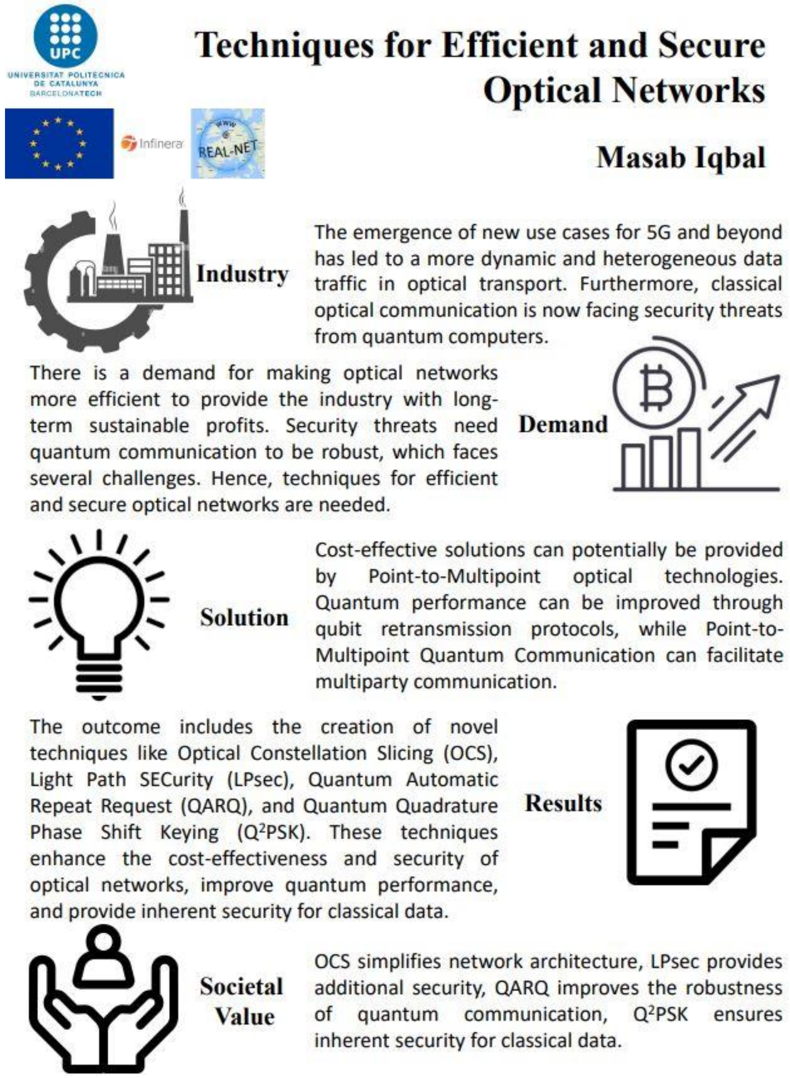
Cybersecurity Management
GCS 2.5 – Quantum Security

2022-2023

Prof. Marc Ruiz

marc.ruiz-ramirez@upc.edu

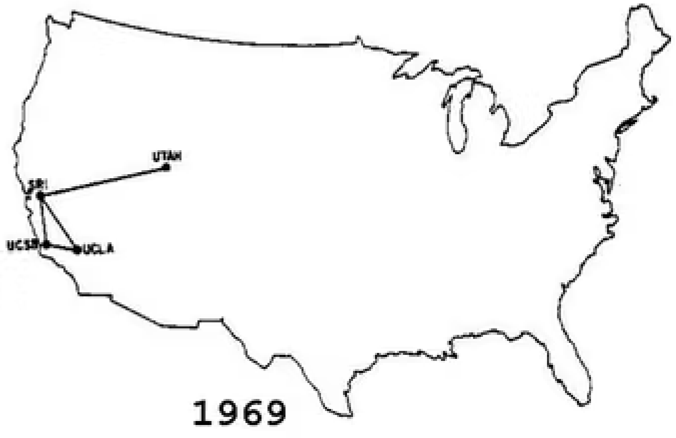
Quantum Networks 101 (by Dr. Masab Iqbal)



Quantum – Where we are?

Like at the birth of the Internet…

29 October 1969
LOGIN
We typed the L and asked on the phone: “Did you see the L?”
“ Yes, we see the L”
We typed the O and asked on the phone: “Did you see the O?
“ Yes, we see the O”
Then we typed G and the System actually crashed



Taking from the talk of Stephanie Wehner

Warm start

- https://www.youtube.com/watch?v=90za6mazNps

Classical vs Qubit

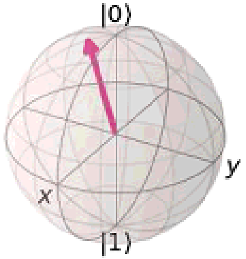
Classical

0

1

Quantum

0+1



$$|\Psi\rangle_{a_0} = \alpha\,|0\rangle_{a_0} + \beta\,|1\rangle_{a_0}$$

Bit vs Qubit

- If we had four bits, the possible value a classical computer can take is one of the following

0000	**1000**
0001	**1001**
0010	**1010**
0011	**1011**
0100	**1100**
0101	**1101**
0110	**1110**
0111	**1111**

Bit vs Qubit

- If we had four qubits, quantum computer can take all the values at the same time!

α_0	**0000**	α_8	**1000**
α_1	**0001**	α_9	**1001**
α_2	**0010**	α_{10}	**1010**
α_3	**0011**	α_{11}	**1011**
α_4	**0100**	α_{12}	**1100**
α_5	**0101**	α_{13}	**1101**
α_6	**0110**	α_{14}	**1110**
α_7	**0111**	α_{15}	**1111**

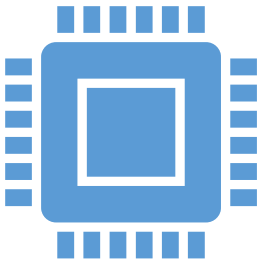
$$2^N$$

Bit vs Qubit

With 275 qubits, we can represent more basis states than the number of atoms in the observable universe

2^{275}

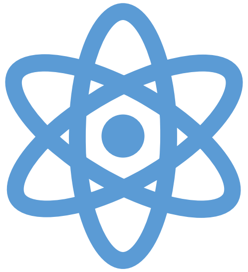
Quantum Technologies



Quantum computing

Speed-up tasks

- Quantum database search (Grover's algorithm)
- Quantum prime number factorization (Shor’s algorithm)

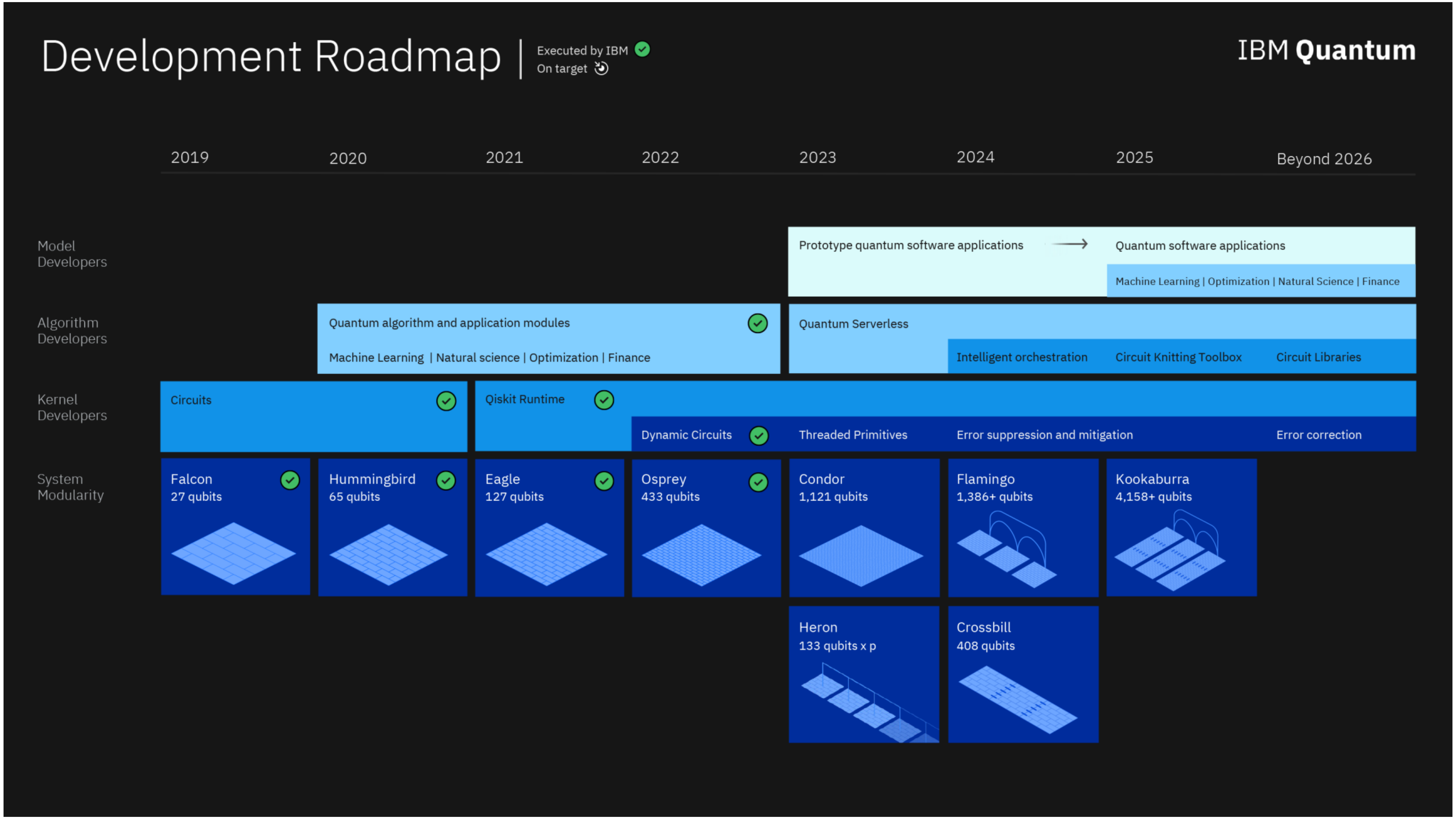


Quantum communication

Secure communication

Efficiency

Quantum Computing – Where we are?



False claims

Quantum computers will replace all classical computers.

Quantum Computers are super powerful computers and are much faster than classical computers.

Quantum computers will break all existing encryptions.

RSA-2048 needs more than 4000 qubits to break encryption

Quantum computer is a solution for everything.

Applications of Quantum Communication

- Secure Communication
- Secure Quantum Computing in the cloud
- Secure Identification
- Clock Synchronization
- Position Verification
- Online Games

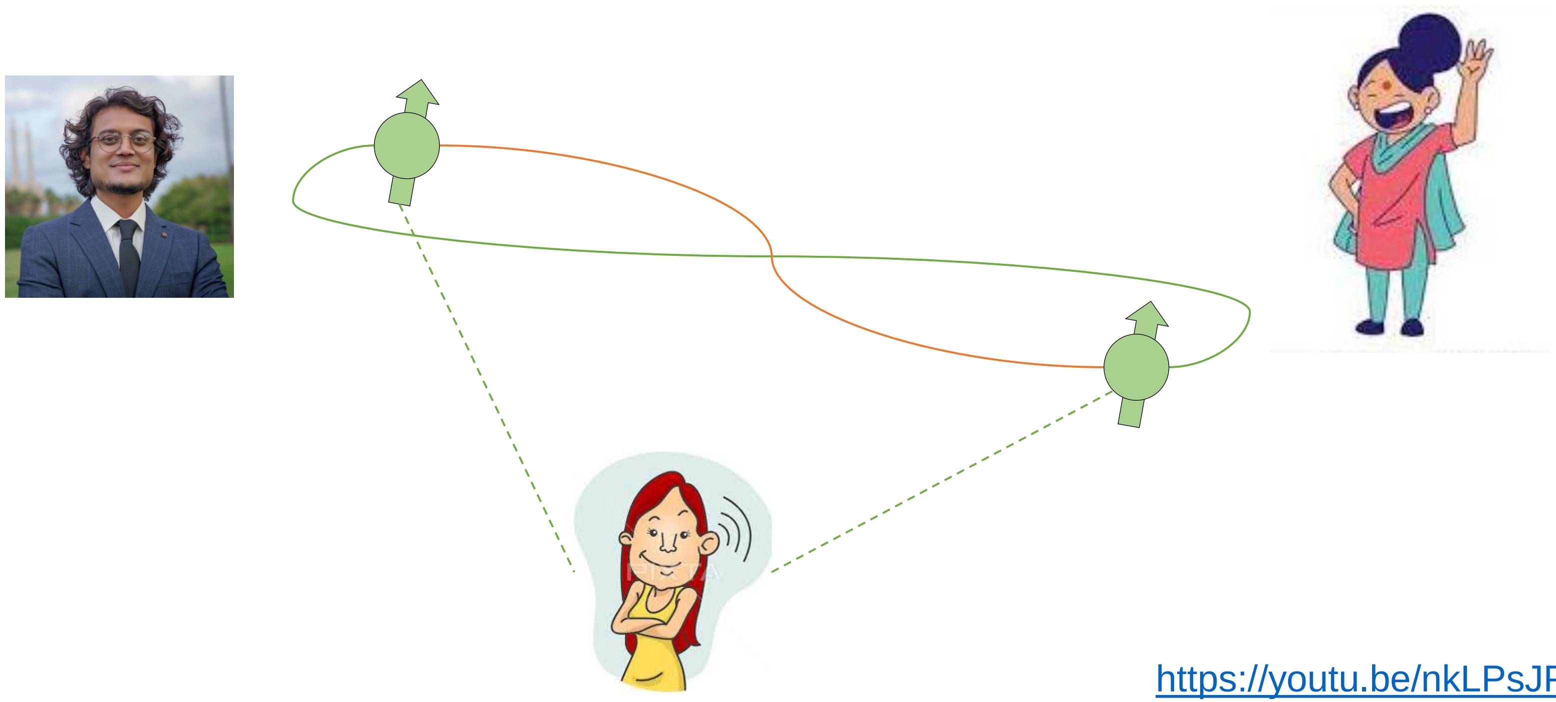
No-Cloning theorem

- The no-cloning theorem states that it is impossible to create an independent and identical copy of an arbitrary unknown quantum state

Good or bad?

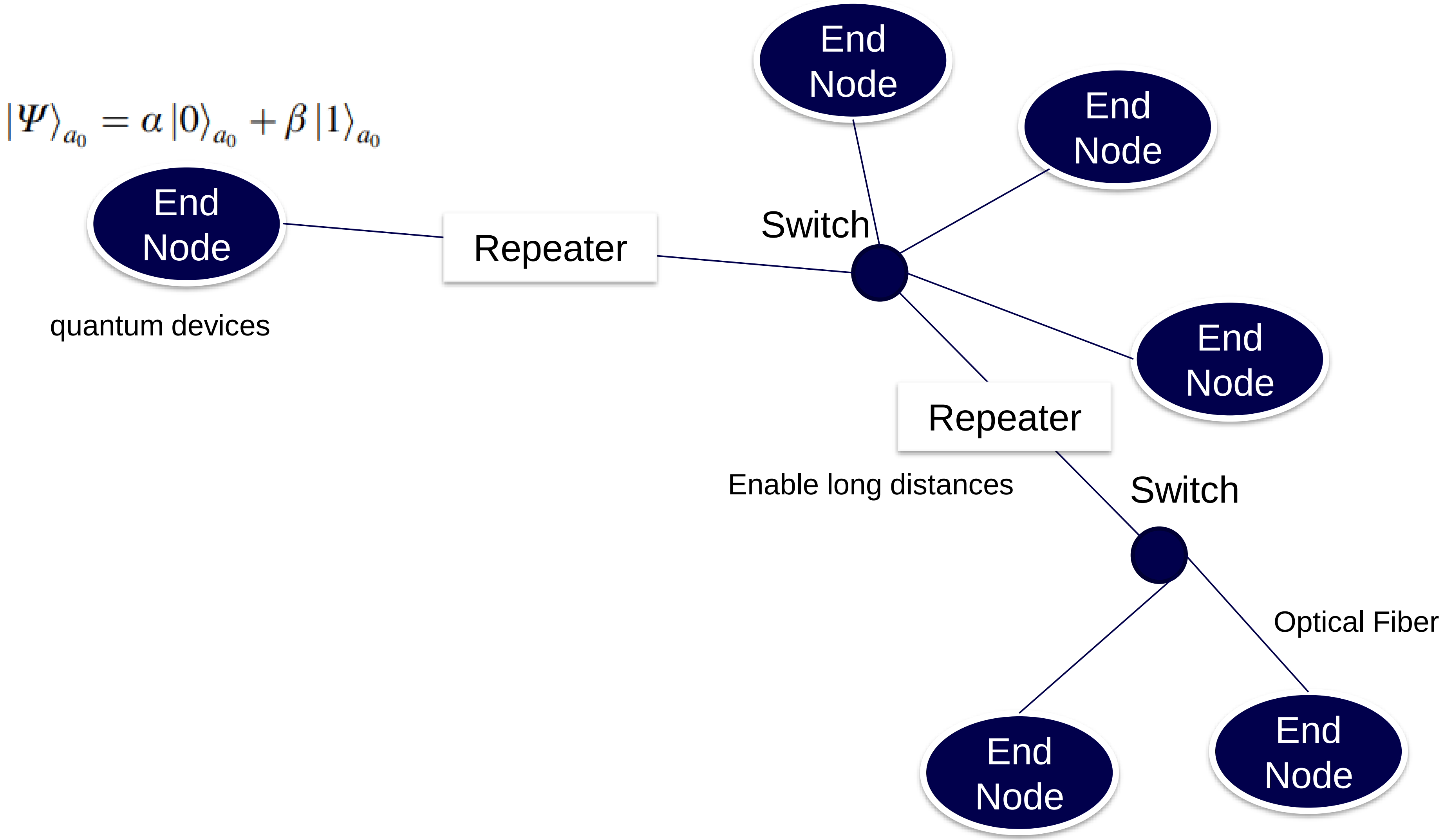
Entanglement

It strongly correlates two particles, that measurement of one can tell the measurement result of the other, even if they are far apart.

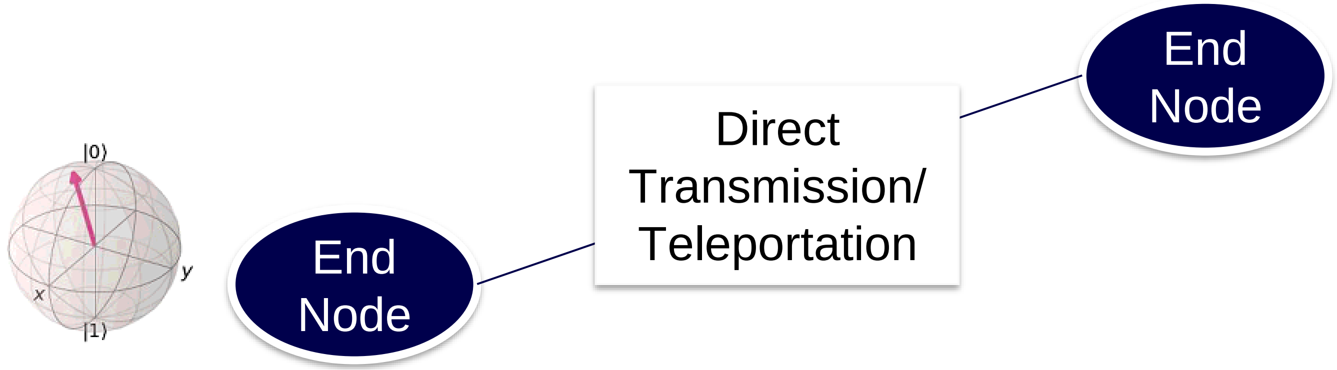


https://youtu.be/nkLPsJPxad0

Quantum Network

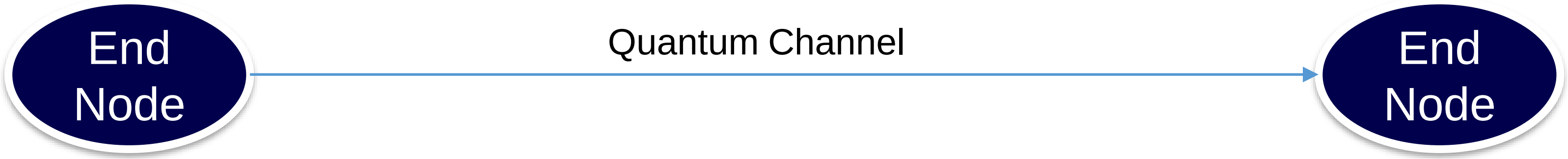


Methods of qubit transmission



Direct Transmission: Using Quantum Channel
Teleportation: Take advantage of two classical bits and an entangled qubit pair and avoid using quantum channel

Challenges of direct transmission



Transmission Losses

- Losses in transmission media

Decoherence

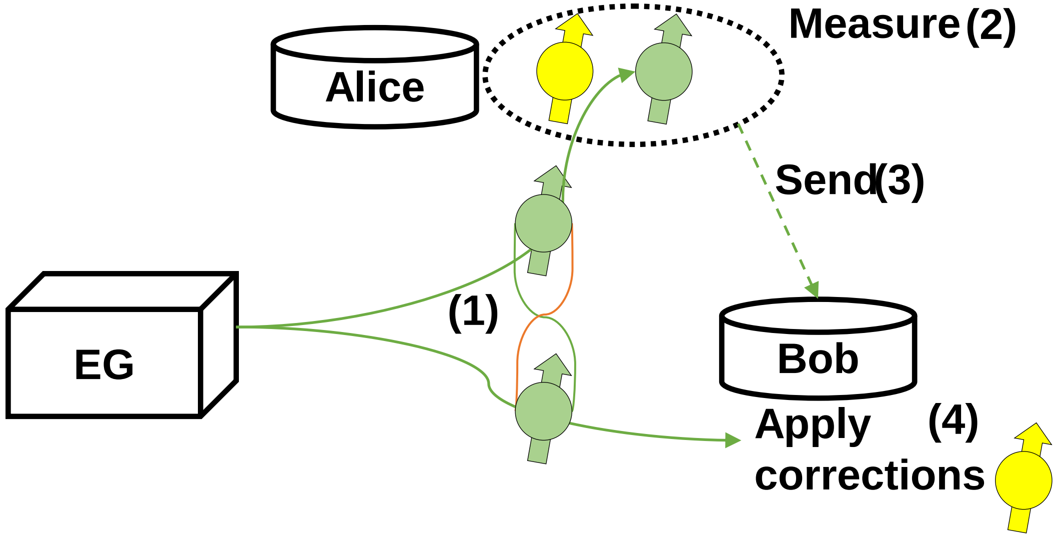
- Interaction with environment

No cloning theorem

- Qubits can’t be copied

Teleportation Protocol

- Alice prepares the state, she wants to send.
- An entanglement is created and shared between Alice and Bob.
- Alice performs measurement.
- Alice sends the measurement results to Bob.
- Bob applies gates according to results



Takeaway of Teleportation

- Instead of sending the qubit directly into the quantum channel send entanglement pairs via the quantum channel and utilize entanglement to teleport the qubit

Challenges of teleportation

Transmission Losses

- Losses in transmission media

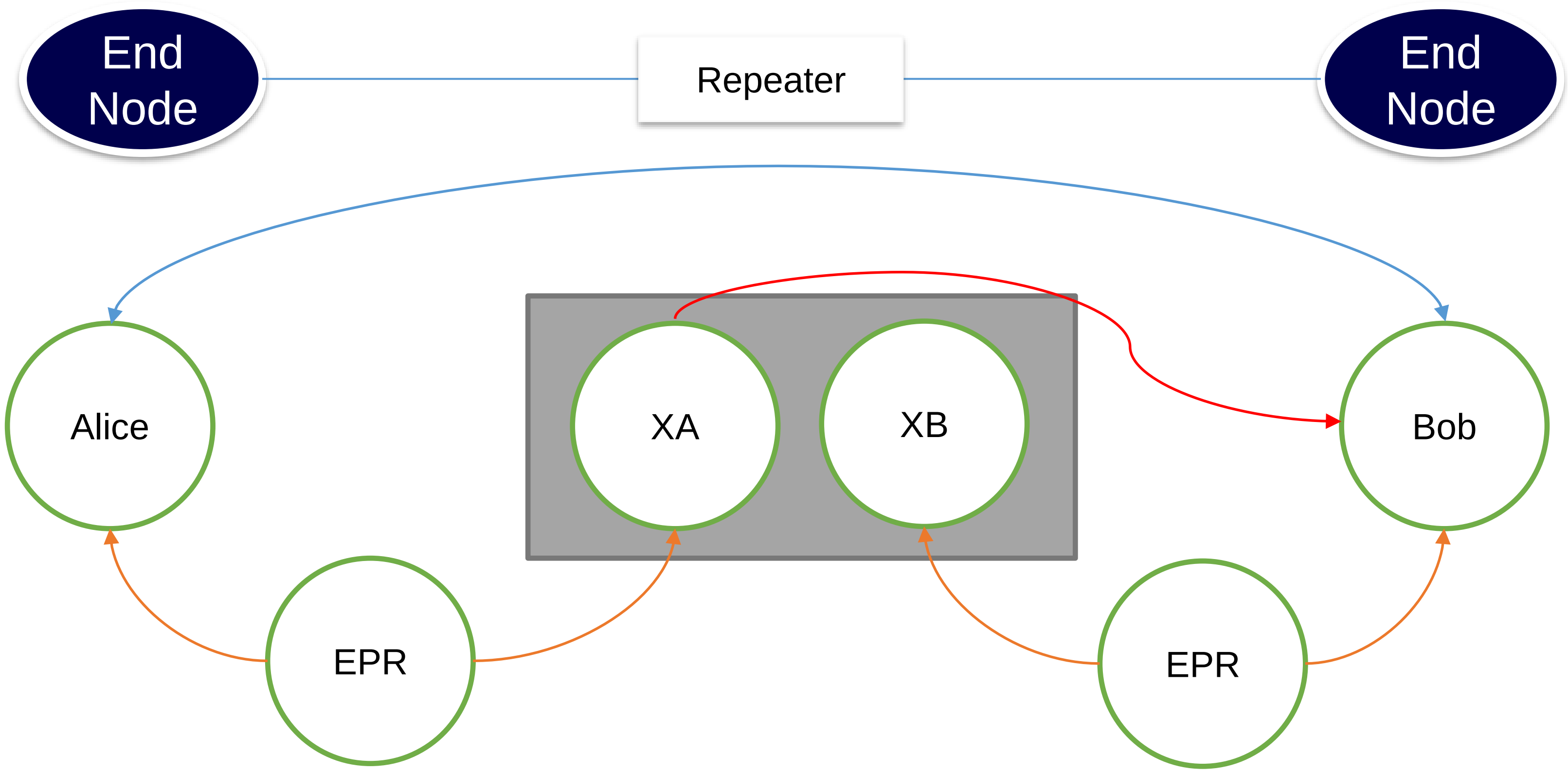
Decoherence

- Interaction with environment

Source fidelity

- Quality of generated entanglement pairs

Entanglement Swapping (Repeaters)



Takeaways

Qubits are very fragile and are prone to many losses.

So, we don’t transmit Qubits over long distances

We can use entanglement assistance to teleport the qubit without transmitting the qubit through a quantum channel.

But entanglement pairs are also qubits, so we can’t send the pair over long distances too.

So, we generate multiple entanglement pairs, and through teleportation perform entanglement swapping to enable long-distance entanglement distribution.

Quantum Key Distribution

“The” encryption: One Time Pad

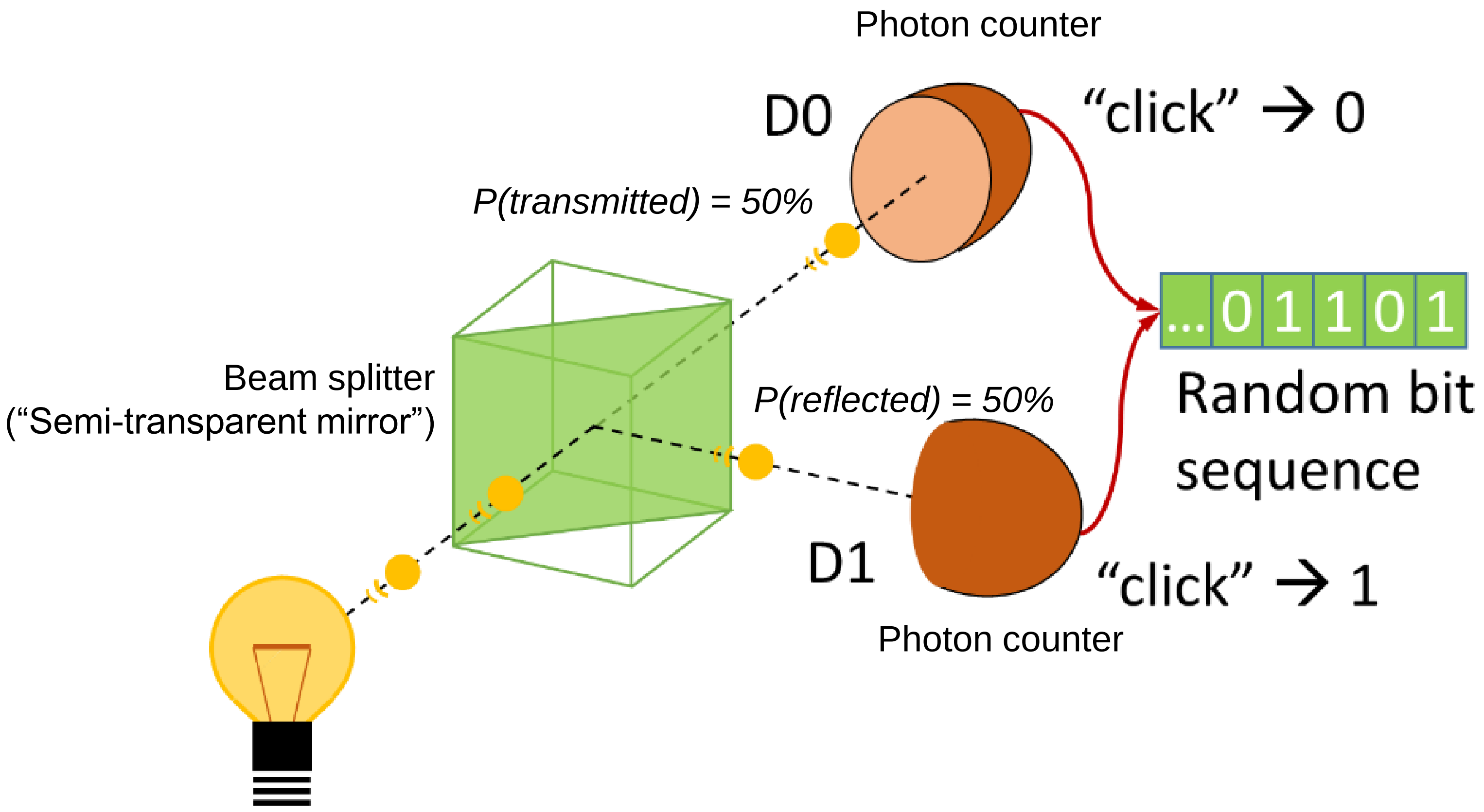
Text	1	1	0	0	1	1	0	1
$\oplus$								
Key	0	1	0	1	1	0	1	0
Cyphertext	1	0	0	1	0	1	1	1

XOR	0	1
0	0	1
1	1	0

- **Proven security if:**
    - Length text = Length key
    - Key is used one time only
    - Key is generated **randomly**

Quantum Random Number Generators (QRNG) can do this!!!

QRNG

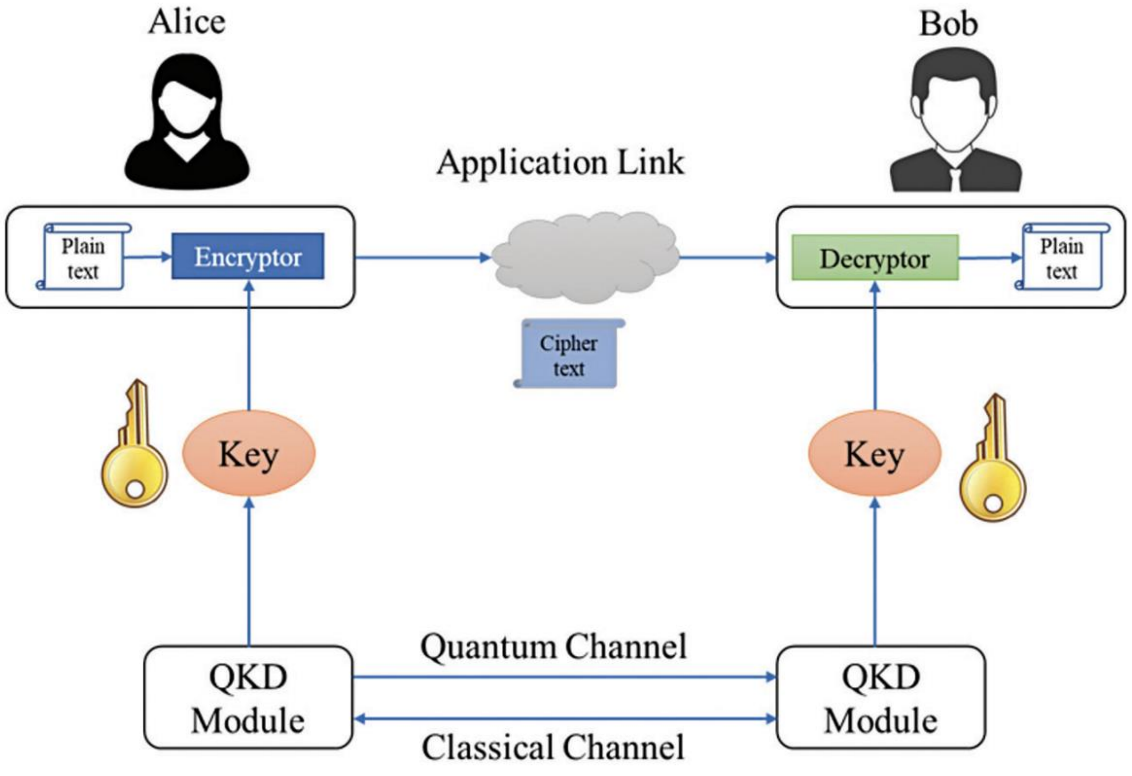


https://idquantique.com

Currently, they achieve low rates: ~4 Mb/s

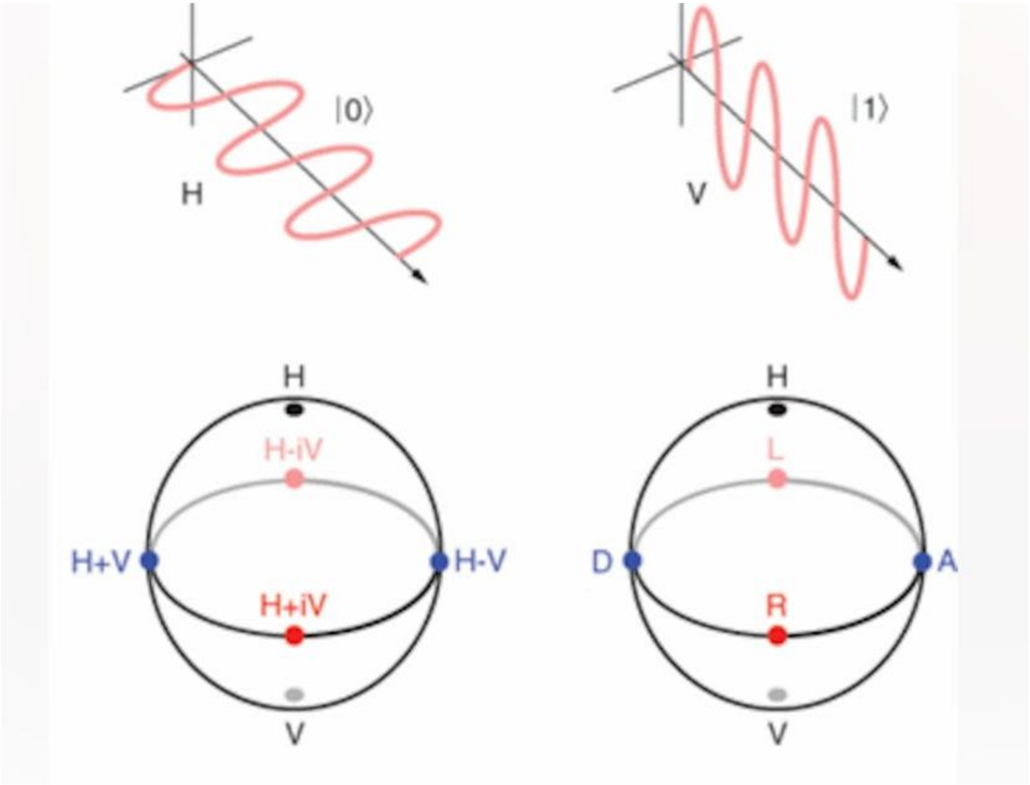
Quantum Key Distribution (QKD)

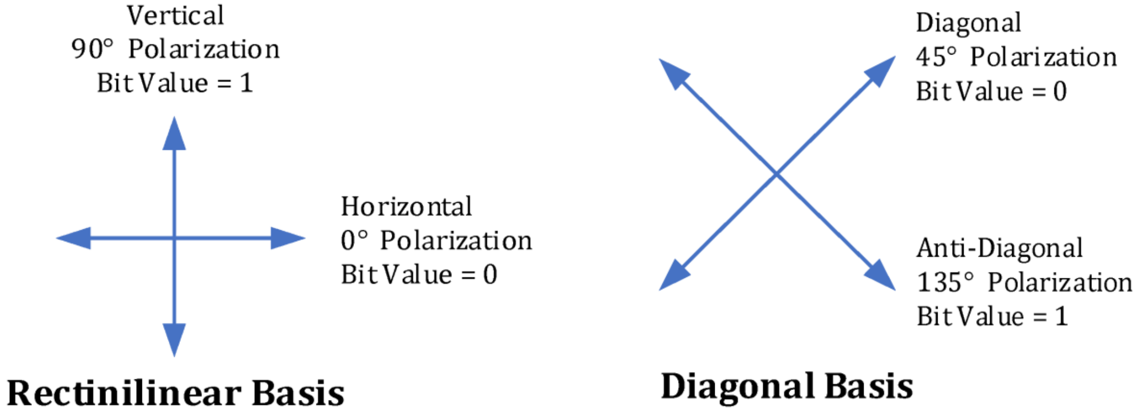
- It enables two parties to produce a shared random **secret key** known only to them, which can then be used to encrypt and decrypt messages
- The two communicating users can detect the presence of any third party trying to gain knowledge of the key (**eavesdropping**)
- Qubits are coded into quantum particles (photons), e.g., using polarization
- Any measurement by an eavesdropper will alter qubit state (photon polarization) and this perturbation is going to be detected
- However other sources of noise (no eavesdropping) can introduce perturbations



https://www.youtube.com/watch?v=Hm2Nmw_gnMQ

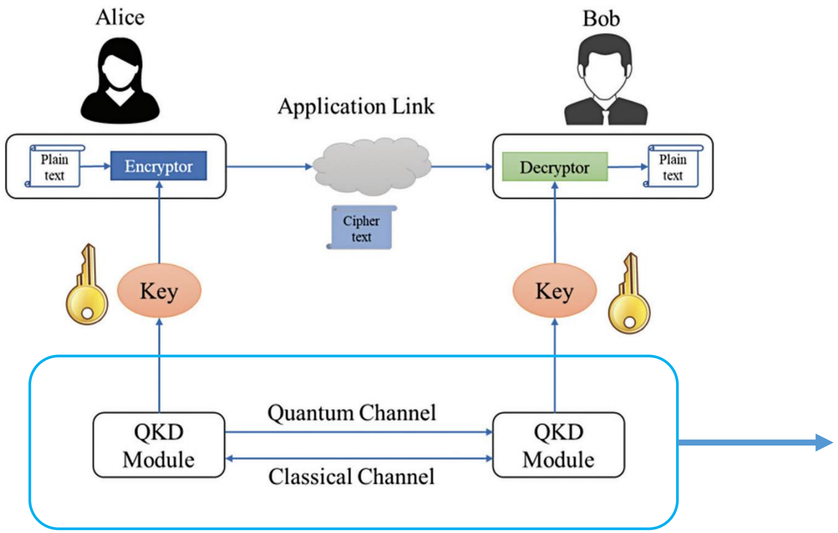
Encoding qubits as photons

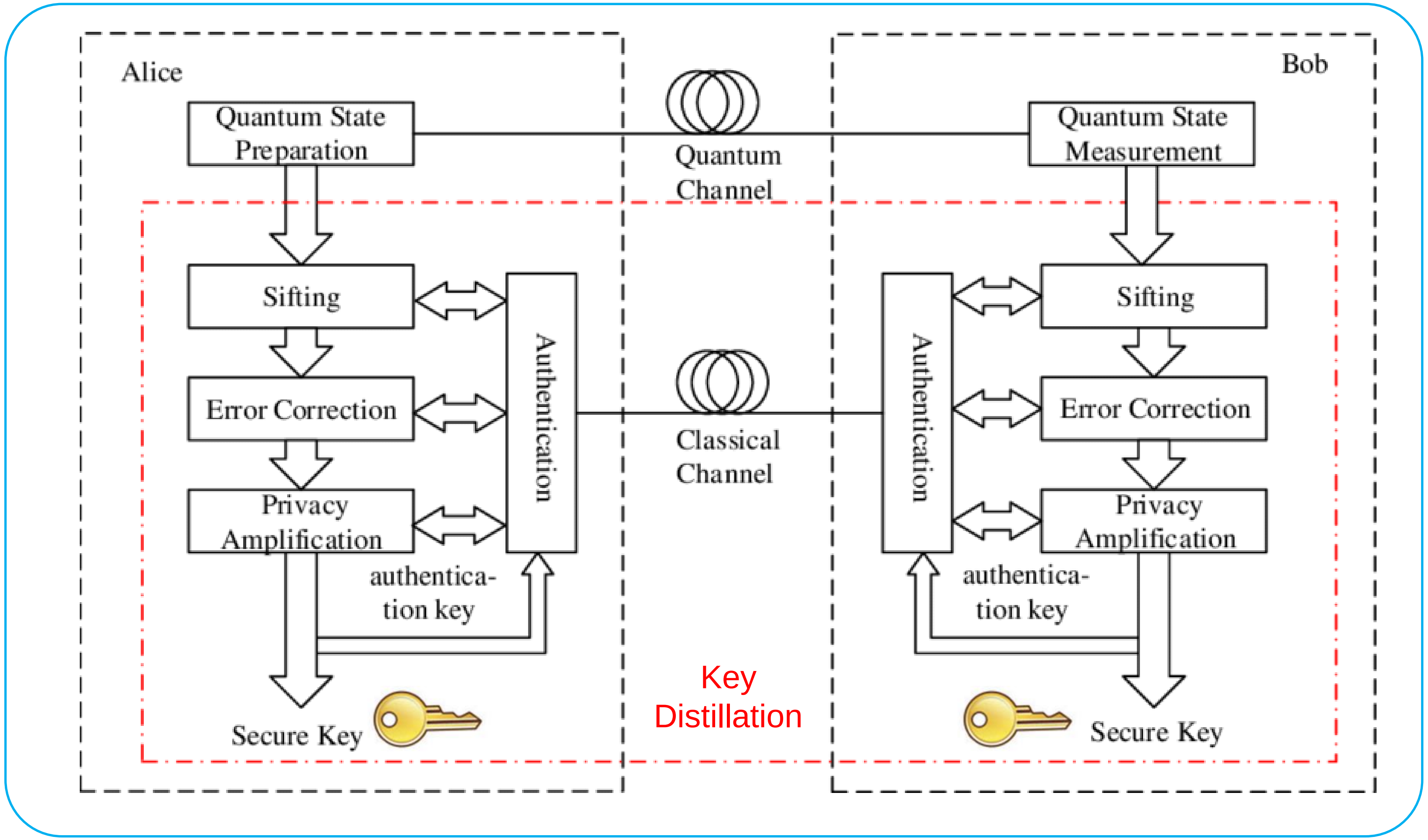




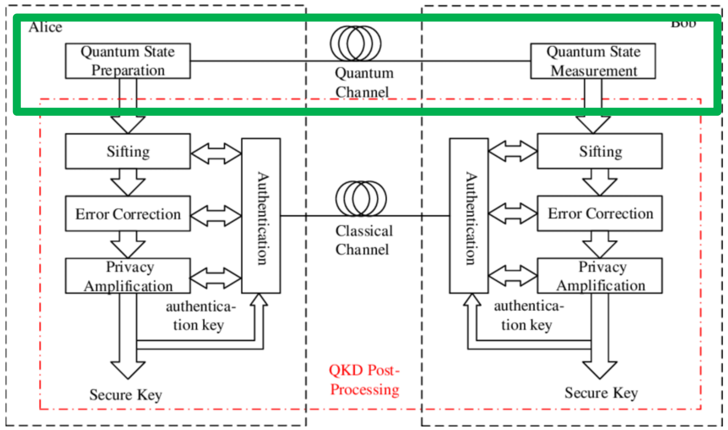
BB84 Protocol

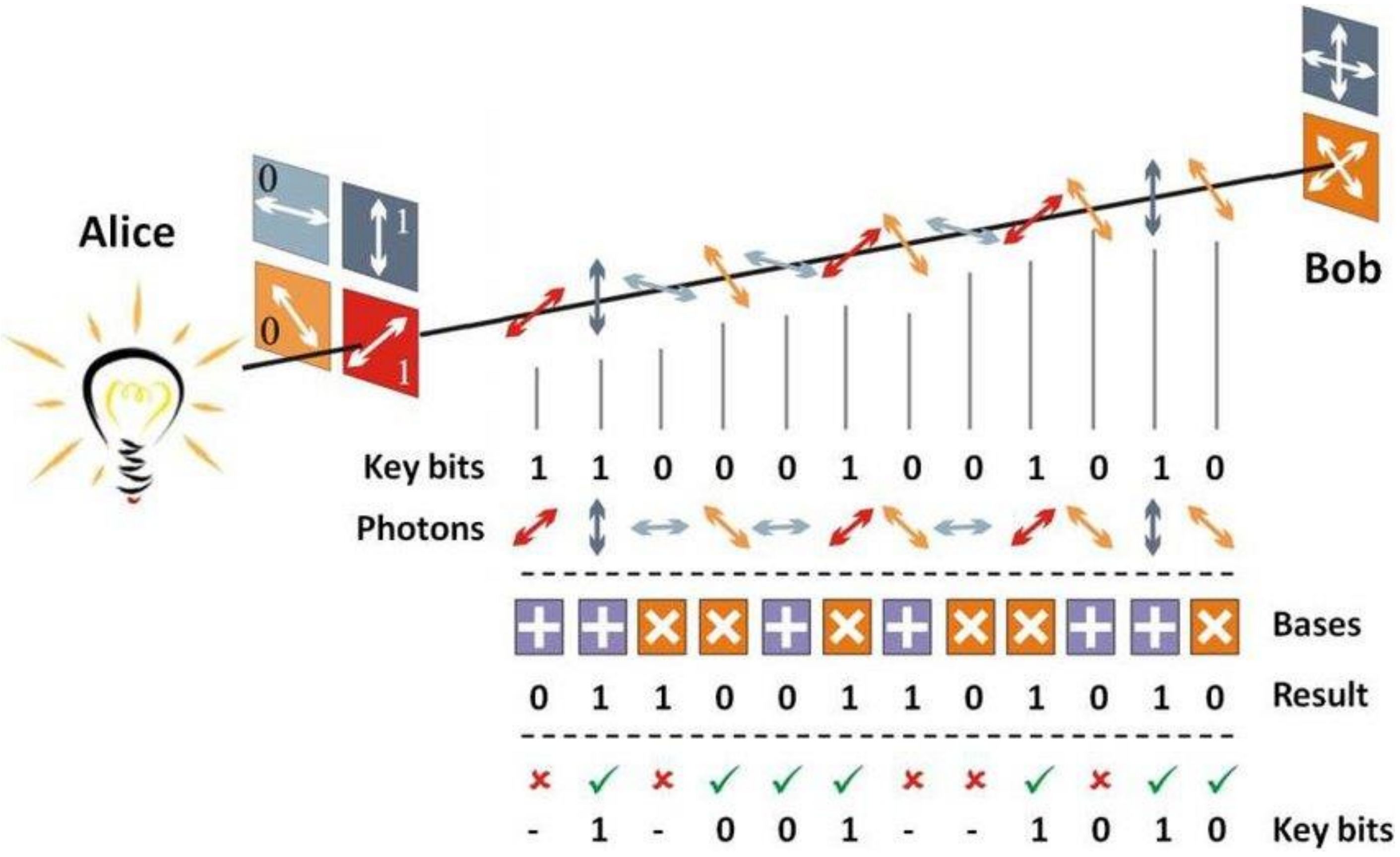
- Oldest protocol, works for polarization-encoded QKD systems
- Several phases:
  - Distribution
  - Sifting
  - Error estimation and correction
  - Privacy amplification



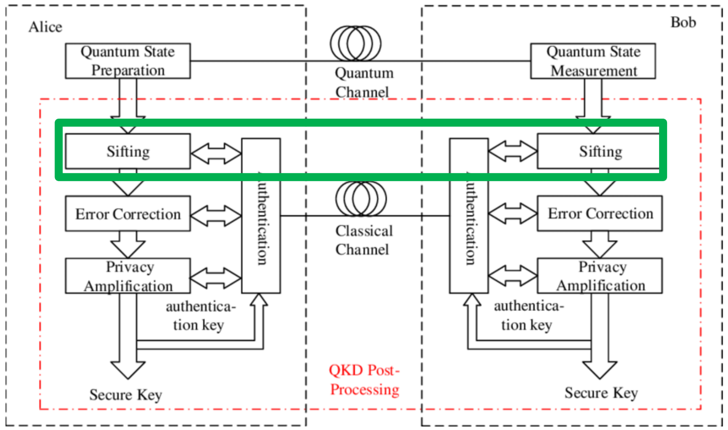


BB84 - Distribution



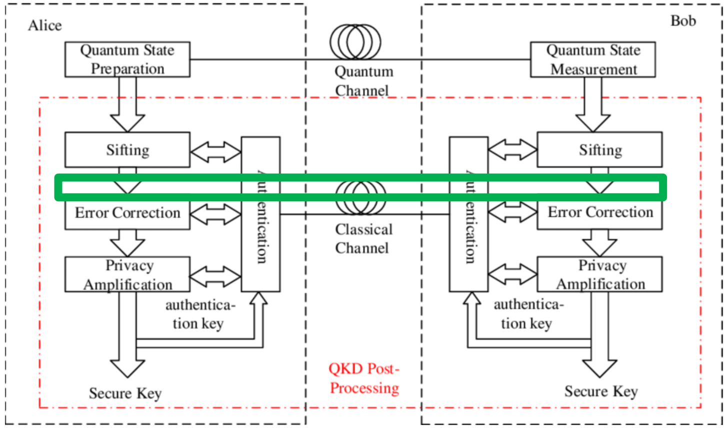


BB84 – Key sifting



Alice's selected basis	+	x	x	+	x	+	+	+	x	+	x	x
Alices's selected states	↑	↗	↗	→	↘	→	↑	↑	↗	→	↘	↘
Alice's raw-key	1	0	0	0	1	0	1	1	0	0	1	1
Bob's selected basis	+	+	x	+	x	X	+	+	x	+	+	x
Bob's measured states	↑	→	↗		↘	↘	↑	↑	↗	→		↘
Bob's raw-key	1	0	0		1	1	1	1	0	0		1
Alice's sifted-key	1		0		1		1	1	0	0		1
Bob's sifted-key	1		0		1		1	1	0	0		1

BB84 – Error estimation

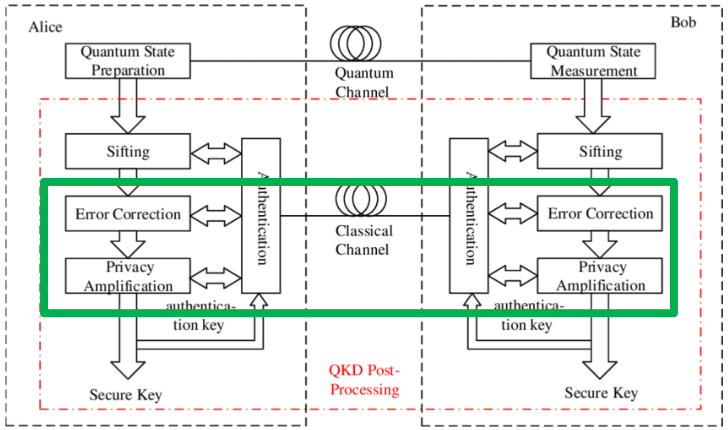


A sample is chosen, shared, and if **errors > 10%**, it is assumed that there is **eavesdropping** and the key is **discarded**

https://www.youtube.com/watch?v=2kdRuqvlaww

Alice's selected basis	+	x	x	+	x	+	+	+	x	+	x	x
Alices's selected states	↑	↗	↗	→	↘	→	↑	↑	↗	→	↘	↘
Alice's raw-key	1	0	0	0	1	0	1	1	0	0	1	1
Bob's selected basis	+	+	x	+	x	X	+	+	x	+	+	x
Without eavesdropping												
Bob's measured states	↑	→	↗		↘	↘	↑	↑	↗	→		↘
Bob's raw-key	1	0	0		1	1	1	1	0	0		1
Alice's sifted-key	1		0		1		1	1	0	0		1
Bob's sifted-key	1		0		1		1	1	0	0		1
With eavesdropping												
Bob's measured states	↑	→	↗		↗	↘	↑	↑	↗	↑		↘
Bob's received bits	1	0	0		0	1	1	1	0	1		1
Alice's sifted-key	1		0		1		1	1	0	0		1
Bob's sifted-key	1		0		0		0	1	0	1		1

BB84 – Last steps



- Error correction
  - Aka, information reconciliation
  - Needed to correct the rest of bits that were not discarded during error estimation
  - Using a cascade protocol, Bob can correct errors exposing (leaking) a minimum amount of bits through the classical channels
  - Eavesdropper can get significant information about keys in this phase
  - Process ends with identical Alice and Bob secret keys

- Privacy amplification
  - Using a hash function, a secret key of length *n* is transformed into a shorter one of length *m*<<*n*
  - In this way, potential information retrieved by eavesdropper is cancelled.

Some numbers

Obtained with https://www.qkdsimulator.com

Initial Configuration

Property Qubit Count	Basis choice bias delta	Eve basis choice bias delta	Eavesdropping	Eavesdropping rate	Error estimation sampling rate	Biased error estimation	Error tolerance
1000	0.5	0.5	0	0.1	0.2	0	0.11

Statistics and Overview

Property	Value
Initial number of qubits	1000
Final key length	343
Raw key mismatch before error correction	0.0
Raw key mismatch after error correction	0
Information leakage (Total number of disclosed bits)	52
Overall key cost for authentication	256
Key length before error correction	415
Bit error probability	0.0
Bits leaked during error correction	20

Some numbers

Obtained with https://www.qkdsimulator.com

Initial Configuration

Property Qubit Count	Basis choice bias delta	Eve basis choice bias delta	Eavesdropping	Eavesdropping rate	Error estimation sampling rate	Biased error estimation	Error tolerance
1000	0.5	0.5	1	0.2	0.2	0	0.11

Statistics and Overview

Property	Value
Initial number of qubits	1000
Final key length	234
Raw key mismatch before error correction	0.0438
Raw key mismatch after error correction	0
Information leakage (Total number of disclosed bits)	166
Overall key cost for authentication	256
Key length before error correction	420
Bit error probability	0.0405
Bits leaked during error correction	134

Commercial QKD

- IDquantique

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Back to products

Clavis XG QKD System

Quantum Key Distribution for production environments requiring high key transmission rate or extended range interconnection

- Long range (up to 150 km)
- High key rate (>100 kb/s)
- Complex network topologies (ring, hub and spoke, meshed, star)
- Controlled and monitored centrally
- Interoperability with major Ethernet and OTN encryptors

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VIEW USE CASES

HOW TO BUY

Local SME on Quantum

- LuxQuanta -> Continuous Variable QKD

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Easy network integration

High performance at metro distances

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A clear path to future scalability via full photonic integration

Recent research

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 40, NO. 13, JULY 1, 2022 4119

Cost-Effective ML-Powered Polarization-Encoded Quantum Key Distribution

Morteza Ahmadian, Marc Ruiz, Jaume Comellas, and Luis Velasco

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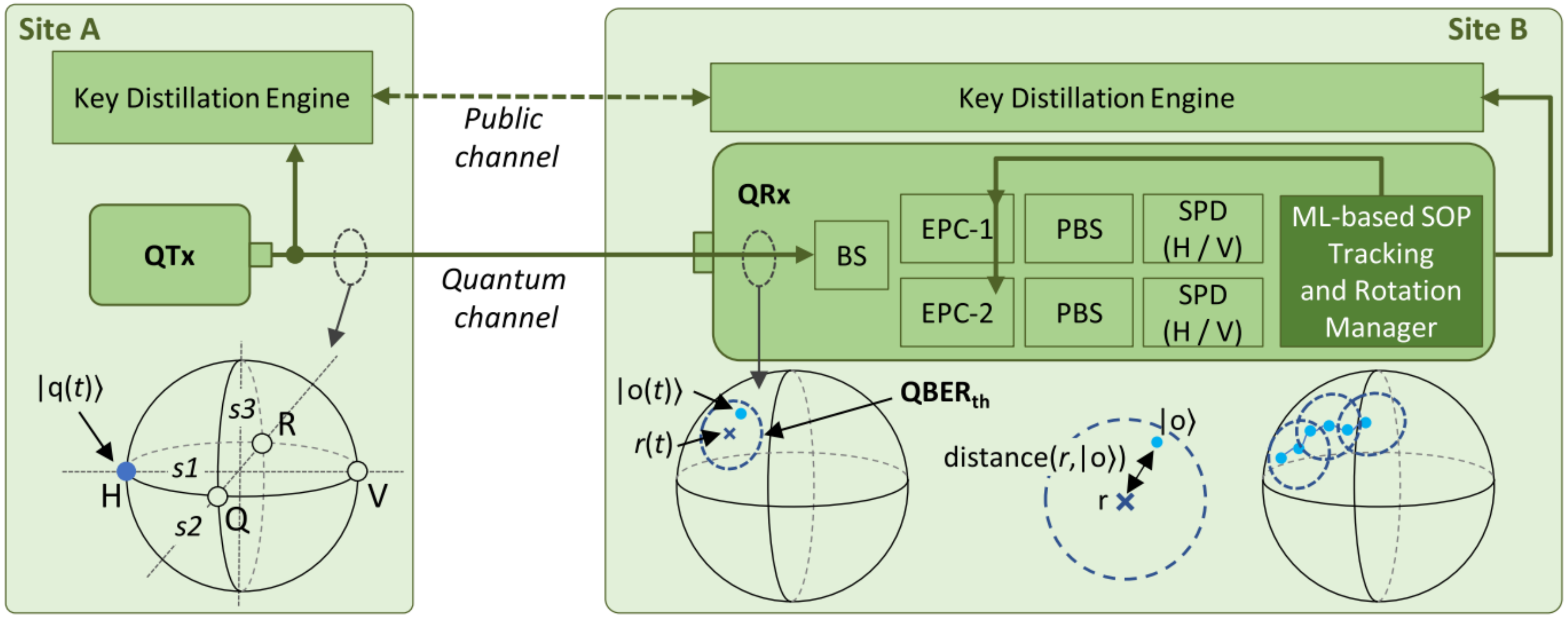

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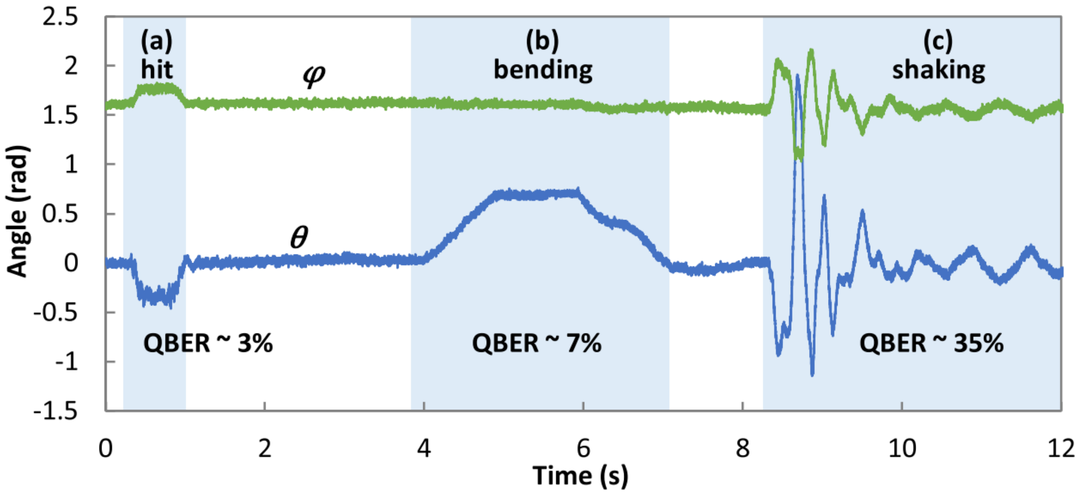

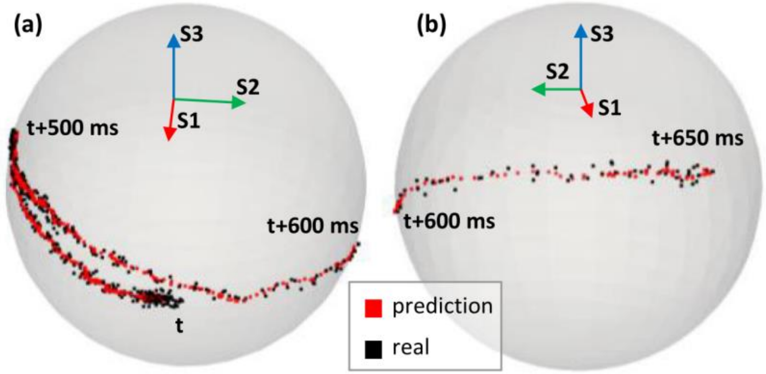

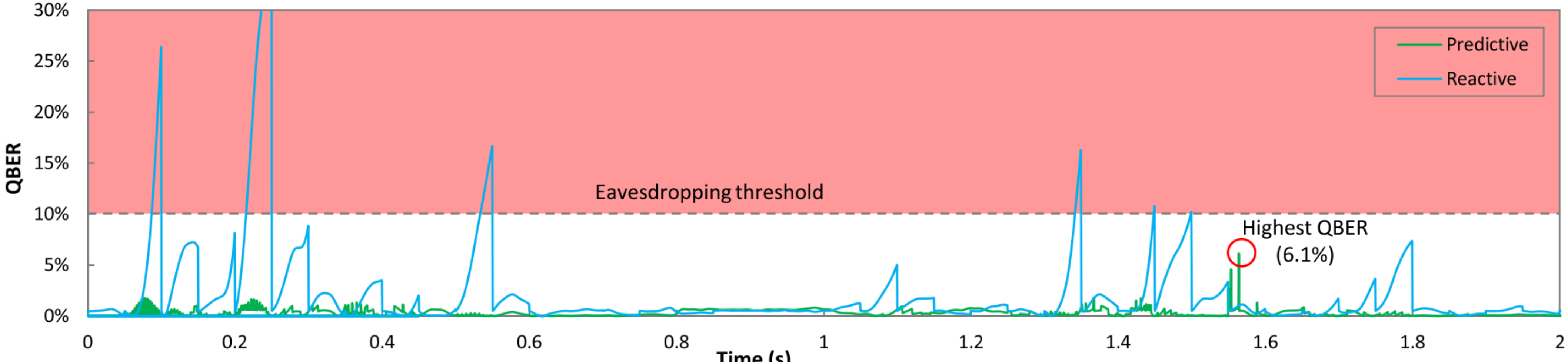

References QKD

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- BB84 short video
  - https://www.youtube.com/watch?v=2kdRuqvIaww
- Online QKD simulator
  - https://www.qkdsimulator.com/
- Open-Source Quantum Development
  - https://qiskit.org/

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marc.ruiz-ramirez@upc.edu