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

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USRA

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Presented by

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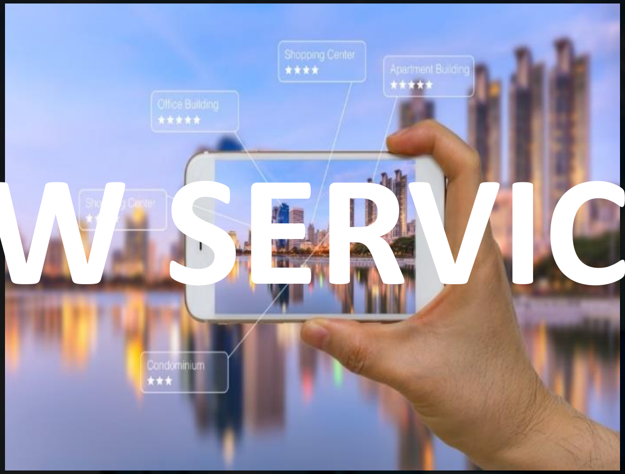
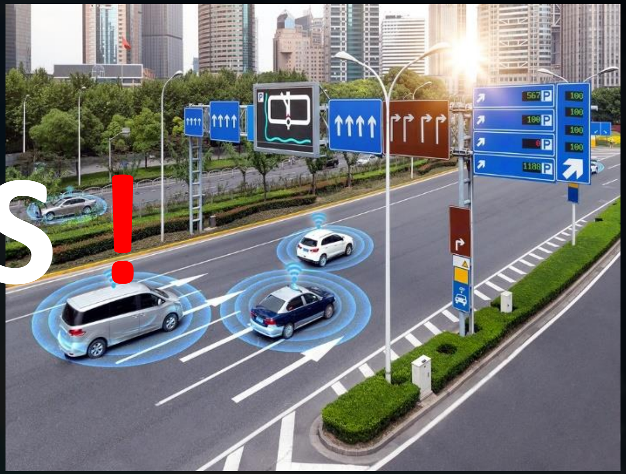
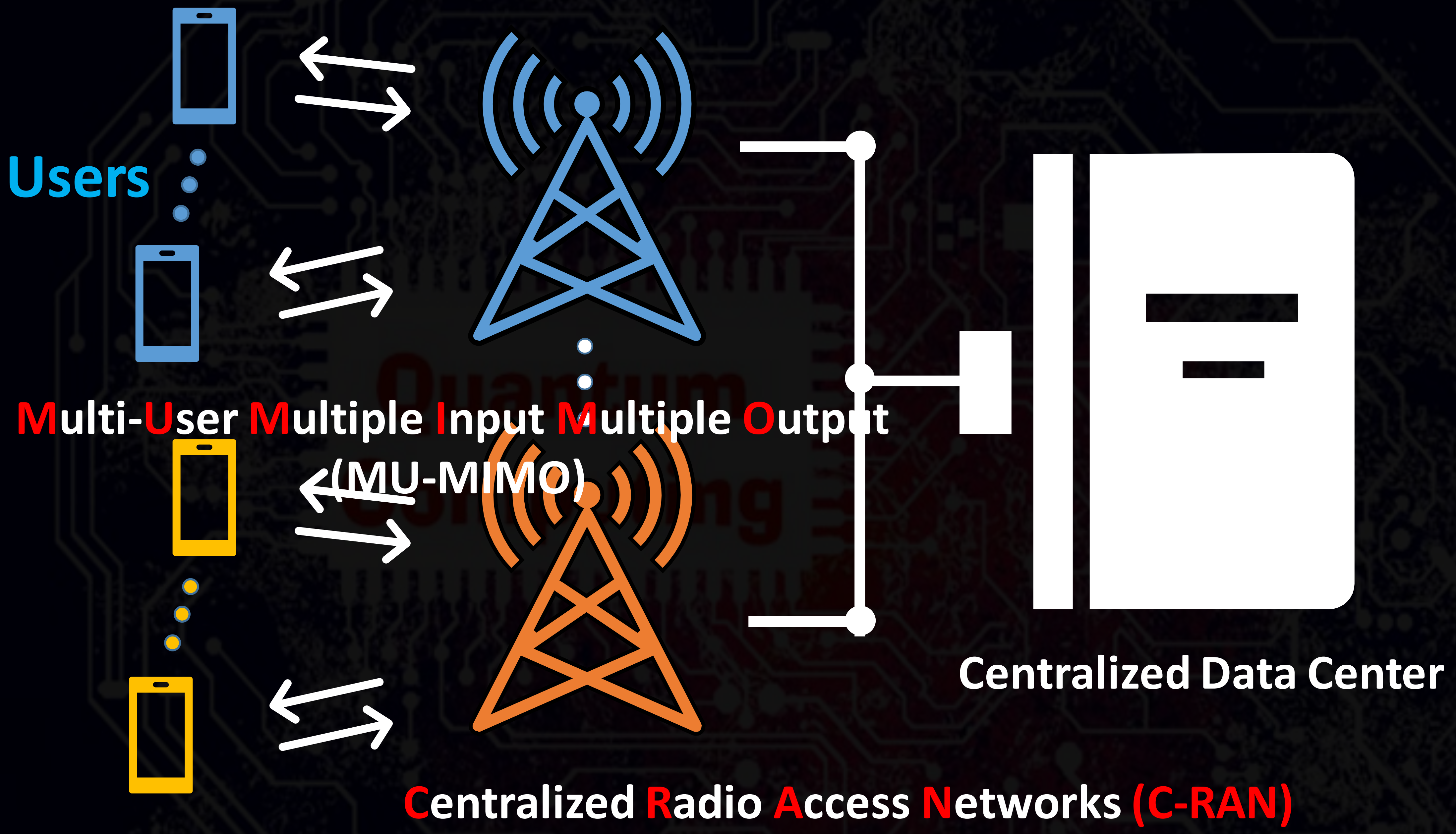




NEW SERVICES !

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

Wireless Capacity has to increase !

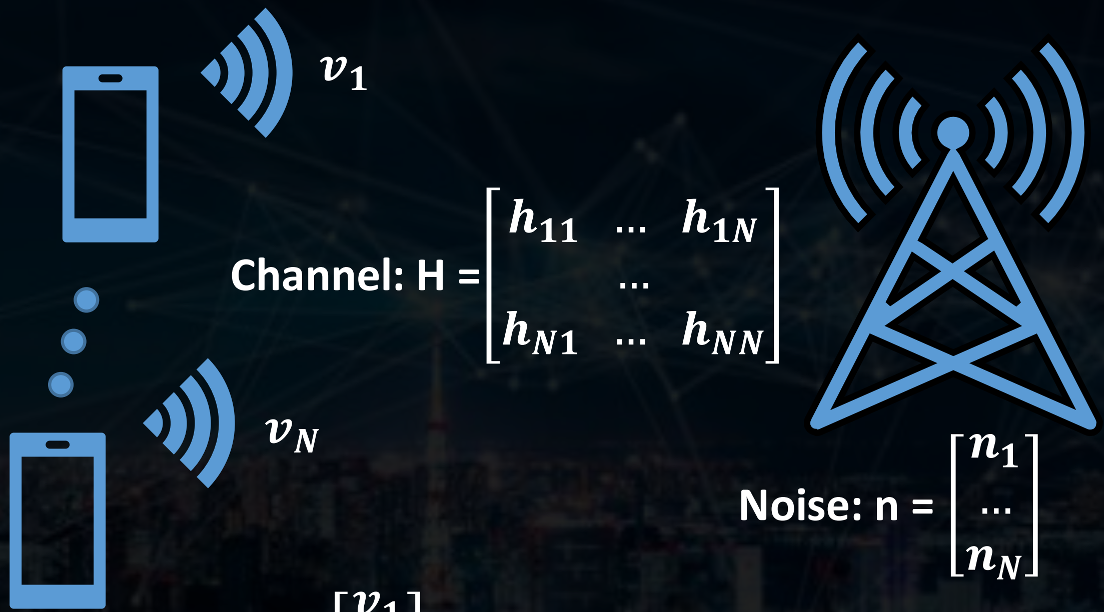

Users
Multi-User Multiple Input Multiple Output
(MU-MIMO)
Centralized Data Center
Centralized Radio Access Networks (C-RAN)

MIMO Detection

Demultiplex Mutually Interfering Streams

Maximum Likelihood (ML) MIMO Detection

: Non-Approximate but High Complexity



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

Received Signal: y (= Hv + n)

Wireless Channel: H

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

$2^{N \log_2 M}$ 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 ($\triangle$)
30×30	15×15	8×8	≈ 1900 ($\times$)

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

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

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

Received Signal: y (= Hv + n)

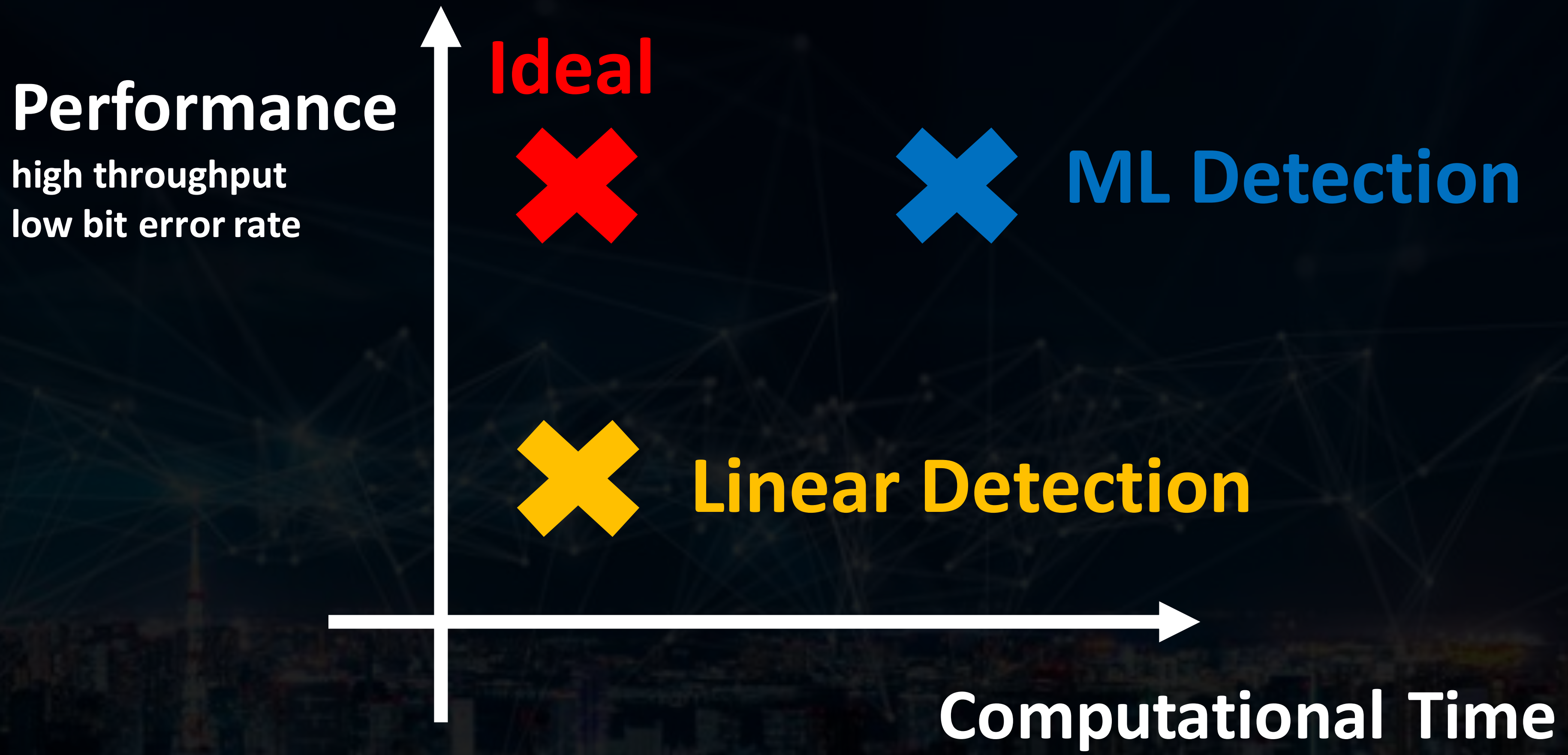
Wireless Channel: H

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

Opportunity: Quantum Computation !

QuAMax: Main Idea

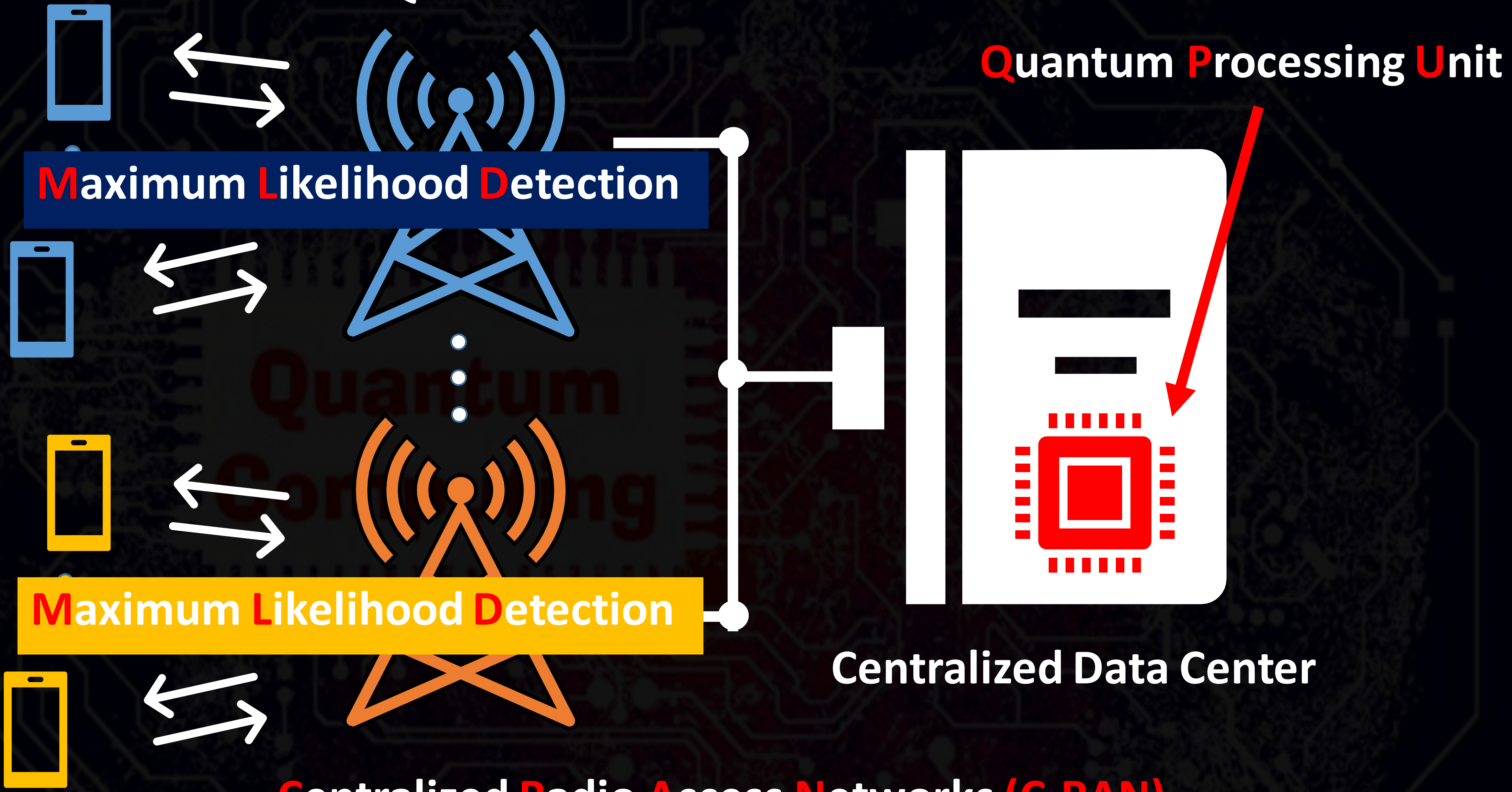
MIMO Detection
Maximum Likelihood (ML) Detection

Quantum Computation
Quantum Annealing

Better Performance ?

Motivation: Optimal + Fast Detection = Higher Capacity

QuAMax Architecture



Centralized Radio Access Networks (C-RAN)

Maximum Likelihood Detection

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Quadratic Unconstrainted Binary Optimization

↓

Quantum Processing Unit

D-Wave 2000Q
(Quantum Annealer)

1. PRIMER: QUBO FORM
2. QUAMAX: SYSTEM DESIGN
3. QUANTUM ANNEALING & EVALUATION

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

Variables (0 or 1)

Coefficients (real)

- **Example (two variables)**

Q upper triangle matrix :

$$\mathbf{Q} = \begin{bmatrix} Q_{11} & Q_{12} \\ 0 & Q_{22} \end{bmatrix} = \begin{bmatrix} 2 & -4.5 \\ 0 & 0.5 \end{bmatrix}$$

QUBO objective : $2q_1 + 0.5q_2 - 4.5q_1q_2$

State (q_1, q_2)		QUBO Energy
= (0,0)	->	0
= (0,1)	->	0.5
= (1,0)	->	2
= (1,1)	->	-2

Contents

- **Maximum Likelihood MIMO detection:**

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

- **QUBO Form:**

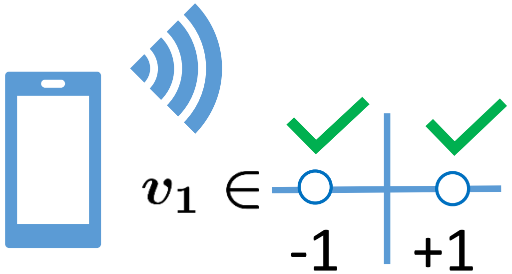
$$\hat{q}_1, \ldots, \hat{q}_N = \arg\min_{\{q_1,\ldots,q_N\}} \sum_{i \le j}^{N} Q_{ij} q_i q_j$$

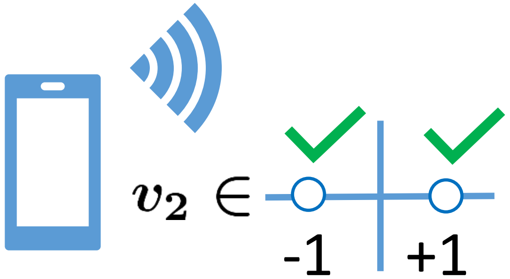
QUBO Form!

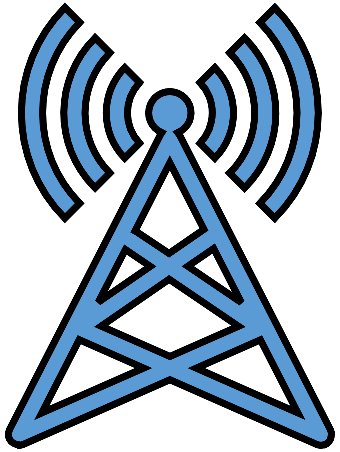
The key idea is to represent possibly-transmitted **symbol v** with **0,1 variables.**
If this is **linear**, the expansion of the norm results in **linear & quadratic** terms.

Linear variable-to-symbol transform T

Example: 2x2 MIMO with Binary Modulation







Received Signal: y

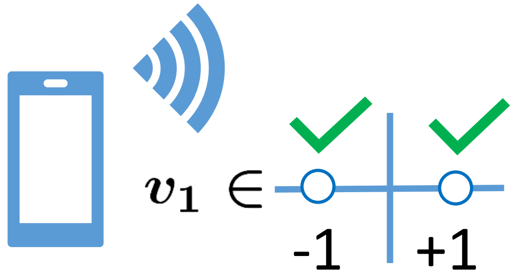
Wireless Channel: H

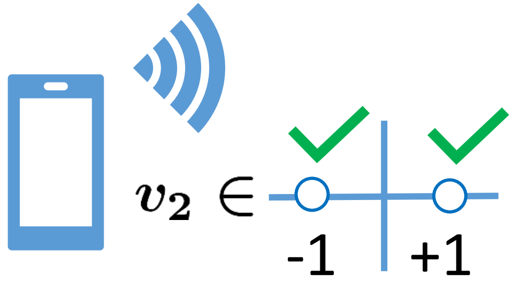
$$\hat{\mathbf{v}} = \arg \min_{\text{possible } \mathbf{v}} \|\mathbf{y} - \mathbf{H}\mathbf{v}\|^2$$

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

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

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:

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

2. Replace symbol vector v with transform T in $\|\mathrm{y} - \mathrm{Hv}\|^2$**:**

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

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

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

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

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

↓

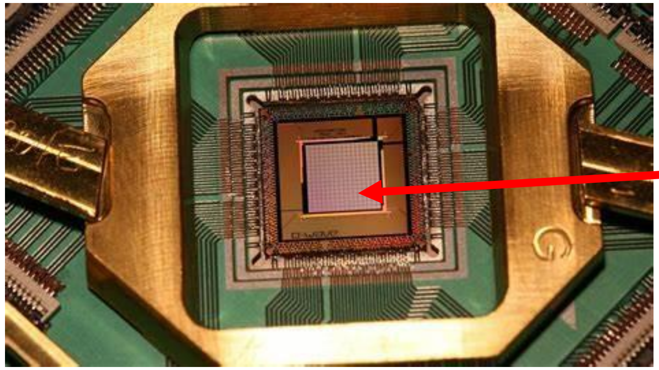
Quantum Processing Unit

D-Wave 2000Q
(Quantum Annealer)

Contents

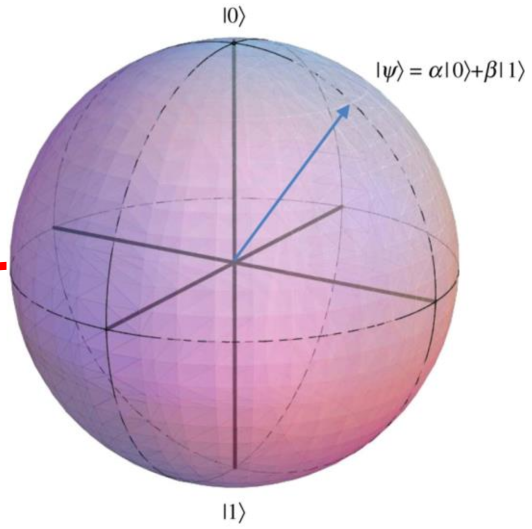
- Quantum Annealing (QA) is analog computation (unit: qubit) based on quantum effects, superposition, entanglement, and quantum tunneling.

N qubits can hold information on 2^N states simultaneously.
At the end of QA the output is one classic state (probabilistic).



D-Wave chip

superconducting circuit

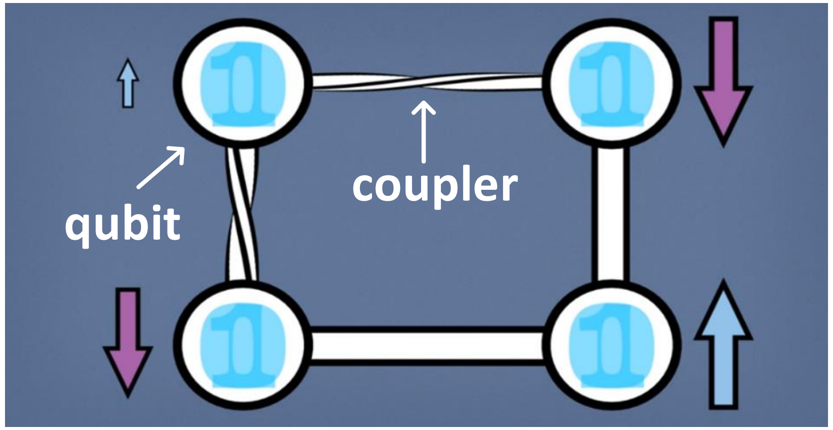


qubit

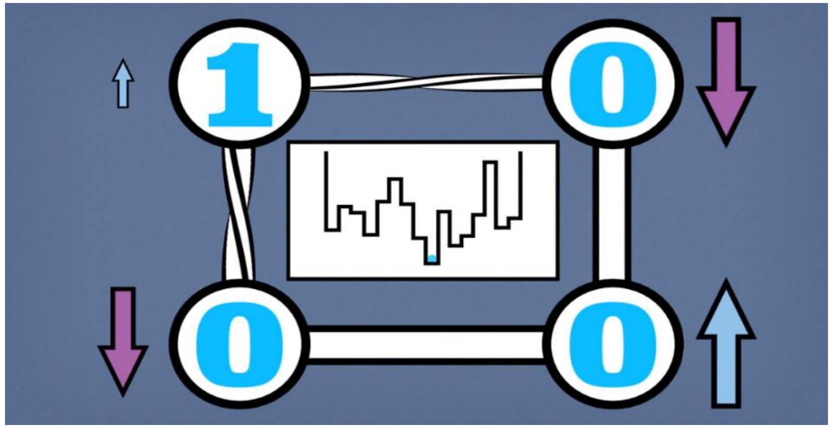
QUBO on Quantum Annealer

Example QUBO with 4 variables : $-q_1 + 2q_2 + 2q_3 - 2q_4 + 2q_1q_2 + 4q_1q_3 - q_2q_4 - q_3q_4$

Linear (diagonal) Coefficients : Energy of a single qubit
Quadratic (non-diagonal) Coefficients : Energy of couples of qubits



Quantum Annealing →



From D-Wave Tutorial

- **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?

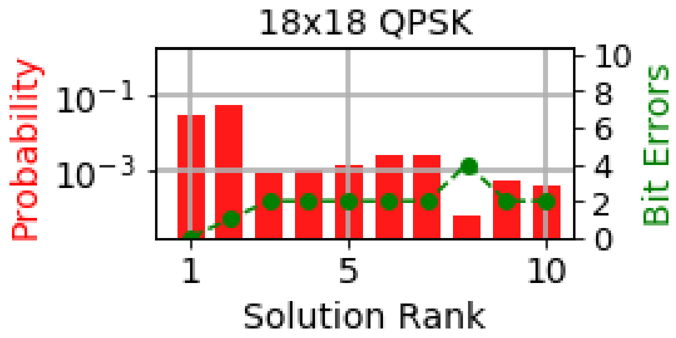
↑ **Target**
Bit Error Rate (BER)

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

QuAMax's Empirical QA results

- Run enough number of anneals N_a for statistical significance.
- Sort the L ($\leq N_a$) results in order of QUBO energy.
- Obtain the corresponding probabilities and numbers of bit errors.

Example.



●●● *L-th Solution*

QuAMax's Expected Bit Error Rate (BER)

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

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

=

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

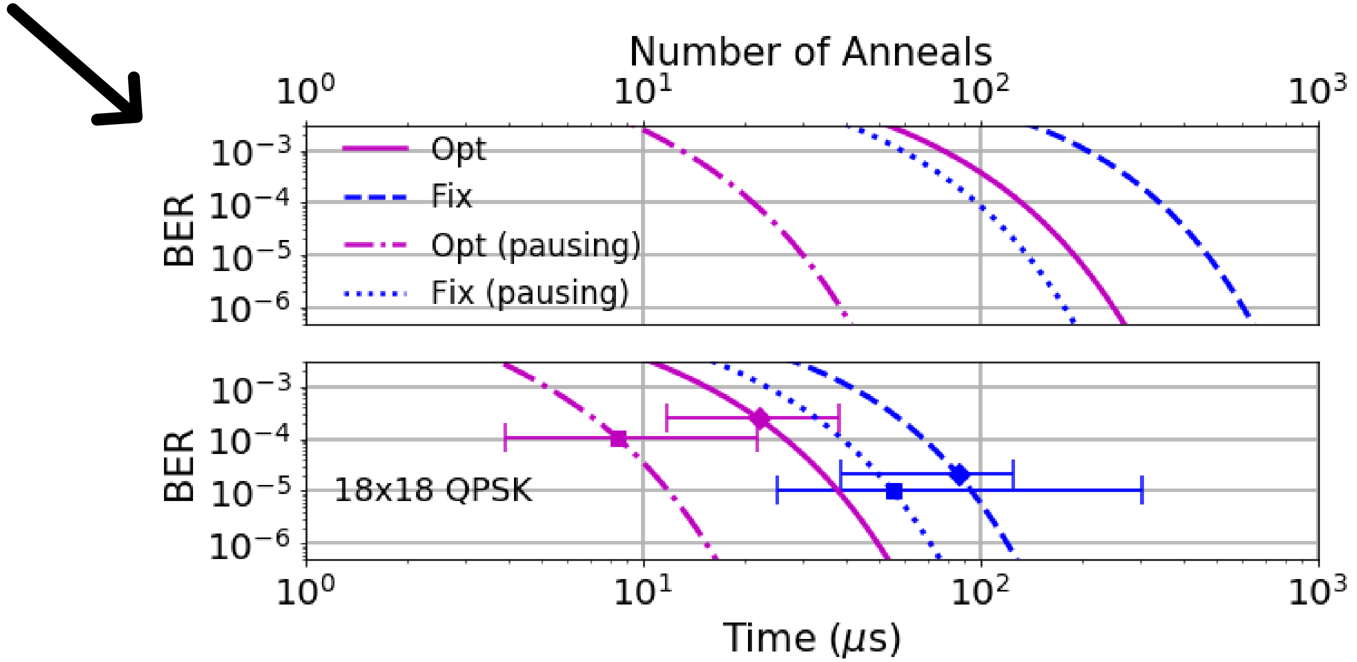
QA parameters: embedding, anneal time, pause duration, pause location, …

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

QuAMax’s Evaluation Methodology

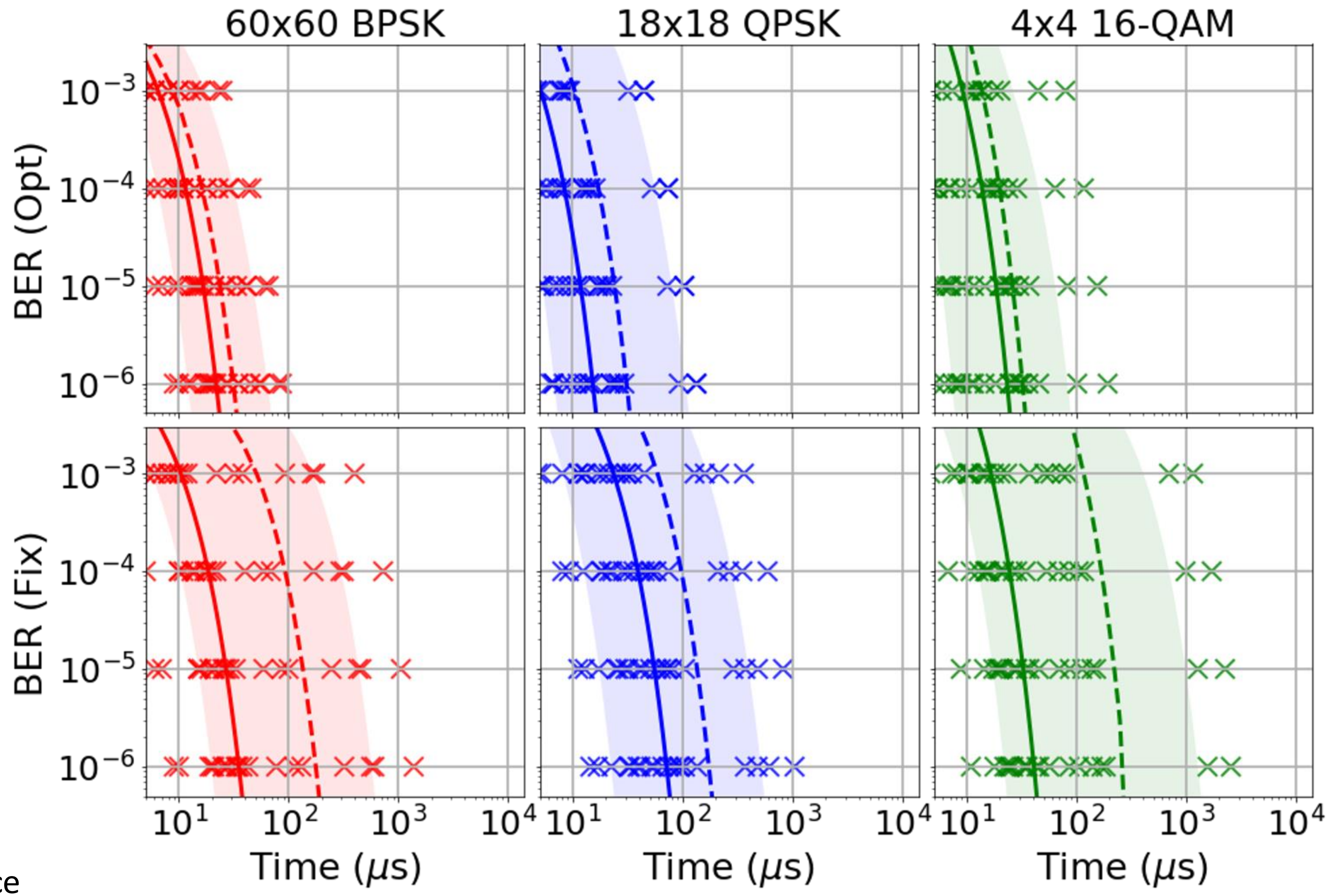
- Opt: run with optimized QA parameters per instance (oracle)
- Fix: run with fixed QA parameters per classification (QuAMax)

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



Time-to-BER (TTB)

Time-to-BER for Various Modulations

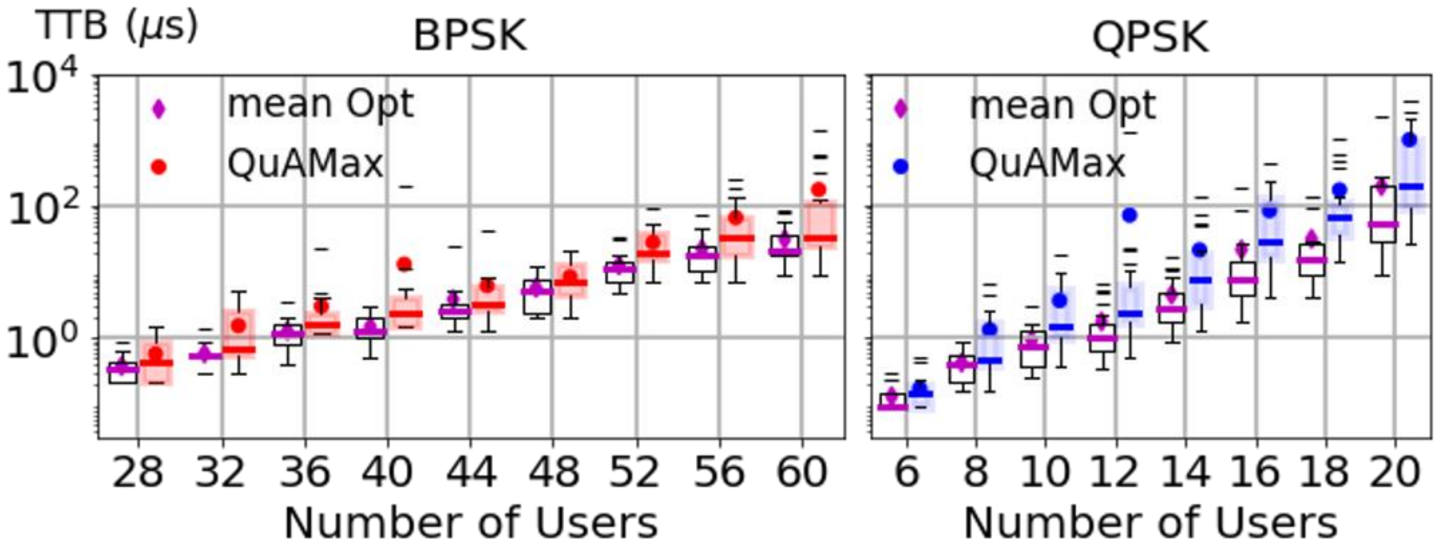


Lines: Median

Dash Lines: Average

x symbols: Each Instance

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

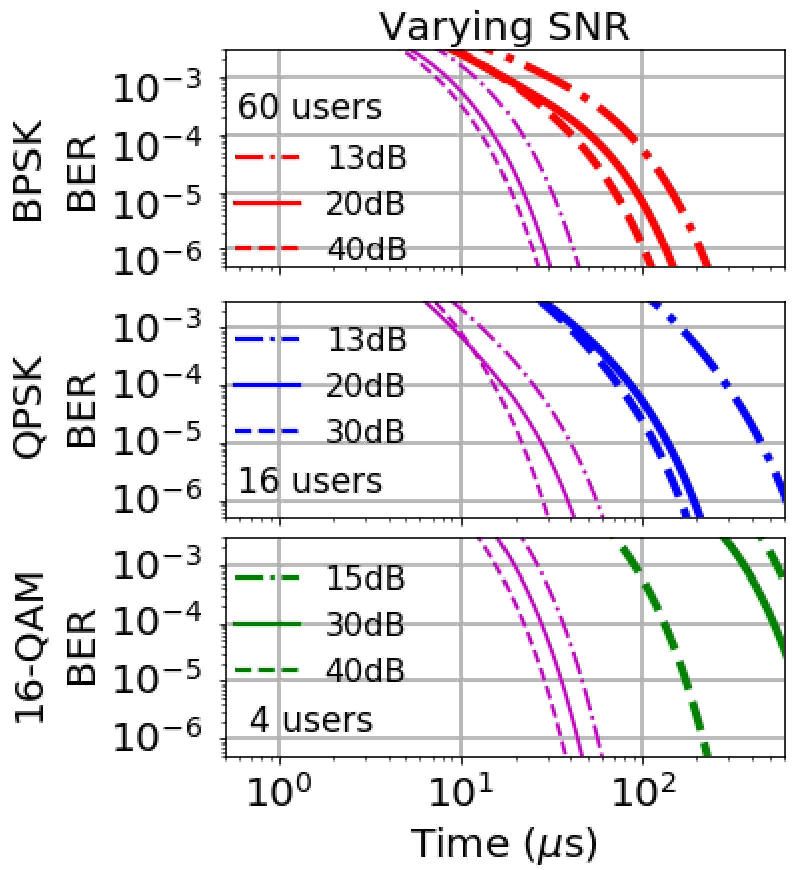


Practicality of Sphere Decoding

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

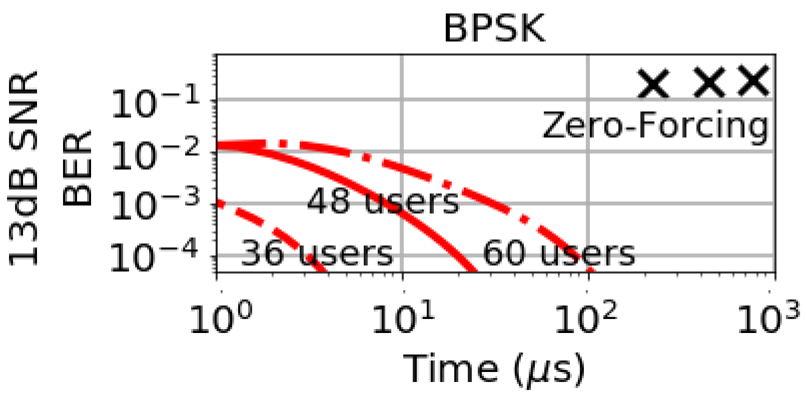
Well Beyond the Borderline of Conventional Computer

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 Trend of 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 could hold the potential to overcome the computational limits in wireless networks, but technology is still not mature.
- Our work paves the way for quantum hardware and software to contribute to improved performance envelope of MIMO.

Supported by

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Thank you!