Quantum Technologies for UAS (QTech)

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Motivation

- Recent advances in small Unmanned Aerial System (sUAS) lower the barrier of entry for all participants
- Advances are likely to lead to greater vehicle densities, a more heterogeneous mix of vehicles and equipment and levels of autonomy
- These advances will increase the chance for communications disruptions which can impact safety and security

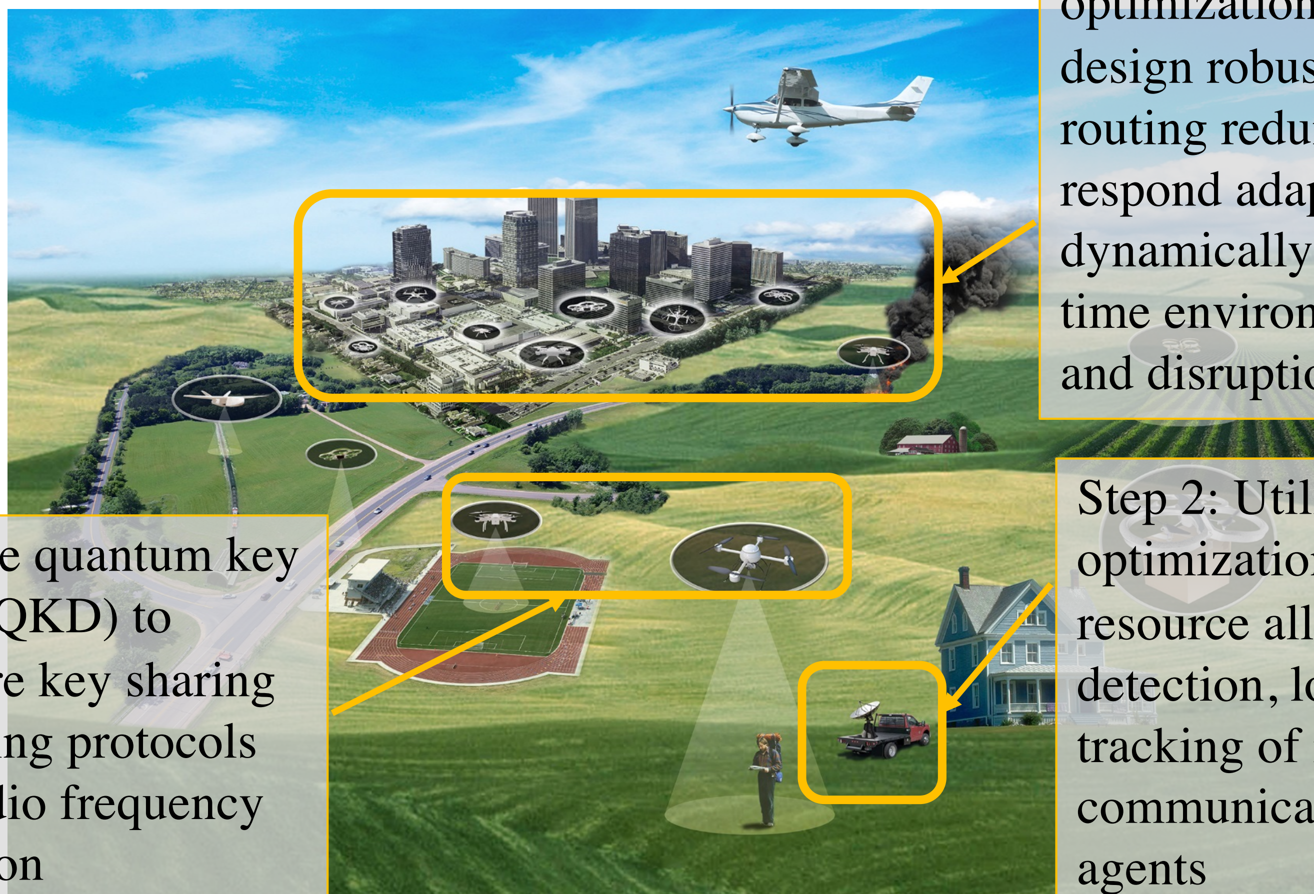
Outline

- Robust Network Design Methodology
- Brief Overview of Quantum Annealing
- Mapping and Embedding
- Results
- Conclusions

Methodology for Enabling Robust Communications

Harness the power of quantum technologies to enable robust communications for sUAS operations through a three pronged approach

Methodology for Enabling Robust Communications



Step 1: Utilize quantum optimization algorithms to design robust networks with routing redundancy that can respond adaptively to dynamically changing real-time environmental changes and disruptions

Step 2: Utilize quantum optimization algorithms resource allocation for detection, localization, and tracking of mobile communications disruptions agents

Step 3: Utilize quantum key distribution (QKD) to execute secure key sharing in anti-jamming protocols for secure radio frequency communication

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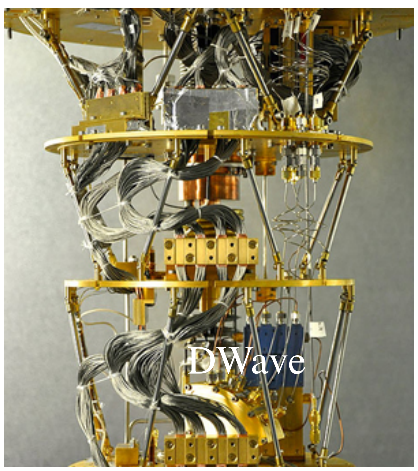
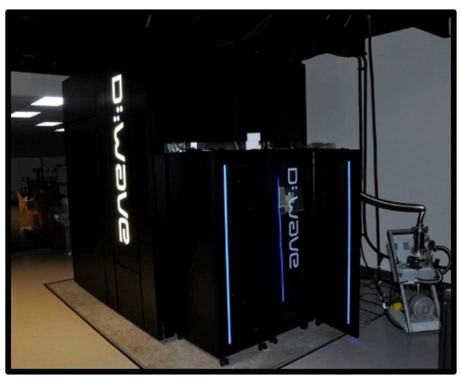
Emerging Quantum Hardware

Special purpose

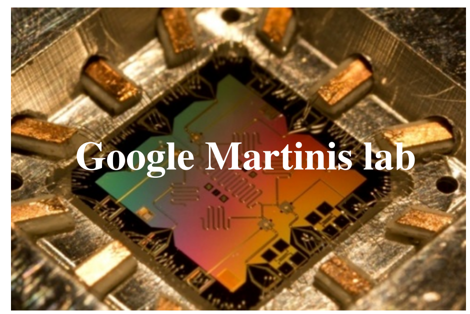
Quantum annealers, which run one type of quantum heuristic for optimization

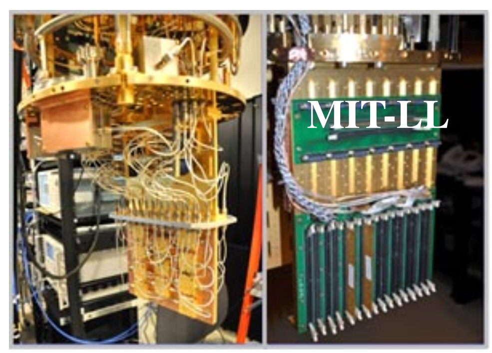


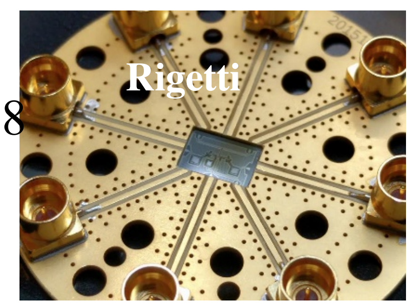


General purpose

Universal quantum computers

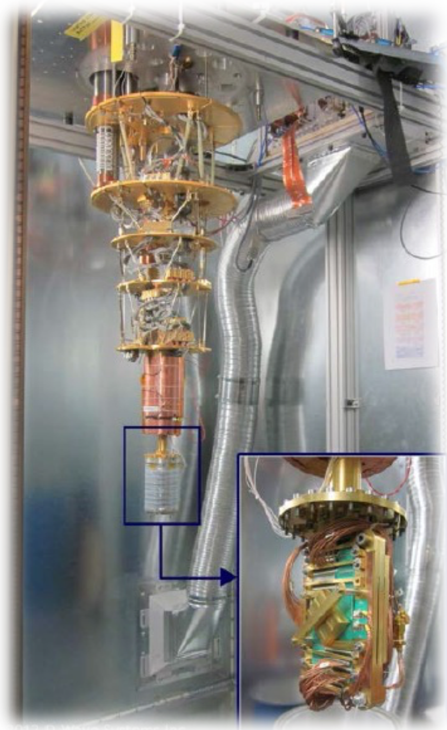


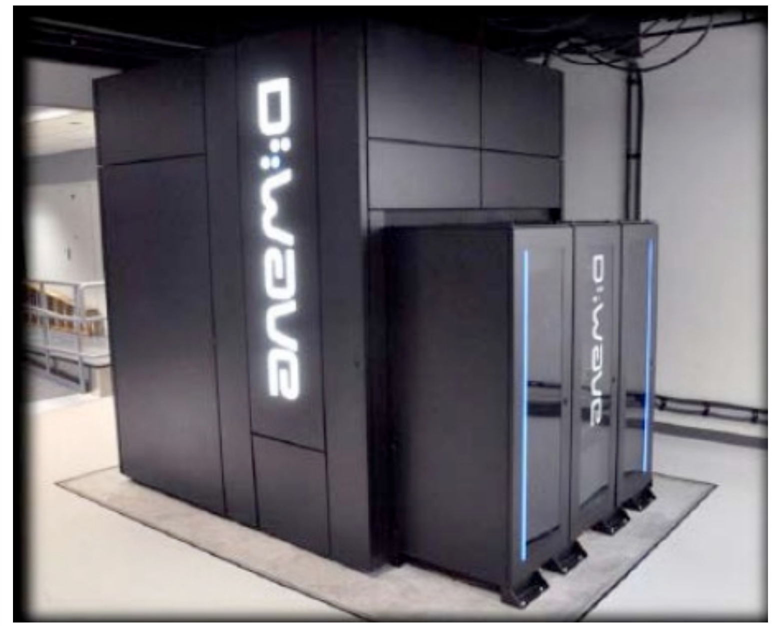


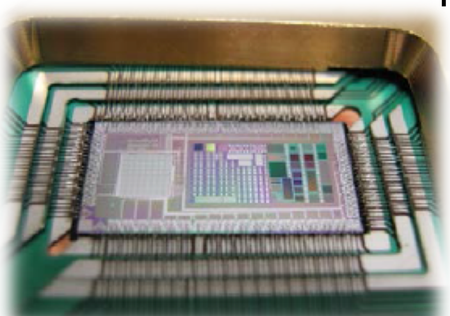


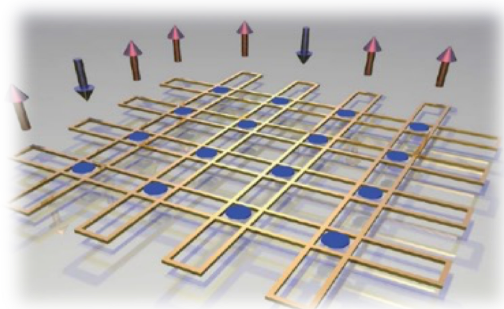
D-Wave System Hardware

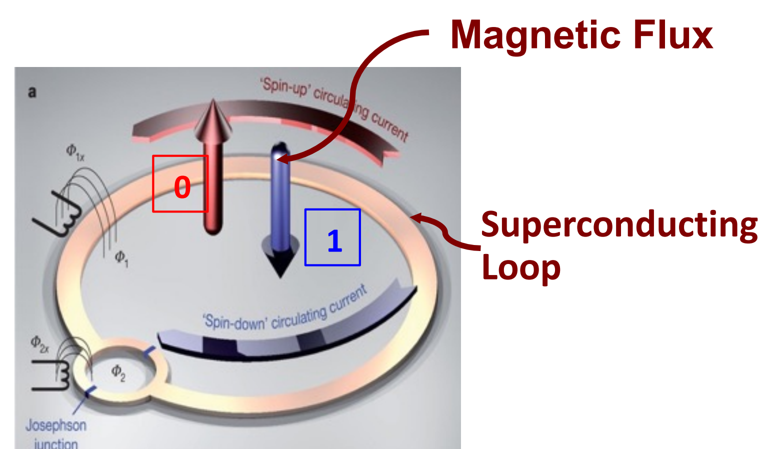
- Collaboration with Google and USRA led to installation of system at NASA Ames
- Started with 512-qubit Vesuvius processor (currently upgrading to 2000-qubit Whistler)
- 10 kg metal in vacuum at ~15 mK
- Magnetic shielding to 1 nanoTesla
- Protected from transient vibrations
- Single annealing takes 20 μs
- Typical run of 10,000 anneals (incl. reset & readout takes ~4 sec)
- Uses 12 kW of electrical power











Focused on solving discrete optimization problems using quantum annealing

Foundational Theory of Quantum Annealing

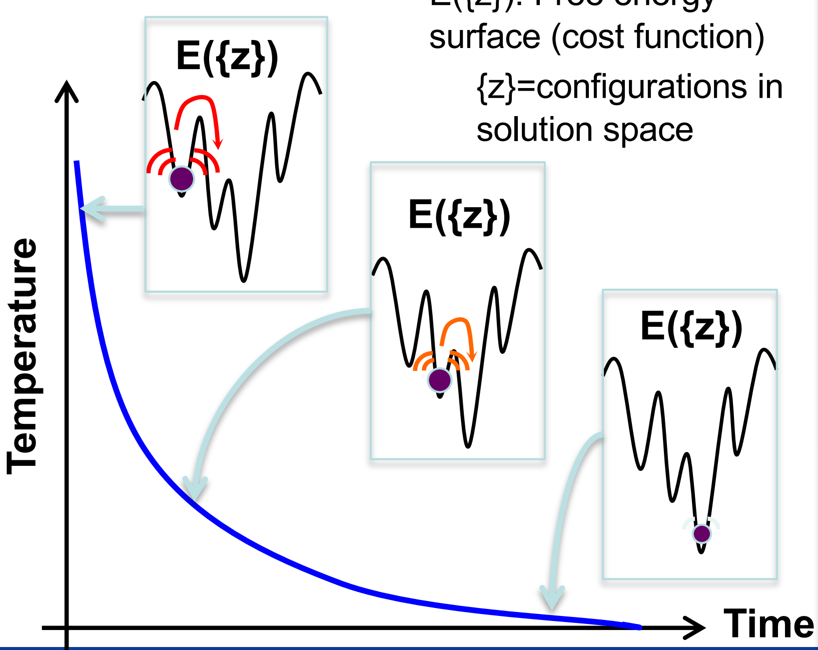
Simulated Annealing

(Kirkpatrick et al., 1983)

- **Algorithm:** Start with high temperature; then, gradually reduce intensity of thermal fluctuations to obtain optimal configuration
- Transitions between states via jumping over barriers due to thermal fluctuations

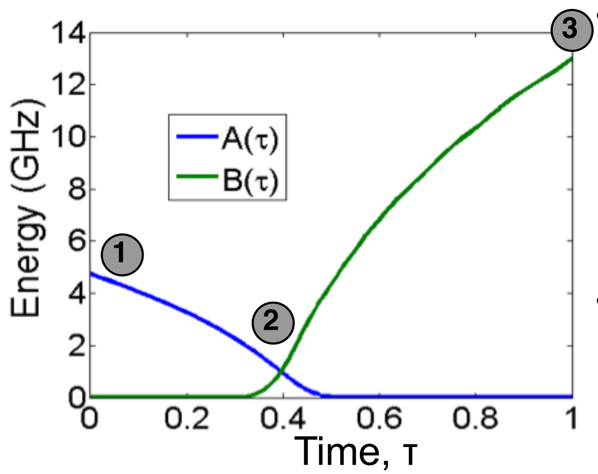
E({z}): Free energy surface (cost function)

{z}=configurations in solution space

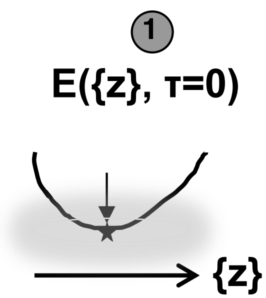


Quantum Annealing

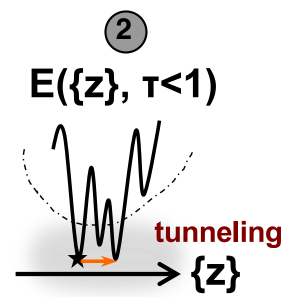
(Finnila et al., 1994, Kadawaki & Nishimori, 1998, Farhi et.al., 2001)



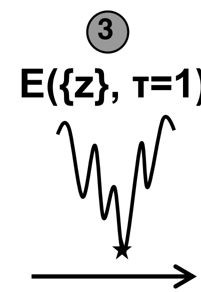
- **Algorithm:** Start with large amplitude A(τ) responsible for quantum fluctuations; then, gradually turn it off while turning on the cost function of interest B(τ)
- Transitions between states via tunneling through barriers due to quantum fluctuations



Initialize in an easy to prepare full quantum superposition



Quantum states explored by quantum tunneling



Final state a bit string encoding the solution with probability

Mapping problems to quantum annealing

1. **Identify** potential applications, **design** problems and benchmarks, **evaluate** near-term suitability
2. **Map** problems to Quadratic Unconstrained Binary Optimization (QUBO)
3. **Embed** into hardware (limited connectivity and number of qubits)
4. **Run and analyze** results

Each step has its research challenges

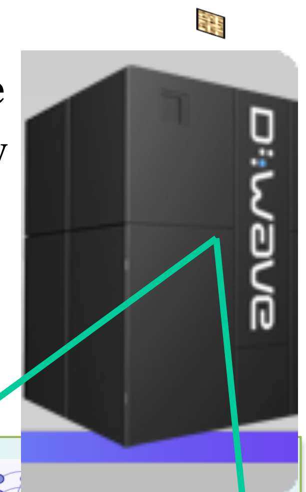
```
((define (domain graph-coloring-strips)
(:requirements :strips)
(:types color)

(:predicates
  (dummy)  (colored1)
  (color_of_1 ?c - color)
  (colored2)
   …
)
(:action color1
 :parameters (?c - color)
 :precondition (and
   (not (colored1))
 :effect (and
   (colored1)
)
```

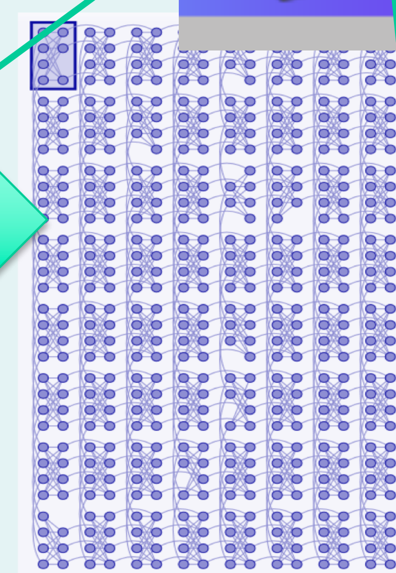
Map

QUBO

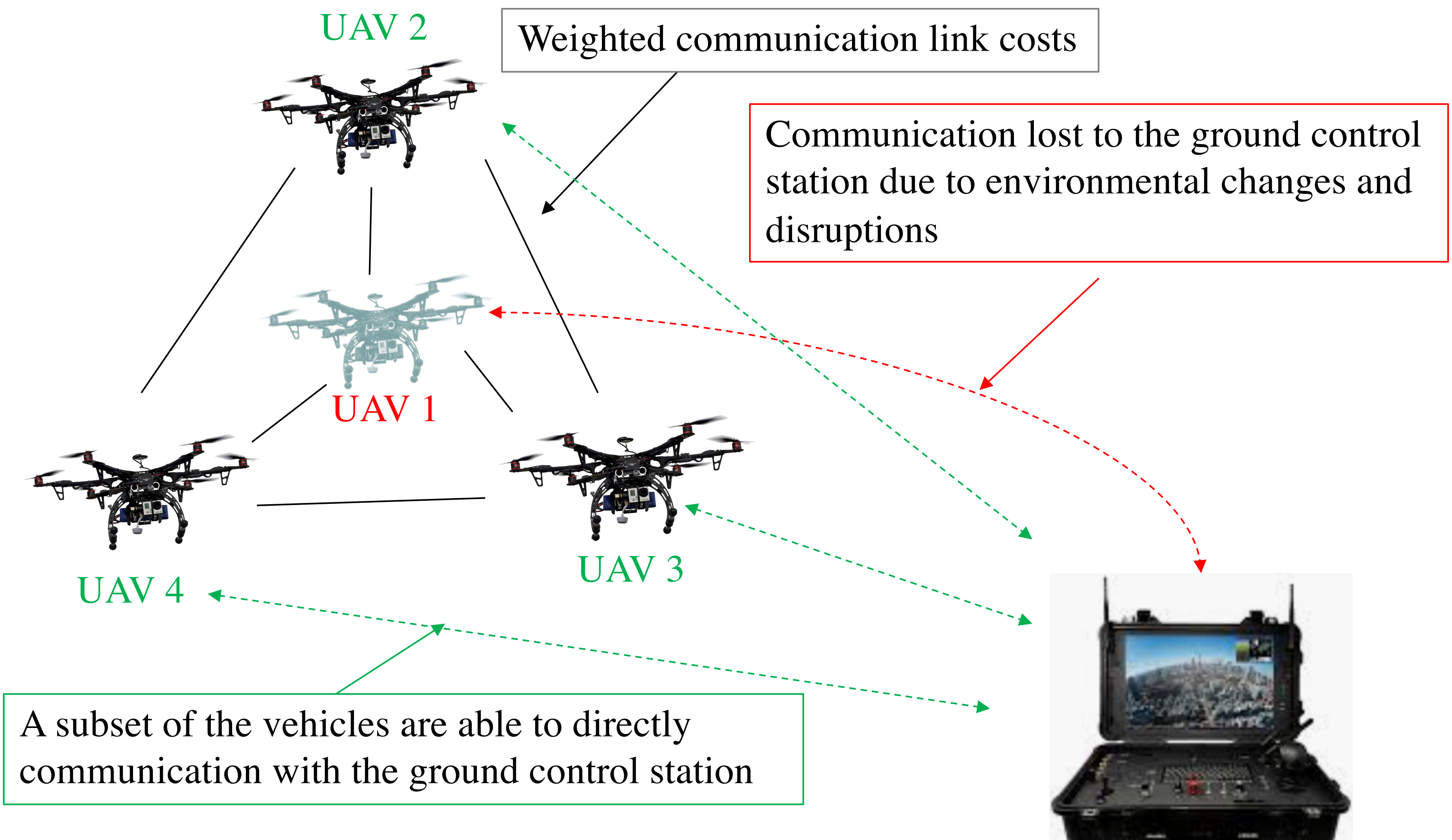
$$H_P = -\sum_{i=1}^{N} h_i \hat{\sigma}_i^z - \sum_{i<j} J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

Embed



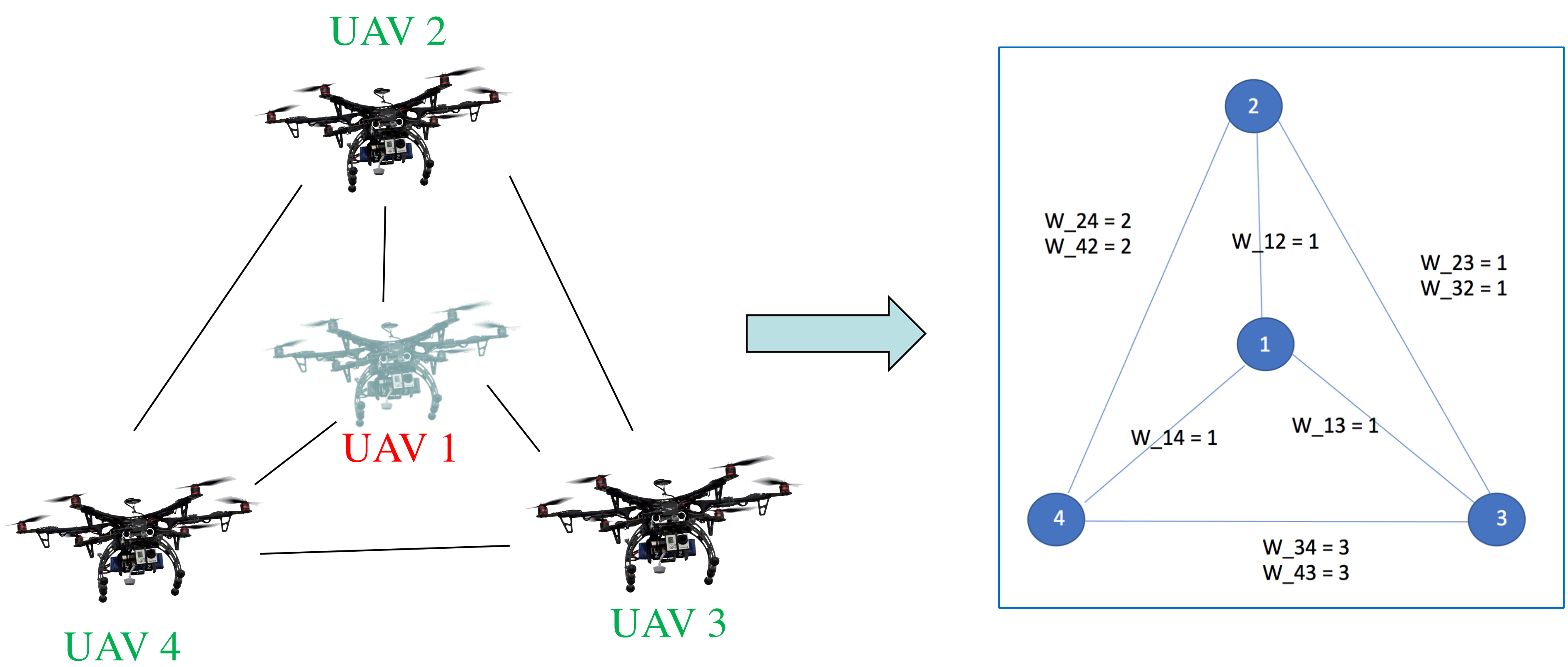


Our Application



What is an optimal approach to leverage vehicle-to-vehicle communications to re-establish connectivity to the ground control station?

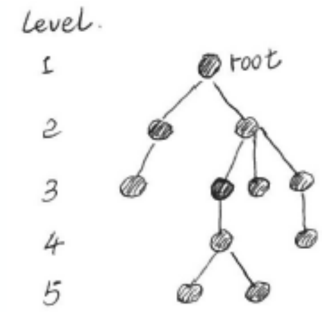
Our Application Mapped to a Weighted Graph



Solutions to the weighted spanning tree optimization problem with maximal degree constraints provide solutions to our vehicle-to-vehicle networking problem [this is an NP-hard problem]

Mapping to QUBO: Level Based Mapping

Assign the communications denied vehicle as the root of the tree



Level: distance to the root in the tree.

Variables: $x_{p,v} = \begin{cases} 1 & p \text{ is parent of } v \\ 0 & p \text{ is not parent of } v \end{cases}$ $\quad y_{v,l} = \begin{cases} 1 & v \text{ is on level } l \\ 0 & v \text{ is not on level } l \end{cases}$

We seek to minimize the weight of a spanning tree $C_0 = \sum_{p,u} w_{pv} x_{u,v}.$

Each node v (other than root) has exactly one parent $C_{pen1} = \sum_{v\in\{2,\ldots,n\}} \left(\sum_{p:(pv)\in E} x_{p,v} - 1 \right)^2.$

Each node v has exactly one level (only root is on level 1) $C_{pen2} = \sum_{v\in\{2,\ldots,n\}} \left(\sum_{\ell=2}^{n} y_{v,\ell} - 1 \right)^2.$

Tree has degree at most delta

$$C_{pen3} = \sum_{p=2}^{v} \left(\sum_{v:(pv)\in E} x_{p,v} - \sum_{j=1}^{\Delta-1} z_{p,j} \right)^2 + \left(\sum_{v=2}^{d_r} x_{1,v} - \sum_{j=1}^{\Delta} z_{1,j}\right)^2$$

Node v's parent must be one-level lower than v

$$C_{pen4} = \sum_{p,v} \sum_{\ell=3}^{n} x_{p,v} y_{v,\ell} (1 - y_{p,\ell-1}) + \sum_{v=2}^{d_r} x_{1,v} (1 - y_{v,2}).$$

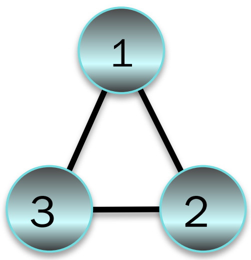
Our overall QUBO is

$$H_c = C_0 + A(C_{pen1} + C_{pen2} + C_{pen3} + C_{pen4})$$

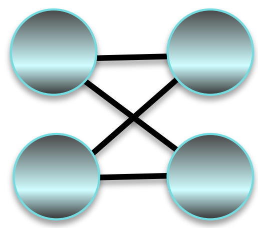
Embedding the QUBO

Embed a triangle onto a bipartite graph

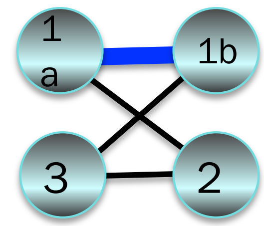
original QUBO



hardware connectivity



QUBO embedded



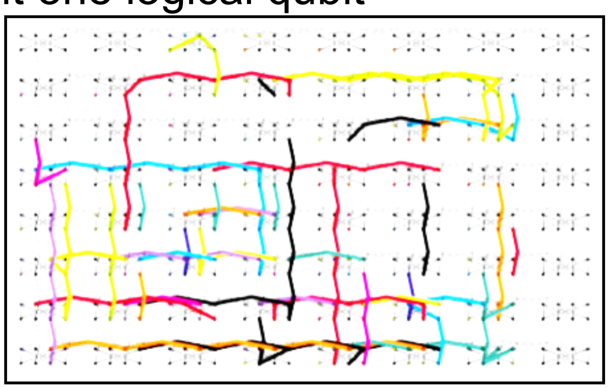
$$H_0 = J_{12}x_1x_2 + J_{23}x_2x_3 + J_{13}x_1x_3$$

$$H_1 = J_{12}x_{1a}x_2 + J_{23}x_2x_3 + J_{13}x_{1b}x_3 + \underline{J_{\texttt{Ferro}}}x_{1a}x_{1b}$$

Strong, but not too strong, ferromagnetic coupling between physical qubits x_{1a} and x_{1b} encourages them to take the same value, thus acting as a single logical qubit x_1

Embedding a realistic problem instance:

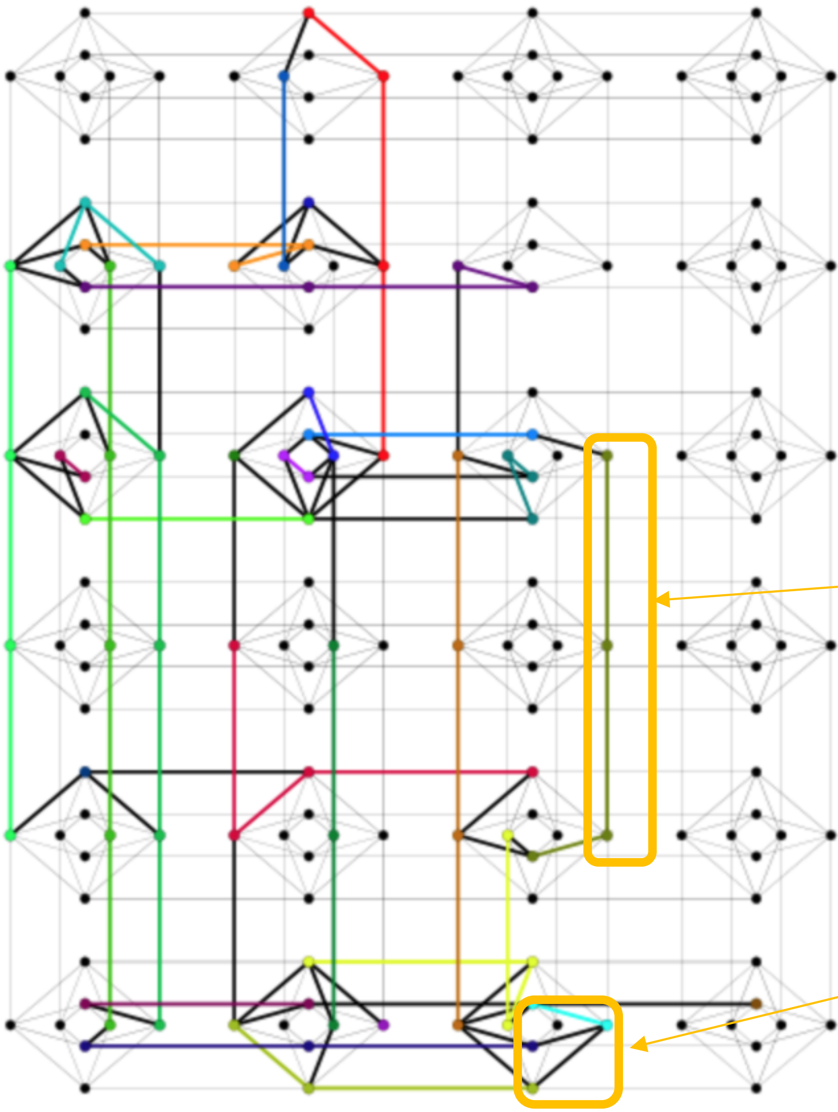
Physical qubits on each colored path represent one logical qubit



H_0 and H_1 have the same ground state but the energy landscape of the search space differs

Current research investigation: How best to set the magnitude of these “strong” couplings to maximize probability of success

Sample Embedding for 4 Vehicles



D-Wave Chimera graph showing physical qubit coupling

Qubits with similar node and edge colors represent chains used to map logical qubits to physical qubits on the hardware and coupling strength is set by J_ferro

Black edges represent connections between the logical qubits in our mapping and coupling strength is set by J_ij

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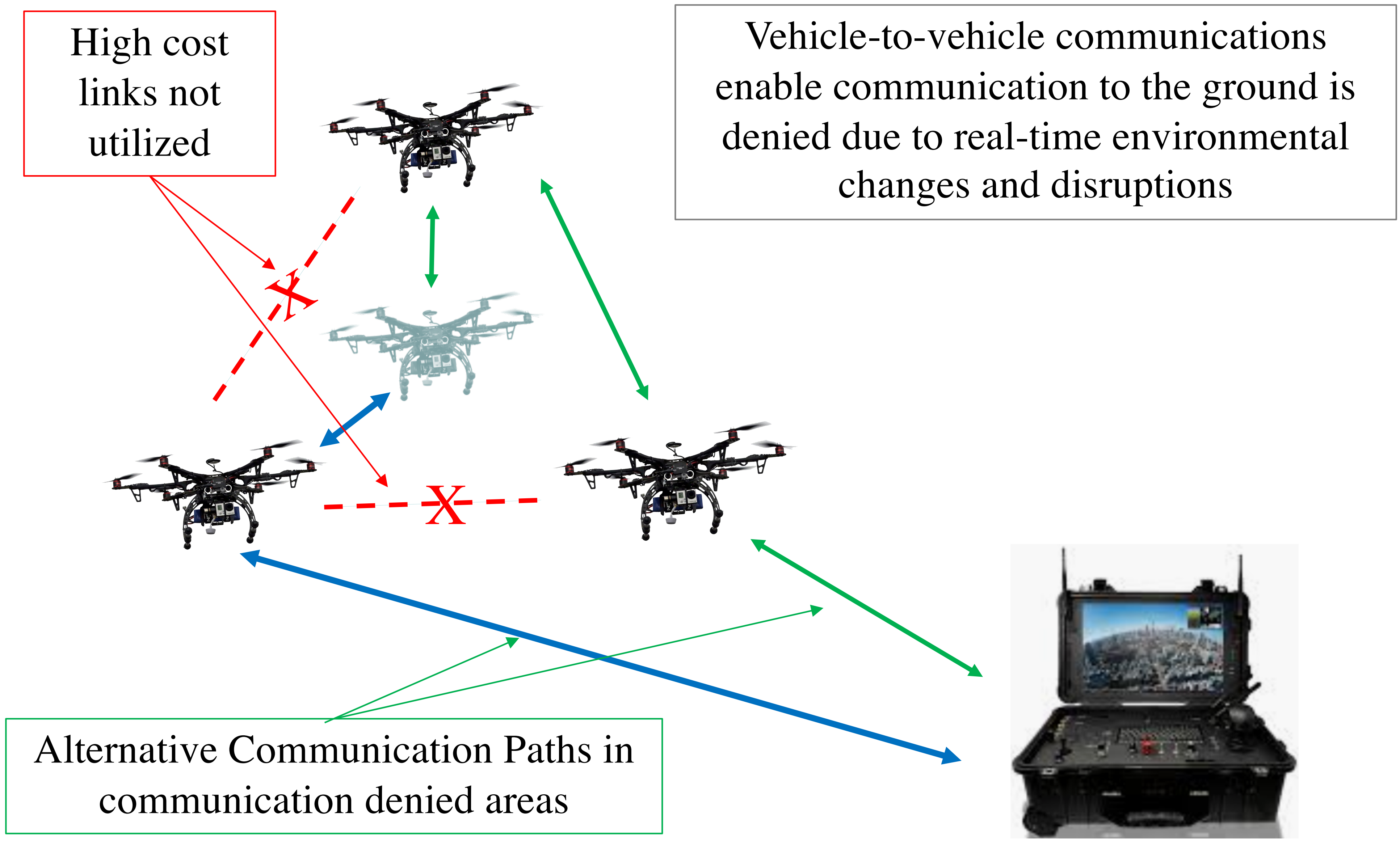
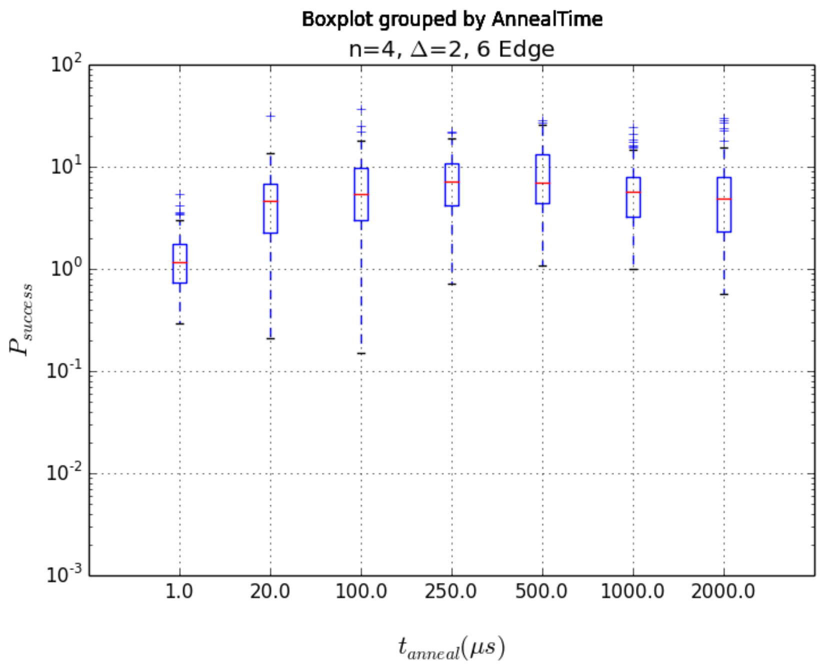
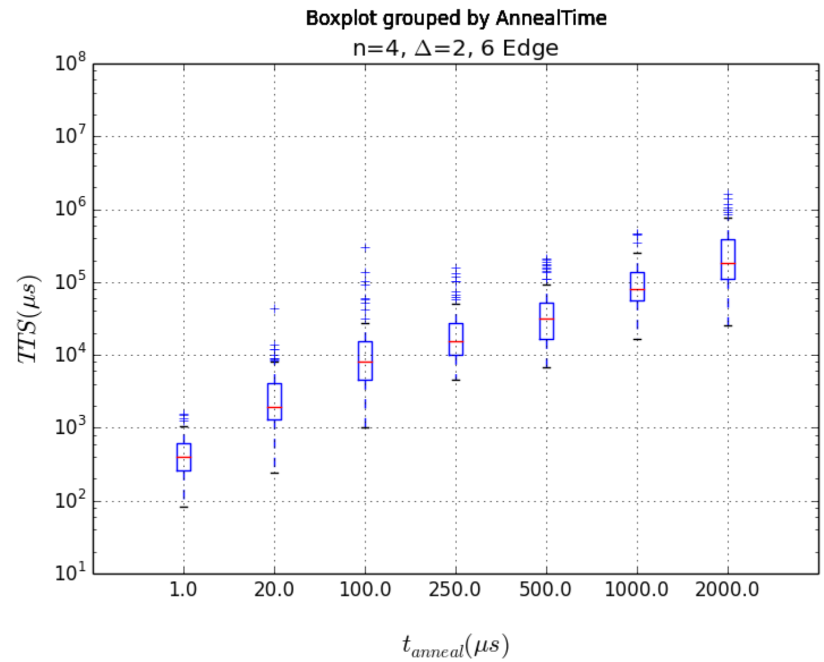
Minimum Cost Solution



Probability of Success for Four Vehicle Scenario





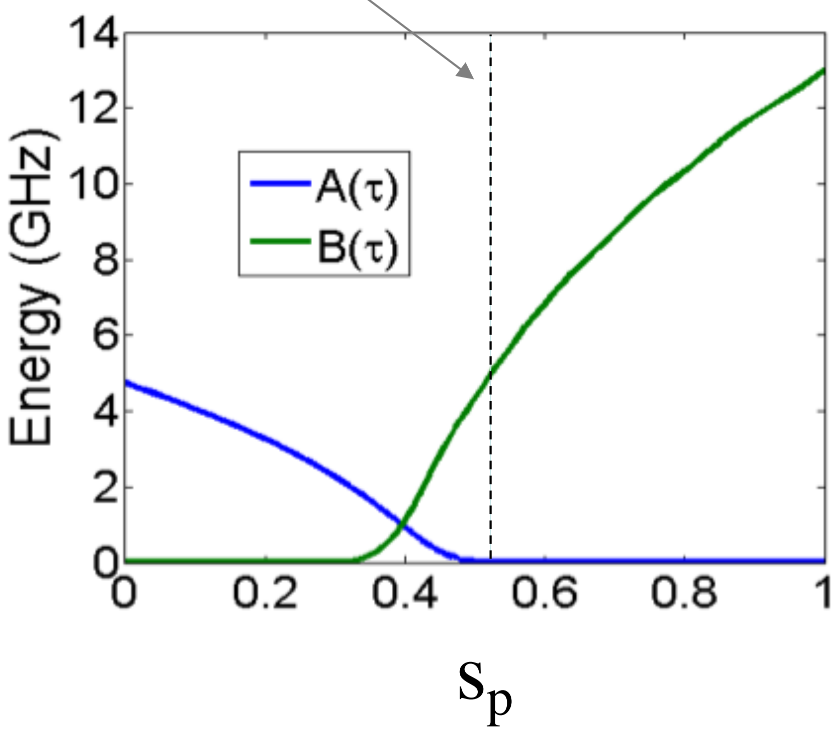
$$TSS = \frac{ln(1-0.99)}{ln(1-P_{success})} \cdot t_{anneal}$$

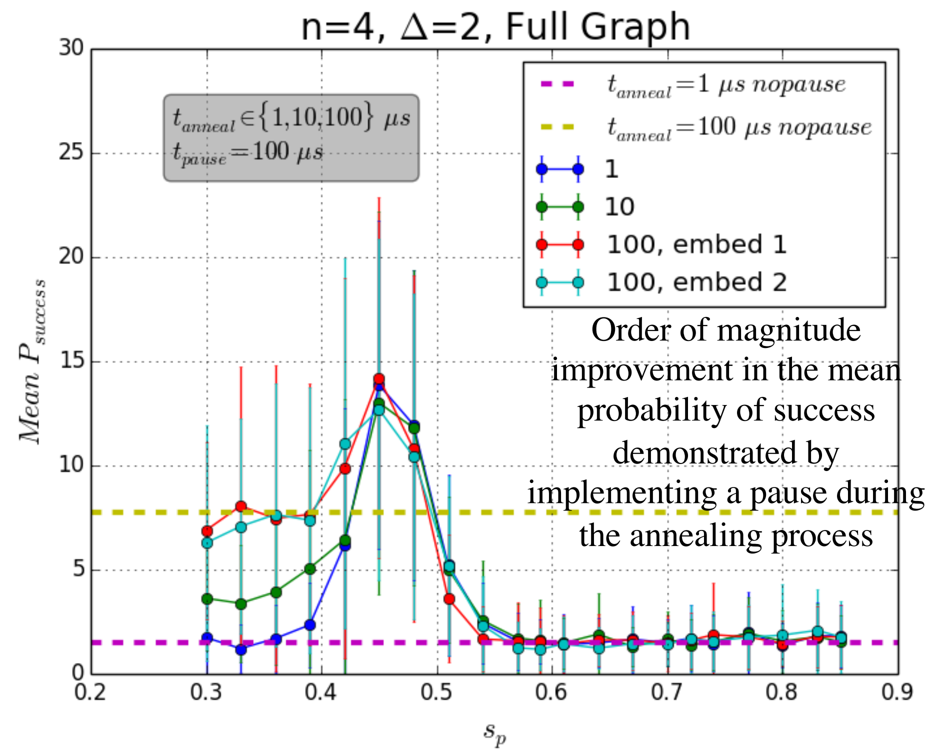
Expected anneal time to obtain a 99% success probability

Time to solution increase with increasing annealing times

Annealing Pause

Annealing Pause Location, s_p





Order of magnitude improvement in the mean probability of success demonstrated by implementing a pause during the annealing process

Conclusions

- Novel quantum algorithms for computational problems underlying robust network design can be solved on commercially available quantum annealing hardware

- Order of magnitude improvement in the mean probability of success demonstrated by implementing a pause during the annealing process

- Two orders of magnitude in the time to solution observed when increasing the annealing time from 1 to 2,000 microseconds

- Demonstration that commercially available quantum annealing hardware is able to solve embedded application problems