Wireless Myths, Realities and Futures: From classic radio-frequency to visible-light and quantum-solutions...

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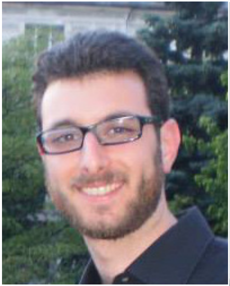
Overview

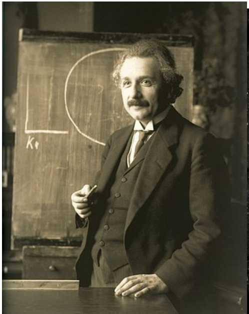
- **The myths & realities**
- **Moore's Law leads to nano-scale integration**
- **Global momentum in quantum technologies**
- **Superposition, entanglement and all that...**
- **What is quantum computing?**
- **What is quantum communication?**
- **EXAMPLE 1 - Quantum codes for mitigating quantum decoherence**
- **The Future?**
- **EXAMPLE 2 - Quantum-Internet: Routing above the clouds using quantum search algorithms**

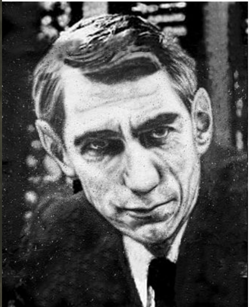
The Dream-Team





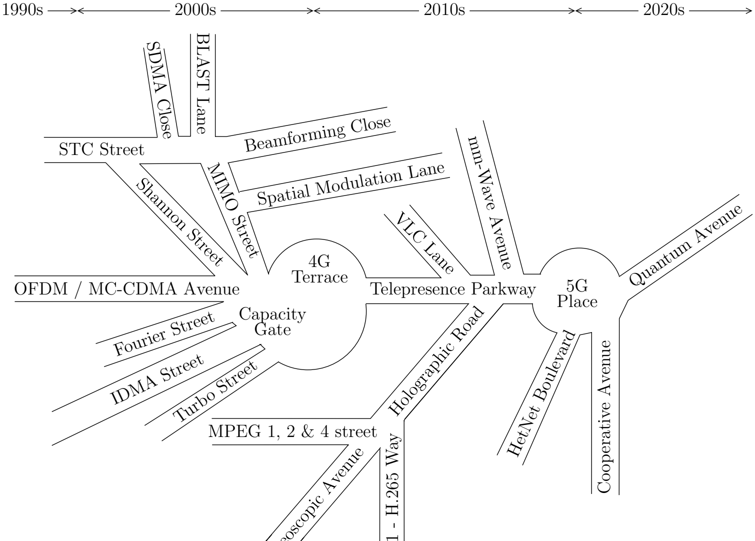

The Founders of our Field ©Hanzo *et al.*





Wireless Myths & Realities...

A Stroll with Shannon to Next-Generation Plaza...©Hanzo *et al.*



The Electromagnetic Spectrum

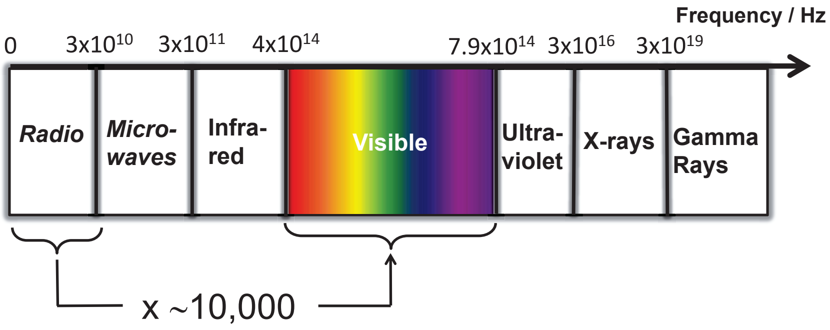
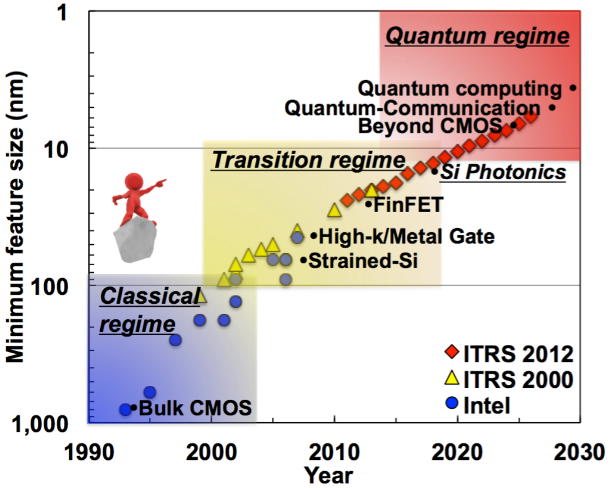


Figure: The electromagnetic spectrum ©H. Haas

- L. Hanzo, H. Haas, S. Imre, D. O'Brien, M. Rupp, and L. Gyongyosi, "Wireless myths, realities, and futures: From 3g/4g to optical and quantum wireless," *Proceedings of the IEEE*, vol. 100, pp. 1853 –1888, 13 2012, Invited Paper in the Centennial Issue

Moore's Law...ⒸCCBY



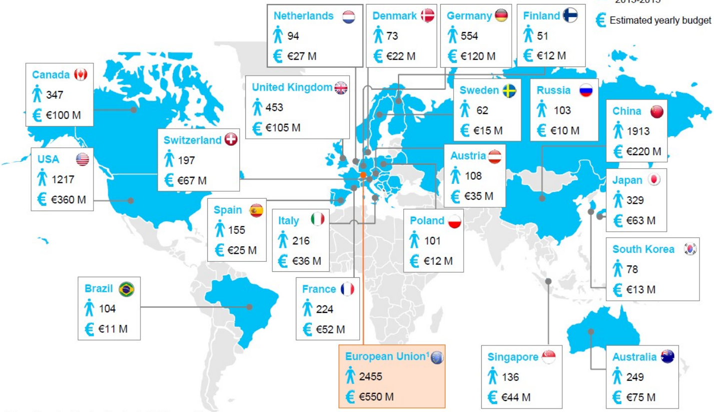
Source: http://theconversation.com/uk/technology

Worldwide, ~7000 researchers work with budget of ~€1.5 B, expected to increase to ~€5 B

NON-CLASSIFIED

Nr of unique authors 2013-2015

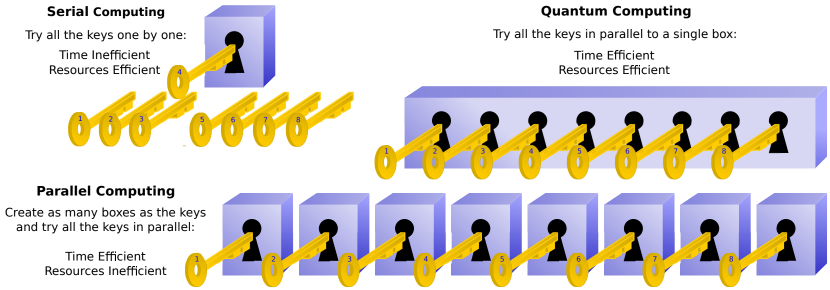
€ Estimated yearly budget



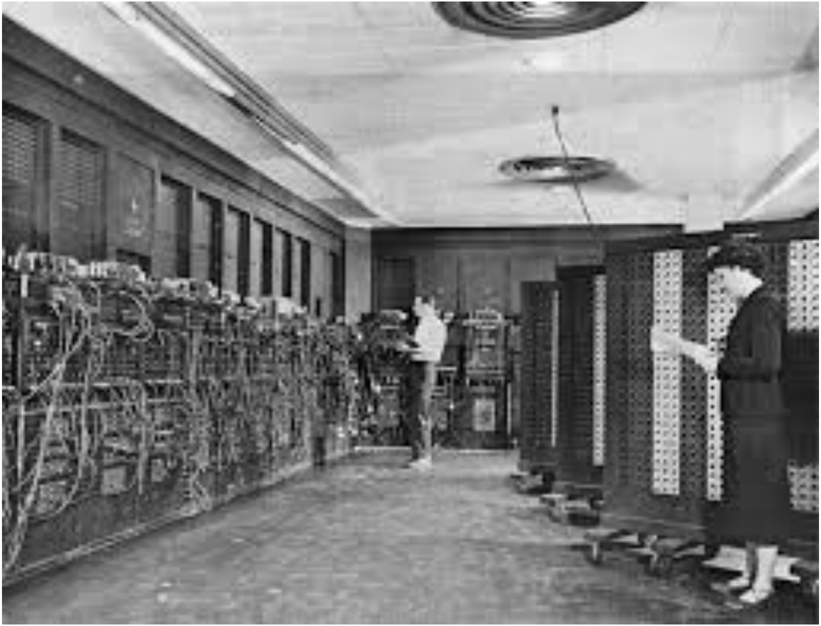
1 Combined estimated budget of EU countries

What is Quantum Computing...?

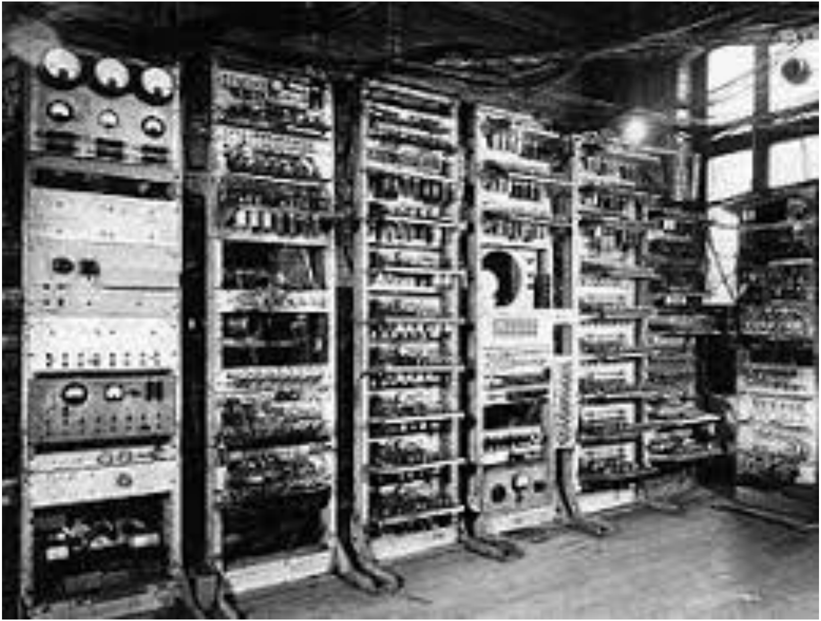
- "I think there is a world market maybe for five computers."
  T.J. Watson, Chairman of IBM, 1943
- We already have more than five quantum computers in 2018



- **[Hanzo et al.]** Wireless Myths, Realities and Futures, Proc. of the IEEE, 13th of May 2012, Centennial Issue, Xplore Open Access
- **[Botsinis, Ng & Hanzo]**: Quantum Search Algorithms, Quantum Wireless and a Low-Complexity Maximum Likelihood Iterative Quantum Multi-User Detector Design, IEEE Access, May 2013, Xplore Open Access

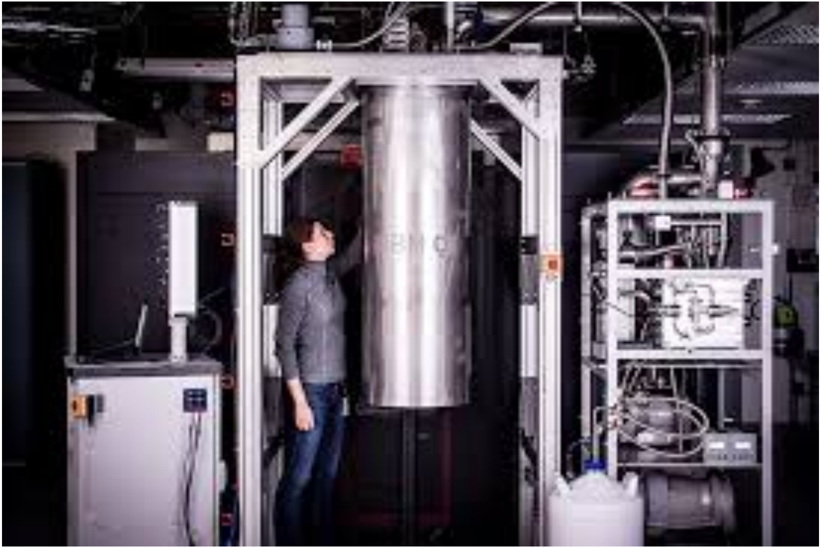


The First Computers in the 1950s ©CCBY



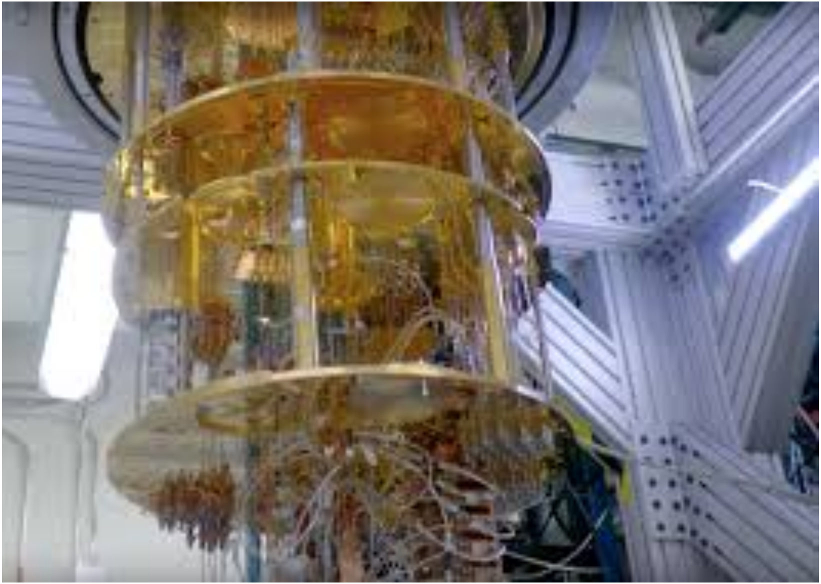
The First Computers in the 1950s ©CCBY

The 17-Qubit IBM Quantum Computer in 2018 ©CCBY

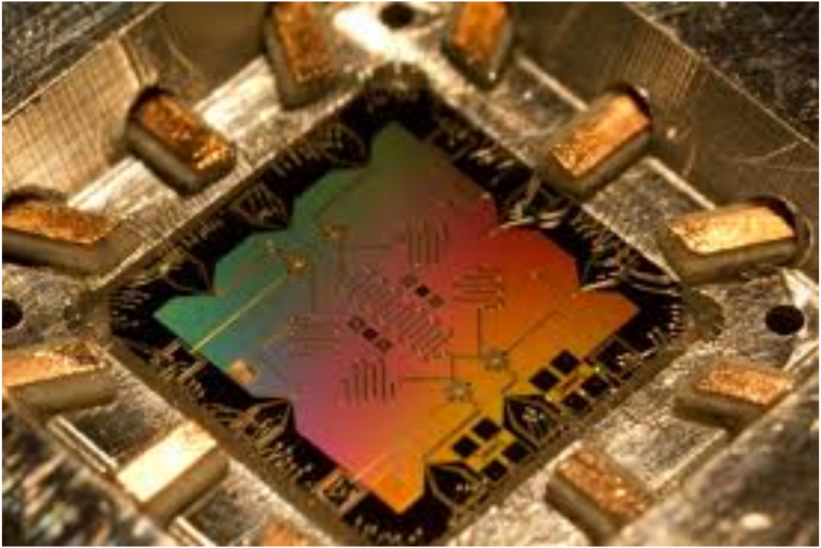


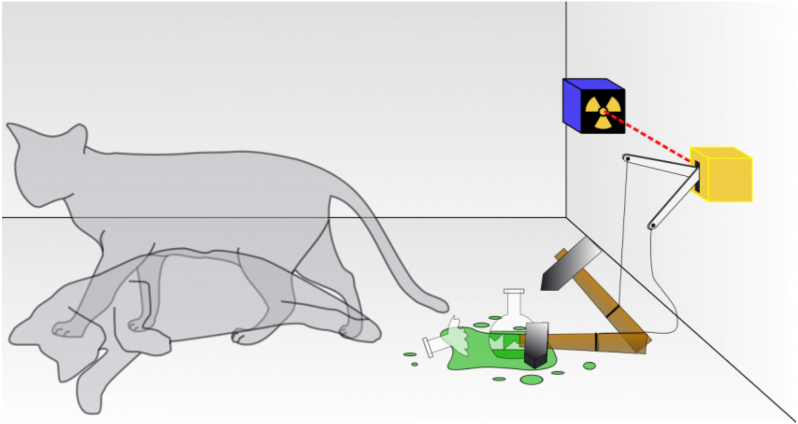
The First IBM Quantum Computers in 2018 ©CCBY

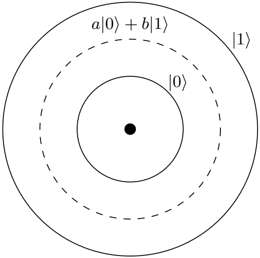
The First IBM Quantum Computers in 2018 ©CCBY



The First IBM Quantum Computers in 2018 ©CCBY







An atom with one electron orbiting around the nucleus having two legitimate energy levels (solid orbits). Quantum mechanics allow the electron to be in an arbitrary superposition of these two energy levels (dashed orbit), but when it is observed it may only be found in one of the two legitimate orbits.

Superposition of Qubits ©Hanzo *et al.*

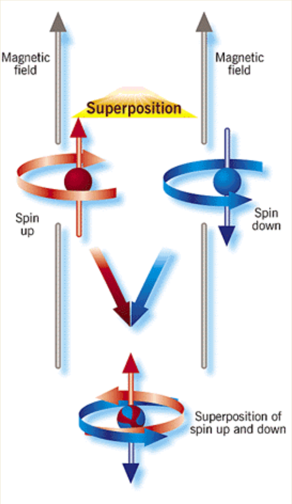
- Spinning Coin in a Black Box:
  - 50% "Heads" AND 50% "Tails".
    Both at the same time!
  - Observation (by opening the box): "Heads" OR "Tails".
  - Idea: Keep the coin spinning and manipulate it without opening the box.

- Coins in computing:
  - Classic bit: 0 or 1.
  - Quantum bit (Qubit): 0 or 1, or any combination of them.
- Ket notation: $|q\rangle = a|\text{HEADS}\rangle + b|\text{TAILS}\rangle = a|0\rangle + b|1\rangle$,
  where $|a|^2 + |b|^2 = 1$ and $a, b \in \mathbb{C}$.
  Provides any possible superposition of 0 and 1!
- Observation:
  - $|a|^2$ probability to observe $|0\rangle$
  - $|b|^2$ probability to observe $|1\rangle$

  The qubit's state becomes the observed one with probability 1.
- 2 qubits: $|q\rangle = 0.5|00\rangle + 0.5|01\rangle + 0.5|10\rangle + 0.5|11\rangle$

Motivation: Quantum Parallelism ©Hanzo *et al.*

Qubit: $\alpha|0\rangle + \beta|1\rangle$



http://abyss.uoregon.edu/ js/cosmo/lectures/lec08.html

Quantum Measurement

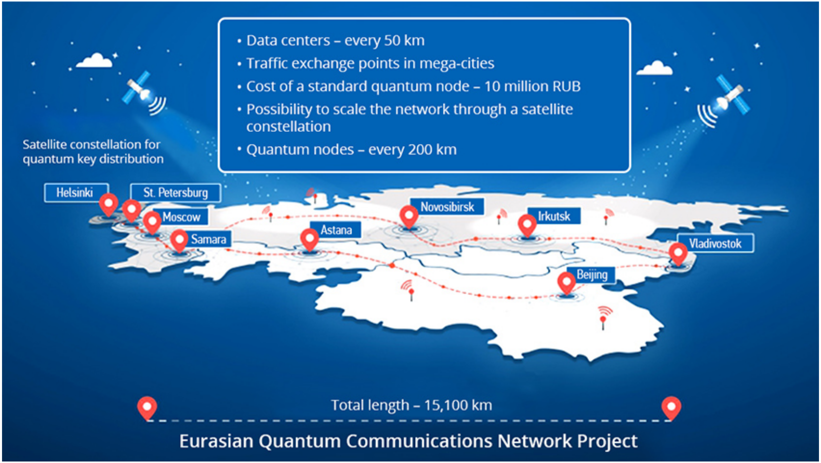
$$\alpha|0\rangle + \beta|1\rangle \xrightarrow{|\alpha|^2} |0\rangle$$
$$\xrightarrow{|\beta|^2} |1\rangle$$

So, What is Quantum Communications?

The Chinese Micius Experiment ©CCBY

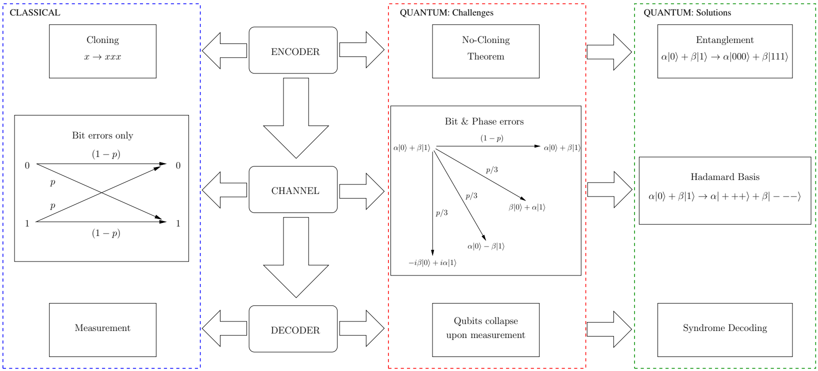
The Chinese Micius Experiment ©CCBY

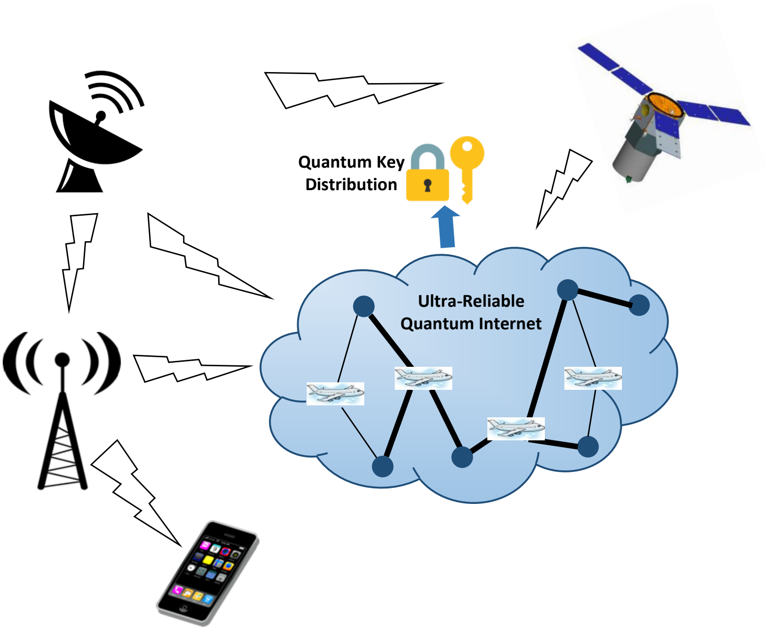
The Russian QKD Experiment ©CCBY



The Russian QKD Experiment ©CCBY

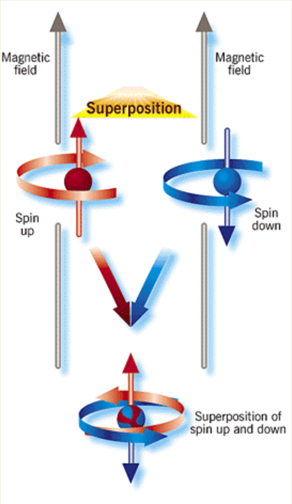
Pauli-to-Classical Isomorphism ©Hanzo *et al.*




Quantum Key
Distribution
Ultra-Reliable
Quantum Internet

Motivation: Quantum Parallelism ©CCBY

Qubit: $\alpha|0\rangle + \beta|1\rangle$



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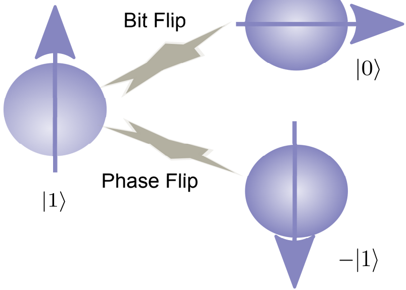
Quantum Measurement

$$\alpha|0\rangle + \beta|1\rangle \xrightarrow{|\alpha|^2} |0\rangle$$
$$\xrightarrow{|\beta|^2} |1\rangle$$

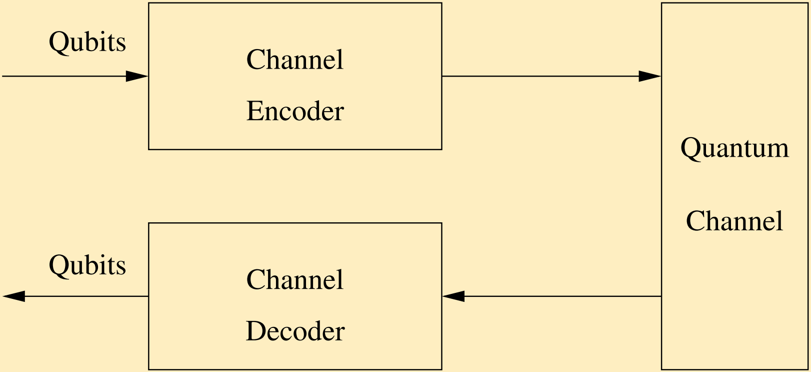
The Benefits of Quantum Codes



Quantum decoherence/noise characterized by bit and phase flips.

Quantum Error Correction Codes (QECCs) are vital for reliable quantum computing and communication sys- tems

Design efficient error correction codes for reliable quantum systems by exploiting the underlying quantum-to-classical isomorphism.



- 1995
  - **Shor Code** is a 9-qubit code correcting a single qubit.
- 1996
  - **Steane Code** is a 7-qubit code correcting a single qubit.
  - **Laflamme Code** is the "perfect" 5-qubit code correcting a single qubit.
- 1997
  - The general formulation of syndrom-based QSCs was proposed.
  - **Toric Codes**, where the qubits are arranged on a torus.
- 1998
  - **Surface Codes**, where the qubits can be arranged on a surface.
  - **Quantum GF(4) Codes** derived from classical error correction codes based on the GF(4).
- 1999
  - **Quantum BCH Codes**, inspired by classical BCH codes.
  - **Quantum Reed-Solomon Codes** inspired by classical Reed-Solomon codes.
  - **Quantum Reed-Muller Codes** inspired by classical Reed-Muller codes.

1999

Entanglement was proposed for transforming the classical codes into their quantum counterparts.

Quantum Convolutional Codes inspired by classical trellis-based error correction codes.

2002

2003

Quantum LDPC Codes based on sparse graph codes, surveyed by Babar *et al.* in 2015

2004

Colour Codes, member of the so-called topological codes.

2006

Quantum Turbo Codes based on serial concatenated quantum CCs, surveyed by Babar *et al.*

2009

Hyperbolic Surface Codes

2012

Hypergraph Product Codes

2013

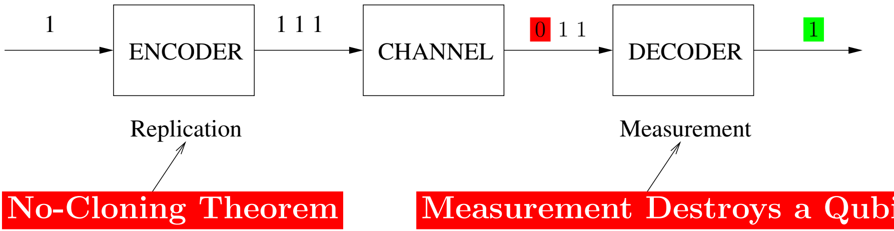
2014

Quantum Polar Codes

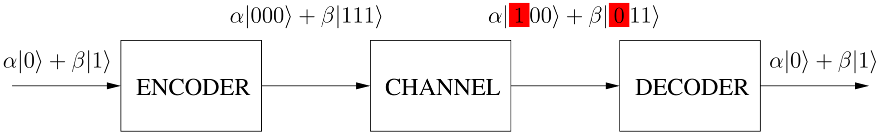
Hyperbolic Colour Codes

Homological Product Codes

Classical Error Correction



Quantum Error Correction



We wish to determine the error without observing the qubit!!

Solution: Measure the error without reading the data.

Quantum Error Correction → Majority-Based Syndrome Decoding

- Check 1: Modulo 2 addition of first and second qubits.
- Check 2: Modulo 2 addition of first and third qubits.

Syndrome Checks	**Correction/Action**
00	No Error
11	Bit error on 1st Qubit
10	Bit error on 2nd Qubit
01	Bit error on 3rd Qubit

Classical Parity Check Matrix (PCM)-based Syndrome Decoding

$$s = yH^T = (x+e)H^T = eH^T$$

- For the 3-bit Repetition code, we have:

$$H = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \end{pmatrix}$$

- Valid codewords are (0 0 0) and (1 1 1).
- Let $y = (0\ 1\ 1)$, then:

$$s = \begin{pmatrix} 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 1 \end{pmatrix}$$

Phase Error Correction

- Encode the basis states $|0\rangle$ and $|1\rangle$ in the Hadamard basis, i.e.

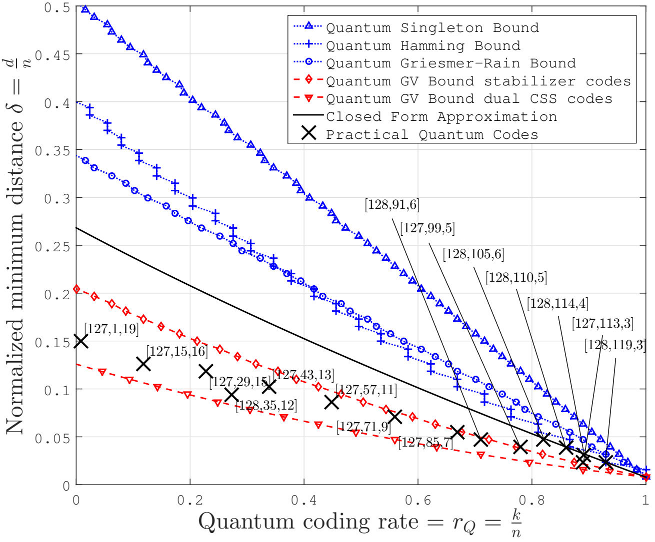
$$|0\rangle \rightarrow |+++\rangle \qquad |1\rangle \rightarrow |---\rangle$$

  where we have:

$$|+\rangle \rightarrow \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad |-\rangle \rightarrow \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

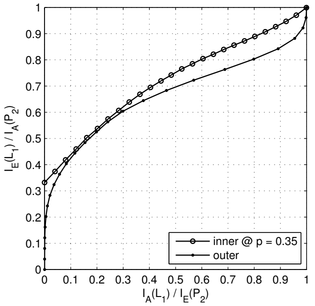
- Check 1: Compare the first and second qubits.
- Check 2: Compare the first and third qubits.
- For example, the information word $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ is encoded into $|\overline{\psi}\rangle = \alpha|+++\rangle + \beta|---\rangle$. If phase error occurs on the first qubit, we receive $|\hat{\psi}\rangle = \alpha|-++\rangle + \beta|+--\rangle$.

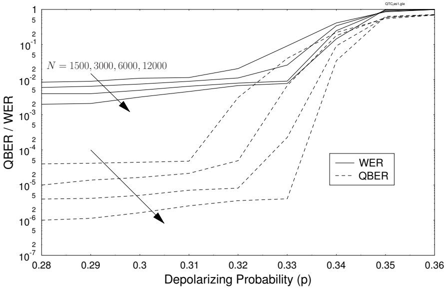
Quantum coding rate r_Q versus normalized minimum distance δ for finite-length QSCs, $n = 127$ & $n = 128$



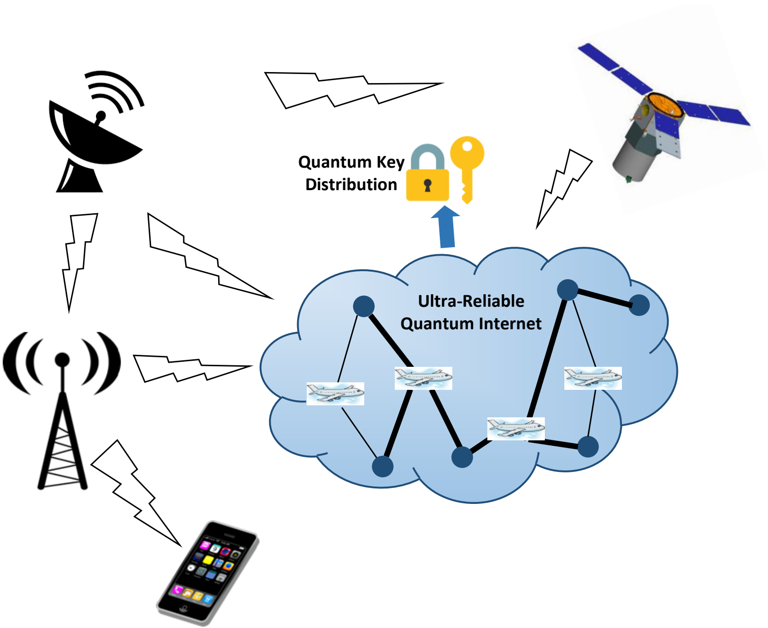
Results I: Optimized Quantum Turbo Code Design ©Hanzo *et al.*

- Design Criterion: Find the optimal inner and outer components, which yield a marginally open tunnel between the EXIT curves of the inner and outer decoders at the highest possible depolarizing probability.



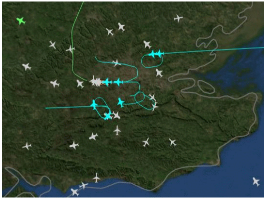


Our optimized QTC operates within 0.3 dB of the capacity limit re

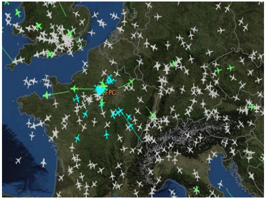

Quantum Key
Distribution
Ultra-Reliable
Quantum Internet

- Quantum Key Distribution;
- Q-Memory, Q-Repeaters, Q-Search Algorithms;
- Free-Space Optical Communications;
- What can we transplant from the classical into the quantum domain?
- **The Quantum-Internet Above the Clouds Based on Pareto-Optimization Using Quantum-Search Algorithms**

Aircraft mobility pattern for LHR, in the European airspace and over the North Atlantic ©Hanzo *et al.*



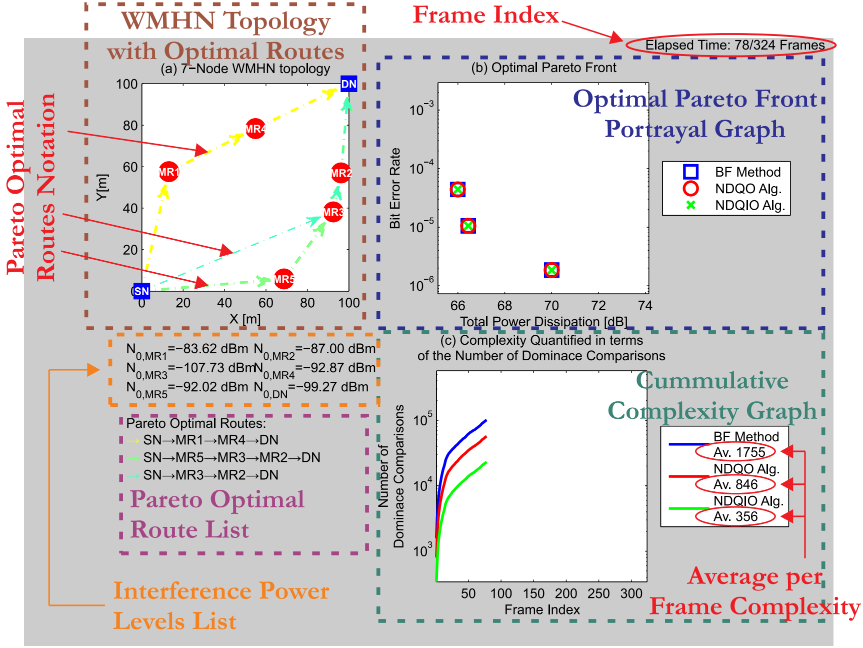
Heathrow Airport



European Airspace

North Atlantic

- https://uk.flightaware.com/live/airport/EGLL


WMHN Topology with Optimal Routes
(a) 7−Node WMHN topology
Y[m]
X [m]
SN
MR1
MR2
MR3
MR4
MR5
DN
Pareto Optimal Routes Notation
Frame Index
Elapsed Time: 78/324 Frames
(b) Optimal Pareto Front
Optimal Pareto Front Portrayal Graph
Bit Error Rate
Total Power Dissipation [dB]
BF Method
NDQO Alg.
NDQIO Alg.
N0,MR1=−83.62 dBm N0,MR2=−87.00 dBm
N0,MR3=−107.73 dBm N0,MR4=−92.87 dBm
N0,MR5=−92.02 dBm N0,DN=−99.27 dBm
Pareto Optimal Routes:
SN→MR1→MR4→DN
SN→MR5→MR3→MR2→DN
SN→MR3→MR2→DN
Pareto Optimal Route List
Interference Power Levels List
(c) Complexity Quantified in terms of the Number of Dominace Comparisons
Cummulative Complexity Graph
Number of Dominace Comparisons
Frame Index
BF Method Av. 1755
NDQO Alg. Av. 846
NDQIO Alg. Av. 356
Average per Frame Complexity