Efficient Underwater Sensor Network Data Collection Employing Unmanned Ships

Jie Wang
Fourth Year Undergraduate Student
The Chinese University of Hong Kong, Shenzhen
Network Coding Lab

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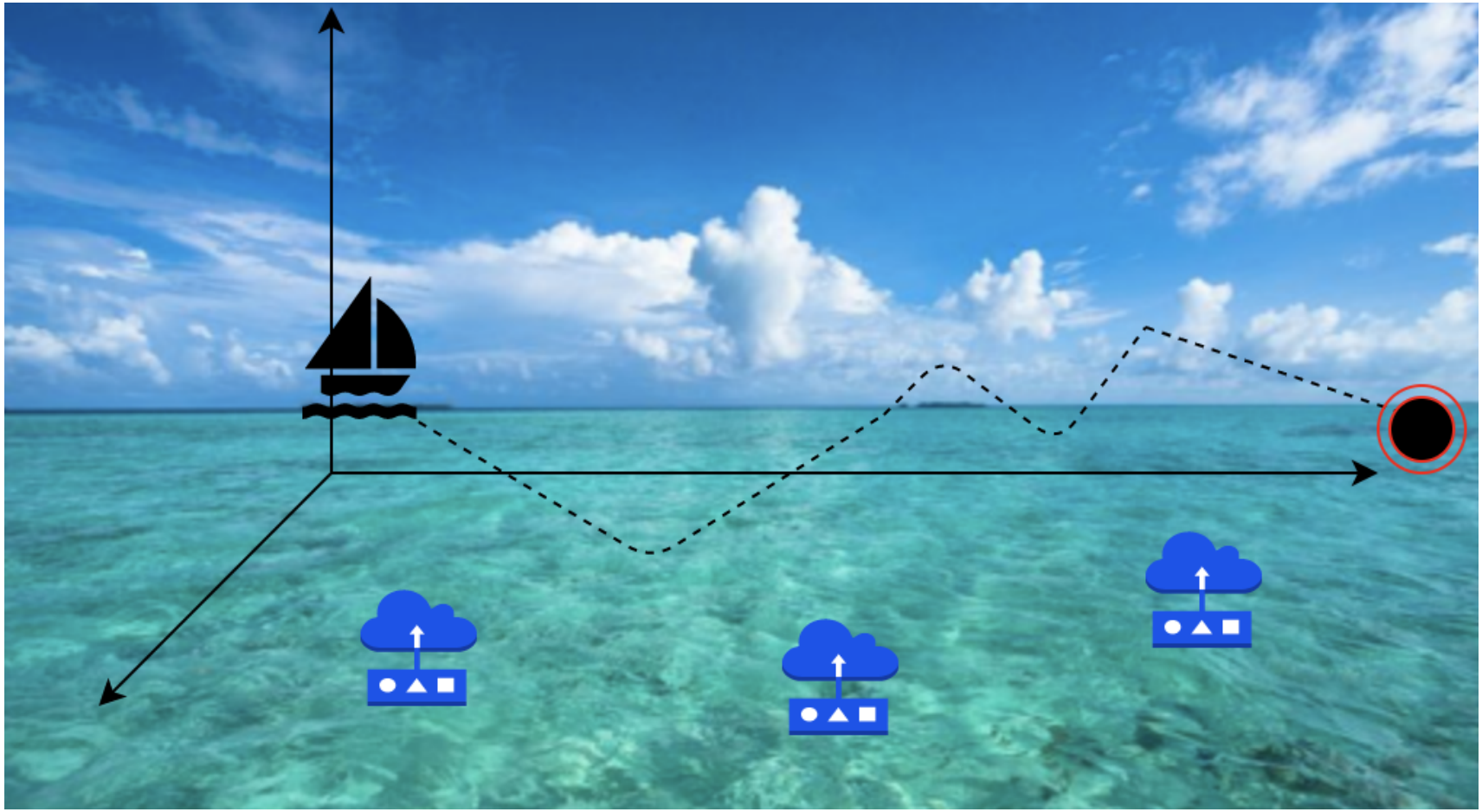
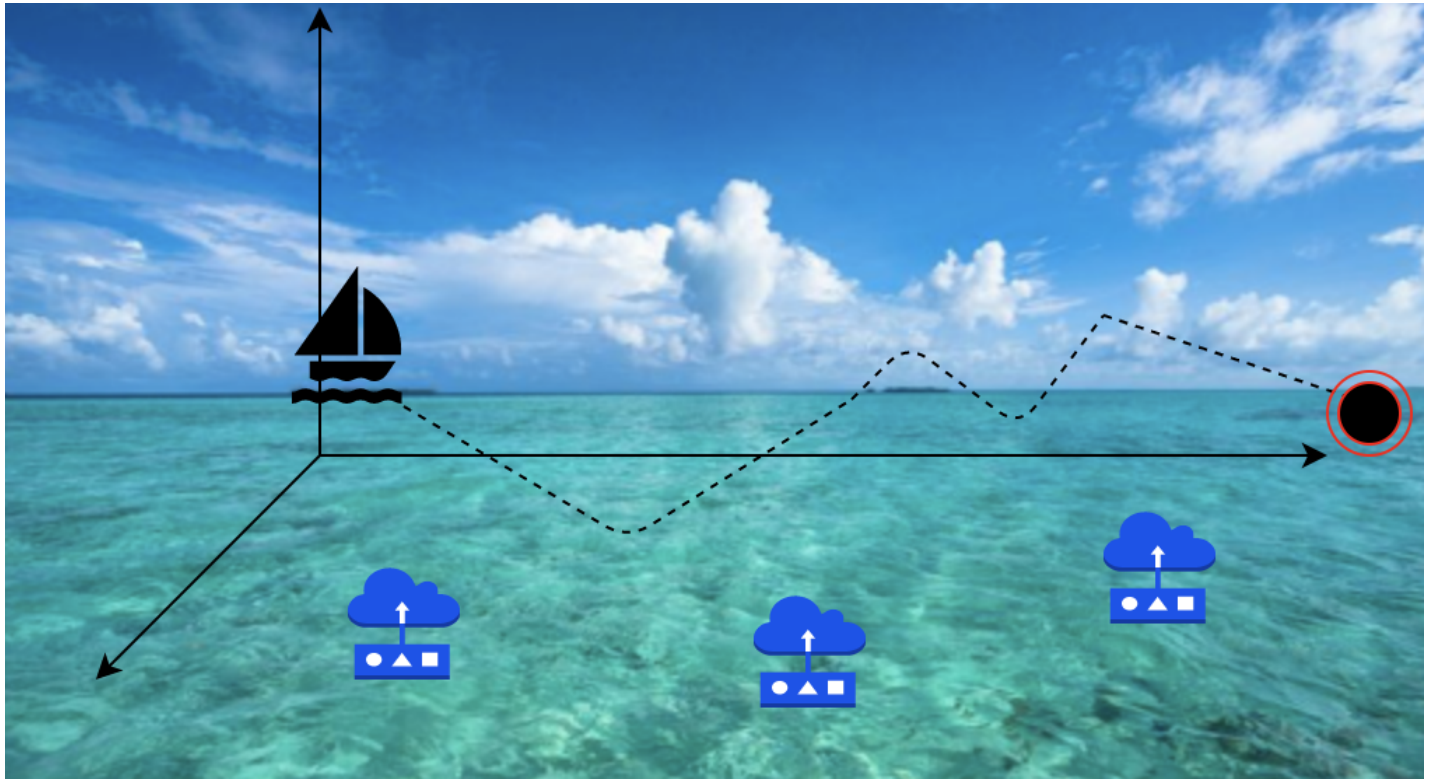
Conventional Underwater Data Collection Methods

Techniques	Limitations
Cable Communication	• High cost • Distance-limited
Satellite Communication with sea surface buoys	• High cost • High latency
Multi-hop Communication	• Deployment cost • Maintenance cost

Data Collection by Unmanned Ships

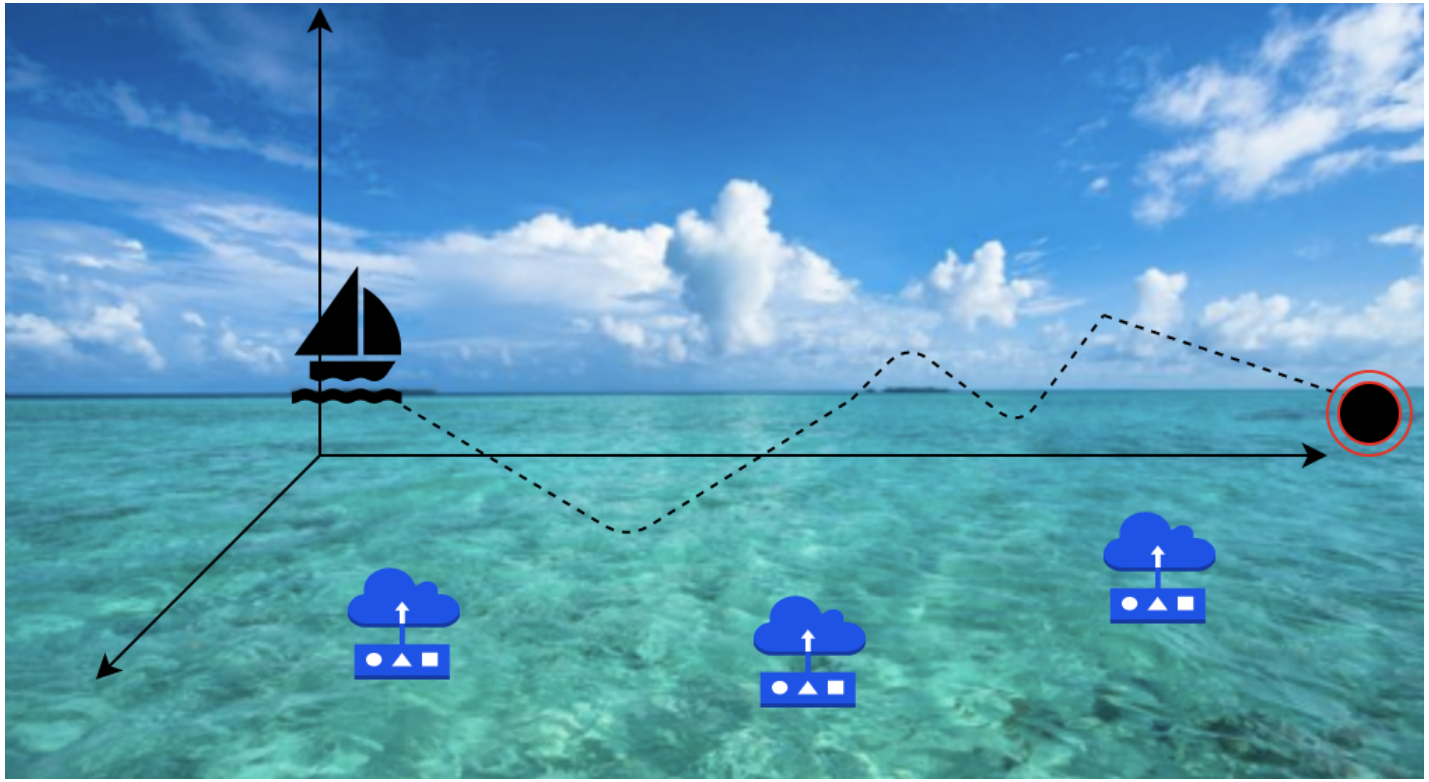


Two Crucial Facts



- Limited power of underwater sensor networks (USNs)
- Loss for communication is exponentially increasing!

Two Crucial Facts



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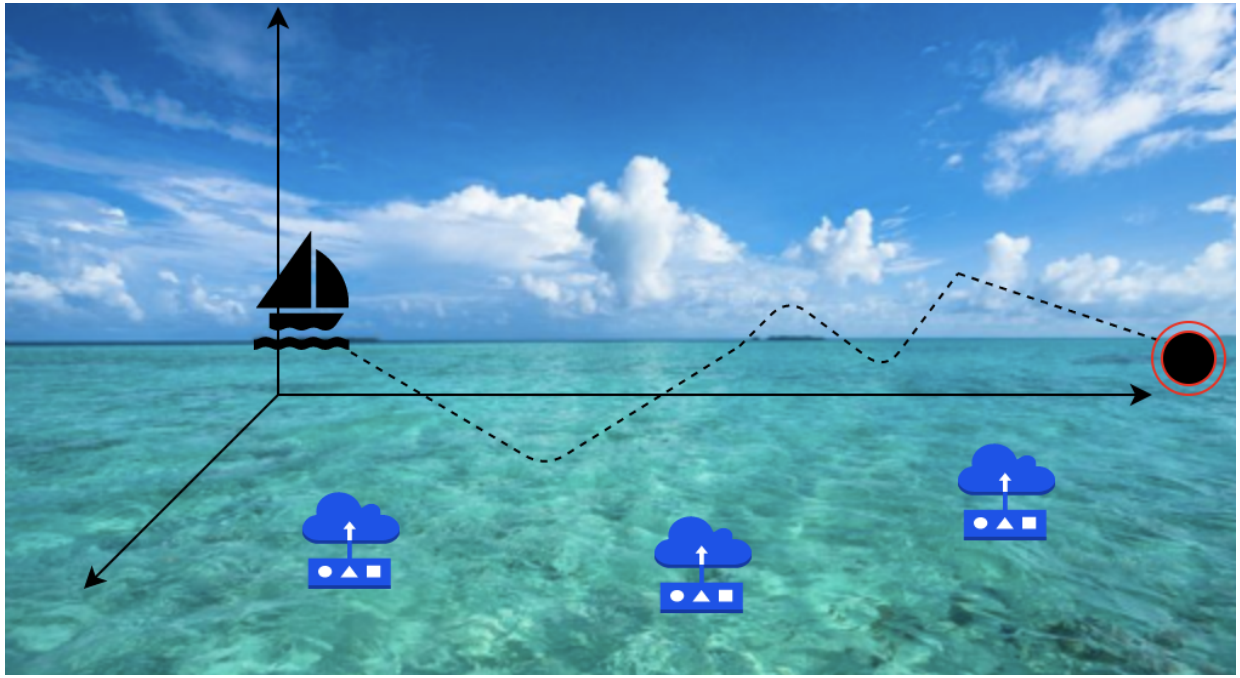
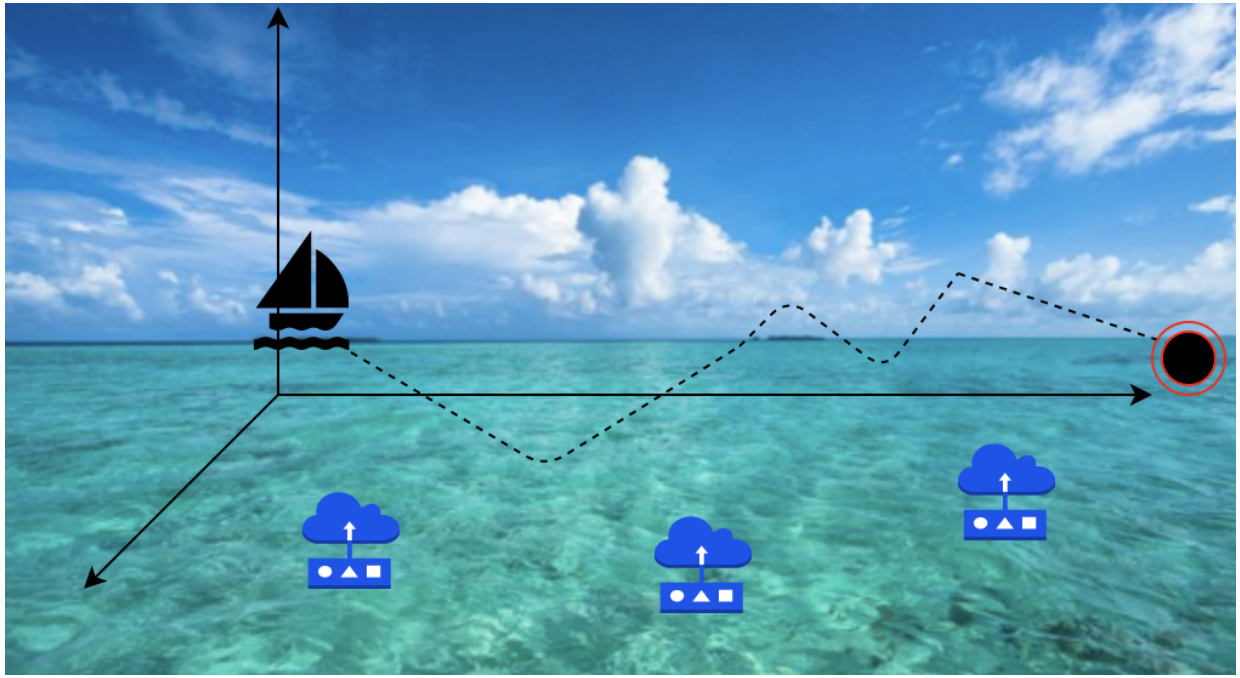
Proposed Schemes



- The path of the ship is designed.
- Wake-up policy and transmission power for USNs are also optimized.

Proposed Schemes



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Underwater Acoustic Channel Model

Key assmptions[1]:

1. Gaussian Noise;
2. The k-th node transmits with power p_k;
3. Channel is separated into sub-channels, each with bandwith Δf and frequency f_i.

Transmission Rate Approximation

The transmission rate for the k-th node over distance d is approximated as

$$C(d,k) = \sum_i \log_2 \left[1 + \frac{p_k/\Delta f}{N(f_i) \cdot A(d, f_i)}\right] \Delta f$$

where $A(d,f)$ denotes the attenuation factor; $N(f)$ denotes noise p.s.d.

1. Milica Stojanovic. 2007. On the relationship between capacity and distance in an underwater acoustic communication channel.

System Model

- An unmanned ship is to collect data from K USNs;
- Total time horizon is discretized into M time slots equally;
- Decision variable:

$\boldsymbol{q} := \{\boldsymbol{q}[m], 0 \leq m \leq M\}$	Path of unmanned ship
$\boldsymbol{x} := \{\boldsymbol{x}_k[m], 0 \leq m \leq M, 1 \leq k \leq K\}$	Wake-up schedule
$\boldsymbol{p} := \{p_k, 1 \leq k \leq K\}$	Transmission power of USNs

- Objective: minimize the maximum energy consumption for all USNs

$$\min_{\boldsymbol{p},\boldsymbol{q},\boldsymbol{x}} \quad \max_{k} \sum_{m=0}^{M} x_k[m] p_k$$

System Constraints

- The path of the ship satisfies initial and final location constraints:

$$\boldsymbol{q}[0] = \boldsymbol{q}_0, \quad \boldsymbol{q}[M] = \boldsymbol{q}_f.$$

- The maximum speed constraints of the unmanned ship:

$$\|\boldsymbol{q}[m] - \boldsymbol{q}[m-1]\| \leq V_{\max}$$

- Wake-up mechanism:

$$\begin{cases} \sum_{k=1}^{K} x_k[m] \leq 1, & \forall m \\ x_k[m] \in \{0,1\}, & \forall m, \forall k \end{cases}$$

- Data Load Constraint:

$$\sum_{m=1}^{M} x_k[m] R(p_k, \boldsymbol{q}[m]) \geq b_k, \quad \forall k$$

Formulated Optimization Problem

The data collection scheme is formulated as the optimization problem[1]:

$$
\begin{aligned}
\min_{\boldsymbol{p},\boldsymbol{q},\boldsymbol{x},\theta} \quad & \theta \\
\text{s.t.} \quad & \sum_{m=1}^{M} x_k[m] p_k \delta \le \theta, \quad \forall k = 1, \ldots, K \\
& \boldsymbol{q}[0] = \boldsymbol{q}_0, \quad \boldsymbol{q}[M] = \boldsymbol{q}_f \\
& \|\boldsymbol{q}[m] - \boldsymbol{q}[m-1]\| \le V_{\max} \\
& \sum_{k=1}^{K} x_k[m] \le 1, \quad \forall m \\
& \sum_{m=1}^{M} x_k[m] R(p_k, \boldsymbol{q}[m]) \ge b_k, \quad \forall k \\
& x_k[m] \in \{0, 1\}, \quad \forall m, \forall k
\end{aligned}
$$

1. Cheng Zhan, Yong Zeng, and Rui Zhang. 2018. Energy-efficient data collection in UAV enabled wireless sensor network

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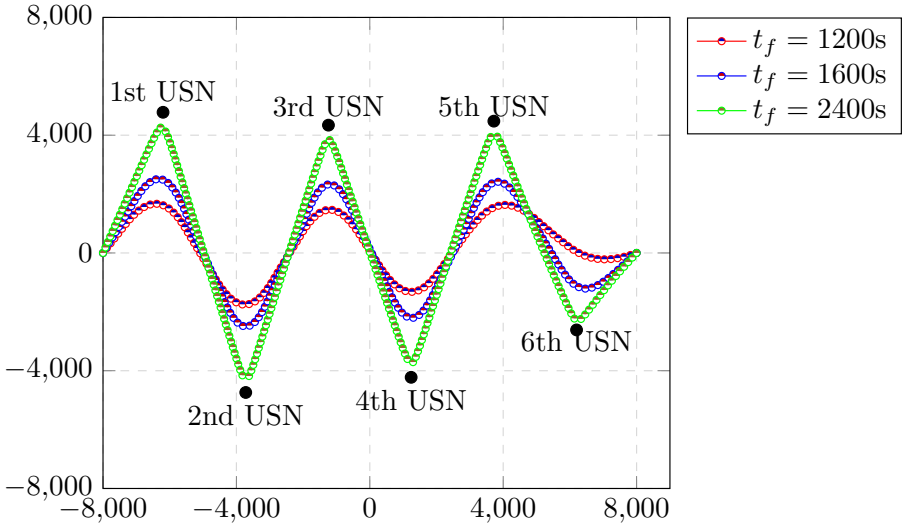
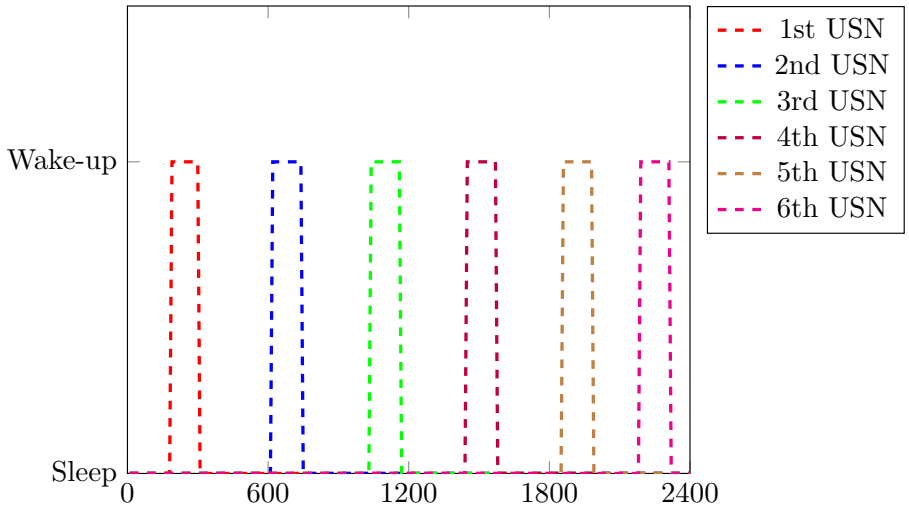
Numerical Results



(a) The unmanned ship's path;



(b) Wake-up schedule of USNs;