Leveraging Quantum Annealing for Large MIMO Processing in Centralized Radio Access Networks

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QUBITS North America 2019

PRINCETON UNIVERSITY

USRA

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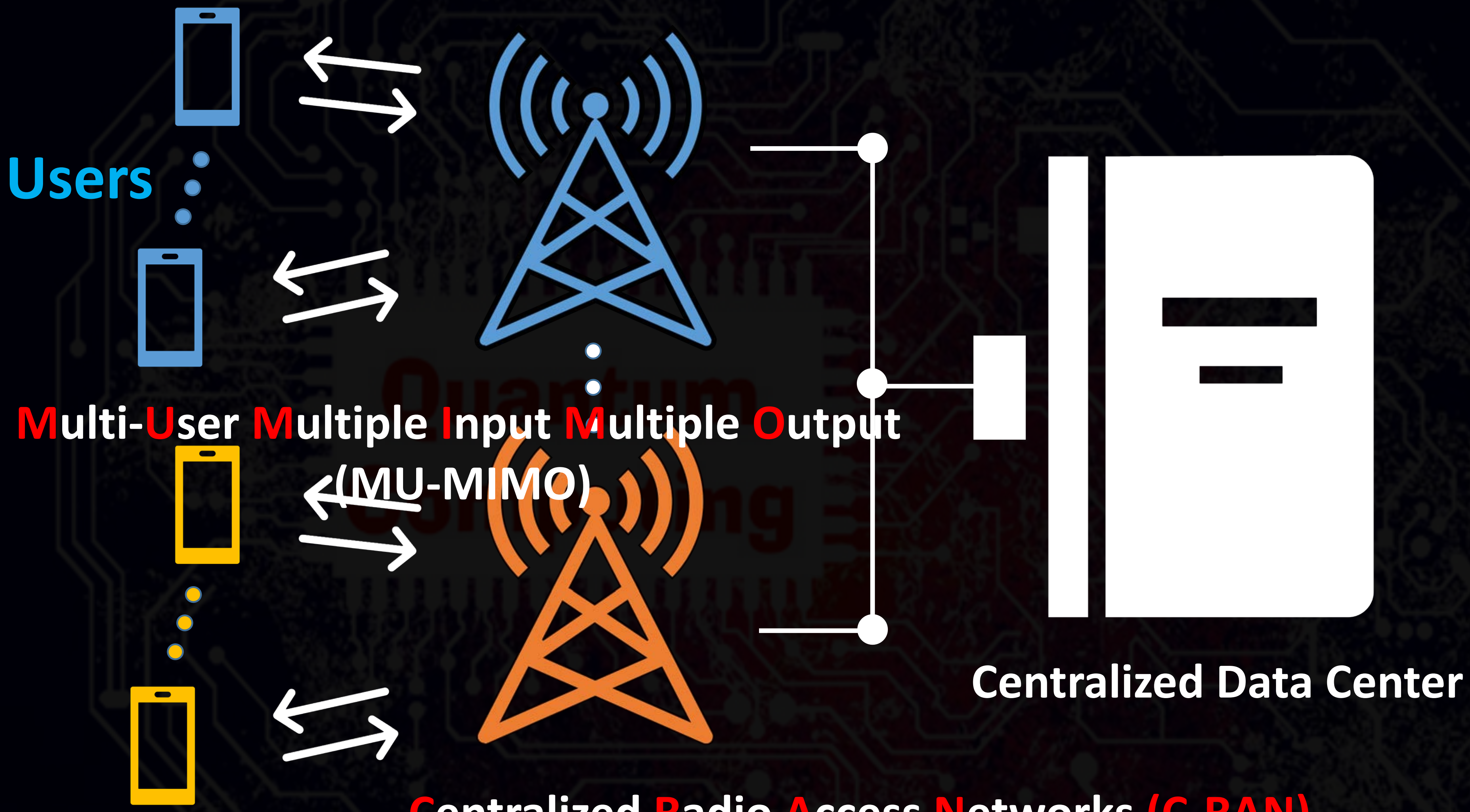
New Services!

- Global mobile data traffic is increasing **exponentially**
- User demand for high data rate outpaces supply

Drives Wireless Capacity to increase!



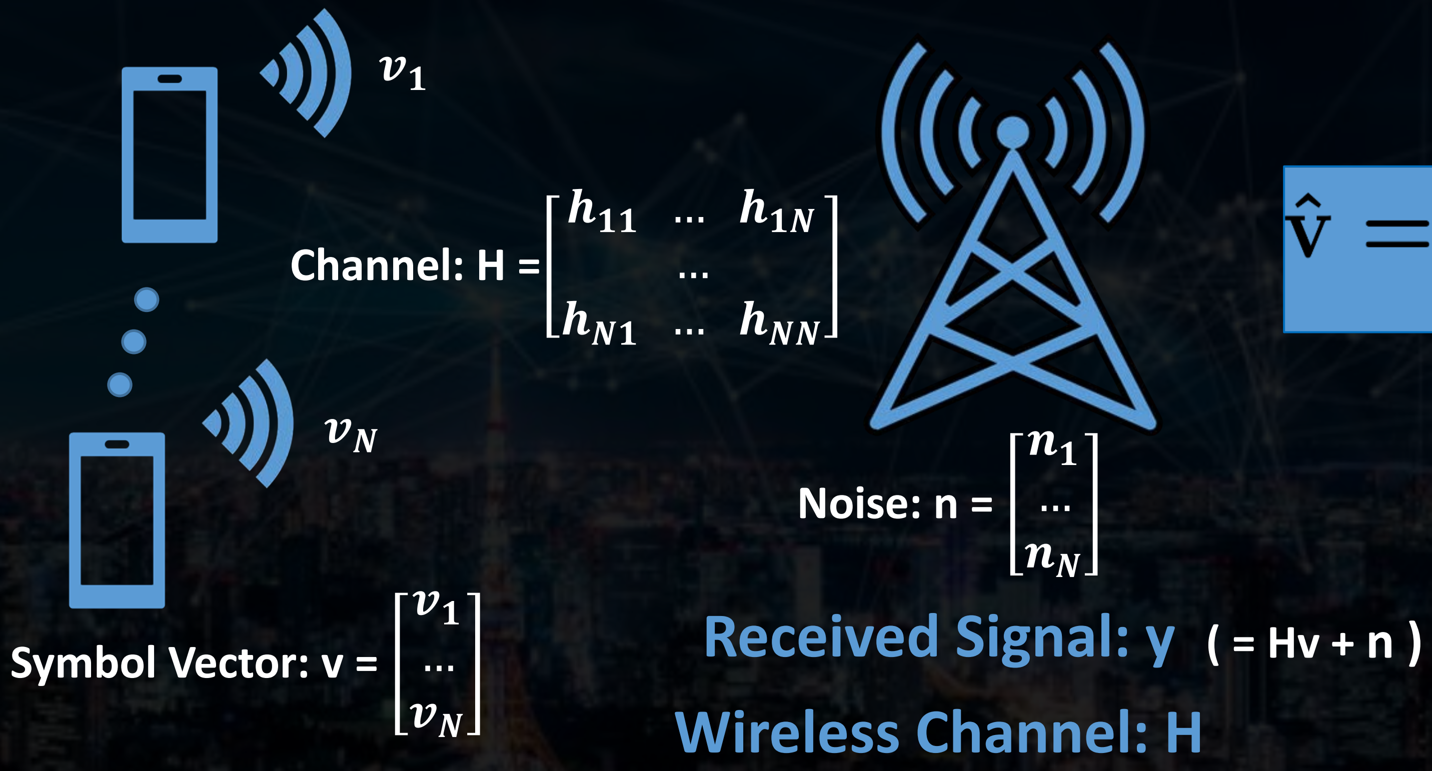
Centralized Radio Access Networks (C-RAN)

MIMO Detection

Demultiplex Mutually Interfering Streams

Maximum Likelihood (ML) MIMO Detection

: Non-Approximate but High Complexity



$$\hat{\mathrm{v}} = \arg \min_{\text{possible v}} \|\mathrm{y} - \mathrm{Hv}\|^2$$

$2^{N \log_2 M}$ possibilities for *N* x *N* MIMO with *M* modulation

Time available for processing is at most 3-10 ms.

Sphere Decoder (SD)
: Non-Approximate but High Complexity

Maximum Likelihood (ML) Detection → Tree Search with Constraints

Reduce search operations but fall short for the same reason

BPSK	QPSK	16-QAM	Complexity (Visited Nodes)
12×12	7×7	4×4	≈ 40 (♡)
21×21	11×11	6×6	≈ 270 (△)
30×30	15×15	8×8	≈ 1900 (×)

Parallelization of SD
[Flexcore, NSDI 17],
[Geosphere, SIGCOMM 14],
...
Approximate SD
[K-best SD, JSAC 06],
[Fixed Complexity SD, TWC 08],
....

Linear Detection

: Low Complexity but Approximate & Suboptimal

v_1

v_N

Channel: H = $\begin{bmatrix} H_{11} & \cdots & H_{1N} \\ & \cdots & \\ H_{N1} & \cdots & H_{NN} \end{bmatrix}$

Noise: n = $\begin{bmatrix} n_1 \\ \cdots \\ n_N \end{bmatrix}$

Symbol Vector: v = $\begin{bmatrix} v_1 \\ \cdots \\ v_N \end{bmatrix}$

Received Signal: y (= Hv + n)

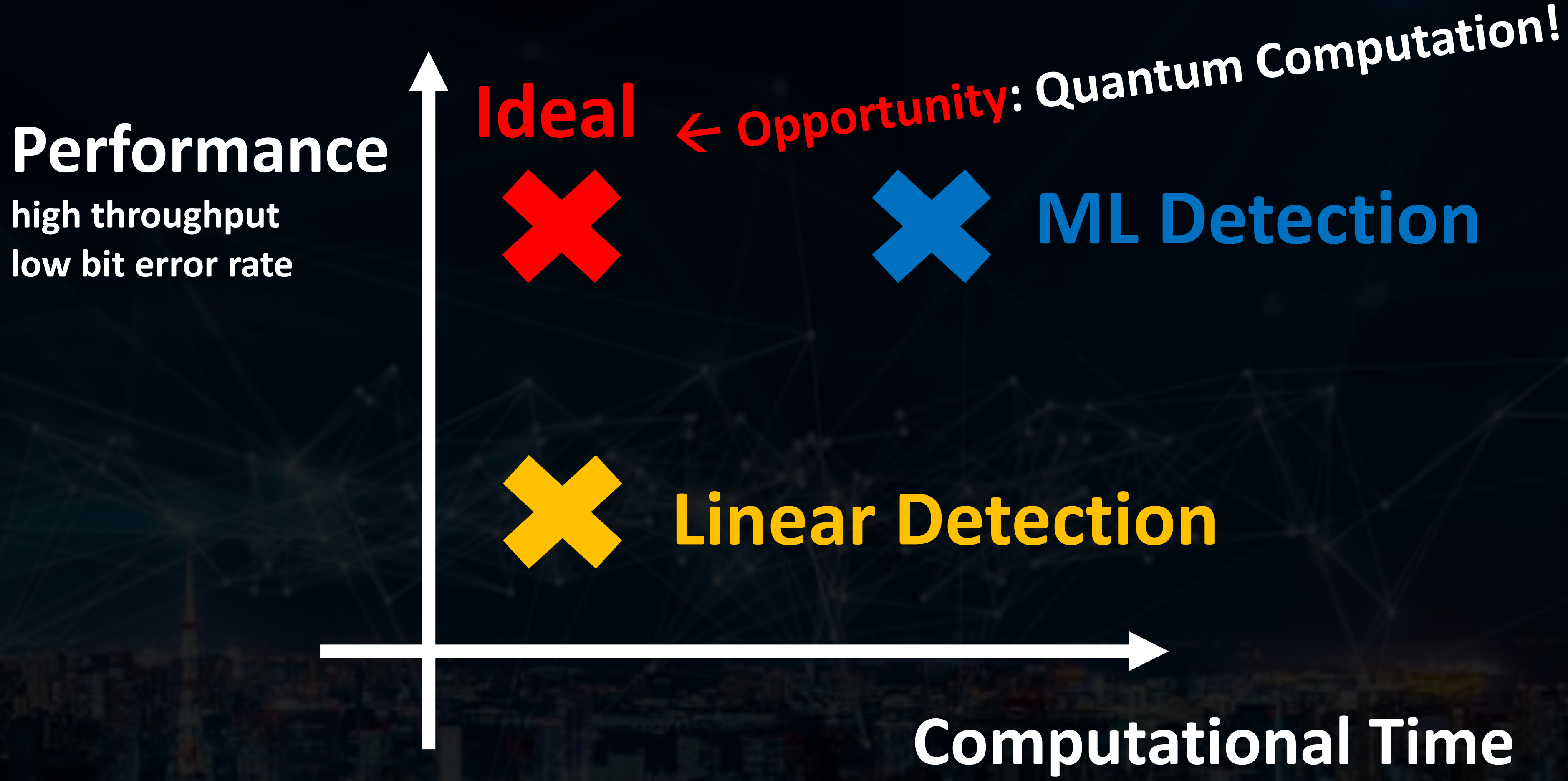
Wireless Channel: H

Zero-Forcing [BigStation, SIGCOMM 13], [Argos, MOBICOM 12], …

Nullifying Channel Effect:

$$\mathbf{H}^{-1}y = \mathbf{H}^{-1}\mathbf{H}\mathbf{v} + \mathbf{H}^{-1}\mathbf{n}$$

Performance Degradation due to Noise Amplification



Ideal: High Performance & Low Computational Time

QuAMax: Main Idea

MIMO Detection

Maximum Likelihood (ML) Detection

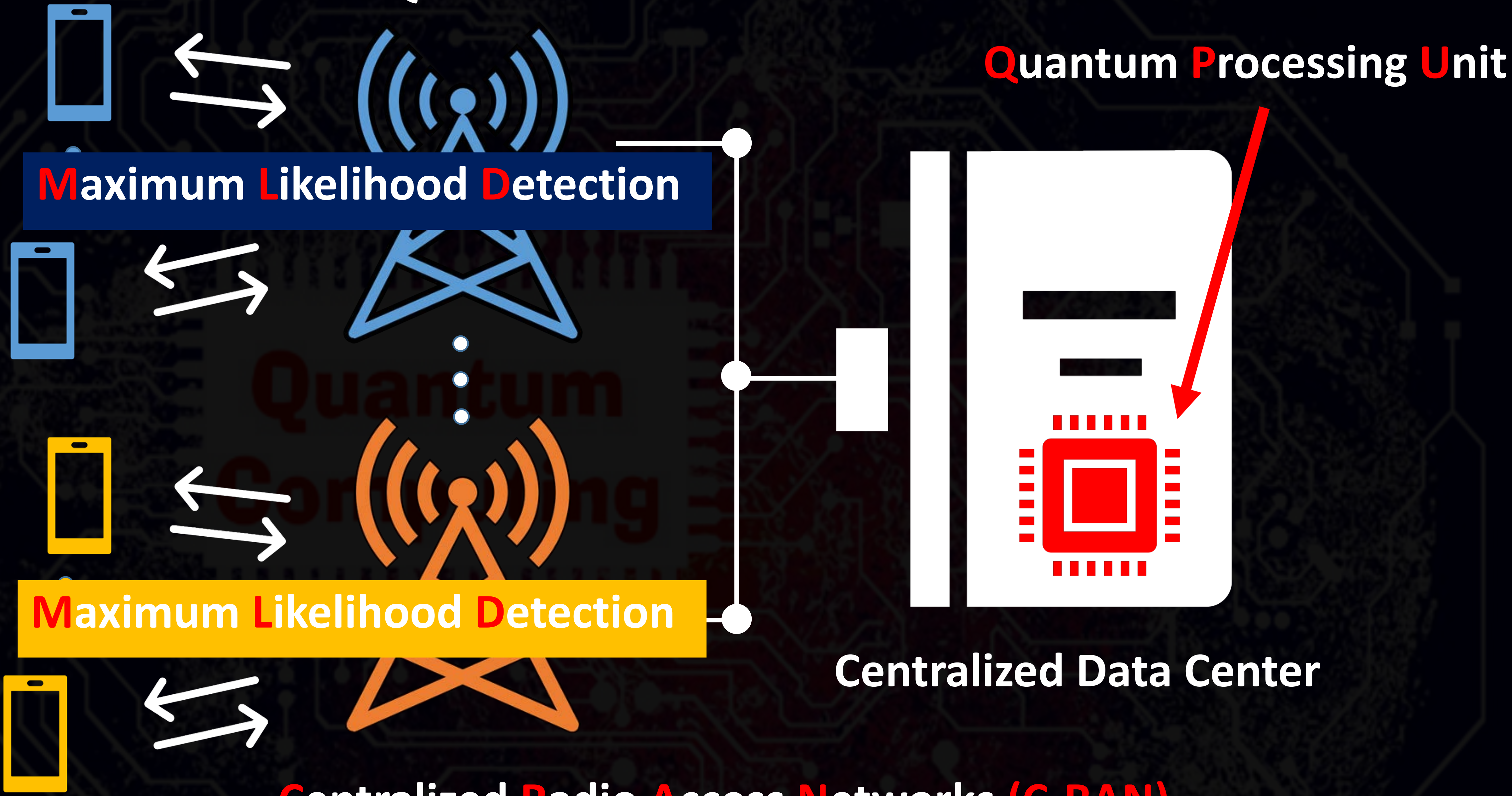
Quantum Computation

Quantum Annealing

Better Performance ?

Motivation: Optimal + Fast Detection = Higher Capacity

QuAMax Architecture



Centralized Radio Access Networks (C-RAN)

Maximum Likelihood Detection

↓

Quadratic Unconstrainted Binary Optimization

↓

Quantum Processing Unit

D-Wave 2000Q
(Quantum Annealer)

Rest of Today

1. QUAMAX: SYSTEM DESIGN

2. QUANTUM ANNEALING & EVALUATION

Key Idea of ML-to-QUBO Problem Reduction

- **Maximum Likelihood MIMO detection:**

$$\hat{\mathbf{v}} = \arg\min_{\mathbf{v}} \|\mathbf{y} - \mathbf{H}\mathbf{v}\|^2$$

- **QUBO Form:**

$$\hat{q}_1, \ldots, \hat{q}_N = \arg \min_{\{q_1, \ldots, q_N\}} \sum_{i \le j}^{N} Q_{ij} q_i q_j$$

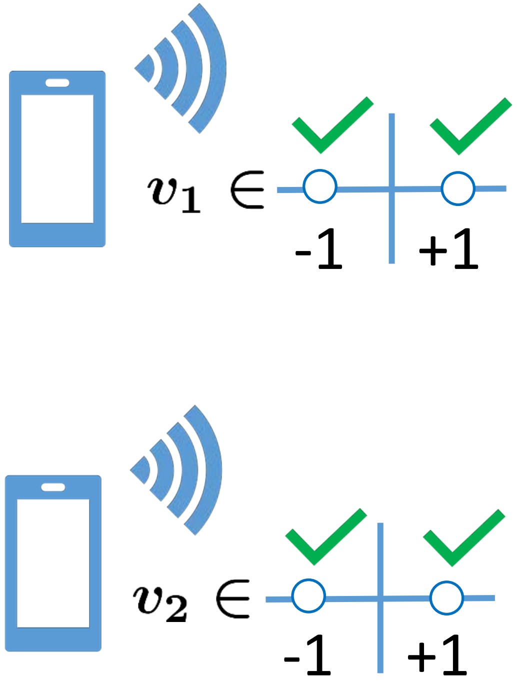
QUBO Form!

The key idea is to represent possibly-transmitted **symbol v** with **0,1 variables.**
If this is **linear**, the expansion of the norm results in **linear & quadratic** terms.

Linear variable-to-symbol transform T

Revisiting ML Detection

Example: 2x2 MIMO with Binary Modulation



Symbol Vector: $\mathbf{v} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$

Received Signal: y

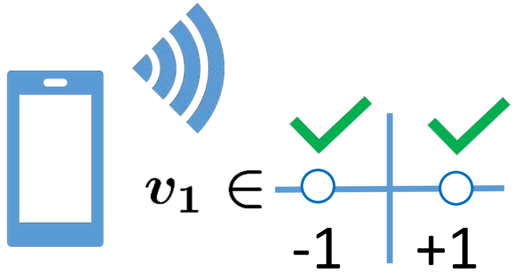
Wireless Channel: H

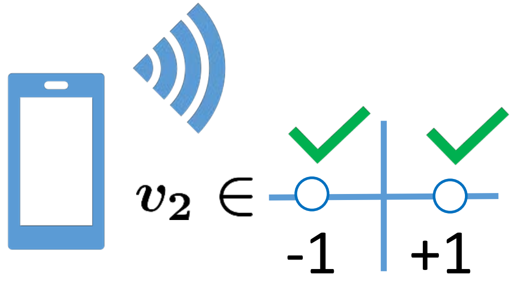
$$\hat{\mathbf{v}} = \arg \min_{\text{possible } \mathbf{v}} \|\mathbf{y} - \mathbf{H}\mathbf{v}\|^2$$

$$\text{possible} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \in \begin{bmatrix} +1 \\ +1 \end{bmatrix}, \begin{bmatrix} +1 \\ -1 \end{bmatrix}, \begin{bmatrix} -1 \\ -1 \end{bmatrix}, \begin{bmatrix} -1 \\ +1 \end{bmatrix}$$

QuAMax's ML-to-QUBO Problem Reduction

Example: 2x2 MIMO with Binary Modulation





Symbol Vector: $\mathbf{v} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$

1. Find linear variable-to-symbol transform T:

$$2q_i - 1 \leftrightarrow v_i \qquad \begin{matrix} (\text{if } q_i = 1)\ 2q_i - 1 = +1 \\ (\text{if } q_i = 0)\ 2q_i - 1 = -1 \end{matrix}$$

2. Replace symbol vector v with transform T in $\|\mathbf{y} - \mathbf{H}\mathbf{v}\|^2$:

$$\text{possible} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} \in \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix} \Leftrightarrow \text{possible} \begin{bmatrix} 2q_1 - 1 \\ 2q_2 - 1 \end{bmatrix} \in \begin{bmatrix} +1 \\ +1 \end{bmatrix}, \begin{bmatrix} +1 \\ -1 \end{bmatrix}, \begin{bmatrix} -1 \\ -1 \end{bmatrix}, \begin{bmatrix} -1 \\ +1 \end{bmatrix}$$

3. Expand the norm $(q^2 = q)$

$$\hat{q}_1, \hat{q}_2 = \underset{q_1, q_2}{\arg\min}\ f_1(\mathbf{H}, \mathbf{y}) q_1 + f_2(\mathbf{H}, \mathbf{y}) q_2 + g_{12}(\mathbf{H}) q_1 q_2$$

$$\mathbf{Q} = \begin{bmatrix} f_1(\mathbf{H}, \mathbf{y}) & g_{12}(\mathbf{H}) \\ 0 & f_2(\mathbf{H}, \mathbf{y}) \end{bmatrix}$$

QUBO Form!

QuAMax's linear variable-to-symbol Transform T

BPSK (2 symbols)	$v_i \leftrightarrow 2q_i - 1$
QPSK (4 symbols)	$v_i \leftrightarrow 2q_{2i-1} - 1 + j(2q_{2i} - 1)$
16-QAM (16 symbols)	$v_i \leftrightarrow 3q_{4i-3} - 2q_{4i-2} - 1 + j(3q_{4i-1} - 2q_{4i} - 1)$

- Coefficient functions *f(H, y)* and *g(H)* are generalized for different modulations.
- Computation required for ML-to-QUBO reduction is insignificant.

Maximum Likelihood Detection

↓

Quadratic Unconstrainted Binary Optimization

↓

Quantum Processing Unit

D-Wave 2000Q
(Quantum Annealer)

Rest of Today

1. QUAMAX: SYSTEM DESIGN

2. QUANTUM ANNEALING & EVALUATION

QuAMax's Performance Metrics

- **One run on QuAMax includes multiple QA cycles.**
  - Number of anneals (N_a) is another input.
- **Solution (state) that has the lowest energy is selected as a final answer.**

Evaluation Metric: How Many Anneals Are Required?

↑ **Target**
Bit Error Rate (BER)

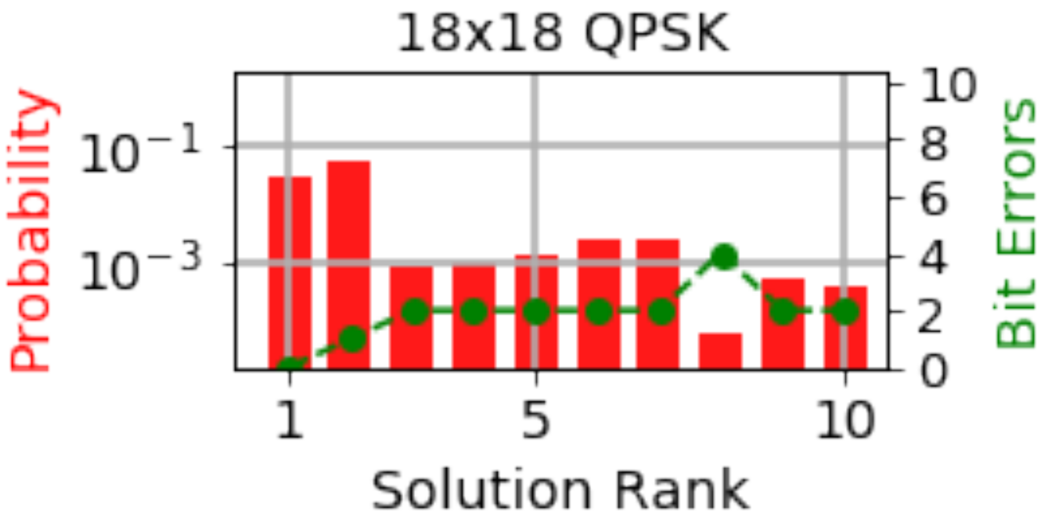
↑ **Solution's Probability**
Empirical QA Results

Experimental Methodology

1. Run enough number of anneals N_a for statistical significance.

2. Sort the L ($\leq N_a$) results in order of QUBO energy.

3. Obtain the corresponding probabilities and numbers of bit errors.



● ● ● L^{th} Solution

Wireless Performance Metric: Bit Error Rate (BER)

QuAMax's BER = BER of the lowest energy state after N_a Anneals

$$\mathbf{E}(BER(N_a)) = \sum_{k=1}^{L}$$ Probability of *k*-th solution being selected after N_a anneals ✖ Corresponding BER of *k*-th solution

=

Probability of [never finding a solution better than k-th solution; finding k-th solution at least once]

This probability depends on number of anneals N_a

Expected Bit Error Rate (BER) as a Function of Number of Anneals (N_a)

QuAMax's Comparison Schemes

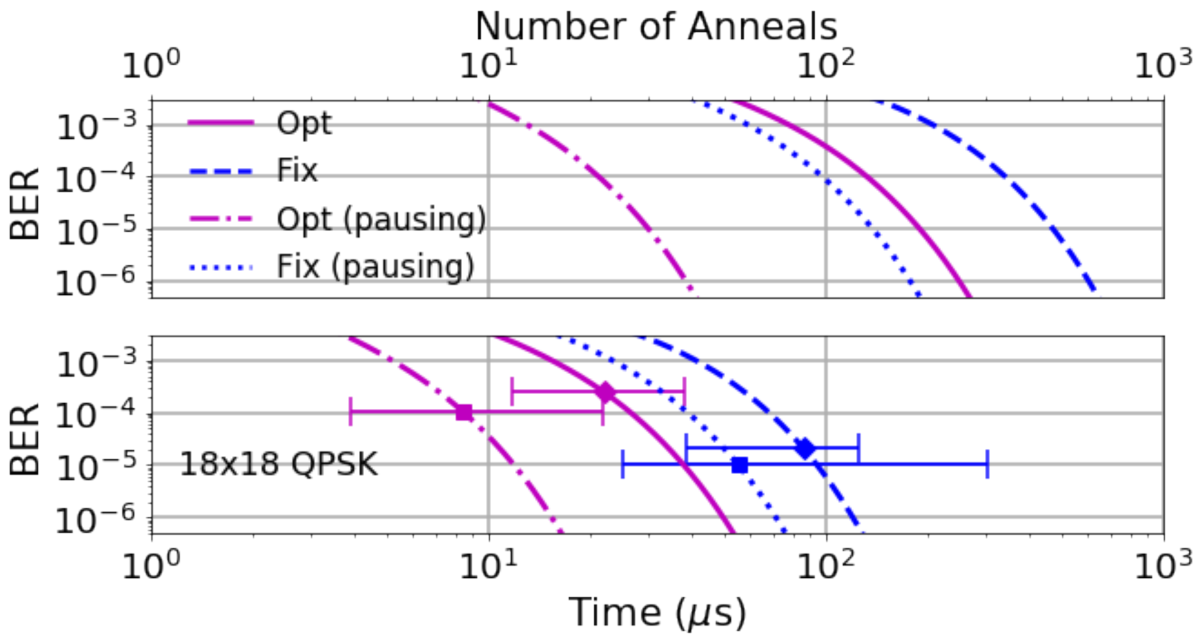
QA parameters: embedding, anneal time, pause duration, pause location, …

- **Opt:** run with optimized QA parameters per instance (Oracle)
- **Fix:** run with fixed QA parameters per classification (QuAMax)

Quantum Compute-Wireless Performance Metric: *Time-to-BER*

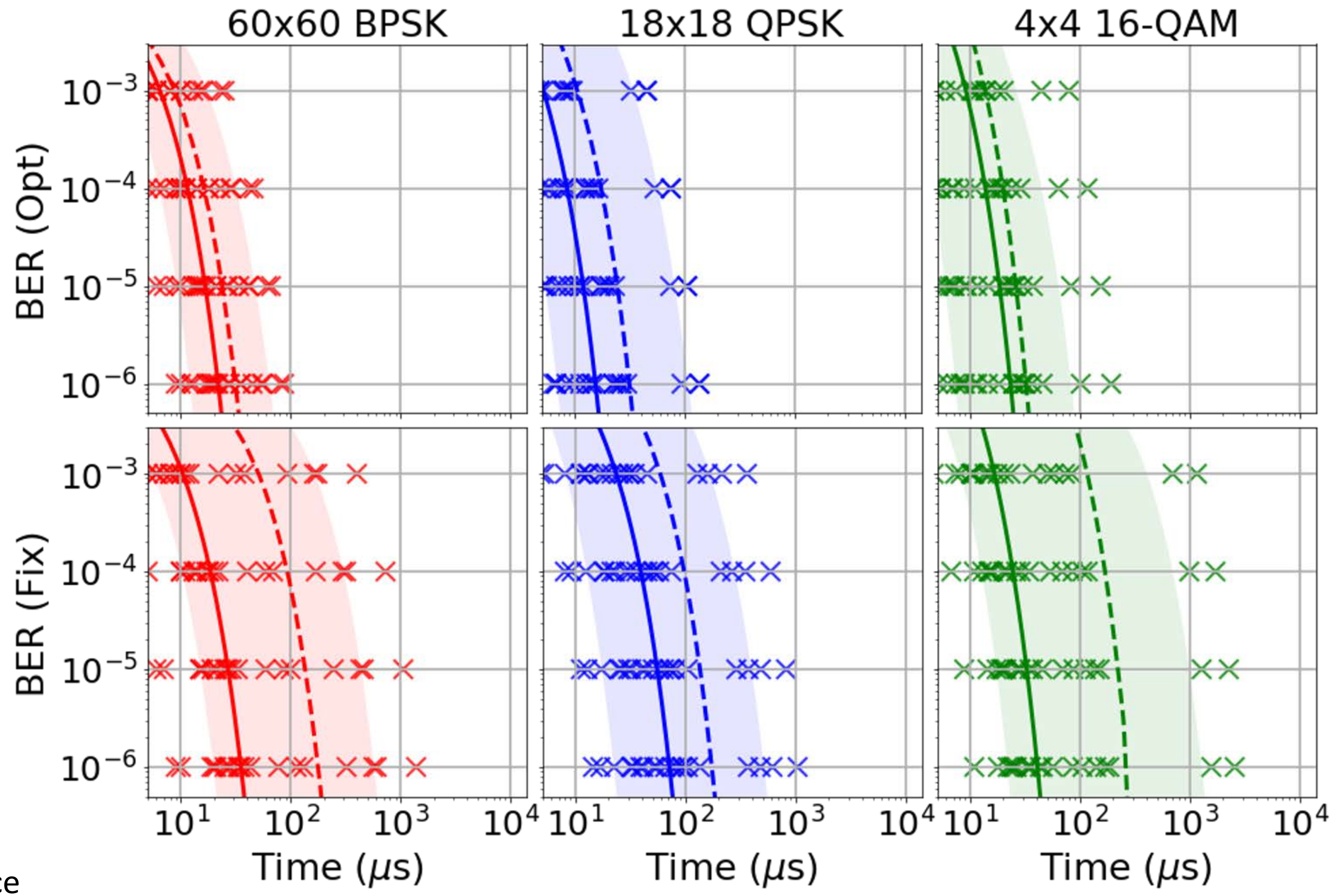
- Opt: run with optimized QA parameters per instance (oracle)
- Fix: run with fixed QA parameters per classification (QuAMax)

Expected Bit Error Rate (BER) as a Function of Number of Anneals (N_a)



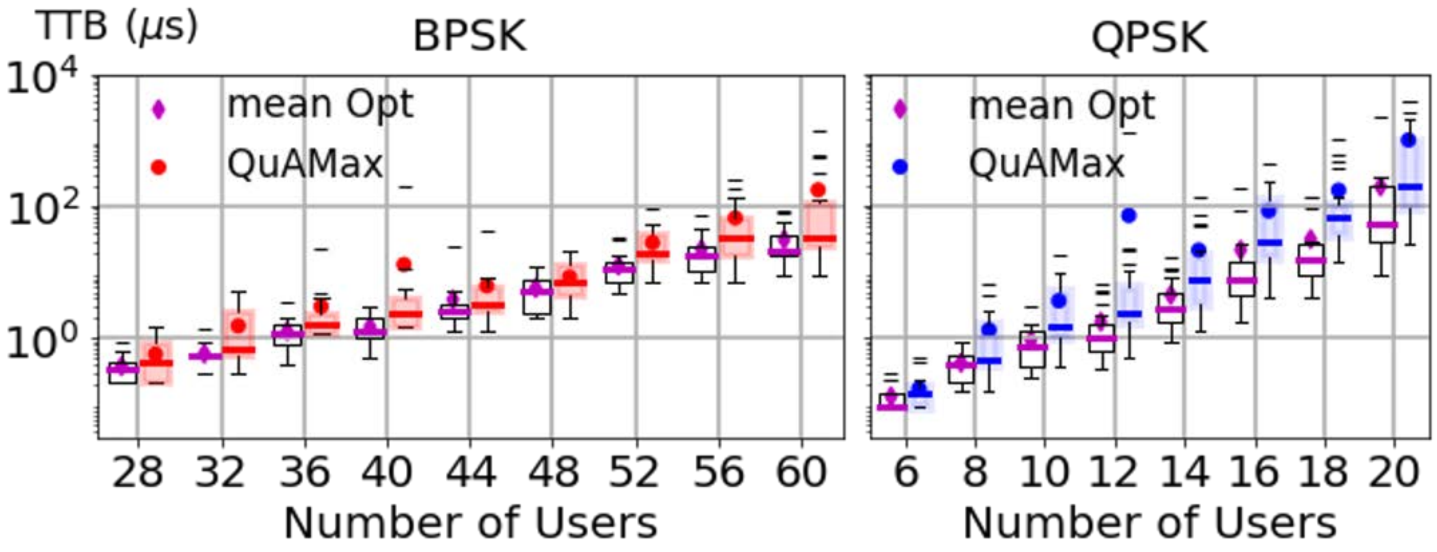
***Time-to-BER* (TTB)**

Time-to-BER for Various Modulations



Lines: Median
Dash Lines: Average
x symbols: Each Instance

QuAMax's Time-to-BER (10^{-6}) Performance



Practicality of Sphere Decoding

BPSK	QPSK	16-QAM	Complexity (Visited Nodes)
12×12	7×7	4×4	≈ 40 (♡)
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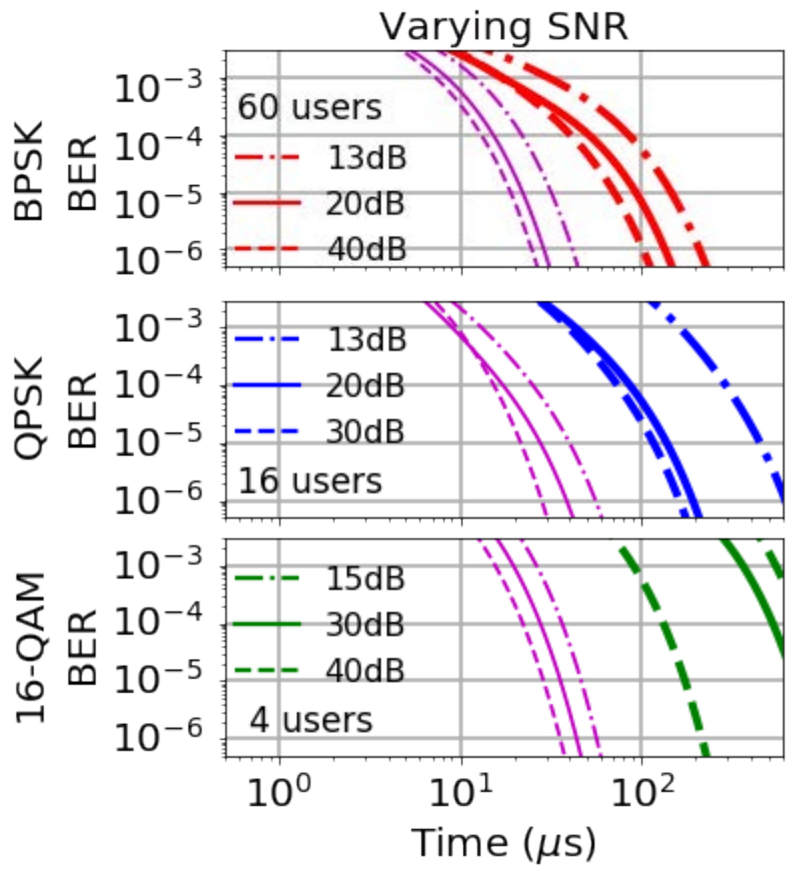
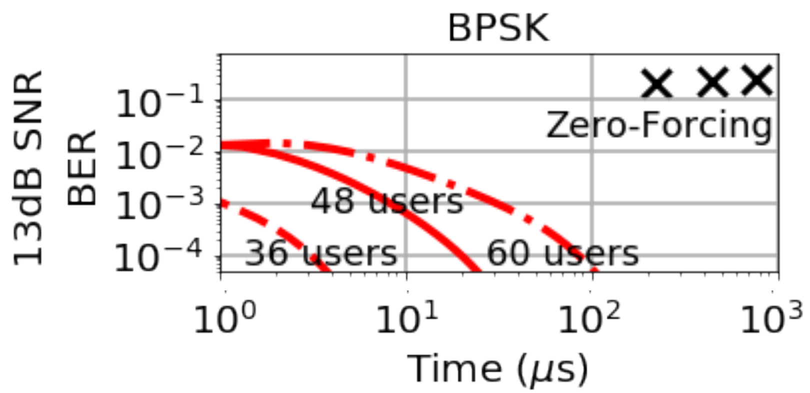
Well Beyond the Borderline of Conventional Computer

QuAMax's Time-to-BER Performance with Noise



Same User Number
Different SNR

- When user number is fixed, higher TTB is required for lower SNRs.



Comparison against Zero-Forcing

- Better BER performance than zero-forcing can be achieved.

Practical Considerations

- Significant Operation Cost:
  About USD $17,000 per year

- Processing Overheads (as of 2019):
  Preprocessing, Read-out Time,
  Programming Time = hundreds of *ms*

D-Wave 2000Q (hosted at NASA Ames)

Future Trends in QA Technology

More Qubits (x2), More Flexibility (x2), Low Noise (x25), Advanced Annealing Schedule, …

Contributions

- First application of QA to MIMO detection
- New metrics: BER across anneals & Time-to-BER (TTB)
- New techniques of QA: Anneal Pause & Improved Range
- Comprehensive baseline performance for various scenarios

Conclusion

- QA may hold the potential to overcome computational limits in wireless networks, but technology & integration yet to mature
- Our work paves the way for quantum hardware and software to contribute to improved performance envelope of Massive MIMO

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