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Reference Scenarios for Evaluation of Disruption Tolerant Networking Technologies

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Abstract

In this paper we present three Disruption Tolerant Networking (DTN) reference scenarios that can be used to evaluate DTN Technologies. The scenarios are Earth observation, Lunar communication and Mars communication; they have been prepared using the current state of the art and short-term future (3-10 years) expectations in their respective domains. Having standard reference scenario will facilitate evaluation of proposed technologies such as Bundle Protocol extensions, routing algorithms and security solutions. We selected some key characteristics that define a scenario behaviour and give the opportunity to widen the usefulness of the scenarios to a wider range of activities. Having such key characteristics will allow researchers and developers to reference to a specific scenario but vary specific aspects, e.g. using different link data rates while keeping the other aspects stable. It is also possible to extend the topologies by e.g. considering additional lunar surface networks connected to the lunar surface node or by replicating certain elements to experiment with scalability of proposed solutions. To allow efficient simulation scaling factors can be applied to data volumes, data rates, latencies and simulation can be run in simulated time faster than real time. It is intended to publish the DTN reference scenarios definitions under CCSDS to facilitate interoperability testing and comparison of different technological solutions. In addition, we provide scenario definition files to facilitate their usage and will include all scenarios with their configuration files and scripts for set-up and configuration as part of the ESA Bundle protocol implementation. We believe that by providing such DTN reference scenarios, we will stimulate more research in DTN and support standardisation by avoiding the need to define scenarios from scratch and have a common basis for technologies comparison.

Keywords: Delay-Tolerant Networking (DTN), Bundle Protocol (BP), DTN Infrastructure, Interoperability, Testing and Validation, Solar System Internet.

1. Introduction

The definition of DTN Reference Scenarios comes from the necessity to compare, test and validate DTN technologies in the context of future missions. The idea is to provide agencies, industry and research institutes with a common basis to work on DTN technologies and validate their work against different implementations and expected network behaviours. The DTN Reference Scenarios allows demonstration and validation of Bundle Protocol and extensions, such as:

- BP Quality of Service (QoS) [1].
- Compressed Custody Transfer [2].
- BPSec Key Management [3].
- Network Management.
- Multi-destination Bundle Delivery.
- Video streaming.

and other desirable functionalities running over a DTN network. The scenarios abstract away from a specific mission and network topology, but they expose relevant characteristics in terms of data rates, contacts, traffic generation, link errors, etc. which still allow meaningful demonstration and validation activities. Although the scenarios as currently defined may not be fully adequate for all mentioned topics, they at least define a basis to build upon for more complex requirements.

It is intended to publish the DTN Reference Scenarios in CCSDS as a Yellow Book and make scenario definition files available. For CCSDS, DTN Reference scenarios shall be limited to scenarios which could reasonably expected in the next 3 – 10 years, with a limited number of nodes considered and a focus on agency activities. However, this does not preclude extensions to much larger scenarios.

2. DTN Scenarios definition and characteristics

In defining the reference scenarios, we have aimed to make them as simple as possible while still maintain relevant characteristics. We define three DTN scenarios:

- An Earth Observations scenario with a single spacecraft communicating with two ground stations, a mission control centre and a payload control centre.
- A Lunar communication scenario with three users with lunar assets and two different LunaNet [4] communication service providers. The scenario includes two lunar surface assets, three relays orbiting the moon, two ground stations, two relay control centres and two user control centres.
- A Mars communication scenario, similar to the lunar communication scenario, but with longer communication delays and fewer nodes in the network.

Two CSV files and two JSON files provides all the information necessary to define the scenarios and provide the necessary information to run them. The four files are defined in section 3 and the characteristics they provide in subsection 2.1.

2.1 Characteristics

The reference scenarios are defined by a set of key characteristics, that makes them realistic enough to provide technical relevance during testing and simulations, without adding unnecessary complexity. The characteristics are the following:

- The *Network Topology* defines the network structure with all DTN nodes and all links.
- *Link Data Rate* defines the maximum link throughput per link.
- *Link Latency* defining the latencies for each link.
- Link *Data Loss* defines error characteristics per link based on a Markov model to simulate burst errors, as modelled by Ulierte et al. [5].
- The scenarios' *Contacts* provide the times when two DTN nodes are expected to communicate and when they can actually communicate, the former is defined in *Planned Contacts* (see 3.1) and the latter in *Actual Contacts* (see 3.2).
- *Data Generation* defines the amount and patterns of data generation at source DTN nodes.

These characteristics are provided to the user in four files. In this section we will firstly explain the characteristics and we will leave the data representation to section 3, where the four files are shown and explained.

2.1.1 Topology

The network topology is fundamental, as it contains the nodes and available links at any given time. The topologies definition is non-trivial for the scenarios, they are derived from publicly available information, and we tried to keep them as simple as possible, as we noticed complexity rise proportionally to the number of nodes. A visual representation containing all the nodes of a specific scenario can aid understanding the scenario's structure and can be used to prepare the simulation. Topologies can be programmatically derived from the scenarios' files; In particular, the *Nodes* file contains all the nodes and DTN addresses of the scenario, and the *Planned Contacts* file contains all the potential links over the simulation time.

2.1.2 Data Rates

Every scenario defines the maximum data rates for all the links present in the topology. The data rates are not the actual link usages, but the theoretical maximum amount of traffic at any given time; the actual usage may be lower and depends on the application traffic volumes (see 2.1.6). The data rates are the results of research and internal surveys conducted on current and future missions. They have been adjusted to be as realistic as possible without compromising the simulation execution. For instance, for optical links with high throughput, a scaling factor can be applied to the whole simulation in order to have more manageable throughput during the simulation.

2.1.3 Contacts

The contacts describe the network link behaviour between the scenarios' assets. We define two different files that have different roles in the scenario's execution. The *Planned Contacts* is the results of a mission planning applied to the assets visibility, that has been previously computed using Godot, the ESA flight dynamics software [6]. It describe what is the expected contact behaviour during the simulation. In a second step, where the error model is applied to the *Planned Contacts*, we produce the *Actual Contacts* file that describes instead the real link availability after error model application. A contact can become shorter or disappear altogether in this second step, more details are provided in section 3.2.

2.1.4 Latency

The latency is computed by the ESA Godot flight dynamic software [6] using the distance of two assets at the start of their visibility window. Although it should realistically be variable, as the assets are constantly moving, for the sake of simplicity we decided to simplify it to the value at the beginning of the contact. Having variable latency would complicate the scenarios without adding significant value to them.

2.1.5 Link Error Model

A link error model is necessary to simulate data losses in the scenarios. The error model we are currently considering is based on a Markov Chain model proposed by Ulierte [4] and it considers all type of errors that can occur during a contact. All the possible errors are given a certain probability to occur and ultimately determine the state of the link when the contact happens. The link error model does not only take errors related to the physical properties of the link, typically expressed in bit or frame error rates and caused by e.g., atmospheric attenuation or weather effects. The model does also aim to account for link interruptions or complete failure to acquire a link due to factors such as human errors, misconfiguration of communicating assets or pointing errors. The proposed model is currently being validated and calibrated using real-world data.

2.1.6 Application traffic types and volumes

The scenarios define how data is generated by the nodes in the simulation, how often and how much data. It further defines which link a certain type of data can go through. These behaviours are explained in section 3.3 where the corresponding <u>*Node*</u> file is shown. Data generation type and volumes are based on current missions' literature and medium-term expectations, so that the scenarios maintain relevance for near future activities. Updated versions of data volumes could be provided in the future if new versions are released, following the versioning approach presented in section 5.

3. DTN Scenarios Files Format for characteristics representation

With just four files we can define all the relevant characteristics necessary to run a scenario. We tried to keep the number of files small and avoid information duplication.

3.1. Planned Contacts

The first file is called *Planned Contacts*. Its generation requires multiple steps and background information that are not relevant for the final results, but that are here explained for the sake of completeness. The planned contacts are computed starting from the ESA Godot software library [6], where assets coordinates and orbital data are inserted, to compute physical visibility and distance. After this first step, mission and ground station planning are applied to the results of the visibility computation to obtain what we call the *Planned Contacts*. These contacts are the expected contacts between two assets from a mission control point of view. The planned contact file is the input to the scenarios' nodes Bundle Protocol Agents (BPA) and dictate when DTN nodes are actively sending and receiving data. Please note that if a node is actively listening and/or sending, it does not imply that data is actually flowing between nodes, but that there is an expectation of data flow at that time. Whether the data will effectively flow, is dictated by the *Actual Contacts* file. This file contains is a subset of the *Planned Contacts,* considering link errors, missed, or partial contacts (see subsection 3.2). For constant contacts, such as terrestrial IP connections, the contacts are prepended at the beginning of the file and start at time zero until the end of the simulation represented with a value of -1.

To summarize, the *Planned Contacts* file is used by the various BPAs in the scenario to determine when a node should be actively listening/sending data and consequently, how bundles should be forwarded at a specific time.

```
source,destination,contact_start(s),contact_end(s), data_rate(bps), latency(s),link_type
eogs1,eomcc,0,-1, 100000000,0.010,eth
eomcc,eogs1,0,-1, 100000000,0.010,eth
eosat,eogs1,1270.982,1370.139,1000000000,0.007,hi_bw
eogs1,eosat,1375.305,1378.958,0.060,0.010,lo_bw
eosat,eogs1,1504.294,1704.443,1000000000,0.007,hi_bw
```

Figure 1: example of Planned Contacts CSV file

The file is in CSV format, and it is illustrated in Fig. 1. Every line represents a single contact and the columns composing the file are:

- **source**: the link source node identifier, both **source** and **destination** are also used to map these identifiers to a “node_id” in the *Nodes* file (see 3.3).
- **destination**: the link destination node identifier.
- **contact_start(s)**: the start time of the contact, in seconds, relative to the start of the simulation time (zero).
- **contact_end(s)**: the end time of the contact, in seconds, relative to the start of the simulation time (zero).
- **data_rate(bps)**: the link throughput in bits per second.
- **latency(s)**: the link latency in seconds, calculated using the physical distance of the two assets at the beginning of the contact.
- **link_type**: the link type, that is a label used to route specific application data over specific link types, e.g. using S-Band for housekeeping downlink and Ka-Band for science data; both links may be active at the same time.

3.2 Actual Contacts

The second file is called *Actual Contacts*, and it is directly derived from the first one. The idea of this file is to provide an input to the simulator running the scenario, to turn on and off links, depending on an error model (see 2.1.5). For instance, a *Planned Contact* entry can be split into multiple sub entries, can start late, finish early or can be dropped altogether. In this case the Bundle Protocol Agent will be sending or be listening for incoming data, expecting a link that is not there, resulting in bundle loss and potentially data retransmission. The file format is identical to *Planned Contacts* file shown in Fig.1.

3.3 Nodes

The *Nodes* file is a mapping file that contains all nodes present in the topology in JSON format. The file is necessary to map a node identifier to a specific DTN node ID and adds a node name for visualisation purposes and user convenience.


```json
{
  "nodes": {
    "eogs1": {
      "name": "Ground Station 1",
      "node_id": "ipn:10.0"
    },
    "eogs2": {
      "name": "Ground Station 2",
      "node_id": "ipn:20.0"
    },
    "eomcc": {
      "name": "Mission Control Centre",
      "node_id": "ipn:30.0"
    },
    "eopcc": {
      "name": "Payload Control Centre",
      "node_id": "ipn:40.0"
    },
    "eosat": {
      "name": "Earth Observation Satellite",
      "node_id": "ipn:50.0"
    }
  }
}
```


Figure 2: Nodes JSON file example for the Earth Observation scenario

Fig. 2 shows an example of the file with data from the Earth Observation scenario. The JSON structure contains a single root called “nodes” that is a dictionary containing all the nodes present in the scenario definition, with their respective names and node identifiers. Please note that the “node_id” field is a string that does not preclude the use of different naming scheme.

3.4 Application Data

The last file necessary to define a scenario is the *Application Data* JSON file. This file defines the traffic generation and traffic flow in the simulated network. As shown in the example file of Fig. 3, the file is composed by two main fields, the *traffic_type* and the *traffic_generation*. The *traffic_generation* defines a bundle generation policy inside the simulation. A bundle generation policy can be applied to multiple nodes, and it is composed by the following parameters:

- **info**: an informational field aiding the user in the file configuration.
- **src**: the source endpoint id from which the generated traffic is sent.
- **dst**: the destination endpoint id to which the generated traffic shall be delivered.
- **start_time**: the data generation start time in seconds, relative to the simulation start time.
- **end_time**: the data generation end time in seconds, relative to the simulation start time.
- **type**: the traffic type, referring to the *traffic_type* parameter that must be defined in the same file.


```
{
  "traffic_type": {
    "TC": {
      "link_restrictions": [],
      "bundle_size": 1000,
      "generation_rate_per_second": 1
    },
    "TM_high": {
      "link_restrictions": [
        "eth",
        "hi_bw"
      ],
      "bundle_size": 1000,
      "generation_rate_per_second": 1
    },
    "TM_low": {
      "link_restrictions": [
        "eth",
        "hi_bw"
      ],
      "bundle_size": 1000,
      "generation_rate_per_second": 1
    },
```

```
  "traffic_generation": [
    {
      "info": "eosat [ipn:50.0] -> eomcc [ipn:30.0]",
      "src": "ipn:50.1",
      "dst": "ipn:30.1",
      "start_time": 0,
      "end_time": -1,
      "type": "TM_low"
    },
    {
      "info": "eosat [ipn:50.0] -> eopcc [ipn:40.0]",
      "src": "ipn:50.5",
      "dst": "ipn:40.5",
      "start_time": 0,
      "end_time": -1,
      "type": "PAYLOAD"
    },
    {
      "info": "eomcc [ipn:30.0] -> eosat [ipn:50.0]",
      "src": "ipn:30.1",
      "dst": "ipn:50.1",
      "start_time": 0,
      "end_time": -1,
      "type": "TC"
    }
  ]
```


Figure 3: Application Data JSON file example.

The user must pay careful attention when preparing the traffic generation, as misconfiguration can occur if the source endpoint id does not correspond to any node identifier defined in the *nodes* file; this is also the reason why the info parameter has been added and can be programmatically added for new potential scenarios, it tries to bridge the gap between the two files without introducing direct referencing, that can be hard to read for a novice user.

The *traffic_type* part of the file contains the definitions of the traffic types used in the definition of the traffic generation. A type is composed by three elements:

- **link_restrictions**: defines which link types can be used for this particular traffic type. If empty, any link type can be used.
- **bundle_size**: the size of the generated bundle for this traffic type.
- **generation_rate**: the rate at which the bundles are generated, in seconds.

The link restrictions are necessary to cover scenarios where certain traffic types, e.g. housekeeping data and science, are restricted to certain links.

4. DTN Scenarios

In this section we describe the three scenarios in more details. We propose three scenarios that covers a variety of DTN deployments based on current and near future missions. The scenarios have been designed to be as simple as possible while maintaining relevant characteristics for testing and validation activities. They should be easy to expand to fit potential research and development purpose but are also representative enough to conduct DTN validation without further modification. The aim is to simplify DTN technologies testing and validation for Earth observation missions and lunar/mars exploration missions. The state of the art in terms of near future missions communication expectations [4, 7]has been consulted and current practices and capabilities in agencies missions [8] has been used to determine realistic values for the scenarios' characteristics.

4.1 Earth Observation Scenario

The Earth Observation (EO) scenario is the simplest DTN scenario with a single satellite, 2 ground stations, 1 mission control centre (MCS) and 1 payload centre. In this scenario the satellite passes are frequent, and data can be downlinked at both high and low speed from different stations.

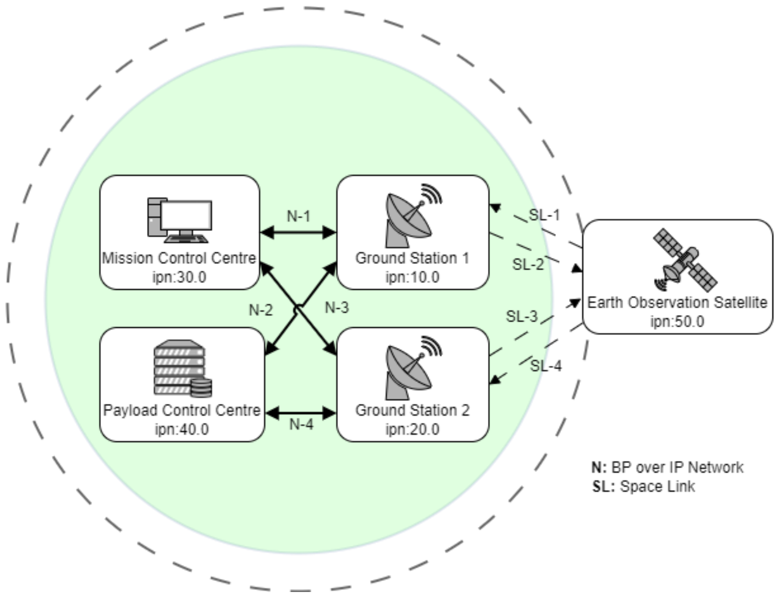

Figure 4: Earth Observation Scenario topology

A typical EO mission orbit has a large inclination and relatively low altitude. In this scenario the inclination is 90 degrees, and the elevation is 7000 Km from the centre of the earth. The ground stations with best visibility are the one at high latitude, close to the poles. For terrestrial IP links (N in Fig. 4) we have a maximum throughput of 1 Gbps and a 10 ms latency. While on the space links (SL), we have different throughput on different link directions and ground stations, such as 10 Gbps downlink for payload data, 8 Mbps for housekeeping telemetry and 64 kbps uplinks. Having much larger downlink data rates for the space link then on the terrestrial link is quite typical for upcoming Earth Observation missions and requires data buffering and complex data distribution concepts on ground [9]. Earth Observation missions are good candidates to exploit DTN capabilities where high throughput links can be used to move large quantity of data from orbit to earth.

4.2 Lunar Communication Scenario

The Lunar Communication scenario has two service providers with similar assets. Each service provider has 1 control centre, 1 relay control centre, 1 ground station, 1 Relay and 1 Lunar asset. In addition, a third relay (Lunar Gateway) is orbiting the moon, able to communicate with all ground stations and relays as well as lunar assets. The

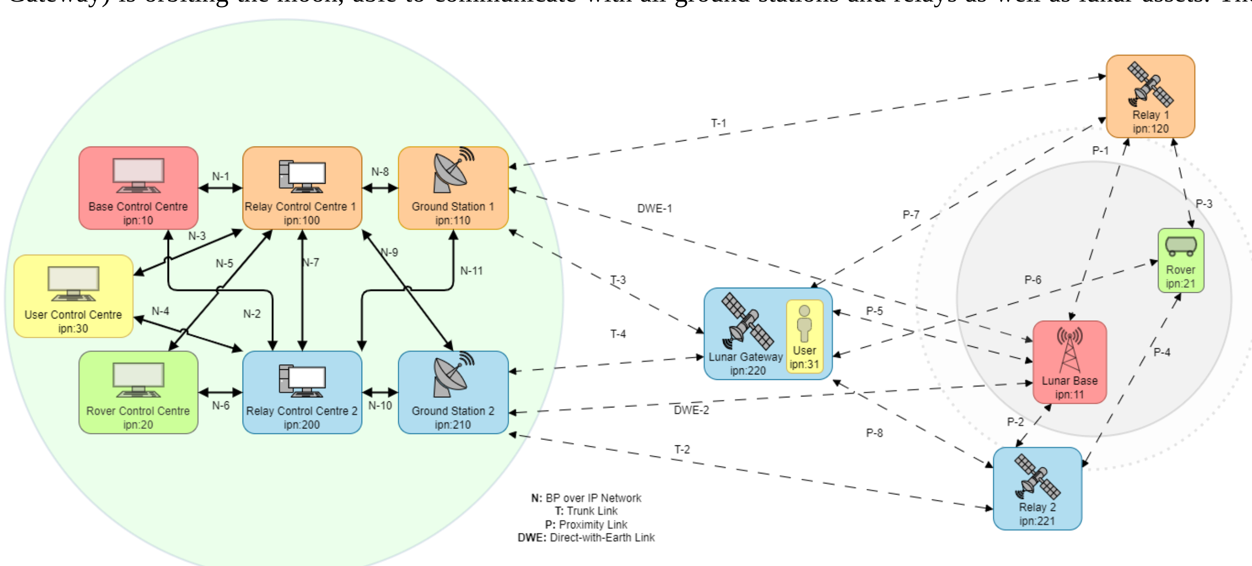

Figure 5: Lunar Communication Scenario

orbit considered for the Lunar Gateway is realistic, while the two other Relays orbits are approximation of potentially realistic orbits for a lunar constellation [10]. Also, the lunar assets position has been considered to be realistically accurate for a future lunar exploration missions [11]. In Fig. 5 different assets of different organisational entities are represented with different colours and cross support is possible between the two entities managing the relay satellites and ground stations. The lunar base position is considering solar illumination and zones of interests for exploration [11]. The rover is placed on the far side of the moon so that the DTN capabilities can be properly tested in a sparsely connected environment. In this scenario we have a variety of link throughput and latencies. Terrestrial IP network in this scenario has a maximum throughput of 100 Mbps, the trunk links have a 100 Mbps downlink and 30 Mbps uplink. For lunar assets maximum throughputs are harder to define as different sources provide different capabilities, from 30 Mbps down to 2 Mbps for the rover and lunar base uplink and downlink. At the time being, discussions on the rates that will be published for the CCSDS Yellow book are still to be confirmed and are not completely reported here to avoid future confusion.

4.3 Mars Communication Scenario

The last scenario concerns Mars communication and exploration and keeps a similar infrastructure to the Lunar one. However, in this scenario relays cannot communicate between each other (no inter-satellite links) and links have much larger delays between Earth and Mars.

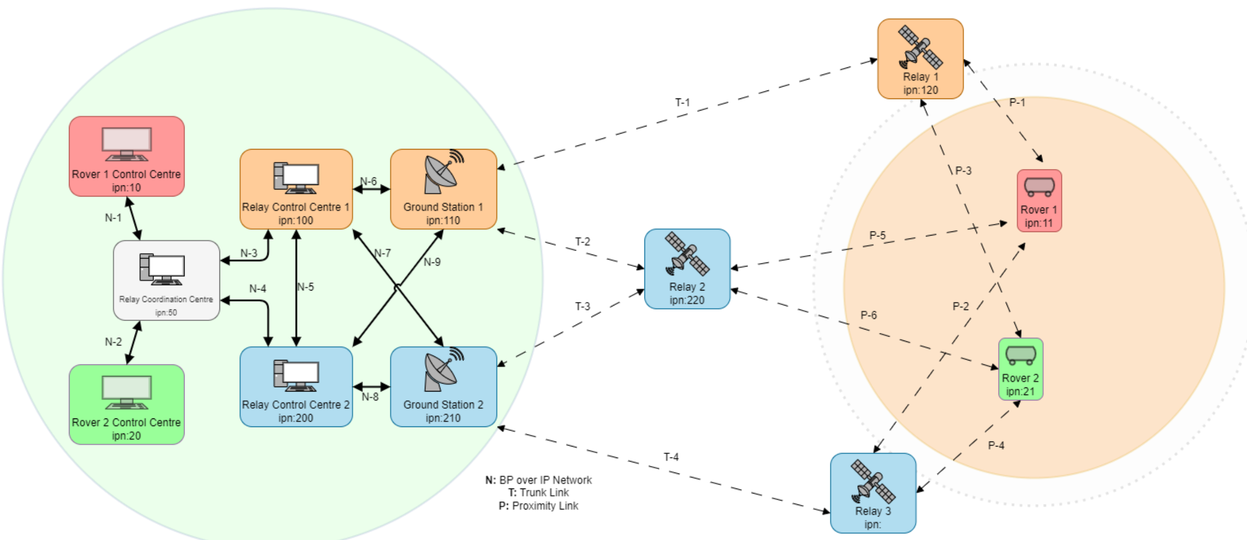

Figure 6: Mars Communication Scenario

In this scenario we have two service providers, with respectively one and two relay orbiters. Both providers have a low altitude orbiter and the second provider a high altitude one as well. In this scenario the contacts are much more sparse and shorter in time, providing a more challenging communication environment. Direct links with Earth are not available, and relays do not communicate between each other to relay data, as it is the case for current Mars relays. For this scenario the Mars Relay Network [8] and the IOAG report on Mars [12] have been an important source of information to determine relay orbits and links capabilities. The maximum links throughput is very similar to the Lunar Communication scenarios. However, the average latency for non-terrestrial links is much larger, with an average of 10 minutes. The latency and short contacts pose a more interesting challenge for DTN storage and buffering and may results very useful for technology robustness testing.

5. Versioning and availability

In order to maintain and update the scenarios to keep them relevant thought DTN technologies development, we will publish them as a CCSDS Yellow book each with independent version numbers. The book will describe the scenarios and reference the scenarios' files, that will also be publicly available. Having versioning of the scenarios allows for precise referencing to them. A change to a single scenario should not influence the version of the other and will avoid confusion. Depending on the importance of the data changes in a new version, a major or minor version change would be applied. For instance, a change to topology would be reflected in a major version change while changes in data rates or latencies in a minor version change.

For easier fruition, configuration for reference scenarios can be included in BP implementations. ESA is planning to release tooling and configuration files to support running the scenarios with the ESA implementation to aid experimentation with Bundle Protocol. We hope this will become common practice for other implementations as well as it would aid interoperability testing and research in the DTN field.

6. Conclusions

We propose three DTN reference scenarios with different characteristics that we hope can be adopted for validation and testing activities of DTN technologies. The scenarios do not aim to provide a comprehensive environment to test any possible combination of technologies and implementation. They do provide a common basis for testing, interoperability and benchmarking that could be very valuable in the coming years. The three scenarios pose different challenges for DTN operations providing different link capabilities, latencies, contacts frequency and duration; they aim to provide a solid testing environment, flexible and extendible, to fit a variety of activities that can benefit from direct results comparison and general performance assessment. We hope the scenarios will receive broad adoption at the time of publication in CCSDS, from both agencies and research institutes and that they will aid DTN adoption in future missions.

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