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

Integrating network stack and astronautical physics simulators

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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 systems 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 astronautical 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 astronautical 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 astronautical physics simulators, which are directly suited to the space environment.

Astronautical 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 astronautical 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.
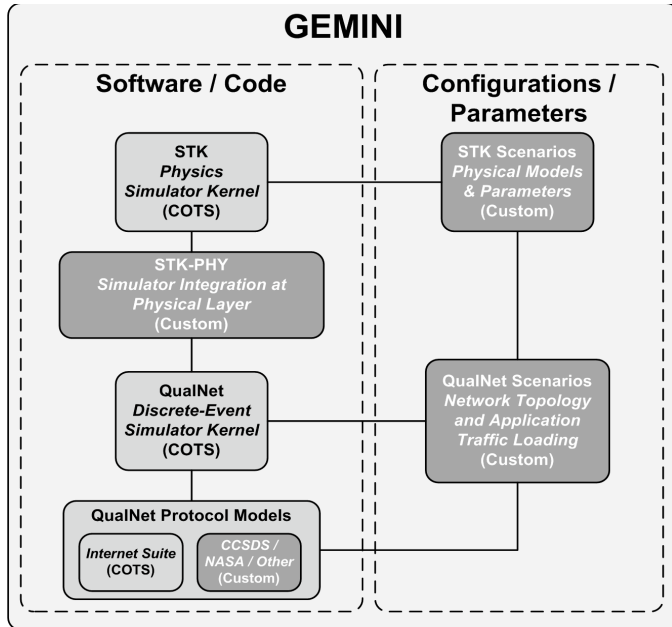

GEMINI

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

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-specified 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

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 astronautical 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).
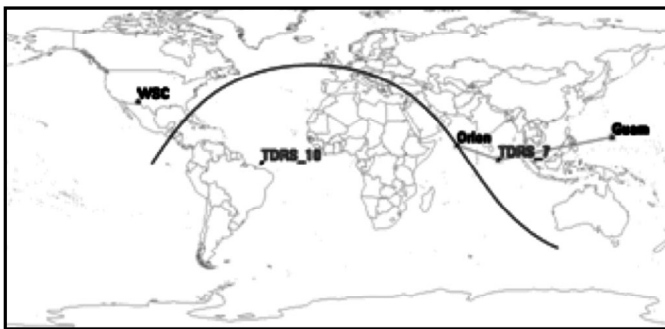

Fig. 2. Initially, Orion communications are relayed through a White Sands Complex ground terminal via a TDRS over the Atlantic Ocean

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.
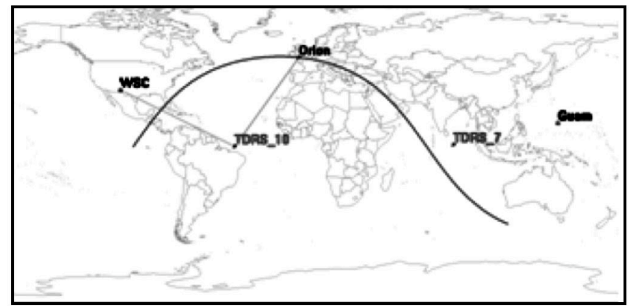

Fig. 3. After losing access to WSC, Orion communications are relayed through a Guam ground terminal via a TDRS over the Indian Ocean.

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.
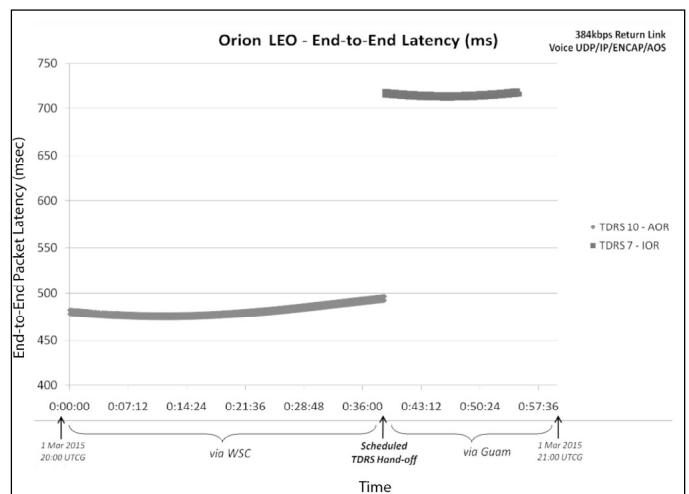

Fig. 4. End-to-end voice application latency is observed to change over time, with a substantial increase occuring after the SN schedule change.

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

simulator [6]. 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 space 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.
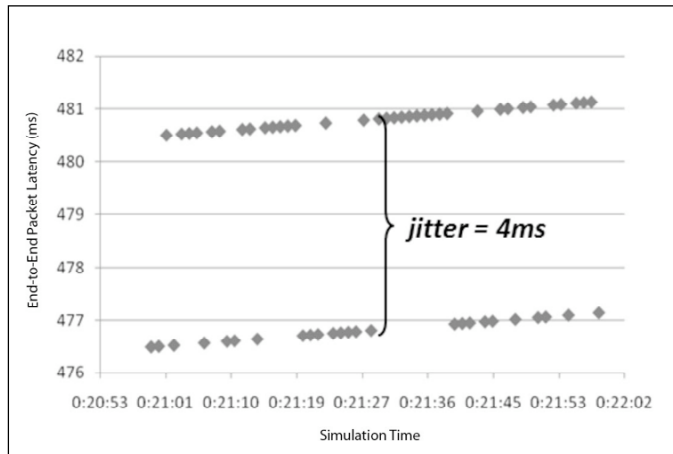

Fig. 5.   After losing access to WSC, Orion communications are relayed through a Guam ground terminal via a TDRS over the Indian Ocean.

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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