Unified Approach to Modeling & Simulation of Space Communication Networks and Systems

Integrating network stack and astronomical physics simulators

Brian Barritt
DB Consulting Group, Inc.
NASA Glenn Research Center
Cleveland, Ohio, USA
Brian.Barritt@nasa.gov

Kul Bhasin, Ph.D.
Space Operations Project Ofc.
NASA Glenn Research Center
Cleveland, Ohio, USA
kul.b.bhasin@nasa.gov

Wesley Eddy
MTI Systems
NASA Glenn Research Center
Cleveland, Ohio, USA
wesley.m.eddy@nasa.gov

Seth Matthews
DB Consulting Group, Inc.
NASA Glenn Research Center
Cleveland, Ohio, USA
seth.matthews@nasa.gov

Abstract—Network simulator software tools are often used to model the behaviors and interactions of applications, protocols, packets, and data links in terrestrial communication networks. Other software tools that model the physics, orbital dynamics, and RF characteristics of space systems have matured to allow for rapid, detailed analysis of space communication links. However, the absence of a unified toolset that integrates the two modeling approaches has encumbered the system engineers tasked with the design, architecture, and analysis of complex space communication networks and systems. This paper presents the unified approach and describes the motivation, challenges, and our solution—the customization of the network simulator to integrate with astronomical analysis software tools for high-fidelity end-to-end simulation.

Keywords—space; communication; systems; networking; simulation; modeling; QualNet; STK; integration; space networks

I. INTRODUCTION

The motive for developing a unified approach to the modeling and simulation of space communication networks is twofold. First, there is an increased need for internetworking in space ever since missions started using Internet Protocol (IP) endpoints onboard space assets in the 1990s. In the near future, the need for a robust network of networks becomes essential for NASA’s proposed lunar, Martian, and deep space exploration missions. The communications architectures proposed for these missions are more complex than any prior, so there is a need for thorough, end-to-end simulation during the formulation phases [1] [2] [3].

Furthermore, such higher-fidelity system simulations require an integration of existing capabilities from the subject matter expert domains of networking, satellite communications, and mission planning. Discrete-time, event-based network simulators are often used for terrestrial network projects, but they have limited capability for modeling the physics of space links, orbits, spacecraft attitude, microwave interference sources, and other astronomical concerns.

While some network simulations, such as the Network Simulator - ns-2, OMNeT++, OPNET, and QualNet, include the advanced propagation and antenna models necessary for space link modeling, they lack the breadth of tunable parameter-space found in astronomical physics simulators, which are directly suited to the space environment.

Astronomical physics simulators, such as the Satellite Tool Kit (STK), have become very common in the aerospace industry for mission planning and communications, but their communications capability is limited to physical-layer link analysis. Therefore, a complete solution requires a combination of both tools.

Cross-disciplinary systems engineering is another factor motivating our unified approach. Mission planning and other engineers make extensive use of astronomical physics simulators and have major investments in spacecraft models, planned trajectories, etc., whereas the engineers responsible for the design and definition of the network protocol stack and topology make their investments in test beds for emulation or modeling in network simulators. Thus, a major goal of a unified toolset is to allow the reuse of existing vetted models developed by subject-matter experts across both domains.

There have been prior attempts at combining these tools [4], but they have undesirable limitations. One approach was to use the tools separately in a serial mode by first generating space link data from the physics simulator, then importing the data into the network simulator for use in end-to-end simulations [5]. This has several disadvantages. First, since the two tools are separate, the respective models and configuration parameters must be maintained separately despite their overlaps. Also, given that the duration of simulated scenarios can be lengthy, the generation of space link data before running the network simulation can require approximations, such as interpolation, which may lead to loss of precision. Other attempts at integrating the two approaches were focused on terrestrial wireless applications, and they were found to be insufficient for modeled the complexities of certain space links, such as bent-pipe relay satellites and deep space communications between multiple central bodies. Further, this type of simulation is not capable of modeling the effects of communication system performance on the dynamics of the space vehicle itself; for instance, dynamic loss or latency in the command path impacting timing of spacecraft operations.

Alternative attempts for simulating communication systems were encountered within NASA. These attempts involved the chaining of piecemeal simulations developed separately by mission planning, RF, and network engineers in an effort to quantify end-to-end performance. This has also led to inconsistencies with overlapping models as well as the
aforementioned loss of precision due to approximations, and
the possibility for errors due to mismatched assumptions within
the end-to-end system model.

II. APPROACH

Our approach, named GEMINI ([NASA] Glenn’s
Environment for Modeling Integrated Network Infrastructure),
is, to our knowledge, the first solution to successfully address
all of these problems. GEMINI is a dynamic integration
environment, meaning that the two specialized simulators run
concurrently in parallel, and data is exchanged between them as
necessary for space link events. Since GEMINI makes a clear
partition leveraging the core capabilities of each of the two
simulators, effectively replacing the network simulator’s
physical layer propagation models when bits are radiated across
space links, the models and configuration parameters can be
consistently maintained without any duplication.

For implementation we chose two COTS tools, the QualNet
network simulator from Scalable Network Technologies and
Satellite Tool Kit (STK) aeronautics and astronautics physics
simulator from Analytical Graphics Inc. QualNet is the
outgrowth of the DARPA funded GloMoSim project from the
1990’s, and STK is widely used throughout the aerospace
industry.

III. DESIGN

QualNet and STK are large, complex software tools, so a
proper design of GEMINI depended on determining the
specific integration points and analysis of the desired
simulation data flow.

GEMINI

As the network simulator models the flow of outbound
simulated application traffic through the transport, network,
and data-link layers of the network stack, a network simulator
calculates the added overhead and timing delays as application
data is translated into packets and frames. The data-link layer
model informs the proper physical layer model when an
outbound frame is ready to be radiated by the physical layer
radio model. The simulator’s physical layer model is
responsible for modeling the behavior of the radio, imposing
link serialization and other transmission delays, and providing
the simulator’s propagation model with the information
required to calculate propagation delay and signal loss through
the medium.

Our integration of the QualNet network simulator and STK
occurs at the physical layer of the simulated network stack. For
each outbound frame that is provided to the simulator’s
physical layer model for radiation across a space link, our
custom model queries a specified mission scenario in STK.
STK uses user-specific parameters and models to calculate the
link budget for the space link at the corresponding time
instance, and it responds to the query by providing both the bit-
error rate (BER) and propagation delay for the link. Note that
our QualNet/STK interface is only invoked by the network
simulator for explicitly configured space links; for terrestrial
and other links (e.g. WANs, backhaul links, cellular structures,
etc.), QualNet uses its own capabilities for physical layer
modeling. GEMINI considers the complete end-to-end
network as a system with space links as components within that
network.

For detailed simulation of space links, in order to correctly
integrate the physical layer models of both QualNet and STK,
the parameters and settings entered in to both tools need to be
consistent with the front-end flow between the space link
transmitter and receiver. In our solution, the QualNet physical
layer model is responsible for computing the transmit
serialization delay of the entire frame based on the data rate
and length, which includes forward error correction coding and
frame synchronization overhead.

IV. USE CASE

NASA’s Space Communications and Navigation (SCaN)
Program is responsible for the development and operation of
NASA’s space communication architecture. One of SCaN’s
assets is the NASA Space Network (SN). The SN consists of
space and ground segments that provide tracking and data relay
for spacecraft, satellites, and expendable launch vehicles. The
SN space segment consists of a number of Tracking and Data
Relay Satellite (TDRS) systems in geostationary orbit (GEO),
and the ground segment includes a number of ground terminals
located at the White Sands Complex (WSC) near Las Cruces,
New Mexico and a remote site in Guam.

The SN will be responsible for providing communications
for the Orion spacecraft, which has been developed as part of
NASA’s Constellation (Cx) Program. Orion has been designed
to initially transport astronauts to and from the International
Space Station (ISS) in low-earth orbit (LEO); but later phases
of the Cx program plan to use Orion to transport astronauts to
the moon, Mars, and beyond.

To demonstrate the practical use of GEMINI, we
considered a mission scenario in which the Orion spacecraft is
sending and receiving digital voice traffic with the Mission
Control Center (MCC) at Johnson Space Center (JSC) in

Fig. 1. GEMINI consists of both COTS and custom components

Development of the GEMINI toolset was funded and supported by
NASA’s Space Communication and Navigation (SCaN) Program.
Houston, Texas for approximately one hour in LEO using the NASA Space Network. Like the Internet protocol suite, the Cx program’s network design uses layering to provide abstraction of protocols and services. Applications communicating between the spacecraft and the MCC use transport, network, and data link protocols to send and receive data. Prediction of end-to-end communications performance for such a mission is difficult using a network simulator alone, as the space link fidelity and signal propagation times vary throughout the scenario according to the orbital dynamics of the transmitter and receiver in the space environment. Likewise, solely using an astronomical physics or link budget calculation tool would be insufficient; data on the fidelity and propagation delay of the space link paints a relatively poor picture of end-to-end application performance across a network using the layered protocol paradigm. Additional performance disturbances due to factors such as adjustments in spacecraft attitude, antenna masking by structures, solar occlusion, and other performance impacts are not easily accounted for in a pure networking simulator.

In our scenario, bidirectional full-duplex voice traffic using a fixed-rate codec is created by two constant bit rate (CBR) applications, one onboard Orion and the other at the MCC, each sending a 40 byte packet every 20 ms for the duration of the scenario. Data from the simulated digital voice codec is assembled into Internet Protocol (IP) packets, and then encapsulated and framed according to the CCSDS Advanced Orbiting Systems (AOS) space data link protocol [7] with the CCSDS Encapsulation Packet as a shim between IP and AOS. The AOS frames are radiated out of the Orion spacecraft transmitter to the TDRS F10 (also known as TDRS J) spacecraft over the Atlantic Ocean Region (AOR), which relays the data to a ground terminal at the White Sands Complex. In our scenario, the ground terminals process the signal back into frames and reconstruct the stream of IP packets, which are routed across gateways and routers to the MCC using the NASA Internal Services Network (NISN).

This data flow continues until an SN operational schedule change occurs just before the Orion spacecraft travels over the horizon and loses access to the Atlantic Ocean TDRS (at approximately 40 minutes). Afterwards, the Orion spacecraft radiates to a TDRS spacecraft over the Indian Ocean Region (IOR), which relays the data to a ground terminal in Guam.

During the course of the simulation, GEMINI records the end-to-end latency for each voice packet received on the return path (defined as the difference in time between the application-layer transmission and reception of each 40 byte voice packet across the end-to-end network flow). This end-to-end latency data is plotted against the 1-hour orbit time in Fig. 4.

The end-to-end voice application latency was found to change over time, as shown in Fig. 4. The curvature visible in the plot is due to the gradual change in space-link propagation distance that occurs as Orion orbits the Earth. However, the dramatic 300-millisecond jump in end-to-end latency that occurs approximately 40 minutes into the scenario is attributed to the terrestrial links. The terrestrial network topology is such that changing the path of the network flow through the Guam ground terminal adds considerable latency, as the data must eventually be routed back to WSC and eventually to the MCC at Johnson Space Center (JSC) in Houston, TX.

The thickness of the apparent line in the Fig. 4 scatter plot is due to the observed jitter in the voice application packet stream. Closer inspection of the data revealed that the voice application packet latency exhibited a saw-tooth pattern, as shown in Fig. 5. This is due to the insertion of “idle frames” into the AOS space data link, which are automatically inserted by the AOS protocol models that NASA developed for the
Due to the limited data rate of the simulated voice streams, the link layer protocol onboard Orion occasionally finds that there are no network layer packets ready for transmission. As a result, an “idle frame” is sent to keep the synchronous link active and maintain symbol synchronization at the demodulator; any outbound packets arriving into the link layer queue during transmission of this idle frame are required to wait for its completion before they can be transmitted. This contribution to end-to-end latency had not been captured in previous analytical evaluations of network performance, using spreadsheets and other techniques instead of full protocol simulation.

CONCLUSION

In this paper we have demonstrated the benefits of a unified approach to the modeling and simulation of space communication networks and systems. We explained the design of our solution, GEMINI, which leverages the core competencies of two different tools in a dynamic integration of network simulation and astronautics physics simulation software. We have shown the application of GEMINI to predict the end-to-end latency of a digital voice application in an example human spaceflight mission scenario. The results obtained for our example use case illustrated the application-layer performance impact stemming from events and interactions across different communication domains, including physical mobility, network topology, and data-link layer protocol effects.

Such an approach to modeling and simulation benefits the practitioners of systems engineering and architecting in several ways. First, we recognize that engineers involved in mission planning during early-phases of the systems engineering lifecycle operate with different tools, expertise, and domain knowledge than the engineers responsible for architecting end-to-end communications data flows, protocol stacks, and network topologies. Both groups have evolved separate toolsets, each tailored for requirements of practical application in their respective domains. It follows logically therefore new systems-of-systems architectures that bridge disparate domains will find themselves ill suited for analysis using existing tools. Our approach leverages partitions in the architecture – in this case, between the physical-layer functionality and the services provided by the data-link and higher layers – to interface the modeling and simulation tools used by both domains for an optimal solution. In addition, our use of existing tools allows us to reuse the models developed by subject-matter experts in both domains. This further benefits the systems engineering process by facilitating feedback of design trade-off and trade study analysis of the end-to-end communications architecture back into the design decisions and corresponding models of the mission plan, communications payload, and protocols.

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