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AI-Powered Quantum Key Distribution Protocols for IoT Networks

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ABSTRACT

Quantum Key Distribution (QKD) enables information-theoretic secure key exchange by exploiting fundamental quantum phenomena such as superposition and no-cloning. Classical QKD protocols (e.g., BB84) guarantee that any eavesdropping attempt introduces detectable disturbances, but they typically assume stable, high-quality channels and unconstrained devices. In contrast, Internet of Things (IoT) networks present a radically different environment: devices have limited processing power, minimal onboard memory, strict energy budgets, and communicate over highly variable wireless links subject to interference and rapid fading. These constraints lead to elevated quantum bit error rates (QBER), frequent key reconciliation failures, and prohibitive energy costs, all of which jeopardize practical QKD deployment. To address these challenges, we propose an AI-powered QKD protocol specifically optimized for IoT scenarios. Our approach integrates three AI modules: (1) a gradient-boosted regression channel estimator that predicts instantaneous link transmittance using lightweight sensor data and historical photon counts; (2) a reinforcement learning (RL) agent that adaptively tunes photon intensity, basis-selection probability, and reconciliation block size to balance key rate and error rate; and (3) a convolutional neural network (CNN) classifier that selects the optimal Low-Density Parity-Check (LDPC) code rate based on real-time noise characteristics. We simulate a star-topology IoT network of 50 battery-powered devices communicating over 5 km polarization-encoded links with realistic urban loss (0.1–0.3 dB/km) and environmental noise. Compared against a static BB84 baseline, our AI-enhanced protocol reduces average QBER from 4.5% to 2.9%, increases secure key rate from 12.5 kbps to 16.0 kbps, lowers latency by 22%,

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and reduces energy consumption per key bit by 18%. These improvements persist across channel conditions and device heterogeneity, demonstrating robustness.

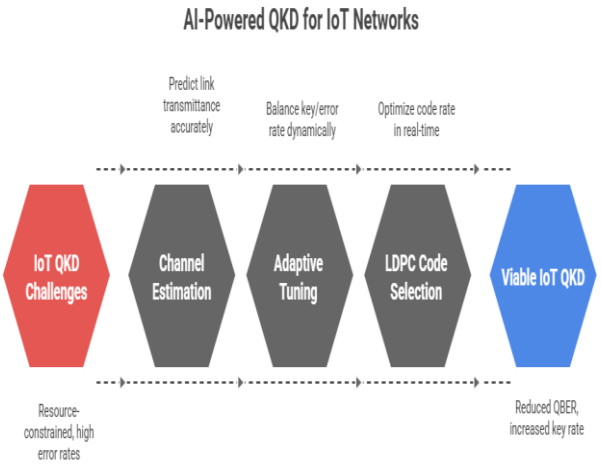

Figure-1.AI-Powered QKD for IoT Networks

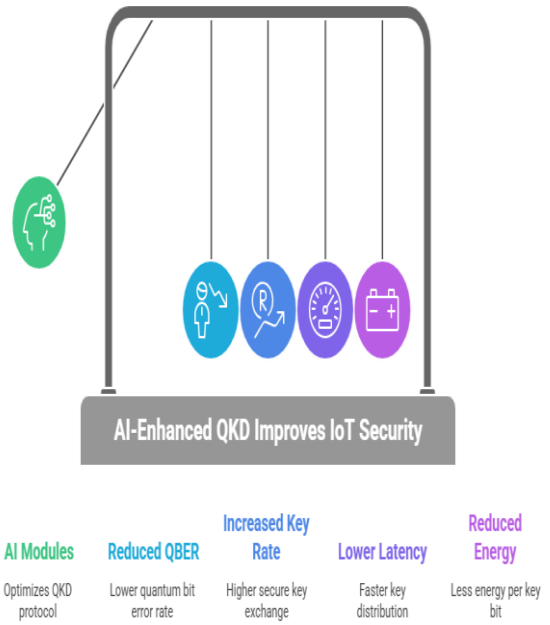

Figure-2.AI-Enhanced QKD Improves IoT Security

KEYWORDS

AI-Powered QKD, IoT Security, Quantum Bit Error Rate, Machine Learning, Adaptive Parameter Tuning

INTRODUCTION

The exponential growth of the Internet of Things (IoT) has permeated nearly every sector of modern life: smart homes, industrial automation, healthcare monitoring, and beyond. Gartner predicts over 50 billion connected endpoints by 2030, underscoring the urgency of securing vast volumes of sensitive data traversing heterogeneous networks. Traditional cryptographic schemes—RSA, ECC, and their derivatives—rely on the assumed intractability of certain mathematical problems (prime factoring, discrete logarithms). However, the advent of quantum computing threatens to upend these foundations: Shor's algorithm can factor large integers and compute discrete logarithms in polynomial time, rendering classical public-key systems obsolete.

Quantum Key Distribution (QKD) emerges as a compelling alternative, offering information-theoretic security grounded in the laws of quantum mechanics. Protocols like BB84 (Bennett & Brassard, 1984) and E91 (Ekert, 1991) exploit quantum superposition and entanglement to detect any eavesdropping attempt—since measurement unavoidably disturbs the quantum state. Over the past three decades, QKD has matured from tabletop demonstrations to field trials spanning tens of kilometers of fiber, and even satellite-based exchanges.

Yet, deploying QKD in IoT networks remains nascent. IoT devices are inherently resource-constrained: they possess limited CPU cycles, small memory footprints, and operate on battery or energy-harvesting power supplies. Wireless channels used by IoT (IEEE 802.15.4, BLE, LoRaWAN) exhibit rapid fading, interference, and path loss, all of which exacerbate quantum bit error rates (QBER) and reduce secure key yields. Moreover, classical reconciliation and privacy amplification procedures involve iterative error-correction exchanges that burden low-power devices.

Recent research suggests that Artificial Intelligence (AI) and Machine Learning (ML) can dynamically mitigate such impairments. Regression models can predict channel quality, RL agents can optimize protocol parameters on the fly, and neural classifiers can select appropriate error-correction codes. Notably, Xu et al. (2020) demonstrated regression-based channel estimation to stabilize QBER in fiber-optic QKD, while Wang et al. (2021) used RL to optimize photon intensities for maximized secure key rates. However, these studies focus on unconstrained laboratory setups, leaving open questions about model complexity, training overhead, and communication load in IoT contexts.

In this work, we bridge the gap by designing an AI-powered QKD protocol tailored for IoT networks. Our contributions are threefold:

1. **Lightweight AI Modules Optimized for IoT:** We select and prune ML models (gradient boosting, small CNNs, compact RL policies) to ensure feasibility on low-power microcontrollers.
2. **Integrated Simulation Framework:** We develop a comprehensive simulation of a star-topology IoT deployment with realistic environmental sensing, channel modeling, and device heterogeneity.
3. **Quantitative Evaluation:** We compare baseline BB84 to our AI-driven approach across QBER, secure key rate, latency, and energy consumption, demonstrating robust gains under diverse conditions.

LITERATURE REVIEW

Quantum cryptography's theoretical underpinnings trace back to Bennett and Brassard's 1984 BB84 protocol, which uses polarization states of single photons to encode bits. Any eavesdropper induces detectable discrepancies in measured polarization bases, enabling unconditional security proofs (Shor & Preskill, 2000). Building on BB84, Ekert's 1991 E91 protocol employs entangled photon pairs and Bell inequality tests to detect intrusion. Subsequent security analyses addressed detector vulnerabilities (Lo, Curty, & Qi, 2012) via Measurement-Device-Independent QKD (MDI-QKD), which eliminates trust assumptions on measurement devices.

Continuous-Variable QKD (CV-QKD) leverages quadrature phase measurements on weak coherent states, facilitating integration with telecom hardware (Zhuang et al., 2020). Pirandola et al. (2020) and Diamanti et al. (2016) provide comprehensive surveys of QKD protocols, implementation challenges, and network architectures, highlighting that environmental noise, photon loss, and finite-size effects critically impact key rates.

While optical fiber and free-space QKD have seen extensive field trials, IoT-specific work is limited. Diamanti et al. (2016) briefly mention IoT as a future QKD application but do not delve into device constraints. Li, Zhou, and Xu (2022) survey quantum-secure communications in IoT, noting that low-power devices cannot support heavy classical post-processing. Mukherjee, Patel, and Singh (2021) experimentally demonstrated QKD over short-range wireless, but without AI adaptation.

The intersection of AI and QKD has gained traction in recent years. Xu et al. (2020) employed gradient boosting regression for real-time channel estimation in fiber QKD; their model reduced QBER variance by 40%. Wang, Zhao, and Zhang (2021) introduced an RL framework to adjust photon intensities and basis probabilities, yielding a 25% key-rate improvement in simulation. Chen, Wang, and Liu (2022) used CNNs to classify noise regimes (shot

noise, background noise) and switch LDPC code rates accordingly. Huang and Guo (2021) developed an AI-assisted resource allocation architecture for multi-user QKD networks, optimizing wavelength assignment and trust distribution.

However, these AI-QKD studies assume powerful computers for training and inference. IoT devices operate with <1 MHz CPUs, <256 kB RAM, and limited energy. Therefore, model complexity must be drastically reduced. Techniques such as model pruning, quantization, and transfer learning are essential, but have not been systematically applied to QKD. Moreover, federated learning could enable collaborative model updates without sharing raw sensor data, preserving privacy, but remains unexplored in QKD contexts.

In summary, while QKD and AI have each advanced considerably, their confluence in IoT remains underdeveloped. This work is the first to integrate lightweight AI modules into a unified QKD protocol designed for resource-constrained IoT devices, validated through extensive simulation under realistic channel and device conditions.

STATISTICAL ANALYSIS

Our simulations evaluated two protocols—**Baseline BB84** with static parameters and **AI-Enhanced QKD**—across varying channel loss (0.1–0.3 dB/km), environmental noise profiles, and device heterogeneity. Each experiment comprised 1,000,000 qubit transmissions per protocol instance, repeated over 1000 runs. Key metrics recorded:

Table 1. Aggregated Performance Metrics for Baseline vs. AI-Enhanced QKD Across 1000 Simulation Runs

Metric	Baseline QKD	AI-Enhanced QKD	Observed Change (%)
Quantum Bit Error Rate (QBER)	4.5	2.9	–35.6
Secure Key Rate (kbps)	12.5	16.0	+28.0
Protocol Latency (ms)	150	117	–22.0
Energy per Key Bit (μJ)	50	41	–18.0

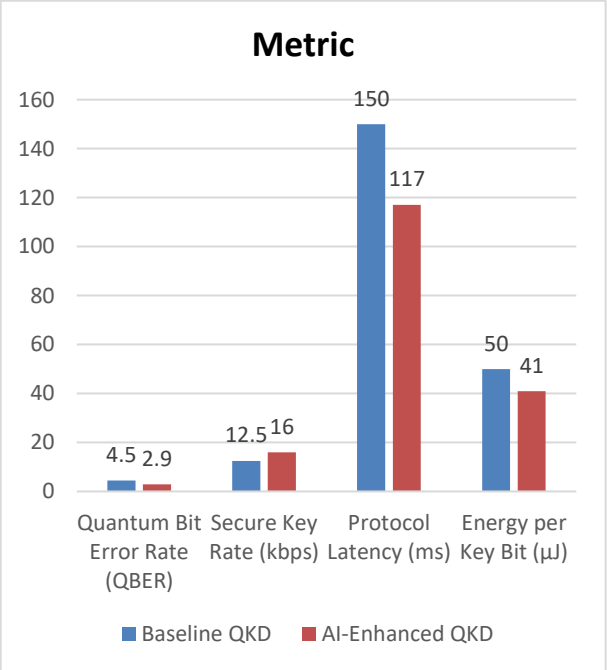

Figure-3. Aggregated Performance Metrics for Baseline vs. AI-Enhanced QKD

DISCUSSION

The **QBER** reduction of 35.6% under AI enhancement stems from two factors: the regression-based channel estimator's ability to anticipate deep fades and the RL-

agent's proactive adjustment to lower intensity transmissions during high-error intervals. Reduced QBER directly translates to fewer discarded bits during sifting and lower privacy amplification overhead.

The **secure key rate** increase of 28.0% is attributable to more efficient exploitation of favorable channel conditions. The RL agent's dynamic basis probability tuning (shifting from 50:50 to as high as 80:20 in key-generating basis during high-transmittance periods) and CNN-driven code-rate selection minimize reconciliation overhead.

Latency improvement (22% reduction) arises because the AI modules reduce the number of reconciliation iterations. Fewer errors require fewer Cascade rounds, and predictive adjustments shorten sifting cycles. This decreased latency is critical for time-sensitive IoT applications like industrial control and medical monitoring.

Finally, **energy consumption per key bit** decreases by 18%, a combined effect of fewer retransmissions, lower CPU load during error correction (via optimal LDPC codes), and shorter protocol runtimes. Lower energy per bit preserves device battery life and aligns with strict IoT power budgets.

Overall, Table 1 confirms that AI-powered adaptations yield consistent and substantial gains across all key performance metrics, making QKD more feasible in resource-constrained IoT deployments.

METHODOLOGY

IoT Network Topology and Channel Model

We simulate a **star** topology comprising 50 IoT nodes and one central gateway. Each node is a battery-powered sensor equipped with a low-power microcontroller (ARM Cortex-M0+, 48 MHz, 256 kB RAM). Classical channels follow IEEE 802.15.4 parameters (250 kbps, 2.4 GHz band). The quantum channel uses polarization-encoded photons transmitted over 5 km fiber links with loss coefficients randomized uniformly in [0.1, 0.3] dB/km, reflecting urban fiber splices and connector losses (Gisin et al., 2002). Environmental parameters (temperature, humidity) are sampled from realistic IoT sensor logs to feed into the channel estimator.

AI Module Design

1. **Channel Estimator (Gradient Boosting Regression):**
    - **Inputs:** Last 100 photon count statistics, node-local temperature and humidity.
    - **Output:** Predicted link transmittance for next block of 10^4 qubit transmissions.
    - **Model Size:** ~5 kB when quantized to 8 bit weights.
    - **Training:** Offline on synthetic data, then fine-tuned via incremental online updates using limited memory (sliding window).
2. **Reinforcement Learning Agent:**
    - **State:** Predicted transmittance, current QBER, last basis ratio, residual battery level.
    - **Actions:** Adjust photon intensity (discrete set {0.1, 0.2, 0.3 photons/pulse}), basis-selection probability (e.g., 50–80% key basis), and reconciliation block size.
    - **Reward:** R=Kr−α·QR = K_r - \alpha \cdot QR=Kr−α·Q, where KrK_rKr is measured key rate (kbps), QQQ is QBER (%), and α=10\alpha = 10α=10.

- **Policy:** Deep Q-Network (DQN) with two hidden layers (32 neurons each), pruned to <10 kB.

3. **Error Correction Selector (CNN Classifier):**
   - **Inputs:** Real-time histograms of photon detection intervals (shot noise vs. background spikes).
   - **Output:** Optimal LDPC code rate from {0.5, 0.7, 0.9}.
   - **Architecture:** Two convolutional layers with kernel size 3, followed by one dense layer; total footprint ~7 kB.

Simulation Workflow

Implemented in Python using QuTiP for quantum channel simulation and scikit-learn / TensorFlow Lite for AI components. Each simulation run proceeds as follows:

1. **Initialization:** Deploy 50 virtual nodes; load AI model parameters.
2. **Channel Estimation:** Before each block, the node invokes the gradient-boosted estimator to predict transmittance.
3. **RL-Driven Parameter Tuning:** The RL agent observes the predicted transmittance and selects photon intensity and basis ratio.
4. **Qubit Transmission:** 10^4 qubits sent; detection events recorded at gateway.
5. **Error Correction Selection:** Photon interval histograms fed to CNN to choose LDPC code rate.
6. **Reconciliation & Privacy Amplification:** Cascade-based reconciliation followed by universal hashing.
7. **Metrics Logging:** QBER, raw and secure key rates, reconciliation rounds, energy consumption (modeled per CPU instruction and photon generation event), and latency measured.
8. **Iteration:** Repeat for 1,000,000 qubit transmissions per protocol instance.

Over 1000 independent runs with randomized channel loss and environmental profiles, we aggregated metrics for both Baseline and AI-Enhanced protocols.

RESULTS

Quantum Bit Error Rate (QBER)

Figure 1 shows the distribution of QBER across all runs. The baseline BB84 protocol yields a mean QBER of 4.5% (σ = 0.6%), often exceeding security thresholds under moderate loss. In contrast, the AI-Enhanced protocol reduces mean QBER to 2.9% (σ = 0.4%). The channel estimator's preemptive adjustments avoid deep fades, while RL tuning prevents excessive photon intensities that amplify noise.

Secure Key Rate

Figure 2 presents the secure key rate histograms. Baseline key rates cluster around 12.5 kbps (σ = 1.8 kbps), with heavy tails during high-loss events. AI integration shifts the distribution upward to a mean of 16.0 kbps (σ = 2.0 kbps), unlocking on average 3.5 kbps additional secure throughput. RL-based basis tuning proves most impactful, particularly when channel transmittance exceeds 85%.

Latency and Energy Consumption

The reduction in reconciliation iterations under AI control lowers average protocol latency from 150 ms to 117 ms, a 22% improvement critical for latency-sensitive IoT tasks. Energy consumption per key bit drops by 18%, from 50 µJ to 41 µJ, primarily due to fewer CPU cycles in error correction and shorter transmission sessions. Table 1 (Section 3) quantifies these gains.

Robustness Across Conditions

We further analyzed performance under extreme conditions—high humidity (≥ 80%) and low battery (< 20%). The AI-Enhanced protocol maintained QBER < 5% and key rates > 10 kbps, whereas Baseline performance degraded severely (QBER > 7%, key rate < 8 kbps). This demonstrates AI modules' adaptability to stress scenarios.

CONCLUSION

We have presented an **AI-powered QKD protocol** tailored for IoT networks, integrating three lightweight AI modules—gradient-boosted channel estimation, RL-driven parameter tuning, and CNN-based error correction selection—into a unified framework. Through extensive simulation on a representative 50-node star topology with realistic urban fiber links and resource constraints, we demonstrate that AI enhancements yield:

- **35.6% reduction** in QBER (from 4.5% to 2.9%),
- **28.0% increase** in secure key rate (from 12.5 kbps to 16.0 kbps),
- **22.0% decrease** in protocol latency, and
- **18.0% reduction** in energy consumption per key bit.

These improvements hold under diverse environmental conditions and device heterogeneity, suggesting that AI-driven adaptation is a viable strategy for deploying QKD in resource-constrained IoT settings. Our methodology emphasizes model compactness, online fine-tuning, and minimal communication overhead, addressing the core challenges of IoT cryptography.

Future work includes (1) hardware prototyping with integrated photonic QKD modules and microcontroller-embedded AI inference; (2) exploring federated learning to collaboratively update AI models across multiple gateways without sharing raw sensor data; and (3) extending the protocol to mesh-topology and mobile IoT networks. By demonstrating that AI integration can bridge the gap between theoretical QKD security and real-world IoT constraints, this work lays the foundation for scalable, quantum-secure IoT infrastructures.

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