

# Center for Quantum Networks

*NSF Engineering Research Center*



## Thrust 1- Quantum Network Architecture

**Don Towsley**

*Thrust 1 Lead*

University of Massachusetts- Amherst

[towsley@cs.umass.edu](mailto:towsley@cs.umass.edu)

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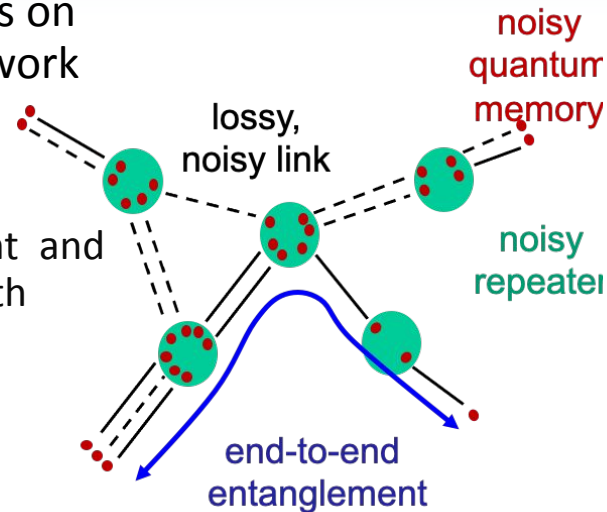
# Thrust 1 Architecture - Overview

**Goal:** Design quantum network (Q-net) architecture that builds on subsystems developed in Thrust 2. This includes design of network protocols, resource allocation algorithms and network management tools that support entanglement distribution.

**Challenges:** Understanding performance limits in a noisy environment and the development of an architecture, algorithms, and tools to deal with noise.

## Projects:

- Project A: Network architecture for entanglement distribution (Towsley, Guha, Englund)
- Project B: Hybrid network architectures (Rozpedek, Towsley, Guha)
- Project C: Routing in entanglement generation networks (Towsley, Guha)
- Project D: Quantum network tomography (Towsley, Bash, Montano)





# Thrust 1 Summary

## Main accomplishments:

- Development of a ZALM-based connectionless Q-network architecture
  - Simple to manage & understand
  - Allows access to rich set of classical network algorithms and protocols
- Design and evaluation of a hybrid (trapped ion-vacancy center) network architecture
- Routing in quantum networks
- Efficient characterization of quantum networks composed of Pauli channels



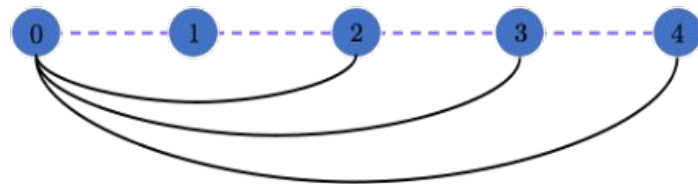
# Connectionless two-way Q-net architecture

**Question:** Can we achieve same ease of management as classical networks for two-way qnet architectures while keeping high rates?

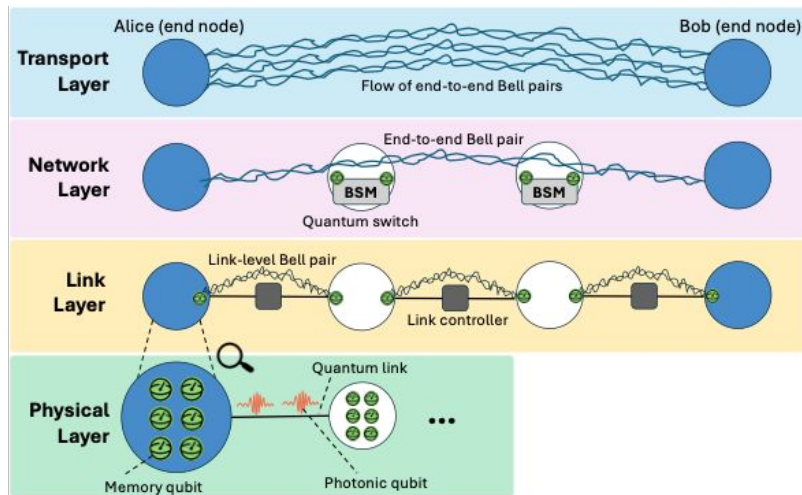
**Approach:** ZALM enabled sequential swapping

- Give link resources to flow **only** when request arrives to it
- Analogous to **datagram service** in classical Internet

No need for path reservation



Two-way Sequential Swapping



- { Quantum TCP
- { Routing and sequential swapping with store and forward
- { Heralded Bell pair generation (link-controller)
- { Quantum operations

# ZALM enabled 2-way Sequential Q-net architecture

## Goals:

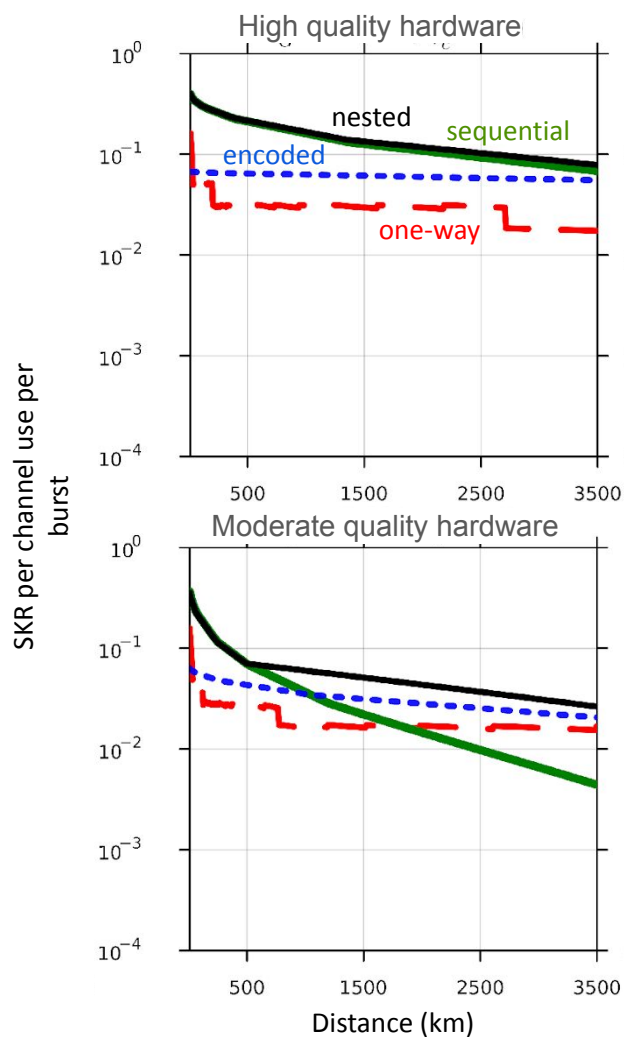
- Performance of ZALM based sequential 2-way architecture.
- Comparison to nested swap, one-way architectures

## Results:

- **Sequential swapping** performs as well as nested and outperforms one-way for high-quality hardware setting, and for short distances for moderate quality hardware
- Two-way schemes incurs lower costs

## Future directions:

- Performance analysis for networks under load; Label switching
- Evaluation using Oregon ZALM traces
- Optimal distillation and swapping scheduling
- Integration with hybrid satellite–terrestrial backbones



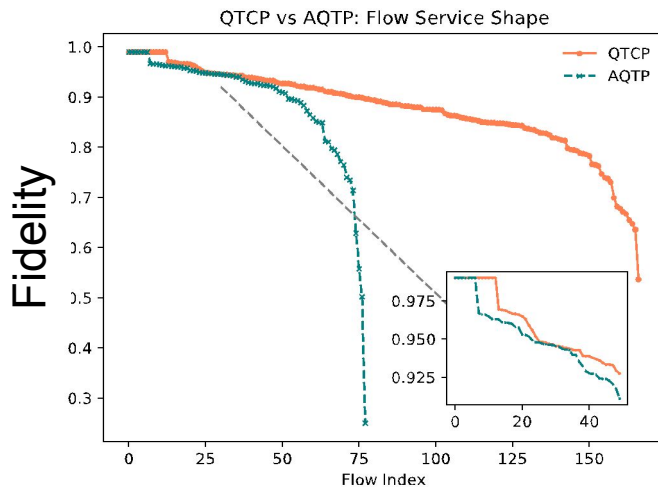
# Connectionless Q-net architecture

## Quantum TCP (proof of concept):

- Rate controller at end node
- Memory decoherence at link
- Memory decoherence management control

## Future directions:

- Resource allocation, routing - borrow & adapt from classical Internet
- Incorporate distillation, error correction
- Evaluation using Oregon ZALM traces



# Quantum Network Utility Maximization

**Goal:** Develop approach for providing fair, application specific performance to multiple applications.

**Challenge:** Mathematical tools developed for classical networks not well suited given presence of noise.

## Results:

- Developed optimization-based framework for allocating resources to diverse set of applications that trade off rate with fidelity.
- Developed distributed QPrimalDual, QPD-approx

## Future directions:

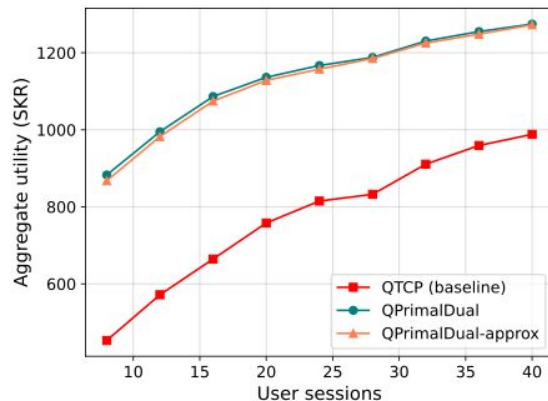
- Evaluate using Oregon ZALM traces with goal of evaluation on UMD testbed.

[IEEE JSAC 2024](#), [arXiv:2404.18818](#), [arXiv:2404.17077](#)

**Goal:**  $\max \sum \log U_r(R_r, F_r)$

s.t.  $\sum_{r:l \in r} R_r \leq d\alpha_l$  link capacity constraints

$F_r > F_r^*$  E2E fidelity constraints

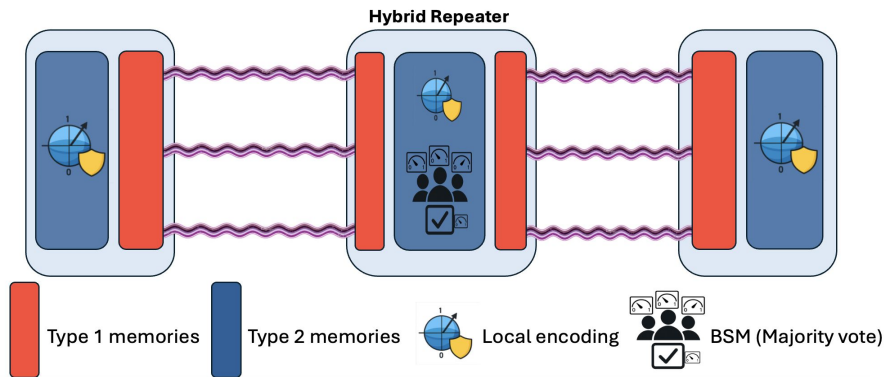


# Encoded hybrid repeater chain architectures

## Project Goals:

- Improve performance through hybrid architectures.
- Design, optimize hybrid architectures combining non-hybrid and hybrid repeaters.
- Develop new entanglement distribution policies.

**Challenges:** Matter-based memories support fast or high-fidelity two-qubit gates, presenting unique optimization challenges.



**Hybrid repeater combines type 1 – “Fast”  
and type 2 – “high fidelity ops.”  
platforms**

# Encoded hybrid repeater chain architectures

## Project Goals:

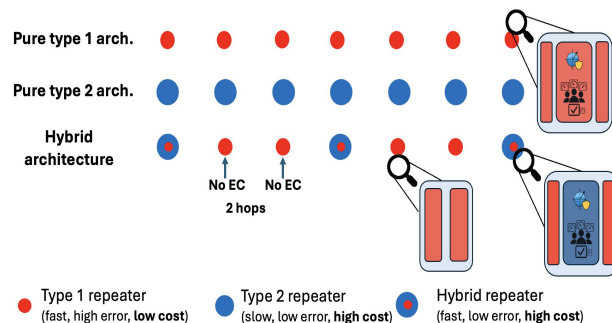
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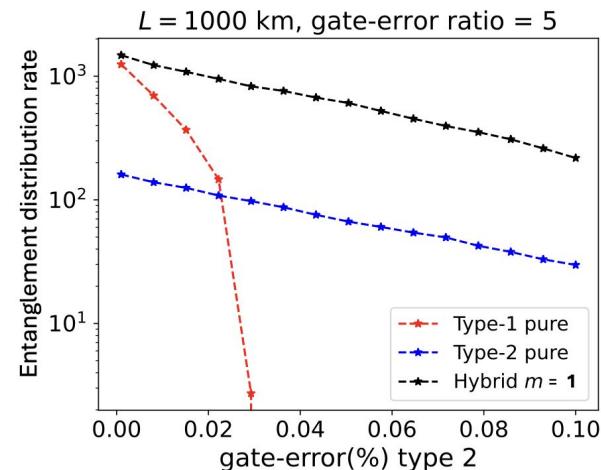
## Results:

- Hybrid schemes outperform monolithic schemes. Non-hybrid and hybrid repeater combinations outperform pure hybrid, monolithic architectures.
- “ASAP”(multiplexed version using distance-based ranking of links) scheduling of operations improves performance compared to nested/swap-all-at-once.
- Optimal number hops for each architecture; depends on hardware parameters.

Architectures combining Hybrid and Pure repeaters



**Hybrid architectures cost-effective.**  
(fewer error correction enabled nodes)

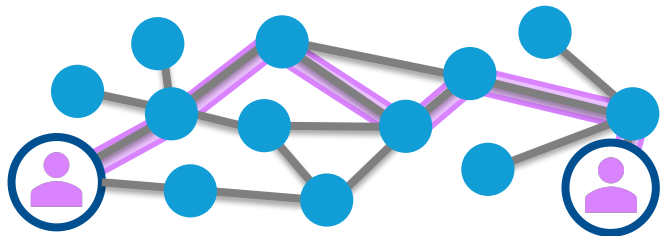


# Entanglement Routing over Networks with Time

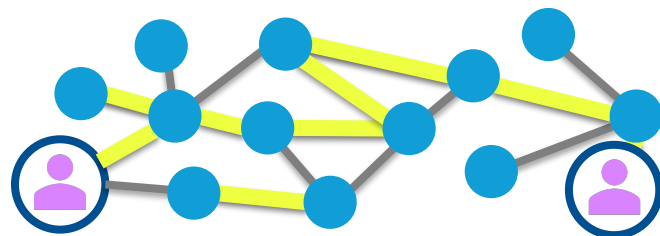
## Multiplexed Repeaters

**Question:** How do dynamic local link state knowledge routing protocols compare to path-based routing? Does time multiplexing or graph topology affect relative performances?

### Fixed Path Based Routing

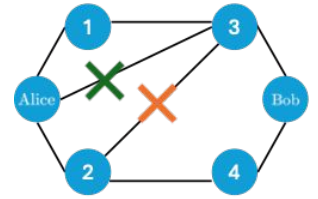


### Dynamic Local Link State Based Routing



**Setting:** Link level entanglement generation (LLEG) attempted  $k$  times.  
Enough quantum memories to accommodate multiple successes.  
Each link succeeds with probability  $p$ .  
BSMs succeed with probability  $q$ .  
Knowledge of nodes limited to network topology and outcomes of local LLEGs

# Entanglement Routing over Networks with Time Multiplexed Repeaters

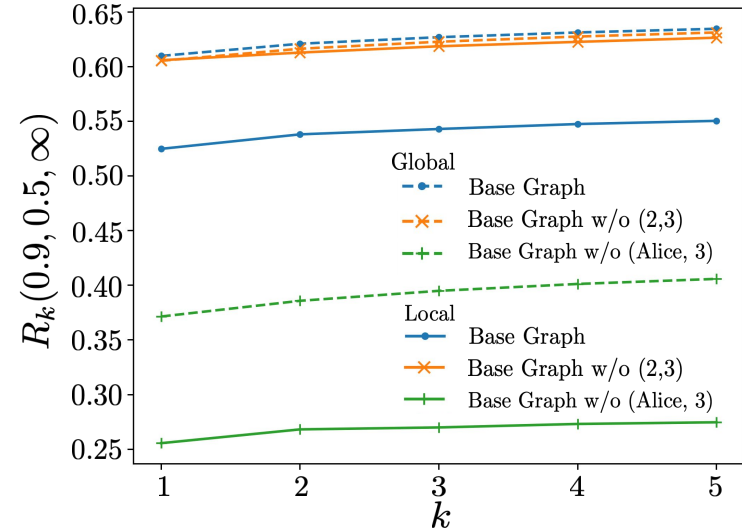


## Outcomes:

- *Dynamic* routing protocols are useful to handle probabilistic link generation.
- *Path-based* routing can prove more reliable, especially when paired with *time multiplexing*.

## Future directions:

- Improved local link state knowledge protocols should be introduced drawing on topology aware routing protocols
- Incorporate imperfect Bell pairs and refined decoherence models for realism
- Multi-user networks with competing demands
- Investigate smart GHZ distribution techniques



# Quantum network tomography (QNT)

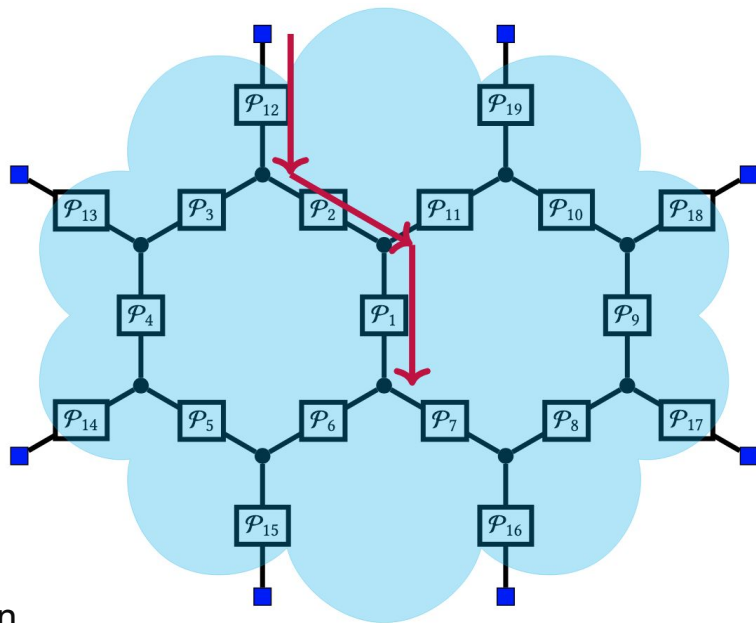
**Goal:** end-to-end link characterization in quantum networks

## System

- Quantum network with Pauli + loss channels (links)
- State Preparation and Measurement (SPAM) errors

## Approaches:

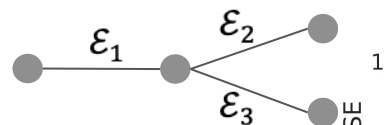
- Distribute bipartite/multipartite entanglement across network
- Perform different measurements at the end-nodes
- Combine statistics to identify parameters
- Select monitoring nodes for end-to-end measurements
- Quantify estimation error with Quantum Fisher Information



# QNT results and future directions

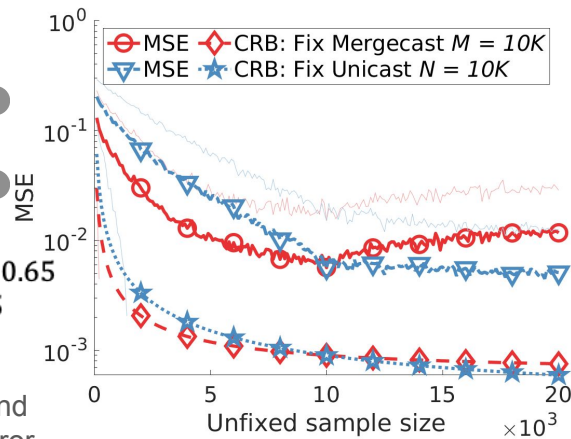
## Multipartite estimation

- Mergecast algorithm
- Arbitrary topology
- SPAM errors



Depolarizing  
 $p_1 = 0.5, p_2 = 0.75, p_3 = 0.65$   
SPAM errors  $s, m = 0.95$   
MSE for  $\varepsilon_1$

CRB - Cramer Rao Bound  
MSE - Mean squared error



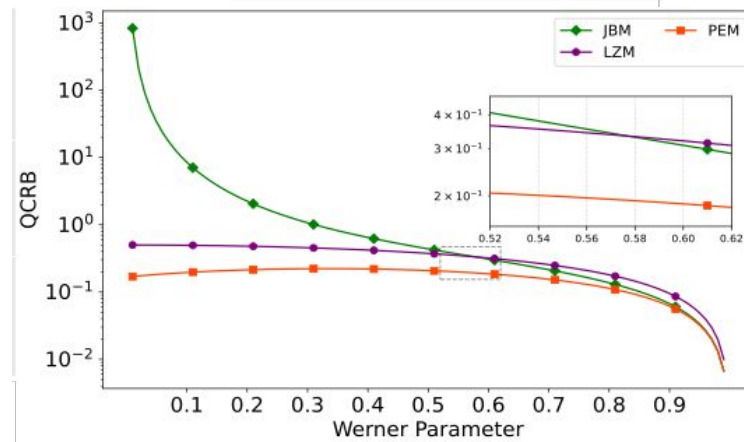
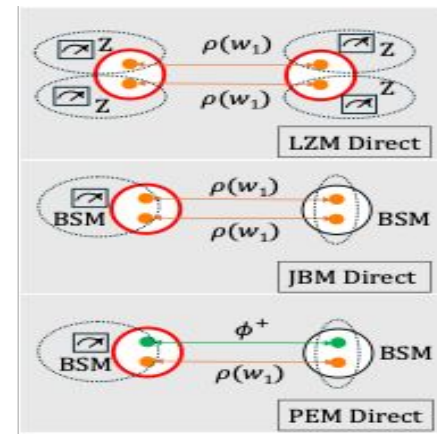
# QNT results and future directions

## Multipartite estimation

- Mergecast algorithm
- Arbitrary topology
- SPAM errors

## Monitor placement (CoQREATE)

- Measurement evaluation (QFIM)
  - Entanglement based vs. non-entanglement based
  - Perfect vs imperfect entanglement
- ILP formulation
  -



Manuscripts under review for all tasks

# QNT results and future directions

## Multipartite estimation

- Mergecast algorithm
- Arbitrary topology
- SPAM errors

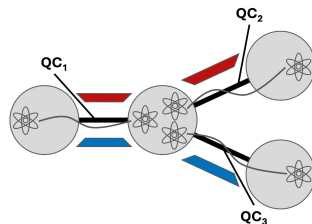
## Monitor placement (CoQREATE)

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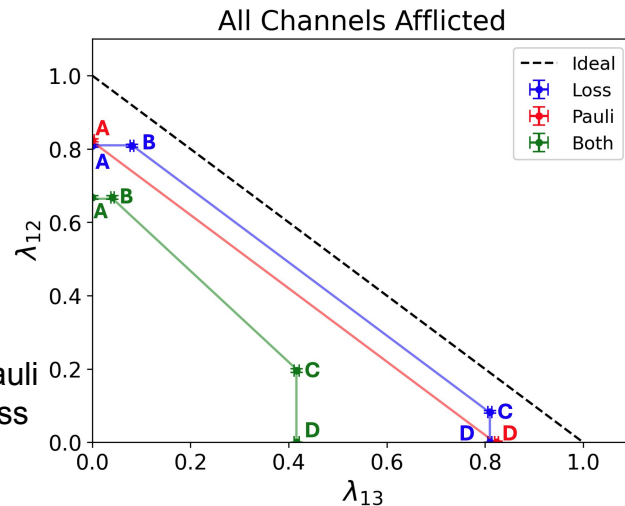
## Tomography with capacity region

- Estimate loss with capacity region
- Detect existence of Pauli errors

Manuscripts under review for all tasks



Blue: 15% loss  
Red: 10% loss + 10% Pauli  
Green: 10% loss + 10% Pauli (QC 1 and 2), QC3 30% loss + 30% Pauli



## Future directions:

- Test on UMd testbed, Oregon lab
- Adapt to support sensing on connectionless networks
- Consider impact of gate noise

# Thrust 1 Integration Across Center

**EWD:** Participation in CQN Winter School; Towsley introduced seminar on distributed quantum computing.

**DCI:** Student rotations through UMass ACQuIRE Lab (Arizona, Northern Arizona University, Trinity College). One REU & one undergraduate honors thesis.

**Thrust 2:** Collaboration on hybrid networks that include ZALM sources, trapped ion and vacancy center repeaters, and on Q-network tomography.

**Thrust 4:** Collaboration on quantum security

**IE:** Customized Research w/ Diamond Members:

- Cisco w D. Towsley on quantum data center networks
- L3Harris w B. Bash on secure communications

Close interactions with ARO MURI on quantum network science, DOE on development of quantum TCP.

Participation in IETF

# Thrust 1 Summary

## **Main accomplishments:**

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- Development of hybrid quantum network architectures
- Routing in quantum networks
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# Year 5-10 Major Milestones

