architecture message latency. Samples of the delay data for message movement through the architecture are provided in the results section.

Radio Model Statistics Descriptions

Measured outputs provided from the CNPC Radio system focus on link performance data and statistics from the functional components of the model needed to provide operation of the CNPC messaging and data applications. A breakdown of this information for the Gen5 model is provided below.

Application Specific Statistics

For each of the CNPC applications defined above each application has individual statistics (in both directions) which are recorded in 60 second buckets. These include:

- Delay – Length of time between generating the message in the PIC or UA model and receiving the message. For ATC voice, the delay is for individual codec blocks of the message, not the entire message.
- Jitter (for ATC Voice only) – Measure of variation in delay between the codec blocks between the PIC and UA. Jitter is calculated according to RFC3550:

$$J_i = J_{i-1} + \frac{|(D_i - D_{i-1}) - J_{i-1}|}{16}$$

  where J_i is jitter at sample i, D_i is delay at sample i

- Traffic Received (sum) – Measure of the traffic received by the PIC/UA in bytes. This is measured at the application level and thus does not contain any lower layer protocol overhead.
- Traffic Sent (sum) - Measure of the traffic sent by the PIC/UA in bytes. This is measured at the application level and thus does not contain any lower layer protocol overhead.

Note: These statistics are currently set to record 1 value for every 60s of simulation time. For delay and jitter, the value reported is the average of all values over the 60s period. For traffic sent and received, the value is the sum of all values over the 60s period. Traffic rates in bytes/sec can be calculated by dividing the traffic sent and traffic received values by 60.

High Level CNPC Stats

The following CNPC statistics are collected in a simulation:

- Resource Utilization – Percentage of the total available resources currently in use for both the uplink and downlink directions. For UA, this statistic represents the percentage of uplink and downlink frames assigned to link streams, and ranges from 0 to 1 in increments of 1/20. For GS, the uplink statistic is based on the number of frames and slots assigned to link streams, and ranges from 0 to 1 in increments of 1/(20*#slots). These simulations use the 24-slot uplink mode. The downlink statistic is based on the number of downlink frequencies allocated and ranges from 0 to 1 in increments of 1/(20*#freqs).
- Attached GS (for UAs only) – The radio address of the both the primary and secondary tower the UA is currently connected to
- Attach results – The number of successful and unsuccessful attachment attempts
- Handoff results – The number of successful and unsuccessful handoff attempts
- Waveform change results – The number of successful and unsuccessful waveform change attempts

These statistics record a value anytime the appropriate conditions change, which is due to handoffs or scanning.

CNPC Service Flow Statistics

For the Service Flows, each service flow records:

- Load (TX service flows only) – The amount of traffic provided by layer 3 for transmission, measured in bytes per second.
- Throughput (RX service flows only) – The amount of traffic received from peer radios and passed back to layer 3, measured in bytes per second.
- Delay (RX service flows only) – The average CNPC link delay (described above) for received packets.

- Compression Rate – The average compression rate (due to layer 3/4 header compression), measured as the total uncompressed packet size divided by the compressed packet size.

These statistics are currently set to record only 100 values per simulation (OPNET Modeler default). For sims ~8hrs long, that provides ~1 sample every 5 minutes.

CNPC Connection Statistics

For the Service Flow Connections, each connection records:

- Received Packet Loss (RX connections only) – Percent of expected packets not received. Each packet contains a sequence number. Loss is detected by receiving non-sequential numbers.
- Queue Delay (TX connections only) – When messages are received by the radio from higher layers for transmission, they're held in a FIFO queue until they can be sent. This statistic is the length of time a message is in the queue
- Queue Overflow (TX connections only) – The transmit queue is set to hold a maximum of 5 packets. If the queue is full and another message is received by the radio from the higher layers for transmission, the oldest message in the queue is dropped and the new one inserted. This statistic is a count of how many times a message is dropped due to the queue being full.
- Total Bytes (same as in prototype radio)
  - Transmitted: The total number of bytes transmitted (excluding Layer2 overhead)
  - Received: The total number of bytes received (excluding Layer2 overhead)
- Total Messages (same as in prototype radio)
  - Transmitted: The total number of messages transmitted
  - Received: The total number of messages received
- Total Packets (same as in prototype radio)
  - Transmitted: The total number of packets (message fragments) transmitted
  - Received: The total number of packets (message fragments) received

These statistics are currently set to record only 100 values per simulation (OPNET Modeler default). For sims ~8hrs long, that provides ~1 sample every 5 minutes. Packet loss is reported as the average of all values over that time period. Total bytes, messages, packets and queue overflows are the sum over that period.

Link Stream Statistics

A link stream is the low-level link between the UA and GS that addresses the radio model physical layer operations. Statistics recorded and available for each link stream are:

- Channel Quality (RX link streams only, same as in prototype radio) – This is a measure of "channel quality" which is a Rockwell Collins statistic based on the correlator output and ranges from 0-2040. It is used as an input for the calculation of the health value. This is modeled as an approximation of the values generated by the prototype radio.
- Distance (RX link streams only) – Distance between the UA and tower in nautical miles
- Received Packet Percentage (RX link streams only, same as in prototype radio) – percentage of packets correctly received
- Received Power (RX link streams only, same as in prototype radio) – measure of the received power (signal + noise) in dBm. It is used as an input for the calculation of the health value. This is a model of the values generated by the prototype radio, not the actual received power.
- Health (RX link streams only, same as in prototype radio) – Measure of signal health from 0 to 6 based on channel quality, received power, SNR, and DRR. DRR model was not ready in the sims ran though.
- SNR (RX link streams only, same as in prototype radio) – Signal to noise ratio in linear units, ranges from 0-16. It is used as an input for the calculation of the health value. This is a model of the values generated by the prototype radio, not the actual SNR.

- DRR (RX link streams only, same as in prototype radio) – Direct to Reflected ratio in dB. It is used as an input for the calculation of the health value. This is a model of the values generated by the prototype radio, not an actual DRR calculation.
- Transmit frame utilization (TX link streams only) – Average percentage of the transmit frame capacity that is utilized by data (not padded).

These statistics record 1 value every second to match the prototype radios. The reported values are the average of all values over a 1s period.

Other Statistics

Additional statistics are also collected in each Large-scale simulation that are necessary for interoperability between the two applications and for synchronization:

- Number of Active UA
- Number of Flights in each channel
- KTG State Data for Each UA, which includes: Airspeed, Altitude, Bank Angle, Flight Path Angle, Heading, Latitude and Longitude

Simulations Description

Simulation Scenarios - Flight Data Sets

Three ACES Flight Data Sets (FDSs) were used for the air traffic scenarios for this report. The first (our baseline FDS) was a UA only, 75Flight FDS, the second is a FDS that is a variation on the 75flight UA FDS with 40 of those UA flights and 49 Piloted aircraft, and the third is a FDS that uses only a handful of flights from the 75Flt FDS and flies those UAs along with small UAS class UA that have been created in Opnet (for Service Class 1 operation). For comparison of operation and messaging for UA, and to see the effect of added air traffic in data from our simulations, we ran variations on the levels of traffic from the 75flight FDS as a Level 1 with 28 UA Flights and a Level 2 with 46 Flights, in separate simulations. For the simulation with Piloted aircraft the piloted flights used were derived from an existing day in the NAS FDS, scaled first for flights that flew within the same time window as our 75Flt FDS (0-20 hour, same day departure times) and for flights that flew within several sectors within ZAU Center to concentrate flights into a region.

The following are some general characteristics of the flights used:

- UA and Piloted flights were concentrated for their routes within ZAU Center (due to our possession of detailed sector airspace volume data that we use regularly to evaluate aircraft/airspace locations and transitions)
- All UA flights departed and arrived at small to medium sized regional airports.
- The mix of UA routes was derived (partially) from routes identified in a UAS Demand study for Weather Observation, Air Cargo, Air Taxi and Strategic Fire detection services. The balance of routes were defined independently as general purpose round-trip and airport-to-airport flights defined for research, security and observation.
- Flights in the ACES FDSs are all mid-size UA that would be capable of carrying the compliment of Comm hardware required for ATC and Data with all supporting systems on board the aircraft to support the Gen5 radio Comm Service Class 4.
- The FDSs provide aircraft (UA and piloted) that depart between midnight and 20:00 GMT. The duration of the total airtime (time to final arrival) is approximately 33 hours for the largest FDS with UA and piloted A/C.
- Piloted flights flown were selected to concentrate aircraft into ZAU55, ZAU56 and ZAU 63 to enable a focused ATM interaction.

Note: Air routes and schedules of the flights in our scenarios are non-conventional, and were derived solely to meet the air traffic loading objectives of this testing.

Simulation Data and Results/Performance

Messaging – Architecture Component Delays and Latency

The ACES application timestamps (to the millisecond level) and stores information related to the movement of each message through the comm architecture. Each message is assigned a unique Message ID associating it with an aircraft as it is moved between the modeled architecture components, and for the transfer of the message information for use by Opnet (via the Comm message Interface) for transfer of the message through the CNPC radio. Also saved in the database are tables for interactions that occur over the RTI for the handoff of message data to the Opnet system, and a table of all message transfer success indications used to determine the combined CNPC Radio processing and uplink/downlink message delay times. By reconstructing these stored data for each message we can detect delays through each modeled component in the system, individual message CPNC uplink/downlink delay and determine the total message latency. Also, as applicable when UA share airspace with other UA and piloted flights, we can determine CNPC downlink delays of situation awareness messages sent to other UA PICs that overhear those messages.

Figure 8 shows the flow of each of the message types through the architecture model components. In red text, are either settings for fixed delay settings used in the simulations, or indications where a delay is varied dependent on the modeled component. For each message type, the components in the system that contribute to the through-the-architecture delay times (i.e. message latency) are indicated in the chart at the bottom. The following sections describe the different FDS/simulation objectives and show samples of selected messages by message type and the different forms of the message data available from a simulation for each.

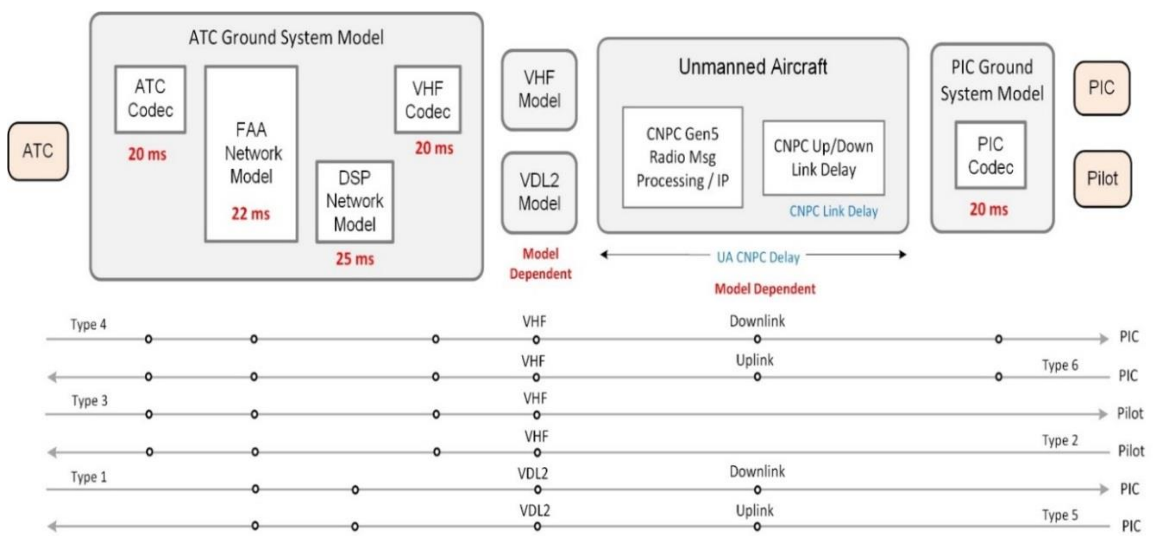


Figure 8: Delay Contributors

Note: In the following sections, the results for UA messaging uplink and downlink delays differ (i.e. are longer than) the CNPC link, uplink and downlink delays shown in the charts for CNPC Data services and delays in subsequent sections. The distinction is indicated above in Figure 9, and is due to the inclusion of IP protocol operations, message conversion and data processing times required onboard the UA, which is part of what is recorded in ACES data tables. Where applicable, the following sections distinguish these as 'UA CNPC Delay' for the through-the-UA delay and 'CNPC link' delay where only the link transmission delay is considered.

Type 4 – ATC to PIC and Type 6 – PIC to ATC Voice Messages

Table 1 below shows a sample of the delay information collected for the forward and return delay contributing component models in the Relay architecture for the same Type 4 and Type 6 voice message, sent to/from the same UA flight, in our Level 1, Level 2 and Level 3 simulation. The FDS for each level of simulation increases the volume of UA traffic from 28 to 75 flights. The message was selected to show a sample result of the message latency determination and the effect of added air traffic on increased communication messaging traffic that occurs with the added traffic load.

Table 1: Type 4 and Type 6 Sample Messages

FDS	Msg Type	Message	Chan ID	F - ATC Gnd System (ms)	R - ATC Gnd System (ms)	VHF Link Access (ms)	UA CNPC DL (ms)	UA CNPC UL (ms)	PIC Gnd Codec (ms)	SA 1 UA CNPC DL Delay (ms)	SA 2 UA CNPC DL Delay (ms)	SA 3 UA CNPC DL Delay (ms)
ATC to UA/PIC – Voice (Type 4 Message)												
L1	ATC to PIC (Voice)	Sector Freq Instruc Msg	ZAU62	62		1	299		20			
L2	ATC to PIC (Voice)	Sector Freq Instruc Msg	ZAU62	62		1	299		20	14 - 297	16 - 298	
L3	ATC to PIC (Voice)	Sector Freq Instruc Msg	ZAU62	62		1	348		20	22 - 348	19 - 349	24 - 396
				Forward – Arch Delay Components Contributions →						Situation Awareness Messages (FltID – UA CNPC D/L Delay)		
PIC/UA to ATC – Voice (Type 6 Message)												
L1	PIC to ATC (Voice)	Sector Contact Request Msg	ZAU62	62		1	296		20			
L2	PIC to ATC (Voice)	Sector Contact Request Msg	ZAU62	62		1	249		20	14 - 291		
L3	PIC to ATC (Voice)	Sector Contact Request Msg	ZAU62	62		1	244		20	24 - 295	19 - 301	
				← Return - Delay Components						Situation Awareness Messages (FltID – UA CNPC D/L Delay)		

In the first line of each group the UA is alone in the airspace and the VHF message is only heard and transferred to/from the target UA over its CNPC radio and on to the intended recipient of the message. In the next two rows of the table the SA columns show that as the traffic load of the simulation increased, other UA shared the airspace when the message was sent. In the shared airspace (shared freq) the message is overheard on the VHF channel by up to 3 other UA flights and is party-line, downlinked (for situation awareness) to the PICs of those other flights through their CNPC radio. For each message, the forward or return latency of the message - sender to target recipient - is the sum of the delay times through each delay component (model) shown in the grey area. The situation awareness columns of the table indicate the other UA flight(s) that received the message and the UA CNPC Radio delay using the format 'Flt ID – UA CNPC Delay time'.

Type 3 – ATC to Pilot and Type 2 – Pilot to ATC Voice Messages

Table 2 shows a sample of the delay information collected from the delay contributing component models in the Relay architecture for the same Type 3 and Type 2 voice message, sent to/from the same piloted flight, in our 40UA 49 Piloted FDS simulation. The message is selected to show a sample result of the message latency determination and the added loading on the CNPC radio of any UA that is operating in the same controlled airspace (on the same VHF channel) as a piloted flight.

Table 2: Type 3 and Type 2 Message Samples

FDS	Msg Type	Message	Chan ID	F - ATC Gnd System (ms)	R - ATC Gnd System (ms)	VHF Link Access (ms)	UA CNPC DL (ms)	UA CNPC UL (ms)	PIC Gnd Codec (ms)	SA 1 UA CNPC DL Delay (ms)	SA 2 UA CNPC DL Delay (ms)	SA 3 UA CNPC DL Delay (ms)	SA 4 UA CNPC DL Delay (ms)
ATC to Pilot – Voice (Type 3 Message)													
49U 40P	ATC to Pilot (Voice)	Sector Freq Instruc Msg	ZAU56	62		1				19 - 296	32 - 298	30 - 298	14 - 298

				Forward – Arch Components Delay Contributions →						Situation Awareness Messages (FltID – UA CNPC D/L Delay)			
Pilot to ATC – Voice (Type 2 Message)													
49U 40P	Pilot to ATC (Voice)	1st ARTCC Contact Request Msg	ZAU56	62		1				19 - 308	32- 310	14 - 310	30 - 410
				← Return – Arch Components Delay Contributions						Situation Awareness Messages (FltID – UA CNPC D/L Delay)			

In each row, the piloted aircraft is sharing the airspace with four UA and the VHF message sent to/from the piloted flight is overheard on its VHF channel by those four UA flights. For the piloted flights the forward or return latency of the message - sender to target recipient - is the sum of the delay times through each delay component (model) shown in the grey area of the table. For the UA that overhear the message, the message is party-line, downlinked (for situation awareness) to the PICs of those UA over their CNPC link. The situation awareness columns of the table indicate the other UA flight(s) that received the message and the UA CNPC Delay using the format 'Flt ID – UA CNPC Delay time'.

Voice Message Summary from Simulations

Table 3 is a summary of all voice message occurrences and related UA CNPC Delay data that occurred in the Level 1 through Level 3 UA only and the UA with Piloted flight simulations run for this report. The table shows increasing trends in the message occurrences expected in the L1-L3 sims, what loading occurred in the combined UA/Piloted sim and UA CNPC Delay/latency average and UA CNPC Delay min/max times for each of the different message types. Delay numbers in general, even with the added message traffic, indicate that the delay times for the UA CNPC uplink and downlink remained relatively constant since the loading on the radios for each CNPC coverage area was very much within the number of UA the Gen5 design was planned for with the traffic defined in these simulations.

In the lower section of the table the summary of the trends for situation awareness messages shows the effect of the adding UA flights in common airspace and what occurred when UA are flown alongside piloted flights. Also collected are the retransmitted and failed message occurrences for all of the simulations.

Table 3: Voice Simulations Message Summary Data

Description	Level 1 Sim (28 UA Flights)	Level 2 Sim (46 UA Flights)	Level 3 Sim (75 UA Flights)	49UA and 40 Piloted Flights
Total # Forward / Return UA Messages (T4 +T6)	1837	2773	4431	2971
Total # Forward / Return Piloted A/C Messages (T2+T3)				1559
Total # Forward Messages – ATC to UA/PIC (as Msg Target) – Type 4	791	1296	2066	1389
Average Delay - Type 4 Message UA CNPC Downlink (ms)	305.5	307.88	305.5	301.8
- Delay Min/Max - Type 4 Message UA CNPC Downlink (ms)	263 / 399	260 / 399	263 / 400	262 / 447
Average Msg Latency - Type 4 Message - ATC to PIC (ms)	388.5	390.9	388.6	384.8
Total # Return Messages – PIC/UA to ATC (as Msg Target) - Type 6	904	1477	2365	1582
Average Delay - Type 6 Message UA CNPC Uplink (ms)	295.3	291.3	296	298.9
- Delay Min /Max - Type 6 Message – Radio CNPC Uplink (ms)	243 / 410	243 / 414	243 / 744	243 / 747
Average Msg Latency - Type 6 Message - PIC to ATC (ms)	378.3	374.3	379	382.04
Total # Forward Messages – ATC to Pilot (as Msg Target) – Type 3				700
Average Msg Latency - Type 3 Message - ATC to Pilot (ms)				63.06
Total # Return Messages – Pilot to ATC (as Msg Target) – Type 2				859
Average Msg Latency - Type 2 Message – Pilot to ATC (ms)				63.09
Total # Situation Awareness Messages	116	262	655	592
Avg UA CNPC Delay - Situation Awareness Messages Downlink (ms)	308.17	308.2	309.7	319.4
Number of Retransmitted / Failed message occurrences in simulation	8 / 0	3 / 0	18 / 2	16 / 4

Type 1 ATC to UA/PIC and Type 5 PIC/UA to ATC CPDLC Messages

As an option on voice messaging, simulations can be configured to replace voice with digital, CPDLC messages using a VDL2 model to convey them to piloted aircraft or to UA. CPDLC uses the relay transfer through the UA over the CNPC link, but uses the CNPC data connection. Use of CPDLC messaging can be configured in a simulation for different airline/aircraft pairs, different message groups or for different phases of flight of an aircraft or UA to investigate this capability in operational scenarios. In our simulations these messages are conveyed as Type 1 and Type 5 messages.

Table 4 shows a sample of the delay information collected from the delay contributing component models in the Relay architecture for a Type 1 and Type 5 CPDLC message, sent to/from a UA flight in our Level 2 simulation configured for using CPDLC Messages in en-route airspace.

Table 4: Type 1 and Type 5 CPDLC Message samples

FDS	Message Name	Chan ID	Comm Type	Msg Length (bits)	F - ATC Gnd System (ms)	R - ATC Gnd System (ms)	VDL2 or VHF Link Access (ms)	UA CNPC Processing + D/L (ms)	UA CNPC U/L + Processing (ms)	PIC Gnd Codec (ms)
ATC to PIC – CPDLC over VDL2 (Type 1 Message)										
L2 using CPDLC for En-route	Sector Contact Ack Msg	ZAU74	CPDLC VDL2	220	47		502	98		N/A
					Forward – Arch Components Delay Contributions →					
PIC to ATC – CPDLC over VDL2 (Type 5 Message)										
L2 using CPDLC for En-route	Sector Freq Instruc Ack Msg	ZAU31	CPDLC VDL2	220		47	510		154	N/A
					← Return – Arch Components Delay Contributions					

When using CPDLC, the system uses a VDL2 radio model to provide a direct, node-to-node connection to the VDL2 radio onboard the UA, and the message content is defined and handed off to the UA CNPC radio in digital format (bit length). For both of these message types, unlike voice over VHF, there is no other situational awareness message that occurs due to other aircraft being located in the same airspace. The CPDLC system uses addressing to direct the message only to/from the target UA VDL2 radio for the connection between the node that is the UA or the VDL2 ground station servicing that airspace. For CPDLC messages, the forward or return latency of the message - sender to target recipient - is the sum of the delay times through each delay component (model) shown in the grey area of the table.

Summary Chart for L2 Sim using Voice in TRACON and CPDLC En-route

Table 5 is a summary of all voice and CPDLC message occurrences and related UA CNPC Delay data that occurred in our Level 2 simulation with CPDLC en-route. The table shows the number of occurrences of the different type of messages and UA CNPC delay/latency average and UA CNPC Delay min/max times for each of the different message types. In the results the UA CNPC delay numbers are lower than what is found for voice messaging, however due to the delays that occur for the VDL2 radio model the overall latency for these digital messages are longer than voice. Delay times and latency for voice messaging that occurred in the TRACONs in these simulations is consistent with the delay/latency numbers in our voice only simulations.

In the lower section of the table the summary of the situation awareness messages and retransmitted/failed messages shows a significant improvement over the voice only simulation where many of the SA messages are eliminated (occurred in en-route airspace in the voice only simulation) and no messages required retransmits or failed.

Table 5: Voice and CPDLC (en-route) Message Summary Data

Description	Level 2 Sim (46 UA Flights)
Total # Forward / Return UA Messages (T1+T5+T4 +T6)	2773
Total # Forward Voice Messages – ATC to UA/PIC (as Msg Target) – Type 4	316
Average Delay - Type 4 Message UA CNPC Downlink (ms)	309.8
- Delay Min/Max - Type 4 Message UA CNPC Downlink (ms)	263 / 447
Average Msg Latency - Type 4 Message - ATC to PIC (ms)	392.9
Total # Return Voice Messages – PIC/UA to ATC (as Msg Target) - Type 6	452
Average Delay - Type 6 Message UA CNPC Uplink (ms)	290.7
- Delay Min /Max - Type 6 Message – UA CNPC Uplink (ms)	243 / 514
Average Msg Latency - Type 6 Message - PIC to ATC (ms)	373.9
Total # Forward CPDLC Messages – ATC to UA/PIC (as Msg Target) – Type 1	980
Average Delay - Type 1 Message UA CNPC Downlink (ms)	188.6
- Delay Min /Max - Type 1 Message – UA CNPC Downlink (ms)	48 / 414
Average Msg Latency - Type 1 Message - ATC to UA/PIC (ms)	738
Total # Return CPDLC Messages – PIC/UA to ATC (as Msg Target) – Type 5	1025
Average Delay - Type 5 Message UA CNPC Uplink (ms)	94.4
- Delay Min /Max - Type 5 Message – UA CNPC Uplink (ms)	44 / 165
Average Msg Latency - Type 5 Message – PIC/UA to ATC (ms)	643
Total Situation Awareness Messages (Voice only)	1
Average UA CNPC Delay - Voice Situation Awareness Messages Downlink (ms)	290.0
Number of Retransmitted / Failed message occurrences in simulation	0 / 0

CPDLC Sample Simulation

As a demonstration of the impact of this capability, the charts below show a comparison of the results from flight UA17 flown in both the L2 simulation with voice messaging only (Figure 9) and in the L2 simulation with voice messaging used in the departure and arrival TRACON airspace and CPDLC messaging used in en-route airspace (Figure 10). For the simulation all flights were configured for CPDLC en-route and the results for all flights were similar. The charts show that for the mixed mode simulation all of the voice messages that occurred en-route, now were sent as CPDLC data messages over the VDL2 model, which would become data traffic over the CNPC radio link.

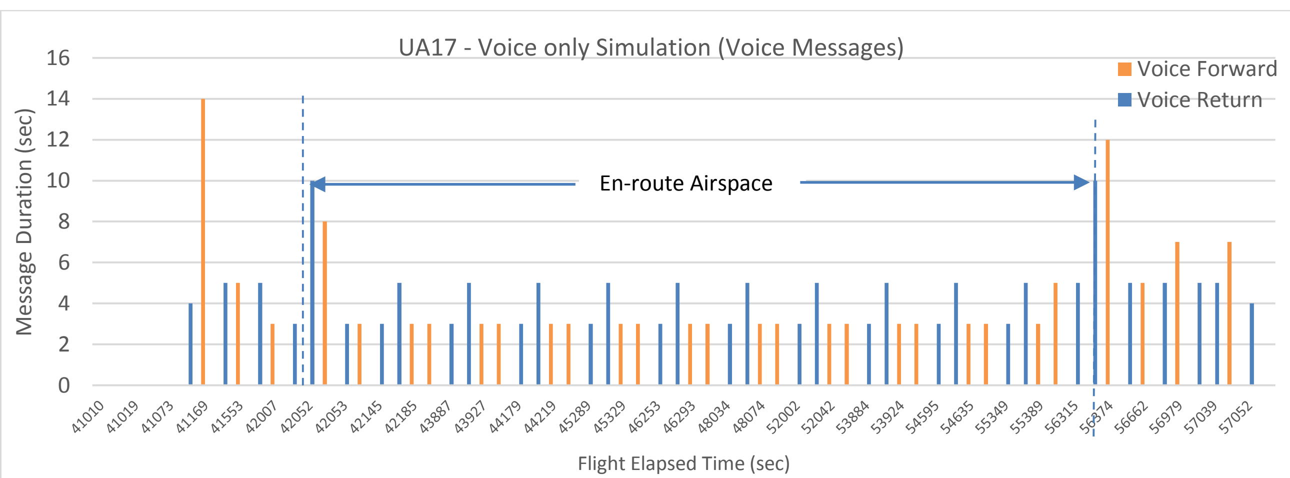


Figure 9: Voice only L2 Sim - Message Chart

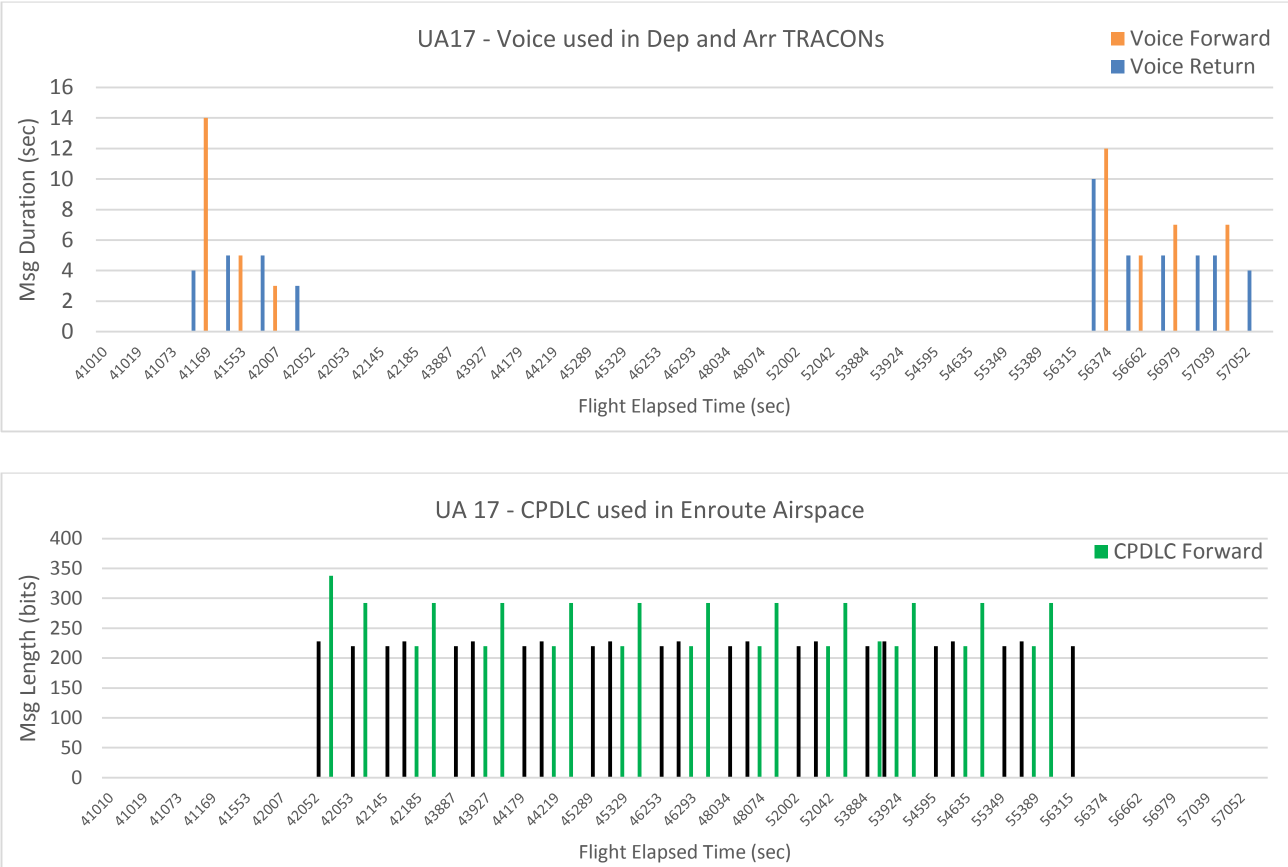


Figure 10: Voice TRACON with CPDLC En-route L2 Message Chart

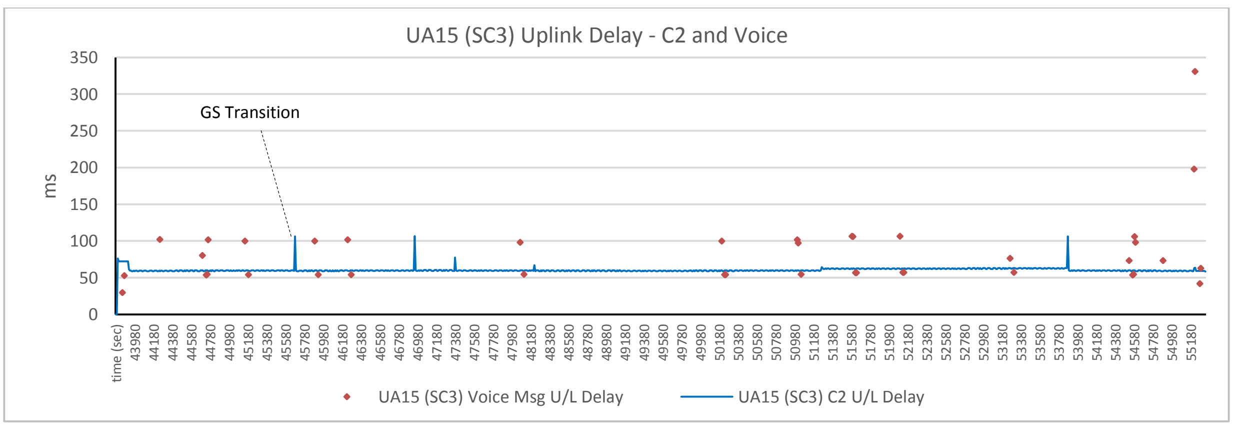
Service Class Application Data and CNPC Link Delays

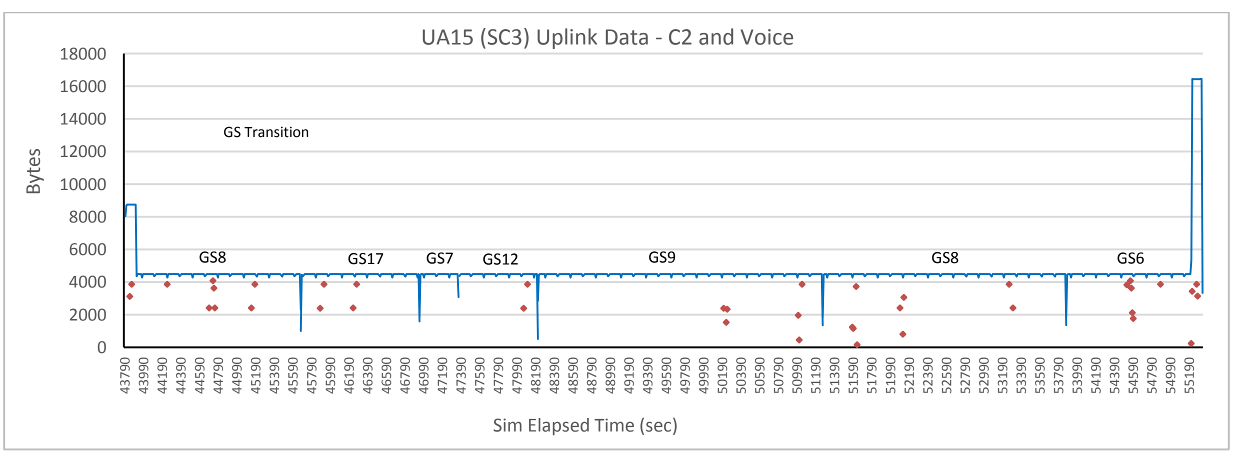
On the Opnet side of a large scale simulation, the Gen5 model provides link management for establishing links to ground stations, GS-to-GS handoffs, service classification and phase of flight settings for data rates and lost link recovery for each UA flight flown. For the service class operations, UA are assigned a UA Comm Service Class settings that defines the uplink and downlink data rates of data traffic types as separate service flows, which allows the radio IP protocol to prioritize data traffic to provide lowest delays to the highest priority data types. For phase of flight data distinctions the CNPC radio provides adaptations that adjust the data rates for more or less demanding data traffic (in more demanding airspace) which in our simulations has been defined for 5 miles after departure and 5 miles prior to arrival. As a flight is initiated in a simulation, the CNPC Radio initiates the connection of the radio to a GS tower and establishes the data connections for the movement of data required as applicable to the comm service class setting for that flight.

This section provides a sampling of results for two UA flights from our Level 3 simulation for their uplink and downlink data traffic rates and associated CNPC uplink and downlink delays for each of the service application data types from these flights. The flights selected are one Service Class 3 UA (UA 15) and one Service Class 4 UA (UA46) to demonstrate and compare the operation of the service class configuration capability. Figure 11 shows the actual flight routes of UA Flight 15 and UA Flight 46 from the simulation and the ground station coverage areas that managed the flights. Data and link delay charts are presented in Figures 12 and 13 on the following pages with some general observations regarding the results.

Figure 11: UA15 and UA46 Flight Routes and GS coverage areas

UAS15 Service Class 3 – Uplink and Downlink Data/CNPC Link Delay





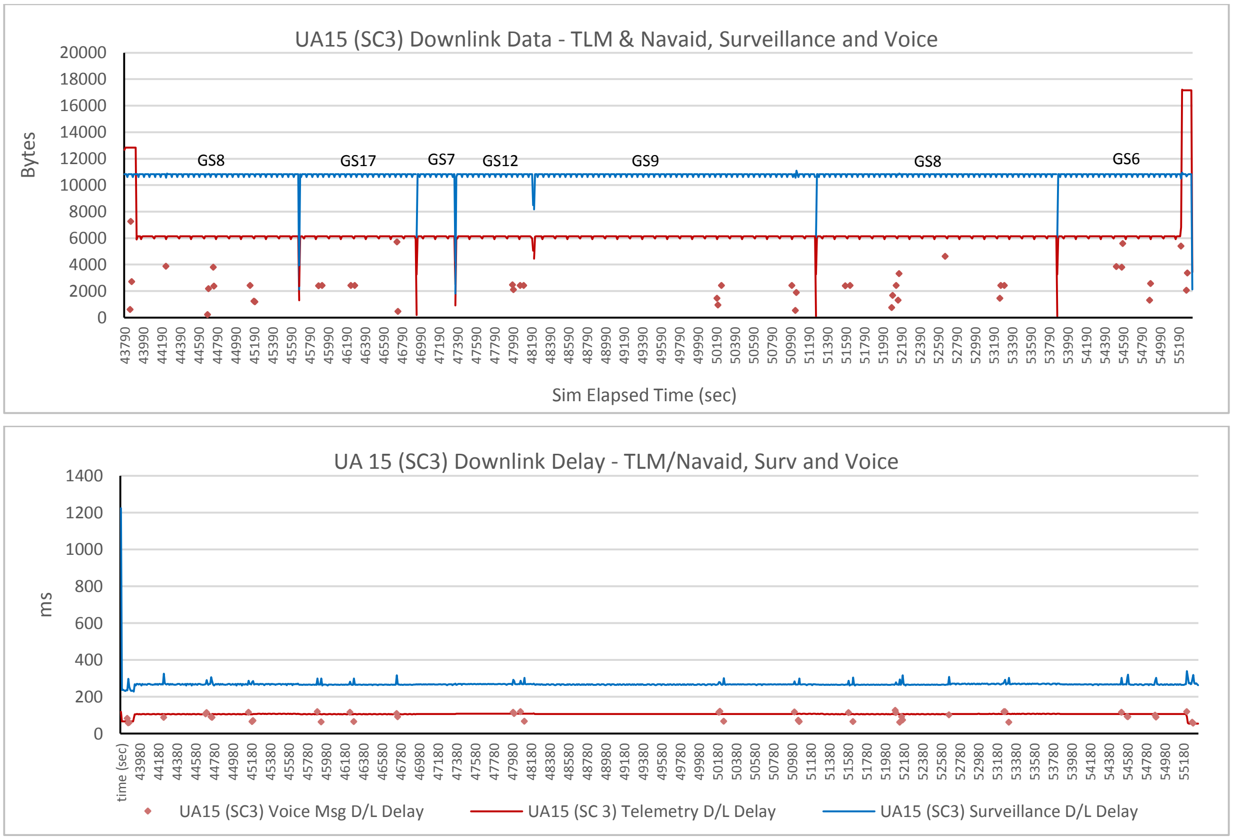
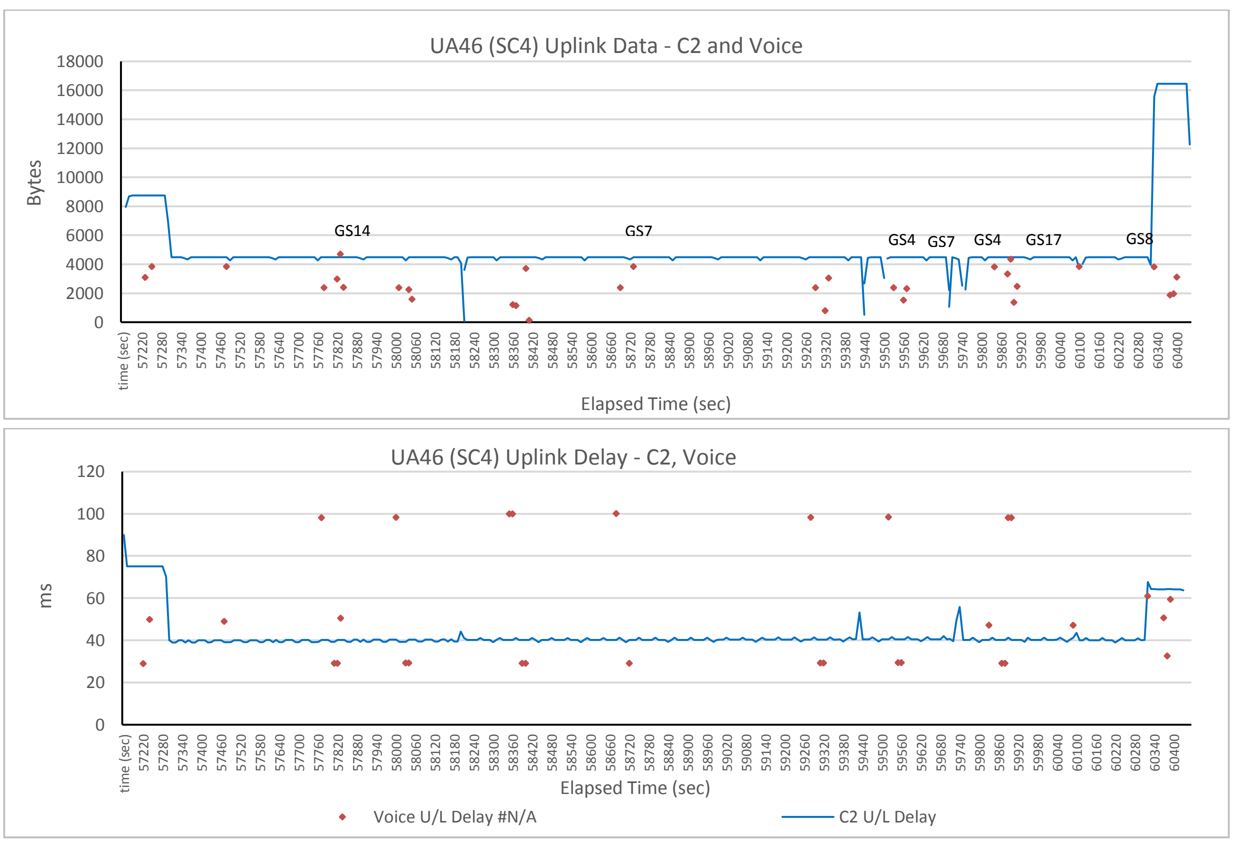
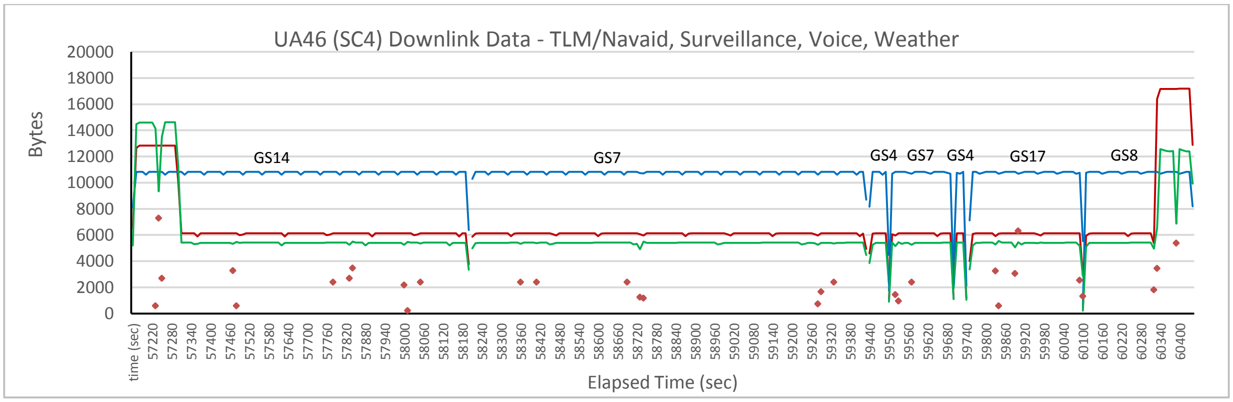


Figure 12: UA15 (SC3) Uplink/Downlink Services Data and Delays

UA46 Service Class 4 - Uplink and Downlink Data/CNPC Link Delay





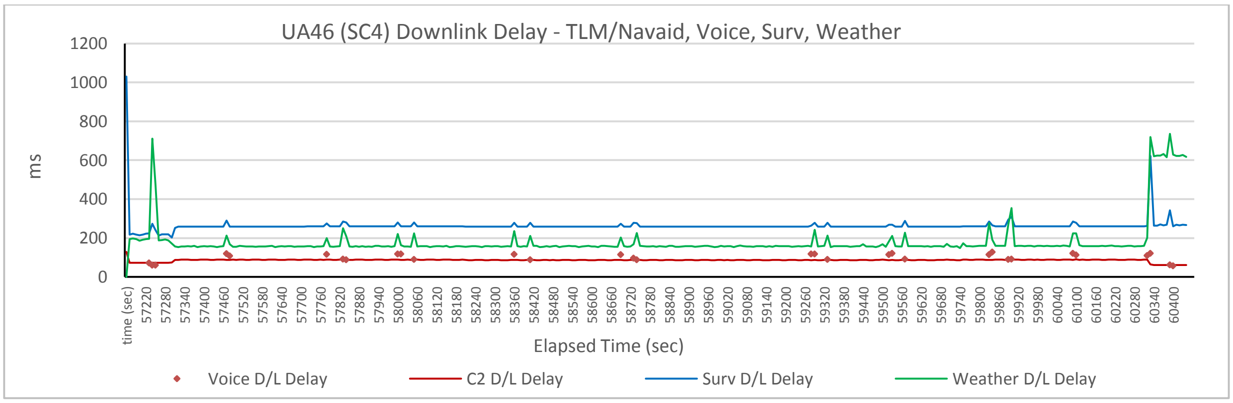


Figure 13: UA46 (SC4) Uplink/Downlink Services Data and Delays

General Observations/Comments - UA17 (SC3) vs. UA46 (SC4) - Data/Delay charts

- Data for the uplink or downlink of Command and Control (C2), Telemetry and Weather data are provided at higher rates within 5 miles of a UA Departure or Arrival Airport to provide enhanced, higher fidelity coverage in more critical airspace.
- Surveillance data rates are consistent for the duration of each flight. Same data requirements for the entire flight route.
- Voice message instances are indicated at their time of occurrence.
- Average of the voice message delay times in the uplink appear to be higher than C2 delays.
- Average of the voice message delay times in the downlink tend to be equivalent to telemetry data delays, but both are lower than surveillance data and weather data.
- Telemetry delays times in the downlink are lower than surveillance data delay times.
- Service Class 4 uplink C2 delay times are approximately 30% lower than for the C2 for Service Class 3 aircraft in en-route airspace.
- Service Class 3 and Service Class 4 surveillance data delays are equivalent.
- Service Class 4 telemetry data delays ran approximately 10% lower than for Service Class 3.

Data in the charts is plotted as Bytes aggregated over a 10 sec window. The bit rate (bps) delivered to/from the UA for each service can be approximated by: Bytes/10sec [from the chart] / 10 * 8 bits/byte.

Voice data from the charts can be used to determine the duration of a message in seconds by: Voice Msg Byte value [from the chart] * 8 bits/byte * 1 sec/2400 bits [codec conversion rate]

Small UAS Operation in Large Scale Simulations

Since the Gen5 Radio model adds Service Class distinctions to the radio model capabilities, this version of the large scale application has added small-class UA aircraft for simulations to be configured to match the type of aircraft and flight profile suited for the Service Class 1 communications profile. Small UAS flights are typically flown at lower altitudes with high maneuverability for unique service applications in uncontrolled airspace. This added aircraft configured for SC1 can be used in simulations to add compliments of small UA, sharing CNPC ground stations with larger class UA, to add comm traffic loading on the CNPC ground stations for evaluations of more varied UA traffic scenarios.

For these aircraft, two sUAS flights were developed to run on the Opnet side of the large-scale application in parallel with ACES FDS simulations. The flight profiles were selected from a mix of UA applications identified in a UAS demand study that looked at most likely future applications for UA, where a profile for an Air Quality monitoring application and one for municipal Traffic Monitoring were decided upon. Each of these UA flights is a round trip flight defined by a flat file for trajectory with simple aircraft flight dynamics, and can be transitioned to any airport and with any orientation. The control of the schedule for these flights is defined in Opnet script file for departure times.

As a sample of this capability and the interaction of the small UAs in simulations, a traffic profile was set up in Opnet using the Air Quality sUAS flown out of Gary Regional Airport. The schedule for the Opnet sUAS flights included six sUAS flights departing from KGYY every 2 hours. With the intent in the simulation to capture sUAS comm interaction with flights defined in ACES, several ACES Service Class 4 UA flights were defined and flown in a FDS along with the sUAS. The flights were selected for routes defined to fly over, and in the vicinity of, the flight path for the Air Quality flights, hoping to find a timeframe in the simulation where one of the SC4 flights and one of the sUAS shared the same GS for their service applications. The routes of the two aircraft where this interaction occurred is shown below in Figure 14 and the comm service data and CNPC uplink and downlink delay charts from the simulation are shown in Figure 15 and Figure 16.

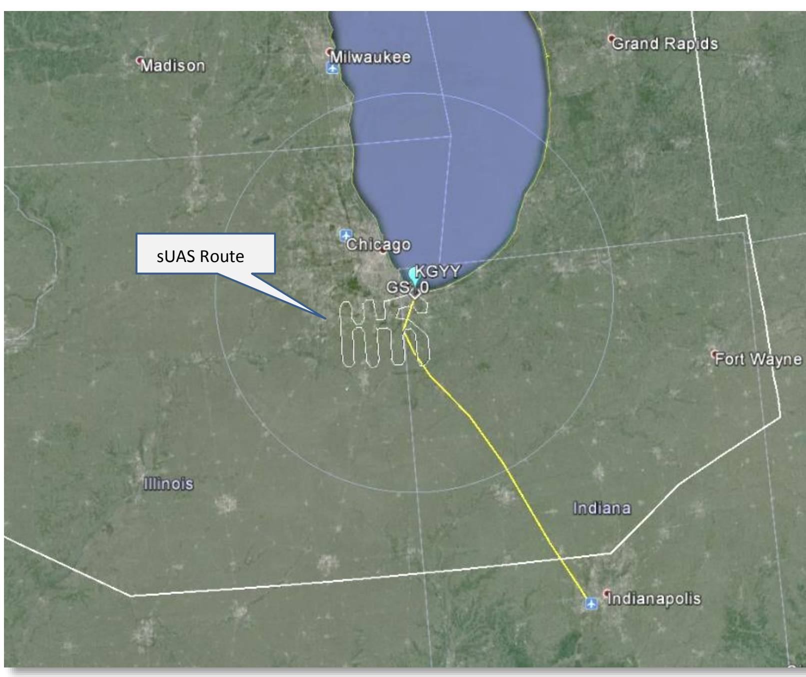


Figure 14: sUAS (SC1) with SC4 UA flight

Small UAS and SC4 UA – Uplink and Downlink Data/CNPC Link Delay

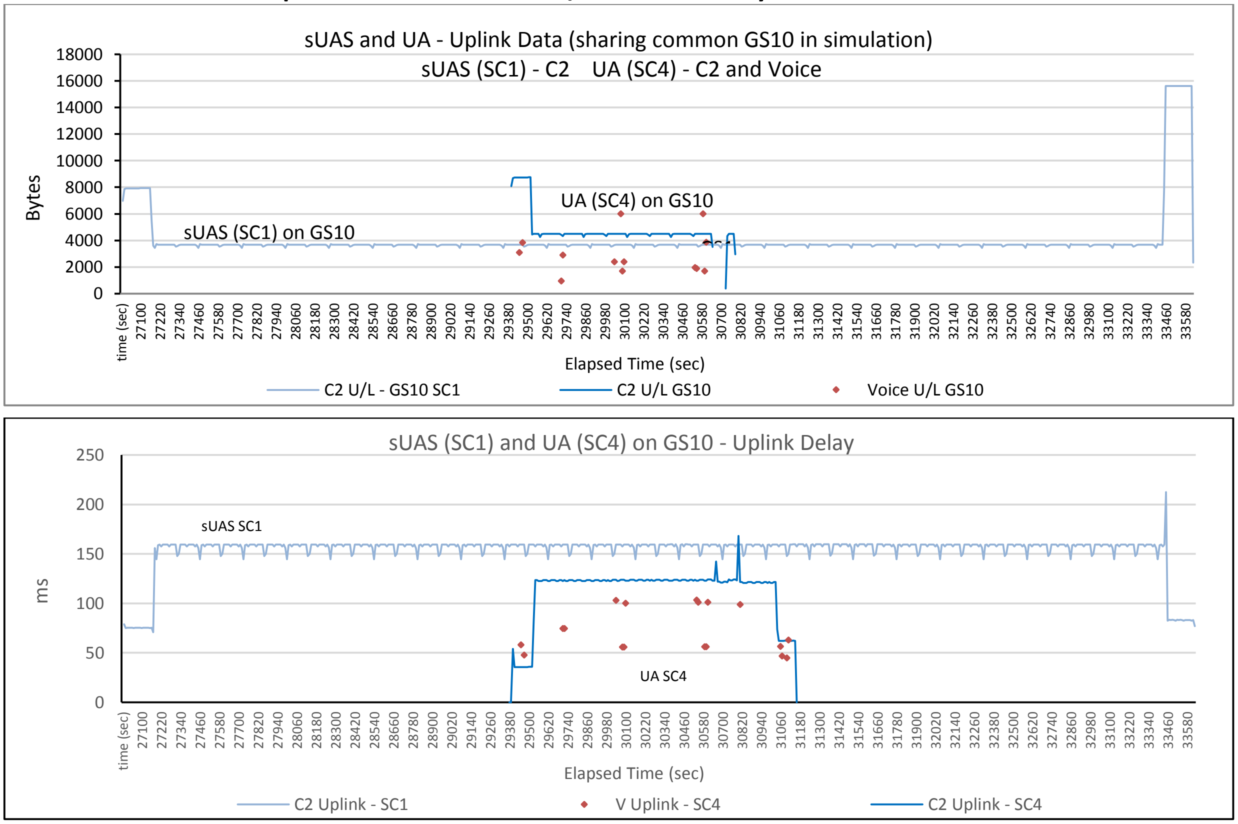


Figure 15: sUAS (SC1) and UA (SC4) Uplink Data/Delay

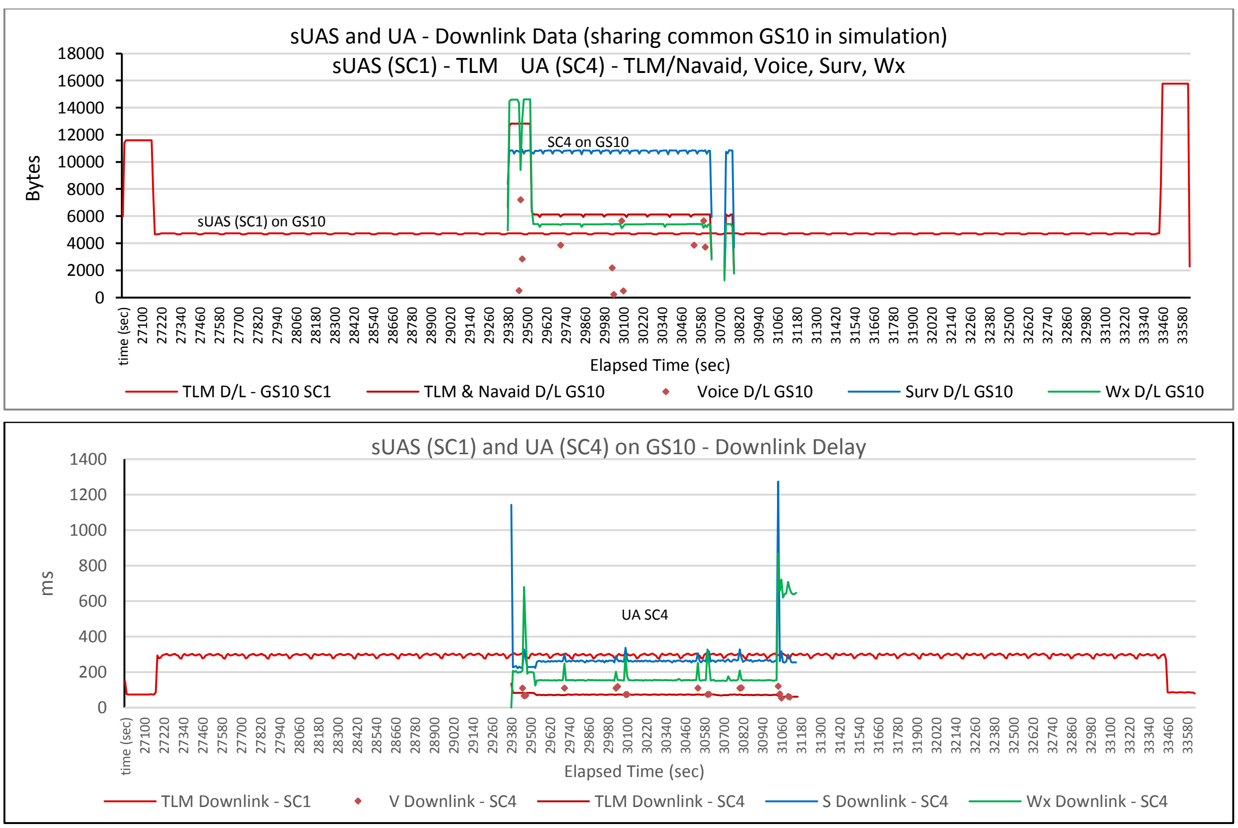


Figure 16: sUAS (SC1) and UA (SC4) Downlink Data/Delay

The charts above are the data and CNPC link delay information, collected from Opnet, for the entire route of the Service Class 1 UA and for an overlapping 24 minute window where the Service Class 4 UA shared ground station 10 for their comm operations. For the SC4 UA, the 24 min window actually is the departure of the SC4 UA from KGYY, so the characteristics of the data/delay information include the increased data rates for the first 5 miles of the flight. The data that is shown for the SC4 aircraft is data for its connection to GS10 only, and shows what appears to be a gap in coverage at the tail end of the initial operation on GS10. But what actually occurred (not shown) is that the SC4 UA transitioned to another GS for a short period of time and then back to GS 10 after that. Beyond this the SC4 UA flew in the simulation managed by other GSs not show in these charts which were intended to show the operation overlap on a GS and a comparison between the SC1 and SC4 services operation.

General Observations/Comments – sUAS (SC1) vs. UA (SC4) – Data/Delay Charts

- The Service Class 1 aircraft only uses C2 data in its uplink and downlinks only Telemetry data.
- For both the sUSC SC1 aircraft and the UA SC4 aircraft, data for the uplink or downlink of Command and Control (C2), Telemetry and Weather data are provided at higher rates within 5 miles of a UA Departure or Arrival Airport to provide enhanced, higher fidelity coverage in more critical airspace.
- Data rates for C2 uplinked to the Service Class 4 aircraft are higher that data rates to the Service Class 1 aircraft in departure and enroute.
- Uplinked C2 data delay for the SC4 aircraft is lower than the data delay to the SC1 aircraft.
- Downlinked data rates for telemetry, surveillance and weather data for the UA SC4 aircraft are all greater than the downlinked data rate from the SC1 sUAS.
- Downlink data delay for telemetry, surveillance and weather data from the UA SC4 aircraft are lower than the delay of the telemetry data from the SC1 uUAS.
- Comparing similar uplink and downlink performance results from Service Class 4 aircraft from other simulations shows no significant change in SC4 aircraft data or delay results.

Data in the charts is plotted as Bytes aggregated over a 10 sec window. The bit rate (bps) delivered to/from the UA for each service can be approximated by: Bytes/10sec [from the chart] / 10 * 8 bits/byte.

Voice data from the charts can be used to determine the duration of a message in seconds by: Voice Msg Byte value [from the chart] * 8 bits/byte * 1 sec/2400 bits [codec conversion rate]

ATC Ground Network Model Configuration/Options

In both the Relay and Non-relay architectures, the ACES side of the system includes an ATC and PIC Ground System model. These models are comprised of several internal component models that include local area networks to provide routing and distributing different message types (digitized voice and CPDLC) within the framework of the ground architectures in the message paths and to provide A-D or D-A conversions as necessary for the movement of message traffic through the architecture Each of the internal component models contribute to the end-to-end architecture operation and will contribute to message delays.

For the operation of these component models, each has been developed to allow users the ability to configure for varying delay characteristics to keep the architecture as flexible as possible. The configuration of the models is done in an ACES configuration file prior to a simulation. Depending on the component model, options in the configuration settings vary from a fixed delay setting to user-programmed characteristics (which could be coupled with the use of other simulation inputs) that are applied as messages pass through each of the ground system models. The options provided include:

Codec models - Configurable for fixed delays or variable delays within a range (randomly selected)

Network models - Configurable for fixed delays, for variable delays within a range (randomly selected), or programmable using algorithms to simulate dynamic network operations.

For this version of the large scale simulation, a general network model was developed to operate as a WAN within each Center in the ATC Ground Model which serves to represent both the FAA and DSP networks shown in the architecture diagram in Figure 1. The model calculates simulated network delays for all forward and return messages by determining per-hop, propagation and queuing delays and total hop count required for the current distance between the ATC site and the site of the in-use VHF or VDL2 ground station based on the current UA airspace location. For the propagation and queuing delay calculations the model draws current total UA and piloted flight air traffic load information and total number of per-Center, VHF and VDL2 ground stations from ACES, and uses common network characteristics to determine the voice and data traffic, network loading currently active in the network. For the hop count determination for each message, the ATC site is provided a real location (as an ARTCC in each Center). When a message is sent, the model uses the ARTCC site and the location of the GS currently servicing the UA (in its current airspace – Sector, TRACON, etc) to determine distance between and a hop/miles factor to determine the baseline number of hops the message will encounter in the network. In addition to this baseline value, the network configuration was evaluated on a per Center basis to determine the complexity of the network node configuration within each Center, and a complexity factor is also added to the baseline hop count to reflect the impact of message routing complexity within the Center. The final delay value determination takes the final value of hop count and simply multiplies it by the total of the propagation plus queuing delay to provide the delay of either a Voice or CPDLC message through the ATC Ground Model network.

Figure 17 shows the characteristic delay plots for ZAU Center generated independently using the ATC ground network model for Voice and CPLDC messages. Each chart shows the distance between the ARTCC (i.e. ATC site) and UA connected VHF or VDL2 GS vs. delay times for varying air traffic loads in a specific Center for 0 -500mile distances at 25 mile increments. The plots are provided for a 5UA and 5 Piloted flight traffic loading in the center, for a 25UA and 25 Piloted Flights loading and for a 50UA and 50 Piloted flight loading with trend lines drawn to give a general sense of the delay expectations for these air traffic load scenarios.

ATC Gnd Network Model Characterization charts – ZAU Center Voice and CPDLC message delays

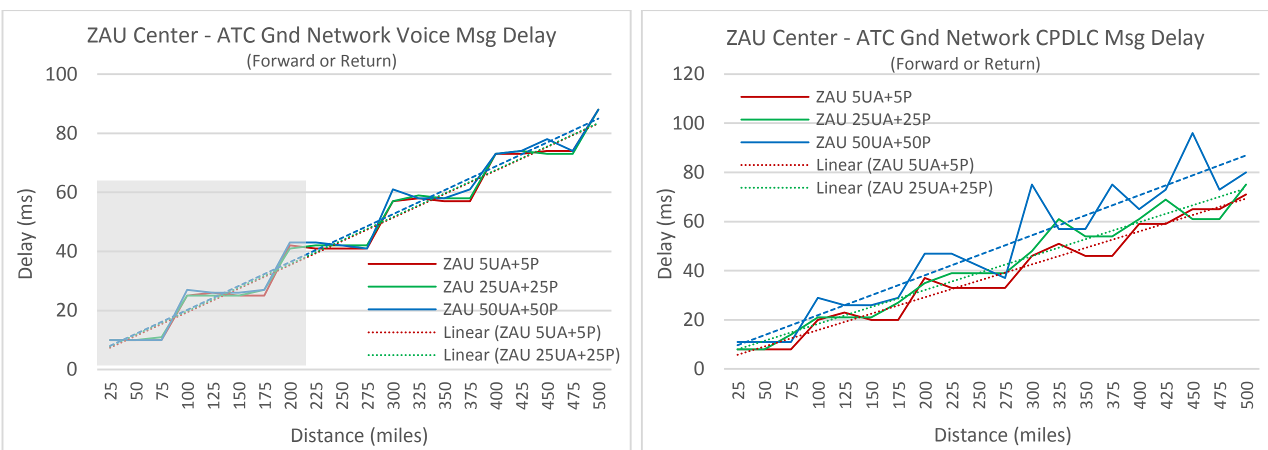


Figure 17: ZAU ATC Network Delay Characterization - Voice and CPDLC Msgs

To test the network model, two voice only simulations were run, one using the combined UA and Piloted FDS, and one using the same FDS but with additional air traffic added by base loading the model with 30 UA flights and 50 piloted flights in ZAU Center. Data from those simulations for actual distances between the GSs and ARTCC used by each aircraft for each message vs. the delay time used in the FAA network for messages sent in the forward or return direction are shown in the charts in Figure 18 and some general observations are made below.

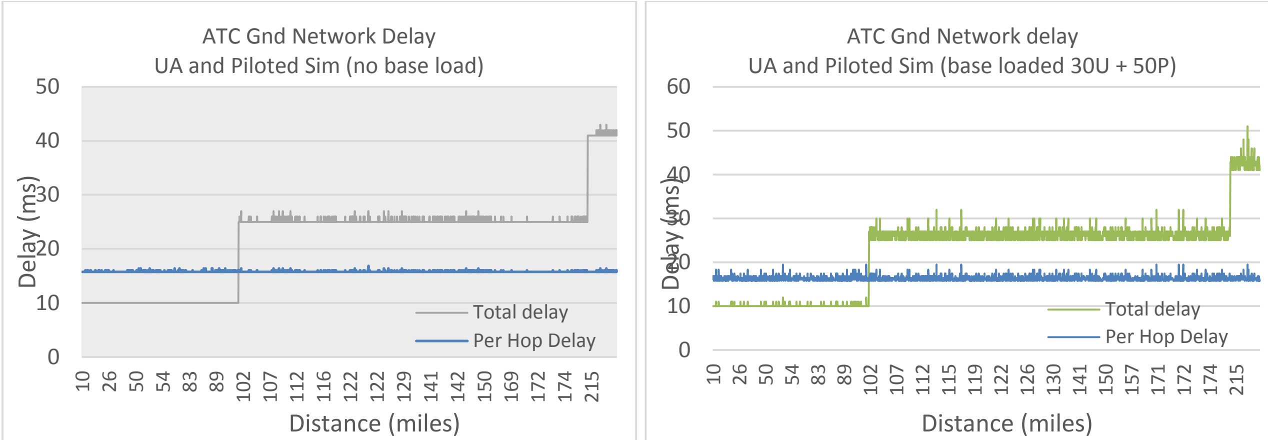


Figure 18: Sample ATC Gnd Network Delays from simulation

General Observations/Comments – ATC Network Model delay Charts

- In our simulations the performance of the ATC network model tracked well with what was expected based on the characterization charts for the traffic load for distances (ARTCC to GS) of 9 – 221 miles (comparison made in shaded area of plot shown in Figure 17 and 18). Note: For ZAU Center, 221 miles was the furthest distance between a VHF GS and the ARTCC. Larger Centers will produce greater hop counts.
- Both charts show steps in the delay values. This is due to fact that the air traffic load and therefore the network load do not change much over time, keeping the per—hop delay relatively constant. However when ARTCC to GS distances exceed certain breakpoints the number of hops required increases and delay levels increase sharply with added hops required. Note: 100miles/hop is used in the model.
- Variations in the delay times in the base loaded data are more pronounced (and in general average to higher per hop delays) than those of the no load simulation due to the impact of air traffic/network loading on per-hop model delay calculation. For this testing, one additional sim was also run with an even higher base loading to verify this impact. Comparing these, the average per hop delays were found to be: No base load – 15.7ms, 30UA 50P base load – 16.3ms, and for a sim with 50UA 100P base load – 17.7ms.

Finally the last table here shows a comparison between two same messages sent in each of these FDSs, and how the latency of a message would be affected using the ATC Gnd Model network model. Although not making a real impact, the use of the model does dynamically vary delays for our messages based on air traffic, the physical nature of a distributed network and based on network characteristics in the model used in the delay calculations, which was the objective of adding the model. At the time of this writing, no data was available from a simulation using the full system simulation (i.e. with Gen5), so the UA CNPC up/downlink delay times shown are values from the averages presented in Table 3. Full simulations to collect message delay information with this model are planned shortly to complete this characterization.

	Msg Type	F - ATC Gnd System (ms)	R - ATC Gnd System (ms)	VHF Link Access (ms)	UA CNPC DL (ms)	UA CNPC UL (ms)	PIC Gnd Codec (ms)	ATC to PIC Latency (ms)	PIC to ATC Latency (ms)
	Type 4 Msg - ATC Gnd Network Model operating in ATC Gnd Model (no base load) – GS 88miles from ATRCC								
no base load	***ATC to PIC*** *(ZAU92)*	50		1	301.8		20	372.8	
base loaded	***ATC to PIC*** *(ZAU92)*	51		1	301.8		20	373.8	
	Type 6 Msg - ATC Gnd Network Model operating in ATC Gnd Model (base load 30U + 50P) – GS 221miles from ARTCC								
no base load	***PIC to ATC*** *(ZAU56)*		81	1		298.9	20		400.9
base loaded	***PIC to ATC*** *(ZAU56)*		83	1		298.9	20		402.9

Summary

The large-scale, UA Relay architecture, communication simulation system described here provides a simulation capability for end-to-end NAS comm operation within a concept communication architecture planned for UAS-in-the-NAS operation using CNPC datalink radios. The system integrates a validated model of the Gen5 radio developed at NASA GRC to provide data services to the UA and relay of messaging through the UA, with a system ground infrastructure that replicates NAS ATM components and communication systems also intended to be used in this architecture concept. The system provides the capability to create and operate UA flights for varying UA applications. UA flights can be flown that represent different UA classes of aircraft using varying comm service classifications, along with piloted flights in air traffic scenarios managed by established NAS airspace rules provided in the ACES application.

Over the past year since the first prototype of the system architecture was tested with the prototype Gen2 radio model, the system has been evaluated for its performance, and many improvements have been developed and added. Among these have been: 1) the completion of the Gen5 model and its verification, validation and integration, 2) a complete upgrade to the comm management functions handled by the VHF voice model to provide better human factor operations and message collision detection, 3) a system mechanism to detect and log the occurrence of lost-link conditions in the CNPC model while maintaining simulation stability, 4) the addition of a dynamic network model that represents two network components for the distribution of ATC messaging in the ground system for UA and piloted flights, and 5) the inclusion of small UAS flights for use in the application.

Simulations that we ran were tailored for air traffic profiles intended to exercise system operations and modeled component performance targeted for this report. The simulations provided data in ACES and Opnet that has been collected and presented as performance characteristics for critical architecture/component operations as samples of the information available. Data is also presented that demonstrates trends that occur in the comm system concept, especially for messaging, where as an example, situation awareness messages are transferred over the CNPC link to controllers to keep them aware of airspace activity, and as the number of UA that share airspaces increases, the volume of message traffic needed to be conveyed over the CNPC downlink increases. As for the data presented in the report, the information presented here is only a small subset of what is available, and greatly understates the amount of information from a simulation that can be used for analysis. On the ACES side of simulations, the ACES LDC not only maintains comm components data and message data, but also records all aircraft information for the duration of all flights, which can be useful for evaluations of the impact comm operations have on air traffic operations. On the CNPC radio (Opnet) side of the simulations, data is maintained for the radio and its operation as an IP network component to a very high level of detail for performance of the radio. In the system all information and data is available synchronized in time through use of the RTI and positioning of the aircraft using a common trajectory generator.

For future work on the large-scale simulation system, the near term plan is to revisit adding additional messages into our message configuration file to more closely replicate message traffic profiles for specific applications of UA. This was hoped to be accomplished by this time and has been started, but has not yet been completed. Once this is done we need to address the completion of the Non-relay architecture by integrating a WAN network model that provides complete, end-to-end messaging operations, replacing the relay of the messaging through the UA. This is hoped for completion by April 2016. Once both of these item are ready we will be looking at using both simulation architectures in a plan to do NAS comm performance comparisons, and target the impact of these comm architectures on ATM operations to meet one of our project objectives with these comparisons. Beyond that, our objectives also identified the use of SatCom in this simulation capability and that will be addressed by introducing what we can of a ROM satcom link, which would create the framework for any possible addition of a more detailed CPNC satellite radio integration and link operation for comparative evaluation with the current datalink CNPC system.