Space Network Emulation Using High-Rate Delay Tolerant Networking

Capstone Report

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This project report was created on TexStudio editing platform using $\LaTeX$. All the figures were drawn using draw.io online software tool.

Electrical and Computer Engineering
Nazarbayev University
http://www.nu.edu.kz

Title:
Space Network Emulation Using High-Rate Delay Tolerant Networking

Theme:
Space Communication

Project Period:
Fall 2024 - Spring 2025

Project Group:
N/A

Participant(s):
Abylay Tokbergen

Supervisor(s):
Refik Caglar Kizilirmak

Copies: 1

Page Numbers: 20

Date of Completion:
April 25, 2025

Abstract:

This capstone project is intended to provide an insight into the development of a space technology, NASA's High Rate Delay Tolerant Networking (HDTN) system, which is a breakthrough technology to compensate high rate delay tolerant networking in interplanetary networks. The work consists of designing and implementing a virtual testbed environment based on STK, Netropy, Docker Swarm and HDTN software modules. It also evaluates the performance of the DTN protocols such as BPv6, BPv7, and BPSec over LTP and TCPCL convergence layers. Realistic scenarios were tested under variable link conditions, core functions of HDTN, such as ingress, egress, routing and storage. Simulation results proved the reliability of data transmission, effectiveness of custody transfer and robustness of the encryption. Results in this thesis demonstrate that HDTN provides the potential for order of magnitude scalability, reliability and security improvement in space networks and serve as basis for future cognitive networking applications in space communication systems.

Contents

Preface

From the beginning of this work, I have become increasingly familiar with the intricacies of space networking, particularly those introduced by delay tolerant communication. I would like to thank my supervisor for his never ending encouragement, technical insights and useful feedback during the development of this project. I also value the resources and academic environment at Nazarbayev University that helped to complete this work.

This report is not only about the technical results of the project, but also about the research, innovation, commitment to engineering solutions that can be used in future space exploration missions, and I would like to express my sincere gratitude to my supervisor, Prof. Refik Caglar Kizilirmak, for his guidance and support during this project.

Nazarbayev University, April 25, 2025

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Chapter 1

Introduction

Space communication networks have grown under the significant rise in the number of satellite deployments. New topologies in space networking systems are continuously emerging, with this increase, and new challenges for routing protocols are created. To overcome these complexities, NASA Glenn Research Center has developed the High Rate Delay Tolerant Networking (HDTN) system, a practical implementation of Delay Tolerant Networking (DTN) for increasing IPNs communication efficiency and flexibility over highly heterogeneous interplanetary networks (IPNs.) [1, 2, 3, 4, 5, 6, 7, 8].

Despite these advancements, the evaluation of HDTN in realistic network environments remains intricate. Traditional approaches, such as the use of virtual machines or physical laboratory equipment, often prove inadequate for simulating the long-duration, large-scale requirements of space communications [4]. These limitations hinder robust performance testing and analysis of DTN-based systems under space-relevant conditions.

Network emulation tools provide us with a practical controlled test environment from which to surmount such constraints. DTN as defined in RFC4838 and RFC5050 [1, 4, 9] are for communication networks with high latency, intermittent connectivity and limited resources. Its fundamental operations of storage, carrying and forwarding bundles support data delivery even in highly disrupted environments. DTNs operate under the assumption of no end to end connectivity, and no rapid feedback loops [1].

Dynamic and often hostile conditions seen to a lesser extent in space lying communications, long signal delays, disrupted pathways and constrained bandwidth, are the typical conditions replicated by these emulation tools. In cases where assumptions such as low latency, or even exceptional reliability around connectivity, don't necessarily hold true, DTN systems are especially suitable [5, 6, 10]. Beyond deep space missions, their effectiveness also applies to aerial, remote, and disaster stricken networks [11, 12, 13].

The DTN architecture allows for communication based on a simplified communication model at the network layer to ensure node interoperate on various node types [14]. The store-carry-forward mechanism is a critical feature that allows preservation of data and eventual delivery even when persistent connectivity is not available [14, 9].

The HDTN initiative also explores integration with high performance computing elements that are well suited for size, weight, and power constrained platforms in addition to core communication capabilities. This allows the development of advanced features including cognitive networking. Furthermore, emerging technologies in artificial intelligence, machine learning in combination which depend on the GPUs, SSDs, and data intensive computing platforms [3, 6, 11] bolster the potential even further.

The focus of this project is on the implementation and routing strategies in DTNs with two important aspects: (1) communication management between nodes such as satellites, ground stations and research facilities; (2) packet transmission or deletion prioritization according to system requirements [12, 15]. Tight interconnections exist between these functions, routing decisions, scheduling of the message queues and the strategic allocation of communication resources.

1.1 Ethical and Professional Responsibilities

- **Ethical Responsibility:** (250-300 words)
  Ethical responsibilities are very important during the development and implementation of this project, particularly, data privacy, security and access to technology. In case of DTN, applications may be used in disaster assistance or humanitarian aid, and the use of emulation tools and network systems may involve the storing of sensitive data. Third parties can misuse and transeffer data in terms of information of locations, files, information of the servers and transmitted data. In order to avoid potential dangers or breaches, the data has to be admitted that it will be securely transmtted and protected from unauthorized access. In underdeveloped or marginalised areas, there is probability of a risk that the technology will be distributed and available to all third parties equally. Regarding matters of data privacy and security, the project ensures data privacy and safety by implementing some robust data protection and data encryption industry standard. This point will make sure that the point where sensitive information is confidential and protected. Moreover, the project aims to enable the use of the proposed solutions for several socioeconomic contexts. It is done in bridging the digital divides and that the benefits of technology should be available. Additionally, the project will be connected with ethical considerations at every stage. It includes transparency in the process of making decisions and accountability in the process of development of the project and transparency in distribution of the risk assesment. These ideals have to have priority in the project to contribute to a future that is more sustainable.

- **Informed Judgments:** (250-300 words)
  The problem addressed by the project is that of unstable and dependable communication in various conditions, which is relevant in the global context. In remote areas or space where normal infrastructures are unstable or not available, alternative proposition of Delay Tolerant Networking (DTN) technology is ensured. The projects' impacts are dependent on the specific situations of implementation. Implementation of this can be done during emergencies situations, where DTN technology can hold essential communication opportunities with other networks. Functions may have purpose in coordinating rescue possibilities, delivering aid and keeping the basic services. The DTN technology are capable of usage and application in the specialized domains such as the aerial and space networks or scientific research in more technologically developed countries. It can be used as the example to transmit data from remote studies or to improve communication between transmission towers and satellites. The project's global implementation has cultural and legal implications. Sometimes security, accessibility and privacy

of data can vary from region to region. The project is ensure to carefully admit these factors and to apply specific needs and output in the diverse of community globally. The project is intended to be flexible so as to allow application of the project to international conditions without compromising functionality by accommodating differences in the informed judgements.

- **Global Context:** (250-300 words)
  In this regard, the project has its focal point on the need for reliable communication in such moments as in the context of worldwide situations. DTN technology would be an important option, especially in areas: remote areas or outer networks, such as in areas in which standard infrastructure is not existnent. The impacts in the project are contingent on the particular situation of the implementation of the DTN. In such emergency situations, traditional networks are unreliable due to their allocation, and so DTN technology will provide supply in communication ability for developing countries and dangerous regions, in survival situations. This proposition will be essential for coordinating rescue actions, by providing humanitarian aid and continuing with critical emergency services. DTN technology can be used as an example to establish emergency communication networks during a natural disaster, which can coordinate with rescue efforts and serve injured people. It can be impleneted in some areas of the scientific studies or airborne communication systems in countries with higher levels of technological progress. On data security, accessibility and privacy factors, regional differences might play a role. In regions where data protection regulation exists, like data protection and privacy standards, changes will be needed to be able to observe with local laws. However, it could improve airborne systems in terms of the protection.

- **Economic Impact:** (250-300 words)
  The economy is affected by the project in short and long term periods. There are significant costs to be processed in the short term for testing, development and research. Resource allocation is involved in creating and using DTN systems and emulation platforms. However, the financial revenue in the long term run could offset the costs. Technology would have the potential to begin in building up the economy and the effectiveness of businesses, governments and thrid parties by providing reliable communication propositions to underdeveloped and underserved regions. Expenses in configuration and equipment control in regions with limited resources is one of the most possible challenge. The project is aimed at developing a finance effective, adaptable and flexible DTN solution for operation in different economic fields. This component involved exploring partnerships with governmental and private companies in combining resources and reduction of costs. Additionally, the project will work on the development of open source software

and hardware elements to achieve accessibility and affordability. The project is to put these actions in place in order to reduce the cost for communities, while maximizing the economic advantages of DTN technology.

- **Environmental Impact:** (250-300 words)
  The goal of the project is to minimize the environmental footprint by considering the remote communications, its networks, and space. Efforts are made to minimize the resource usage in testing and operation processes in the development of technologies such as DTN systems and various emulation tools. Furthermore, the project's design intends to prevent environmental damage and to reduce the percentage of pollution or pollution that affects the ecosystems most especially in isolated areas. The sustainability ideas of the project are the production of ecological friendly products and energy efficient devices in the infrastructure of communication network. Additionally, environment monitoring may be used to control unforeseen ecological impacts of the capstone project. The project has an aim to ensure that the environmental issues are secured and all individuals are given the improved communication technologies. The aim would be to avoid any digital divides and ensure that the advantages of the technology are enjoyed by everyone equally. In this project, there is participation in building solution that can be inclusive and adaptable to different cultural and language settings. The objective is to ensure that technological advancements are spread out equally among people and make society more fairness and equality.

- **Societal Impact:** (250-300 words)
  The goal of the project is to minimize the environmental footprint by considering the remote communications, its networks, and space. Efforts are made to minimize the resource usage in testing and operation processes in the development of technologies such as DTN systems and various emulation tools. Furthermore, the project's design intends to prevent environmental damage and to reduce the percentage of pollution or pollution that affects the ecosystems most especially in isolated areas. The sustainability ideas of the project are the production of ecological friendly products and energy efficient devices in the infrastructure of communication network. Additionally, environment monitoring may be used to control unforeseen ecological impacts of the capstone project. The project has an aim to ensure that the environmental issues are secured and all individuals are given the improved communication technologies. The aim would be to avoid any digital divides and ensure that the advantages of the technology are enjoyed by everyone equally. In this project, there is participation in building solution that can be inclusive and adaptable to different cultural and language settings. The objective is to ensure that technological advancements are spread out equally

among people and make society more fairness and equality.

Chapter 2

Background

HDTN's additional capabilities enable transmission of more data from spacecraft to Earth. Due to the high-resolution imaging, environmental monitoring and complex scientific experiments, missions with such capabilities require this. Scientists can get richer datasets from HDTN that helps them do deeper and more comprehensive analysis and understand all things such as planetary atmospheres, surface conditions and cosmic events [3, 13].

The networks of the space missions are often out of predictability, having variable connectivity, and significant delay. In these challenging environments, HDTN is designed to maintain reliable communication [1, 2, 5]. This reliability guarantees, as is necessary under time critical experiments and for the success of a long duration mission, critical data transmission is safe against loss.

Increased autonomy of spacecraft requires effective communication system to support real-time decision making. HDTN allows autonomous systems to send data back to Earth for analysis and to receive commands or updates so that it can be more complex systems and less susceptible to continued manual control [6].

HDTN's particular capabilities are most applicable to future interplanetary and interstellar missions, during which communication delays can span minutes, hours, and much longer. HDTN can also make sure that data that is collected from distant missions is transmitted in an efficient way even if the spacecraft is not always in contact with Earth [2, 9, 8].

NASA's High Rate Delay Tolerant Networking (HDTN) project is a major effort to improve space mission communication capabilities [13, 15]. With the increase of complexity and data rate in space missions, traditional networking protocols fail to satisfy the requirements of variable connectivity and long delay of space communication. To overcome these challenges, the HDTN project aims to build a robust networking framework which is capable to reliably transmit the data between such spacecraft and its ground stations steadily through the intermittent connectivity and high latency [4, 5, 10].

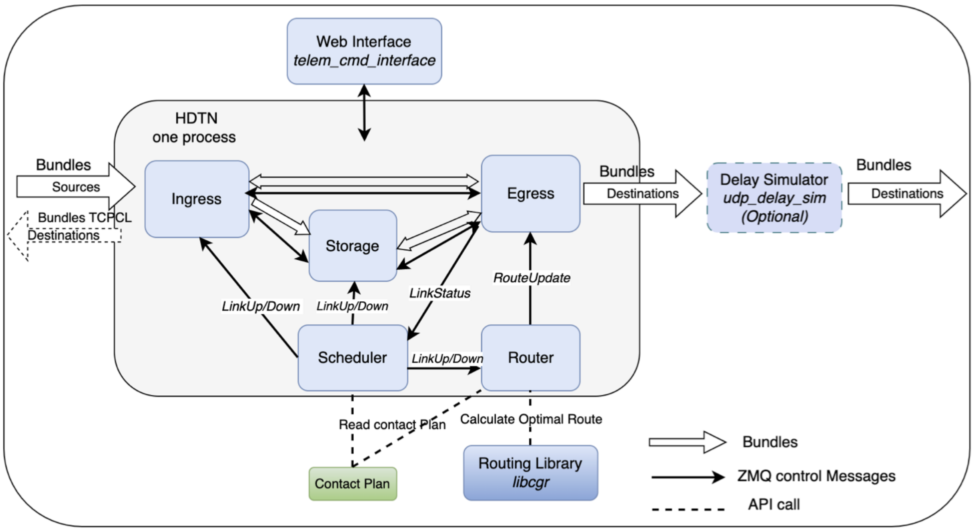

Figure 2.1: HDTN Architecture.

The HDTN is based on Delay Tolerant Networking (DTN) principle [2, 9] that is intended for use in environments where end-to-end connectivity is not assured. The data transport layer designed in this project makes use of existing protocols and standards like the Bundle Protocol (BP) and Licklider Transmission Protocol (LTP) in order to achieve flexibility and efficiency. The HDTN attempts to achieve a significant improvement in the volume and reliability of scientific data returned from space missions by implementing a high rate variant of these protocols [13, 6, 7].

To handle disruptions, DTN was designed to use a store and forward architecture using the bundle protocol. This is important for interplanetary missions with communication delays spanning large durations because of large distances [2, 9, 8]. As the number of deployed satellites and the space network are increasing, routing becomes a critical challenge than in large scale, dynamic topology [14, 16, 7]. Simulation methods that have been developed for HDTN node analysis are insufficient to scale to this large number of nodes in future space missions. To tackle this, a new simulation tool, (H)DtnSim, was created in order to facilitate efficient testing and evaluation of HDTN performance in such complex environments [4, 15, 17].

Chapter 3

Methodology

3.1 Methods and Procedure of Data Collection

HDTN is a technology that is applicable to most space applications. This testing process showed that HDTN can be run on low level ARM based systems and in parsed architecture. This is a more universal compatibility and mission infusion into HDTN is a versatile technology that can work in most space applications. In this testing process HDTN demonstrated that it can run on low level ARM based systems and in a parsed architecture. This makes the door open to more universal compatibility and mission infusion. One use case for HDTN is the operation on a variety of new systems and thus, small robotic missions are one use case. The direction of data flow, number of devices and number of nodes in the network have little effect on payload data rates for TCPCL and LTP over UDP. The same distributed architecture was benchmark tested in a similar manner as the testing of a single HDTN implementation. Based on the results from the benchmark testing, these implementation options and capabilities are examined to gain how they can extend the DTN use cases, especially for small robotic missions.

Used Protocols for the simulations:

1. TCP Convergence Layer Protocol (TCLP): TCLP is a protocol that allows TCP/IP based communication to change to suit the environment of a DTN. Furthermore, it ensures reliable delivery of bundles over TCP and is great for predictable links, but could hit some obstacles when the network is highly delaying or disrupted. Setting up TCP sockets and making sure it is compatible with DTN protocols for bundle transmission is configuration.

2. LTP (Licklider Transmission Protocol) – a transport protocol designed for long delay and disorder environments such as space. In efficient retransmission of critical data it divides data to red (reliable) and green (unreliable) segments. Setting the parameters like segment sizes, retransmission timers, acknowledgment settings are needed for configuration.

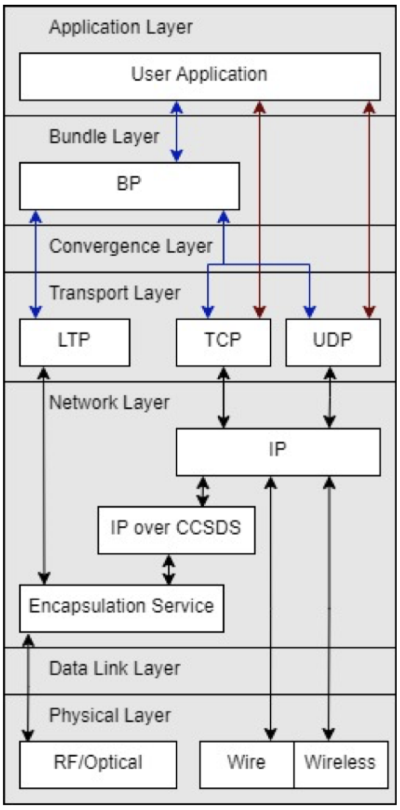

Figure 3.1: HDTN Protocol Stack.

3. BPSec - provides security features such as authentication and encryption. Transmitting data integrity and confidentiality is always enabled.

3.2 Methods and Procedure of Data Analysis

The Ingress module takes bundles, decodes the header fields, and uses the source and destination fields to determine the source and destination of the bundles. The bundles are sent to the Storage module if the link is down or custody transfer is enabled (i.e., the responsibility for reliable delivery of bundles is transferred to other DTN nodes in the network), or if the link is available, Ingress sends the bundles in a cut through mode to Egress [24].

It is a multi-threaded implementation which distributes storage across multiple disks, and handles custody transfer. It receives messages to decide when stored bundles can be released and forwarded to Egress [23].

One of the algorithms in the routing library is used to get the next hop and best route to the final destination, which is returned by the Router module. Currently, the router supports Contact Graph Routing (CGR), Dijkstra's algorithm (the default algorithm used), and Contact Multigraph Routing (CMR), a modified version of Dijkstra's algorithm using a multigraph structure instead of a contact graph and offering a significant performance improvement [17]. When Egress receives the RouteUpdate event from the Router, it updates its outduct to the outduct of that next hop. When the link goes down unexpectedly or the contact plan changes, the Router is notified, resends the RouteUpdate event to Egress, and Egress updates its outduct to reflect the new next hop.

Router computes the optimal route and forwards bundles received from Storage or Ingress to the correct outduct and next hop based on this route using the Egress module. Heart checks unexpected link updates and contact plan changes via an event driven approach that is based upon ZeroMQ pub-sub sockets. Egress will send a LinkStatus update message to the Scheduler, which will cause the Scheduler to send a LinkDown or LinkUp event to Ingress, Storage and Router to see if the route should be re-calculated or if bundles should be stored.

3.2.1 System Architecture and Components

The simulation involves three nodes, each performing specific tasks in the HDTN network:

- **Node 1** (BPGEN): This node generates bundles at a specified rate and size and forwards them to **Node 2**. It uses the **BPGEN** (Bundle Protocol Generator) function.
- **Node 2** (Intermediate Node): This node receives bundles from **Node 1** and forwards them to **Node 3**. It supports two transport protocols: **TCPCL** and **LTP over UDP**, which affect the transmission speed and reliability.
- **Node 3** (BPSink): This node receives bundles from **Node 2** and processes them using the **BPSink** (Bundle Protocol Sink) function.

Each node has a configuration file that defines various parameters such as:

- **Node ID**: A unique identifier for each node.
- **Bundle Size**: The size of each bundle in bytes.
- **Bundle Rate**: The rate at which bundles are generated or processed.
- **Transport Protocol**: Specifies whether **TCPCL** or **LTP over UDP** is used.
- **Destination Node**: The next node in the network that will receive the bundle.

- **Max Bundles**: Limits the number of bundles processed during the simulation.
- **Contact Window**: The time window within which a node can send or receive bundles, defined by `startTime` and `endTime`.

The simulation proceeds by sending bundles from **Node 1** to **Node 2** and then from **Node 2** to **Node 3**, based on the contact plan and node configurations.

3.2.2 Simulation Design

Bundle Generation (BPGEN)

Node 1 generates bundles based on the specified `bundleRate` (bundles per second) and `bundleSize` (bytes). The **BPGEN** function in **Node 1** ensures that bundles are generated until the specified `maxBundles` limit is reached.

Transmission and Forwarding

Node 1 forwards the generated bundles to **Node 2**. **Node 2**, depending on its availability as defined by the contact window, receives the bundles and forwards them to **Node 3**.

Transport Protocols

Node 2 supports two transport protocols: **TCPCL** and **LTP over UDP**. Each protocol has different characteristics:

- **TCPCL (TCP Convergence Layer)**: Slower transmission due to TCP overhead, which ensures reliable data delivery but introduces additional delays.
- **LTP over UDP**: A faster protocol operating over UDP, with lower overhead and no retransmission or acknowledgment, leading to reduced delays compared to TCPCL.

Rate Calculation

The time taken for transmission is divided by the bundle size to get the transmission rate for each bundle. The rate is reported in `bytes per second` and is then converted to `Mbit/sec`. Other statistics tracked for each node is the following:

- **Total Rate**: The total data rate of bundles transmitted.
- **Highest Rate**: The highest observed transmission rate.
- **Lowest Rate**: The lowest observed transmission rate.

- **Average Rate**: The average rate of transmission for the node.

These rates help compare the performance of **TCPCL** and **LTP over UDP**.

Bundle Processing (BPSink)

Node 3 processes the bundles received from **Node 2** using the **BPSink**. It simulates the processing of bundles by logging their contents and calculating the processing rate. **Node 3** also simulates packet corruption. A bundle may encounter a random error during transmission, which is flagged as corrupted.

3.2.3 Simulation Flow

1. **Initialization**: The simulation initializes **Node 1**, **Node 2**, and **Node 3** based on their respective configuration files (e.g., `hdtn_node1.json`, `hdtn_node2.json`, `hdtn_node3.json`).
2. **Bundle Generation**: **Node 1** generates bundles according to the specified configuration and forwards them to **Node 2**.
3. **Bundle Forwarding**: **Node 2** receives bundles, checks its availability (based on the contact window), and forwards them to **Node 3**.
4. **Bundle Processing**: **Node 3** receives the bundles and processes them using the **BPSink**.
5. **Performance Metrics**: Throughout the simulation, performance metrics for each node are calculated, such as bundle count, total rate, highest rate, lowest rate, and average rate.
6. **Termination**: The simulation stops once **Node 1** has generated and forwarded the maximum number of bundles specified by the `maxBundles` parameter.

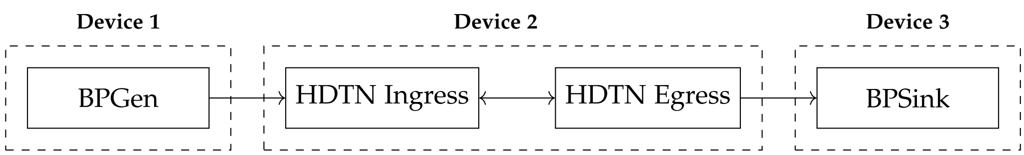

Figure 3.2: Distributed HDTN Instance Topology: Device 1 (BPGen), Device 2 (HDTN Core), Device 3 (BPSink)

3.2.4 Variations in terms of simulation

Three topological representations of increasing network complexity were made:

In Test 1, Device 1 had BPGen and HDTN modules, Device 2 had BPSink module.

Test 2 is a chain of three Device that extended the chain from two to three nodes, adding one more middle HDTN node, simulating a multi hop environment.

Test 3 emerged at four Device to enable a more distributed and realistic space communication test scenario.

System logs and performance statistics were collected and analyzed during all parts of the simulation to determine each convergence layer protocol's behavior in identical conditions. The resulting data helped validate HDTN as a useful mechanism to adapt between TCPCL and LTP in stable environments and between LTP and lossy environments to handle high latency.

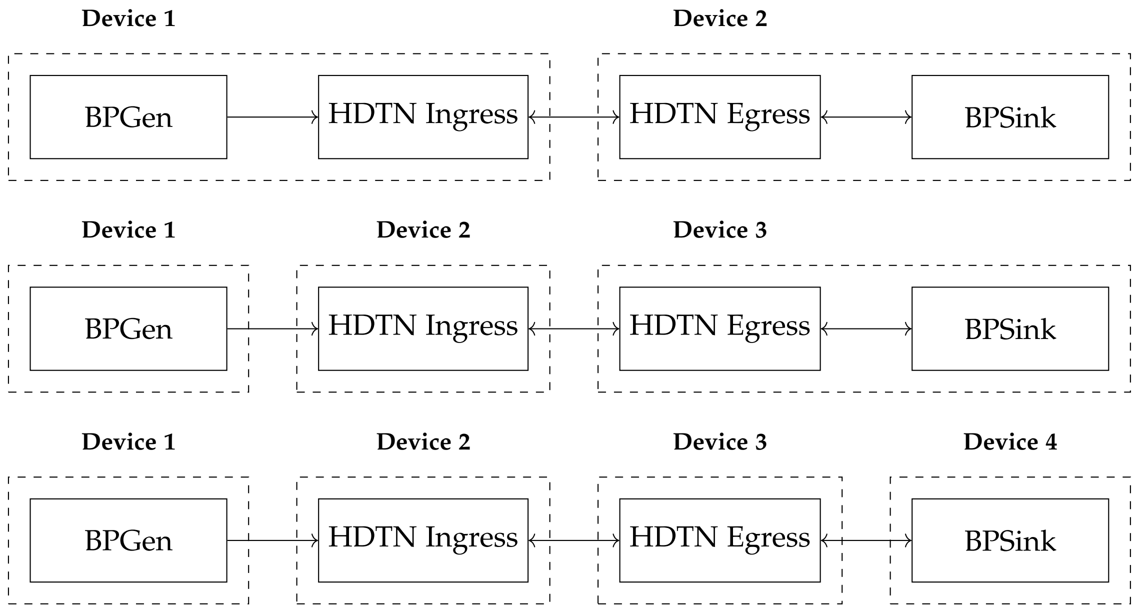

Figure 3.3: Simulation Topologies: HDTN Components with BPGen and BPSink

Chapter 4

Results and Discussions

4.1 Results

Table 4.1: LTP over UDP Performance Metrics

Node	Total Rate (Mbps)	Highest Rate (Mbps)	Lowest Rate (Mbps)	Average Rate (Mbps)
Node 1	512.464	532.426	490.568	520.446
Node 2	460.253	470.111	440.79	455.341
Node 3	400.403	410.394	390.00	400.532

Table 4.2: LTP over UDP Performance Metrics

Node	Total Rate (Mbps)	Highest Rate (Mbps)	Lowest Rate (Mbps)	Average Rate (Mbps)
Node 1	140.805	143.206	139.226	13.924
Node 2	126.724	128.885	120.507	122.880
Node 3	101.379	104.344	96.411	97.692

Comparison of single and multi bundles shows that while LTP can handle single bundles throughputs at a moderate scale, its performance is dramatically improved in the case of multiple bundles. In particular, the average rate increased from 13.924 Mbps in the single bundle case to 520.00 Mbps in Node 1.
The results show that LTP is suitable for delay tolerant applications with high data throughput when multiple concurrent bundles are handled. The implications to space communication networks and terrestrial DTNs that require both reliability and performance scalability are direct.

Table 4.3: Performance Comparison of TCPCL and LTP over UDP

Convergence Layer	Payload Only Rate (Mbit/s)	Total Rate (Mbit/s)	Highest Rate (Mbit/s)	Lowest Rate (Mbit/s)	Bundle Count	Bundle Rate (Bundles/s)
Test 1						
TCPCL	513.6572	508.2653	525.2508	454.3803	191034	625.4546
LTP over UDP	112.9602	110.8121	94.4893	104.1558	42186	107.2906
Test 2						
TCPCL	506.6042	508.2560	534.7744	442.1416	197101	651.2022
LTP over UDP	90.3734	98.3282	118.5590	109.4428	40125	153.5426
Test 3						
TCPCL	502.9780	506.8543	523.6574	471.5428	194710	633.8227
LTP over UDP	114.6460	117.2029	106.9530	112.2443	39588	119.1285

Using a range of configurations, ranging from the number of nodes and convergence layers, the system performance was evaluated in the HDTN simulation. The key performance metrics are summarized in Table 4.1 for three different test cases and compared between TCPCL and LTP over UDP protocols.

TCPCL provided 513.66 Mbit/s payload only rate and 508.27 Mbit/s total throughput, more than 4.5 times better than LTP (112.96 Mbit/s payload, 110.81 Mbit/s total) for Test 1. The same trend was observed in Tests 2 and 3. TCPCL was notably higher in throughput and bundle counts (for instance, Test 2 has 197101 bundles instead of 40125 as LTP) than LTP, yet LTP proved more resilient across tests.

The protocols also varied in the highest and lowest throughput rates. The performance volatility of TCPCL was wider (442.14 Mbit/s to 534.77 Mbit/s) compared to TCPB. On the other hand, LTP had a more restricted and predictable range in Tests 2 and 3.

Figure 3.2 shows that these tests were executed over a distributed architecture, where BPGens, HDTN nodes (Ingress/Egress) and BPSinks were scaled from two to four nodes across the tests. It allowed both scalability and protocol efficiency to be assessed.

4.2 Discussions

The results clearly show that TCPCL outperforms TCP in HDTN environments, in particular when link reliability is high. Because TCPCL is dependent on the TCP/IP stack, it enjoys the benefits of well optimized congestion control and reliability mechanisms which results in higher bundle throughput and faster transmission rates. It is therefore ideal for relatively stable or terrestrial segments of the network.

LTP over UDP, though with lower throughput, is designed for disrupted or deep space links. It supports its segmentation strategy (red and green segments) that enables it to concentrate critical data through minimal overhead and retransmission management for high latency and lossy space communication scenario.

LTP's performance consistency across tests also represents the design for resilience and predictability under constrained conditions. In Test 3, LTP may experience a slight boost in throughput comparison to other tests due to more efficient link utilization over several nodes and that LTP performs well under a distributed HDTN topology.

Figure 3.2: Simulation topologies (incremental complexity starting from two nodes to four) show HDTN's modular scalability. The routing and bundle management were kept at high efficiency, and even more so through dynamic updates of the HDTN Router component using CGR and CMR algorithms as the system expanded.

HDTN was implemented with protocols such as BPv6, BPv7, BPSec and transport layers like TCPCL and LTP that showed HDTN's ability to cope with the high latency and disrupted environments. Key to the system's maturation, the particular uniqueness of this achievement was the ability of the system to keep data flow efficient, and to perform custody transfers while maintaining integrity of the loop in the case of link outages. It was demonstrated that the routing capabilities, in case of algorithms like Contact Graph Routing (CGR) and Contact Multigraph Routing (CMR), allow routing of bundles to globally optimized paths which can dynamically react to changes in the topology.

Chapter 5

Conclusion

The High Rate Delay Tolerant Networking (HDTN) framework presented in this paper offers a novel approximation method to evaluate tThis project demonstrates the validity of the HDTN framework as a seminal contribution to solving the communication problems in deep space and intermittently connected environments. The project then completed an evaluation of the HDTN performance, adaptability and reliability based on a comprehensive emulation environment which it had built. HDTN achieves strong fault tolerance with efficient routing mechanism and integrated security based on BPSec, and the results show they work very well to manage data transfer.

Also, HDTN has a modular and distributed architecture that makes it easy to scale, and to integrate in multiple missions from Earth orbiting satellites to interplanetary probes. For operational deployment in unpredictable environments, the system is ready to dynamically update routing decisions in real time under the circumstance of disturbance to the connection and the dynamic adaptation capability of the system highlights its capacity for adaptation to disturbance.

Finally, HDTN is suitable for testing and validating of DTN protocols in realistic scenarios in future space infrastructure. This work lays the groundwork for future research on the cognitive networking and AI enhanced routing mechanism, and by doing so, it pushes the boundaries for the achievable in autonomous, delay tolerant communication system.

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