On Efficient Data Collection Using Autonomous Underwater Vehicles

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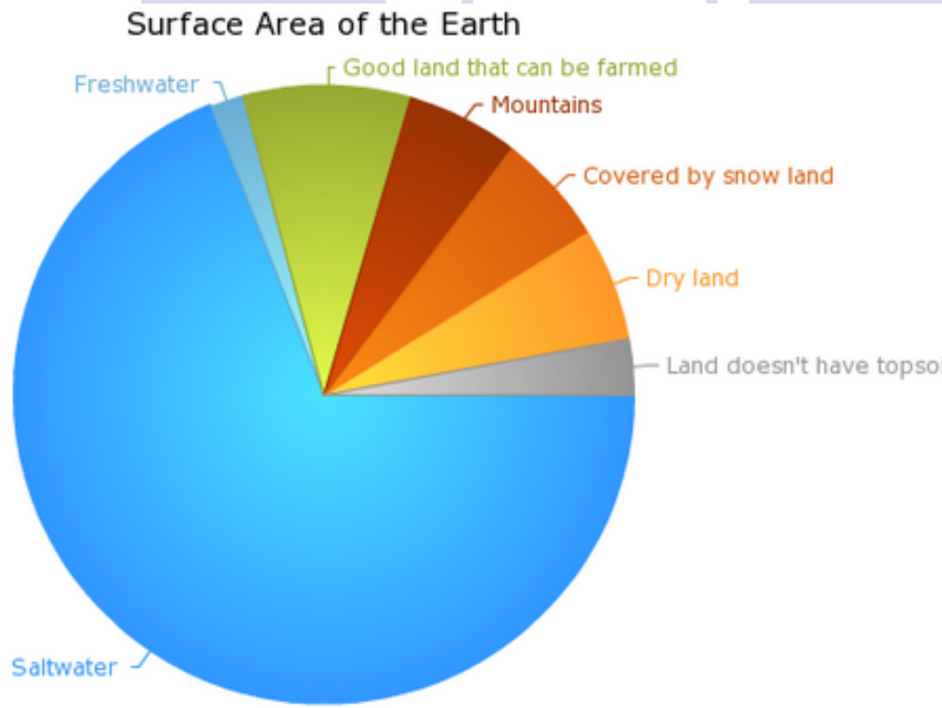
Road Map

1. Introduction
2. Optimal AUV Resurfacing
3. Constructing A Cycle
4. Cycle Enhancement
5. Extensions
6. Experiments
7. Conclusions and Future Work

1. Introduction

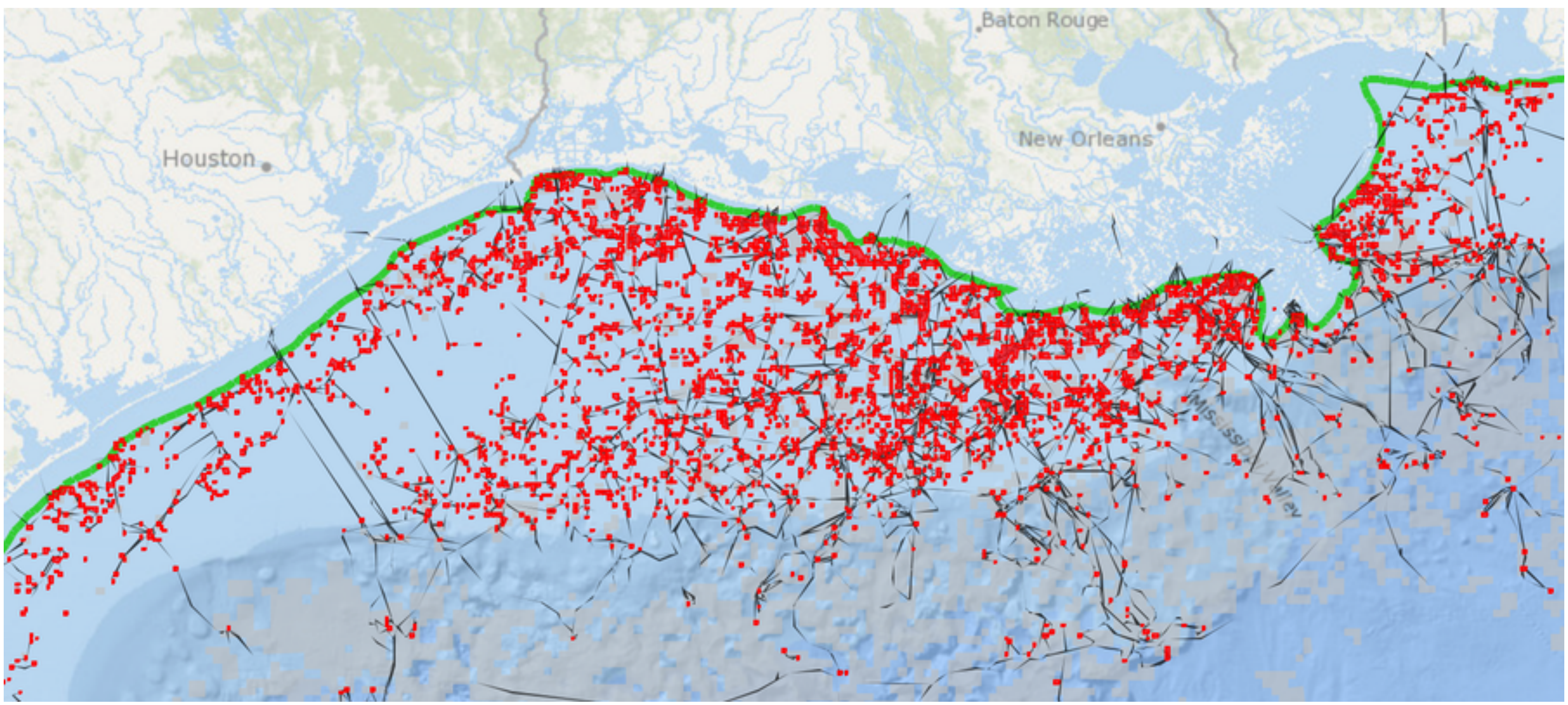
- Earth is mostly sea
  - > 70 % of the surface



- Signal propagation
  - Electromagnetic signal decays quickly in the water
  - Acoustic signal has limited bandwidth and long delay
    - Speed: 10 kbps
    - Distance: 100 m

1. Introduction

- Efficient search in deep sea is notoriously difficult
  - The detection of oil pipe leak in Mexico



1. Introduction

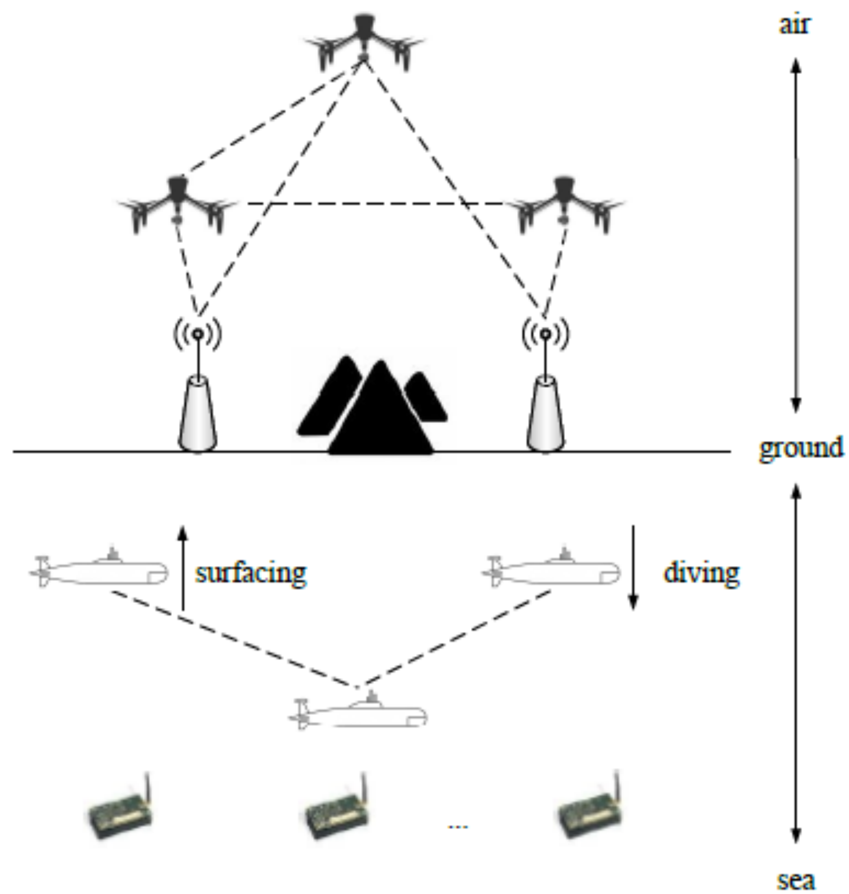
Malaysia Airlines MH 370

- DigitalGlobe
  - Crowdsourcing volunteers comb satellite photos for Malaysia Airlines jet
- March 11, 2014 (from CSU prof. email)

  I just saw on our local Denver Fox news (KDVR.com) that a local company, DigitalGlobe, has reoriented their satellites to take high-res images in the area where the plane may have crashed. Crowdsourcing efforts are on to have people scan these images and find signs of debris. I was reminded of Jie Wu's talk earlier this month.

1. Introduction

- Multi-tiered networks
  - In the air
    Unmanned Aerial Vehicle (UAV)
  - On the ground
  - Under the sea
    Autonomous Underwater Vehicle (AUV)



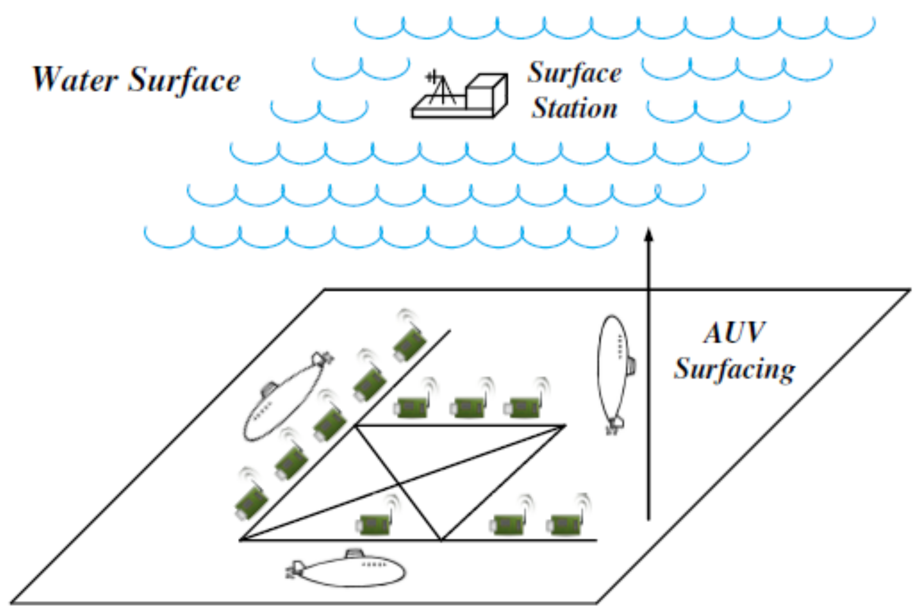
- Communication
  - A2A (Air-to-Air), A2G, and G2A
  - G2G (Ground-to-Ground)
  - U2U (Underwater-to-Underwater), U2G, and G2U

UAVs and AUVs: swarm intelligence

J. Wu, "A Multi-tiered Network with Aerial and Ground Coverage," Computer Communications, 40-years special issue, 2018

1. Introduction

- Surfacing of multiple AUVs to transmit collected data
  - Parallel 2-D search space (a set of connected line segments) to the water surface
- Examples:
  - Undersea tunnel
    - Depth: 75m~300m
  - Sensors on oil pipes
    - Depth: 200m~5,000m
  - Submarine cable
    - Depth: up to 8,000m



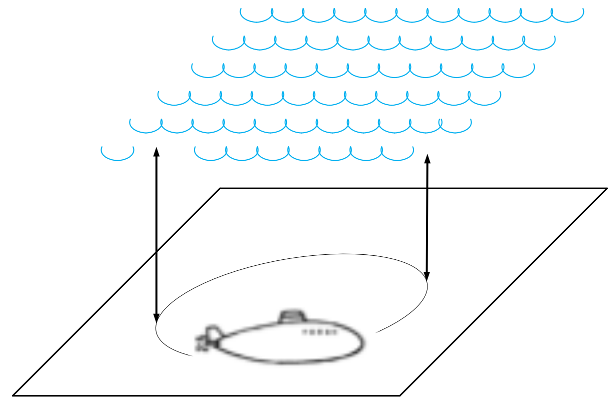
How to Solve It

- If you can't solve a problem, then there is an easier problem you can solve: find it
- Four principles
  - Understand the problem
  - Devise a plan
  - Carry out the plan
  - Look back

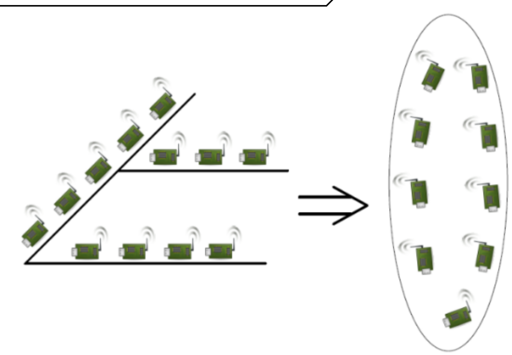
Polya

2. Optimal AUV Resurfacing

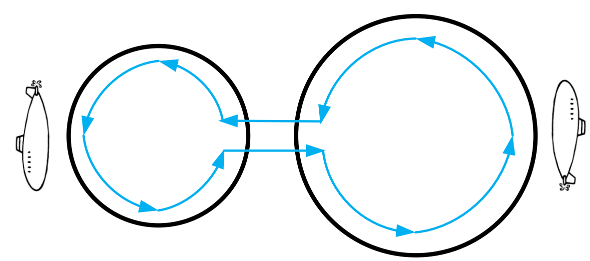
- AUV trajectory planning: minimizing the average delay
  - How can we schedule AUVs to resurface optimally in a circular search space (Eulerian cycle)?



  - How can we schedule multiple AUVs to resurface in general search space?

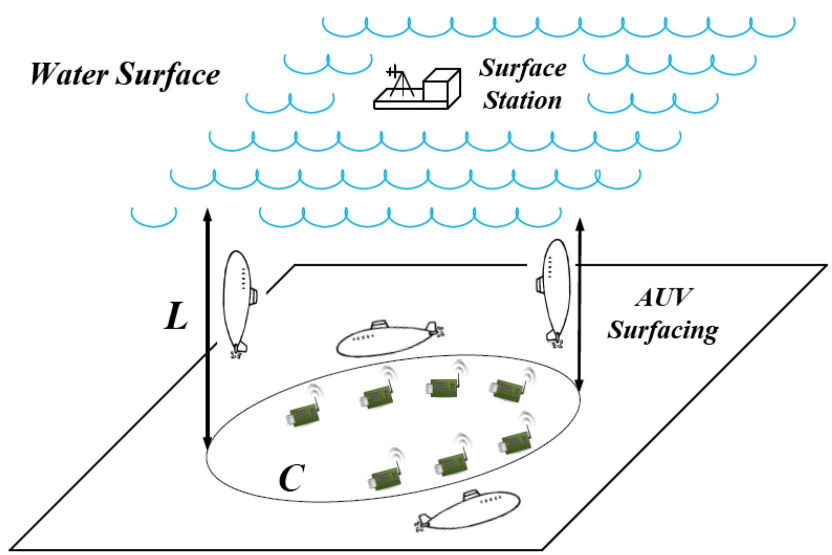


  - How can we convert a search space to a circular search space?
  - How can we merge the cycles to reduce the average delay?



2. Optimal AUV Resurfacing

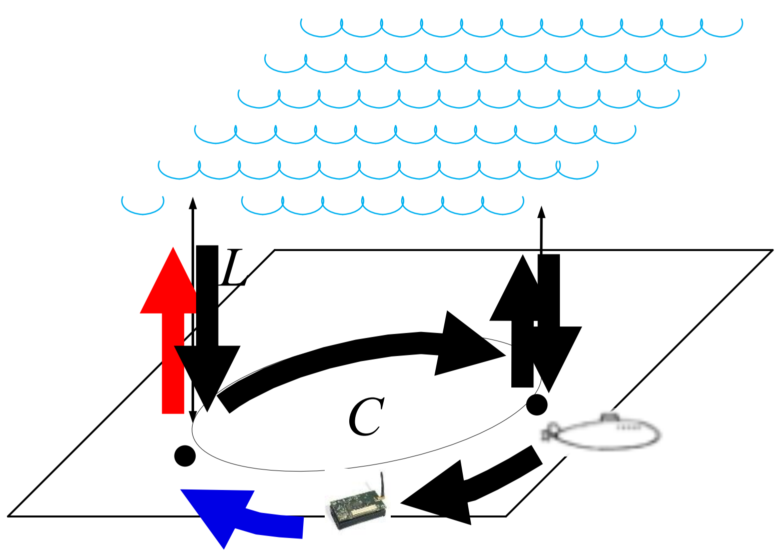
- Data are uniformly distributed with a fixed generation rate
- **Objective**: minimize the long-term average delay to the water surface
- The speed of a AUV is unit
  - C : the cycle circumference
  - L : the depth of the search space
  - k : the frequency of resurfacing



Unit speed through distance scaling
(cruising speed: 37 km/h, diving/surfacing: 26 km/h, current: 5 km/h)

2. Optimal AUV Resurfacing

- A larger AUV resurfacing frequency
  - can bring node A's data to the water surface more quickly
  - However, node A's data needs to wait for the next AUV for a longer time, since resurfacing takes additional time



$$\boxed{D = \frac{C + 2kL}{2} + \frac{C}{2k} + L}$$

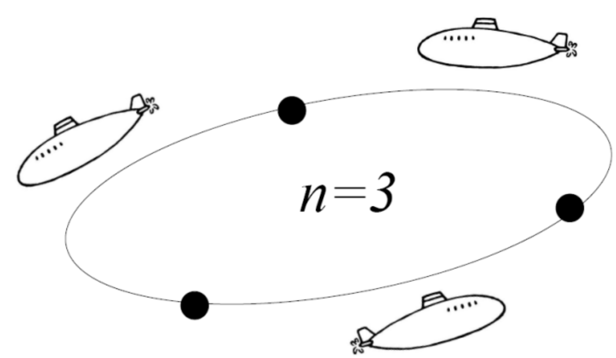
$$D_{min} = \frac{C}{2} + \sqrt{2LC} + L \text{ when } \boxed{k = \sqrt{\frac{C}{2L}}}$$

$$\boxed{C/k = \sqrt{2LC}}$$

2. Optimal AUV Resurfacing

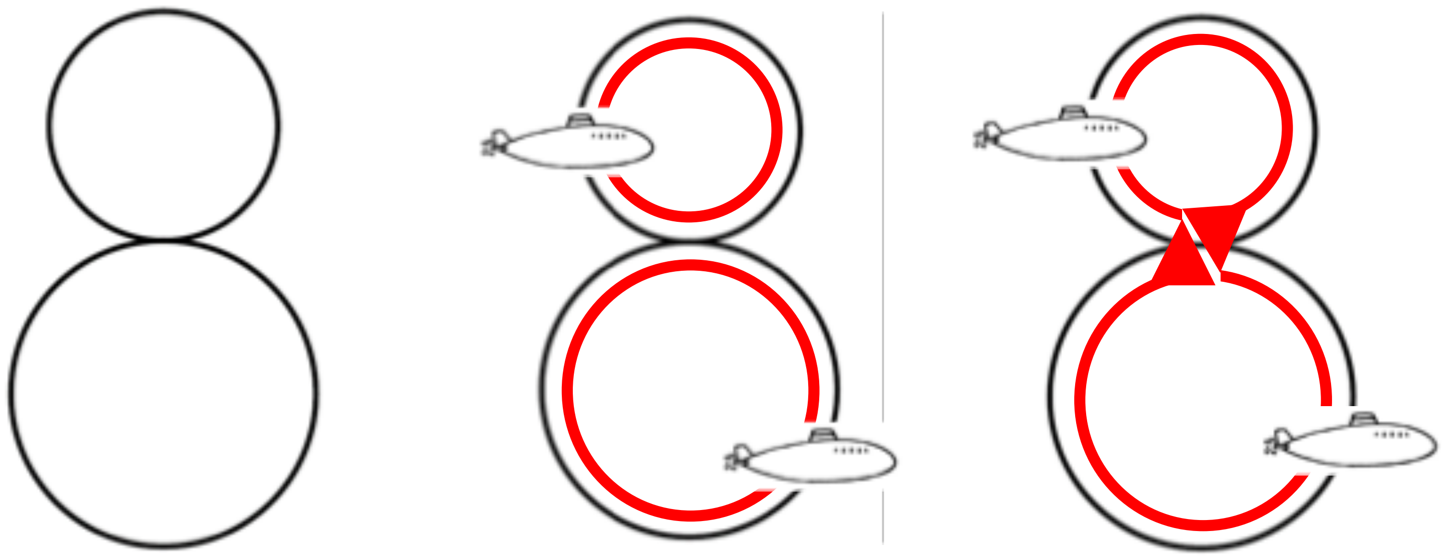
- **Theorem 1**: Optimally, the AUV resurfaces after traveling a distance of $\sqrt{2LC}$ on the original cycle (if only one AUV is used)

- If we have multiple AUVs (n AUVs)
  - Evenly distribute these AUVs on the cycle
  - Each AUVs resurfaces after traveling a distance of $\sqrt{\frac{2LC}{n}}$



3. Constructing A Cycle

- Why do we use only one large cycle instead of multiple small cycles to cover the search space?



Search space　　Scheme 1 (non-shared)　　Scheme 2 (shared)

- **Theorem 2**: Scheme 2 is no worse than Scheme 1, due to more balanced cycling tasks among AUVs.

3. Constructing A Cycle

- General search space: a set of connected line segments (called sensing edges in the graph)

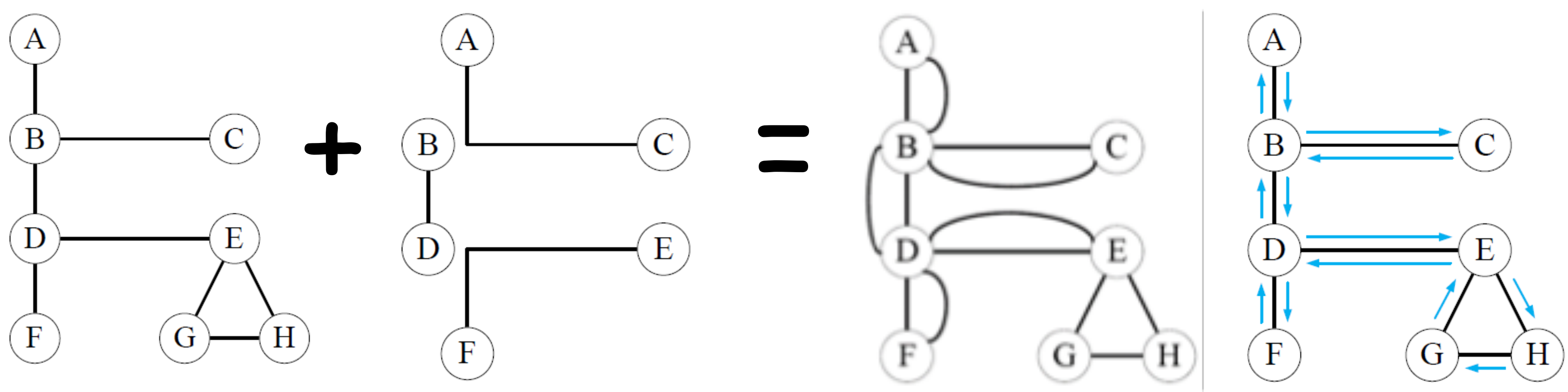
- Graph with an even degree for every vertex
  - An Eulerian cycle exists (i.e., a cycle that visits each edge once and only once)

- Graph has vertices with odd degrees
  - Add redundant edges to make odd degree even
  - We need to minimize pairwise odd degree nodes by adding one link (There is an even number of vertices with odd degrees)

3. Constructing A Cycle

- **Algorithm 1**: construct an Eulerian cycle by adding sensing edges

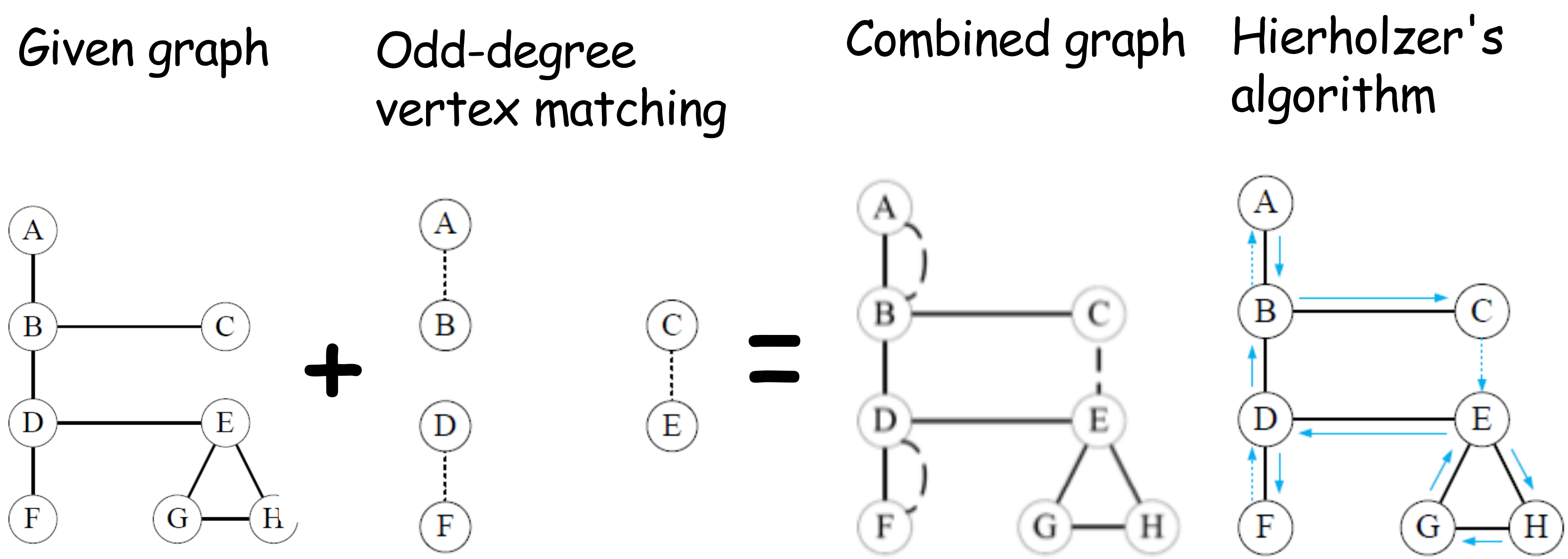
Given graph | Odd-degree vertex matching | Combined graph | Hierholzer's algorithm



- Some sensing edges are visited for multiple times

4. Cycle Enhancement

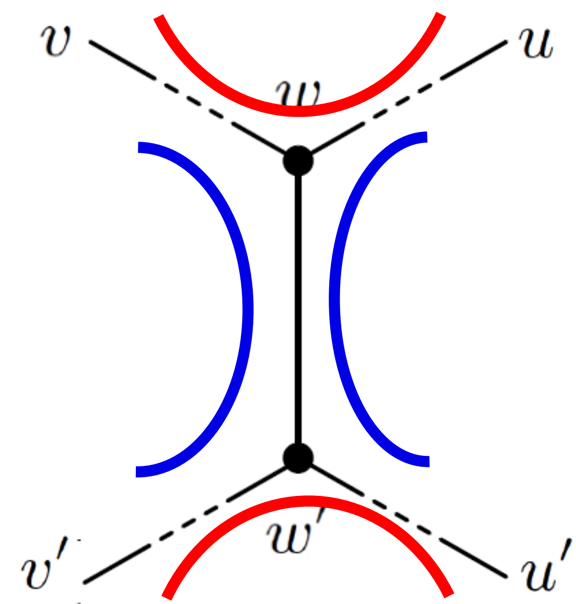
- Geometric shortest non-sensing edges (which may not be in the search space) can shorten the cycle circumference, although no data is collected from them
- **Algorithm 2**: construct the cycle by adding non-sensing edges



4. Cycle Enhancement

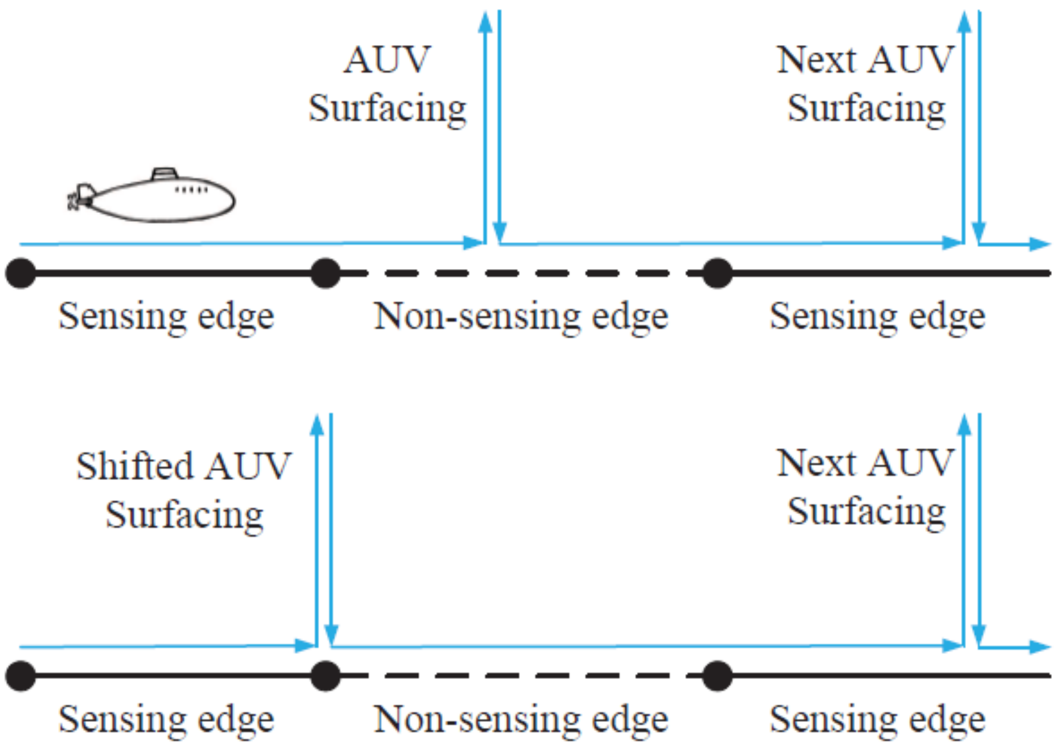
- **Theorem 3:** In the enhanced cycle construction, the total length of the non-sensing edges is no larger than the total length of sensing edges.

  - No single edge will appear in the shortest paths of two matching pairs using sensing edges
  - In the worst case, all the edges in the given graph are used once in pair matching
  - Moreover, non-sensing edges provide "short-cuts" for all pairs using sensing edges



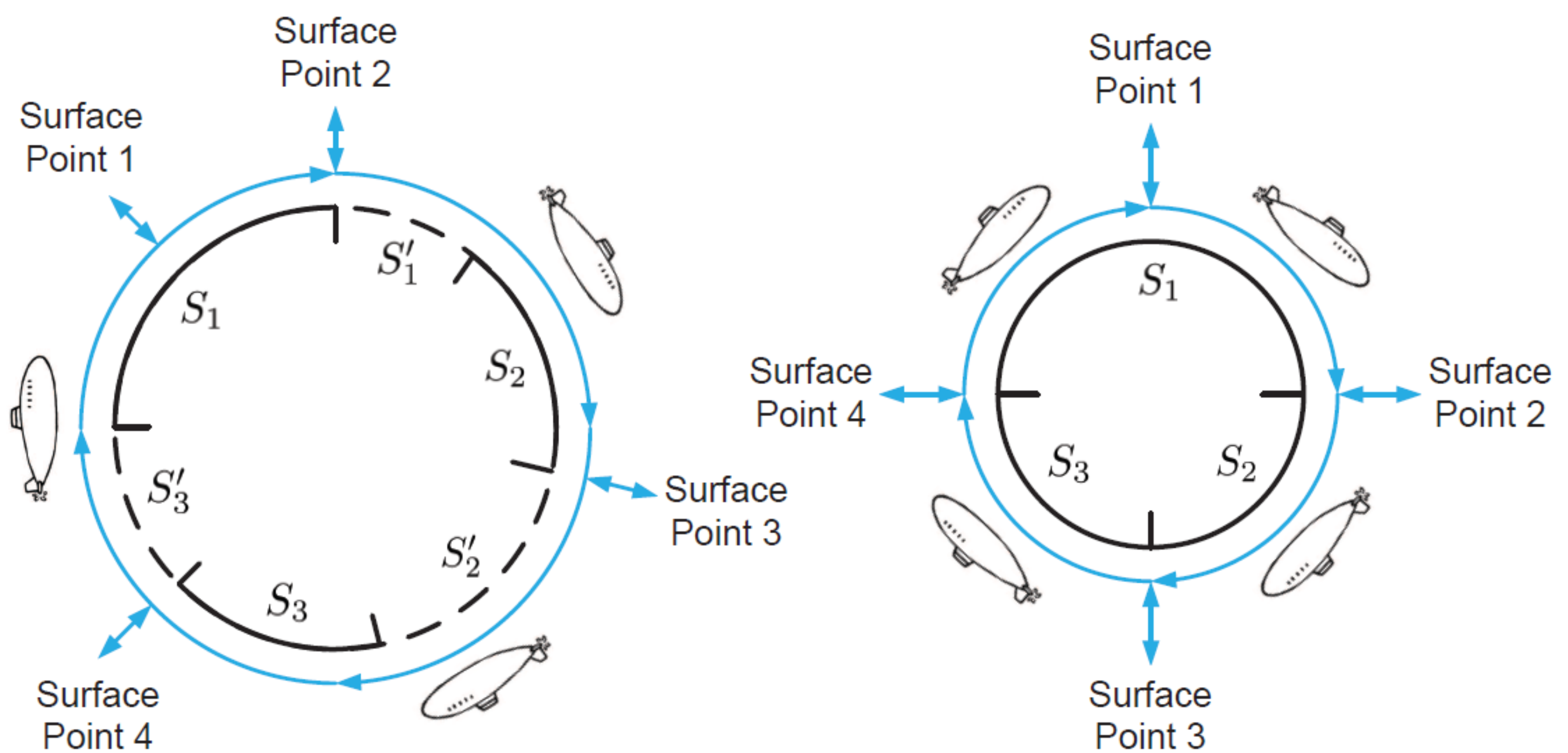
4. Cycle Enhancement

Algorithm 2s (cycles with non-sensing edges): shift the surface point from each non-sensing edge to the end of the last sensing edge (i.e., change resurfacing locations)



4. Cycle Enhancement

- **Algorithm 2r** (cycles with non-sensing edges): by removing non-sensing edges (and change both resurfacing frequency and locations)
  - Optimal when C^* is the total circumference of sensing edges and the length of each sensing edge is an integer multiple of $\sqrt{2LC^*}$



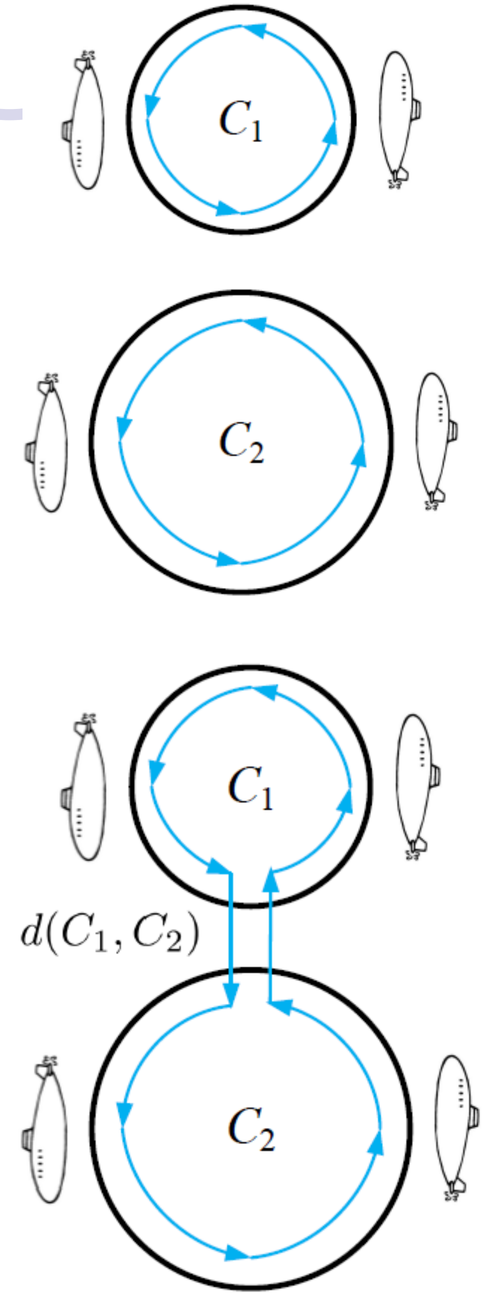
5. Extensions

- Greedy Cycle Merge
  - Initialize each connected component in the search space as a cycle
  - Merge two cycles in each greedy iteration
  - Average data delay before merge

$$\frac{C_1 \times (\frac{C_1}{2n_1} + \sqrt{\frac{2LC_1}{n_1}} + L) + C_2 \times (\frac{C_2}{2n_2} + \sqrt{\frac{2LC_2}{n_2}} + L)}{C_1 + C_2}$$

  - Estimated average data delay after merge

$$\frac{C_1 + C_2 + 2d(C_1, C_2)}{2(n_1 + n_2)} + \sqrt{\frac{2L[C_1 + C_2 + 2d(C_1, C_2)]}{(n_1 + n_2)}} + L$$

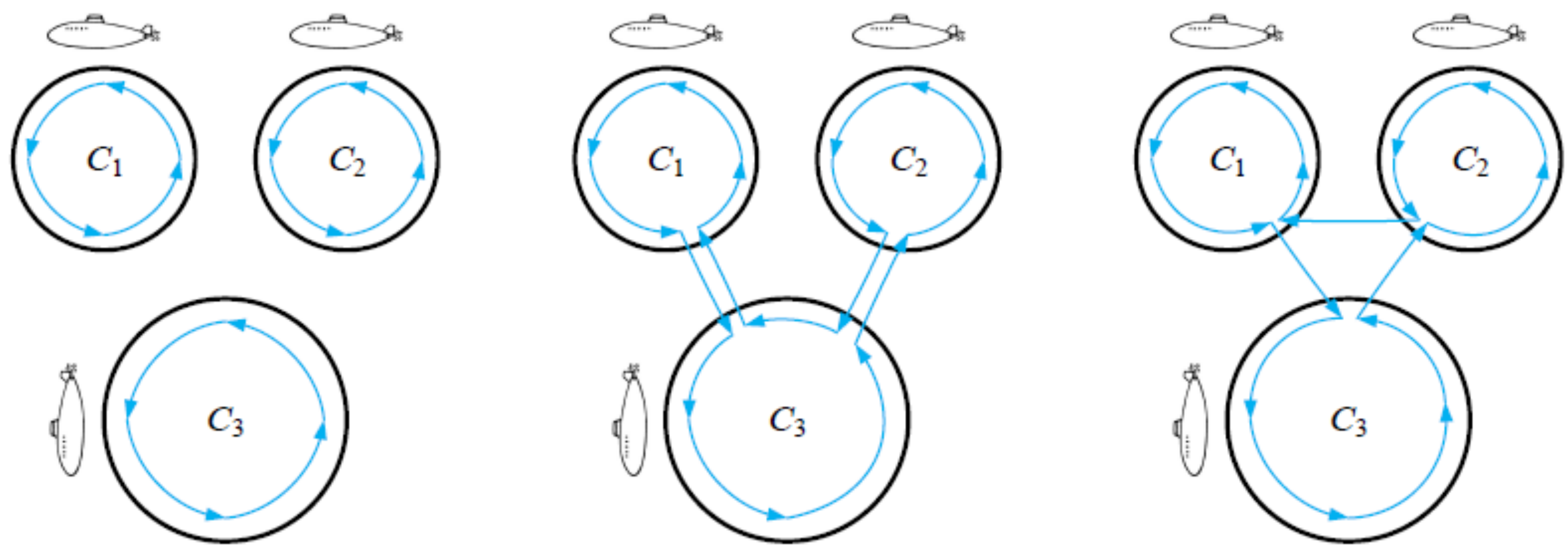


5. Extensions

- Two-way Merge Criterion
  - **Algorithm 3**: largest average delay reduction
  - **Algorithm 4**: largest cycle circumference difference (with delay reduction threshold)
  - **Algorithm 5**: closest geographical distance (with delay reduction threshold)
- Merge Termination
  - When no merges are available

5. Extensions

- Three-way merge

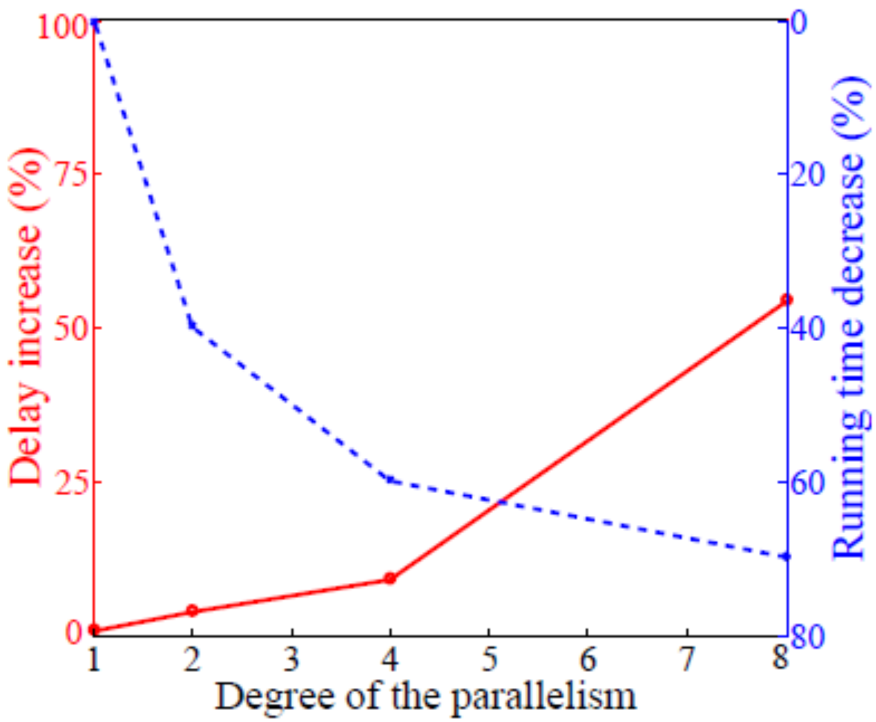


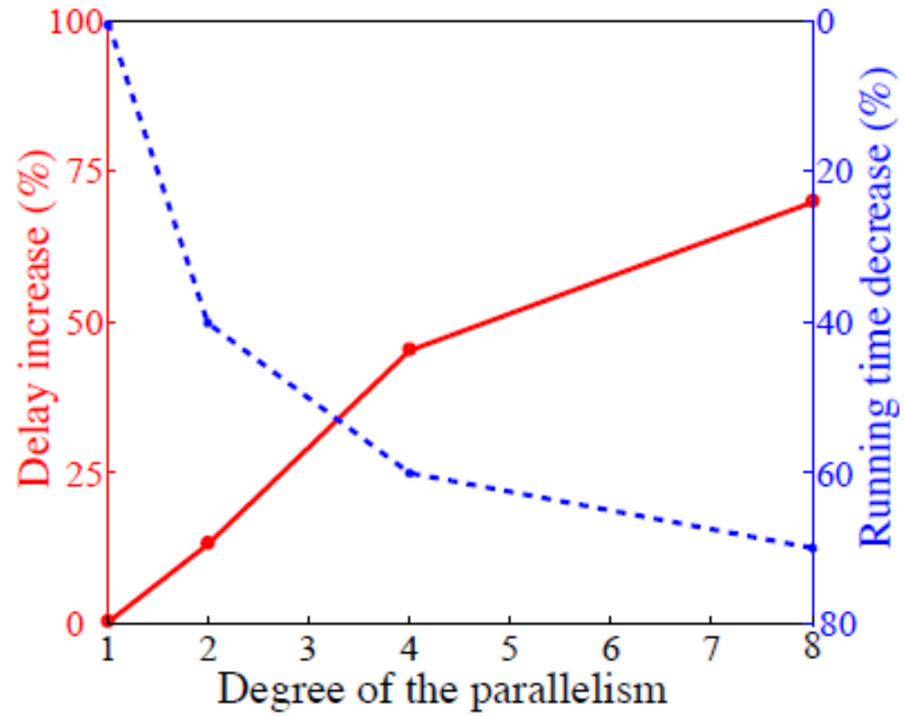
(a) Three cycles. (b) Two-way merge. (c) Three-way merge.

- Parallel Cycle Merge Implementation
  - Parallelism by dividing the scenario into small regions

5. Extensions

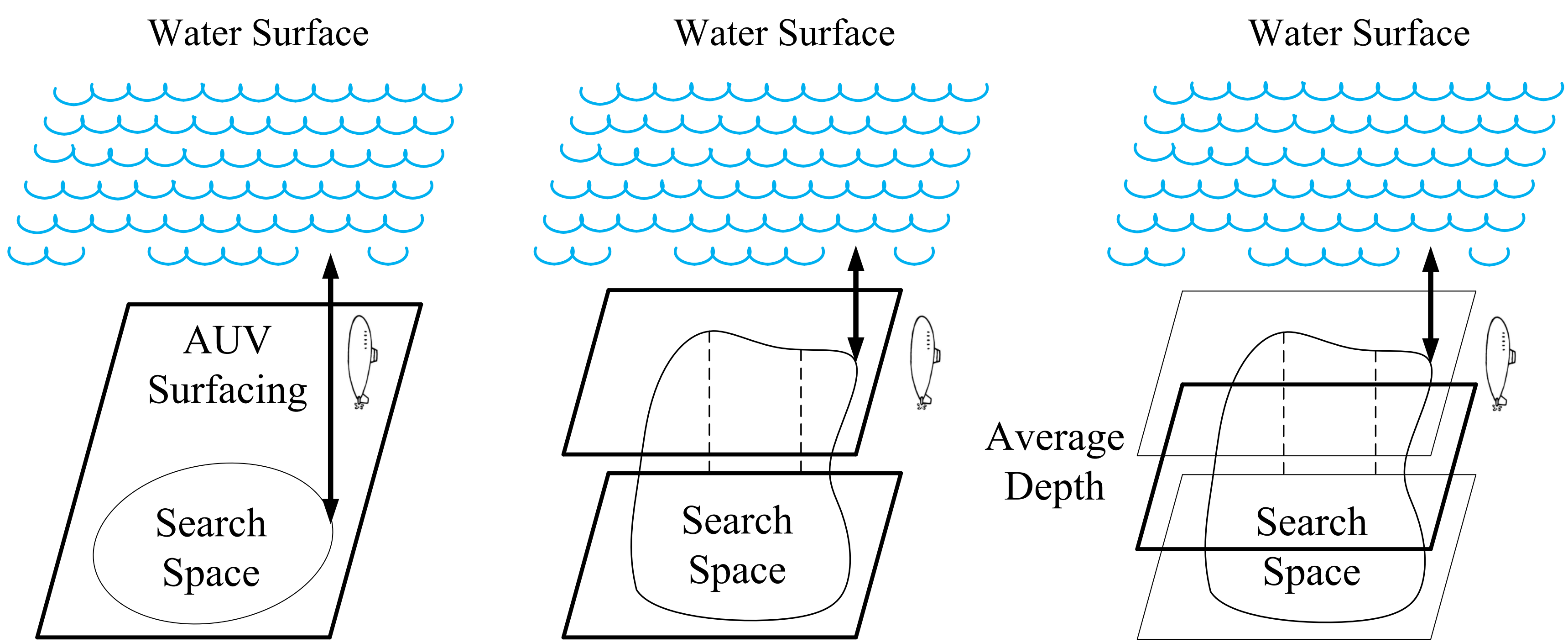
- Parallelism performance tradeoff
  - 500m by 500m with 10 cycles (sparse) and 25 cycles (dense)
  - Circle circumference is randomly chosen from 40m, 60m, 80m





5. Extensions

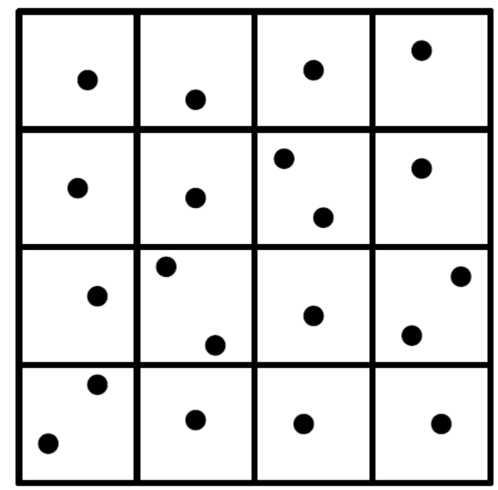
- 3-D search space
  - Use average sea depth to estimate

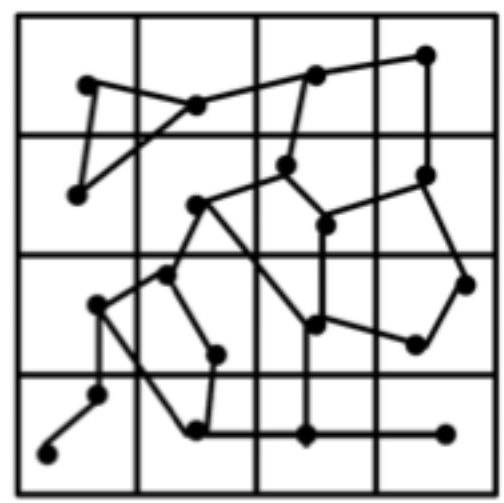


Basic 2-D scenario   General 3-D scenario   Average depth

6. Experiments

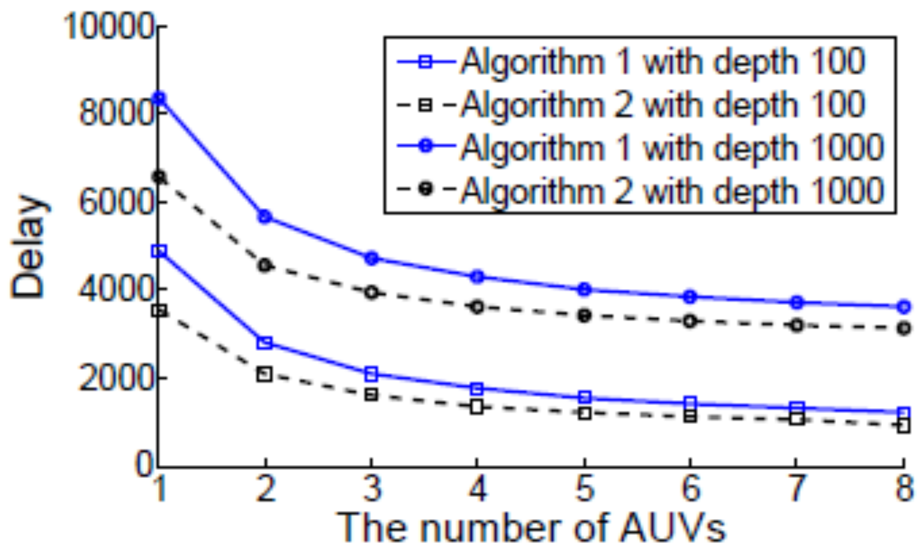
- Settings
  - The test is based on a synthetic trace
  - A 100*100 square unit with a depth 100
  - To guarantee the graph connectivity, a spanning tree is constructed
  - Additional edges, with given total numbers of 20 and 100, are added
  - AUV has unit speed





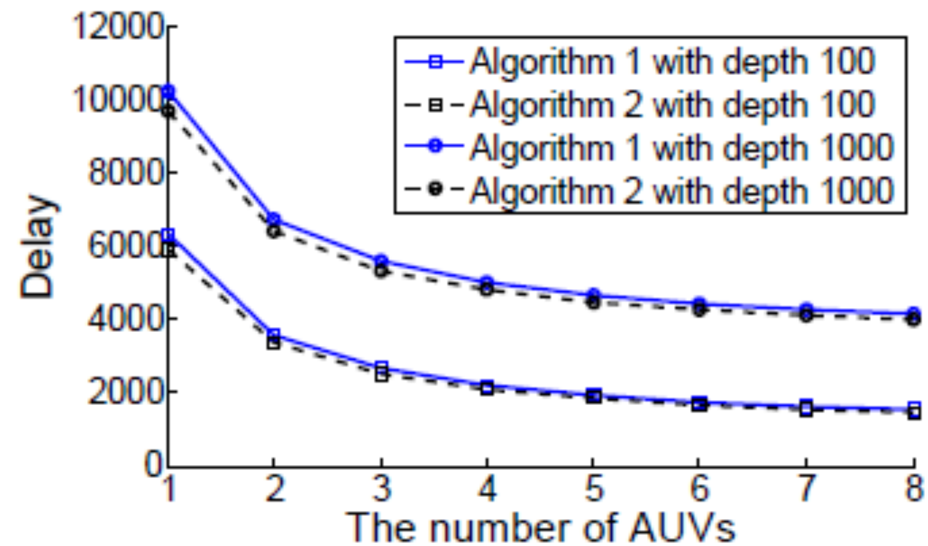
6. Experiments

- Simulation results:



(a) Given 20 additional edges.

Sparse graph



(b) Given 100 additional edges.

Dense graph

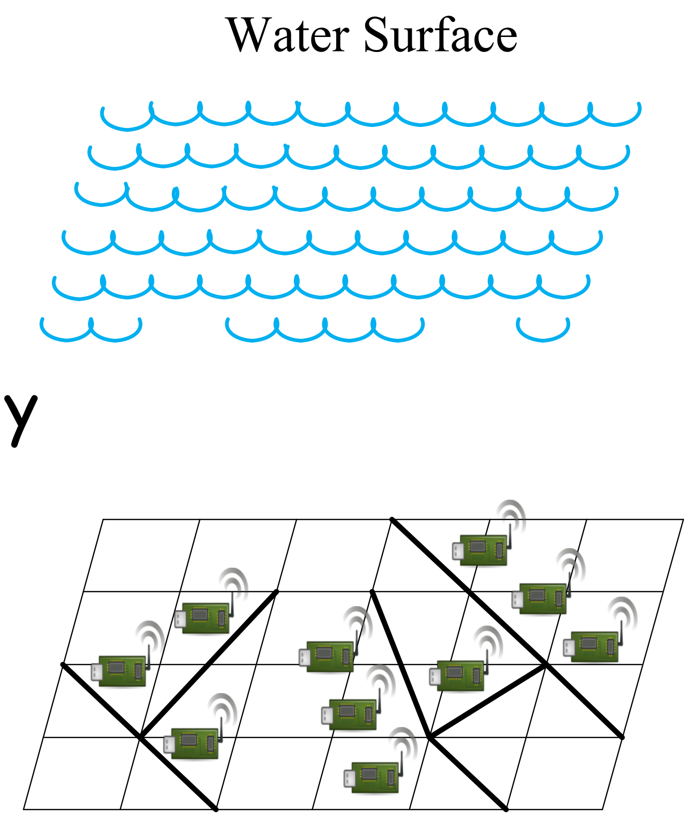
Algorithms 1 and **2**: cycles with sensing edges and non-sensing edges

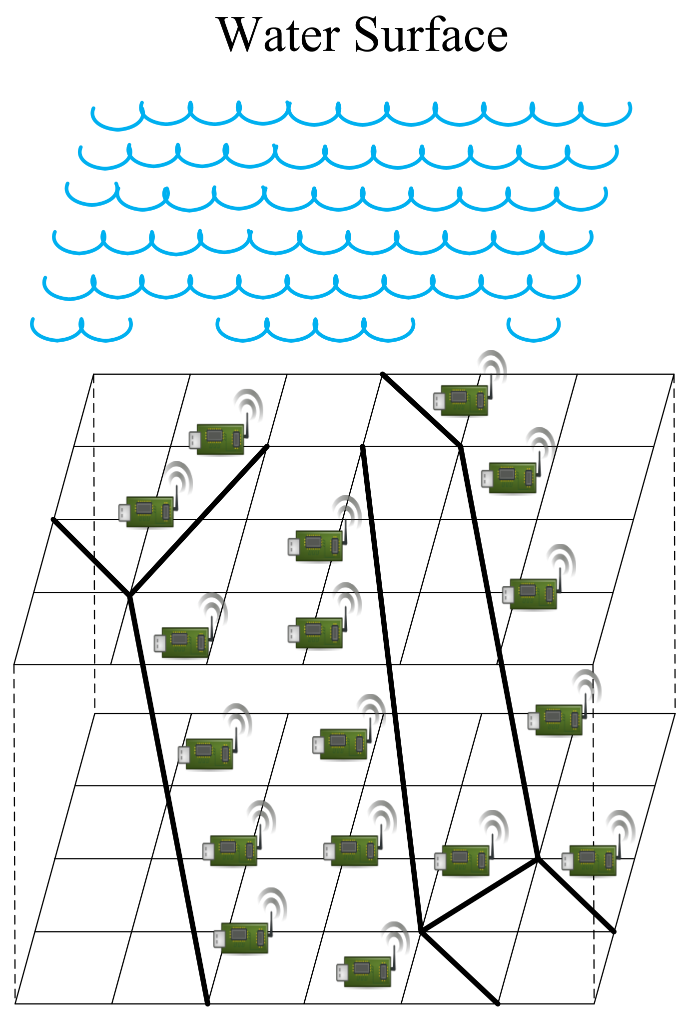
6. Experiments

- Summary:
  - A sparser graph leads to a larger gap between **Algorithms 1** and **2**
  - The gap between **Algorithms 1** and **2** is becoming smaller, when the trace gets denser
  - The delay reduction brought by one additional AUV decreases (i.e., the effect of diminishing return)

7. Experiments

- 2-D and 3-D pseudo search space
- 10 AUVs
- Depth randomly chosen from 50 to 150





6. Experiments

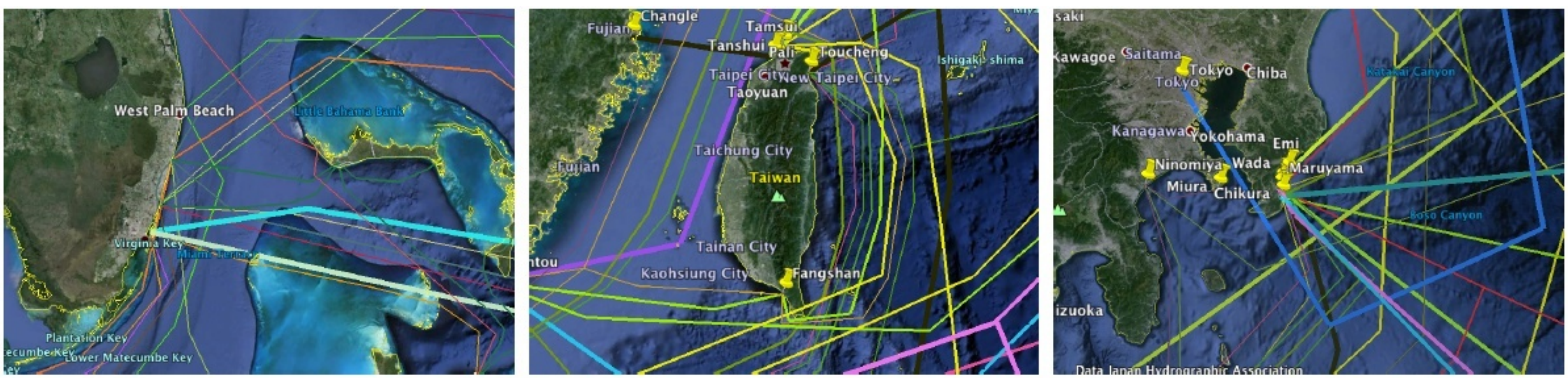
- Results for 2-D and 3-D search spaces

Trace setting	Comparison algorithms	The scenario	
		2-D scenario	3-D scenario
100 sensing edges	Algorithm 1	1853s	1954s
	Algorithms 2, 2s, 2r	1805s, 1724s, 1796s	1865s, 1794s, 1843s
	Algorithms 3, 4, 5	1643s, 1704s, 1694s	1734s, 1783s, 1755s
500 sensing edges	Algorithm 1	4175s	4421s
	Algorithms 2, 2s, 2r	4104s, 4053s, 4089s	4363s, 4312s, 4355s
	Algorithms 3, 4, 5	3861s, 3978s, 3942s	4144s, 4301s, 4234s

  - **Algorithms 1** and **2:** cycles with sensing edges and non-sensing edges
  - **Algorithms 2s** and **2r**: adjust the surface point at the end of sensing edges, and round off the length of sensing edges in **Algorithm 2**
  - **Algorithms 3**, **4**, and **5**: cycle merges with three merging criteria: largest delay reduction, largest cycle circumference difference, closest geographical distance

6. Experiments

- Real data-driven experiments
  - Oil pipes in Florida, Taiwan, and Japan
  - Sea depth 3,790m (average depth over the world)
  - AUV cruising speed 37km/h
  - AUV diving/surfacing speed 26km/h



(a) Florida oil pipes. (b) Taiwan oil pipes. (c) Japan oil pipes.

6. Experiments

- Results for Florida (in hours)

Trace setting	Comparison algorithms	The number of AUVs	
		10 AUVs	20 AUVs
Florida oil pipe trace	Algorithm 1	0.59h	0.36h
	Algorithms 2, 2s, 2r	0.52h, 0.49h, 0.52h	0.34h, 0.32h, 0.34h
	Algorithms 3, 4, 5	0.45h, 0.43h, 0.40h	0.26h, 0.23h, 0.21h

  - **Algorithm 1**: cycle with only sensing edges
  - **Algorithms 2**, **2s**, and **2r**: cycle with non-sensing edges, adjust resurface points, and round off sensing edge schedules
  - **Algorithms 3**, **4**, and **5**: cycle merges with three merging criteria: largest delay reduction, largest cycle circumference difference, closest geographical distance

6. Experiments

- Results for Taiwan (in hours)

Trace setting	Comparison algorithms	The number of AUVs	
		10 AUVs	20 AUVs
Taiwan oil pipe trace	Algorithm 1	7.87h	7.51h
	Algorithms 2, 2s, 2r	7.49h, 7.26h, 7.29h	7.24h, 7.05h, 7.04h
	Algorithms 3, 4, 5	6.76h, 6.95h, 6.86h	6.47h, 6.67h, 6.61h

- Results for Japan (in hours)

Trace setting	Comparison algorithms	The number of AUVs	
		10 AUVs	20 AUVs
Japan oil pipe trace	Algorithm 1	9.84h	8.92h
	Algorithms 2, 2s, 2r	8.65h, 8.22h, 8.17h	8.13h, 7.85h, 7.85h
	Algorithms 3, 4, 5	7.75h, 7.56h, 7.81h	7.43h, 7.29h, 7.38h

6. Experiments

- Summary:
  - There is a significant performance gap between **Algorithms 1** and **2**, since the real trace is sparse
  - **Algorithm 2s** can reduce the average data reporting delay of **Algorithm 2** by about 5% (AUVs should not resurface at non-sensing edges)
  - **Algorithm 2r** may not outperform **Algorithm 2s**
  - **Algorithms 3**, **4**, and **5** have different performances, depending on the trace

7. Conclusions and Future Work

- The AUV trajectory planning determines the AUV resurfacing frequencies and their locations
- The deep sea trajectory planning is simplified to an extended Euler cycle problem
- Future Work
  - More sophisticated AUV routing & resurfacing policies
  - More real data-driven experiments in 3-D search
  - Extension to the notion of age of information
  - Overall architectural design for multi-tired networks

Questions

- J. Wu and H. Zheng, "On efficient data collection and event detection with delay minimization in deep sea," *Proc. of ACM CHANTS*, 2014.
- H. Zheng, N. Wang, and J. Wu, "Minimizing deep sea data collection delay with autonomous underwater vehicles," *Journal of Parallel and Distributed Computing*, 2017.