Heuristic IG-TDMA Protocol for Underwater Acoustic Sensor Networks

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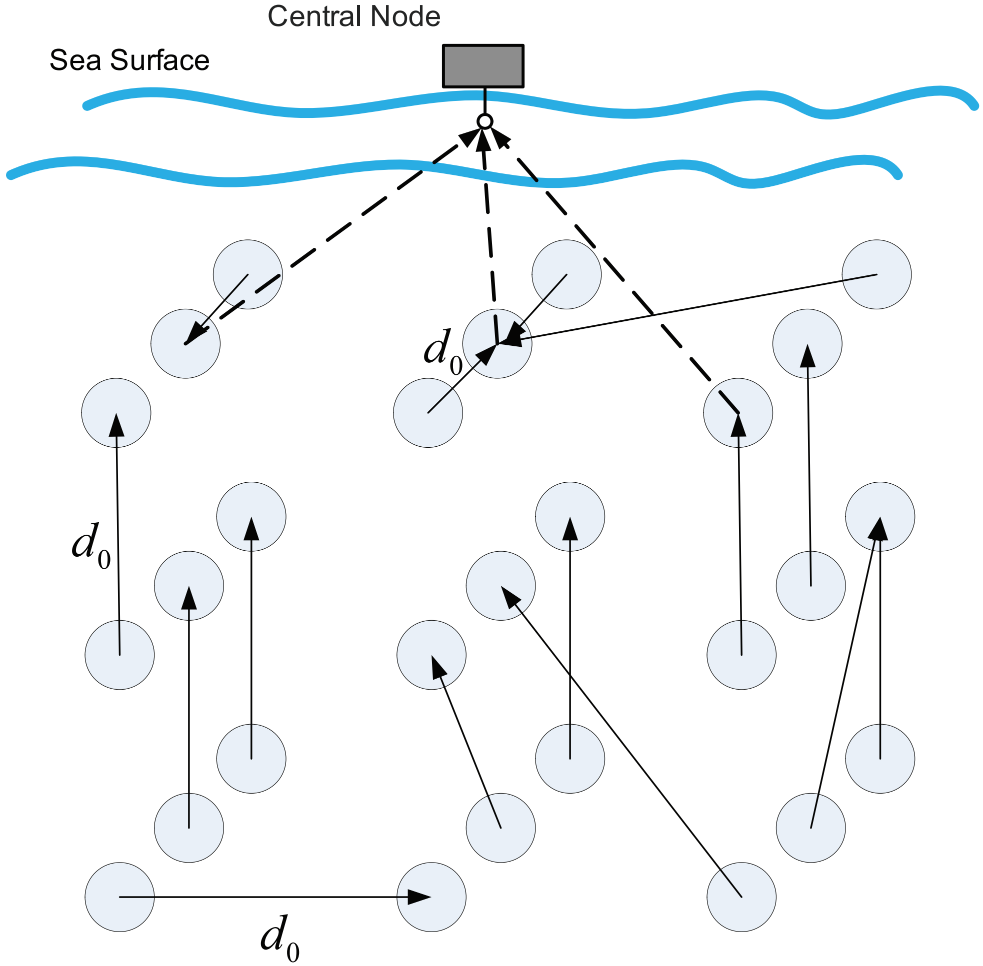
Outline

- Underwater acoustic sensor network (UWASN) system model
- Interference-graph-based TDMA protocol
- Interference graph construction
- Interference graph clustering algorithms
  - Optimal IG-TDMA and heuristic IG-TDMA protocols
- Simulation results
- Summary

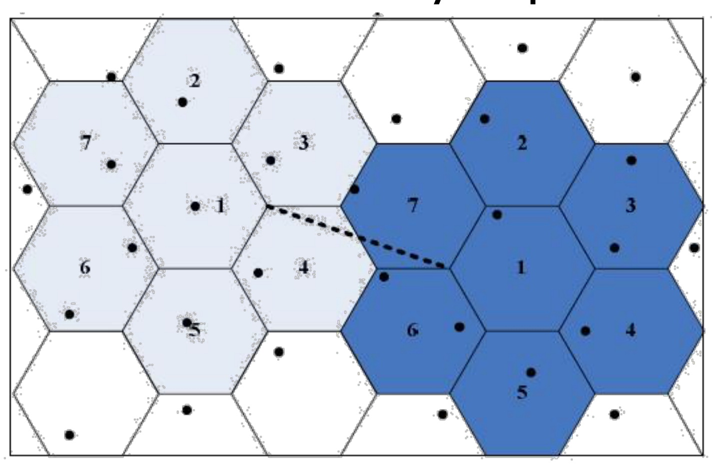
UWASN System Model



- Sensor nodes sense data of interest.
- Central node gathers sensing data from sensor nodes.
- Sensing data are forwarded to the central node along a path pre-generated by a routing protocol.

TDMA Protocols

- Traditional TDMA protocol
  - ✓ Effectively avoid the interference by allowing at most one node to transmit at any given time slot
  - ✘ The consequent network throughput is greatly limited for large networks.
- Cellular MAC (C-MAC) protocol [Ma-Guo-Feng-Jiang-Feng'09]
  - TDMA-based protocol
  - Divides network into many cells clustered like cellular network
  - ✓ Allow cells with same index from different clusters to transmit simultaneously
  - ✘ Spatial reuse not fully explored → throughput still limited



Network Division

TDMA Protocols

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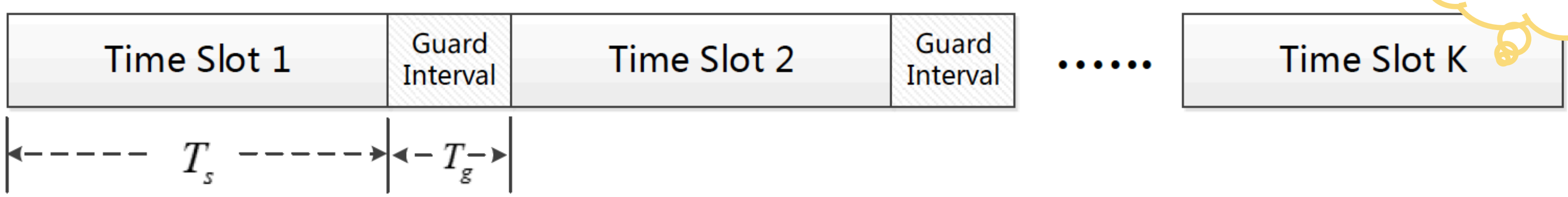
- Cellular MAC (C-MAC) protocol [Ma-Guo-Feng-Jiang-Feng'09]
  - TDMA-based protocol
  - Divides network into many cells clustered like cellular network
  - ✓ Allow cells with same index from different clusters to transmit simultaneously
  - ✘ Spatial reuse not fully explored → throughput still limited
- Interference-graph-based TDMA (IG-TDMA) protocol
  - Dynamic and flexible spatial reuse that allows multiple nodes to transmit concurrently
  - ✓ Significantly improve network performance
  - ✓ Low complexity and easy for application

IG-TDMA Protocol

- Central node makes the resource scheduling decision.
- Step 1: Information collection
  - Central node collects individual information of each communication link including positions, velocities, and amount of data to be transmitted.
- Step 2: Interference graph construction
  - For each time slot in the scheduled transmission frame, based on the predicted positions of the active sensor nodes, an undirected interference graph is constructed.

frame structure



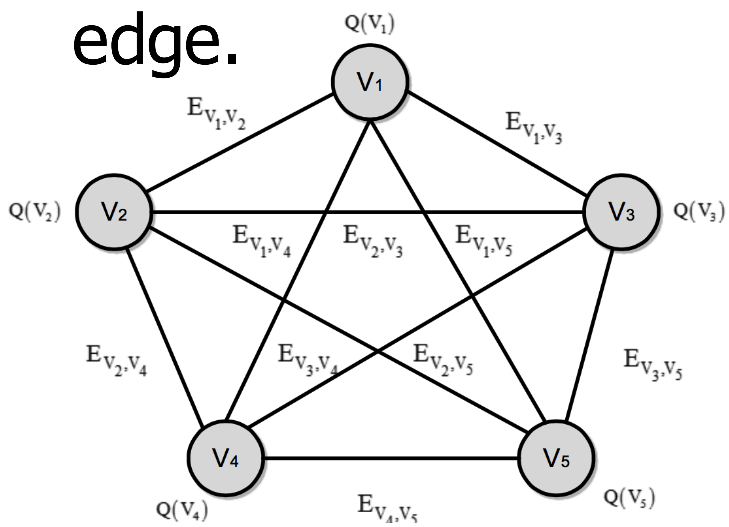
- Step 3: Interference graph clustering
  - Find a simultaneously transmitting nodes set
  - Chosen communication links are interference-free.
- Step 4: Data transmission
  - Central node broadcasts the scheduling decision.

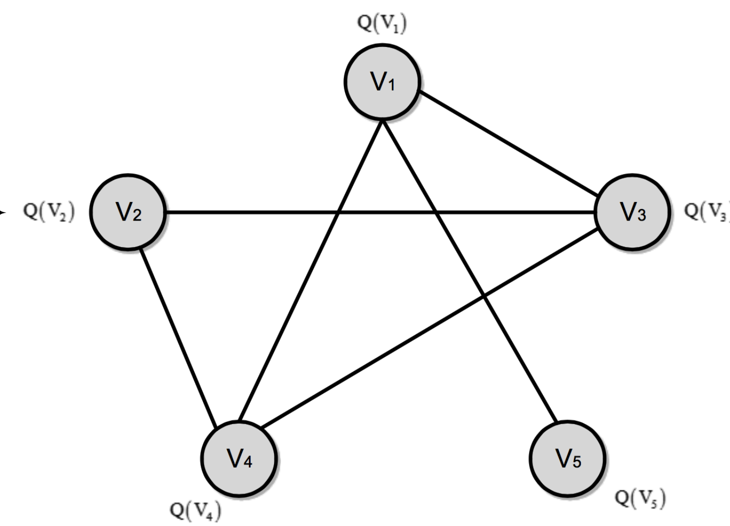
Interference Graph Construction

- Original undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$
  - Each vertex $V_i \in \mathcal{V}$: a link that has communication request
  - Edge $E_{V_i,V_j} \in \mathcal{E}$ indicates mutual interference of V_i and V_j
    - Two vertices have weight 1 if they interfere with each other, and weight 0 otherwise.

$$E_{V_i,V_j} = \begin{cases} 1, & \text{if } V_i \in \mathcal{N}(V_j) \text{ or } V_j \in \mathcal{N}(V_i), \\ 0, & \text{otherwise.} \end{cases}$$

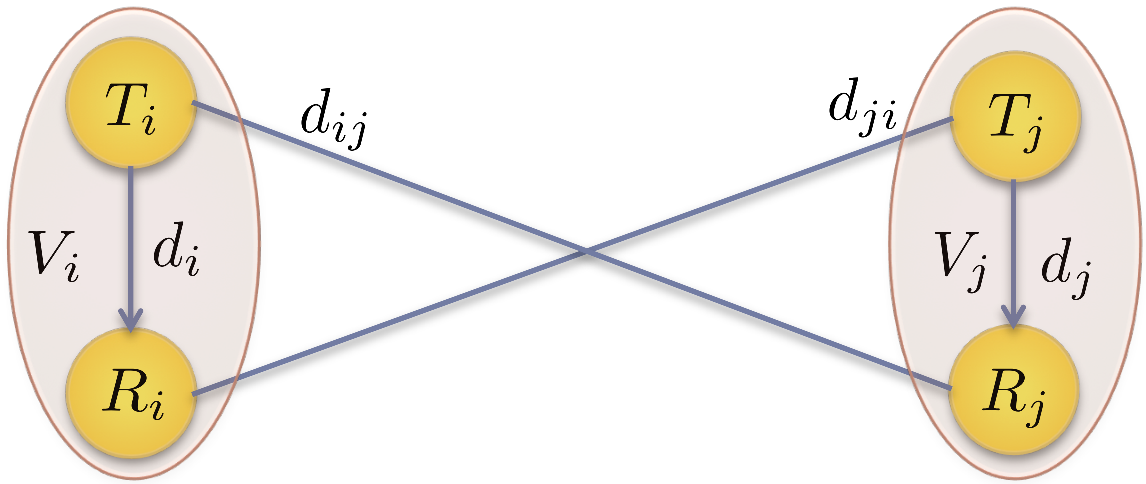
- Interference graph $\mathcal{G}_{in} = (\mathcal{V}, \mathcal{E}_{in})$ retains 0 -weight edge.





- Original graph
- Interference graph

Edge Weight Determination



- Relationship between two vertices V_i and V_j
  - d_i: transmission distance between transmitting node and receiving node in V_i
  - Effective distance d_{ij} : distance from transmitting node of V_i to receiving node of V_j
  - Edge weight $E_{V_i,V_j} = 0$ between vertices V_i and V_j if
    $20\log_{10}|H(d_i, f_c)| - 20\log_{10}|H(d_{ji}, f_c)| \geq \alpha$
    $20\log_{10}|H(d_j, f_c)| - 20\log_{10}|H(d_{ij}, f_c)| \geq \alpha$
    - α : interference-free threshold ($\alpha > 0$)

Interference Graph Clustering

- Each vertex V_i has an attribute named Q -value

$$Q(V_i) = \frac{\log_2\left(1 + \frac{P_t|H(D_i, f_c)|^2}{\sigma^2}\right)}{\mathcal{W}(V_i)}$$

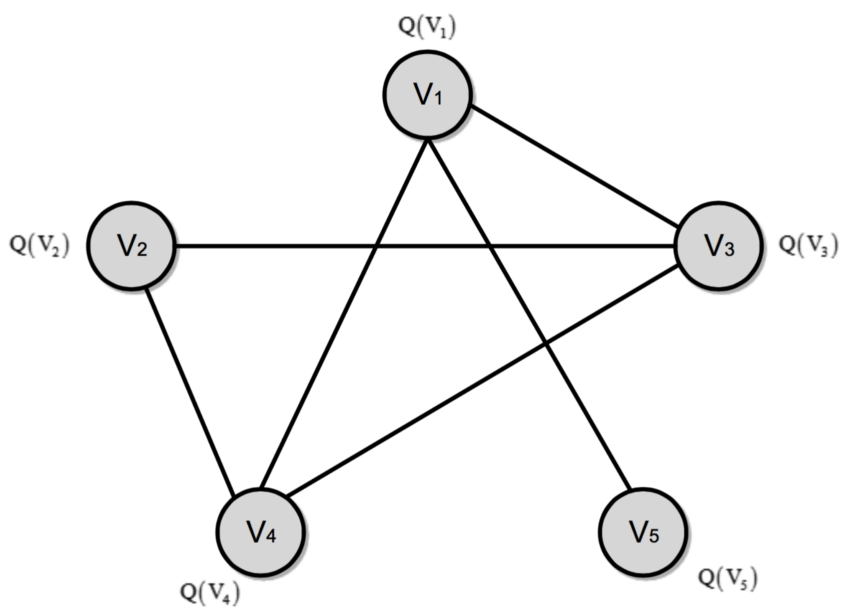
  - $\mathcal{W}(V_i)$: the number of successfully transmitted packets of V_i within a window size t_w
  - Proportional fairness: guarantee QoS of communication links suffering from poor channel condition
- Problem formulation
  - Given $\mathcal{G}_{in}$, find a simultaneous interference-free transmission group with maximum group Q -value

$$\mathcal{T}_{max} = \max_{\mathcal{T} \subseteq \mathcal{V}} \sum_{V_i \in \mathcal{T}} Q(V_i),$$

$$\text{s.t.} \quad \begin{cases} \mathcal{G}_{in} = (\mathcal{V}, \mathcal{E}_{in}), \\ E_{V_i,V_j} = 0, \ \text{for} \ \forall\, V_i, \forall\, V_j \in \mathcal{T}. \end{cases}$$

Optimal IG Clustering Algorithm

- Clique: a subset of the vertex set, such that for every two vertices in the subset, there exists an edge connecting them.
- Maximal clique: the clique with the largest possible vertex size and cannot be extended by including one more adjacent vertex.



- Maximal cliques:

$$\{V_1, V_3, V_4\}$$
$$\{V_2, V_3, V_4\}$$
$$\{V_1, V_5\}$$

Optimal IG Clustering Algorithm

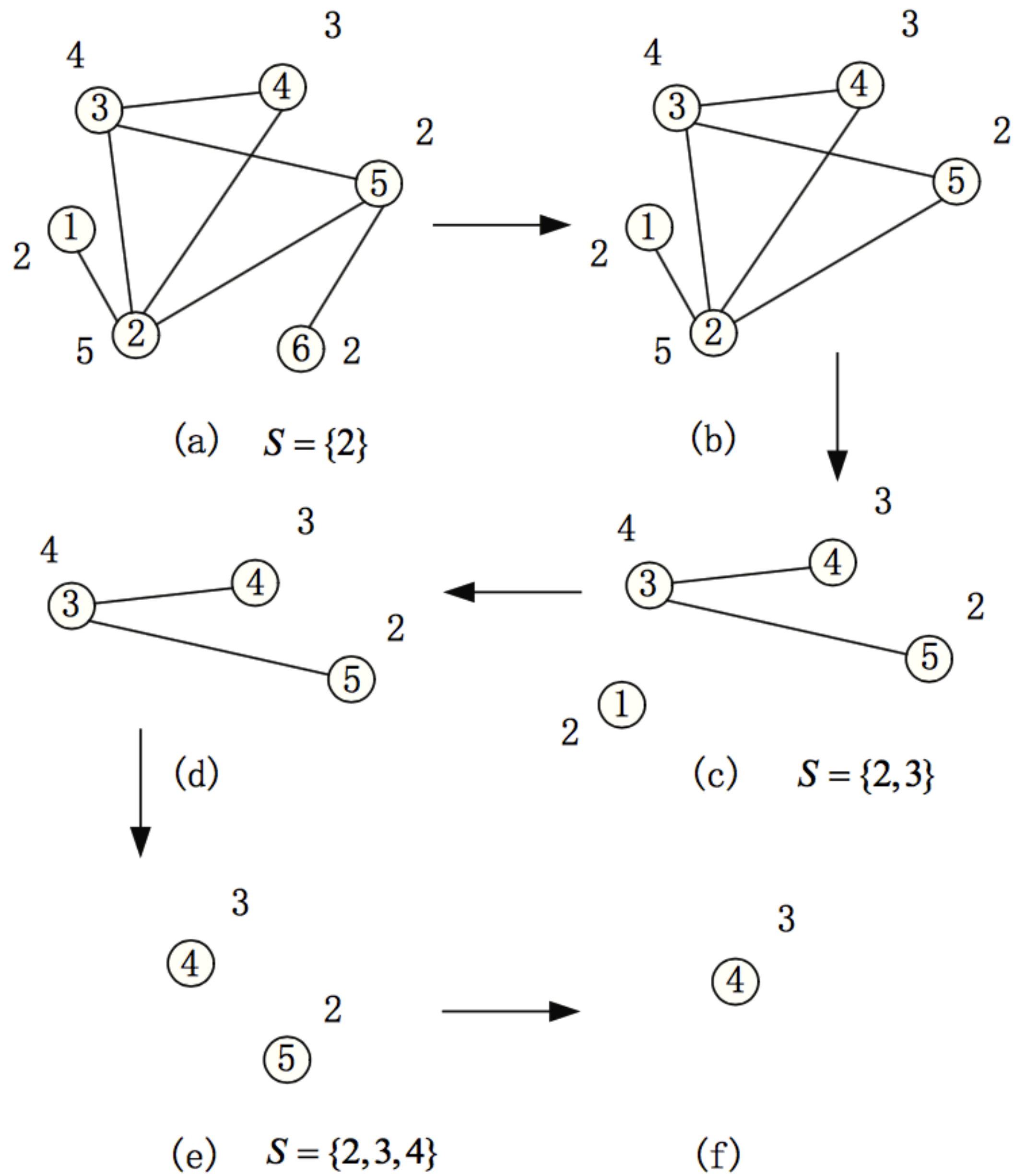
- Clique: a subset of the vertex set, such that for every two vertices in the subset, there exists an edge connecting them.
- Maximal clique: the clique with the largest possible vertex size and cannot be extended by including one more adjacent vertex.
- Optimal IG clustering algorithm:
  - Obtain all the maximal cliques in the interference graph
    - Bron-Kerbosch algorithm [Bron-Kerbosch'73]
  - Find the maximal clique with highest group Q-value
- Complexity of Bron-Kerbosch algorithm: $O(3^{|V|/3})$
  - ✘ Not suitable for large network with high $|V|$
  - Low complexity suboptimal solution needed

Heuristic IG Clustering

- Procedure
  - Initialize $\mathcal{V}_0 = \mathcal{V}$ and maintain a clique set $\mathcal{S}$
  - Add the vertex $V_i \in \mathcal{V}_0$ with highest Q -value to $\mathcal{S}$
  - Remove vertices that are not connect to V_i from $\mathcal{V}_0$ (they can't be added to S to form a new clique)
  - Remove vertices in V_i from $\mathcal{V}_0$
  - Repeat above steps until $\mathcal{V}_0$ is empty
  - Output $\mathcal{S}$

- Complexity reduced to $O(|V|^2)$:
  - Suitable for large system

Heuristic IG Clustering



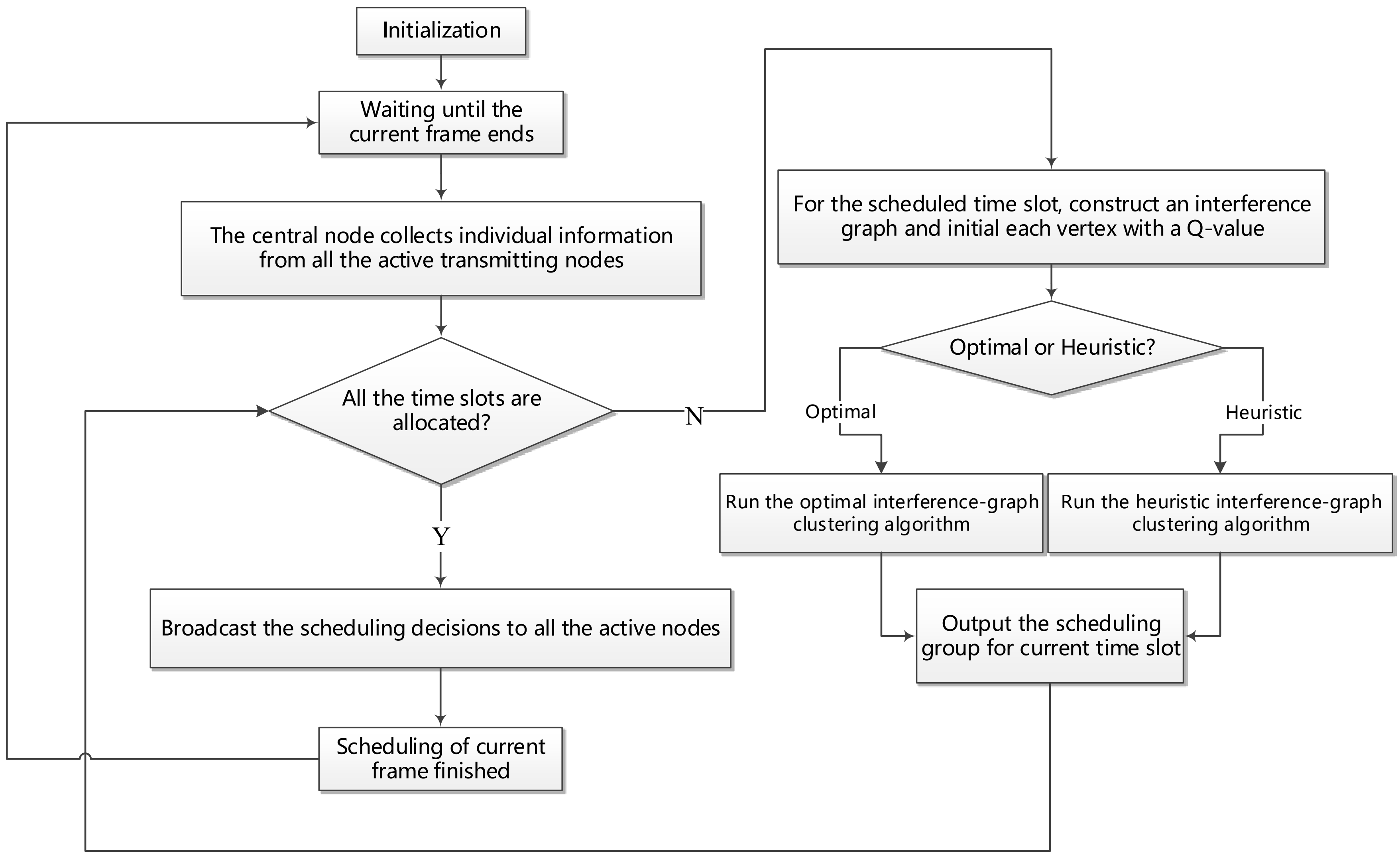
Heuristic IG Clustering Algorithm

- Input: Given $\mathcal{G}_{in} = (\mathcal{V}, \mathcal{E}_{in})$ where $\mathcal{V} = \{V_1, V_2, \cdots, V_{|V|}\}$
  Each vertex V_i has an individual Q-value $Q(V_i)$.

- for $n = 1, 2, \cdots, |V|$ do
- Initialization: $\mathcal{V}_0 = \mathcal{V}$ and $\mathcal{S}_n$ is an empty set;
- Step 1: Add V_n into $\mathcal{S}_n$
- Step 2: Remove vertices not connected with V_n from $\mathcal{V}_0$;
- Step 3: Remove vertex V_n from $\mathcal{V}_0$;
- Step 4: Find $V_i = \arg\max_{V_i \in \mathcal{V}_0} Q(V_i)$ and add V_i into $\mathcal{S}_n$;
- Step 5: Remove vertices not connected with V_i from $\mathcal{V}_0$;
- Step 6: Remove vertex V_i from set $\mathcal{V}_0$;
- Step 7: If $\mathcal{V}_0$ is not empty, go back to Step 4;
- Step 8: Calculate $Q(\mathcal{S}_n) = \sum_{V_k \in \mathcal{S}_n} Q(V_k)$
- end

- Output : $\mathcal{S} = \arg\max_{\mathcal{S}_n, n \in \{1,2,\cdots,|V|\}} Q(\mathcal{S}_n)$

Flow Diagram of IG-TDMA Protocol Scheduling Procedure



Simulation Settings

- UWA channel model
  - The path loss $\mathcal{A}$ over distance d at frequency f_c:

$$\mathcal{A}(d, f_c) = d^k a(f_c)^d$$

    - $k = 1.5$: practical path loss factor
    - Thorp's formula [Stojanovic'06, Berkhovskikh-Lysanov'82]

$$10\log a(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + 2.75 \cdot 10^{-4} f^2 + 0.003$$

  - For a transmission distance d and the carrier frequency f_c, channel frequency response is:

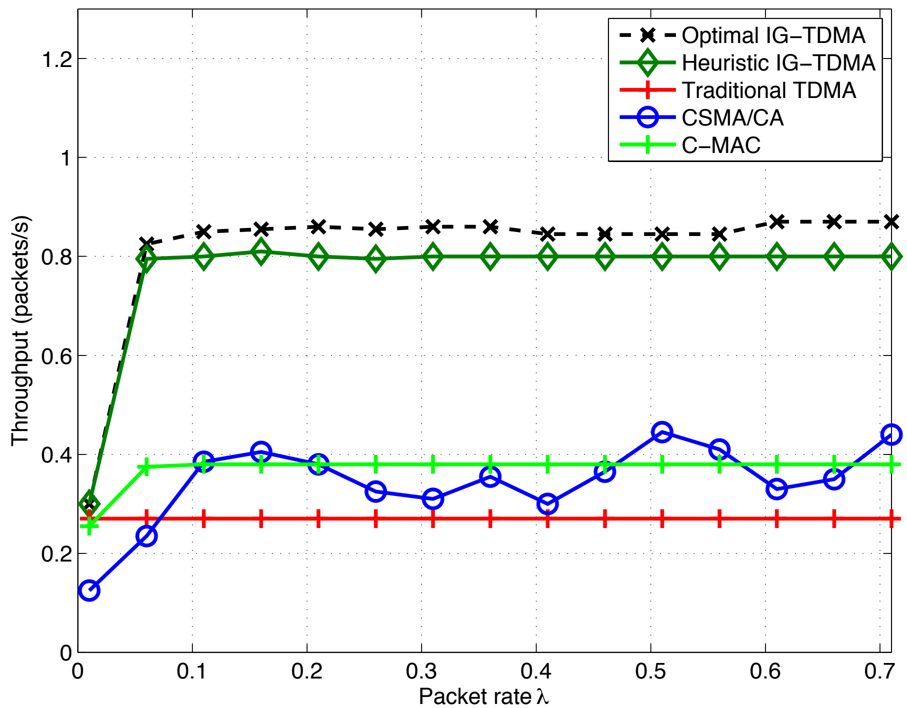
$$H(d, f_c) = \frac{1}{\sqrt{\mathcal{A}(d, f_c)}}$$

    - With transmit power P_t, the received signal power at distance d is $P_t|H(d, f_c)|^2$.

System Parameters

- Cube size: $3 \times 3 \times 3 \text{ km}^3$
- Nodes' velocity: 2 knots
- Transmit power: 60 dB
- Bandwidth: 5 kHz
- Carrier frequency: 17 kHz
- Packet length: 2 s
- Time slot length: 2 s
- Frame length: 200 s
- Transmitting nodes: 60%
- Receiving nodes: 40%
- Nodes' initial position: uniformly distributed

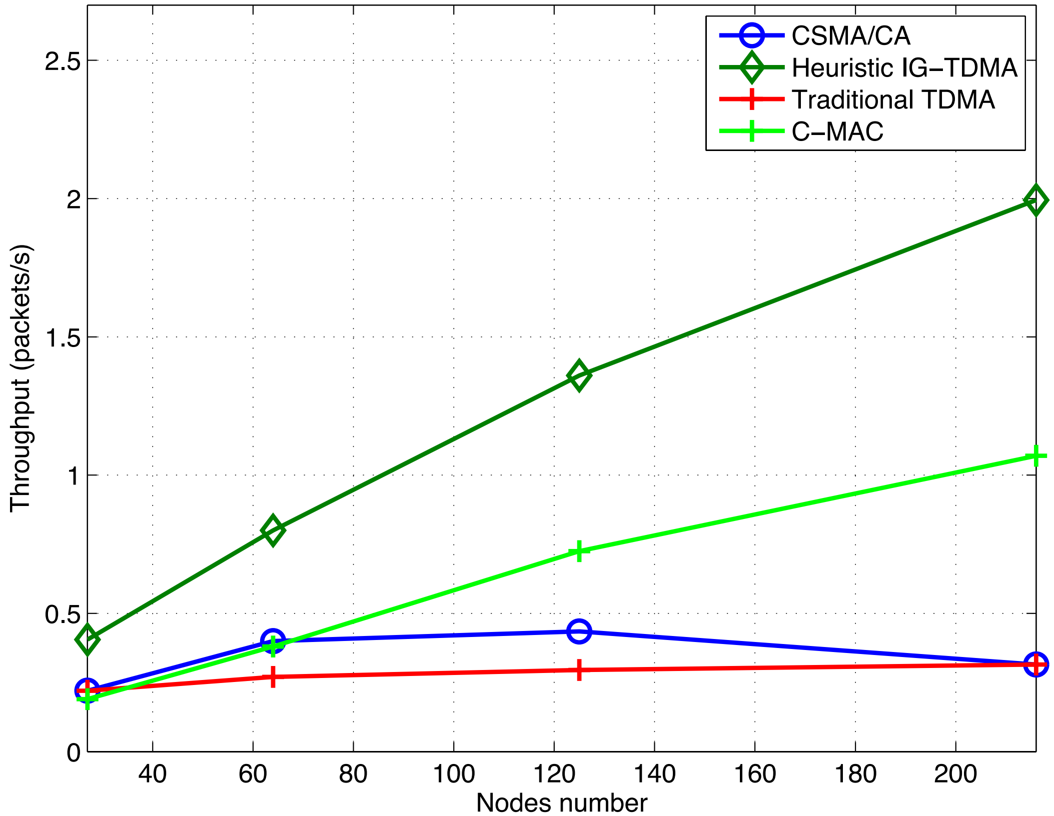
Network Throughput Comparison



- 64 nodes
- $\alpha = 10$ dB
- Packet successfully received if $10\log_{10}(\min \gamma(t)) > 2$ dB $t \in [0, T_p]$

- Traditional TDMA protocol: lowest throughput
- C-MAC: spatial reuse not fully explored ➔ throughput still limited
- CSMA/CA protocol: limited performance due to severe packet collisions in a large-scale and dense network
- Optimal IG-TDMA: significant performance improvement due to effective spatial reuse and interference management
- Heuristic IG-TDMA: close performance compared with optimal IG-TDMA

Effect of Node Density



- Node density:
  - Number of sensor nodes in $3 \times 3 \times 3 \text{ km}^3$ cubic space

- IG-TDMA: performance increases with node density
  - Node density increases ➔ Transmission and interference distances decrease ➔ more interference-free nodes can transmit simultaneously in a time slot
- C-MAC: performance increases with node density
  - Spatial reuse not fully explored ➔ throughput still limited
- CSMA/CA: performance deteriorates with node density
  - Increasing node density could cause more packet collisions.

Summary

- Interference-graph-based TDMA (IG-TDMA) scheduling protocol for UWASN
  - Constructed a dynamic interference graph to indicate the interference condition among different transmitting links in the network
  - Heuristic IG-TDMA clustering: can realize a near-optimal network performance and much lower computational complexity
  - The proposed IG-TDMA protocol can significantly improve the network performance.

Thank you!