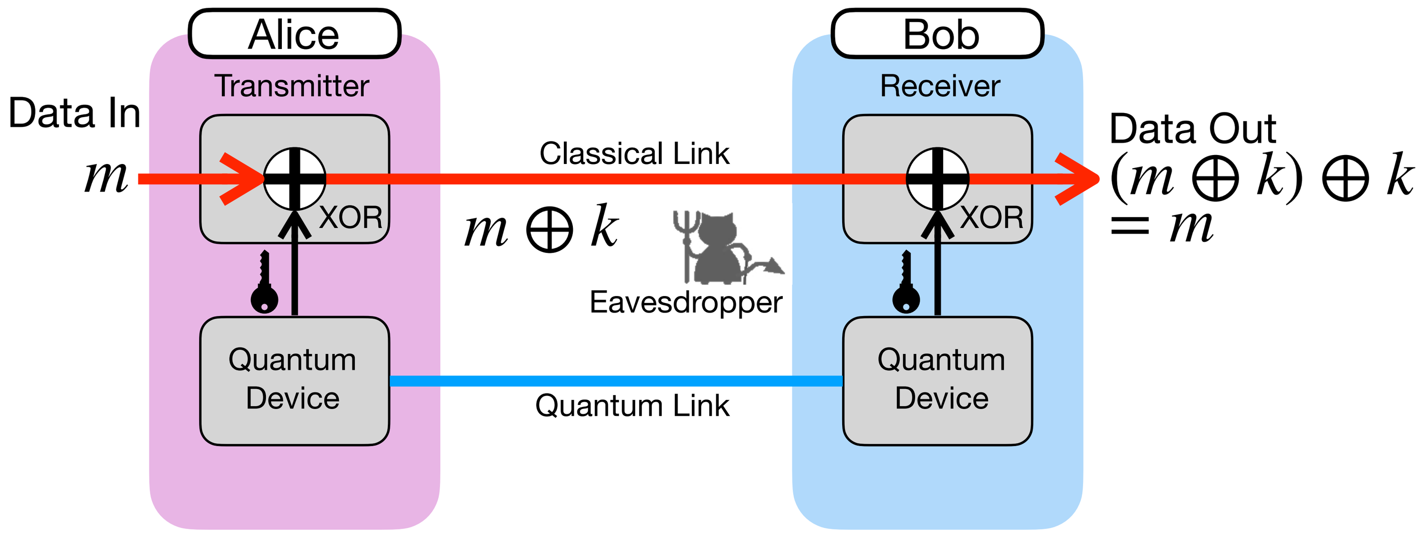
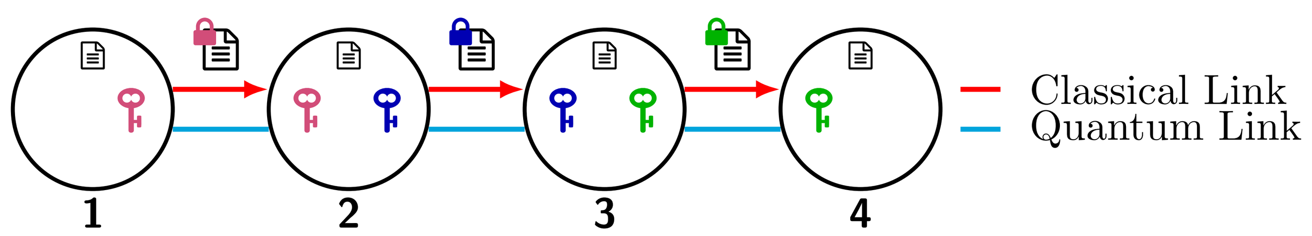
Tandem Queue Decomposition: A Throughput-Optimal Routing Policy for Quantum Key Distribution Networks

Shahbaz Akhtar*, Krishnakumar G*, Vishnu B*, Abhishek Sinha†

Introduction



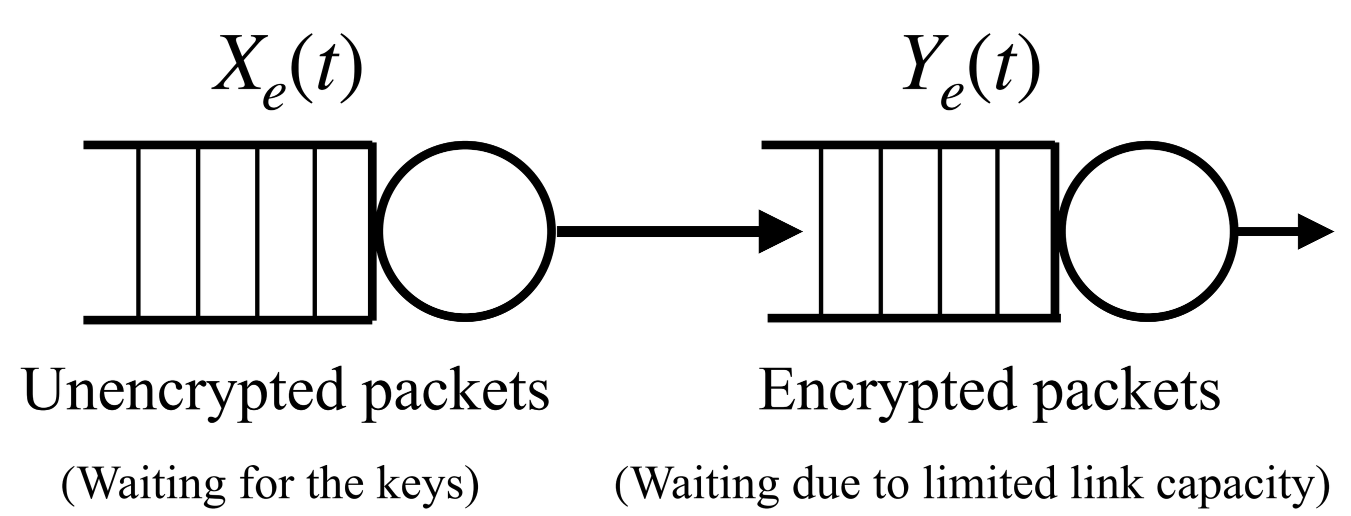
- Quantum key distribution (QKD) enables two geographically separate communicating parties to exchange symmetric private keys, whose information-theoretical security is guaranteed by the fundamental principles of quantum mechanics
- Top figure shows Alice and Bob equipped with a quantum link and classical link exchanging a sufficiently long quantum key k through quantum link to encrypt the message m that is sent over the classical link
- We consider trusted node architecture where nodes are assumed to be secure and only the links can be compromised . The architecture is shown in the figure below



Model

- We consider a network with arbitrary topology, represented by a graph $\mathcal{G}(V, E)$, where V denotes the set of nodes ($|V| = n$) and E denotes the set of edges ($|E| = m$)
- Physical link capacity is γ_e and quantum key generation rate at η_e. for edge e. Packet arrival is assumed to be i.i.d. across the time slots

Tandem Queue Decomposition



Associate Virtual Queues $\tilde{X}_e$ and $\tilde{Y}_e$ for every X_e and Y_e

Algorithm

Tandem Queue Decomposition (TQD) Policy at slot t

Require: Graph $\mathcal{G}(V, E)$, Virtual Queue lengths $\{\tilde{X}_e(t), \tilde{Y}_e(t), \forall e \in E\}$ at the slot t

1: **(Edge-Weight Assignment)** Assign each edge $e \in E$ a weight $W_e(t) \leftarrow \tilde{X}_e(t) + \tilde{Y}_e(t)$.

2: **(Route Assignment)** For all incoming packets, compute a Min-Weight Route in the weighted graph $\mathcal{G}(V, E)$.

3: **(Key Generation)** Generate symmetric private keys for every edge $e \in E$ via QKD and store them in key banks.

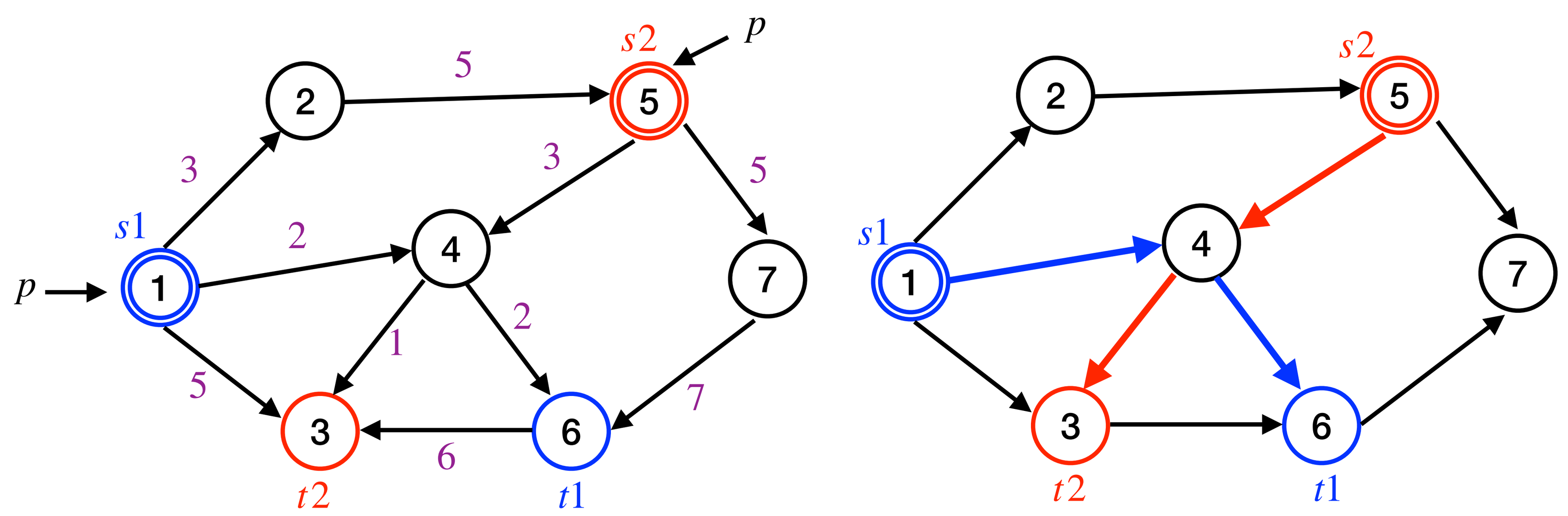
4: **(Encryption)** Encrypt the data packets waiting in the physical queue X_e with available keys in the key bank and internally transfer the encrypted packets to the downstream queue Y_e for every edge $e \in E$.

5: **(Packet Forwarding)** Forward the encrypted packets from queue Y_e to the queue $X_{e'}$ for every edge e according to some packet scheduling policy (ENTO [3] , FIFO, etc.). Here e' is the next edge in the assigned route of a packet.

6: **(Decryption)** Decrypt the data packets received at physical queue X_e for every edge e using the symmetric key generated earlier via the QKD process.

7: **(Updating the Virtual Queues)** Update the virtual queues assuming a precedence- relaxed system, i.e.,

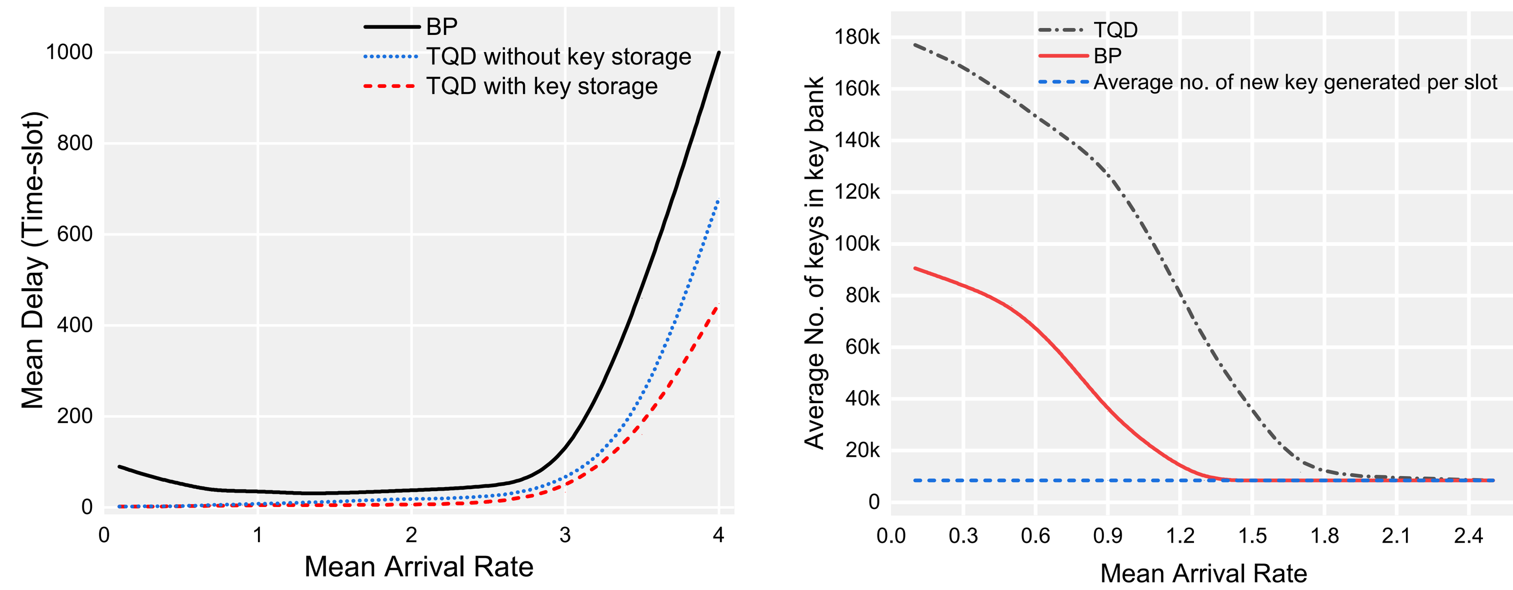
$$\tilde{X}_e(t+1) \leftarrow \left(\tilde{X}_e(t) + A_e^{\pi}(t) - \kappa_e(t)\right)^+, \forall e \in E$$
$$\tilde{Y}_e(t+1) \leftarrow \left(\tilde{Y}_e(t) + A_e^{\pi}(t) - \gamma_e(t)\right)^+, \forall e \in E.$$



Edge-Weight Assignment

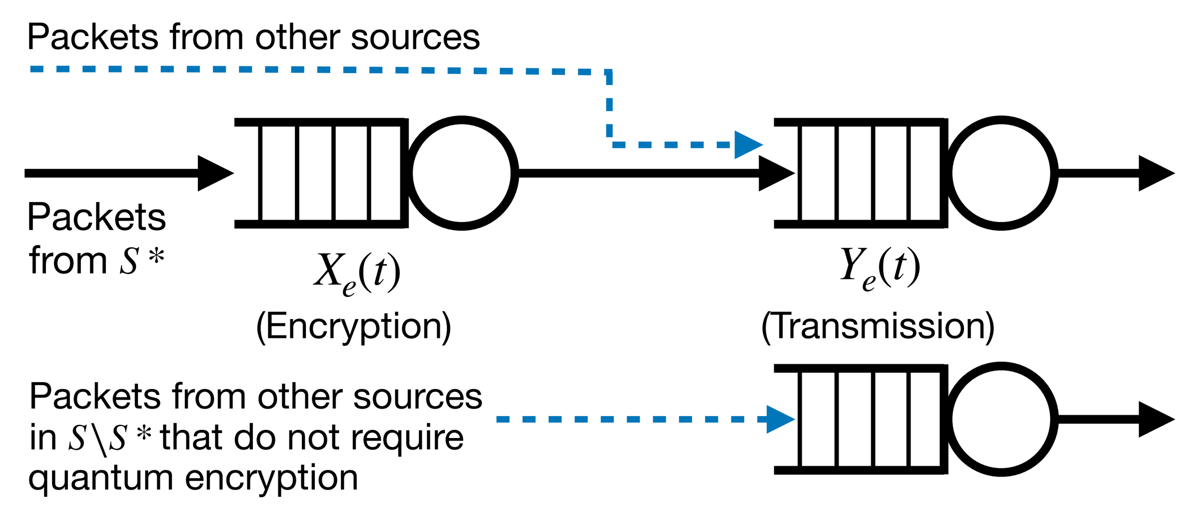
Route Assignment

Numerical Results



- Left figure shows the variation of mean packet delay as a function of the mean arrival rate λ for unicast flow
- Backpressure performs poorly due to small congestion gradients and poor in-network residual key management at lower & higher arrival rates respectively

Extension to Multilevel Security



- Denote $S*$ to be the group of users requiring quantum encryption. In practice, some packets $S \backslash S*$ might not require quantum encryption. Those skip the X_e and join the Y_e queues directly
- $E_S \subseteq E$ be the set of edges equipped with the QKD module. The shortest path is computed on the induced graph $\mathcal{G}(V, E_S)$ for packets originating from some source in the set $S*$
- Packets from other sources are routed along the edges that lack QKD module. We call this extension to be e-TQD

References

- Vishnu B and Abhishek Sinha. Fast and secure routing algorithms for quantum key distribution networks. *In 2022 14th International Conference on COMmunication Systems NETworkS (COMSNETS)*
- Abhishek Sinha and Eytan Modiano. Optimal Control for generalized Network Flow Problems. *IEEE/ACM Transactions on Networking* 2018.
- David Gamarnik. Stability of adaptive and non-adaptive packet routing policies in adversarial queueing networks. *In proceedings of 31st annual ACM symposium on Theory of Computing* 1999.

*Indian Institute of Technology Madras, †Tata Institute of Fundamental Research