Space Mobile Network: A Near Earth Communications and Navigation Architecture

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Abstract— **This paper shares key findings of NASA's Earth Regime Network Evolution Study (ERNESt) team resulting from its 18-month effort to define a wholly new architecture-level paradigm for the exploitation of space by civil space and commercial sector organizations. Since the launch of Sputnik in October 1957 spaceflight missions have remained highly scripted activities from launch through disposal. The utilization of computer technology has enabled dramatic increases in mission complexity; but, the underlying premise that the diverse actions necessary to meet mission goals requires minute-by-minute scripting, defined weeks in advance of execution, for the life of the mission has remained. This archetype was appropriate for a "new frontier" but now risks overtly constraining the potential market-based opportunities for the innovation considered necessary to efficiently address the complexities associated with meeting communications and navigation requirements projected to be characteristics of the next era of space exploration: a growing number of missions in simultaneous execution, increased variance of mission types and growth in location/orbital regime diversity. The resulting ERNESt architectural cornerstone – the Space Mobile Network (SMN) – was envisioned as critical to creating an environment essential to meeting these future challenges in political, programmatic, technological and budgetary terms. The SMN incorporates technologies such as: Disruption Tolerant Networking (DTN) and optical communications, as well as new operations concepts such as User Initiated Services (UIS) to provide user services analogous to today's terrestrial mobile network user. Results developed in collaboration with NASA's Space Communications and Navigation (SCaN) Division and field centers are reported on. Findings have been validated via briefings to external focus groups and initial ground-based demonstrations. The SMN opens new niches for exploitation by the marketplace of mission planners and service providers.**

1. INTRODUCTION

The Earth Regimes Network Evolution Study (ERNESt) was completed in May 2015 [1]. The study was chartered by NASA's Space Communications and Navigations (SCaN) Program; responsible for all NASA space communication and navigation activities through the Deep Space Network (DSN), Near Earth Network (NEN), and Space Network (SN). The study was instituted by a multi-center team led by NASA's Goddard Space Flight Center (GSFC). The ERNESt team set out to create a next generation near-Earth space communications and navigation architecture for 2025 and beyond. This architecture would provide communication and navigation services to missions within 2M kilometers of the Earth (just beyond the Earth-Sun L2 point). The architecture would also be customizable and scalable to allow room to include industry and international partners, helping the network to advance new science and technologies, while driving down commoditized costs.

The resulting ERNESt architectural framework was named the "Space Mobile Network (SMN)," to accentuate the focus on the user experience with analogies to the terrestrial mobile wireless smartphone user experience. This paper will describe a future user operational scenario and desired experience with the associated desired future network attributes. Example operations concepts will be described to highlight SMN architecture features. These architectural features will identify technology development areas and goals which will be described.

2. THE SMN USER EXPERIENCE

The evolution of the terrestrial wireless communication systems and smartphones has transformed not just how individuals communicate, but how they go about their daily activities. The awareness that one could get a connection and access others connected to the same network at any time, combined with current position knowledge and hand-held computing power has allowed for daily activities such as travel, dining, and shopping to happen with minimal pre-planning. Activities are no longer constrained by having to meet at a pre-determined time and location, to find a phone, or possibly get lost. The Space Mobile Network describes an architecture that brings an analogous user experience to future space missions.

For the future space mission, the user experience begins with increased service performance with the primary performance parameters being data volume delivery, position accuracy, timing accuracy, reliability, and availability. The specification of data volume delivery instead of data rate is a significant difference from terrestrial communications networks. Terrestrial users have come to expect full bandwidth end-to-end communications whenever they have a connection – live video on demand, for example. Support of Near Earth space users have shown that most users operate with the knowledge that a link is not always available and thereby, store their data onboard, and transmit the data based on a latency requirement. The latency requirement either comes from a requirement to deliver the data all the way to the final destination for a science need (update of the hurricane forecast, for example) or a requirement to offload the onboard storage before it overflows and data is lost. The observation that the user set has a majority of "delay tolerant users" allows the space communications architecture to have more implementation flexibility while still meeting user requirements. The architecture needs to ensure that the user's data volume is delivered to the desired destination in the science driver case or delivered off of the user platform in the onboard storage limitation case within a latency requirement.

Improved service performance will not be a requirement for all missions; however, missions satisfied with today's performance levels will continue to be seeking ways to minimize their user burden. User burden includes the Size, Weight, and Power (SWaP) required for the flight systems. Reductions in SWaP allows for either more resources for mission payloads or an overall smaller spacecraft. User burden also includes the complexity required to obtain the network services. This complexity includes the pre-launch planning, design, and test phase, as well as the operational phase. Excessive planning and scheduling for every contact and complete end-to-end testing for the addition of any ground station or data destination will limit the flexibility

and scalability of the network and user missions, and increase lifecycle costs. The user experience should be the same as today's Internet cloud experience where a user knows that once they connect themselves to "the cloud," services, sources, and destinations are available (Figure 1).
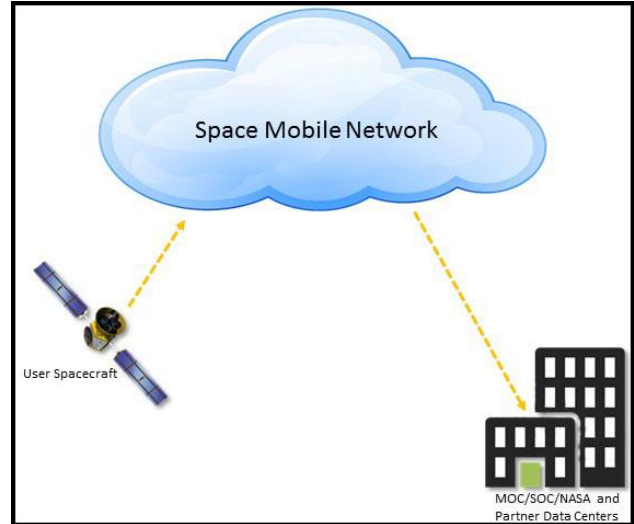

Figure 1. SMN users operate in a similar fashion to cell phone users operate with the network cloud

3. OPERATIONS CONCEPTS

Let's consider the case of a low earth orbiting Earth science spacecraft to illustrate a future operations concept (see Figure 2). The spacecraft has multiple science instruments continually generating data at steady rate with occasional bursts due to science events. Basic spacecraft commanding and housekeeping telemetry functions are available continuously via low rate links. When the spacecraft determines that it requires services, such as a high data rate link, beyond what are provided by these continuous links, it transmits a request to the network over the low rate link. The network determines the next available opportunity to support the mission and responds to the request with the time and information required for the mission to access the service. When the service time arrives, the mission receives the requested service. The requested service could be provided by a space relay or ground station from any compatible and participating provider (NASA, commercial, international, etc.).

The fundamental requirement to point communication apertures to and from the user and network asset accompanies the need for high data rate links. A service request will not only alert the network to the presence of a user and information regarding the user's desire for service, but also provide self-determined state information necessary for the network to provision and fulfill the user's request. User state information will be determined onboard the user platform via autonomous navigation technology

(autonav), in contrast to ground based orbit determination performed today. A robust autonav capability in the near Earth domain will be enabled by the fusion of observations from Global Navigation Satellite Systems (GNSS), radiometric and optimetric observations, a navigation beacon provided by Space Mobile Network assets, inertial reference units, and celestial navigation.
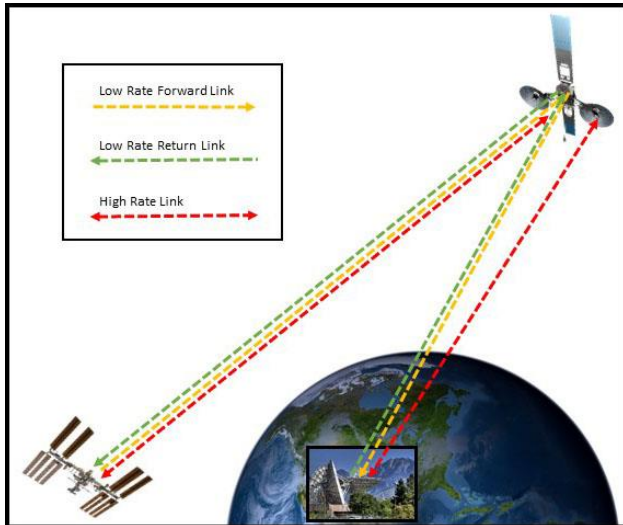

Figure 2. SMN provides continuously available low rate links and enables users to schedule high data rate links through User Initiated Services (UIS)

4. SPACE MOBILE NETWORK ARCHITECTURAL FEATURES

To realize the scenario describe above, the Space Mobile Network must include the following features:

(1) Continuously available low rate forward and return links

(2) High data rate forward and return links

(3) Dynamic link allocation and scheduling

(4) Dynamic end-to-end data path allocation and scheduling

(5) Position, Navigation, and Time services

The first feature of the network architecture identified in the operations concept example are continuously available low rate links. Note that this feature description does not specify what is meant by "low rate" or the physical characteristics (RF, optical, etc.) of the links. The key attribute of this feature is that it is continuously available or at least appears to be continuously available to the user. The data rates and physical characteristics of these links

will evolve based on trades to optimize the availability and maximize the link utility.

The current NASA Space Network is able to provide continuous low rate return links via the TDRSS Multiple Access (MA) system. The system operates at S-Band using a phased array on the TDRS and electronically steering the antenna beams with beamformers at the ground station. Though the current maximum MA data rate of 300 kbps may be too limiting for the future architecture, the bigger limitation is the SWaP required to use the system. A user is required to carry an S-Band transmitter on the order of 5W RF output and associated omni antennas to achieve data rates on the order of 1 kbps. Higher data rates require a proportional increase in the user Effective Isotropic Radiated Power (EIRP). The SMN requires links that are continuously available and minimize required user transmit power and related user burden, while ideally increasing the maximum data rate beyond 300 kbps. The availability requirement likely drives the solution to space-based relays, which in turn leads to a requirement for low relay payload SWaP. The ERNESt team identified candidate technology solutions including Optical MA, Ka-Band MA, and enhanced S-Band MA.

Continuously available forward links have proven to be more difficult to provide via space relay to date, due to the relay onboard resources required. A broadcast beacon may provide the highest availability with minimum relay flight system impact, but will typically have lower data rate capacity than systems that provision enough individual forward links to allow for both higher data rates and high availability. A beacon can provide additional benefits with respect to Position, Navigation and Timing (PNT), as described below.

The second architectural feature are high data rate links. The term "high" is a relative term and its definition is expected to be constantly increasing. The differences between the high data rate links and the low rate links described above will be due to design trades that, in the case of high data rate links, optimize the data rates with the likely consequence of reduced availability. For example, a LEO mission direct to Earth downlinks may be achieved at much higher data rates, but the total view periods to ground stations would be less than the view periods to a GEO relay constellation. These links may be either RF or optical links.

The differentiation between "links" and "end-to-end path" needs to also be understood as the architecture is implemented (Figure 3). A mission that needs to offload data in order to free up onboard storage or meet some other operational constraint is really concerned with the speed of the space link directly connected to the user platform, whereas, a mission with science data delivery timeliness

requirements will be concerned about the effective data rate between the user platform and data destination. The next two features concern the allocation and scheduling of the links and end-to-end paths. In the case of today's terrestrial mobile network user, there are no apparent scheduling activities required for the user to get the desired service. The user pulls out their device and dials, enters a website address, or, as is becoming more prevalent, the mobile device is continuously requesting, receiving, and transmitting data without any required user action. Though there is no apparent scheduling, the network is still constantly allocating bandwidth and other resources to meet all performance requirements.
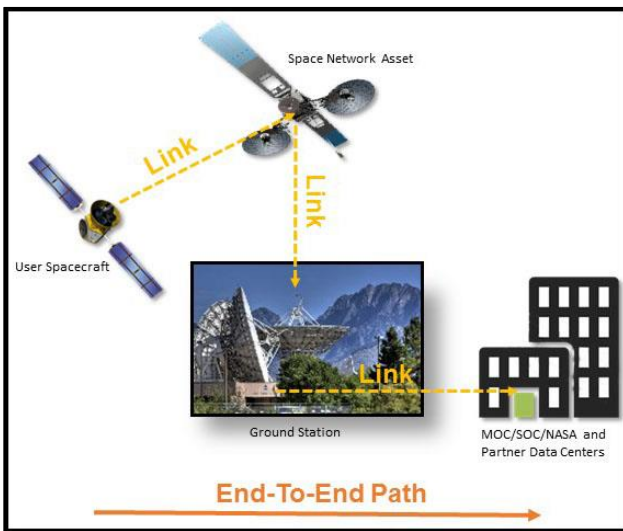

Figure 3. Links vs. End-to-End Path

In the operational scenario described in section 3, the user was able to use the available low rate links to request a high rate service. Since it may be impractical, especially in the build-up of the Space Mobile Network, to have fully capable high rate services available on demand this User Initiated Services (UIS) feature allows the user to request and receive the high rate service, or other not continuously available service, on short notice. Once again, a relative term "short notice" is used and the exact definition is expected to evolve with the implementation and technological developments. The system would still support scheduled services as today, but it would support the larger percentage of users on the continuously available and UIS scheduled services, allowing the network to be more responsive and efficient. The likelihood of receiving the desired service and guaranteed maximum wait time both would have to be within user expectations and requirements or else the service would go unused. This is analogous to the scenario in which a dining party enters a bar and grill. Drinks and limited services may be continuously available at the bar (at least until closing time). Full service would be available at a table when the

group arrived if reservations were made (a prior scheduling). In the UIS analogous case, the party would request a table for dining from the bartender or hostess. If the wait time is too long or the food and service provided are not satisfactory, the group goes elsewhere.

The implementation of UIS requires a protocol for a user to negotiate a service request, either over a space link or terrestrially. The UIS will also require a scheduling system capable of dynamically fielding the requests: comparing them against available resources, schedules, and priorities. The system must also provide a way to dispatch the now scheduled service details to the user systems and provider elements (see Figure 4). Note that the services can be provided by a combination of providers and scheduling systems as long as the peering agreements are in place and the provider scheduling systems are able to exchange requests, status, and schedule information. Success in deployment and use of UIS also depends on the user burden required for users to access the continuously available low rate links. If the user's mission does not require use of those links for any reason other than UIS schedule requests, then absent of any strong science driver, mission designers will be highly unlikely to fly the low rate link systems. The likelihood would greatly increase if the size, weight, and power of those systems was considered negligible compared to the UIS utility. The use of optical links for low rate services was identified in the ERNESt report as a technology path for enabling these systems.
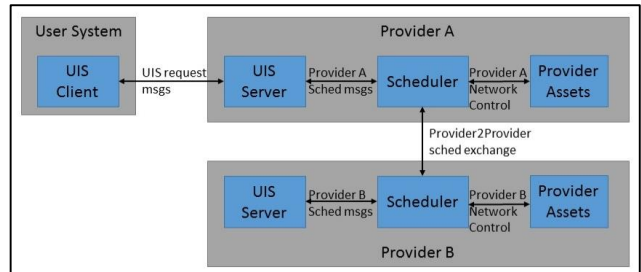

Figure 4. User Initiated Services Functions and Interfaces

As noted earlier, it is typical that the user is not requesting service to deliver data immediately to the final destination but rather requesting service to offload the onboard storage. This difference allows additional flexibility in the implementation, allocation, and scheduling of the end-to-end path. Today's missions will commonly downlink science data at rates in the hundreds of Mbps to ground stations that will buffer and distribute the data over terrestrial links at rates an order of magnitude lower. This provider implementation takes advantage of the relative leniency of the data delivery requirements to save costs on the terrestrial data circuits. The provider can also leverage the same leniency of some users to allow higher priority user data to flow from the provider node first without having to increase data circuit rates. The buffering

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performed today at ground station nodes can have the same benefits if performed onboard space relay nodes. The expected evolution of space relays to incorporate optical communications links brings expected requirements for some amount of onboard storage to address handovers and link outages due to cloud cover [2]. Delay/Disruption Tolerant Network (DTN) protocols have been demonstrated to provide the store-and-forward network capabilities to support the automated data buffering, routing, and quality of service required to provide this dynamic end-to-end path data distribution [3]. A DTN-enabled provider node will permit a user to offload their data at whatever rate their space link allows, while still allowing the provider flexibility to optimally implement, allocate, and schedule all the nodes and links along the rest of the end-to-end path. Though some of this functionality already exists in ground station systems, standard interoperable protocols have not yet been operationally deployed. DTN protocols have been identified as the standards to be implemented [4]. Trades need to be done to determine the amount of processing, storage, and network functionality to include on a space relay node, as opposed to performing these functions in ground-based systems. In the near-earth environment, it is also expected that some scenarios can be supported using IP for the network layer services. Support of DTN and IP within the architecture are not mutually exclusive.

In many cases, knowledge of the relay location will be necessary for the user to radiate the request. Relay orbital data provided by a continually available forward link, in combination with the user's autonav capability, allows the request to be radiated in the proper direction. User state information provided in the request will be used by the automated scheduling system to compute visibility windows, a necessary first step in provisioning high rate service to the customer. Finally, the broadcast channel provided by a beacon will pass notification to the spacecraft when their high rate link will be available.

The continually available forward link identified as a architecture feature for lower data rate user communications and UIS protocol exchanges can also be leveraged to enable the autonomous navigation capabilities necessary to achieve the fully autonomous network operations envisioned. A forward link beacon signal design can be implemented to provide radiometrics or optimetrics for onboard navigation, while carrying individual mission data, as well as other data useful to all missions, such as network status messages and space weather data. The signals could also be utilized for science observations such as reflectometry and limb sounding. The TDRSS Augmentation Service for Satellites Service (TASS) is currently under development to demonstrate such a service (Figure 5).
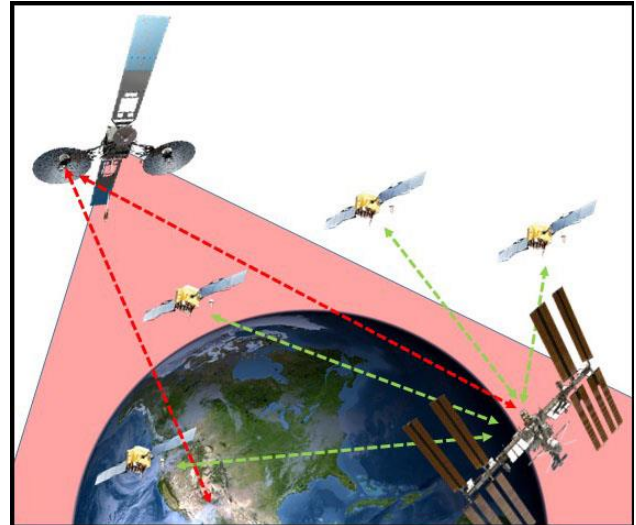

Figure 5: TDRSS Augmentation Service for Satellites (TASS)

5. TRANSITION STRATEGY

The Space Mobile Network architectural framework and operations concept can begin to be implemented before any new space relay nodes or ground station antennas are deployed. The RF bent-pipe design of the TDRSS satellites allows new services to be implemented at ground station locations and expand to provide full orbital coverage. The performance may be limited to lower data rates or longer latency than desired for the next generation network. The implementation; however, will allow for the demonstration of the benefits, and demonstrate the requirements and challenges to specify the future systems, develop the technology, and evolve without having to wait for a first launch to occur.

TASS is a service concept to use the Multiple Access Forward service to provide a continuously available global coverage beacon data signal. This signal can also provide the continuously available low rate forward data service and path for the UIS messages. The already existing Demand Access System (DAS) can provide the continuously available low rate return data service. First implementations of UIS can then be demonstrated using TASS and DAS for the space link communications channels between first instantiations of UIS clients and servers tied into the TDRSS scheduling system. The demonstration can be expanded to tie into the Near Earth Network scheduling system to demonstrate the provider peering ops concept.

Implementations of DTN and IP networking services solely require the location of link and network layer processing equipment at the ground stations (White Sands Complex for space relay or any ground station for direct-to-earth demo). From a user perspective, whether or not the network routing or storage is onboard the relay or at the first ground station may only be noticeable by an increase in latency.
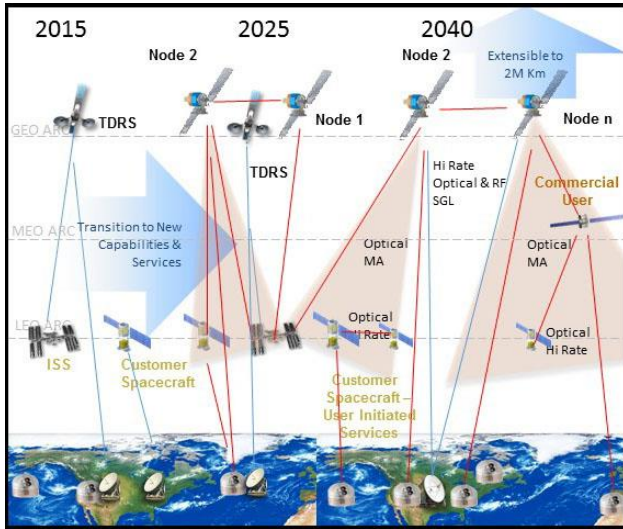

Figure 6: Space Mobile Network Transition Strategy

The launch of the Laser Communications Relay Demonstration (LCRD) in 2019 will expand the architecture to include optical communications relay capabilities in orbit [5]. Over the LCRD two year period of experiments, networking demonstrations can occur between the existing implementations and LCRD systems. Cross-provider scheduling and UIS demonstrations can also be demonstrated, as LCRD can be configured to either look like an external provider from NASA systems or it could be utilized to demonstrate the integration of new capabilities inside a single provider's network. The implementation of new RF ground station systems to support the next generation of LEO Earth science missions during this same timeframe will also provide development and demonstration opportunities.

By the mid-2020's, the first SMN relay node could be launched incorporating some of the new technologies and services onboard. In some cases, such as the networking functionality, the difference to users may just be a decrease in data latency. In the case of optical communications links, the users will begin to experience the SMN ops concepts with increased performance. Following the first launch and deployment of capabilities in ground stations, the implementation of the SMN will depend on the technology development, degree of industry and government partnerships, and evolving mission requirements.

6. CONCLUSIONS

The SMN architecture produced by the ERNESt team has identified architectural features and a transition strategy. Further work is already underway to validate and refine the architecture, to develop the associated technology, and to implement the first demonstrations and early operational capabilities.

The terrestrial mobile network has evolved to 4G and is on the way to 5G [6]. The architecture and ops concept from the user's perspective hasn't really changed over the years, but performance has continued to advance − once it was noteworthy to be able to send a picture from your mobile device and now streaming high definition TV is commonplace. The Space Mobile Network is proposed to be an analogous architectural framework for Near Earth space applications.

ACKNOWLEDGEMENTS

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BIOGRAPHY

David J. Israel *is the Exploration and Space Communications Projects Division Architect and the Principal Investigator for the Laser Communications Relay Demonstration (LCRD) at Goddard Space Flight Center. He has been working on various aspects of space communications systems, since joining NASA in 1989. He received a B.S.E.E from the Johns Hopkins University in 1989 and M.S.E.E. from the George Washington University in 1996. He has led the development of various Space Network/Tracking and Data Relay Satellite System (TDRSS) operational systems and has been the principal investigator for multiple communications technology activities concerning advanced space communications concepts and networking protocols, including the LPT CANDOS experiment on STS-107 and Disruption Tolerant Network demonstrations on the Lunar Laser Communications Demonstration..*

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