



Astromesh: Design, Implementation and Radiation Testing of a LoRa Meshed Network for use in Satellite Constellations

Christina Athanasiadou, Student Number 10328

CERN Supervisors:

Dr. Salvatore Danzeca

Dr. Alessandro Zimmaro

CERN Section: BE-CEM-EPR

Beams Department, Controls Electronics &
Mechatronics Group

Electronics Production & Radiation Testing Section

Academic Supervisor:

Professor Alkiviadis Hatzopoulos

Aristotle University of Thessaloniki

Department of Electrical and Computer Engineering

Telecommunications Division



Astromesh: Σχεδιασμός, υλοποίηση και δοκιμές σε περιβάλλον ακτινοβολίας ενός LoRa δικτύου ασύρματου πλέγματος με εφαρμογές σε αστερισμούς δορυφόρων

Χριστίνα Αθανασιάδου, Αριθμός Μητρώου 10328

Επιβλέποντες CERN:

Δρ. Salvatore Danzeca

Δρ. Alessandro Zimmaro

CERN Section: BE-CEM-EPR

Beams Department, Controls Electronics &
Mechatronics Group

Electronics Production & Radiation Testing Section

Ακαδημαϊκός Επιβλέπων:

Καθηγητής Αλκιβιάδης Χατζόπουλος

Aristotle University of Thessaloniki

Department of Electrical and Computer Engineering

Telecommunications Division

Abstract

Recent advancements in meshed network technology have opened new possibilities in space exploration and particle accelerator applications. These networks offer increased communication redundancy, efficient data routing, and reduced reliance on terrestrial infrastructure. For the Future Circular Collider (FCC), where extreme radiation levels and extensive distances make traditional cabling impractical, wireless meshed networks could enable seamless communication across different accelerator sections.

CERN has developed Astromesh, an innovative modular platform, designed to create a decentralized, resilient mesh network. Astromesh uses LoRa Modulation for power efficiency and maximum coverage, employing a radiation-tolerant architecture with specialized electronics to ensure longevity in harsh environments. Supporting 868 MHz, Industrial, Scientific and Medical (ISM) (2.4 GHz), and Ultra-Wideband (UWB) (3.5 - 6.5 GHz) transceivers, the platform's modular design ensures versatility across different communication requirements.

This thesis presents a study structured around the following objectives. First, a literature review analyzing LoRa technology, meshed network architectures, hierarchical versus non-hierarchical topologies, radiation effects on electronics, and the operations of CERN radiation facilities. This review establishes the theoretical foundation and highlights the novelty of developing the first LoRa-based meshed network validated for radiation environments.

The core technical contribution involves the development of modular embedded software for the Astromesh platform, ensuring compatibility across the supported transceivers. This implementation enables flexible deployment across different communication scenarios while maintaining compatibility with 868 MHz, ISM, and UWB bands.

Experimental validation is performed through radiation testing at PSI and CHARM CERN facilities, comparing the performance and reliability of meshed network architectures against hierarchical LoRa networks under radiation. Additional tests include power consumption analysis to quantify functionality degradation and determine the advantages of decentralized approaches in harsh environments.

The final component comprises a mission analysis and link budget study for meshed network deployment in Low Earth Orbit, exploring different possible satellite constellation configurations. Detailed analysis will be performed for the 868 MHz and ISM bands to determine coverage capabilities and communication performance in space applications. This work contributes to next-generation space communication and high-energy physics by validating the first radiation-tolerant LoRa meshed network.

Περίληψη

Οι εξελίξεις των τελευταίων ετών στα δίκτυα mesh άνοιξαν νέους ορίζοντες τόσο στη διαστημική έρευνα όσο και στις εφαρμογές επιταχυντών σωματιδίων. Τα δίκτυα αυτά εγγυώνται πλεονασμό στην επικοινωνία, αποδοτική δρομολόγηση δεδομένων και περιορισμένη εξάρτηση από τις γήινες υποδομές. Στην περίπτωση του Μελλοντικού Κυκλικού Επιταχυντή (FCC), όπου τα ακραία επίπεδα ακτινοβολίας και οι μεγάλες αποστάσεις καθιστούν τα συμβατικά καλωδιακά συστήματα ασύμφορα, τα ασύρματα δίκτυα mesh θα μπορούσαν να εξασφαλίσουν αδιάλειπτη επικοινωνία ανάμεσα στα επιμέρους τμήματα του επιταχυντή.

Στο πλαίσιο αυτό, το CERN ανέπτυξε το Astromesh, μια καινοτόμο αρθρωτή πλατφόρμα για τη δημιουργία αποκεντρωμένων, ανθεκτικών δικτύων mesh. Η πλατφόρμα αξιοποιεί τη διαμόρφωση LoRa για χαμηλή κατανάλωση ισχύος και μέγιστη κάλυψη, ενσωματώνοντας αρχιτεκτονική ανεκτική σε ακτινοβολία με εξειδικευμένα ηλεκτρονικά κυκλώματα που διασφαλίζουν αξιόπιστη λειτουργία σε δυσμενή περιβάλλοντα. Με υποστήριξη πομποδεκτών στις ζώνες 868 MHz, ISM και UWB, ο αρθρωτός σχεδιασμός της προσφέρει ευελιξία σε ποικίλα σενάρια επικοινωνίας.

Η παρούσα διπλωματική εργασία οργανώνεται γύρω από τους ακόλουθους άξονες. Αρχικά, πραγματοποιείται βιβλιογραφική ανασκόπηση που καλύπτει την τεχνολογία LoRa, τις αρχιτεκτονικές δικτύων mesh, τη σύγκριση ιεραρχικών και μη ιεραρχικών τοπολογιών, τις επιδράσεις της ακτινοβολίας στα ηλεκτρονικά, καθώς και τη λειτουργία των εγκαταστάσεων δοκιμών ακτινοβολίας του CERN. Η ανασκόπηση αυτή θέτει τις θεωρητικές βάσεις και αναδεικνύει τον πρωτοποριακό χαρακτήρα του εγχειρήματος: πρόκειται για το πρώτο δίκτυο mesh βασισμένο σε LoRa που επικυρώνεται πειραματικά σε συνθήκες ακτινοβολίας.

Η κεντρική τεχνική συνεισφορά έγκειται στην ανάπτυξη αρθρωτού ενσωματωμένου λογισμικού για την πλατφόρμα Astromesh, πλήρως συμβατού με όλους τους υποστηριζόμενους πομποδέκτες. Η υλοποίηση αυτή επιτρέπει ευέλικτη εγκατάσταση σε διαφορετικά επικοινωνιακά σενάρια, διατηρώντας πλήρη λειτουργικότητα στις ζώνες 868 MHz, ISM και UWB.

Η πειραματική επικύρωση γίνεται μέσω δοκιμών ακτινοβολίας στις εγκαταστάσεις PSI και CHARM του CERN, όπου συγκρίνονται η απόδοση και η αξιοπιστία δικτύων mesh έναντι ιεραρχικών δικτύων LoRa υπό πραγματικές συνθήκες ακτινοβολίας. Συμπληρωματικές δοκιμές κατανάλωσης ισχύος ποσοτικοποιούν την υποβάθμιση λειτουργικότητας και αναδεικνύουν τα πλεονεκτήματα της αποκεντρωμένης προσέγγισης σε αντίξοα περιβάλλοντα.

Τέλος, διεξάγεται ανάλυση σεναρίων αποστολής και προϋπολογισμού ζεύξης (link budget) για την ανάπτυξη δικτύου mesh σε χαμηλή γήινη τροχιά (LEO), εξετάζοντας εναλλακτικές διατάξεις αστερισμών δορυφόρων. Αναλύονται ειδικότερα οι ζώνες 868 MHz και ISM ως προς τις δυνατότητες κάλυψης και την επικοινωνιακή απόδοση σε διαστημικές εφαρμογές. Το έργο αυτό συμβάλλει στη διαμόρφωση της επόμενης γενιάς διαστημικών επικοινωνιών και στη φυσική υψηλών ενεργειών, επικυρώνοντας πειραματικά το πρώτο δίκτυο mesh LoRa ανθεκτικό σε ακτινοβολία.

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“A good plan violently executed now is better than a perfect plan next week.”

— 33rd Akin’s Law of Spacecraft Design [1]

Acronyms

ADC	Analog-to-Digital Converter
ADCS	Attitude Determination and Control System
BW	Bandwidth
CERN	European Organization for Nuclear Research
CHARM	CERN High-energy Accelerator Mixed-field facility
DUT	Device Under Test
EIRP	Equivalent Isotropic Radiated Power
FSPL	Free Space Path Loss
GW	Gateway
HEH	High Energy Hadrons
HPOP	High-Precision Orbit Propagator
IC	Ionization Chamber
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
ISL	Inter-satellite Link
LDEERR	Leading Edge Detection Error
LEO	Low Earth Orbit
LHCP	Left-Hand Circular Polarization
LoRa	Long Range
LTAN	Local Time of Ascending Node
MCU	Microcontroller Unit
MQTT	MQ Telemetry Transport
N1MeV	neutrons with energy above 1 MeV
PCB	Printed Circuit Board
PIF	Proton Irradiation Facility
PS	Proton Synchrotron
PSI	Paul Scherrer Institute
PSU	Power Supply Unit
RF	Radio Frequency
RHCP	Right-Hand Circular Polarization
RSSI	Received Signal Strength Indicator
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEL	Single Event Latchup
SF	Spreading Factor
SNR	Signal-to-Noise Ratio
SSO	Sun-Synchronous Orbit
STK	Systems Tool Kit
ThN	Thermal Neutrons
TID	Total Ionizing Dose
UWB	Ultra-Wideband

Greek Summary

Αντικείμενο της παρούσας διπλωματικής εργασίας αποτελεί ο σχεδιασμός, η υλοποίηση και ο έλεγχος ακτινοβολίας ενός ασύρματου δικτύου mesh που στηρίζεται στην τεχνολογία LoRa (Long Range), με εφαρμογές τόσο σε αστερισμούς δορυφόρων όσο και σε περιβάλλοντα επιταχυντών σωματιδίων. Η εργασία εκπονήθηκε στο CERN, στο πλαίσιο συνεργασίας με το Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης, και επικεντρώνεται στην πλατφόρμα Astromesh — μια πλατφόρμα που αναπτύχθηκε ειδικά για τη διερεύνηση της σκοπιμότητας δικτύων mesh υπό συνθήκες ακτινοβολίας.

Πλαίσιο και στόχοι

Τα δίκτυα mesh υπερτερούν σημαντικά έναντι των κλασικών ιεραρχικών τοπολογιών: εξασφαλίζουν πλεονασμό στην επικοινωνία, δυνατότητα δρομολόγησης μέσω ενδιάμεσων κόμβων και ελαχιστοποίηση της εξάρτησης από μεμονωμένα σημεία αστοχίας. Σε ένα τέτοιο δίκτυο, κάθε κόμβος μπορεί ταυτόχρονα να λειτουργεί ως αναμεταδότης, με αποτέλεσμα η απώλεια ενός ή ακόμη και περισσότερων κόμβων να μην διακόπτει κατ' ανάγκη τη συνδεσιμότητα. Το χαρακτηριστικό αυτό αποκτά ιδιαίτερη βαρύτητα σε περιβάλλοντα όπου η ακτινοβολία ή οι ακραίες συνθήκες ενδέχεται να προκαλέσουν αστοχίες σε επιμέρους εξαρτήματα.

Στον Μελλοντικό Κυκλικό Επιταχυντή (FCC) του CERN, τα υψηλά επίπεδα ακτινοβολίας σε συνδυασμό με τις μεγάλες αποστάσεις καθιστούν τα καλωδιακά συστήματα δυσεφάρμοστα ή υπερβολικά δαπανηρά. Τα ασύρματα δίκτυα mesh αποτελούν ελκυστική εναλλακτική λύση για τη διασύνδεση διαφορετικών τμημάτων του επιταχυντή. Παράλληλα, η επικοινωνία μεταξύ δορυφόρων (inter-satellite links) σε αστερισμούς χαμηλής τροχιάς (LEO) απαιτεί ανθεκτικά συστήματα με χαμηλή ενεργειακή κατανάλωση, δεδομένου ότι η τροφοδοσία γίνεται κατά κανόνα από φωτοβολταϊκά πάνελ και κάθε milliwatt μετράει. Η τεχνολογία LoRa, αξιοποιώντας τη διαμόρφωση διασποράς φάσματος τύπου chirp (CSS) και τις παραμέτρους spreading factor (SF), bandwidth (BW) και coding rate (CR), συνδυάζει μεγάλη εμβέλεια με χαμηλή κατανάλωση ισχύος — ιδιότητες ιδανικές για τις εν λόγω εφαρμογές. Η εργασία τονίζει ιδιαίτερα την καινοτομία που συνεπάγεται η ανάπτυξη του πρώτου δικτύου mesh βασισμένου σε LoRa με πειραματική επικύρωση σε περιβάλλοντα ακτινοβολίας.

Οι κύριοι στόχοι της εργασίας συνοψίζονται ως εξής: (α) θεωρητική θεμελίωση μέσω βιβλιογραφικής ανασκόπησης της τεχνολογίας LoRa, των δικτύων mesh, της σύγκρισης ιεραρχικών και μη ιεραρχικών τοπολογιών, των επιδράσεων ακτινοβολίας στα ηλεκτρονικά, καθώς και της λειτουργίας των εγκαταστάσεων δοκιμών του CERN (CHARM, PSI), (β) ανάπτυξη αρθρωτού (modular) λογισμικού για την πλατφόρμα Astromesh, συμβατού με πομποδέκτες στις ζώνες 868 MHz, ISM και UWB, (γ) πειραματική επικύρωση μέσω δοκιμών ακτινοβολίας στο PSI και στο CHARM, συμπεριλαμβανομένων μετρήσεων κατανάλωσης ισχύος και θερμικής ποδηλασίας, και (δ) ανάλυση σεναρίων αποστολής και link budget για ανάπτυξη δικτύου mesh σε τροχιά LEO, υπό διάφορες διατάξεις αστερισμών.

Θεωρητικό υπόβαθρο

Η εργασία εδράζεται σε εκτενή θεωρητική βάση. Αρχικά αναλύεται η τεχνολογία LoRa και το πρωτόκολλο LoRaWAN με την τοπολογία star-of-stars: τερματικές συσκευές, πύλες, εξυπηρετητής δικτύου και εξυπηρετητές εφαρμογών. Εξετάζονται οι παράμετροι SF, CR, BW, η ισχύς εκπομπής και η συχνότητα λειτουργίας, οι κατηγορίες συσκευών LoRaWAN (A, B, C) και ο αλγόριθμος Adaptive Data Rate (ADR). Στη συνέχεια, συγκρίνονται οι μη ιεραρχικές (mesh) τοπολογίες με τις ιεραρχικές και αναδεικνύονται τα πλεονεκτήματα της αποκεντρωμένης δρομολόγησης. Τέλος, παρουσιάζονται τα φαινόμενα ακτινοβολίας που επηρεάζουν τα ηλεκτρονικά κυκλώματα – Total Ionizing Dose (TID), Single Event Effects (SEE) και latch-up – καθώς και η λειτουργία των εγκαταστάσεων CHARM (CERN High-energy Accelerator Mixed-field facility) και PIF (Proton Irradiation Facility) στο Paul Scherrer Institute (PSI). Το υπόβαθρο αυτό θέτει τα θεμέλια για την κατανόηση τόσο των απαιτήσεων της πλατφόρμας Astromesh όσο και της σπουδαιότητας των δοκιμών σε πραγματικά πεδία ακτινοβολίας.

Πλατφόρμα Astromesh και λογισμικό

Η πλατφόρμα Astromesh εξελίχθηκε με βάση την κληρονομιά του SpaceRadMon-NG. Αποτελείται από μια κεντρική πλακέτα (main board) και μια προαιρετική πλακέτα επέκτασης (mezzanine). Η κεντρική πλακέτα ενσωματώνει FPGA Microchip ProASIC3L για τον συντονισμό του συστήματος και τις υψηλής ταχύτητας διεπαφές, μικροελεγκτή ATSAM21G18 (ARM Cortex-M0+) για την επικοινωνία LoRa, την ανάγνωση αισθητήρων και τον εποπτικό έλεγχο, κύκλωμα διανομής ισχύος, καθώς και δύο ενσωματωμένους πομποδέκτες LoRa σε διαφορετικές ζώνες συχνοτήτων. Η πλακέτα mezzanine επεκτείνει τις δυνατότητες επικοινωνίας, κυρίως για ζεύξεις μεταξύ δορυφόρων. Η επιλογή υλικού διέπεται από κριτήρια ανοχής σε ακτινοβολία (radiation-tolerant COTS).

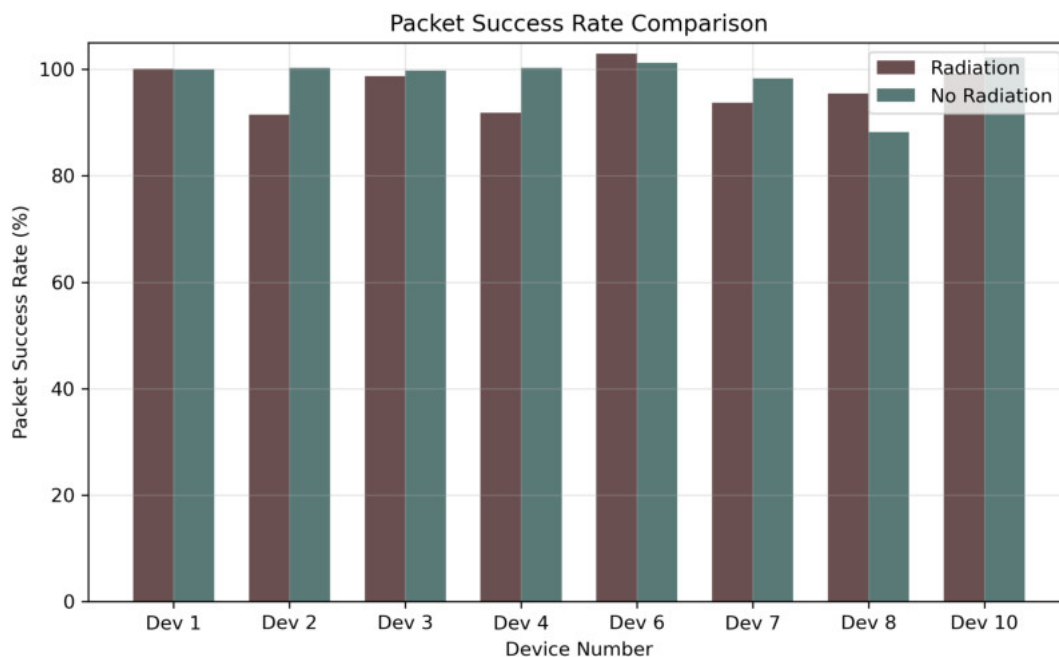
Το αρθρωτό λογισμικό που αναπτύχθηκε στο πλαίσιο αυτής της εργασίας παρέχει δυναμική ανακάλυψη διαδρομών, προώθηση πακέτων μέσω ενδιάμεσων κόμβων και ενημέρωση της τοπολογίας του δικτύου. Η υλοποίηση βασίζεται σε C με περιτύλιγμα (wrapper) σε C++, αξιοποιεί τη βιβλιοθήκη RadioHead, και ο ίδιος κώδικας εκτελείται χωρίς τροποποιήσεις σε όλες τις υποστηριζόμενες ζώνες (868 MHz, ISM, UWB), εγγυώμενος ευελιξία και φορητότητα σε ποικίλα σενάρια επικοινωνίας.

Δοκιμές ακτινοβολίας

Ιεραρχικό δίκτυο LoRa στο CHARM

Στην εγκατάσταση CHARM δοκιμάστηκε ιεραρχικό δίκτυο LoRa αποτελούμενο από οκτώ τερματικές συσκευές Feather M0 και τρεις πύλες LoRaWAN (Dragino LPS8N). Καταγράφηκαν από 4 έως 110 επανεκκινήσεις ανά συσκευή, με εκείνες που βρίσκονταν στη θέση R1 (υψηλότερη δόση ακτινοβολίας) να εμφανίζουν τα μεγαλύτερα ποσοστά. Υπολογίστηκαν ενεργές διατομές SEE (Single Event Effect) για κάθε συσκευή: η πύλη 2 αποδείχτηκε η πιο ευαίσθητη ($\sigma \approx 1,5 \times 10^{-9} \text{ cm}^2$), ενώ η τερματική συσκευή 3 η πιο ανθεκτική ($\sigma \approx 2 \times 10^{-11} \text{ cm}^2$). Η αξία της πλεονάζουσας διάταξης με τρεις πύλες επιβεβαιώθηκε ξεκάθαρα: ακόμη κι όταν μία πύλη τέθηκε εκτός λειτουργίας, η συνδεσιμότητα του

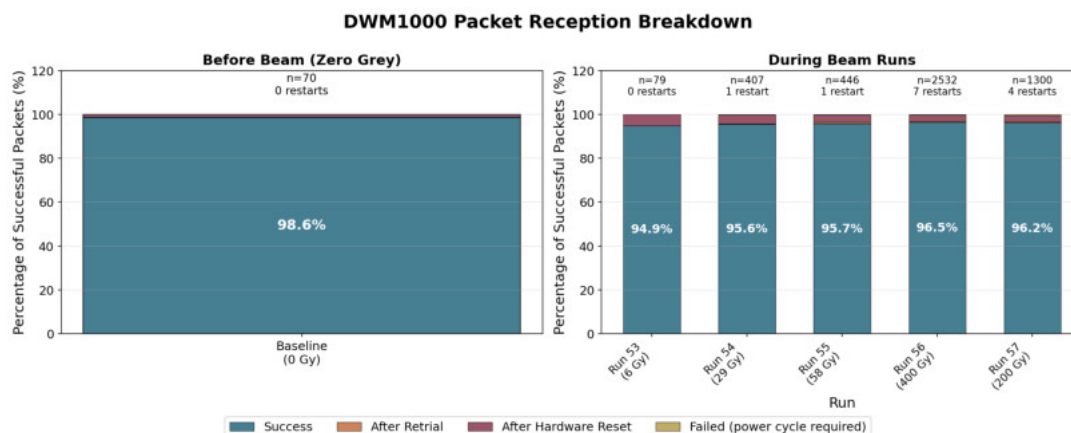
δικτύου παρέμεινε ανεπηρέαστη χάρη στις υπόλοιπες.



Σχήμα 1: Ποσοστό επιτυχίας πακέτων ανά τερματική συσκευή – σύγκριση λειτουργίας υπό ακτινοβολία και χωρίς αυτήν.

Δοκιμή πομποδέκτη UWB στο PSI

Ο πομποδέκτης UWB DWM1000 υποβλήθηκε σε δοκιμές στο Proton Irradiation Facility (PIF) του PSI, με δέσμη πρωτονίων ενέργειας 200 MeV, κατά τη διάρκεια πέντε περιόδων ακτινοβολήσης (Run 53–57). Η αθροιστική δόση έφτασε τα 693,7 Gy, με συνολική ροή σωματιδίων $1,13 \times 10^{12}$ p/cm². Καταγράφηκαν 13 διακοπές λειτουργίας τύπου SEFI (Single Event Functional Interrupt) που χρειάστηκαν χειροκίνητη επέμβαση, με αντίστοιχη ενεργό διατομή $\sigma_{SEFI} \approx 1,2 \times 10^{-11}$ cm²/συσκευή. Επιπλέον, κατά την τελευταία περίοδο εμφανίστηκε ένα μεμονωμένο SEL (Single Event Latchup), που εκδηλώθηκε ως αύξηση του ρεύματος κατανάλωσης από 155 mA σε 184 mA. Οι ενσωματωμένοι μηχανισμοί αυτόματης ανάκτησης του λογισμικού (ακολουθίες hardware reset στον δέκτη) αντιμετώπισαν με επιτυχία την πλειονότητα των παροδικών σφαλμάτων – τα SEFI αντιπροσωπεύουν μόνο τις περιπτώσεις στις οποίες η αυτόματη ανάκτηση δεν επαρκούσε.



Σχήμα 2: Κατάταξη κύκλων επικοινωνίας ανά κατηγορία αποτελέσματος (επιτυχία, ανάκτηση μετά από επαναφορά, αποτυχία) για κάθε περίοδο ακτινοβολήσης στο PSI.

Ανάλυση αποστολής και προϋπολογισμός ζεύξης

Για τον υπολογισμό του προϋπολογισμού ζεύξης (link budget) εφαρμόστηκε η τυπική μεθοδολογία RF: υπολογισμός EIRP, απωλειών ελεύθερου χώρου (FSPL), απωλειών πόλωσης και περιθωρίου ζεύξης. Αξιολογήθηκαν οι τρεις πομποδέκτες της πλατφόρμας Astromesh:

- **RF95 (868 MHz):** Μέγιστη αξιόπιστη εμβέλεια περίπου 4.200 km (SF12, 125 kHz).
- **SX1280 (2,4 GHz):** Μέγιστη αξιόπιστη εμβέλεια περίπου 500 km (SF12, 203 kHz) — αισθητά μικρότερη λόγω αυξημένων απωλειών διάδοσης στην υψηλότερη συχνότητα.
- **LR1121 (868 MHz):** Κορυφαία επίδοση με μέγιστη αξιόπιστη εμβέλεια περίπου 7.800 km (SF11, 62,5 kHz) — ο καταλληλότερος πομποδέκτης για ζεύξεις μεταξύ δορυφόρων.

Η τροχιακή ανάλυση πραγματοποιήθηκε με το λογισμικό Ansys STK, σε ηλιοσύγχρονη τροχιά (SSO) ύψους 550 km. Για αστερισμό χωρίς διατήρηση θέσης (station keeping), δύο δορυφόροι με διαφορά μάζας της τάξης του 0,5% απομακρύνονται σταδιακά λόγω διαφορικής ατμοσφαιρικής αντίστασης, φτάνοντας μέγιστη απόσταση περίπου 5.505 km, με παράθυρο επικοινωνίας 3–4 μηνών. Για πλήρη τροχιακή κάλυψη με station keeping, χρειάζονται τουλάχιστον 8 δορυφόροι στο ίδιο τροχιακό επίπεδο (LTAN), ισοκατανεμημένοι ανά 45° (απόσταση ~5.302 km), με $\Delta V \approx 1,095$ m/s ανά δορυφόρο και χρόνο διαχωρισμού περίπου 19 ημερών. Για δορυφόρους σε διαφορετικό LTAN, η μέγιστη επιτρεπόμενη χρονική απόκλιση είναι 1,5 ώρες, προκειμένου να εξασφαλιστεί οπτική επαφή. Οι πομποδέκτες στη ζώνη 2,4 GHz, με μέγιστη εμβέλεια κάτω των 541 km, θα απαιτούσαν αστερισμό 164 δορυφόρων — καθιστώντας τους ακατάλληλους για ζεύξεις μεταξύ δορυφόρων με τα τρέχοντα χαρακτηριστικά κεραιών.

Συμπεράσματα

Η παρούσα εργασία συμβάλλει στην εξέλιξη της επόμενης γενιάς διαστημικών επικοινωνιών και στη φυσική υψηλών ενεργειών, αναπτύσσοντας και επικυρώνοντας πειραματικά το πρώτο δίκτυο mesh LoRa ανθεκτικό σε ακτινοβολία. Τα πειράματα στο CHARM επιβεβαίωσαν αξιόπιστη λειτουργία υπό μικτό πεδίο ακτινοβολίας, με ποσοστά επιτυχίας πακέτων άνω του 91%, ενώ η πλεονάζουσα διάταξη τριών πυλών απέδειξε την αποτελεσματικότητά της. Ο πομποδέκτης UWB αντέξε δόση 693,7 Gy, ανακάμπτοντας αυτόματα από την πλειονότητα των σφαλμάτων. Ο πομποδέκτης LR1121 στα 868 MHz αναδείχθηκε ως η βέλτιστη επιλογή για διαδορυφορικές ζεύξεις, εξασφαλίζοντας παράθυρο επικοινωνίας αρκετών μηνών σε αστερισμούς LEO χωρίς station keeping. Τα ευρήματα αυτά εδραιώνουν την πλατφόρμα Astromesh ως βιώσιμη λύση τόσο για περιβάλλοντα επιταχυντών (FCC) όσο και για διαστημικές αποστολές.

1. Introduction

1.1 Background

Wireless communication in harsh environments—such as particle accelerator facilities and space—faces unique challenges: extreme radiation, long distances, and the need for reliable, power-efficient links without relying on fixed infrastructure. Meshed network architectures, in which nodes can relay traffic for one another, offer increased redundancy and resilience compared to traditional star or hierarchical topologies. If some nodes fail or links degrade, the network can often maintain connectivity through alternative paths. This property is especially relevant for the Future Circular Collider (FCC) at CERN, where radiation levels and the scale of the machine make conventional cabling impractical, and for satellite constellations in Low Earth Orbit (LEO), where inter-satellite and in-satellite links must operate under radiation with limited power and mass.

LoRa (Long Range) is a low-power, long-range modulation technology well suited to such scenarios. It uses chirp spread spectrum (CSS) and configurable parameters—spreading factor, bandwidth, coding rate—to trade data rate for range and robustness. LoRaWAN, the dominant protocol built on LoRa, typically employs a star-of-stars topology with gateways and a central network server. Mesh topologies, where nodes forward packets for others, are less common in the LoRa ecosystem and have not been systematically validated in radiation environments. Closing this gap is important for both accelerator and space applications.

CERN has developed the Astromesh platform to evaluate the feasibility of LoRa-based mesh networks in radiation-prone environments. The platform is modular, supports multiple transceivers (868 MHz, ISM, and UWB), and uses radiation-tolerant design choices. It targets use as an inter-satellite and in-satellite communication system and as a testbed for wireless mesh concepts relevant to the FCC and similar facilities.

1.2 Motivation

The motivation for this work is threefold.

First, *decentralized connectivity* is desirable where a single point of failure (e.g., a gateway) is unacceptable. In a mesh, end devices can reach each other or a sink via multiple hops, improving availability under radiation-induced or other failures. Comparing mesh and hierarchical LoRa networks under realistic radiation conditions provides evidence for the benefits of decentralization in such environments.

Second, *radiation hardness* of communication systems must be demonstrated by test, not assumption. Components and protocols that perform well on the bench can degrade or fail under total ionizing dose (TID) and single-event effects (SEE). Radiation testing at facilities such as CHARM (CERN) and the Proton Irradiation Facility at PSI is therefore essential to validate the Astromesh platform and the associated mesh software before deployment in accelerators or space.

Third, *mission-level feasibility* for space applications requires more than functional hardware and soft-

ware: link budgets and constellation geometry must show that sufficient margin and coverage are achievable. A mission analysis and link budget study for mesh deployment in LEO, for the 868 MHz and ISM bands supported by Astromesh, bridges the gap between platform validation and realistic mission design.

Together, these elements support the goal of establishing the first radiation-tolerant LoRa mesh network validated by test and analysed for use in both accelerator and satellite contexts.

1.3 Objectives

The objectives of this diploma thesis are:

1. **Theoretical foundation.** Conduct a literature review covering LoRa technology, meshed and hierarchical network architectures, radiation effects on electronics, and the operation of CERN radiation facilities (CHARM, PSI). This review sets the context and highlights the novelty of a LoRa-based mesh network validated for radiation environments.
2. **Embedded software.** Develop embedded software for the Astromesh platform that implements mesh networking (e.g., route discovery, packet forwarding) with compatibility across the supported transceivers (868 MHz, ISM, UWB), enabling flexible deployment in different communication scenarios.
3. **Experimental validation.** Perform radiation testing at PSI and CHARM, comparing meshed and hierarchical LoRa network performance and reliability under radiation.
4. **Mission analysis and link budget.** Carry out a mission analysis and link budget study for mesh deployment in LEO, exploring different constellation configurations and performing detailed analysis for the 868 MHz and ISM bands to assess coverage and communication performance for space applications.

The work that was performed by the author of this thesis includes the embedded software (driver for the UWB transceiver, mesh network in C utilizing the existing RadioHead library for the RF95 transceiver), the radiation test instrumentation and preparation (instruments' control code, harness), the data analysis scripts in Python, the STK modelling and analysis and the link budget analysis scripts.

1.4 Thesis Outline

The remainder of the thesis is organised as follows.

- **chapter 2 (Theoretical Background)** introduces LoRa and LoRaWAN, including star-of-stars topology, device classes, and the adaptive data rate (ADR) concept. It compares hierarchical and non-hierarchical (mesh) topologies and summarises radiation effects on electronics and the operation of CHARM and PSI irradiation facilities.

- **chapter 3 (Astromesh Platform)** describes the Astromesh hardware and system architecture, including the main board, mezzanine, and supported transceivers. It presents the design and implementation of the modular mesh networking software and its integration with the platform.
- **chapter 5 (Radiation Testing)** reports the radiation test campaigns at CHARM and PSI. It describes the hierarchical LoRa test setup, the mesh versus hierarchical comparisons, and supporting analyses (e.g., packet delivery, power, thermal). Results are used to assess the robustness of the mesh architecture under radiation.
- **chapter 4 (Mission Analysis)** presents the link budget methodology (EIRP, free-space path loss, link margin) and applies it to LEO scenarios. It discusses constellation options and analyses the 868 MHz and ISM bands to evaluate coverage and feasibility for Astromesh-based mesh networks in space.

The thesis concludes with a summary and outlook.

2. Theoretical Background

2.1 LoRa & Hierarchical Networks and Non-Hierarchical Networks

2.1.1 Introduction to LoRa

LoRa (Long Range) is a spread spectrum modulation technique derived from Chirp Spread Spectrum (CSS) technology, developed and patented by Semtech [2]. It enables long-range, low-power wireless communication, making it particularly well-suited for Internet of Things (IoT) applications [3]. LoRa has gained significant traction in recent years due to its ability to provide connectivity over distances of several kilometres (with record links exceeding 1300 km) while maintaining minimal power consumption, which is critical for battery-operated sensor nodes deployed in remote or hard-to-reach locations.

The CSS modulation technique employed by LoRa consists of encoding information with a linear variation of frequency over time, known as frequency chirps. This approach provides enhanced robustness against noise and interference compared to traditional modulation schemes, enabling reliable long-range and low-power communication links. The frequency-based modulation also facilitates frequency hopping and multi-channel schemes, further improving system resilience [4].

LoRa demonstrates superior performance in long-range and low-power applications compared to traditional modulation schemes such as Frequency Shift Keying (FSK). However, FSK schemes typically achieve higher data rates, representing a fundamental trade-off between range/power efficiency and throughput [4]. A foundational empirical characterisation of this trade-off was provided by Augustin et al. [5], who systematically measured the sensitivity and throughput achievable across the full spreading factor range under real-world conditions, confirming that a device operating at SF12 and 125 kHz bandwidth achieves receiver sensitivity around -135 dBm but throughput as low as 28 bytes/s, while SF7 recovers approximately 780 bytes/s at the cost of roughly 12 dB in sensitivity.

Five main parameters govern LoRa modulation. The interplay between these parameters allows network designers to fine-tune the trade-off between range, data rate, power consumption, and robustness against interference:

- **Spreading Factor (SF):** Determines the number of chips per symbol and is directly related to the data rate (number of chirps per second). Higher SF increases range and robustness at the cost of data rate and increased power consumption. LoRa supports spreading factors from SF7 to SF12, where each increment roughly doubles the time on air. SF7 provides the highest data rate with lower sensitivity and communication range, while SF12 offers the best coverage and sensitivity at the expense of significantly increased power consumption and reduced throughput. The optimal SF value depends on environmental conditions and application requirements [4].
- **Coding Rate (CR):** Controls the level of forward error correction applied to the transmitted data. The coding rate represents the proportion of the transmitted data stream (bits) that is useful, and it is directly related to the time-on-air. A higher coding rate provides better error resilience

but reduces the effective data throughput. A smaller coding rate increases the time-on-air of the transmission. LoRa features cyclic error coding, which enables forward error correction and enhances protection against interference [4].

- **Bandwidth (BW):** Defines the frequency range over which the chirp signal is spread. Common bandwidths are 125 kHz, 250 kHz, and 500 kHz. A wider bandwidth increases data rate but reduces sensitivity. The bandwidth is one of the main parameters along with SF and CR that characterise LoRa communication.
- **Transmission Power:** Sets the output power of the radio transmitter. Higher power extends the communication range but increases energy consumption. Typical values range from low power settings around 2 dBm to maximum values of 14–20 dBm depending on regional regulations.
- **Center Frequency (f):** The carrier frequency used for communication, typically in the sub-GHz ISM bands (e.g., 868 MHz in Europe, 915 MHz in North America and 868.5 MHz band commonly used in experimental setups).

It is important to note that the performance of LoRa in real-world, non-line-of-sight deployments can deviate substantially from open-field expectations. Lee and Ke [6] demonstrated that indoor sensors located on lower floors of multi-storey buildings could not reach a gateway directly even at SF12, due to the attenuation imposed by reinforced concrete structures. Similarly, Cattani, Boano, and Römer [7] found through long-term measurements that link quality fluctuates significantly with environmental and meteorological conditions, reinforcing the need for adaptive or redundant communication strategies in deployments that require sustained reliability.

2.1.2 Star-of-Stars Topology

LoRaWAN, the networking protocol built on top of the LoRa physical layer, employs a star-of-stars topology [3, 8]. Unlike traditional point-to-point or mesh architectures, this topology centralises network intelligence at the server level while keeping end devices as simple and energy-efficient as possible. The architecture consists of four main components:

- **End devices:** The edge nodes that collect data or perform actions. These devices communicate directly with one or more gateways using LoRa modulation.
- **Gateways:** Relay messages between end devices and the network server. A single gateway can serve thousands of end devices simultaneously.
- **Network server:** Manages the network, handles routing, and performs de-duplication of packets received by multiple gateways.
- **Application servers:** Process and store the application-level data received from end devices.

LoRaWAN Gateways

LoRaWAN gateways serve as the communication bridge between end devices and the network server [3]. They communicate with end devices using LoRa radio modulation and connect to the network server via standard IP connections (Ethernet, WiFi, Cellular). A key design principle of LoRaWAN is that multiple gateways can receive the same transmission, providing spatial diversity and redundancy in the network. The network server is then responsible for selecting the best copy and discarding duplicates. Importantly, there is no association between devices and specific gateways, meaning any gateway within range can forward a device's message to the network server. This design simplifies device management and improves network resilience, as the loss of a single gateway does not disconnect any end device that remains within range of another gateway.

LoRaWAN Network Server

The network server is the central network management system in a LoRaWAN architecture [8]. It acts as the intelligence layer of the network, coordinating communication between gateways and application servers while ensuring efficient use of the radio spectrum. Its core functions include:

- Duplicate packet elimination from messages received by multiple gateways
- **Adaptive Data Rate (ADR)** algorithm for optimising transmission parameters
- Security and authentication, including device activation and encryption key management
- Message routing between devices and applications
- Network monitoring and administration

LoRaWAN Application Servers

Application servers are responsible for processing application-specific data messages received from end devices, as well as the generation of application-layer downlink packets. They interface with the network server to receive decoded payloads and can trigger actuations or alerts based on the received data. In a typical deployment, multiple application servers may coexist, each handling a different use case or data stream.

2.1.3 ADR Algorithm

The Adaptive Data Rate (ADR) algorithm is a key feature of the LoRaWAN network server. It dynamically determines the appropriate data rate for each end device in order to improve overall network performance and maximise both battery life and network capacity [8]. By analysing the signal quality of received uplink frames, the ADR algorithm adjusts the following parameters:

- Spreading factor

- Bandwidth
- Transmission power

The standard ADR mechanism, as defined by the LoRa Alliance, operates on a simple principle: if the link margin is sufficient, the network server instructs the device to use a lower spreading factor and/or reduced transmission power. However, this approach has known limitations in scenarios involving mobile nodes, variable interference, or dense deployments, which has motivated significant research into improved ADR algorithms [9, 10].

2.1.4 LoRaWAN Device Classes

LoRaWAN defines three device classes, each offering a different trade-off between power consumption and downlink latency [3, 8]. All devices must implement Class A, while Classes B and C are optional extensions:

- **Class A:** Class A devices offer bi-directional communication with an uplink-initiated scheme. After each uplink transmission, the end device opens two short receive windows for potential downlink messages. This is the most energy-efficient class, as the device spends the majority of its time in sleep mode, making it ideal for battery-powered sensors that primarily send data.
- **Class B:** Class B extends Class A by adding scheduled receive slots. The gateway periodically broadcasts time-synchronised beacons, allowing the network server to know when a device is listening. This enables the server to send downlink messages at predictable intervals, reducing latency compared to Class A while still maintaining reasonable power consumption.
- **Class C:** Class C devices maintain a continuously open receive window, closing it only during transmission. This provides the lowest possible downlink latency, as the server can send a message to the device at virtually any time. However, this comes at the cost of the highest power consumption among the three classes, making Class C suitable primarily for mains-powered devices where energy is not a constraint.

2.1.5 LoRaWAN Improvements

Despite the success of LoRaWAN in many IoT deployments, several limitations have been identified that motivate ongoing research. These efforts have focused on improving LoRaWAN in two main areas: the ADR algorithm and the network architecture [3].

ADR Improvements

The standard ADR algorithm has been shown to perform poorly in certain conditions, particularly for mobile devices or in environments with high interference [8, 9]. Various improved ADR schemes have been proposed in the literature to address these shortcomings:

- A new-dynamic ADR algorithm was proposed specifically for moving nodes, adapting more rapidly to changing link conditions [11].
- A collision-aware ADR scheme was introduced that takes into account the probability of packet collisions when assigning spreading factors, thereby reducing the overall collision rate in the network [12].
- A dynamic LoRa transmission control system was developed aimed at improving energy efficiency in dense IoT deployments by adaptively configuring transmission parameters based on network conditions [13].

Network Architecture Improvements

Beyond ADR optimisation, multi-hopping has been proposed as a key architectural improvement to the traditional star-of-stars topology [3]. In a multi-hop configuration, end devices can relay messages through intermediate nodes before reaching a gateway, offering several benefits:

- Reduces the need for deploying additional gateways, lowering infrastructure costs
- Reduces the chances of packet collisions, as far-away end devices can use a smaller spreading factor thanks to shorter hop distances
- Extends the overall coverage capability of the network, enabling connectivity in areas beyond the direct range of any single gateway

The practical impact of multi-hop operation was demonstrated conclusively by Lee and Ke [6], whose campus-scale experiment with 19 nodes showed that relaxing the hop-count limit from one to three raised the average packet delivery ratio from 58.7% to 88.49%, with several indoor nodes recovering from 0% to over 90% delivery. This result is particularly significant because it was achieved without deploying any additional gateways, demonstrating that mesh networking can substitute for gateway proliferation.

Several complementary approaches to enabling multi-hop communication over LoRa have been explored in the literature. Dias and Grilo [14] demonstrated that a DSDV-based relay protocol can be made compatible with the existing LoRaWAN specification, extending uplink coverage to sensors in locations with strong electromagnetic attenuation such as basements and underground infrastructure. Their evaluation in linear and bottleneck topologies showed acceptable packet reception rates across up to four hops, with the routing overhead remaining tractable due to the simplified routing table maintained at each node. Lundell et al. [15] adopted a different protocol foundation (a hybrid of HWMP and AODV adapted to LoRa's constraints) which added only modest header overhead while enabling gateway-to-gateway multi-hop communication validated through field tests. A broad survey and taxonomy of these approaches, covering use cases ranging from underground pipeline monitoring to aerial drone swarms, was provided by Centelles et al. [16], who identified decentralisation and coverage extension as the two most under-addressed design goals in the existing literature.

2.1.6 LoRa Networks in Space

Beyond terrestrial deployments, LoRa and LoRaWAN have been extended to support direct communication with Low Earth Orbit (LEO) satellites, typically operating at altitudes between 500 km and 2000 km [17, 18]. This extension is motivated by the fact that only approximately 10% of the Earth's surface benefits from terrestrial LoRaWAN coverage, leaving vast remote regions — oceans, polar areas, deserts, and infrastructure-sparse regions — unserved by conventional deployments [18, 19].

Two complementary architectures define how LoRa integrates with satellite networks [18]. In the **indirect** model, terrestrial LoRaWAN gateways aggregate data from ground-based end devices and use satellite links as a backhaul to reach the core network — well-suited to rural areas that can justify a local gateway but lack fibre or cellular backhaul. In the **direct-to-satellite** (DtS) model, individual IoT devices transmit directly to a passing LEO satellite acting as an orbiting gateway, with no ground infrastructure required between the device and the space segment, enabling truly infrastructure-free global coverage [18].

At the hardware level, LoRa transceivers have been integrated directly into CubeSat and nanosatellite platforms, enabling low-cost orbital IoT gateways [20]. These platforms leverage the low mass and power requirements of LoRa radio chipsets, with communication ranges exceeding 14 km demonstrated in link tests. Broader surveys of LPWAN technologies for LEO constellations identify radiation tolerance of on-board electronics as one of the key open challenges for future deployment [19], directly motivating the co-design of radiation-hardened LoRa nodes that forms the basis of the Astromesh platform.

2.1.7 Hierarchical vs Non-Hierarchical Networks

Wireless network architectures can be broadly classified into two categories: hierarchical (centralised) and non-hierarchical (decentralised or mesh) networks [21, 22]. The choice between these two approaches has a significant impact on network performance, scalability, fault tolerance, and deployment complexity [3].

Hierarchical Networks

In a hierarchical network, nodes are organised in layers with distinct roles and responsibilities. The standard LoRaWAN star-of-stars topology is a prime example of this approach: end devices communicate exclusively with gateways, which in turn forward data to a centralised network server [8]. This architecture offers several advantages:

- Simplified end device design, as nodes only need to transmit and receive without routing logic
- Centralised network management, enabling efficient resource allocation and coordination
- Well-defined data flow, simplifying security implementation and data processing

However, hierarchical networks also present notable limitations. The reliance on gateways creates

single points of failure: if a gateway becomes unavailable, all end devices within its exclusive coverage area lose connectivity. Additionally, the coverage of the network is fundamentally constrained by the placement and range of gateways, making it difficult to extend the network into remote or obstructed areas without deploying additional infrastructure [3]. This gateway dependency was directly observed in the CERN radiation monitoring deployment described by Manzano et al. [23], where coverage was confined to areas within approximately 700 m of an installed gateway.

Non-Hierarchical (Mesh) Networks

In a non-hierarchical or mesh network, all nodes can potentially communicate with each other, and messages are relayed through multiple hops to reach their destination. There is no strict separation between end devices and relay nodes — any node in the network can act as both a data source and a router [3]. Akyildiz, Wang, and Wang [21] identified scalability, self-organisation, and fault tolerance as the defining properties that distinguish mesh architectures from both cellular and conventional ad hoc topologies, while Bruno, Conti, and Gregori [22] noted that commodity multi-hop networks become practically viable when routing overhead is controlled and link quality estimation is reliable. This architecture provides several key benefits:

- **Increased resilience:** The network can dynamically reroute traffic around failed or unreachable nodes, making it inherently more fault-tolerant than hierarchical designs
- **Extended coverage:** Multi-hop communication allows the network to reach areas far beyond the range of any single node, without requiring additional gateway infrastructure
- **Self-healing capability:** When a node fails, neighbouring nodes can adapt their routing tables to maintain connectivity, ensuring continuous operation
- **Scalability:** New nodes can be added to the network without reconfiguring the existing infrastructure, as routing is handled dynamically
- **Decentralised operation:** The absence of central infrastructure enables deployment in environments where fixed infrastructure is impractical or impossible

The main trade-offs of mesh networks include increased complexity in routing protocols, higher energy consumption due to relay duties, and potentially higher latency as messages traverse multiple hops before reaching their destination [3]. Furthermore, the implementation of mesh networking over LoRa presents unique challenges, as the LoRaWAN protocol was originally designed for a star topology and does not natively support multi-hop communication [3].

Mesh operation also introduces practical deployment constraints that are not present in star topologies. Nodes acting as routers must keep their radio transceivers active for extended periods, which substantially increases power consumption and often necessitates mains power for relay nodes [6]. Additionally, as demonstrated by Zirak, Shashev, and Shidlovskiy [24] in a flying ad-hoc network context using LoRa, the half-duplex nature of LoRa transceivers introduces a 1–2 second delay between uplink and downlink phases, which can be mitigated by dedicating separate hardware for transmission

and reception. Their results also showed that hop-count-based load balancing was more stable than GPS-distance-based routing in dynamic topologies, a finding with relevance to any deployment where node positions or link qualities vary over time.

Comparison

The choice between hierarchical and non-hierarchical architectures depends on the specific requirements of the application. Hierarchical networks are well-suited for deployments where gateway infrastructure can be readily installed and maintained, where centralised control is desirable, and where end device simplicity and low power consumption are paramount. Non-hierarchical mesh networks, on the other hand, are preferable in scenarios where infrastructure deployment is impractical, where network resilience and self-healing are critical, or where coverage needs to extend over large or irregularly shaped areas [3].

For applications in harsh or remote environments, such as inside particle accelerators or in satellite constellations, mesh networks offer a compelling advantage. The ability to operate without centralised infrastructure and to dynamically adapt to node failures makes them particularly suitable for environments where maintenance access is limited and reliability is essential [2, 4]. This is the motivation behind the Astromesh platform, which leverages LoRa-based mesh networking to provide resilient communication in radiation environments and space applications.

2.2 Radiation Effects on Electronics

Electronic systems deployed in radiation-harsh environments face degradation mechanisms arising from energetic particle interactions with semiconductor materials. Understanding these effects is essential for designing reliable wireless communication systems in space and particle accelerator facilities [25, 2].

2.2.1 Particle-Matter Interaction Physics

When energetic particles traverse matter, they deposit energy through distinct interaction mechanisms depending on particle type and energy. Photons interact via photoelectric absorption at low energies, Compton scattering at intermediate energies, and pair production above 1.022 MeV. Charged particles primarily deposit energy through Coulombic interactions with orbital electrons, causing ionisation and excitation. Neutrons interact exclusively through nuclear processes including elastic scattering, inelastic scattering, and absorption reactions.

Energy deposition manifests as either ionising energy loss (IEL) or non-ionising energy loss (NIEL). IEL generates electron-hole pairs in semiconductor materials, while NIEL transfers energy to atomic nuclei, displacing them from lattice positions. The stopping power quantifies total energy loss per unit path length, combining both mechanisms [25, 2].

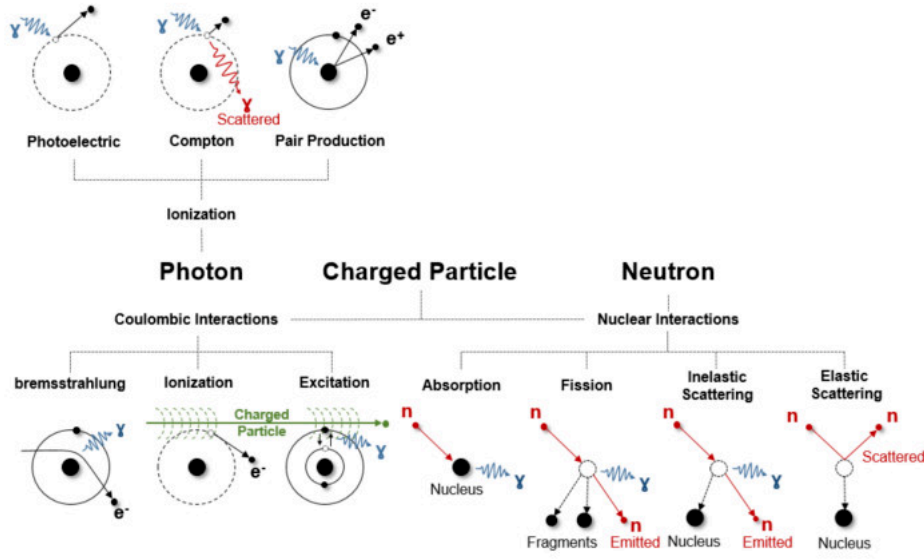


Figure 2.1: Radiative particle interactions [25].

2.2.2 Total Ionising Dose

Total ionising dose (TID) represents cumulative ionisation damage in materials, measured in Gray (1 Gy = 1 J/kg) or rad (1 Gy = 100 rad). For charged particles, TID depends on linear energy transfer (LET), which quantifies energy deposited per unit distance ($\text{MeV}\cdot\text{cm}^2/\text{mg}$). The dose from a particle with fluence Φ is:

$$\text{TID} = K_{\text{Gy}} \frac{\text{LET}(E)}{\rho} \Phi(E) \quad (2.1)$$

where $K_{\text{Gy}} = 1.6 \times 10^{-7} \text{ Gy}\cdot\text{g}/\text{MeV}$ and ρ is material density.

Photons deposit dose through their mass energy transfer coefficient μ_{en}/ρ , which relates incident photon energy to kinetic energy transferred to electrons. In mixed radiation fields containing multiple particle species, total dose accumulates as the integral over all particle types and energies.

In MOS devices, ionisation creates electron-hole pairs in silicon dioxide layers. While electrons rapidly drift away, holes migrate slowly and become trapped at defect sites within the oxide or at Si/SiO₂ interfaces. These trapped charges shift threshold voltages, increase leakage currents, and degrade transistor performance [26, 2]. Silicon requires 3.6 eV per electron-hole pair, while SiO₂ requires 18 eV, yielding generation rates of 4×10^{15} and 8.2×10^{14} pairs $\cdot\text{Gy}^{-1}\cdot\text{cm}^{-3}$ respectively [25, 2].

2.2.3 Single Event Effects

Single event effects (SEE) occur when a single energetic particle deposits sufficient charge in a sensitive device region to cause malfunction. These stochastic events range from recoverable soft errors to permanent device destruction.

1. **Soft errors** include single event upsets (SEU), where bit states flip in memory elements or registers; single event transients (SET), producing voltage or current spikes that propagate through logic circuits; and single event functional interrupts (SEFI), causing temporary malfunction requiring system reset. When a charged particle traverses a transistor, generated electron-hole pairs drift under electric fields, creating transient currents. If collected charge exceeds the critical charge threshold, the device state changes.
2. **Hard errors** permanently damage devices. Single event latchup (SEL) triggers parasitic thyristor structures, creating low-resistance paths between power and ground that can thermally destroy the device. Single event burnout (SEB) causes regenerative avalanche breakdown in power transistors. Single event gate rupture (SEGR) deposits charge at gate oxide interfaces, creating dielectric breakdown [27, 28].

SEE probability is quantified by cross-section $\sigma = N/\Phi$, where N is observed events and Φ is particle fluence (cm^{-2}). For space applications, high energy hadron (HEH) fluence above 20 MeV provides the relevant metric, as lower energy hadrons rarely trigger SEE in modern electronics [27, 28].

2.2.4 Displacement Damage

Displacement damage (DD) occurs when particles transfer sufficient energy to displace atoms from semiconductor lattice positions. An incident particle creates a primary knock-on atom (PKA), which may displace additional atoms, forming vacancy-interstitial pairs (Frenkel pairs), isolated vacancies or interstitials, or clustered defect regions.

The PKA energy determines defect type and quantity. Low-energy PKAs below 2 keV create individual Frenkel pairs (21 eV threshold in silicon) or small clusters. Intermediate PKAs (2–12 keV) from 10–20 MeV heavy ions form single dense defect clusters. High-energy PKAs above 12 keV from >20 MeV heavy particles generate cascades of multiple large defect regions [26, 29].

Displacement damage is characterised by non-ionising energy loss (NIEL), quantifying energy transferred to atomic nuclei. Like TID, displacement effects are expressed as equivalent 1 MeV neutron fluence through the hardness factor $\kappa = \text{NIEL}(E)/\text{NIEL}_{n,1\text{MeV}}$ [26, 29].

In semiconductor devices, lattice defects act as carrier traps and recombination centres, reducing minority carrier lifetime, increasing leakage current, and degrading detector performance. Optoelectronic devices experience particularly severe degradation, with reduced light output and quantum efficiency [29].

2.2.5 System-Level Testing in Wireless Networks

Radiation effects occur at the system level through several failure modes observed in wireless mesh network deployments [2]. Transceiver transmission failures occur when SEE disrupt radio operation while the microcontroller continues executing, creating nodes unable to communicate despite appearing functional. Device lockups result from bit flips in control logic or state machines, rendering nodes unresponsive until power cycled. Bit flips in SRAM affect transmitted data, configuration registers,

node identifiers, and routing tables, with impact severity depending on which memory locations are corrupted [28, 2].

Software mitigation strategies address these failures. Watchdog timers detect frozen processors and trigger automatic recovery. Periodic configuration register verification and correction prevents malfunction from corrupted settings. Error detection codes and triple modular redundancy protect critical variables [28, 2]. At the network level, mesh topology inherently provides resilience through alternate routing paths when individual nodes fail.

2.2.6 Radiation Environment Characteristics

Space radiation comprises three sources: trapped particles in Earth's Van Allen belts (electrons up to 10 MeV, protons up to 500 MeV), galactic cosmic rays (highly energetic protons and heavy ions with GeV energies, flux inversely proportional to solar activity), and solar particle events (energetic protons and ions from solar flares, intensity varying with the 11-year solar cycle) [2].

Particle accelerator facilities like CERN's LHC create complex mixed-field environments containing high-energy hadrons, charged particles (electrons, muons, pions), photons from electromagnetic cascades, and thermal to high-energy neutrons [25, 27]. Dose rates in accelerator tunnels reach several Gy/hour during operation, with cumulative doses exceeding several MGy in high-radiation areas over equipment lifetime [27, 30]. The CHARM facility provides controlled mixed-field testing reproducing accelerator radiation conditions [31, 32, 33].

3. AstroMesh Platform

AstroMesh is a modular communication platform designed and developed at CERN to evaluate the feasibility of mesh networks operating in radiation-prone environments such as space missions and particle accelerator facilities. The platform serves as an inter-satellite and in-satellite communication system for satellites, developed within the framework of the CERN Venture Connect Knowledge Transfer program.

3.1 Platform Heritage and Design Philosophy

The AstroMesh platform design is based on the SpaceRadMon-NG radiation monitoring payload previously developed by CERN [34]. SpaceRadMon-NG is the new design of CELESTA (CERN Latchup and RadMon Experiment Student Satellite), the original CERN payload. After the successful flight of CELESTA on a 1U-CubeSat mission launched in July 2022, SpaceRadMon-NG was developed as an evolution incorporating FPGA-MCU design for performance improvement of a space payload for radiation monitoring [2]. It is currently deployed on the ISS, Radio-X mission, and TRISAT-R mission [34].

Building upon the heritage and lessons learned from SpaceRadMon-NG and the CELESTA mission, AstroMesh incorporates several key improvements:

- Enhanced modularity through separate main board and mezzanine board architecture
- Extended communication capabilities with multiple transceiver options
- Greater flexibility for adapting to different mission requirements

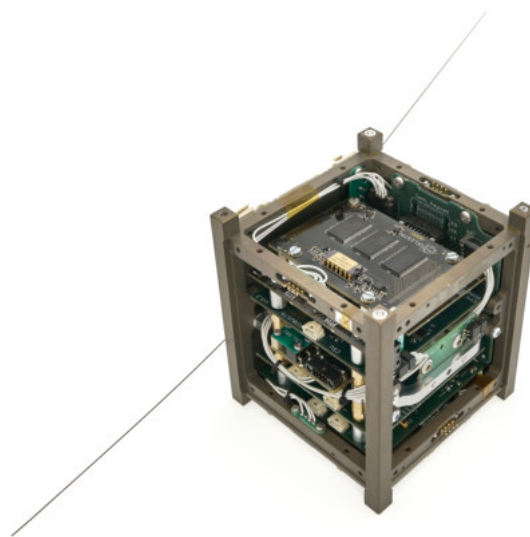


Figure 3.1: CELESTA CubeSat

The microcontroller unit (MCU) employed in AstroMesh is the same ARM Cortex-M0+ based device successfully used in the BatMon (Battery Monitoring) application, which has demonstrated reliable performance in radiation environments [28]. The MCU contains an embedded ADC, providing higher radiation tolerance, low-power mode capabilities, and enhanced flexibility compared to discrete ADC solutions.

3.2 Hardware Overview

The platform consists of two stackable boards: the main board containing the core processing and communication elements, and the mezzanine board providing extended transceiver capabilities for inter-satellite links. Figure 3.2 shows the design of the AstroMesh main board.

3.3 System Architecture

3.3.1 Main Board

The main board ($96.00 \times 92.00 \times 16.56 \text{ mm}^3$), which is compatible with the PC104 standard [35] integrates the core system components (all tested under radiation until 500 Gy [34]):

- **Field Programmable Gate Array (FPGA):** Microchip ProASIC3L low-power COTS FPGA featuring clock gating capability for dynamic power reduction. The FPGA handles high-speed parallel sensor interfacing, memory sensor access, and serves as the primary system coordinator. It operates at 1.2 V and 3.3 V and communicates externally using the I²C protocol.
- **Microcontroller Unit (MCU):** ARM Cortex-M0+ 8-bit-based flash microcontroller operating at 48 MHz with 256 KB flash memory, 32 KB SRAM, and operating at 3.3 V. The MCU provides low-power serial interfacing, mixed-signal sensor readout through its embedded 14-channel 12-bit ADC, and supervisory control. The MCU interfaces the LoRa transceivers and communicates with the FPGA through Serial Peripheral Interface (SPI).
- **Power Distribution System:** Multiple power regulators providing the different voltages required by system components (1.2 V, 3.3 V, 5 V).
- **Communication Interfaces:** I²C for external communication, SPI for FPGA-MCU communication, and transceiver interfaces.
- **Integrated LoRa Transceivers:** Two LoRa transceivers operating at different frequency bands for robust inter-satellite link communication (see Table 3.1).

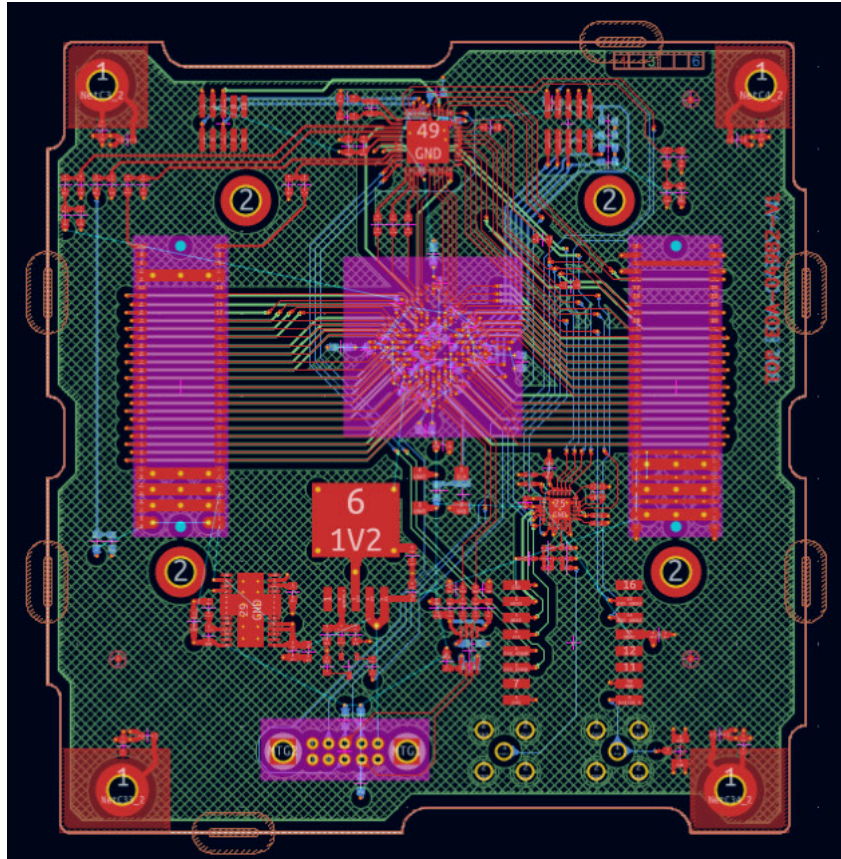


Figure 3.2: KiCad PCB layout of the main board

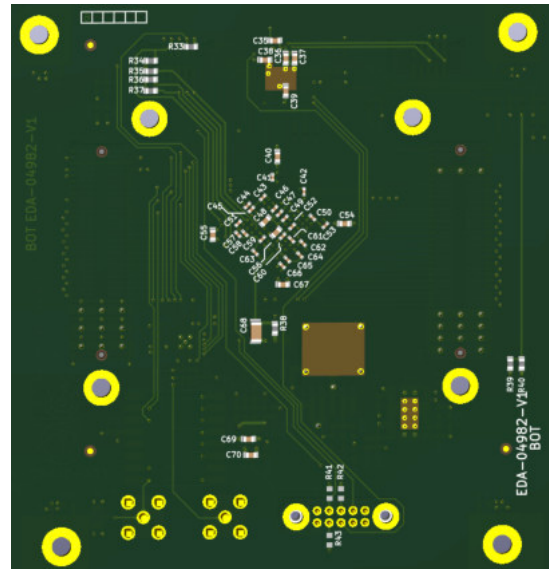
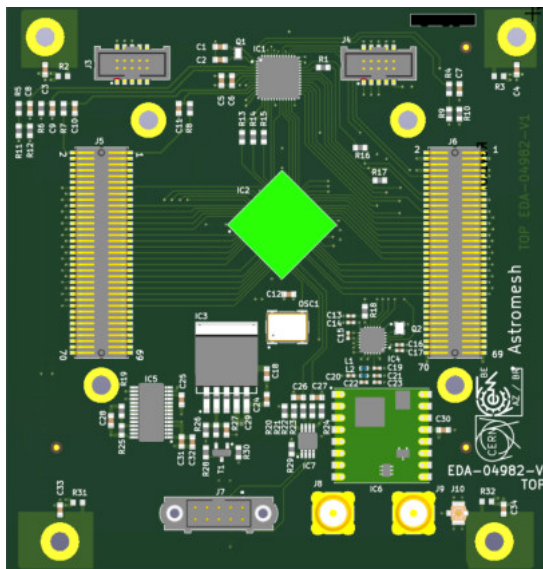


Figure 3.3: AstroMesh main board: (left) top view showing FPGA, MCU, and integrated LoRa transceivers; (right) bottom view showing power distribution and interface circuitry.

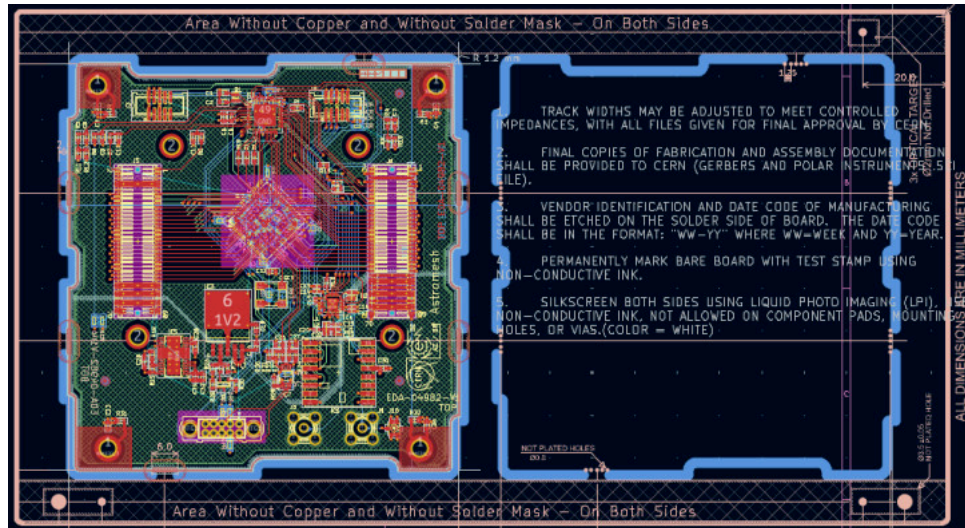


Figure 3.4: KiCad PCB layout of the main board, along with PCB assembly details

3.3.2 Mezzanine Board

The mezzanine board ($53 \times 77 \times 3 \text{ mm}^3$) extends the communication capabilities of the platform with two additional transceivers: an ultra-wideband (UWB) transceiver for in-satellite communication and a multi-band LoRa transceiver for inter-satellite link (ISL) communication (see Table 3.1).

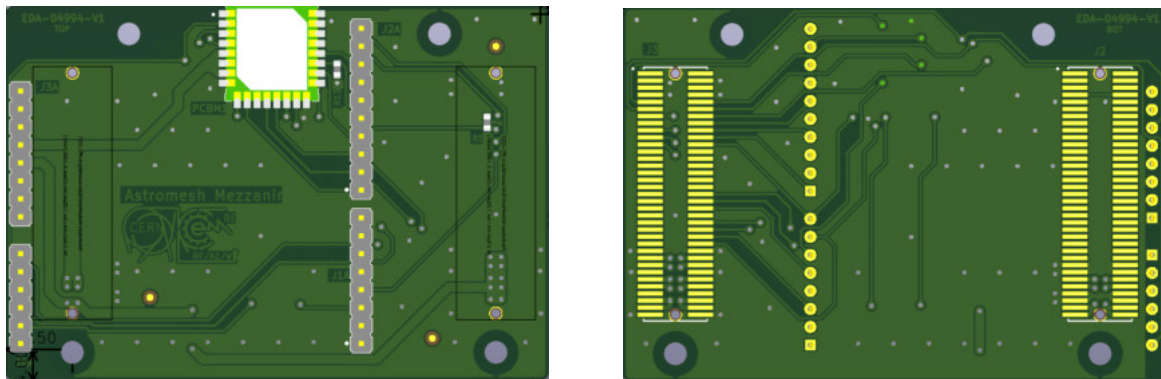


Figure 3.5: AstroMesh mezzanine board: (left) top view; (right) bottom view showing the LR1121 and DWM1000 transceivers.

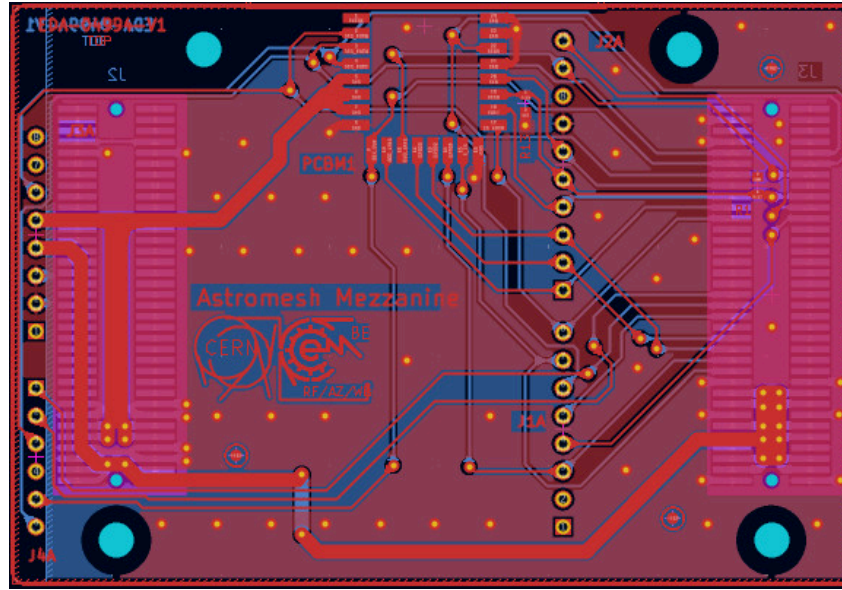


Figure 3.6: Mezzanine board PCB layout showing the placement of transceivers and interconnection to the main board.

3.4 LoRa Transceiver Specifications

The AstroMesh platform supports multiple LoRa and UWB transceivers (see Figure 3.7). Table 3.1 summarizes the four transceiver options available on the platform:

Table 3.1: AstroMesh Platform LoRa and UWB Transceiver Specifications

Parameter	HopeRF RFM95W	Semtech SX1280	Semtech LR1121	Qorvo DWM1000
Location	Main Board	Main Board	Mezzanine	Mezzanine
Application	ISL	ISL	ISL	In-satellite
Frequency	868 MHz	2.4 GHz	150–960 MHz 2.4 GHz 2.1 GHz S-Band	3.5–6.5 GHz

- **HopeRF RFM95W (868 MHz):** Sub-GHz transceiver operating in the 868 MHz ISM band in Europe [36]. Provides the longest range capability (several kilometers) at the cost of lower data rates. Ideal for establishing inter-satellite link connectivity within satellite constellations. The lower frequency provides better diffraction around obstacles and deeper penetration.
- **Semtech SX1280 (2.4 GHz):** Higher frequency transceiver operating in the globally available 2.4 GHz ISM band [37]. Offers a balance between range (up to 1 km) and data rate. The 2.4 GHz band enables smaller antennas and higher data throughput compared to sub-GHz options, suitable for moderate-distance inter-satellite communication.
- **Semtech LR1121 (150–960 MHz, 2.4 GHz, 2.1 GHz S-Band):** Multi-band transceiver providing exceptional flexibility with support for sub-GHz frequencies (150–960 MHz), 2.4 GHz, and S-band

(2.1 GHz) commonly used in space applications [38]. This versatility enables adaptive frequency selection based on link conditions and regulatory requirements. It is thus particularly valuable for inter-satellite links, where different frequency bands may be optimal depending on orbital geometry and distance.

- **Qorvo DWM1000 (3.5–6.5 GHz):** UWB transceiver operating in the 3.5–6.5 GHz range [39]. While offering shorter range (< 300 m) compared to LoRa options, UWB provides significantly higher data rates and precise ranging capabilities. This makes it suitable for short-range, high-bandwidth in-satellite communication or precision applications within the satellite.



Figure 3.7: AstroMesh transceiver modules: RFM95W (868 MHz), SX1280 (2.4 GHz), LR1121 (multi-band), and DWM1000 (UWB 3.5-6.5 GHz).

3.5 Power Consumption and Operating Modes

The AstroMesh platform is designed with multiple power modes to optimize energy efficiency, critical for battery-operated systems in space applications. The power consumption characteristics are shown in table 3.2

Table 3.2: AstroMesh Platform Power Consumption

Operating Mode	Current Consumption
MCU Sleep, FPGA Disabled	3 mA
MCU Sleep, FPGA Enabled	13 mA
MCU Awake, FPGA Disabled	13 mA
MCU Awake, FPGA Enabled	30 mA
MCU Awake, FPGA Enabled, Tx RFM95W	120 mA
MCU Awake, FPGA Enabled, Tx SX1280	137 mA
MCU Awake, FPGA Disabled, Tx DWM100	151 mA

The platform operates from a 5 V supply and is designed for a temperature range of -20°C to +80°C.

3.6 Radiation Tolerance and Mitigation Schemes

AstroMesh incorporates radiation mitigation strategies at both hardware and firmware levels, leveraging the experience gained from the SpaceRadMon-NG and BatMon applications [34]:

3.7 Qualification and Validation

The AstroMesh platform benefits from extensive qualification and validation heritage. The SpaceRadMon-NG payload, upon which AstroMesh is based, underwent testing (based on [34]):

- **Mechanical and Environmental Testing:** Vibration, thermal cycling, and thermal vacuum testing per CubeSat standards
- **Component-level Testing:** Individual components tested with 200 MeV proton beam to verify radiation tolerance
- **System-level TID Testing:** Full system tested at CERN's Co⁶⁰ facility for total ionizing dose effects
- **Mixed-field Testing:** Validation in CHARM facility under accelerator-representative mixed-field radiation conditions, evaluation of the system functionalities in a mixed field environment in a test position representative of to LEO important satellites
- **In-orbit Validation:** SpaceRadMon-NG successfully operated on CELESTA mission, providing flight heritage

The SpaceRadMon-NG payload did not exhibit any Single Event Functional Interruptions (SEFIs) corresponding to an upper limit cross-section of $\leq 8.58 \times 10^{-12} \text{ cm}^2$ at 95% confidence level, with the system withstanding over 418 Gy without degradation or single event functional interrupts during testing [34].

3.8 Primary Applications

The AstroMesh platform aims to demonstrate robust, fault-tolerant wireless communication networks using the LoRa protocol in harsh environments. Primary application scenarios include:

- **Inter-Satellite Communication:** Establishing mesh networks within satellite constellations for distributed data collection and relay.
- **Particle Accelerator Facilities:** Wireless sensor networks in areas with high radiation levels and limited access for maintenance.
- **Radiation-Tolerant IoT:** Enabling Internet of Things deployments in radiation environments.

3.9 Software Architecture and Transceiver Implementation

To validate the AstroMesh platform's communication capabilities and demonstrate mesh networking in radiation environments, a layered software stack was developed. All transceiver-related code, excluding the RadioHead library, which is used as-is, was written and integrated for the AstroMesh MCU (ATSAMD21G18) and build system. Figure 3.8 summarises the architecture.

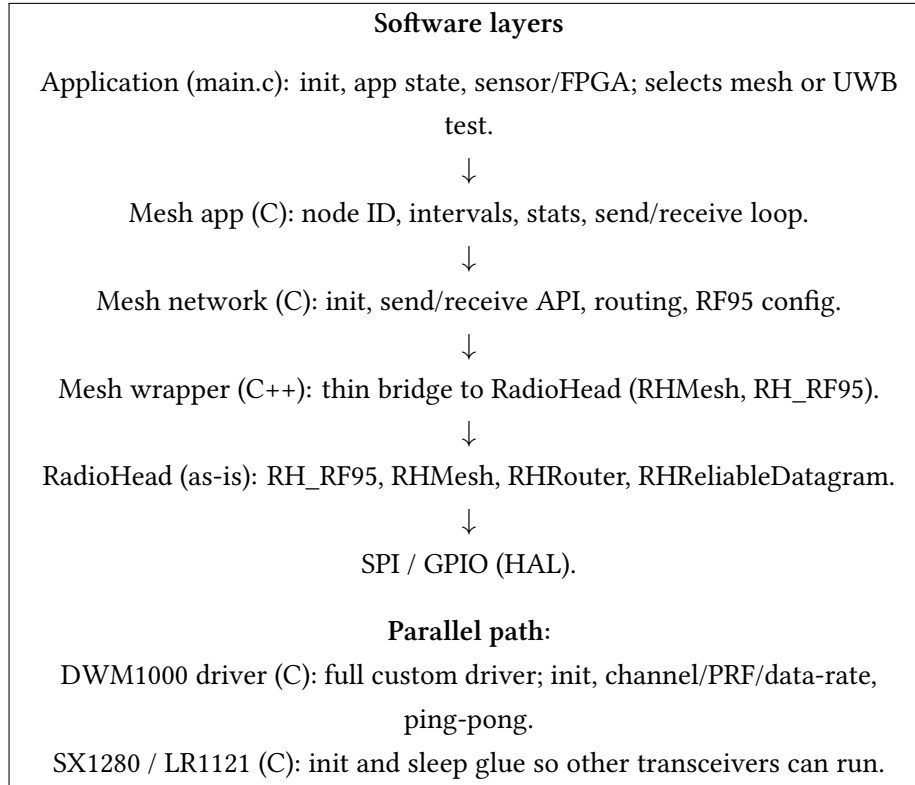


Figure 3.8: Simplified software architecture: application and mesh stack on top of RadioHead (used as-is) and custom transceiver drivers.

3.9.1 Layer Overview

The application entry point (`main.c`) initialises the board, ADC, sensor board, and SPI. It then runs either the inter-satellite mesh path (RFM95W) or the in-satellite UWB path (DWM1000); the choice is compile-time or runtime configurable. All transceiver drivers share the same MCU SPI bus; chip-select and reset pins are managed so that only one transceiver is active at a time. The SX1280 and LR1121 drivers provide initialisation and sleep sequences so that when the RFM95W or DWM1000 is in use, the other radios do not drive the bus.

For the inter-satellite link, the RadioHead packet radio library is used unchanged. RadioHead is a C++ library providing the RFM95W driver (RH_RF95), the mesh manager (RHMesh), and supporting classes (e.g. RHRouter, RHReliableDatagram). No modifications were made to the RadioHead source. Integration is done via a small C++ wrapper (`mesh_wrapper.cpp`) that exposes a C API: create/init driver and mesh manager, send and receive messages, and read routing and RSSI/SNR. The rest of the mesh stack is implemented in C: `mesh_network.c` implements the mesh init, send/receive, and RF95 param-

eter configuration (frequency, TX power, spreading factor, bandwidth, coding rate), and `mesh_app.c` implements the application logic (node ID, message interval, statistics, and the main send/receive loop). This keeps the C++ boundary minimal and confines RadioHead to the wrapper plus the underlying RH_RF95 and RHMesh calls.

For in-satellite communication, a full custom driver was developed for the Qorvo DWM1000 UWB transceiver. The driver is implemented in C and does not use RadioHead. It comprises register definitions and configuration (`DWM1000_config.h`), low-level SPI read/write and sub-register access, channel and RF configuration (channel, PRF, preamble codes, data rate, power), and higher-level primitives for init, transmit, receive, and ping-pong. Parameters such as channel, PRF, preamble length, and data rate (e.g. 6.8 Mbps) are configurable so that link tests and throughput can be evaluated. Ping-pong tests between two boards validate bidirectional frames and basic timing.

3.9.2 Inter-Satellite Link: Mesh with RFM95W and RadioHead

The inter-satellite mesh network uses the RFM95W at 868 MHz with the RadioHead library taken as-is. The wrapper and C mesh layer provide a single, consistent C API for the application: initialise by node ID, send messages to a destination node, and receive messages with optional timeout. Route discovery, packet forwarding, and retries are handled inside RadioHead's RHMesh and related classes.

A mesh topology was successfully demonstrated with multiple AstroMesh boards and can be observed in fig. 3.10, where the packets and the RSSI of 4 nodes (seen in fig. 3.9) are captured and plotted. The implementation supports dynamic route discovery, packet forwarding at intermediate nodes, and network topology awareness. Error handling and retransmission are provided by the library. The only platform-specific integration is the C++ wrapper (which instantiates RH_RF95 and RHMesh and forwards calls from `mesh_network.c`) and the RadioHead hardware abstraction (SPI and interrupt pins) so that the same library code runs on the AstroMesh MCU.

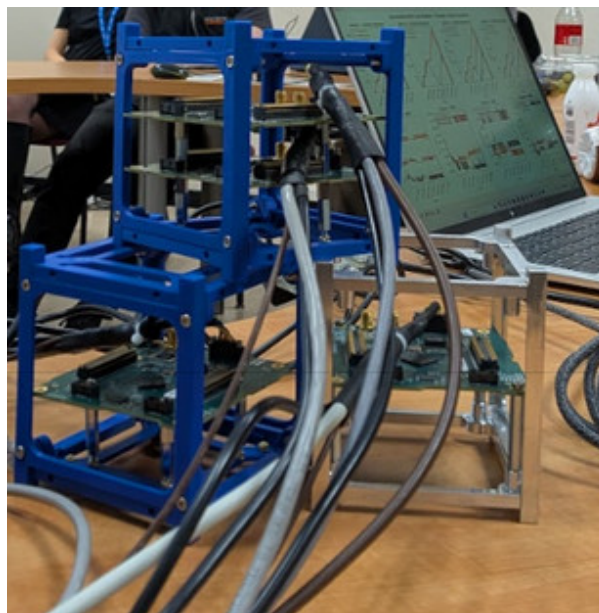


Figure 3.9: AstroMesh boards mounted in 3U CubeSat frames in a meshed network configuration

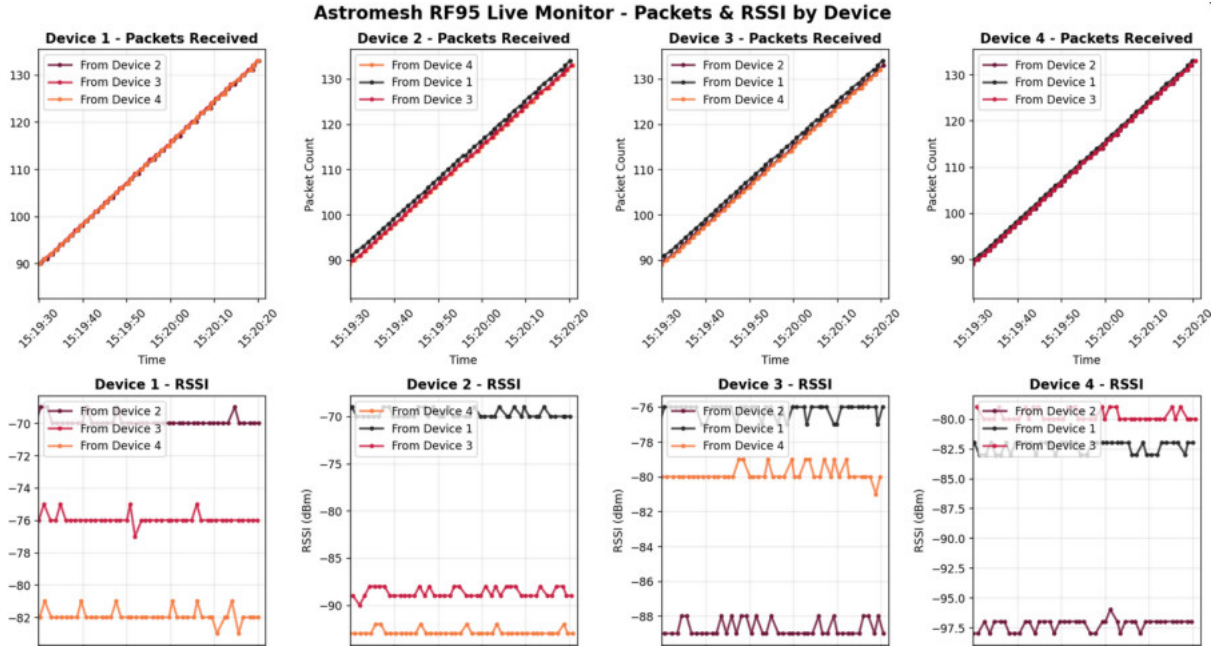


Figure 3.10: AstroMesh board data from a meshed network configuration in a User Interface developed for demonstration purposes

3.9.3 In-Satellite Communication: Custom DWM1000 Driver

The in-satellite link uses the Qorvo DWM1000 UWB transceiver with a complete custom C driver. The driver includes register and bit definitions aligned with the DW1000 manual, SPI transaction helpers (including multi-byte and sub-register access), and a full init sequence (reset, device ID check, LDE microcode load, system and channel configuration). Channel, PRF, preamble code, and data rate are set from a small set of presets (e.g. Channel 1 or 5, 16 or 64 MHz PRF, 6.8 Mbps). Transmit and receive paths are polling-based: the application fills the TX buffer, sets frame length and TX start, then polls status until TX complete; similarly, RX is enabled and status is polled until a frame is ready, then the payload is read and status cleared. Ping-pong is implemented on top of these primitives: one board sends a ping and waits for a pong; the other waits for a ping and replies with a pong. Frame format is a small header (message type, sequence number) plus a configurable payload (e.g. up to 120 bytes within the standard 127-byte frame limit). This design validates the physical layer and timing without depending on an external stack, and allows straightforward parameter sweeps (payload size, preamble length, data rate) for throughput and link margin.

3.9.4 Summary

The software architecture separates the application and mesh logic (C) from the RadioHead library (C++, used as-is) via a thin C++ wrapper, and implements a fully custom driver for the DWM1000. All transceiver integration, configuration, and application-level behaviour are part of the developed codebase; the only third-party component is the unmodified RadioHead library for the RFM95W mesh.

4. Mission Analysis

The analysis performed in this chapter was conducted with the Ansys SYstems Tool Kit (STK) 12.10 [40].

4.1 Link Budget Analysis

The link budget analysis determines the feasibility of intersatellite communication by calculating the signal power at the receiver and comparing it to the receiver sensitivity threshold [41]. A positive link margin indicates a viable communication link.

4.1.1 Link Budget Methodology

The link budget follows the standard approach for Radio Frequency (RF) communications, accounting for all gains and losses in the signal path.

Equivalent Isotropic Radiated Power (EIRP)

EIRP represents the effective power radiated by the transmitter in the direction of the receiver:

$$\text{EIRP dBm} = 10 \cdot \log_{10}(P_{tx} \times 1000) - L_{line} + G_{ant} \quad (4.1)$$

where P_{tx} is the transmit power in watts, L_{line} is the line loss in dB, and G_{ant} is the antenna gain in dBi.

Free Space Path Loss (FSPL)

FSPL quantifies signal attenuation due to geometric spreading:

$$\text{FSPL dB} = 20 \cdot \log_{10} \left(\frac{4\pi df}{c} \right) \quad (4.2)$$

Or equivalently:

$$\text{FSPL dB} = 32.45 + 20 \cdot \log_{10}(f_{\text{MHz}}) + 20 \cdot \log_{10}(d_{\text{km}}) \quad (4.3)$$

where the constant 32.45 incorporates unit conversion factors: $20 \cdot \log_{10}(10^6) = 120$ dB for Hz to MHz, and $20 \cdot \log_{10}(10^3) = 60$ dB for m to km.

Isotropic Signal Level

The isotropic signal level at the receiver accounts for path loss and additional losses:

$$P_{iso} = \text{EIRP} - \text{FSPL} - L_{pol} - L_{atm} - L_{ion} \quad (4.4)$$

where L_{pol} is polarization loss, L_{atm} is atmospheric loss, and L_{ion} is ionospheric loss.

Received Power and Link Margin

The received power and link margin are calculated as:

$$P_{rx} = P_{iso} + G_{rx} - L_{rx,line} - L_{pointing} \quad (4.5)$$

$$\text{Link Margin} = P_{rx} - S_{rx} \quad (4.6)$$

where S_{rx} is the receiver sensitivity. A link margin of at least 3 dB is required for reliable communication.

4.1.2 Link Budget Parameters

Line Losses

Line losses account for signal attenuation in coaxial cables, connectors, and any RF splitters or components:

- 868 MHz: 0.13 dB per 10 cm cable, with $3\times$ margin applied = 0.4 dB total
- 2.4 GHz: 0.127 dB per 12 cm cable, with $3\times$ margin applied = 0.4 dB total

The 3 times margin accounts for variations in cable length and connector losses in a worst-case scenario. The exact numbers were derived from table 4.1 and table 4.2.

Table 4.1: Coax Cable Signal Loss (Attenuation) in dB per 100 ft [42]

Freq.	RG-174	RG-58	RG-8X	RG-213	RG-6	RG-11	RF-9914
1 MHz	1.9 dB	0.4 dB	0.5 dB	0.2 dB	0.2 dB	0.2 dB	0.3 dB
10 MHz	3.3 dB	1.4 dB	1.0 dB	1.0 dB	0.6 dB	0.3 dB	0.5 dB
50 MHz	6.6 dB	3.3 dB	2.5 dB	1.6 dB	1.4 dB	1.4 dB	0.9 dB
100 MHz	8.9 dB	4.9 dB	3.6 dB	2.8 dB	2.0 dB	1.6 dB	1.3 dB
200 MHz	11.9 dB	7.3 dB	5.4 dB	3.6 dB	3.4 dB	2.8 dB	2.0 dB
400 MHz	17.3 dB	11.2 dB	7.9 dB	5.4 dB	4.7 dB	3.8 dB	2.6 dB
700 MHz	26.0 dB	16.9 dB	11.0 dB	5.6 dB	5.6 dB	4.7 dB	3.6 dB
900 MHz	27.9 dB	20.1 dB	12.6 dB	6.4 dB	6.0 dB	5.3 dB	4.2 dB
1 GHz	32.0 dB	21.5 dB	13.5 dB	6.3 dB	6.1 dB	5.6 dB	4.5 dB
Imped.	50 Ω	50 Ω	50 Ω	50 Ω	75 Ω	75 Ω	50 Ω

Table 4.2: Attenuation of various transmission lines in the VHF/UHF/Microwave Amateur and ISM Bands in dB/100 ft (dB/100 m) [42]

Cable Type	144 MHz	220 MHz	450 MHz	915 MHz	1.2 GHz	2.4 GHz	5.8 GHz
RG-58	6.2 (20.3)	7.4 (24.3)	10.6 (34.8)	16.5 (54.1)	21.1 (69.2)	32.2 (105.6)	51.6 (169.2)
RG-8X	4.7 (15.4)	6.0 (19.7)	8.6 (28.2)	12.8 (42.0)	15.9 (52.8)	23.1 (75.8)	40.9 (134.2)
LMR-240	3.0 (9.8)	3.7 (12.1)	5.3 (17.4)	7.6 (24.9)	9.2 (30.2)	12.9 (42.3)	20.4 (66.9)
RG-213/214	2.8 (9.2)	3.5 (11.5)	5.2 (17.1)	8.0 (26.2)	10.1 (33.1)	15.2 (49.9)	28.6 (93.8)
9913	1.6 (5.2)	1.9 (6.2)	2.8 (9.2)	4.2 (13.8)	5.2 (17.1)	7.7 (25.3)	13.8 (45.3)
LMR-400	1.5 (4.9)	1.8 (5.9)	2.7 (8.9)	3.9 (12.8)	4.8 (15.7)	6.8 (22.3)	10.8 (35.4)
3/8" LDF	1.3 (4.3)	1.6 (5.2)	2.3 (7.5)	3.4 (11.2)	4.2 (13.8)	5.9 (19.4)	8.1 (26.6)
LMR-600	0.96 (3.1)	1.2 (3.9)	1.7 (5.6)	2.5 (8.2)	3.1 (10.2)	4.4 (14.4)	7.3 (23.9)
1/2" LDF	0.85 (2.8)	1.1 (3.6)	1.5 (4.9)	2.2 (7.2)	2.7 (8.9)	3.9 (12.8)	6.6 (21.6)
7/8" LDF	0.46 (1.5)	0.56 (1.8)	0.83 (2.7)	1.2 (3.9)	1.5 (4.9)	2.3 (7.5)	3.8 (12.5)
1 1/4" LDF	0.34 (1.1)	0.42 (1.4)	0.62 (2.0)	0.9 (3.0)	1.1 (3.6)	1.7 (5.6)	2.8 (9.2)
1 5/8" LDF	0.28 (0.92)	0.35 (1.1)	0.52 (1.7)	0.77 (2.5)	0.96 (3.1)	1.4 (4.6)	2.5 (8.2)

Polarization Loss

Antenna polarization describes the orientation of the electromagnetic field produced by the antenna. The three types are linear (horizontal or vertical), circular (Right-Hand Circular Polarization (RHCP) or Left-Hand Circular Polarization (LHCP)), and elliptical [43, 44].

The selected antennas use vertical polarization. A 3 dB polarization loss is included as a placeholder, pending actual measurements in an anechoic chamber.

Atmospheric and Ionospheric Losses

For intersatellite links in Low Earth Orbit (LEO), atmospheric loss is considered zero since the line-of-sight path does not traverse the atmosphere. Ionospheric loss is also assumed to be zero for the direct intersatellite link geometry.

Pointing Loss

With omnidirectional antennas, pointing loss is considered zero as there are no strict pointing requirements. This eliminates the need for complex Attitude Determination and Control System (ADCS) systems but limits the achievable antenna gain.

4.1.3 Analysis for the 3 on-board transceivers

RF95 (868 MHz)

Table 4.3: RF95 transceiver parameters

Parameter	Value
Transmit Power	100 mW (20 dBm)
Tx/Rx Antenna Gain	6 dBi
Line Losses	0.4 dB
Polarization Loss	0.5 dB
EIRP	25.6 dBm
Available Bandwidths	125, 250, 500 kHz
Spreading Factors	Spreading Factor (SF)6 – SF12

Maximum reliable distance (link margin ≥ 3 dB) varies by configuration:

Table 4.4: RF95 maximum reliable distances

SF / Bandwidth (BW)	Sensitivity	125 kHz	250 kHz	500 kHz
SF7	−123 dBm	962 km	681 km	482 km
SF10	−132 dBm	2665 km	1887 km	1336 km
SF12	−136 dBm	4208 km	2979 km	N/A

Best case scenario: SF12, 125 kHz bandwidth achieves approximately 4200 km maximum reliable distance.

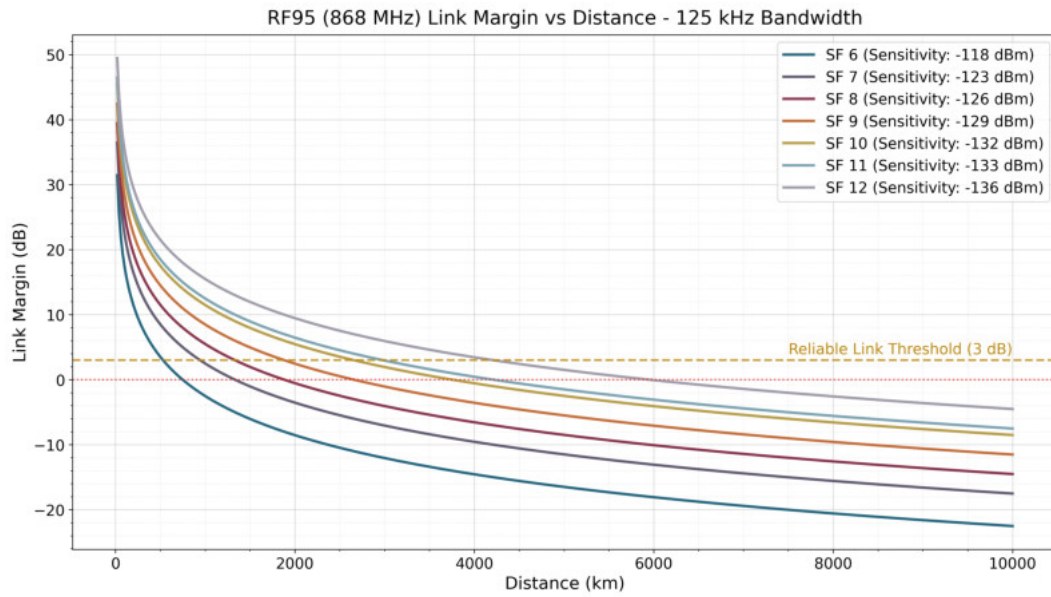


Figure 4.1: RF95 (868 MHz): link margin vs distance, best case (125 kHz bandwidth).

SX1280 (2.4 GHz)

Table 4.5: SX1280 transceiver parameters

Parameter	Value
Transmit Power	17 mW (12.3 dBm)
Tx/Rx Antenna Gain	8 dBi
Line Losses	0.4 dB
EIRP	19.9 dBm
Available Bandwidths	203, 406, 812, 1625 kHz
Spreading Factors	SF5 – SF12

Maximum reliable distances are significantly reduced due to higher path loss at 2.4 GHz:

Table 4.6: SX1280 maximum reliable distances

SF	203 kHz	406 kHz	812 kHz
SF7	92 km	73 km	65 km
SF10	253 km	201 km	160 km
SF12	501 km	398 km	317 km

Best case scenario: SF12, 203 kHz bandwidth achieves approximately 500 km maximum reliable distance. For higher bandwidths, the link becomes very unreliable. This could potentially be improved with a directional (patch) antenna, but this introduces strict pointing and power requirements.

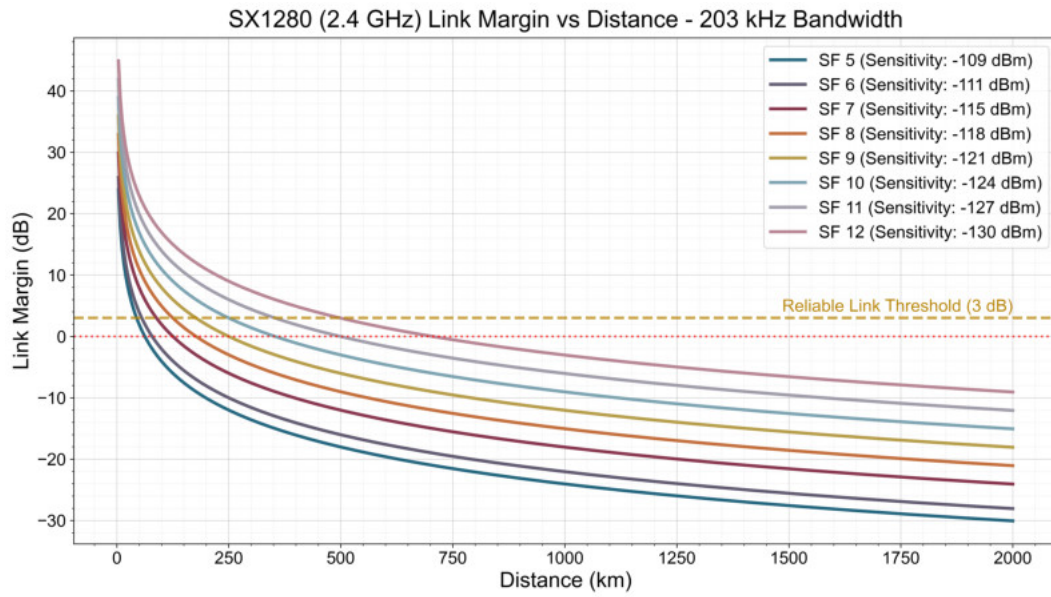


Figure 4.2: SX1280 (2.4 GHz): link margin vs distance, best case (203 kHz bandwidth).

LR1121 (868 MHz and 2.4 GHz)

The LR1121 is a dual-band transceiver supporting both 868 MHz and 2.4 GHz operation.

At 868 MHz:

Table 4.7: LR1121 transceiver parameters at 868 MHz

Parameter	Value
Transmit Power	158.4 mW (22 dBm)
Tx/Rx Antenna Gain	6 dBi
Line Losses	0.4 dB
EIRP	27.6 dBm
Available Bandwidths	62.5, 125, 250, 500 kHz
Best Sensitivity (SF11, 62.5 kHz)	-139.2 dBm
Max Reliable Distance	~7675 km (SF11, 62.5 kHz)

Best case scenario: SF11, 62.5 kHz bandwidth achieves approximately 7800 km maximum reliable distance—the most reliable link configuration analyzed.

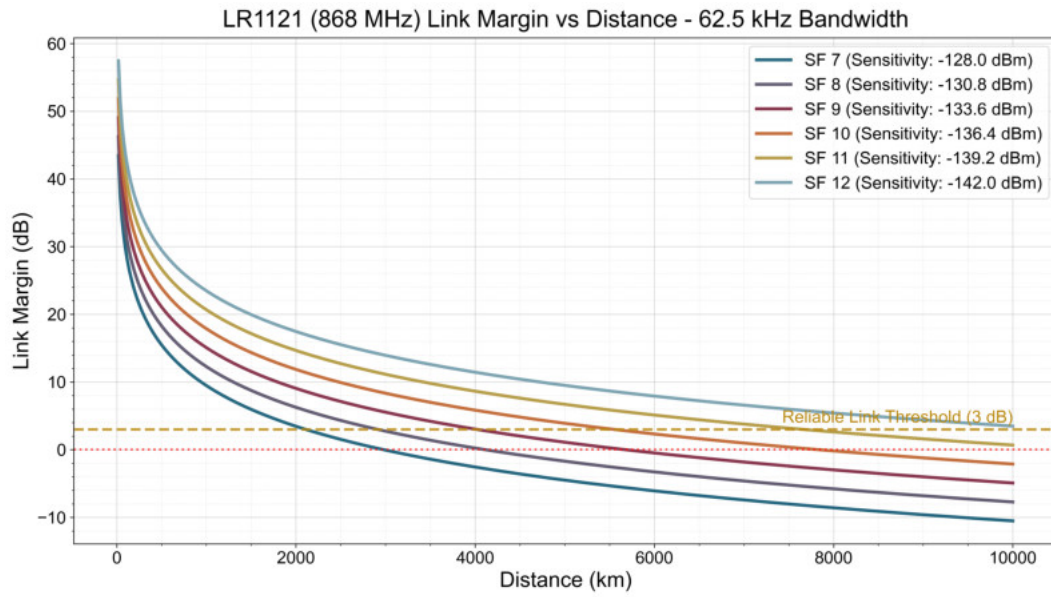


Figure 4.3: LR1121 (868 MHz): link margin vs distance, best case (62.5 kHz bandwidth).

At 2.4 GHz: Maximum reliable distance is approximately 540 km with SF12 and 125 kHz bandwidth.

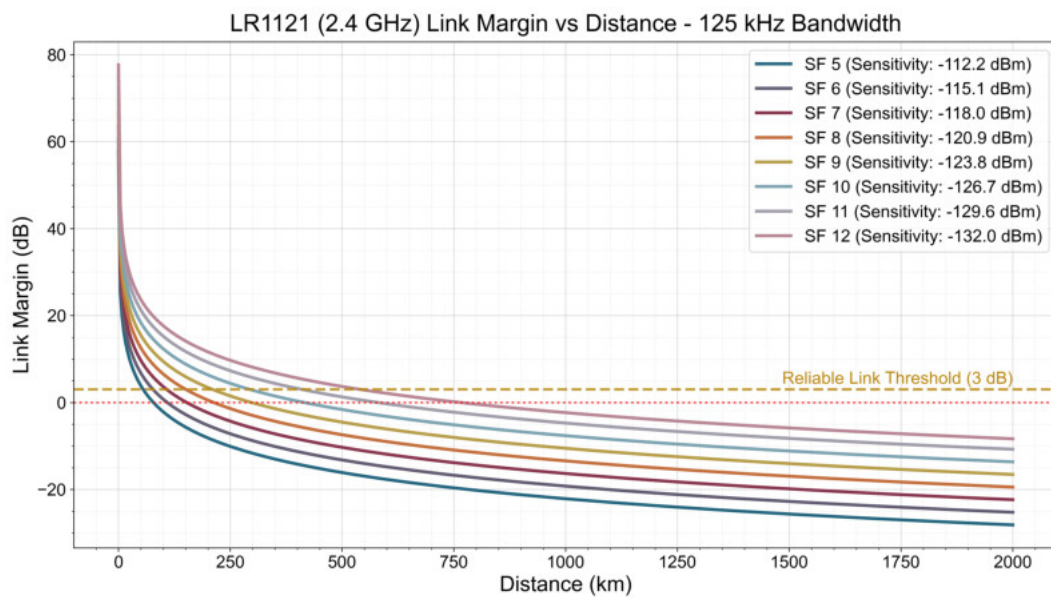


Figure 4.4: LR1121 (2.4 GHz): link margin vs distance, best case (125 kHz bandwidth).

4.1.4 Link Budget Summary

Table 4.8: Summary of transceiver performance

Transceiver	Frequency	Max Distance	Best Config
RF95	868 MHz	~4200 km	SF12, 125 kHz
SX1280	2.4 GHz	~500 km	SF12, 203 kHz
LR1121	868 MHz	~7800 km	SF11, 62.5 kHz
LR1121	2.4 GHz	~540 km	SF12, 125 kHz

These results are calculated in accordance with distance, but do not take into account the loss of line of sight in the orbit. The summary of the link budget for the various configurations can be seen in fig. 4.5.

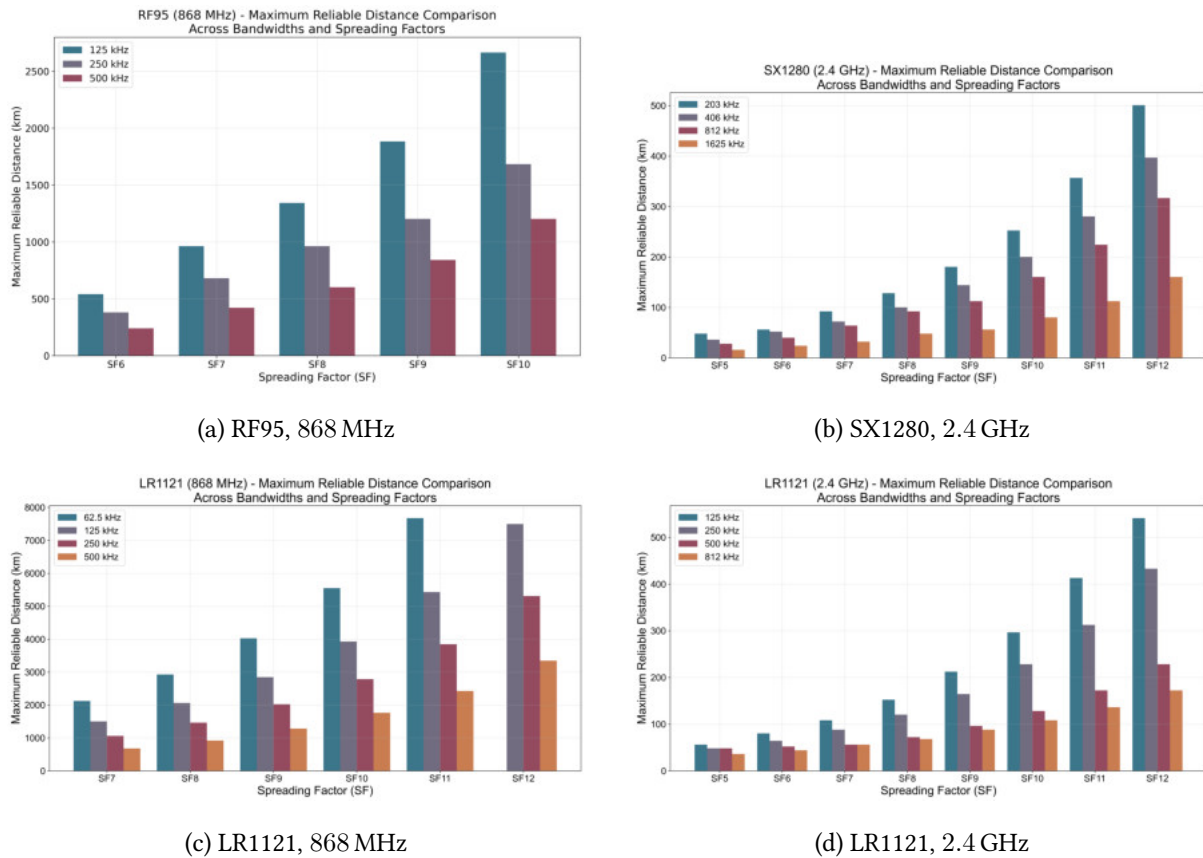


Figure 4.5: Maximum reliable distance comparison (bar plots) for each transceiver: (a) RF95, (b) SX1280, (c) LR1121 at 868 MHz, (d) LR1121 at 2.4 GHz.

4.1.5 Key Findings

868 MHz Operation:

- Intersatellite link is feasible during the first months of the mission in LEO with omnidirectional antennas

- The LR1121 transceiver provides the best performance with maximum reliable distances up to 7800 km (terrestrial Long Range (LoRa) record links have exceeded 1300 km [45]).
- Satellites will drift apart based on mass differences and initial velocity uncertainties

2.4 GHz Operation:

- Link is significantly weaker due to higher path loss
- Maximum reliable distance limited to approximately 500 km with best configurations
- Could be improved with directional antennas but this adds pointing and power requirements

4.2 Mission and orbital analysis

4.2.1 Launch configuration

For the initial analysis, the baseline orbit for all satellites is a Sun-Synchronous Orbit (SSO) at 550 km altitude. The key parameter affecting the mission is the Local Time of Ascending Node (LTAN), which determines the relative phasing between satellites.

Same Launcher Configuration

When satellites are deployed from the same launcher, they share the same LTAN. This results in satellites initially being in close proximity but gradually drifting apart due to differences in their area-to-mass ratios caused by manufacturing tolerances and varying drag characteristics.

Different Launcher Configuration

Using different launchers allows satellites to be placed in orbits with different LTAN. This configuration provides larger communication windows, particularly near the poles where orbital paths converge. However, this approach significantly increases mission cost.

Table 4.9: Comparison of orbital configurations

Configuration			Advantages	Disadvantages
Same Launcher	LTAN (Same)	(Same Launcher)	Lower cost, simplified logistics	Satellites drift apart over time
Different Launcher	LTAN (Different)	(Different Launcher)	Larger communication windows near poles	Significantly increased cost

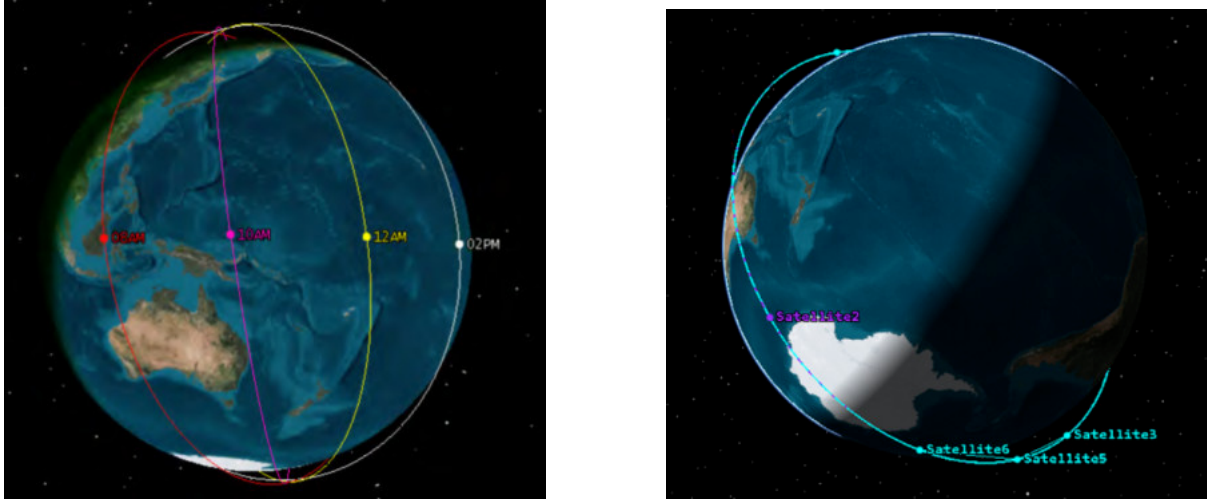


Figure 4.6: Satellites launched in the same LTAN (right) and different LTAN (left) (images generated by Ansys STK)

4.3 Link budget for constellation of satellites with the same LTAN

Satellites launched together (even if they are designed to be identical) will experience differential drag due to small variations in their physical properties. This section analyzes how these differences affect the constellation geometry over the mission lifetime, when there is no mechanism for station keeping performance.

4.3.1 Drag-Induced Drift Mechanism

Atmospheric drag in LEO is the primary perturbation affecting satellite's orbit propagation. The drag force is given by:

$$F_D = \frac{1}{2} \rho v^2 C_D A \quad (4.7)$$

where ρ is the atmospheric density, v is the velocity, C_D is the drag coefficient, and A is the cross-sectional area. Even small differences (approximately 0.5–1%) in area-to-mass ratio between satellites lead to differential orbital decay rates, causing the satellites to drift apart over time.

For a 1U CubeSat with typical dimensions of $10 \times 10 \times 10$ cm, the area-to-mass ratio variations considered in this analysis are $0.01 \text{ m}^2 \text{ kg}^{-1}$ versus $0.011 \text{ m}^2 \text{ kg}^{-1}$, representing approximately a 10% difference.

4.3.2 Constellation without station keeping

The first constellation configuration that was analyzed consists of satellites that launch with the same vehicle and do not have a propulsion mechanism. This means that the distance between them depends only on the drag area difference, thus the mass difference, as there is no mechanism to keep the distance fixed. The HPOP propagator as utilized for this in the Ansys STK software.

Two-Satellite Scenario

In the two-satellite configuration with the same LTAN and approximately 0.5% mass difference:

- **Initial separation:** Near-zero (deployed together)
- **Maximum separation:** Approximately 5505 km
- **Line-of-sight duration:** 3-4 months before exceeding line of sight
- **Distance range over mission:** 0 to 5505 km

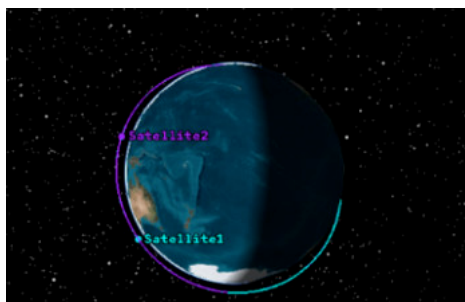


1 month

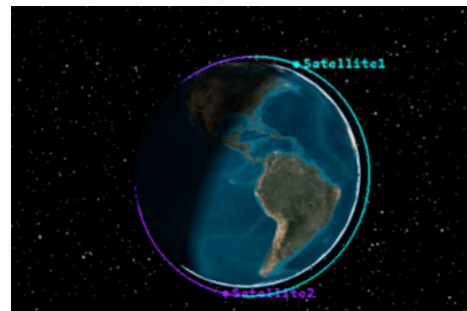


6 months

Figure 4.7: Two-satellite configuration flat projection at 1 month and 6 months.



1 month



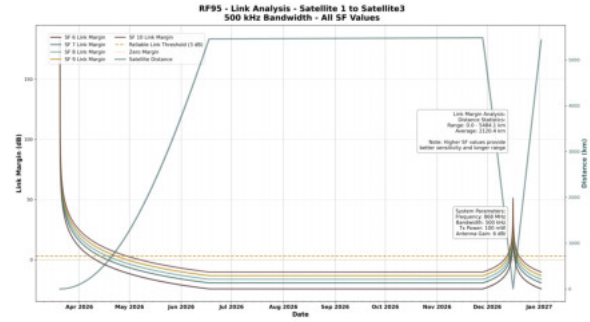
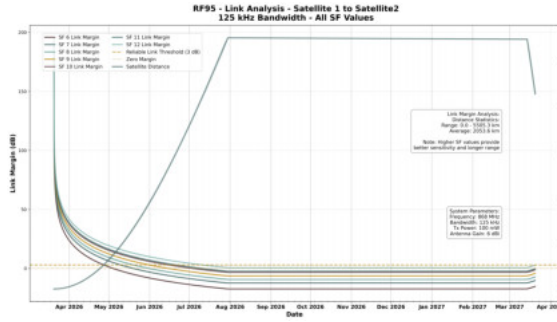
6 months

Figure 4.8: Two-satellite configuration Earth view at 1 month and 6 months (images generated by Ansys STK.)

The satellites drift apart with time. The best and worst case scenario for all frequency bands and transceivers are plotted in fig. 4.9.

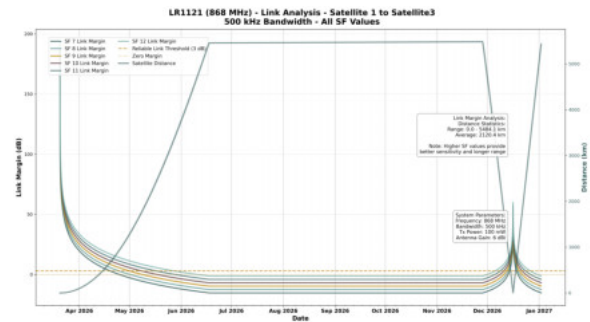
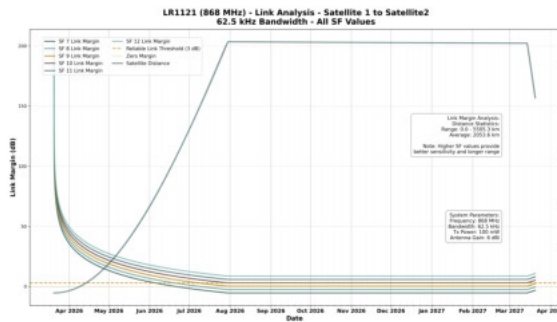
Best case

Worst case



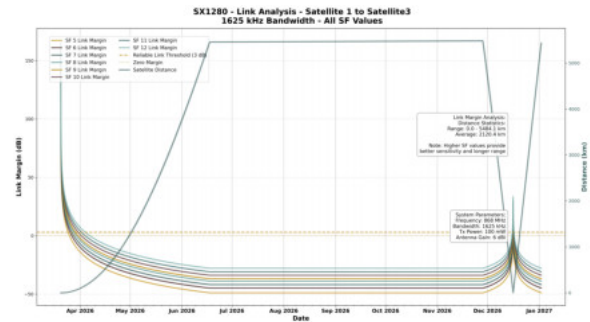
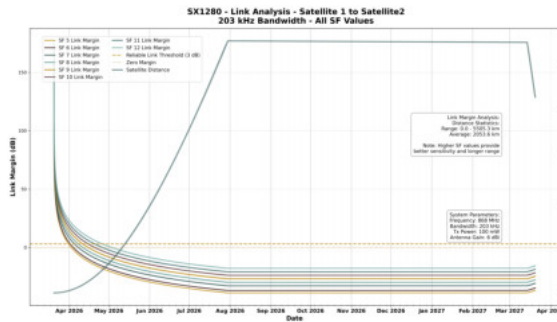
RF95, 868 MHz, 125 kHz (Sat. 1→2)

RF95, 868 MHz, 500 kHz (Sat. 1→3)



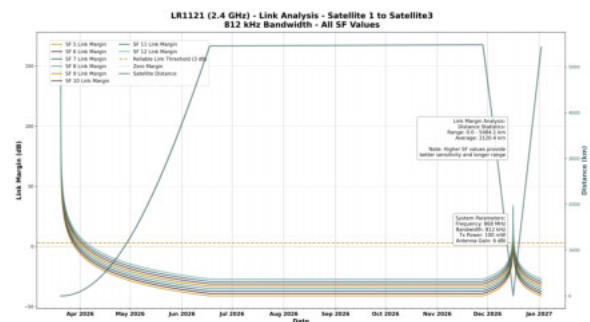
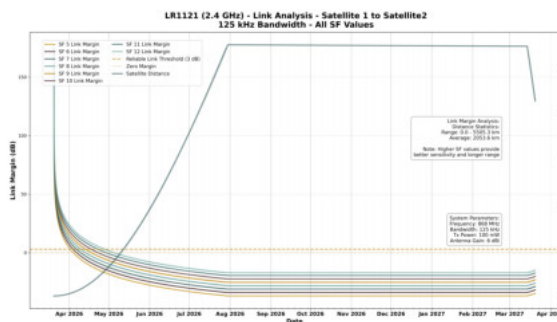
LR1121, 868 MHz, 62.5 kHz (Sat. 1→2)

LR1121, 868 MHz, 500 kHz (Sat. 1→3)



SX1280, 2.4 GHz, 203 kHz (Sat. 1→2)

SX1280, 2.4 GHz, 1625 kHz (Sat. 1→3)



LR1121, 2.4 GHz, 125 kHz (Sat. 1→2)

LR1121, 2.4 GHz, 812 kHz (Sat. 1→3)

Figure 4.9: Two-satellite LoRa link analysis: best case (left) and worst case (right) for the four transceiver bands. Best case: narrowest bandwidth and Sat. 1→2; worst case: widest bandwidth and Sat. 1→3.

The rest of the cases, for all the spreading factor and bandwidth values are included in the Annex.

Six-Satellite Scenario

For a six-satellite constellation, as seen in fig. 4.10, deployed from the same launcher with approximately 5–10% mass variations:

- More access periods between different satellite pairs
- Maximum satellite-to-satellite ranges: 5454–5509 km
- Communication window per satellite pair: 3–4 months

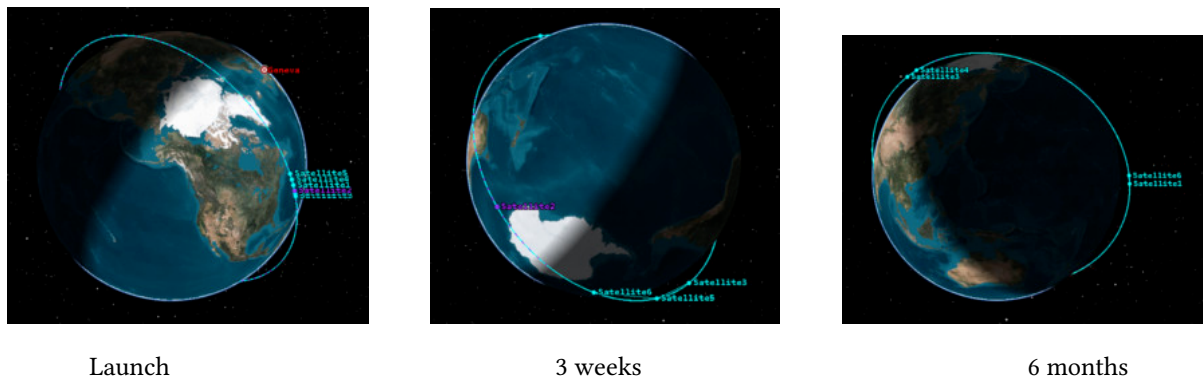


Figure 4.10: Six-satellite constellation showing progressive drift from launch to 6 months (images generated by Ansys STK).

The six-satellite configuration provides overlapping communication windows between different pairs, effectively extending the mission's useful communication lifetime. However, as seen in fig. 4.11, after 3 months, the communication windows are reduced and are non-existent for significant periods of time.

The communication window for 6 satellites in orbit can be observed in fig. 4.11, where it's visible that after the 3 first months the communication windows become rare and sporadic. The access windows can be observed in table 4.10.

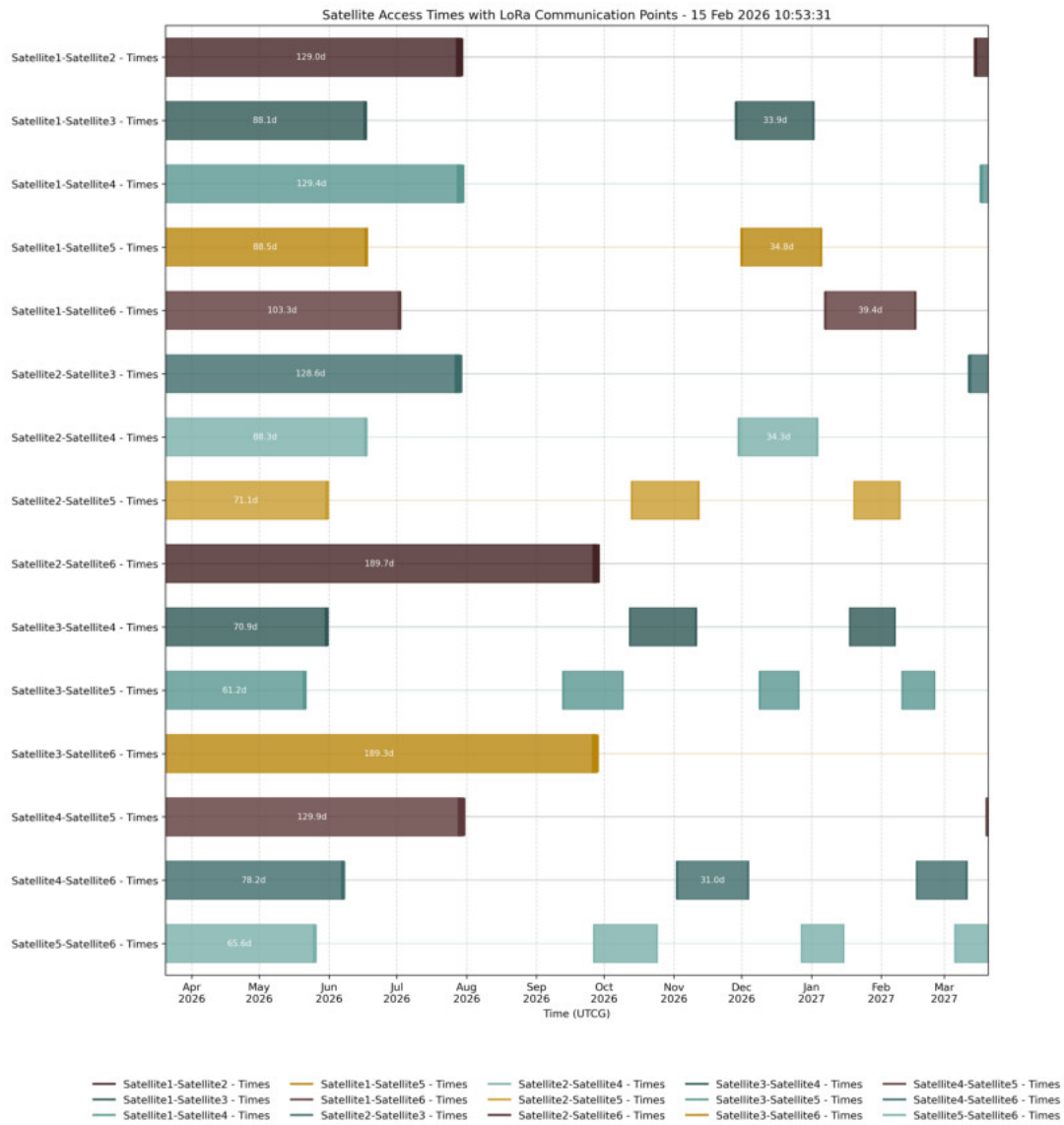


Figure 4.11: Inter-satellite access windows for the six-satellite constellation, showing periods where LoRa communication is feasible.

Inter-Satellite Access Windows

Table 4.10: Inter-satellite access windows for six-satellite constellation

Satellite Pair	Maximum Range (km)	Initial Access Duration
Satellite 1 – Satellite 2	5505	~129 days
Satellite 1 – Satellite 4	5509	~129 days
Satellite 1 – Satellite 5	5496	~88 days
Satellite 2 – Satellite 6	5454	~190 days

Note: The mass difference percentages are inherently unpredictable due to manufacturing tolerances. A larger constellation increases the probability of achieving desired communication patterns.

4.3.3 Constellation with station keeping

As a resolution to the reduced communication window issue that was described in the previous section, an additional analysis was conducted, taking into account that the satellites have a station keeping mechanism and can perform formation flying.

Firstly, for the 550km orbit, the maximum angle between 2 satellites in the same LTAN was calculated. Taking into account that Earth's radius is 6371km and the defined orbit is 550km

$$\theta = \arccos \frac{r}{\rho} = \arccos \frac{6371}{6921} = 23^\circ \quad (4.8)$$

Based on the above and on the geometries illustrated in fig. 4.12, the maximum angle between the satellites in order to maintain line of sight is 46° .

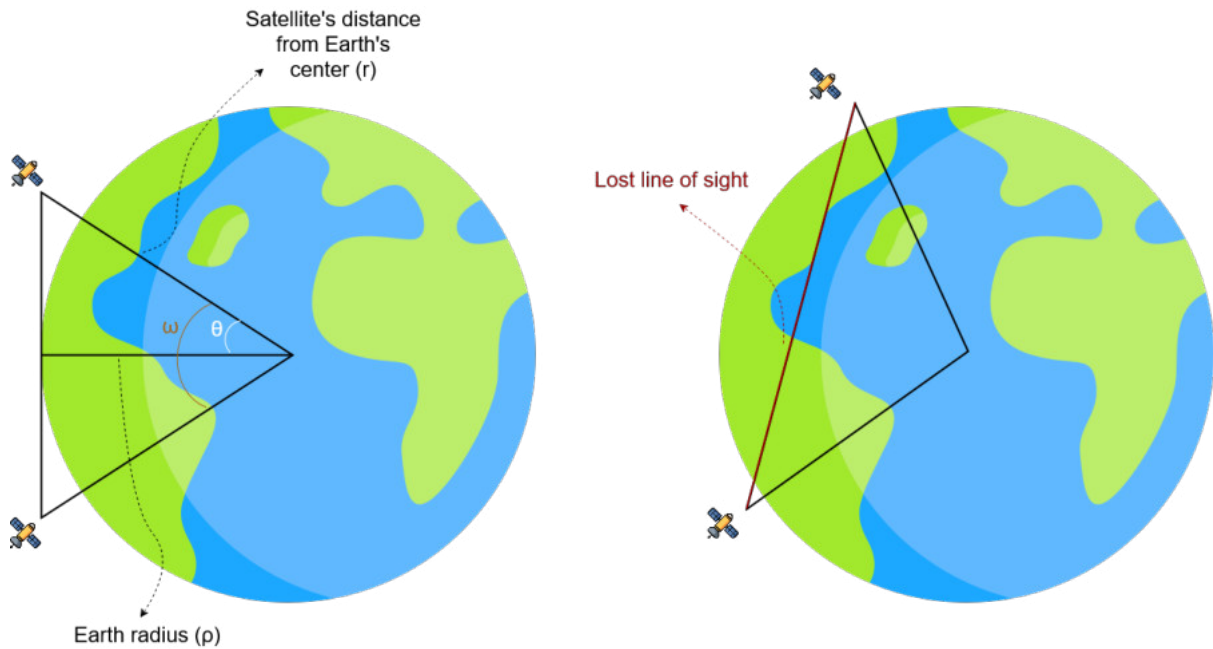


Figure 4.12: Maximum angle between satellites in LEO, allowing line of site (left), Lost line of sight (right)

The J2Perturbation propagator was used, in order to simulate the station keeping between 2 satellites, in the worst case scenario of 46° angle between them. The orbital parameters are included in table 4.11.

Table 4.11: Orbital Parameters - J2 Perturbation

Parameter	Value
Epoch Start	20 Mar 2026 10:00:00.000 UTCG
Epoch End	20 Mar 2026 10:00:00.000 UTCG
Step Size	60 sec
Semimajor Axis	6928.14 km
Eccentricity	9.35593×10^{-16}
Inclination	97.5977°
Argument of Perigee	0°
RAAN	179.454°
True Anomaly	314.04°

For the worst case scenario, the distance between the 2 spacecraft is 5409.625km, calculated with Ansys STK.

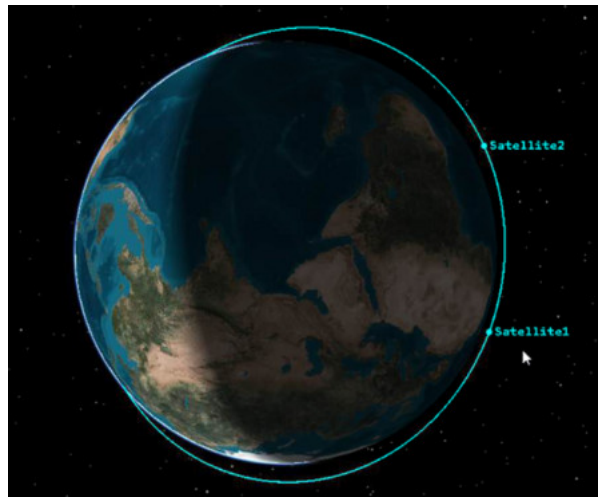


Figure 4.13: 2 satellites with static distance of 5409.62 km (image generated by Ansys STK)

The link budget is calculated for this scenario as well, for all the transceivers as seen in fig. 4.14.

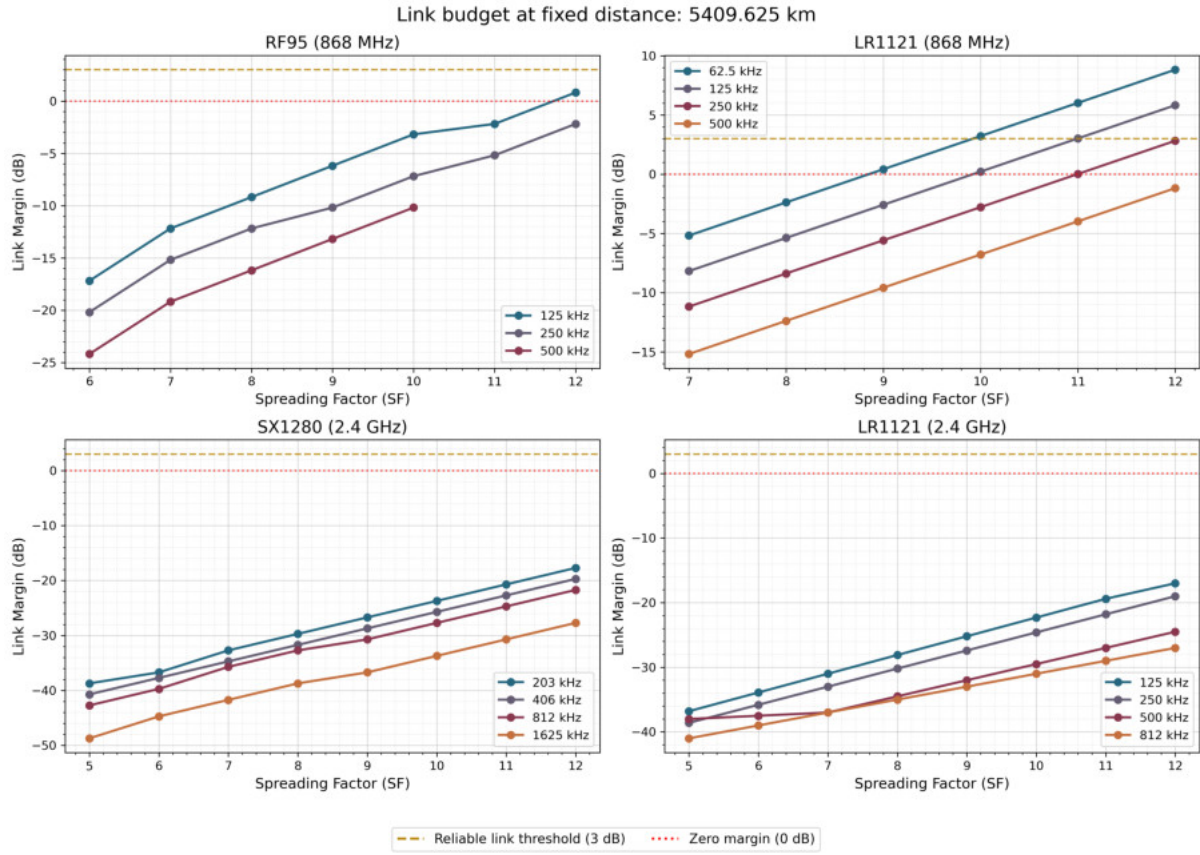


Figure 4.14: Link budget for all transceivers for 2 satellites with static distance of 5409.625 km

In order to achieve coverage of the whole orbit, the minimum number of satellites can be calculated by using the maximum allowable angle as calculated before.

$$N = \frac{360}{46} = 7.82 \quad (4.9)$$

The calculated number is rounded up to 8 spacecraft and the new angle is calculated as

$$\theta = \frac{360}{8} = 45^\circ \quad (4.10)$$

and the constellation is visualized in fig. 4.15

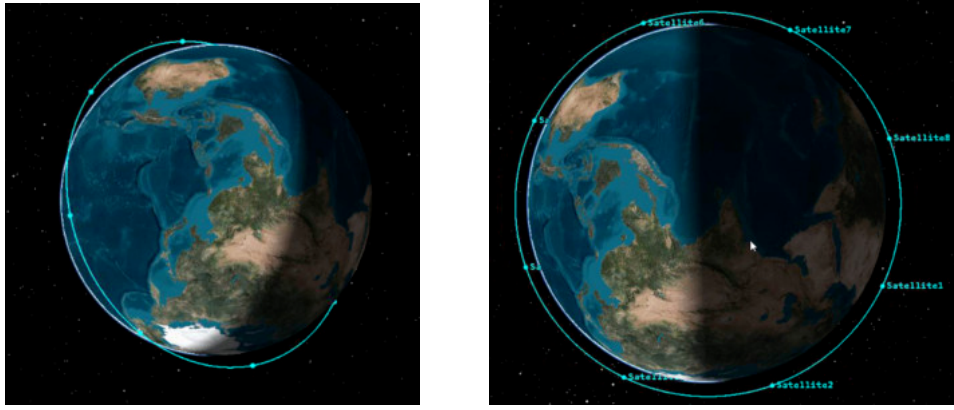


Figure 4.15: 8 satellite configuration for full orbit coverage

The link budget for this scenario can be seen in fig. 4.16.

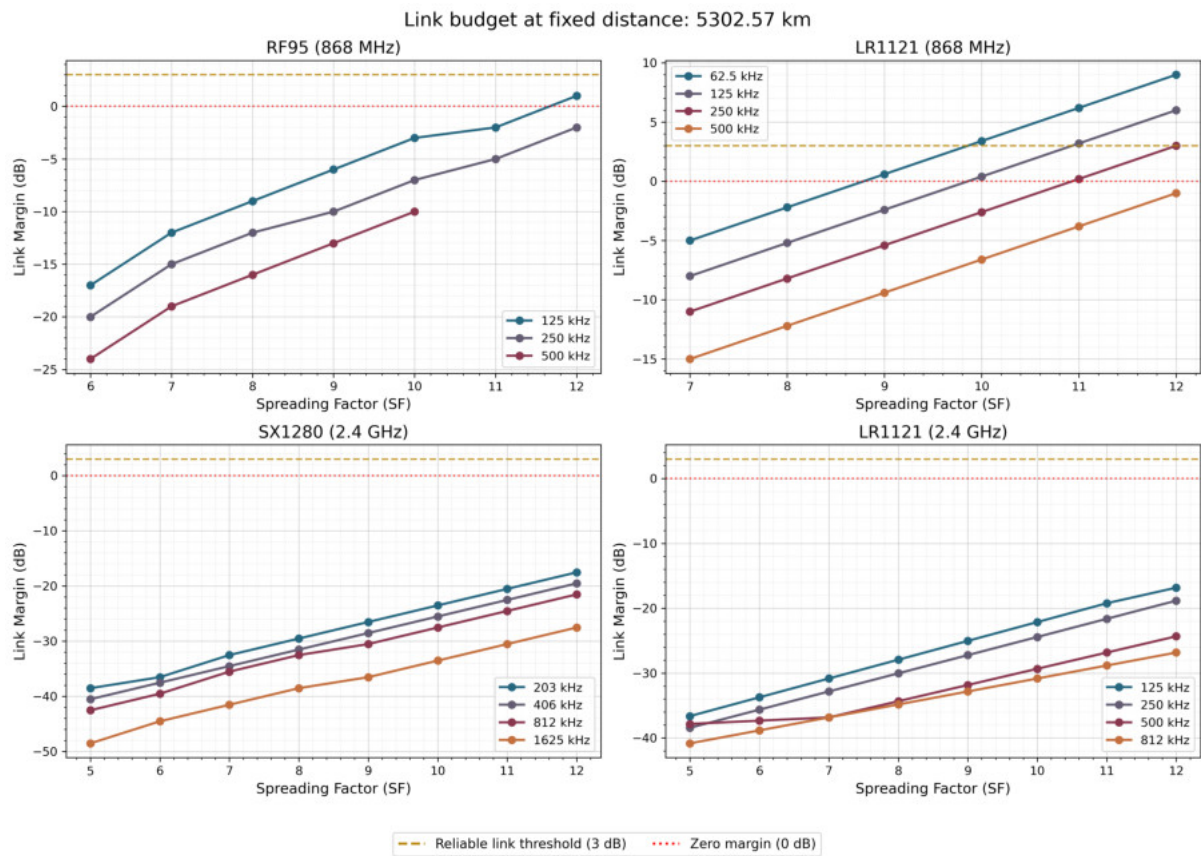


Figure 4.16: Link budget for all transceivers for 2 satellites with static distance of 5302.57km

In order to achieve positive link margin in the higher frequency band, as calculated in section 7.1.4, the distance has to be less than 541km. The link budget for this scenario can be seen in fig. 4.17.

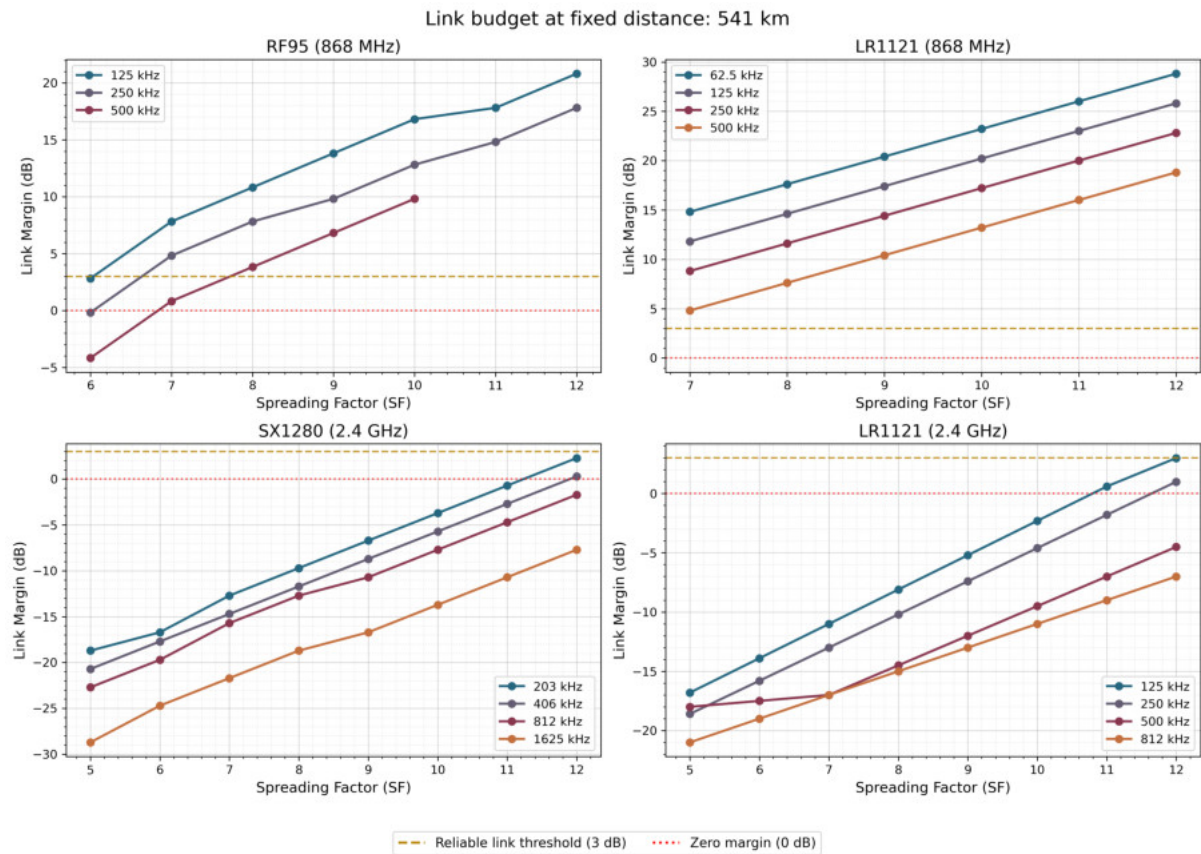


Figure 4.17: Link budget for all transceivers for 2 satellites with static distance of 541km

In order to calculate the number of required spacecraft for this case, the geometries presented in fig. 4.12 are used, resulting in an angle of 2.2° . This is translated to 164 satellites in orbit, thus resulting in the S-Band transceivers of the Astromesh board being not appropriate for inter-satellite communication.

Same launch

Time and ΔV Required to Reach the Desired Distance

Same launch

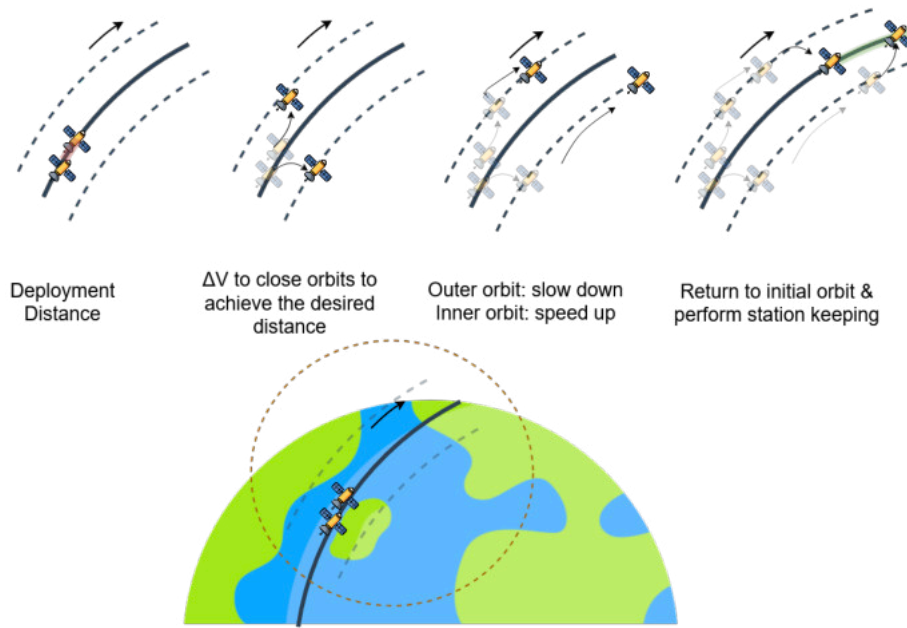


Figure 4.18: Maneuver and ΔV required to achieve the desired distance, when starting from the launcher separation (same location)

Assuming that the satellites are launched with the same launcher, a set of maneuvers is needed to obtain the desired separation distance. As seen in fig. 4.18:

1. The satellites begin co-located at the initial orbit of 550 km SSO.
2. The two satellites are transferred to adjacent orbits via Hohmann transfers:
 - **Inner orbit** (549 km): a retrograde burn reduces the satellite's speed, placing it in a lower, faster orbit.
 - **Outer orbit** (551 km): a prograde burn increases the satellite's speed, placing it in a higher, slower orbit.
3. Due to the difference in angular velocity, the satellites drift apart. Once the desired separation is achieved after time T , both satellites perform return Hohmann transfers back to the 550 km orbit.
4. The separation distance is subsequently maintained with station keeping [46].

ΔV Calculation

The ΔV required for a Hohmann transfer between two circular orbits of radii r_i and r_f is computed using the vis-viva equation [46]. The semi-major axis of the transfer ellipse is:

$$a_{\text{trans}} = \frac{r_i + r_f}{2} \quad (4.11)$$

The circular orbital velocities at the initial and final orbits are:

$$v_i = \sqrt{\frac{\mu}{r_i}}, \quad v_f = \sqrt{\frac{\mu}{r_f}} \quad (4.12)$$

The velocities at the periapsis and apoapsis of the transfer ellipse are:

$$v_{\text{trans},a} = \sqrt{\frac{2\mu}{r_i} - \frac{\mu}{a_{\text{trans}}}}, \quad v_{\text{trans},b} = \sqrt{\frac{2\mu}{r_f} - \frac{\mu}{a_{\text{trans}}}} \quad (4.13)$$

The two burns required are:

$$\Delta v_a = v_{\text{trans},a} - v_i, \quad \Delta v_b = v_f - v_{\text{trans},b} \quad (4.14)$$

The total ΔV for a single Hohmann transfer is:

$$\Delta V_{\text{Hohmann}} = |\Delta v_a| + |\Delta v_b| \quad (4.15)$$

where $\mu = 3.986 \times 10^{14} \text{ m}^3 \text{ s}^{-2}$ is Earth's gravitational parameter and $R_{\oplus} = 6\,378\,137 \text{ m}$. Since each satellite must perform an outbound transfer to the drift orbit and a return transfer back to 550 km, the total ΔV per satellite is $2 \times \Delta V_{\text{Hohmann}}$.

Algorithm 1 Hohmann Transfer ΔV Computation

Require: μ, r_i, r_f

- 1: $a_{\text{trans}} \leftarrow (r_i + r_f)/2$
- 2: $v_i \leftarrow \sqrt{\mu/r_i}; \quad v_f \leftarrow \sqrt{\mu/r_f}$
- 3: $v_{\text{trans},a} \leftarrow \sqrt{2\mu/r_i - \mu/a_{\text{trans}}}; \quad v_{\text{trans},b} \leftarrow \sqrt{2\mu/r_f - \mu/a_{\text{trans}}}$
- 4: $\Delta v_a \leftarrow v_{\text{trans},a} - v_i; \quad \Delta v_b \leftarrow v_f - v_{\text{trans},b}$
- 5: $\Delta V_{\text{Hohmann}} \leftarrow |\Delta v_a| + |\Delta v_b|$

Ensure: $\Delta v_a, \Delta v_b, \Delta V_{\text{Hohmann}}$

Separation Time Calculation

Once placed in their respective drift orbits, each satellite has orbital period:

$$T_{\text{orb}} = 2\pi \sqrt{\frac{a^3}{\mu}} \quad (4.16)$$

and angular velocity $\omega = 2\pi/T_{\text{orb}}$. The differential angular velocity between the two satellites is:

$$\Delta\omega = |\omega_1 - \omega_2| \quad (4.17)$$

The angular separation $\Delta\theta$ corresponding to the desired chord distance d at orbital radius $r_0 = R_{\oplus} +$

550 km is:

$$\Delta\theta = 2 \arcsin\left(\frac{d/2}{r_0}\right) \quad (4.18)$$

The time required to drift to the desired separation is then:

$$T_{\text{drift}} = \frac{\Delta\theta}{\Delta\omega} \quad (4.19)$$

Algorithm 2 Drift Time Computation

Require: $\mu, R_{\oplus}, h_1, h_2$, desired separation d , reference altitude h_0

- 1: $r_0 \leftarrow R_{\oplus} + h_0; \quad r_1 \leftarrow R_{\oplus} + h_1; \quad r_2 \leftarrow R_{\oplus} + h_2$
- 2: $T_1 \leftarrow 2\pi\sqrt{r_1^3/\mu}; \quad T_2 \leftarrow 2\pi\sqrt{r_2^3/\mu}$
- 3: $\omega_1 \leftarrow 2\pi/T_1; \quad \omega_2 \leftarrow 2\pi/T_2$
- 4: $\Delta\omega \leftarrow |\omega_1 - \omega_2|$
- 5: $\Delta\theta \leftarrow 2 \arcsin(d/2r_0)$
- 6: $T_{\text{drift}} \leftarrow \Delta\theta/\Delta\omega$

Ensure: T_{drift}

For the scenario of 8 satellites sharing the same LTAN orbit, the desired separation distance is $d = 5302.57$ km, with drift orbits at 549 km and 551 km, i.e. 1 km above and below the operational altitude. The computed results are presented in table 4.12.

Table 4.12: Computed ΔV and drift time for the same-launch scenario

Parameter	Outer satellite (551 km)	Inner satellite (549 km)
Δv_a (first burn)	0.274 m/s	−0.274 m/s
Δv_b (second burn)	0.274 m/s	−0.274 m/s
$\Delta V_{\text{Hohmann}}$ (single transfer)	0.547 m/s	0.547 m/s
ΔV_{total} (outbound + return)	1.095 m/s	1.095 m/s
Desired separation d	5302.57 km	
Angular separation $\Delta\theta$	45.00°	
Drift time T_{drift}	1 656 690 s $\approx$ 19.17 days	

Different launch

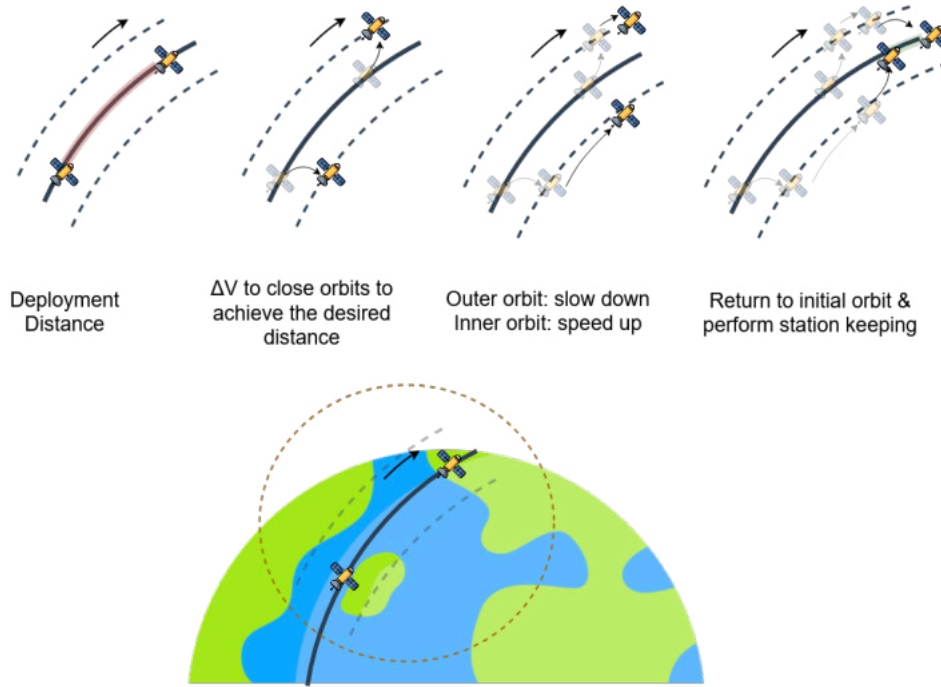


Figure 4.19: Maneuver and ΔV required to achieve the desired distance, when starting from a distance larger than the desired one

If the satellites are launched on different launchers but into the same orbit, they will generally be too far apart and must be brought closer together. This is achieved with an analogous set of maneuvers, as seen in fig. 4.19: one satellite is raised to a higher drift orbit (reducing its angular velocity) while the other is lowered, causing them to drift toward each other. Once the desired separation is reached, both satellites return to the 550 km operational orbit via return Hohmann transfers. The ΔV expressions are identical to those derived above; only the drift direction differs. The convergence time is computed as follows, where d_0 is the initial separation and d is the desired separation:

$$\Delta\theta = \theta_0 - \theta_f = 2 \arcsin\left(\frac{d_0/2}{r_0}\right) - 2 \arcsin\left(\frac{d/2}{r_0}\right) \quad (4.20)$$

$$T_{\text{converge}} = \frac{\Delta\theta}{\Delta\omega} \quad (4.21)$$

Algorithm 3 Hohmann Transfer ΔV and Convergence Time for Different-Launch Scenario

Require: $\mu, R_{\oplus}, h_1, h_2$, initial separation d_0 , desired separation d , reference altitude h_0

- 1: $a_{\text{trans}} \leftarrow (r_i + r_f)/2$
- 2: $v_i \leftarrow \sqrt{\mu/r_i}; \quad v_f \leftarrow \sqrt{\mu/r_f}$
- 3: $v_{\text{trans},a} \leftarrow \sqrt{2\mu/r_i - \mu/a_{\text{trans}}}; \quad v_{\text{trans},b} \leftarrow \sqrt{2\mu/r_f - \mu/a_{\text{trans}}}$
- 4: $\Delta V_{\text{Hohmann}} \leftarrow |v_{\text{trans},a} - v_i| + |v_f - v_{\text{trans},b}|$
- 5: $r_0 \leftarrow R_{\oplus} + h_0; \quad r_1 \leftarrow R_{\oplus} + h_1; \quad r_2 \leftarrow R_{\oplus} + h_2$
- 6: $T_1 \leftarrow 2\pi\sqrt{r_1^3/\mu}; \quad T_2 \leftarrow 2\pi\sqrt{r_2^3/\mu}$
- 7: $\omega_1 \leftarrow 2\pi/T_1; \quad \omega_2 \leftarrow 2\pi/T_2$
- 8: $\Delta\omega \leftarrow |\omega_1 - \omega_2|$
- 9: $\theta_0 \leftarrow 2 \arcsin(d_0/2r_0)$ ▷ Initial angular separation
- 10: $\theta_f \leftarrow 2 \arcsin(d/2r_0)$ ▷ Desired angular separation
- 11: $\Delta\theta \leftarrow \theta_0 - \theta_f$ ▷ Arc to close
- 12: $T_{\text{converge}} \leftarrow \Delta\theta/\Delta\omega$

Ensure: $\Delta V_{\text{Hohmann}}, T_{\text{converge}}$

ΔV required to perform station-keeping

In order to maintain the inter-satellite link, the relative positions of the satellites with respect to each other have to be maintained, in a process called relative station-keeping. In the examples presented above, one has to maintain the altitude of the satellites to achieve in-track station-keeping and thus ensure the inter-satellite link. To estimate the ΔV required to perform station-keeping, the in-track station-keeping strategy described by Wertz [47] will be used. This strategy minimizes maneuver frequency by using the slow orbital decay of satellites in LEO due to atmospheric drag to perform altitude maintenance, effectively reintroducing the ΔV that is lost due to atmospheric drag by performing orbital maneuvers.

To perform station-keeping once the satellites have reached their desired positions, a "box" with a specified altitude and phase error is defined around each satellite, as seen in Figure 4.20. The dimensions of the box can be adjusted to achieve specific mission needs: for less frequent station-keeping the altitude dimension may become larger and in this context the phase error can be adjusted to guarantee the inter-satellite link.

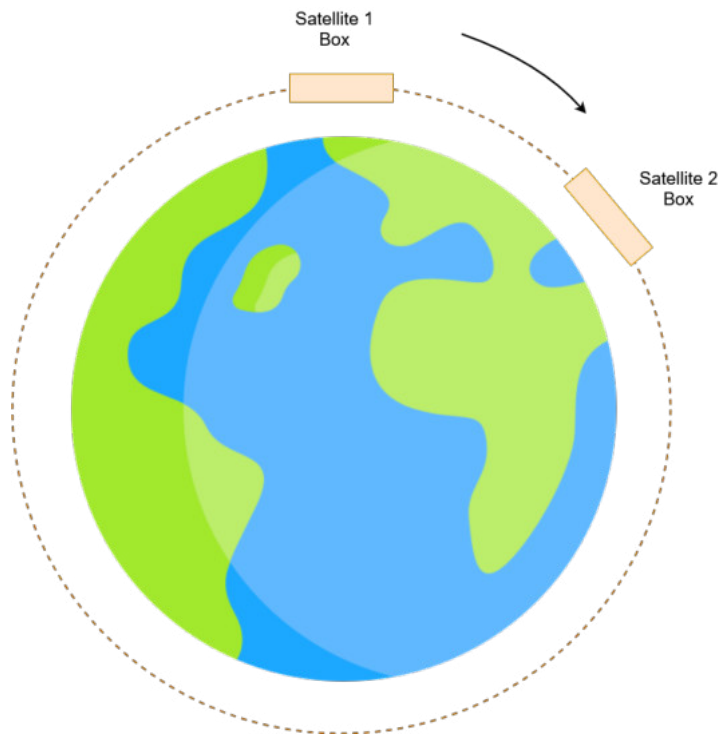


Figure 4.20: In-track station-keeping strategy. Each satellite is constrained in a pre-defined mathematical box, which is designed to guarantee the inter-satellite link

The behavior of the satellite inside the box and the point where a maneuver is required is described in Figure 4.21. The satellite begins its journey at the top right of the box, above the target altitude and with a positive phase error. Above the target altitude, the satellite moves at a slower speed compared to the target altitude and the phase error slowly decreases. The satellite slowly loses altitude due to the atmospheric drag. This process continues until the target altitude is reached, at which point the phase error remains constant.

Once the satellite drops below the target altitude, its speed becomes faster than the target altitude, and thus the phase error slowly increases. Once the satellite reaches the bottom right corner of the box, a maneuver needs to be performed to increase the altitude and place the satellite at the top right of the box. At that point, the cycle is complete and will repeat once again.

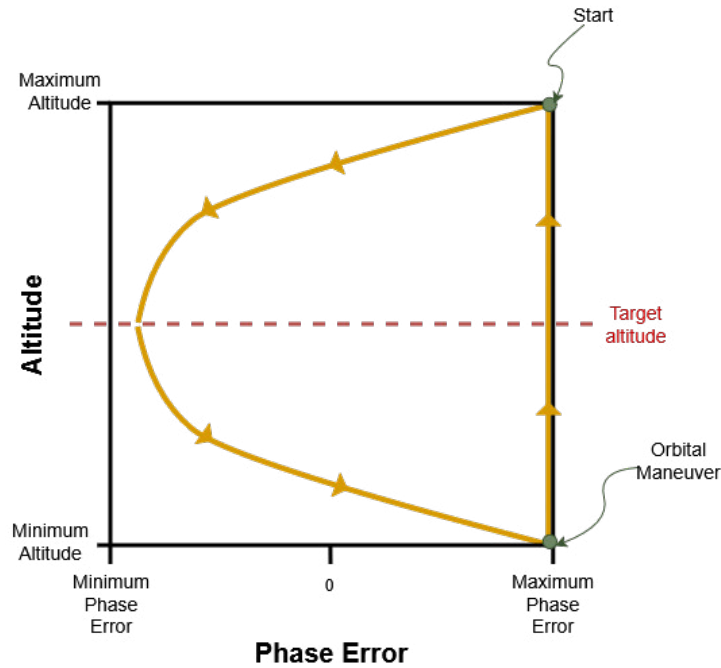


Figure 4.21: Strategy used to maintain the altitude and relative phasing between the two satellites, seen inside the station-keeping box

To simplify calculations, the altitude will be raised using the Hohmann transfer used above. In this case since drag is taken into consideration, the drag area of the satellite must be known in order to compute how much ΔV is required for station-keeping. A 6U CubeSat is used as a example, with a total drag area of 0.06 m^2 and a total mass of 10 kg. Using the High-Precision Orbit Propagator (HPOP) propagator with a fictitious launch date in 2027 and as starting condition a SSO orbit at an altitude of 550 km, the decay rate of the satellite is computed to be -8 km/year. With this in mind, the number of maneuvers and the ΔV required for different sizes of the station-keeping box can be computed using the Hohmann transfer method. The results can be seen in Table 4.13.

Table 4.13: Number of maneuvers and ΔV required for each maneuver for different box sizes

Total altitude box size [km]	Time to reach bottom of the box [days]	ΔV required per maneuver [m/s]	Maneuvers per year
0.4	18.25	0.2189	20
0.5	22.8125	0.2737	16
0.8	36.5	0.4379	10
1.6	73	0.8758	5
2	91.25	1.0948	4
4	182.5	2.1896	2
8	365	4.3793	1

4.4 Link budget for constellation of satellites with different LTAN

This analysis examines different orbital configurations and their impact on inter-satellite communication windows. All simulations were performed using Ansys Systems Tool Kit (STK) [40] software in 550km LEO orbits. A station keeping configuration was implemented for a 2-satellite constellation, where the satellites maintain the minimum distance between the 2 orbits, after achieving it either with propulsion or differential drag manoeuvres. As the orbit progresses, the inter-satellites distance reaches 2 minima and 2 maxima, since they approach each other when reaching Earth's poles. This is illustrated in fig. 4.22.

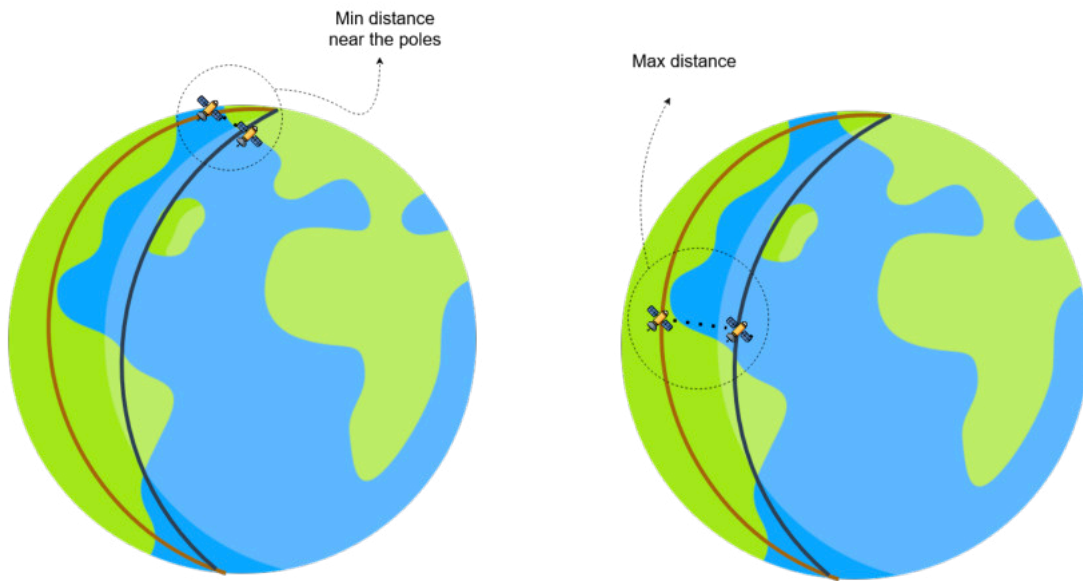


Figure 4.22: Minimum and maximum between 2 satellites with different LTAN that perform station keeping

In order to calculate the maximum allowable LTAN difference between the 2 spacecraft with the requirement that they do not lose line of sight, the calculated angle of 46° is used. The maximum allowable LTAN difference corresponds to 1.53 hours difference between the launch times. The maximum allowable LTAN range is illustrated in fig. 4.23.

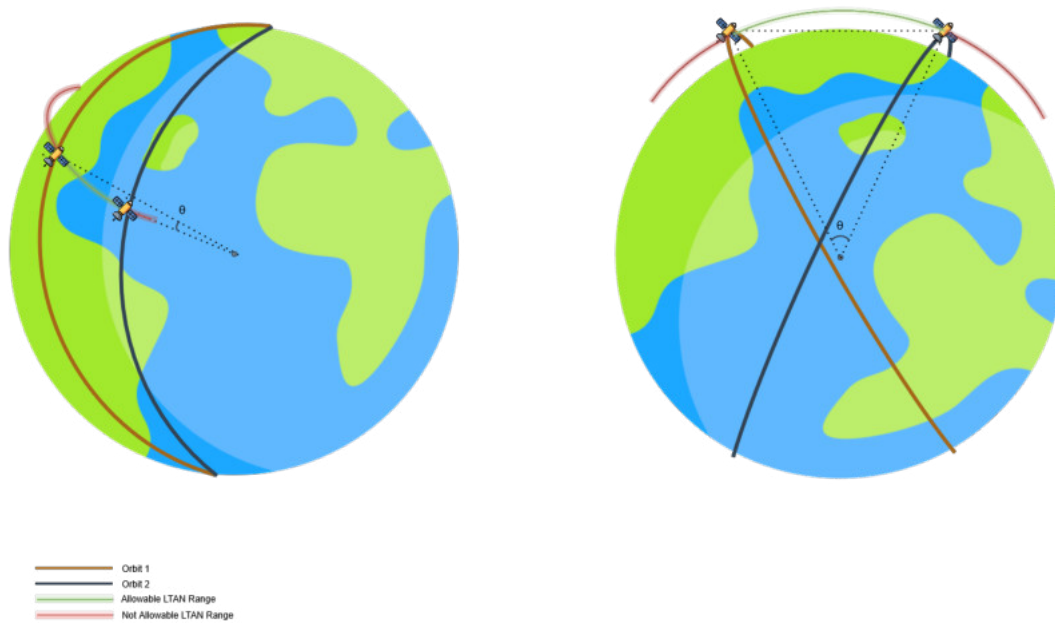


Figure 4.23: Maximum allowable LTAN range between 2 satellites in different LTAN to achieve line of sight

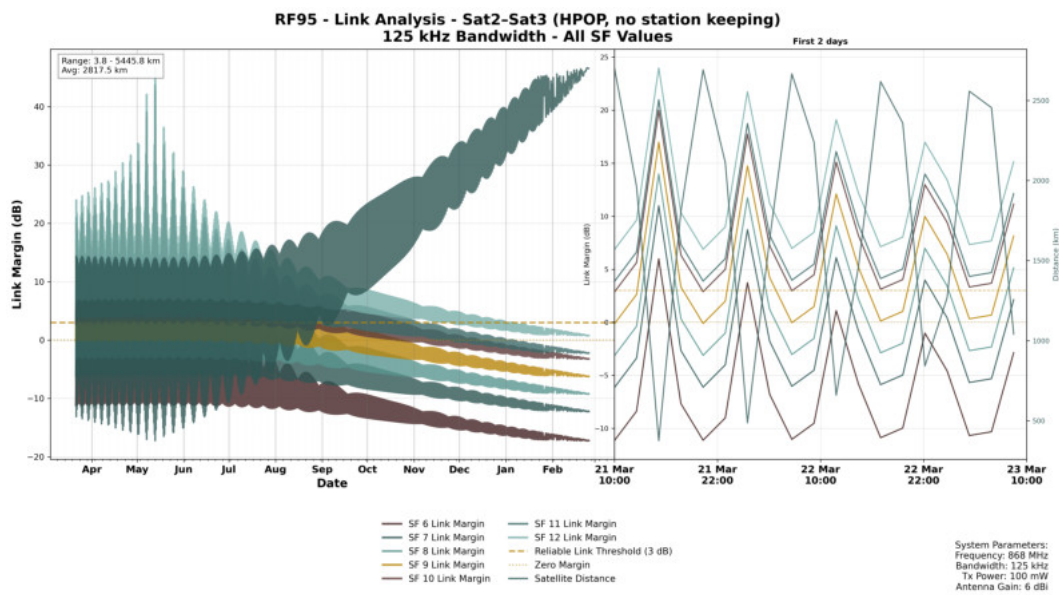
4.4.1 Constellation without station keeping

In the case that there is no mechanism that can be used for station keeping, the satellites drift apart. The HPOP propagator is used, to model 2 different scenarios and extract the link budget and access data.

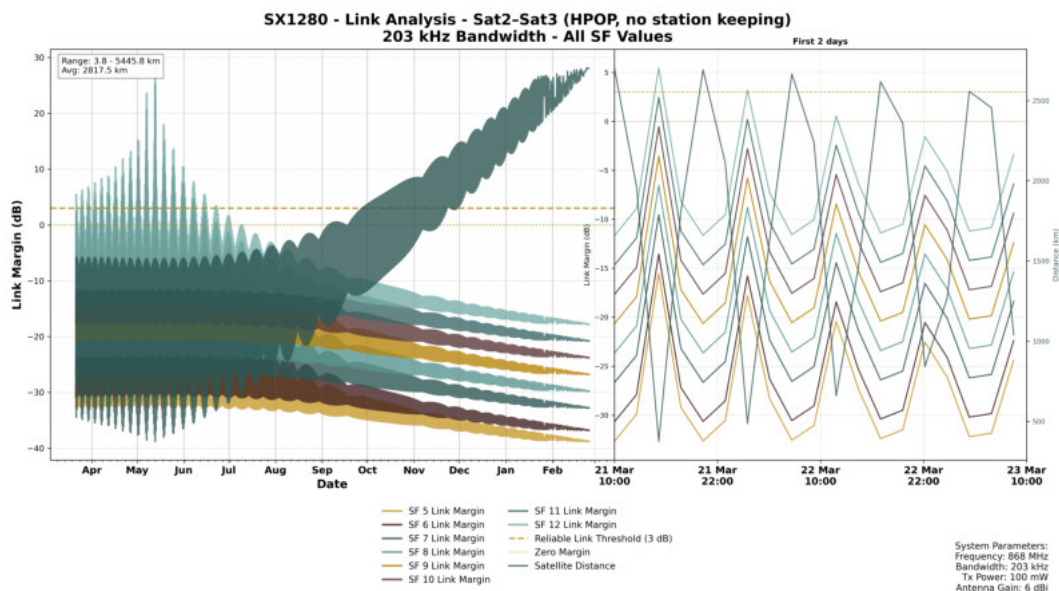
2 satellite scenario

The link budget results for a 2-satellite scenario are plotted in fig. 4.24, with data taken from an analysis in 550 km SSO orbit with the HPOP propagator.

Two satellites, different LTAN, no station keeping (HPOP)



RF95, 868 MHz, 125 kHz



SX1280, 2.4 GHz, 203 kHz

Figure 4.24: Two-satellite constellation without station keeping (HPOP, different LTAN): link margin and distance over time for 868 MHz and 2.4 GHz bands (full year with 2-day inset).

The full set of bandwidth and spreading factor combinations for this scenario is included in the Annex. Similarly with this analysis, a scaled up configuration would present the same behavior, depending on the difference between the time of launch, as the presented scenario is the worst case scenario in terms of link margin. In terms of time, 2 days were chosen, since the behavior will be repeatable (due to the station keeping).

6 satellite scenario

In the 6 satellite scenario, a variation of 2-5% was applied in the areamass ratio. The positions of the

satellites in different timepoints can be seen in fig. 4.25

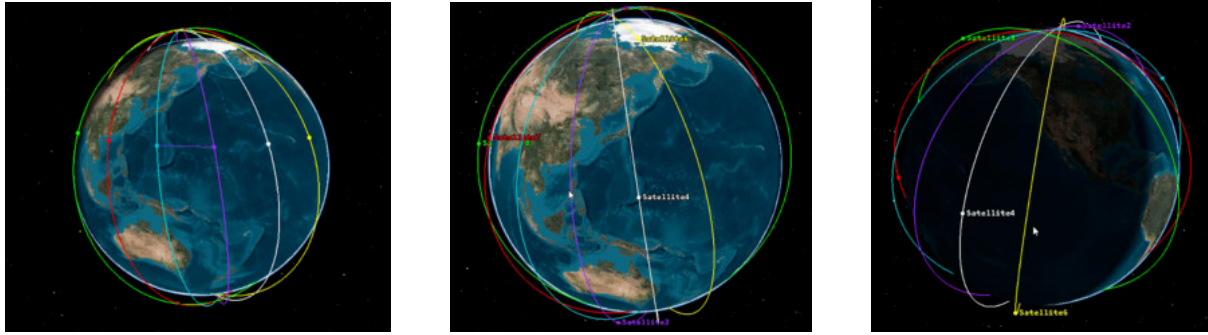


Figure 4.25: 6 satellites without station keeping drift over time in different LTAN. From left to right: initial configuration, after 3 months, after 8 months.

The access times are seen in fig. 4.26.

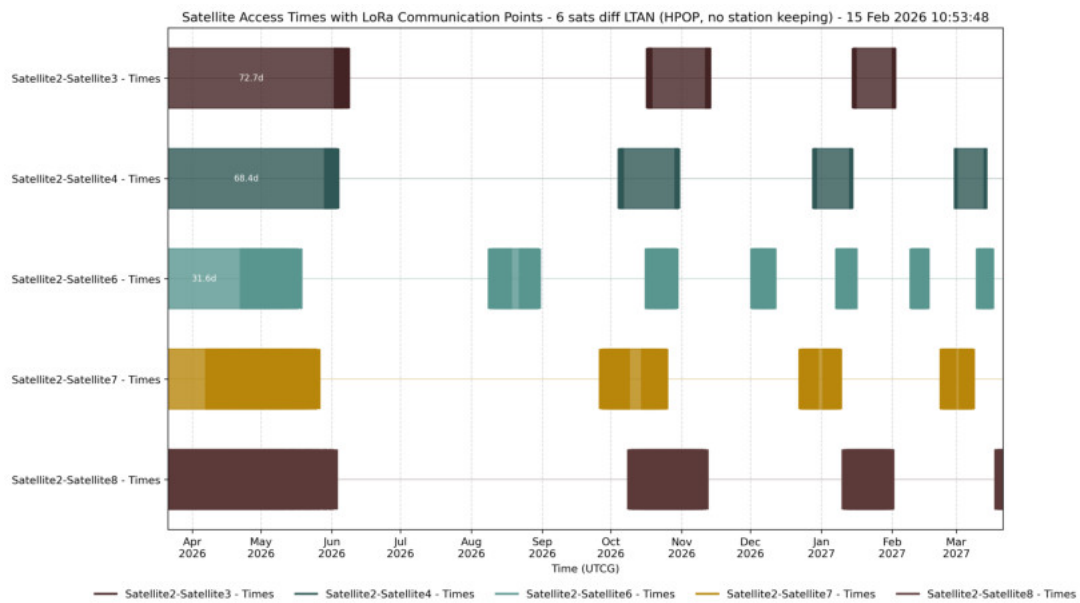


Figure 4.26: Inter-satellite access windows for the six-satellite constellation with different LTAN, showing periods where LoRa communication is feasible.

4.4.2 Constellation with station keeping

2 Satellite scenario

With the calculated maximum LTAN difference of 1.5 hours, the visualization of the 2-satellite constellation can be seen in fig. 4.27.

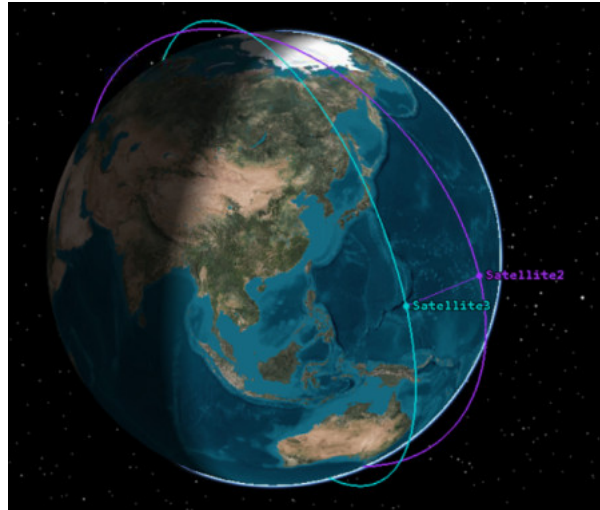


Figure 4.27: 2 satellites with LTAN difference of 1.5h

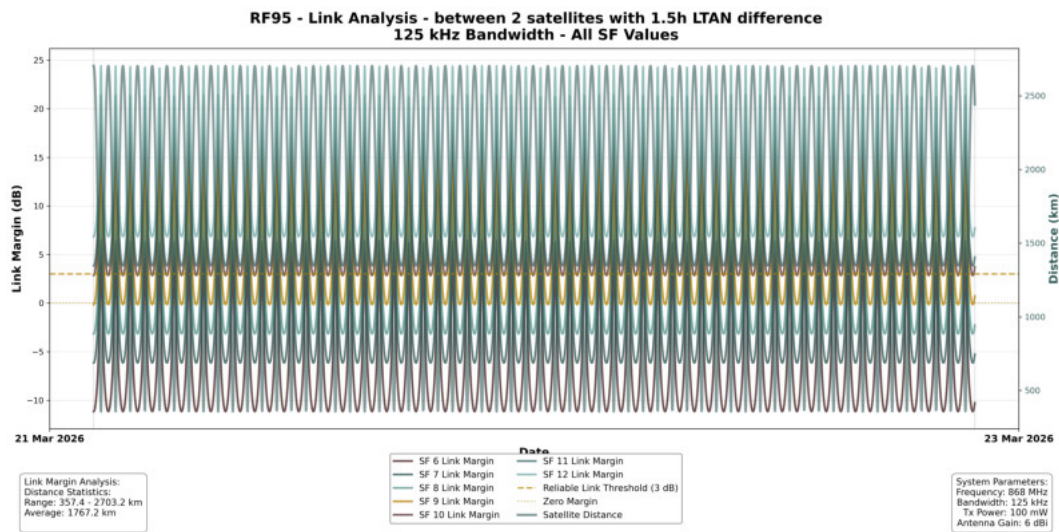
The orbital parameters are included in table 4.14 and the J2Perturbation propagator was chosen, to simulate the station keeping between them.

Table 4.14: Orbital Parameters for Satellite 1 and Satellite 2

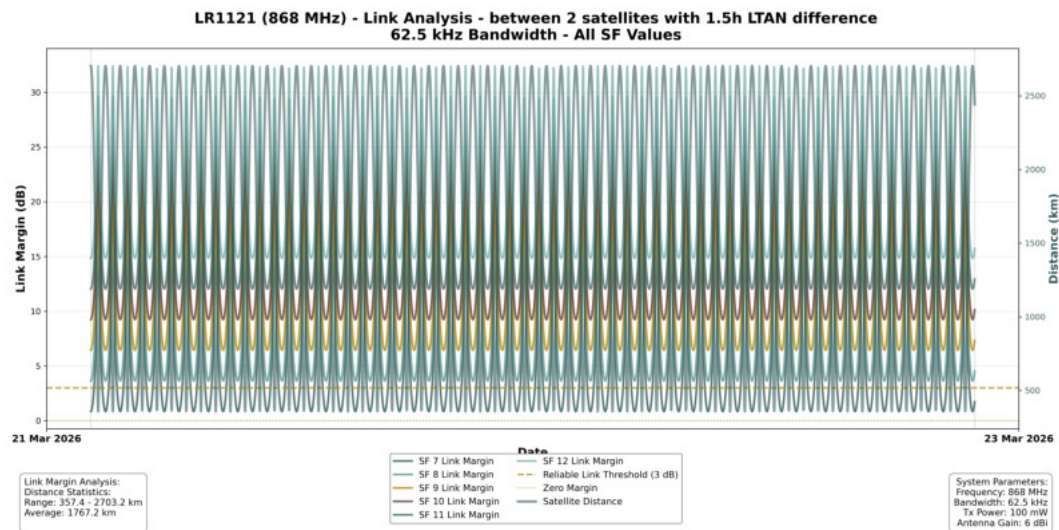
Parameter	Satellite 1	Satellite 2
Orbit Epoch	21 Mar 2026 10:00:00.000 UTCG	21 Mar 2026 10:00:00.000 UTCG
Coord Epoch	21 Mar 2026 10:00:00.000 UTCG	21 Mar 2026 10:00:00.000 UTCG
Step Size	60 sec	60 sec
Semimajor Axis	6928.14 km	6928.14 km
Eccentricity	0	0
Inclination	97.5977°	97.5977°
Argument of Perigee	0°	0°
RAAN	328.939°	351.439°
True Anomaly	0°	0°

The time-resolved link analysis for the 1.5 h LTAN difference scenario was performed using the same transceivers. The best case scenario for each band (narrowest bandwidth for best sensitivity) is shown in fig. 4.28.

Best case (2 satellites, 1.5 h LTAN difference)



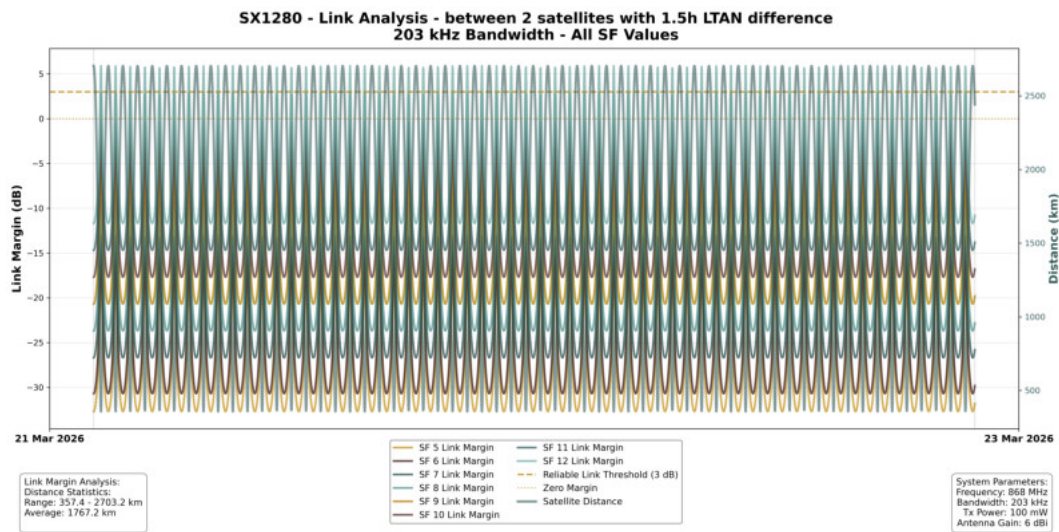
RF95, 868 MHz, 125 kHz



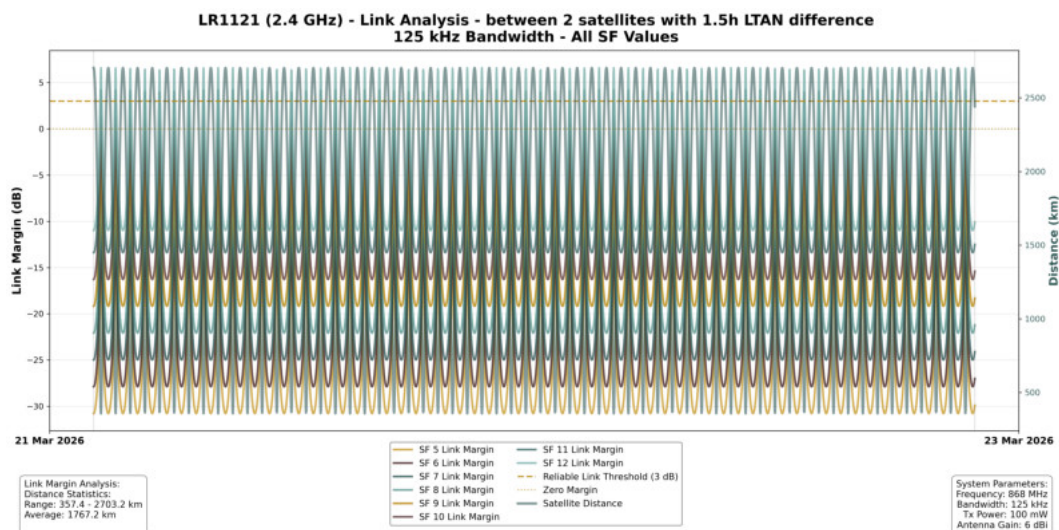
LR1121, 868 MHz, 62.5 kHz

Figure 4.28: Two-satellite constellation with station keeping (1.5 h LTAN difference): best case link analysis for each transceiver band.

Best case (2 satellites, 1.5 h LTAN difference)



SX1280, 2.4 GHz, 203 kHz



LR1121, 2.4 GHz, 125 kHz

Figure 4.29: Two-satellite constellation with station keeping (1.5 h LTAN difference): best case link analysis for each transceiver band.

Time and ΔV required to reach the desired distance

The ΔV calculation is identical to the one described for the same LTAN scenario and the maneuver required is illustrated in fig. 4.30.

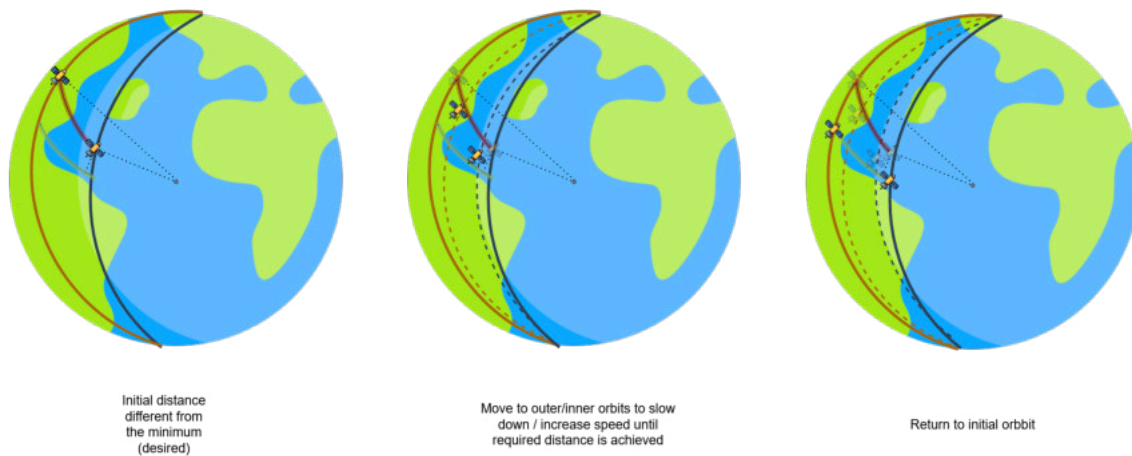


Figure 4.30: Maneuver to achieve the desirable distance when 2 satellites are in orbits with different LTAN

4.5 Ground Station Considerations

Ground station analysis for Geneva shows approximately 6 passes per day per satellite. Access duration statistics:

- Minimum: 33.8 s
- Maximum: 730.6 s
- Mean: 561.9 s

The TinyGS open-source ground station network provides a potential infrastructure for LoRa satellite communication [48]. Other relevant satellite Internet of Things (IoT) and ground station initiatives include FOSSA Systems [49] and NASA's Starling swarm mission [50, 51].

5. Radiation Testing

5.1 Hierarchical LoRa network test in CHARM

5.1.1 CHARM Facility

The CERN High energy Accelerator Mixed field facility (CHARM) is an irradiation test facility for electronics located at CERN [31, 32]. The initial proton beam of 24 GeV for CHARM is extracted from the PS accelerator. The beam is then guided to the experimental area where it hits a cylindrical copper or aluminium target. The resulting secondary mixed radiation field is used to test electronic equipment at predefined test positions. Depending on the test position selected (from 1 to 13), the test equipment is exposed to different particle spectra. In addition, four movable blocks with a thickness of 40 cm and made out of concrete or iron can be placed between the target and the test locations.

The CHARM facility, because of the size of its experimental area, can host different user experiments and the irradiation conditions are requested by the primary user, while other users withstand the conditions. In the course of these experiments, a target composed of copper was utilized without any protective shielding inserted. The dose and fluences are determined through detailed calibration performed by the CHARM team using the RadMon system. RadMon detectors are placed close to the DUTs during irradiation to verify the calibration measurements of the dose and fluences. An uncertainty of 30% is estimated taking into account the fluence uncertainty at CHARM.

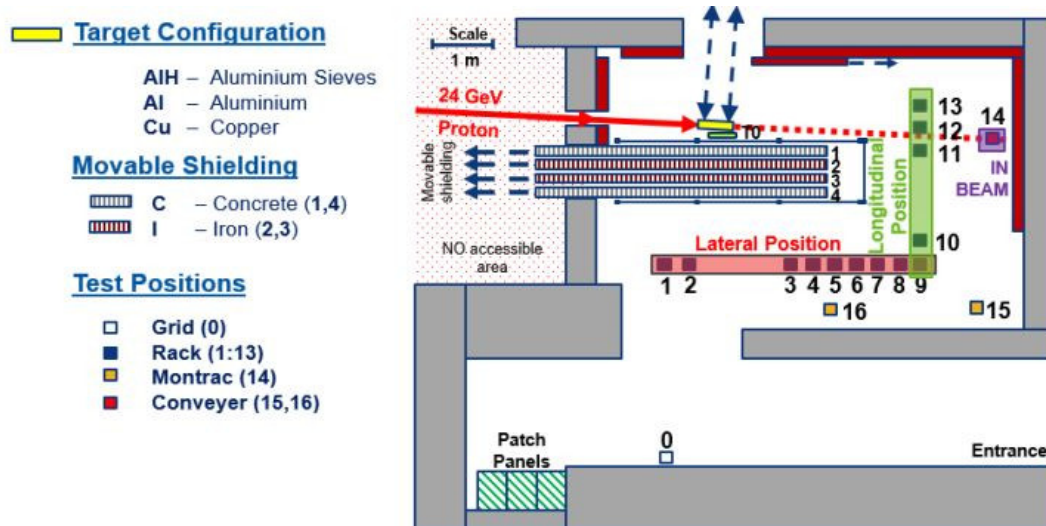


Figure 5.1: CHARM irradiation room layout.

5.1.2 Test Setup and Data Sources

The test was conducted at the CHARM facility at CERN. The network had a hierarchical structure: nine Feather M0 boards (identical Microcontroller Unit (MCU) and transceiver RRF95 with Astromesh) acted as end devices transmitting uplink packets, and three LoRa gateways (Dragino LPS8N Indoor LoRaWAN Gateway Semtech) collected the packets. The analysis includes eight end devices (device

numbers 1, 2, 3, 4, 6, 7, 8, and 10); device 5 was not deployed, and device 9 is excluded from the reported analysis. Gateway health was monitored via periodic pings and reset logs. The analysis considers the test as starting on 2025-06-11 at 17:30. MQTT protocol was used to receive the data from the devices.

The end devices were placed in the following areas of the testing facility:

- **R1:** two Feather M0 boards (device numbers 7 and 8).
- **Patch panel:** three Feather M0 boards (device numbers 2, 3, and 4).
- **G0:** two Feather M0 boards (device numbers 1 and 6).
- **Overhead:** one Feather M0 board (device number 10)

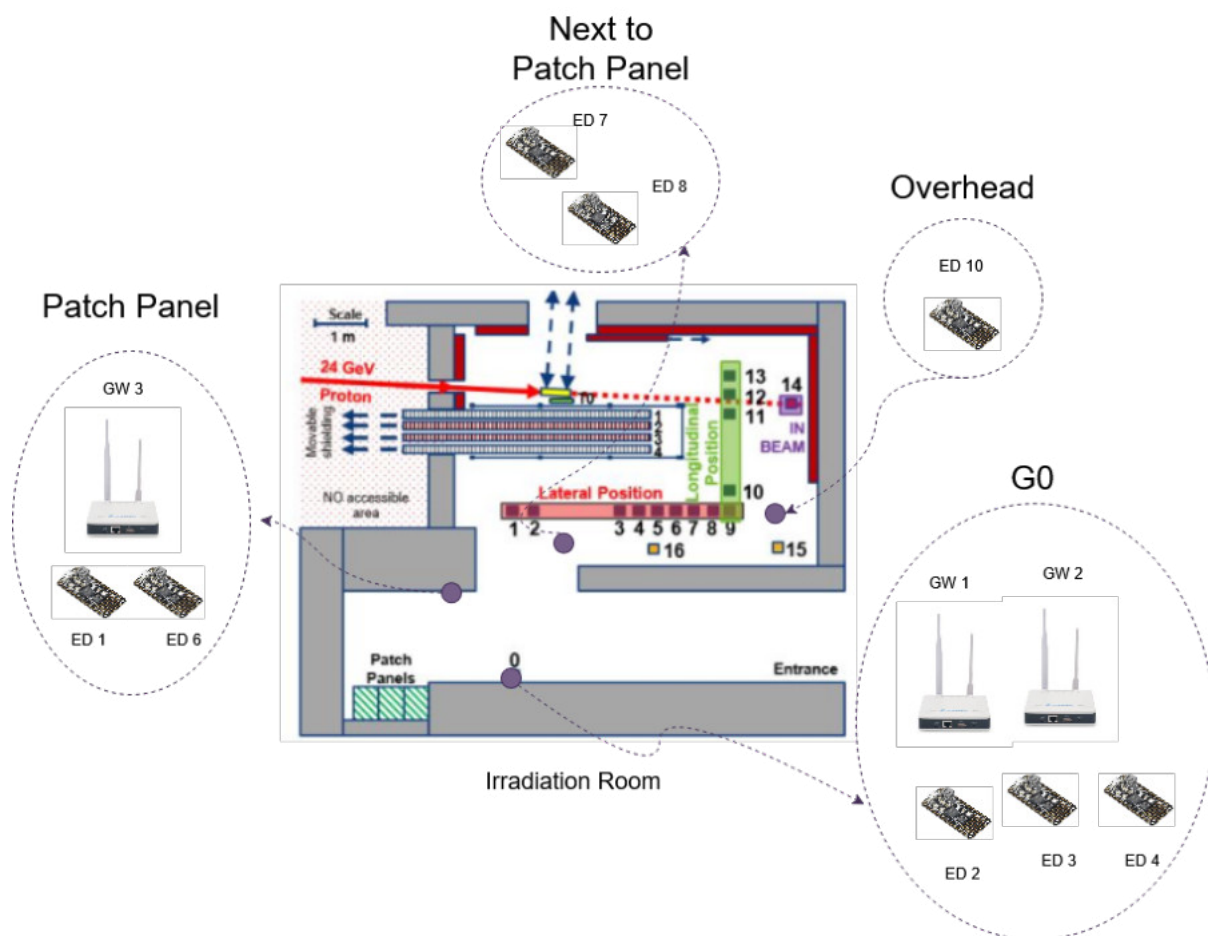


Figure 5.2: Setup inside the CHARM irradiation room



Figure 5.3: Devices in G0



Figure 5.4: Devices in G0

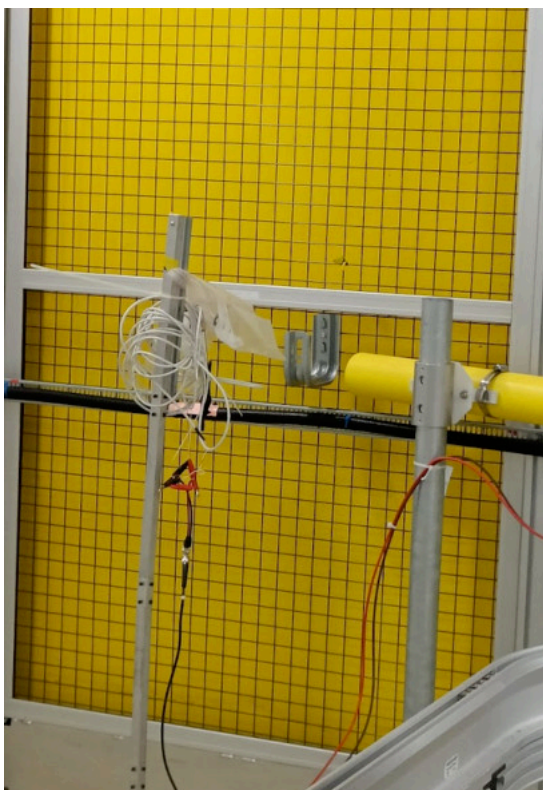


Figure 5.5: Devices in R1



Figure 5.6: Devices in overhead

Data sources are as follows:

1. **For the gateways:** ping logs (each line indicates SUCCESS or FAILED for a given gateway at a given timestamp), reset logs, and PSU current and voltage logs.
2. **For the end devices:** MQTT packet logs containing devEUI, frame counter (fCnt), and rxInfo (receiving gateways, RSSI, SNR), and reset logs from the monitoring script. End devices were configured to transmit at a 5-minute interval; the expected number of packets per device per condition is the test duration in minutes divided by 5.

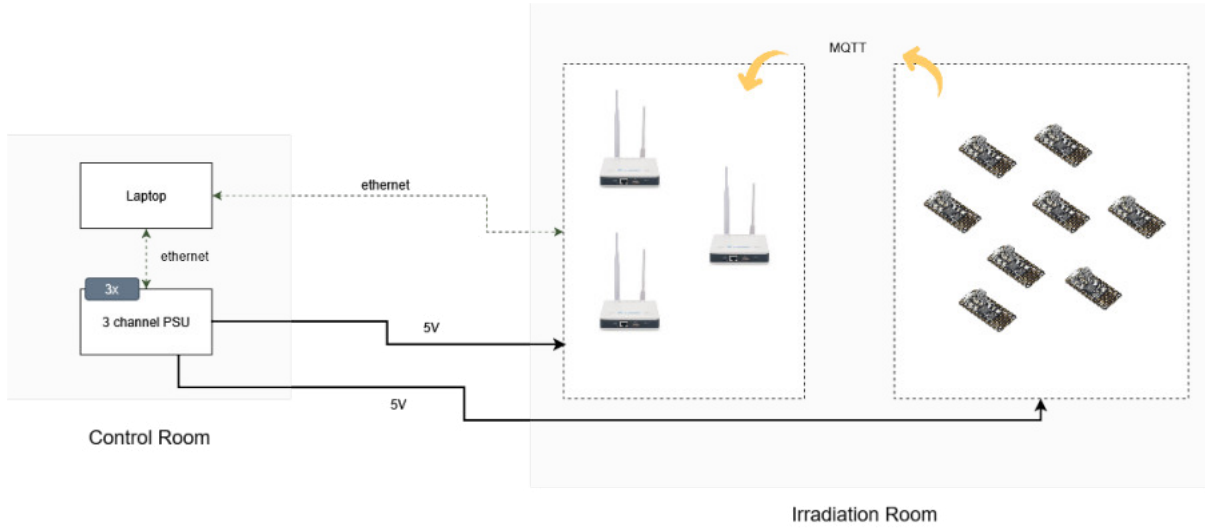


Figure 5.7: Electrical setup and communication configuration during the non hierarchical network test in CHARM

5.1.3 Gateway-Level Analysis and Interpretation

Gateway-level analysis uses the ping and reset logs to characterise availability and redundancy. For each gateway, uptime is the fraction of pings that succeeded, expressed as a percentage:

$$\text{uptime} = \frac{1}{K} \sum_{k=1}^K s_k \times 100 \quad (5.1)$$

where K is the total number of ping samples and $s_k \in \{0, 1\}$ indicates SUCCESS (1) or FAILED (0). The analysis also computes total number of pings, number of failures, number of resets, mean time between resets, and reset frequency (resets per hour).

A status matrix is built with one row per timestamp and one column per gateway. At each timestamp, the number of gateways that failed is counted. Simultaneous failures of multiple gateways are interpreted in the analysis as potential radiation-induced events. The report distinguishes: events where all three gateways failed, events where two failed, and events where only one gateway failed.

Redundancy is evaluated for the pair GW1 and GW2. At each timestamp the state is classified as: both online, one online (the other offline), or both offline. “Redundancy effectiveness” is the percentage of

time at least one of GW1 or GW2 was online:

$$\text{redundancy effectiveness} = \frac{n_{\text{both}} + n_{\text{one}}}{K} \times 100 \quad (5.2)$$

where n_{both} is the number of samples with both online and n_{one} with exactly one online. The analysis also computes total system downtime (when both are offline), identifies consecutive downtime periods, reports the longest outage, and counts how often GW1 was up when GW2 was down and vice versa.

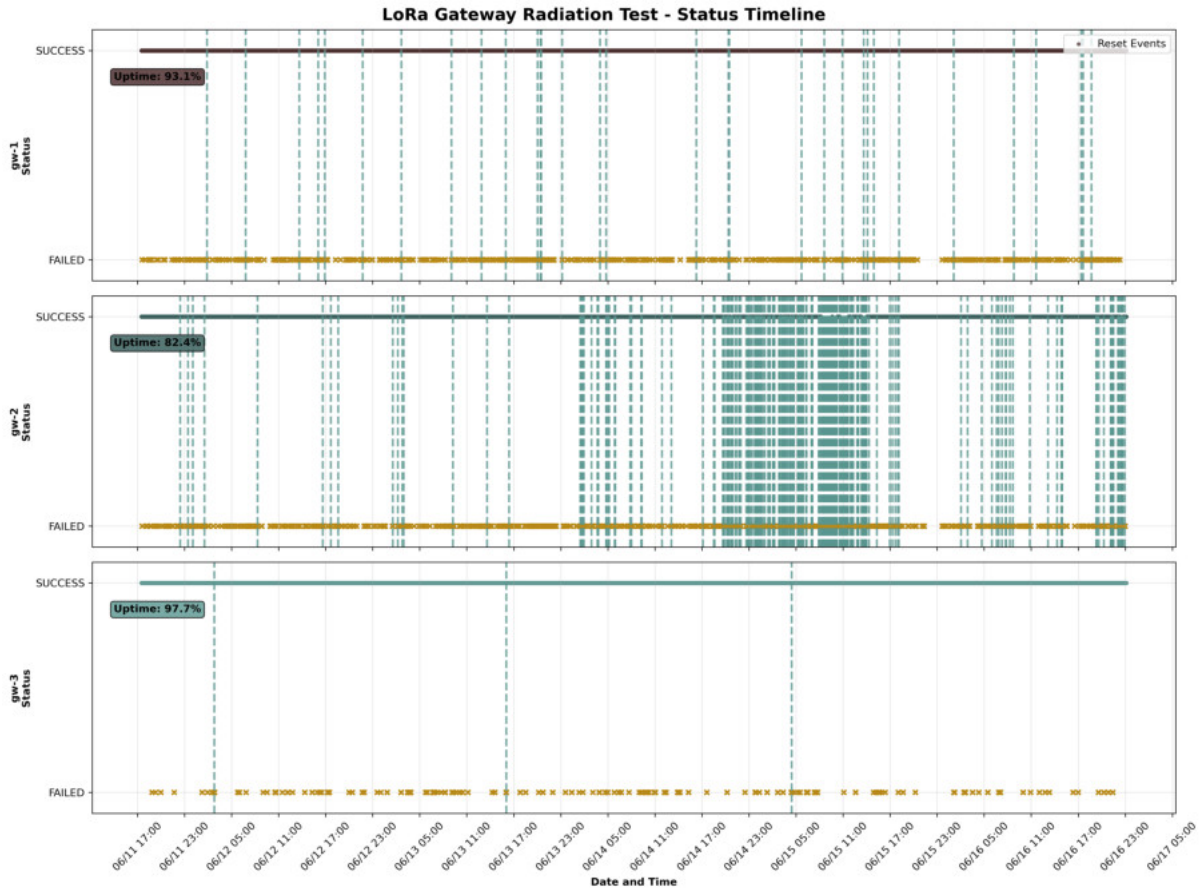


Figure 5.8: (a) Gateway status: SUCCESS or FAILED for each gateway at each ping time.

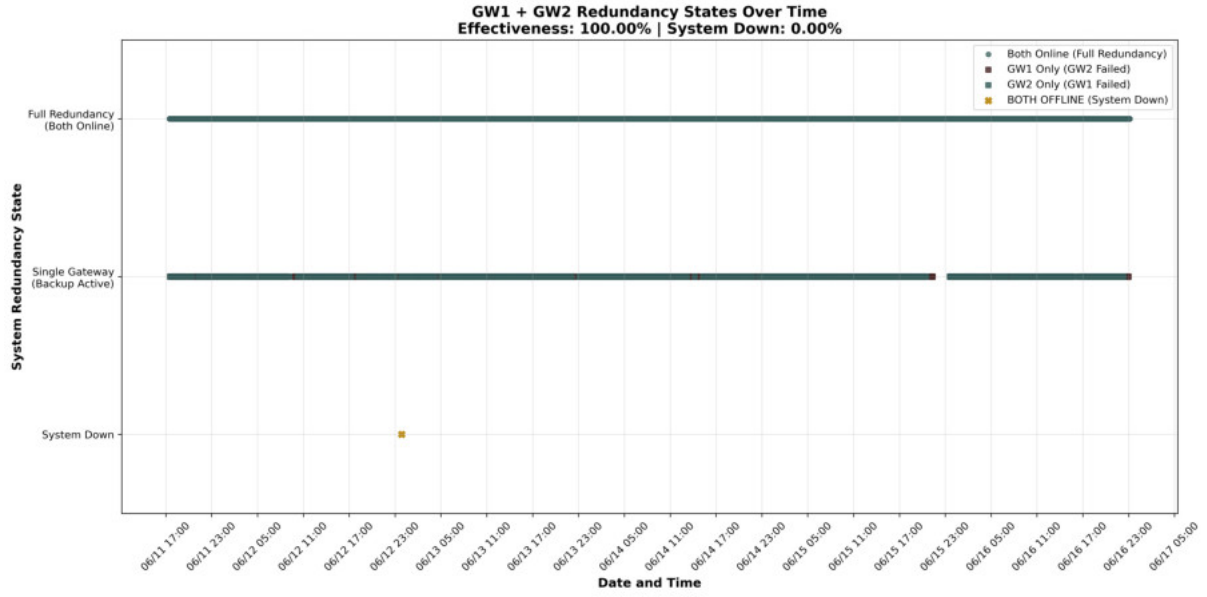


Figure 5.9: Redundancy state: both online, one online, or both offline versus time.

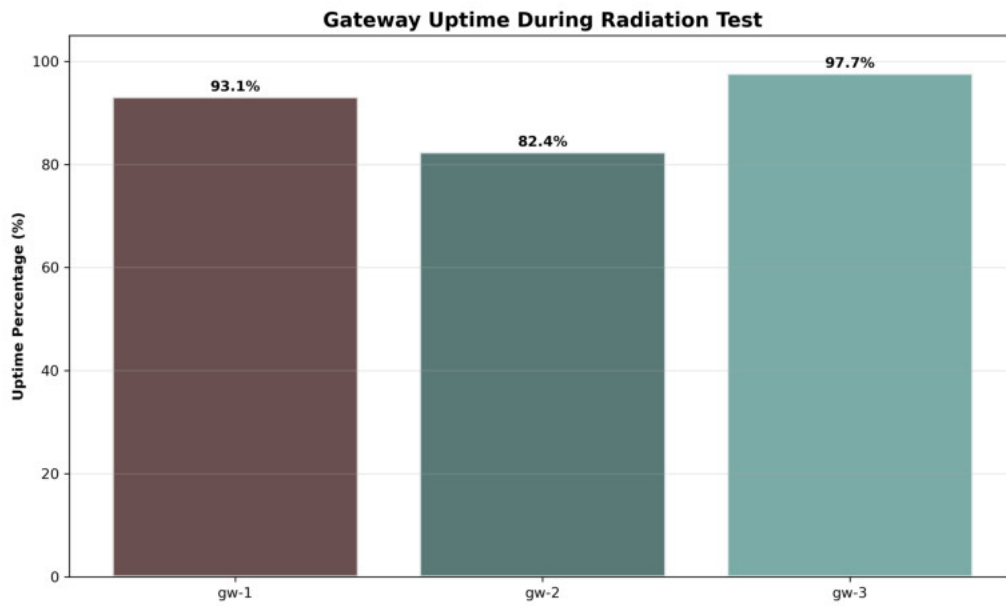


Figure 5.10: Per-gateway uptime summary

5.1.4 End-Device Packet and Reliability Analysis

End-device analysis uses MQTT packet logs and reset logs. For each device and each condition (radiation or no radiation), the expected number of packets is

$$N_{\text{exp}} = \left\lfloor \frac{t_{\text{dur}}}{T_{\text{int}}} \right\rfloor \quad (5.3)$$

where t_{dur} is the test duration in minutes and $T_{\text{int}} = 5$ min is the packet interval. The packet success rate (%), loss rate (%), and bit-flip rate (% of expected packets) are

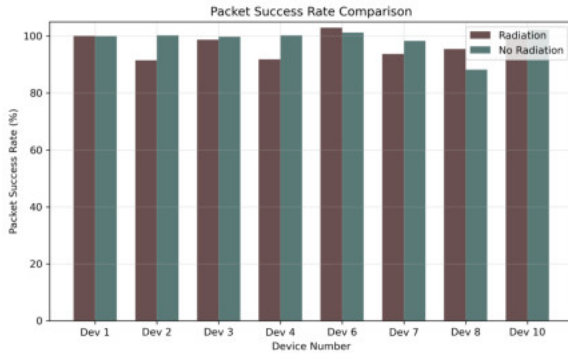
$$\text{success rate} = \frac{N_{\text{recv}}}{N_{\text{exp}}} \times 100, \quad \text{loss rate} = \frac{N_{\text{lost}}}{N_{\text{exp}}} \times 100, \quad \text{bit-flip rate} = \frac{N_{\text{bf}}}{N_{\text{exp}}} \times 100 \quad (5.4)$$

with N_{recv} the number of packets received, N_{lost} the number of lost packets (gaps in the fCnt sequence not classified as bit flips), and N_{bf} the number of candidate bit-flip events.

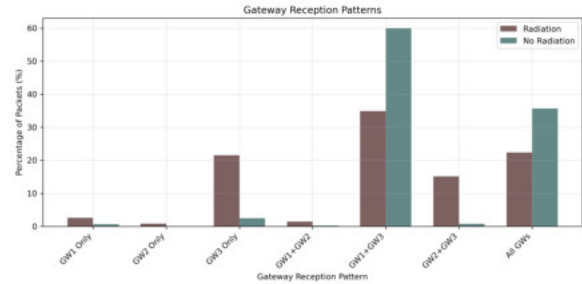
Resets are attributed from two sources. “Script resets” are those recorded in the reset logs (script-initiated or timeout-induced). “fCnt resets” are inferred when the frame counter decreases between two consecutive packets from the same device, indicating that the device restarted and the counter was reset. Lost packets are identified from gaps in the fCnt sequence: when the next fCnt is greater than the current fCnt plus one, the missing increments are counted as lost packets unless the gap is classified as a potential bit flip.

The analysis treats certain fCnt jumps as potential bit flips (candidate single-event effects in the frame counter). A jump is considered consistent with a single-bit flip if the gap matches patterns of the form $2^n - 1$ or the jump matches 2^n for some bit index n , or if several packets are missing within a short time window (under 6–9 minutes) in a way that suggests a more complex bit flip. These events are reported separately from ordinary lost packets.

Gateway reception patterns are derived from the rxInfo of each packet: which gateways received the packet. For each pattern (e.g. GW1 only, GW1+GW2, all three), the percentage is $100 \times n_{\text{pattern}} / N_{\text{total}}$ where n_{pattern} is the count of packets with that reception set and N_{total} is the total number of packets. These metrics are used to discuss diversity and redundancy at the link layer. All the metrics are listed in table 5.1 and in table 5.2.



(a) Packet success rate



(b) Gateway reception patterns.

Figure 5.11: Key performance metrics: (a) packet success rate (radiation vs. no radiation); (b) gateway reception patterns.

Device	Succ. (%)	Exp.	Recv.	Resets	Man.	Lost	Loss (%)	BitFl	GWs
1	100.1	1507	1509	25	0	28	1.9	0	3
2	91.4	1507	1378	43	0	30	2.0	0	3
3	98.7	1507	1488	4	0	32	2.1	0	3
4	91.8	1507	1384	19	0	96	6.4	0	3
6	102.9	1507	1551	27	0	41	2.7	1	3
7	93.7	1507	1412	110	2	47	3.1	0	3
8	95.4	1507	1438	110	2	28	1.9	3	3
10	99.3	1507	1496	105	13	30	2.0	0	3

Table 5.1: Radiation condition: success rate (%), expected packets, received, total resets, manual resets, lost packets, loss (%), bit flips, number of gateways. Data from `end_devices_detailed_results.csv`.

Device	Succ. (%)	Exp.	Recv.	Resets	Man.	Lost	Loss (%)	BitFl	GWs
1	100.0	1507	406	0	0	1	0.1	0	3
2	100.2	1507	407	0	0	0	0.0	0	3
3	99.8	1507	405	0	0	2	0.1	0	3
4	100.2	1507	407	0	0	0	0.0	0	3
6	101.2	1507	411	0	0	1	0.1	0	3
7	98.3	1507	399	2	0	0	0.0	0	3
8	88.2	1507	358	2	0	51	3.4	3	3
10	102.2	1507	415	13	0	0	0.0	0	3

Table 5.2: No-radiation condition: success rate (%), expected packets, received, total resets, manual resets, lost packets, loss (%), bit flips, number of gateways. Data from `end_devices_detailed_results.csv`.

5.1.5 Gateway Availability and Packet-Loss View

A complementary view of gateway behaviour is obtained from actual uplink reception rather than from ping status. For each gateway, the analysis computes the percentage of MQTT packets that were *not* received by that gateway (packet loss per gateway). Loss is also analysed by combination: which gateway or which pair of gateways failed to receive a packet. Various combinations' packet loss is calculated in fig. 5.12, showcasing the redundancy of the gateway pairs.

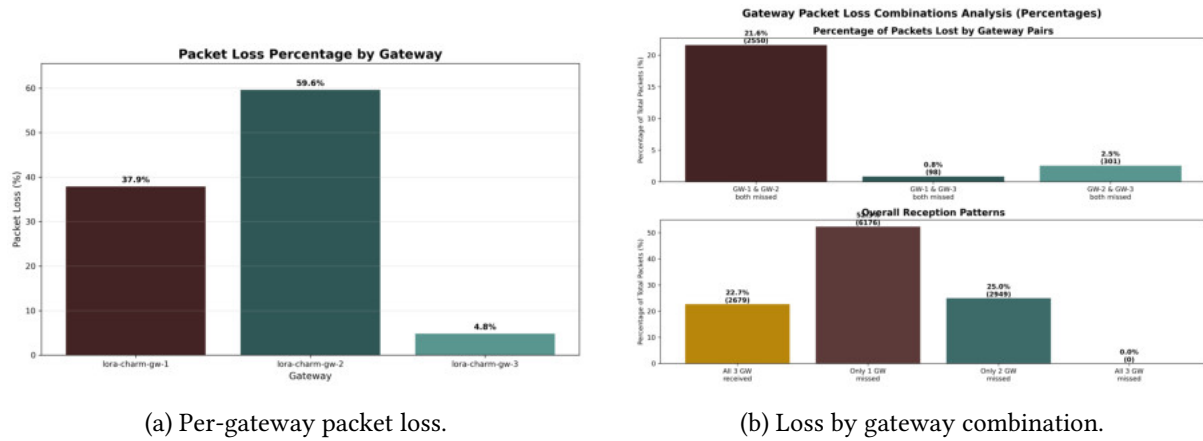
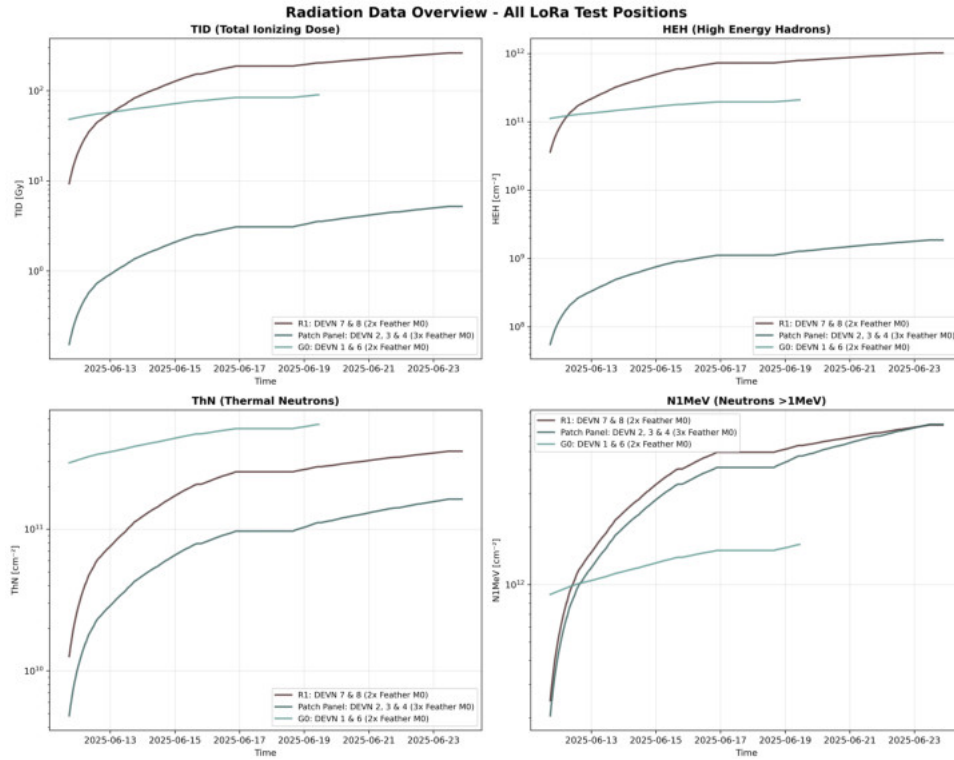


Figure 5.12: (a) Per-gateway packet loss (% of MQTT packets not received). (b) Packet loss by gateway combination.

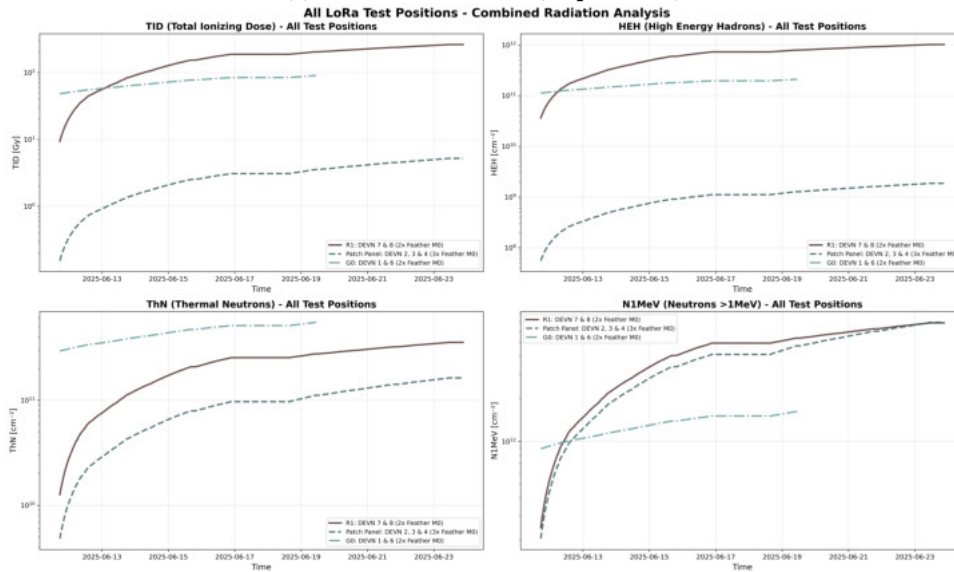
5.1.6 Radiation Environment and Correlation with LoRa Behaviour

Radiation data from the three positions (R1, patch panel, G0) provide time series of TID, HEH, ThN, and N1MeV. Overview plots show these quantities versus time for all positions. Detailed and interpolated plots are produced per location. Radiation data are interpolated onto the LoRa test timestamps so that dose and fluence can be compared in time with communication metrics.

Separate scripts plot TID over time together with gateway reset rate or downtime. These figures support the discussion of dose accumulation and gateway reliability (e.g. whether resets or outages correlate with TID or with beam periods).



(a) Radiation overview (all positions).



(b) Combined radiation view.

Figure 5.13: (a) TID, HEH, ThN, and N1MeV versus time for R1, patch panel, and G0. (b) Combined radiation view for all locations.

The total lifetime of the 2 gateways over long term testing, along with the increase of resets is shown in fig. 5.14.

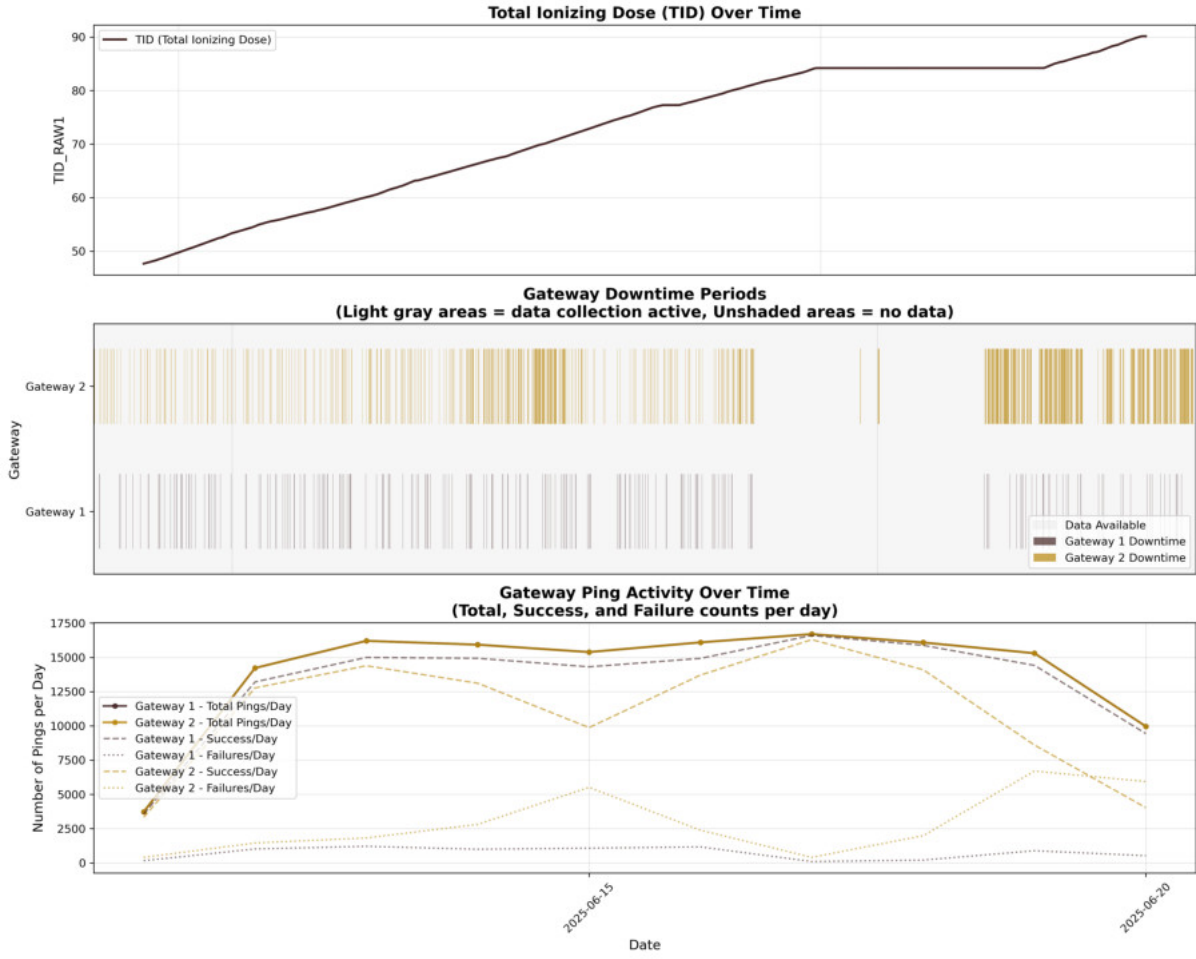


Figure 5.14: TID versus gateway resets or downtime (combined radiation and gateway analysis).

5.1.7 Cross section calculation

The Single Event Effect (SEE) cross-section quantifies the sensitivity of a device to radiation-induced events and is calculated as:

$$\sigma = \frac{N_{SEEs}}{Fluence} [cm^2] \quad (5.5)$$

where N_{SEEs} is the number of observed single event effects and the fluence represents the total number of particles per unit area incident on the device. The cross-section effectively represents the probability of an SEE occurring per unit particle fluence, with larger values indicating higher susceptibility to radiation effects.

Due to the statistical nature of radiation testing, the cross-section values are presented with confidence intervals. The uncertainty bounds were calculated assuming a Poisson distribution for the number of observed events, which is appropriate for counting rare, independent occurrences. Devices with fewer observed events exhibit wider confidence intervals, reflecting greater statistical uncertainty. For instance, End Device 3 with only 4 observed events shows a larger relative uncertainty compared to Gateway 2 with 287 events. The mean cross-section values range from approximately $2 \times 10^{-11} cm^2$

for the most radiation-tolerant device (End Device 3) to $1.5 \times 10^{-9} \text{ cm}^2$ for Gateway 2, indicating significant variation in radiation sensitivity across the tested devices.

Table 5.3: Cross-section analysis for gateway and end device resets.

Device	NoE	σ Cross-section (cm^2)		
		Lower	Upper	Mean
Gateway 1 resets	32	9.23E-11	2.47E-10	1.64E-10
Gateway 2 resets	287	9.97E-10	1.94E-09	1.47E-09
End device 1	25	6.86E-11	2.00E-10	1.28E-10
End device 2	43	1.30E-10	3.21E-10	2.20E-10
End device 3	4	4.36E-12	5.29E-11	2.04E-11
End device 4	19	4.87E-11	1.59E-10	9.71E-11
End device 6	27	7.53E-11	2.13E-10	1.38E-10
End device 7	110	3.66E-10	7.67E-10	5.62E-10
End device 8	110	3.66E-10	7.67E-10	5.62E-10
End device 10	105	3.48E-10	7.34E-10	5.37E-10

5.1.8 Summary of Results and Interpretation

At the gateway layer, the main outcomes are redundancy effectiveness (percentage of time at least one of GW1 or GW2 was available), the frequency and duration of full outages (both GW1 and GW2 down), the counts of simultaneous failures (interpreted as possible radiation-induced events), and reset rates per gateway. These are summarised in Figures 5.8.

At the end-device layer, the analysis reports packet success rate under radiation and under no radiation, reset rates (script and fCnt-based), lost packets, and candidate bit flips in the frame counter (interpreted as potential single-event effects). The comparison and summary figures support the discussion of device-level robustness.

At the network level, the role of multiple gateways is captured by the reception patterns (which gateways received each packet) and by the packet-loss and availability metrics. Together, gateway availability, per-gateway packet loss, and device-level metrics characterise the hierarchical robustness of the LoRa network under the CHARM radiation test.

Comparison with Mesh Network Results (Mancini, 2025)

A directly comparable radiation test of a LoRa-based wireless mesh network (WMN) at the CHARM facility was conducted by Mancini [4], using the same Feather M0 platform and the same facility conditions. The key differences in experimental setup are summarised in Table 5.4: Mancini's network employed FSK modulation at 868 MHz in a flat four-node mesh topology (all nodes co-located at position G0), whereas the test presented in this chapter used a LoRaWAN hierarchical topology with nine end devices distributed across multiple facility positions (G0, R1, patch panel, overhead) and three

gateways.

Table 5.4: Comparison of CHARM test parameters: mesh (Mancini, 2025) vs. hierarchical LoRaWAN (this work).

Parameter	Mesheed Network	Hierarchical Network
Modulation	FSK, 868 MHz, 2 kbps	LoRa, 868 MHz (LoRaWAN)
Topology	4-node flat mesh (WANET)	Star-of-stars (9 devices, 3 GWs)
Node positions	All at G0	G0, R1, patch panel, overhead
Test duration	~240 h	~125 h
Packet interval	~130 ms (2 kbps)	5 min
PDR / success rate (radiation)	>99.99%	91.4%
Packet loss (radiation)	~0.02% per GW; 0.001% combined	1.9–6.4% per device
Total power cycling events	48 (all nodes)	4–110 per device
Node SEE cross-section (mean)	$7.3\text{--}15.6 \times 10^{-11} \text{ cm}^2$	$2.0\text{--}56.2 \times 10^{-11} \text{ cm}^2$

The mesh network achieved substantially higher packet delivery reliability under radiation, with a PDR consistently above 99.99% throughout the experiment and a combined two-gateway packet loss of only 0.001%. By contrast, the hierarchical LoRaWAN network presented in this work showed per-device success rates as low as 91.4% and packet loss rates up to 6.4%, with reset counts for the most affected devices (7, 8, and 10) reaching 105–110 events.

Several factors contribute to this difference. First, all of meshed network’s nodes were placed at the G0 position, whereas the devices in this test campaign were distributed across positions with varying radiation intensity, including the higher-flux R1 location, since the devices placed there (numbers 7 and 8) are precisely those with the highest reset counts (110 each). Second, the LoRaWAN 5-minute transmission interval means that each gateway failure or device reset corresponds to a much larger gap in the packet record, making the success-rate metric inherently more sensitive to individual events than the near-continuous FSK traffic used by the meshed network. Third, and most importantly, the mesh topology’s dual-gateway scheme reduced combined packet loss by roughly a factor of 20 compared to either single gateway alone (from ~0.02% to 0.001%), directly demonstrating the resilience advantage of decentralised architectures. Mancini estimated the probability of simultaneous failure of both gateways at 9.1×10^{-21} , rendering network availability effectively 100%.

In terms of radiation sensitivity, the Feather M0 SEE cross-sections from both campaigns are consistent: meshed network’s gateway nodes (at G0) yielded $7.3\text{--}15.6 \times 10^{-11} \text{ cm}^2$, which aligns with the values obtained for G0 and patch panel devices in this work ($2.0\text{--}22.0 \times 10^{-11} \text{ cm}^2$), while the R1 and overhead devices showed higher cross-sections ($\sim 53\text{--}56 \times 10^{-11} \text{ cm}^2$) consistent with the higher fluence at those positions. This agreement across both campaigns confirms that the observed performance differences are attributable to topology, position, and protocol rather than platform variability, and provides a strong quantitative motivation for the mesh architecture being developed on the Astromesh platform.

5.2 Ultra-Wideband Transceiver Radiation Test at PSI

This section presents a radiation test campaign of an Ultra-Wideband (UWB) transceiver conducted at the Proton Irradiation Facility (PIF) of the Paul Scherrer Institute (PSI). The DWM1000 UWB radio transceiver, manufactured by Qorvo, was tested using a 200 MeV proton beam to characterize its radiation tolerance for potential integration into the AstroMesh platform's mezzanine board.

5.2.1 PSI Proton Irradiation Facility

The Proton Irradiation Facility (PIF) at PSI receives its initial proton beam from the PROSCAN accelerator [33]. A primary energy degrader allows setting discrete initial beam energies in the range from 200 MeV down to 30 MeV. The beam is subsequently guided to the Experimental Area where PIF is located. A further set of collimators is placed before the DUT to set lower energy. For this test campaign, the primary energy was set to 200 MeV with a 5 cm collimator used to target the chips.

The beam flux is measured by means of two ionization chambers (IC1 and IC2) placed upstream and downstream of the collimators respectively. The counting is calibrated to measure the beam flux at the DUT position, 5 cm downstream from IC2. Total Ionizing Dose (TID) is provided by the facility in Gy(Si).

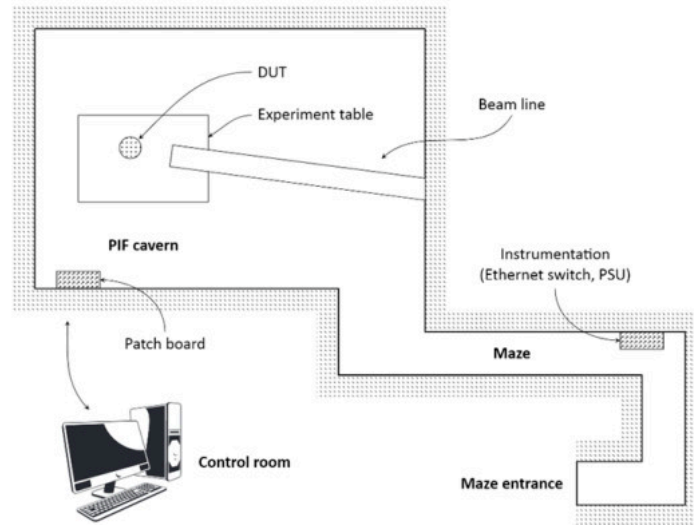


Figure 5.15: PSI-PIF irradiation facility layout.

5.2.2 Device Under Test

The DUT was the DWM1000 UWB IC, a complete single-chip UWB transceiver based on the DecaWave DW1000 architecture. The DWM1000 is designed for applications requiring precise ranging and location capabilities, operating in the frequency range from 3.5 to 6.5 GHz. For this test campaign, the transceivers were configured on Channel 1 with a 16 MHz Pulse Repetition Frequency (PRF) and Preamble Code 1.

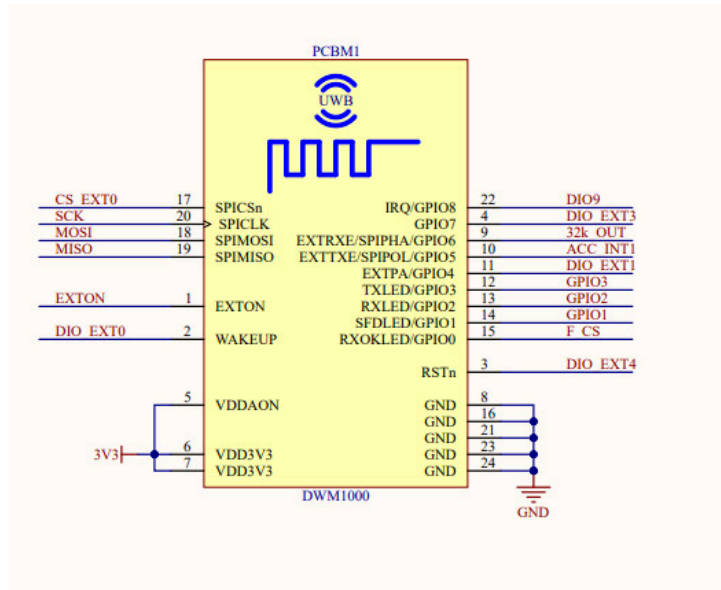


Figure 5.16: DWM1000 test board schematic.

5.2.3 Test Board and Setup

The test infrastructure was distributed across three main zones: the irradiation room, the maze, and the control room. Figure 5.20 provides an overview of the complete test setup.

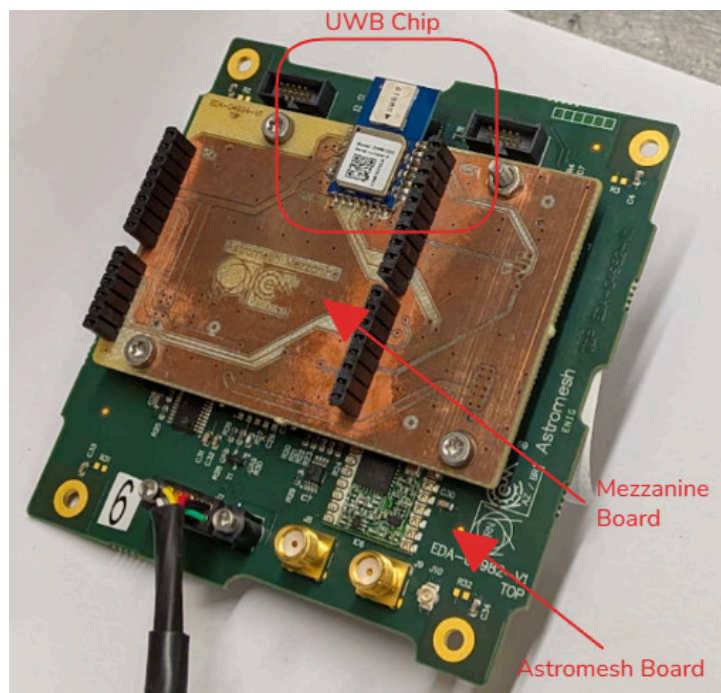


Figure 5.17: DWM1000 radiation test board.

A Keysight 8-channel PSU was used to power the test boards. Two AstroMesh boards hosting the DWM1000 transceivers were used in a Ping-Pong communication configuration:

- **Initiator:** non-irradiated board (connected to PSU channel 2 and COM4), placed behind lead

shielding

- **Responder:** irradiated board (connected to PSU channel 3 and COM5), positioned in the proton beam

The collimator was chosen and aligned in order to direct the mean line on the transceiver and not on the MCU, as seen in fig. 5.18.

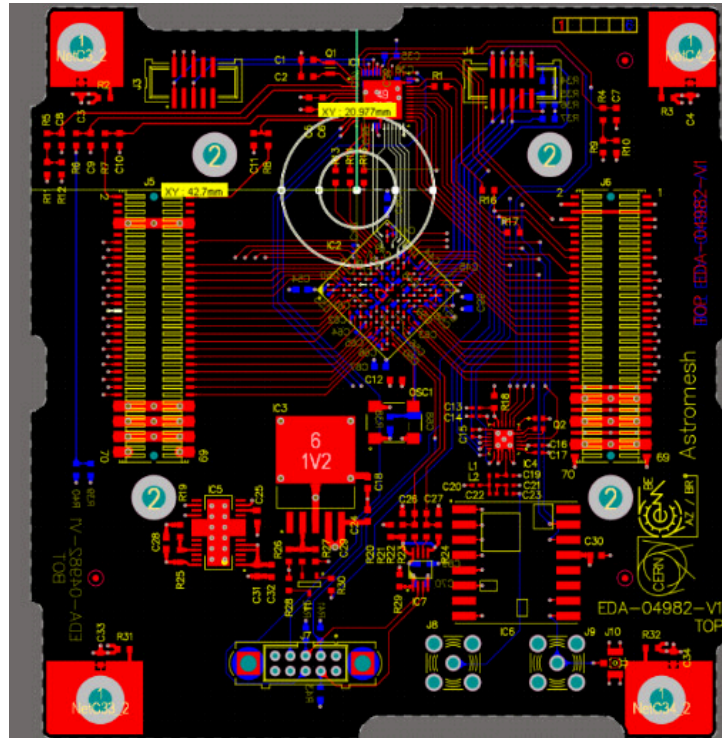


Figure 5.18: Alignment of beamline on CAD

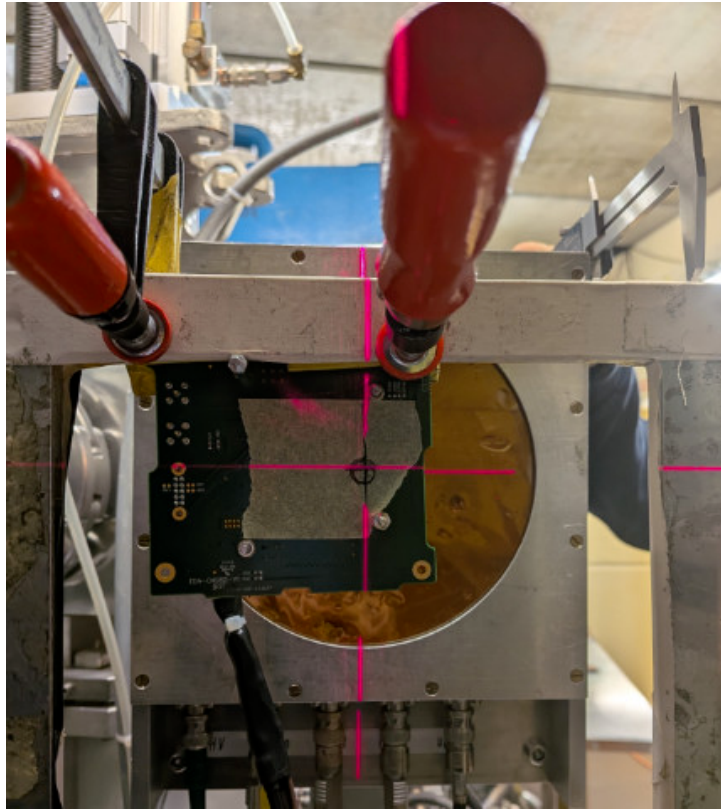


Figure 5.19: DWM1000 test board mounted in irradiation facility.

Power was supplied via 15-meter DB25 cables from the PSU. All instruments in the maze were connected to an Ethernet router, which forwarded data to the control room laptop for remote monitoring and logging. Only the DUT board was placed inside the irradiation room to minimize equipment exposure and avoid activation.

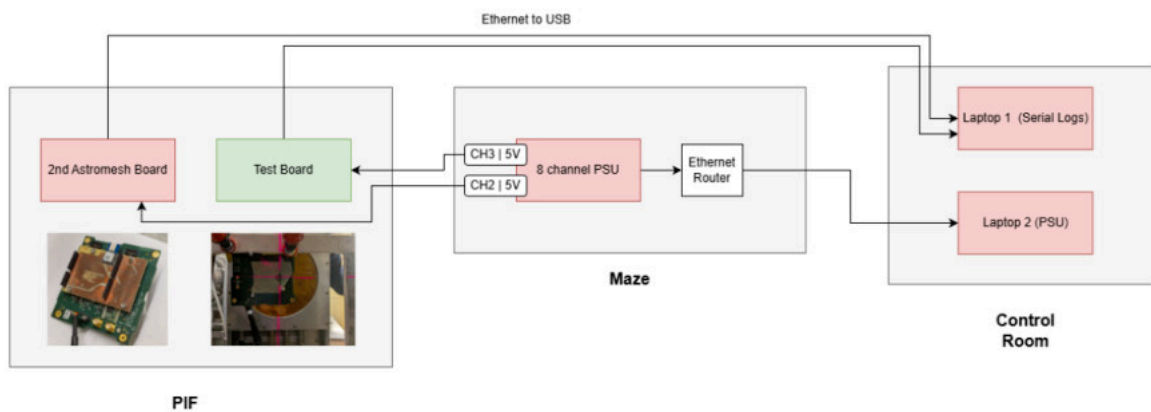


Figure 5.20: DWM1000 radiation test setup at PSI-PIF.

5.2.4 Test Procedure

The two boards communicated in a Ping-Pong configuration, where once one board transmitted a packet, the other received it and responded with a new packet. Each transmitted packet was 13 bytes

in length, structured as follows: a 1-byte packet type identifier (0x01 for PING, 0x02 for PONG), a 2-byte little-endian sequence number for tracking message ordering, 2 reserved bytes, and an 8-byte payload filled with 0xAA pattern bytes.

The data acquired during the test included all packets sent and received from both boards, errors categorized based on register information, software and hardware reset time points, voltage and current measurements, and radiation data provided by the facility.

Prior to irradiation, a dry run was performed to gather ambient data in the same environment. The first irradiation run was Run 53, followed by four additional runs (54–57).

5.2.5 Irradiation Conditions

Table 5.5 summarizes the radiation test runs performed at PSI. All runs used a 200 MeV proton beam. The DUTs were irradiated to a total TID of 693.7 Gy, a proton fluence of 1.13×10^{12} p/cm², and a Displacement Damage Equivalent Fluence (DDEF) of 1.13×10^{12} n_{eq}/cm² (1 MeV neutron equivalent).

Run	Start	Stop	Duration (s)	Current (nA)	Dose (Gy)	Dose Rate (Gy/h)	Fluence (p/cm ²)	Restarts
53	21:42:17	21:43:15	57	5	5.9	373	1.0×10^{10}	0
54	21:50:16	21:54:56	280	5	29.2	375	5.0×10^{10}	1
55	21:58:16	22:04:28	371	7.5	58.3	566	1.0×10^{11}	1
56	22:06:12	22:38:07	1914	10	400.2	753	6.8×10^{11}	7
57	22:39:54	22:55:53	958	10	200.1	752	3.4×10^{11}	4
Total	–	–	3580	–	693.7	–	1.13×10^{12}	13

Table 5.5: Summary of radiation test runs at PSI. All runs used a 200 MeV proton beam.

Run 53 served as the initial low-flux characterization at 5 nA beam current. Run 54 continued at 5 nA with extended exposure time; one restart was required due to logging interruption, and the MCU experienced a freeze requiring a power cycle. Run 55 increased the beam current to 7.5 nA, with an MCU freeze occurring that required a power cycle. Run 56 was the longest run, targeting 400 Gy total dose at maximum beam current (10 nA), requiring the most interventions (7 restarts) due to system lockups and serial communication failures. During this run, the device was observed entering an abnormal state with repeated preamble detection without frame completion. Run 57 was the final radiation run at 10 nA, targeting 200 Gy additional dose, with four restarts required due to logging interruptions.

5.2.6 Data Analysis Methodology

This section describes the analysis methodology applied to the DWM1000 radiation test data, including data sources, cycle definition, outcome categories, derived quantities, and associated uncertainties.

Data Source and Run Selection

The analysis uses the timestamped event stream recorded during the radiation campaign (serial output from both boards). Start and stop times for each run (baseline and beam runs) are taken from the experiment logbook; only events with timestamp t satisfying $t_{\text{start}} \leq t \leq t_{\text{stop}}$ are attributed to that run. Absorbed dose (Gy) per run is taken from the logbook and used for labelling and comparison; it is not used in the reception or data-rate calculations.

Event Types and Cycle Definition

Events are processed in chronological order. Four event types drive the analysis:

1. **PSU restart:** A system boot (power cycle) is detected when the board reports its boot message. The first occurrence is treated as initial boot; each further occurrence increments the PSU restart counter and starts a new reset epoch.
2. **Hardware RX reset:** A hardware RX reset is attributed to the ping-pong cycle that was active at the time it was performed; that cycle is then classified as having experienced a hardware reset.
3. **TX PING:** A transmission attempt is recorded as a PING with sequence number n and optional attempt number m . This defines or updates the cycle with key $(epoch, n)$ and the maximum attempt number for that cycle.
4. **Completion:** A cycle $(epoch, n)$ is marked completed when the corresponding PING-PONG cycle completion is recorded.

A large backward jump in sequence number (e.g., $n < n_{\text{last}} - 10$) is treated as a new reset epoch so that cycles before and after the jump are distinguished.

Outcome Categories

Each communication cycle is assigned exactly one outcome category based on the following priority:

- **Success (immediate):** Completed, no hardware reset during the cycle, and only one attempt (no retry).
- **Successful after retri**al: Completed, no hardware reset, and at least one retry (attempt > 1).
- **Successful after hardware reset:** Completed and a hardware RX reset occurred during the cycle (regardless of retries).
- **Failed:** Not completed (e.g., timeout or unrecovered error; power cycle may be required).

Priority is applied in that order: if a cycle completed and had a hardware reset, it is counted as “after hardware reset” even if it also had retries. The *reception rate* (success rate) is the fraction of cycles that are successful in any of the three successful categories.

Exclusions and Boundary Effects

The *last* cycle in each run (by sequence number in the latest epoch) is excluded from the totals if it is incomplete, to avoid counting cycles truncated by the run stop time. All other cycles are included. Total cycle count n and success count k used for reception and data rate calculations refer to included cycles only.

5.2.7 Experimental Results

Current Analysis

The restart events can be observed in Figure 5.21, shown as vertical lines. The restarts are categorized as either intentional (performed before each run) or error-induced (board restarts or user-initiated power cycles). Figure 5.22 provides a categorization of the error-induced resets.

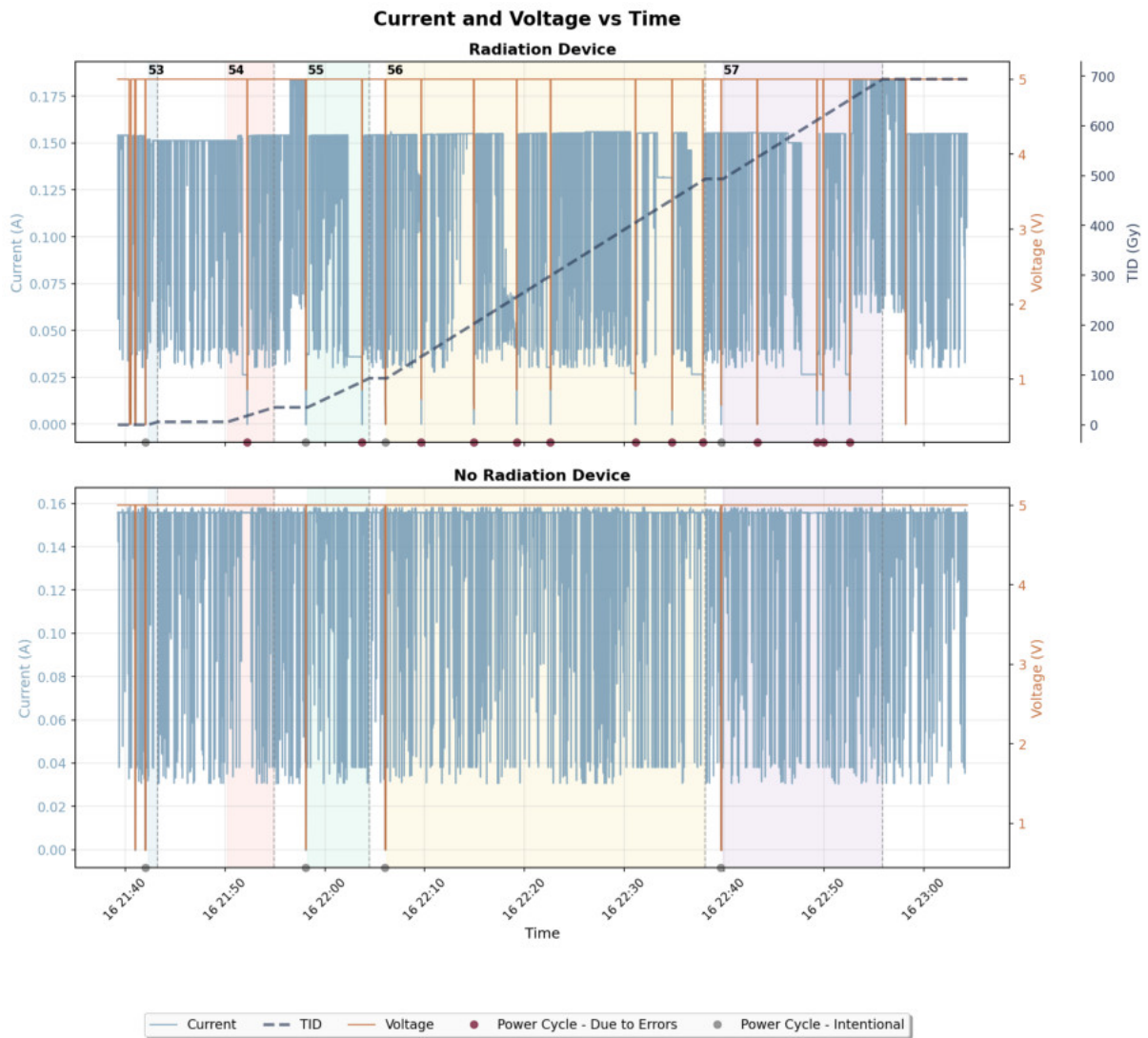


Figure 5.21: Current, voltage, and TID over time during the PSI radiation test.

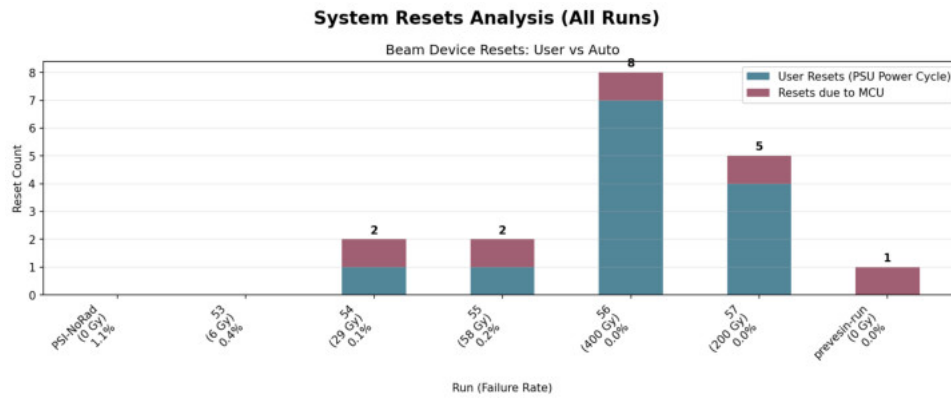


Figure 5.22: Categorization of resets during the radiation test.

Packet Success Rate and Error Classification

Communication cycles were classified into several categories for analysis:

- **Success (No HW Reset):** Cycles that completed successfully without requiring a hardware reset, including cycles with no errors and cycles that encountered a Leading Edge Detection Error (LDEERR) but recovered automatically.
- **HW Reset Recovery:** Cycles that encountered a timeout or error but successfully recovered after one or more hardware resets.
- **Power Cycle (Intentional):** System power cycles occurring within ± 10 seconds of the run start time, used for system initialization.
- **Power Cycle (Unintentional):** System power cycles during run execution (more than 10 seconds after run start), representing unexpected power interruptions potentially caused by radiation effects.
- **Failed: Stuck:** Cycles that failed due to a frame stuck condition without LDEERR.
- **Failed: LDEERR+Stuck:** Cycles with both LDEERR and frame stuck conditions.
- **Failed: LDEERR:** Cycles that failed due to LDEERR without frame stuck.

Figure 5.23 presents the success rate and error distribution across all runs.

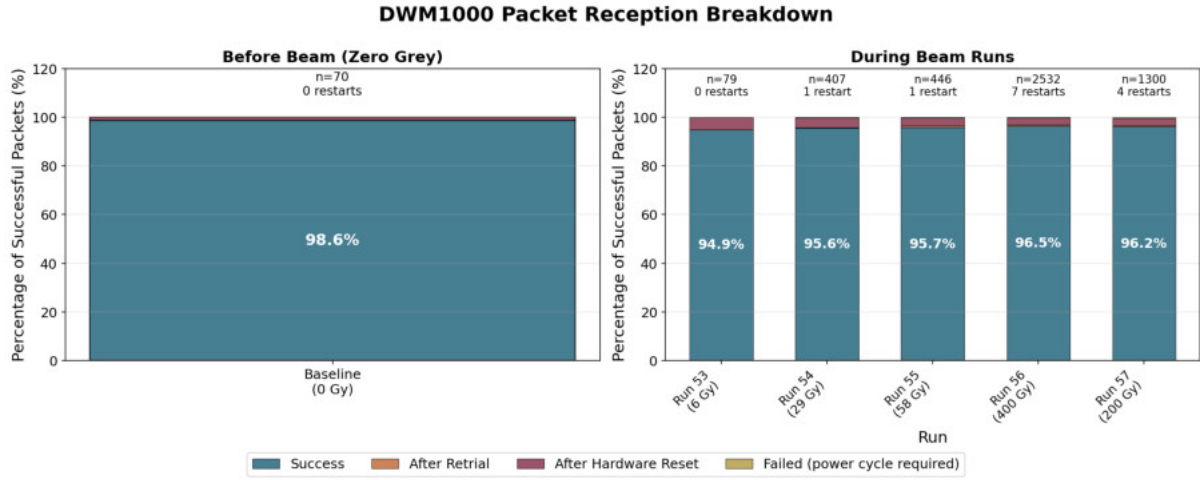


Figure 5.23: Communication cycle success rate and error classification across all runs.

Derived Quantities and Metrics

The reception rate (success fraction) is calculated as:

$$p = \frac{k}{n}, \quad k = n_{\text{imm}} + n_{\text{retrial}} + n_{\text{hw}}, \quad (5.6)$$

where n is the total number of included cycles and k is the number of successful cycles (immediate + after retrial + after hardware reset). This is reported as a percentage, e.g., 100 p %.

The data rate is derived from the packet reception summary per run:

$$R_{\text{packets}} = \frac{k}{T}, \quad R_{\text{data}} = R_{\text{packets}} \times L_{\text{packet}} \times 8 \quad \text{bits/s}, \quad (5.7)$$

where T is the run duration in seconds (from the logbook stop minus start time) and $L_{\text{packet}} = 13$ bytes. Efficiency is 100 k/n %.

Single Event Functional Interrupt (SEFI) Results

Single Event Functional Interrupts (SEFI) were observed as events requiring manual operator intervention to restore device functionality. A total of 13 manual resets were recorded across the five irradiation runs, with the frequency increasing with accumulated dose and flux.

Run 53 (5.9 Gy, 1×10^{10} p/cm²) completed without any SEFI events. Runs 54 and 55 each required one manual reset, primarily due to MCU communication failures. The SEFI rate increased significantly during high-flux exposures: Run 56 (400.2 Gy at 3.6×10^8 p/cm²/s) required 7 manual interventions, including instances where the DWM1000 became stuck in a preamble detection loop. Run 57 required 4 manual resets, all attributed to communication hangs.

The observed SEFI manifestations can be categorized into two types: MCU freeze requiring full power cycle (detected by serial communication failure), and DWM1000 transceiver state machine lockup characterized by continuous preamble detection without frame completion (SYS_STATE: 0x00050002). Au-

tomatic software-level recovery mechanisms (hardware RX reset sequences) successfully resolved the majority of transient errors; SEFI events represent only those cases where internal recovery logic failed.

The SEFI cross-section, estimated from the 13 events over a cumulative fluence of $1.13 \times 10^{12} \text{ p/cm}^2$, is approximately $1.2 \times 10^{-11} \text{ cm}^2/\text{device}$.

Single Event Latchup (SEL) Results

One Single Event Latchup (SEL) was observed during the last cycle, where the current increased from 0.155 A to 0.184 A (at 22:52:54). The recorded event stream for this period shows a sequence of LDEERR events, timeout errors, and retries; the system was attempting to transmit PING sequence #987 when the latchup occurred:

```
2025-11-16 22:52:54 [COM4] [DEBUG] Preamble detected (State: 0x00010000)
2025-11-16 22:52:54 [COM4] [ERROR] LDEERR detected during frame reception
2025-11-16 22:52:55 [COM4] [ERROR] No PONG received - timeout (expected #987)
```

The SEL manifested as a 19% increase in supply current (from 155 mA to 184 mA), which persisted until a power cycle was performed at 22:58 to verify whether power consumption would return to the pre-irradiation baseline, resulting in returning to nominal consumption.

5.2.8 Uncertainties and Error Analysis

Reception Rate Uncertainty (Binomial Proportion)

The number of successful cycles k out of n cycles is treated as a binomial outcome with success probability p . The standard error of the proportion $\hat{p} = k/n$ is:

$$\sigma_{\hat{p}} = \sqrt{\frac{\hat{p}(1 - \hat{p})}{n}}. \quad (5.8)$$

When reporting the reception rate as a percentage, the uncertainty (one standard error) is:

$$\sigma_{\text{reception}} = 100 \sigma_{\hat{p}} \quad (\%). \quad (5.9)$$

For small or large $\hat{p}$, or small n , a Wilson score interval or other binomial interval may be preferred for confidence limits; the standard error above is still a useful summary of statistical uncertainty.

Data Rate Uncertainty

The count uncertainty arises because the number of successful packets k in a run has binomial variance $np(1 - p)$. The rate k/T thus has approximate standard error $\sqrt{np(1 - p)}/T$ packets/s. Propagating to data rate in bits/s with fixed $L_{\text{packet}} = 13 \times 8$ bits gives a statistical error on the data rate from count fluctuation.

Regarding duration uncertainty, the run duration T is taken from the logbook (start/stop). Any systematic offset or rounding in these times affects the data rate (e.g., $\Delta R/R \approx -\Delta T/T$). No explicit uncertainty on T is applied in the current analysis.

Systematic and Classification Caveats

Several systematic effects should be considered when interpreting results:

- **Time window:** Results depend on the chosen run start/stop times; misalignment with the actual beam-on or DWM activity window can bias cycle counts and rates.
- **Last-cycle exclusion:** Excluding the last cycle only when incomplete avoids one obvious truncation bias; any other boundary effects (e.g., first cycle after beam-on) are not corrected.
- **Category assignment:** Outcome categories are inferred from the recorded event types (hardware reset, completion, attempt count). Misclassification can occur if events are missing or duplicated in the recorded stream.
- **PSU restarts:** The number of PSU restarts is reported separately; cycles after a restart are still classified as success/failure by the same rules. No separate uncertainty is assigned to the restart count.

5.2.9 Summary

The radiation test of the DWM1000 UWB transceiver at PSI revealed several radiation-induced effects. The device accumulated a total dose of 693.7 Gy with 13 SEFI events requiring manual intervention, yielding a SEFI cross-section of approximately $1.2 \times 10^{-11} \text{ cm}^2/\text{device}$. One SEL event was observed at the end of the test campaign. The automatic software recovery mechanisms proved effective at handling the majority of transient errors, with SEFI events representing cases where these mechanisms were insufficient. The results indicate that while the DWM1000 experiences radiation-induced effects at the tested dose levels, appropriate mitigation strategies such as watchdog timers, automatic recovery sequences, and latchup protection circuits could enable its use in radiation-tolerant systems.

The analysis derives per-run reception rates and data rates from the recorded event stream and logbook run windows. Cycles are defined by TX PING and PING-PONG completion events, and classified into immediate success, success after retrial, success after hardware reset, or failed. The reception rate is reported as a percentage with a binomial standard error; data rate uncertainty follows from count and duration uncertainty. Systematic effects from time windows, boundary exclusions, and event identification should be borne in mind when interpreting the results.

6. Conclusions and Summary

This thesis presented the design, implementation, and experimental validation of Astromesh, the first LoRa-based meshed network platform validated for radiation environments, targeting applications in satellite constellations and particle accelerator facilities. The work addressed four main objectives: establishing a theoretical foundation, developing modular embedded software, performing radiation testing, and conducting a mission analysis with link budget study. The key contributions and findings are summarised below.

Embedded Software

A layered software architecture was developed for the Astromesh platform, enabling mesh networking across the supported transceivers (868 MHz, ISM 2.4 GHz, and UWB 3.5–6.5 GHz). The inter-satellite link path integrates the RadioHead library (used unmodified) through a thin C++ wrapper, exposing a clean C API for route discovery, packet forwarding, and reliable datagram exchange via the RFM95W at 868 MHz. For the in-satellite link, a fully custom C driver was developed for the Qorvo DWM1000 UWB transceiver, implementing register-level configuration, SPI transaction handling, and a ping-pong communication protocol. The modular design ensures that only one transceiver is active on the shared SPI bus at any time, while the SX1280 and LR1121 drivers provide initialisation and sleep management. Mesh operation was successfully demonstrated with multiple Astromesh boards in a four-node topology, validating dynamic route discovery and multi-hop packet forwarding.

Radiation Testing at CHARM

A hierarchical LoRaWAN network comprising nine Feather M0 end devices and three gateways was tested under mixed-field radiation at the CHARM facility. The per-device packet success rate under radiation ranged from 91.4% to approximately 98%, with packet loss rates between 1.9% and 6.4%. Reset counts varied from 4 (End Device 3) to 110 (End Devices 7, 8, and 10), with devices at the higher-flux R1 position exhibiting the highest sensitivity. The measured Single Event Effect (SEE) cross-sections ranged from $2.0 \times 10^{-11} \text{ cm}^2$ for the most radiation-tolerant device to $56.2 \times 10^{-11} \text{ cm}^2$ for devices at R1 and overhead positions.

A direct comparison with the mesh network radiation test conducted by Mancini (2025) at the same CHARM facility revealed a clear resilience advantage for the mesh topology. The mesh network achieved a Packet Delivery Rate (PDR) consistently above 99.99% and a combined two-gateway packet loss of only 0.001%, reducing losses by roughly a factor of 20 compared to either single gateway alone. The Feather M0 SEE cross-sections from both campaigns are consistent ($7.3\text{--}15.6 \times 10^{-11} \text{ cm}^2$ at G0 for the mesh versus $2.0\text{--}22.0 \times 10^{-11} \text{ cm}^2$ for equivalent positions in this work), confirming that the observed performance differences are attributable to topology, protocol, and node placement rather than platform variability. These results provide strong quantitative motivation for the decentralised mesh architecture implemented on the Astromesh platform.

Radiation Testing at PSI

The DWM1000 UWB transceiver was characterised for radiation tolerance at the PSI Proton Irradiation Facility using a 200 MeV proton beam across five irradiation runs. The device accumulated a total dose of 693.7 Gy with a proton fluence of 1.13×10^{12} p/cm². A total of 13 Single Event Functional Interrupts (SEFIs) requiring manual intervention were recorded, yielding a SEFI cross-section of approximately 1.2×10^{-11} cm²/device. One Single Event Latchup (SEL) was observed during the final run, manifesting as a 19% increase in supply current (from 155 mA to 184 mA) that persisted until a power cycle was performed. The automatic software recovery mechanisms—hardware RX reset sequences built into the firmware—proved effective at handling the majority of transient errors, with SEFI events representing only those cases where internal recovery was insufficient. These results indicate that, while the DWM1000 experiences radiation-induced effects at the tested dose levels, appropriate mitigation strategies such as watchdog timers, automatic recovery sequences, and latchup protection circuits could enable its use in radiation-tolerant systems.

Mission Analysis and Link Budget

The link budget analysis, performed using Ansys STK for a 550 km Sun-Synchronous Orbit (SSO), evaluated the inter-satellite communication feasibility of the three Astromesh transceivers. At 868 MHz, the RF95 achieves a maximum reliable distance of approximately 4 200 km (SF12, 125 kHz), while the LR1121 offers the best performance at approximately 7 800 km (SF11, 62.5 kHz). The 2.4 GHz transceivers (SX1280 and LR1121) are limited to approximately 500–540 km, rendering them unsuitable for inter-satellite links with the current antenna configuration.

For constellations sharing the same orbital plane (same LTAN), two satellites without station keeping can maintain communication for 3–4 months before differential atmospheric drag causes them to exceed the link budget. Full orbit coverage with station keeping requires a minimum of eight satellites equally spaced at 45° intervals (separation $\sim 5\,302$ km), with a ΔV budget of approximately 1.095 m/s per satellite and a deployment separation time of about 19 days. For constellations with different LTAN, a maximum temporal offset of 1.5 hours ensures line-of-sight visibility. The 2.4 GHz band, with its maximum range below 541 km, would require a constellation of 164 satellites to achieve equivalent coverage, confirming that the sub-GHz bands are the only viable option for LoRa-based inter-satellite links using omnidirectional antennas.

Overall Significance

Taken together, the results of this work establish the Astromesh platform as a viable foundation for radiation-tolerant LoRa mesh networks in both accelerator and space environments. The radiation test campaigns at CHARM and PSI provided the first experimental evidence that LoRa-based mesh topologies offer superior reliability compared to hierarchical architectures under realistic radiation conditions. The mission analysis demonstrated that 868 MHz inter-satellite links are feasible in LEO with practical constellation sizes, bridging the gap between platform validation and mission-level design.

This work contributes to the advancement of next-generation wireless communication for high-energy physics facilities such as the Future Circular Collider and for CubeSat-based satellite constellations.

Future Work

Several directions for future investigation emerge from this thesis. First, radiation testing of the full Astromesh mesh network (rather than only the hierarchical baseline) at CHARM would allow a direct, same-campaign comparison of mesh and hierarchical performance under identical radiation conditions. Second, the DWM1000 latchup protection and automatic recovery mechanisms should be further developed and validated under extended irradiation campaigns to refine the SEL cross-section estimate and assess long-term TID degradation. Third, in-orbit demonstration of the Astromesh platform on a CubeSat mission would provide flight heritage and validate the link budget predictions under real space conditions. Finally, the integration of adaptive data rate and topology-aware routing algorithms into the mesh firmware could improve throughput and energy efficiency, particularly for multi-hop scenarios in large-scale constellations.

7. Appendix

7.1 Complete Link Budget Analysis Results

This annex collects the full set of link margin vs. distance plots, maximum reliable distance comparisons, data rate trade-off charts, and the corresponding numerical results for every transceiver and bandwidth configuration analysed. A link margin of at least 3 dB was considered for reliable communication.

7.1.1 RF95 (868 MHz)

125 kHz Bandwidth

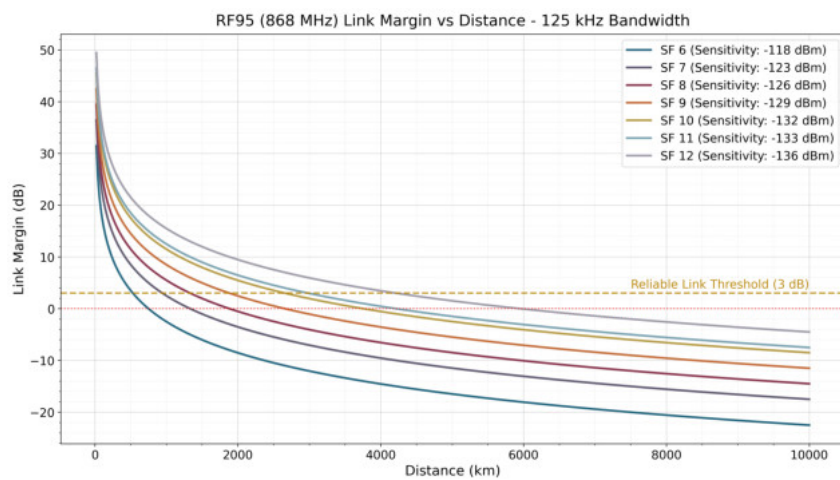


Figure 7.1: RF95 link margin vs. distance for all spreading factors at 125 kHz bandwidth.

Parameters	
EIRP	25.6 dBm
Frequency	868 MHz
Tx Antenna Gain	6 dBi
Rx Antenna Gain	6 dBi
Bandwidth	125 kHz

Max. Reliable Distance (125 kHz)	
SF 6	541.1 km
SF 7	961.9 km
SF 8	1342.7 km
SF 9	1883.8 km
SF 10	2665.3 km
SF 11	2986.0 km
SF 12	4208.4 km

250 kHz Bandwidth

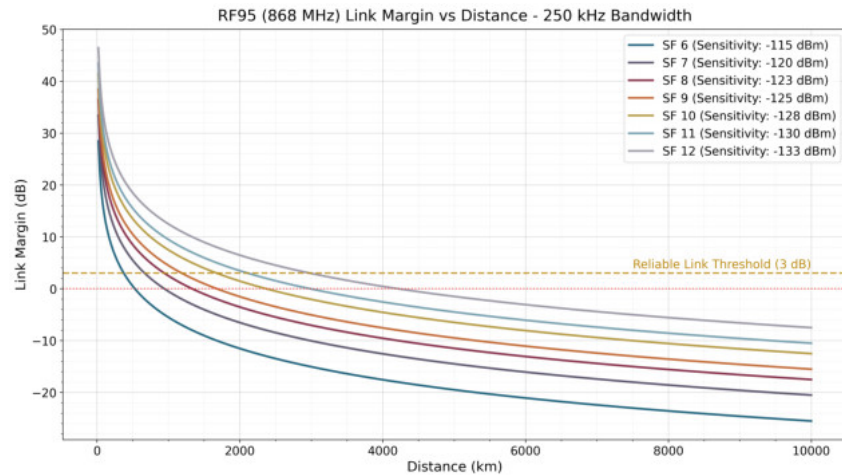


Figure 7.2: RF95 link margin vs. distance for all spreading factors at 250 kHz bandwidth.

Parameters	
EIRP	25.6 dBm
Frequency	868 MHz
Tx Antenna Gain	6 dBi
Rx Antenna Gain	6 dBi
Bandwidth	250 kHz

Max. Reliable Distance (250 kHz)	
SF 6	380.8 km
SF 7	681.4 km
SF 8	961.9 km
SF 9	1202.4 km
SF 10	1683.4 km
SF 11	2124.2 km
SF 12	2986.0 km

500 kHz Bandwidth

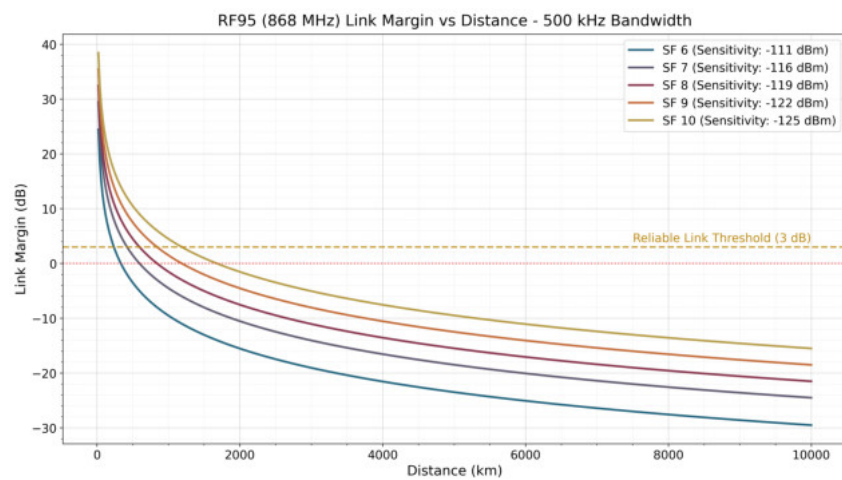


Figure 7.3: RF95 link margin vs. distance for all spreading factors at 500 kHz bandwidth.

Parameters	
EIRP	25.6 dBm
Frequency	868 MHz
Tx Antenna Gain	6 dBi
Rx Antenna Gain	6 dBi
Bandwidth	500 kHz

Max. Reliable Distance (500 kHz)	
SF 6	240.5 km
SF 7	420.8 km
SF 8	601.2 km
SF 9	841.7 km
SF 10	1202.4 km

Maximum Distance Comparison

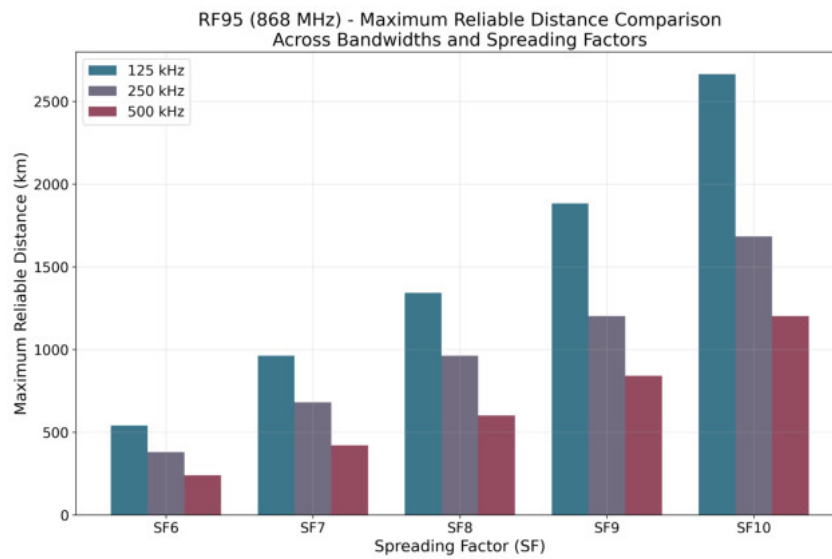


Figure 7.4: RF95 (868 MHz) maximum reliable distance comparison across bandwidths and spreading factors.

7.1.2 LR1121 (868 MHz)

62.5 kHz Bandwidth

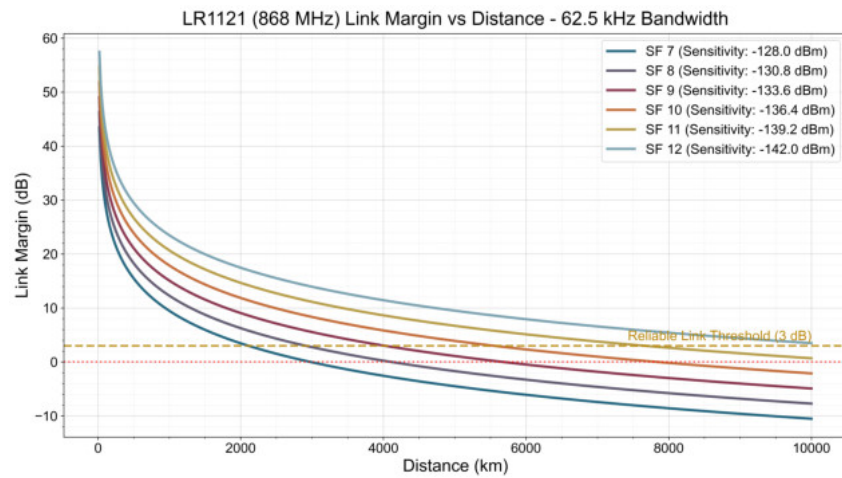


Figure 7.5: LR1121 (868 MHz) link margin vs. distance for all spreading factors at 62.5 kHz bandwidth.

Parameters	
Tx Power	158.4 mW
EIRP	27.6 dBm
Frequency	868 MHz
Tx Antenna Gain	6 dBi
Rx Antenna Gain	6 dBi
Tx Line Losses	0.4 dB
Rx Line Losses	0.4 dB
Bandwidth	62.5 kHz

Max. Reliable Distance (62.5 kHz)	
SF 7	2124.2 km
SF 8	2925.9 km
SF 9	4028.1 km
SF 10	5551.1 km
SF 11	7675.4 km

125 kHz Bandwidth

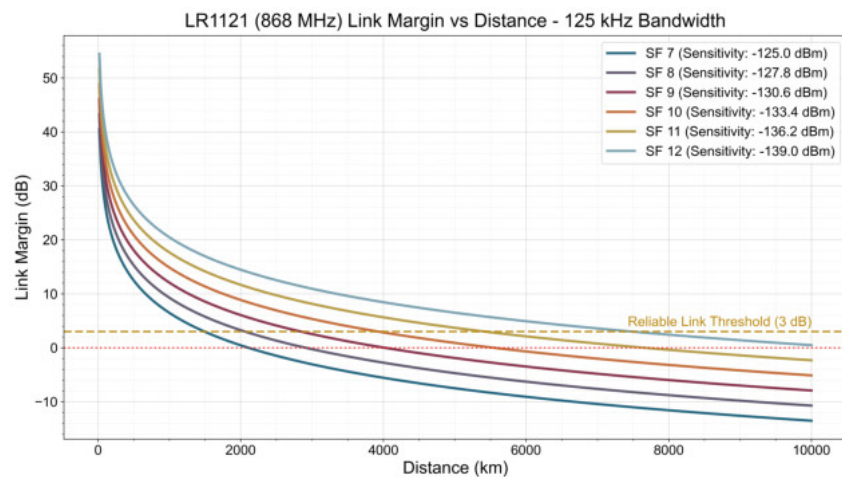


Figure 7.6: LR1121 (868 MHz) link margin vs. distance for all spreading factors at 125 kHz bandwidth.

Parameters	
Tx Power	158.4 mW
EIRP	27.6 dBm
Frequency	868 MHz
Tx Antenna Gain	6 dBi
Rx Antenna Gain	6 dBi
Tx Line Losses	0.4 dB
Rx Line Losses	0.4 dB
Bandwidth	125 kHz

Max. Reliable Distance (125 kHz)	
SF 7	1503.0 km
SF 8	2064.1 km
SF 9	2845.7 km
SF 10	3927.9 km
SF 11	5430.9 km
SF 12	7495.0 km

250 kHz Bandwidth

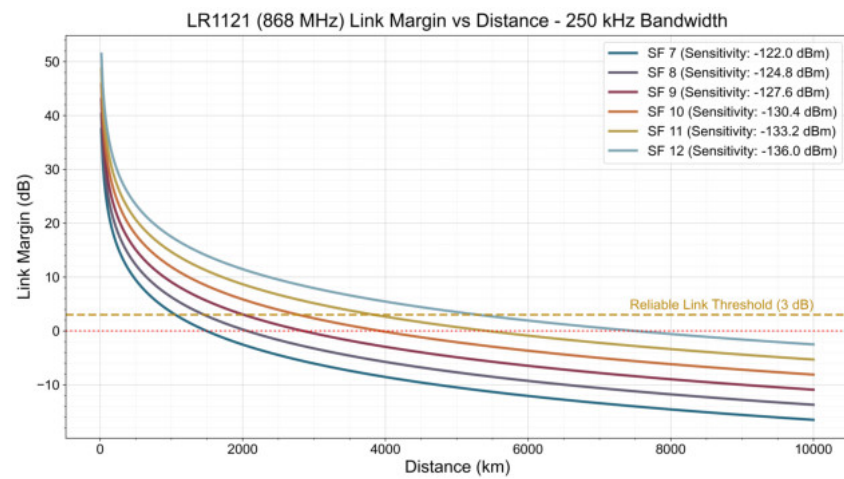


Figure 7.7: LR1121 (868 MHz) link margin vs. distance for all spreading factors at 250 kHz bandwidth.

Parameters	
Tx Power	158.4 mW
EIRP	27.6 dBm
Frequency	868 MHz
Tx Antenna Gain	6 dBi
Rx Antenna Gain	6 dBi
Tx Line Losses	0.4 dB
Rx Line Losses	0.4 dB
Bandwidth	250 kHz

Max. Reliable Distance (250 kHz)	
SF 7	1062.1 km
SF 8	1462.9 km
SF 9	2024.0 km
SF 10	2785.6 km
SF 11	3847.7 km
SF 12	5310.6 km

500 kHz Bandwidth

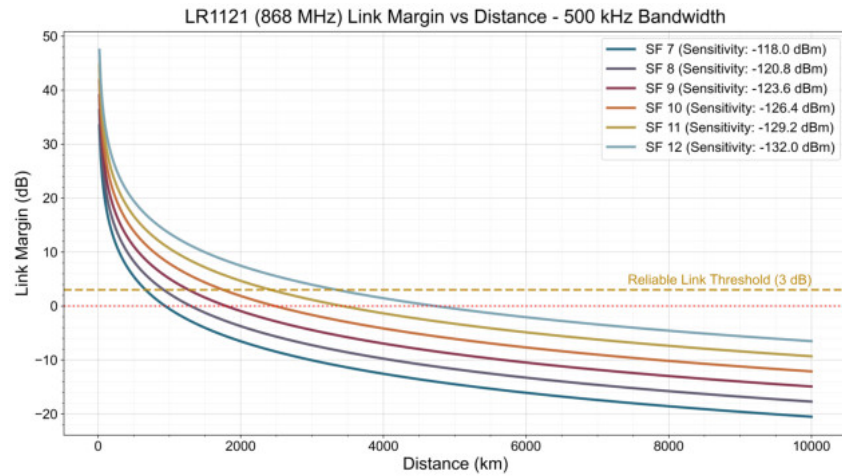


Figure 7.8: LR1121 (868 MHz) link margin vs. distance for all spreading factors at 500 kHz bandwidth.

Parameters		Max. Reliable Distance (500 kHz)	
Tx Power	158.4 mW	SF 7	681.4 km
EIRP	27.6 dBm	SF 8	921.8 km
Frequency	868 MHz	SF 9	1282.6 km
Tx Antenna Gain	6 dBi	SF 10	1763.5 km
Rx Antenna Gain	6 dBi	SF 11	2424.8 km
Tx Line Losses	0.4 dB	SF 12	3346.7 km
Rx Line Losses	0.4 dB		
Bandwidth	500 kHz		

Maximum Distance Comparison

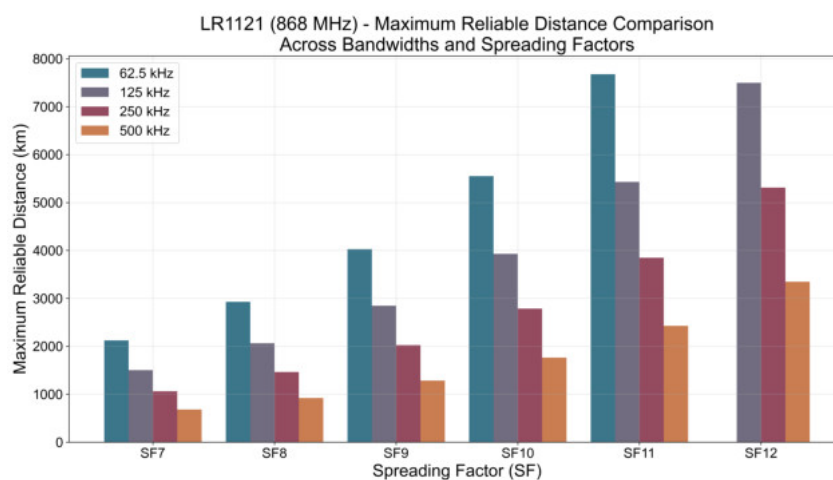


Figure 7.9: LR1121 (868 MHz) maximum reliable distance comparison across bandwidths and spreading factors.

7.1.3 SX1280 (2.4 GHz)

203 kHz Bandwidth

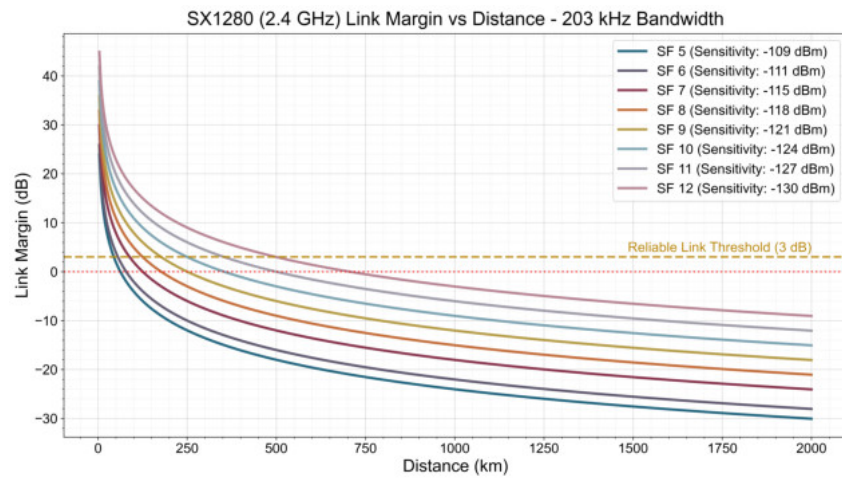


Figure 7.10: SX1280 link margin vs. distance for all spreading factors at 203 kHz bandwidth.

Parameters	
EIRP	19.9 dBm
Frequency	2400 MHz
Tx Antenna Gain	8 dBi
Rx Antenna Gain	8 dBi
Bandwidth	203 kHz

Max. Reliable Distance (203 kHz)	
SF 5	48.1 km
SF 6	56.1 km
SF 7	92.2 km
SF 8	128.3 km
SF 9	180.4 km
SF 10	252.5 km
SF 11	356.7 km
SF 12	501.0 km

406 kHz Bandwidth

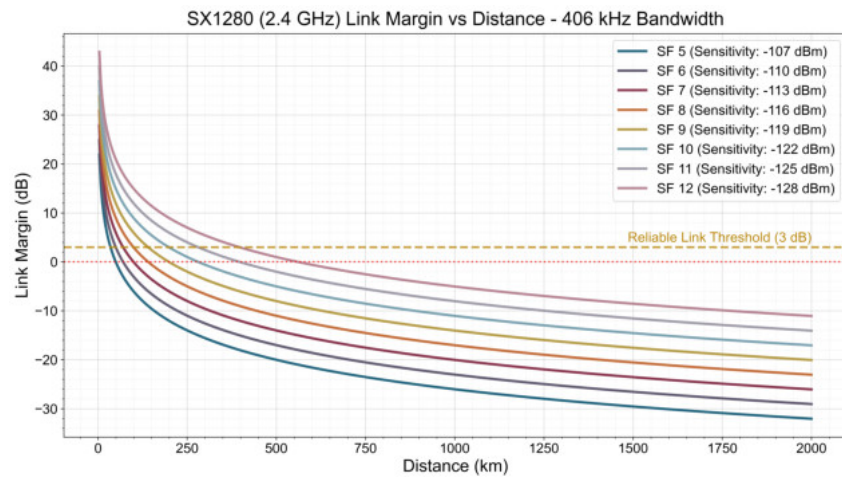


Figure 7.11: SX1280 link margin vs. distance for all spreading factors at 406 kHz bandwidth.

Parameters	
EIRP	19.9 dBm
Frequency	2400 MHz
Tx Antenna Gain	8 dBi
Rx Antenna Gain	8 dBi
Bandwidth	406 kHz

Max. Reliable Distance (406 kHz)

SF 5	36.1 km
SF 6	52.1 km
SF 7	72.1 km
SF 8	100.2 km
SF 9	144.3 km
SF 10	200.4 km
SF 11	280.6 km
SF 12	396.8 km

812 kHz Bandwidth

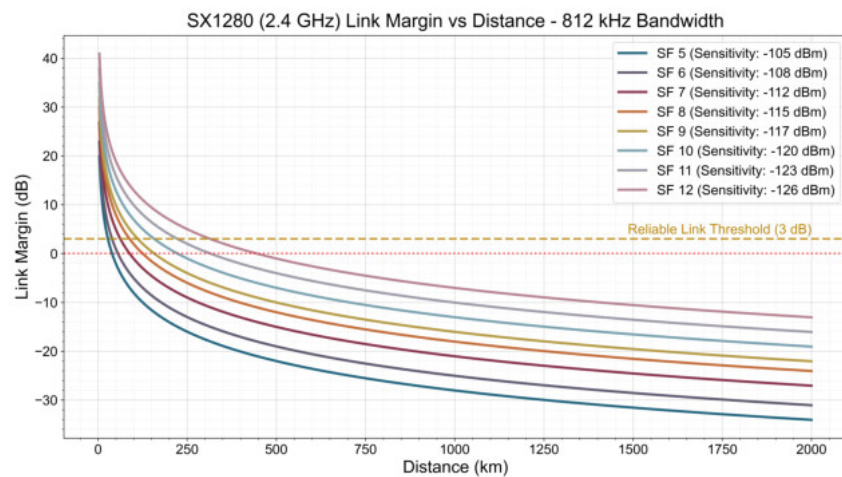


Figure 7.12: SX1280 link margin vs. distance for all spreading factors at 812 kHz bandwidth.

Parameters	
EIRP	19.9 dBm
Frequency	2400 MHz
Tx Antenna Gain	8 dBi
Rx Antenna Gain	8 dBi
Bandwidth	812 kHz

Max. Reliable Distance (812 kHz)

SF 5	28.1 km
SF 6	40.1 km
SF 7	64.1 km
SF 8	92.2 km
SF 9	112.2 km
SF 10	160.3 km
SF 11	224.4 km
SF 12	316.6 km

1625 kHz Bandwidth

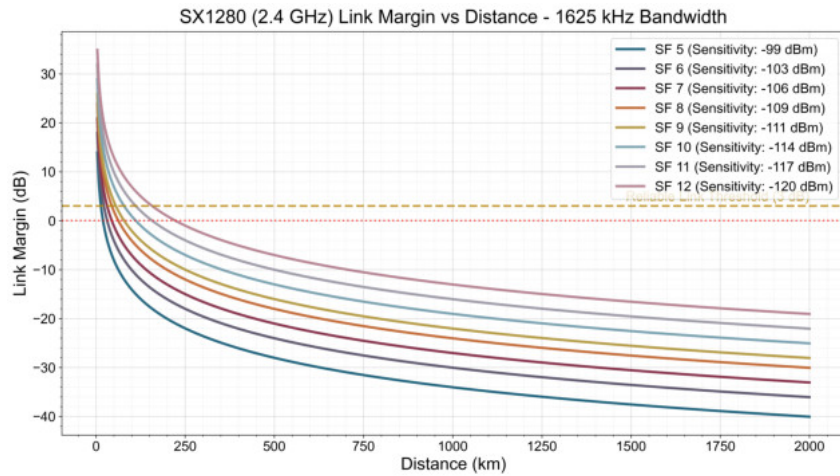


Figure 7.13: SX1280 link margin vs. distance for all spreading factors at 1625 kHz bandwidth.

Parameters	
EIRP	19.9 dBm
Frequency	2400 MHz
Tx Antenna Gain	8 dBi
Rx Antenna Gain	8 dBi
Bandwidth	1625 kHz

Max. Reliable Distance (1625 kHz)

SF 5	16.0 km
SF 6	24.0 km
SF 7	32.1 km
SF 8	48.1 km
SF 9	56.1 km
SF 10	80.2 km
SF 11	112.2 km
SF 12	160.3 km

Maximum Distance Comparison

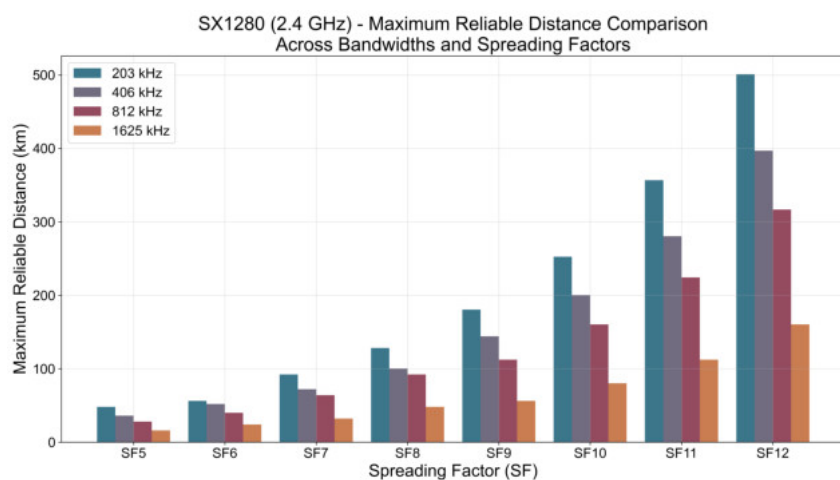


Figure 7.14: SX1280 (2.4 GHz) maximum reliable distance comparison across bandwidths and spreading factors.

7.1.4 LR1121 (2.4 GHz)

125 kHz Bandwidth

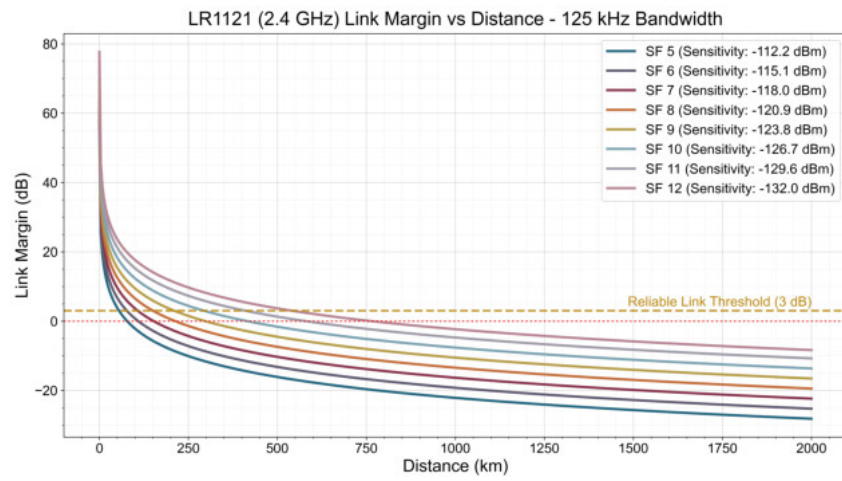


Figure 7.15: LR1121 (2.4 GHz) link margin vs. distance for all spreading factors at 125 kHz bandwidth.

Parameters		Max. Reliable Distance (125 kHz)	
Tx Power	20.0 mW (13.0 dBm)	SF 5	56.2 km
EIRP	20.6 dBm	SF 6	80.3 km
Frequency	2400 MHz	SF 7	108.3 km
Tx Antenna Gain	8 dBi	SF 8	152.4 km
Rx Antenna Gain	6 dBi	SF 9	212.5 km
Tx Line Losses	0.4 dB	SF 10	296.7 km
Rx Line Losses	0.4 dB	SF 11	412.9 km
Bandwidth	125 kHz	SF 12	541.2 km

250 kHz Bandwidth

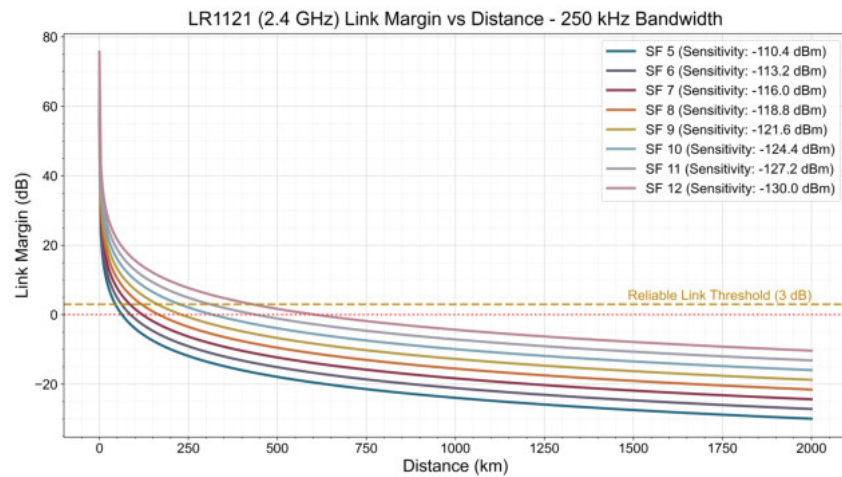


Figure 7.16: LR1121 (2.4 GHz) link margin vs. distance for all spreading factors at 250 kHz bandwidth.

Parameters		Max. Reliable Distance (250 kHz)	
Tx Power	20.0 mW (13.0 dBm)	SF 5	48.2 km
EIRP	20.6 dBm	SF 6	64.2 km
Frequency	2400 MHz	SF 7	88.3 km
Tx Antenna Gain	8 dBi	SF 8	120.3 km
Rx Antenna Gain	6 dBi	SF 9	164.4 km
Tx Line Losses	0.4 dB	SF 10	228.5 km
Rx Line Losses	0.4 dB	SF 11	312.7 km
Bandwidth	250 kHz	SF 12	432.9 km

500 kHz Bandwidth

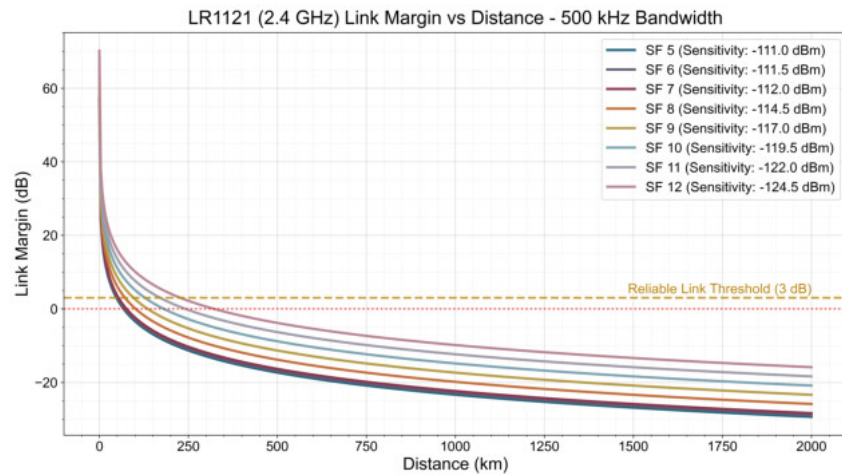


Figure 7.17: LR1121 (2.4 GHz) link margin vs. distance for all spreading factors at 500 kHz bandwidth.

Parameters		Max. Reliable Distance (500 kHz)	
Tx Power	20.0 mW (13.0 dBm)	SF 5	48.2 km
EIRP	20.6 dBm	SF 6	52.2 km
Frequency	2400 MHz	SF 7	56.2 km
Tx Antenna Gain	8 dBi	SF 8	72.2 km
Rx Antenna Gain	6 dBi	SF 9	96.3 km
Tx Line Losses	0.4 dB	SF 10	128.4 km
Rx Line Losses	0.4 dB	SF 11	172.4 km
Bandwidth	500 kHz	SF 12	228.5 km

812 kHz Bandwidth

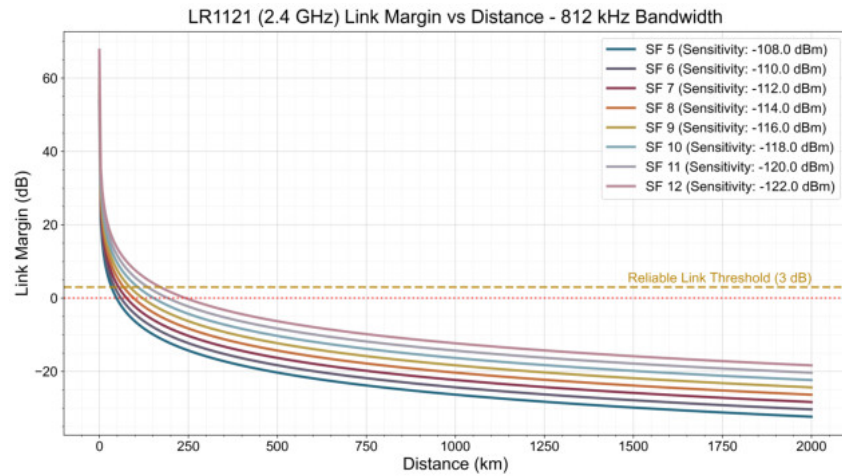


Figure 7.18: LR1121 (2.4 GHz) link margin vs. distance for all spreading factors at 812 kHz bandwidth.

Parameters		Max. Reliable Distance (812 kHz)	
Tx Power	20.0 mW (13.0 dBm)	SF 5	36.2 km
EIRP	20.6 dBm	SF 6	44.2 km
Frequency	2400 MHz	SF 7	56.2 km
Tx Antenna Gain	8 dBi	SF 8	68.2 km
Rx Antenna Gain	6 dBi	SF 9	88.3 km
Tx Line Losses	0.4 dB	SF 10	108.3 km
Rx Line Losses	0.4 dB	SF 11	136.4 km
Bandwidth	812 kHz	SF 12	172.4 km

Maximum Distance Comparison

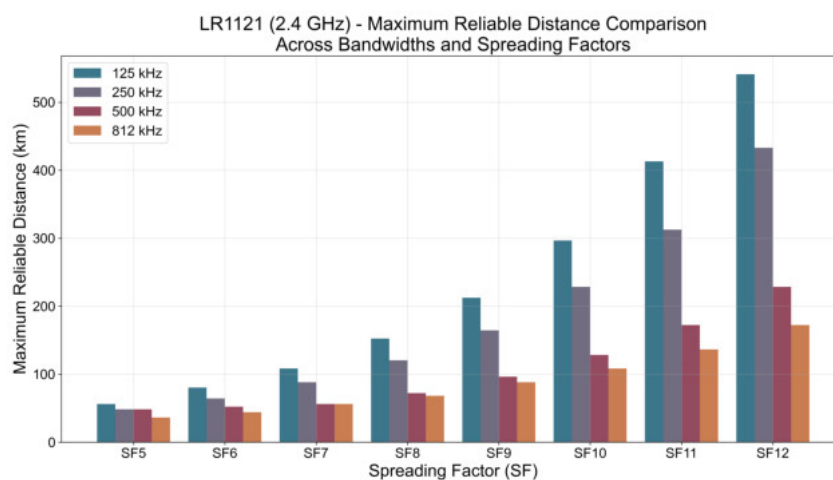


Figure 7.19: LR1121 (2.4 GHz) maximum reliable distance comparison across bandwidths and spreading factors.

7.1.5 Formation Flying and Access Analysis

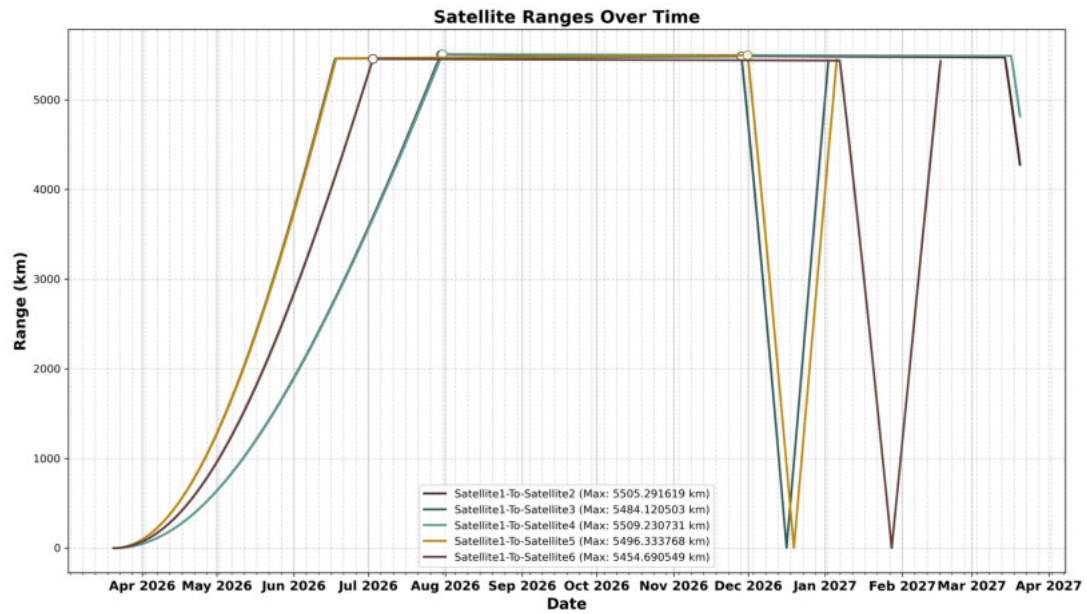


Figure 7.20: Inter-satellite range vs. time for all satellite pairs in the six-satellite constellation.

Time-Resolved Link Analysis (RF95, 125 kHz)

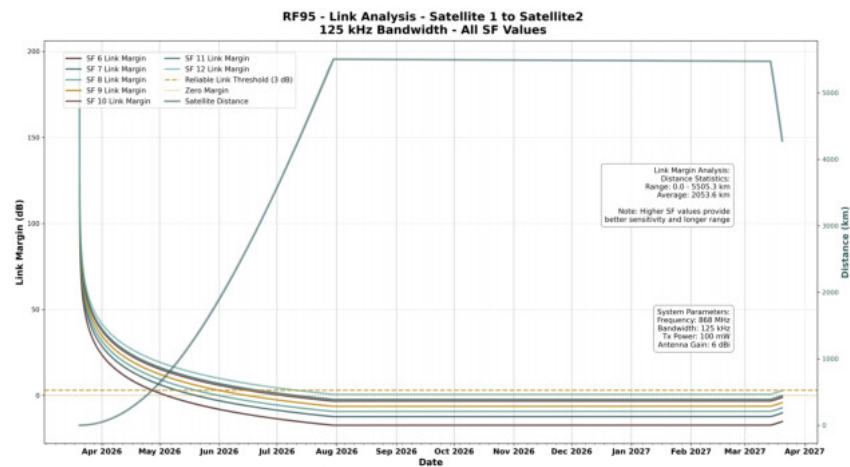


Figure 7.21: Link analysis: Satellite 1 to Satellite 2, RF95, 868 MHz, 125 kHz.

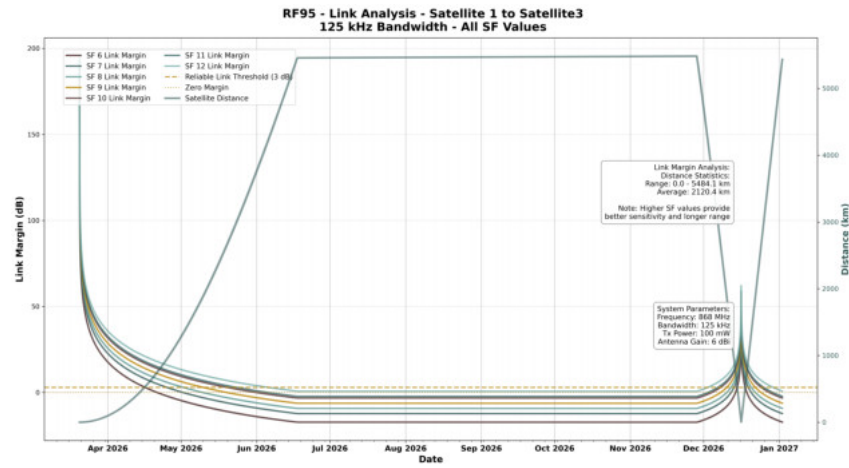


Figure 7.22: Link analysis: Satellite 1 to Satellite 3, RF95, 868 MHz, 125 kHz.

Time-Resolved Link Analysis (RF95, 250 kHz)

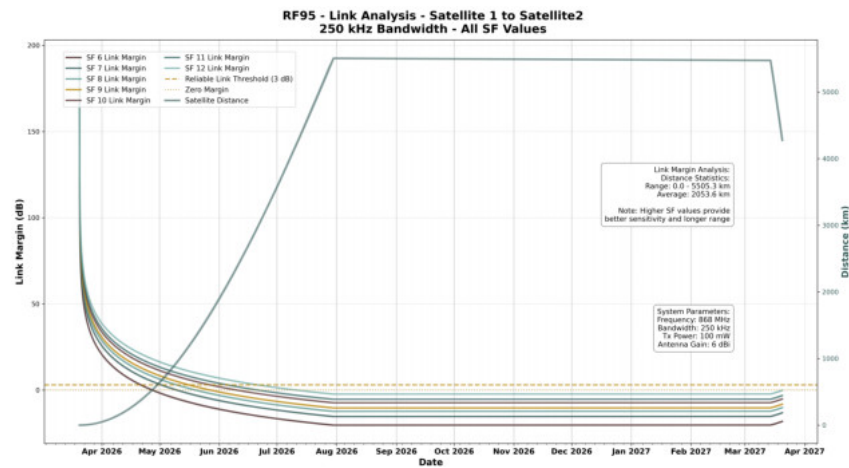


Figure 7.23: Link analysis: Satellite 1 to Satellite 2, RF95, 868 MHz, 250 kHz.

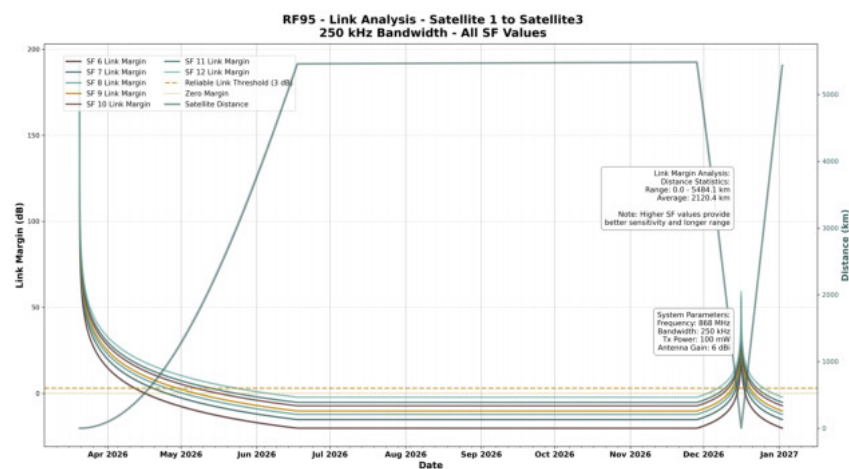


Figure 7.24: Link analysis: Satellite 1 to Satellite 3, RF95, 868 MHz, 250 kHz.

Time-Resolved Link Analysis (RF95, 500 kHz)

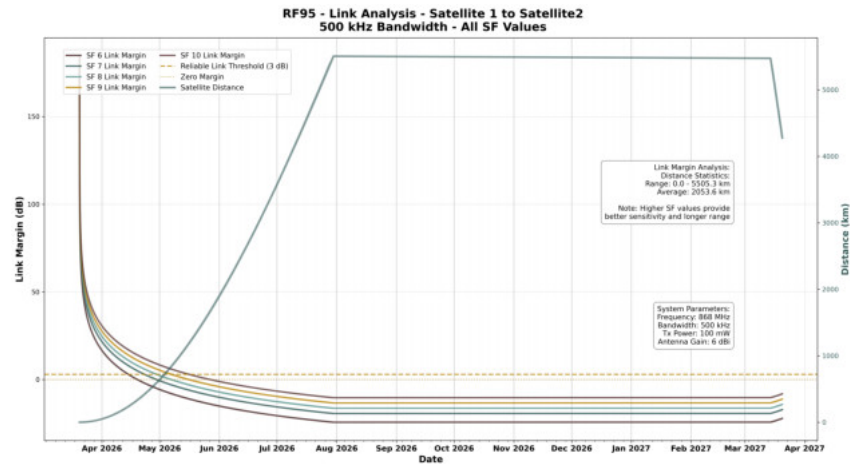


Figure 7.25: Link analysis: Satellite 1 to Satellite 2, RF95, 868 MHz, 500 kHz.

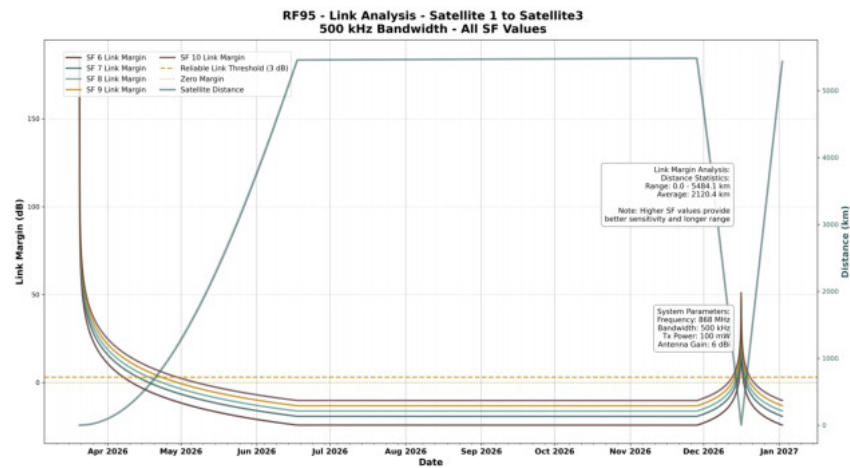


Figure 7.26: Link analysis: Satellite 1 to Satellite 3, RF95, 868 MHz, 500 kHz.

Time-Resolved Link Analysis (LR1121, 868 MHz)

62.5 kHz

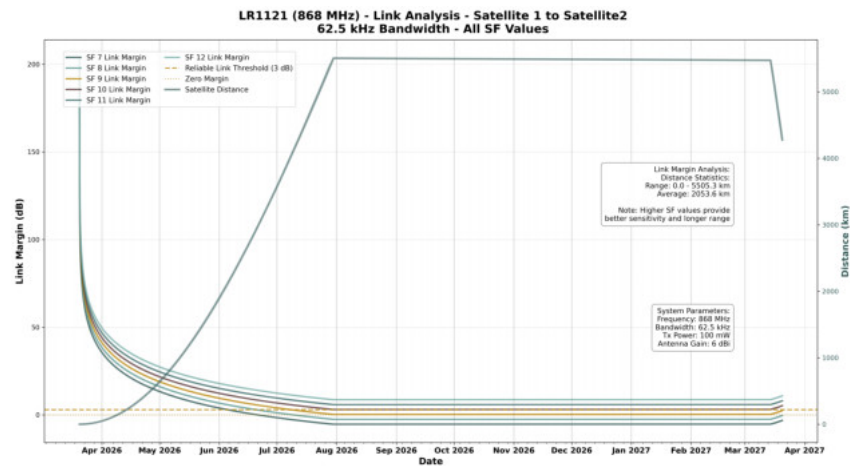


Figure 7.27: Link analysis: Satellite 1 to Satellite 2, LR1121, 868 MHz, 62.5 kHz.

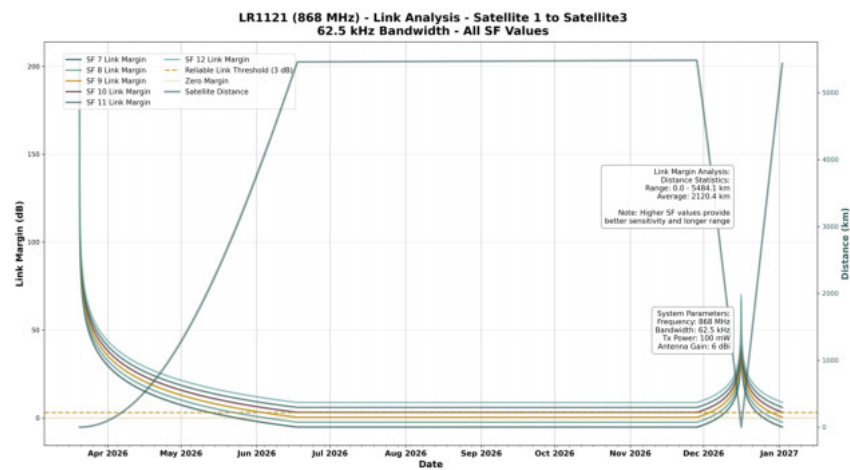


Figure 7.28: Link analysis: Satellite 1 to Satellite 3, LR1121, 868 MHz, 62.5 kHz.

125 kHz

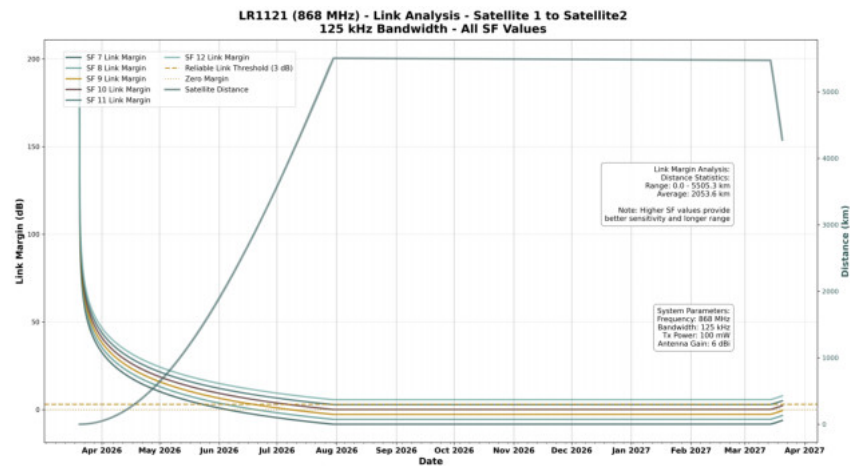


Figure 7.29: Link analysis: Satellite 1 to Satellite 2, LR1121, 868 MHz, 125 kHz.

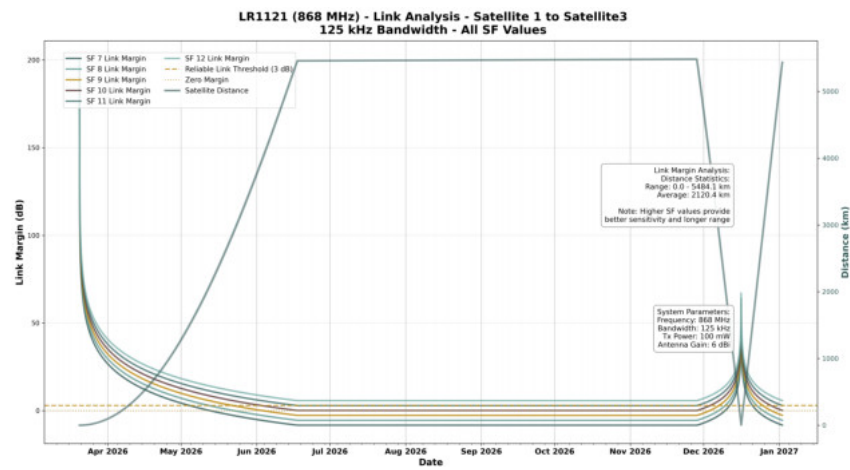


Figure 7.30: Link analysis: Satellite 1 to Satellite 3, LR1121, 868 MHz, 125 kHz.

250 kHz

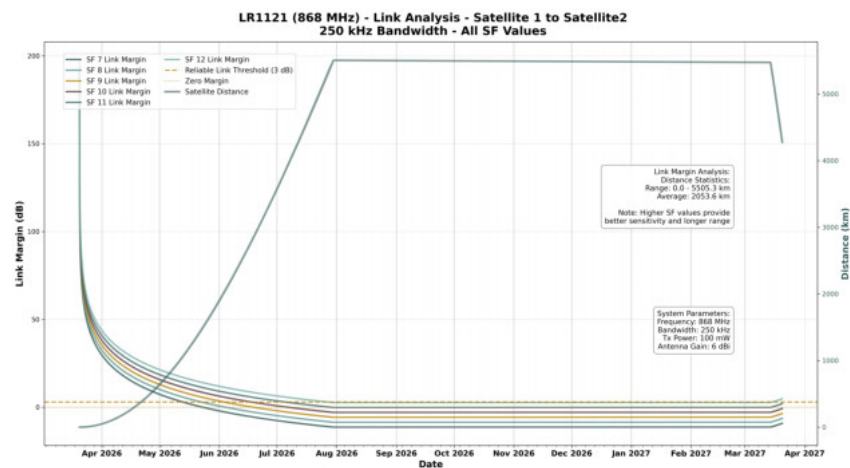


Figure 7.31: Link analysis: Satellite 1 to Satellite 2, LR1121, 868 MHz, 250 kHz.

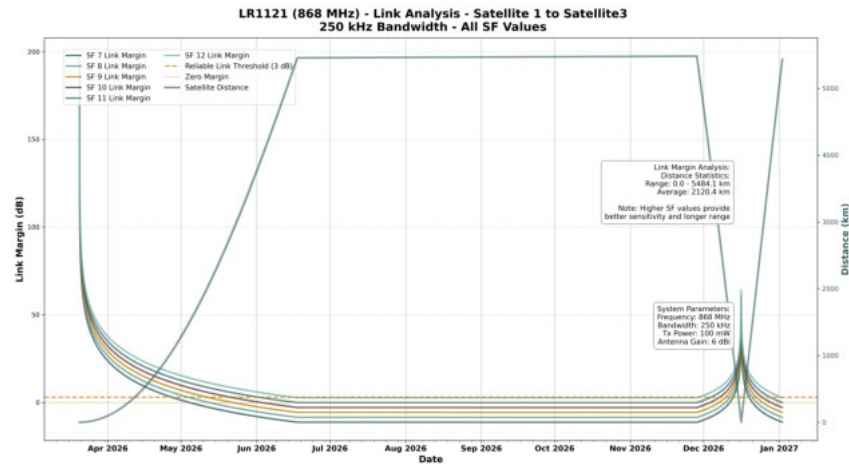


Figure 7.32: Link analysis: Satellite 1 to Satellite 3, LR1121, 868 MHz, 250 kHz.

500 kHz

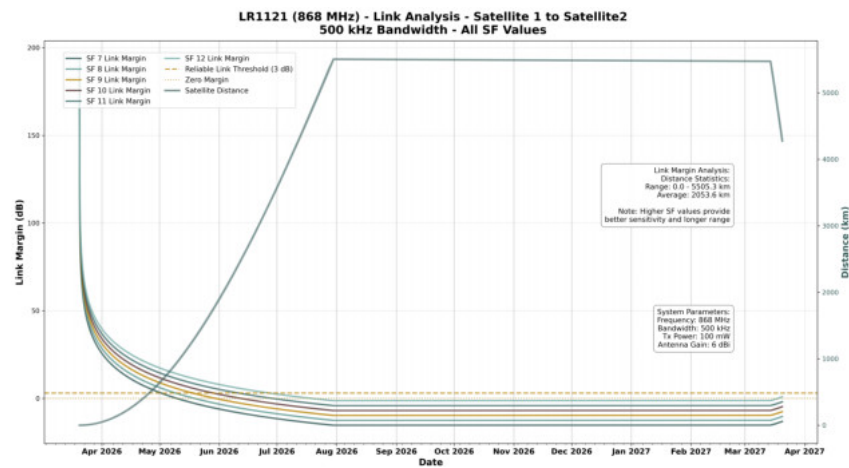


Figure 7.33: Link analysis: Satellite 1 to Satellite 2, LR1121, 868 MHz, 500 kHz.

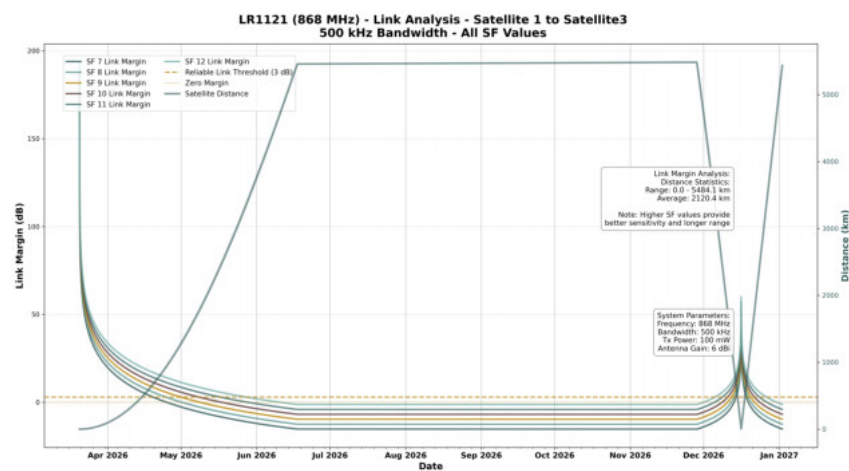


Figure 7.34: Link analysis: Satellite 1 to Satellite 3, LR1121, 868 MHz, 500 kHz.

Time-Resolved Link Analysis (SX1280, 2.4 GHz)

203 kHz

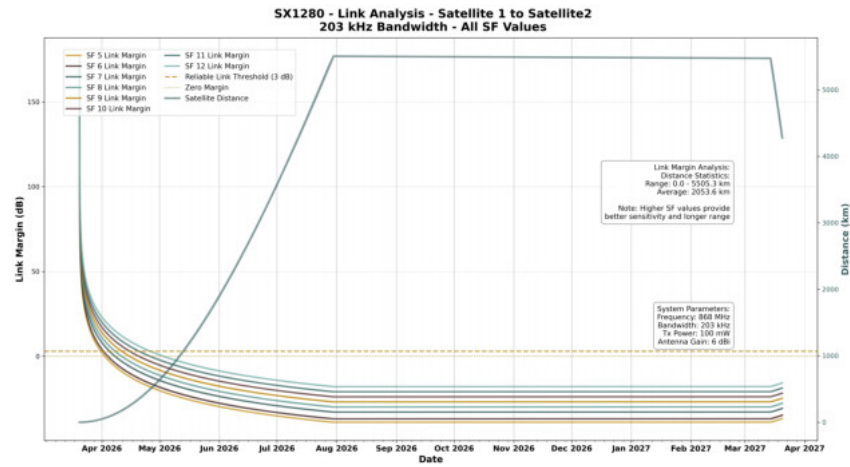


Figure 7.35: Link analysis: Satellite 1 to Satellite 2, SX1280, 2.4 GHz, 203 kHz.

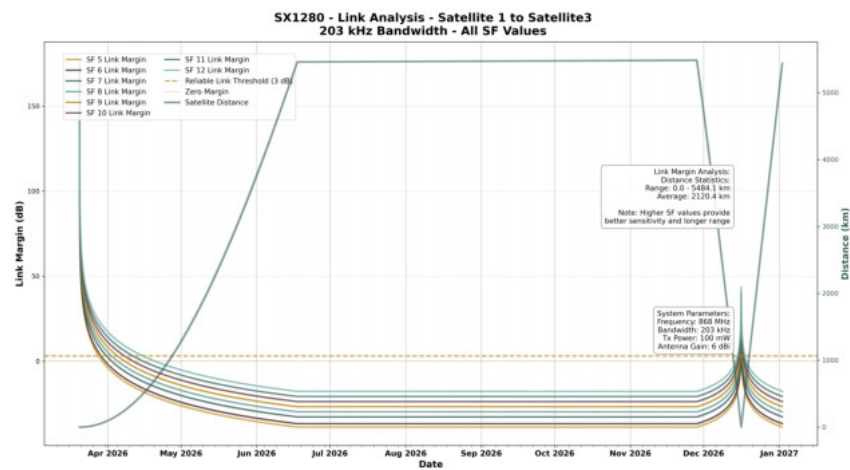


Figure 7.36: Link analysis: Satellite 1 to Satellite 3, SX1280, 2.4 GHz, 203 kHz.

406 kHz

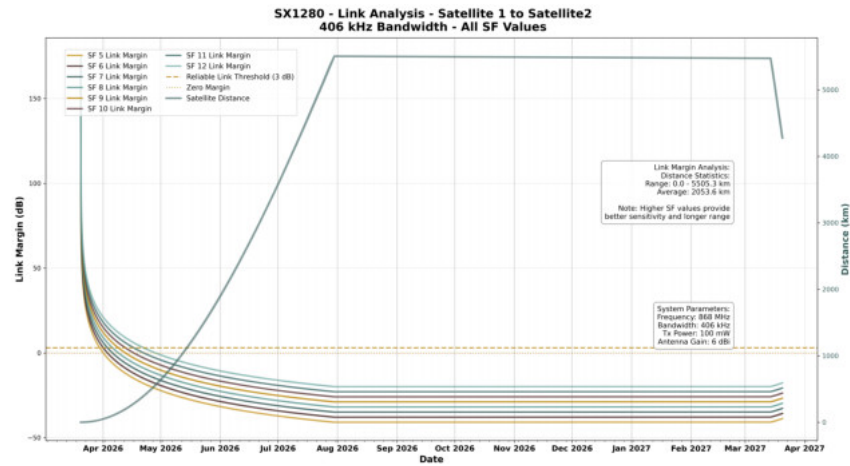


Figure 7.37: Link analysis: Satellite 1 to Satellite 2, SX1280, 2.4 GHz, 406 kHz.

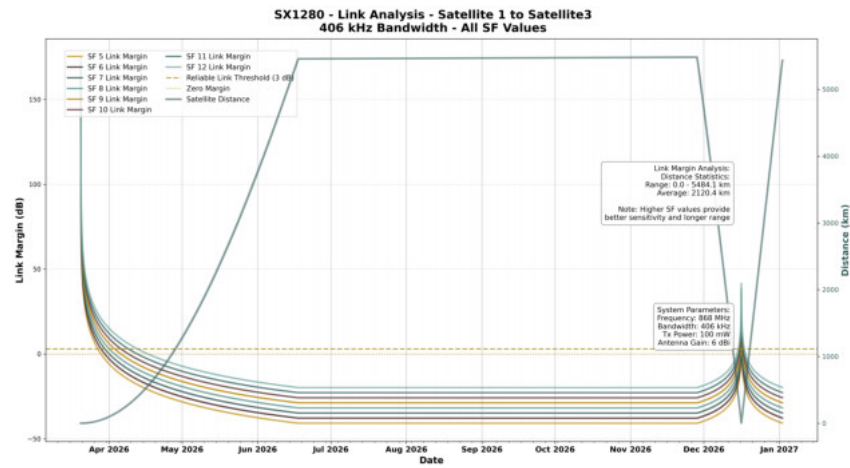


Figure 7.38: Link analysis: Satellite 1 to Satellite 3, SX1280, 2.4 GHz, 406 kHz.

812 kHz

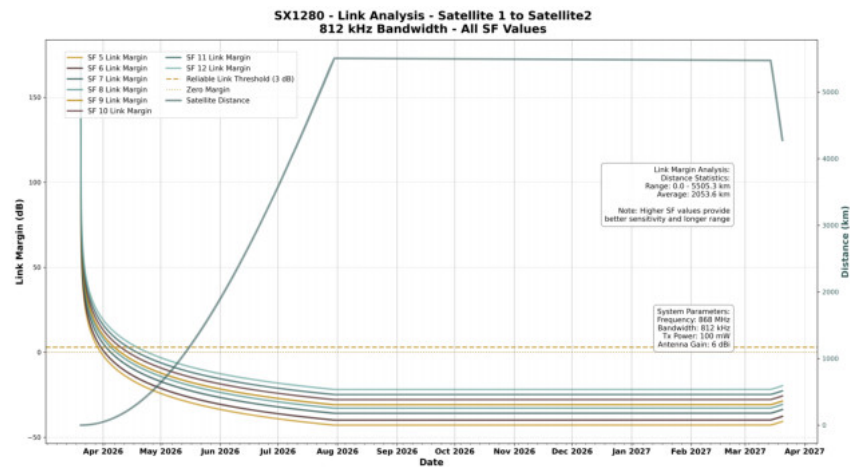


Figure 7.39: Link analysis: Satellite 1 to Satellite 2, SX1280, 2.4 GHz, 812 kHz.

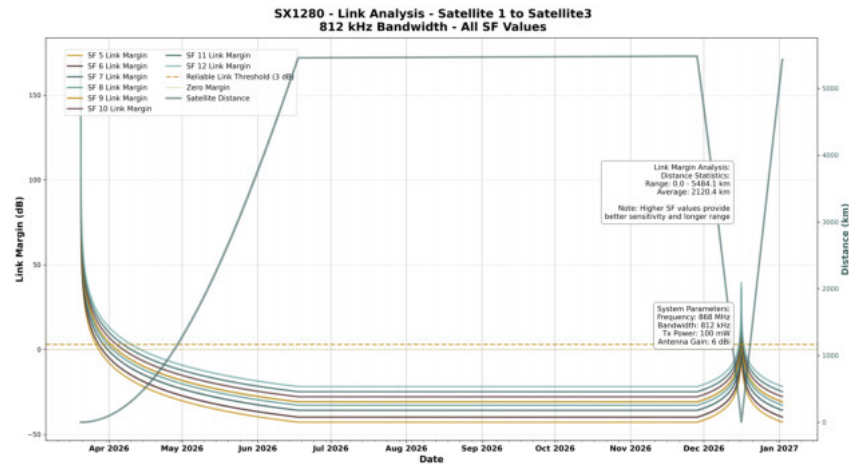


Figure 7.40: Link analysis: Satellite 1 to Satellite 3, SX1280, 2.4 GHz, 812 kHz.

1625 kHz

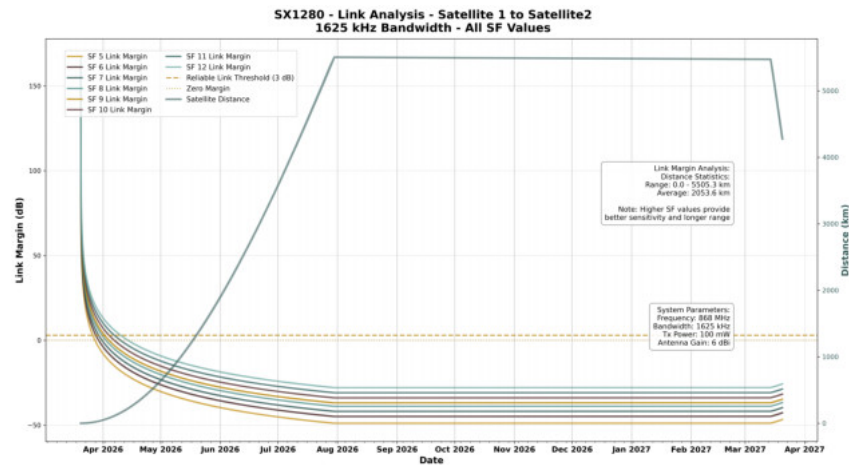


Figure 7.41: Link analysis: Satellite 1 to Satellite 2, SX1280, 2.4 GHz, 1625 kHz.

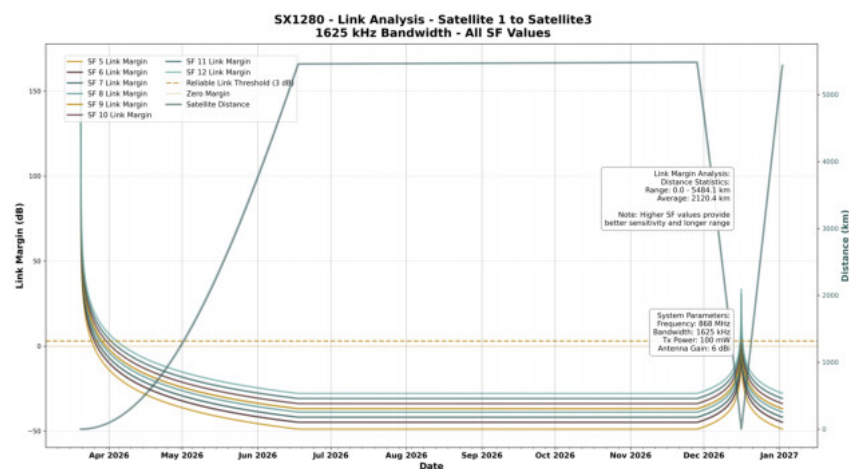


Figure 7.42: Link analysis: Satellite 1 to Satellite 3, SX1280, 2.4 GHz, 1625 kHz.

Time-Resolved Link Analysis (LR1121, 2.4 GHz)

125 kHz

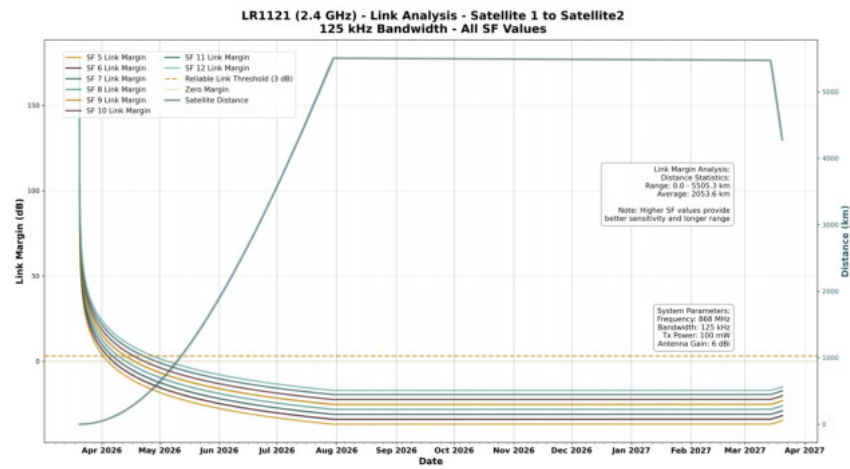


Figure 7.43: Link analysis: Satellite 1 to Satellite 2, LR1121, 2.4 GHz, 125 kHz.

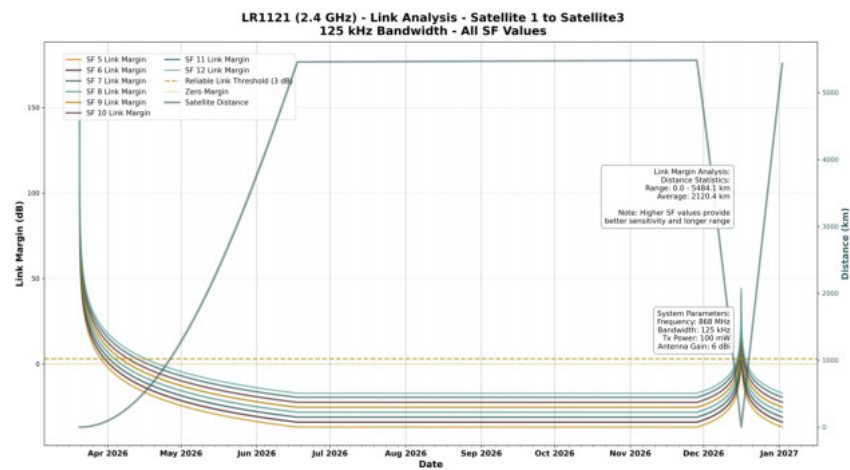


Figure 7.44: Link analysis: Satellite 1 to Satellite 3, LR1121, 2.4 GHz, 125 kHz.

250 kHz

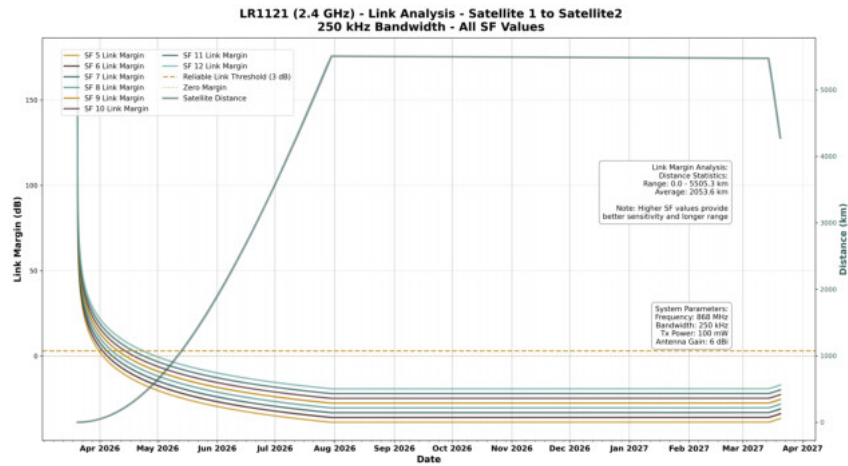


Figure 7.45: Link analysis: Satellite 1 to Satellite 2, LR1121, 2.4 GHz, 250 kHz.

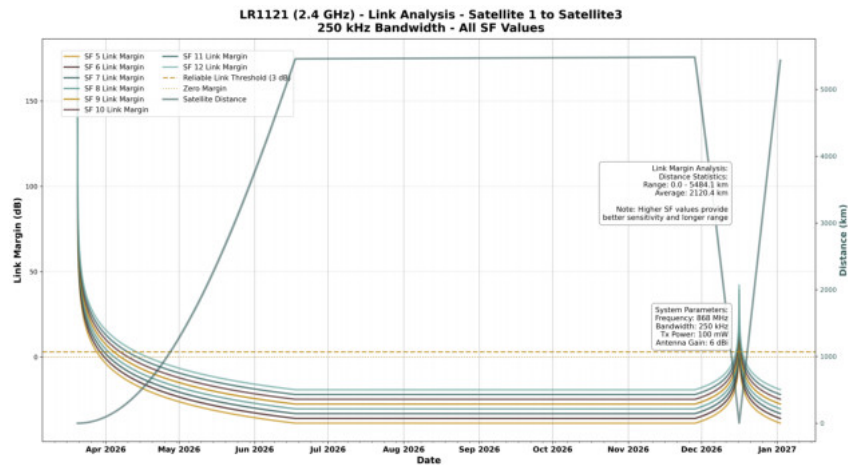


Figure 7.46: Link analysis: Satellite 1 to Satellite 3, LR1121, 2.4 GHz, 250 kHz.

500 kHz

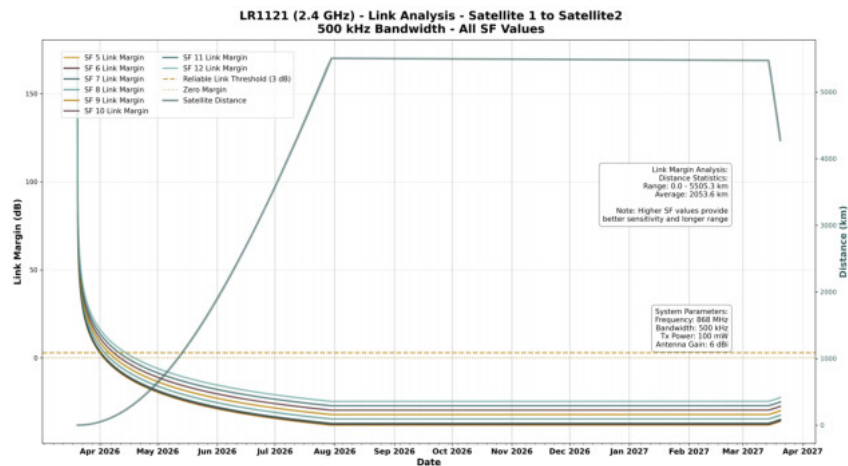


Figure 7.47: Link analysis: Satellite 1 to Satellite 2, LR1121, 2.4 GHz, 500 kHz.

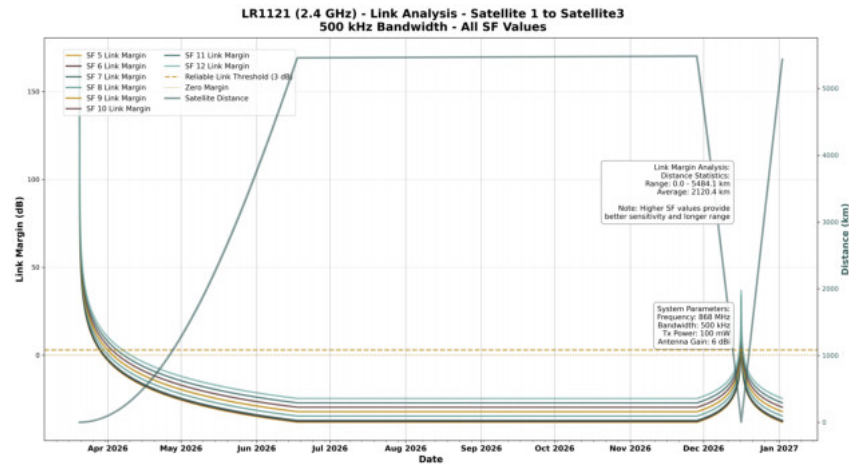


Figure 7.48: Link analysis: Satellite 1 to Satellite 3, LR1121, 2.4 GHz, 500 kHz.

812 kHz

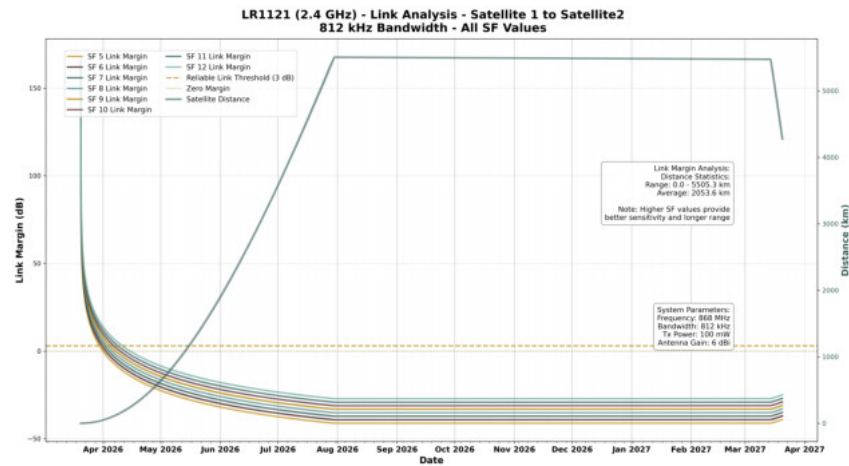


Figure 7.49: Link analysis: Satellite 1 to Satellite 2, LR1121, 2.4 GHz, 812 kHz.

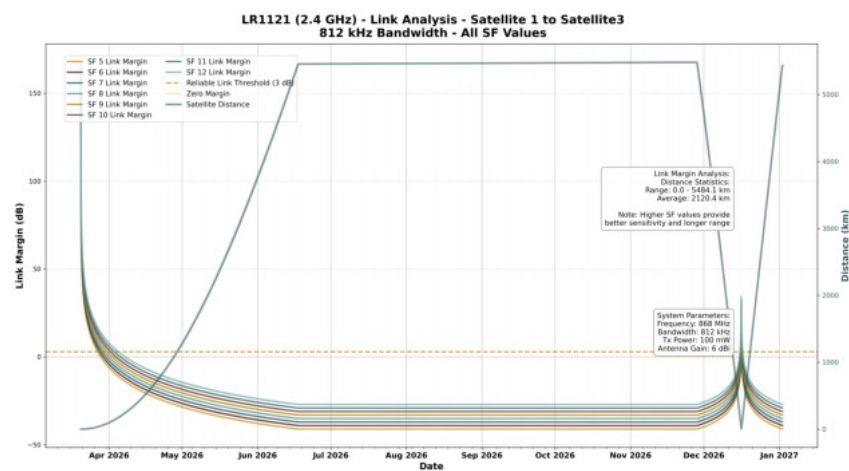


Figure 7.50: Link analysis: Satellite 1 to Satellite 3, LR1121, 2.4 GHz, 812 kHz.

7.1.6 Time-Resolved Link Analysis: Two Satellites with 1.5h LTAN Difference

RF95 (868 MHz)

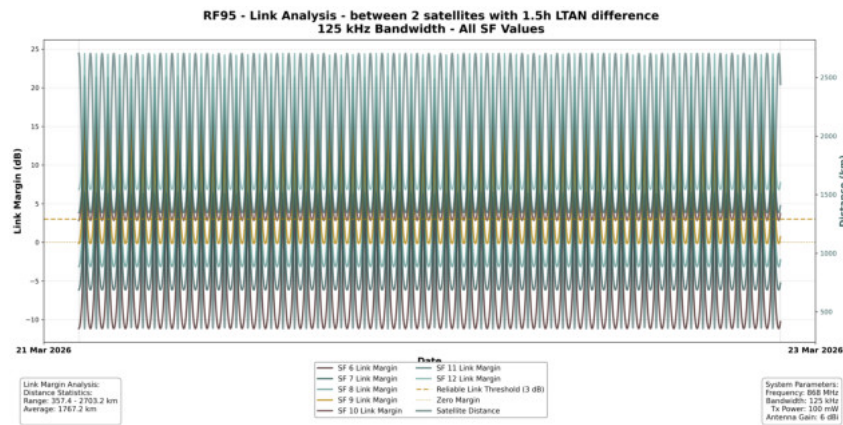


Figure 7.51: Link analysis: 2 satellites, 1.5h LTAN difference, RF95, 868 MHz, 125 kHz.

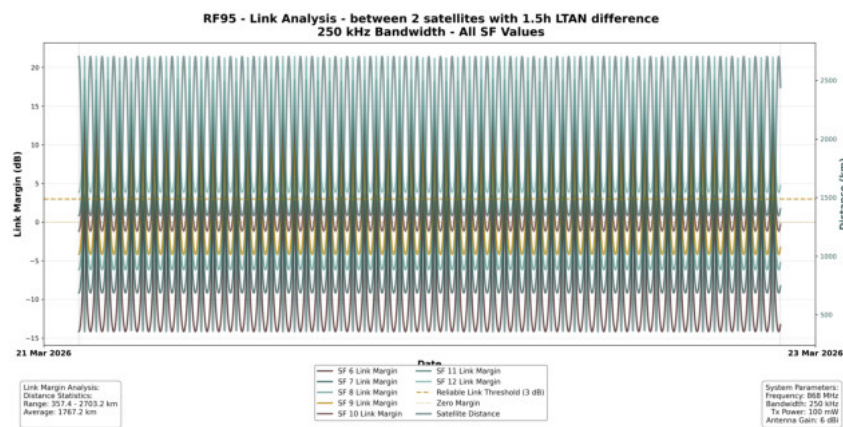


Figure 7.52: Link analysis: 2 satellites, 1.5h LTAN difference, RF95, 868 MHz, 250 kHz.

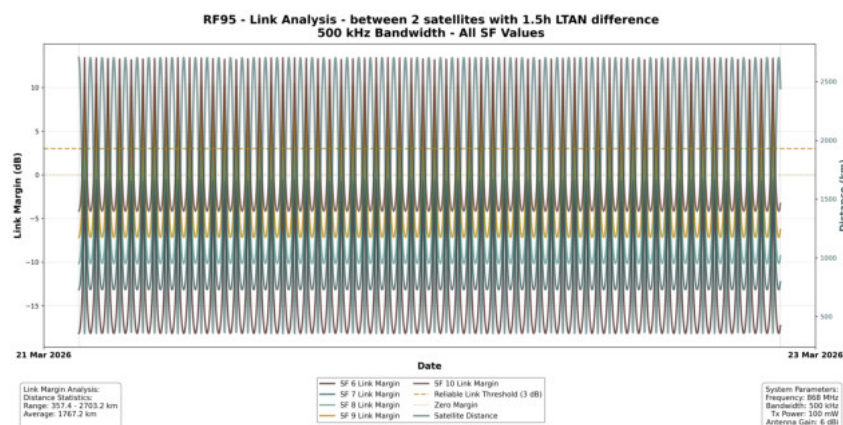


Figure 7.53: Link analysis: 2 satellites, 1.5h LTAN difference, RF95, 868 MHz, 500 kHz.

LR1121 (868 MHz)

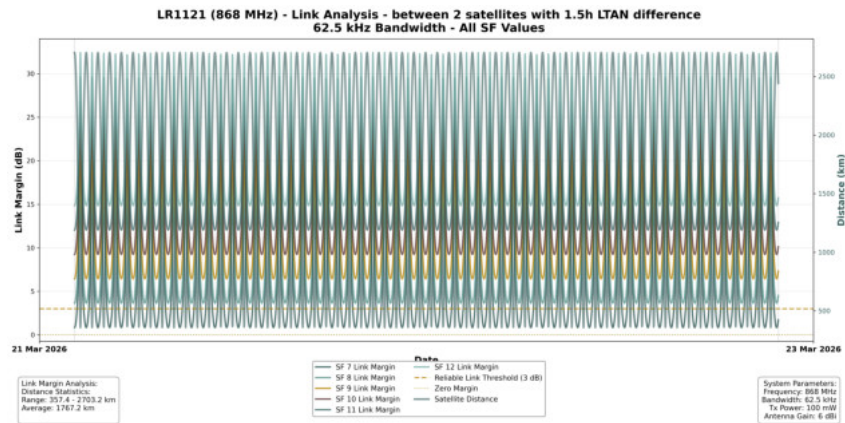


Figure 7.54: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 868 MHz, 62.5 kHz.

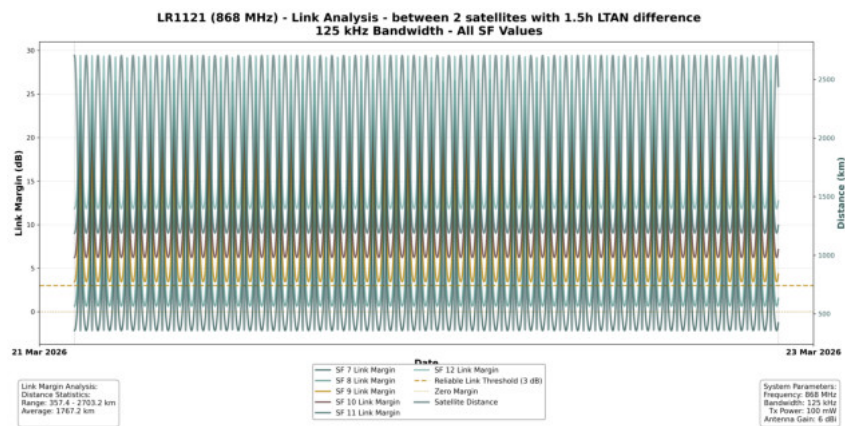


Figure 7.55: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 868 MHz, 125 kHz.

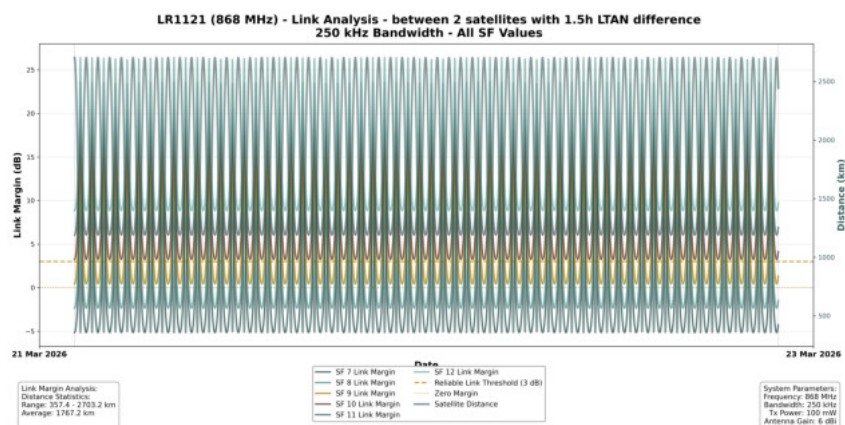


Figure 7.56: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 868 MHz, 250 kHz.

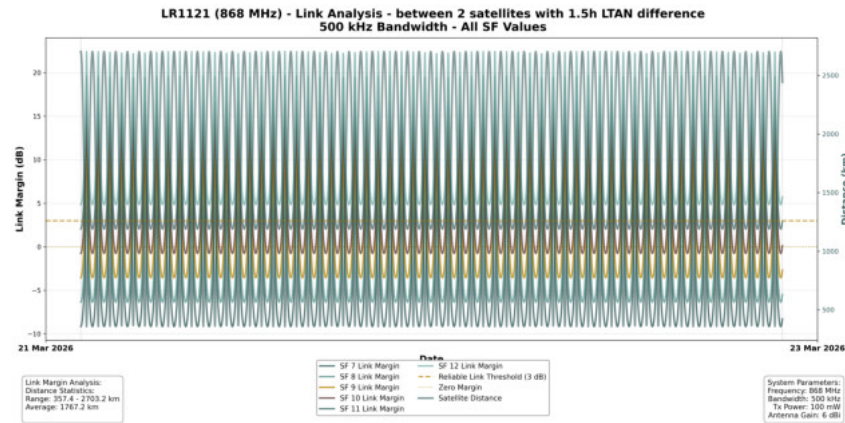


Figure 7.57: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 868 MHz, 500 kHz.

SX1280 (2.4 GHz)

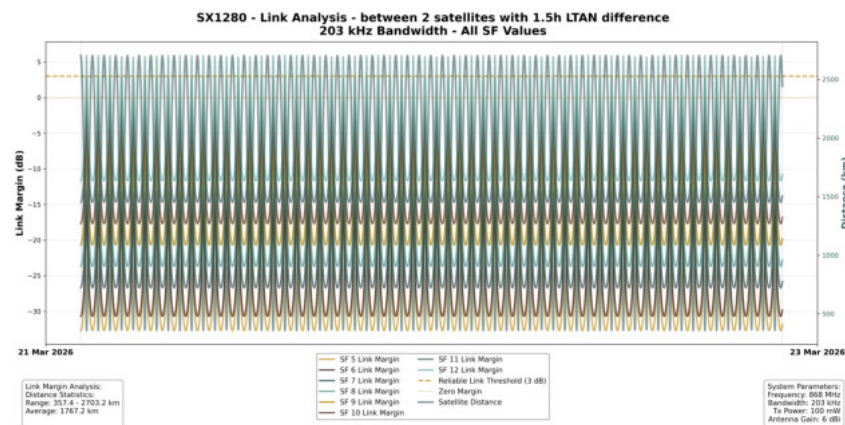


Figure 7.58: Link analysis: 2 satellites, 1.5h LTAN difference, SX1280, 2.4 GHz, 203 kHz.

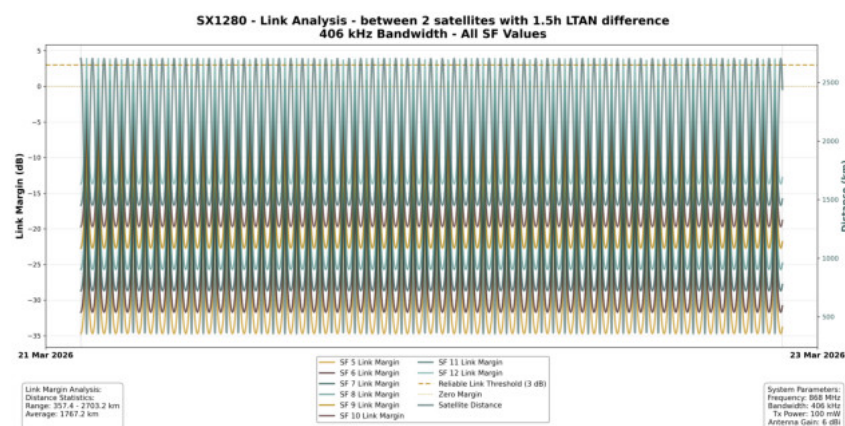


Figure 7.59: Link analysis: 2 satellites, 1.5h LTAN difference, SX1280, 2.4 GHz, 406 kHz.

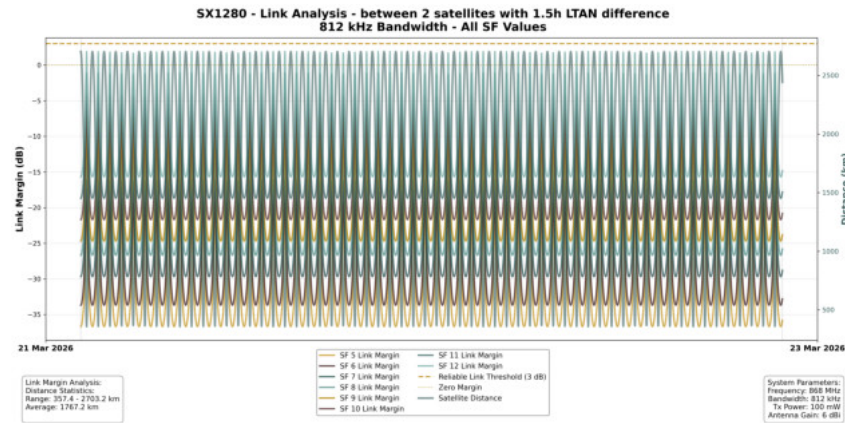


Figure 7.60: Link analysis: 2 satellites, 1.5h LTAN difference, SX1280, 2.4 GHz, 812 kHz.

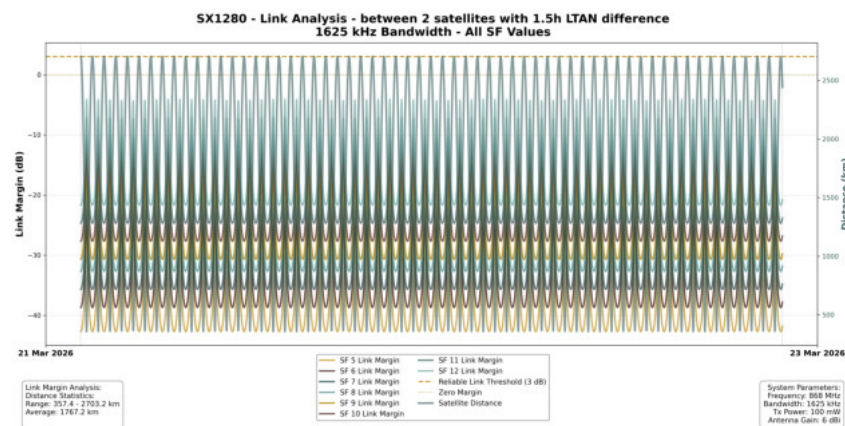


Figure 7.61: Link analysis: 2 satellites, 1.5h LTAN difference, SX1280, 2.4 GHz, 1625 kHz.

LR1121 (2.4 GHz)

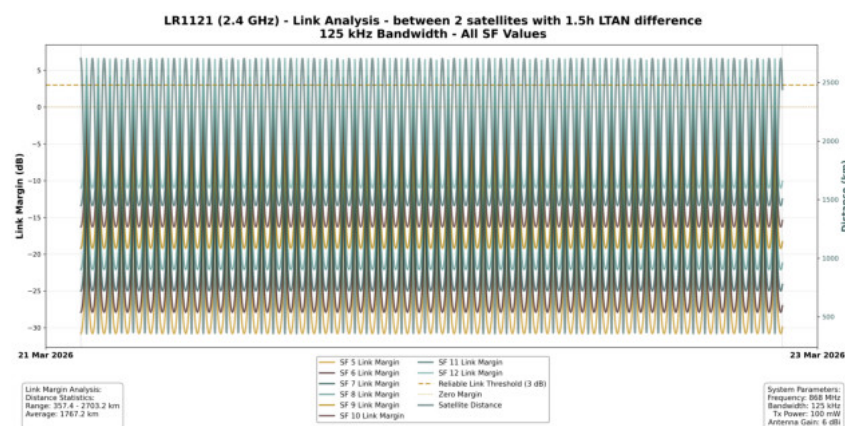


Figure 7.62: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 2.4 GHz, 125 kHz.

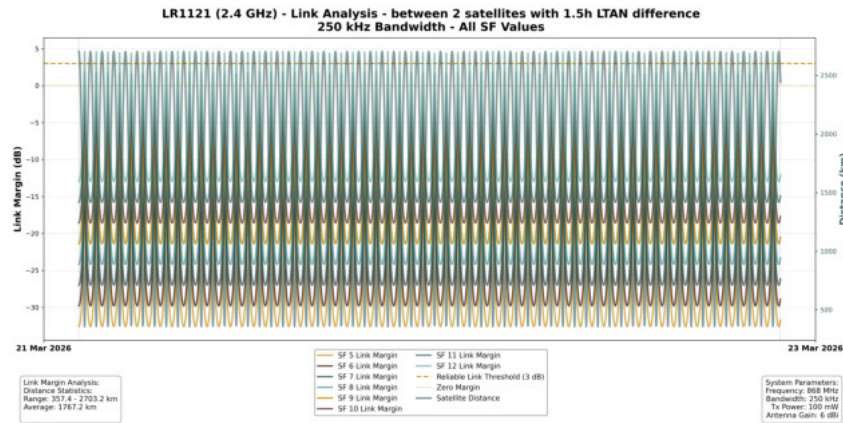


Figure 7.63: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 2.4 GHz, 250 kHz.

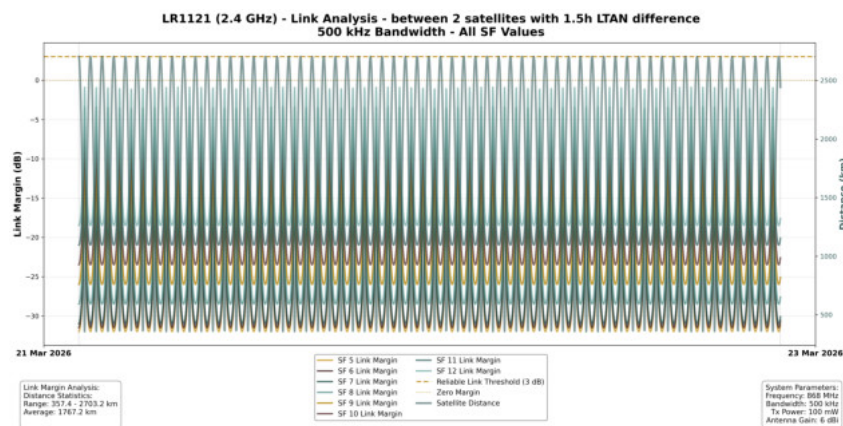


Figure 7.64: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 2.4 GHz, 500 kHz.

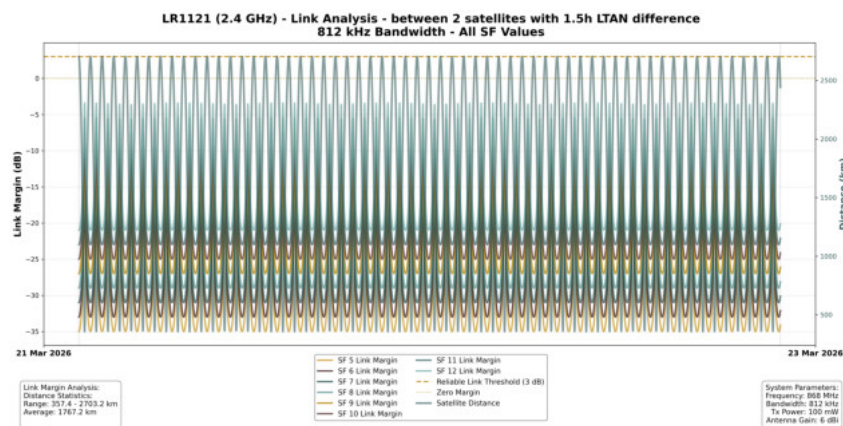


Figure 7.65: Link analysis: 2 satellites, 1.5h LTAN difference, LR1121, 2.4 GHz, 812 kHz.

7.1.7 Time-Resolved Link Analysis: Two Satellites, Different LTAN, No Station Keeping (HPOP, 2-Day Inset)

Full-year link margin and distance with first 2 days shown in inset. HPOP propagator, no station keeping.

RF95 (868 MHz)

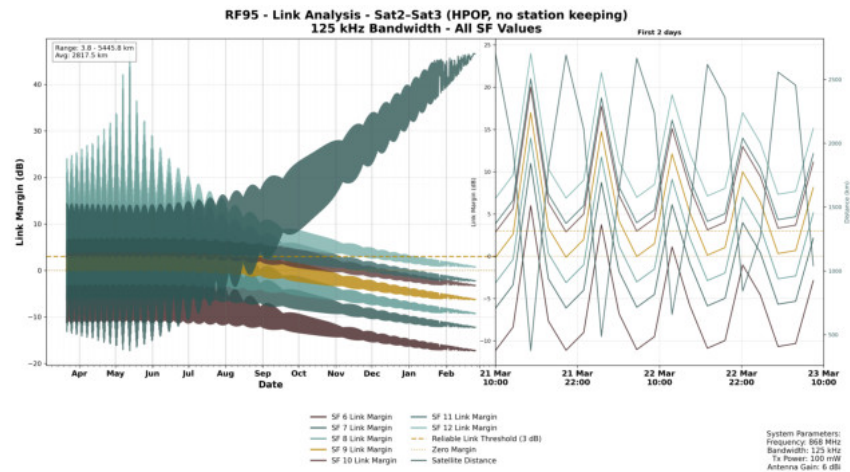


Figure 7.66: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), RF95, 868 MHz, 125 kHz.

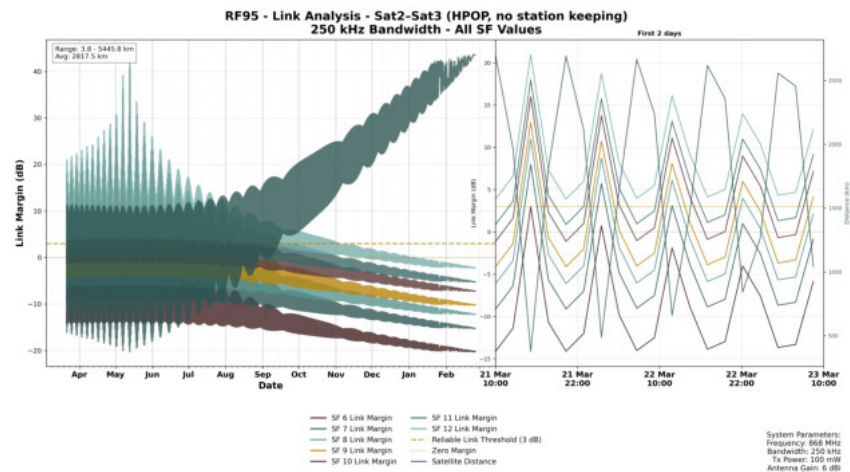


Figure 7.67: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), RF95, 868 MHz, 250 kHz.

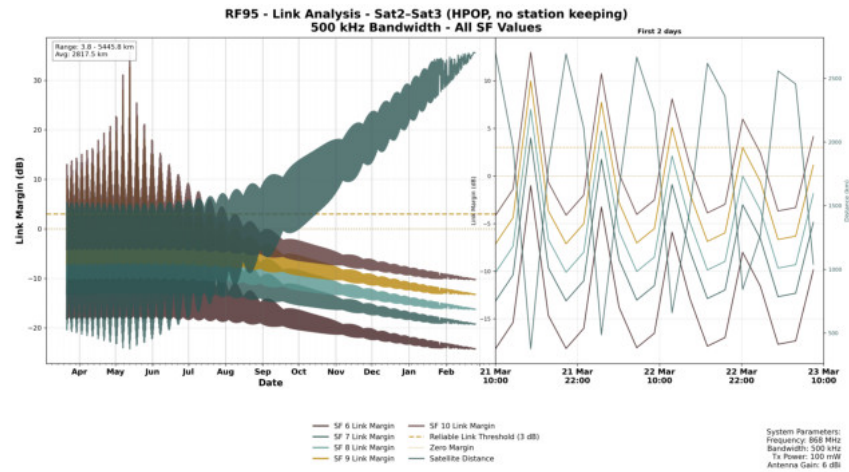


Figure 7.68: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), RF95, 868 MHz, 500 kHz.

LR1121 (868 MHz)

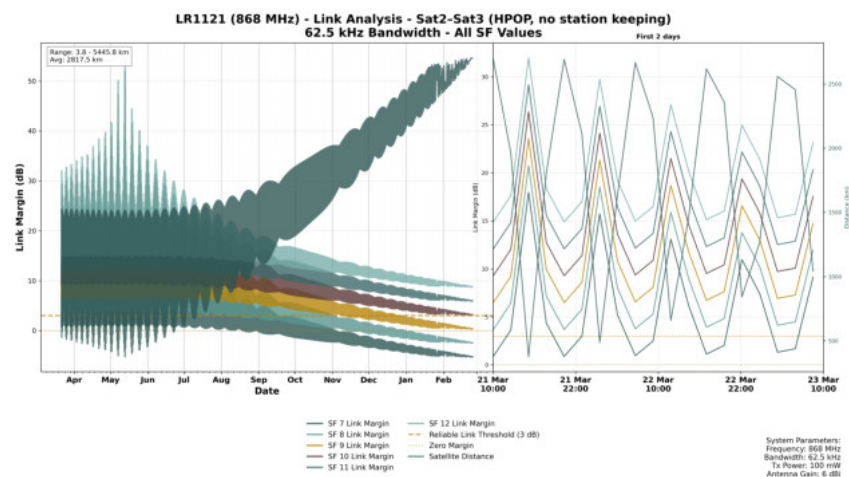


Figure 7.69: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 868 MHz, 62.5 kHz.

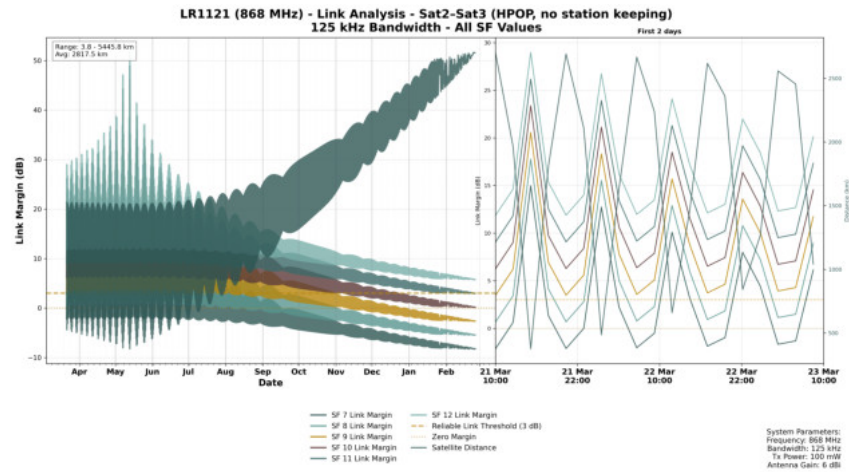


Figure 7.70: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 868 MHz, 125 kHz.

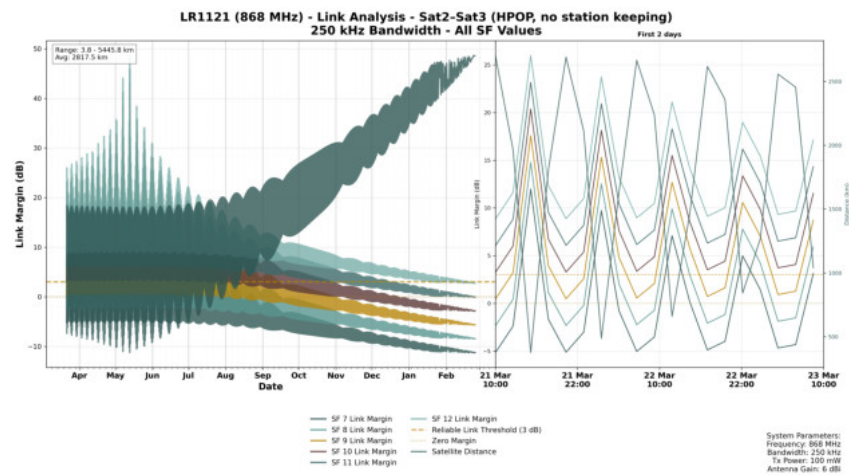


Figure 7.71: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 868 MHz, 250 kHz.

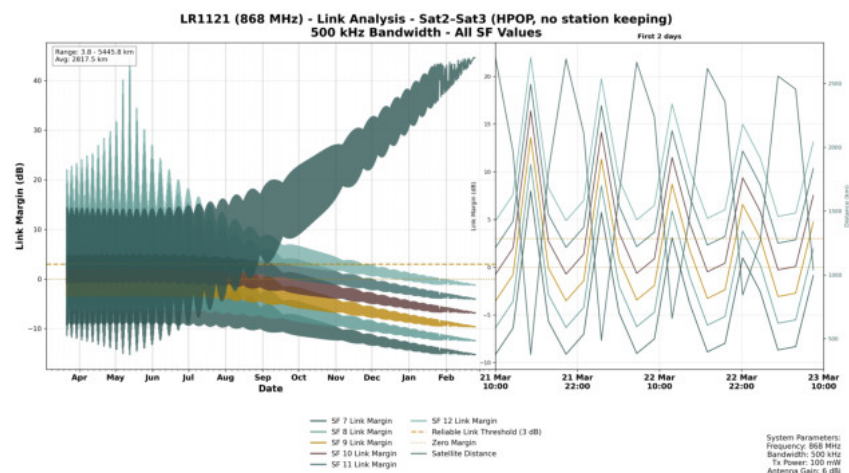


Figure 7.72: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 868 MHz, 500 kHz.

SX1280 (2.4 GHz)

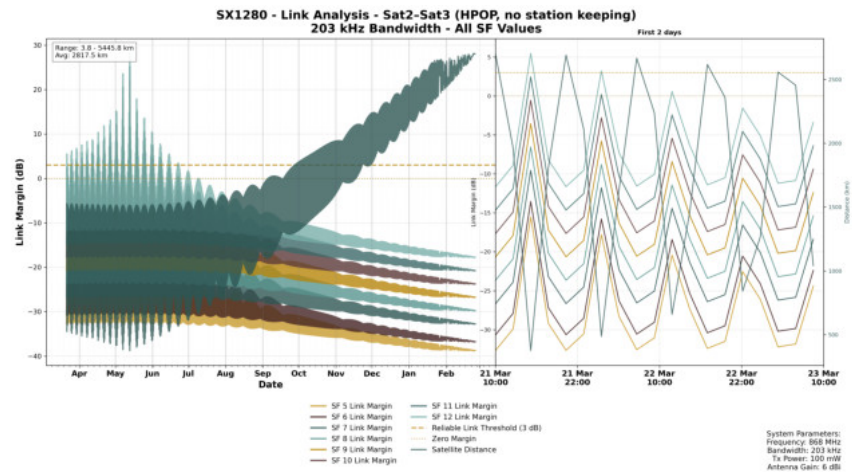


Figure 7.73: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), SX1280, 2.4 GHz, 203 kHz.

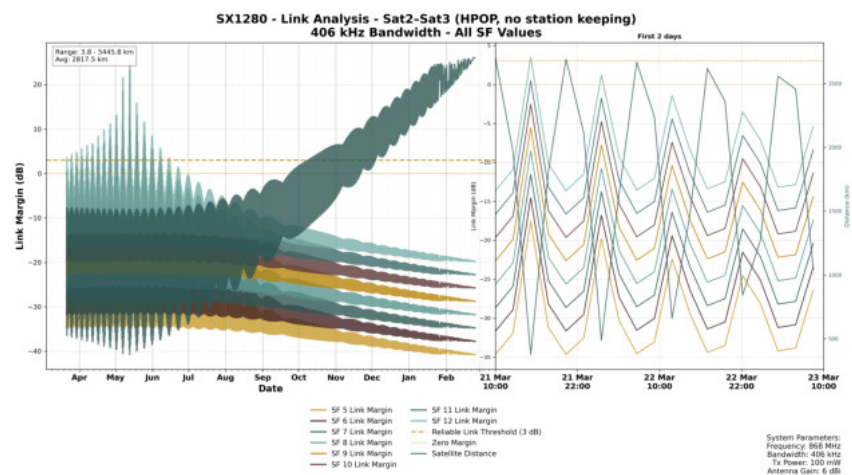


Figure 7.74: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), SX1280, 2.4 GHz, 406 kHz.

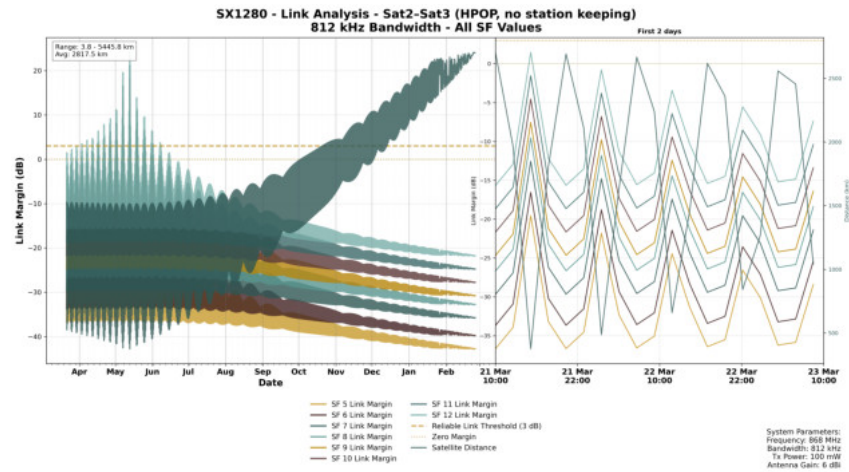


Figure 7.75: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), SX1280, 2.4 GHz, 812 kHz.

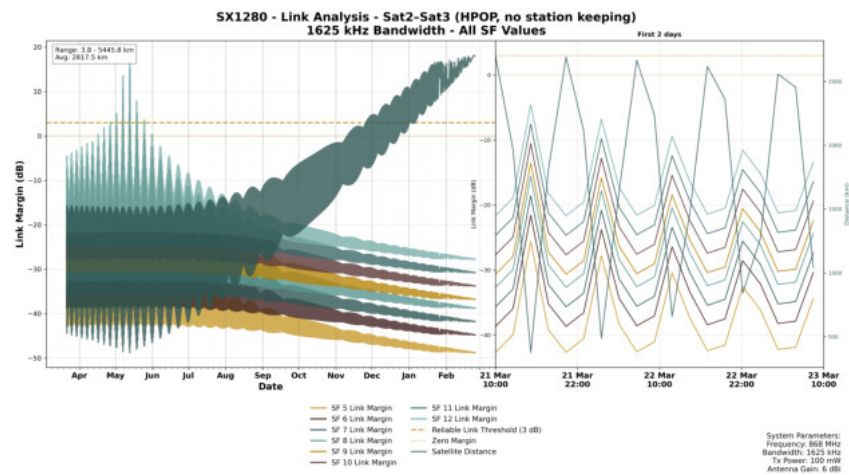


Figure 7.76: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), SX1280, 2.4 GHz, 1625 kHz.

LR1121 (2.4 GHz)

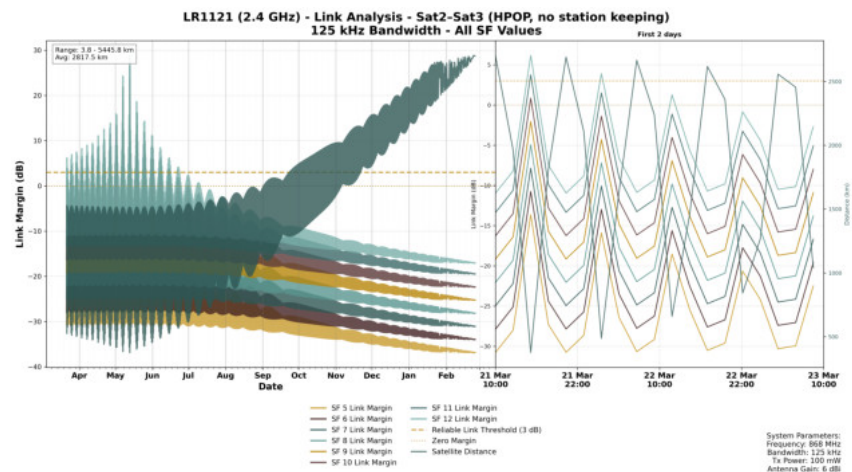


Figure 7.77: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 2.4 GHz, 125 kHz.

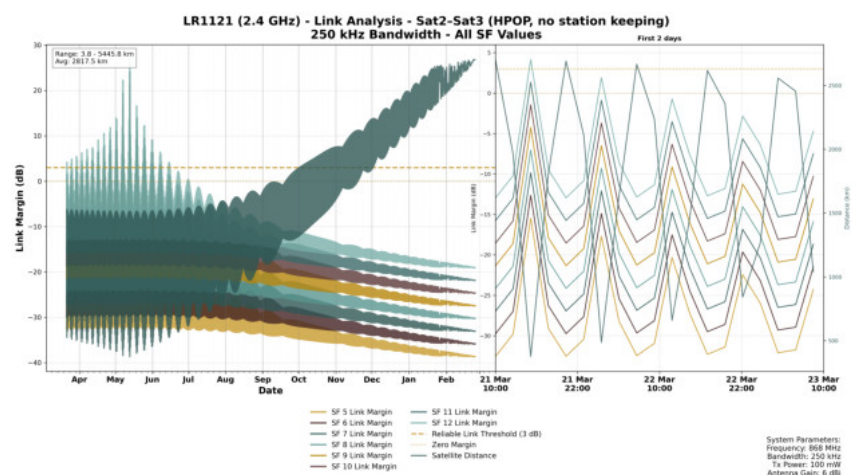


Figure 7.78: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 2.4 GHz, 250 kHz.

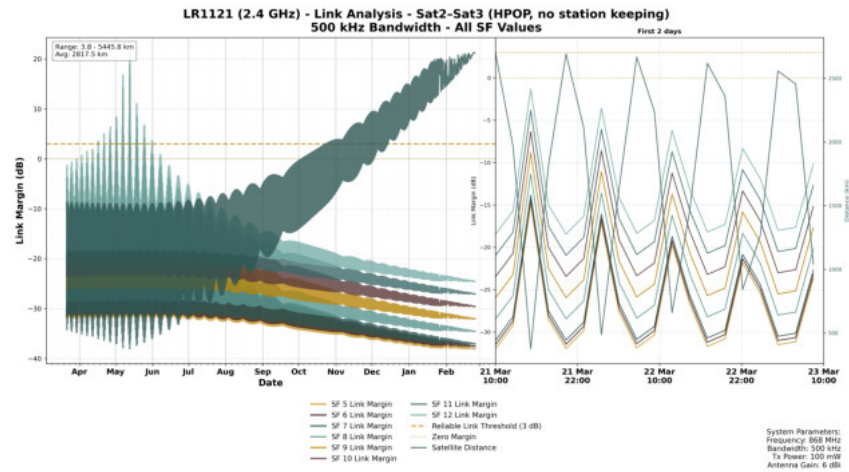


Figure 7.79: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 2.4 GHz, 500 kHz.

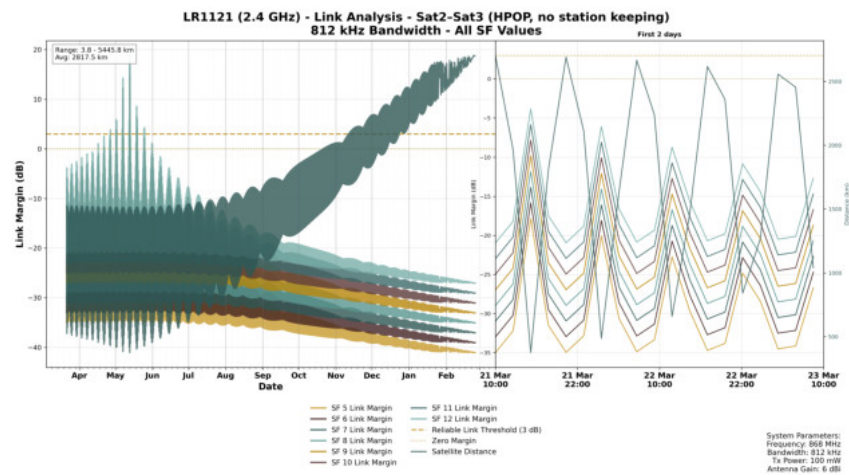


Figure 7.80: Link analysis: 2 satellites, different LTAN, no station keeping (HPOP), LR1121, 2.4 GHz, 812 kHz.

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