Distributed Spacecraft Crosslink Study

Part 2

Distributed Spacecraft Crosslink Communications System Requirements Report

DRAFT

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Authorization

Distributed Spacecraft Crosslink Communications System
Requirements Report

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1.1 Purpose & Background

1.1.1 Background

Emerging spacecraft systems plan to deploy multiple satellites in various "distributed" configurations ranging from close proximity formation flying to widely separated constellations in both near-earth orbit and in deep space. Distributed spacecraft configurations provide advantages for science exploration and operations since many activities useful for missions may be better served by distributing them between spacecraft. For example, many scientific observations can be enhanced through spatially separated platforms, such as for deep space interferometry.

Operating multiple distributed spacecraft as a mission requires coordination that may be best provided through inter-satellite communications. The choice of frequency and lower layer protocols (physical and data link layers) for this link involves the mission operations and requirements, hardware availability, and regulatory considerations. The link may be in the radio frequency range or could involve infrared or optical communications.

Unlike existing "bent-pipe" relay networks supporting space missions, no standard or widely-used method exists for crosslink communications. Consequently, to support these future missions, the characteristics necessary for inter-satellite communications need to be examined, including frequency band, protocol, and technology considerations.

This report is one part of a three part study reviewing Distributed Spacecraft System (DSS) requirements for crosslinks and identifying recommendations concerning spectrum, standards, and technology. The three parts of the study are:

1. **Spectrum Requirements and Allocation Survey**: required spectrum, frequency band choices, and upgrades (if necessary)
2. **Requirements**: identifies requirements and examines existing protocols and standards
3. **Technology Roadmap**: the technology necessary to provide inter-satellite communications capability based on high-level requirements

1.1.2 Purpose & Scope

The objective of this document is to provide a preliminary overview of Crosslink Communications System (CCS) operations, capabilities, functions that lead to a set of prototype requirements based on a survey of planned Distributed Spacecraft Missions (DSM) targeted over the period from 2001 to 2020. Section 1 provides background information, the purpose and scope of the document, a summary of findings, and recommendations. Section 2 provides a general overview of the Distributed Spacecraft Mission types, architectures, and general crosslink features. Section 3 contains the results of the crosslink communications system prototype requirement derivation process. The crosslink communications system is defined in this document to be limited to those functions that establish and maintain a reliable communications connection between two spacecraft. The derived prototype requirements take into to account the diverse nature of the missions and attempt to address the common crosslink capabilities that need to be performed by all of the missions. Additional constraints such as the interoperability of crosslinks between missions within the larger context of spacecraft-to-spacecraft networking are also included in forming the capabilities that underlie these requirements. A top-down perspective of distributed spacecraft crosslink communications is taken to identify the functions, information flows, operations scenarios, and the resultant prototype requirements that stem from this preliminary analysis. The prototype requirements can be viewed as belonging to the generic crosslink communications system that represents the needs of a cross-section of the distributed spacecraft missions encountered in the survey.

Once a set of functional and performance requirements exist, it is natural to compare them to existing communications standards to determine their adequacy as means of expediting the implementation of the requirements in hardware and software. To this end, existing standards for wireless, network, and spacecraft communications are examined in Section 4 of this document within the context of crosslink communications system functionality. The potential availability of Commercial Off the Shelf (COTS) products make the prospects of applicable standards an attractive alternative to developing new crosslink communications system standards for hardware and software.

1.2 Findings

The distributed spacecraft missions already in the early planning stages have diverse architectures and operational needs that make their crosslink communications requirements differ from mission to mission. However, there is a subset of requirements associated with the establishing, maintaining, and terminating crosslink communications that are basic to all of the mission communication operations. In addition to these considerations, there are networking constraints on individual crosslinks that add basic requirements. First, there are the varied networking aspects of inter-spacecraft communications within a distributed spacecraft mission. Second, there is the possibility of inter-mission crosslink communications operations associated with the Sensor Web concept of future inter-spacecraft communications. Both of these networking capabilities impose additional requirements on distributed spacecraft crosslink communications systems. While networking requirements within a single mission can be unique, the crosslink interoperability principle behind the Sensor Web assumes that some, if not all, aspects of communications signal waveform and network protocols be standardized for crosslink communications systems.

Variations in crosslink communications system requirements from mission to mission can be related to the architectural complexity of the mission. For example, the complexity of crosslink operations will be minimal for small, simple topologies with spacecraft that maintain relatively fixed spatial relationships between the mission members. For most of these "rigid" distributions, fixed antenna beam patterns will suffice to maintain crosslink connections and multiple access schemes will manage the shared resources. In most instances, the networking requirements in small distributions will not require complicated datagram routing between spacecraft. Direct spacecraft-to-spacecraft exchanges will be managed via the mission's multiple access technique. Fully autonomous crosslink communications operations will not be taxed with overly demanding on-board processing requirements.

The complexities of large distributions with a large inter-spacecraft separations and a large number of possible crosslink combinations requires a significantly more demanding approach to mission communications operations. Highly flexible spatial architectures such as those imposed on distributed spacecraft by the effects of large gravitational gradients (e.g., distributed spacecraft systems in the vicinity of planetary bodies) may require constant reassessments of the changing architecture on the part of fully autonomous crosslink communications systems in order to track the changing relative spacecraft locations within the group for antenna beam forming purposes. In addition to relying on continuous high gain antenna control operations, dynamic crosslink datagram routing operations within the distribution may become an important means of communications over long distances as well as in situations where potential crosslinks within the varying architecture are intersected by a planetary body. Under these conditions, datagrams can be relayed through various spacecraft within the distribution via multiple crosslinks hops in order to achieve the desired end-to-end communications objectives that cannot be realized by direct, line-of-sight crosslink communications. Fully autonomous crosslink operations under these conditions, require the integrated knowledge of the changing crosslink geometries and the best crosslink paths to take at any instant to route datagrams through the changing topology. These distributed spacecraft missions will be taxed with relatively demanding on-board processing requirements in order to implement fully autonomous crosslink communications operations under these conditions.

Finally, all of these considerations leads to a set of functions and associated high-level requirements for inter-satellite communications. Using mission operations concepts and a functional analysis approach, this report identifies the needed capabilities and the context (see Figure 1-1) and functional decomposition of inter-satellite communication systems. These lead to a set of high-level crosslink communication system prototype requirements.

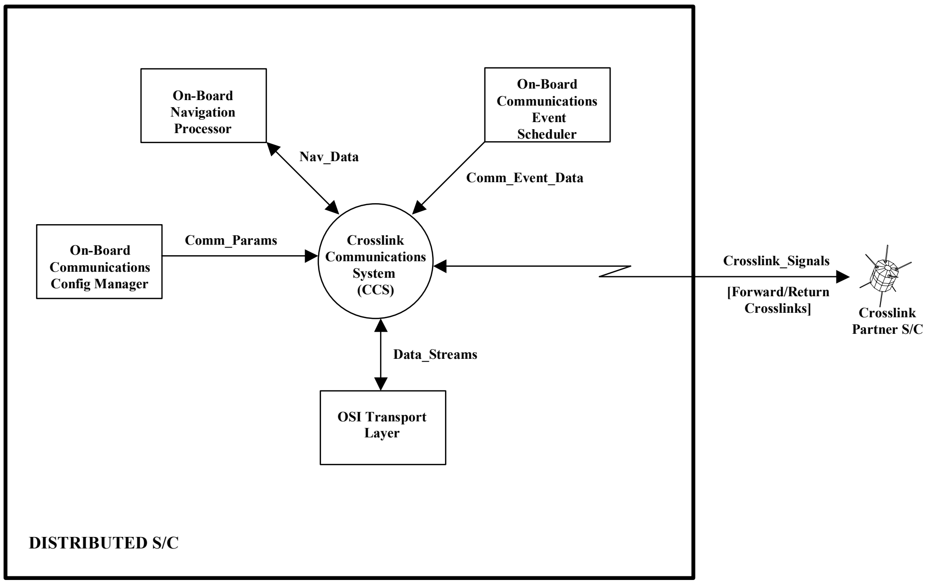

Figure 1-1: Crosslink Communication System Context Diagram

1.3 Recommendations

The high-level requirements derivation process undertaken in Section 3 of this document provides a framework of functional areas for crosslink communications system requirements that includes the control of the RF connection between spacecraft and those aspects of networked communications that are related directly to the control of exchange of information over distributed spacecraft mission crosslinks. Many current activities associated with crosslink communications system development are bottoms-up endeavors that are directed at the immediate requirements of a specific mission. The system-level prototype requirements presented in this document represent a starting point for developing a top-down perspective of crosslink communications systems for the range of distributed spacecraft missions presented in the Spectrum Requirements and Allocation Survey and Recommendation document.

Specifically, the high-level requirements for inter-satellite communications for distributed spacecraft presented in Section 3 can be used by two communities:

1. **Technology Sponsors and Developers**. The requirements can guide the activities of technology sponsors and developers by establishing needs based on a mission system-level perspective. The high-level requirements can be used to identify those technology areas that not only support the development of inter-satellite communications but also meet the performance required.
2. **Mission Planners & Designers**. Mission planners and designers can use the requirements and associated information to characterize their missions' crosslink communications requirements within the context of the broad-based prototype requirements presented here. The high-level requirements can provide a template for developing the specific requirements for the mission communications sub-system.

The prototype requirements information can serve to encourage an orchestrated distributed spacecraft mission crosslink communications system evolution towards developing a wide range of common distributed spacecraft mission solutions to similar categories of crosslink communications problems rather than a series of diverse bottoms-up attempts at specific solutions.

2 Distributed Spacecraft Missions and Crosslinks

The section provides a general overview of distributed spacecraft missions and crosslinks in order to provide a foundation for the requirements derivation process that follows in Section 3.

2.1 Distributed Spacecraft Missions

Distributed satellite spacecraft missions consist of multiple satellites that interact and cooperate to achieve mission goals. A large segment of the distributed spacecraft will accomplish their interactions via direct communications between spacecraft via RF or optical crosslinks. These spacecraft will operate with varying degrees of autonomy thereby limiting the need for frequent ground segment intervention to carry out mission objectives. Other distributed spacecraft missions will collaborate by supplying data to the ground segment via space-to-ground links for the purpose of consolidation and reduction. These missions will require a high degree of ground segment interactions with the spacecraft to carryout the mission objectives. Since this report is concerned with crosslink communications, the distributed spacecraft missions that rely entirely on space-to-ground link communications will not be addressed. Two types of crosslink missions are considered in the report. These are distributed spacecraft constellation and formation flying missions.

Constellation missions typically involve satellites in orbits about a planetary body or the sun that share science information via crosslinks. They do not rely on each other for information required to make autonomous on-board orbital navigation corrections. Navigation data corrections that support spacecraft maneuvers are made via information obtained from the ground segment. Formation flying missions rely on crosslinks to exchange navigation data between spacecraft for the purpose of fully autonomous spacecraft navigational corrections. Formation flying missions typically maintain tight tolerances on the positions of there spacecraft in order to meet mission science objectives. The formation's navigation management function is located on one or more spacecraft and the members exchange navigation data and commands to allow real-time maintenance of the group's physical topology. Science and spacecraft health status may be exchanged among the mission spacecraft members via the crosslinks.

2.1.1 Missions

A survey of distributed spacecraft missions was undertaken as a basis for arriving at recommendations for future distributed spacecraft crosslink frequency allocations. Table A-1 in Appendix A of the Spectrum Requirements and Allocation Survey and Recommendation document contains a list of planned distributed satellite missions for a time span that covers the next twenty years. Near-term plans for distributed spacecraft missions are concentrated on an effort to establish a formation flying space based test bed to incrementally develop the capabilities that lead to fully autonomous, collective navigation. The Orion program is a rapid, low cost demonstration that is geared for showing the capabilities of interactions, cooperation, and a common system wide behavior between formation spacecraft in the 2002 to 2006 time frame. Other programs such as the Magnetic Imaging Constellation (MAGIC), Magnetospheric Multiscale (MMS), Constellation-X, Laser Interferometer Space Antenna (LISA), and Planet Imager (PI) are planned to work in parallel to provide diverse, fully capable, and robust solutions that will support the needs of Earth and Space Science Communities over the next twenty years.

2.1.2 Classification of Missions

distributed spacecraft missions consist of fleets of space vehicles that exhibit all or some subset of the following characteristics:

- Interact and cooperate to achieve mission goals,
- Collectively manage science data gathering,
- Collectively manage vehicle positioning,

- Evolve over time by extending and enchancing mission capabilities, and
- Operate autonomously over periods of time to minimize ground segment support.

Figure 2-1 illustrates distributed spacecraft mission classifications from a communications hierarchical perspective. Distributed spacecraft cooperation methods can be divided into two communications categories: ground link and crosslink coordinated information communications. Ground link communications allows information to be collected from each spacecraft via space-to-ground links. These distributed spacecraft do not exchange information directly with each other to meet the common objectives of the group. The ground segment collects and processes the information from each mission spacecraft and then it constructs a composite mission perspective both in the area of science and navigation operations. In general, missions operating in this category are highly dependent on the ground segment, which serves as a centralized controller for the distributed S/C. Some distributed spacecraft missions described as constellations cooperate via space-to-ground link communications alone.

Crosslink communications missions have a reduced dependence on ground segment control in comparison to the missions that rely entirely by the ground segment for science and navigation operations. They require minimal ground contact to obtain mission planning directives and to supply science data to the ground segment. Constellations and formation flying missions use crosslink communications to exchange data between spacecraft. Constellations that use crosslinks typically share information that is related directly to science data collection operations.

Unlike constellation missions which may or may not use a crosslink communications architecture, formation flying missions are predicated on the existence of inter-spacecraft crosslinks to operationally achieve the mission objectives. Formation flying spacecraft exchange navigation data and commands among mission spacecraft with the objective of maintaining high tolerances in the required positions of the spacecraft in order to meet mission science objectives. The communications architectures for missions can be varied in general. Two extremes identified in Figure 2-1 are the centralized and the distributed topologies. These topologies are depicted spatially in Figure 2-2.

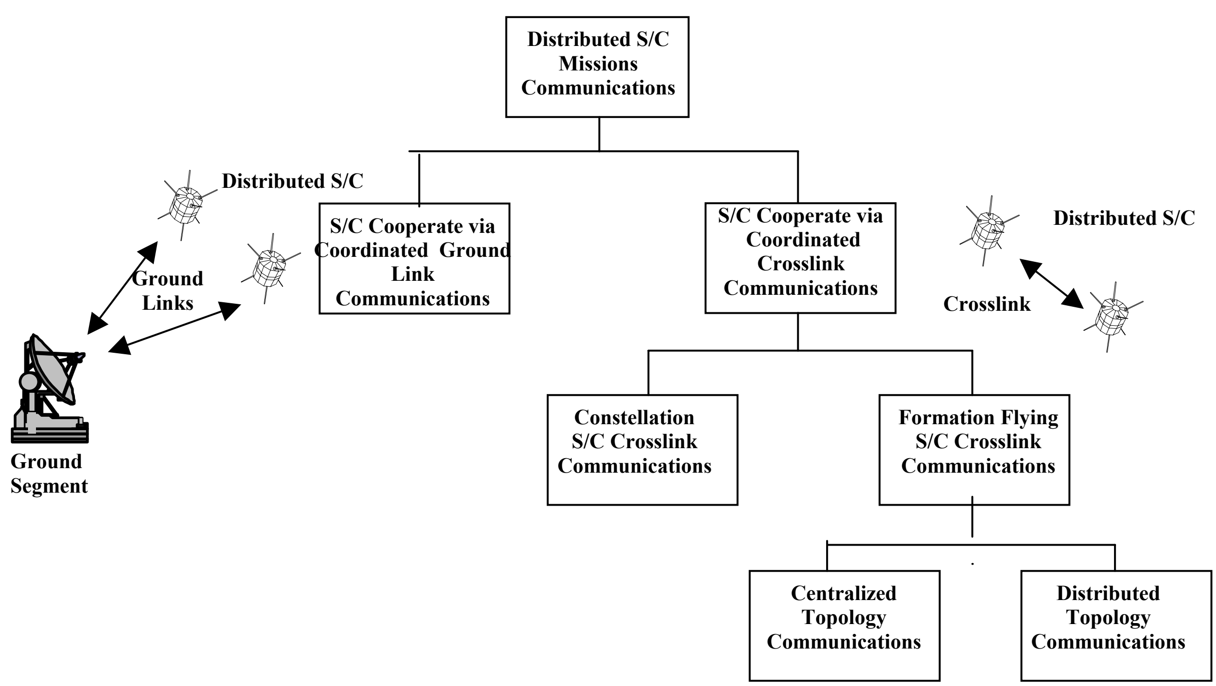

Figure 2-1 Distributed Spacecraft Communications Architecture Hierarchy

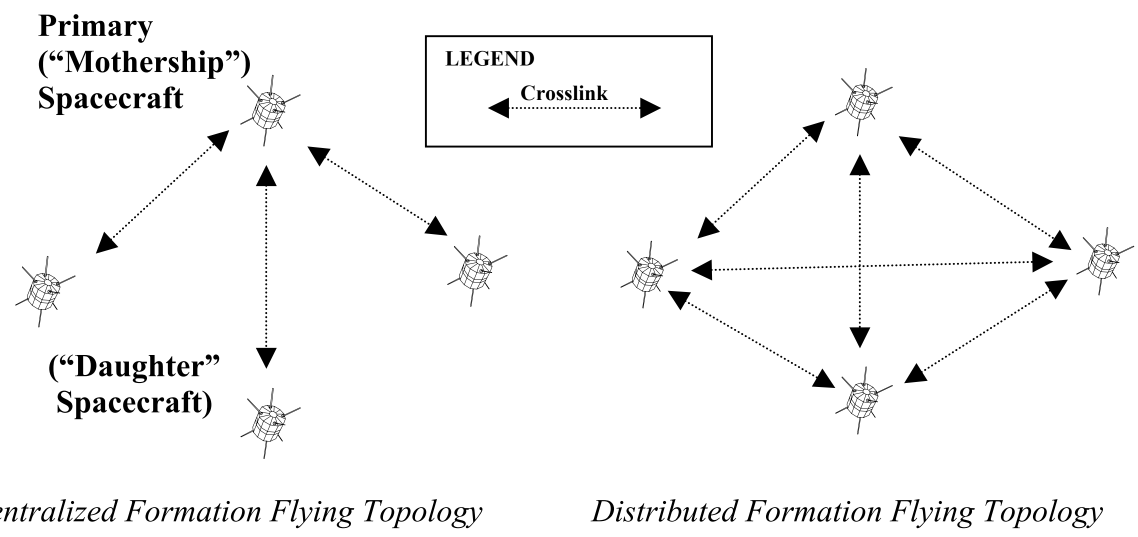

Figure 2-2 Basic Formation Flying Communications Topologies

The centralized formation flying topology shown in Figure 2-2 consists of a "mothership" as the primary spacecraft, and "daughter" spacecraft as secondary spacecraft. The "mothership" acts as the control point for the formation. Centralized formation navigation and/or science processing takes place on the "mothership". Crosslinks serve as conduits for the daughter spacecraft to pass information to the "mothership" from the "daughter" spacecraft. Likewise, the "daughter" spacecraft supplies information to the "mothership" via the crosslinks. "Daughter" spacecraft do not communicate with each other via crosslinks. The "mothership" orchestrates mission objectives based on fully autonomous on-board formation control processing. The "mothership" is a single point of failure due to its unique capabilities and its centralized role within the formation.

The distributed formation flying topology shown in Figure 2-2 does not have a single point of control within the formation. Instead, all of the spacecraft have the same operations capabilities relative to the fully autonomous maintenance of the formations collective objectives. The crosslinks are used to share spacecraft navigation and science related information with all other spacecraft in the group. Unlike the centralized formation, the distributed formation does not have a single point of failure since all the spacecraft have the same functionality relative to the overall formation. This robustness comes at the expense of more sophistication built into each spacecraft. The failure of a few spacecraft in missions with large number of spacecraft can usually be tolerated without requiring that the mission be aborted.

Hybrid formations consisting of sub-groupings or clusters of the centralized and distributed topologies can also exist for large formations. For example, local groupings of spacecraft in a large formation may operate as a cluster. Each cluster could then report the local distributed formation information to a "mothership" that coordinates all the sub-groups from a high-level centralized topology perspective. In some formation flying situations, the topologies might evolve with time as the formation analyzes science data and reacts in an autonomous manner to the real-time changing circumstances that arises as the mission unfolds.

distributed spacecraft systems can be grouped into several mission types based on the location of the spacecraft and the objectives of the mission. These types are Earth Science Mission, Technology Demonstrator, and Space Science Mission. Earth Science Missions are located in the Near-Earth environment with missions typically placed in Low Earth Orbits (LEOs), Medium Earth Orbits (MEOs), High Earth Orbits (HEOs), or Geosynchronous Earth Orbits (GEOs). The objectives of these missions are directed at obtaining information about the Earth and the Earth-related physical phenomena that extended beyond the Earth into the region of space surrounding it. Examples of the Earth's physical features under observation by these missions are surface, atmospheric, gravitational field, and magnetic field. Technology Demonstration Missions are aimed at demonstrating new technologies that can be deployed in future distributed satellite missions. Space Science Missions are situated in inter-planetary space or around other planets. Examples of Space Science Missions are stellar interferometry, solar atmospheric monitoring, solar system planetary monitoring, and extra-solar system planetary observing missions. Further classification separates missions that plan to use crosslink communications from those that will function without crosslinks.

2.2 Inter-Satellite Communications for Distributed Spacecraft Missions

2.2.1 Overview

Communications between distributed spacecraft will be achieved by the use of radio frequency (RF), infrared, and optical crosslinks. RF crosslinks are defined as a means of providing an Inter-Satellite radio communications service. This study concentrates only on RF crosslinks between science satellites in the same or different missions. It does not include crosslinks between science satellites and communications relay satellites used by some missions as an intermediate satellite to exchange information between the distributed satellites and their mission ground segments.

2.2.2 General Crosslink Capabilities

- **<u>Introduction</u>**

The capabilities needed for mission crosslink communications are dependent on mission goals, operations strategies, spacecraft physical and cost considerations as well as the topology of the mission spacecraft. Bandwidth requirements derived from mission science requirements are the driving factor in the development of crosslink requirements. For example, formation flying missions that have a centralized topology such that a "mothership" frequently processes large volumes of data collected by the "daughter" spacecraft will require crosslink that support significantly higher bandwidth than those missions where the sole function of the crosslink is to infrequently exchange low volume navigation and health status information between the spacecraft. The physical aspects of the crosslink such as the antenna gain and the power of the transmitter must be selected in order to satisfy the free space propagation constraints of the mission. Small spacecraft are limited to small antennas that typically do not support wide bandwidths. As such, low-cost missions with centralized topologies that require high date rate crosslinks may not be able to meet the bandwidth requirements due to the limited crosslink equipment options. Figure 2-3 shows the general process for assessing a crosslink communications system for a distributed spacecraft mission whose bandwidth requirements, physical constraints, technological constraints, and cost constraints are provided as part of the mission objectives and operations strategies.

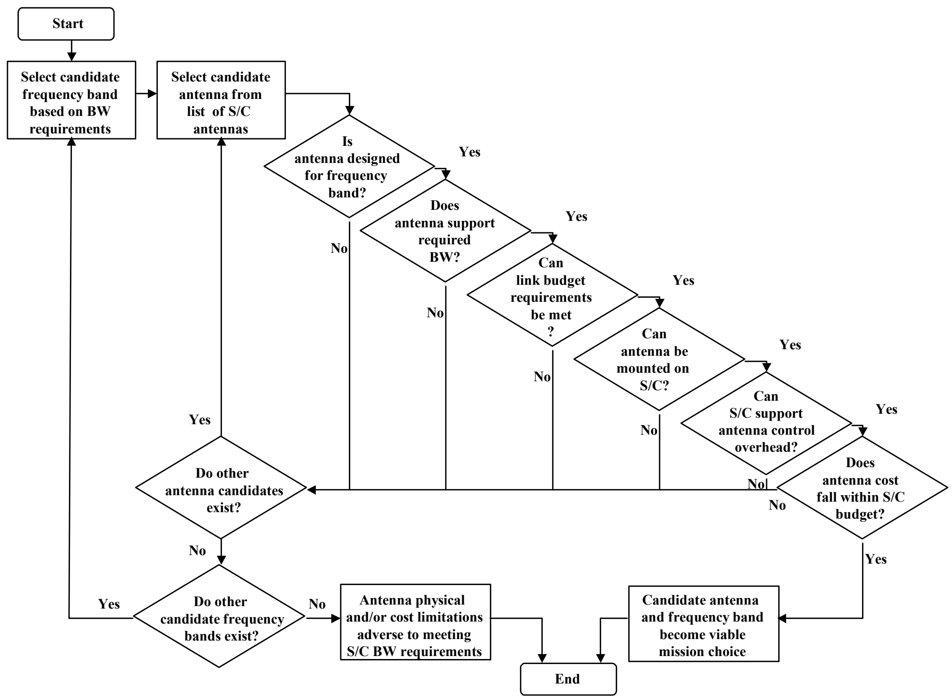

Figure 2-3 Process for Assessing a Candidate crosslink communications system

❑ Multiple Access Capabilities

The number of spacecraft in the mission architecture imposes restrictions on the operations of the crosslinks. These constraints are manifested in the multiple access techniques used by the mission crosslink communications system to manage the each spacecraft's access to the shared frequency resource. Multiple crosslinks that operate at the same frequency require that a time sequenced protocol be implemented among all the spacecraft in order to avoid the interference that results from attempted simultaneous transmissions. This constraint reduces the overall mission information throughput performance since each spacecraft must wait their turn to access the shared frequency.

This throughput reduction can be avoided by having crosslinks operate at different frequencies. However, this solution comes at the added expense of unique transceiver frequency implementations which in turn drives up the cost of the spacecraft. In addition, more of the available frequency spectrum must be reserved for the mission. Simultaneous transmissions can also be achieved at the same center frequency using spread spectrum techniques. Even with spread spectrum techniques, there is a limit as to how many simultaneous broadcast can occur simultaneously due to the mutual noise floor making it necessary to have large distributed systems partitioned into frequency subgroups to avoid exceeding the noise limit. The spread spectrum technique is inherently wideband due to the pseudo-random spreading modulation that is superimposed on the signal to achieve the spread. As such, spread spectrum crosslinks require relatively wide segments of the existing spectrum.

❑ Crosslink Bandwidth Capabilities

Distributed spacecraft crosslink bandwidth capabilities depend on the science, navigation, command, and spacecraft health status data exchanged between spacecraft. These four crosslink data types can vary significantly in terms of volume and transmission frequency from mission to mission.

Formation flying missions requiring centralized, on-board processing of science data gathered by member spacecraft can require the widest crosslink bandwidths. For these missions, science data gathered by formation spacecraft is transmitted to a centralized processing facility on-board the "mothership" for reduction. In the case of science imaging missions, this can result in large volumes of image data being transferred frequently across crosslinks to the "mothership". By contrast, some formation flying missions may choose to process all of the science data on the ground using downlink capabilities to off load the science data. These missions types will require significantly less bandwidth capability on their crosslinks than the centralized processing type described above.

The volume and frequency of the navigation data is tightly coupled to the nature of the mission. For example, interferometric formation flying spacecraft missions with centralized topologies typically require that tight relative spacecraft position tolerances (some measured in terms of wavelengths of the science signals) be maintained in order that the interferometer can function properly. This requires that the formation spacecraft continuously monitor their positions and attitudes and report the navigation measurements via crosslink data exchanges for assessment by an overall formation topology management function within the formation. This function in turn provides navigation corrections to the spacecraft to command any drifting spacecraft back within the mission position tolerances via guidance system operations. The tight loop-back communications associated with this scenario requires significantly greater crosslink navigation bandwidth requirements than those missions requiring kilometer level positional accuracy.

Broadcasting health status messages across the crosslinks allows members of a distributed system to evaluate the operational state of the transmitting spacecraft in order to determine if the on-board equipment is functioning properly. This information allows the other members of the distributed spacecraft system to include or ignore data that is being received from another spacecraft. In general, health status data is very low volume and would be broadcast less frequently than the science and navigation data. As such, health status data is a very narrow bandwidth contributor to the overall crosslink bandwidth when science, navigation, and health status data are considered together.

2.2.3 Classification of Crosslinks

Missions will vary in terms of science objectives, spatial location, duration, and spacecraft complexity. However, from a communications perspective, there are a number of basic features in common to all missions. Table 2-1 shows the taxonomy of crosslinks characterized by inter-satellite communications distances and maximum data rates for information transferal over the crosslink. This method of classification provides a means of categorizing all missions on the basis of their crosslink maximum signal path length and maximum data rate requirements. These two parameters, when taken together, form a primary constraint on minimum transmit power level and antenna gain needed to provide the signal quality needed at the receiving end of the crosslink to close the crosslink communications loop. Secondary communications factors such as inherent equipment noise levels and code error correction techniques further refine the quality of the crosslink from an operational performance perspective. Replacing the maximum signal path length and data rate with the class indicator listed in Table 2-1 provides a single index of crosslink classification that spans the range of all conceivable distributed spacecraft mission possibilities.

Table 2-1 Classification via Crosslink Communications Parameters

	Maximum Inter-Satellite Communication Distance		
Maximum Data Rate	<10 Km	10 Km – 1000 Km	>1000 Km
<100 Kbps	Class 1a	Class 1b	Class 1c
100 Kbps – 1 Mbps	Class 2a	Class 2b	Class 2c
1 Mbps – 10 Mbps	Class 3a	Class 3b	Class 3c

	Maximum Inter-Satellite Communication Distance		
10 Mbps – 100 Mbps	Class 4a	Class 4b	Class 4c
100 Mbps – 600 Mbps	Class 5a	Class 5b	Class 5c
>600 Mbps	Class 6a	Class 6b	Class 6c

3 Distributed Spacecraft High-level crosslink communications system Prototype Requirements

3.1 Overview of Prototype Requirements Derivation Process

This section describes of the process used to derive high-level requirements for networked, distributed spacecraft crosslink communications systems. The requirements are identified as prototypes due to the general nature of this document, which provides a high-level assessment of expected trends in the evolution of distributed spacecraft crosslink communications from now until 2020. Instead of being requirements for a particular mission, the derived requirements represent the general characteristics observed across the distributed spacecraft missions surveyed in the Spectrum Requirements and Allocation Survey and Recommendation document. As such, no mission might need all of the derived requirements. Figure 3-1 presents an overview of the process used to derive high-level crosslink requirements for distributed spacecraft missions. The derivation process starts with the identification of crosslink operations concepts and proceeds through functional analysis to determine the requirements.

The process begins in Step 1 with the assessment of the distributed spacecraft crosslink missions using the information about these missions collected in the Spectrum Requirements and Allocation Survey and Recommendation document. In Step 2, the Open Systems Interconnection (OSI) Model functions for general networking purposes were identified for the Physical, Data Link, and Network Layers since networking principles will be a dominant factor in the development of crosslink communications systems. As such, the requirements levied on crosslink communications systems should be compatible with the basic tenets of networking. The network perspective of crosslink communications is seated in the Sensor Web and related concepts of future inter-spacecraft communications. OSI Layers above the Network Layer were not directly addressed as part of this process since they do not have a direct impact on maintaining reliable and efficient crosslink operations. As depicted in Step 3, high-level crosslink system functions were extracted from the crosslink capabilities information obtained from a review of the different types of distributed spacecraft missions undertaken in the Spectrum Requirements and Allocation Survey and Recommendation document. In Step 4, the general crosslink functions associated with all the distributed spacecraft missions were combined with those associated with the Physical, Data Link, and Network Layers of the OSI Model in order to provide a complete set of high-level crosslink communications system Functions within the context of networking. In Step 5, the resultant set of high-level functions produced in Step 4 were used to identify basic crosslink functional and performance prototype requirements for distributed spacecraft system crosslink communications systems.

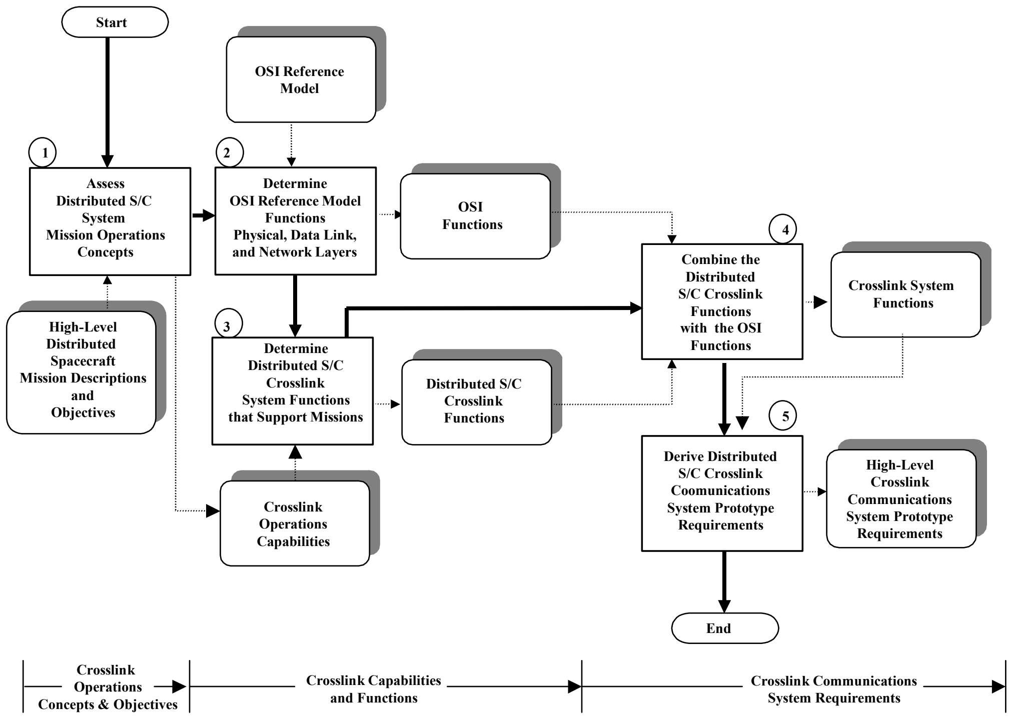

Figure 3-1 crosslink communications system Prototype Requirements Derivation Process

3.2 Distributed Spacecraft Crosslink Communications System Operations Capabilities

The distributed spacecraft systems that will use crosslink communications have been divided into three categories: constellation, distributed formation flying, and centralized formation flying missions. Examining the descriptions of planned distributed spacecraft crosslink missions in the time frame from now until 2020 reveals that existence of crosslink operations concepts that are common to all three categories of missions. Each of these mission types has one or more pairs of crosslinks that share a common set of operational capabilities. These common crosslink system operations concepts can be described in terms of the following principle capabilities that underlie crosslink operations:

- target multiple crosslink partner spacecraft with antenna beams to support multiple crosslink connections,
- establish multiple operational crosslink,
- manage multiple spacecraft access to the shared crosslink RF communications resource,
- conduct network operations for the distributed spacecraft mission,
- exchange data between multiple spacecraft over established operational crosslinks.
- measure crosslink signal characteristics for navigation purposes, and
- terminate operational crosslinks.

In addition to these fundamental capabilities, the preparation of the survey of distributed spacecraft missions presented in the Spectrum Requirements and Allocation Survey and Recommendation document provided insights into the emergence of desirable long-term crosslink communications systems capabilities for future missions. These general capabilities can be expressed as follows:

- provide viable communications equipment alternatives for the growing number of planned missions that will be composed of small (nanosat) spacecraft by using low power transceivers,
- provide crosslink networking capabilities among distributed spacecraft system members,
- provide the real-time sharing of science information between different distributed spacecraft missions on the Sensor Web via an interoperable crosslink capability,
- provide the real-time sharing of science navigation data and formation positioning control commands among mission spacecraft,
- provide reduced costs to the distributed spacecraft missions through the use of COTS based crosslink communications products

The following sections elaborate on the description of each of these capabilities.

3.2.1 Target Partner Spacecraft Capability

The capability to target the crosslink partner spacecraft with an antenna beam consists of positioning the beam of the transmitting or receiving spacecraft over the transmit and receive antenna of the opposite spacecraft of the crosslink pair prior to establishing crosslink communications. For distributed spacecraft in different orbits around a planetary body, this operation is dynamic in the sense that orbital motion always presents a changing geometrical perspective of the member's of the distribution as viewed from any one member of the group. Therefore, the distributed spacecraft will continually need to know the position of their target partners to ensure that they can control the position of the crosslink antenna beam to ensure that crosslink communications can be realized. Depending upon the specific nature and design of the mission, the activity of continuous crosslink targeting will result in many instances in the switching between fixed antenna beams or the continuous repositioning of steerable antenna beams. In general, the crosslink communications systems should be capable of targeting multiple partner spacecraft to support simultaneous crosslink.

For fixed beam low gain antennas, this corresponds to selecting the antenna that is on the correct side of the spacecraft to allow beam coverage of the target spacecraft. The selection criteria, in general, will change with time as the positions of the spacecraft change with respect to each other while the spacecraft undergoing their own unique orbital motion. Antenna beam blockage by the body of the spacecraft will change requiring the transition between operational fixed beam antennas to occur at various times in the spacecraft orbits. High gain steerable beam antennas will require complicated beam control support systems that rely on navigation information about both pairs of spacecraft to operate in these dynamic environments.

Distributed spacecraft antenna control capabilities can vary significantly in terms of the constraints placed on antenna control operations. For example, the minimum sized distribution consisting of two spacecraft in the same circular orbit about a planetary body (leader-follower pairs) requires very little in antenna control throughout the mission life-time. A single fixed beam crosslink antenna is sufficient since the relative position of the spacecraft remains fixed. Complications arise if the science objectives of the mission require that the members undergo attitude changes. This may induce the need to have multiple fixed antenna on each spacecraft with the added processing complexity need to switch between these crosslink antennas as the vehicles' attitudes change.

The other extreme of significant crosslink communications architecture complexity lies with large distributions consisting of tens or hundreds of spacecraft spread over large regions of space around planetary bodies in large, highly elliptical orbits that vary significantly in period from one spacecraft to the next. For example, this is a possible situation for planetary magnetospheric mapping missions. For such distributions, the well-behaved, somewhat static relationships of the ideal distributed spacecraft topologies, may not be realized and the relative location and inter-spacecraft distances can change significantly. Establishing and maintaining a fixed geometry crosslink communications architecture may be impractical. The lack of a somewhat fixed topology demands that processing for real-time antenna control can be quite sophisticated for fully autonomous operations.

Similarly, deep-space distributed spacecraft missions may escape this problem if they are located far enough from planetary bodies that could induce relatively large perturbation effects on there motion thereby causing large displacements that are impractical to continually counter-correct their positions with limited on-board guidance system fuel supplies. The majority of distributed spacecraft missions examined in the Spectrum Requirements and Allocation Survey and Recommendation document may require dynamic control of their crosslink beams.

3.2.2 Establish Operational Crosslink Capability

The establishment of an operational crosslink follows the successful targeting of the S/C destined to be paired in the crosslink partnership by the crosslink initiating S/C. This involves the transmission of an RF signal carrier encoded bit stream and acquisition data frames by the crosslink initiating S/C. In general, the crosslink communications system must be capable of establishing multiple crosslinks.

For bi-directional crosslink operations, the partner spacecraft mirrors the acquisition operation by sending an acquisition signal to the receiver on the crosslink initiating S/C. The receivers detect the acquisition bit streams and lock on to the bi-directional crosslink signal. The report of both receiver locks to the their respective transmitting S/C indicates that the crosslink is ready for data exchange and the optional navigation ranging operation. Bit streams with imbedded idle frames are exchanged between the two S/C while waiting for the onset of steady-state crosslink data transfer operations. For one-way crosslinks, this type of "handshaking" is not necessary and a simple forward "beacon" type transmission can be used to establish the operational crosslink.

In order to be interoperable with other missions, the data exchange capability must conform to standardized waveform characteristics. The type of modulation used in transforming bit stream data into an IF waveform depends on the characteristics of the mission.

The distance between the pair of spacecraft forming the crosslink pair must be calculated for variable, low power communications systems. For example, large distributed spacecraft nanosat missions requiring a wide range of crosslink pairs will find combinations of crosslink signal path lengths that vary significantly over time. Minimizing power consumption for the nanosats demands that the transmit power output be selected to match each particular crosslink implementation. Closely matching transmit power to the signal path length will reduce the likelihood of interference problems amongst Earth orbiting distributed spacecraft systems.

The crosslink information exchanges take place within the context of distributed spacecraft communications network operations. Each time that a crosslink connection is made between two distributed spacecraft, a portion of the total communications network that characterizes the topology of the entire distribution is realized. The number of simultaneous crosslink pairs that can be formed depends on the multiple access scheme used in the distribution's crosslink communication architecture. On one extreme, the minimum size distribution consisting of two spacecraft could maintain a virtually permanent crosslink connection between both spacecraft. On the other extreme, large distributions consisting of tens or even hundreds of spacecraft may be constrained to organize into communications architecture that subdivides the entire distribution into sub-topologies wherein members can communicate between nearest neighbors and longer distance intra-spacecraft communications is accomplished via network routing techniques within the overall distribution. In these situations, certain members of the sub-topologies would have spacecraft nodes that serve as distribution network routers the would communicate with router nodes in other sub-topologies to provide distribution wide exchanges of network datagrams in a manner that is identical to terrestrial internet operations.

3.2.3 Manage Crosslink RF Media Access Capability

The capability to manage crosslink RF media access provides an organized approach that allows all members of a distributed spacecraft mission to communicate with each other without the mutual interference that potentially exists when multiple crosslink transmitters emit RF signals. The four principle methods for a multiple access protocols are Time Division Multiplex Access (TDMA), Frequency Division Multiple (FDMA), Code Division Multiple Access (CDMA), and Random Access (RA). TDMA and RA protocols both use time as the discriminating factor that separates transmissions from mutually interfering with one another. TDMA protocols assign time slots to transmitters in which only one transmitter can operate. RA protocols check for a transmission in progress prior to broadcasting. If no transmission is detected, then the transmitter broadcasts. If a transmission is already in progress, the attempt to broadcast is delay by a random amount of time before it is attempted again. FDMA uses different frequencies to separate the transmissions making simultaneous broadcasts possible. CDMA uses frequency spreading schemes to randomly distribute components of the signal across a frequency band such that multiple transmitters can operate simultaneously without major interference. Table 3-1 summarizes the capabilities of the classic MA methods applied to crosslink communications. In addition to elaborating on these capabilities, there is with a brief overview of the advantages and disadvantages of each MA method presented in the table.

Table 3-1: Characteristics of Classic Multiple Access Methods for Crosslink Mission Types

Classic Multiple Access Method	Basic Characteristics	Advantages	Disadvantages
TDMA	• Unique operations time slots must be assigned to each crosslink S/C • Each crosslink transaction in the distribution limited to the assigned time slot	• Single frequency needed for implementation for all crosslinks • Low cost crosslink solution due to replicate crosslink design	• Crosslink transmissions must occur one crosslink at a time • Time synchronization needed between all distribution S/C • Light-time delay corrections must be applied when crosslink signal path lengths vary in order to avoid signal collisions • The greater the number of S/C, the longer the duty interval for crosslink transmissions by a given S/C resulting in lower the overall data throughput for the distribution • Changing S/C distances of separation requires dynamic assessments of time slot allocations to compensate for variable signal delays
FDMA	• Unique frequencies needed for each crosslink	• Multiple crosslink transmissions can occur simultaneously	• One center frequencies needed for each crosslink implementation • The larger the distribution of S/C the greater the frequency band allocation required for the mission • Increased cost due to frequency variation in the crosslink design
CDMA	• Crosslink signal must be randomly spread across a portion of the frequency band via PN code	• Multiple crosslink transmissions can occur simultaneously • Relative range measurements for the crosslink can be made simultaneously with communication operations	• Total number of simultaneous crosslink transmissions is limited by the CDMA code noise floor • Complex signal processing needed for implementation • Complexity in design adds to communications system cost

Classic Multiple Access Method	Basic Characteristics	Advantages	Disadvantages
RA (e.g., ALOHA)	• Crosslink transmission must be attempted only when no other crosslink operations are detected • Attempt at a crosslink transmission during a detected transmission of another crosslink must be postponed by a random amount of time until a reattempt can be made	• Single frequency needed for implementation for all crosslinks • Low cost crosslink solution due to replicate crosslink design	• Transmissions must occur one crosslink at a time limiting data throughput • The greater the distance between S/C, the greater the likelihood of crosslink collisions due to light-time delays masking ongoing crosslink session startups • The greater the number of S/C, the more likely that postponements of crosslink transmissions thus reducing overall data throughput within the distribution

Hybrid versions involving mixes and variations of these four multiple access techniques are possible and some hybrid versions are currently being proposed for some near-term distributed spacecraft missions using crosslinks. In addition to the four classic MA methods listed in Table 3-1, spatial isolation of antenna beams can provide a means of preventing interference between competing crosslink signals. This requires the use of high gain antennas with narrow beams. By restricting signals to narrow beams, multiple crosslinks can transmit simultaneously without interfering with each other. The disadvantage of this method of sharing the RF media lies in the complexity of such antennas and their control systems making them unsuitable for low cost small spacecraft missions. However, some missions may benefit from spatially isolated crosslinks to solve the MA requirements problems.

3.2.4 Conduct Network Operations Capability

distributed spacecraft system architectures form natural structures to support network crosslink communications between the spacecraft. For example, the centralized formation flying distribution introduced in the Spectrum Requirements and Allocation Survey and Recommendation document can support a star topology as a network architecture for the formation due to the equality in spatial geometries of the formation and the network architecture. A simple centralized formation consisting of a "mothership" and several "daughter spacecraft" could form the basis of a Local Area Network (LAN). A network router on the "mothership" would provide "daughter-to-daughter" spacecraft communications through the router. This adds simplicity to the crosslink communications system by providing each "daughter spacecraft" with one crosslink partner, i.e., the "mothership". Using a TDMA communications scheme, would allow each "daughter spacecraft" to establish a crosslink connection with the "mothership" for a specified time period. Using a round robin algorithm, each "daughter spacecraft" would pass datagrams to the "mothership" for queuing until the destination "daughter spacecraft" forms its crosslink with the "mothership". At this time the queued datagram would be retrieved and sent to the destination spacecraft. This approach reduces the complexities of the overhead associated with the repeated targeting spacecraft and establishing crosslinks at the expense of maintaining crosslink network capabilities with datagram flow control. More complicated distributed spacecraft topologies could be viewed as groupings of LANs that are bound together to form a large Wide Area Network (WAN) in order to simplify the crosslink communication system operations over the entire distribution of spacecraft.

In general, distributions involving large number of spacecraft may be organized into sub-topologies or clusters that exchange information within LANs associated with each cluster. Local networks could communicate with each other using WAN principles. This implies the existence of a router associated with each LAN that provides access to the WAN to provide bi-directional communications paths across the entire distribution allowing a spacecraft to communicate with any other spacecraft via WAN rather than direct spacecraft-to-spacecraft crosslink communications. This capability can significantly reduce the combinations of crosslink pairs that must be formed in large distributions.

The concept of the Sensor Web in space introduces an interoperability dimension into distributed spacecraft crosslink communications. To be compatible with the Sensor Web concept, future distributed spacecraft operations should be flexible enough to allow two spacecraft belonging to different missions to communicate with each other via their inherent crosslink communications capabilities. Different science missions may find it useful to share science event information via crosslinks exchanges. In order to achieve this objective, it is necessary to conform to standard networking methods to ensure that the information available on the crosslink data exchange will be compatible with the common network communications standards.

3.2.5 Exchange Crosslink Data Capability

Bit streams containing science, navigation, health status, and command data are transferred between the two S/C across the crosslink. Bit streams with imbedded idle frames are exchanged between the two S/C during periods when data is not imbedded in the bit stream. In general, the crosslink communications system must be capable of exchanging crosslink data between multiple S/C simultaneously.

3.2.6 Measure Crosslink Signal Characteristics Capability

distributed spacecraft missions requiring precision S/C-to-S/C range measurements can meet this objective by the use of Discrete Sequence Spread Spectrum signal structures during crosslink transmissions. Crosslink signal structures that consist of pseudorandom noise codes can be processed to determine the range time delay and thus the relative distance between the two spacecraft that form the crosslink pair. In general, the crosslink communications system must be capable of measuring signal characteristics for multiple crosslinks simultaneously.

3.2.7 Terminate Operational Crosslink Capability

Change visibility conditions due to orbital dynamics and mission crosslink operations scenarios can lead to the need to periodically terminate a crosslink. This must be done as an orderly shutdown process that allows both crosslink pair S/C to transition to an idle operations state and wait for the next crosslink event to be undertaken.

3.3 Overview of OSI Model

crosslink communications systems must adhere to networking principles in order to meet the Sensor Web objective of a standard method of networked data exchange between spacecraft. This is important if crosslink communications are to evolve in the direction of intra-mission capabilities, which is the thrust of the Sensor Web concept associated with communications interoperability.

The International Organization for Standardization's (ISO) OSI Model is a 7-layer reference that is used to characterize the segmentation of the general network implementation. The OSI Model serves as a reference for identifying similar or identical concepts among different standards and implementations of network architectures. It is an abstract description of the communications between applications processes operating on two different computer systems. The layering within the model divides the activities associated network communications into nearly independent strata of operations that allow application programs on one computer to successfully communicate with applications on another computer to which the first is networked. This isolates functional aspects of the communications implementation into domains that can be developed or modified independently without impacting the other layers. A variety of communications protocols have been developed at each level to provide various efficiencies in the overall network operations. The OSI Model provides a reference for discussing specific protocol implementations, which may differ to varying degrees from the ideal layering of the model. Figure 3-2shows the layering of the functionality within the reference model.

Distributed spacecraft engaged in inter-computer communications through information exchanges via the crosslinks will implement a layered model of protocols to ensure the reliable transfer of data between application software at both ends of a crosslink. This document will be concerned with the first three layers, that is, the Physical, Data Link, and Network Layers from the point of view of functions and requirements that are impacted by the nature of crosslink communications system operations. These three layers have been selected due to their role in network operations within the varied architectures associated with distributed spacecraft crosslink communications systems. The Physical Layer is responsible for maintaining the physical connection between the two spacecraft. The Data Link Layer is responsible for maintaining the integrity of information transferring across the physical connection as well as managing access to the RF media. The Network Layer is responsible for routing information through the distributed spacecraft mission network.

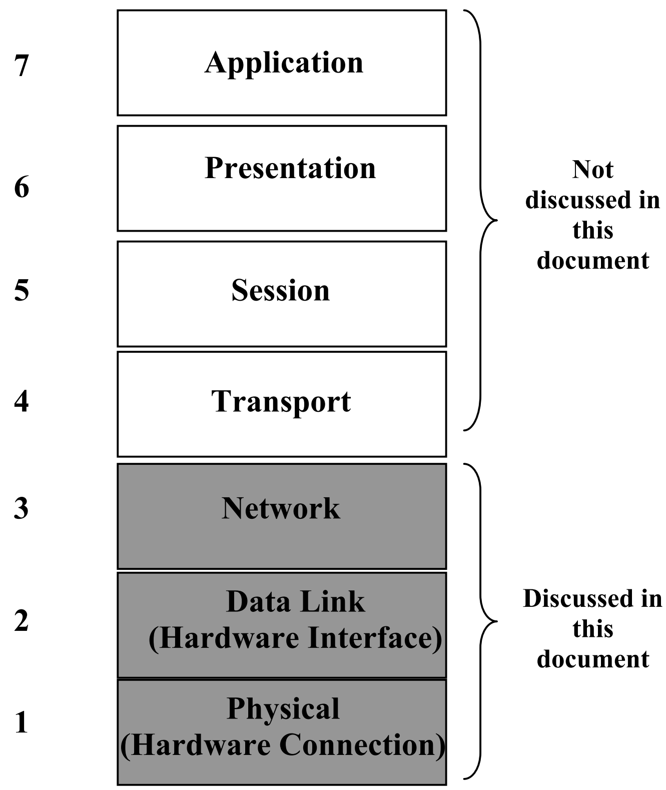

Figure 3-2 OSI 7-Layer Reference Model for Networking Protocols

3.4 OSI Model and Crosslink Functions

The first level or Physical Layer of the OSI Model as applied to distributed spacecraft consists of the crosslink communications functions associated with the RF bit stream transfers between the two crosslink transceivers. The major crosslink functions expressed in terms of OSI Physical Layer functions are:

- establish, maintain, and terminate the connection (RF link) between two or more crosslink transceivers,
- participate in the process whereby crosslink resources are shared among distributed spacecraft transceivers, and
- transform the bit stream of digital data produced by equipment on-board the spacecraft into the corresponding forward RF signals transmitted over the crosslink to one or more Crosslink Partner S/C, and

- transform return RF signals from one or more Crosslink Partner S/C into separate bit streams

The principle implementation components of these Physical Layer functions are power, frequency, beam pattern, modulation type, channel coding, data rates, bandwidth, and other radiometric data parameters. The principle performance parameters associated with these functions are bit error rate, carrier frequency stability, residual amplitude modulation, carrier phase noise, and out of band spurs.

The second level or Data Link Layer of the OSI Model as applied to distributed spacecraft consists of the crosslink communications functions associated with the interfacing of the upper level networking functions with the hardware of the Physical Layer. The major crosslink functions expressed in terms of OSI Data Link Layer functions are:

- manage multiple spacecraft access to the shared crosslink RF media,
- create data frames from datagrams received from the Network Layer,
- create data frames from bit stream data received from crosslink partner spacecraft,
- manage data frames that contain encapsulated data from higher OSI Model layers,
- apply physical addressing to the data frames to support reliable transmission on the crosslink,
- control the flow of frames across the crosslink, and
- provide error detection and correction for the data frames.

The third level or Network Layer of the OSI Model as applied to distributed spacecraft consists of the crosslink communications functions associated with the datagram construction and the routing of datagrams. The major crosslink functions expressed in terms of OSI Network Layer functions are:

- create datagrams destined for crosslink partner spaceraft from on-board science and engineering information processing applications,
- route datagrams among the crosslink partner spacecraft based on a logical addressing scheme, and
- extract science and engineering data contained in datagrams obtained from other spacecraft.

3.5 Crosslink Communications System Functional Analysis

The functions presented in the following sections are derived from the crosslink operations capabilities outlined in Section 3.2 and the OSI Model Physical Layer functions presented in Section 3.4. The capabilities represent the basis of operations that are realized by the orchestration of multiple functions that form the crosslink communications system. This section derives the functions and relates them to the capabilities through the static and dynamic diagrams and tables that form the basis of systems requirements modeling. This modeling will outline what must be done by the crosslink communications system and does not attempt to determine how it will be accomplished. How the system will accomplish the objectives is a design issue associated with a specific mission that is not addressed in this document. The components of this system modeling process are:

- crosslink communications system context diagram,
- function and information flow diagrams,
- information flow dictionary,
- state transition diagram, and
- typical crosslink communications system scenarios.

3.5.1 Crosslink Communications System Context Diagram

The crosslink communications system is defined here to be the waveforming components, low-level networking functions, and antenna controller, i.e., that portion of a networked communications system needed to physically establish and maintain a reliable RF crosslink communications connection between two spacecraft. Figure 3-3 shows the context diagram for a crosslink communications system which is a subsystem of the Distributed S/C. The diagram contains the information interfaces between the communications system and its outside world. The crosslink communications system is represented by the circle that lies within the distributed spacecraft. The circle forms the boundary between the crosslink communications system and its outside world. The boundary of the circle was chosen such that the waveforming, low-level networking, and antenna control capabilities reside within the crosslink communications system for the following requirements analysis. The external entities, with which the communications system interfaces, are represented by the rectangular structures and a single Crosslink Partner S/C in Figure 3-3. Multiple Crosslink Partner S/C are not shown for purposes for pictorial simplicity. However, multiple Crosslink Partner S/C are considered later in the document as an extension of the single S/C analysis in the analysis that immediately follows. Arrows depict the direction of flow of information across the external interfaces to and from the crosslink communications system. Two-way arrows depict bi-directional information flows. Only the major system level information flows are shown in Figure 3-3.

The Crosslink Partner S/C is the second spacecraft engaged in forming the pair of spacecraft that define the crosslink. The same Cross Link Communications System that is shown within the Distributed S/C shown in Figure 3-3 exists on the Crosslink Partner S/C. The portion of the bi-directional crosslink that carries information to the Crosslink Partner S/C from the crosslink communications system shown in the Figure 3-3 is called the forward crosslink. The part that carries information from the Crosslink Partner S/C to the crosslink communications system shown in Figure 3-3 is called the return link. The On-board Navigation Processor provides the spatial information needed to control the antenna beam relative the positions of both spacecraft engaged in forming the crosslink. The On-Board Communications Event Scheduler provides the temporal information needed to decide when crosslink communications services will occur based on mission operations scenarios. The On-Board Communications Configuration Manager provides the signal transmission and reception parameters needed to configure the system for crosslink operations by translating mission operations specifications into communications equipment commands. The OSI Transport Layer resides in an on-board processor that supplies data streams to and receives data streams from the network layer (not shown in Figure 3-3) imbedded in the crosslink communications system.

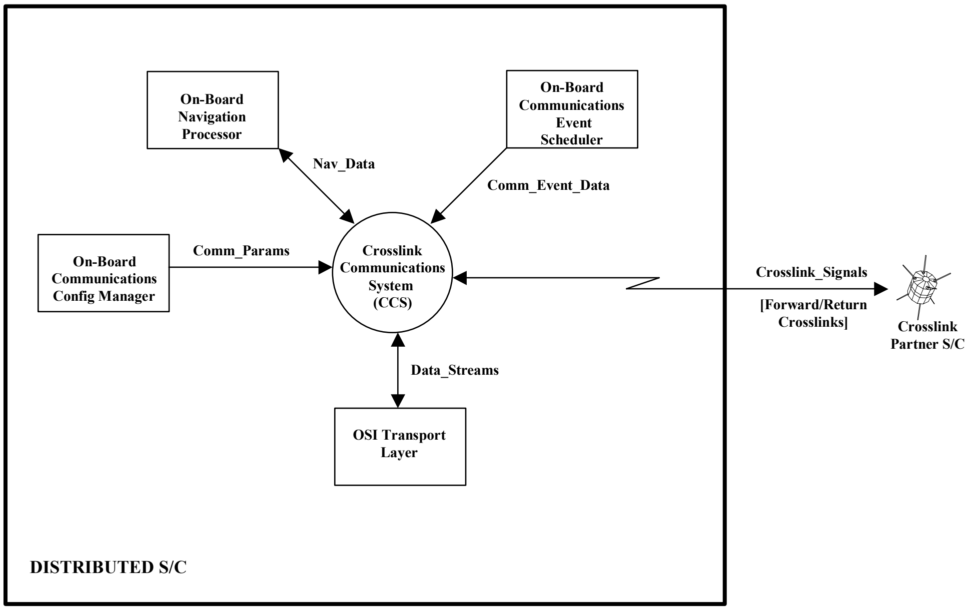

Figure 3-3: crosslink communications system Context Diagram

3.5.2 Crosslink Communications System Functions

Figure 3-4 shows the decomposition of the crosslink communications system presented in Figure 3-3 into its major functions each of which is represented by a circle. This representation is a static functional requirements model of the system independent of any particular design implementation. The circles shown in Figure 3-4 do not differentiate hardware functions from software functions since this is a system level information flow diagram. The functions transform incoming information and output the resultant information. Each function interacts with another system function or an entity that is external to the system via the information flows that are represented by arrows that indicate the direction of the flow. Only the major information system level flows are shown in Figure 3-4. Secondary flows are such as those containing status, acknowledgements, reports, etc. are not depicted to eliminate complexity in this preliminary requirements model. The same external entities that are interfaced to the crosslink communications system in Figure 3-3 are shown in Figure 3-4 interfaced to the system functions. The external interfaces are decomposed into their component information flows. For example the Data_Stream flow shown in Figure 3-3 is equivalent to the Return _Data_Stream and the Trans_Data_Stream information flows that are described. Similarly, the Comm_Params information flow is composed of the Rec_RF_Params and the Rec_Demod_Params and the Trans_RF_Params and the Trans_Demod_Params information flows. Other flows may have subordinate components and will be described as such later on this document.

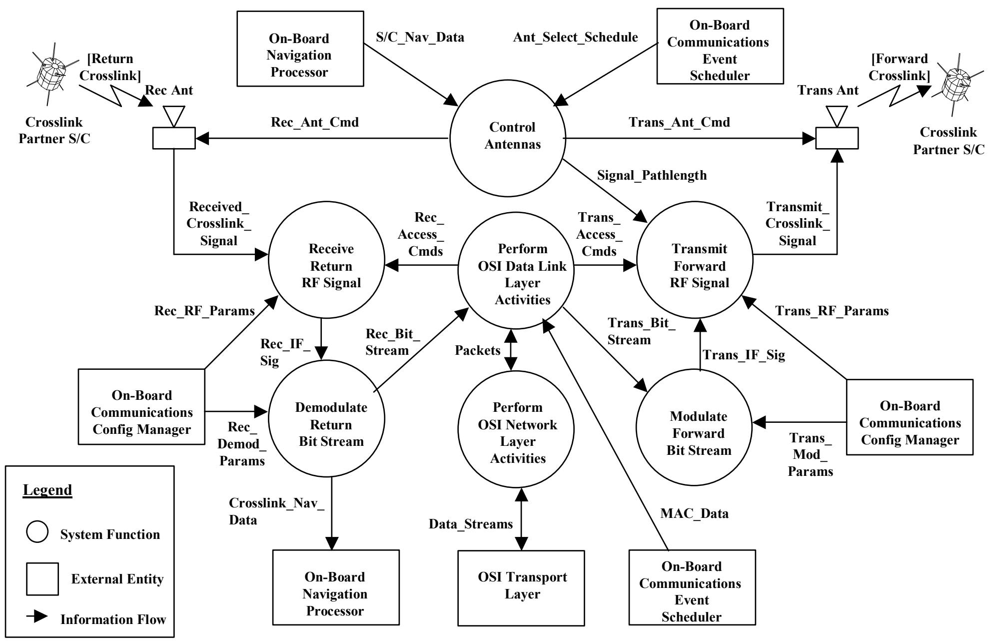

Figure 3-4 High-Level crosslink communications system Functional Requirements Model

Figures 3-5 and 3-6 provide the further decomposition of the functions Perform Data Link Layer Activities and Perform Network Layer Activities, respectively, into their subordinate functions. Each high-level function can be decomposed into low level-functions provided that the external interfaces to the high-level function are preserved in the decomposition process.

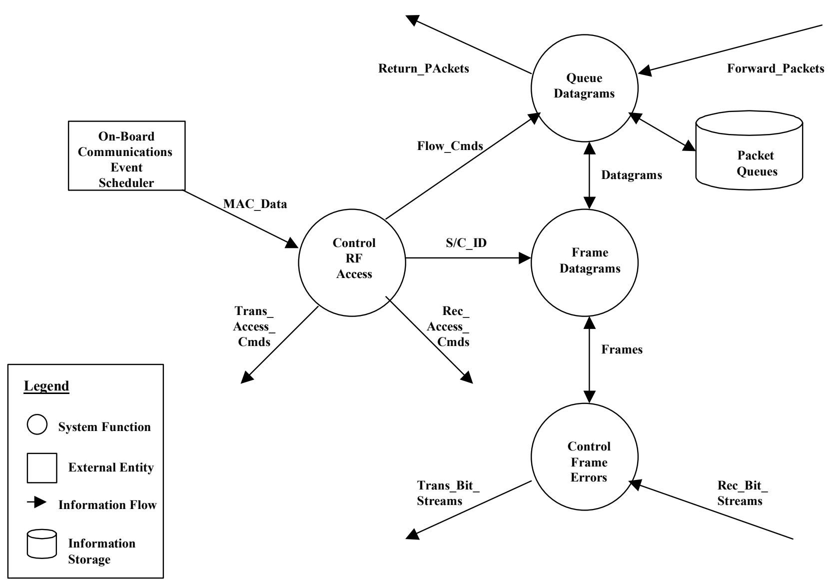

Figure 3-5 Decomposition of the Function Perform OSI Data Link Layer Activities

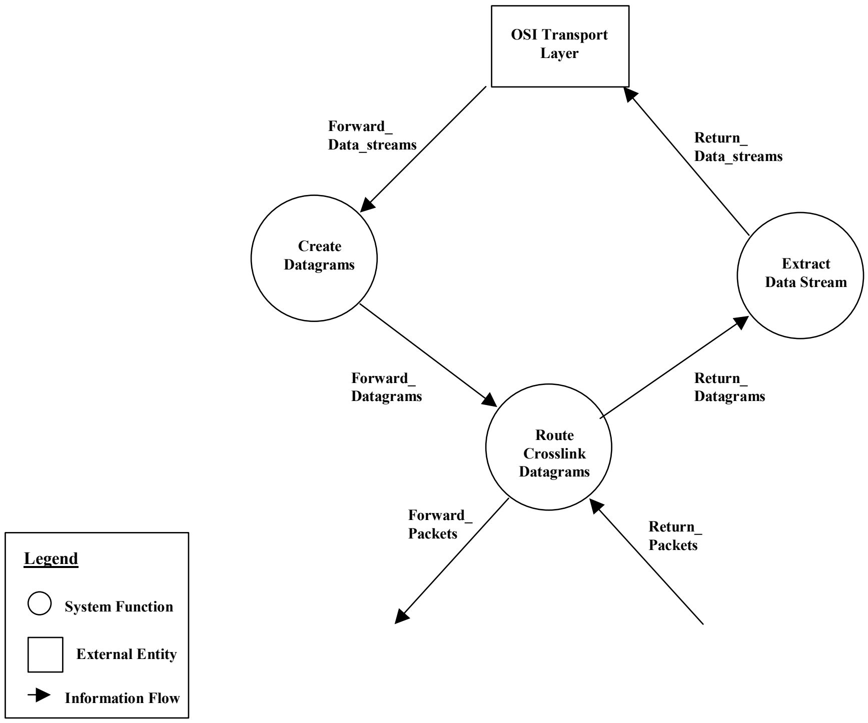

Figure 3-6 Decomposition of the Function Perform OSI Network Layer Activities

Table 3-2 provides a cross-reference between the crosslink communications system Capabilities presented in Section 3.2 and the functions shown in Figure 3-4, 3-5, and 3-6. In general, multiple functions are needed to satisfy the high-level operations capabilities.

Table 3-2: Cross-Reference Between crosslink communications systems Capabilities and Functions

crosslink communications system Operations Capabilities	Control Antenna Function	Modulate Forward Bit Stream Function	Transmit Forward RF Signal Function	Receive Return RF Signal Function	Demodulate Bit Stream Function	Perform OSI Data Link Layer Activities Function	Perform OSI Network Layer Activities Function	Queue Datagrams Function	Frame Datagrams Function	Control Frame Errors Function	Control RF Access Function	Create Datagrams Function	Extract Datagrams Function	Route Crosslink Datagrams Function
Target Partner Spacecraft	X					X	X		X					X
Establish Operational Crosslink		X	X	X	X	X	X	X	X	X	X	X	X	X
Manage Crosslink RF Media Access			X	X		X		X			X			
Network Distributed Spacecraft	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Exchange Crosslink Data		X	X	X	X	X	X	X	X	X	X	X	X	X
Measure Crosslink Signal Characteristics		X	X	X	X						X			
Terminate Operational Crosslink		X	X	X	X	X	X	X	X	X	X	X	X	X

The information flows that are interfaced to the crosslink communications system Functions are briefly described in dictionary provided in Table 3-3. The first column identifies the information flow which is depicted by one or more arrows in the Figures 3-3, 3-4, 3-5, and 3-6. The second and third columns represent the functions or entities external to the crosslink communications system that serve as the sources and destinations, respectively, of the information in the flows. The fourth column contains the name of the parent flow of the information flow. Some flows decompose into several flows with the decomposition of the system functions. Flows that do not decompose are considered to be principal information flows. The last column contains a brief description of the contents of the information flow.

Table 3-3: Dictionary of crosslink communications system Information Flows

Information Flow	Source crosslink communications system Function/ External Entity	Destination crosslink communications system Function/ External Entity	Principal Flow to which this Information Flow Belongs	Information Content
Ant_Select_ Schedule	On-Board Communications Event Scheduler	Control Antennas	Comm_Event_Data	Scheduling information used to determine for what period of time an antenna is to be used to support a crosslink connection
Comm_Event_ Data	On-Board Communications Event Scheduler	crosslink communications system	None: Principal Flow	Crosslink communications event scheduling data (S/C, event start time, event stop time, etc.)

Information Flow	Source crosslink communications system Function/ External Entity	Destination crosslink communications system Function/ External Entity	Principal Flow to which this Information Flow Belongs	Information Content
Comm_Params	On-Board Communications Config Manager	Modulate Forward Bit Stream,/Transmit Forward RF Signal/ Receive Return RF Signal/ Demodulate Return Bit Stream	None: Principal Flow	Service event modulation type, data rate, encoding type, crosslink frequency for both transmit and receive aspects of transceiver
Crosslink_Nav_ Data	Demodulate Return Bit Stream	On-Board Navigation Processor	Nav_Data	Relative navigation measurements made on the crosslink signal
Crosslink_ Signals	Distributed S/C /Crosslink Partner S/C	Crosslink Partner S/C /Distributed S/C	None: Principal Flow	Forward and return signal RF waveforms that transport the crosslink information between the two distributed S/C
Data_Streams	OSI Transport Layer/crosslink communications system	crosslink communications system/ OSI Transport Layer	None: Principal Flow	Bi-directional flow carrying return data to and forward data from the high-level OSI layers.
Datagrams	Queue Datagrams/Frame Datagrams	Frame Datagrams/ Queue Datagrams	None: Principal Flow	Bi-directional flow of datagrams carrying application data packaged for OSI Network Layer routing and assessment
Flow_Cmds	Control RF Access	Queue Datagrams	None: Principal Flow	Information for synchronizing datagram flow control with RF media access control operations
Forward_Data_ Streams	OSI Transport Layer/	Create Datagrams	Data_Streams	Contains data from the high-level OSI layers destined for Partner S/C.
Forward_ Datagrams	Create Datagrams	Extract Data Streams	Datagrams	Datagrams destined for framing and insertion onto the forward crosslink.
Forward_Packets	Route Crosslink Datagrams	Queue Datagrams	Packets	Datagrams sent by the Distributed S/C to the Crosslink Partner S/C
Frames	Frame Datagrams/ Control Frame Errors	Control Frame Errors/ Frame Datagrams	None: Principal Flow	Bi-directional information flow of data frames generated by the Distributed S/C and the Crosslink Parnter S/C
MAC_Data	On-Board Communications Event Scheduler	Perform OSI Data Link Layer/Control RF Access	Comm_Event_Data	Data that provides hardware with controlled access to the RF media
Nav_Data	On-Board Navigation Processor/Demodulate Return Bit Stream	Demodulate Return Bit Stream/ On-Board Navigation Processor	None: Principal Flow	Bi-directional information flow containing navigation data describing the position and velocity of other S/C in the distribution and navigation data obtained from on-board crosslink signal measurements
Packets	Perform OSI Data Link Layer/ Perform OSI Network Layer Activities	Perform OSI Network Layer Activities/ Perform OSI Data Link Layer	None: Principal Flow	Bidirectional information flow of datagrams generated by the Distributed S/C and the Crosslink Parnter S/C
Rec_Access_ Cmds	Perform OSI Data Link Layer/Control RF Access	Receive Return RF Signal	None: Principal Flow	Data that synchronizes the receiver access to the RF resource with the front end reception return crosslink signal
Rec_Ant_Cmd	Control Antennas	Rec Ant	None: Principal Flow	Control commands used to select or steer the crosslink receive antenna
Rec_Bit_Stream	Demodulate Return Bit Stream	Control Frame Errors	None: Principal Flow	Stream of binary data obtained for the Crosslink Partner S/C
Rec_Demod_ Params	On-Board Communications Config Manager	Demodulate Bit Stream	Comm_Params	Parameters that define the return crosslink data modulation attributes (data rate, modulation type, etc.) for the crosslink service
Rec_IF_Signal	Receive RF Signal	Demodulate Bit Stream	None: Principal Flow	IF waveform containing the modulated/coded data stream obtained from the Crosslink Partner S/C
Rec_RF_Params	On-Board Communications Config Manager	Receive RF Signal	Comm_Params	Communications parameters used to set up the front end of crosslink receiver for return services
Received_ Crosslink_Signal	Rec Ant	Receive RF Signal	Crosslink_ Signals	Return crosslink RF waveform transporting the modulated data from the Crosslink Partner S/C

Information Flow	Source crosslink communications system Function/ External Entity	Destination crosslink communications system Function/ External Entity	Principal Flow to which this Information Flow Belongs	Information Content
Return_Data_ Streams	Perform OSI Network Layer Activities/Extract Data Stream	OSI Transport Layer	Data_Streams	Return portion of Data_Stream information flow.
Return_ Datagrams	Perform OSI Network Layer Activities/Route Crosslink Datagrams	Perform OSI Network Layer Activities/Extract Data Stream	Datagrams	Datagrams received by the Distributed S/C from the Crosslink Partner S/C
Return_Packets	Perform OSI Data Link Layer Activities/Queue Datagrams	Perform OSI Network Layer Activities/Route Crosslink Datagrams	Packets	Datagrams received by the Distributed S/C from the Crosslink Partner S/C
Signal_ Pathlength	Control Antenna	Transmit Forward RF Signal	None: Principal Flow	Distance between the crosslink antennas on both members of the crosslink S/C
S/C_ID	Control RF Access	Frame Datagrams	None: Principal Flow	S/C service identification for use in determining frame physical addresses
S/C_Nav_Data	On-Board Navigation Processor	Control Antennas	Nav_data	S/C position information for both members of the crosslink pair used to select the appropriate crosslink antenna or to steer the antenna beam
Trans_Access_ Cmds	Perform OSI Data Link Layer/Control RF Access	Transmit Forward RF Signal	None: Principal Flow	Data that synchronizes access to the RF resource with the transmission of the forward crosslink signal
Trans_Ant_Cmd	Control Antennas	Trans Ant	None: Principal Flow	Control commands used to select or steer the crosslink transmit antenna
Trans_Bit_ Stream	Perform OSI Data Link Layer Activities/Control Frame Errors	Modulate Forward Bit Stream	None: Principal Flow	Stream of binary data destined for the Crosslink Partner S/C
Trans_IF_Sig	Modulate Forward Bit Stream	Transmit RF Signal	None: Principal Flow	IF waveform containing the modulated/coded data stream destined for the Crosslink Partner S/C
Trans_Mod_ Params	On-Board Communications Manager	Modulate Bit Stream	Comm_Params	Parameters that define the forward crosslink data modulation attributes (data rate, modulation type, etc.) for the crosslink service
Trans_RF_ Params	On-Board Communications Manager	Transmit RF Signal	Comm_Params	Communications parameters used to set up the forward crosslink transmitter
Transmit_ Crosslink_ Signal	Transmit RF Signal	Trans Ant	Crosslink_ Signals	Forward crosslink RF waveform transporting the modulated data to the Crosslink Partner S/C

The following paragraphs provide a description of the information processing performed by each of the functions shown in Figure 3-4, 3-5, and 3-6 with respect to the information input and output relative to the functions. Each function transforms the incoming information to produce one or more information outputs to related functions or external entities. The descriptions below briefly summarize the transformation processes associated with each function.

- **<u>Modulate Forward Bit Stream Function</u>**

The Modulate Forward Bit Stream Function shown in Figure 3-4 accepts bit stream data (Trans_Bit_Stream) from the Data Link Layer without regards to the frame data units produced by the Data Link Layer. Once the bit stream is flowing from the Data Link Layer to the Physical Layer's Modulate Forward Bit Stream Function, the function encodes (convolution, block codes, etc.) the bit stream to permit error detection once the information is received by the receive portion of the Physical Layer of the crosslink communications system located on the Crosslink Partner S/C. After the encoding operation has been performed, the encoded bit stream is transformed into an IF waveform representation via modulation processing. The modulated IF waveform (Trans_IF_Sig) is then output from the Modulate Bit Stream Function for input to the Transmit RF Signal Function. The On-Board Communications Manager provides data rates, modulation type (BPSK, QPSK, FSK, etc.), etc. via the specifications (Trans_Mod_Params) in order to support the crosslink service. Subfunctions of the Modulate Forward Bit Stream Function are:

- Set Modulation Data Rate
- Select Forward Modulation Type
- Select Coding Type
- Accept Forward Bit Stream
- Encode Data
- Modulate Data
- Generate IF Signal

❑ **Transmit Forward RF Signal Function**

The Transmit Forward RF Signal Function shown in Figure 3-4 accepts the modulated IF waveform (Trans_IF_Sig) from the Bit Stream Function. The Transmit Forward RF Signal Function upconverts the center frequency of the IF waveform to the carrier center frequency at RF. The Antenna Control Function supplies (Signal_Pathlength) the position of the Crosslink Partner. The upconverted waveform is amplified to a power level that is sufficient to achieve communications with the receiver portion of the crosslink communications system of the Crosslink Partner S/C. The Transmit Forward RF Signal Function accepts frequency, etc. parameters (Trans_RF_Parms) from the On-Board Communications Manager to meet the specifications of the communications event. This function receives RF media access forward crosslink service event scheduling information (Trans_Access_Cmds) from the Control RF access Function. This function outputs the amplified RF signal (Transmit_Crosslink_Signal) to the transmitting antenna (Trans Ant). Subfunctions of the Transmit Forward RF Signal Function are:

- Select Transmit Frequency
- Select Power Level
- Upconvert IF Signal
- Amplify RF Signal
- Transmit RF Crosslink Signal

❑ **Control Antennas Function**

The Control Antennas Function is responsible for ensuring that the crosslink communications can be maintained according to the communications schedule by controlling the positioning of the crosslink antenna beam on the Crosslink Partner S/C. This function accepts S/C navigation data (S/C_Nav_Data) containing position information about both position of both S/C that comprise the crosslink pair from the On-Board Navigation Processor. The function determines the crosslink signal path length from the S/C position data and sends this information to the Transmit RF Signal Function to determine the forward crosslink signal power level determination. The function accepts antenna scheduling data (Ant_Select_Schedule) from the On-Board Communications Event Scheduler that defines the time intervals in which the antenna(s) will be used to support the scheduled crosslink services. This function sends control commands to the transmitter and receiver antennas (Trans_Ant_Cmd and Rec_Ant_Cmd, respectively) to enable and maintain the crosslink connection. The commands may be either switching commands to select between different fixed beam antennas or continuous positioning commands for steerable beam antennas. Subfunctions of the Control Antennas Function are:

- Calculate Spacecraft Positions
- Determine Bore-sight Position Vector

- Calculate Maximum Signal Path Length
- Generate Antenna Control Commands
- Issue Antenna Control Commands

Receive Return RF Signal Function

The Receive Return RF Signal Function shown in Figure 3-4 accepts RF signals (Received_Crosslink_Signal) from the Receiver Antenna (Rec Ant). This function receives RF media access return crosslink service event scheduling information (Rec_Access_Cmds) from the Control RF access Function. The received RF signal is downconverted to IF (Rec_IF_Sig) by translating its center frequency to an IF frequency. This function accepts receiver return RF parameters (Rec_RF_Params) that specify the crosslink service from the On-Board Communications Configuration Manager. Subfunctions of the Receive Return RF Signal Function are:

- Select Receive Frequency
- Amplify Return RF Signal
- Downconvert RF Signal

Demodulate Return Bit Stream Function

The Demodulate Return Bit Stream Function shown in Figure 3-4 accepts IF waveforms (Rec_IF_Sigs) produced by the Receive Return RF Signal Function. The Demodulate Bit Stream Function decodes and demodulates the IF waveform to produce an output bit stream (Rec_Bit_Stream) that is passed to the Crosslink Data Link Layer Function. The On-Board Communications Configuration Manager supplies the Demodulate Bit Stream Function with demodulation parameter (Rec_Demod_Params) such as data rate, modulation type (BPSK, QPSK, FSK, etc.), etc to support the return crosslink service event. The function measures the signal structure to determine the relative separation between the pair of crosslink spacecraft and sends the results (Crosslink_Nav_Data) to the On-Board Navigation Processor. Subfunctions of the Demodulate Return Bit Stream Function are:

- Select Return Modulation Type
- Select Demodulation Data Rate
- Select Type of Decoding
- Accept Return IF Signal
- Compensate for Doppler Shift
- Demodulate IF Signal
- Extract Navigation Data

Control RF Access Function

The Control RF Access Function shown in Figure 3-5 manages the Transmit RF Signal and Receive RF Signal Functions according to the implemented Multiple Access scheme. The function accepts media access event scheduling information (MAC_Data) from the On-Board Communications Event Scheduler. The function transforms the information into transmitter and receiver directives (Trans_access_cmds and Rec_Access_Cmds, respectively) that synchronize the physical transmission and reception of crosslink RF waveforms with the media access control subfunction within the Crosslink Data Link Layer Function. Flow control commands (Flow_Cmds) are sent to the Queue Datagrams Function to provide coordination of queuing and dequeing activities with the access time intervals. The function outputs the identity of the spacecraft (S/C_ID) to the Frame Datagrams Function to provide physical addressing information to the transmission frames.

Queue Datagrams Function

The Queue Datagrams Function shown in Figure 3-5 manages the flow of datagrams into and from the Data Link Layer. Forward datagrams (Forward_Packets) from the Perform Network Layer Activities Function are queued and dequeued (in Packet Queues Storage) by this function in coordination with the information (Flow_Cmds) supplied by the Control RF Access Function. When RF access is available, forward datagrams are extracted from the Packet Queues Storage and sent (Datagrams) to the Frame Datagrams Function. When RF access is not available, the datagrams remain queued. Return datagrams (Datagrams) from the the Frame Datagrams Function are received by this function and queued or passed (Return_Packets) to the Perform Network Layer Activities Function shown in Figure 3-4.

Frame Datagrams Function

The Frame Datagrams Function shown in Figure 3-5 manages the packing of datagrams into frames for transmission across the crosslink. The forward data frames are created by this function and sent (Frames) to the Control Frame Errors Function. The physical addressing for the forward frame is determined form information (S/C_ID) obtained from the Control RF Access Function relative to the participants in the scheduled crosslink communications event. Return data frames (Frames) are received from the Control Frame Errors Function and decomposed into return datagrams (Datagrams) for transmission to the Queue Datagrams Function.

Control Frame Errors Function

The Control Frame Errors Function shown in Figure 3-5 manages the error correction operations at the frame level of data transmission. This function receives forward frame data (Frames) from the Frame Datagram Function and performs Forward Error Correction (FEC) operations on the frame. After FEC operations have been completed, the frame is output as a forward bit stream (Trans_Bit_Streams) to the Modulate Forward Bit Stream Function shown in Figure 3-4. The Control Frame Errors Function accepts return bit streams (Rec_Bit_Streams) from the Modulate Return Bit Stream Function shown in Figure 3-4. The return bit stream data is assessed in terms of frames by the Control Frame Errors Function and FEC is applied to correct any frame errors that occurred during the crosslink transmission. After the FEC operation is completed, the return data frames (Frames) are sent to the Frame Datagrams Function.

Create Datagrams Function

The Create Datagram Function shown in Figure 3-6 manages the construction of datagrams from the stream of application level message data (Forward_Data_Streams) obtained from the OSI Transport Layer. After creation, the forward datagrams (Forward_Datagrams) are sent to the Route Crosslink Datagrams Function.

Extract Data Stream Function

The Extract Data Stream Function shown in Figure 3-6 manages the retrieval of application level message data (Return_Datagrams) from the Route Crosslink Datagrams Function. After extraction, the return data is then sent (Return_Data_Streams) to the OSI Transport Layer.

Route Crosslink Datagrams Function

The Route Crosslink Datagram Function shown in Figure 3-6 manages the flow of datagrams (Forward_Datagrams, Return_Datagrams, Forward_Packets, and Return_Packets) through the crosslink system. Routing is accomplished by the application of logical addresses to the datagrams. This function determines the best path to route the datagram through the distributed spacecraft Network. If the topology of the distribution is such that the spacecraft maintain the same or nearly the same relative positions with respect to each other, routing can be implemented with a fixed routing table. If the relative positions of the members of the distribution change significantly, dynamic routing tables must be maintained based on the time varying geometry of the distribution. In the latter case, navigation and communications event scheduling information (not shown in Figure 3-6) would be needed for this function to determine the best path through the distributed spacecraft system Network.

3.5.3 Crosslink Communications System State Transitions

The functional decomposition of the crosslink communications system described above does not show the time-dependent behavior of that system. The time-dependent behavior of the system can be depicted in a state transition diagram such as the shown in Figure 3-7. This representation is a dynamic model of a crosslink communications system that can support up to N independent crosslinks services simultaneously.

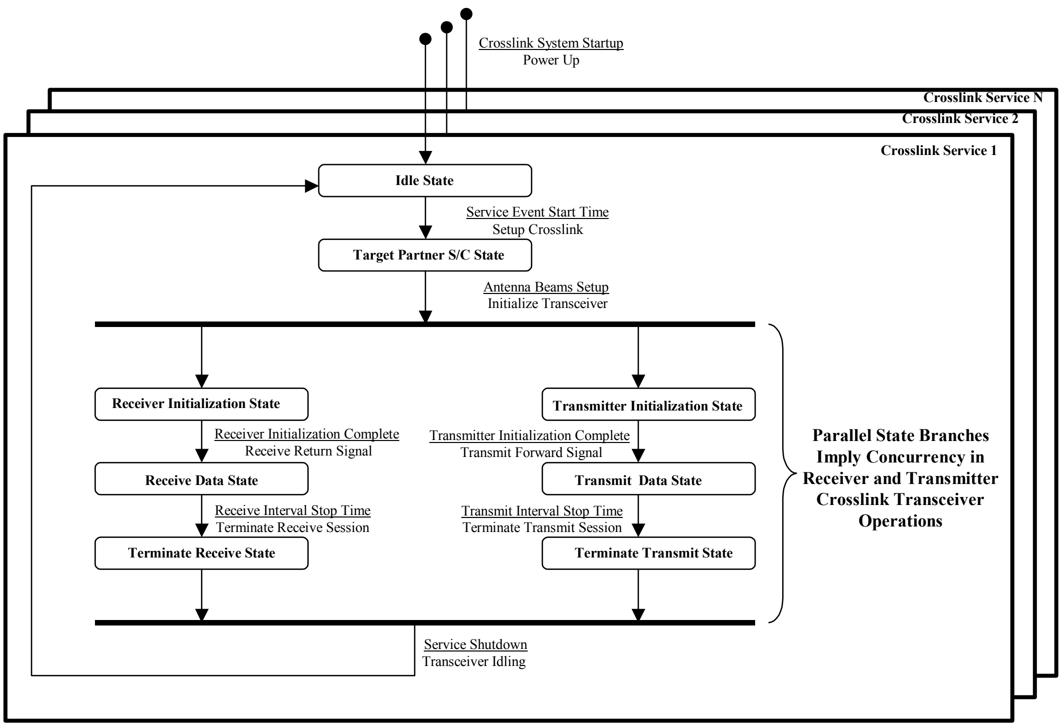

Figure 3-7 crosslink communications system Transition Diagram

The parallel planes shown in Figure 3-7 represent the collective states for each of the N crosslink services (1,2,…,N) supported simultaneously by the crosslink communications system. Each plane is a duplicate of the first plane that is labeled Crosslink Service1. Except for the common power up operations of the transceiver to the initial Idle State operations, each plane of crosslink service states operates independent of any other plane. This implies that the operational state of anyone service is not dependent on the operational state of any other service at any given time. As shown for Crosslink Service 1, the states on a plane are represented by the rectangular structures and the arrows that interconnect them represent the transitions that carry the system between states. The labels on the arrows define the condition that triggers the transition and the actions that arise as the result of the condition. The condition is shown above the horizontal line and the resultant action is presented below the line. The bold horizontal, parallel lines in the diagram indicate that the two branches of state sequences bounded by the two lines are capable of occurring concurrently during crosslink service sessions. The following sections summarize the operations that take place in each of the Crosslink Service 1 states shown in Figure 3-7. The same state descriptions and relationships apply to the other Crosslink Services 2 through N.

- **Idle State**

The Idle State characterizes the crosslink communications system operations during those periods when a RF connection does not exist with another distributed spacecraft. Both the transmit and receive functions are placed in an idle mode. Antenna control is no longer operational. The communications system waits for new crosslink service instructions from the Communications Event Scheduler.

- **Target Partner S/C State**

This state encompasses all those activities need to be performed to choose and setup the crosslink antenna that will be used to support an upcoming crosslink service event. Navigation assessments are performed to assess the existing spatial relationship between the spacecraft that will engage in the service. The appropriate antenna will be chosen for optimal performance. If the available beams are fixed relative to the body of the spacecraft, the choice will be made based on the line-of-sight and gain alternatives. If the beam is steerable, the beam will be positioned on the Partner S/C and beam tracking operations will begin. In missions with simple, relatively fixed topologies this state may be optional since single antenna coverage could provide continuous coverage without the need for targeting for special case distributed spacecraft architectures.

- **Transmit Initialization State**

This state encompasses the establishing of the carrier on the forward crosslink from the distributed spacecraft and its Crosslink Partner S/C. General configuration of the transmitter occurs when this state is invoked prior to the onset of a crosslink service. The configuration of the transmitter complies with that of the receiver on the Crosslink Partner S/C. The power-level will be selected based on the signal path length between the two spacecraft. Frequency, modulation, data rates, and other communications parameters are installed in the transmitter front-end and modulation sections of the transceiver. Signal acquistion frames and idle frames are placed on the carrier to setup the forward crosslink before science communications can begin. These operations continue until the onset of steady-state science and engineering data can begin.

- **Transmit Data State**

This state represents the steady-state exchange of science and engineering data associated with the scheduled crosslink service. Crosslink network flow control manages the insertion of frames into the crosslink bit streams. Queues containing science and engineering data are emptied and their frames are transferred to the Crosslink Partner S/C. When the queues are emptied and no further science data is forthcoming from the on-board science equipment, idle frames are generated to keep the crosslink active until the next burst of science and engineering data arrives to be forwarded to the Partner S/C.

- **Terminate Transmit State**

This state encompasses the operations associated with the graceful termination of a forward crosslink service. The transmitter no longer outputs an RF signal, data modulation ceases, and network flow control terminates the insertion of queued datagrams into the forward crosslink information stream.

- **Receiver Initialization State**

This state encompasses the configuration of the receiver with the communications attributes that define the return crosslink service. The configuration complies with the configuration of the Transmitter on the Partner S/C. Frequency, modulation, data rates, and other communications parameters are installed in the receiver front-end and demodulation sections of the transceiver. This state is operational during the acquisition of the return crosslink signal. Once acquisition has been accomplished, idle frames are processed until the onset of steady-state return crosslink services commence.

- **Receive Data State**

This state encompasses the steady-state receipt of the return crosslink signal from the Crosslink Partner S/C and extraction of science and engineering information from that signal. Bit streams are extracted by the demodulation function and return frames are constructed from the resultant bit streams.

- **Terminate Receive State**

This state encompasses the operations associated with the graceful termination of a return crosslink service. The receiver no longer processes return signal data.

The functions derived in Section 3.5 participate in establishing the states described above. One or more functions must be invoked when the crosslink communications system is in a given operations state. Table 3-4 relates the functions to the operational states for a single Crosslink of the crosslink communications system. It is representative of the of the relationship that must exist between the states and functions that are supported by each Crosslink Service implemented by the crosslink communications system.

Table 3-4: Participation of crosslink communications system Functions in Operational States

crosslink communications system Operations States	Control Antenna Function	Modulate Forward Bit Stream Function	Transmit Forward RF Signal Function	Receive Return RF Signal Function	Demodulate Bit Stream Function	Perform OSI Data Link Layer Activities Function	Perform OSI Network Layer Activities Function	Queue Datagrams Function	Frame Datagrams Function	Control Frame Errors Function	Control RF Access Function	Create Datagrams Function	Extract Datagrams Function	Route Crosslink Datagrams Function
Idle State								X			X			
Target Partner S/C State	X							X			X			
Transmitter Initialization State	X	X	X			X	X	X	X	X	X	X	X	X
Transmit Data State	X	X	X			X	X	X	X	X	X	X	X	X
Terminate Transmit State	X	X	X			X	X	X	X	X	X	X	X	X
Receiver Initialization State	X			X	X	X	X	X	X	X	X	X	X	X
Receive Data State	X			X	X	X	X	X	X	X	X	X	X	X
Terminate Receive State	X			X	X	X	X	X	X	X	X	X	X	X

3.5.4 Crosslink Communications System Operations

This section describes three basic crosslink communications system operations scenarios in terms of the system functions, information flows, and external entities described in Section 3.5.2. The scenarios provide another time-sequenced or time dependent perspective of the crosslink communications system functions from the standpoint of three fundamental crosslink communications operations that must take place in the distributed spacecraft environment in order to provide a single communications services. These operations are:

- Crosslink antenna control operations,
- Forward crosslink data transfer operations, and
- Return crosslink data transfer operations.

The scenarios are presented in the form of tables. Each table has row entries that correspond to a specific information flow described above. Table 3-5 characterizes the activities associated with the targeting of the Crosslink Partner S/C. Tables 3-6 and 3-7 characterize the activities associated with information exchanges on the forward and return crosslinks, respectively. The order of the information flow events as they occur in the scenario is from top to bottom in the table. The number in the first column of the table indicates the order in the overall sequence. The name of the flow is presented in column two of the table. The order of the subsets of information flows is not always unique. The shaded columns correspond to the external entities to which the crosslink communications system interfaces. The remaining columns identify the functions and antennas associated with the crosslink communications system. Each row has an S and a D recorded in it indicating the source and destinations, respectively, of the information flows. The crosslink communications system transmit and receive and antennas occupy two columns in the tables.

Table 3-5: Crosslink Antenna Control Operations Scenario

Scenario Event Sequence Number	Information Flow	Crosslink Partner S/C	On-Board Navigation Processor	On-Board Communications Event Scheduler	On-Board Communications Configuration Manager	OSI Transport Layer	Transmit Antenna	Receive Antenna	Control Antenna Function	Modulate Forward Bit Stream Function	Transmit Forward RF Signal Function	Receive Return RF Signal Function	Demodulate Bit Stream Function	Queue Datagrams Function	Frame Datagrams Function	Control Frame Errors Function	Control RF Access Function	Create Datagrams Function	Extract Datagrams Function	Route Crosslink Datagrams Function
1	Ant_Select_Schedule			S					D											
2	S/C_Nav_Data		S						D											
3	Trans_Ant_Cmd						D		S											
4	Rec_Ant_Cmd							D	S											

Table 3-6: Forward Crosslink Data Transfer Operations Scenario

Scenario Event Sequence Number	Information Flow	Crosslink Partner S/C	On-Board Navigation Processor	On-Board Communications Event Scheduler	On-Board Communications Configuration Manager	OSI Transport Layer	Transmit Antenna	Receive Antenna	Control Antenna Function	Modulate Forward Bit Stream Function	Transmit Forward RF Signal Function	Receive Return RF Signal Function	Demodulate Bit Stream Function	Queue Datagrams Function	Frame Datagrams Function	Control Frame Errors Function	Control RF Access Function	Create Datagrams Function	Extract Datagrams Function	Route Crosslink Datagrams Function
1	MAC_Data			S													D			
2	Flow_Cmds													D			S			
3	S/C_ID														D		S			
4	Trans_Access_Cmds										D						S			
5	Trans_Mod_Params				S					D										
6	Trans_RF_Params				S						D									
7	Forward_Data_Streams					S												D		
8	Forward_Datagrams																	S		D
9	Forward_Packets													D						S
10	Datgrams													S	D					
11	Frames														S	D				
12	Trans_Bit_Streams									D						S				
13	Trans_IF_Sig									S	D									
14	Transmit_Crosslink_Si g						D				S									
15	Forward Crosslink	D					S													

Table 3-7: Return Crosslink Data Transfer Operations Scenario

Scenario Event Sequence Number	Information Flow	Crosslink Partner S/C	On-Board Navigation Processor	On-Board Communications Event Scheduler	On-Board Communications Configuration Manager	OSI Transport Layer	Transmit Antenna	Receive Antenna	Control Antenna Function	Modulate Forward Bit Stream Function	Transmit Forward RF Signal Function	Receive Return RF Signal Function	Demodulate Bit Stream Function	Queue Datagrams Function	Frame Datagrams Function	Control Frame Errors Function	Control RF Access Function	Create Datagrams Function	Extract Datagrams Function	Route Crosslink Datagrams Function

1	**MAC_Data**			S													D			
2	**Flow_Cmds**													D			S			
3	**S/C_ID**														D		S			
4	**Rec_Access_Cmds**																S			
5	**Rec_RF_Params**				S							D								
6	**Rec_Demod_Params**				S								D							
7	**Return Crosslink**	S						D												
8	**Received_Crosslink_Signal**							S				D								
9	**Rec_IF_Sig**											S	D							
10	**Rec_Bit_Stream**												S			D				
11	**Frames**														D	S				
12	**Datagrams**													D	S					
13	**Return_Packets**													S						D
14	**Return_Datagrams**																		D	S

3.6 High-Level Crosslink Communications System Prototype Requirements

This section provides the high-level crosslink communications system functional and performance prototype requirements derived from the crosslink communications functions presented from various requirements modeling perspectives described in Section 3.5. These system-level requirements are considered to be prototype requirements since they are not for a specific mission but instead are intended to represent general requirements common to a cross-section of the missions reviewed in the Spectrum Requirements and Allocation Survey and Recommendation document. Different subsets of the prototype requirements will apply to specific missions. Table 3-8 provides a both functional and performance requirements for the crosslink communications system. The requirements presented in Table 3-8 are grouped by the functions identified in the requirements modeling information provided above. Since these are prototype requirements that can apply to the entire range of distributed spacecraft missions, TBD is used to represent a position holder for the numerical values that would be included in the requirements for a specific mission.

Table 3-8: crosslink communications system High-Level Functional and Performance Prototype Requirements

crosslink communications system Function	Functional Requirements	Performance Requirements
Control Antennas	1. The crosslink communications system must accept navigation data for both S/C in the crosslink pair. 2. The crosslink communications system must calculate the position of both S/C in the crosslink pair. 3. The crosslink communications system must use the attitude of the distributed Spacecraft to determine the relative angle of the antenna bore-sight with-respect-to a line joining the crosslink S/C pair. 4. The crosslink communications system must select the fixed beam crosslink antenna option that provides the maximum gain for a crosslink implementation. 5. The crosslink communications system must guide moveable beam crosslink antennas such that the bore site stays on the target S/C. 6. The crosslink communications system must target a Crosslink Partner S/C via its physical network address within the Distributed S/C group. 7. The crosslink communications system must control multiple crosslink beams to support multiple simultaneous crosslink services.	8. The crosslink communications system must be able to switch between fixed beam crosslink antennas within TBD seconds. 9. The crosslink communications system must be able to slew a moveable beam crosslink antenna to a new target within TBD seconds prior to the onset of the crosslink service. 10. The crosslink communications system must be able to target moveable beam crosslink antenna bore-sights within TBD degrees of the calculated position of the Partner S/C. 11. The crosslink communications system must simultaneously target up to TBD Crosslink Partner S/C.
Control Frame Errors	1. The crosslink communications system must perform Forward Error Correction (FEC) operations on Distributed S/C network frames. 2. The crosslink communications system must generate forward crosslink bit streams from the forward crosslink frames. 3. The crosslink communications system must detect return crosslink frames from the return crosslink bit streams. 4. The crosslink communications system must detect return crosslink frame errors.	5. The crosslink communications system must be able to simultaneously perform FEC data recovery operations on TBD demodulated return bit streams. 6. The crosslink communications system must be able to simultaneously perform FEC data preparation operations on TBD forward bit streams.

crosslink communications system Function	Functional Requirements	Performance Requirements
Control RF Access	1. The crosslink communications system must accept coordinating information from the On-Board Communications Event Scheduler for MA management. 2. The crosslink communications system must control crosslink transmitter emissions such that different crosslink pairs within a mission do not interfere with each other. 3. The crosslink communications system must control crosslink receiver reception such that the designated Crosslink Partner S/C signal is received according to the service event schedule. 4. The crosslink communications system must accept the time schedule for Distributed S/C TDMA operations. 5. The crosslink communications system must compensate for propagation delays in TDMA operations. 6. The crosslink communications system must accept S/C crosslink frequency assignments for Distributed S/C FDMA operations. 7. The crosslink communications system must use a distribution time standard to determine time slot boundaries for TDMA operations. 8. The crosslink communications system must accept S/C PN code assignments for Distributed S/C CDMA operations. 9. The crosslink communications system must detect crosslink transmissions for collision avoidance among Distributed S/C RA transmit operations.	10. The crosslink communications system must maintain a time standard to an accuracy of TBD seconds to support TDMA operations. 11. The crosslink communications system must wait TBD seconds after a collision condition is detected prior to attempt to broadcast using RA MA operations. 12. The crosslink communications system must manage RF access for TBD S/C.
Create Datagrams	1. The crosslink communications system must create datagrams from on-board science and engineering applications. 2. The crosslink communications system must assign logical addresses to each datagram. 3. The crosslink communications system must insert data from on-board science and engineering applications into the datagrams.	

crosslink communications system Function	Functional Requirements	Performance Requirements
Demodulate Return Bit Stream	1. The crosslink communications system must demodulate the received IF signal using the implemented service data rate. 2. The crosslink communications system must demodulate the received IF signal using the service modulation type (BPSK, QPSK, FSK, etc.) 3. The crosslink communications system must apply the Doppler compensation corrections to the IF signal. 4. The crosslink communications system must transform the return crosslink bit streams using a decoding algorithm. 5. The crosslink communications system must apply the service PN code to despread the return crosslink CDMA IF signals. 6. The crosslink communications system must perform cross-correlations on two-way crosslink signal pseudorandom codes to estimate the range delay. 7. The crosslink communications system must provide an alternative for demodulating Sensor Web waveforms on the return crosslink.	7. The crosslink communications system must acquire the return crosslink signal within TBD seconds after the initial detection of signal energy. 8. The crosslink communications system must demodulate TBD return IF signals simultaneously into bit streams.
Extract Data Stream	1. The crosslink communications system must extract data streams from the received datagrams. 2. The crosslink communications system must supply data streams to the on-board science and engineering applications via the ISO Transport Layer.	3. The crosslink communications system must simultaneously extract at least TBD data streams from the return datagrams.

crosslink communications system Function	Functional Requirements	Performance Requirements
Frame Datagrams	1. The crosslink communications system must frame forward crosslink datagrams. 2. The crosslink communications system must manage the fragmenting of datagrams across frames. 3. The crosslink communications system must assign a Distributed S/C network physical address to each frame. 4. The crosslink communications system must order received frames according to the order in which they are sent. 5. The crosslink communications system must detect the absence of a frame in the sequence of received frames. 6. The crosslink communications system must request retransmission of missing received frames from the Partner S/C when connection based operations are underway. 7. The crosslink communications system must extract datagrams from return crosslink frames. 8. The crosslink communications system must control the flow of frames on the forward crosslink. 9. The CSS must construct standardized frames to be interoperable with other spacecraft on the Sensor Web. 10. The crosslink communications system must have access to the physical addresses of other spacecraft on the Sensor Web.	11. The crosslink communications system must simultaneously manage the framing of TBD independent forward crosslink datagrams. 12. The crosslink communications system must manage the simultaneous extraction of datagrams from TBD independent return crosslink frames.

crosslink communications system Function	Functional Requirements	Performance Requirements
Modulate Forward Bit Stream	1. The crosslink communications system must transform digital bit streams into IF waveforms. 2. The crosslink communications system must modulate the forward IF signal using the service modulation type (BPSK, QPSK, FSK, etc.) 3. The crosslink communications system must accept data rate designation parameters to support a crosslink service. 4. The crosslink communications system must modulate PN codes onto forward crosslink IF waveforms for CDMA operations. 5. The crosslink communications system must transform the forward crosslink bit streams using an encoding alogorithm. 6. The crosslink communications system must use pseudorandom code sequences that are long enough to support unambiguous range measurements over the length of the crosslink. 7. The crosslink communications system must provide modulation alternatives that are compatible with the Sensor Web modulation standards.	8. The crosslink communications system must modulate bit stream data onto TBD forward IF signals simultaneously.
Queue Datagrams	1. The crosslink communications system must queue forward crosslink datagrams to provide flow control. 2. The crosslink communications system must queue return crosslink datagrams to provide flow control. 3. The crosslink communications system must release queued datagrams when flow density is below the congestion threshold.	4. The crosslink communications system must maintain a queue size of TBD forward datagrams. 5. The crosslink communications system must simultaneously queue datagrams for up to TBD S/C.
Receive Return RF Signal	1. The crosslink communications system must acquire the return crosslink RF signal. 2. The crosslink communications system must transform return crosslink RF waveforms into IF digital waveforms. 3. The crosslink communications system must filter out extraneous RF signal energy.	4. The crosslink communications system must be able to receive TBD crosslink signals simultaneously. 5. The crosslink communications system must simultaneously transform TBD independent RF crosslink signals into individual IF waveforms.

crosslink communications system Function	Functional Requirements	Performance Requirements
Route Crosslink Datagrams	1. The crosslink communications system must route a forward crosslink datagrams using logical S/C addresses. 2. The crosslink communications system must determine the best path for routing a datagram through a distributed spacecraft system Network. 3. The CSS must route return crosslink datagrams to other S/C when the logical address is associated with another S/C. 4. The crosslink communications system must maintain static routing tables for a fixed topology Distributed S/C architecture. 5. The crosslink communications system must maintain dynamic routing tables for a time varying topology Distributed S/C architectures. 6. The crosslink communications system must determine the routing path for time varying topologies using the Distribution's navigation data. 7. The crosslink communications system must route datagrams to spacecraft beyond the bounds of its distribution when Sensor Web situations demand crosslink information exchanges.	
Transmit Forward RF Signal	1. The crosslink communications system must transform forward crosslink IF or digital waveforms into RF waveforms. 2. The crosslink communications system must transmit RF waveforms according to the MA protocol. 3. The crosslink communications system must adjust the output transmitter power to close the crosslink between the two S/C in the crosslink pair. 4. The crosslink communications system must accept the crosslink transmit frequency. 5. The crosslink communications system must filter transmitted waveforms to remove extraneous signal energy.	6. The crosslink communications system must be able to transmit TBD RF crosslink signals simultaneously. 7. Thes crosslink communications system must simultaneously transform TBD forward IF (or digital) waveforms into individual RF forward crosslink signals. 8. The crosslink communications system must transmit the forward crosslink at a frequency of TBD Hz. 9. The crosslink communications system must transmit on the forward crosslink with BERs equal to or less than. TBD. 10. The crosslink communications system must transmit with a carrier frequency stability of TBD Hz. 11. The crosslink communications system must transmit the unmodulated carrier with a phase noise less than TBD RMS when integrated between TBD Hz and TBD Hz. 12. The crosslink communications system must maintain a residual amplitude modulation of the phase modulated RF signal less than TBD % RMS.

4 Survey of Potential Crosslink Communications System Standards

4.1 Overview

This section is provided in order to summarize a high-level assessment of existing communications standards within the context of the crosslink communications system functions described in Section 3. Evaluating exiting standards can provide the benefit of reducing the work needed to arrive at a potential crosslink communications system standard for distributed spacecraft missions. While it cannot be expected that the existing standards can provide a complete set of specifications that meets all of the goals established by the prototype requirements presented in Table 3-8, certain aspects of these standards may be useful for adoption as part of some future crosslink communications system standard. Section 4.2 summarizes the findings relative to the review of the existing standards. The standards that are addressed for comparisons in this section are:

- **Spacecraft Communications Standards**
  - Base Consultative Committee on Space Data Systems (CCSDS)
  - Proximity-1
  - Iridium
- **Wireless Standards**
  - Institute of Electrical and Electronic Engineers (IEEE) Standard 802.11
  - IEEE Standard 802.11a
  - IEEE Standard 802.11b
  - IEEE Standard 802.15
  - IEEE Standard 802.16
  - Bluethooth Standard
  - Home RF Standard
- **Network Protocol Standards**
  - Ethernet (ALOHA Spread Spectrum)

4.2 Standards Survey Summary

Table 4-1 provides a comparison of the of various standards described in Sections 4.3 through 4.6 in terms of a subset of functions presented in Section 3 that readily lend themselves to this high-level assessment. Columns one and two contain the crosslink communications system functions and columns 3 through 13 contain the standards. A review of the high-level description of the standards within the objective of identifying the functions produced the distilled information presented in Table 4-1. Yes and No entries indicate whether the function was addressed by the standard. NS indicates that the description of the standard did not specify any information about the function.

The information presented in Table 4-1 suggests that the identification of existing standards for crosslink communications system adoption is complicated by many factors. In general, the ideal characteristics for crosslink communications system adoption do not lie in a single standard but instead they are spread across multiple standards. For example, some standards have milliwatt level power specifications that are ideal for nanostat applications but they have maximum ranges of tens of meters that limit their usefulness except for the most compact distributed spacecraft missions. None of the standards address the complicated antenna control issues associated with distributed spacecraft mission operations. This is to be expected since the unique geometrical characteristics of distributed spacecraft missions are not a problem for terrestrial wireless systems. distributed spacecraft missions with compact architectures that lend themselves to simple omni antenna solutions can most likely benefit from some of the wireless standards. Large distributed spacecraft missions with long crosslink signal path lengths and dynamic distribution architectures will require augmented implementation solutions if a particular wireless standard is to be adopted. For example, higher power levels and the addition of antenna control standards need to be added to any existing wireless standard.

Table 4-1: Comparison of Reviewed Communications Standards within the Context of crosslink communications system Functions

Major crosslink communications system Functions	Lower Level Physical and Data Link Layer Functions	Base CCSDS	Proximity-1	802.11	802.11a	802.11b	HomeRF	Bluetooth	802.15	802.16	Iridium	Ethernet (ALOHA Spread Spectrum)
Modulate Forward Bit Stream	Set Modulation Data Rate	NS	2 Mbps	2 Mbps	6-54 Mbps	11 Mbps	2 Mbps	700 Kbps	20-55 Mbps	260 Mbps	2.4 Kbps	10 Mbps
	Select Modulation Type (BPSK, QPSK, FSK, etc.)	NS	PSK PSK-Coherent	GFSK	BPSK QPSK 16/64 QAM	DBPSK DQPSK	2GFSK 4GFSK	GFSK	16/32/64 QAM	QPSK 16/64 QAM	QPSK	NS
	Select Coding Type [Convolution (CON) and Reed-Solomon (RS) codes]	CON Turbo codes RS codes	CON RS codes CRC	CON	CON	CCK	NS	CVSD	Trellis Code Modified	FEC	NS	NS
	Accept Forward Bit Stream	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Encode Data	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Modulate Data	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Generate IF Signal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Transmit Forward RF Signal	Select Transmit Frequency	No	Yes (401Mhz 437Mhz) 26 Ghz	Fixed 2.4 Ghz	Fixed 5 Ghz	Fixed 2.4 Ghz	Fixed 2.4 Ghz	Fixed 2.56 Ghz	Fixed 2.45 Ghz	Yes 10-66 Ghz 2-11 Ghz 5-6 Ghz	Y (1625 MHz, 19.4 Ghz)	No

Major crosslink communications system Functions	Lower Level Physical and Data Link Layer Functions	Base CCSDS	Proximity-1	802.11	802.11a	802.11b	HomeRF	Bluetooth	802.15	802.16	Iridium	Ethernet (ALOHA Spread Spectrum)
	Select Power Level	NS	NS	NS	NS	NS	100 mW	1 mW	NS	NS	NS	NS
	Upconvert RF Signal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Amplify RF Signal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Transmit RF Crosslink Signal	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control Antennas	Calculate Spacecraft Positions	No	No	No	No	No	No	No	No	No	No	No
	Determine Bore-sight Position Vector	No	No	No	No	No	No	No	No	No	No	No
	Calculate Maximum Signal Path Length	No	No	No	No	No	No (40 m Max)	No (10 to 100 m Max)	No (10 m Max)	No	No	No
	Generate Antenna Control Commands	No	No	No	No	No	No	No	No	No	No	No
	Issue Antenna Control Commands	No	No	No	No	No	No	No	No	No	No	No
Receive Return RF Signal	Select Receive Frequency	No	Yes (401Mhz 437Mhz) 26 Ghz	Fixed 2.4 Ghz	Fixed 5 Ghz	Fixed 2.4 Ghz	Fixed 2.4 Ghz	Fixed 2.56 Ghz	Fixed 2.45 Ghz	Yes 10-66 Ghz 2-11 Ghz 5-6 Ghz	Yes (1625 MHz, 19.4 Ghz)	No
	Amplify Return RF Signal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Downconvert RF Signal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Demodulate Return Bit Stream	Select Demodulation Date Rate	NS	2 Mbps	2 Mbps	6-54 Mbps	11 Mbps	2 Mbps	700 Kbps	20-55 Mbps	260 Mbps	2.4 Kbps	10 Mbps
	Select Demodulation Type (BPSK, QPSK, FSK, etc.)	NS	PSK PSK-Coherent	GFSK	BPSK QPSK 16/64 QAM	DBPSK DQPSK	2GFSK 4GFSK	GFSK	16/32/64 QAM	QPSK 16/64 QAM	QPSK	NS
	Select Coding Type [Convolution (CON) and Reed-Solomon (RS) codes]	CON Turbo codes RS codes	CON RS codes CRC	CON	CON	CCK	NS	CVSD	Trellis Code Modified	FEC	NS	NS
	Accept Return IF Signal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Compensate for Doppler Shift	NS	Yes	No	No	No	No	No	No	No	No	No
	Demodulate IF Signal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Major crosslink communications system Functions	Lower Level Physical and Data Link Layer Functions	Base CCSDS	Proximity-1	802.11	802.11a	802.11b	HomeRF	Bluetooth	802.15	802.16	Irridium	Ethernet (ALOHA Spread Spectrum)
Control RF Access	Manage RF Access	TDMA	NS	FHSS CDMA	OFDM	DSSS	TDMA CSMA/CA	FHSS	FHSS CDMA	TDMA DAMA	FDMA TDMA CDMA	Better than TDMA FDMA CDMA

Abbreviations & Acronyms

BPSK	Binary Phase Shift Keying
CCS	Crosslink Communications System
CCSDS	Consultative Committee for Space Data Systems
CDMA	Code Division Multiplexed
COTS	Commercial Off the Shelf
DSM	Distributed Spacecraft Mission
DSS	Distributed Spacecraft System
FDMA	Frequency Disvion Multiplexed
FEC	Forward Error Correction
FSK	Frequency Shift Keying
GEO	Geosynchronous Earth Orbit
HEO	High Earth Orbit
Hz	Hertz
IF	Intermediate Frequency
ISO	International Organization for Standardization's
LAN	Local Area Network
LEO	Low Earth Orbit
LISA	Laser Interferometer Space Antenna
MA	Multiple Access
MAGIC	Magnetic Imaging Constellation
MEO	Medium Earth Orbit
MHz	Megahertz
MMS	Magnetic Multiscale
OSI	Open Systems Interconnection
PI	Planet Imager
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RF	Radio Frequency
RMS	Root-Mean-Squared
S/C	Spacecraft
TBD	To Be Determined
TDMA	Time Division Multiple Access
WAN	Wide Area Network