Quantum Compute-Enabled Wireless Networks

Cosener's Multi-Service Networks Workshop

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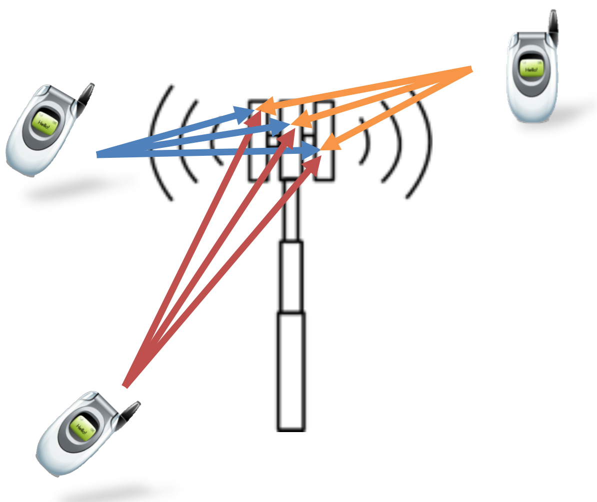
Shift to Computational Problems *in support of* Wireless Networks

- **For key subsystems,** best performance is **highly compute-intensive** and under **tight time constraints**

- **Therefore:** Shift from pure wireless → **best computational structures** to support wireless

  - **Requires:** Systems, Computer Architecture, and Wireless Communications **Co-Design**

Massive MIMO Detection



- ***Linear Detectors*** offer **low complexity,** but **highly suboptimal throughput:**

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

- ***Maximum Likelihood (ML) Detectors*** **maximize throughput,** but are **computationally complex,** have a **sequential tree search structure**

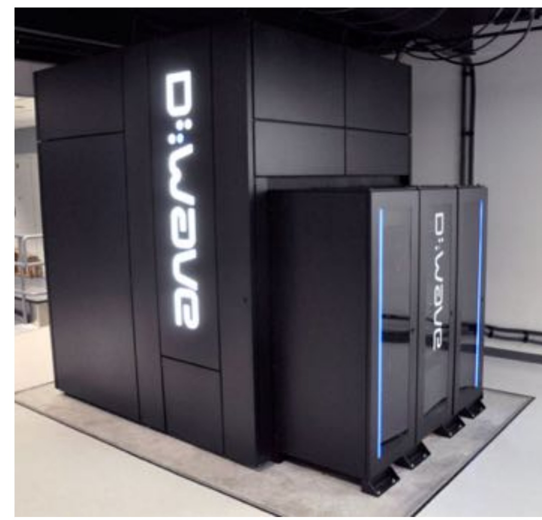
Data rate:	BPSK	QPSK	16-QAM	Complexity (Visited Nodes)
Users × Base Station Antennas:	12×12	7×7	4×4	≈ 40 (feasible)
	21×21	11×11	6×6	≈ 270 (borderline)
	30×30	15×15	8×8	$\approx 1{,}900$ (unfeasible)

(Feasibility for Intel Skylake Core i7 Architecture)

Quantum Computation for Mobile Networks

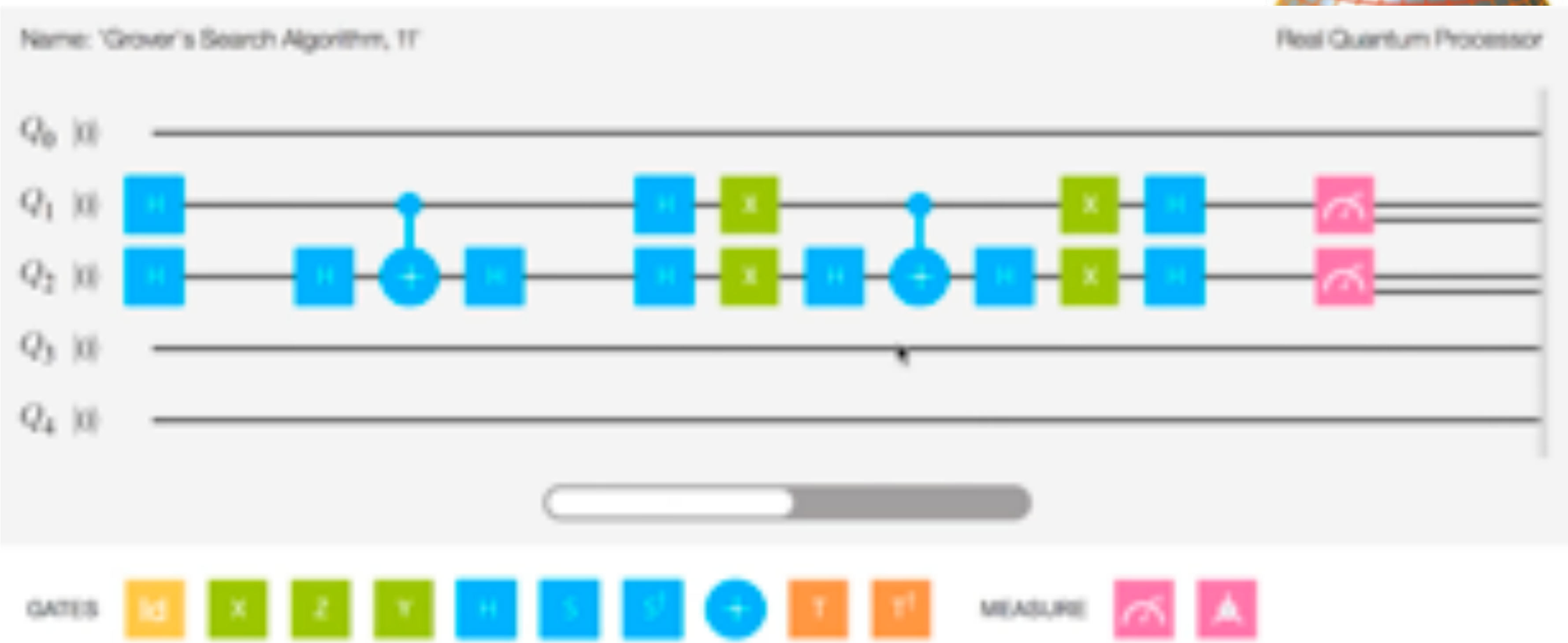
- ***Centralized Radio Access Network* architecture:** Move physical layer processing from base stations to central location (datacenter)
  - **Advantage** of aggregating multiple base stations' processing

- **Medium-term (10 year)** case for quantum computation in the datacenter
  - **Goal**: **High performance,** tractability on today and tomorrow's quantum computers
  - **New collaboration** with NASA Ames, engaging D-Wave and others

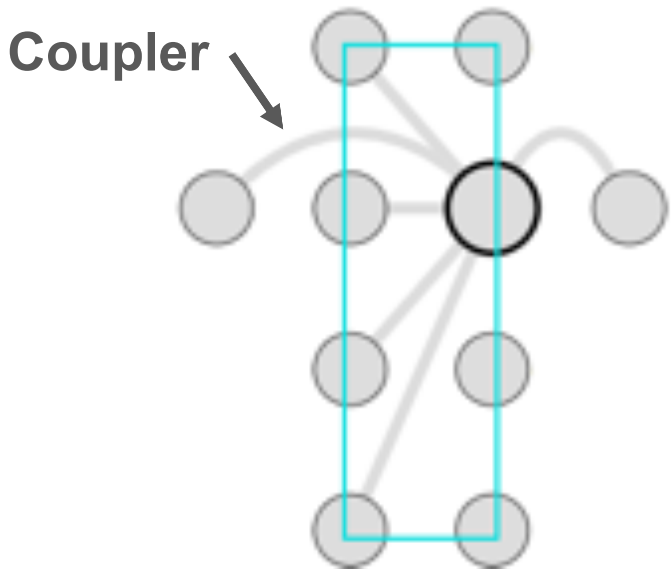


D-Wave 2000Q quantum annealer

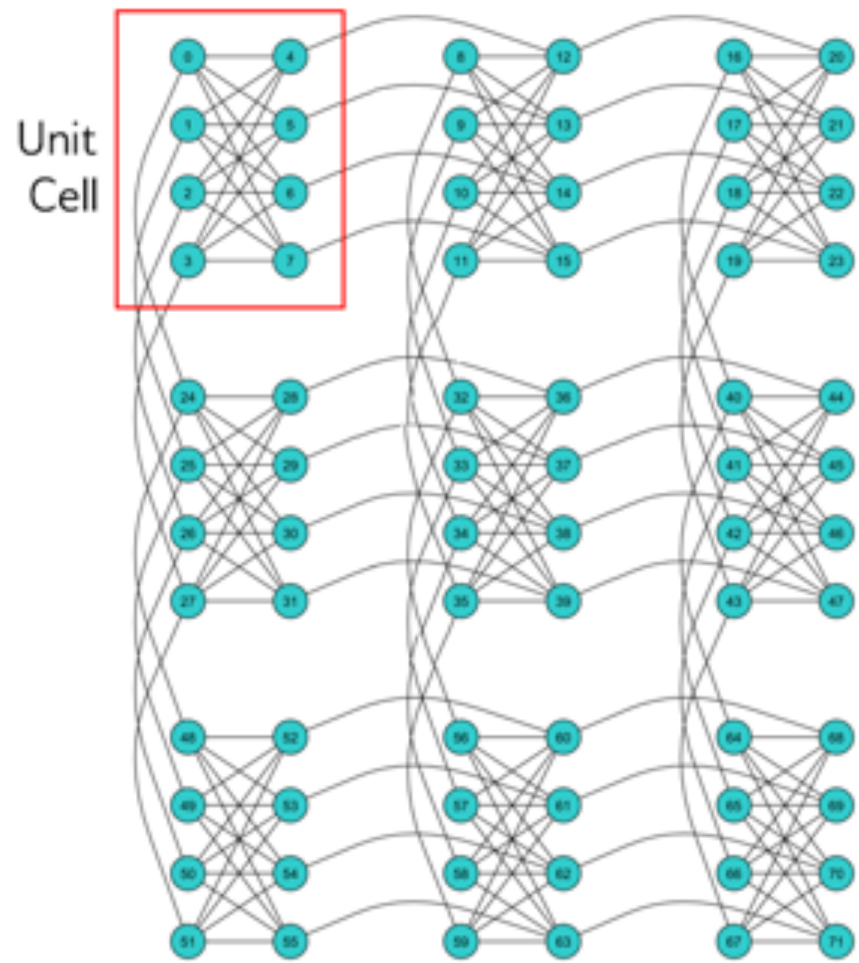
Qubits and Gate Model Computation



Quantum Annealer



Unit Cell

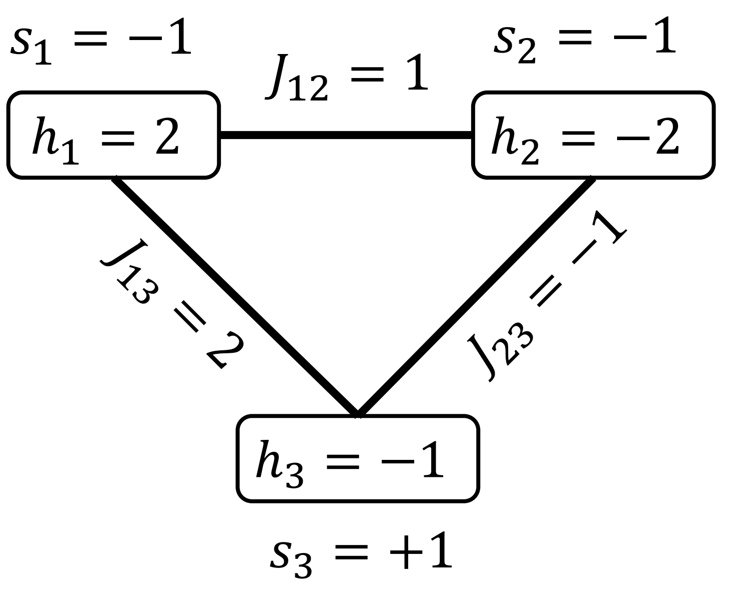


Quantum Annealers Solve the *Ising Model*

- Given graph $G = (V, E)$ with ***vertex weights*** h_i and ***edge weights*** J_{ij} find ***spins*** $s_i = \pm 1$ on each vertex that **minimize** energy function

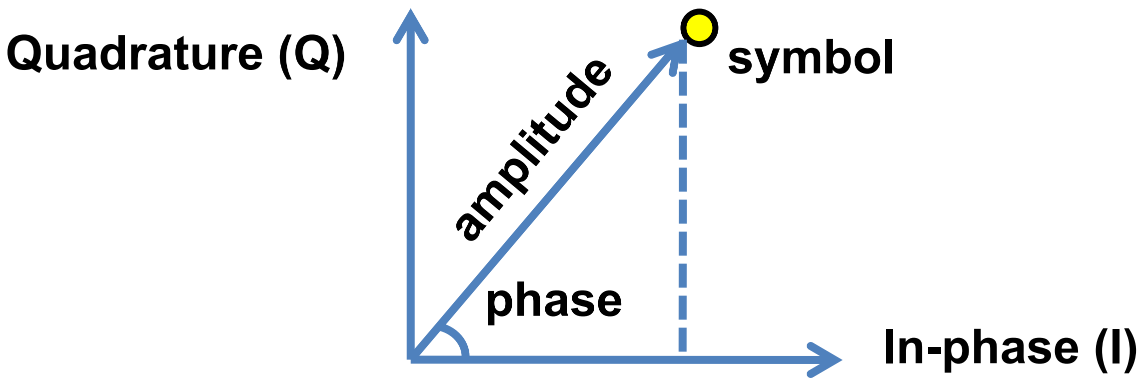
$$E(\{s_i\}) = \sum_{i \in V} h_i s_i + \sum_{(i,j) \in E} J_{ij} s_i s_j$$

- **Example:**

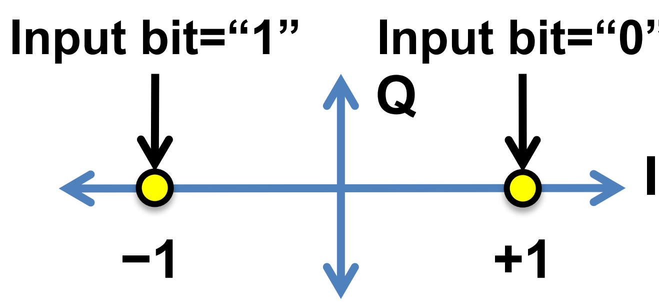


From bits to symbols...

- ***Modulate*** means **to change.** Change what? The **amplitude** and ***phase* (angle)** of a radio ***carrier signal***

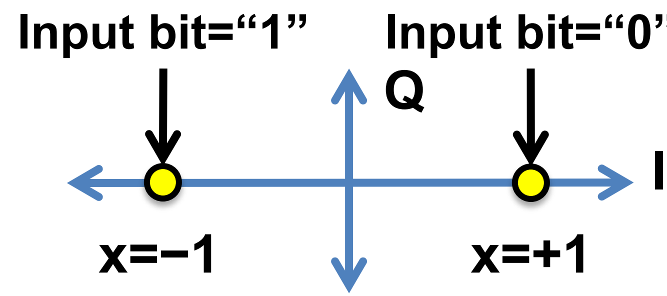


- ***Digital modulation:*** Use only a **finite set** of choices (*i.e., **symbols***) for how to change the carrier and phase



From Maximum Likelihood to Ising...

$$\hat{x}_i = 2q_i - 1 \text{ and } q \in \{0,1\}$$



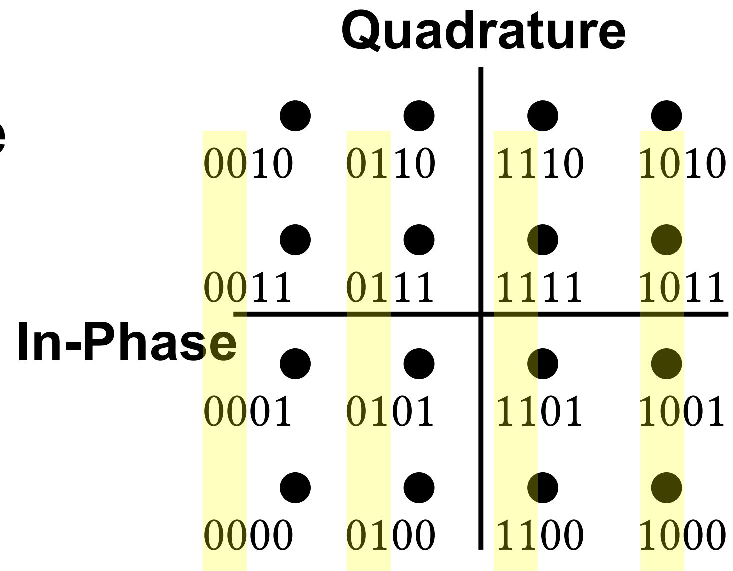
$$\|\mathbf{H}\hat{\mathbf{x}} - \mathbf{y}\|^2 = \left\| \begin{matrix} h_{11}\hat{x}_1 + h_{12}\hat{x}_2 - y_1 \\ h_{21}\hat{x}_1 + h_{22}\hat{x}_2 - y_2 \end{matrix} \right\|^2$$

$$= f_1(H,y)q_1 + f_2(H,y)q_2 + f_3(H,y)q_1q_2 + constant$$

Higher Order Modulations

- For 16-QAM with Gray Coding, the in-phase term is:

$$x_I = 2(2q_1 - 1) - (q_1 - q_2)^2 - 1$$



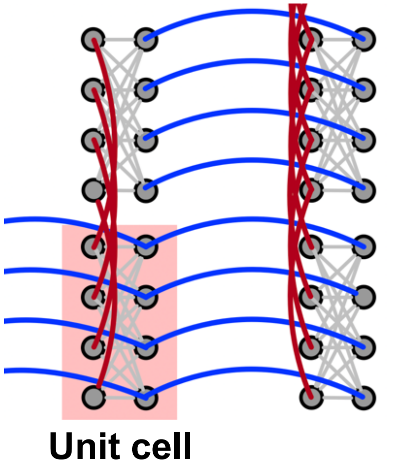
- We cannot solve the 16-QAM problem in this way since the objective function includes **higher-order polynomials:**
  - *e.g.*, $12H_{I,11}H_{I,12}q_1q_2q_5 - 4H_{I,11}H_{I,12}q_1q_2q_6$

This is NOT an Ising problem!

Embedding into the Quantum Annealer Graph Structure

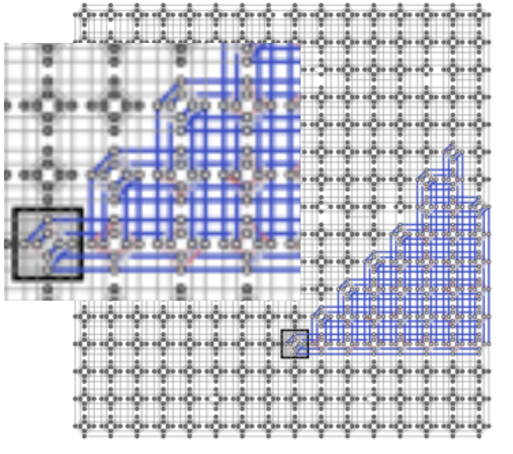
1. **Machine topology** has only **partial connectivity**

   – ***Unit cell:*** complete bipartite topology (4, 4)
   - Left side connects to North, South neighbors
   - Right side connects to East, West neighbors



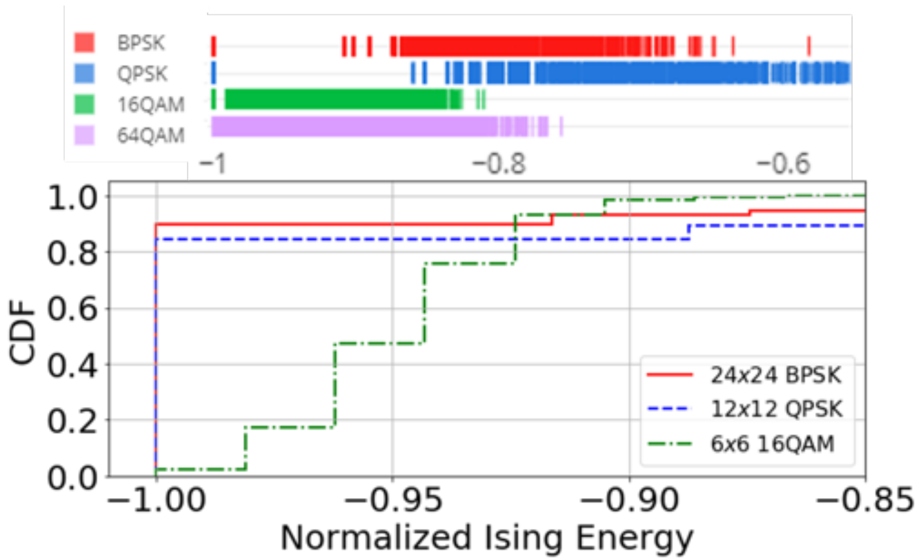
2. Only *ca.* **90% hardware fabrication yields,** so hardware graph is a subset of above ideal topology

- **Embed the problem** into the hardware graph:



What’s Different about Wireless?

- More machine iterations, **greater likelihood** of finding optimal solution:



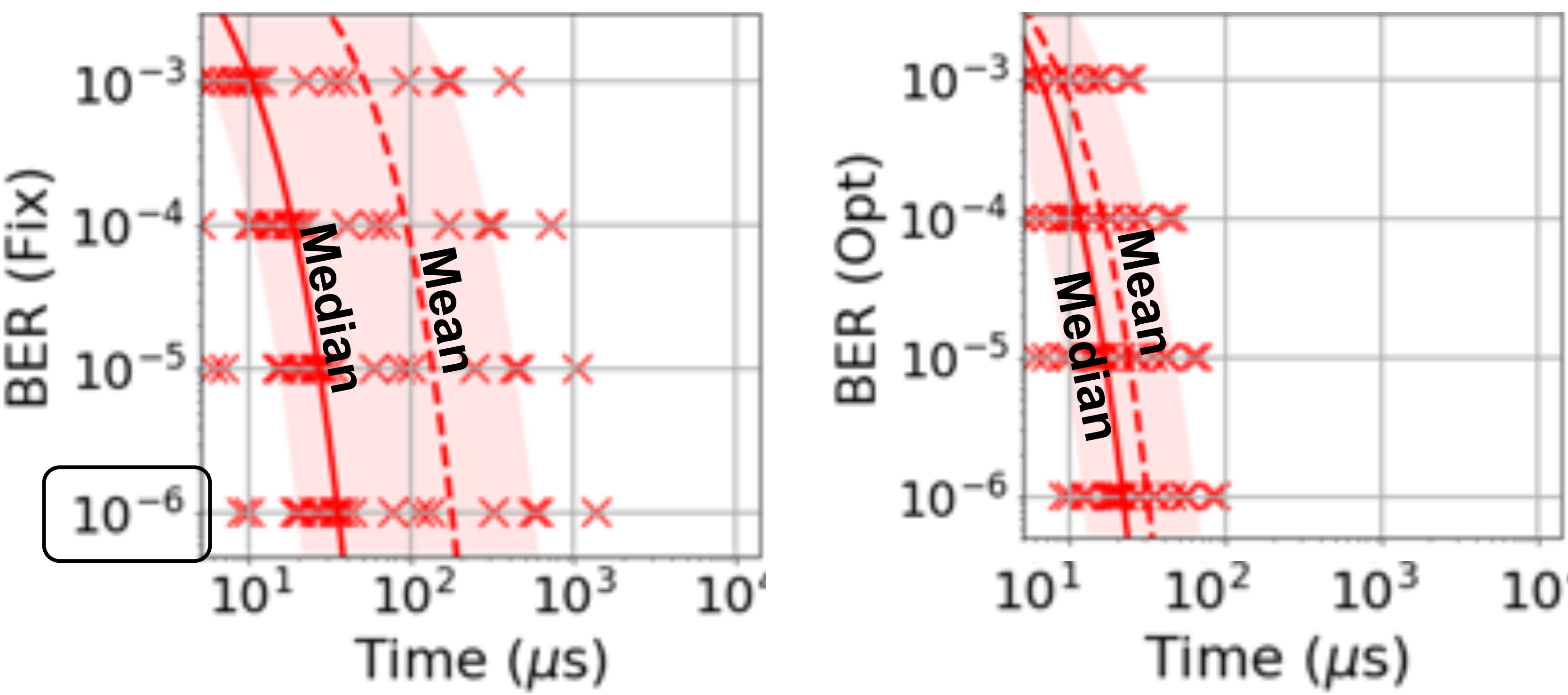
- Metric **Time-to-Solution** → our new metric, **Time-to-Bit Error Rate**

36 users, 36 access point antennas, BPSK

9 users, 9 access point antennas, 16-QAM

60 users on a Fully-Occupied Base Station

60 users, 60 base station antennas



Conclusion

- **End-to-end considerations**
  - Quantum machine **programming time**
  - Quantum machine **read-out time**

In the SIGCOMM 2019 paper:

- **Sensitivity analysis** to various quantum annealer **parameters**
- Scaling up to **higher data rates,** numbers of users
- Performance under **real-world wireless channels**