Decentralized Space-Data Dissemination for Low-Cost, Dense Satellite Networks

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Abstract— **Recent trends in scientific Low Earth Orbit (LEO) satellite missions involve small, low-cost satellites, communicating with multiple low-cost ground stations. We propose a peer-to-peer multicast ground distribution scheme accompanied by a best-effort, broadcasting mechanism with randomized retransmissions, tailored for such satellite missions. Through our simulation tools we assess the performance of the new, low-cost model, evaluate the benefits of a decentralized ground distribution and quantify the tradeoff between data reliability and data return volume.**

Index Terms—**Earth Observing System, Low Earth Orbit (LEO) satellites, ns-2 simulator, peer-to-peer computing, space-terrestrial communication, telecommunication network reliability.**

I. INTRODUCTION

SPACE agencies and research institutes organizing Earth observation missions worldwide focus on employing Low Earth Orbit (LEO) satellites due to the close proximity of LEO to the Earth surface. Operating at approximately 200-2000 km, LEO satellites provide much finer observation capabilities than their Medium Earth Orbit (MEO) and Geosynchronous Equatorial Orbit (GEO) counterparts, which orbit at approximately 20,000 km and 35,786 km, and have been mainly used for navigation and telecommunication applications, respectively [1]. Most operational LEO scientific missions rely on large, expensive satellites that include high-end communication subsystems, contacting stations on the ground over point-to-point, bidirectional links. Once the physical connection locks, the satellite downlinks the collected data in a reliable fashion. In special cases, data transfer may take place following a broadcast approach.

Recent trends in aerospace engineering include the development of smaller, low-cost satellites, enabling institutes with limited budget to build their own spacecraft [2] and, also, allowing for the deployment of highly populated constellations (termed “satellite swarms”) [3]. Likewise, corresponding ground communication equipment is inexpensive and easy to setup, allowing for extensive deployment that leads to more frequent contact opportunities, albeit of considerably lower capacity. These new technologies are bound to extend space-data access to a much wider audience [4], but also, considering the vast amounts of scientific data produced by modern satellite equipment, significantly complicate the management of space-data on the ground. Due to the high volume of mission data, the ground distribution process, rather than the space link, may become the bottleneck, calling for efficient data distribution, storage, and retrieval schemes.

In light of these advances, ESA is exploring data dissemination paradigms that will better suit the characteristics of low-cost, high-population satellite networks and will also be able to cope with the vast amounts of scientific data collected by modern satellite equipment. Building on the concept described in ESA’s statement of work [5], we propose a broadcast-based, peer-to-peer (P2P) return model for satellite data and present our end-to-end, from space to the end-user, simulation model for evaluating the proposed solution.

The original contribution of our work unfolds in three directions: a) proposing a broadcast-based, variable reliability transmission scheduling in space combined with a P2P data distribution on the ground for low-cost, dense satellite networks, b) describing our developed simulation tools modeling traditional point-to-point vs. broadcast transmission, and traditional centralized vs. decentralized ground distribution schemes, c) presenting select end-to-end simulation results reporting on the performance of various delivery models with respect to the data requirements of each space application type.

The simulation framework can be used to support various design decisions related to low-cost, dense satellite networks and assist in determining appropriate systems parameters depending on the mission requirements. Our simulations explore the extent to which a large number of satellites and a dense network of ground stations may compensate for the limited bandwidth achieved by low-cost telecommunication equipment. In the hands of mission designers our tools may be combined with equipment cost information in order to address cost-benefit types of questions, such as whether installing additional ground stations or implementing reliability mechanisms could improve the mission cost-per-byte.

Our proposed model includes a best-effort, broadcast transmission with optional delivery feedback that can be deployed over well-known space-data transmission protocols including CFDP [6], and the DTN Bundle Protocol [7][8]. The transmission scheduling algorithm assumes a data acquisition rate lower than the available bandwidth and exploits the

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excess bandwidth for selectively retransmitting data employing a randomized retransmission mechanism. Data dissemination on the ground implements a peer-to-peer multicast distribution scheme, similar to a push variant of the popular BitTorrent protocol [9]. Adopting a peer-to-peer multicast approach targets at eliminating duplicate network traffic and offloading central nodes, traditionally burdened with the role of collecting and distributing mission data. Moreover, acquired data can be readily available, through such a distribution scheme, to interested end-users located in the vicinity of the receiving ground station, avoiding any delays caused by central collection and processing.

The presented simulation tools have been developed in STK [10] and ns-2 [11] simulation environments and model all stages of the data lifecycle: acquisition on-board the satellite, packaging, fragmentation, transmission scheduling, ground distribution, delivery feedback, reassembly, and end-user delivery. The main focus of this paper is on the ns-2 network simulation, which utilizes the results of the physical simulation conducted in STK.

The rest of this paper is organized as follows. In chapter II we cover the related work in the subjects of satellite data transmission, space networking, ground data distribution and satellite network simulation. In chapter III we categorize mission requirements, present reference missions and develop the data delivery models. In chapter IV we give a detailed description of the simulation model and in chapter V we present the simulation setting and the simulation results. In chapter VI we summarize our conclusions and describe our future work plans.

II. RELATED WORK

LEO satellites have been, for some decades now, a basic pillar of Earth observation missions, due to their ability to capture more detailed data in comparison with satellites in GEO orbits. Constellations of two or more satellites bearing the same scientific payload have also been employed to gather data more frequently, and, thus, in a more timely fashion, mitigating the problem of long revisit periods inflicted by LEO orbits. Typically for this type of missions, scientific data are downlinked to designated ground stations, and even broadcast to multiple end-users with suitable equipment, as in the case of NASA's EOS Terra, Aqua and NPP missions [12]. GEO satellites can also be employed as a means to relay data (e.g. Tracking and Data Relay System [13], European Data Relay System [14]) significantly increasing the downlink capacity. The Morning and Afternoon-Train (A-Train) constellations [15], comprising satellites belonging to NASA's Earth Observation System, ESA's Sentinels [16], Disaster Monitoring [17] and Rapid Eye [18] are some notable examples of Earth Observation satellite missions mainly operated by major space agencies.

Contrasting this pattern of high-end, high-cost satellites, the QB50 mission envisages a low-cost, distributed LEO satellite network [19]. QB50 aims to be the first space mission to deploy a cluster of 50 Cubesats for multi-point, in-situ measurements in the lower thermosphere. These Cubesats will be supported by the Global Educational Network for Satellite Operations (GENSO), a network of low-cost ground stations spread across the globe. Motivated by the growing interest in such small satellite constellations the authors in [20] develop analytical models and simulation tools that evaluate the space communication capacity of federated ground station networks (FGSNs). The presented models and tools can be used in order to maximize the data returns of small satellite missions.

Departing from these types of missions and data return models, our concept builds on a constellation of small, inexpensive satellites broadcasting scientific data to low-cost ground terminals. Contrary to the practice followed by NASA's EOS [12] missions, where broadcasting is used as a complementary mechanism, we consider broadcasting as the primary means of data transmission. Our transmission model provides adjustable reliability over unidirectional links, but also, incorporates an optional delivery feedback mechanism for improving system performance. In this context, our proposal differentiates from other broadcast or multicast protocols, which are either incapable of utilizing delivery feedback, such as FLUTE [21], or strictly require delivery feedback for their operation, such as NORM [22] and RMUS [23].

The transmission of space-data may be facilitated by a number of space communication protocols standardized by the Consultative Committee for Space Data Systems (CCSDS). Common data-link protocols include the Telemetry/ Telecommand (TM/TC) [24][25] and Advanced Orbiting Systems (AOS) [26]. On top of these protocols files can be transferred using the CCSDS File Delivery Protocol (CFDP) [6]. Space protocols may also be combined with traditionally terrestrial protocols. Researchers in [27] employ CFDP on top of TCP/IP and UDP/IP and report on a cislunar application of the proposed protocol stack.

More recently, the Delay- and Disruption-Tolerant architecture (DTN) [7] and the Bundle Protocol (BP) [8] have been developed in order to support seamless communication in the space and ground segments alike. The BP achieves hop-by-hop reliability for long-haul space links with the help of the Licklider Transmission Protocol (LTP) [28]. The performance of LTP over long-delay asymmetric links, typical in space communications, is analytically characterized by researchers in [29]. In space DTN routing is facilitated by the Contact Graph Routing (CGR) [30] algorithm which relies on predetermined contacts among space assets. CGR may be enhanced with additional mechanisms such as the Bundle Delivery Time Estimation (BDTE) [31] allowing for bundle route prediction, and calculation of plausible arrival times.

Once space-data have been successfully received on the ground, their distribution and management typically involves end-user access through online portals. An FTP or HTTP download is initiated as soon as the end-user selects the data he/she is interested in. ESA's "Earth Online" [32] and NASA's "NASA Earth Observations" [33] portals are two prominent examples of websites offering this type of space data access. A DTN overlay is employed in the Space-Data Routers project [34] to deliver data to end-users. The latter can optionally filter unnecessary data out through an online web-interface. We approach the issue of data dissemination by setting a P2P multicast overlay that effectively eliminates multiple data transmissions and provides shorter routes to interested parties.

Through the integration of broadcasting in space and multicasting on the ground, we propose a novel end-to-end, space-to-ground networking architecture. Our architecture exploits low-cost space and ground assets to deliver space-data to interested end-users. The versatile transmission scheduling mechanism is appropriate for both unidirectional, as well as bidirectional links, and also, supports asynchronous delivery feedback through designated ground stations.

During the design of mission return models, simulation tools can be of great importance for making educated decisions. To the best of our knowledge, currently available simulation tools mainly focus on the space segment and provide no means for modeling terrestrial data distribution entities, thus prohibiting complete end-to-end simulations. In [35], the authors couple the STK tool with Matlab to analyze the performance of CubeSat constellations based on a store-and-forward communications model; a feature that is not currently supported by the STK Engine. The authors in [36][37] follow a methodology similar to ours simulating coverage ability and inter-satellite links performances of constellations in STK, while simulating delay, throughput and jitter in ns-2. The respective ns-2 extension employed in [36] constitutes a highly customized solution suitable only for simulating specific LEO communication scenarios. Furthermore, none of the ns-2 extensions employed either in [36] or [37] support store-and-forward data distribution, a feature that is natively supported in our proposed simulation framework.

III. SYSTEM DESCRIPTION

A. Mission Requirements

Huge volumes of Earth observation data are produced daily by space missions orbiting the Earth. Once these raw data are received on the ground, they are processed by scientists so that useful information can be extracted. These higher-level products can then be exploited by a wide set of applications, ranging from water management to large-scale mapping and from space-weather monitoring to soil protection. It is exactly this diverse nature of space-related applications that creates the need for different types of data and data transmission models, as depicted in Fig. 1.

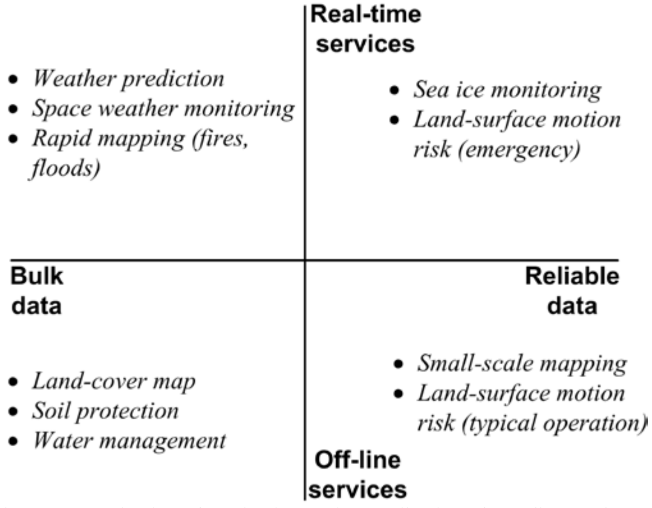

Fig. 1. Categorization of Earth Observation applications depending on the type of space-data they consume.

Applications related to emergency response situations, such as flooding or fire mapping, typically require real-time data in order to produce meaningful results. Indeed, space-generated photographic data of disaster-struck areas need to be transmitted as soon as possible; otherwise they may not be useful to emergency response personnel that operate in the area. On the other hand, Earth observation data are also used in off-line applications, such as water management or land mapping, which do not require real-time data to meet their objectives.

Another differentiating factor characterizing space applications is the reliability requirements they set on the Earth observation data they consume. Applications such as small scale mapping require high reliability, since any lost data will result in missing tiles on the map. Other applications, though, such as lower-resolution land-cover mapping services, can operate even if some data are lost. The same applies to real-time applications where high resolution imaging is not necessary. A prominent example of this type of applications is space weather monitoring, where data containing radiation measurements around the globe are transmitted in near-real time, to allow for accurate predictions.

It is quite apparent, considering the diversity of Earth observation missions and their corresponding data requirements, that a single data production and distribution model that fits all types of missions cannot exist. Therefore, communication models should enable mission planners to adjust the system parameters in order to optimize performance and efficiency according to the targeted application.

B. Space Link Models

Modeling of the space links takes place in the STK simulator and enables performance comparisons among traditional and newly proposed satellite communication patterns. The space link models used in the present study fall into the following three categories: *Direct point-to-point*, *relay point-to-point* and *low-cost broadcast*. The point-to-point models represent communication patterns that are currently in use by space agencies, whereas the low-cost broadcast models correspond to the recent developments that focus on large numbers of inexpensive satellites and ground stations.

In the direct point-to-point communication pattern, we consider short, direct, high-speed contacts between a single satellite and 3 ground stations (one at any given time). This is similar to a traditional setting where a satellite bearing high-end communication equipment connects to a limited number of ground stations with matching equipment, once per orbit. In the relay point-to-point case, we consider a single high-end satellite that communicates with 3 GEO relay satellites (again one at any given time), each relaying data to its corresponding ground station on Earth. Due to possible multiplexing at the relay satellites, the bandwidth of the inter-satellite link is assumed to be lower than the bandwidth of the direct connection. However, the relay connection yields much higher overall downlink capacity due to the almost continuous visibility provided by the GEO relays. The reference communication platform in this case is the European Data Relay System [14]. Finally, the low-cost broadcast communication pattern assumes low-cost satellites with matching ground equipment, yielding a large number of short, low-speed, and possibly overlapping contacts. The low-cost broadcast communication pattern has been applied to various simulation topologies with one or more satellites and a dense network of ground stations. Namely, the topologies contain 1 satellite with 52, 100 and 140 ground stations and 6 and 46 satellites with 52 ground stations.

C. End-to-End Data Delivery

The data produced on board the satellite are transported over the space links and through the network to interested end-users. This section includes an overview of the end-to-end data delivery models highlighting the relationship between the space link type and the ground segment layout. The network elements that participate in the data delivery models are: satellites (Sat), ground stations (GS), mission control centers (MCC), end-users (EU), principal investigators (PI) and uplink ground stations. Satellites, ground stations and end-users are included in all models, whereas a mission control center, a principal investigator and uplink ground stations take part in a subset of the models.

The ground segment layout may be either centralized or decentralized. In a centralized layout satellite, data received at the ground stations are forwarded to a mission control center. The mission control center is then responsible for forwarding the data to the interested end-users in a client-server fashion. In the decentralized layout satellite, data are tagged with a Type-of-Service (ToS) identifier and forwarded to the end-users over a P2P multicast network, similar to a push version of the BitTorrent protocol. End-users subscribe to the desired ToS in order to receive only relevant data, possibly produced by certain scientific instruments. The subscribed nodes in each ToS form a P2P multicast network.

The point-to-point space link models described in the previous section (direct and relay) are combined with a centralized ground segment representing the current practice in organizing space missions. Here we assume bidirectional space links with ground stations sending acknowledgments over the uplink when they successfully receive data. The corresponding end-to-end models are referred to as *direct* and *relay*. The low-cost broadcast link model is combined with both a centralized and a decentralized ground segment, which are referred to as *broadcast client-server* and *broadcast P2P* respectively. The broadcast P2P model represents a fully distributed network setting, where end-users have immediate access to satellite data received at nearby ground stations, and corresponds to the architecture proposed in the original ESA statement of work. The broadcast client-server model is used comparatively with broadcast P2P in order to quantify the benefits of a distributed vs. a centralized ground data distribution approach. In the broadcast P2P model, one of the end-users can be designated as the principal investigator, responsible for generating acknowledgments, and one of the ground stations as the uplink, responsible for transmitting the acknowledgments to the satellite. The acknowledgments are sent from the principal investigator to the uplink ground station and transmitted during the next contact with the satellite.

In a real deployment, data produced on the satellite could be transported as DTN bundles or CFDP data units, encapsulated over the space link in TM or AOS packets. Ground stations receiving the satellite data should be aware of the higher layer protocols and forward incoming packets onto the appropriate network nodes, depending on the implemented distribution scheme. The overall system architecture is depicted in Fig. 2.

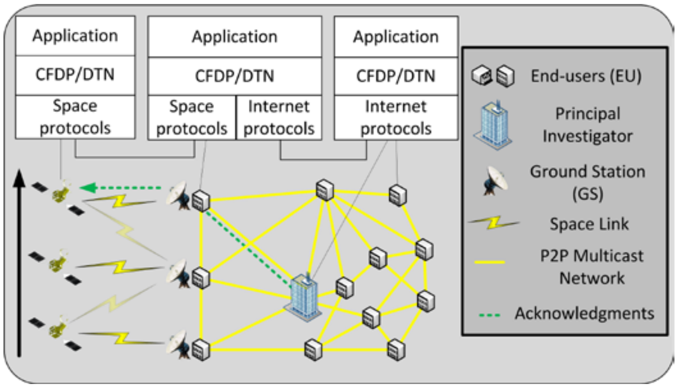

Fig. 2. Overall system architecture.

D. Data Production and Transmission Scheduling

Application data production on the satellite is assumed to follow a uniform pattern. Scientific instruments continuously acquire data at a constant rate, package them into Application Data Units (ADUs) of a specified size and pass them on to the networking subsystem. In order for an ADU to be created the appropriate amount of data must be first acquired; thus, the networking subsystem receives ADUs of the specified size in regular intervals. The size of the ADU must be greater than or equal to the minimum useful granule of data for a certain application (e.g. an Earth observation image and associated metadata, or a set of measurements). For performance reasons multiple data units may be combined into a single ADU, especially in case of extremely small data units (e.g. a single temperature measurement). The networking subsystem fragments incoming ADUs into a number of PDUs, according to a specified PDU size and inserts these PDUs into the transmission buffer. Old PDUs may need to be removed in case a certain buffer threshold is exceeded, thus, imposing an implicit data time-to-live (TTL). PDUs may be transported via diverse routes and reassembled at the destination nodes (the mission control center or some end-user).

The transport agent at the satellite continuously broadcasts PDUs at a rate imposed by the available bandwidth. Newly created data are given higher priority over data that have been transmitted at least once, so new PDUs are transmitted as they arrive in a first-come-first-served order. When all data have been transmitted at least once an ADU is randomly selected from the buffer and transmission resumes with the first PDU belonging to the selected ADU. Transmission continues sequentially until all PDUs belonging to the selected ADU have been transmitted, at which point a new ADU is randomly selected for retransmission and the process iterates. If at any point during the randomized retransmission phase new PDUs arrive, the process is interrupted and the new PDUs are transmitted first. The data TTL plays an important role in this process as it dictates how retransmission effort will be distributed among old and recently created PDUs. A high TTL value would favor older PDUs while a low TTL value would favor newer PDUs.

Fig. 3 shows an example case where the transmission buffer contains 4 ADUs of 5 PDUs each. While transmitting PDU 3 of ADU 2 a new ADU arrives (ADU 4) interrupting the retransmission of ADU 2 so that ADU 4 can be transmitted for the first time. As soon as all PDUs belonging to ADU 4 have been transmitted retransmission of ADU 2 resumes with the transmission of PDU 4. When ADU 2 finishes retransmitting (i.e. PDU 5 is transmitted) one of the four stored ADUs is randomly selected for retransmission and the process repeats.

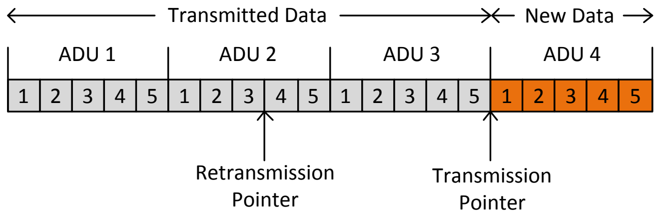

Fig. 3. Transmission buffer example with 4 ADUs of 5 PDUs each.

At the event of an acknowledgment reception the corresponding PDU is removed from the buffer so that future retransmission is avoided. If reception feedback is not available (as in the case of broadcasting with no uplink capability), it is possible that PDUs already received on the ground may be retransmitted wasting downlink bandwidth. This is also possible during the time the relevant acknowledgments are buffered at the uplink ground station awaiting the next available contact. If ground stations initiate the acknowledgments (as in the point-to-point models) unnecessary retransmissions are eliminated. It is evident that a delivery feedback mechanism is an optional enhancement, but not a requirement for the system.

Transmission at the satellite may be limited only when at least one ground station is within range. The benefit from limiting transmission is two-fold: a) transmitted PDUs are more likely to be received on the ground (they are transmitted only when someone is receiving), b) valuable satellite energy is conserved. In case of point-to-point connections (i.e. direct and relay point-to-point models), information on the presence of a receiving ground station is readily available due to the bidirectional nature of the physical link. In the broadcast models such information is not available, due to the general lack of an uplink channel, calling for some out-of-band mechanism. Transmission intervals may either be directly preloaded on the satellites or, alternatively, the ground station locations may be preloaded and transmission could suspend/resume depending on the current satellite location.

IV. SIMULATOR AND EXPERIMENTAL METHODOLOGY

The communication patterns and data delivery models of the previous section are simulated by a combination of STK as the physical simulator modeling the satellite orbits, and ns-2 as the network simulator modeling the end-to-end network, from the satellite application to the end-user (EU). The STK simulator calculates the physical characteristics of the space links (i.e. link up-down events, bandwidth, error rate and delay), which are then imported into ns-2 and incorporated in the end-to-end topology.

The STK simulation takes into consideration the physical aspects of the reference missions, including the orbit geometry of the satellite, geographical locations and coverage of ground stations, as well as the start epoch and duration for each scenario. Link budgets for each contact between satellites and ground stations are calculated using detailed models of the satellite transmitter and ground station receiver, already available in STK. The STK simulation experiments are based on three templates (direct point-to-point, relay point-to-point and low-cost broadcast), corresponding to the space link models described in section III.B.

In ns-2 the entire topology is modeled as an IP network using UDP in space and TCP on the ground. The central entity of the network simulation is a Store-and-Forward (SnF) agent that we have developed in ns-2 and is based on a DTN simulation model described in [38]. The SnF agent is deployed as an overlay on the relevant nodes (i.e. satellites, ground stations, mission control center, end-users, principal investigator), while the rest of the topology consists of pure IP nodes, relaying upper layer traffic. The STK output is used in order to create links with the appropriate characteristics between satellite and ground station nodes and also to set these links to the up/down state accordingly during simulation.

A. *Ns-2 Store-and-Forward Agent*

The SnF agent can be deployed over TCP or UDP, both in space and on the ground. The agent exposes an interface that accepts the number of bytes to be transmitted and, optionally, the data Type-of-Service (ToS). Through this interface the agent creates ADUs, which are then fragmented into one or more PDUs, based on the maximum PDU size parameter. The PDUs are inserted into a sending buffer of a user-defined capacity. Newly arrived PDUs may cause the eviction of old PDUs in the case of buffer space shortage.

Each SnF agent maintains a list of virtual connections to neighboring SnF agents. These connections function as routing table entries while also hold information on the TCP or UDP agents involved in the connection with the SnF peer. Selecting connections for forwarding incoming PDUs is done at simulation time based on criteria described in later sections. PDUs belonging to the same ADU are merged, and, if the original ADU is fully reconstructed, delivered to the application.

B. *Satellite Operation*

Data production is simulated by a custom application module that is configured to produce an ADU of a certain size every some time period. The user sets the desired daily data production rate as well as the ADU size and the simulation script calculates the ADU production period. Each application tags the ADUs it creates with a ToS number. An arbitrary number of application modules can be attached to the same SnF agent, enabling the simulation of complex data generation patterns. ADUs received at the SnF agent are fragmented into the appropriate number of PDUs and entered into the buffer.

In the general case, satellites continuously broadcast to any ground station that may be receiving. Satellite-deployed SnF agents use UDP as the underlying protocol of the space link with ground stations. The packet/frame size overhead can be configured based on the total overhead of the underlying protocols, independently of the PDU header imposed by the higher layer protocol (i.e. CFDP, DTN, etc).

Data broadcasting is simulated through a group of point-to-point links from the satellite (Sat) to the ground stations (GS). Each Sat node has links to all GS nodes. The state of each link is set to up or down by utilizing the dynamic topology capabilities of ns-2, according to the STK output. When setting a link to the up or down state the corresponding SnF virtual connections are created or destroyed respectively. The point-to-point approach was preferred over a pure broadcast method (i.e. using a wireless protocol such as 802.11), since it allows for precise control over the space link characteristics (bandwidth, delay, error rate).

The SnF agent at the satellite implements the randomized retransmission pattern described in previous sections. Once all new PDUs are transmitted for the first time a random PDU is selected from the buffer. Transmission resumes at the first PDU of the ADU that the randomly selected PDU belongs to. At the reception of an acknowledgment the corresponding PDU is removed from the buffer. Transmission at the satellite agent may freeze by some external trigger, while normally accepting new data, facilitating the simulation of the suspend/resume mechanism.

C. Ground Network

PDUs received at a GS are forwarded to the appropriate nodes of the SnF overlay based on route calculations taken place prior to simulation start. Route calculation involves creating one overlay multicast distribution tree per GS, per ToS, utilizing the virtual connection feature of the agent. Pruning is employed during simulation in order to avoid duplicate data transmission.

The SnF agent supports optional uplink functionality, in which case acknowledgments are either generated directly at the receiving GS or at a principal investigator (possibly subscribed to all ToS) and routed to a designated uplink GS. At the next contact the uplink GS forwards all stored acknowledgements to the satellite.

The ground segment may include a Mission Control Center (MCC) entity, in which case, routing is done in two tiers. In the first tier routes are setup between the MCC and each GS for all ToS and, in the second tier, routes are setup from the EUs to the MCC.

Finally, the EUs connected to the overlay may subscribe for receiving data belonging to one or more ToS and also act as routers in the corresponding application-layer multicast trees. ToS subscription is an important feature of our proposed scheme, since it allows for categorizing space-data. However, the simulations presented in this paper employ a single ToS, which all participating EUs are subscribed to. Experimenting with data prioritization on the basis of different ToS is part of our future plans.

D. Topology

The ground topology has been created using the gt-itm tool [39], shipped as part of the ns-2 distribution. We used the original Waxman model [40] with alpha and beta parameters of 0.12 and 0.3 respectively, and created 200 nodes on a square plane of edge size 100 units. The alpha and beta parameters, reflecting the edge probability and the long to short edge ratio respectively, were selected so that the produced graph would be well-connected and of a relatively short diameter. The resulting graph consists of a single biconnected component with an average degree of 8.29 (average number of links per node), a diameter of 5 hops (maximum hop count between any two nodes) and an average depth of 4.055 (average hop count between all pairs of nodes). The average length for the graph edges was 37.1 units.

The created graph is converted into an ns-2 topology file where the delay of each link is set to the link length scaled by 0.1 ms, resulting in an average link delay of 3.71 ms. The link bandwidth is globally set to a user-defined value for all ground links. In most cases the bandwidth value is adequately high so that ground links are not the bottleneck (1Gbps and 18 Mbps for the point-to-point and the low-cost broadcast cases respectively).

Depending on the configuration, only a subset of the 200 nodes is used for hosting SnF agents, while the remaining nodes function as pure IP nodes. The assignment of the SnF agents to the topology nodes follows the order of GS, MCC and then EU. Due to their special characteristics satellite nodes are created separately, resulting in a higher number of overall simulated nodes.

Simulations that focus on the space segment performance employ only one EU, so that simulation time is not unnecessarily prolonged. Multiple EUs are used only in the scenario where the ground segment performance is studied.

E. Performance Metrics

The results of the simulation experiments are reported with the help of the following performance metrics:

--Delivery Ratio: The percentage of the created ADUs successfully delivered to all end-users:

$$\frac{ReceivedADUs}{CreatedADUs * EU\_Number}$$

--Delivery Latency: The average data latency between the production time of on the satellite and their delivery to the EUs.

--Data Volume: The total amount of actual data, not including the headers, that was delivered successfully to the EUs. ADUs received at multiple EUs contribute multiple times their size.

F. Data Unit Sizing

Ns-2 simulates network protocols at the packet level and so computational complexity is determined by the overall number of processed PDUs. Due to the high level of simulation detail ns-2 is normally used for small-scale experiments. In order to adapt it for large-scale simulations (i.e. length of 10 days and GBs of data), we tried to lower complexity while maintaining fidelity of the results. In this spirit, we experimented with larger PDUs, reducing the number of PDUs for a certain level of data production rate. However, increasing the PDU size does not allow using the BER that is calculated by STK (i.e. for large PDU size all PDUs would be corrupted). In order to overcome this problem, we calculated the Packet Error Rate that corresponds to the given BER for a realistic nominal PDU size. The calculated PER was then applied to the larger PDUs of the simulation yielding analogous error effect.

The BER was converted to PER using the well-known conversion formula:

$$PER = 1 - (1 - BER)^{8*PacketSize}$$

PacketSize was set to the value of 65,000 bytes (approximately 64 KB) as this is the maximum size for a TM encapsulation packet. The validity of the conversion approach was confirmed through a series of short comparative simulations, using an always up, high-speed link such as the one from the direct point-to-point model.

Based on the previous analysis the sizes of the ADU and PDU are set at 10^9, 10^8 bytes (approximately 1 GB, 100 MB) for the point-to-point models and 10^7, 10^6 bytes (approximately 10 MB, 1 MB) for the low-cost models respectively. In all cases an ADU consists of 10 PDUs.

V. Simulation Results

A. *Physical Simulations*

The simulations conducted in the STK simulator calculate the contact opportunities in the direct point-to-point, relay point-to-point and low-cost broadcast space link models, described in section III.B. First, a selection of transmission systems based on UHF-, S- and X-Bands were compared so that the most efficient system for the low-cost broadcast model would be found, in terms of contact opportunities duration, communication link quality and power consumption. The results indicated that S-band is the most appropriate solution, since it allows for longer uninterrupted contacts, increased total contact time and decreased Bit Error Rate (BER) at system level. The calculated BER corresponds to the effective error after Forward Error Correction has been applied on the physical link. Due to space limitations elaborating on physical simulation details is omitted from the current paper.

The physical parameters finally selected for each space link model are:

--Direct point-to-point: 1 Satellite, X-Band at 520 Mbps, BER 10^{-7}, 3 ground stations.

--Relay point-to-point: 1 Satellite, X-Band, inter-satellite link at 100 Mbps, BER 10^{-7}, 3 GEO satellites.

--Broadcast (S-Band 3 Mbit/s, BER 10^{-7}):

--52, 100 and 140 ground stations with 1 satellite.

--6 and 46 satellites with 52 ground stations (QB50-like mission models).

In all cases, satellites are orbiting in sun-synchronous orbit at 700 Km, with an inclination of 96.7 degrees. Sun synchronous orbit, the most common orbit for imaging applications, is selected here because it provides better coverage of the Earth surface, resulting in a higher number of contact opportunities. The ground stations are spread across the globe, including areas and places such as Europe, Canada, overseas territories, world-wide embassies and ESA-operated ground station locations. Finally, the duration of the simulations is set at 10 days, which is a full period for the satellite orbit (i.e. the satellite passes over the same locations). The link-up and link-down events for each of these contacts are defined as when the calculated bit error rate exceeds a configurable threshold parameter, typically set at 10^{-7} in our simulations.

Table I presents contact opportunities statistics for each one of the examined scenarios. Avg. Duration is the average contact duration, and Total Duration and Total Capacity are the contact duration and capacity after any overlapping contacts have been merged.

TABLE I
Contact Opportunities Statistics

Link Model	Avg. Duration	Total Duration	Total Capacity
Direct	8 mins	23.6 hours	5.5 TB
Relay	1.3 hours	10 days	10.8 TB
Broadcast (52 GSs, 1 Sat)	7.4 mins	1.3 days	43.4 GB
Broadcast (100 GSs, 1 Sat)	7.4 mins	3.1 days	100 GB
Broadcast (140 GSs, 1 Sat)	7.4 mins	3.7 days	119 GB
Broadcast (52 GSs, 6 Sats)	6.6 mins	8.1 days	260 GB
Broadcast (52 GSs , 46 Sats)	5.8 mins	40.7 days	1.3 TB

B. *Point-to-Point Simulations*

Our aim in the point-to-point case was to study the system behavior and gauge its capacity under the conditions commonly used nowadays. The satellites only transmit data during contacts and ground stations immediately acknowledge received PDUs over bidirectional links. First, we experimented with the direct model (i.e. no relay satellite) using a daily data production of 400 GB and varying the Time-to-Live (TTL) for the satellite data (by appropriately adjusting the transmission buffer), in an attempt to specify an appropriate TTL value. It can be seen in the chart of Fig. 4 that the delivery ratio increases with the TTL up to the 12 hour value, where it slightly exceeds 97%. For a TTL of 24 hours results are identical, so we select 12 hours as an appropriate TTL for the transmission mechanism. The delivery latency increases with the delivery ratio since higher TTL values give older data better chances of being received, contributing to the average delivery latency reported on the chart.

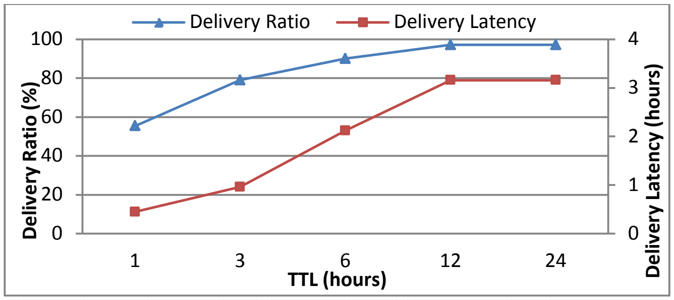

Fig. 4. Direct point-to-point delivery ratio and latency varying data TTL.

For the selected TTL of 12 hours, we experimented with various daily data production values ranging from 100 to 600 GB. The results are shown in the chart of Fig. 5. For low daily data production values (100 and 200 GB), the delivery ratio is over 99%, while the total system throughput is quite poor at 1 and 2 TB, respectively. The system throughput increases up to a daily data production value of 400 GB, where the delivery ratio is slightly over 97% and the data volume is 4 TB. For higher data production values the delivery ratio drops and the system throughput remains the same or drops as well. The small percentage of lost data for a daily data production up to 400 GB amounts mostly to data produced towards the end of the simulation, allowed only limited time in order to be delivered (data production continues until the simulation end). From the above discussion we deduce that the maximum data that the system can reliably accommodate is 400 GB per day. Following the same methodology, we found that for the relay point-to-point model the corresponding value was 1 TB per day.

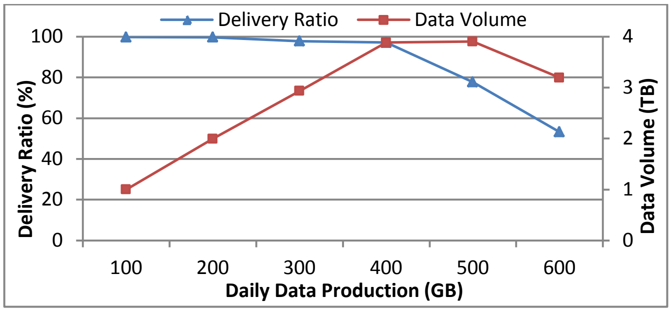

Fig. 5. Direct point-to-point delivery ratio and data volume varying the daily data production.

C. *Baseline Broadcast Simulations*

Similarly to the previous section, this section includes simulation experiments aiming at selecting an appropriate data TTL and probing the system capacity for the broadcast models. Since a single EU is used the ground distribution method (P2P or client-server) does not significantly affect the simulation outcome, so the results apply to both cases. Using a moderate daily data production of 2 GB, we experimented with data TTL values ranging from 1 to 24 hours, assuming the collected data are time-insensitive.

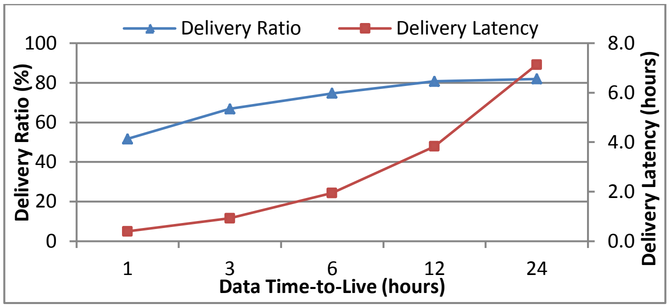

Fig. 6. Low-cost broadcast delivery ratio and latency varying data TTL.

Our findings, which are depicted in Fig. 6, show that the data delivery ratio exhibits a steady increase up to a 12-hour TTL and remains almost the same (slightly over 80%) for the 24-hour TTL case. However, the delivery latency in the 24-hour case is almost double that of the 12-hour case, so we select the 12 hours TTL value, as in the point-to-point models.

Using the 12-hour TTL we experimented with daily data production values ranging from 0.5 to 30 GB. The chart of Fig. 7 clearly highlights the tradeoff between the achieved delivery ratio and the total volume of delivered data. For very small data production values, the delivery ratio is almost 100%, while the data volume is a mere 5 GB (0.5 GB per day for 10 days). For a data production of 2 GB the data volume is 16.5 GB at a delivery ratio of 82.7%. Increasing the data production increases the data volume to almost 37 GB, which is close to the maximum theoretical capacity of 45 GB reported in section V.A. The corresponding value for the delivery ratio is as low as 12%. For time insensitive applications requiring data reliability, such as small scale mapping and typical land surface motion, a TTL of 12 hours and a data production below 2 GB would be appropriate system parameters. Applications requiring data bulk such as soil protection and water management could push data production to around 10 GB, achieving 31 GB of data at a 30% delivery ratio.

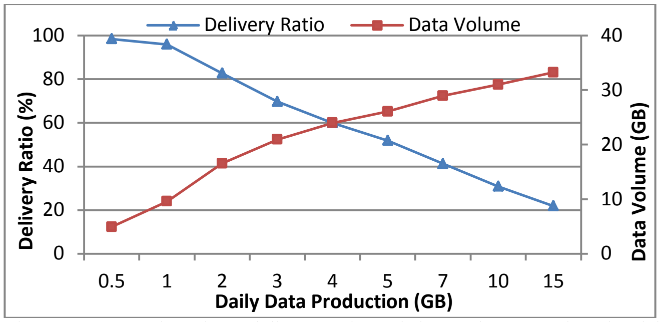

Fig. 7. Low-cost broadcast delivery ratio and data volume varying the daily data production.

Similar simulations have been carried out assuming time sensitive data, discarded when the expiration time elapses. In this case the data TTL on the satellite is set to the data expiration date, as there would be no use in transmitting already expired data. Fig. 8 shows the delivery ratio and the data volume for a data time sensitivity of 0.5 and 2 hours. In the 0.5-hour sensitivity case the delivery ratio starts at 36% and drops slowly as the daily data production increases while the data volume steadily increases. In the 2-hour sensitivity case the delivery ratio starts at 72% for 0.5 GB of daily data production and drops to around 20% for the maximum value of 15 GB. The results here show that while the previously observed tradeoff between data reliability and data bulk is apparent, for highly sensitive data a low production rate does not significantly increase reliability and, therefore, data bulk may not be worth sacrificing. Real time services requiring high reliability such as sea ice monitoring and emergency land surface motion may opt for moderate daily data production (approximately 3-4 GB) at the expense of only a small delivery ratio reduction. At high daily data production values, results for both cases converge to virtually identical values.

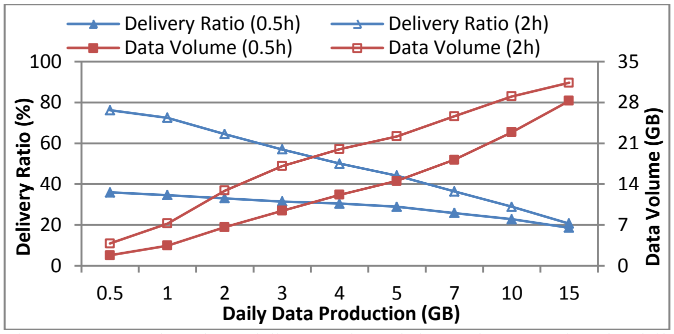

Fig. 8. Low-cost broadcast delivery ratio and data volume varying the daily data production for time-sensitive data.

D. *Space Segment Broadcast Simulations*

This section includes simulations varying the number of ground stations and the number of satellites with a low-cost broadcast space link model. In the first set of simulations, the number of ground stations providing downlink services to a single LEO satellite varies among 52, 100 and 140 units, in order to evaluate the system performance for different ground station geographical distribution. In the second set of simulations, a fixed number of 52 ground stations is used, while the number of satellites varies among 1, 6 and 46 units. Comparing the broadcast P2P model, supported by a single satellite solely, against the direct model and relay point-to-point models would be largely unfair due to the major difference in the associated deployment cost and equipment specifications. Therefore, the purpose of the second case is to estimate the total data return achieved by the broadcast P2P model in configurations that employ several low-cost satellites. This estimate will give us a general idea of the comparative performance of dense, low-cost satellite networks vs. the traditional high-end approach. The focus of these simulations was on the space segment so a single EU was employed. The data TTL on the satellite was set to the previously specified value of 12 hours.

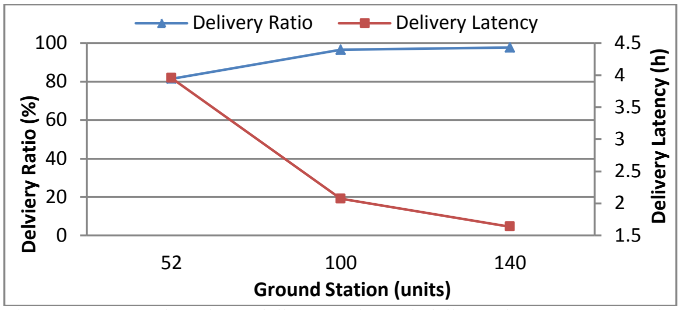

Fig. 9. Low-cost broadcast delivery ratio and delivery latency varying the number of ground stations.

Fig. 9 presents the results of the first test case, which clearly show that employing more ground stations has a positive impact on the overall performance of the system. Delivery latency is significantly decreased while all other KPIs, including delivery ratio, are improved. Furthermore, a trade-off between the number of the employed ground stations, closely associated to their respective geographical locations, and the improvement of system's performance is also revealed. From a critical point (100 ground station units in this particular case) and onwards, the increase on the number of ground stations providing downlink services to the LEO satellite does not seem to have a significant impact to the overall system performance.

Results regarding the second test case are presented in Fig. 10. We can observe that the data return increases linearly with the number of employed satellites for the 1 and 6 satellite cases, (when 6 satellites are employed the data return is 6 times higher than the single satellite configuration). This linear increase does not hold true for the 46 satellites configuration where data return of the system improves only by a factor of 3.8 vs. a 7.7 increase in the number of satellites compared to the 6 satellites configuration. This fact indicates that ground stations network is transformed into a bottleneck; an argument that it is also supported by the low values of delivery ratio metric in comparison to the previous cases (i.e. single and 6 satellites cases). Since the creation of the bottleneck cannot be related to the ground station link bandwidth, the total number and duration of contact opportunities between the satellites and ground stations seems to be the only remaining factor that could cause this issue. This indicates the existence of a trade-off between the number of employed satellites and the number/location of the ground stations providing downlink service.

In the 46-satellite case the total volume of data delivered on the ground reaches 562 GB. This value is approximately 1/7 of the maximum 3.9 TB amount of data delivered by the high-end scenario in the direct point-to-point model (section V.B). Apparently, a direct comparison of the performance of the low-cost vs. the high-end satellite mission types would clearly favor the latter. However, the results are, indeed, promising, considering the vast gap between the specifications of the two systems (i.e. 3 Mbps vs. 520 Mbps). Furthermore, due to practical purposes, the 46 satellite simulation included a limited number of 52 GSs, restricting the overall contact time (a larger number of GSs would increase the achieved data volume). The comparison could lead to more useful insights in case economic data were utilized for the calculation of the cost-per-byte in each type of mission. Such analysis is not part of the present study, but it may present an interesting possibility for the continuation of our work.

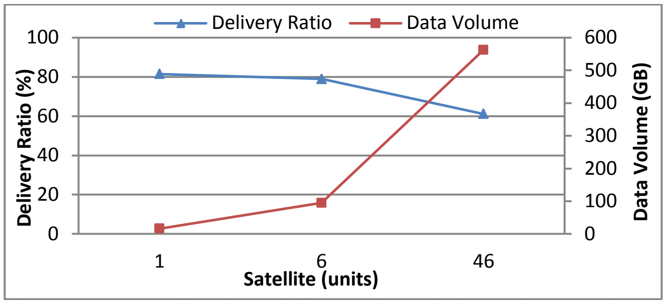

Fig. 10. Low-cost broadcast delivery ratio and data volume varying the number of satellites.

E. *Reliability Mechanisms Broadcast Simulations*

In this set of simulations we present comparative results of the basic broadcasting mode of operation that was used in the previous sections and includes no delivery feedback (*Plain*) with the acknowledged mode of operation (*Ack*) and the acknowledged/transmission limited mode of operation (*Ack & Limit*). A single EU is used so that the focus remains on the space segment. As detailed in sections III.C and III.D, data in the *Ack* mode is acknowledged via a designated uplink ground station and, in the *Ack & Limit* mode, additionally to the data acknowledgment, transmission is limited during contacts. In this set of simulation runs, a daily data production of up to 4 GB was employed as this is the maximum theoretical capacity of the contacts, guaranteeing relatively high delivery ratio values.

The chart of Fig. 11 depicts the delivery ratio achieved in the three modes of operation. For a daily data production of 1 GB all three cases achieve almost 100% reliability. For higher data production values, the Ack & Limit mechanism achieves consistently higher delivery ratio than the other two and the Ack mode of operation achieves higher delivery ratio than the Plain mode. At the maximum data rate of 4 GB per day, the delivery ratio for the Ack & Limit, Ack and Plain modes of operation is 87%, 72% and 60% respectively.

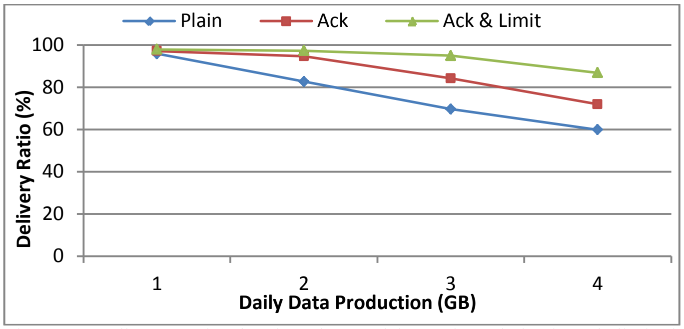

Fig. 11. Delivery ratio for broadcast plain, acknowledged and limited transmission varying the daily data production.

Regarding the delivery latency, it can be observed in Fig. 12 that the Ack & Limit mode has the highest performance ranging from 2 to 3.3 hours. For low data production rates the Ack mode performs considerably better than the "Plain" mode. For higher data production rates the Ack mode exhibits a bit higher latency due to the significantly higher delivery ratio it achieves (84% vs. 70% and 72% vs. 60%). The results in this section show that employing "smart" transmission mechanisms including delivery feedback and/or transmission suspension can substantially improve system performance and should be considered as an option during mission design.

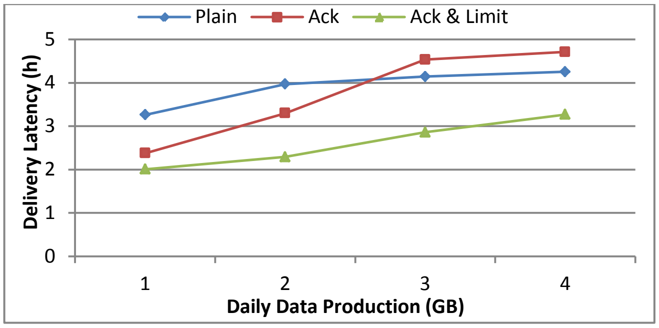

Fig. 12. Delivery latency for broadcast plain, acknowledged and limited transmission delivery latency varying the daily data production.

F. Ground Segment Broadcast Simulations

In this set of simulations, the ground network includes 100 EUs, so that the performance gains of a peer-to-peer vs. a centralized ground data distribution scheme could be quantified. The ground links use links of lower bandwidth than the rest of the simulations (10 Mb vs. 18 Mb) and no acknowledgments or transmission limitation mechanisms are employed (*Plain* mode).

Fig. 13 depicts the delivery ratio and delivery latency for both ground distribution schemes. At low data production values the delivery ratio is identical in both cases, while the delivery latency is slightly higher in the centralized case. As the data production rate increases the delivery ratio deteriorates more quickly in the centralized case reaching 31% vs. 60% of the P2P case at a daily data production of 4 GB. In the centralized distribution scheme the links around the MCC become congested and end-users located far from it are less likely to receive data within the simulation duration. In the P2P case, however, data received at a certain ground station becomes directly available to nearby EUs and dissipates over the multicast tree, evenly loading the network links. This becomes more apparent when examining the delivery latency line. In the P2P case delivery latency stabilizes at around 4 hours for higher data production values, when it exceeds 8 hours in the centralized case. The results suggest that a push, peer-to-peer ground data distribution would be highly beneficial especially for applications involving high volume, time-sensitive data, such as rapid mapping for fires and floods and weather prediction.

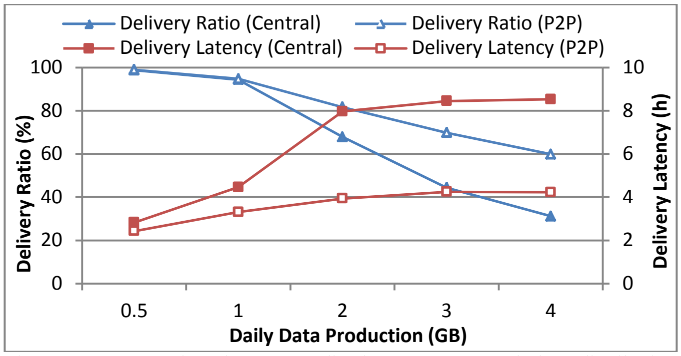

Fig. 13. Low-cost broadcast centralized vs. P2P ground data distribution delivery ratio and delivery latency, varying the daily data production.

VI. CONCLUSIONS AND FUTURE WORK

In this paper we proposed a space-data dissemination paradigm that extends traditional satellite communications in order to accommodate low-cost, dense satellite networks with limited, or no, uplink opportunities. We also presented a comprehensive set of simulation tools and select simulation results that can assist in the design of end-to-end space mission data return schemes. Our paradigm consists of a broadcast-based, P2P multicast ground distribution scheme and a best-effort transmission scheduling for space-data. Simulation experiments showed that the P2P ground distribution improves both the data reliability and timeliness over a centralized distribution, and is especially beneficial to applications involving high volumes of time-sensitive data (i.e. rapid mapping, weather prediction). Additionally, our versatile transmission scheduling mechanism is able to adjust data reliability even in the absence of delivery or reception feedback, while it can utilize such feedback for improving performance when available.

Through the simulation experiments, we were able to quantify the tradeoff between data reliability and data volume. For applications involving time-insensitive, reliable data, such as small scale mapping and land surface motion, a single satellite network transfers 16 GB at 83% delivery ratio, whereas for applications involving time-insensitive, bulk data, such as soil protection and water management, 31 GB can be transferred at 30% delivery ratio. For data of higher sensitivity, the data reliability/volume tradeoff becomes less apparent and the delivery ratio decreases significantly with the data expiration time. Employing mechanisms such as delivery acknowledgments and transmission limitation during contacts substantially improves the system performance up to 40% in terms of data volume and 50% in terms of data latency.

Expectedly, the performance of currently used, high-end networking equipment was found to be considerably higher than that of the low-cost equipment in the case of a single satellite. However, when multiple, low-cost satellites are employed the performance gap related to the total data return closes, rendering the deployment of a low-cost broadcasting approach a promising alternative in economic terms. In a future study, simulation results could be combined with economic data in order to calculate cost vs. performance indices for each mission type and support related mission design decisions.

Our future plans for the proposed paradigm include the improvement of the transmission scheduling by adding support for various data prioritization schemes through weighted probabilities. Prioritization can be based on criteria such as data age, retransmission counter, or ToS. Future simulations could also report on the energy expenditure of the proposed communication patterns, since prudent energy management is vital for the satellite operation. Finally, we plan to study the system behavior under alternative data acquisition schemes, limiting the data collection process over specific areas of interest.

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