

Coarse-Grain Bandwidth Estimation Techniques for Large-Scale Space Network

Kar-Ming Cheung
Jet Propulsion Lab, California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-0662
Kar-Ming.Cheung@jpl.nasa.gov

Esther Jennings
Scalable Network Technologies, Inc.
6100 Center Drive, Suite 1250
Los Angeles, CA 90045
ejennings@scalable-networks.com

Abstract - In this paper, we describe a top-down analysis and simulation approach to size the bandwidths of a store-and-forward network for a given network topology, a mission traffic scenario, and a set of data types with different latency requirements. We use these techniques to estimate the wide area network (WAN) bandwidths of the ground links for different architecture options of the proposed Integrated Space Communication and Navigation (SCaN) Network.

Index Terms- Coarse-grain, bandwidth estimation, large-scale network.

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I. INTRODUCTION

This paper addresses the network design problem of sizing the ground communication bandwidths of a space network architecture option that offer different service classes to meet the latency requirements of different mission data types. Unlike a large commercial wide-area-network (WAN) that shares diverse network resources among diverse users and has a complex topology that requires routing mechanism and flow control, the ground communication network of a space network operates under the assumption of a guaranteed dedicated bandwidth allocation between specific sparse endpoints in a star-like topology. Also data traffic flows are driven by spacecraft downlinks, and are offered and serviced as constant bit rate (CBR) flows over pre-determined time intervals.

Given the nature of the space network described above, the analysis methodology to estimate the ground communication bandwidths involves the following steps:

1. We assume a given network topology that provides the connectivity of the source nodes, intermediate network nodes, and the destination nodes. The network topology is defined by mission scenario and network architecture option.
2. We assume a user traffic generation model that specifies the different data types and their corresponding data generation statistics and end-to-end latency requirements.
3. We exercise the user traffic generation model to simulate mission data that flows into the network. The network regulates the data flow via the store-and-forward techniques. We then estimate the bandwidth of each individual network path using the min-max approach of selecting the minimum “pipe” size that would allow the maximum aggregated traffic to flow through the path within the course of user traffic simulation.

The novelty of this approach lies in the modeling of the store-and-forward mechanism of each network node. The term store-and-forward refers to the data traffic regulation technique in which data is sent to an intermediate network node where they are temporarily stored and sent at a later time to the destination node or to another intermediate node. Store-and-forward can be applied to both space-base networks that have intermittent connectivity, and to ground-based network with deterministic connectivity. For ground-based network, the store-and-forward mechanism is used to regulate the network data flow and link resource utilization such that the user data types can be delivered to their destination nodes without violating their respective latency requirements.

A high-level view of the store-and-forward mechanism is that for a communication pass which consists of one or more data types, each with a given latency requirement, the store-and-forward process spreads out each data type across a longer time horizon but without violating the latency requirement.

There are commercial off-the-shelf (COTS) network simulation tools like Qualnet [1] and Opnet [2], which provide high-fidelity simulation of data flow through a well-defined network¹ to evaluate protocol performance and latency behavior. However these COTS tools might not be well suited to estimate the bandwidths of a large-scale network for the following reasons:

1. A large-scale network that supports a large number of users can have an aggregate data rate of hundreds of Mbps at any time. High-fidelity simulation of a large-scale network might be too complicated and memory intensive for typical COTS tools.
2. The COTS tools are designed to perform direct simulation of the protocol performance and latency behavior for a given network configuration, and not to analyze the reverse problem of sizing the network for a given set of latency requirements for the various data types.

In light of the above challenges, we developed a new analytical approach, which we call the “leveling scheme”, to model the store-and-forward mechanism of the network data flow. The term “leveling” refers to the spreading of data across a longer time horizon² without violating the corresponding latency requirement of the data type. We present two versions of the leveling scheme:

1. Straight-Forward Leveling Scheme - The Straight-Forward Leveling Scheme simply spread the data of each data type across the time horizon and does not take into account the interactions among data types within a pass nor between data types across overlapping passes at a network node, and is inherently sub-optimal. This sub-optimal estimation of bandwidths provides a conservative approach to size the bandwidth of a network architecture option.
2. 2-State Markov Leveling Scheme – The 2-State Markov Leveling Scheme takes into account the second order behavior of the store-and-forward mechanism, the interactions among data types within a pass. This leveling scheme is theoretically elegant, yet simple to implement, and more accurate than the Straight-Forward Leveling Scheme.

Both leveling schemes estimate the network bandwidths based on latency requirements of data types, and do not require the computational and memory resources to perform high-fidelity simulation as the objective is not

¹ Well-defined network refers to a network whose bandwidths between the nodes and storage capacities of the nodes are given.

² Thus lowering the required bandwidth.

to analyze detailed protocol behavior and protocol overhead.

The rest of the paper is organized as follows: Sections 2 and 3 describe the details of the Straight-Forward Leveling Scheme and the 2-State Markov Leveling Scheme respectively. Section 4 discusses the applications of the two leveling schemes to a trade study on the Integrated Network Architecture (INA) under which the three communication networks of the National Aeronautics and Space Administration (NASA) will be re-architected into a single network. Section 5 provides the concluding remarks and discusses future work.

II. STRAIGHT-FORWARD LEVELING SCHEME

The following outlines the procedure to implement the “straight-forward” leveling scheme. Consider a given pass of duration L and rate $R = R_1 + R_2 + \dots + R_i + \dots + R_N$, $1 \leq i \leq N$, where R_i is the rate of data type i , which has latency requirement L_i . A “straight-forward” approach for the store-and-forward mechanism to reduce the required bandwidth for data type i without violating the latency requirement L_i is to “level” R_i to R_i' , where R_i' is computed as $R_i' = R_i \frac{L}{L + L_i}$, and the pass duration after the store-

and-forward processing (modeled by the leveling scheme) is $L + L_i$. Apply the leveling scheme to all N data types of the link, and this results in a staggered data rate profile as shown in Figure 1. Figure 1 illustrates pictorially how the “straight-forward” leveling scheme works.

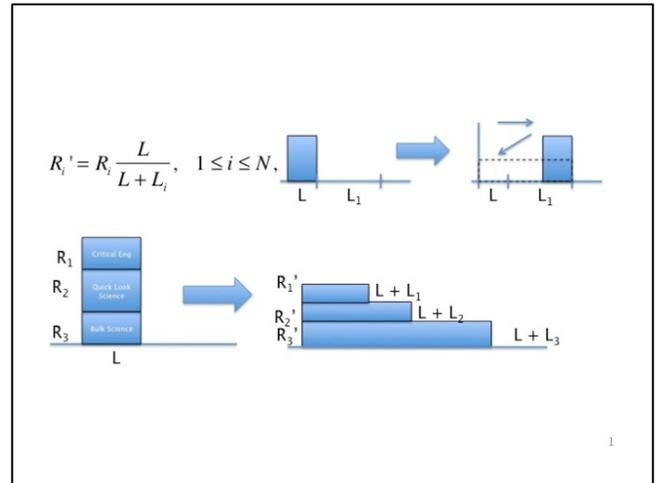


Figure 1: “Straight-Forward” Leveling Scheme

Note that to ensure the latency requirements are not violated R_1', R_2', \dots, R_N' tends to aggregate at the beginning of a pass, thus providing a larger bandwidth than toward the end of a pass.

We observe a number of weaknesses in the “straight-forward” leveling scheme. First, as we perform the leveling of each data types at the start of the pass, the beginning of a pass is unnecessarily penalized with higher aggregate data rate. Second, when one or more data types have much longer latency requirements L_i 's compared to the pass duration L , the straight-forward leveling scheme might not be effective in distributing the data along the timeline so as to minimize the maximum required data rate. We illustrate this scenario in Figure 2 with pass duration L , and data types 1 and 2 with rates R_1 and R_2 and latency requirements L_1 and L_2 respectively, where L_1 is comparable to L and $L_2 \gg L$. In this case, a more effective bandwidth sizing approach is not to stack the leveled data with longer latency at the beginning of a pass, but to fill up the vacant timeline between $L + L_1$ and $L + L_2$ with data type 2 (with rate R_2) first before filling the timeline between 0 and $L + L_2$. We illustrate this point with the following example. Let the data rate $R = 200$ kbps. R is made up of 10% engineering data with data rate $R_1 = 20$ kbps and latency requirement $L_1 = 5$ seconds, and 90% bulk science data with data rate $R_2 = 180$ kbps and latency requirement $L_2 = 8$ hours. The Straight-Forward Leveling Scheme yields a bandwidth $R' = 40$ kbps for this link. By filling up the vacant timeline between $L + L_1$ and $L + L_2$ prior to filling the whole timeline, a more effective bandwidth $R' = 20.3$ kbps is achieved. The later approach amounts to modeling the interaction between the engineering data and the bulk science data. We generalize this approach in the next section that model the interaction between data types $i - 1$ and i in the 2-state Markov Leveling Scheme.

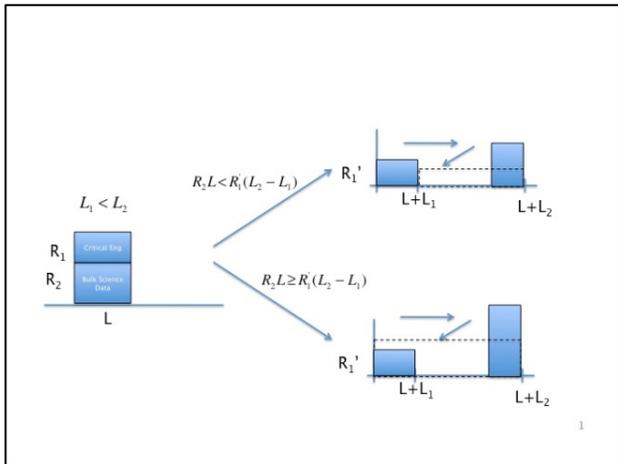


Figure 2 Better Leveling Scheme when $L_i \gg L$

III. 2-STATE MARKOV LEVELING SCHEME

As the name implies, the 2-State Markov Leveling Scheme mimics the store-and-forward mechanism using a simple 2-state Markov model. Each state is described by the shape of the data profile in a timeline diagram as discussed in the Straight-Forward Leveling Scheme in the previous section. State 0 corresponds to a data profile shape of a rectangle in a timeline diagram, and State 1 corresponds to a data profile shape of two rectangles, with the rectangle on the left higher than the rectangle on the right along the timeline. This is illustrated in Figure 3.

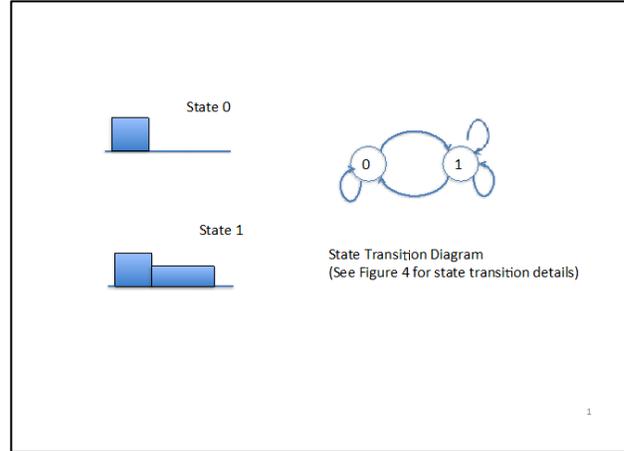


Figure 3: 2-State Markov Model

We use the same notations as in the previous section, with the additional assumption that $L_1 \leq L_2 \leq \dots \leq L_N$. The various leveling options of data type i along the timeline are represented by the state transition paths as shown in the 2-state Markov model. The resulting leveled bandwidth R'_i is a function of R_i and L_i , and their interactions with the data profile resulting from leveling of data types $1, 2, \dots, i - 1$ (with leveled bandwidth R'_{i-1}). To describe the states and the state transitions, we introduce the following definitions: after the leveling of data type $i - 1$, if the resulting state is 0 (data profile has the shape of a single rectangle), the height of the rectangle (namely the resulting data rate) is defined to be $Rx1$ and the width of the rectangle (namely the time duration) is defined to be $Lx1$. If the resulting state is 1 (data profile has a shape of two rectangles), the height and width of the right rectangle are defined as $Rx1$ and $Lx1$ respectively, and the height and width of the left rectangle are defined as $Rx2$ and $Lx2$ respectively. This is illustrated in Figure 4, where the shaded regions on the right correspond to the spreading of data type i over the data profile resulting from leveling of data types $1, 2, \dots, i - 1$. It can be shown that state 0 can transition into one state 0 and one state 1, and state 1 can transition into one state 0 and two state 1's according to the following transition rule:

1. Initial state 0:
If $R_i L < Rx1 (L + L_i - Lx1)$, next state is 1;
Else next state is 0.
2. Initial State 1:
If $R_i L < (Rx1 - Rx2) Lx2$, next state is 1;
Else If
 $R_i L - (Rx1 - Rx2) Lx2 < Rx1 (L + L_i - Lx1 - Lx2)$
next state is 1;
Else next state is 0.

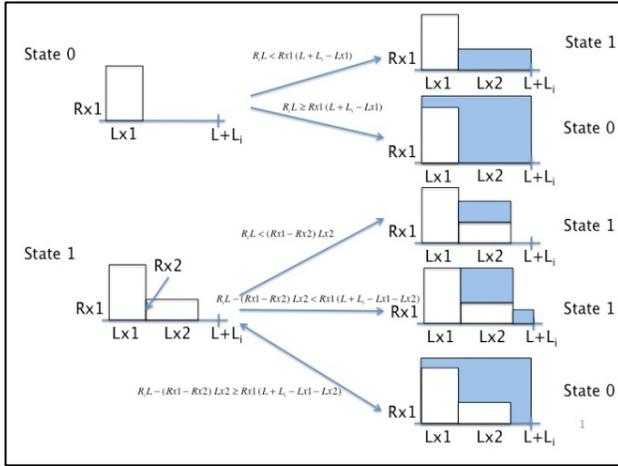


Figure 4: State Transition of Markov Model

Note that the resulting shapes of data profile along the timeline after the spreading of data type i are either one rectangle (state 0) or two rectangles (state 1). By iteratively applying the procedure depicted in Figure 4 for data types $1, 2, \dots, N$, one can constructively simulate the store-and-forward mechanism that effectively minimizes the required bandwidth and at the same time meets the latency requirements of all data types.

We want to point out that there are other bandwidth allocation schemes that can be more efficient than the 2-State Markov Leveling Scheme. However they are more difficult to construct and cannot be easily represented as a 2-state Markov model. Also the improvement in bandwidth allocation compared to the 2-State Markov Leveling Scheme may be minor.

IV. APPLICATION OF THE LEVELING SCHEMES TO THE INTEGRATED SCAN NETWORK

The National Aeronautics and Space Administration (NASA) communication infrastructure consists of three distinct networks – the Space Network (SN), the Near-Earth Network (NEN), and the Deep Space Network (DSN). The SN, NEN, and DSN are managed by the Space Communication and Navigation (SCaN) Program of NASA.

The SCaN Program System Engineering (PSE) Team conducted a trade study on the Integrated Network Architecture (INA) under which the three NASA networks will be re-architected into a single network. Depending on the degree of integration, there can be an Integrated Network Operation Center (INOC) that provides allocated network management and service execution functions for the entire integrated network. It is expected that the shift from a distributed architecture to a unified one will promote standardization and commonality among different network assets. This may in turn reduce the operational costs of NASA’s space communications and navigation infrastructure, and simplify the user missions’ interface to secure communications and navigation services. The goal of the study is to identify the architecture that provides that best value in terms of lower life cycle cost and risk, and higher technical performance.

The INA study examines two key aspects of the integrated network: a) Integrated Network Management (INM), and b) Integrated Service Execution (ISE). The INM provides mission users a set of standard network service management functions primarily implemented using Consultative Committee for Space Data Systems (CCSDS) service management standards. The ISE provides four standard categories of network services to flight missions – forward data delivery services, return data delivery services, radiometric services, and position and timing services.

There can be many options for ISE architecture based on the allocation of network signal processing and data delivery functions between the ground station sites (GSS’s) and the INOC. Each ISE option depicts a different ground network topology. For the INA study, four ISE architecture options have been identified:

- ISE-1: Signal processing functions at GSS’s and there is no INOC. Processed data products are sent from GSS’s to Mission Operation Centers (MOC’s).
- ISE-2 Signal processing up to link layer at GSS’s, higher layer processing and data delivery at INOC.
- ISE-3: Signal processing up to quantized coded symbols at GSS’s which are then sent on to INOC; link layer and higher processing and data delivery at INOC.
- ISE-4: Radio frequency/Intermediate frequency (RF/IF) waveforms are sampled and quantized at ground station sites and sent to INOC; all other signal processing and data delivery performed at INOC.

One important consideration that differentiates among the ISE architecture options is the wide area network (WAN) bandwidth required to provide data flow for the return data services among SCaN ground network assets as well as data delivery from SCaN to the user missions. The WAN bandwidth required for each ISE option represents a substantial portion of recurring cost, and in some cases a significant technical risk. For ISE-3 and ISE-4, the GSS-

INOC links are bit-streams with no rate buffering³, and WAN link sizes are driven by the instantaneous aggregated data rates. All other ground links (INOC-MOC links in ISE-3 and ISE-4, and all links in ISE-1 and ISE-2) are store-and-forward links, and link sizes are driven by the combined effects of mission data rates, data types with different latency requirements, and duty cycles.

The purpose of this section is to demonstrate the use of store-and-forward modeling schemes as described in Sections 2 and 3 to model the end-to-end data flow of the ISE options. Since the return data services represent the bulk of the data flow⁴, only the mission return links are considered. For the purpose of this study, we assume the following ground station configurations:

1. The SN ground sites consist of the White Sand Ground Terminal (WSGT), Secondary TDRS Ground Terminal (STGT), and the Guam Remote Ground Terminal (GRGT).
2. The NEN ground sites only include the NASA-owned sites in the 2018 era, which includes the Wallops Flight Facility (WFF), McMurdo Ground Station (MGS), Alaska Satellite Facility (ASF), White Sands Complex (WSC), and Svalbard Ground Station (SGS).
3. The DSN ground sites are located at Goldstone (United States), Canberra (Australia), and Madrid (Spain).
4. The INOC is assumed to be located at White Sands, New Mexico⁵.

Based on the above assumptions, the topological diagrams of the four ISE options are shown in Figure 5.

The modeling of the end-to-end data flow of the Integrated SCA_N Network consists of two main efforts:

1. The modeling of NASA mission return data traffic as received by the SCA_N network assets.
2. The modeling of mission traffic data flow from the ground stations through the Integrated SCA_N Network to the MOC's of user missions.

Figure 6 illustrates the process flow of the overall modeling effort. Based on the Space Communication Mission Model (SCMM), the mission traffic model generates the mission

traffic for downlink passes⁶ from all NASA missions during the 31-day period in July 2018. The mission traffic is then fed into the network simulator, which provides additional modeling of the mission traffic characteristics and simulates the data flow through the network topology. This is where we apply the leveling schemes to model the store-and-forward mechanism of the SCA_N ground network to estimate the required WAN bandwidths for the GSS-INOC links and the INOC-MOC links for each of the ISE architecture options.

A detailed description on SCMM mission traffic and the associated different data types modeling is given in an overview paper [3]. In this section, we discuss the relevant SCA_N signal processing and data conversion mechanisms along the signal processing chain that affect the required bandwidths of the ISE architecture options.

³ For ISE-3 and ISE-4 the GSS generates quantized coded symbols and RF/IF samples respectively, and has no visibility into the data content.

⁴ Manned mission links are exceptions as the forward links carry audio/video data. However they only represent a small fraction of the total data flow of the SCA_N network thus, forward links are not architecture discriminators and are not considered.

⁵ The ground links between the GSS's at White Sand and the INOC are considered as local area network (LAN), and are not considered in the costing.

⁶ Each downlink pass is characterized by the start time, the end time, the data rate, and the coding scheme used.

Figure 5: Topology Diagram of ISE Options

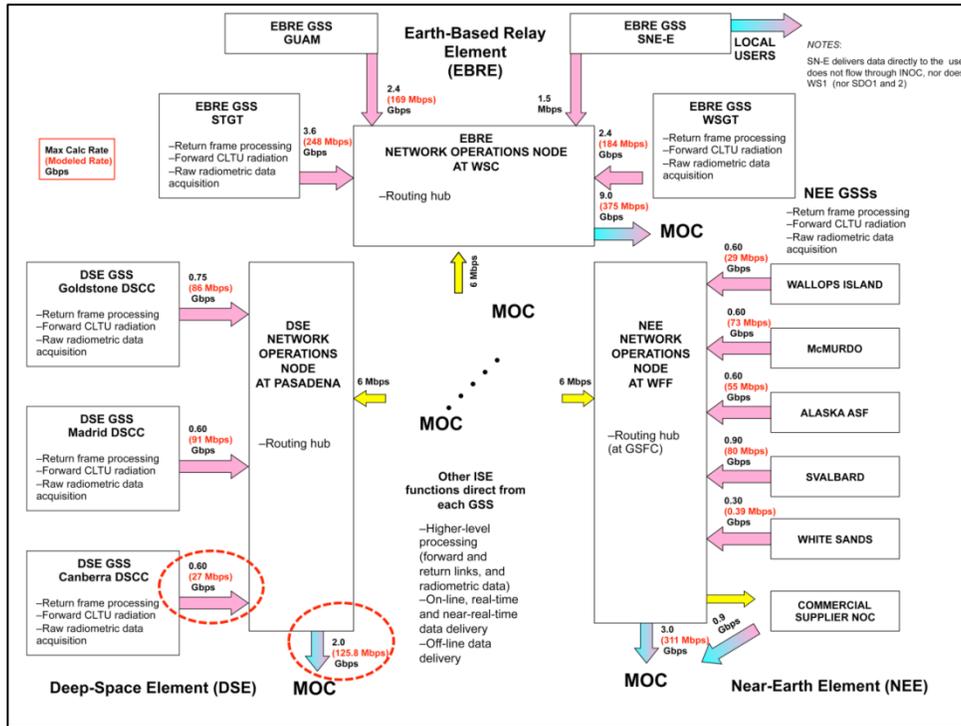


Figure 5a: ISE Option 1

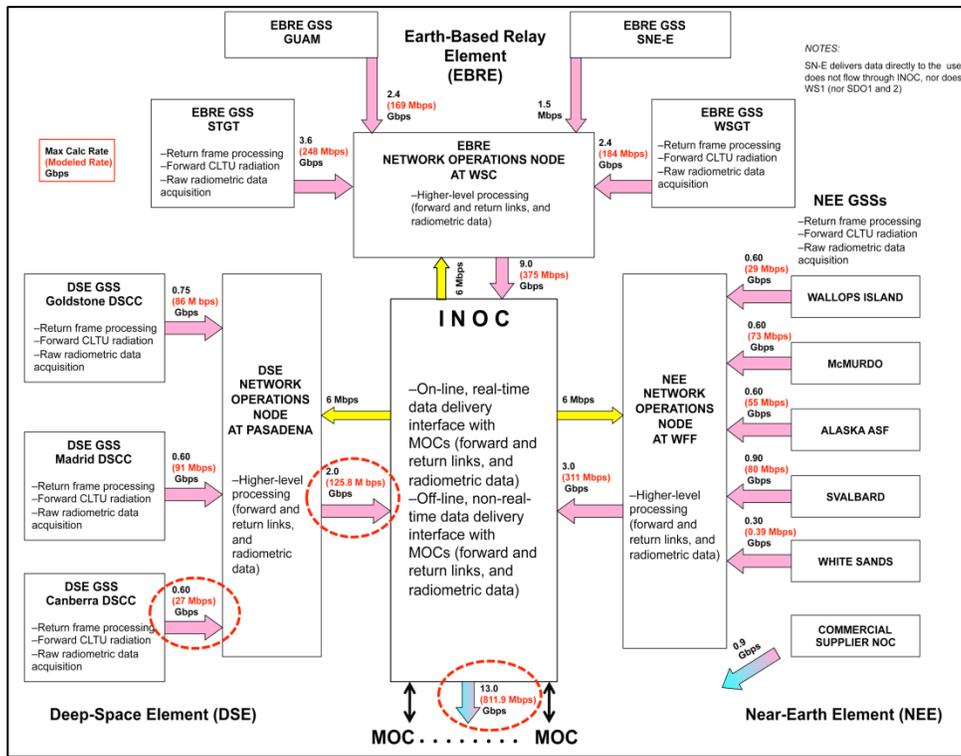


Figure 5b: ISE Option 2

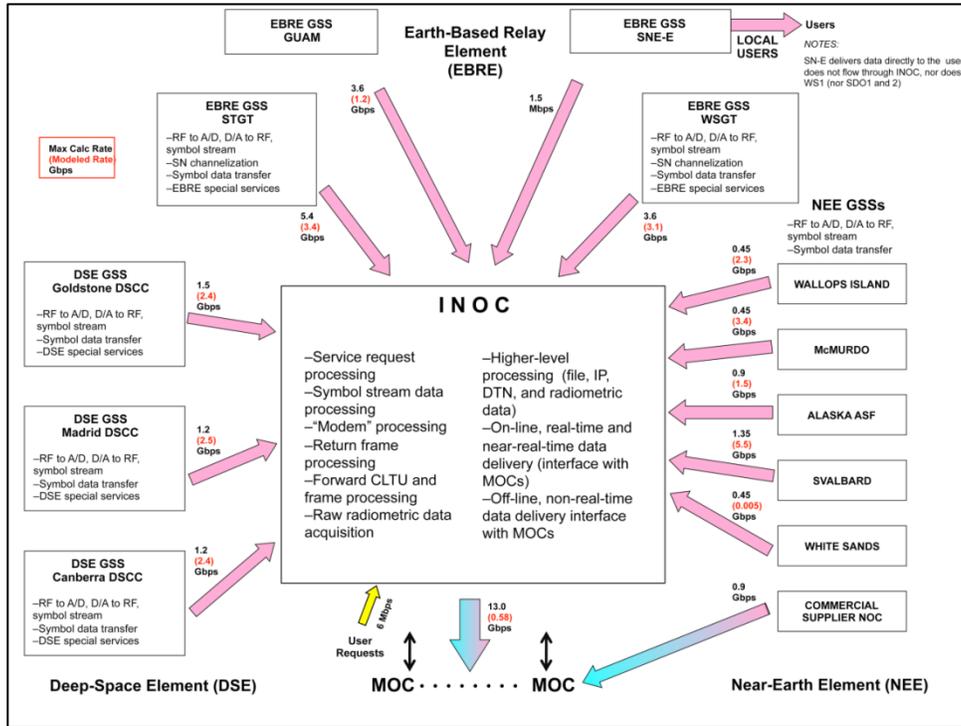


Figure 5c: ISE Option 3

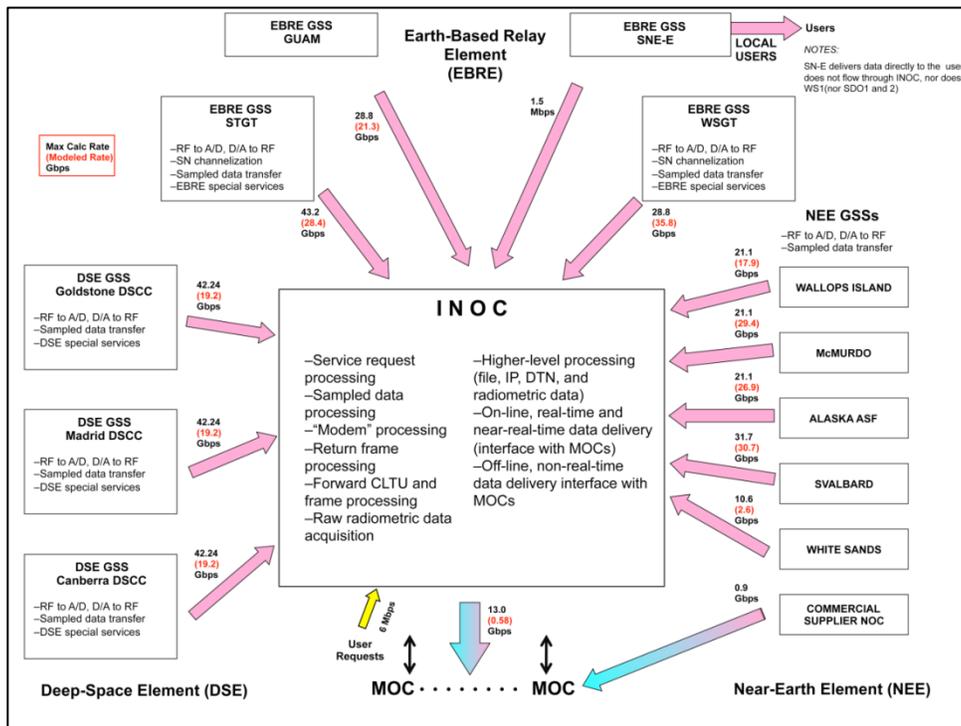


Figure 5d: ISE Option 4

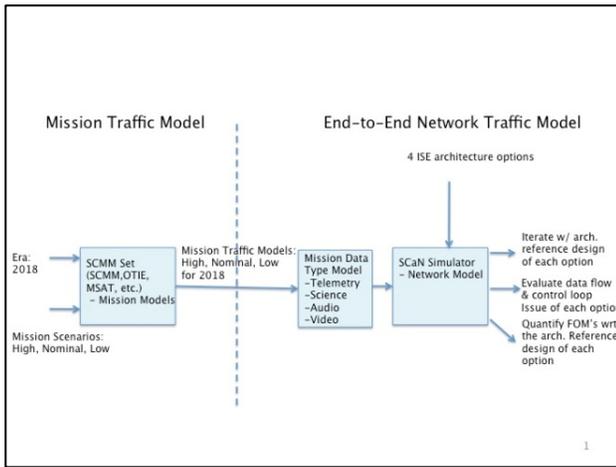


Figure 6: Process Flow of the Overall Modeling Effort

When the spacecraft radio frequency (RF) waveform is incident on an aperture of the SCA_N network, it undergoes a number of signal and data processing steps that transform the waveform into different intermediate signal and data types before converting back to the intended information bits as transmitted by the spacecraft. Depending on the allocation of signal processing and data delivery functions between the GSS's and the INOC⁷, different intermediate data types with vastly different quantities would be sent from the GSS's to the INOC, which in turn would send the processed mission data products to the MOC's of the user missions.

Latency Requirements of Mission Data Types – to quantify the service classes offered by SCA_N to the different mission data types, we assume the following latency requirements that are based on the draft SCA_N Service Requirement Document:

1. Audio/video data – 2 seconds.
2. Engineering telemetry – 5 seconds.
3. Quick-look science – 30 minutes.
4. Bulk science – 1 hour or 8 hours⁸.

RF/IF front ends and sampling rates for ISE-4 – by 2018 it is expected that the Space Network Ground Segment Sustainment (SGSS) Project will have upgraded and modernized the SN ground segment, and the third-generation TDRS (K and L) will have launched and will provide demand access service to LEO spacecraft. Also the NEN and DSN will be equipped with high-rate, low-rate, and high-sensitivity receivers. The SCA_N network front-

ends⁹ are expected to have the following RF/IF sampling rates:

1. SN S-Band Single Access (SSA) link: 804.66 Mbps.
2. SN Ku-Band Single Access (KSA) link: 4.71 Mbps.
3. SN Ka-Band Single Access (KaSA) link: 14.14 Gbps.
4. SN 30 elements Multiple Access (MA) (TDRS F3-F7, K, L): 6.29 Gbps for one to five missions.
5. SN MA space-based beam-forming (TDRS F8-F10): 201.17 Mbps per mission.
6. NEN/DSN high-sensitivity link (< 1 Mbps): 1.28 Gbps.
7. NEN/DSN low-rate link (1 – 10 Mbps): 2.56 Gbps.
8. NEN/DSN high-rate link (10 Mbps – 1.2 Gbps): 12.8 Gbps.

Code rates and quantization schemes for ISE-3 – it is expected that each mission will specify the error-correction coding (ECC) schemes and their respective code rates. However many 2018 missions will not have decided on the coding schemes. For those missions we use the following ECC assumptions:

1. For DSN missions, we assume Low Density Parity Check (LDPC) code with rate $R_c = 1/2$, codeword size $CW = 2048$ bits, and quantization level $Q = 8$ bits. For a data rate R , the coded symbol rate (including quantization) is $8xR/R_c = 16xR$.
2. For SN and NEN missions, we assume 50% of the missions will use rate 7/8 LDPC code and 50% of the missions will use concatenated code. The average code rate $R_c = 0.58$, the average codeword length $CW = 4500$ bits, and the average quantization level $Q = 4$ bits. For a data rate R , the coded symbol rate (including quantization) is $4xR/R_c = 6.90xR$.

Network delay estimations – in the SCA_N network signal processing chain and data delivery process, various latency factors are introduced and SCA_N has to make sure that the overall latency will meet the mission data delivery requirements. The following are the key latency contributions in the SCA_N end-to-end traffic flow:

1. Store-and-Forward delay: this is the buffering delay for a mission data type introduced at each network node according to the service class (priority) assigned to the data type. The SCA_N network uses the store-and-forward mechanism to regulate the network data flow, to control the end-to-end delay and network resource utilization, and to ensure expedient delivery of mission data according to the respective latency requirements.

⁷ An exception is ISE-1, which does not have an INOC.

⁸ We will show analysis and simulation results for both cases.

⁹ The SN RF/IF front-end design assumes the TDRSS Digital Signal Distribution (TDS_D) reference architecture, circa July 2009.

- Codeword buffering delay – we assume the codeword frame synchronization mechanism will require 3 code frames to acquire and to confirm frame sync. Let R denote the data rate. Thus the codeword buffering delay for DSN missions and SN/NEN missions are $3 \times 2048/R$ and $3 \times 4500/R$ respectively (in unit of seconds).
- Frame buffering delay – we assume a Space Link Extension (SLE) frame size of 10240, and frame sync can be acquired and confirmed in one frame. Thus the frame buffering delay is $10240/R$ (in unit of seconds).
- Ground transmission delay – from prior statistics for DSN data delivery over the NISN lines, we observe that the long-haul latency between DSN sites and JPL Central is approximately 2 times the propagation delay. As ground transmission latency is a small fraction compared to the other delays, we use the rough estimation of two times propagation delay to model the ground transmission delay.

Using the Straight-Forward Leveling Scheme we estimate the link sizes of the network paths of the four ISE options for the “base” case and “high” case traffic scenarios, both for bulk science latency requirements of 1 hour and 8 hours, respectively. The aggregated WAN bandwidths of the four ISE options for both cases are given in Tables 1 and 2.

Latency = 1 hr	Option 4	Option 3	Option 2a	Option 1
Base Case	182.444	15.742	3.514	2.352
High Case	207.353	43.612	8.209	6.021

Table 1: Aggregated WAN Bandwidths (Gbps) for Bulk Science Latency of One Hour, Straight-Forward Leveling Scheme

Latency = 8 hr	Option 4	Option 3	Option 2a	Option 1
Base Case	182.157	15.456	2.259	1.712
High Case	206.606	42.865	5.847	4.145

Table 2: Aggregated WAN Bandwidths (Gbps) for Bulk Science Latency of Eight Hours, Straight-Forward Leveling Scheme

Similarly we apply the 2-State Markov Leveling Scheme, and the aggregated WAN bandwidths of the four ISE options for the base and high cases are given in Table 3 (with bulk science latency of 1 hour) and Table 4 (with bulk science latency of 8 hours).

Latency = 1 hr	Option 4	Option 3	Option 2a	Option 1
Base Case	182.207	15.505	2.664	1.938
High Case	206.809	43.068	7.116	4.708

Table 3: Aggregated WAN Bandwidths (Gbps) for Bulk Science Latency of One Hour, 2-State Markov Leveling Scheme

Latency = 8 hr	Option 4	Option 3	Option 2a	Option 1
Base Case	182.010	15.308	1.789	1.444
High Case	206.211	42.470	4.644	3.210

Table 4: Aggregated WAN Bandwidths (Gbps) for Bulk Science Latency of Eight Hours, 2-State Markov Leveling Scheme

To validate the accuracy of the leveling schemes, we choose the DSN’s GSS-MOC links for the ISE option-1 for the case when the bulk science latency requirement is one hour, and compare the bandwidth estimates generated by the Straight-Forward Leveling Scheme and those generated by direct simulation using MACHETE¹⁰. The comparison results are shown in Table 5.

Base Case (Mbps)	Goldstone	Canberra	Madrid
Leveling Scheme	136.4	102.0	120.9
Qualnet	139.5	99.6	121.9

Table 5: Comparison of “Straight-Forward” Leveling Scheme with Qualnet Simulation for ISE Option-1

The above comparison indicates that the “straight-forward” leveling scheme is a close approximation to the Qualnet direct simulation in the case when the bulk science latency requirement is relatively small (one hour), thus ensuring that the bandwidth estimation results generated by the analytical leveling approach can be used in costing of the architecture options¹¹.

The end-to-end traffic flow simulations reveal the following interesting facts:

- For ISE-3 and ISE-4, the GSS-INOC links are real-time bit streams and the link sizes are driven by the instantaneous aggregated data rates.

¹⁰ NASA JPL’s Multi-mission Advanced Communication Hybrid Environment.

¹¹ WAN cost is a major recurring cost component for the ISE options, and the INA Study Review Board has decided to do costing analysis based on the bulk science latency requirement of one hour.

2. All other links are store-and-forward links, and the link sizes are driven by the combined effects of mission data rates, data types with different latency requirements, and duty cycles.
3. For ISE-3 and ISE-4, the aggregated WAN bandwidths are insensitive to data type latency requirements as their WAN bandwidths are dominated by the real-time GSS-INOC links.
4. For ISE-4 with two different bulk science latency requirements, the aggregated WAN bandwidths for the high-case are only 20% higher than those of the nominal case. This is because the ISE-4 WAN bandwidths are dominated by GSS-INOC links that transport RF/IF samples, and are independent of the data rates.
5. For ISE-3, ISE-4, and ISE-5, the aggregated WAN bandwidths of the “high” case are approximately three times as those of the “base” case. This is consistent with the fact that the “high” case consists of future mission data rates that are 3 times those of the “base” case.
6. The WAN bandwidths of ISE-3 and ISE-4 are much higher than those of ISE-1 and ISE-2.

V. CONCLUDING REMARKS AND FUTURE WORK

In this paper, we describe new leveling schemes to model the traffic flow and buffering mechanism of a large-scale store-and-forward network. We apply these techniques to estimate the wide area network (WAN) bandwidths of the ground links for different architecture options of the proposed Integrated Space Communication and Navigation (ScaN) Network. Future works that can improve the fidelity of the leveling schemes and enhance the INA Study are as follows:

1. Use statistical description to define link bandwidth requirements. The current analysis uses the min-max approach to estimate the link sizes of a network as described in Section 4. A better approach to quantify the link sizes is to describe the individual link size in terms of mean and variance based on the simulated traffic that flows through the link. By invoking the Gaussian assumption and using the 2nd order statistics gathered from the traffic flow simulation, one can specify the link sizes based on the statistical confidence level to prevent overflow.
2. Provide data type modeling for each individual mission. The current analysis makes blanket assumptions on mission data types across all the missions as described in Section 4. When data type allocation information is available for an individual mission, we can implement the specific data type allocation for that particular mission to improve the simulation fidelity.
3. Include other latency contributions. The current analysis only models the store-and-forward delay

based on the latency requirements of the data types, which accounts for the majority of the latency in the data delivery operation. We can improve the accuracy of the analysis by modeling the additional latency contribution of codeword buffering delay, frame buffering delay, and ground transmission delay as described in Section 4.

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BIOGRAPHIES



Kar-Ming Cheung is a Principal Engineer and Technical Group Supervisor in the Communication Architectures and Research Section (332) at JPL. His group supports design and specification of future deep-space and near-Earth communication systems and architectures. Kar-Ming Cheung received NASA's Exceptional Service Medal for his work on Galileo's onboard image compression scheme. He has authored or co-authored 30+ journal papers and conference papers in the areas of error-correction coding, data compression, image processing, and telecom system operations. Since 1987 he has been with JPL where he is involved in research, development, production, operation, and management of advanced channel coding, source coding, synchronization, image restoration, and communication analysis schemes. He got his B.S.E.E. degree from the University of Michigan, Ann Arbor in 1984, his M.S. degree and Ph.D. degree from California Institute of Technology in 1985 and 1987 respectively.



Dr. Esther Jennings is a Team Lead and Senior Member of Technical Staff at Scalable Networks Technologies. Prior to this, she was a research staff with the Communications Architectures and Research Section of the Jet Propulsion Laboratory where she was the task manager of "Hybrid Simulation Environment for the Interplanetary Network" under the Interplanetary Network Directorate Information Technology Program. She received a Ph.D. in Computer Science from Luleå University of Technology, Sweden. After that, she was a postdoctoral fellow at the Industrial Engineering Department at Technion, Israel Institute of Technology. She also worked as an assistant professor at the Computer Science Department of California State Polytechnic University, Pomona.