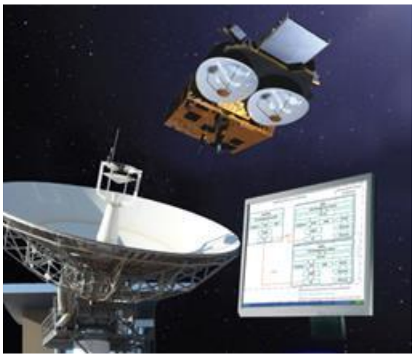
APPLICATION OF A BITTORRENT-LIKE DATA DISTRIBUTION MODEL TO MISSION OPERATIONS

(ESA CONTRACT 4000108835/13/F/MOS)



DELIVERABLE D7 – PART 2
EXECUTIVE SUMMARY

Prepared for:
European Space Agency

Prepared by:

TELETEL (ESA Bidder Code: 63051)

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1 Scope

1.1 Scope of the document

The scope of this document is to provide the Executive Summary report of the “Application of a BitTorrent-like data distribution model to Mission Operations” contract.

The main objectives of this study included:

- To analyse the applicability of a BitTorrent-like data distribution model to Mission Operations concept and evolve its definition as required.
- To define reference scenarios and KPIs against which the model can be assessed.
- To specify the entities and their technical components of such a network.
- To perform simulations to assess the effectiveness of the model.

1.2 Applicable and reference documents

1.2.1 Applicable documents (ADs)

[AD1] ESA Contract No. 4000108835/13/F/MOS with TELETEL.

[AD2] TELETEL’s proposal reference 13042600401/752, dated 26 April, 2013.

[AD3] Kick Off meeting minutes

[AD4] SRM1 meeting minutes

[AD5] SRM2 meeting minutes

[AD6] SRM3 meeting minutes

1.2.2 Reference documents (RDs)

[RD1] Thales Alenia Space - France, INRIA, "D1: Feasibility Assessment Report with CFDP Compatibility Analysis," Deliverable of the "Application of a BitTorrent-like data distribution model to mission operations" project, ESA, 2013

[RD2] Thales Alenia Space - France, INRIA, "D2: Baseline concept definition, reference scenario for the comparison of BT vs EDRS vs classic data delivery models, and KPIs," Deliverable of the "Application of a BitTorrent-like data distribution model to mission operations" project, ESA, 2013

[RD3] TELETEL, Thales Alenia Space - France , “D3: Technical specification of network building blocks,” Deliverable of the "Application of a BitTorrent-like data distribution model to mission operations" project, ESA, 2014.

[RD4] TELETEL, Thales Alenia Space - France , “D4: Trade-off of hardware elements leading to recommendations,” Deliverable of the "Application of a BitTorrent-like data distribution model to mission operations" project, ESA, 2014.

[RD5] INRIA, Thales Alenia Space - France, "D5: Simulation Test Plan & Results (Task 3) ,” Deliverable of the "Application of a BitTorrent-like data distribution model to mission operations" project, ESA, 2014.

1.3 Terms, Definitions and Abbreviated Terms

AD	Applicable Documents
AH	Authentication Header
BT	BitTorrent
CCSDS	Consultative Committee for Space Data Systems
CFDP	CCSDS File Delivery Protocol
COTS	Consumer Of The Shelf
CRC	Cyclic Redundancy Check
DVB-S2	Digital Video Broadcasting - Satellite - Second Generation
ECSS	European Cooperation for Space Standardization
EDRS	European Data Relay System
ESA	European Space Agency
ESP	Encapsulating Security Payload
FMS	File Management Service
FTP	File Transfer Protocol
FTS	File Transfer System
GPS	Global Positioning System
ID	IDentifier
IKE	Internet Key Exchange
IP	Internet Protocol
IPR	Intellectual Property Rights
IPsec	Internet Protocol Security
KPI	Key Performance Indicator
LEO	Low Earth Orbit
MGS	Main Ground Station(s)
PDU	Protocol Data Unit
RD	Reference document
RF	Radio frequency
S/C	Spacecraft
SGS	Secondary Ground Stations
VPN	Virtual Private Network

BITTORRENT-specific terminology

Name	**Description**
Torrent	It is the object being downloaded. It may correspond to a single or multiple files
Peer	It is one client of the BitTorrent network; each peer at the same time downloads a torrent and contributes to its spreading by uploading it
Swarm	It is the set of all peers downloading and/or contributing to the same torrent
Tracker	It is a centralized entity keeps track of the peers currently involved in the exchange of a torrent

Pieces and Blocks	Content is transferred through BitTorrent split in pieces, and each piece is split in blocks. Blocks are the transmission unit on the network, but the protocol only accounts for transferred pieces. In particular, partially received pieces cannot be served by a peer, only complete pieces can
Seed (or Seeder)	A peer that has all the pieces of a torrent
Leecher	A peer that downloads a torrent but does not yet have all pieces
.torrent file	A file that contains the list of pieces the torrent
Initial Seed	Initial seed is the peer that is the first source of the torrent
Peer Set	A list of known peers maintained by a single peer (also known as neighbor set)

2 Introduction

Current evolution of IP networks has raised the opportunity to consider the use of well-established and mature Internet communication models for use in space missions. One of the most attractive of these models, particularly in terms of distributed and resilient data delivery, is the 'torrent'. A complete implementation of the CCSDS File Delivery Protocol (CFDP) [AD1] has been recently delivered to ESOC. Although CFDP does not rely on IP networks (indeed, it is independent of underlying communication technologies), it does provide a set of services that could be used to implement a torrent-like distribution model.

As identified by ESA, a study is needed to assess technical feasibility, data transfer capacity and true compatibility with CFDP services of the space-ground and ground-ground communications in the proposed network model.

Following the announcement of in the Invitation to Tender from ESA (AO/1-7454/13/F/MOS), TELETEL has been awarded the ESA/ESOC 4000108835/13/F/MOS contract, having as main target to perform a proof of concept study to assess the technical feasibility of a BitTorrent-like data distribution model to Mission Operations (space-ground and ground-ground communications).

The team was managed by TELETEL as study Prime with the support of Thales Alenia Space France and INRIA, constituting a complementary combination of backgrounds and expertise in the following main competence fields:

- Space Segment Software architecture and avionics
- Ground Segment design including networking of stations
- RF expertise for link budget establishment
- CFDP, BitTorrent and TCP/IP protocols knowledge
- Simulation capabilities through the use of STK and NS3

In order to assess the applicability of the proposed BitTorrent-like data distribution model for Mission applications, two reference scenarios are selected:

- A high performance LEO satellite with a payload file transfer system used as an independent and dedicated payload communication system for data dissemination. This scenario targets an earth observation mission in a 500-1500km LEO orbit. It considers classical satellite architectures targeting optimal utilization of BitTorrent network capabilities. This implies that the satellite DHS and communication system is adapted to the BitTorrent application within the capabilities of current Earth Observation satellite systems.
- A low cost LEO constellation based on the QB50 concept. QB50 has the scientific objective to study in situ the temporal and spatial variations of a number of key constituents and parameters in the lower thermosphere (90-320 km) with a network of about 40 double CubeSats, separated by a few hundred kilometres and carrying identical sensors. This low-cost system provides limited capabilities in communication system implementations, which prevents the usage of data-relay satellites form the EDRS type (laser & Ka-Band). It could however make use of a transparent RF repeater such as MTG UHF service, Hub-based and DTN services and will also be used as a low-level performance comparator between these services.

The team covered all the competences listed above with some overlap allowing effective sharing and cross-verification of activities between team members enhancing the overall quality of the work performed.

3 BitTorrent Space Segment and Ground Segment system architecture

The proposed ground network consists of both new entities as well as existing network entities, which are enhanced in order to support the new concepts and functionalities imposed by the BitTorrent-like data distribution model. Its main entities include:

- **Main Ground Station (MGS):** The main ground station is one of the entities interlinking the satellite(s) and the ground network. It includes receive and transmit terminals, which are receiving the data transmitted by the satellite(s) but also provide TM/TC capabilities.
- **Secondary Ground Station (SGS):** The secondary ground station is one of the entities inter-linking the satellite(s) and the ground network. It includes receive-only terminals, which are receiving the data transmitted by the satellite(s).
- **Data Center:** The data center is the entity that serves as the main archiving entity and act as the main re-assembler of the different files that are submitted through the satellites. This entity can provide the files to potential subscribers (end user communities).

It is organized into two BitTorrent networks, the first one is a closed BitTorrent network in which only MGSs and SGSs participate; we refer to this network as BitTorrent+. The second BitTorrent network is formed among users. The Data Center is the interface point between the 2 networks.

Therefore with respect to these BitTorrent networks the aforementioned entities hold the following roles:

MGS: It includes the tracker of the BitTorrent+ network and it serves as a peer. Once it receives a piece of a file from the satellite through the terminal, it stores it locally in its peer client. MGS also includes:

- **Control Center (part of MGS):** The control center is the entity that is responsible for managing the torrent network. It includes a Torrent File Server, which maintains the information about the files that can be shared over the torrent network. These files can be created by peers. This file contains metadata (e.g. video, audio, image, application, text) about the files to be shared and about the Tracker, the entity that coordinates the file distribution. The control center also acknowledges the reception of all the pieces of a particular file by the torrent network peers to guarantee their integrity. It also monitors the status of the network nodes in order to allow the detection of malfunctions and other problems.
- **Tracker (part of MGS):** The tracker is the entity that maintains the lists swarms that are participating in the different torrents. It provides peer sets and it maintains statics regarding the activity of each torrent

SGS: It serves as peer in the torrent network. Once it receives a piece of a file from the satellite through the terminal, it stores it locally in its peer client (that will then be able to share with other peers, including the MGS and the data center).

Data Center: The data center acts as an interface point between the BitTorrent+ network and the secondary BitTorrent network formed among the users. The data center assemblies the files received from the satellite by the ground stations and acts as the initial seed for the users BitTorrent network. The data center may also act as the tracker for secondary BitTorrent network.

Figure 1 illustrates the ground network architecture. As it can be seen from this figure there can be multiple MGS, in order to provide better connectivity with the satellite; however **only one of the MGSs participates in the BitTorrent+ network**.

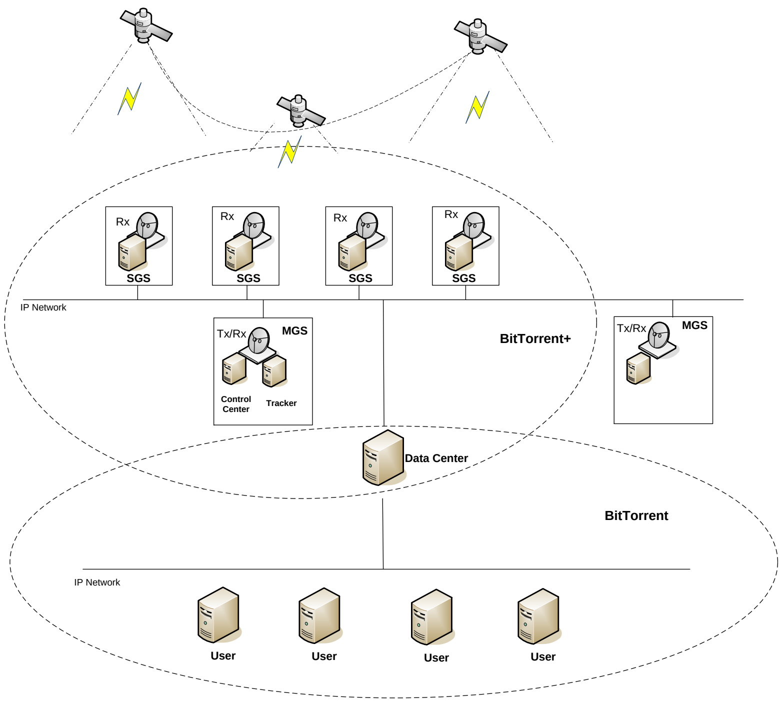
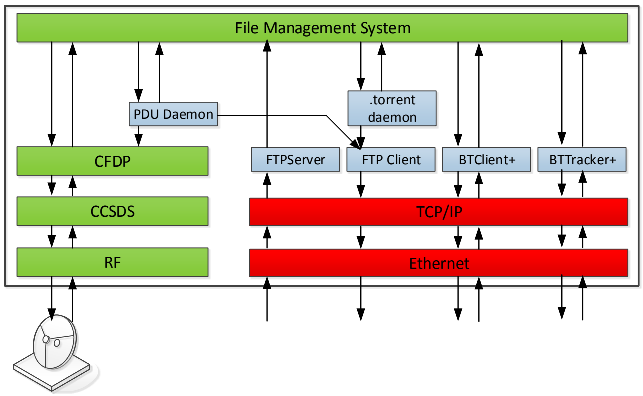


Figure 1: Satellite/Ground network architecture

Figure 2 shows a complete view of the components that compose an MGS, whereas Figure 3 shows the components that compose an SGS and Figure 4 shows the components that compose the Data Center.



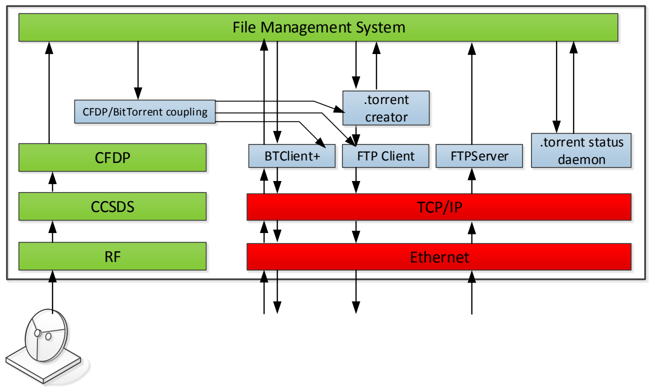


Figure 2: The components of an MGS

Figure 3: The components of an SGS

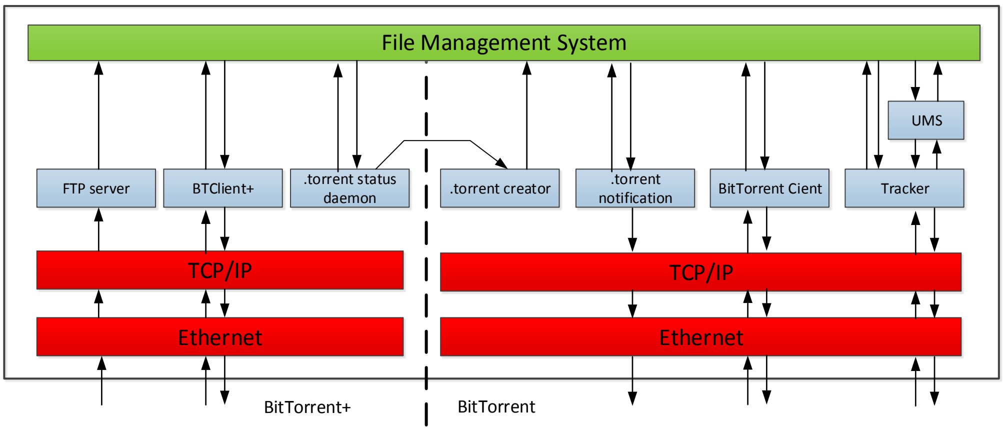


Figure 4: Components of a data center

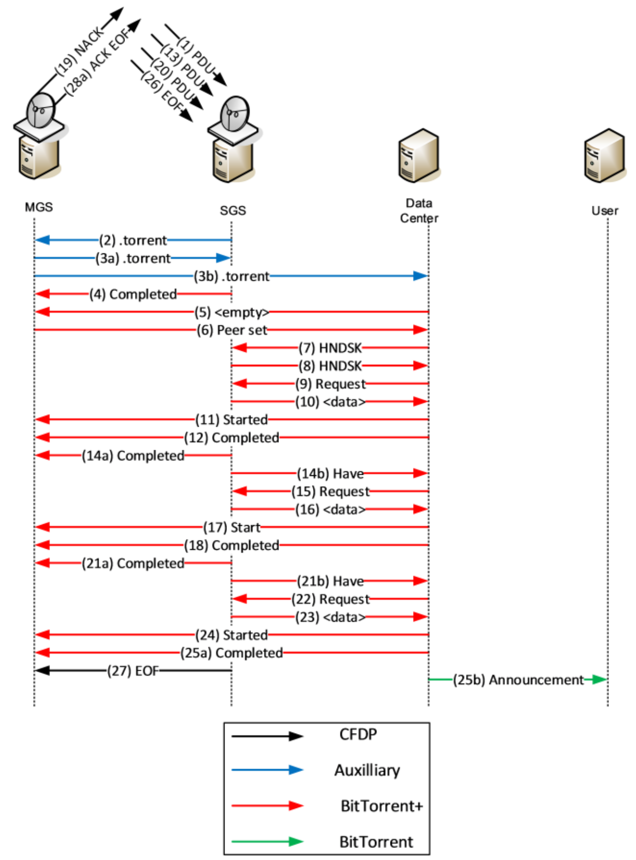
The ground network architecture supports a set of auxiliary functions for the creation and the distribution of the .torrent files, the CFDP-BitTorrent coupling and error handling.

These functions are supported by a set of auxiliary components. Table 1 shows a cumulative list of these auxiliary components and their functionality.

Name of component	Location	Functionality
FTP client/Server	MGS, SGS	It used to transfer .torrent files and EOF PDUs between receiving entities
.torrent daemon	MGS	It monitors the folder used by the FTP protocol to store files and detects newly created .torrent files. When a new .torrent file is detected, it initiates its transmission to all receiving entities
.torrent status daemon	MGS, SGS	It monitors the folder used by the FTP protocol to store files and detects EOF PDUs. If an EOF PDU is detected the transaction in which it belongs is marked as completed
.torrent creator	MGS, SGS	It creates .torrent files for new transmissions, using the CFDP metadata information. If the components is located in a SGS, it also transfers the .torrent file to the MGS
PDU daemon	MGS	It monitors the order of reception of the CFDP PDUs and detects missing PDUs. Moreover it initiates the EOF PDU transfer to all receiving entities
CFDP/BitTorrent coupling middleware	MGS, SGS	It monitors incoming CFDP PDUs. Depending on the PDU type it may initiate the .torrent creation procedure, it may inform the BitTorrent+ client about a new piece, or it may transfer the PDU to the MGS

Table 1: Auxiliary components and their functionality

In order to present a complete use case scenario of the proposed network architecture, we consider the transmission of a file from the satellite to the ground network when the first PDU is received by an SGS station. This use case scenario includes the following main steps: transmission and reception of the first PDU packet (with initial file data) at an SGS, the torrent file creation at the MGS, the joining of the torrent file in the swamp, the exchange of BitTorrent pieces, the retransmission mechanism and the completion of file download from the satellite. Figure 5 illustrates the complete scenario with the detailed steps with CFDP class 2 (re-transmissions are enabled).



Step 1:	An SGS receives a PDU
Step 2:	The SGS creates a .torrent file and stores it in the MGS
Step 3a/b:	The MGS sends the .torrent file to all entities
Step 4:	The BitTorrent+ client in SGS sends a "completed" event to the tracker for the first PDU
Step 5:	The BitTorrent+ client of the Data Center sends an empty event to the tracker
Step 6:	The tracker responds to the Data Center with the peer set
Steps 7,8:	The Data Center and the SGS perform a handshake
Steps 9,10:	The Data Center requests the first chuck of the file and starts receiving it
Step 11:	The Data Center sends a "started" event to the tracker at the beginning of the download
Step 12:	The Data Center sends a "completed" event when the download is finished
Step 13:	The SGS receives another PDU
Step 14a/b:	The SGS sends a "completed" event to the tracker and informs the Data Center that "it has" a new chuck
Steps 15 - 18:	The Data Center requests this new chuck and the download procedure is repeated
Step 19:	The PDU monitor daemon in the MGS realizes that a PDU is missing and requests its retransmission by sending a NACK for this PDU
Step 20:	The PDU is retransmitted and received by the SGS
Step 21a/b:	The SGS sends a completed event to the tracker, announces the new chuck to the data center
Steps 22-25a:	The download procedure is again followed (22-25a).
Step 25b:	Supposedly that was the last chunk of the file the Data center announces this file to the BitTorrent network
Step 26:	The satellite transmits the EOF PDU which is received by the SGS
Step 27:	The SGS forwards the EOF PDU to the MGS
Step 28:	The MGS sends an ACK for the EOF

Figure 5: Overview of the whole process

Nevertheless, the following considerations shall be made for the applicability of the classical BitTorrent network concepts in space applications:

- When the .torrent file is created not all chucks are available, therefore .torrent files do not contain the hash of the chunks.
- Since a seed may receive a chunk from the satellite instead of the BitTorrent+ network, it may send a "completed" event to the tracker without having sent a "start" event.
- The "IP" and the "Port" fields of the messages sent from a peer to the tracker are omitted, since this information is well-known.
- All optional parameters are omitted, since they are preconfigured in the BitTorrent+ network nodes.
- The "no_peer_id" parameter of the messages sent from a peer to the tracker is omitted since an alternative representation of the peers is used.
- The "interval" parameter of the messages sent from the tracker to the peers is omitted, since it is preconfigured to the BitTorrent+ clients.
- The tracker responds to the peers using a BitTorrent+ specific representation of the peer set.
- If CFDP class 1 is used tracker, responses to the peers include a list of lost chucks (due to errors in the satellite link).
- Peers contact the tracker at varying frequency.
- Peer selection process is modified, based on the facts that the location of all peers in known and all peers are honest.

As far as the security aspects, three technologies were investigated including VPN, SSL and IPsec and we the IPsec solution is selected as the ideal candidate for the aforementioned system. All the three solutions provide the desired security functionalities, i.e., all provide data integrity, data confidentiality (through encryption) and end-point authentication. Moreover all these solutions are well supported in most operating systems. However these solutions differs in terms of scalability, ease of configuration and extendibility where IPsec is preferred since, it is very scalable and existing applications can be extended with new ones without any modification although IPsec configuration is not as trivial as VPN due to the certificate generation and security policy definition in each network node.

IPsec, as shown in Figure 6, is introduced between the Ethernet component and the BitTorrent+ and Auxiliary components. All applications are oblivious about its existence.

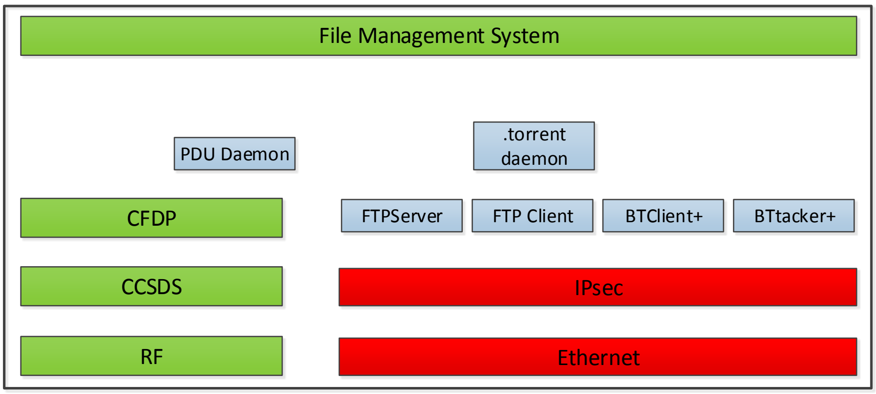


Figure 6: Protocol of an MGS wih the introduction of IPsec

Finally, the main hardware specifications that are recommended for the deployment of the BitTorrent-enabled ground network entities are summarised in the Table 2 including: processing and memory capabilities, communication interfaces and storage capabilities based on the communication and operational requirements defined in this study.

Network Elements / Hardware Categories	Main Ground Station	Secondary Ground Station	Data Center	User Station
Processor	○ 2 x CPU Intel® Xeon® Processor E5-2403	○ 1 x CPU Intel® Xeon® Processor E3-1220 v3	○ 2 x CPU Intel® Xeon® Processor E5-2403	○ Inter® Core i3-3240
Memory	○ 24GB RAM (6 x 4GB) - DDR3 1600MHz	○ 4GB RAM - DDR3 1600MHz	○ 24GB RAM (6 x 4GB) - DDR3 1600MHz	○ 2x2GB - DDR3 1600MHz
Communication interfaces	○ Integrated LAN 4 x 1GbE	○ 1GbE Integrated LAN	○ Integrated LAN 4 x 1GbE	○ 1GbE Integrated LAN

Network Elements / Hardware Categories	Main Ground Station	Secondary Ground Station	Data Center	User Station
	○ RF terminal (Satcom modem)	○ RF terminal (Satcom modem) ○ 1 PCI-e GbE LAN t for the RF terminal		
Storage capabilities	○ 2 x SSD 2.5" 128GB disk drive ○ Supporting 8 x 3.5"/2.5" Hot-swap drives	○ 2 x SSD 2.5" 128GB disk drive	○ 2 x SSD 2.5" 128GB disk drive ○ 4 x HDD 3.5" 2TB (8TB Total) ○ Supporting 8 x 3.5"/2.5" Hot-swap drives	○ 1 x 250GB disk drive for data storing and O/S
Estimated Cost[1]	Main Station: 2100€ RF Terminal (QB50): 45k€ Total (QB50): <50k€ per unit For EOS, the usage of an ESOC station is recommended	Main Station: 850€ RF Terminal: - QB50: 45k€ - ECSS EOS: [~175-370]k€ - DVB-S2 (EOS): [~60-75]k€ Total QB50: <50k€ per unit Total EOS/ECSS: [~175 – 370]k€ per unit Total EOS/DVB-S2: [~61 – 76]k€ per unit	Total: 2400€ per unit	Total: 450€ per unit

Table 2: Main hardware specification of BitTorrent-enabled network entities

[1] Indicative estimated cost as calculated at the time of the preparation of this report.

4 Network Modelling and Simulation

4.1 Overview

In this study three scenarios were evaluated in order to assess the applicability of the BitTorrent-like data distribution model to Mission Operations:

1. QB50 satellite in equatorial orbit (Scenario 1): considers the analysis of a QB50 satellite in equatorial orbit communicating with a network made of 1 Main Ground Station (Malindi, Kenya) and 14 Secondary Ground Stations selected in a belt of approximately +/-20° around the equator.
2. EOS satellite in polar orbit (Scenario 2): considers classical satellite architectures based on Sentinel-3 and placed in polar orbit with N-orbit repetitive cycles with a network made of 2 Main Ground Stations (Troll, Antarctica and Kiruna, Sweden) and 31 Secondary Ground Stations.
3. QB50 satellite in polar orbit (Scenario 3): considers a QB50 satellite (as in Scenario 1) in polar orbit with 2 Main Ground Stations (Troll, Antarctica and Kiruna, Sweden) and 44 Secondary Ground Stations.

The simulation analysis has been performed using STK and NS3 simulations for each of the previous scenarios. The STK simulations provide the computation of visibility windows for each scenario based on the network topology and stations coverage. Using the communication windows obtained through STK simulations, NS3 simulations were performed for each scenario both for the proposed BitTorrent-like distribution model and for the Hub-based distribution model. The Hub-based distribution model is the main alternative envisaged to the proposed BitTorrent-like distribution model where the different ground stations simply push the pieces they receive from the satellite the MGS. The MGS in turn, forwards each piece to the ground stations that haven't received it (without the need to get the whole file before).

From the NS3 simulations, the following performance metrics are collected:

- Offered load: the amount of data generated at the satellite normalized by the maximum that can be transferred for a given orbit and set of GSs.
- End-to-end delay: time interval between the file generation and its retrieval at a GS or at a user.
- Consolidation time: time interval between the file generation and its retrieval at all the nodes in a given set (it may be the GSs' set or the users' set).
- Buffer occupancy: the amount of buffer memory needed to store the files for which the satellite has not received yet the reception ack from one MGS.

Moreover, the following alternative network communication models were also evaluated for each scenario compared with the proposed BitTorrent network [RD5]:

- **Single Ground Station communication**: in this model, the satellite communicates with a single Ground Station and it is considered that all visibility sessions are used. The protocol stack employed in this model is CFDP (class 2)+CCSDS as for the BitTorrent board-to-ground link, providing a 3% overhead due to the protocol encapsulation using maximal packet sizes and frames compatible with a RS(255,233,I=5) coding which is the most standard implementation for TT&C applications.
- **Relay through geostationary satellite**: in this model, the satellite communicates with a geostationary satellite which relays the file segments to a single Ground Station and it is considered that all visibility sessions are used and that the relay satellite does not introduce major communication link degradation. The protocol stack employed in this technique is CFDP(class 2)+CCSDS as for the BitTorrent board-to-ground link, providing a 3% overhead due to the protocol encapsulation using maximal packet sizes and frames compatible with a RS(255,233,I=5) coding which is the most standard implementation for TT&C applications. An RF repeater is considered with a simple encapsulation protocol for addressing the packets through the relay satellite to the destination.
- **Relay through the Ground Station network using DTN**: in this model, the satellite communicates with the same Ground Station topology as for the BitTorrent model but using DTN (BP+LTP) as relay protocol. DTN has advantage over CFDP to be able to cope with dynamic networks which is ideal for communicating with multiple relay points. DTN is configured to route the file segments always to the MGS as final user while the secondary ground stations are merely relay points.

4.2 Performance assessment

The main outcomes of the simulation analysis and performance assessment for each scenario are presented in the following paragraphs.

Scenario 1: QB50 satellite in equatorial orbit

Following the STK and NS3 analysis of this scenario for the BitTorrent-like and the Hub-based model, it should be highlighted that there is not much difference between end-to-end delay and consolidation time at the GSs while the GSs have plenty of time to exchange among themselves all the pieces. In addition, only the buffer occupancy seems to be dependent from the offered load (and it is still negligible in comparison to the available satellite storage capacity). According to the limitation on the generation rate (1 file every 4541s according to the scenario configuration options) there can be at most two files generated while the satellite is out of visibility from the MGS. If every file is retrieved by at least one GS before the generation of the consecutive one, there can be at most 3 files present in the buffer at a given time (1 generated before the previous communication window with the MGS but not yet available at the MGS during the communication window, and two generated after it).

Basically no difference between these two architectures can be observed, mainly, due to the fact that the bottleneck of the distribution system is the satellite channel and the ground topology is able to transfer very fast the file pieces even in a star configuration. Only the complexity of the protocol varies.

Comparing with the alternative models, it can be noted that BitTorrent, Hub and DTN approaches are more efficient versus the classical single GS solution while the GEO relay solution is affected by Earth shadowing from GEO orbit with a 0° orbit inclination (equatorial).

Scenario 2: EOS satellite in polar orbit

Scenario 2 is computationally heavier than scenario 1 with higher maximum rate but smaller files than in scenario 1. Based on the NS3 simulation results for both BitTorrent and Hub-based model simulations, it has been identified that the BitTorrent-like distribution model may indeed outperform the hub-based distribution model in realistic cases. Due to the higher satellite transmission rate information distribution may be limited by the available bandwidth at the ground network, thus the BitTorrent-like approach may be able to better exploit the available resources in comparison to the hub-based approach

Comparing with the alternative models, it can be noted that BitTorrent, Hub and DTN approaches are more efficient versus the classical GS solution, although the GEO relay solution enables the better performance as fewer Earth shadowing occurs when communicating from a 901km orbit at 81° inclination versus the equatorial orbit plus the fact that the overall data rate is not limited by the Ground network.

The main advantage of BitTorrent in this scenario is the speed at which the data is broadcasted over the full network. The GEO relay operation enables very high throughput but we have to take into account the limiting factor of the Ground Network.

Scenario 3: QB50 satellite in polar orbit

Scenario 3 has similar configuration with scenario 1 but polar orbit and additional MGSs and SGSs stations are considered. In this scenario the bottleneck of any distribution system is the satellite channel capacity while buffer limit is not a practical constraint. The simulations show that the performances of the BitTorrent-like architecture and of the hub-based one are equivalent, but the second solution is simpler and then to be preferred.

Compared with the alternative models, the GEO relay solution enables the better performance as providing a better average visibility duration over the satellite orbits (350km orbit at 81°) while BitTorrent, Hub and DTN approaches are also provide a better performance in terms of downloadable files per day versus the classical GS solution.

5 Overall recommendations and remarks

Following the technical analysis for the application of a BitTorrent-like data distribution model to Mission Operations the definition of the satellite and ground network topology and building blocks have been defined and the performance assessment of this approach has been conducted through the network simulation of reference scenarios and their comparison to alternative models.

As we derived from the technical analysis for the application of a BitTorrent-like data distribution model to Mission Operations, the proposed satellite-to-ground network architecture is composed of two networks, a closed network where the BitTorrent+ protocol is used and a second network where the tradition BitTorrent protocol is applied. These networks interface through the data center. In the BitTorrent+ network, PDU received by a satellite, using the CFDP protocol, are exchanged utilizing BitTorrent+: the coupling of CFDP with the BitTorrent+ network creates challenges related with a) the fact that PDUs are exchanged before the transmission is completed and b) that only a single entity is able to transmit data back to the satellite. Thus, for the BitTorrent+ and CFDP coupling the following specifications were derived: CFDP transaction ID shall be included in the .torrent file, the format and the sequence of the transmitted messages should be modified in order to handle missing pieces and pieces received directly from the satellite, new components were introduced that are responsible for creating .torrent files based on the received PDUs, proactively storing mechanisms for .torrent files in the SGSs are considered in order to be able to participate in ongoing CFDP sessions and modifications are proposed to the peer selection algorithm based on the fact that the network topology is well known and all peers are honest.

The building blocks and the information flows of the ground network can be easily implemented using publicly available open source software. The BitTorrent+ protocol can be implemented using libraries such as libtorrent (for the clients) and MLDonakey (for the tracker running on MGSs), whereas the auxiliary functions can utilize open source ftp servers such as the vsftpd. IPsec is implemented in all mainstream OS, including Linux, Windows, MacOS Android and IOS. The CA can be implemented using OpenSSL. Regarding the CFDP protocol implementation, it can be performed either in software (Thales Alenia Space, SpaceBel and SciSys have already implemented CFDP in software) or hardware (e.g. CFDP FPGA board developed by JPL, ESA CFDP IP-core study submitted by ESA, new generation MM such as TAS-I SSMM).

The proposed modifications on the BitTorrent-like data distribution model affect the performance of the system and are closely related on the particular network topology, the type of links used and the used case scenario. In this concept three reference scenarios were used to evaluate the applicability of the proposed BitTorrent-like approach based on the QB50 and Earth Observation satellite systems with different network requirements and variable network density (e.g. 1-2 MGS, 14-44 SGS). The strong interest of BitTorrent versus other protocols (DTN, Hub-based) arises when the Ground Network (and not satellite-to-ground communication) is the challenging and limiting factor for the data distribution, especially when data broadcasting worldwide is a mission requirement. Moreover, BitTorrent is especially adapted to high disparity of Ground links performance versus the other protocols as relying on collaborative behaviours of the Ground nodes.

Following the STK and NS3 simulations as well as the performance assessment with alternative distribution models for the different reference scenarios, the better performance is achieved using a geostationary satellite as communication relay. Nevertheless, it should be taken into account that communicating with such a relay is quite demanding on platform design, requires a specific on-board communication system, and of course, requires the leasing of the relay satellite bandwidth, which might prove more expensive than the BitTorrent approach and is anyway not feasible for the QB50 constellation as these satellites cannot communicate with the GEO orbit. Although the overall costing could not be made in the frame of this activity as requiring information which is not available to this study consortium, a formula have been provided to enable this calculation.

Hub-based and DTN approaches rely on the same Ground infrastructure than the BitTorrent approach. Their infrastructure cost is identical but we have to take into account the BitTorrent's higher robustness to harsh ground conditions versus demanding throughputs and the low maturity of the current DTN solutions. The capability of BitTorrent to broadcast data over the full network and to better exploit the available network resources are probably its biggest advantages over the other distribution models.