

Quantum Information Network Simulator (QINSim)

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ABSTRACT

The quantum internet on its implementation will represent a paradigm shift of information networks enabled by the distribution of entanglement across disparate nodes. Quantum information networks will usher in an era of unbreakable encryption, highly synchronised atomic clocks and interconnected quantum computers. Although fibre networks offer useful infrastructure for metropolitan networks, international and inter-continental connectivity will require satellite communications. A simulator that can accurately model a range of quantum information network topologies with specific building blocks that also accounts for satellite dynamics is not yet available, and such a tool will be invaluable for defining future quantum satellite missions. Here we present the Quantum Information Network Simulator (QINSim), an ESA-funded simulator for satellite-enabled quantum network architectures, designed as a community tool for assessing the feasibility of diverse network topologies. QINSim allows a user to extract key performance indicators (KPIs) such as end-to-end system fidelity and entangled bit rate by utilising either a graphical user interface or command line interface. KPIs can be generated in several modes, namely for an instantaneous link, a single satellite overpass or over a longer period of time such as weeks or months to extract an overall e-bit volume, and the impact of satellite orbits and optical ground station locations can be assessed. Users can also utilise a dedicated sensitivity analysis mode to understand the impact of component performance on KPIs, such as source pair rates, quantum memory coherence times, wavelengths etc. This work provides a powerful tool for defining optimum architectures for the future satellite-enabled quantum internet

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1. INTRODUCTION

There is a growing European and global effort to advance quantum networks. However, to date quantum networks have been primarily focused on point-to-point quantum communications (i.e. quantum key distribution or QKD) in terrestrial environments, due to pace of delivery and ease of implementation of fibre networks.¹⁻⁴ Fibre deployments are limited to metropolitan networks but satellite quantum optical links increase network scale by utilising free-space links that don't suffer the same exponential loss as fibre⁵ and enable more dynamic network topologies through satellite relays. Currently, there are several satellite QKD (S-QKD) missions planned globally (QKDSat, Eagle-1,⁶ QEYSSAT,⁷ SPOQC,⁸ and others) and optical ground station (OGS) infrastructure deployments to communicate with these satellites. There are also a growing number of metropolitan fibre QKD networks⁹⁻¹¹ which require connecting together via satellite links. Many of these S-QKD systems have different wavelengths, link configurations and protocol implementations, so while there is extensive link budget and protocol modeling for each mission, they are limited to trusted node and prepare and measure QKD implementations. This limits their ability to be integrated into a wider range of use cases as demand for quantum technologies grows.

There are several additional use cases of quantum networks, which rely on the distribution of entanglement for applications including quantum sensing, distributed quantum computing and untrusted-node QKD.¹² This

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distribution of entanglement allows for many quantum devices to connect in a global network, often called the quantum internet.¹³

Simulating dynamic network configurations is crucial for designing the quantum internet as it enables modelling of complex environments including variable free-space links and interfaces to fibre-based static architecture. Although individual simulators exist that handle certain elements of this independently, such as SatQuMa¹⁴ which focuses on prepare and measure QKD only for a limited satellite overpass geometry, or NetSquid¹⁵ which is a discrete event simulator that is well suited to single static links, but infeasible to use for the dynamics of satellite overpasses and longer horizon simulations, no simulator exists that currently integrates all the required functionality together.

In this work, we present the Quantum Information Network Simulator (QINSim),¹⁶ a tool designed to allow a user to model dynamic satellite entanglement distribution networks, extracting key performance indicators of entangled bit (e-bit) rates and state fidelities for linear networks.

2. METHODS

2.1 Simulator architecture

QINSim predicts the end-to-end performance of an entanglement distribution network whose nodes may be fixed ground terminals or satellites in arbitrary orbits. It is organised around four functional elements: a configuration layer, a simulation core, an orbit propagator, and a free-space channel model.

A single machine-readable configuration file defines an entire scenario: the nodes, the channels that connect them, and the analysis to be performed. The graphical and command-line front ends are thin clients over a common core and share that configuration format, so a scenario assembled interactively can be re-run unattended, and configurations can be generated programmatically by other tools. The configuration file is therefore the simulator’s external interface as much as it is a save format. The architecture of the simulator and functional flow is depicted in Figure 1.

Free-space channel modelling is provided by Qrackling,¹⁷ an open-source satellite quantum channel simulator developed by the Free-Space QKD Lab at Heriot-Watt University, accessed through a Python interface, PyQrackling. Qrackling accounts for atmospheric transmission and turbulence, beam divergence, pointing error and link geometry on both uplink and downlink, and carries parameterised models of commercial single-photon detectors together with standard atmospheric visibility conditions. QINSim contributes everything above the individual channel: the network representation, the physical semantics of entanglement sources, swapping nodes and quantum memories, the logic that reduces a multi-node network to an end-to-end figure of merit, the treatment of satellite visibility over time, and the analysis modes of Section 2.6. Delegating the channel physics to an established tool avoids duplicating a well-solved problem and keeps QINSim’s own scope on the network layer, where no comparable capability existed.

2.2 Network representation

A network is described as a set of nodes joined by channels. The central abstraction is the link: an object that delivers photons carrying quantum correlations to both of its ends. Every channel in a scenario is a link of some type, and the simulation proceeds by combining links until a single link spans the two endpoints of interest.

Each node carries a role that determines how it combines the links either side of it, as summarised in Table 2. A node’s position is specified independently of its role, either as a fixed geodetic location or as an orbit, so a source, swap or relay may sit on the ground or on a spacecraft as the scenario requires. Four channel types are available. Uplink and downlink channels are free-space satellite links and require at least one endpoint in orbit. Fibre channels are terrestrial. Adjacent channels carry a pre-computed loss and fidelity and have zero length and zero propagation delay, and so represent two nodes that are effectively co-located, for example an entanglement source and a detector housed within the same ground station.

The current implementation evaluates path topologies, that is, chains with a single source-destination pair. A scenario may contain several satellites, which is how a multi-satellite mission is represented: more spacecraft give more passes over a given ground station and therefore greater total delivered capacity. What cannot be

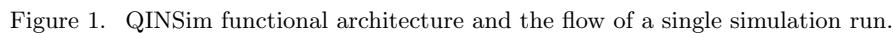


Table 1. Node roles and channel types available in QINSim. A node’s role determines how it combines the links either side of it, and is specified independently of whether the node is on the ground or in orbit.

Node role	Function
Source	Emits entangled pairs into two links; combines entangled bit rates
Swap	Interferes and measures photons from two links; entangles their partners
Relay	Transparent pass-through; combines link losses
Detector	Terminates a path and measures the arriving photons
Channel type	Defining parameters
Uplink, downlink	Terminal apertures, efficiencies, pointing jitter, atmosphere
Fibre	Length, attenuation coefficient, connector losses
Adjacent	Pre-computed loss and fidelity; zero length

Satellite geometry is generated by propagating each spacecraft under a J_2 gravitational model.¹⁸ An orbit may be specified either by its Keplerian elements, with the option of deriving the inclination automatically for a sun-synchronous orbit, or by supplying an externally computed ephemeris. The same parameterisation covers low, medium and geostationary altitudes, and the ephemeris route allows a higher-fidelity orbit to be substituted where the J_2 approximation is insufficient.

Rather than sampling uniformly across the requested interval, the simulator first resolves the periods during which a given satellite is visible from a given ground station above a specified minimum elevation, then constructs one simulation session per visibility window. The network topology is therefore defined over an interval during which the relevant links physically exist, and no computation is expended on periods when no space-to-ground link is available. This is what makes it practical to assess delivered capacity over a full mission lifetime rather than over a handful of passes.

Within a session, each channel builds and evaluates its own model at every time step, returning loss, entangled bit rate and fidelity. Free-space channels are evaluated through Qrackling using the telescope apertures, efficiencies, pointing jitter and atmospheric conditions declared for the terminals at each end. Fibre channels are evaluated from their attenuation and connector losses. Detector behaviour enters through efficiency, dark count rate, afterpulse probability and the coincidence gate width.

2.4 Link and node combination

The core of the simulator is the reduction of a multi-node network to a single equivalent link. This is performed as an ordered sequence of three combination stages, one for each of the combining node roles.

Relay combinations are performed first. At each relay node a new link is formed whose loss is the sum of the losses of its two neighbours. The order in which relay nodes are collapsed is immaterial, because loss addition is associative. Once all relays have been absorbed, the network consists of source and swap nodes in strict alternation; a network that does not reduce to this form is not physically realisable and is rejected.

Source combinations follow. The entangled bit rate a source establishes between the far ends of its two links is determined only by local quantities, namely the source pair rate and the losses of the two links either side of it. Because source nodes are by construction separated by swap nodes, these calculations are independent of one another and may likewise be performed in any order.

What remains is a swapping network: swap nodes joined by links that now carry both a loss and an entangled bit rate, where the process is outlined in Figure 2. This leaves precisely the structure treated in the theoretical literature on entanglement swapping, and because it has a single source-destination pair an optimal swapping schedule is known.¹⁹ The schedule forms a balanced, or as nearly balanced as the network permits, tree of swapping operations: swapping is performed at every second swap node, the network is redrawn, and the process repeats until no swap nodes remain. For a network with k swap nodes this completes in $\lceil \log_2(k + 1) \rceil$ passes.

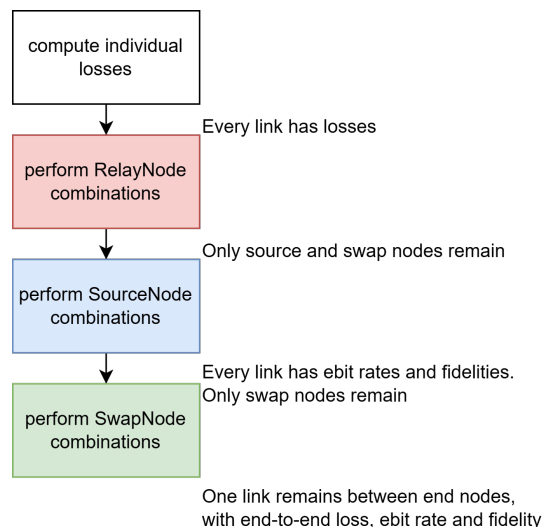


Figure 2. Reduction of a multi-node network to a single equivalent link

2.5 Quantum memories and fidelity

Quantum memories are modelled as a component attached to a swap node rather than as a node type of their own, which reflects the physical arrangement of interest: a swap node holding a pair of memories, one facing each of its links. Each memory is characterised by a preparation time, a dephasing time and an efficiency. The underlying model distinguishes emissive from absorptive platforms, according to whether the relevant storage interval is a single-trip or a round-trip photon time, and treats sequential and concurrent loading of the memory pair as separate cases; round-trip storage with sequential loading is the case exercised here. The treatment follows the single-repeater-node analysis of Luong *et al.*,²⁰ and inherits that work's assumption of memories with an unbounded number of modes.

Where the two links meeting at a swap node have unequal loss, the memory expected to dephase is taken to be the one on the shorter link, on the grounds that it is the more likely to absorb a photon first, and the dephasing it experiences therefore corresponds to the single-trip photon time on the longer of the two links. The consequence is that the achievable entangled bit rate is bounded by the lossier of the two links meeting at that node, so an asymmetric repeater configuration is limited by its weaker arm rather than rewarded for its stronger one.

End-to-end fidelity is accumulated along the path as the links are combined, so that each combining node contributes its own degradation to the fidelity of the equivalent link it produces. The contributions represented are the intrinsic fidelity of the source and the multi-pair emission characterised by its $g^{(2)}$, the fidelity of the swap operation itself, dark counts falling within the coincidence gate, and, where a memory is present, dephasing over the storage interval together with the memory's read and write efficiency. Effects not currently represented include the distinguishability of photons arriving at a swap node, and hence the loss of interference visibility, quantum frequency conversion, and any adaptive correction of the free-space coupling efficiency.

2.6 Analysis modes, figures of merit and optimisation

The reported figures of merit are the entangled bit rate in ebit/s, the end-to-end fidelity, and the channel loss expressed both as a dimensionless factor and in decibels. Three analysis modes determine how these are sampled. Instantaneous mode evaluates the network at a single epoch, specified either as an absolute time or as the moment at which a nominated satellite reaches a given elevation over a nominated ground station. Session mode identifies the best available pass of a satellite over a ground station and evaluates the network across that pass as a time series. Horizon mode sweeps a date range at a chosen time step and aggregates the result over hours, days, weeks or months, yielding availability and total delivered entangled bits over entire mission lifetimes.

Two exploratory capabilities are layered on the instantaneous and session modes. A sensitivity analysis sweeps a single nominated parameter across a list of values, running each variant and overlaying the figures of merit, which is the natural way to establish a limiting value such as a maximum tolerable fibre length. An optimisation capability, currently in beta and due for public release ahead of this conference, inverts the question: the user nominates several parameters and their bounds, declares which figures of merit are to be maximised or minimised, and optionally imposes hard constraints on others.

The optimiser functions using NSGA-II²¹ which is a Multi-Objective Evolutionary Algorithm (MOEA) and implemented via the pymoo library.²² It begins by sampling an initial population of candidates, each having random parameter values generated within the bounds set. The simulator is ran for every candidate returning their Key Performance Indicators (KPIs), which are used to rank the population by non-domination and diversity, keeping the best candidates across all objectives as parents. These parents are used to breed a new generation through crossover and mutation of their parameter values. This creates a repeating cycle of evaluate, rank, select and breed for each generation, where each generation subsequently improves on the last. The cycle repeats until a termination criterion is met, such as a fixed number of generations or time spent. As the generations progress the population generally converges towards the best performing regions of the search space, converging towards the Pareto Front. On a graph this should be represented by continued generations converging towards a single point, where the objectives do not conflict, or converging towards a curve, where the objectives trade off against each other. The optimiser contains no physics of its own; it drives the existing simulation core through the same parameter-override interface used by the sensitivity analysis. Because a satellite quantum network

trades entangled bit rate against fidelity almost everywhere, presenting a designer with a front of defensible compromises is more useful than presenting a single optimum.

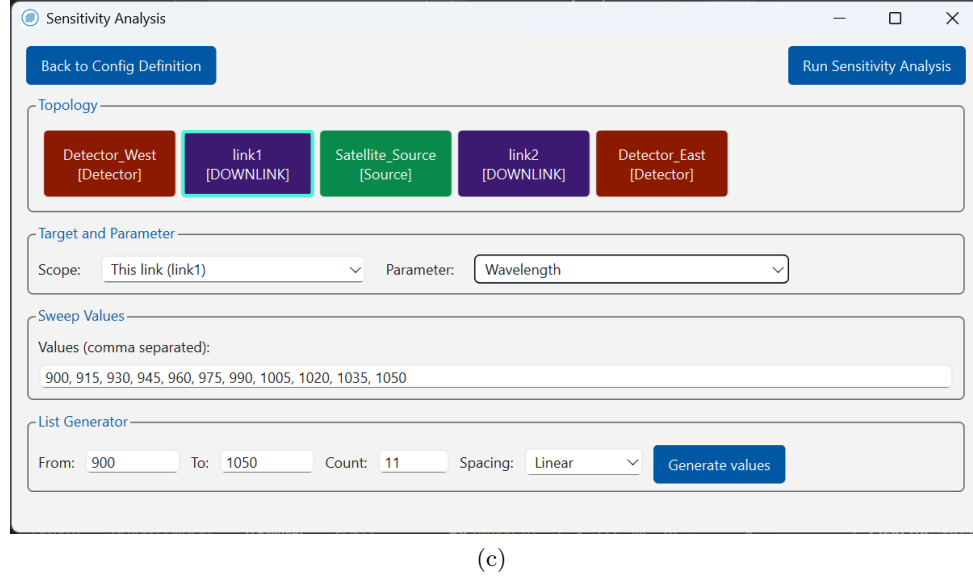
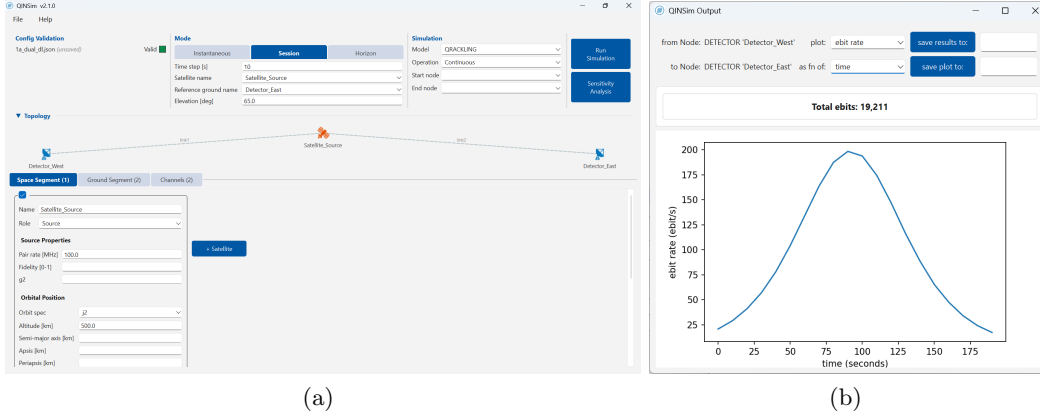


Figure 3. Graphical interface, shown for a dual downlink scenario in session mode: scenario configuration with live validation (a), session results (b), and a configured sensitivity sweep (c).

3. RESULTS

The focus on the design of QINSim is to make a tool that is useful for the community. As an example of the insights the functionality of QINSim can enable, we analyse the impact of memory coherence time (known as dephasing time in line with²⁰) on the network KPIs as shown in Figure 4. We adopt a relatively simple network topology for this analysis, with a satellite downlink configuration, a swapping node at a single OGS and that OGS being linked over a 10km length of fibre to another source.

We find that a memory dephasing time (T_2) of over 30 seconds is required to clear the fidelity threshold of 90%, which we note is challenging to achieve. As discussed in section 2.5, we note that the model adopted from²⁰ makes some optimistic assumptions about the implementation of the memory, such as the number of acceptance modes being effectively infinite, the presence of quantum non-demolition measurements and others, which do not accurately reflect the real implementation of quantum memories and swapping nodes. Similarly, we assume the wavelength of sources are perfectly tuned for compatibility with the memories at the swapping node and perfect mode overlap is achieved at the swapping nodes.

Table 2. Parameters for baseline simulation scenario

Parameter	Value
Satellite altitude	500 km
Satellite optical terminal aperture	0.1 m
Satellite pointing jitter	$2 \mu rad$
Optical Ground Station aperture	0.8 m
Source Pair Rates	100 MHz
Free-space wavelength	780 nm
Quantum memory efficiency	0.9

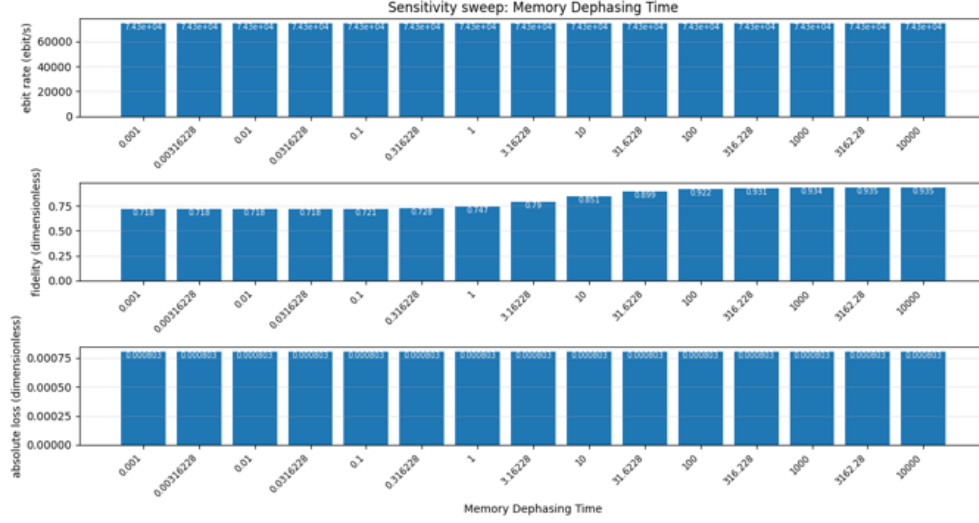


Figure 4. KPI sensitivity with memory dephasing time

A further example utilises the optimisation functionality to assess the choice of satellite altitude for a dual downlink configuration. This is a potentially interesting case to assess as the higher the altitude, the longer the contact time with each OGS pair, but the longer links results in a geometric loss as the beam will diverge over a greater distance. Therefore assessing this trade off by examining the volume of ebits distributed would enable a user to decide where to place a potential satellite. We perform this optimisation in Figure 5 and find that the optimal point is where the satellite is closest, suggesting link loss has a higher bearing than contact time.

4. CONCLUSION

In this work, we introduce the Quantum Information Network Simulator (QINSim), a powerful user-friendly tool for assessing dynamic satellite-based quantum networks. The simulator allows a user to asses various linear network topologies and analyse the performance of KPIs, either through manual setting of parameters, or by using QINSim’s sensitivity analysis or optimisation functionalities. A user can also integrate QINSim into their own Python scripts by means of a Command Line Interface. We hope this work will provide a valuable resource to the quantum networking community and those looking to define future missions as part of the quantum internet.

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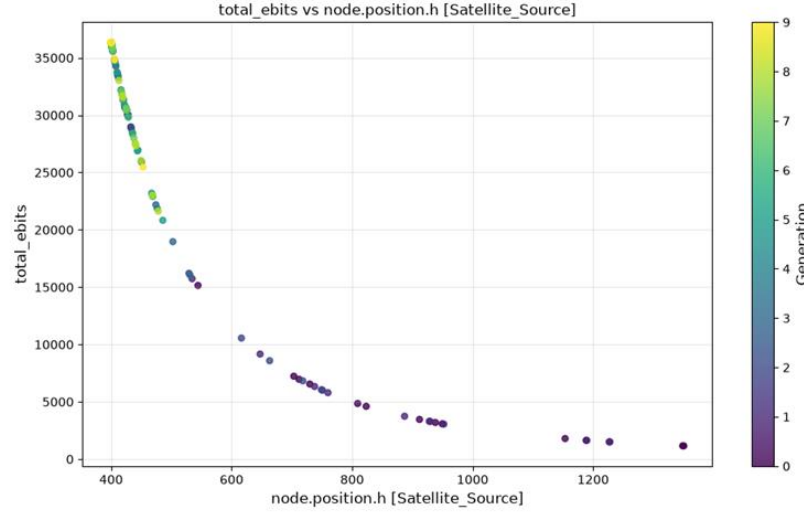


Figure 5. Optimisation of e-bit volume for a single overpass with respect to satellite altitude

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