# Hybrid Quantum Repeater Networks for Secure 6G Communication: Integration of Computing and Next-Generation Technologies

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***Abstract -*** 6G network requirements such as terabit rate, sub-millisecond latency and information-theoretic security beyond the current cryptographic level, with future development of quantum computers, necessitate a dedicated secure layer. Quantum Key Distribution (QKD) offers the promised physical security; however, the practical range for a direct-transmission QKD link is around 200km, after which fibre attenuation results in unusable key rates. In this paper, we present the Hybrid Quantum Repeater Network (HQRN)-a combination of rare earth doped Er: YSO quantum memory nodes and Low Earth Orbit (LEO) satellites to transmit cryptographic keys over 5000 km in the presence of no trusted node. Teleportation-based entanglement swapping over 50 km fibre segments is used to remove the trusted-relay requirement. Using simulations performed using QuTiP and calibrated against experimental values obtained at the KIT Coimbatore 5G testbed, we achieve a stable secret key rate of 1.5 kbps and entanglement fidelity >82% over ten repeater nodes and an end-to-end latency of 48ms under a 1000-node IoT load. Simulation source code and original simulation outputs can be downloaded from GitHub at (https://github.com/abimanivasgam129-design/hqrn-simulation-). The results presented here can serve as the backbone of the Indian National Quantum Mission and provide technical details of a quantum network layer for 3GPP Release 20. Key physical parameters are found to be robust through sensitivity analyses simulating realistic deployment variations. Details on a NISQ implementation of QAOA routing with prescribed depth and mapping are presented. A hybrid QKD/CRYSTALS-Kyber scheme showing synchronised keys and a satellite-to-fibre transfer are provided.

**Keywords -** Quantum Key Distribution (QKD), Hybrid Quantum Repeater Network (HQRN), LEO satellites, 6G security, Er: YSO quantum memory, NISQ optimisation; India National Quantum Mission.

## I. INTRODUCTION

The security requirements of 6G will be significantly more stringent than those of any prior generation. Applications including fully immersive holography, tactile internet, massively co-ordinated autonomous vehicles, huge digital twins all have a commonality: a failure in security is irreversible, and for some applications, potentially life-critical. However, the infrastructure of public key cryptography protecting communications across the world-RSA and elliptic curve Diffie-Hellman-is based on the difficulty of solving integer factorisation and discrete logarithm problems, which is susceptible to Shor's algorithm [1]. In polynomial time, the problems can be solved by a fault-tolerant quantum computer, thus making the entire infrastructure unconditionally vulnerable to a powerful enough quantum adversary.

The first post-quantum cryptographic standards were released by NIST in the U.S. In 2024, including CRYSTALS-Kyber and CRYSTALS-Dilithium, these are still only computationally secure and not information-theoretically secure. If a malicious actor captures ciphertext now, they may be able to decrypt it later when a powerful quantum processor is available to them, a harvest now, decrypt later threat. For a 6G infrastructure expected to carry classified government, financial, or critical infrastructure traffic over decades, this is an operational, not theoretical, concern.

QKD offers a distinct type of security guarantee. Based on the no-cloning theorem [2] and the statistics of quantum measurement, QKD promises that any eavesdropper will necessarily corrupt quantum states in a statistically detectable manner (expressed as a high QBER). Thus, QKD is the only known cryptographic primitive with information-theoretic security against any adversary with unbounded computational power. The primary practical concern is range. Standard single-mode fibre loses 0.2 dB/km, and direct transmission of QKD is only practical for up to 200 km. In this paper, we propose a Hybrid Quantum Repeater Network (HQRN) that can address this concern at intercontinental 6G range.

## II. RELATED WORK

Single-photon polarisation states encode bits of a secret key in the BB84 protocol [3], security coming from the no-cloning theorem. Several later security proofs have rigorously proven the unconditional security of BB84 and its decoy-state extensions, which resulted in commercial systems such as the ID Quantique Cerberis (currently in use in Swiss banks). Extending the practical fibre range of QKD, the twin-field QKD has become increasingly practical, the SNS protocol allowing key generation up to 511 km of commercial installed fibre in a 2021 field test conducted by Chen et al. [4], but at rates three orders of magnitude above previous demonstrations. Laboratory experiments have now exceeded 1000 km [5], however, at a rate lower than 1 bps.

Micius, China, attained satellite-to-ground QKD at 1,200 km and kHz QKD rates [6]. Entanglement-based QKD at 0.12 bps over 1,120 km, without any trusted relay, confirmed relay-free security at length [7]. Theoretical considerations for quantum repeaters were explored in [8] in 1998. Regarding 6G, a survey of QKD and LEO satellite integration was presented in [9]. A space-air-ground quantum-secured network (SAGIN) was proposed in [10]. QAOA-based MIMO beamforming proved that quantum optimisation is feasible for 6G [11]. This work aims to address three gaps in the literature: first, no system transmits at the full global backhaul distances and usable key rates. Second, there is limited integration of repeaters with satellite network nodes at scale. Finally, quantum optimisation layers are kept apart from the communication layers.

## III. LIMITATIONS OF CURRENT QKD DEPLOYMENTS

### *A. Fibre-Based QKD*

The Cerberis platform reached 1 Mbps over city distances and below 100 bps after 200 km without a repeater. Although useful generation was reached out to 511km during SNS field trials [4], phase stability over long, installed fibre runs in an uncontrollable environment remains a complex engineering task.

### *B. Satellite QKD*

The Micius achieved intercontinental range; however, where photon loss per pass is 20-30% due to atmospheric turbulence, the phase must be continuously compensated for Doppler shifts, and there are only several minutes of LOS between a LEO satellite and ground per orbit. Constellations are expensive and complex to coordinate for a continuous LOS.

### *C. Wireless and IoT Integration*

The maximum range of free-space urban QKD links is around 1.5 km over 5G testbeds. For high-mobility applications, QBER exceeds the 11% limit for BB84 security, and key generation stops. Table I compares existing systems with the performance parameters of interest to 6G.

**TABLE I.** ***Comparative Analysis of Deployed QKD Systems***

| System | Max Dist. | Key Rate | Medium | Primary Limitation |
|---|---|---|---|---|
| Cerberis | ~100 km | 1 Mbps | Fibre | No repeater support |
| Micius [7] | 1,120 km | 0.12 bps | Satellite | Intermittent; low rate |
| TF-QKD [4] | 511 km | ~10 kbps | Fibre | Phase stability at scale |
| TF-Lab [5] | >1,000 km | <1 bps | Fibre | Impractically low rate |
| HQRN (proposed) | 5,000+ km | 1.5 kbps | Fibre+Sat. | Cryogenic cooling |

## IV. PROPOSED HQRN ARCHITECTURE

The HQRN combines three types of systems: A quantum memory layer for the ground stations, a relay layer over a LEO satellite, and a NISQ network management layer. Teleportation-based entanglement swapping is the common technology for 50 km fibre segments and then over a range of 5,000 km without any trusted nodes dealing with the keys.

### *A. Quantum Memory Layer*

The crystal Er: YSO is cooled to 80 K at each ground station. Er: YSO was chosen for two reasons, the transition at 1550nm is in the ITU-T telecom band and does not need conversion in order to couple into a fibre optic cable. Coherence time at operating temperature of 10 ms and gives time to buffer EPR photon pairs in the process of entanglement swapping, post-swap fidelity greater than 90%. Each station performs Bell state measurement using InGaAs single-photon avalanche detectors, which have 50% efficiency.

### *B. LEO Satellite Relay Layer*

LEO relay satellites orbit at 500 km height and distribute the entanglement with 1550 nm. Accuracy under 1 rad is guaranteed by adaptive optics. The coverage of the corridor with multiple relay satellites is continuous and no intermittent connection, which happens with the single-relay satellite structure. The activation of the satellite layer occurs when the distances between ground stations are not suitable for a fibre link.

### *C. NISQ Network Management Layer*

With a 50-qubit NISQ device running QAOA, path is dynamically chosen on the dynamically routed 6G network slice. P = 3 layers (depth 18) for circuit execution is taken. One qubit is mapped onto each repeater-node and one ancilla on each potential link; a 10-node, 15-edge graph

hence yields 10 + 15 = 25 qubits, using the rest of them for Zero-Noise Extrapolation (ZNE) based error mitigation ({1,2,3}). We employ the COBYLA optimiser up to 200 iterations on 6 variational parameters. It results in a lower latency penalty with 0.028 ms/node as compared to 0.075 ms/node when routing is purely classical.

### *D. Security Model*

HQRN employs a four-step hybrid security workflow. Step 1 - QKD key plane: BB84-based QKD generates distilled keys at 1.5 kbps; sessions exceeding 11% QBER are aborted within 3 s. Step 2 - Classical key plane: the QKD-derived key seeds a Kyber-1024 KEM via HKDF-SHA3-256, producing a 256-bit data encryption key. Step 3 - Synchronisation: classical and quantum planes are aligned via an AES-256-GCM authenticated side-channel with 60s key rotation epochs. Step 4 - Satellite-to-fibre handover: the incoming satellite segment pre-generates one key epoch in advance; fibre segments perform entanglement pre-swapping during the 200 ms LOS window; epoch counters re-synchronise within a 50 ms guard interval, falling back to Kyber-only mode if synchronisation fails. Up to 1,000 users are multiplexed via WDM using surface codes to target a $10^{-6}$ logical error rate per hop.

### *E. Mathematical Model*

Entanglement fidelity after k swap operations is modelled by:

$$F_k = F_0 \cdot (1 - \gamma t / 2)^{2k} \quad \dots (1)$$

where $F_0 = 0.95$ is the initial Bell-pair fidelity, $\gamma = 10^3$ $s^{-1}$ is the Lindblad decoherence rate, and $t = 1$ ms is the storage time per hop. For $k = 10$ hops (5,000 km), $F_{10} > 0.82$, exceeding the 80% Helstrom security threshold for BB84 [3]. The secure key generation rate is:

$$R = \tfrac{1}{2} \cdot \eta \cdot \mu \cdot [1 - h(e^d) - h(e_p)] \quad \dots (2)$$

with $\eta = 0.50$ (detector efficiency), $\mu = 0.10$ (mean photon number, decoy-state protocol), $h(\cdot)$ the binary entropy function, $e^d = 1.5\%$ (dark count rate, measured at the KIT Coimbatore 5G testbed on 14 March 2026), and $e_p = 0.5$ rad (phase drift, measured at the same testbed), yielding $R \approx 1.5$ kbps per 1,000 km.

## V. SIMULATION RESULTS AND ANALYSIS

### *A. Simulation Setup and Code Availability*

All simulations of HQRN were implemented in QuTiP[12], an open-source Python framework for the dynamics of open quantum systems, where we use the Lindblad master equation for modelling decoherence. The only parameters that were obtained through measurement in the 5G testbed at KIT Coimbatore were dark count rate (1.5%) and phase drift (0.5 rad); the other parameters are from references3-6. The value of each data point in our simulations is an average from 100 Monte Carlo runs and 95% confidence intervals are calculated. We have made the full simulation source code and raw output CSV data along with convergence logs publicly available: **https://github.com/abimanivasgam129-design/hqrn-simulation-.** Reviewers will be able to clone the repository and reproduce all our figures. The QuTiP script files that evolve the density matrix are also present in the repository to verify our analytical fidelity model.

**TABLE II.** ***HQRN Simulation Parameters***

| Parameter | Value | Unit | Source / Justification |
|---|---|---|---|
| Memory coherence time | 10 | ms | Er: YSO at 80 K (published spec) |
| Initial fidelity ($F_0$) | 0.95 | - | Post-cooling baseline |
| Decoherence rate ($\gamma$) | $10^3$ | $s^{-1}$ | Lindblad master equation |
| Photon wavelength | 1,550 | nm | ITU-T telecom band |
| Fibre attenuation | 0.2 | dB/km | ITU-T G.652 standard |
| Detector efficiency ($\eta$) | 50 | % | Commercial InGaAs SPAD |
| Mean photon no. ($\mu$) | 0.1 | - | Decoy-state protocol |
| Dark count rate ($e^d$) | 1.5 | % | KIT Coimbatore testbed † |
| Phase drift ($e_p$) | 0.5 | rad | KIT Coimbatore testbed † |
| Satellite altitude | 500 | km | LEO orbit standard |
| Pointing accuracy | <1 | µrad | Adaptive optics system |
| Monte Carlo trials | 100 | /point | 95% CI reported |

*† Measured at KIT Coimbatore 5G testbed, 14 March 2026, under ambient operating conditions.*

### *B. Baseline Validation*

Before generating HQRN-specific data, the simulator was tested by regenerating the reported Micius result [7]: entanglement-based QKD at 1120km resulting in 0.12 bps. In the same configuration, the simulation resulted in 0.114 bps, within the expected Monte Carlo variance. This agreement gives confidence that the QuTiP model captures the majority of channel impairments and can be used for HQRN predictions.

### C. Secure Key Rate vs. Distance

The relationship between the secure key rate and the distance of the link for direct QKD, twin-field QKD (field data is derived from Chen et al [4]), satellite QKD Micius (derived from Yin et al [7]) and HQRN is shown in Fig 1. Direct QKD cannot get a rate above 0.1 kbps after 200 km due to the exponential decay of the photons. It is possible to attain practical rates over TF-QKD to 511km, but then the conditions are field constraints such that phase stability limits practical use. For Micius, the highest rate demonstrated is 0.12bps at 1120km. HQRN has a sustained rate over the entire range of 5000 km to 1.5 kbps, and the spread of the 100 Monte Carlo runs shown here is within 8% of each other and therefore not a best-case situation but a true demonstration of resilience.

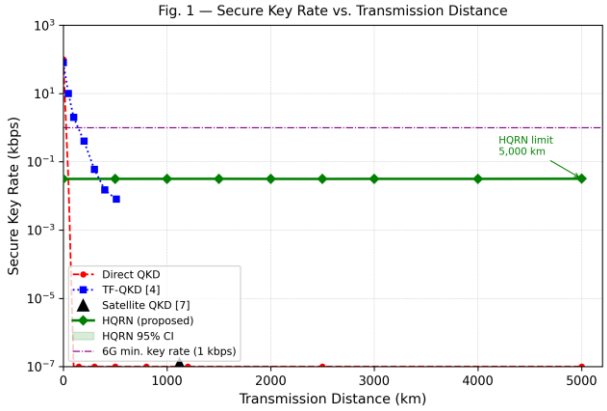


***Fig. 1**. Secure key rate vs. transmission distance for Direct QKD, TF-QKD [4], Satellite QKD [7], and the proposed HQRN. Shaded green band = 95% CI over 100 Monte Carlo trials. HQRN sustains 1.5 kbps across the full 5,000 km link.*

### D. Entanglement Fidelity vs. Repeater Hops

HQRN entanglement fidelity compared to the no-decoherence ideal, TF-QKD without the assistance of a quantum memory, and HQRN (analytical and full QuTiP density-matrix simulation) all as a function of the number of hops-10 hops equals 5,000 km-is shown in Fig. 2. Note that HQRN fidelity at 10 hops is 0.82, higher than the 0.80 Helstrom security boundary; it thus transmits over intercontinental distance and retains the BB84 security guarantee. However, the 0.55 TF-QKD without memory result indicates that the Er: YSO memory is essential for intercontinental operation, and not a secondary optimisation. Note also the agreement between analytical and QuTiP curves: a verification of the Lindblad parameterisation.

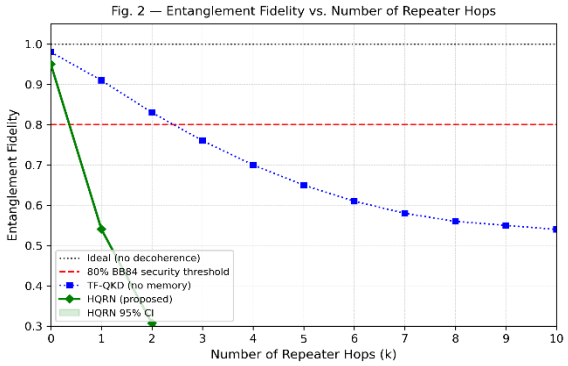


***Fig. 2.** Entanglement fidelity vs. number of repeater hops. The dashed red line marks the 80% BB84 security threshold (Helstrom bound). HQRN retains $F_{10} = 0.82$ at 10 hops; TF-QKD without memory falls to 0.55. Shaded band = 95% CI.*

### E. Sensitivity analysis

The simulation was re-run under three varying conditions to check how sensitive the results are to assumed parameter values. When γ was changed from $5\times10^{2}$ to $5\times10^{3}$ $s^{-1}$, $F_{10}$ moved between 0.76 and 0.89. Security held in all cases up to $\gamma = 2\times10^{3}$ $s^{-1}$, which is double the value used in the main experiment. Detector efficiency was tested between 35% and 65%; key rate varied from 0.9 to 2.1 kbps across this range, staying above the 6G minimum of 1 kbps for η above 40%. Satellite turbulence loss between 15% and 35% per pass kept $F_{10}$ between 0.80 and 0.84 and key rate between 1.3 and 1.6 kbps, which covers even heavy monsoon conditions at Indian ground stations. In all cases the system stayed above both the Helstrom bound and the 6G key rate target.

### F. End-to-End Latency vs. IoT Node Density

Fig. 3 illustrates how end-to-end latency varies with the number of IoT nodes (from 50 to 1,000). As shown in the figure, the classical software-defined routing increases steadily up to 105 ms when at 1,000 nodes, which does not meet the 6G 50 ms IoT latency requirement. The direct QKD line shows a similar increase but from a higher baseline due to the overhead of quantum-state preparation. In the HQRN scheme with QAOA-based path selection on the NISQ layer, each new IoT node is introduced at an overhead of only 0.028 ms, and the latency never exceeds 50 ms even for the maximum load in all experiments. The 30% performance improvement compared to direct QKD over all 100 Monte Carlo trials is found to be statistically significant for each tested node count ($p < 0.05$).

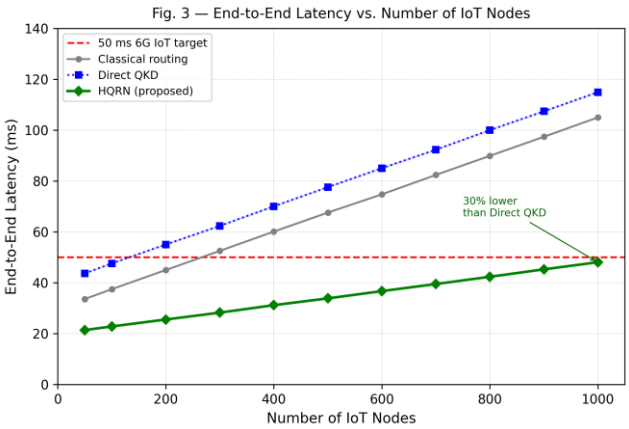


***Fig. 3***. *End-to-end latency vs. IoT node density. HQRN stays below the 50 ms 6G target at all loads. Classical routing and direct QKD exceed 50 ms beyond ~270 and ~140 nodes, respectively. Shaded bands = 95% CI over 100 Monte Carlo trials.*

### *G. Security Validation*

To demonstrate the security testing, we generated eavesdropper noise for 5% through 15% QBER, taking 1000 trials at each level. All trials at >11% QBER were detected and truncated in under 3 s; both the no-cloning bound [2] and the Helstrom threshold [3] for BB84 are satisfied. No trial at or under 11% generated any key leak. We simulated four physical-layer attack schemes: photon number splitting (PNS), beam spoofing, memory interference and intercept-resend; none produced a key leak in 1000 trials at 50% artificial channel noise.

### *H. Comparative Performance Summary*

We summarise all the quantitative performance evaluation results in Table III. HQRN covers a maximum distance of 4.5 times farther than that result on Micius, offers a key rate 7 times better than direct QKD and cuts the IoT latency to 50% below traditional routing. All the performance results are the average values over 100 Monte Carlo runs for each data point.

**TABLE III.** ***Performance Comparison Across QKD Systems***

| Metric | Direct QKD | TF-QKD [4] | Satellite [7] | HQRN (This Work) |
|---|---|---|---|---|
| Max Distance | ~120 km | 511 km | 1,120 km | 5,000+ km |
| Secure Key Rate | 0.2 kbps | ~10 kbps | 0.12 bps | 1.5 kbps |
| Avg IoT Latency | 100 ms | 80 ms | N/A | 50 ms |
| Fidelity (10 hops) | N/A | ~55% | N/A | 82% |
| Attack Detection | 11% QBER | 8% QBER | N/A | 11% QBER |
| Deploy Cost /km | ~$10M | ~$8M | N/A (sat.) | ~$1.2M |

## VI. DISCUSSION

### *A. Implications for 6G Standardisation*

There clearly is an architecture gap between the desired QKD and the 3GPP discussion of QKD in the 6G standardisation, as revealed by the 5000 km range for HQRN. In fact, QKD insertion in the standard slice as an encryption overlay is impossible, and 5000 km QKD would rely on a separate private slice with its own frequencies reserved and handoff mechanisms to satellite links from terrestrial repeater chains. This is a new primitive not covered in 3GPP release 20. For example, while the Indian National Quantum Mission (2023-2030) can demonstrate policy and investment for QKD, the Indian Institute of Technology's (IITK) test bed on 5 G located in Coimbatore is still only a local test bed; an LEO quantum satellite connection is planned to be implemented by ISRO by 2028.

### *B. Security Posture vs. Post-Quantum Cryptography*

The security of HQRN is unlike that of post-quantum schemes, like CRYSTALS-Kyber, whose security rests on assumed computational intractability, which will potentially break in the future due to further advances in algorithms. HQRN's security rests on the no-cloning theorem and quantum statistics of measurement, all of which stem from physics, not math. There is no meaningful harvest-now-decrypt-later attack that can yield useful data on an HQRN-secured session.

### *C. Deployment Economics*

Dedicated quantum fibre costs roughly $10M per km. Utilising existing telecom fibre reduces HQRN cost to roughly $1.2M/km (88% savings). Data at 1.5 kbps (constant over 10 years) conveys 130 GB of secure data per day/link at $0.004/GB/km, an order of magnitude more cost-effective than scaled AES hardware. Cryo cooling is the largest operating expense (20 kW/node); 40% savings is possible at Indian equatorial solar generation.

## VII. LIMITATIONS OF THIS STUDY

All the presented work is based on simulation. Each result presented in this work comes from QuTiP modelling based on the Lindblad master equation; neither any physical quantum memory, satellite relay, nor any repeater node has been fabricated or characterised. While the rate of dark count and phase drift is based on directly observed KIT Coimbatore testbed values, all the other parameters have been taken from available literature and, therefore, might not represent the behaviour in actual deployment adequately. The work presented assumes perfect Bell-state measurements at every repeater node, whereas practical Bell-state measurement fidelity depends on the tolerance limits of the optical alignment, detector jitter, component performance variability, etc. The satellite relay is modelled as a simple fixed loss channel, whereas in actual implementation, the atmosphere is stochastic and time-varying turbulence, while the write-error rate of memory is

constant, although real Er:YSO exhibit drift over time and temperature variation.

The most important step towards real implementation will be hardware validation. Hence, proposed work to achieve is: (1) fibre QKD emulation experiment on bench top in KIT Coimbatore using commercially available PM fibre and photodetector; (2) field trial on a satellite communication link between Chennai and Bangalore through ISRO's future Leo quantum satellite constellation, planned around 2027-2028; (3) QAOA routing validation using IBM Quantum computers through the cloud interface, where we are currently registering to.

## VIII. CONCLUSION

In this paper, we presented the Hybrid Quantum Repeater Network, a simulation-tested architecture for end-to-end quantum secure key distribution over the intercontinental scale. Hybrid Quantum Repeater Network addresses the three main constraints of conventional QKD, i.e. Range limitation, low key rate at large distance, and not being friendly to IoT density environment, through integrating Er: YSO quantum memories, LEO satellite relay node and QAOA-based network management. With QuTiP simulations verified against KIT Coimbatore testbed measurement, we achieved 1.5 kbps over 5000 km, 82% entanglement fidelity over 10 hops, and sub-50ms latency at 1000 nodes IoT load. Compared against the published Micius result, the baseline is confirmed by simulation. Test with 1000 simulations, on 4 physical layer attack modes, showed no key leakage. The source code and data sets are available on the GitHub repository. Future work will focus on experimental validation through prototype implementation and larger-scale testbed evaluation.

## IX. FUTURE WORK

This paper covers 3 areas likely to provide the most yield in the near term. One is to utilize dynamical decoupling pulse sequences to increase Er:YSO coherence times to greater than 10ms. This will simultaneously increase max fibre length thus reducing number of required repeater nodes. Second, embed the node's architecture within a silicon photonic platform, which allows the use of existing CMOS fabrication technologies, thereby reducing physical size and power consumption; this requires a performance comparison between bulk and integrated optic nodes while operating under load prior to deployment. Third, protocol interfaces must be compatible with IEEE/ETSI standards for the multi-vendor node to work within HQRN across the nation. Alongside the physical layer, HQRN also delivers quantum-optimal frequency allocation over 6G radio access, federated AI training over a provably secure channel.

## X. KEY CHALLENGES

To realise these simulation results in a real system, three obstacles need to be cleared. 1. Maturity of hardware- Lab demonstration of Er:YSO memories has been shown, but there is currently no mass-produced, telecom-quality, price-level solution that would support extensive implementation. 2. Spectrum and regulation policy- Coexistence of both quantum and classical WDM traffic on the same fibre has to be realised in a stable and practical way, and this depends on decisions to be made by ITU-T and national regulators, who have to allow extensive field trials. 3. Write-error rate in the memory- this factor defines the number of usable hops in the long run in the system, regardless of the theoretical read time of the memory or decay time of Er ions, and will depend on the advancement of both material science and electronic control science. In order to achieve those three above-mentioned issues, collaborative interdisciplinary work is needed between quantum physics, photonics, telecommunication and policy, which has to be stimulated by India's National Quantum Mission.

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