QNTN: Establishing a Regional Quantum Network in Tennessee

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Introduction to Quantum Internet

Applications:

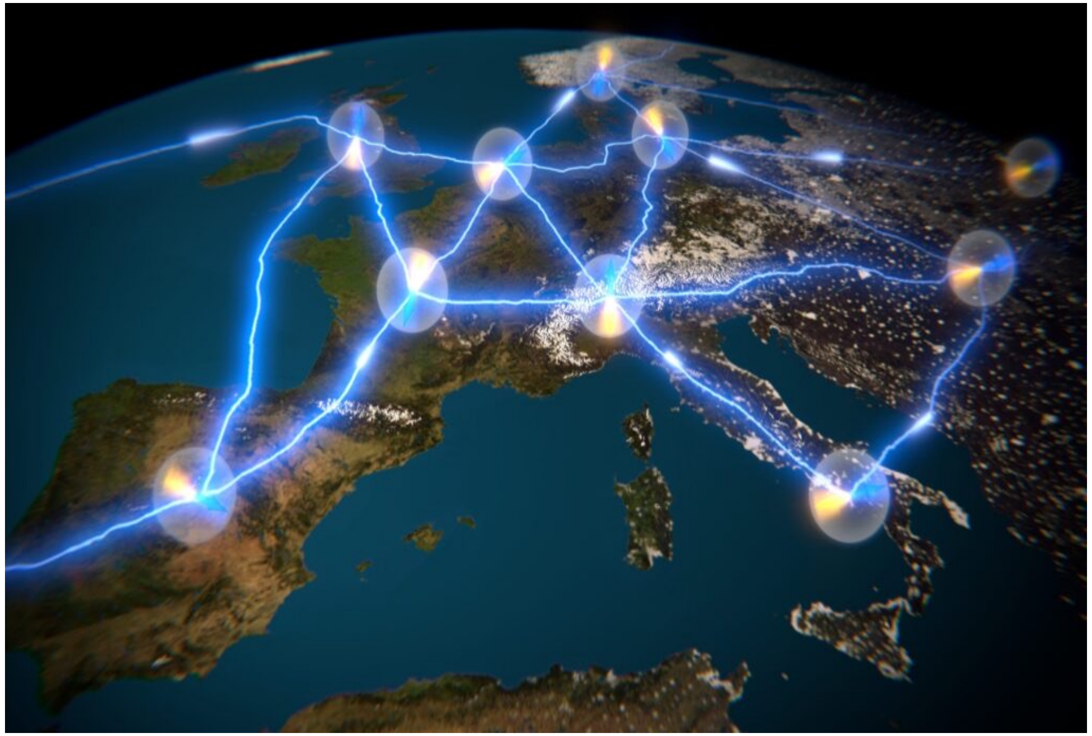
- Computing, Communication, Sensing, Intelligence, Security

Challenge:

- Connecting distant nodes efficiently with minimal photon loss

Key Solution Strategies:

- Fiber Optics: Limited range due to photon loss
- Free Space Optical (FSO): Better for long distances but still has limitations



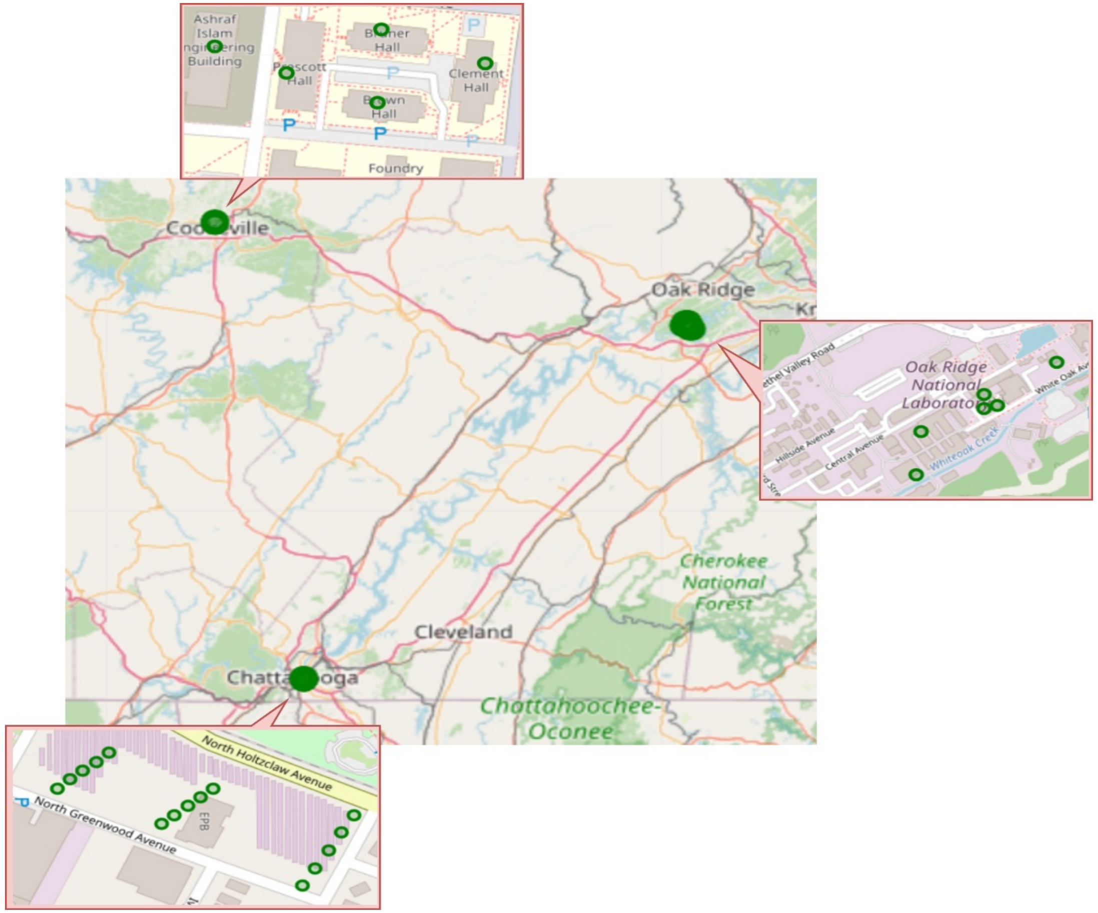
Related Works

Desirable Properties	EBP [1]	[2]	[3]	[4]	EuroQCI [5]	Micius [6]	Our work
Long distance connections	✗	✗	✓	✓	✓	✓	✓
Quantum communication	✓	✓	✗	✗	✓	✗	✓
Regional coverage	✗	✗	✓	✓	✓	✗	✓
Uninterrupted Coverage	✓	✓	✓	✗	✗	✗	✓
Comprehensive analysis comparing different architectures	✗	✗	✗	✗	✗	✗	✓

- Existing implementations focus on local networks using fiber optic communication.
- Existing work primarily focus on QKD services and do not address broader quantum communications.
- There is a lack of analysis comparing air-ground architecture with space-ground architecture in terms of coverage period, served requests, and entanglement fidelity.

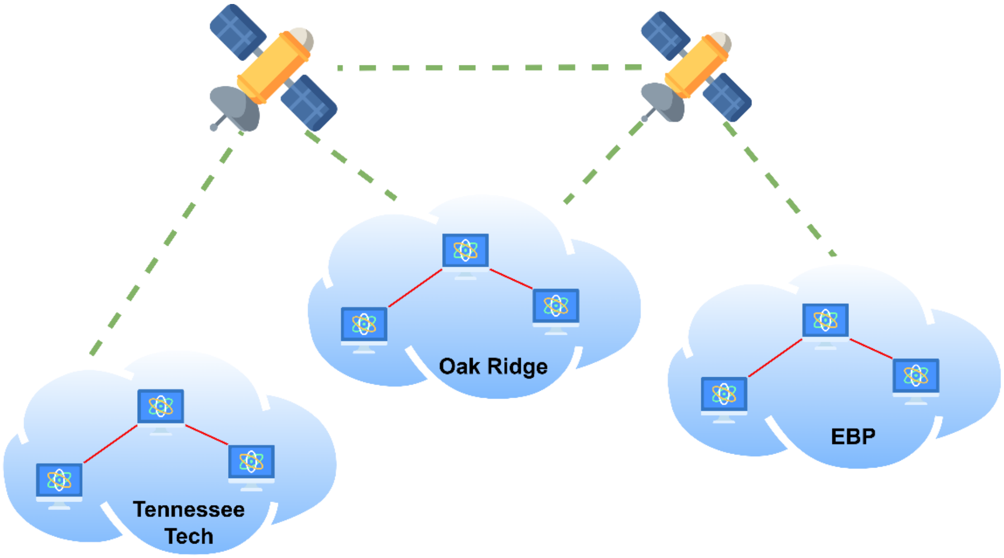
Objective

- We aim to design a regional Quantum Network in Tennessee (QNTN):
- We explore two architectures for connecting distant local quantum networks:
  - Space-ground architecture utilizing constellation of satellites
  - Air-ground architecture employing HAPs.



Space-Ground Architecture

- In this architecture, satellites are employed to link the three local networks.
- We explore different configurations of LEO constellation to optimize coverage.
- Satellites are positioned at an altitude of 500 km.
- We tested configurations with 6 to 108 satellites.



Orbital Design

- For the first 36 satellites, we use a Walker Delta constellation configuration.
- This setup includes 6 orbital planes inclined at 53 degrees.
- Each plane is spaced 60 degrees apart in the RAAN.
- Each plane consists of 6 satellites.
- We add 12 additional orbital planes, ensuring that all planes are spaced 20 degrees apart in the RAAN.
- Each new plane also contains 6 satellites.

Property	Value
Semimajor access	6871 km
Inclination	53 deg
RAAN	0 deg
True Anomaly	0 deg

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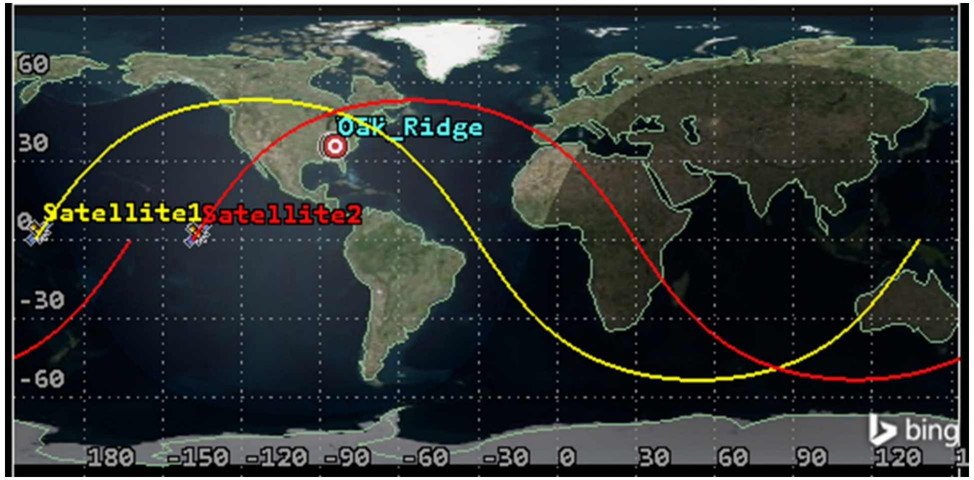

Property	Value
Semimajor access	6871 km
Inclination	53 deg
RAAN	60 deg
True Anomaly	0 deg

Orbital Design

- For the first 36 satellites, we use a Walker Delta constellation configuration.
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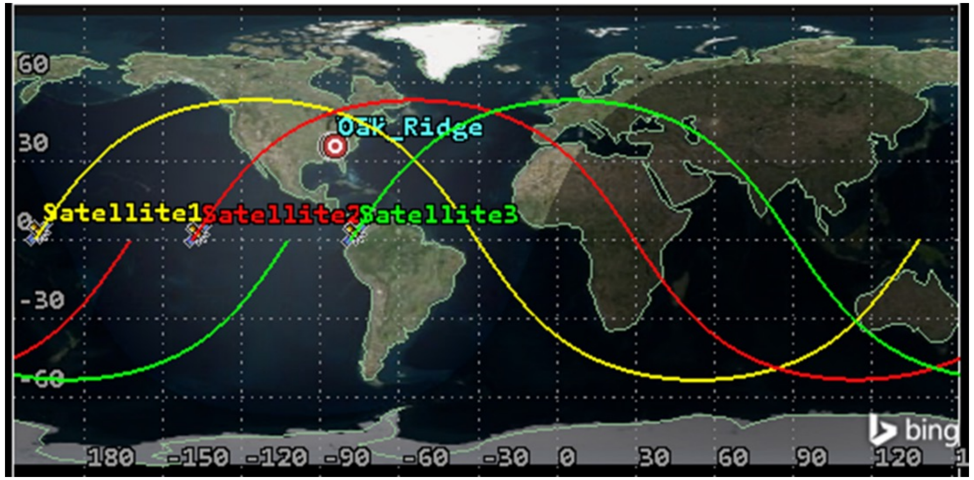

Property	Value
Semimajor access	6871 km
Inclination	53 deg
RAAN	120 deg
True Anomaly	0 deg

Orbital Design

- For the first 36 satellites, we use a Walker Delta constellation configuration.
- This setup includes 6 orbital planes inclined at 53 degrees.
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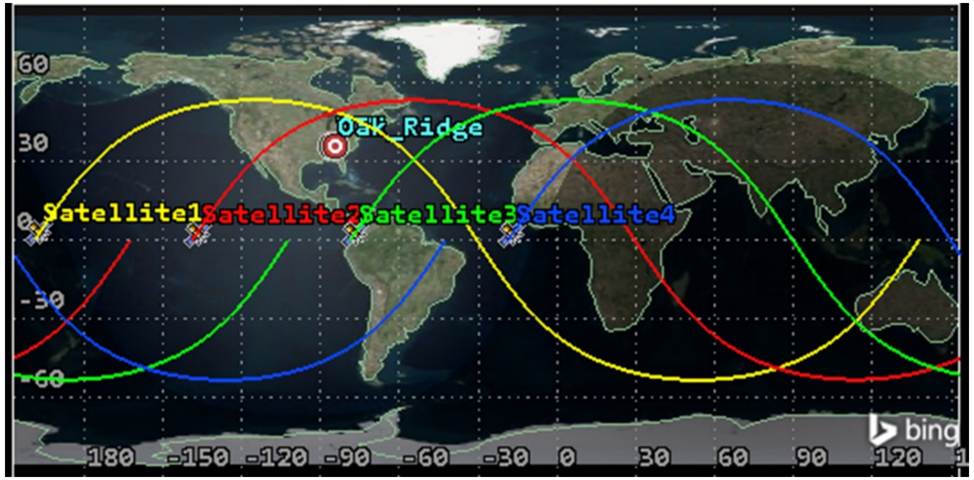
- Each plane consists of 6 satellites.
- We add 12 additional orbital planes, ensuring that all planes are spaced 20 degrees apart in the RAAN.
- Each new plane also contains 6 satellites.



Property	Value
Semimajor access	6871 km
Inclination	53 deg
RAAN	180 deg
True Anomaly	0 deg

Orbital Design

- For the first 36 satellites, we use a Walker Delta constellation configuration.
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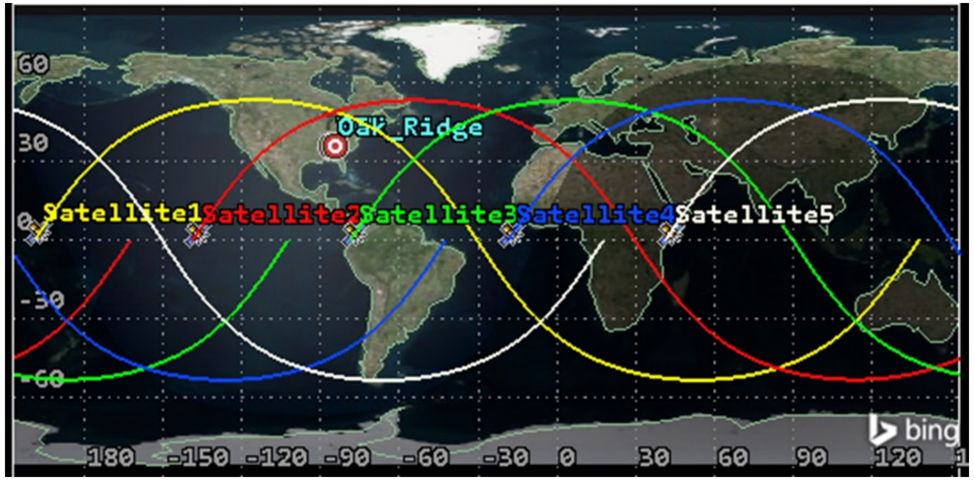
- We add 12 additional orbital planes, ensuring that all planes are spaced 20 degrees apart in the RAAN.
- Each new plane also contains 6 satellites.



Property	Value
Semimajor access	6871 km
Inclination	53 deg
RAAN	240 deg
True Anomaly	0 deg

Orbital Design

- For the first 36 satellites, we use a Walker Delta constellation configuration.
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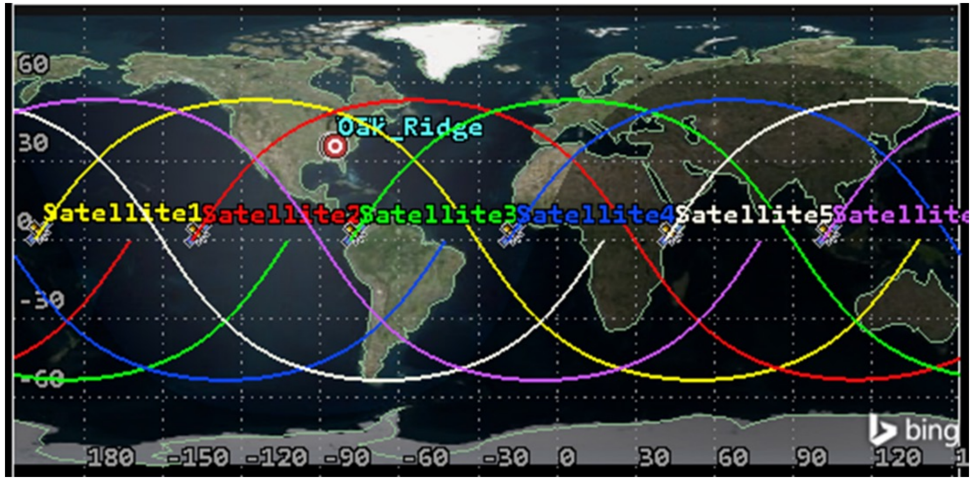
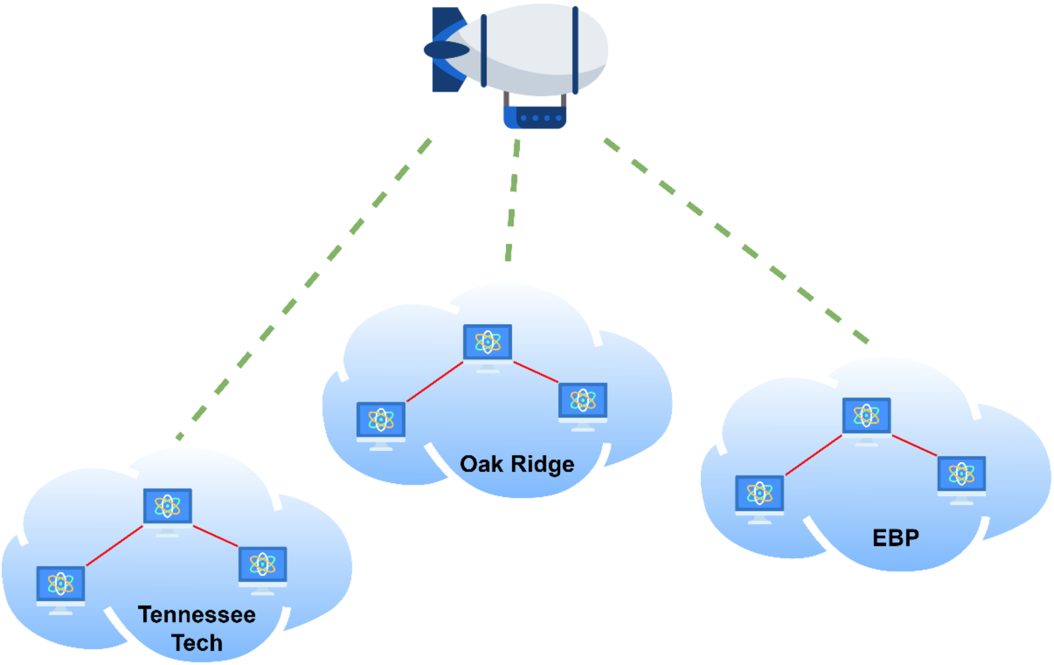
- Each new plane also contains 6 satellites.



Property	Value
Semimajor access	6871 km
Inclination	53 deg
RAAN	300 deg
True Anomaly	0 deg

Air-Ground Architecture

- In this architecture, aerial vehicles are utilized to connect the three local networks.
- These vehicles can be UAVs or HAPs.
- In this work, we employ a single HAP at an altitude of 30 km to connect the three networks.



Comparison

Space-Ground

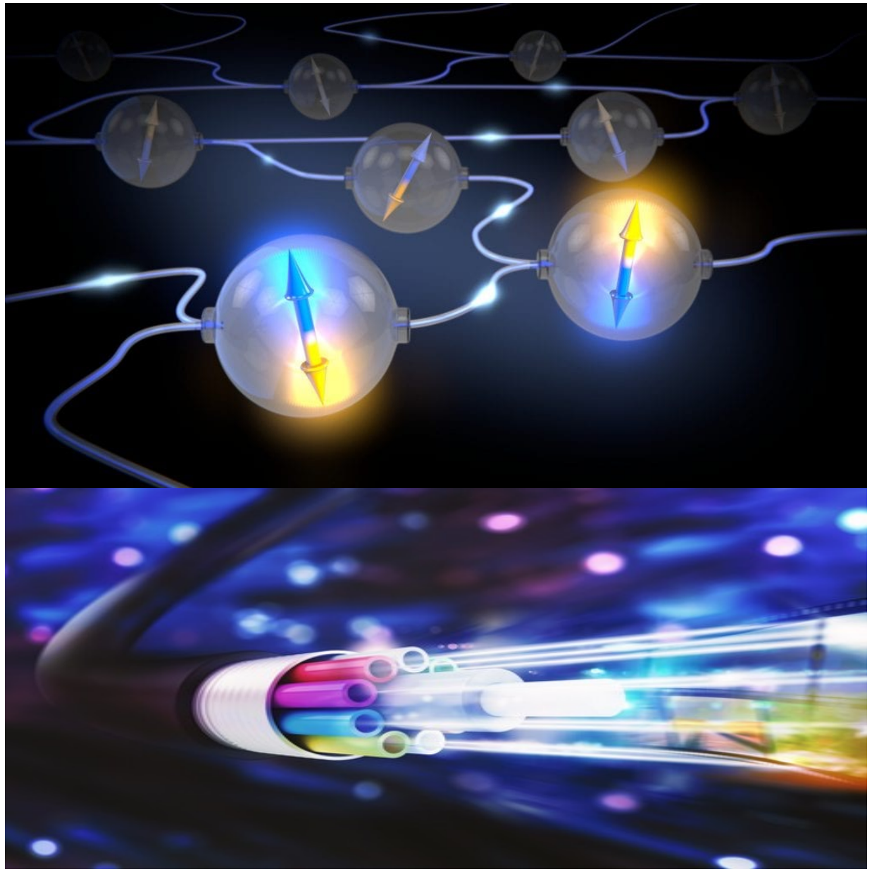
- Offers wide coverage and high-altitude operation.
- Reduces atmospheric interference and enables global communication.
- It comes with significant challenges such as high latency, high deployment costs, and limited maneuverability.

Air-Ground

- Provides lower latency as HAPs operate closer to the ground.
- Flexible deployment and repositioning capabilities, and generally lower costs.
- HAPs have smaller coverage areas, susceptible to weather conditions, and have shorter operational lifespans.

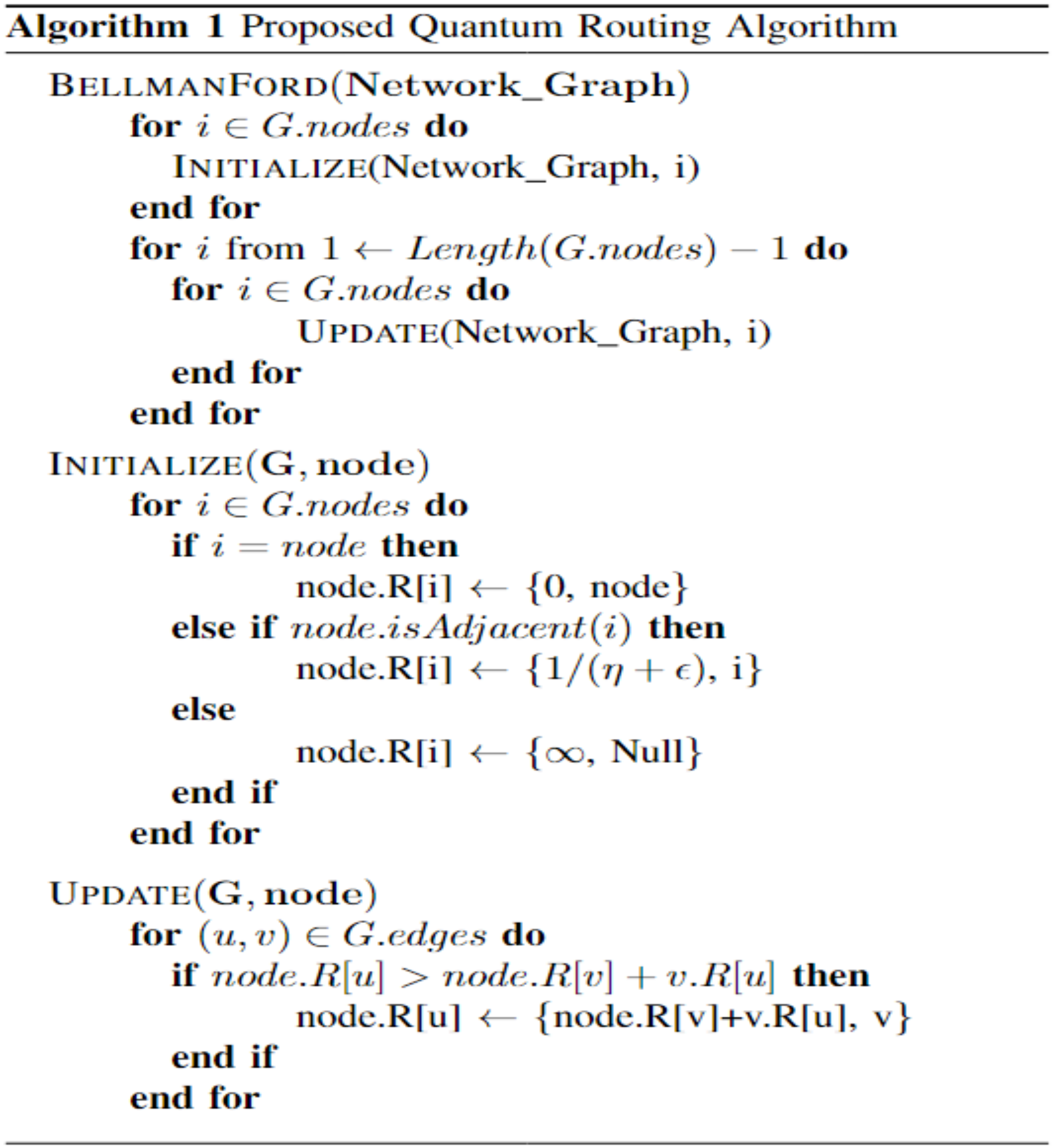
Channel Models

- Fiber optic channels to connect ground nodes.
- FSO channels are employed between satellites, and for connecting satellites and the HAP with ground nodes.
- For each channel, transmissivity is used as a metric to characterize the optical losses encountered during communication.
- An amplitude damping channel is used to degrade quantum states based on the transmissivity.



Entanglement Routing

1. Each node constructs a routing table setting the visiting cost to itself to zero, the visiting cost to adjacent nodes to $\frac{1}{\eta+\epsilon}$, and the remaining costs to ∞.
2. Each node shares its constructed routing table with its adjacent nodes.
3. Each node adjusts the visiting cost to each node by choosing the minimum between directly visiting the node and visiting the node from an adjacent node.
4. Steps 2 and 3 are repeated $N-1$ times, where N is the number of nodes in the network.



Algorithm 1 Proposed Quantum Routing Algorithm

```
BELLMANFORD(Network_Graph)
    for $i \in G.nodes$ do
        INITIALIZE(Network_Graph, i)
    end for
    for $i$ from 1 $\leftarrow Length(G.nodes) - 1$ do
        for $i \in G.nodes$ do
            UPDATE(Network_Graph, i)
        end for
    end for
INITIALIZE(G, node)
    for $i \in G.nodes$ do
        if $i = node$ then
            node.R[i] $\leftarrow$ {0, node}
        else if $node.isAdjacent(i)$ then
            node.R[i] $\leftarrow$ {$1/(\eta + \epsilon)$, i}
        else
            node.R[i] $\leftarrow$ {$\infty$, Null}
        end if
    end for
UPDATE(G, node)
    for $(u, v) \in G.edges$ do
        if $node.R[u] > node.R[v] + v.R[u]$ then
            node.R[u] $\leftarrow$ {node.R[v]+v.R[u], v}
        end if
    end for
```

Quantum Network Simulator

- Existing quantum network simulators are limited to ground nodes.
- We have upgraded QuNetSim and integrated it with the STK.

QuNetSim

- We implemented an FSO channel model.
- New classes are also introduced for satellites and HAPs.
- Functions are also developed to model the degradation of entangled states and to measure entanglement fidelity.

STK

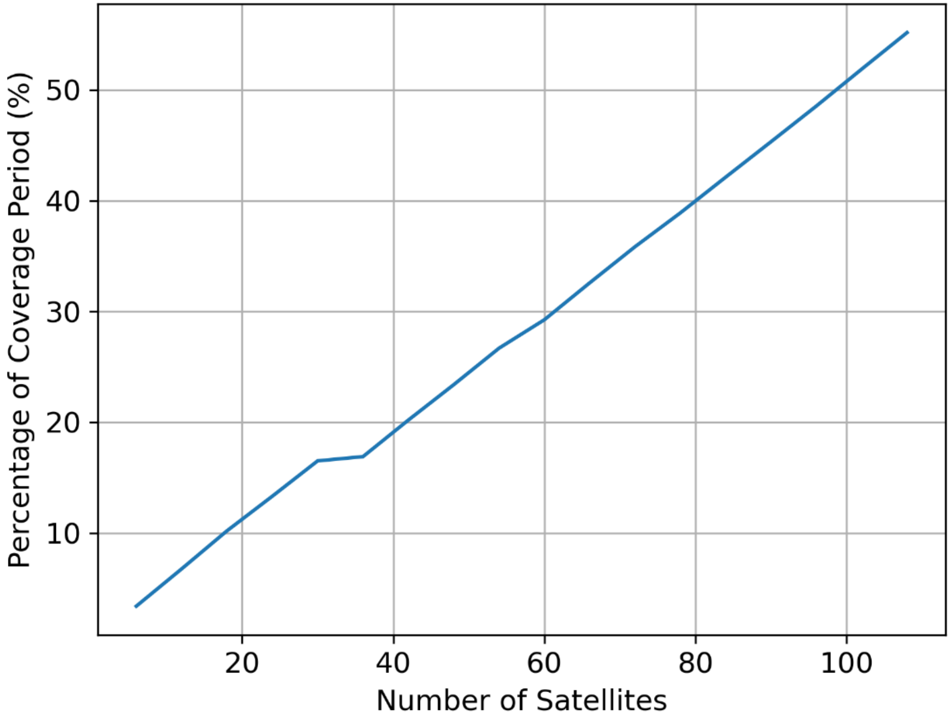
- The STK simulator is utilized to model satellite movements.
- Each satellite is initialized in its orbit, and the simulation runs to track satellite movements throughout a day, recording positions at 30-second intervals.

Assumptions Used

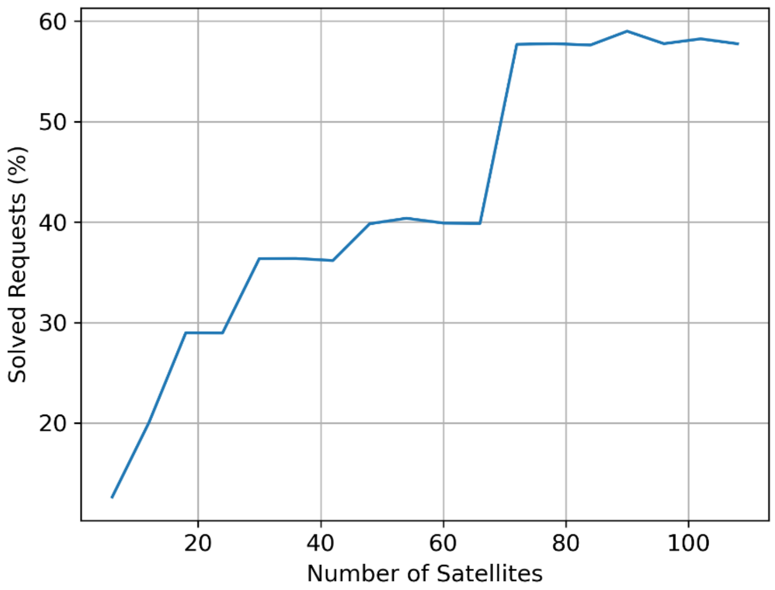
- Our simulation assumes a perfect setup and ideal conditions:
  - Stable weather
  - Stable flight for HAPs
  - Unlimited flight time
  - Infinite queue capacity
- Specifically, we assume that each node can serve all entanglement requests while in range.
- These assumptions are made to generate preliminary results and will be adjusted in future research to better reflect real-world conditions.

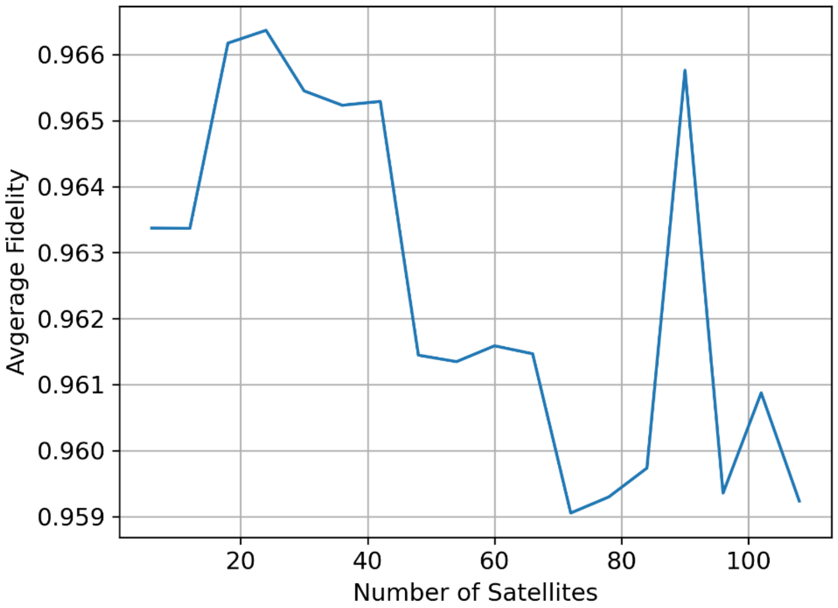
Space-Ground Approach

- We analyze the coverage period of the space-ground network.
- We measure the percentage of the coverage period for a dynamic number of satellites.
- 108 satellites can provide coverage for 55.17% of the day.



Space-Ground Approach





- 108 satellites can meet 57.75% of entanglement distribution demand.

The average entanglement fidelity is 0.96.

Air-Ground Approach

- Unlike satellites, the HAP hovers in place and is continuously available during its flight time.
- Therefore, this architecture can provide coverage for the entire day and serve 100% of the entanglement distribution requests.
- The simulation results show that the air-ground architecture can distribute entanglement pairs with an average entanglement fidelity of 0.98.

Architecture	P	Serving Requests	Entanglement Fidelity
Space-Ground	55.17%	57.75%	0.96
Air-Ground	100%	100%	0.98

Discussion

- Our simulations are carried out under perfect setup and ideal conditions.
- The air-ground architecture faces significant challenges.
  - Limited flight time due to power constraints.
  - Environmental factors such as vibrations.
  - Adverse weather conditions.

Architecture	P	Serving Requests	Entanglement Fidelity
Space-Ground	55.17%	57.75%	0.96
Air-Ground	100%	100%	0.98

Conclusion

- We have explored and compared two approaches for connecting local quantum networks across three cities in Tennessee.
  - Space-ground architecture utilizing satellite constellations.
  - Air-ground architecture employing HAPs.
- The space-ground architecture requires a significant number of satellites to achieve moderate coverage, while the air-ground approach offers continuous coverage and higher performance in both serving requests and entanglement fidelity.
- However, our simulations are carried out under perfect setup and ideal conditions.
- It is important to note that HAPs have limitations in operational time, coverage area, and susceptibility to environmental factors such as vibrations and weather conditions.

Future work

- Future work will study the impact of environmental factors on HAP stability and signal transmission and develop countermeasures to mitigate the effects of vibrations and adverse weather conditions.
- Additionally, we will study how each architecture will deviate from the ideal scenario when considering real-world constraints.
- Subsequently, we will investigate hybrid solutions that combine the strengths of both space-ground and air-ground architectures.

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THANK YOU!

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