Quantum Communication Limits

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QCIT Webinar (14 Jan 2026)

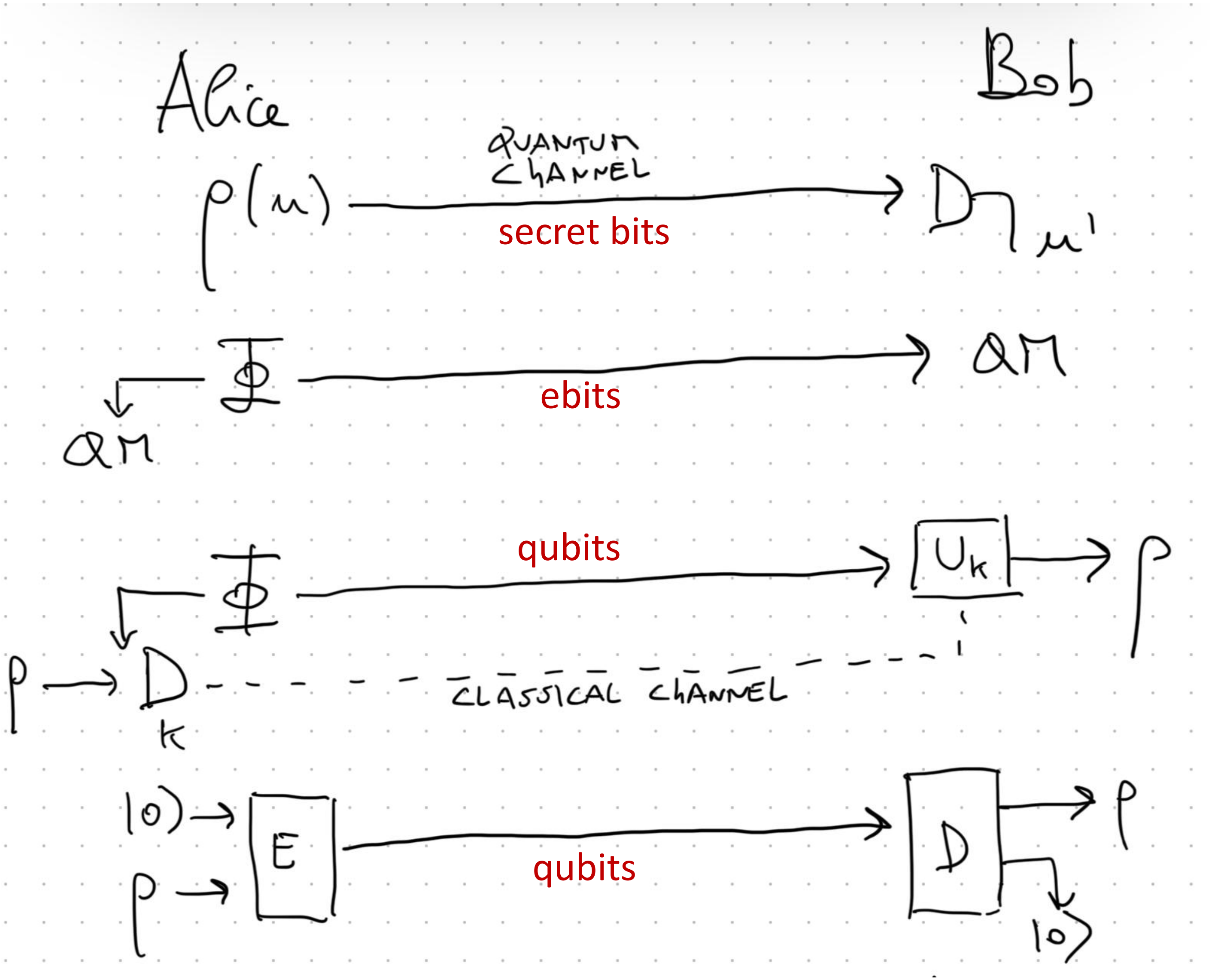
Outline

- ❑ Quantum Communication Protocols and Capacities
- ❑ Holography -> Repeaterless PLOB bound
- ❑ Limits of quantum comms (e.g., max QKD rates)
- ❑ Limits of repeater chains
- ❑ Limits of quantum communication networks
- ❑ Limits of free-space quantum comms
- ❑ Satellite quantum comms

Main Quantum Communication Protocols

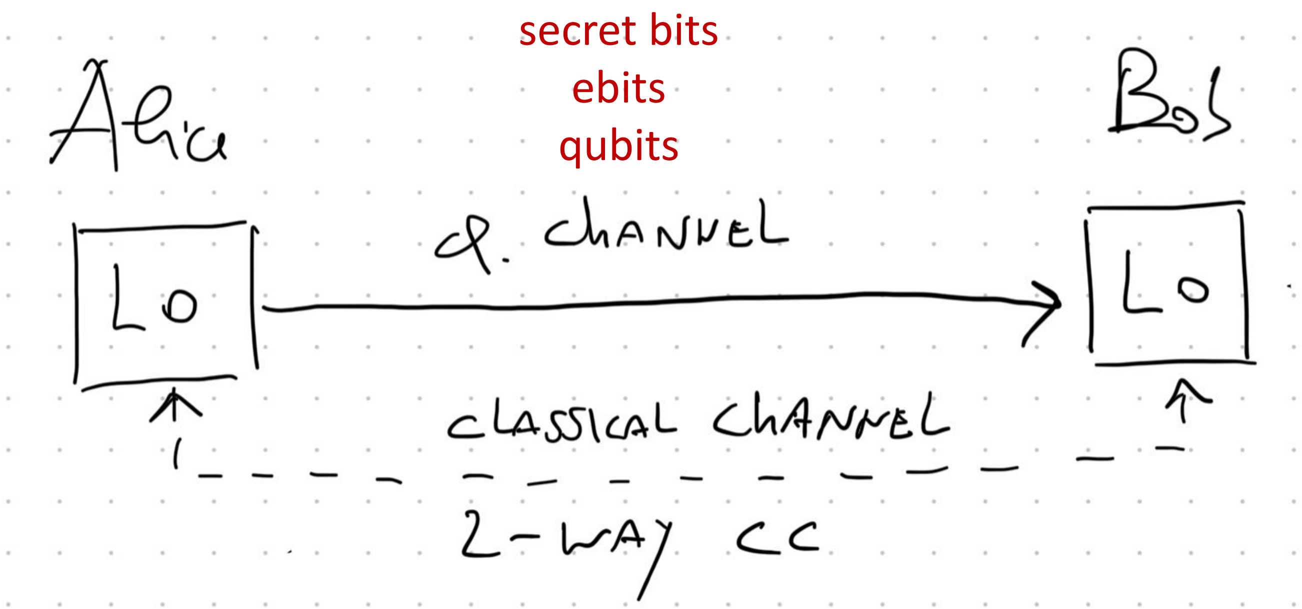
- ❑ Quantum key distribution (QKD)
- ❑ Entanglement distribution (ED)
- ❑ Quantum teleportation (QT)*
- ❑ QEC-based Transmission (QEC)*

*These are forms of Quantum Information Transmission (QIT)



Generic Quantum Communication Protocol

- Alice performs a quantum local operation (LO) at the input
- She sends a quantum system through the channel
- Bob performs a LO on the output
- They use a side channel for 2-way classical communication (CC)
- They optimize their LO adaptively using the classical info exchanged



Quantum Communication Capacities

Given a quantum channel between Alice and Bob, we optimize over all possible communication protocols to establish the maximum rates for:

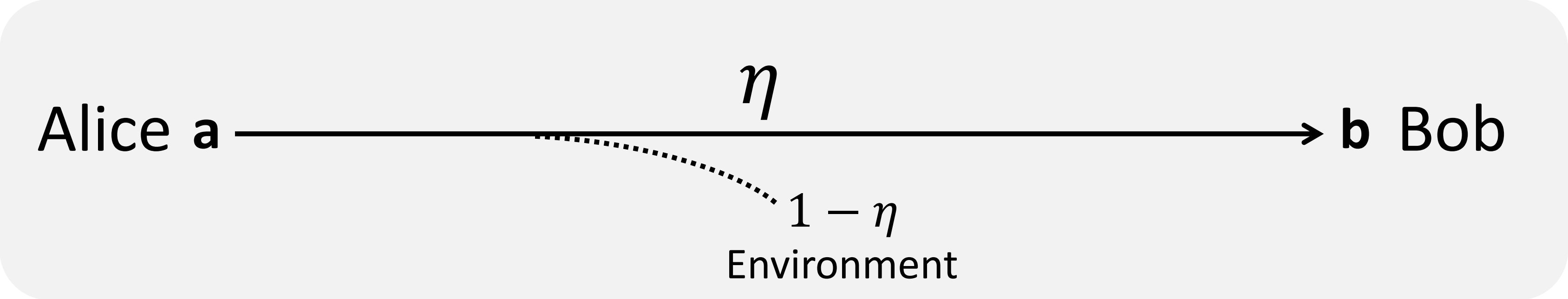
- ❑ QKD (secret bits/channel use) – Secret Key Capacity
- ❑ ED (ebits/channel use) – Entanglement Distribution Capacity*
- ❑ QIT (qubits/channel use) – Quantum Capacity*

To simplify, let us use a compact notation and define a generic quantum communication capacity K. Depending on the specific task of the protocol (QKD, ED, QIT), it can be specified to one of the capacities listed above.

*Technically, these are called the 2-way assisted capacities

Quantum Communication Capacities

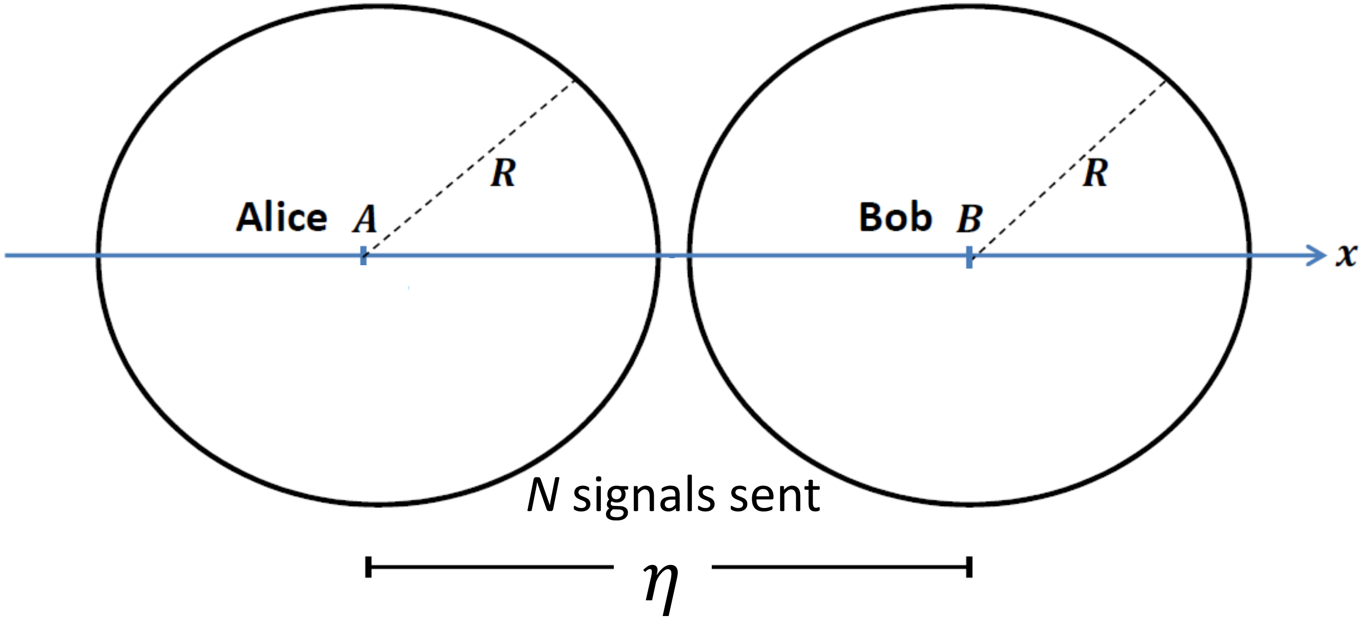
In particular, consider a "lossy" quantum channel with transmissivity η



Quantum Communication Capacity $K = K(\eta)$

To find this, we need upper bound and lower bound

Holographic Upper bound



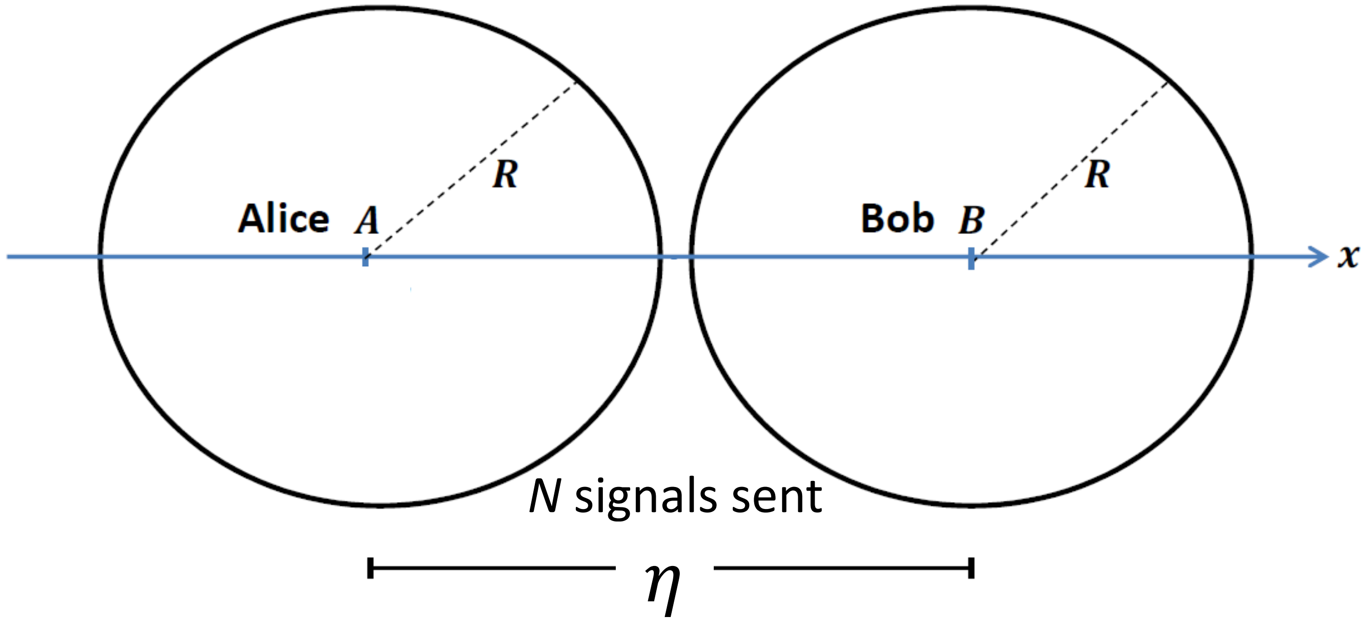
Spherical Entropy Bound

$$S^{\mathrm{th}} \leq \frac{k\mathcal{A}}{4l_p^2} = \frac{\pi k R^2}{l_p^2}$$

$$K \lesssim \left(1 + 8\varepsilon + 8N\sqrt{\frac{\eta}{1-\eta}}e^{-\frac{\pi}{2}R_p^2}\right)[-\log_2(1-\eta)]$$

Pirandola, *Holographic Limitations and Corrections to Quantum Information Protocols*, Phys. Rev. Res. 6, 013157 (2024)

Holographic Upper bound



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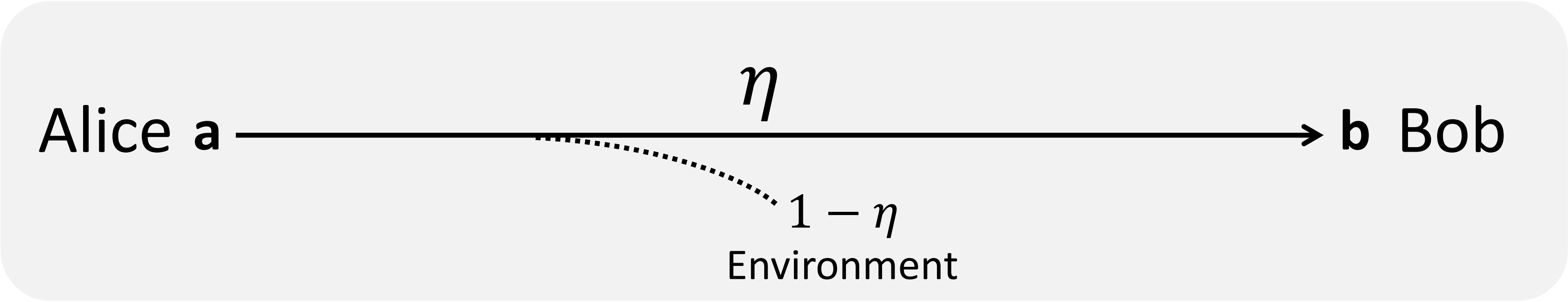


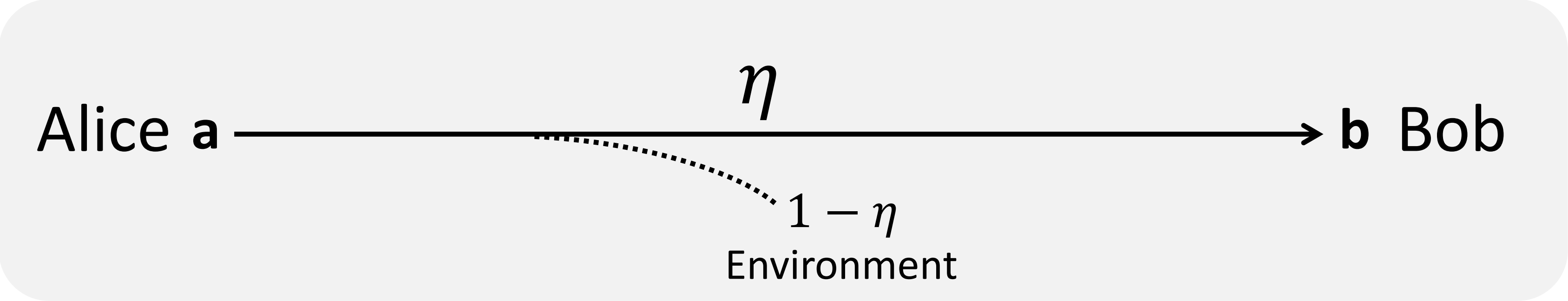
$$K \leq -\log_2(1-\eta)$$

Upper bound (converse part) [1,2]

[1] Pirandola, *Holographic Limitations and Corrections to Quantum Information Protocols*, Phys. Rev. Res. 6, 013157 (2024)

[2] Pirandola, Laurenza, Ottaviani, Banchi, Nature Comm 8, 15043 (2017)

Lower bound



$$K \leq -\log_2(1-\eta)$$

Upper bound (converse part) [1,2]

$$K \geq -\log_2(1-\eta)$$

Achievability (direct part) [3]

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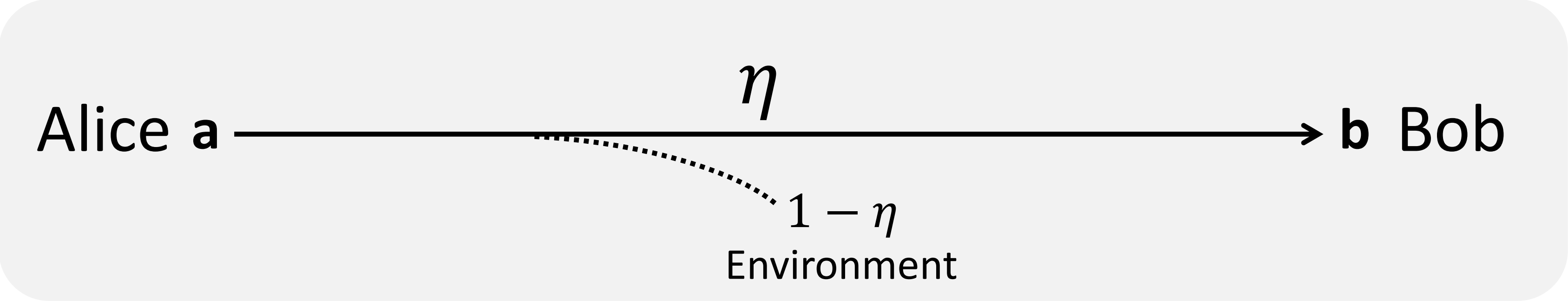
[2] Pirandola, Laurenza, Ottaviani, Banchi, Nature Comm 8, 15043 (2017)

[3] Pirandola, Patron, Braunstein, Lloyd, PRL 102, 050503 (2009)

Exact Capacity



$$K \leq -\log_2(1-\eta)$$ Upper bound (converse part) [1,2]

$$K \geq -\log_2(1-\eta)$$ Achievability (direct part) [3]

$$K = -\log_2(1-\eta)$$

- Quantum/entanglement distribution capacity
- Secret-key capacity
- Known as PLOB bound

[1] Pirandola, *Holographic Limitations and Corrections to Quantum Information Protocols*, Phys. Rev. Res. 6, 013157 (2024)

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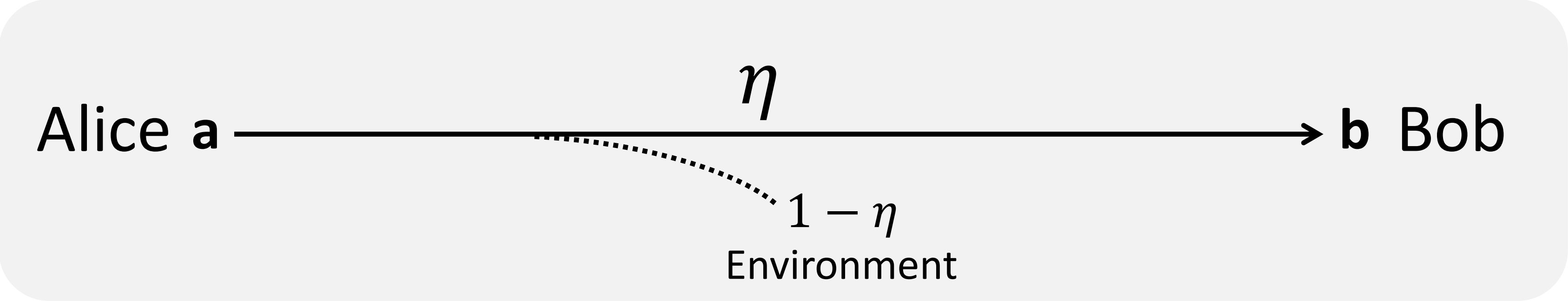
Fundamental limits of quantum communications

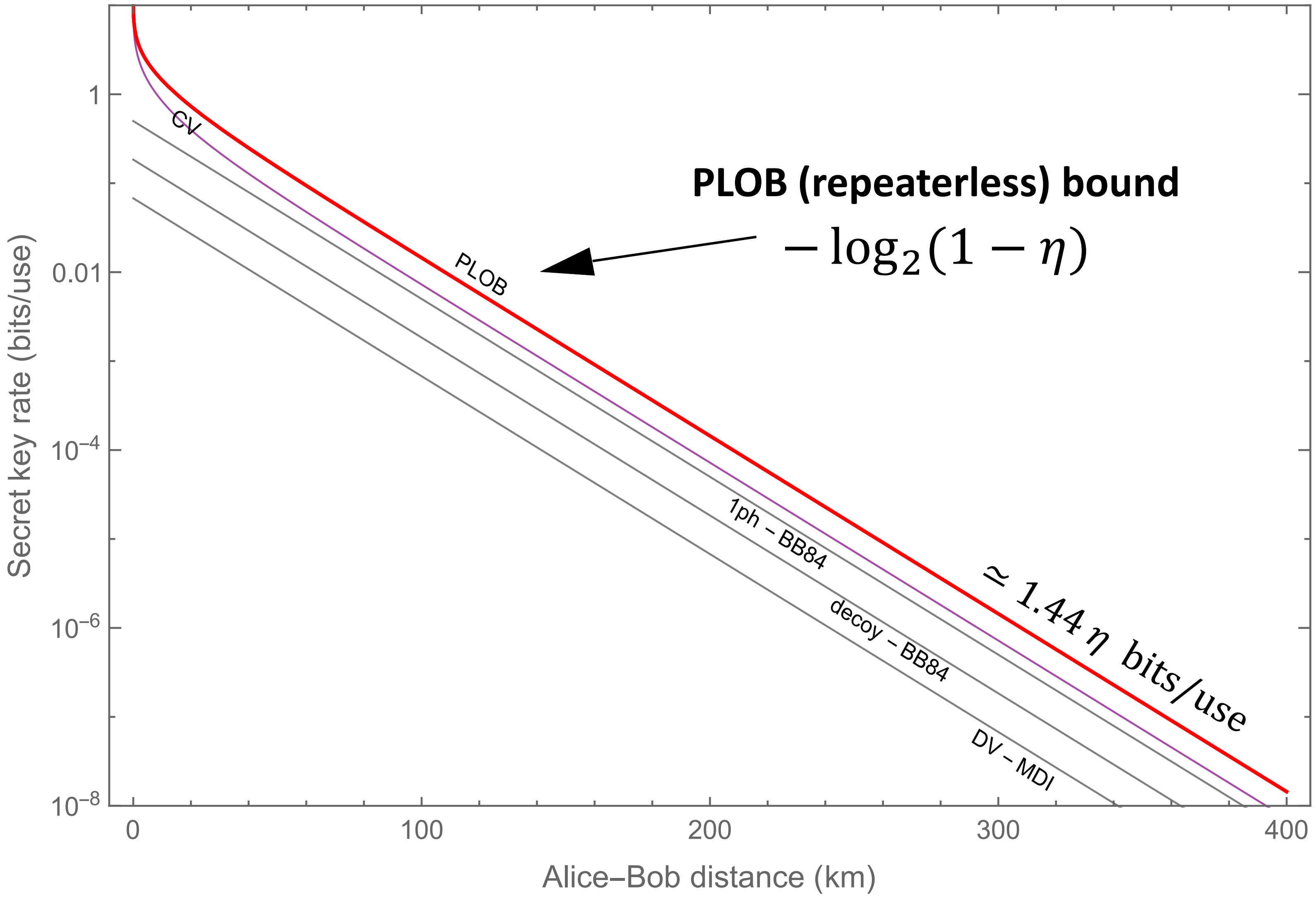


$$K = -\log_2(1-\eta)$$

PLOB bound is the fundamental benchmark for quantum communications:

- Provides the ultimate performance of quantum communication protocols over a quantum channel, in the absence of repeaters (repeaterless bound)
- Establishes if a quantum repeater effectively *repeats*

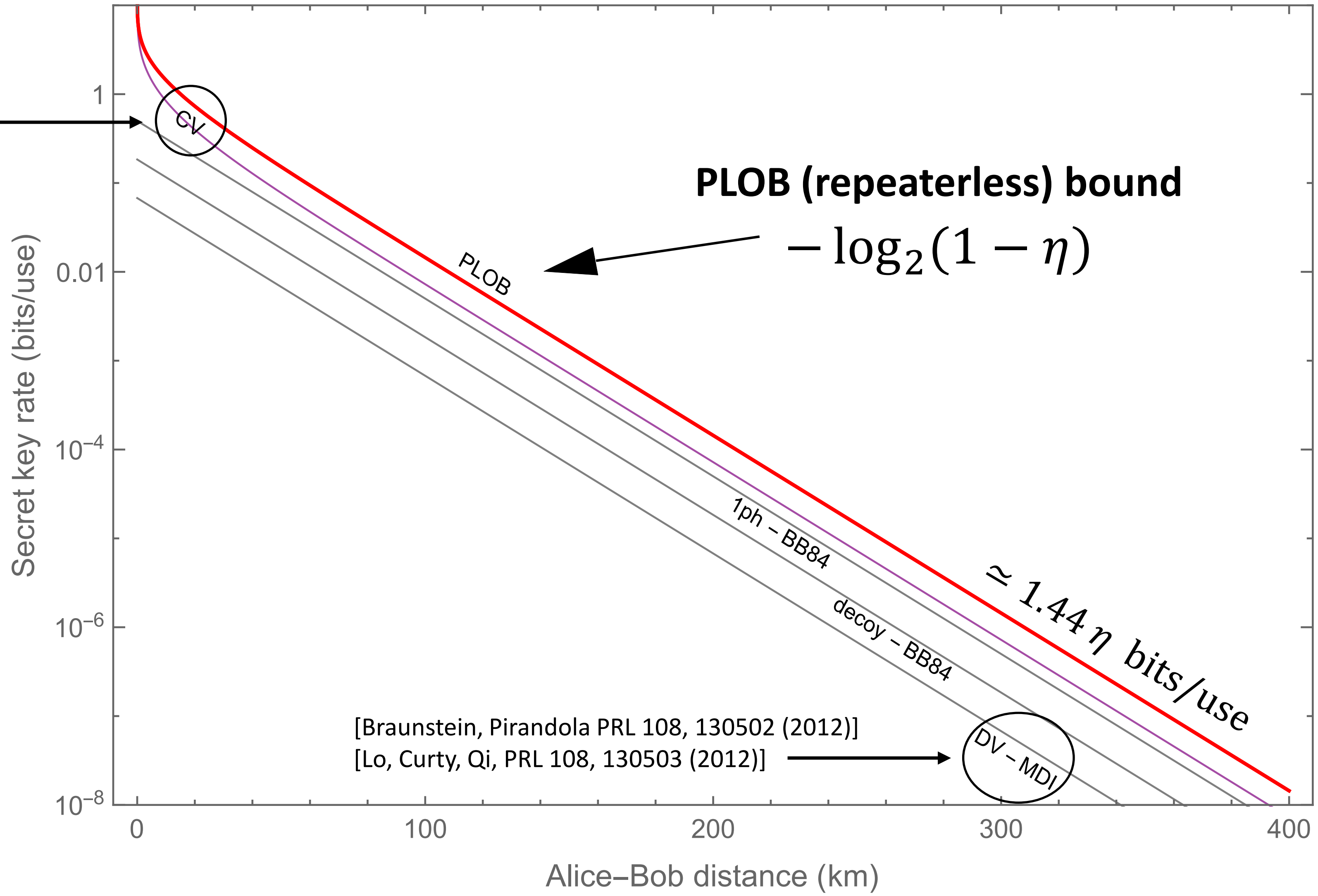
QKD limits before PLOB



[Pirandola et al., *Advances in Quantum Cryptography*, AOP 12, 1012-1236 (2020)]

QKD limits before PLOB

- GG02
- Het protocol,
- CV-MDI-QKD
[Pirandola et al, Nature Photonics 9, 397 (2015)]

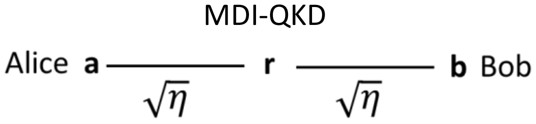


PLOB (repeaterless) bound

$-\log_2(1-\eta)$

$\simeq 1.44\,\eta$ bits/use

[Braunstein, Pirandola PRL 108, 130502 (2012)]
[Lo, Curty, Qi, PRL 108, 130503 (2012)]



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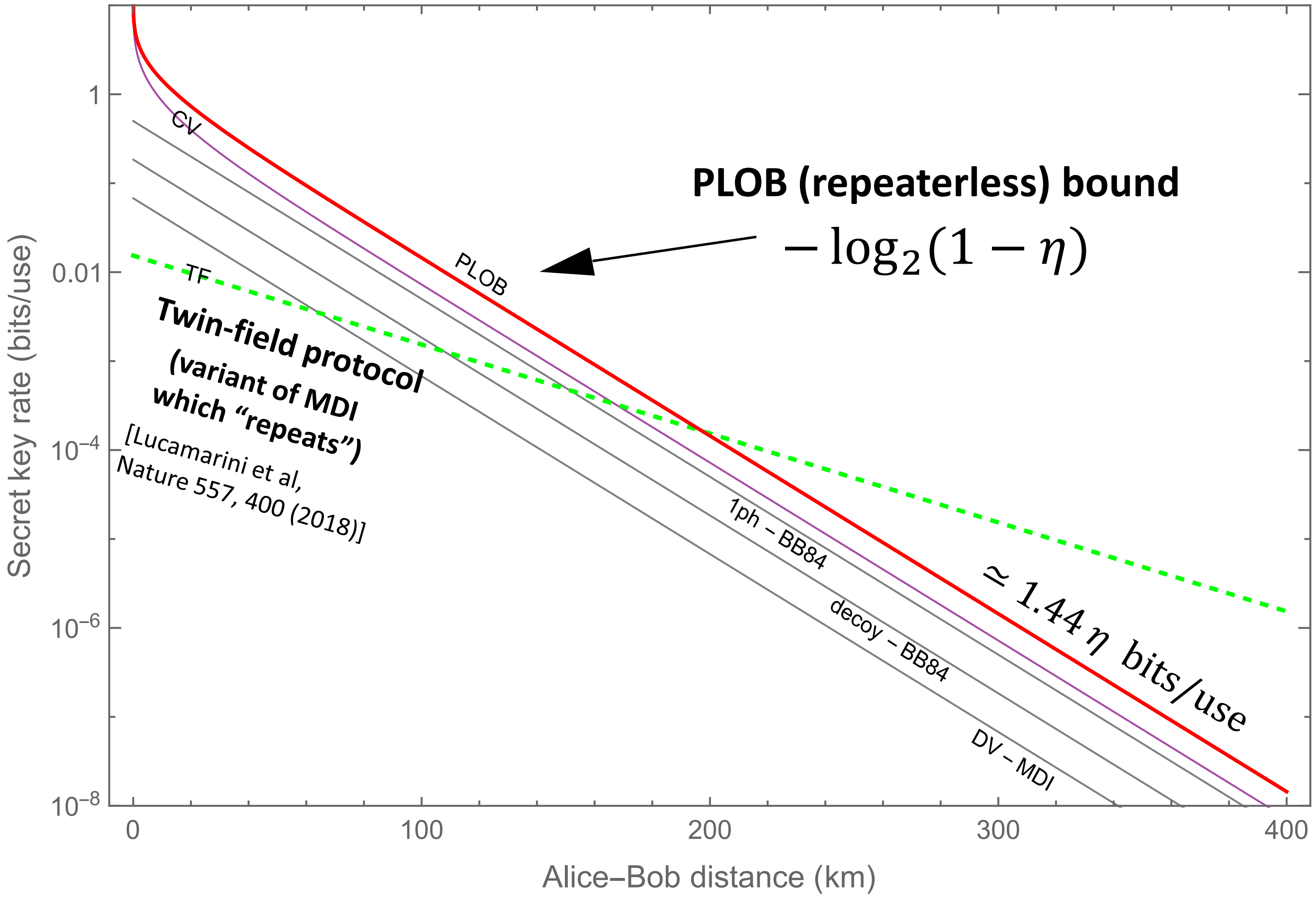
Repeater-assisted protocols introduced after PLOB



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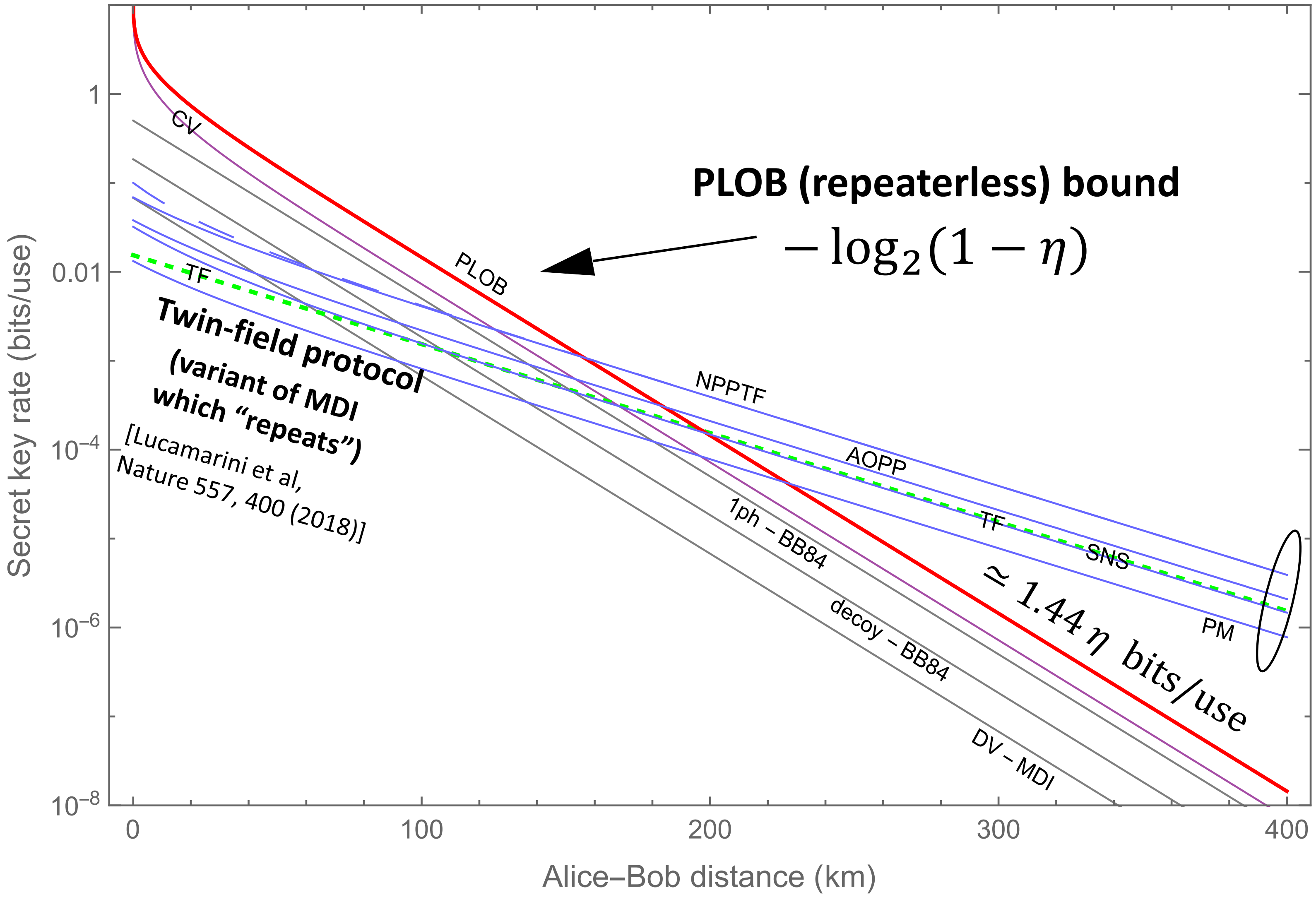


- ❑ Sending or not sending (SNS)

  Wang et al, PRA 98, 062323 (2018)

  Jiang et al, PRApp 12, 024061 (2019)

- ❑ Active odd-parity pair (AOPP)

  Xu et al., PRA 101, 042330 (2020)

- ❑ No-phase-postselected (NPPTF)

  Cui et al., PRApp 11, 034053 (2019)

  Grasselli, NJP 21, 073001 (2019)

- ❑ Phase-matching (PM)

  PRX 8, 031043 (2018)

Other repeater-assisted protocols

[Pirandola et al., *Advances in Quantum Cryptography*, AOP 12, 1012-1236 (2020)]

Limits of repeater-assisted quantum communications

Optical link with transmissivity η

Alice **a** ⟶ **b** Bob

PLOB bound $K = -\log_2(1-\eta)$

only beaten by effective repeaters

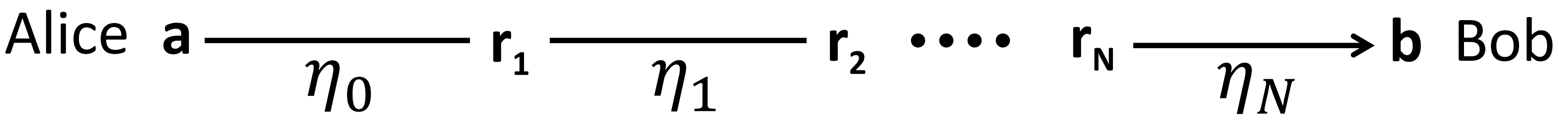
Next question: what are the optimal rates achievable by repeater-assisted protocols?

Limits of repeater-assisted quantum communications

PLOB bound $K = -\log_2(1-\eta)$

only beaten by effective repeaters

Consider a chain of M ideal repeaters between Alice and Bob



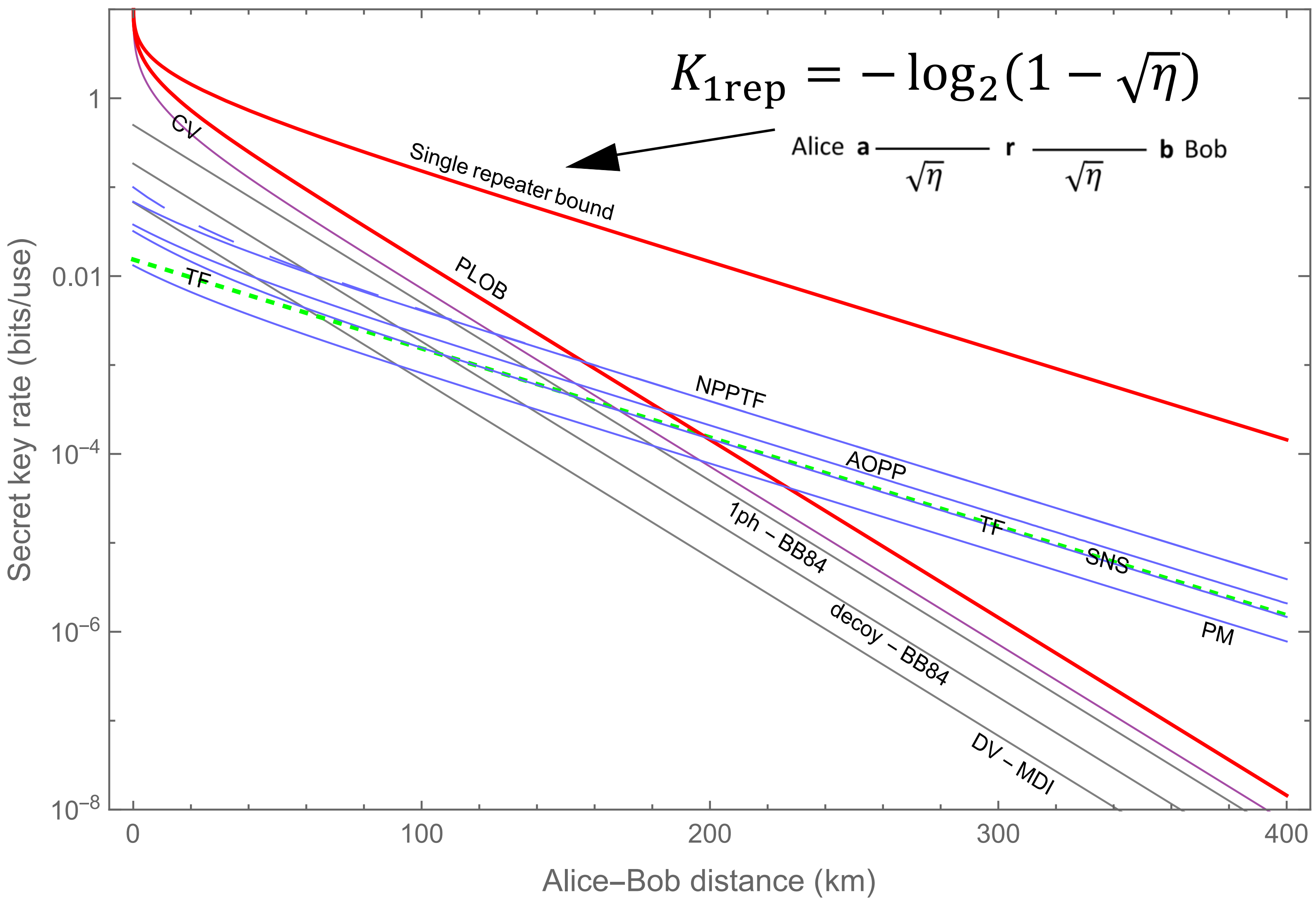
The capacity of the chain is given by the min transmissivity

$$K = -\log_2(1 - \min_i\{\eta_i\})$$

Techniques:
-Lower bound (simple, by composition)
-Upper bound (difficult, via REE and teleportation simulation)

[Pirandola, *End-to-end capacities of a quantum communication network*, Communications Physics 2, 51 (2019)]

Limits of repeater-assisted quantum communications



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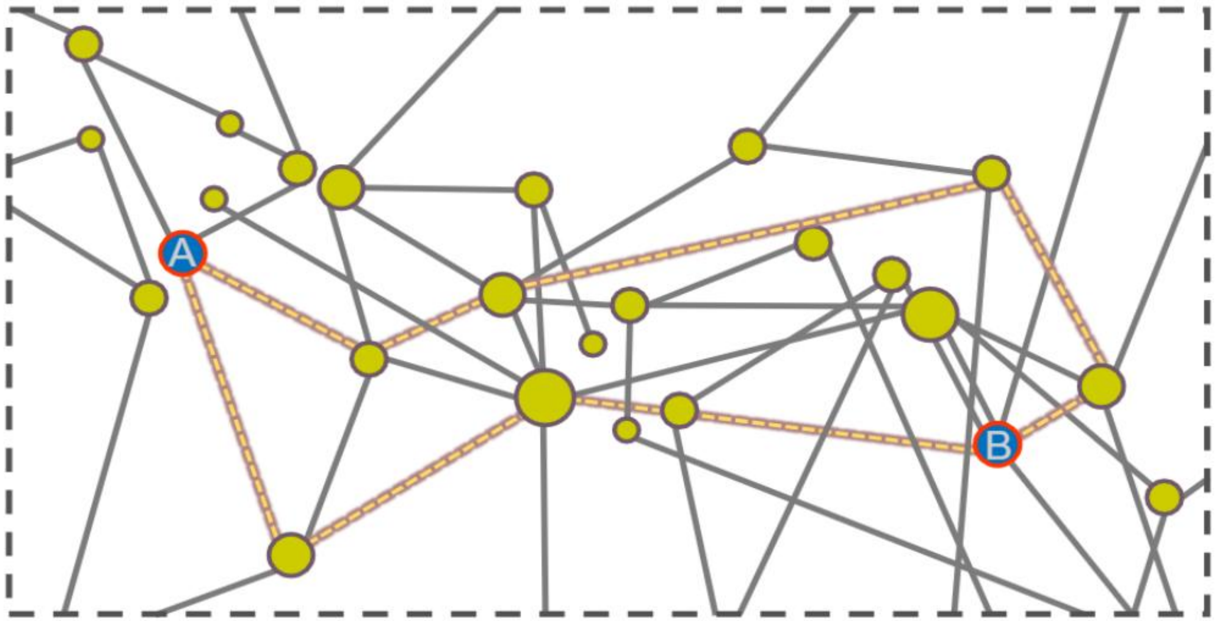
Limits of network quantum communications

Can we beat repeater chains? Yes: quantum networks



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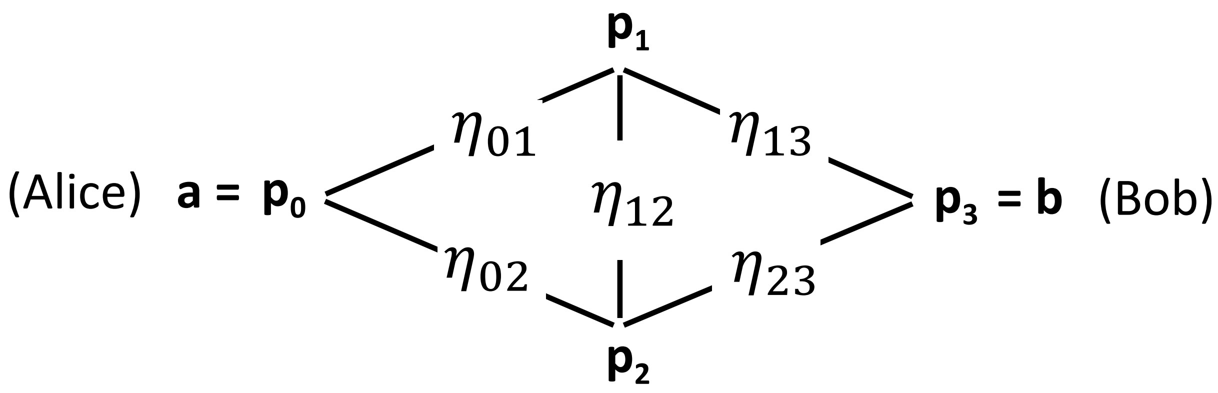

Alice and Bob can communicated following two basic routing strategies:
Single-path or Multi-path (flooding)

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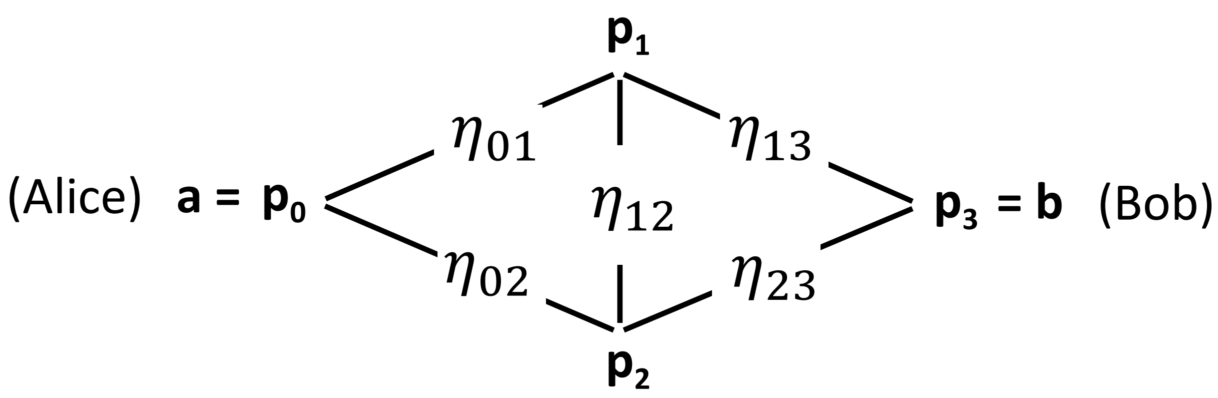

Alice and Bob can communicated following two basic routing strategies:
Single-path or Multi-path (flooding)

Corresponds to a good repeater-chain in the network

More powerful

Limits of network quantum communications

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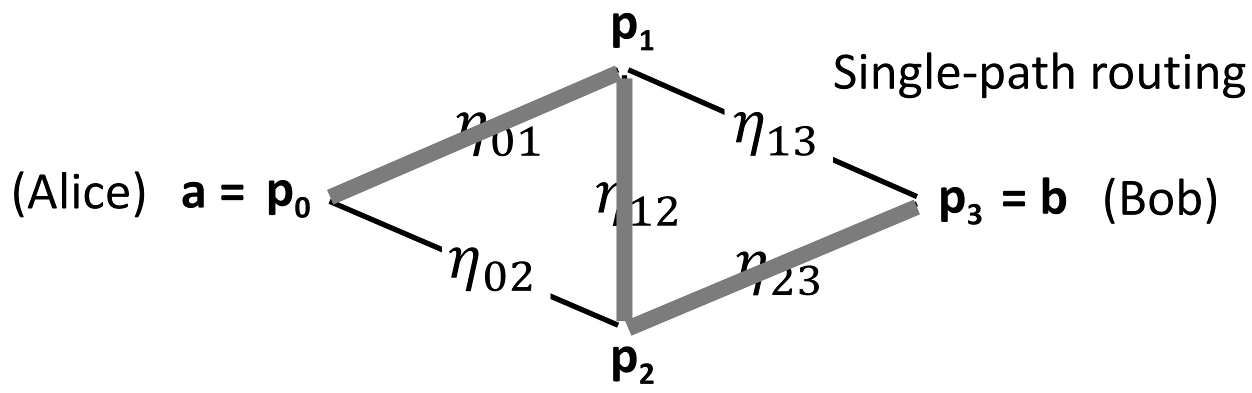

- Transmissivity of a path ω

$$\eta_{\omega} = \min_{(\mathbf{x},\mathbf{y})\in\omega} \eta_{\mathbf{xy}}$$

- Maximize over all paths $\Omega = \{\omega\}$

$$\tilde{\eta} = \max_{\omega\in\Omega} \eta_{\omega}$$

➡ Single-path capacity is $K_{\text{s-path}} = -\log_2(1-\tilde{\eta})$

[Pirandola, *End-to-end capacities of a quantum communication network*, Communications Physics 2, 51 (2019)]

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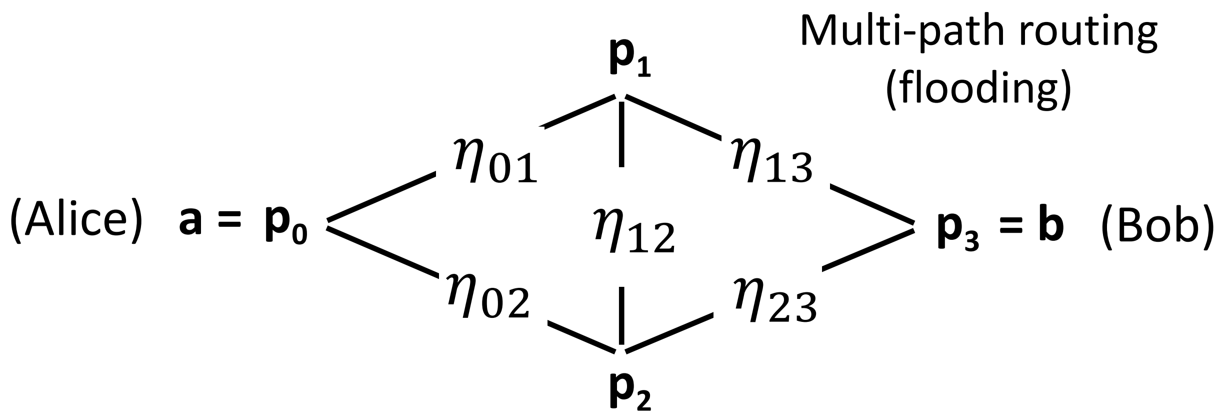

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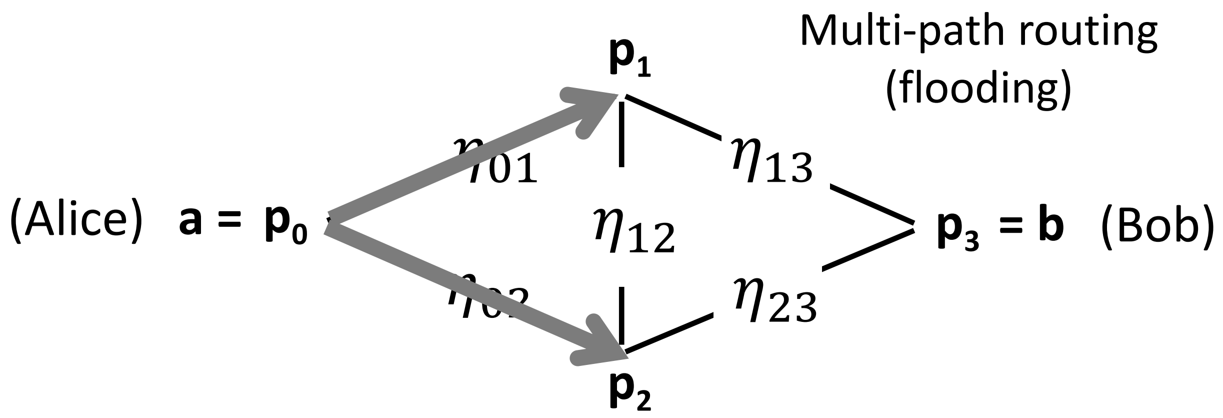

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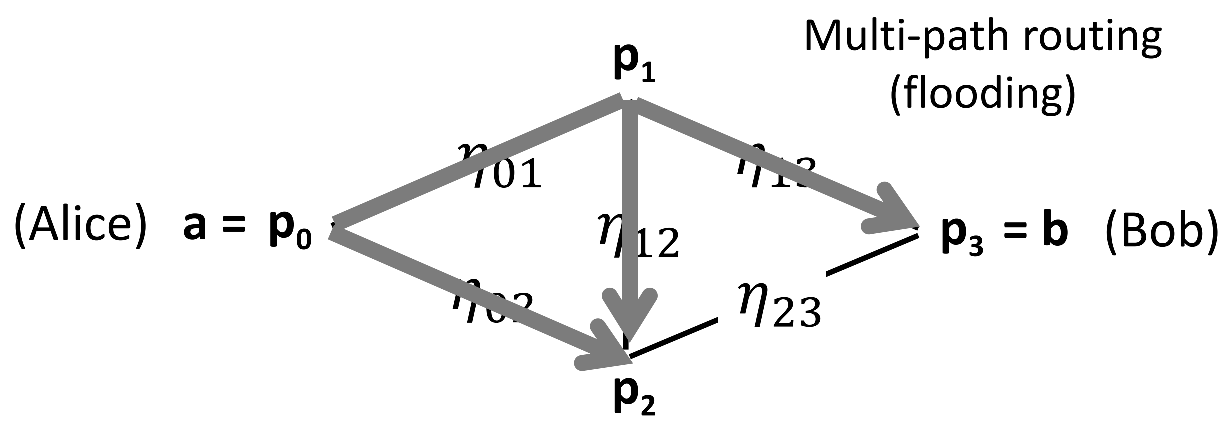

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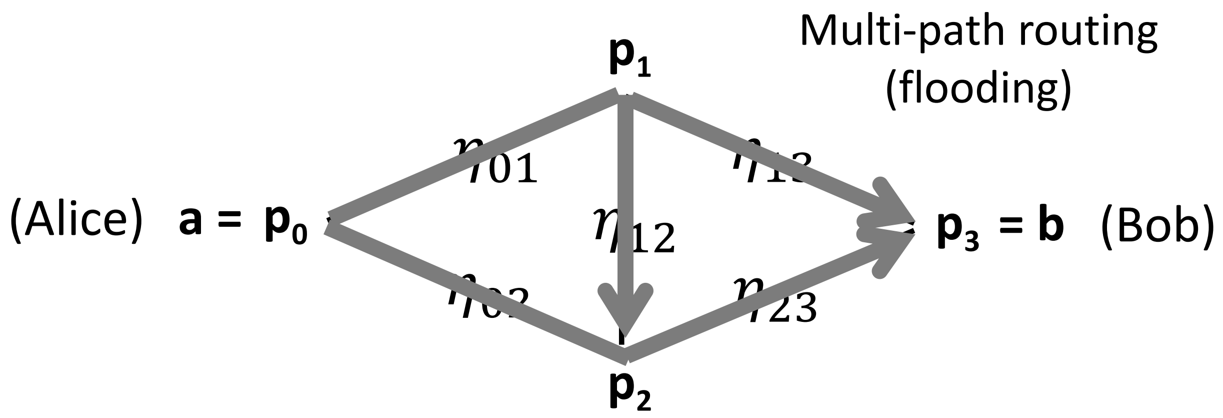

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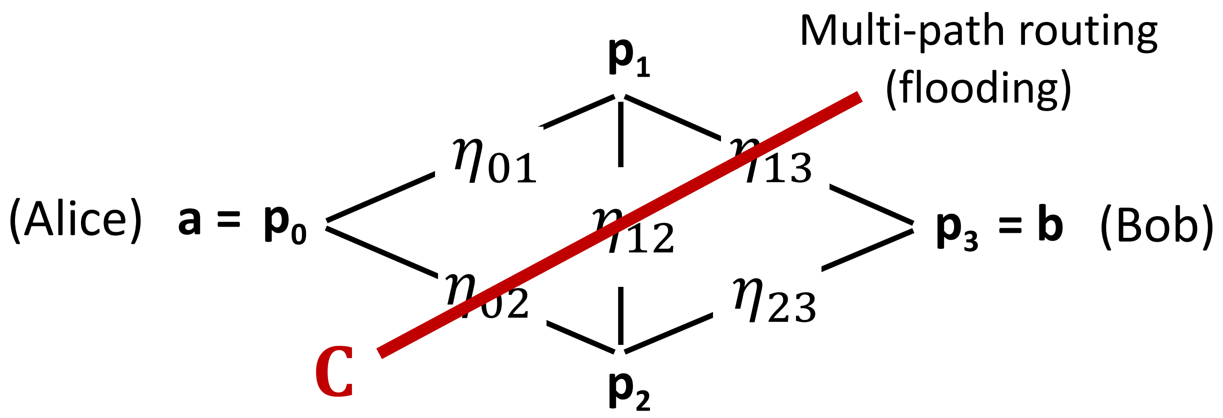

To compute capacity we extend max-flow/min-cut theorem from classical to quantum communications

Limits of network quantum communications

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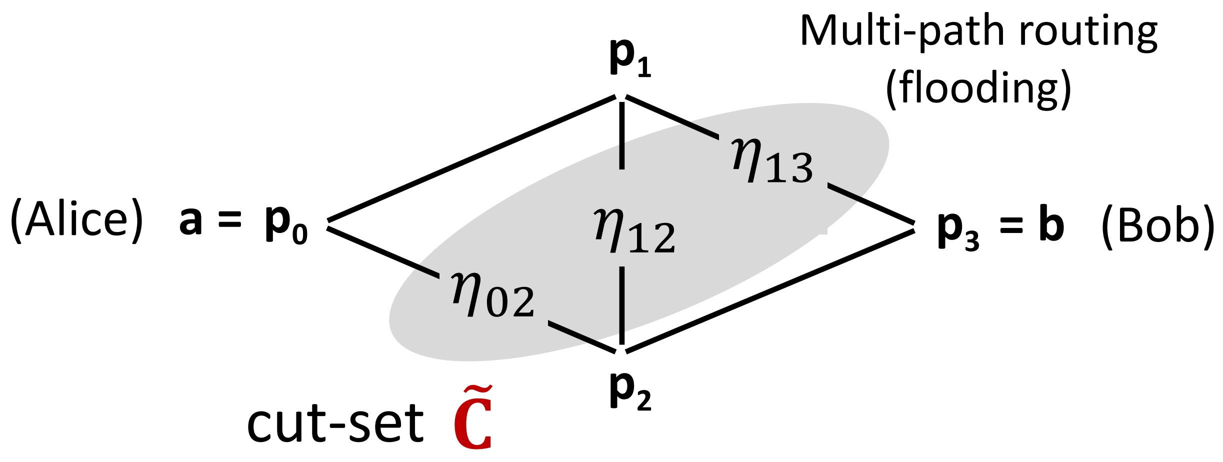

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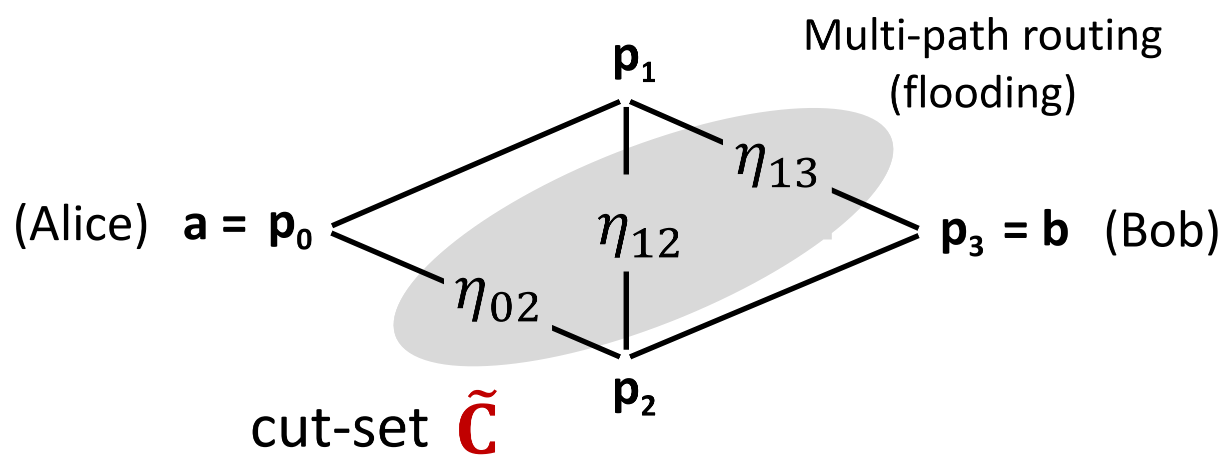


- Loss of the cut

$$l(C) := \prod_{(\mathbf{x},\mathbf{y})\in\tilde{C}} (1-\eta_{\mathbf{xy}})$$

- Loss of network

$$l(\mathcal{N}_{\text{loss}}) := \max_C l(C)$$

➡ Multi-path (flooding) capacity

$$K_{\text{m-path}} = -\log_2 l(\mathcal{N}_{\text{loss}})$$

[Pirandola, *End-to-end capacities of a quantum communication network*, Communications Physics 2, 51 (2019)]

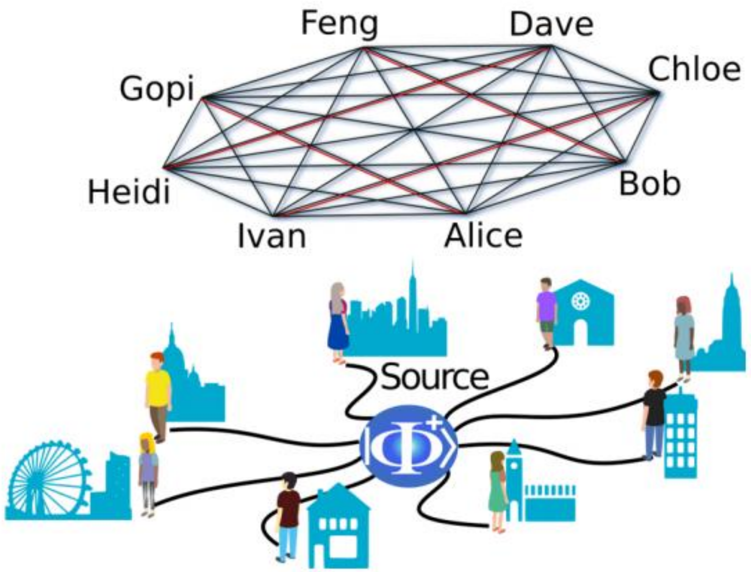
Limits of network quantum communications

Can we beat repeater chains? Yes: quantum networks

$$K_{\mathrm{m-path}} \geq K_{\mathrm{s-path}}$$

Idea exploited in an experimental work

[N. R. Solomons, A. I. Fletcher, D. Aktas, N. Venkatachalam, S. Wengerowsky, M. Lončarić, S. P. Neumann, B. Liu, Ž. Samec, M. Stipčević, R. Ursin, S. Pirandola, J. G. Rarity, S. K. Joshi, arXiv:2101.12225; PRX Quantum (2022)]



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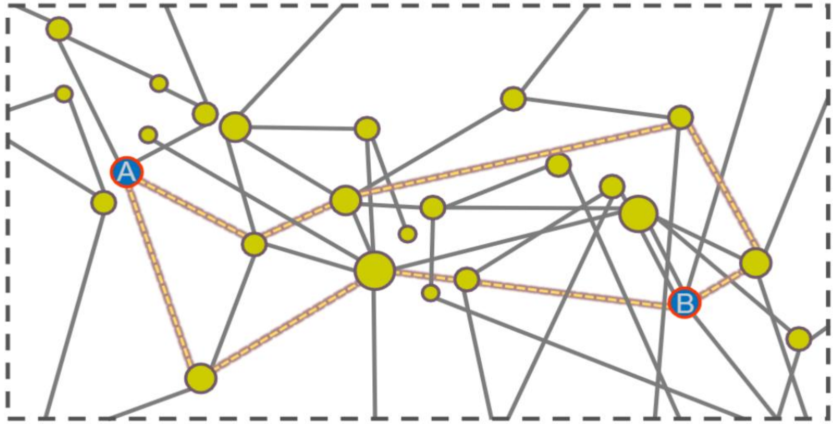
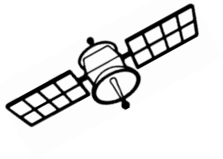
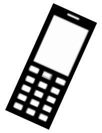
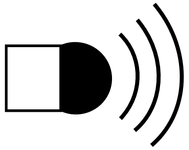
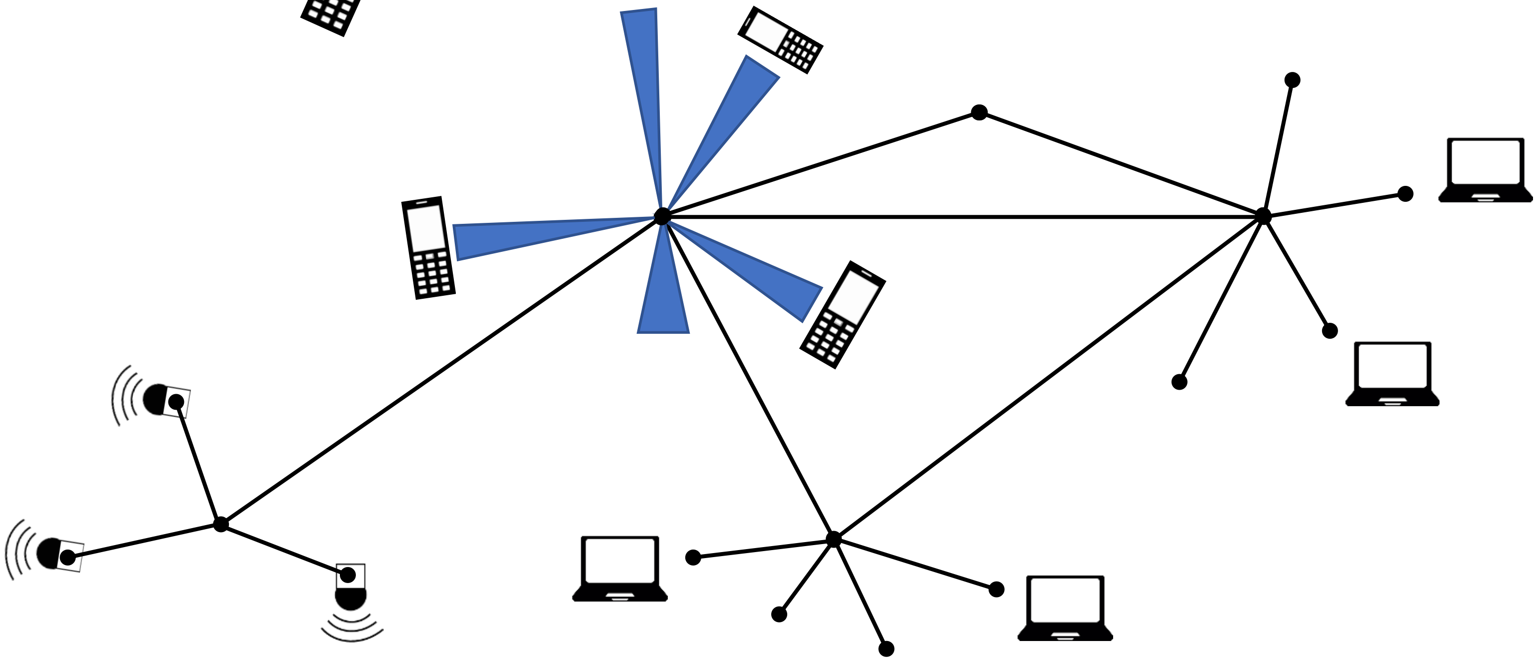
Quantum network architecture



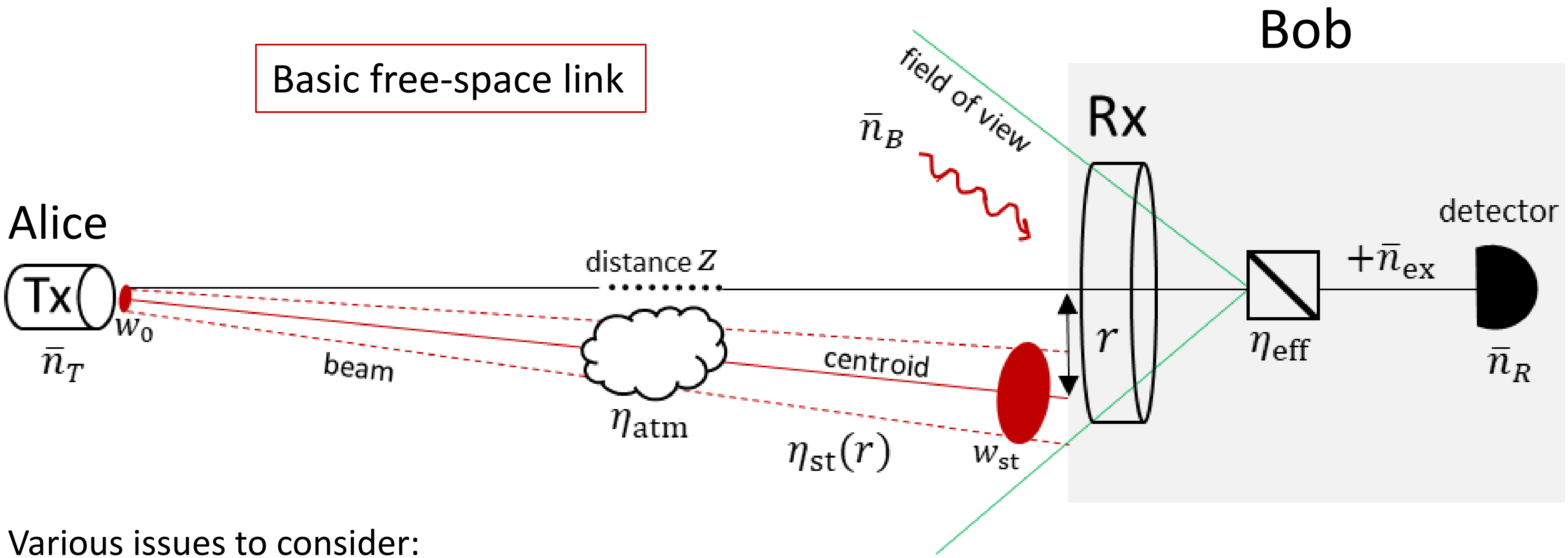
Theory well developed for wired connections (optical fibres)

Need to integrate free-space links

- Satellite links (global quantum network) 
- Local wireless sub-networks with mobile devices 
- Sensors (IoT) 



Limits and security of free-space quantum communications

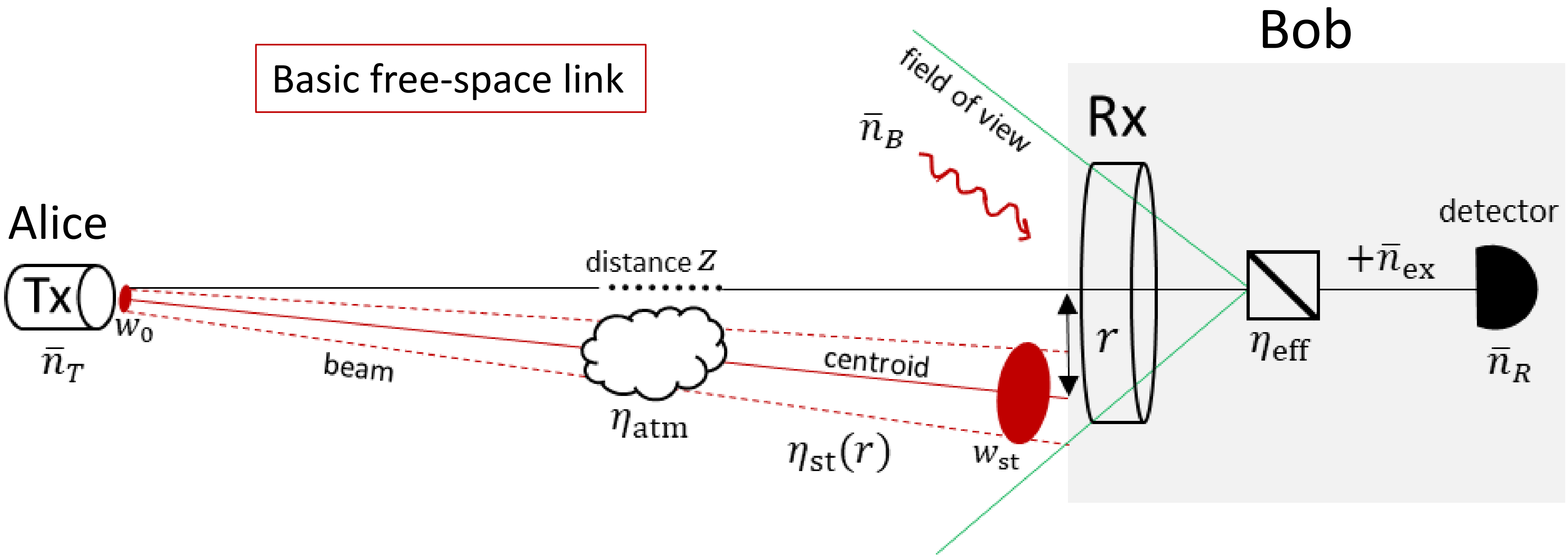


Various issues to consider:

- Free-space diffraction
- Atmospheric extinction (Beer-Lambert model)
- Beam deflection and pointing errors
- Weak turbulence (beam spreading and wandering; H-V model)
- Background thermal noise (sky brightness)
- Setup imperfections (<1 efficiency, electronic noise etc.)

[Pirandola, *Limits and security of free-space quantum communications*, Physical Review Research 3, 013279 (2021)]

Limits and security of free-space quantum communications



η	max transmissivity
σ^2	variance due to fading
$\bar{n}$	total noise

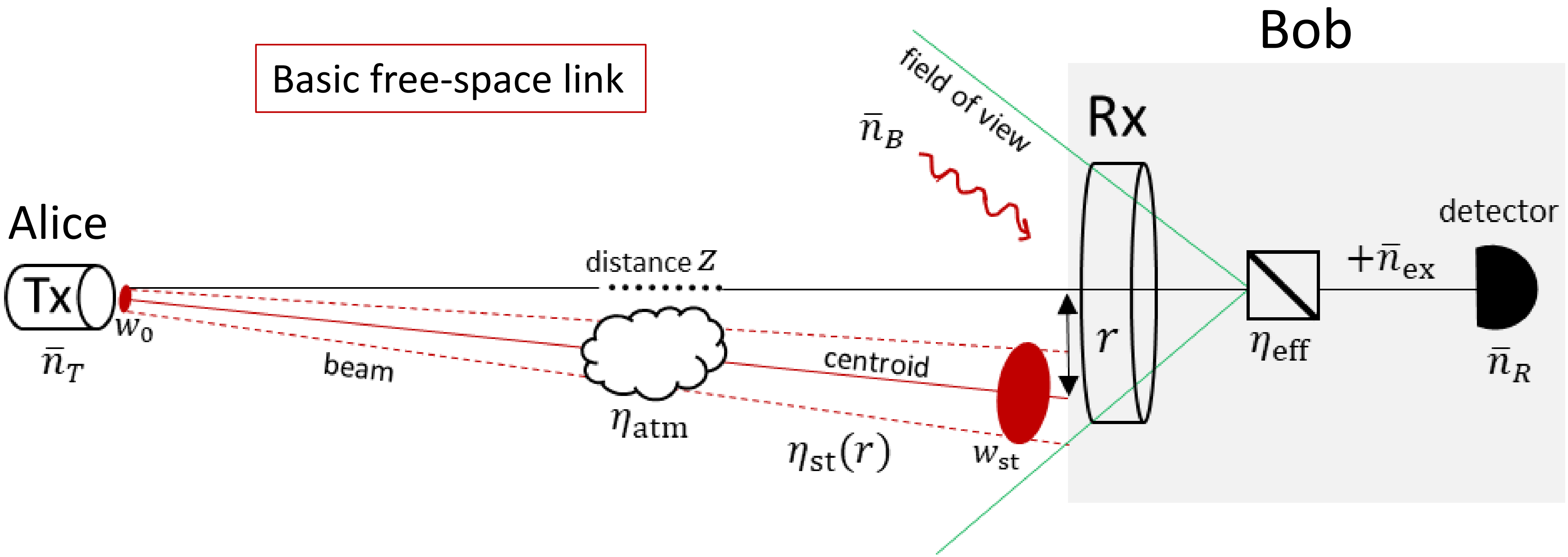
Free-space limit for q. comms

$$K_{free} \leq -\Delta(\eta, \sigma) \log_2(1-\eta)$$

fading correction

[Pirandola, *Limits and security of free-space quantum communications*, Physical Review Research 3, 013279 (2021)]

Limits and security of free-space quantum communications



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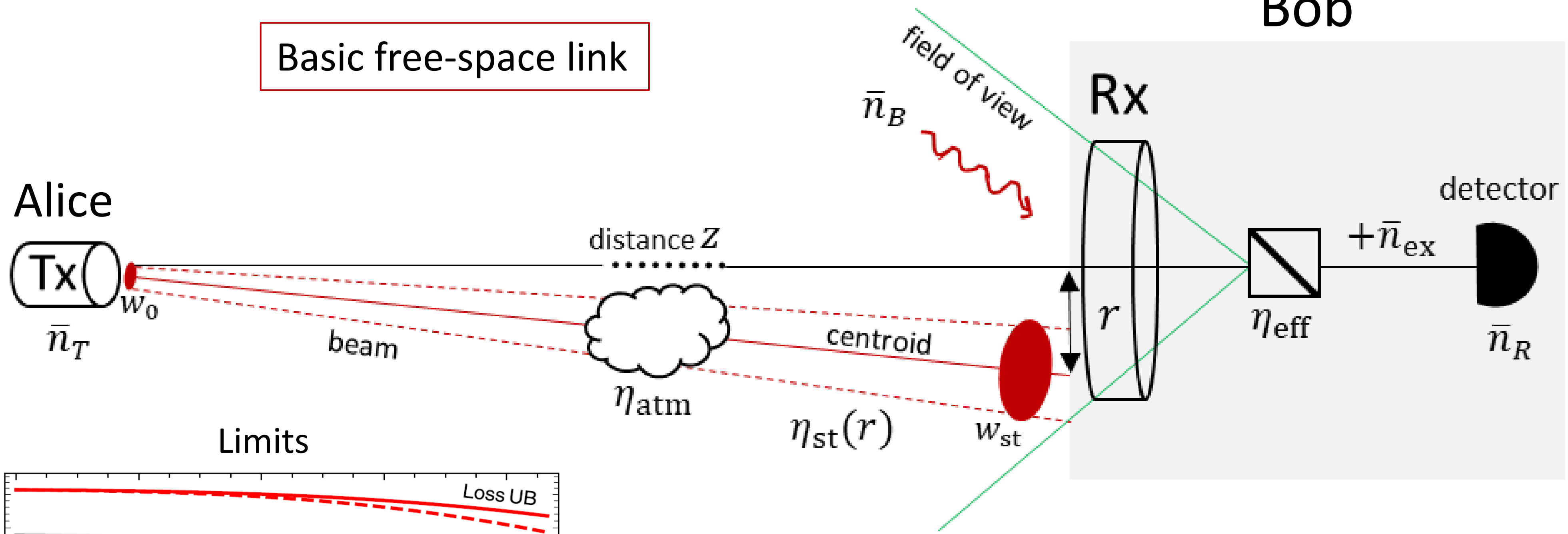
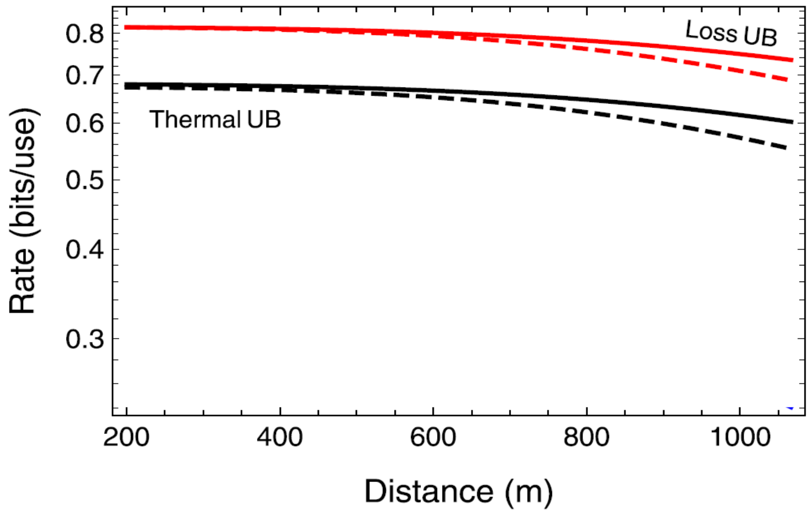
Limits and security of free-space quantum communications

Basic free-space link



Limits



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[Pirandola, *Limits and security of free-space quantum communications*, Physical Review Research 3, 013279 (2021)]

Satellite versus repeater chain

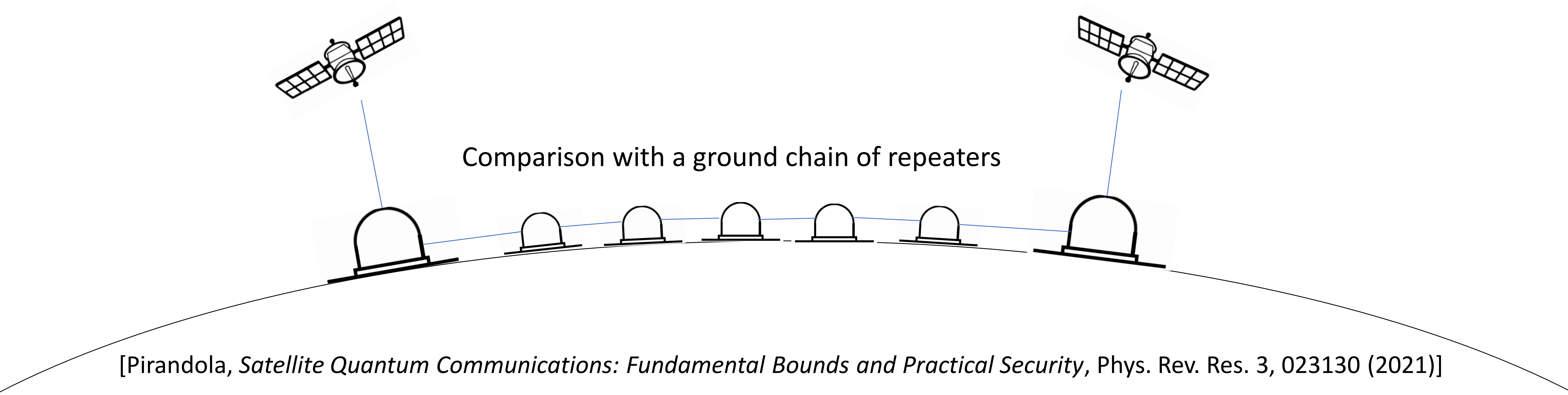
Consider a sun-synchronous satellite (almost circular orbit) which crosses the zenith points of two remote ground stations

Daily rate of secret bits that the satellite can distribute between the two stations

	Night	Day
Downlink (530 km)	$\approx 6.13 \times 10^7$	$\approx 6.08 \times 10^7$
Uplink (103 km)	$\approx 1.69 \times 10^7$	$\approx 1.09 \times 10^7$

*Clock 10 MHz

Comparison with a ground chain of repeaters



[Pirandola, *Satellite Quantum Communications: Fundamental Bounds and Practical Security*, Phys. Rev. Res. 3, 023130 (2021)]

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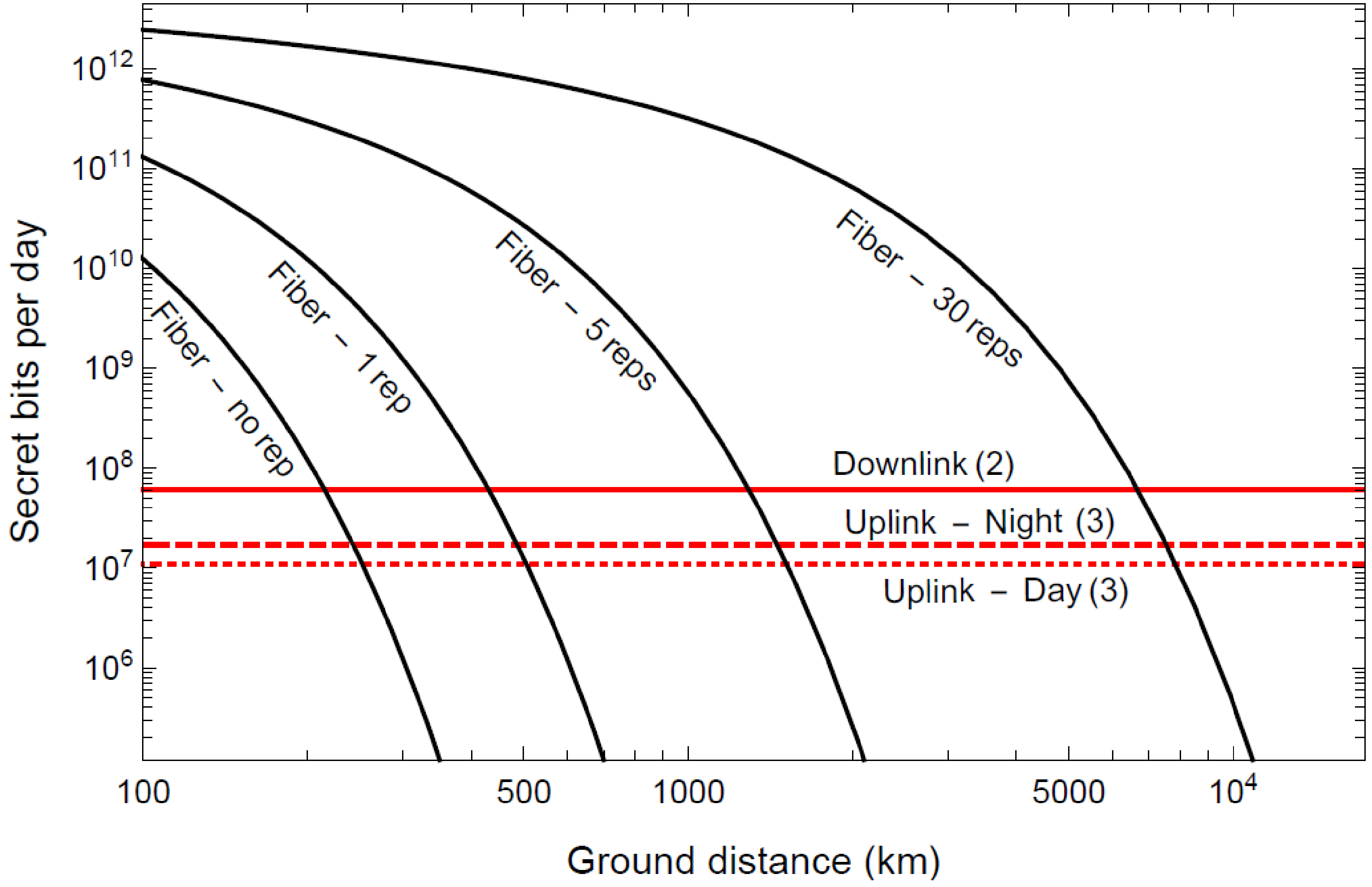

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Thx for your attention