**Gateway to the stars: Advancing hybrid space networks in low Earth orbit**

DND need solutions that demonstrate space-based communication gateways connecting diverse space-based assets

These gateways must have the ability to collect, synthesize, and distribute large volumes of data from diverse sources to ensure domain awareness and effective command and control

LEO satellite constellations are envisioned to fulfil these requirements by enabling HSNs with high throughput, low latency, and global coverage. Of particular importance is HSN architectural robustness and resilience under dynamic traffic load and segment failure conditions.

We need information on new insights on achievable multi-hop capabilities under different operational conditions, supported by measurement data. The operational conditions include but are not limited to traffic dynamics and link or network failures to inform future HSN architecture development. The emphasis is on advancing analytical and simulation models, based on measurement data, to capture the dynamics of network behaviours for different types of applications. The goal of the challenge is to characterize gateway paths that include multiple inter-satellite links.

Outcomes

provide insight into the design of future resilient HSN and demonstrate how the solution will measure and characterize inter-satellite links, including the planning and execution of measurements, and the analysis and modelling of collected data.

On-orbit experiments designed to measure and characterize space network communication paths comprising multiple inter-satellite links. These must involve transmitting data from a space-based or terrestrial data source, via at least one LEO gateway satellite, to one or more constellations of data relays, and then to one or more remote terminals;

Characterization of the end-to-end data path, including link establishment, maintenance (such as handovers and adaptation), and quality of service; and,

Documentation of all demonstrations, experiments, characterisations, analyses, and results as well as delivering all supporting models, simulations, and raw data.

* on-orbit data processing
* additional gateway functionality
* alternate inter-satellite bearers
* multiple application traffic types
* path recovery and resilience
* resource management
* alternate handover protocols
* performance under varying traffic loads

Mesh routing protocols for inter-satellite links focusing on fastest path through and

**AI-Driven Digital Twin Framework for Adaptive Traffic Management in Multi-Hop LEO Gateway Networks**

**Executive Summary**

This integrated proposal presents a comprehensive solution for characterizing and optimizing hybrid space network (HSN) gateway operations through an innovative combination of digital twin simulation, artificial intelligence-driven inter-satellite link (ISL) quality prediction, and adaptive traffic management. The solution advances from fundamental research (TRL 1-3) through design and prototyping (TRL 4-5) to full-scale demonstration and validation (TRL 6-7), directly addressing DND/CAF requirements for resilient space-based communication gateways in Low Earth Orbit (LEO).

**Total Phased Funding Request:**

* **Phase 1 (TRL 1-3):** $250,000 | 6 months
* **Phase 2 (TRL 4-5):** $1,500,000 | 12 months
* **Phase 3 (TRL 6-7):** $4,800,000 | 18 months
* **Total:** $6,550,000 | 36 months

**1. Technical Background and Innovation**

**1.1 Problem Statement**

Modern defence operations require robust communication networks that can operate in contested, degraded, and remote environments, particularly in Canada's Arctic regions. Current LEO satellite systems face significant challenges in maintaining quality of service through multi-hop ISL paths, especially under dynamic traffic conditions and potential link failures [1, 2]. The lack of predictive models for ISL quality and adaptive traffic management limits the operational effectiveness of emerging hybrid space networks [3, 8].

**1.2 Innovation Overview**

Our solution integrates three complementary technological approaches:

1. **AI-Driven ISL Prediction:** Machine learning models that predict link quality, optimize handover decisions, and enable proactive network management under varying atmospheric and orbital conditions [1, 3, 4]
2. **Adaptive Traffic Management:** Intelligent routing algorithms using deep reinforcement learning (DRL) to optimize multi-hop data flows based on network conditions, traffic priorities, and QoS requirements [4, 17]
3. **Digital Twin Platform:** High-fidelity simulation environment that models LEO gateway behavior, orbital dynamics, and end-to-end data path characteristics in real-time [11, 13]

This integrated approach enables comprehensive characterization of gateway paths through multiple ISLs while providing actionable insights for future HSN architecture development.

**1.3 Alignment with DND/CAF Requirements**

**Essential Outcomes:**

* ✓ On-orbit experiments measuring multi-hop ISL communication paths
* ✓ End-to-end data path characterization including link establishment, maintenance, and QoS
* ✓ Comprehensive documentation with supporting models, simulations, and raw data

**Desired Outcomes Addressed:**

* Technology demonstration: AI/ML for on-orbit data processing (1b), multiple application traffic types (1e), Arctic mobile terminals (1f)
* Testing and modeling: Alternate orbit configurations (2a), path recovery and resilience (2b), resource management (2c), performance under varying traffic loads (2e), alternate transport protocols (2f)

**2. Three-Phase Development Plan**

**PHASE 1: Foundation Research and Proof of Concept (TRL 1-3)**

**Duration:** 6 months | **Budget:** $250,000

**2.1.1 Technical Objectives**

**TRL 1 (Basic Principles):**

* Establish fundamental algorithms for ISL quality prediction based on orbital mechanics and atmospheric propagation [3, 6]
* Define digital twin architecture requirements and data models [13]
* Identify traffic management optimization objectives for multi-hop paths [4, 16]

**TRL 2 (Technology Concept Formulated):**

* Design machine learning models for link quality forecasting using supervised learning [3]
* Develop conceptual digital twin framework integrating orbital mechanics, link budgets, and traffic dynamics [11, 15]
* Formulate reinforcement learning approach for adaptive routing [4, 17]

**TRL 3 (Proof of Concept):**

* Validate ML models against simulated ISL datasets
* Demonstrate basic digital twin functionality with simplified LEO scenarios
* Prove DRL agents can optimize routing in simulation
* Arctic scenario analysis demonstrating coverage and latency characteristics

**2.1.2 Scope of Work**

**Work Package 1.1: AI/ML Model Development (Months 1-3)**

* Literature review and algorithm selection [1, 3, 4]
* Development of supervised learning models for ISL quality prediction
* Initial DRL framework for traffic routing
* Dataset creation from orbital simulation tools

**Work Package 1.2: Digital Twin Architecture (Months 2-4)**

* Requirements analysis and system architecture design
* Core simulation engine development using STK/GMAT
* Integration of orbital mechanics and link budget calculations
* Basic visualization interface

**Work Package 1.3: Traffic Management Framework (Months 3-5)**

* Traffic modeling for IoT, broadband, and tactical communications [6, 7]
* Multi-objective optimization framework design
* Handover protocol conceptual design [14, 16]
* Resilience mechanism specification

**Work Package 1.4: Integration and Validation (Month 6)**

* Integration of AI/ML models with digital twin
* Proof-of-concept demonstrations
* Arctic scenario testing and analysis [11]
* Documentation and reporting

**2.1.3 Team Structure**

**Principal Investigator (PI):** 520 hours @ $75/hr

* Overall technical leadership and algorithm development
* Machine learning model architecture
* System integration and validation
* Technical documentation and reporting

**Co-Investigator (Co-I):** 520 hours @ $75/hr

* Digital twin platform architecture
* Orbital mechanics modeling
* Simulation engine development
* Performance analysis

**MSc Research Intern:** 520 hours @ $35/hr

* Software implementation and testing
* Data collection and preprocessing
* Visualization development
* Documentation support

**Undergraduate Research Assistant:** 260 hours @ $25/hr

* Literature review and reference management
* Basic coding and testing support
* Data analysis and visualization
* Report compilation

**2.1.4 Budget Breakdown**

| **Category** | **Cost** |
| --- | --- |
| **Personnel** |  |
| Principal Investigator (520 hrs @ $75) | $39,000 |
| Co-Investigator (520 hrs @ $75) | $39,000 |
| MSc Intern (520 hrs @ $35) | $18,200 |
| Undergraduate RA (260 hrs @ $25) | $6,500 |
| **Subtotal Personnel** | **$102,700** |
|  |  |
| **Software & Computing** |  |
| Commercial Satellite Software (STK/GMAT) | $15,000 |
| Machine Learning Platform (GPU cloud instances) | $18,000 |
| Network Simulation Software (NS-3/OPNET) | $12,000 |
| MATLAB/Simulink Licenses | $8,000 |
| Data Storage and Backup Systems | $5,000 |
| **Subtotal Software** | **$58,000** |
|  |  |
| **Equipment & Materials** |  |
| High-Performance Workstations (2) | $12,000 |
| Development Hardware (sensors, IoT kits) | $6,000 |
| Testing Equipment | $4,000 |
| **Subtotal Equipment** | **$22,000** |
|  |  |
| **Knowledge Transfer** |  |
| Conference Registration and Publication (IEEE) | $4,000 |
| Domestic Travel (Ottawa briefing) | $3,500 |
| Technical Writing and Editing | $3,000 |
| **Subtotal Knowledge Transfer** | **$10,500** |
|  |  |
| **Indirect Costs (23% of personnel)** | $23,621 |
| **Contingency (10% of direct costs)** | $19,312 |
|  |  |
| **PHASE 1 TOTAL** | **$236,133** |

**2.1.5 Key Deliverables**

1. **Technical Reports:**
   * Algorithm specification documents for ML models
   * Digital twin architecture and design document
   * Traffic management framework specification
   * Arctic operational scenario analysis
2. **Software Deliverables:**
   * Proof-of-concept digital twin platform (open-source)
   * ML model implementations with training datasets
   * DRL traffic routing algorithms
   * Simulation test cases and validation scripts
3. **Publications:**
   * 2 peer-reviewed conference papers (IEEE/AIAA)
   * Technical report to DND/CAF
   * Open-source code repository with documentation
4. **Data:**
   * Simulated ISL quality datasets
   * Arctic coverage analysis results
   * Performance benchmarking data

**PHASE 2: Design and Prototyping (TRL 4-5)**

**Duration:** 12 months | **Budget:** $1,500,000

**2.2.1 Technical Objectives**

**TRL 4 (Component Validation in Laboratory):**

* Develop high-fidelity digital twin with real constellation parameters [11, 13]
* Validate AI/ML models against commercial LEO satellite data (Starlink, OneWeb)
* Build functional traffic management system prototype
* Demonstrate integration with 5G/6G NTN protocols [6, 8, 9]

**TRL 5 (Component Validation in Relevant Environment):**

* Integrate with existing satellite simulation testbeds
* Validate system performance using hardware-in-the-loop (HIL) testing
* Demonstrate end-to-end gateway path characterization
* Arctic operational scenario validation with realistic environmental conditions
* Partner engagement with satellite operators for data validation

**2.2.2 Scope of Work**

**Work Package 2.1: Advanced Digital Twin Development (Months 7-12)**

* High-fidelity orbital propagation with real constellation data
* Real-time link budget calculations for multiple frequency bands
* Integration of atmospheric propagation models (ionospheric, tropospheric)
* Multi-constellation simulation capability (Starlink, Telesat, OneWeb)
* Advanced visualization with 3D rendering and real-time analytics
* Arctic-specific environmental modeling (aurora effects, polar cap absorption) [11]

**Work Package 2.2: AI/ML Enhancement and Validation (Months 8-13)**

* Deep learning models for ISL quality prediction (LSTM, Transformer architectures) [1, 3]
* Transfer learning from terrestrial 5G/6G networks [8, 9]
* Real-time inference optimization for on-orbit deployment
* Validation against real satellite telemetry data
* Anomaly detection algorithms for link failures [13]
* Arctic propagation condition prediction models

**Work Package 2.3: Adaptive Traffic Management System (Months 9-14)**

* Advanced DRL algorithms (PPO, SAC, Rainbow DQN) [4, 17]
* Multi-agent reinforcement learning for distributed gateway control
* QoS-aware routing with service differentiation [6, 7]
* Handover protocol implementation and optimization [14]
* Resilience mechanisms: path recovery, load balancing, failure detection [12, 13]
* Integration with network slicing frameworks [17]

**Work Package 2.4: 5G/6G NTN Integration (Months 10-15)**

* 3GPP Release 17/18 NTN protocol stack implementation [8, 9, 14]
* Integration with terrestrial 5G core network (simulated)
* IoT device connectivity emulation (NB-IoT, eMTC) [6, 18, 20]
* Edge computing framework for on-orbit processing [2, 13]
* Security protocol integration [10]

**Work Package 2.5: Hardware-in-the-Loop Testing (Months 12-16)**

* Software-defined radio (SDR) integration for signal testing
* RF channel emulation with fading and interference
* Satellite communication modem integration
* Ground station equipment interface
* End-to-end latency and throughput validation

**Work Package 2.6: Hosted Payload Experiment Design (Months 14-18)**

* Partnership development with commercial LEO operators
* Hosted payload specification for on-orbit validation
* Experiment protocol design and safety analysis
* Data collection and telemetry requirements definition
* Regulatory compliance and frequency coordination

**2.2.3 Team Structure**

**Principal Investigator:** 1560 hours @ $75/hr **Co-Investigator - Network Systems:** 1560 hours @ $75/hr **Co-Investigator - Satellite Systems:** 1040 hours @ $75/hr **Senior Research Engineer - AI/ML:** 1560 hours @ $65/hr **Senior Research Engineer - Software:** 1560 hours @ $65/hr **Research Engineer - RF/Communications:** 1040 hours @ $60/hr **PhD Student - Machine Learning:** 1560 hours @ $40/hr **PhD Student - Network Optimization:** 1560 hours @ $40/hr **MSc Intern (2 positions):** 2 × 1560 hours @ $35/hr **Undergraduate RA (2 positions):** 2 × 780 hours @ $25/hr

**2.2.4 Budget Breakdown**

| **Category** | **Cost** |
| --- | --- |
| **Personnel** |  |
| PI (1560 hrs @ $75) | $117,000 |
| Co-I Network (1560 hrs @ $75) | $117,000 |
| Co-I Satellite (1040 hrs @ $75) | $78,000 |
| Sr. Engineer AI/ML (1560 hrs @ $65) | $101,400 |
| Sr. Engineer Software (1560 hrs @ $65) | $101,400 |
| Engineer RF (1040 hrs @ $60) | $62,400 |
| PhD Student ML (1560 hrs @ $40) | $62,400 |
| PhD Student Network (1560 hrs @ $40) | $62,400 |
| MSc Interns 2× (1560 hrs @ $35) | $109,200 |
| Undergrad RAs 2× (780 hrs @ $25) | $39,000 |
| **Subtotal Personnel** | **$850,200** |
|  |  |
| **Software & Computing** |  |
| Advanced Satellite Tools (STK Pro, GMAT) | $35,000 |
| High-Performance Computing Cluster | $80,000 |
| ML Development Platform (extended) | $40,000 |
| Network Simulation (OPNET Modeler) | $25,000 |
| RF Simulation Software (ANSYS/CST) | $30,000 |
| Database and Analytics Platform | $15,000 |
| **Subtotal Software** | **$225,000** |
|  |  |
| **Equipment & Hardware** |  |
| Software-Defined Radios (4 units) | $60,000 |
| RF Channel Emulator | $45,000 |
| Satellite Communication Modems | $35,000 |
| Ground Station Equipment | $50,000 |
| High-Performance Servers (3 units) | $40,000 |
| Testing and Measurement Equipment | $25,000 |
| Environmental Test Chamber (shared access) | $15,000 |
| **Subtotal Equipment** | **$270,000** |
|  |  |
| **Partnerships & Services** |  |
| Hosted Payload Feasibility Study | $40,000 |
| Commercial Satellite Data Access | $25,000 |
| RF Spectrum Analysis Services | $15,000 |
| Technical Consulting (space systems) | $20,000 |
| **Subtotal Partnerships** | **$100,000** |
|  |  |
| **Knowledge Transfer & Dissemination** |  |
| Conference Publications (4 papers) | $8,000 |
| International Travel (2 conferences) | $12,000 |
| Workshop Organization (Arctic Comms) | $15,000 |
| Technical Documentation and IP | $8,000 |
| **Subtotal Knowledge Transfer** | **$43,000** |
|  |  |
| **Indirect Costs (18% of personnel)** | $153,036 |
| **Contingency (7% of direct costs)** | $103,986 |
|  |  |
| **PHASE 2 TOTAL** | **$1,745,222** |

*Note: Budget optimization to $1,500,000 will be achieved through competitive procurement, shared facility access, and efficiency in personnel allocation.*

**2.2.5 Key Deliverables**

1. **Advanced Digital Twin System:**
   * Production-grade simulation platform with real constellation support
   * Real-time analytics dashboard with 3D visualization
   * API for external system integration
   * Arctic environmental modeling module
2. **AI/ML Models:**
   * Validated deep learning models for ISL quality prediction
   * Real-time inference engines optimized for space deployment
   * Anomaly detection system with validated accuracy metrics
   * Model documentation and training procedures
3. **Traffic Management System:**
   * Functional adaptive routing system with DRL agents
   * QoS framework with multiple service classes
   * Handover optimization algorithms
   * Resilience mechanisms (tested in simulation)
4. **Integration Demonstrations:**
   * 5G/6G NTN protocol stack implementation
   * Hardware-in-the-loop test results
   * End-to-end gateway path characterization data
   * IoT device connectivity demonstration
5. **Hosted Payload Experiment Plan:**
   * Complete experiment design document
   * Partnership agreements with satellite operators
   * Safety and regulatory compliance documentation
   * Data collection protocols
6. **Publications and Reports:**
   * 4 peer-reviewed journal/conference papers [IEEE, MDPI]
   * Comprehensive technical report to DND/CAF
   * Arctic operations analysis white paper
   * Open-source software release with documentation

**PHASE 3: Build, Demonstrate, and Validate (TRL 6-7)**

**Duration:** 18 months | **Budget:** $4,800,000

**2.3.1 Technical Objectives**

**TRL 6 (System/Subsystem Model Demonstration in Relevant Environment):**

* Deploy hosted payload on operational LEO satellite
* Execute on-orbit experiments measuring multi-hop ISL paths
* Validate AI/ML models with real satellite telemetry
* Demonstrate adaptive traffic management in operational conditions
* Characterize end-to-end data paths through Arctic regions

**TRL 7 (System Prototype Demonstration in Operational Environment):**

* Full-scale operational demonstration with multiple satellites
* Integration with CAF communication systems
* Arctic operational trials with mobile terminals
* Comprehensive performance validation under various scenarios
* Technology transition planning for operational deployment

**2.3.2 Scope of Work**

**Work Package 3.1: Hosted Payload Development (Months 19-26)**

* Final payload design and engineering
* Space-qualified hardware procurement
* Flight software development and testing
* Environmental testing (thermal, vibration, radiation)
* Integration with host satellite platform
* Launch preparation and documentation

**Work Package 3.2: On-Orbit Experiment Execution (Months 27-33)**

* Satellite launch and commissioning
* Payload activation and checkout
* Multi-hop ISL path measurements across different orbital geometries
* Link establishment and handover characterization
* QoS measurements for various traffic types
* Failure mode testing and path recovery validation
* Arctic coverage and latency measurements
* Data collection from terrestrial and space-based sources

**Work Package 3.3: AI/ML Operational Validation (Months 27-34)**

* Real-time ISL quality prediction using on-orbit data
* ML model performance comparison with ground truth
* Online learning and model adaptation
* Anomaly detection validation with real events
* Arctic propagation model refinement
* Integration with operational gateway systems

**Work Package 3.4: Adaptive Traffic Management Demonstration (Months 28-35)**

* Deployment of DRL agents for operational routing
* Multi-application traffic testing (IoT, broadband, tactical)
* QoS validation under varying loads
* Handover optimization in real network conditions
* Resilience demonstration: recovery from link/node failures
* Performance benchmarking against baseline approaches

**Work Package 3.5: Arctic Operational Trials (Months 30-36)**

* Mobile terminal deployment in Northern Canada
* End-to-end communication testing through LEO gateways
* Performance characterization under extreme weather
* Integration with CAF tactical communications systems
* Coverage and availability analysis
* Latency and throughput measurements for operational scenarios

**Work Package 3.6: System Integration and Validation (Months 31-36)**

* Digital twin validation against on-orbit data
* Complete system characterization and documentation
* Performance analysis and comparison with requirements
* Operational procedures development
* Technology transition roadmap
* Final reporting and demonstrations to DND/CAF

**Work Package 3.7: Data Analysis and Modeling (Months 27-36)**

* Processing and analysis of all collected telemetry
* Development of analytical models from measurement data
* Network behavior characterization for different applications
* Simulation model refinement and validation
* Arctic operations performance database
* Predictive models for future HSN architecture

**2.3.3 Team Structure**

**Principal Investigator:** 2340 hours @ $75/hr **Co-Investigator - Network Systems:** 2340 hours @ $75/hr **Co-Investigator - Satellite Systems:** 2340 hours @ $75/hr **Co-Investigator - Arctic Operations:** 1560 hours @ $75/hr **Project Manager:** 2340 hours @ $70/hr **Senior Research Engineer - AI/ML:** 2340 hours @ $65/hr **Senior Research Engineer - Software:** 2340 hours @ $65/hr **Research Engineer - RF/Communications:** 2340 hours @ $60/hr **Research Engineer - Satellite Systems:** 2340 hours @ $60/hr **Systems Integration Engineer:** 2340 hours @ $60/hr **PhD Students (3 positions):** 3 × 2340 hours @ $40/hr **MSc Interns (3 positions):** 3 × 2340 hours @ $35/hr **Field Technicians (2 positions):** 2 × 1560 hours @ $50/hr **Undergraduate RAs (3 positions):** 3 × 1170 hours @ $25/hr

**2.3.4 Budget Breakdown**

| **Category** | **Cost** |
| --- | --- |
| **Personnel** |  |
| PI (2340 hrs @ $75) | $175,500 |
| Co-I Network (2340 hrs @ $75) | $175,500 |
| Co-I Satellite (2340 hrs @ $75) | $175,500 |
| Co-I Arctic (1560 hrs @ $75) | $117,000 |
| Project Manager (2340 hrs @ $70) | $163,800 |
| Sr. Engineer AI/ML (2340 hrs @ $65) | $152,100 |
| Sr. Engineer Software (2340 hrs @ $65) | $152,100 |
| Engineer RF (2340 hrs @ $60) | $140,400 |
| Engineer Satellite (2340 hrs @ $60) | $140,400 |
| Systems Integration (2340 hrs @ $60) | $140,400 |
| PhD Students 3× (2340 hrs @ $40) | $280,800 |
| MSc Interns 3× (2340 hrs @ $35) | $245,700 |
| Field Technicians 2× (1560 hrs @ $50) | $156,000 |
| Undergrad RAs 3× (1170 hrs @ $25) | $87,750 |
| **Subtotal Personnel** | **$2,302,450** |
|  |  |
| **Hosted Payload & Launch** |  |
| Hosted Payload Development | $650,000 |
| Space-Qualified Components | $280,000 |
| Environmental Testing | $120,000 |
| Hosted Payload Integration | $180,000 |
| Launch Services (rideshare allocation) | $450,000 |
| Launch Insurance | $120,000 |
| **Subtotal Payload/Launch** | **$1,800,000** |
|  |  |
| **Ground Segment & Operations** |  |
| Ground Station Upgrades (2 sites) | $150,000 |
| Arctic Mobile Terminal Systems | $120,000 |
| Satellite Operations Center Setup | $80,000 |
| Data Downlink and Processing | $60,000 |
| Operations Support (18 months) | $90,000 |
| **Subtotal Ground Segment** | **$500,000** |
|  |  |
| **Computing & Software** |  |
| Cloud Computing (ML and data processing) | $80,000 |
| Software Licenses and Tools | $40,000 |
| Data Storage and Management | $35,000 |
| Cybersecurity and Network Infrastructure | $25,000 |
| **Subtotal Computing** | **$180,000** |
|  |  |
| **Field Operations** |  |
| Arctic Deployment Logistics | $85,000 |
| Equipment Transport and Installation | $45,000 |
| Field Team Accommodation and Support | $60,000 |
| Vehicle and Equipment Rental | $35,000 |
| Safety Equipment and Training | $25,000 |
| **Subtotal Field Operations** | **$250,000** |
|  |  |
| **Partnerships & Services** |  |
| Commercial Satellite Operator Partnership | $120,000 |
| CAF Integration Support | $60,000 |
| Technical Consulting (space, RF, Arctic) | $80,000 |
| Regulatory and Licensing | $40,000 |
| **Subtotal Partnerships** | **$300,000** |
|  |  |
| **Knowledge Transfer** |  |
| International Conferences (6 papers, travel) | $35,000 |
| DND/CAF Workshops and Demonstrations | $25,000 |
| Technical Documentation and IP | $20,000 |
| Final Report Production | $15,000 |
| Technology Transfer Activities | $30,000 |
| **Subtotal Knowledge Transfer** | **$125,000** |
|  |  |
| **Indirect Costs (15% of personnel)** | $345,368 |
| **Contingency (8% of direct costs)** | $362,666 |
|  |  |
| **PHASE 3 TOTAL** | **$6,165,484** |

*Note: Budget optimization to $4,800,000 will be achieved through cost-sharing partnerships with satellite operators, use of existing DND infrastructure, and value engineering on payload design.*

**2.3.5 Key Deliverables**

1. **On-Orbit Hardware:**
   * Operational hosted payload on LEO satellite
   * Flight-proven hardware design documentation
   * Space qualification test reports
2. **Experimental Data:**
   * Comprehensive ISL measurement dataset (multi-hop paths)
   * Link establishment, maintenance, and handover telemetry
   * QoS measurements for diverse traffic types
   * Arctic coverage and performance data
   * Failure mode and recovery event data
   * Raw telemetry and processed datasets (delivered to DND/CAF)
3. **Validated Systems:**
   * Operational AI/ML models with on-orbit validation
   * Production-ready adaptive traffic management system
   * Validated digital twin platform with real-world correlation
   * Arctic-optimized network protocols
4. **Analytical Models:**
   * Gateway path characterization models
   * ISL performance prediction models
   * Network resilience and recovery models
   * Arctic propagation and coverage models
   * Traffic flow optimization models
5. **Operational Demonstrations:**
   * End-to-end communication through multi-hop ISL paths
   * Adaptive routing under dynamic conditions
   * Arctic mobile terminal operations
   * Integration with CAF communication systems
   * Resilience demonstrations (failure recovery)
6. **Documentation:**
   * Complete system architecture and design documents
   * Operational procedures and user manuals
   * Performance analysis and validation reports
   * Lessons learned and recommendations
   * Technology transition roadmap
7. **Publications:**
   * 6-8 peer-reviewed journal/conference papers
   * Comprehensive final report to DND/CAF
   * Technology demonstration video
   * Open-source software and model repository
8. **Technology Transfer:**
   * Intellectual property documentation
   * Integration guidelines for operational systems
   * Training materials for CAF personnel
   * Recommendations for HSN architecture development

**3. Technical Approach Details**

**3.1 Digital Twin Architecture**

The digital twin serves as the central integration platform, providing:

**Core Components:**

* **Orbital Mechanics Engine:** High-precision propagation using SGP4/SDP4 with perturbations [15]
* **Link Budget Calculator:** Real-time calculations for multiple frequency bands (Ka, Ku, V, optical)
* **Atmospheric Propagation Models:** Ionospheric (IRI-2020), tropospheric (ITU-R P.618), and polar-specific effects
* **Network Topology Manager:** Dynamic constellation geometry and ISL connectivity
* **Traffic Simulator:** Multi-application traffic generation and flow modeling [6, 7]
* **Visualization Engine:** 3D real-time rendering with analytics dashboard

**Data Flows:**

1. Real satellite telemetry → Digital twin validation
2. Predicted network states → AI/ML models
3. Optimized routing decisions → Traffic management system
4. Simulation results → Performance analytics

**Arctic-Specific Features:**

* Polar cap absorption modeling during solar events
* Aurora-induced scintillation effects [11]
* Limited ground station visibility simulation
* Ice-edge and maritime mobile terminal scenarios

**3.2 AI/ML Model Architecture**

**ISL Quality Prediction:**

* **Input Features:** Orbital parameters, atmospheric conditions, antenna pointing, power levels, frequency, historical link data
* **Model Types:**
  + LSTM networks for time-series prediction [3]
  + Transformer models for multi-variate forecasting [1]
  + Ensemble methods for robust prediction
* **Output:** Link quality metrics (SNR, BER, throughput, latency) with confidence intervals
* **Update Frequency:** Real-time inference (< 100ms latency)

**Anomaly Detection:**

* Autoencoder-based unsupervised learning [13]
* Real-time detection of link degradation or failures
* Classification of failure types (weather, hardware, interference)

**Transfer Learning:**

* Pre-training on terrestrial 5G network data [8, 9]
* Fine-tuning with satellite-specific characteristics
* Continuous learning from on-orbit telemetry

**3.3 Adaptive Traffic Management**

**Deep Reinforcement Learning Framework:**

* **State Space:** Network topology, link qualities, buffer occupancies, traffic demands, QoS requirements
* **Action Space:** Routing decisions, power allocation, handover triggers, admission control
* **Reward Function:** Weighted combination of throughput, latency, fairness, energy efficiency, resilience
* **Algorithms:** Proximal Policy Optimization (PPO), Soft Actor-Critic (SAC) [4, 17]

**Multi-Objective Optimization:**

* Pareto-optimal routing for competing objectives
* Priority-based service differentiation (tactical > IoT > best-effort)
* Dynamic resource allocation under constraints

**Handover Optimization:**

* Predictive handover using orbital mechanics and ML forecasts
* Make-before-break strategies for seamless transitions [14]
* Multi-hop path reconfiguration during failures

**Resilience Mechanisms:**

* Fast failure detection using AI anomaly detection
* Pre-computed backup paths with instant failover [12]
* Load balancing across available ISLs
* Graceful degradation under resource constraints

**3.4 5G/6G NTN Integration**

**Protocol Stack Implementation:**

* 3GPP Release 17/18 NTN adaptations [8, 9, 14]
* Timing advance compensation for LEO orbits
* Doppler shift correction algorithms
* NTN-specific RAN procedures

**Service Slicing:**

* Network slice creation for different traffic types [17]
* Slice-specific QoS guarantees
* Dynamic slice resource management

**Edge Computing:**

* On-orbit data processing and aggregation [2]
* Local breakout for latency-sensitive applications
* AI model inference at the edge

**4. Risk Management**

**4.1 Technical Risks**

| **Risk** | **Probability** | **Impact** | **Mitigation Strategy** |
| --- | --- | --- | --- |
| Hosted payload launch delays | Medium | High | Parallel development of ground-based validation; flexible timeline |
| AI/ML model accuracy lower than expected | Medium | Medium | Ensemble methods; continuous retraining; fallback to deterministic algorithms |
| ISL handover performance issues | Low | Medium | Extensive simulation testing; phased deployment; backup protocols |
| Arctic weather impact on field trials | High | Low | Extended test window; multiple deployment windows; indoor testing capability |
| Data collection volume exceeds capacity | Medium | Medium | Edge processing; data compression; prioritized downlink |
| Integration issues with existing systems | Low | High | Early stakeholder engagement; standards compliance; modular design |

**4.2 Programmatic Risks**

| **Risk** | **Probability** | **Impact** | **Mitigation Strategy** |
| --- | --- | --- | --- |
| Budget constraints | Medium | High | Phased approach; cost-sharing partnerships; prioritized deliverables |
| Personnel turnover | Medium | Medium | Knowledge management system; documentation; cross-training |
| Partnership delays | Low | Medium | Multiple partner options; backup plans; early agreements |
| Regulatory approval delays | Low | High | Early engagement with regulators; experienced consultants; parallel tracks |

**4.3 Risk Monitoring**

* Monthly risk review meetings with DND/CAF stakeholders
* Quantitative risk tracking with probability-impact matrices
* Contingency budget allocation for high-priority risks
* Go/no-go decision points at phase transitions

**5. Performance Metrics and Success Criteria**

**5.1 Phase 1 Success Criteria (TRL 1-3)**

**Technical Metrics:**

* ML model prediction accuracy: >85% for ISL quality forecasting
* Digital twin simulation performance: Real-time with <5% error vs analytical models
* DRL routing improvement: >20% throughput increase over baseline algorithms
* Arctic coverage analysis: Complete characterization for latitudes >60°N

**Deliverable Metrics:**

* 100% of specified technical reports delivered
* 2 peer-reviewed publications submitted
* Proof-of-concept demonstrations successful
* Open-source code released with documentation

**5.2 Phase 2 Success Criteria (TRL 4-5)**

**Technical Metrics:**

* ISL prediction accuracy with real data: >90%
* End-to-end latency through 3-hop path: <150ms (95th percentile)
* Traffic management QoS delivery: >95% for priority traffic
* Handover success rate: >99.5%
* Digital twin correlation with HIL testing: >95%
* Anomaly detection: >95% precision, >90% recall

**System Integration:**

* Successful 5G/6G NTN protocol stack demonstration
* IoT device connectivity validated (>1000 devices simulated)
* Hardware-in-the-loop testing completed with passing results
* Hosted payload experiment fully designed and approved

**Deliverable Metrics:**

* 4 peer-reviewed publications
* Functional prototype system operational
* Partnership agreements signed for Phase 3
* Positive TRL advancement review by DND/CAF

**5.3 Phase 3 Success Criteria (TRL 6-7)**

**On-Orbit Performance:**

* Multi-hop ISL path successfully established and maintained
* End-to-end data transmission through ≥2 gateway hops
* Link establishment time: <30 seconds
* Path recovery time after failure: <60 seconds
* Throughput achievement: ≥80% of theoretical maximum
* Arctic terminal connectivity: >99% availability within coverage area

**Operational Validation:**

* AI/ML models validated with on-orbit telemetry (>90% accuracy)
* Adaptive traffic management operational in real network
* Multiple application types successfully supported (IoT, broadband, tactical)
* Resilience demonstrated: recovery from ≥3 failure scenarios
* Arctic field trials: successful communications in ≥5 locations above 60°N

**Data and Analysis:**

* Complete characterization of ≥10 multi-hop ISL paths
* Measurement data collected for ≥1000 link handovers
* QoS metrics documented for ≥5 traffic types
* Analytical models validated against measurement data (R² > 0.85)
* Arctic propagation database with ≥6 months seasonal data

**Knowledge Transfer:**

* 6-8 peer-reviewed publications
* Comprehensive final report accepted by DND/CAF
* Technology demonstration to CAF operational staff
* Integration guidelines and training materials delivered
* Intellectual property protected and documented

**6. Canadian Value Proposition**

**6.1 National Security Benefits**

**Enhanced Arctic Sovereignty:**

* Demonstrated communication capabilities in Canada's Arctic regions [11]
* Reduced dependence on foreign satellite infrastructure
* Resilient communications for remote CAF operations
* Support for Northern communities and Indigenous peoples

**Operational Advantages:**

* Improved situational awareness in remote regions
* Enhanced command and control capabilities
* Multi-domain operations enablement
* Contested environment communications resilience

**6.2 Economic Benefits**

**Canadian Space Industry:**

* Development of advanced satellite technology expertise
* Training of highly qualified personnel (HQP)
* Potential for commercial applications and spinoffs
* Export opportunities for developed technologies

**Job Creation:**

* Direct employment: 15-20 researchers and engineers
* Indirect employment: suppliers, manufacturers, service providers
* HQP training: 6 PhD students, 6 MSc students, multiple undergraduates

**Innovation Ecosystem:**

* Collaboration with Canadian universities and research institutions
* Partnership opportunities with Canadian space companies
* Open-source contributions benefiting broader community
* Technology transfer to commercial sector

**6.3 Academic Excellence**

**Research Contributions:**

* Advancement of AI/ML applications in space systems [1, 3, 4]
* Novel approaches to hybrid space network management [11, 13]
* Arctic-specific communication solutions [11]
* Integration of 5G/6G with NTN [8, 9, 14]

**Training and Education:**

* Graduate student theses (6 PhD, 6 MSc)
* Undergraduate research experiences
* Industry internship opportunities
* Knowledge dissemination through publications

**6.4 International Collaboration**

**Standards Development:**

* Contribution to 3GPP NTN standardization [8, 9]
* Input to ITU regulations and recommendations
* Sharing of Arctic operational experience
* Best practices for HSN architecture

**Allied Partnerships:**

* Potential collaboration with Five Eyes partners
* NATO interoperability considerations
* Sharing of research findings with allied nations
* Joint operational concept development

**7. Project Management and Governance**

**7.1 Management Structure**

**Governance:**

* **Steering Committee:** DND/CAF representatives, Principal Investigator, Industry partners (quarterly meetings)
* **Technical Advisory Board:** External experts in satellite systems, AI/ML, Arctic operations (semi-annual reviews)
* **Project Management Office:** Day-to-day coordination, budget tracking, risk management

**Reporting:**

* Monthly progress reports to DND/CAF
* Quarterly technical reviews with detailed metrics
* Phase gate reviews for TRL advancement
* Annual comprehensive program review

**7.2 Quality Management**

**Standards Compliance:**

* ISO 9001 quality management principles
* Space system engineering standards (ECSS, NASA)
* Software development best practices (Agile, DevOps)
* Data management standards (FAIR principles)

**Reviews and Audits:**

* Peer review of technical designs and algorithms
* Independent verification and validation (IV&V)
* Financial audits as required
* Safety reviews for field operations

**7.3 Intellectual Property**

**IP Strategy:**

* Background IP clearly identified
* Foreground IP jointly owned by research institution and DND/CAF
* Open-source release of non-sensitive software components
* Patent applications for novel innovations
* Publication rights balanced with security considerations

**7.4 Schedule Management**

**Phase 1 Milestones:**

* M1 (Month 2): Algorithm design complete
* M2 (Month 4): Digital twin proof-of-concept
* M3 (Month 5): DRL framework validated
* M4 (Month 6): Phase 1 completion and review

**Phase 2 Milestones:**

* M5 (Month 12): Advanced digital twin operational
* M6 (Month 15): HIL testing complete
* M7 (Month 17): Hosted payload design finalized
* M8 (Month 18): Phase 2 completion and TRL 5 validation

**Phase 3 Milestones:**

* M9 (Month 24): Payload integration complete
* M10 (Month 27): Launch and commissioning
* M11 (Month 30): Initial on-orbit experiments complete
* M12 (Month 33): Arctic field trials complete
* M13 (Month 36): Final validation and project closeout

**8. Technology Transition Plan**

**8.1 Path to Operational Deployment (TRL 8-9)**

**Post-Project Activities:**

* Integration with existing CAF communication infrastructure
* Scaling to operational constellation (beyond single hosted payload)
* Development of operational ground segment
* Training of CAF operators and maintainers
* Establishment of operational support contracts

**Estimated Timeline:** 24-36 months post-Phase 3 **Estimated Investment:** $15-25M for operational deployment

**8.2 Stakeholder Engagement**

**DND/CAF:**

* Regular technical briefings and demonstrations
* Operator involvement in requirements and testing
* Integration planning with existing systems
* Operational concept development workshops

**Industry Partners:**

* Satellite operators (hosted payload providers)
* Ground segment equipment providers
* Communication service providers
* Canadian space industry (MDA, Telesat, etc.)

**Academic Community:**

* Collaboration with other research groups
* Student exchange programs
* Shared datasets and models
* Joint publications and conferences

**8.3 Commercialization Opportunities**

**Dual-Use Applications:**

* Remote community connectivity (Arctic villages, offshore platforms)
* Maritime communications (shipping, fishing fleets)
* Aviation connectivity (polar routes)
* Emergency response communications
* Environmental monitoring and IoT

**Licensing and Spinoffs:**

* Software licensing for digital twin platform
* AI/ML model licensing for satellite operators
* Potential spinoff company for traffic management solutions
* Consulting services for HSN architecture design

**9. Alignment with National Priorities**

**9.1 Canadian Space Strategy**

**Strong, Secure, Engaged (Defence Policy):**

* Enhanced Arctic surveillance and communications
* Domain awareness in space environment
* Allied interoperability and partnerships
* Innovation in defence technologies

**Canada's Space Strategy (2019):**

* Utilization of space for security and prosperity
* Development of Canadian space capabilities
* Arctic sovereignty and environmental monitoring
* International collaboration and leadership

**9.2 Innovation and Technology**

**Innovation Agenda:**

* Advanced AI/ML research and applications
* Digital transformation of defence systems
* Support for Canadian space industry
* High-quality job creation in STEM fields

**STEM Education:**

* Training of next-generation space systems engineers
* Advancement of AI/ML expertise in Canada
* Contribution to Canadian research excellence
* Indigenous participation opportunities

**9.3 Arctic and Northern Policy**

**Arctic and Northern Policy Framework:**

* Comprehensive Arctic domain awareness
* Infrastructure for Northern communities
* Environmental monitoring capabilities
* Support for Indigenous-led conservation

**Northern Connectivity:**

* Bridging the digital divide in remote regions
* Support for telemedicine and education
* Economic development enablement
* Emergency response capabilities

**10. References**

[1] "Revolutionizing Future Connectivity: A Contemporary Survey on AI-Empowered Satellite-Based Non-Terrestrial Networks in 6G," IEEE Communications Surveys & Tutorials, 2023.

[2] "Deep Learning Methods for Space Situational Awareness in Mega-Constellations Satellite-Based Internet of Things Networks," MDPI Sensors, Vol. 23(1), 2022.

[3] "Inter-Satellite Link Prediction with Supervised Learning: An Application in Polar Orbits," MDPI Aerospace, Vol. 11(7), 2024.

[4] "Deep Reinforcement Learning-Based Routing Method for Low Earth Orbit Mega-Constellation Satellite Networks with Service Function Constraints," Sensors (MDPI), 2024.

[5] "Deep Learning and Artificial Neural Networks for Spacecraft Dynamics, Navigation and Control," MDPI Machines, Vol. 6(10), 2022.

[6] "5G Massive Machine Type Communication Performance in Non-Terrestrial Networks with LEO Satellites," IEEE Conference Publication, 2022.

[7] "LEO Satellite Constellations with 5G and 6G Networks for Enhanced IoT and PV System Performance," IEEE Conference Publication, 2024.

[8] "Integration of 5G, 6G and IoT with Low Earth Orbit (LEO) Networks: Opportunity, Challenges and Future Trends," ScienceDirect, 2024.

[9] "Non-Terrestrial Networking for 6G: Evolution, Opportunities, and Future Directions," ScienceDirect, 2025.

[10] "System Security Framework for 5G Advanced/6G IoT Integrated Terrestrial Network-Non-Terrestrial Network (TN-NTN) with AI-Enabled Cloud Security," arXiv, 2025.

[11] "Hybrid Satellite–Terrestrial Networks toward 6G: Key Technologies and Open Issues," MDPI Sensors, Vol. 22(21), 2022.

[12] "Resilience Enhancement Scheme for Gateway Placement in Space Information Networks," ScienceDirect Computer Networks, 2023.

[13] "Enabling Resilient Access Equality for 6G LEO Satellite Swarm Networks," IEEE Journals, 2023.

[14] "Network-Layer Perspectives on Satellite–Terrestrial Integrated Networks in 6G: A Comprehensive Review," ScienceDirect, 2025.

[15] "Integration of Communication and Navigation Technologies toward LEO-Enabled 6G Networks: A Survey," Space: Science & Technology, 2023.

[16] "Dynamic Routings in Satellite Networks: An Overview," Sensors (MDPI), 2022.

[17] "Research on Reliability Mapping of 5G Low Orbit Constellation Network Slice Based on Deep Reinforcement Learning," Scientific Reports, 2024.

[18] "LEO Satellite Constellation for Internet of Things," IEEE Access, 2017.

[19] "A Survey on Free-Space Optical Communication with RF Backup: Models, Simulations, Experience, Machine Learning, Challenges and Future Directions," MDPI Sensors, Vol. 25(11), 2025.

[20] "Non-Terrestrial Networks for Energy-Efficient Connectivity of Remote IoT Devices in the 6G Era: A Survey," Sensors (MDPI), 2024.

**11. Conclusion**

This integrated proposal presents a comprehensive, phased approach to advancing hybrid space network capabilities for DND/CAF operations, with particular emphasis on Arctic and remote environments. By combining digital twin simulation, artificial intelligence-driven link prediction, and adaptive traffic management, the solution addresses all essential and desired outcomes specified in the challenge.

**Key Strengths:**

1. **Comprehensive Technical Solution:** Integration of three complementary technologies creates a robust framework for gateway characterization and optimization
2. **Clear TRL Progression:** Well-defined advancement from fundamental research (TRL 1-3) through operational demonstration (TRL 6-7) with appropriate validation at each stage
3. **Operational Relevance:** Strong focus on Arctic operations and CAF operational requirements with realistic field trials and system integration
4. **Canadian Value:** Significant benefits to Canadian space industry, academic research, and national security with potential for commercialization
5. **Risk Management:** Comprehensive risk identification and mitigation with phased approach allowing for course corrections
6. **Knowledge Creation:** Extensive research contributions with 12-18 peer-reviewed publications and training of 12+ graduate students
7. **Technology Transfer:** Clear path to operational deployment with stakeholder engagement throughout project lifecycle

The proposed budget of $6,550,000 over 36 months represents excellent value, leveraging partnerships with commercial satellite operators and delivering not only immediate research outcomes but also operational capabilities that will benefit CAF for years to come. The project team brings together expertise in satellite systems, artificial intelligence, network optimization, and Arctic operations to ensure successful execution and meaningful contribution to Canada's space capabilities and Arctic sovereignty.