An Evaluation of Timely Communications Access Methods Using NASA Space Network

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There is a growing interest among scientists to coordinate diverse and temporally responsive measurements from multiple space and ground-based observatories in order to obtain greater insights into transient scientific events than would otherwise be possible. Many transient scientific events of interest occur randomly and the scientific value of follow-up observations decays with time. As a result, transient science operations among distributed observatories require timely access to communications network services. This paper develops two complimentary methods to improve users' network access timeliness using the NASA Space Network (SN). Descriptive models of each method are developed using Systems Modeling Language. Pathfinder experiments are designed and executed. Suitability of the methods is discussed in light of the experimental results. Innovative applications of the methods are presented. This research establishes that the as-built SN systems have adequate capabilities and capacity to support infusion of the methods to current and future users with emergent time-sensitive service needs. The minimum service access wait time was determined

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to be approximately 10 minutes and is achievable 84% of the time. An average access wait time of approximately 14 minutes is expected when SN resource blocking occurs. A roadmap to improve SN access timeliness is presented.

Nomenclature

$Access_{Min}$ = Minimum wait time to access services when SN resources are available

$Blocking_{i}$ = Discrete duration of time an SN resource is blocked

$E[Access_{Blocking}]$ = Expected wait time to access services when SN resource blocking occurs

$E[Access_{GapFilling}]$ = Expected wait time to access services for the SN gap-filling method

$E[Access_{EventDriven}]$ = Expected wait time to access SN services for the event-driven method

$E[Blocking]$ = Expected duration of time of an SN resource blocking period

$E[Gap]$ = Expected duration of time between service periods

Gap_{i} = Discrete duration of time between pre-scheduled service periods

Gap_{Max} = Maximum duration of time between pre-scheduled service periods

$InterUserSetup$ = Wait time associated with service setup following an SN blocking period

$MinimumLead$ = Minimum duration of time following receipt of an access request and service start

$P[Blocking]$ = Probability of SN resource blocking

$P[Gap_{Max}]$ = Probability an event notification will arrive within the maximum service gap

$RequestBuild$ = Wait time associated with the creation of an SN service access request

T_{0} = Start time of an interval for which measures of effectiveness are evaluated

T_{f} = End time of an interval for which measures of effectiveness are evaluated

ANCC = Alternate Network Control Center

CSTL = Communications Standards and Technology Laboratory

DAS = Demand Access System

DOY = Day of Year

GCN = Gamma-ray Burst Coordinates Network

LEO = Low Earth Orbit

MOC = Mission Operations Center

NASA = National Aeronautics and Space Administration
SAR = Schedule Add Request
SCaN = Space Communications and Navigation
SN = Space Network
SNAS = Space Network Access System
SysML = Systems Modeling Language
TDRS = Tracking and Data Relay Satellite
TUT = TDRS Unused Time
UTC = Coordinated Universal Time

I. Introduction

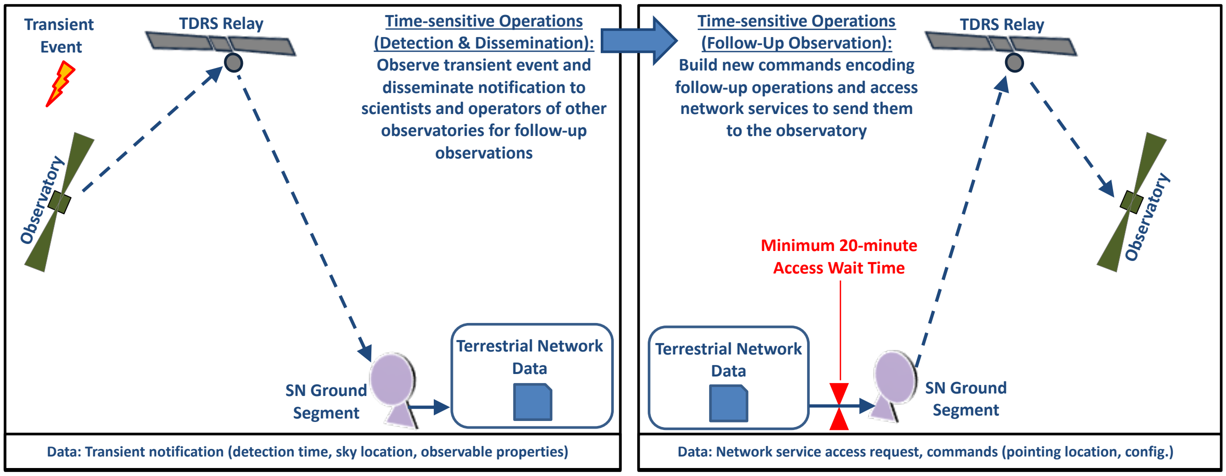
There is growing interest in developing collaborative and time-sensitive science operations concepts involving multiple distributed observatories within the National Aeronautics and Space Administration's (NASA) astrophysics, heliophysics, Earth and planetary science mission domains [1, 2]. For example, a new window on the universe has been opened in astrophysics with the advent of gravitational-wave and high-energy neutrino measurements made possible by new classes of ground-based observatories [3, 4]. The scientific processes originating these observables are poorly understood, but diverse and temporally responsive measurements from multiple distributed space and ground-based observatories provide greater insights than would otherwise be possible [4, 5]. A summary of the state-of-the-practice for NASA's transient science operations is provided in this section, examining the Neil Gehrels Swift Observatory's use of network services as a motivating case study. Additionally, this section discusses the research strategy and paper organization.

A. Background

Launched in 2004, the Neil Gehrels Swift Observatory is a first-of-its-kind multi-wavelength observatory created for the study of gamma-ray bursts (GRB) and other transient astrophysical sources [6]. The Swift observatory is comprised of three complimentary instruments on a single low-Earth orbiting (LEO) spacecraft [6]. Swift's innovative concept of operations is enabled by a direct-to-earth ground station network and a space relay network. High-fidelity science data is collected and stored onboard the observatory from both pre-planned observation targets and from randomly occurring transient scientific sources. Downlink of this data occurs at fixed pre-scheduled intervals to the ground station network via an X-band link service [7]. Concurrently, the ground network provides lower data rate bi-directional S-band link services between the observatory and the mission operations center (MOC) for tracking, telemetry and command data. This data is used to operate, maintain and sustain the observatory. The ground network provides intermittent connectivity to Swift due to limitations associated with ground network coverage, loading and the observatory's orbit geometry.

NASA's Space Network (SN) provides global communications coverage for Swift and other LEO users. The SN consists of a constellation of geosynchronous Tracking and Data Relay Satellites (TDRS) and their associated ground segment. The SN Demand Access System (DAS) provides Swift with on-demand access to S-band space-to-ground (i.e., return) communications services using a code-division multiple-access scheme and pre-allocated communications resources [7]. Upon detection of a transient gamma-ray source, Swift uses DAS to send preliminary data products, such as localization and gamma-ray flux information, to the ground within 20 seconds [7]. Additional quick-look data products associated with its X-ray and ultra-violet optical instruments may follow within minutes [7]. A transient astronomy collaboration service, known as the Gamma-ray Burst Coordinates Network (GCN), further disseminates these data products to the scientific community via the Internet using a publish-subscribe design pattern [8]. GCN information is sometimes used to initiate and coordinate follow-up observations of a transient source among scientists and operators of complimentary optical, radio or other types of space and ground-based observatories. Some ground-based observatories have implemented automated machine-to-machine interfaces to the GCN to minimize their follow-up observation latency [8]. Members of the scientific community can also submit requests for observations of transient sources to the Swift science operations team [6, 8]. Swift scientists receive approximately 1,400 such requests per year, which are categorized by urgency and priority [6]. The most time-sensitive transient sources require unplanned follow-up operations by the Swift observatory within a few minutes to less than four hours from the time of notification [6].

The SN does not presently have the capability to provide users with on-demand access to ground-to-space (i.e., forward) communications services comparable to the timely return services provided by DAS. When Swift receives an urgent and high-priority transient source notification from a GCN participating observatory, its mission operators coordinate by telephone with SN operators to manually arrange expedited access to network services. SN operators report that the minimum wait time for manually arranged service access is 20 minutes. Additionally, Swift and SN operators report that manual intervention imposes substantial task burden. Fig. 1 below illustrates the current concept for time-sensitive multi-observatory science operations involving SN. The left panel illustrates the role of SN DAS (noted by a dashed line) in enabling transient event observation data to be returned quickly from space-based observatories for further dissemination to the scientific community via terrestrial networks. The right panel illustrates the current need for manual operator intervention (noted by the red hourglass) to request and grant network access in order to send user commands directing follow-up observations of externally identified transient events to space-based observatories.



Space observatories send unplanned data to the ground quickly using the SN Demand Access System

Operator arranged network access is current practice to send unplanned data to space observatories

Fig. 1: Current concept for distributed time-sensitive transient science operations using SN.

If timely access to bi-directional space communications services were available, it could be used to transport many types of coordination, management and control traffic among diverse users and network service providers, thus enabling a more network-centric, automated and commercialized space mission enterprise [9]. The literature provides several concepts for improving service access timeliness in direct-to-earth and space relay networks. Notably, pre-scheduled blocks of time are reserved on NASA's Deep Space Network to monitor and respond to beacon tones signaling unplanned service needs from any of several mission spacecraft within a coverage area [10, 11]. The technique of pre-scheduling network service periods to achieve timeliness outcomes for unplanned needs is conceptually similar to the Space Network gap-filling method developed in this research. The Deep Space Network has long network configuration and inter-user setup times (45 min. and 15 min., respectively) and high service utilization, making a timely event-driven service access method impractical [12]. Previous efforts have proposed and demonstrated alternative methods for implementing timely access to SN ground-to-space network services using delay/disruption tolerant networking protocols and broadcast services [13, 14]. However, these efforts have failed to achieve stakeholder consensus on user needs and network requirements within the broader NASA mission and network services architecture. Additionally, the proposed methods have required costly engineering modifications to SN systems. The continued lack of timely access to bi-directional network services presents an obstacle to the scientific discoveries enabled by distributed time-sensitive space mission operations.

B. Research Strategy and Paper Organization

This research addresses the shortcomings of prior efforts and advances the network services roadmap for enabling distributed time-sensitive space mission operations. Two methods for users to obtain timely access to network services using SN are developed within NASA's overarching mission and network architecture. The goals of the conceptual modeling effort are to establish and demonstrate a rigorous, traceable and consistent model-based systems engineering approach for describing and assessing network capabilities within the context of driving user operational scenarios. Next, pathfinder experiments are designed within the constraints of the as-built SN systems to allow the effectiveness of the methods to be demonstrated and evaluated in the context of a time-sensitive Swift operational scenario. In addition, the pathfinder experiments are intended to deliver operational value to existing users, to increase stakeholder advocacy for investments in future network service capabilities, and to clarify system trade-offs and priorities for enabling distributed time-sensitive space operations.

Section I of this paper provides background for this work and introduces the Swift user mission case study. Section II provides architectural context and conceptual development for a pre-determined gap-filling network access method and a random event-driven network access method, including measures of effectiveness and potential applications for each method. Section III presents the experimental design and results of these methods in the context of a Swift operational scenario. Section IV provides a discussion of results and identifies next steps. Section V presents the conclusions from this work.

II. Conceptual Development

This section describes the conceptual development of two network service access methods using a model-based systems engineering approach and discusses applications for each method.

A. Architecture Context

The Space Communications and Navigation (SCaN) Program is responsible for all aspects of the space communications and navigation infrastructure used by NASA's science and human exploration missions [15]. SCaN requirements encompass electromagnetic spectrum policy coordination, advanced technology development and operational network services for user platforms located on or near the Earth, other heavenly bodies and beyond the solar system. SCaN has identified eight broad groupings of use cases, which identify the primary network behaviors and attributes involved in meeting the requirements of its diverse users. SCaN has also defined a set of user need categories and associated parameters which provide a basis for assessing the effectiveness and efficiency of its network capabilities and services across the use case groups. SCaN user need categories are defined and described in Table 1.

Table 1: Network user need categories.

User Need Categories	Description
Data Volume	The amount of data generated or received by the user within a defined period of time. Includes science mission data, engineering telemetry, commands and navigation data.
Latency	The allowable time to deliver data from a source to a destination. Mission latency needs may vary by data type, application or operational scenario.
Dependability	The availability, proficiency and reliability of network services for which network service providers are held accountable to users.
Access	The ability to obtain network services at a specified time, or with a specified timeliness or with a specified frequency.
Navigation	The ability to perform orbit determination, maneuvering and navigation functions based on accurate and precise network time and frequency references, signal observables or data services.
Mission and Platform Specific	The ability of network solutions to satisfy user mission and platform needs and constraints (e.g. operational constraints imposed by science activities, orbital eclipse periods, platform size, weight, power etc.)

This research is concerned with improving the effectiveness and efficiency of network access in support of transient science user operations that involve coordinated and time-sensitive follow-up activities across multiple observatories. Such operations are associated with two groups of SCaN use cases: 1) near-Earth robotic users with low latency and complex data transport needs and 2) user and network mission operations.

Several Systems Modeling Language (SysML) diagrams were developed iteratively to relate and further specify the system architecture associated with the two applicable use case groups. SysML provides a standardized visual vocabulary for describing system architectures using a set of interconnected object-oriented diagrams [16]. SysML is useful for ensuring traceability, consistency, and rigorous specification of system representations at all levels in the system hierarchy [16]. A system-level block definition diagram and activity diagram were developed to demonstrate traceability and conformance to the SCaN architecture. These diagrams serve as the root of the gap-filling and event-driven access methods developed in this research.

A system block definition diagram represents structural aspects of the system, including its boundary, hierarchy and primary interfaces, using blocks that group related functions and resources [16]. The structural model of a transient science space system is presented as a SysML block definition diagram in Fig. 2.

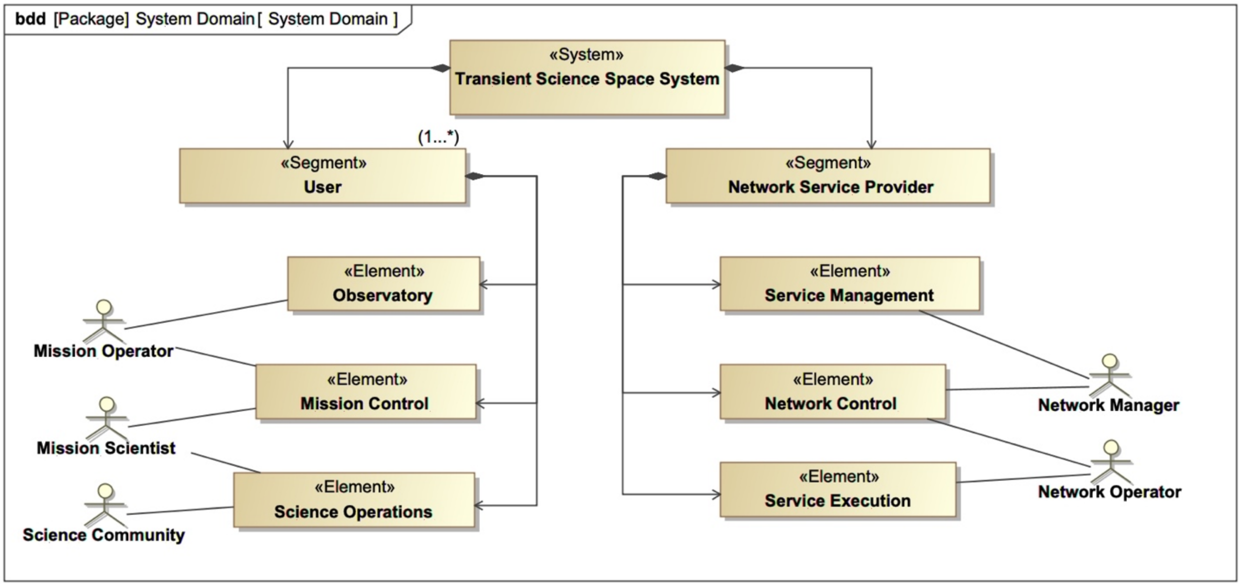


Fig. 2: Structural model of a transient science space system.

A transient science space system is comprised of one or more user segments which interact collaboratively and dynamically through a network service provider segment on timescales that may range from tens of seconds up to several hours. The user segment is further decomposed into three elements supported by three actor classes. The observatory element performs scientific measurements, processes and stores data and commands, and executes spaceflight functions. The mission control element supports the management and control of the technical aspects of observatory operations, including specialized components to create and verify command loads for observatory flight software and to build network service access requests. The mission operator actor uses the observatory and mission control elements to perform user operations. The science operations element supports the management and control of the scientific aspects of observatory operations, including scientific target priorities and scientific data analysis. The mission scientist actor uses the science operations and mission control elements to fulfill the mission's scientific objectives. The science community publishes notifications of transient scientific events associated with the science operations of external space or ground-based observatories to terrestrial Internet Protocol networks. When notified of a transient scientific event from the science community, the mission scientist must decide whether to preempt planned activities in order to conduct follow-up observations. The mission scientist works closely with the mission operator to implement follow-up operations since new observatory commands specifying the observation parameters must be built and unplanned access to network services may be necessary to deliver the commands to the observatory within the overall latency constraints of the observation scenario. The network service provider segment is partitioned in conformance to the interfaces established in the SCaN Architecture Definition Document. It is comprised of three elements and two actors. The abstract network manager actor class represents several specialized roles, including mission commitment managers and service scheduling planners, among others. For the purposes of this research, this actor class is responsible for interacting with users about their network service delivery needs occurring more than one week into the future. Network operators are responsible for the operational monitoring and control functions of the network service provider, including interactions with users for unplanned service access. The service management element ingests service access requests from users. This information is used by network managers to develop deconflicted and prioritized service schedules among all users during the schedule planning phase. The service management interface is also used to provide service access request status information to users. The network control element ingests valid network service tasks provided by the service management element or manually by network operators, issues configuration directives to network resources, and reports status to network operators. Finally, the service execution element performs the functions associated with establishing an end-to-end data transport path between the user's terrestrial and space-based element (i.e., the mission control and observatory elements).

A system activity diagram represents behavioral aspects of the system by defining and relating a set of activities and information involved in performing an operational workflow [16]. The activities are allocated to the structural elements defined in the system block definition diagram, ensuring cohesion of the overall conceptual model [16]. The behavioral model for a transient science space system conducting follow-up observations is presented as a SysML activity diagram in Fig. 3. This representation places the contribution of network access timeliness within the context of other system latency contributors within the transient science follow-up observations operations concept.

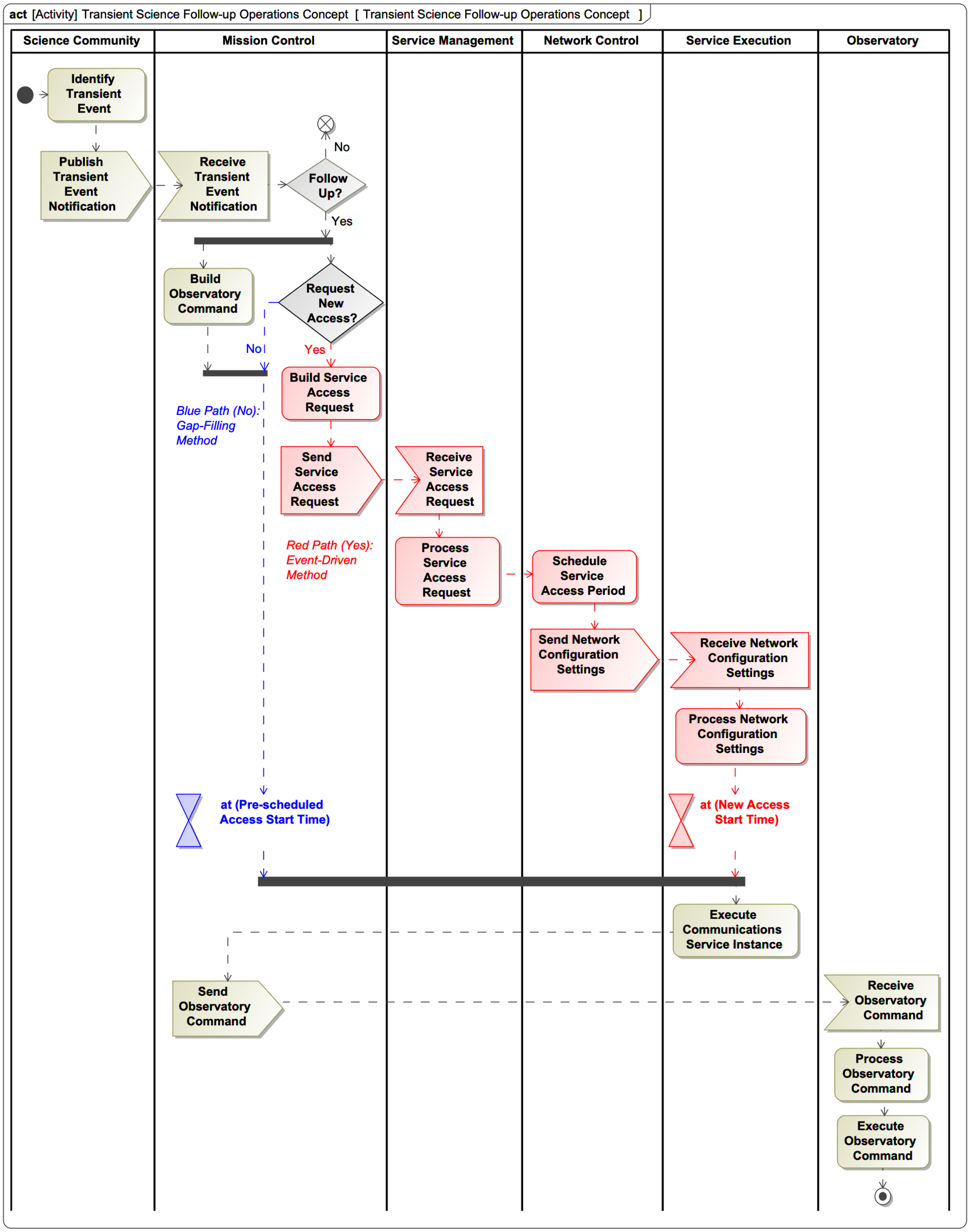


Fig. 3: Operations concept for follow-up observations of an externally identified transient scientific source.

The following preconditions apply to this operations concept: the user mission is conducting nominal pre-planned operations and has been granted network service access periods through the pre-determined network scheduling process. The activity flow is initiated by detection of a transient scientific event by the external science community. The science community identifies salient parameters characterizing the transient event, such as its celestial location and time of detection, and publishes this data as a notification to subscribed space mission users over terrestrial Internet Protocol networks. The transient notification is received by the mission control element. The mission scientist must decide (or delegate to automation) whether to preempt planned activities in order to conduct follow-up operations. This choice is represented by the first decision node in the activity flow (labeled “Follow Up?”). If the mission scientist elects to perform follow-up operations, then a new flight software command load specifying the desired observatory operations must be built by the mission operator or generated autonomously by the mission control element. Timely network service access is needed to send the new command load to the observatory. As a result, the mission scientist must decide (or delegate to automation) whether the next pre-scheduled service access period is sufficiently soon to meet the overall latency objective for the follow-up observation, or if more timely access is necessary. This choice is represented by the second decision node in the activity flow (labeled “Request New Access?”). The two methods developed in this research are pertinent to this second decision. As will be developed further in subsequent sections, the gap-filling method achieves guaranteed timeliness outcomes by increasing the frequency of pre-scheduled service periods during direct-to-earth network coverage gaps, while the event-driven method achieves best-effort timeliness outcomes by reserving a new service period during real-time operations using novel rapid access procedures. The gap-filling method and event-driven method are illustrated respectively by the blue and red activity flow branches. Since the gap-filling method is implemented during the nominal schedule pre-planning phase, if the mission scientist decides not to request new service access, then the new command load must wait to be sent until the next pre-scheduled service access start time, as represented by the blue hourglass. If the mission scientist decides to request new service access, then a sequence of activities to request, reserve and provision services are performed by the system elements indicated in the diagram. Each of these activities contribute to the expected wait time of the event-driven method, represented by the red hourglass. Network services are executed at the service access start time, allowing the new command load to be sent from the mission control element to the observatory element. The observatory element then receives, processes and executes the commands. As a postcondition to this operations concept, the observatory completes the follow-up operations specified by the new command load.

It is important to note that the conceptual model of the transient science space system is abstract. In a fully implemented transient science space system, use of either or both methods may be suitable. Further specification of the transient science space system model is necessary to assess the effectiveness and efficiency of the methods for their application in a defined operational scenario.

B. Gap-Filling Network Access Method Definition and Development

At the present time, NASA's network operations are planned two or more weeks in advance of service execution. Mission users forecast their service needs, compute the set of visibility periods between their orbiting spacecraft and compatible ground or relay communications networks, and formulate service requests in terms of a service configuration code and access time on specific communications nodes. Service providers evaluate these requests based on pre-established priority lists and negotiate conflicts among users. A de-conflicted service schedule is disseminated to users approximately one week before the start of the active execution period. The active schedule execution period is also referred to as the real-time operations phase. The schedule defines a fixed batch of communications service periods over seven days. Prior to the start of the active period, users and network actors build and load command sequences to their respective elements that will execute the specified configurations according to the schedule. Under nominal conditions, the user and network system elements execute the schedule autonomously, with varying degrees of supervision by mission and network operators.

Swift's concept of operations relies on obtaining access to services from two complimentary communications networks. The Swift observatory has two onboard communications subsystems, each tailored for its purpose and for ground or relay network compatibility. Service access requests for the ground network and space relay network (i.e. SN) are handled separately, with different user interfaces and service specification parameters. Swift's typical ground network schedule provides communications access roughly every 30 to 120 minutes, with larger service gaps of 4 to 8 hours also possible due to variations in orbit coverage and resource blocking by higher-priority users. SN DAS resources are pre-allocated so as to be continuously available as the observatory transits the SN's Atlantic, Pacific and Indian Ocean regional service areas. Timely on-demand access is achieved by configuring the Swift relay communications subsystem with pointing and handover information for a reserved SN DAS resource. Although the Swift observatory is compatible with SN pre-scheduled S-band multiple-access services, these capabilities are not routinely used. However, for spacecraft emergencies and the highest-priority transient event notifications, SN service access is requested and allocated manually.

Many transient events of scientific interest occur following a Poisson random arrival process [5, 17, 18]. As a result, it is possible to statistically analyze the access timeliness characteristics for fixed service schedules [19]. The access timeliness characteristics for a fixed schedule can then be evaluated for suitability for a given time-sensitive operational scenario. Three measures of effectiveness are identified and applied from the literature to characterize access timeliness for fixed service schedules: the maximum gap duration, Gap_{Max}, and its likelihood of occurrence $P[Gap_{Max}]$, the expected (mean) gap duration, $E[Gap]$ and the expected user wait time to access services, $E[Access]$ [20].

Consistent with the abstract concept of operations defined previously in Fig. 3, a time-sensitive operational scenario is triggered by the random observation and notification of a transient event by the science community. Transient notifications may follow the arrival rate distribution characteristics of the scientific observable or some other distribution depending on the details of a given operational scenario. The arrival rate distribution can be used to predict the number of occurrences expected within a given fixed schedule (or any subset interval) [19]. This information is useful in evaluating the feasibility and suitability of a given gap-filling method implementation. Regardless of the transient notification arrival rate, the specific arrival time of a given notification is completely random within a fixed schedule interval and is therefore equally likely to occur at any moment in time within it [19]. Continuous access to return communications services, such as with SN DAS, allows notifications of transient events detected by space-based observatories to be disseminated on-demand. However, when external (e.g., ground or other space-based) observatories generate a transient notification, bi-directional communications for sending and verifying receipt of commands to a space-based observatory must wait for the next pre-scheduled communications event to occur[§§]. The probability that a transient notification will arrive in an interval where there is a service gap can be computed as the

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[§§] In principle, if a transient notification arrives during a service period, then the access wait time is zero. However, in practice it may be difficult for current systems to process a transient event notification, generate new commands that update or replace the planned command set for the service period, send the new commands to the observatory and verify their receipt within the remaining duration (i.e., following the notification arrival) of a typical 8 to 10 minute ground network service period. As a result, a more sophisticated model than presented in this paper could be developed that would account for the response processing latencies (i.e., the sum of the factors identified above), the probability of usable service periods given a notification arrival during a service period (i.e., those that contribute zero access wait time), and the increased wait time that would result from unusable service periods. The magnitude of the wait time contribution due to unusable service periods could be bounded by the sum of the response processing time, the service period duration, and the duration of the subsequent service gap. However, the probability of a transient notification arriving during a service period is typically much less than the probability of an arrival during a gap (roughly 10% and 90%, respectively), and unusable service periods would occur at some fraction of the small service period arrival probability. As a result, the overall impact of accounting for these complicating factors on the total expected access wait time for the gap-filling method is small. Accordingly, the model presented in this paper provides a simplified but reasonable estimate of the expected access wait time.

sum of gap durations (Gap_i) divided by the duration of the fixed schedule ($T_f - T_0$). The service gap of maximum duration, Gap_{Max}, is also the most probable gap within which a transient notification should be expected to arrive (i.e., $\mathrm{Gap}_{\mathrm{Max}}$ is the mode of the probability distribution of service gaps within a fixed schedule). The likelihood that a transient notification will arrive within the maximum gap duration of a fixed schedule is given by Eq. (1) below.

$$P[Gap_{Max}] = \frac{Gap_{Max}}{(T_f - T_0)} \tag{1}$$

The expected service gap, *E[Gap]*, is the mathematical mean of the distribution of discrete gap durations, Gap_i, present in a fixed service schedule interval $(T_f - T_0)$. It measures the average length of the service gap found if the gap durations are sampled randomly, as is the case with transient notification arrivals. It is constructed as the sum of each gap duration multiplied by its probability of occurrence within the fixed schedule interval, given by Eq. (2) below.

$$E[Gap] = \sum_{i=1}^{n} Gap_i \left(\frac{Gap_i}{(T_f - T_0)} \right) \tag{2}$$

Random transient notifications are equally likely to arrive at any moment within the interval of the mean gap duration. For example, if a transient notification arrives at the first instant of a service gap, the wait time to service access is approximately equal to the gap duration. However, if the transient notification arrives at the last instant of a service gap, the wait time is approximately zero. Over a large number of arrivals, the average wait time within the gap interval approaches one half of the expected service gap duration, given by Eq. (3) below[***].

$$E[Access_{GapFilling}] = \frac{E[Gap]}{2} \tag{3}$$

Fig. 4 provides a model and summary of the access timeliness measures of effectiveness for fixed service access schedules, illustrated with a notional schedule and three random transient notification arrival events.

[***] A formal proof is presented in Tijms [19, pp. 15-17]

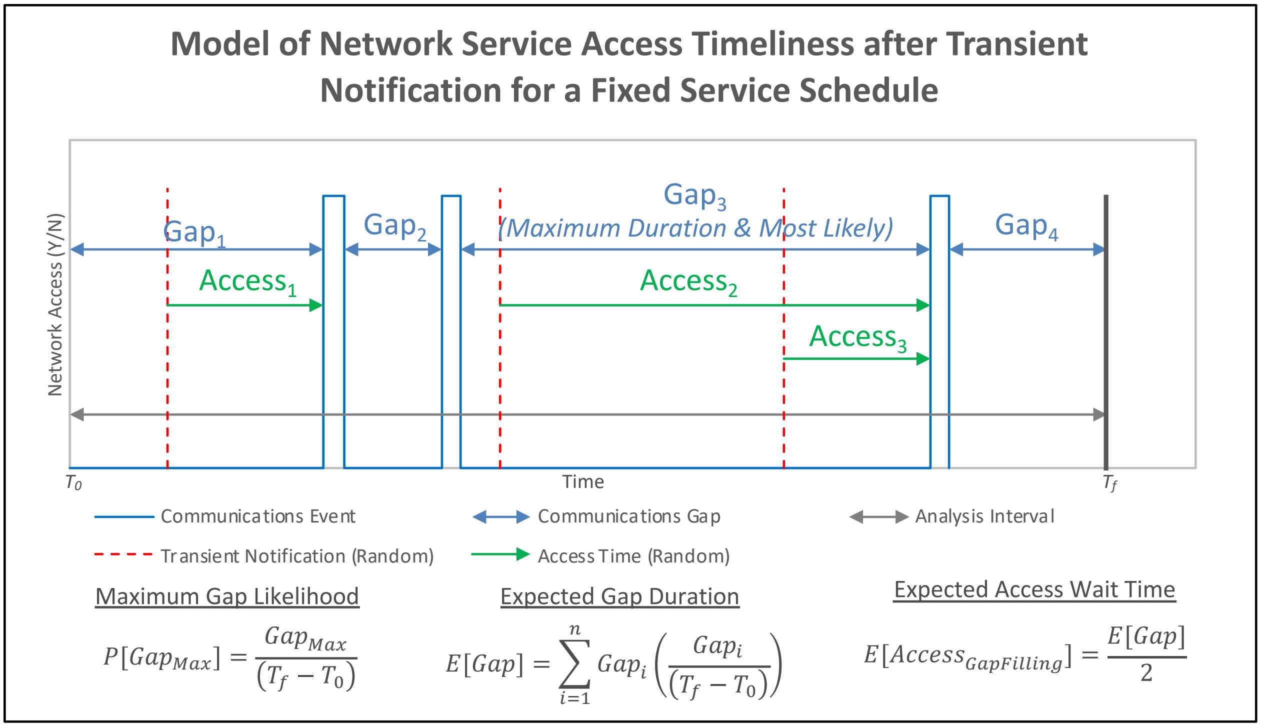

Fig. 4: Model of network service access timeliness for a fixed service schedule.

For missions that only have access to a single ground network service provider, the access timeliness measures of effectiveness are governed by the constraints imposed by coverage, orbital geometry and the network loading from other users. However, missions that have access to more than one network provider (including space relay networks or other ground networks with complimentary coverage) may influence the access timeliness measures of effectiveness for fixed schedules by requesting secondary network service periods to fill the largest and most probable primary network service gaps during the nominal schedule pre-planning phase. In this way, the gap-filling method relies on the frequency of fixed schedule service periods from all provider networks to achieve desired access timeliness outcomes. The gap-filling method is illustrated by the blue colored branch of the concept of operations defined previously in Fig. 3. In the case of Swift, the SN could serve as such a secondary network provider. Since the combined primary and secondary network schedules are pre-determined, the gap-filling method can be used to ensure access timeliness outcomes without the need for real-time manual intervention to access services. The disadvantages include the expenditure of planning resources to reserve secondary network service periods that may not be used (i.e., if a transient notification does not arrive) and potential opportunity costs of the reserved secondary network resources for other uses. Missions seeking to implement the gap-filling method should account for the transient notification arrival rate as well as the temporal decay rate of the scientific value associated with the transient observable in the time-sensitive operational scenario. These factors should be compared to the feasibly achievable access timeliness outcomes of a gap-filling method implementation, with a full accounting of costs and benefits among mission and network stakeholders. For example, although a hypothetical long-term gap-filling method implementation for a rarely occurring transient observable with fast-decaying scientific value may impose prohibitive stakeholder costs, perhaps stakeholders might agree to implement a short-term campaign in order to demonstrate or validate the potential value of a new multi-observatory workflow or to gather new observable signatures for development and training of future onboard algorithms. A notional representation of the gap-filling method concept of operations is provided in Fig. 5 below.

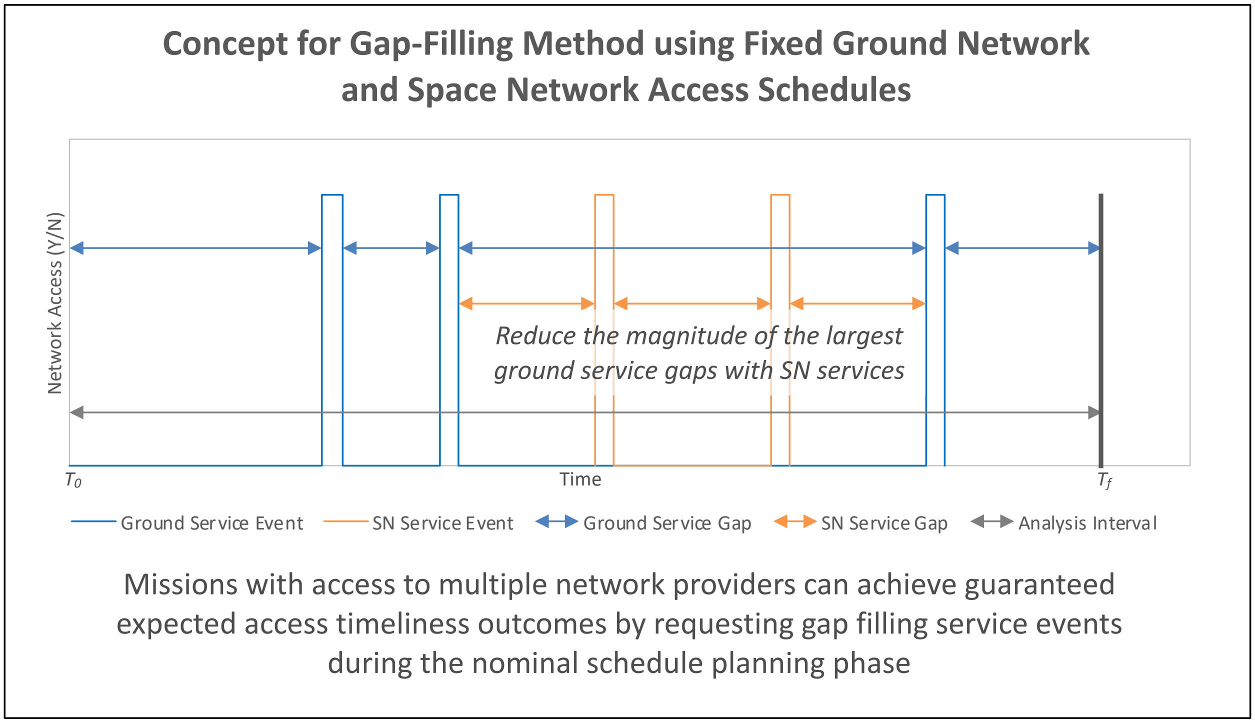

Fig. 5: Concept for achieving guaranteed expected access timeliness outcomes using SN as a secondary provider.

C. Event-Driven Network Access Method Definition and Development

The event-driven network access method involves the activities indicated by the red colored branch of the concept of operations defined previously in Fig. 3. There are several pre-conditions that must be satisfied in order to implement an event-driven service access method. First, it should be possible to close the free-space communications link for the greatest possible duration over the observatory's trajectory, as unavoidable service gaps occur when the link cannot be closed. This is influenced by observatory and network factors such as transmit power, receiver sensitivity, antenna gain patterns, error correction coding, visibility and separation distance, among others. Second, since the service instances are unplanned, the observatory must be in an "always listening" state to detect and acquire the initiation of services. To satisfy the first two preconditions, the observatory requires precise timing and navigational-state awareness, a pre-defined set of possible service access nodes for antenna pointing and tracking, and the ability to correct for trajectory induced doppler frequency effects. The Swift observatory satisfies these preconditions for SN services. Next, network systems must be able to accept and disposition service access requests during the active schedule execution period. Swift's most time-sensitive transient notifications require service access within a few minutes up to four hours. To meet these demands, network systems must also have the ability to execute service periods within minutes or hours following receipt of the access request. This requires sufficiently available resource capacity or advanced traffic management capabilities. Over the summer of 2019, the authors held a series of discussions with SN operators, conducted a thorough review of SN documentation and performed a preliminary analysis of a resource availability dataset for the TDRS multiple-access S-band services. Results from this work established that SN systems satisfy the preconditions for an event-driven service access method. Additionally, the authors identified latent but little known or used SN capabilities that allow users to incorporate flexibility in the specification of service requests, which can result in improved access wait times. The contributors to service access wait time outcomes for the SN event-driven method are identified and developed subsequently.

For nominal pre-planned operations, SN users build and submit batches of service access requests during the fixed schedule planning phase using the SN's service management interface to the MOC. This allows users to request and reserve future service periods using a standard set of messages and configuration parameters that are exchanged between the user MOC systems and SN systems. Once granted, SN service periods are guaranteed in the weekly fixed schedule, except in rare instances of unplanned outages or spacecraft emergencies.

The SN event-driven service access method occurs within the active period of fixed SN schedules and relies on the same service management interface used for fixed schedule service planning. Users may build and submit service access request messages during the active period provided they conform to a set of scheduling ground rules. One such rule specifies that the minimum lead time between receipt of a service access request message and the start of the service period shall be no less than 10 minutes for all SN service types. This lead time accounts for the request processing and SN system configuration setup time. The largest wait time contributor to the 10 minute service start lead time is the 6 minute worst-case inter-user pointing time for the TDRS mechanically steered antenna used for SN single-access services. However, the SN event-driven method uses multiple-access services, which rely on the TDRS electronically steered phased array resources. The inter-user setup time for multiple-access services is specified as 30 seconds. This suggests that the minimum service lead time may be significantly reduced if, in the future, the SN systems could filter requests for multiple-access services from requests for single-access services and apply differing processing constraints.

An important measure of effectiveness for time-sensitive operations is the minimum service access wait time, Access_{Min}. The minimum service access wait time is achievable when the requested SN resource is available, and depends on the wait time contributions of the service access request message build process (*RequestBuild*) and the specified minimum service start lead time (*MinimumLead*). The minimum service access wait time is given by Eq. (4) below.

$$Access_{Min} = RequestBuild + MinimumLead \tag{4}$$

Unlike the guaranteed access provided in fixed schedules, event-driven service access requests are fulfilled using SN's unreserved resource capacity on a first-come-first-served basis. Event-driven service access is blocked by previously reserved time periods for user services and SN maintenance and sustainment activities. As a result, it is important to characterize the durations of blocking periods, $Blocking_i$, for the event-driven method. SN publishes a registry of available resources during the active period, known as the TDRS Unused Time (TUT) registry. The TUT registry includes available and reserved time periods for each TDRS node and service type. The set of blocking periods is measured directly from the TUT registry as the reserved intervals. This allows calculation of the SN blocking likelihood, *P[Blocking]*, and the expected duration of blocking periods *E[Blocking]*.

The blocking probability is computed as the sum of blocking period durations divided by the fixed schedule analysis interval ($T_f - T_0$), described in Eq. (5) below[†††].

[†††] Note, the probability that a TDRS resource is available can be computed similarly, but because resources must either be reserved or available, the probability of resource availability is also equal to one minus the blocking probability.

$$P[Blocking] = \sum_{i=1}^{n} \left(\frac{Blocking_i}{(T_f - T_0)} \right) \tag{5}$$

The expected blocking duration, *E[Blocking]*, is the mathematical mean of the distribution of blocking durations present over the analysis interval. It measures the average duration of the blocking duration found if the blocking durations are sampled randomly, similar to the approach employed in Eq. (2). It is constructed as the sum of each blocking duration, $Blocking_i$, multiplied by its probability of occurrence, *P[Blocking]*, given by Eq. (6).

$$E[Blocking] = \sum_{i=1}^{n} Blocking_i \left(\frac{Blocking_i}{(T_f - T_0)} \right) \tag{6}$$

The magnitude of the expected blocking duration can be reduced by increasing the number of simultaneous multiple-access forward service instances available in an SN service region. This could be achieved by adding additional TDRS nodes in a region or by splitting the forward array on second and third generation TDRS nodes into two independent beams [14]. However, this would require modification to the as-built SN systems.

The expected service access wait time if an SN resource is blocked, $E[Access_{Blocking}]$, encompasses the two wait time contributors found in the minimum access wait time calculation ($Access_{Min}$, provided by Eq. (4)) as well as the added wait time contributed by the expected blocking duration. SN multiple-access resources must also be reconfigured between uses. As a result, a final wait time contributor, (*InterUserSetup*), occurs following an SN blocking period. The expected service access wait time, $E[Access_{Blocking}]$, if blocking occurs is provided in Eq. (7).

$$E[Access_{Blocking}] = Access_{Min} + \frac{E[Blocking]}{2} + InterUserSetup \tag{7}$$

Finally, the total expected service access wait time for the SN event driven method can be calculated as a probability weighted sum of the access wait time outcomes for when a resource is available ($Access_{Min}$) or blocked ($E[Access_{Blocking}]$), provided by Equations (4) and (7) respectively. The total expected service access wait time for the event-driven method, $E[Access_{EventDriven}]$, is given by Eq. (8) below.

$$E[Access_{EventDriven}] = P[Blocking] * E\left[Access_{Blocking}\right] + (1 - P[Blocking]) * Access_{Min} \quad (8)$$

The measures of effectiveness for the event-driven method can be used by mission and network planners to assess the feasibility and value of time-sensitive mission operations concepts. First, the minimum access wait time is useful as a screening mechanism to filter out time-sensitive concepts which require more timely service access than is achievable with SN systems or to identify the degree to which SN wait time contributors must be improved to make a mission concept viable. The probability of blocking provides users with information about how frequently the minimum and blocking access wait time outcomes will occur. The expected duration of blocking periods is useful to users for the specification of flexible service start times. As part of the Schedule Add Request message, SN allows users to indicate service start time flexibility as a plus or minus time tolerance. Service start time flexibility reduces the likelihood that a requested service instance will be blocked. The SN scheduling system will shift the requested service start time according to the specified start time tolerances, ensuring users achieve the minimum wait time by allocating a service instance immediately preceding or following a blocking period. The expected duration of blocking period is also a useful metric for network managers since its magnitude can be reduced by increasing the capacity of supportable service instances within a given service region. The expected access wait time when blocking occurs provides the average wait time outcome when resources are not available. This metric can be used by mission planners to judge the expected value of a time-sensitive operations concept when resources are not available. Finally, the total expected service access wait time for the SN event-driven method provides a weighted average metric for the event-driven method. Users conducting time-sensitive operations are likely to have non-linear timeliness preferences, with their value of an outcome decaying as a function of time. As a result, users may more clearly judge the value of service access timeliness based on the component outcomes and probabilities (i.e., wait times experienced if SN resources are available or blocked) rather than the more abstract probability weighted average, which does not represent a realized operational outcome.

Fig. 6 provides a model of the SN event-driven method and a summary of the measures of effectiveness that are most salient for user access wait time outcomes with the event-driven method. It is comprised of a notional set of blocking periods and two event-driven service instances illustrating access wait times when resources are available and when blocked. Equations for the highlighted measures of effectiveness are also represented.

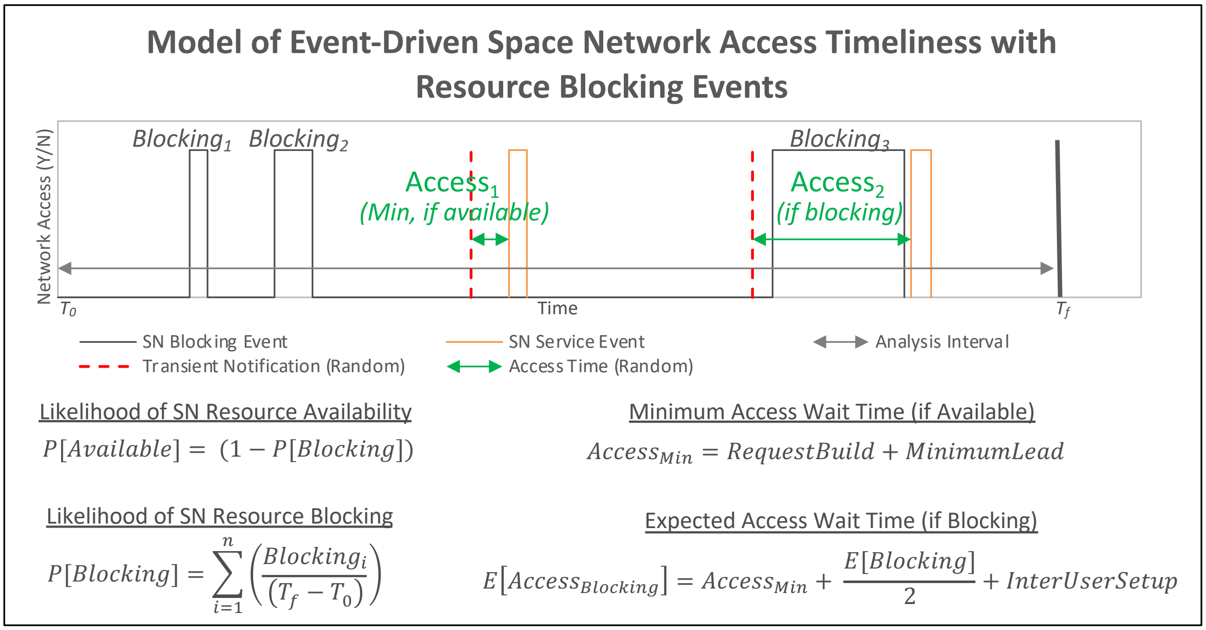

Fig. 6: Model of network service access timeliness for an SN event-driven service access method.

The event-driven access method allows users to request service access as needed, reducing the operational planning and network utilization costs imposed by the gap-filling method. However, service access is not guaranteed due to resource blocking by previously reserved events. Missions seeking to implement the event-driven method should account for the transient notification arrival rate as well as the temporal decay rate of the scientific value associated with the transient observable in the time-sensitive operational scenario. These factors should be compared to the achievable access wait time outcomes provided by the SN event-driven method, with a full accounting of costs and benefits among mission and network stakeholders. Since the event-driven method involves claiming small windows of available resource time for near-term use, it is suitable for long-term transient observation campaigns or campaigns with rarely occurring transient observables. Such campaigns would likely impose prohibitive network utilization costs if implemented using the gap-filling method. Applications for the event-driven method may include demonstration or validation of a new multi-observatory operations workflow or gathering new observable signatures for development and training of future onboard observatory algorithms.

III. Experimental Design & Results

This section develops the service access method pathfinder experiments. It provides details for a specific time-sensitive mission operational scenario, discusses the experimental setup and application of the two service access methods in the context of this scenario, and presents the experimental results.

A. Swift Operational Scenario Definition

A Swift follow-up observation operational scenario was chosen to demonstrate and investigate the suitability of the two service access methods. This operational scenario is consistent with and traceable to the abstract operations concept presented in Fig. 3 and provides the additional details necessary to assess the effectiveness and efficiency of the methods. Detecting the electromagnetic counterparts associated with gravitational-waves is a major new scientific objective in astrophysics. Detectable gravitational-waves are observed with ground-based observatories with an expected arrival rate of one per week [21]. Swift is capable of observing the gamma-ray, X-ray and ultra-violet optical electromagnetic counterparts to gravitational-waves. However, the Swift observatory cannot itself detect gravitational-waves or identify which electromagnetic transient events are associated with them. The Swift observatory continuously feeds instrument data into a working buffer where the data is processed to identify and classify observed transient events. Electromagnetic events which satisfy an observable threshold result in the creation of a transient notification, which is disseminated to the ground through the SN DAS. In addition, the high-fidelity raw data associated with the observation is transferred from the working buffer into persistent storage for downlink to the ground network at the next pre-scheduled access time. Swift's working data buffer is overwritten every 30 minutes. When a ground-based observatory detects a gravitational-wave, a transient notification is created and sent to the Swift MOC via the GCN terrestrial network. If any electromagnetic counterparts were coincidentally observed by the Swift observatory, but do not satisfy the onboard observable threshold, this data is at risk of being overwritten in the working buffer and lost. Therefore, whenever the Swift MOC receives a transient notification from a gravitational-wave observatory on the GCN indicating a gravitational-wave detection event, a follow-up command to transfer data from the observatory's working buffer to its persistent storage must be executed by the observatory within 30 minutes of the gravitational-wave detection event.

B. Gap-Filling Network Access Method Experimental Design and Results

In August 2018, Swift and SN operators held a teleconference to plan a gap-filling method pathfinder experiment. The primary objective of the pathfinder was to measure and assess the benefits and costs to Swift and SN stakeholders to determine if the gap-filling method was truly implementable in an operational environment. As a preliminary strategy, meeting participants agreed that an SN service period would be requested approximately every 60 minutes during the largest ground network coverage gaps, targeting an expected access wait time of 30 minutes. The Swift operations team agreed to provide forecasted view periods between the Swift observatory and TDRS nodes to the SN scheduling office no later than 12 days before the start of the active period week. Swift operators requested a minimum service period duration of 10 minutes to ensure adequate time for signal acquisition and for the Swift flight and ground systems to connect and synchronize. Swift accepted a "low" SN priority designation for the adjudication of gap-filling service periods.

On 2018 Day-of-Year (DOY) 304 Swift operators submitted a batch of nine SN service access requests during the largest anticipated ground network coverage gap for DOY 316. Swift operators received confirmation of both ground network and SN fixed schedules by DOY 310. Six SN service access requests were granted, resulting in an access request success rate of 66.7%. The granted ground network schedule had a maximum gap duration of 4:03:34 (H:MM:SS), beginning at 6:04:46 UTC and ending at 10:08:20 UTC. The next largest gap of 2:56:25 (H:MM:SS) began at 10:21:08 UTC and lasted until 13:17:33 UTC. No attempt was made to reduce the third largest gap of 2:42:58 (H:MM:SS), from 13:26:48 UTC to 16:09:46 UTC. No data were provided for ground network contacts before or after DOY 316. As a result, analysis interval for the experiment is defined from the first and last known ground service periods, from 3:12:29 UTC to 19:32:48 UTC. With a gravitational-wave arrival rate of one per week, Swift's probability of needing to conduct a gravitational-wave follow-up operation within the experimental period was 9.6%.

Notably, Swift operators made duplicative requests for service periods beginning at approximately 6:00:00 UTC and 10:30:00 UTC. This was done because of the uncertainty that requested service periods would be granted. Swift's true need was to have either a ground network or SN service period to avoid a potential gap greater than eight hours beginning at 4:53:57 UTC to 13:17:33 UTC. The duplicative 6:00:00 service periods were both granted, yet only the ground network service period was granted at approximately 10:30:00 UTC. A summary of Swift's requested and granted communications service periods for DOY 316 is provided in Fig. 7 below.

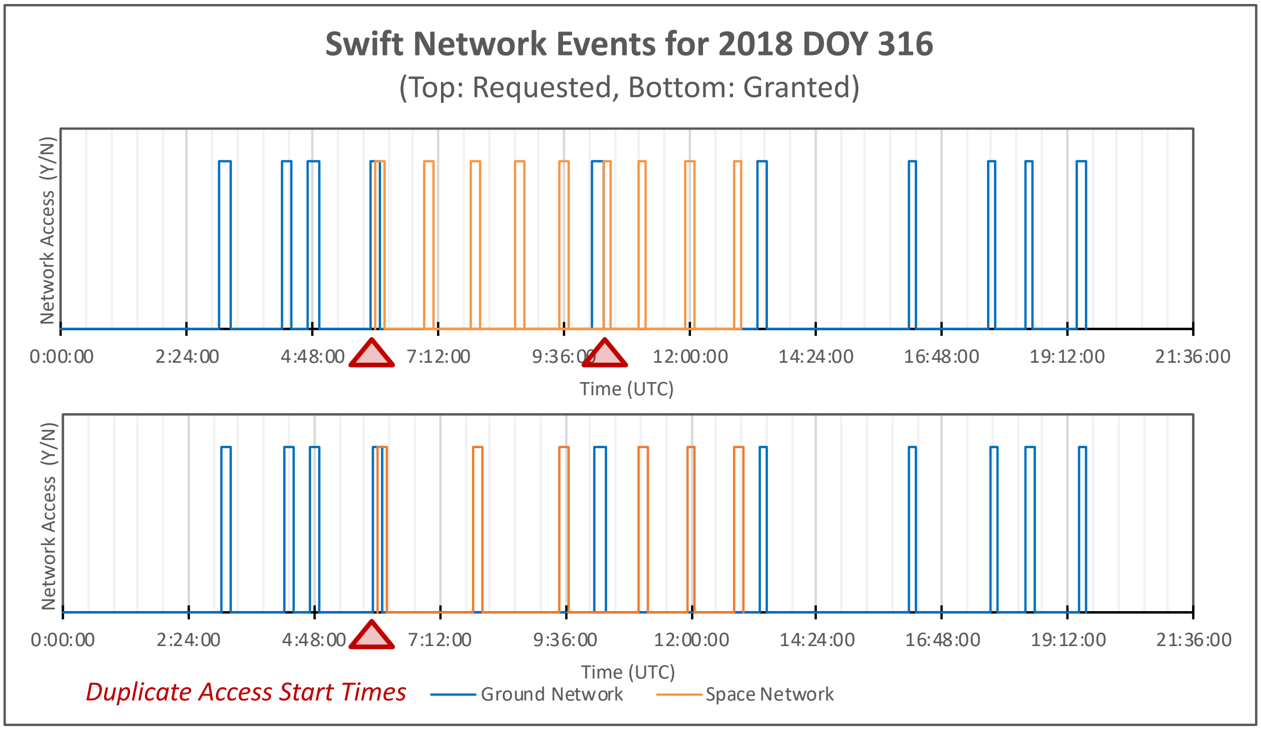

Fig. 7: Summary of requested and granted gap-filling service periods for 2018 DOY 316.

Table 2 provides a summary of the measures of effectiveness for the pathfinder experiment considering three fixed schedule cases: ground network only, ground network and the requested SN service periods, and ground network and the granted (actual) SN service periods.

Table 2: Summary of Swift's access timeliness outcomes from the gap-filling experimental pathfinder.

Fixed Schedule Cases	**Maximum Gap Duration, Gap_{Max}, & Likelihood, $P[Gap_{Max}]$ (H:MM:SS, %)**	**Expected Gap Duration, $E[Gap]$ (H:MM:SS)**	**Expected Service Access Wait Time, $E[Access_{GapFilling}]$ (H:MM:SS)**
Ground Network Only	4:03:34, 25%	2:19:19	1:09:39
Ground + Space Network (Requested)	2:42:58, 17%	0:59:56	0:29:58
Ground + Space Network (Granted)	2:42:58, 17%	1:11:44	0:35:52

Although no gravitational-wave notifications arrived during the experimental period, augmenting the ground network schedule with pre-planned SN service periods resulted in a 49% reduction in expected service access wait time as compared to the ground network only case. The expected access wait time for the granted service periods exceeded the 30 minute threshold for Swift's gravitational-wave follow-up operational scenario. However, the timeliness threshold would have been met if the SN had adequate capacity to grant all of the requested service periods.

In addition, the experimental results compare favorably to the minimum 20-minute access wait time achievable with the state-of-the-practice manual intervention method.

The Swift operations team reported 1.0 additional hour of effort for the planning of the nine SN service access requests. The achieved reduction in access time satisfies many of Swift's other time-sensitive operational scenarios which require responses in less than four hours. Importantly, the timeliness improvements were achieved without the need for real-time operator intervention.

C. Event-Driven Network Access Method Experimental Design and Results

The authors installed an instance of the Space Network's service management element, known as the Space Network Access System (SNAS), at the Goddard Space Flight Center's Communications Standards and Technology Laboratory (CSTL) in October 2019. The CSTL SNAS software client was configured to replicate the Swift MOC SNAS instance, and connected via terrestrial mission network to the SN's Alternate Network Control Center (ANCC) in White Sands, New Mexico. The ANCC is the high-fidelity engineering test instance of the SN's network control element. Together these systems comprise the experimental setup for the event-driven service access method.

The first step for users of the event-driven method to access SN services is to build an SN service access request (*RequestBuild*). The specific message type for SN users to request service access is known as a Schedule Add Request (SAR). Users have three options, with varying degrees of autonomy, for building and submitting SAR messages. The most basic option to create a SAR involves parameter specification via text fields and pull-down menus through the SNAS graphical interface. According to SN scheduling ground rules, the specified service period start time parameter must be no sooner than 10 minutes following receipt of the SAR by the SN network control element. To build a request resulting in the minimum achievable service access wait time, users must compute a time offset following receipt of the transient notification that includes the request build time and the minimum lead time to service period start.

An experimental service access request build procedure which results in a SAR message specifying the minimum allowable wait time ($Access_{Min}$) was documented for the SNAS graphical interface. The authors executed the procedure several times to benchmark SAR build times. Valid and fully specified SAR messages were consistently built in the SNAS user interface within 40 seconds without haste. The procedure was provided to Swift mission operators in December 2019. SNAS also allows users to simplify scheduling of repeated service instances that have the same structure by defining "prototype" SAR messages. Prototype SAR messages reduce the build time and potential for user input error by allowing users to save the configuration of parameters that do not change. All parameters specifying a service instance with the minimum service access wait time, except for the service start time offset, can be saved as a prototype SAR message. As a result, use of the prototype SAR message can reduce SAR build times to approximately 15 seconds. Finally, SN users may implement an External Processing System to extend and automate the service management capabilities of SNAS. Accordingly, computation of the minimum service start time offset and complete specification of an event-driven SAR message can be fully automated. A summary of the SAR build times (*RequestBuild*) for each build option is presented in Table 3 below.

Table 3: Summary of SN service access request build options and associated build times.

Schedule Add Request (SAR) Message Build Options	Build Time, *RequestBuild* (H:MM:SS)	Basis
SNAS Graphical User Interface	0:00:40	Demonstration
Prototype Schedule Add Request	0:00:15	Demonstration
External Processing System (Fully Automated)	0:00:05	Estimate

The authors conducted validation testing of the documented scheduling ground rules that contribute to access wait time using the CSTL SNAS instance and the ANCC. Limited test results indicated that the documented 10-minute minimum lead time (*MinimumLead*) can be reduced to six minutes plus a variable SAR processing delay ranging from 2 to 23 seconds. However, this reduced minimum lead time has not yet been validated on the operational SN network control element. Accordingly, the baseline scheduling ground rule of a 10-minute minimum lead time is presented for the results in this paper. The documented multiple-access service scheduling ground rule for inter-user setup time (*InterUserSetup*) of 30 seconds was experimentally verified.

The authors performed an analysis of over 60 days of operational TDRS Unused Time reports for three TDRS nodes, comprising more than 3,700 blocking periods, to estimate the probabilistic factors that influence access wait time for the event-driven method[‡‡‡]. Each TDRS node selected for this analysis is stationed in a unique service region to ensure global coverage. These nodes constitute the most suitable subset of the larger TDRS constellation for

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[‡‡‡] An analysis of the available period distribution was also performed to ensure that when a resource is (or becomes) available, it is available for the required duration of the requested service period. The minimum operationally validated time to send and verify receipt of a command for Swift is 4 minutes. The probability of an available period being equal to or greater than 4 minutes was found to be 98.7%. The results reported in this paper ignore the small effects of the percentage of available periods that are not long enough to satisfy the minimum user service period duration. Note, because the service period duration is a user-specified parameter in the SAR, SN systems will never allocate available periods that are too small to complete the user's operation. As a result, available but unusable periods manifest as slightly longer (i.e., by the duration of the available but unusable period) blocking periods than would be manifest in the TDRS Unused Time dataset. Improving user flight and ground software synchronization times and user radio signal acquisition performance would minimize the likelihood and impact of this occurrence.

transient science applications, and are currently used by Swift. Each TDRS node has the capacity to support several simultaneous service instances for multiple-access return services. In the dataset analyzed, the TDRS nodes always had unscheduled capacity for least one multiple-access return service instance. Blocking occurred for multiple-access forward services only, as each TDRS node can presently support a single service instance of this type at a time. As a result, blind commanding or using the continuously available DAS for verification that the sent command was received does not provide any improvement in service access wait time. The probabilistic factors associated with SN blocking periods were derived from the TDRS Unused Time dataset, and are as follows: the mean constellation probability of blocking (*P[Blocking]*), the expected duration of a blocking period (*E[Blocking]*), and the expected wait time contribution due to blocking periods (*E[Blocking]/2*).

The analysis of TDRS blocking periods revealed the presence of a number of long duration blocking periods greater than 100 minutes. These long duration blocking periods are associated with SN operational scenarios that do not involve LEO user services, such as SN maintenance and sustainment, pre-launch user compatibility testing and high-altitude balloon campaigns. TDRS nodes have substantial coverage overlap allowing SN planners to minimize the impact of long duration blocking periods on the overall SN service availability. Additionally, LEO missions such as Swift will transit the coverage area of all TDRS nodes in the constellation over the course of each orbit, providing at least three opportunities to obtain service access approximately every 90 minutes. As a result of these factors, the long duration blocking periods increase the expected (mean) access wait time contribution due to blocking periods beyond what is likely to be experienced by LEO users. The median blocking period and associated access wait time contributions were calculated to quantify the degree to which the mean access timeliness metrics are impacted by the long duration blocking periods. The median wait time due to blocking was found to be 28 seconds less than the mean wait time. A summary of the probabilistic factors associated with SN blocking periods, including factors calculated with the median blocking duration, are provided in Table 4 below.

Table 4: Summary of probabilistic factors associated with SN blocking periods.

Expected Duration of Blocking *E[Blocking]* (H:MM:SS)	**Expected Wait Time Added Due to Blocking *E[Blocking]/2* (H:MM:SS)**	**Median Duration of Blocking (H:MM:SS)**	**Median Wait Time Added Due to Blocking (H:MM:SS)**	**Probability of SN Resource Blocking *P[Blocking]* (Mean, 3-node Constellation)**	**Probability of SN Resource Availability *P[Available]* (Mean, 3-node Constellation)**
0:05:55	0:02:58	0:05:00	0:02:30	16%	84%

If the SN resource is blocked, the wait time due to blocking is added to the additional wait time contributors identified in Eq. (7). If the requested SN resource is available, the minimum service access wait time is achievable, and comprised of the factors identified in Eq. (4). A summary of the access wait time outcomes for the three SAR build options are provided in Table 5 below.

Table 5: Summary of SN event-driven method service access wait time outcomes for three SAR build options.

Schedule Add Request Build Option	**Minimum Access Wait Time, $Access_{Min}$ (H:MM:SS)**	**Expected Access Wait Time If Blocking Occurs, $E[Access_{Blocking}]$ (H:MM:SS)**	**Median Access Wait Time If Blocking Occurs (H:MM:SS)**
SNAS Graphical User Interface	0:10:40	0:14:08	0:13:40
Prototype Schedule Add Request	0:10:15	0:13:43	0:13:15
External Processing System (Fully Automated)	0:10:05	0:13:33	0:13:05

Finally, the total expected access wait time for the event-driven method is calculated as a weighted average sum of the access wait time outcomes, accounting for the probability that SN resources are either available or blocked when service access is requested, as described in Eq. (8). The total expected access wait time results for the event-driven method are summarized in Table 6 below.

Table 6: Total expected access wait time for mean and median blocking contributions and each SAR build option.

Schedule Add Request Build Option	**Total Access Wait Time for the Event-Driven Method – Using Expected Blocking Wait Time, $E[Access_{EventDriven}]$ (H:MM:SS)**	**Total Access Wait Time for the Event Driven Method – Using Median Blocking Wait Time (H:MM:SS)**
SNAS Graphical User Interface	0:11:13	0:11:09
Prototype Schedule Add Request	0:10:48	0:10:44
External Processing System (Fully Automated)	0:10:38	0:10:34

IV. Discussion of Results

The SN provides global communications coverage for LEO users, in contrast to the intermittent coverage provided by direct-to-earth ground networks. Transient science missions have relied on manual intervention by SN operators to obtain more timely service access than is possible from fixed ground network service periods. The results of this research provide an evaluation of two complimentary methods for improving service access timeliness outcomes using SN. Table 7 summarizes and compares the state-of-the-practice, gap-filling and event-driven service access methods.

Table 7: Summary of SN timely service access methods.

	State-of-the-Practice	Gap-filling Method	Event-driven Method
Method Implementation	Relies on manual intervention by user and network operators	Relies on the frequency of pre-determined service periods from ground and SN provider networks	Relies on novel SN procedures to quickly access available services
Implementation Timeframe	During real-time operations	During the nominal schedule pre-planning phase	During real-time operations
Degree of Automation	Manual-only	Partial or full automation	Partial or full automation
Dependability	Best-effort due to blocking, staffing and other constraints	Guaranteed based on mission priority	Best-effort due to blocking and first-come-first-served scheduling policy
Timeliness Outcomes	At least 20 min. following service access request	Depends on probability distribution of fixed schedule service gaps	~10 min. wait time achievable 84% of the time; expected wait time < 14 min. if blocking occurs
Application Suitability	Spacecraft emergencies; not suitable for nominal transient science operations	Suitable for short-term use to validate new observation workflows or measurements; suitable for long-term use to mitigate timeliness impacts of the longest ground gaps	Suitable for long-term transient observation campaigns or for rarely occurring transient observables

Traditional space communications service planning and operations processes introduce systemic inefficiencies when users have emergent time-sensitive operational needs. These inefficiencies are amplified in transient science applications, where multiple users must interact and collaborate in dynamic workflows. The systemic inefficiencies can be attributed to the inability of current processes to adequately accommodate random user traffic needs, the inability of users to specify goal-oriented service access parameters to achieve desired outcomes and the lack of shared or coordinated service planning and information among provider networks.

The gap-filling method pathfinder experiment illustrates many of these inefficiencies. Swift operators were required to plan and submit two separate batches of service access requests to the ground network and SN for operations occurring 12 to 19 days in the future. While Swift required the ground network service instances to perform nominal Swift operations, the gap-filling SN service instances were scheduled to reduce the expected service access wait time just in case an unplanned follow-up operation was needed. Each SN service access request included parameters specifying a specific TDRS node at a specific time, setting up a binary resource allocation choice for SN schedulers: either a higher-priority user requested the same resource at the same time or it is available. User adoption of goal-oriented service access requests incorporating flexibility in the specific service delivery node, service start time, or service duration would reduce the impact of SN resource blocking and improve the expected wait time for service access. The SN offers basic flexible scheduling capabilities but these features are not widely known or used at the present time. Widespread adoption of goal-oriented service access requests would allow network service providers more discretion to efficiently allocate service delivery tasks to network resources across partnered commercial or other federated service providers. Future research is planned to understand the lack of user adoption of SN flexible scheduling features, which may reveal a presently unknown barrier to the emergence of a robust network provider ecosystem for LEO users. Finally, the two duplicative service access requests submitted by Swift operators for overlapping ground and SN service periods illustrates user and network planning burden and resource allocation inefficiencies that could be addressed by improved coordination of service planning information among provider networks.

Results from the event-driven pathfinder experiment demonstrate that the 10-minute SN minimum lead time to service period start, as specified in SN documentation, dominates the expected service access wait time contributions from all other sources. Testing performed on the ANCC revealed that the minimum lead time factor is comprised of a fixed 6-minute component and a variable but small delay associated with SAR processing. As a result, it may be possible to reduce the minimum lead time by up to 40% without modification to current SN systems. Future work to operationally characterize the variable processing delay and to validate the fixed component of the SN minimum lead time could result in improved access timeliness beyond the results reported in this paper. Furthermore, the fixed 6-minute component of the minimum lead time appears to be set by the worst-case inter-user pointing time for the TDRS mechanically steered antenna used for single-access services. The event-driven method relies on the electronically steered multiple-access TDRS phased array resources, which have a specified and experimentally verified inter-user setup time of 30 seconds. This suggests that the minimum service lead time may be reduced by up to 95% if the SN systems could filter time-sensitive event-driven multiple-access service requests from requests for the single-access services.

The access wait time outcomes of the event-driven method provide substantial improvements in effectiveness and efficiency when compared to the reported 20-minute minimum service access wait time achievable with the current manual intervention method. The minimum event-driven access wait time outcome is a 47-50% improvement to the manual intervention method depending on the SAR build option selected by the user. The largest expected service access wait time outcome of a little over 14 minutes, which occurs if blocking is present and SARs are built using the graphical interface, is also an improvement over the manual intervention method. Both event-driven method timeliness outcomes satisfy Swift's gravitational-wave follow-up scenario threshold of 30 minutes. Additionally, the event-driven method reduces or eliminates real-time operator burden, depending on the user selected SAR build option. However, an increase in the number of transient science observatories conducting simultaneous follow-up operations will increase the probability of resource blocking, leading to longer user access wait time outcomes. Future work is needed to explore the relationship between the traffic demands of larger-scale multi-observatory transient science workflow concepts and SN service delivery capacity. A summary of the SN access wait time contributors identified by this research and a roadmap for possible improvements is provided in Fig. 8.

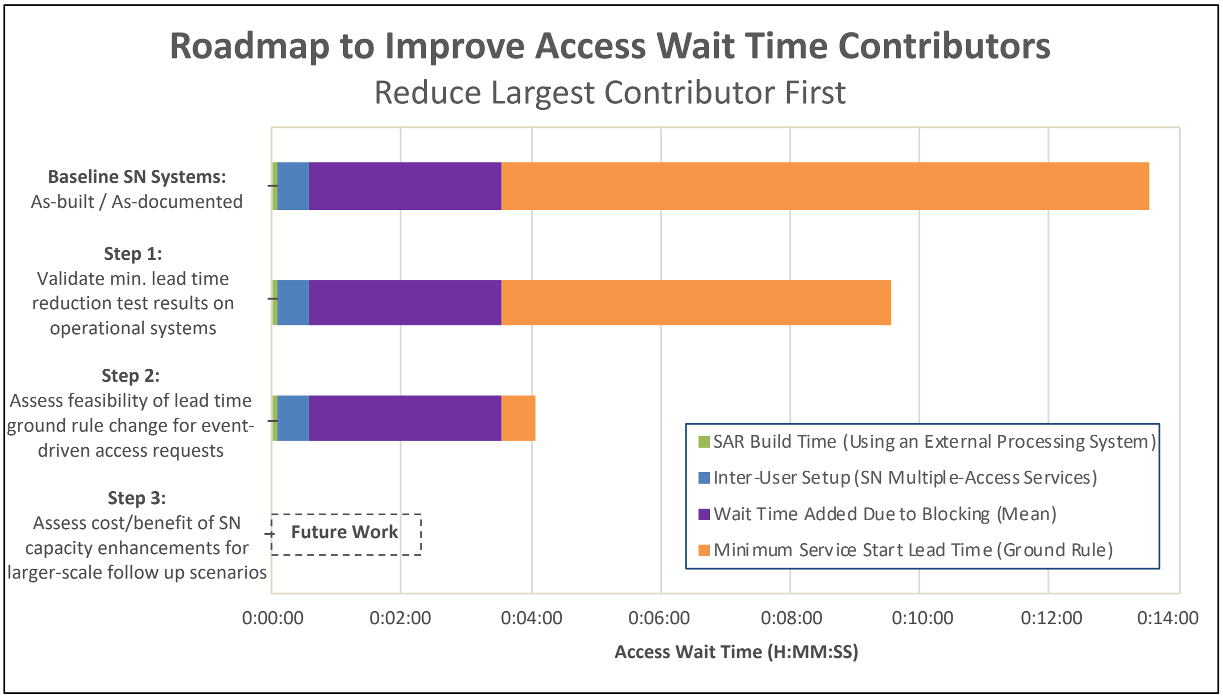

Fig. 8: Roadmap to improve SN access wait time contributors for the event-driven method.

V. Conclusion

The two service access methods developed by this research can be used in complimentary ways to mitigate the systemic inefficiencies of traditional service planning processes for time-sensitive mission operations. Transient science missions can apply the results from this research to automate the analysis of weekly ground network service gaps and identify the number and timing of SN gap-filling service periods that would achieve the desired average service access wait time. Then, the gap-filling batch of SN service access requests could automatically be built and submitted using an External Processing System. This process results in a guaranteed expected service access wait time outcome, which must be balanced with the additional loading imposed on SN resources through negotiations among mission and network stakeholders. For operational scenarios where the gap-filling method is infeasible, the event-driven method can be invoked during the active period to provide users with best-effort access to services using the available (unreserved) SN capacity. Test results indicate that the baseline SN systems can provide event-driven service access in as little as six minutes, with the possibility of reducing access wait times to under one minute if modifications to the processing priority of SN multiple-access service access requests are made.

In summary, the results from this research indicate that the as-built SN systems have adequate capabilities and capacity to support infusion of the gap-filling and event-driven methods to current and future users with time-sensitive mission operational needs. These methods are consistent with and traceable to NASA's overarching network and mission architecture. Process and technical options to substantially improve user service access timeliness outcomes beyond the results reported in this paper were identified. Future work is planned to better understand the impact to access timeliness outcomes caused by the dynamic traffic loading associated with multiple interacting space-based observatories. In addition, future opportunities to conduct pathfinder experiments incorporating commercial service providers are envisioned to meet the increasing need for network services enabling distributed time-sensitive space mission operations.

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