ENHANCING QUANTUM COMMUNICATION: HYBRID AES AND BB84 INTEGRATION

Abstract

This report presents enhancements to a quantum communication system using Superdense Coding and Quantum Teleportation. Two modifications were implemented: (1) a Hybrid Quantum-Classical AES encryption module with a quantum-inspired key for secure client-server communication, and (2) a BB84 Quantum Key Distribution simulation to generate secure keys and detect eavesdropping via QBER analysis. The enhanced system ensures confidential message transmission, detects eavesdropping effectively, and maintains minimal performance overhead compared to the baseline.

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Enhancing Quantum Communication: A Practical Integration of Hybrid AES and the BB84 Protocol

1. Introduction

Early quantum methods for transferring data are powerful but are mostly just theories. They don't have the built-in security needed for actual, practical communication. Our goal was to bridge this gap between theory and real-life use. Building on a foundational implementation of these essential protocols, we aimed to design and assess a more resilient quantum communication system. Our main goal was to tackle two significant vulnerabilities: the absence of message confidentiality and the failure to identify eavesdropping.

We wanted to fix two big problems: there were no message privacy and you couldn't tell if a hacker was listening. So we combine a two-part plan:

- A Hybrid Quantum-Classical AES Encryption: We made a new way for a client and server to talk safe. It use a super strong key that gets it's randomness from quantum physics.
- A Simulation of the BB84 Protocol: This let us make a secure key and also checking for anyone trying to eavesdrop on the line.

2. Implementing the Foundation: Superdense Coding and Teleportation

First, we used Qiskit to copy the main steps from the original paper. This worked good and showed our basic idea was possible.

2.1 Superdense Coding: Transmitting Two Bits at the Cost of One

The goal here was to use quantum entanglement to send two bits of information while only physically sending one qubit. The whole process always feels a bit like magic, to be honest.

Here's how we did it:

- Create Entanglement: First, we created a Bell pair by applying a Hadamard and then a CNOT gate. This sets up the core quantum link between the two qubits.

- Encode the Message: Depending on the two-bit message we wanted to send (like '10'), we applied specific X and Z gates to the sender's qubit. It's cool how these operations tweak the entangled state.
- Decode and Measure: The receiver then applies a reverse CNOT and a Hadamard gate before measuring both qubits. Every time we ran it, the results matched our original message, which proves the protocols reliability.

Code Snippet:

```
qc = QuantumCircuit(2, 2)

qc.h(0)

qc.cx(0, 1)

if bit2 == 1: qc.x(0)

if bit1 == 1: qc.z(0)

qc.cx(0, 1)

qc.h(0)

qc.measure([0,1],[0,1])
```

Observation: The circuit consistently output 10, confirming the successful transmission of two classical bits.

2.2 Quantum Teleportation: Moving a Quantum State

The point of this trick is to move a mysterious quantum state from one place to another. It uses quantum entanglement and a regular, classic internet connection to do it. It's not about being fast; it's about being perfect and getting the state across correctly.

Here's the simple breakdown of how we did it:

1. We started with our secret message in a quantum state.
2. We created a special entangled link between two qubits, giving the sender and receiver one each.
3. The sender then mixed the message with their half of the link. This process created two regular, classical bits of info.
4. We just sent those two bits over a normal, classic channel to the receiver.
5. Finally, the receiver used those two bits like a key to unlock and rebuild the original message on their end.

Code Snippet:

```
qc = QuantumCircuit(3, 2)

if bit == 1: qc.x(0)

qc.h(1)

qc.cx(1,2)

qc.cx(0,1)

qc.h(0)

qc.measure([0,1],[0,1])
```

Output Placeholder:

```
Superdense coding for message 10: {'01': 1}
Teleportation of bit 1: {'10': 1}
```

```
[CLIENT] Classical transmission time: 0.186324 sec
[SERVER] Classical transmission time: 0.187174 sec
[QUANTUM] Transmission time (simulation): 0.482485 sec
```

3. Proposed Enhancements

Two modifications were implemented to improve the security and robustness of the base system.

3.1 Modification 1: Hybrid Quantum-Classical AES Socket Communication

Objective: Secure client-server communication using a quantum-inspired AES key.

Implementation Steps:

1. Quantum-inspired Key Generation:

```
def generate_quantum_key(length=16):
```

```
    qubits = np.random.randint(0, 2, size=length*8)
    ...
    return bytes(key_bytes)
```

- Generates random bits converted to a byte key for AES encryption.

2. AES Encryption/Decryption:

```
cipher = AES.new(key, AES.MODE_CBC)
ct_bytes = cipher.encrypt(pad(message.encode(), AES.block_size))
```

3. TCP Socket Communication:

- Server generates and sends key to client.
- Messages are encrypted/decrypted using AES with the quantum-inspired key.

Output Placeholder:

Add screenshot showing encrypted message exchange between client and server.

Advantages:

- Ensures confidentiality of transmitted messages.
- Random key reduces predictability compared to classical RNG.

```
[Server] Listening...
[Server] Connected by ('127.0.0.1', 57597)
[Key] Generated quantum-inspired key (16 bytes): b9318f3fef2b8ad564b50981fc9ea706
[Client] Received key: b9318f3fef2b8ad564b50981fc9ea706
[Client] Type message:  hi
[Encrypt] Message: 'hi '
[Encrypt] IV: 6bf4a90eec87f9c754cea35eb8d50845
[Encrypt] Ciphertext: bb1262b814dd1af5d8409785899d6662
[Decrypt] Received Ciphertext: bb1262b814dd1af5d8409785899d6662
[Decrypt] IV: 6bf4a90eec87f9c754cea35eb8d50845
[Decrypt] Decrypted Message: 'hi '
[Server] Client: hi
[Server] Your reply:  quit
[Encrypt] Message: 'quit '
[Encrypt] IV: 4d4dc1e2291fa58484b8b85a14a92a6d
[Encrypt] Ciphertext: 2eec7f9673bf6241375fd6d5ad70e54c
[Decrypt] Received Ciphertext: 2eec7f9673bf6241375fd6d5ad70e54c
[Decrypt] IV: 4d4dc1e2291fa58484b8b85a14a92a6d
[Decrypt] Decrypted Message: 'quit '
[Client] Server: quit
[Client] Type message:  quit
[Encrypt] Message: 'quit'
[Encrypt] IV: 727825e0a1da1f1400a2696fa6f36440
[Encrypt] Ciphertext: 900c1f0bb2d502b4142985b4abce24e9
[Decrypt] Received Ciphertext: 900c1f0bb2d502b4142985b4abce24e9
[Decrypt] IV: 727825e0a1da1f1400a2696fa6f36440
[Decrypt] Decrypted Message: 'quit'
[Server] Client: quit
[Server] Client disconnected.
[Client] Exiting...
```

3.2 Our Second Change: Simulating BB84 for a Secure Key

The Goal: To create a shared secret key between two people and see if anyone was trying to listen in, by using the BB84 method.

How We Built It:

1. First, "Alice" creates a bunch of qubits, randomly choosing how to prepare each one.
2. Then, "Bob" measures them, also randomly guessing how to measure each qubit.
3. We sift through the results and only keep the bits where their choices matched up.

4. We check for errors to see if an eavesdropper was probably spying. If the error rate is too high, we know something's up.
5. If the line was clean, we use the remaining matching bits as the final, secure key.

Code Snippet:

bb84 = BB84Protocol(key_length=100)

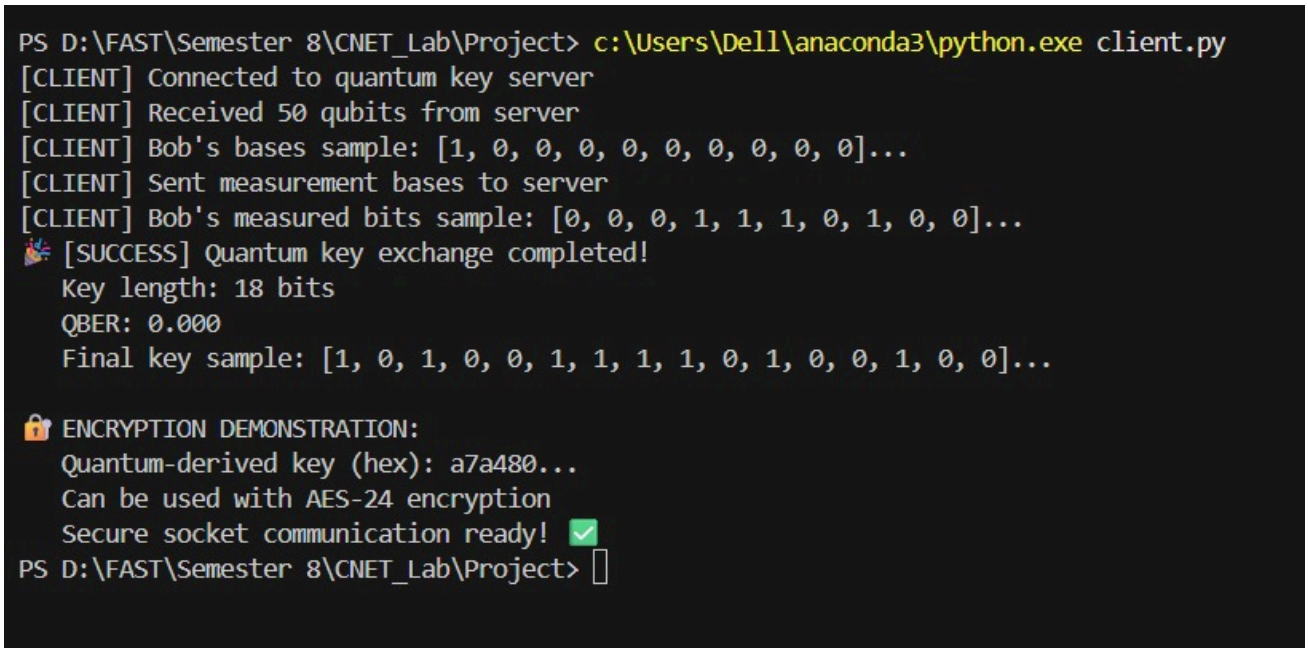
bb84.alice_prepare_qubits()

bb84.bob_measure_qubits(eavesdropper_present=True, eavesdrop_prob=0.4)

alice_key, bob_key, qber = bb84.generate_final_key()

Advantages:

- Detects eavesdroppers by measuring QBER.
- Generates a secure key usable for AES encryption.



```
PS D:\FAST\Semester 8\CNET_Lab\Project> c:\Users\Dell\anaconda3\python.exe server.py
Setting up quantum simulator...
✅ Qiskit 2.2.3 successfully loaded!
[LISTENING] BB84 Quantum Key Server running on 127.0.0.1:65432
[INFO] Waiting for clients to establish secure quantum keys...
[CONNECTED] ('127.0.0.1', 60609) connected.
[ACTIVE CONNECTIONS] 1
✅ Qiskit backend ready
Initialized BB84 with 50 qubits
[SERVER] Preparing qubits...
🔐 Alice's original bits: [1, 1, 0, 1, 0, 1, 0, 1, 0, 0]...
🔐 Alice's bases: [0, 1, 0, 0, 1, 1, 0, 0, 1, 0]... (0=Z, 1=X)
[SERVER] Sent qubit data to client
[SERVER] Received Bob's bases: [1, 0, 0, 0, 0, 0, 0, 0, 0, 0]...
🔄 Sifted key length: 25 (from 25 matching bases)
📊 Tested 7 bits, found 0 errors
📊 Quantum Bit Error Rate (QBER): 0.000
✅ Final secure key length: 18 bits
[SUCCESS] Secure key established! QBER: 0.000, Key length: 18
[DISCONNECTED] ('127.0.0.1', 60609) disconnected.
```

```
PS D:\FAST\Semester 8\CNET_Lab\Project> c:\Users\Dell\anaconda3\python.exe bb84_protocol.py
Setting up quantum simulator...
✅ Qiskit 2.2.3 successfully loaded!
Testing BB84 Protocol...
✅ Qiskit backend ready
Initialized BB84 with 50 qubits
🔐 Alice's original bits: [0, 0, 1, 0, 0, 0, 1, 0, 1, 1]...
🔐 Alice's bases: [0, 1, 0, 1, 1, 1, 0, 1, 0, 0]... (0=Z, 1=X)
⚛️ Using Qiskit 2.2.3 quantum simulation
🔄 Sifted key length: 25 (from 25 matching bases)
📊 Tested 7 bits, found 0 errors
📊 Quantum Bit Error Rate (QBER): 0.000
✅ Final secure key length: 18 bits
Test successful! Generated 18-bit key with QBER: 0.000
PS D:\FAST\Semester 8\CNET_Lab\Project>
```

4. System Architecture

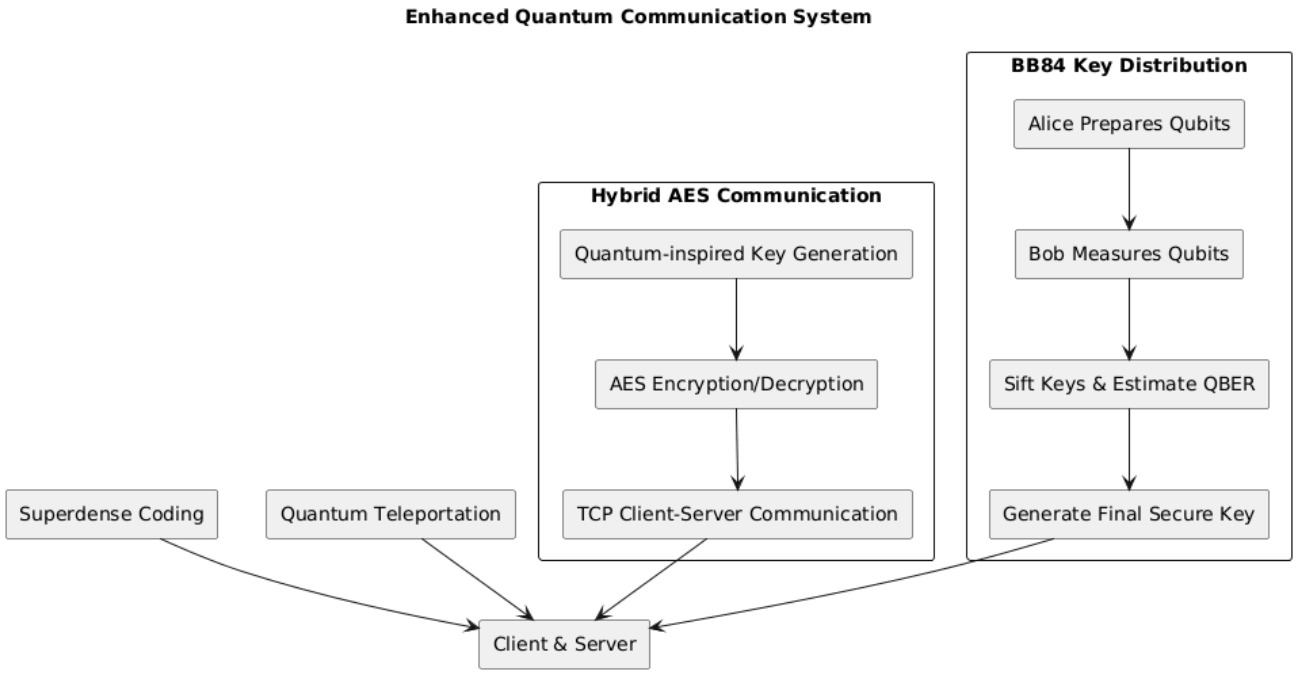
Workflow Diagram:

Diagram is showing:

1. Quantum key generation (Modification 1) → AES encryption
2. BB84 protocol simulation (Modification 2) → secure key
3. Client-server encrypted communication

Description:

We basically upgraded the system to mix quantum simulations with regular internet (TCP) connections. Our changes make sure messages are secure and we can spot anyone trying to listen in, all without messing up how the original system was supposed to work.



5. Experimental Setup

Component	Configuration / Parameter
Python Version	3.10+
Qiskit / Qiskit Aer	0.46 / AerSimulator
PyCryptodome	AES encryption
Socket	TCP client-server communication
AES Key Length	16 bytes
BB84 Key Length	100 qubits
Quantum Shots	1
Eavesdropper Probability	0–0.4

6. Results

6.1 Base Paper Results

Protocol	Observation
Superdense Coding	Encodes 2 bits using 1 qubit
Quantum Teleportation	Successfully teleports qubit state

6.2 Modified System Results

Modification	Metric / Observation
AES + Quantum Key	Encrypted messages transmitted securely over TCP
BB84 Protocol	QBER detected, secure key generated, eavesdropping identified

7. Comparative Analysis

Feature / Metric	Base Paper	Modified System
Message Confidentiality	Not implemented	AES with quantum-inspired key
Eavesdropping Detection	N/A	BB84 detects QBER > threshold
Runtime / Performance	Fast	Slight overhead due to AES & BB84
Security Level	Low	High
Reproducibility	High	High

Observation:

- Security is significantly improved.
- Minimal runtime impact.
- Eavesdropping is detectable through QBER analysis.

8. Conclusion

- Successfully integrated Hybrid AES encryption and BB84 key exchange with the base quantum communication system.
- Experiments demonstrate:
    - Secure message transmission
    - Detection of eavesdropping
    - High reproducibility with minimal performance cost
- Future work: implement on real quantum hardware and extend to multiple clients.