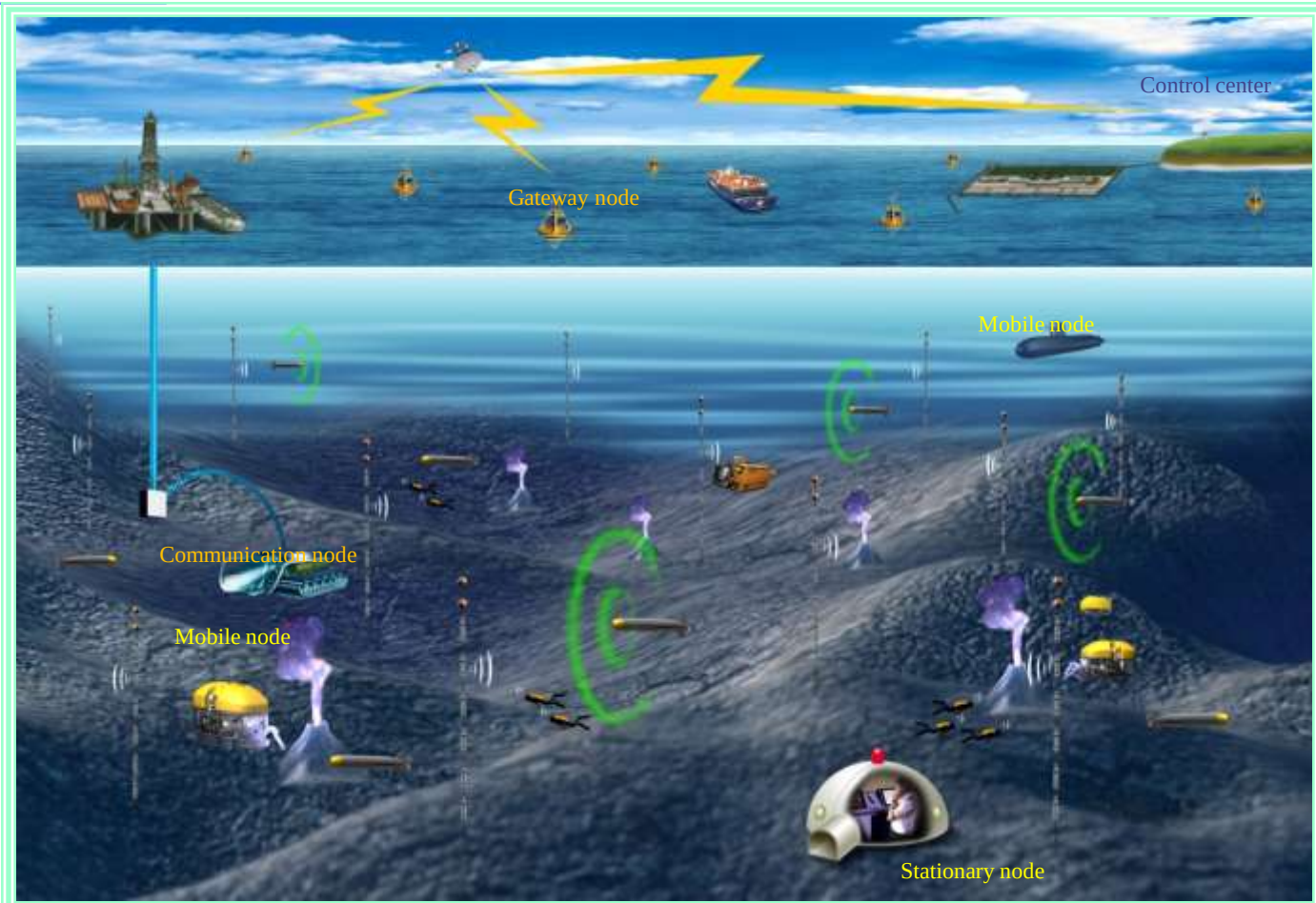


MAC and Swarming Protocols for Undersea Distributed Networked Systems

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Undersea Distributed Networked Systems



Consisting of sensors, unmanned vehicles, platforms, weapons, command and control, and human systems networked together to allow for total control of the undersea battlespace and to enable **Next-Generation Undersea Warfare**

Paradigm Shifts

- ◆ Sensor poor → **sensor** rich
 - Invert the “sensors : warfighter” ratio
 - Medium Access Control (MAC) protocol for acoustic networks
- ◆ Autonomy poor → **autonomy** rich
 - Invert the “simultaneous operations : warfighter” ratio
 - Swarming protocol for AUVs



Time-based Acoustic MAC protocol

Joint work with Justin Yackoski

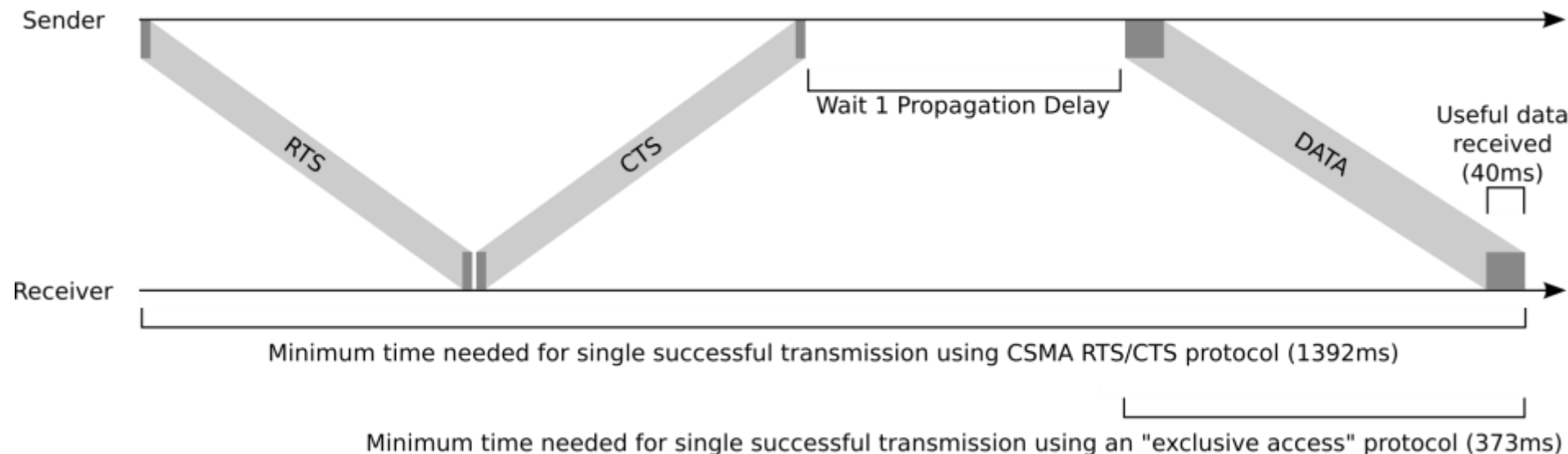


UnderWater Acoustic Networks (UWANs)

- ◆ Example, sending 100 bytes over 250 meters
 - RF: 0.000080s transmit, 0.0000008s propagation
200x slower
 - UW: 0.016000s transmit, 0.1666667s propagation
200,000x slower

Why we shouldn't use Time-based MAC

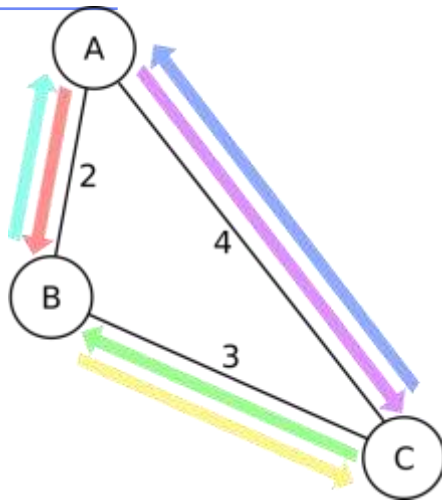
- ◆ High [propagation delay : transmission delay] ratio (3-4 orders of magnitude higher than RF) + **exclusive access** constraint = low utilization
- ◆ Carrier sensing and time synchronization difficult
- ◆ Determining propagation delays difficult
- ◆ Centralized control undesirable



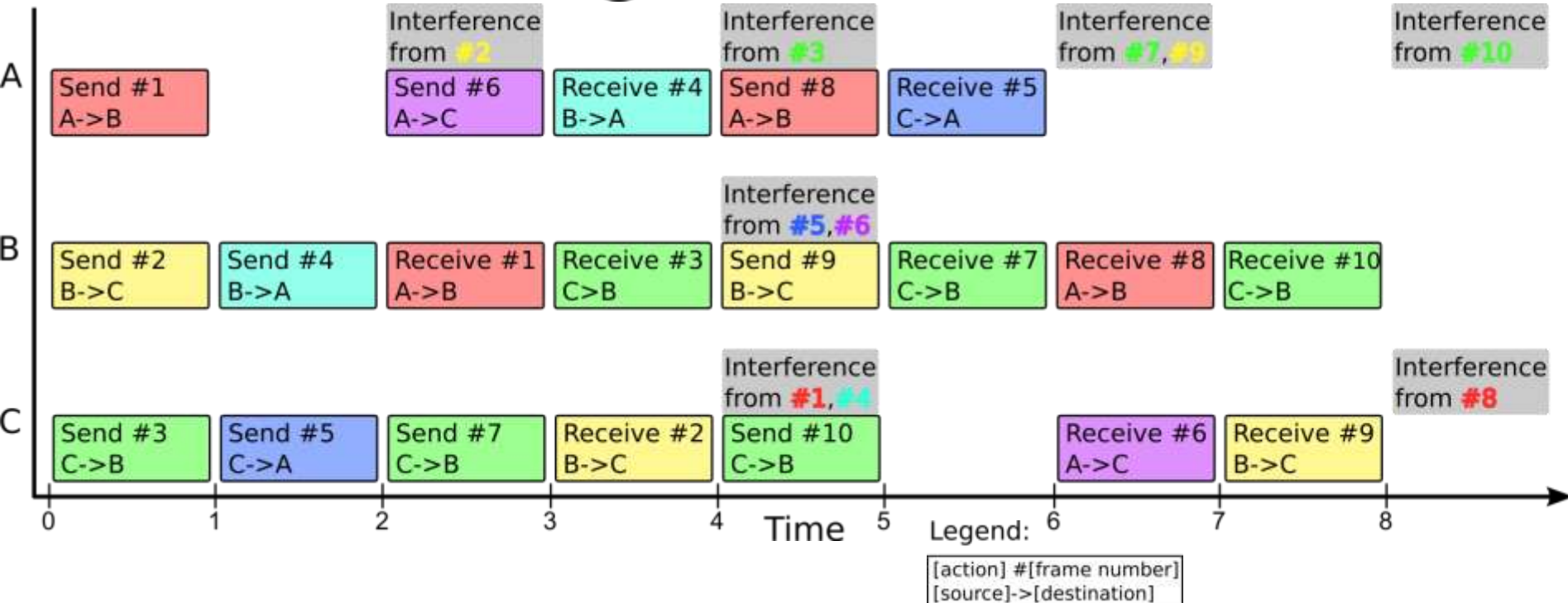
Why we should use Time-based MAC

- ◆ Simpler hardware than CDMA & FDMA
- ◆ Multiple slow channels can be less desirable than a single fast channel
 - More time spent sending/receiving
 - Additional delay and delay is already high
- ◆ More opportunities to sleep

Time-based is not inherently bad



If data transmissions are 1 time unit and propagation between nodes are as shown, could send/receive 10 packets in 8 time units



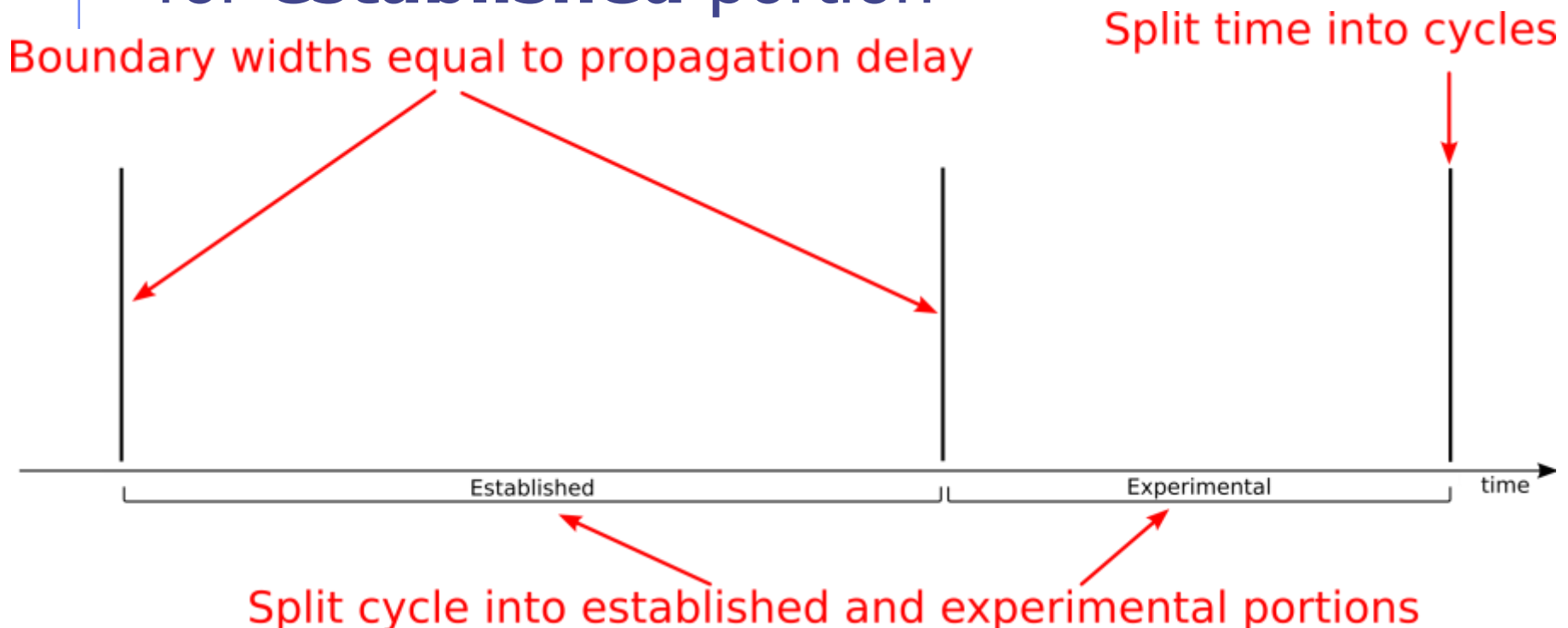
Challenges

For Time-based protocol to be practical, we need

- ◆ No exclusive access constraint
- ◆ No precise clock synchronization
- ◆ No knowledge of propagation delays
- ◆ No large guard times between transmissions
- ◆ Completely decentralized operations

Scheduling Transmissions

- ◆ Loose clock synchronization
- ◆ Send control messages during **experimental** portion to build schedule for **established** portion

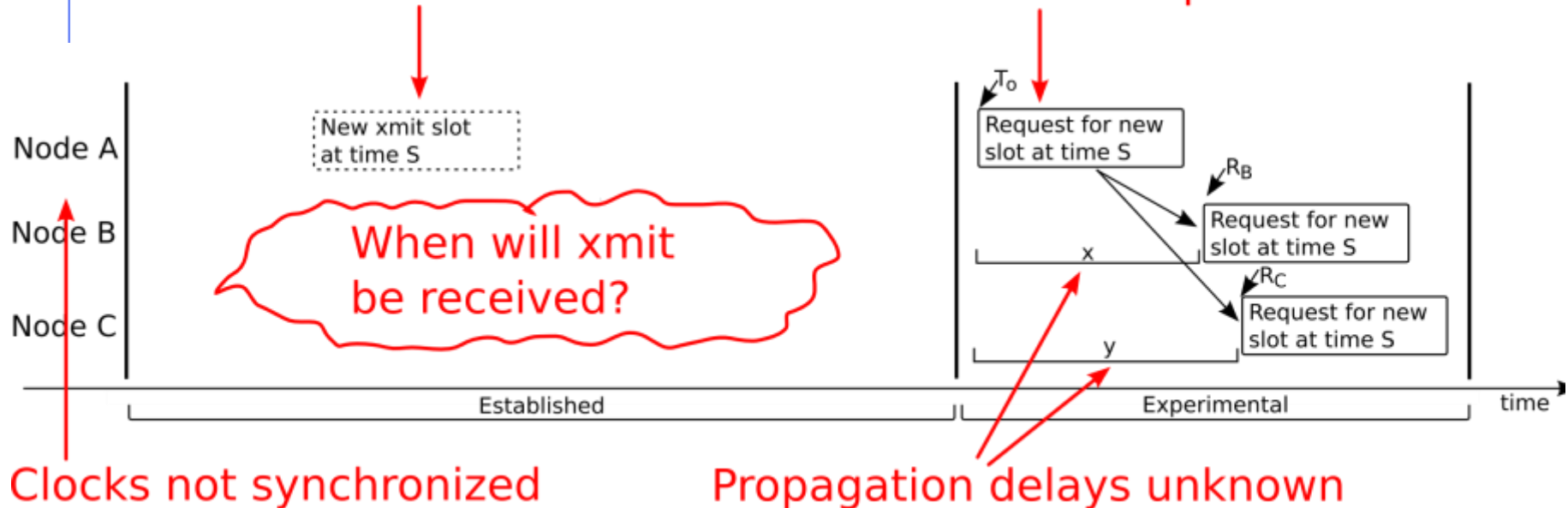


Scheduling Transmissions (2)

- ◆ Nodes can not directly exchange precise time information

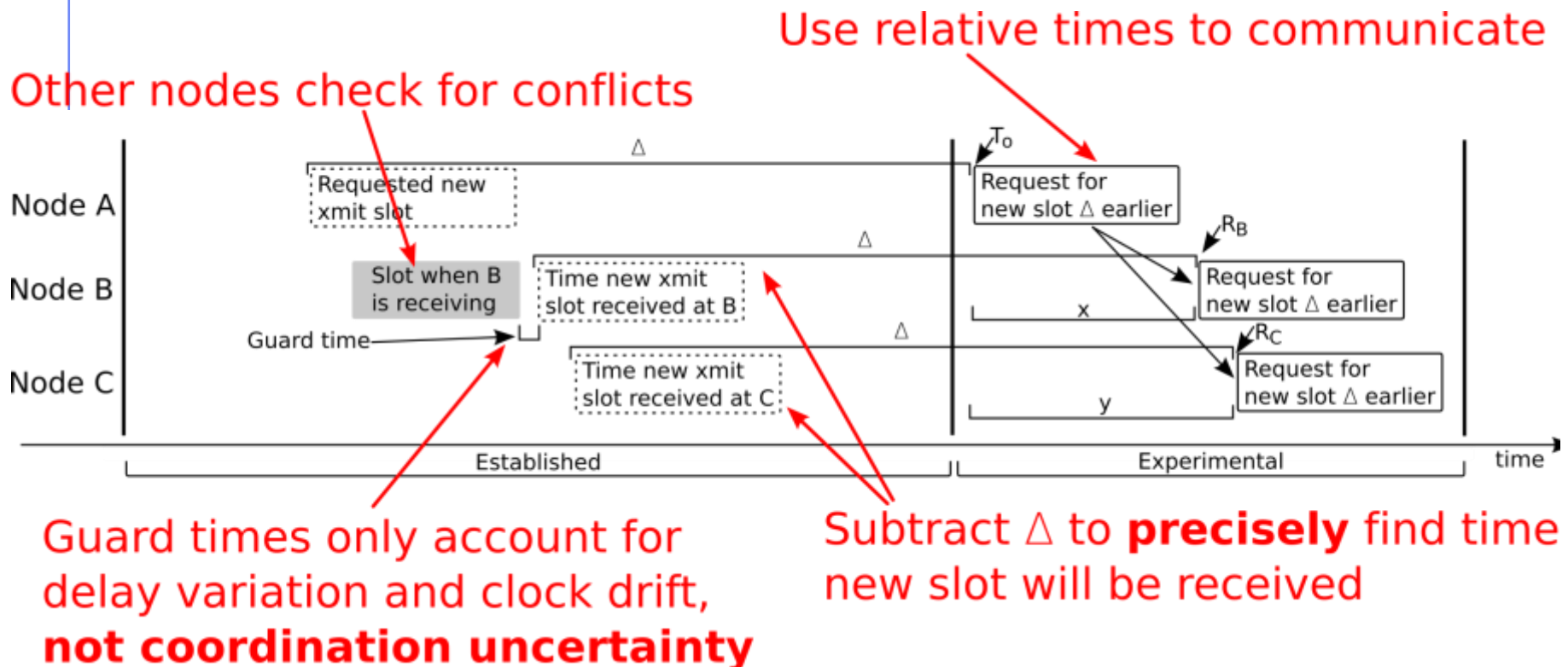
Node A wants to send to B
in new time slot

Node A sends request



Scheduling Transmissions (3)

- ◆ Relative times allow for nodes to exchange precise time information.



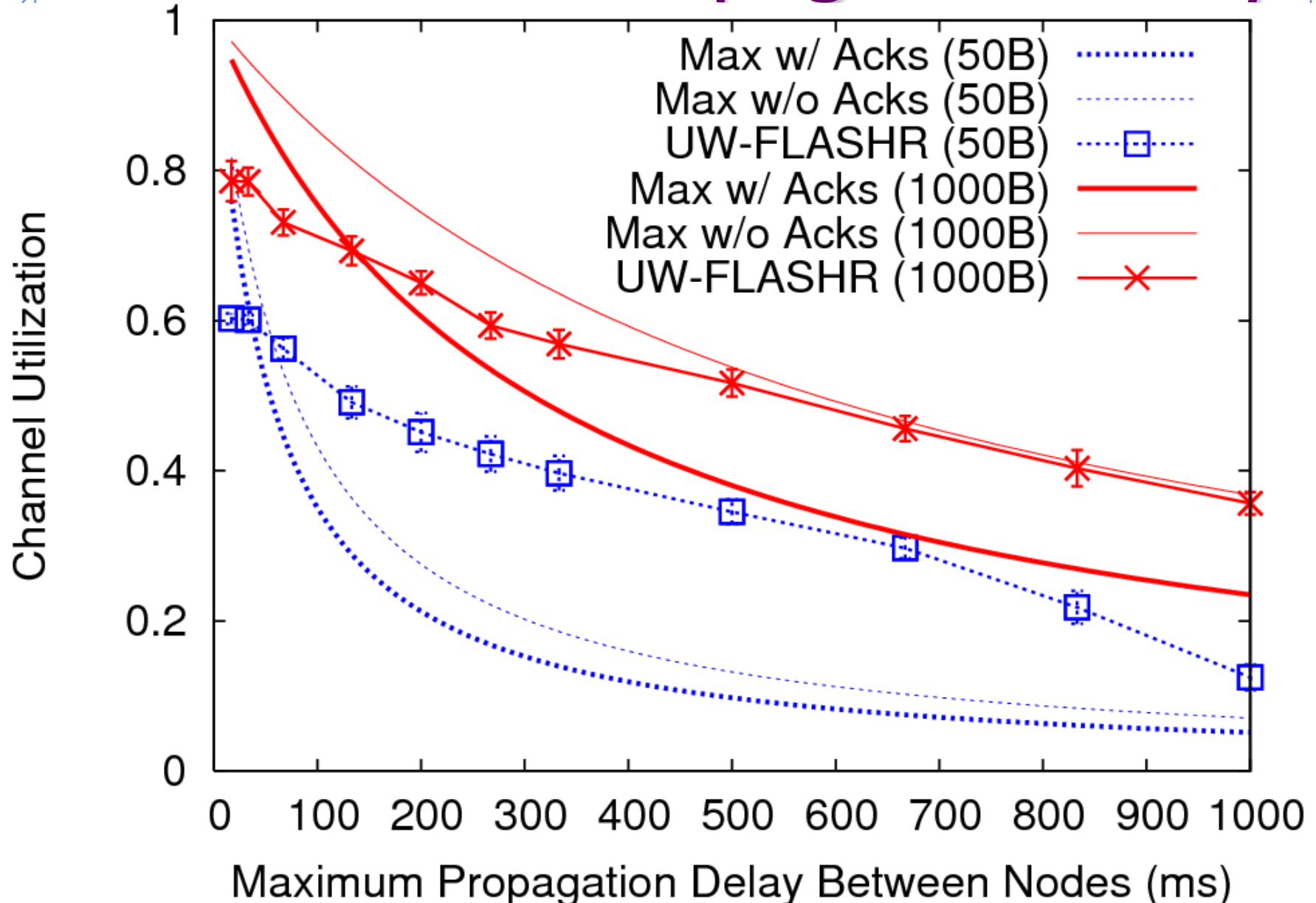
Scheduling Transmissions (4)

- ◆ Process repeats until all transmissions have been scheduled
- ◆ If a conflict occurs, nodes use similar “delta” value exchanges to narrow the search for a suitable time slot
- ◆ ACK frames are scheduled in the same way as DATA frames

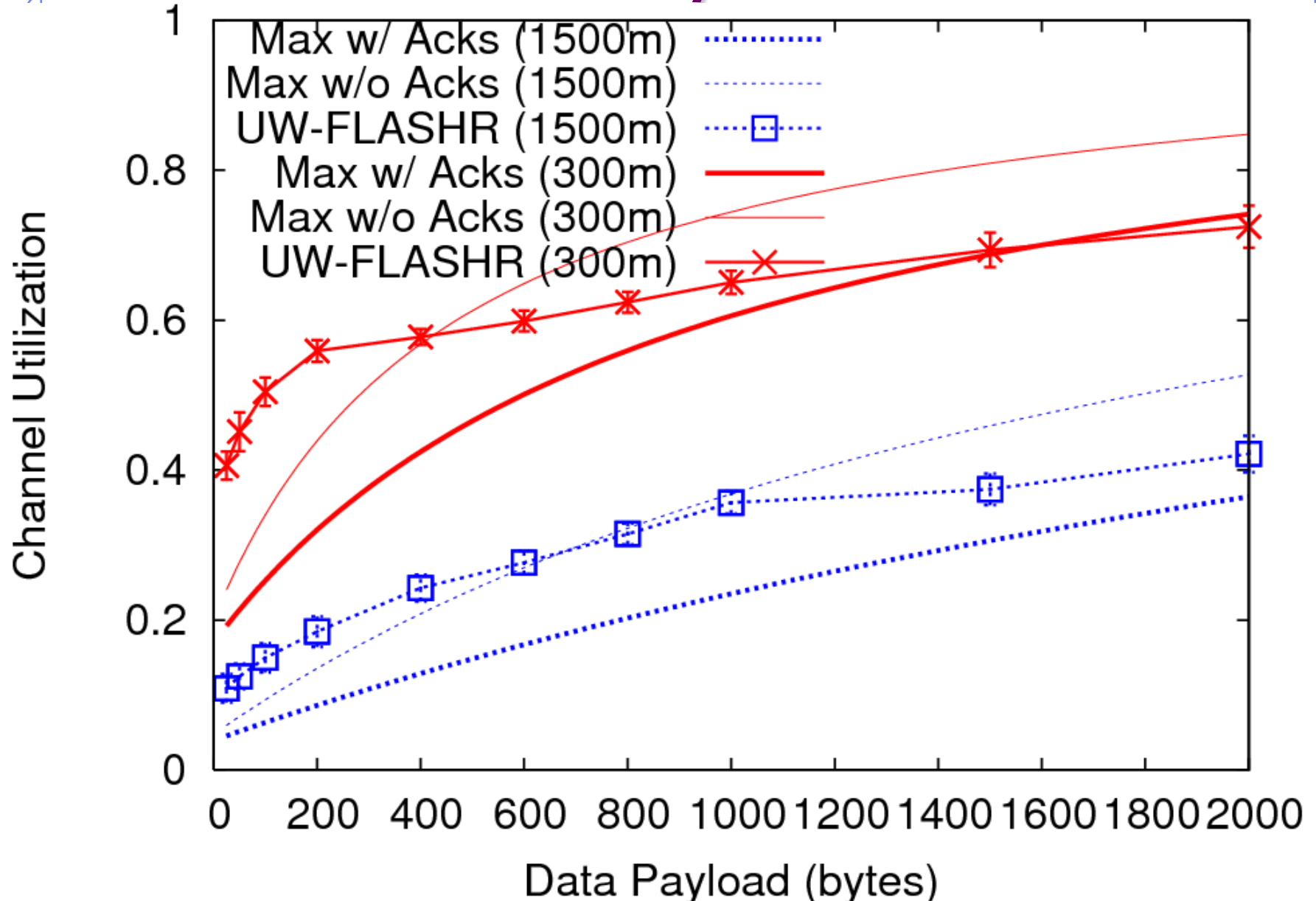
Evaluation

- ◆ QualNet modified to simulate acoustic channel
- ◆ Spherical path loss, Thorp attenuation
- ◆ Nodes randomly placed in square single-hop terrain, max delay between 10ms and 1000ms
- ◆ Node clocks randomly initialized
- ◆ Generate 50 or 1000 byte (76ms or 582ms) CBR traffic between random nodes
- ◆ Utilization is maximum total duration of all DATA and ACK frames received in a single cycle divided by the cycle size (including wasted experimental portion and boundaries)

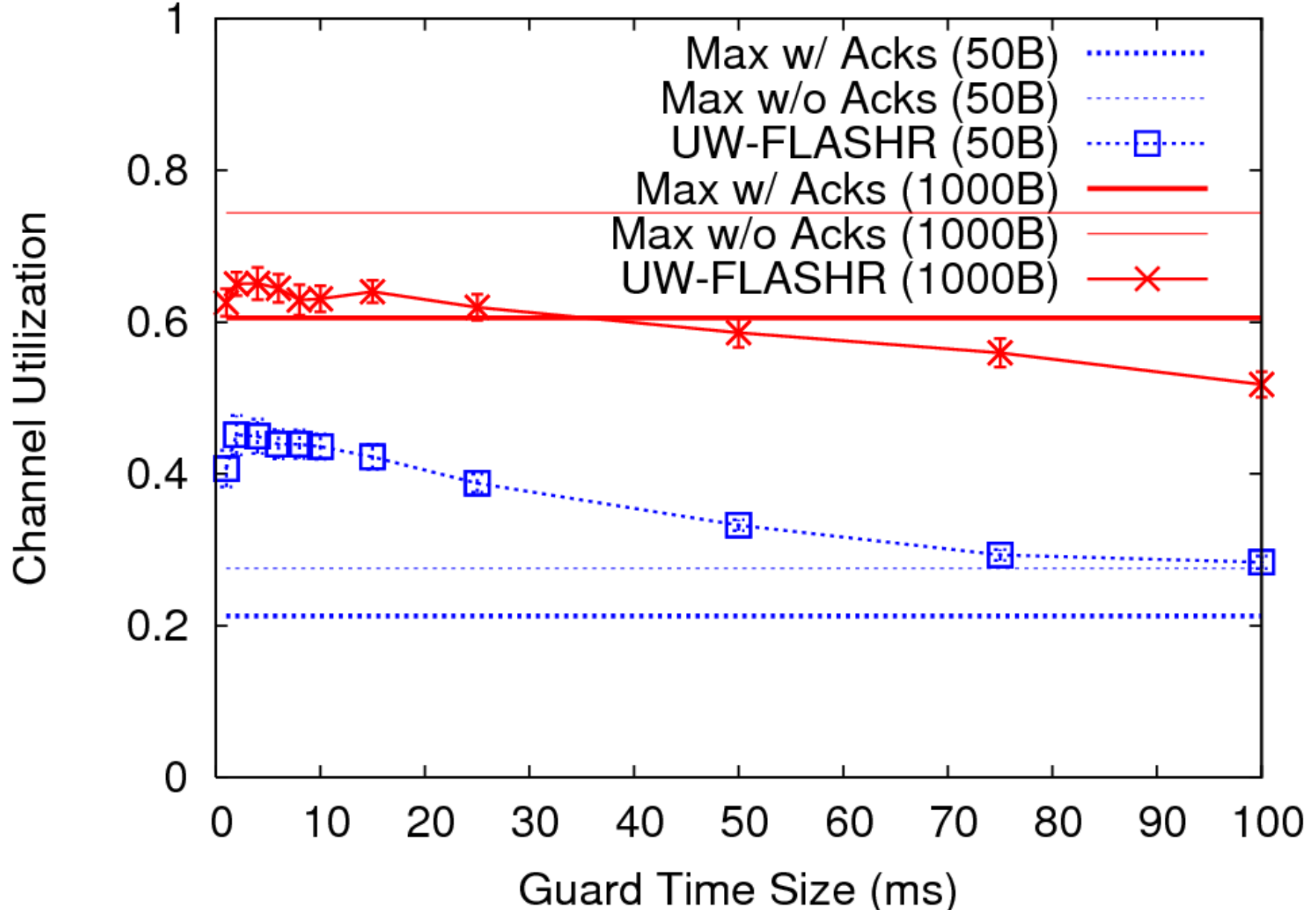
Utilization vs. Propagation Delay



Utilization vs. Payload Size



Utilization vs. Short-Term Variation



Conclusions

- ◆ Time-based MAC protocol can be practical and efficient (both in terms of utilization and energy)
- ◆ For small data payloads, we have shown $\sim 2X$ increase over exclusive access protocols
- ◆ A lot of room to improve scheduling, time wasted in experimental portion and boundaries, etc.



Swarming Protocol for Networked Autonomous Undersea Vehicles (AUVs) - “leadership” problem

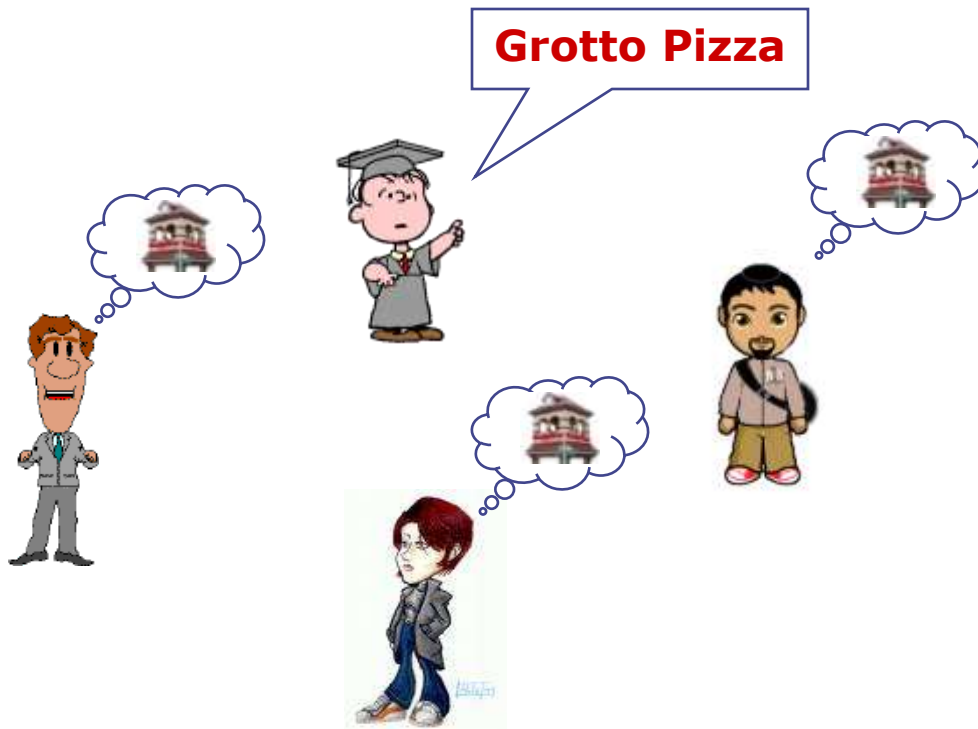
**Joint work with Louis Rossi (Math)
and Xiaofeng Han (Facebook)**



Problem Formulation

◆ Leadership styles

- ❖ Example 1 – ***explicit destination information***
 - ❖ each individual knows the destination



Problem Formulation

◆ Leadership styles

❖ Example 2 – ***explicit leaders***

❖ *non-leaders* follow the *leader*



Problem Formulation

◆ Leadership styles

❖ Example 3 – ***covert leaders***

- ❖ *only a few leaders know the destination*
- ❖ *the destination information and the leaders' identities should remain covert*



Defining “Covertness”

Definition [physical]: A covert individual is statically indistinguishable from others.

Definition [behavioral]: A covert individual has near identical behavior to others.

Inspiration

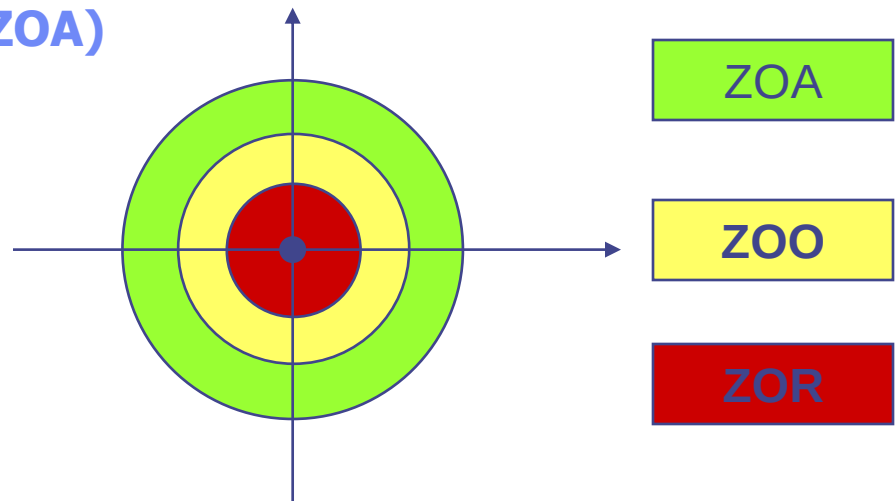
Animals such as birds, ants and fish often navigate in swarms

- ◆ Possess limited intelligence and communication capability
- ◆ Simple interaction mechanisms lead to complex and near optimal behavior in diverse biological systems
- ◆ Covert leaders (animals possessing extra information) exist in different animal swarms

Foundation

Iain Couzin's coordination model for covert leaders in animal swarms

- ❖ I. Couzin, J. Krause, N. Frank, S. Levin, "Effective Leadership and Decision-making in Animal Groups on the Move," **Nature**, Vol. 433, No. 7025, pp. 513-516, 2005.
- ❖ Divide the vision range of each animal into three zones from inside to outside
 - ❖ **zone of repulsion (ZOR)**
 - ❖ **zone of orientation (ZOO)**
 - ❖ **zone of attraction (ZOA)**

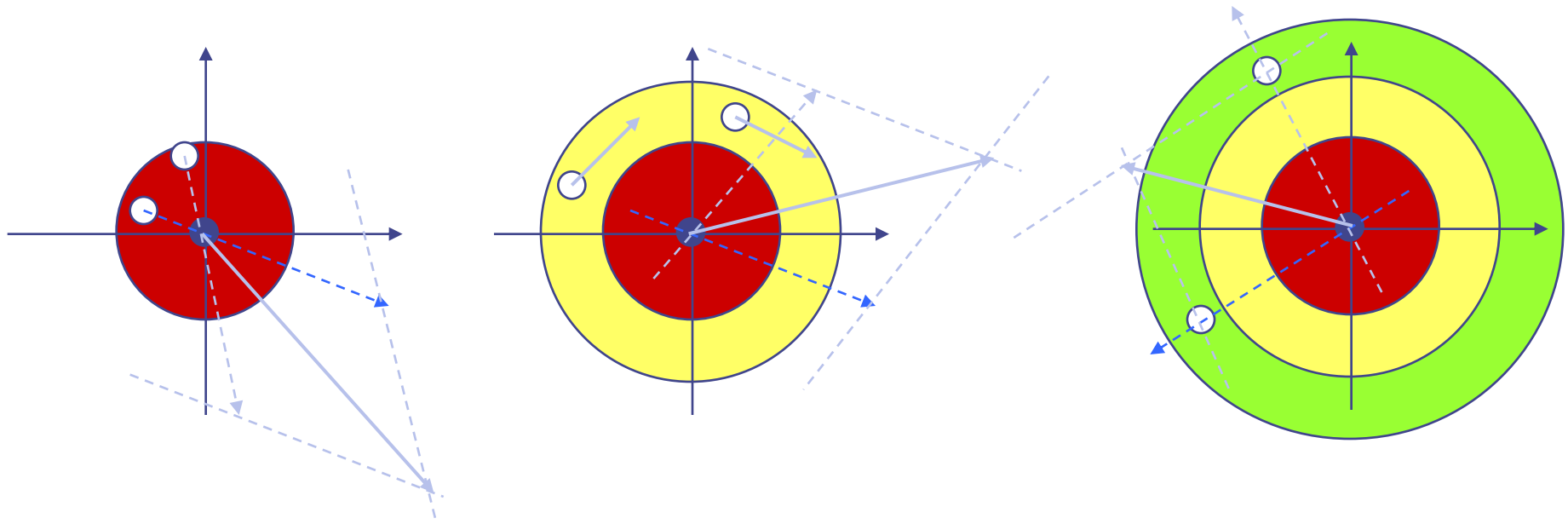


Foundation

Couzin's coordination model (cont.)

Each animal moves at constant speed using sensory coordination rules

- ❖ **ZOR: move away from the neighbors in ZOR (*highest priority*)**
- ❖ **ZOO: align with the neighbors in ZOO**
- ❖ **ZOA: move towards the neighbors in ZOA**



Foundation

Couzin's coordination model (cont'd)

- ❖ The ZOR receives first priority and establishes an upper bound on the swarm density.
- ❖ When the density is acceptable, animals will compromise between orienting with nearby animals and moving toward distant animals.
- ❖ Results: Different combinations of parameters lead to swarms with phases including simple translation, milling and complete disorganization.

Including leadership

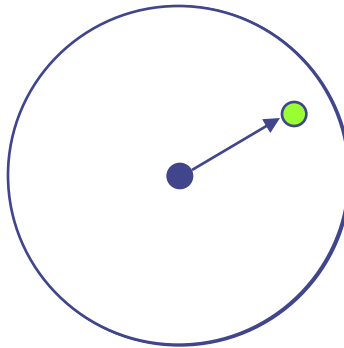
- ◆ Leaders have a modified decision vector.

$$\tilde{d}_i^k = \beta \vec{d}_i^k + (1 - \beta) \vec{g}$$

- ◆ Simulation results show that small **percentage** of leaders (5%) can effectively lead the entire swarm to the destination.
- ◆ An optimal value for β is 1/2. (Open question)

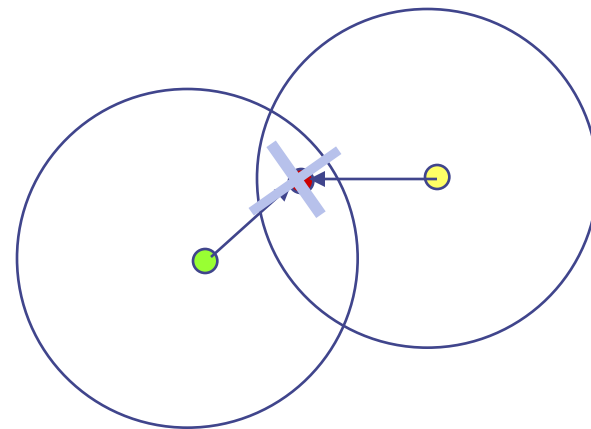
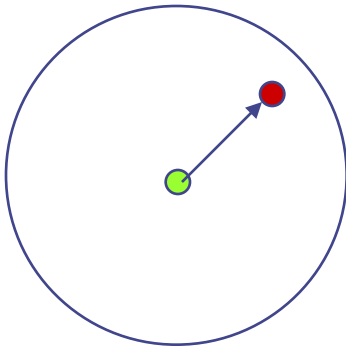
Distributed Navigation Algorithm

- ◆ Extend Couzin's Model for Robot Swarms
 - ❖ Key idea
 - ❖ Map the communication range to vision range of animals
 - ❖ Divide the communication range into three zones and follow the coordination rules



Distributed Navigation Algorithm

- ◆ Extend Couzin's Model for Robot Swarms
 - ❖ Major Challenges
 - ❖ limitation of wireless communications
 - ❖ cannot broadcast continuously
 - ❖ cannot broadcast at the same time

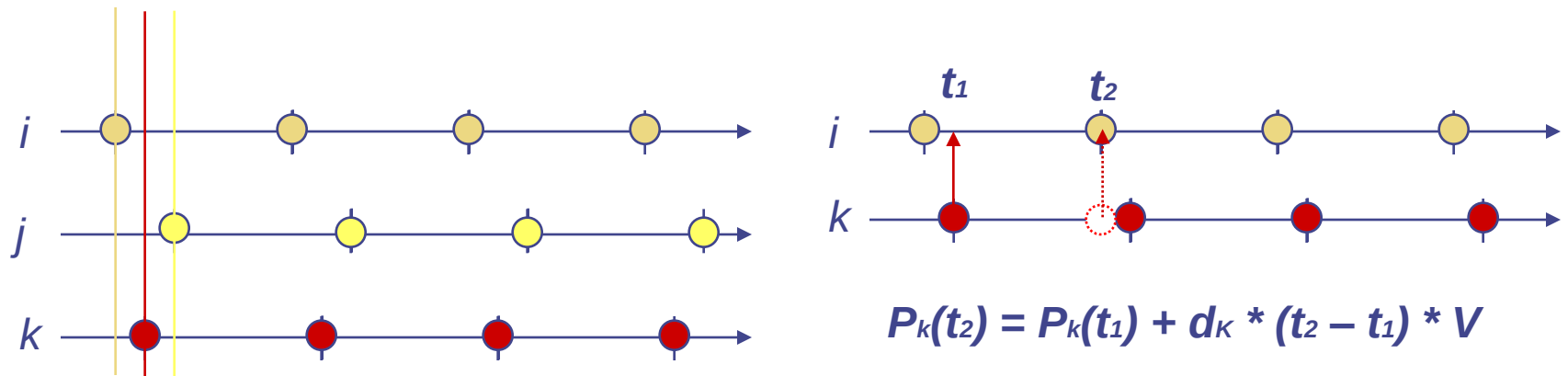


Distributed Navigation Algorithm

◆ Extend Couzin's Model for Robot Swarms

❖ Asynchronous Solution

- ❖ Robots asynchronously divide time into slots with fixed length
- ❖ Robots decide new moving directions at the beginning of each slot and broadcast positions and new moving directions



Distributed Navigation Algorithm

◆ Algorithm

- 1:** each robot asynchronously divides time into slots with equal duration
- 2:** each robot calculates its new moving direction using the coordination rules and broadcast its location and moving direction at the beginning of each time slots

◆ Assumptions

- ❖ constant moving speed
- ❖ end to end delay can be omitted
- ❖ location awareness (through GPS or localization algorithm)

Simulation Results

◆ Evaluation Metrics

❖ Average Arrival Ratio

❖ Successful arrival: in given time, the robot swarm gets to certain place where the destination point is within the *transmission range* of at least one leader, and the network is *connected*

❖ *Average arrival ratio: successful arrivals / total trials*

❖ Average Arrival Time (successful arrivals)

Simulation Result

◆ Simulation Setup

Simulation Platform	QualNet 3.8
PHY and MAC Layer	IEEE 802.11b
Data Rate	5 Mbps
Transmission Range	350 Meters
Broadcast Intervals	2 Seconds
Number of Robots	10 ~ 50
Moving Speed	1 ~ 10 Meters per second
Percentage of Leaders	10% ~ 25%

Simulation Results

◆ Successful Cases

QuickTime?and a
YUV420 codec decompressor
are needed to see this picture.

QuickTime?and a
YUV420 codec decompressor
are needed to see this picture.

Simulation Results

◆ Failed Cases

QuickTime?and a
YUV420 codec decompressor
are needed to see this picture.

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YUV420 codec decompressor
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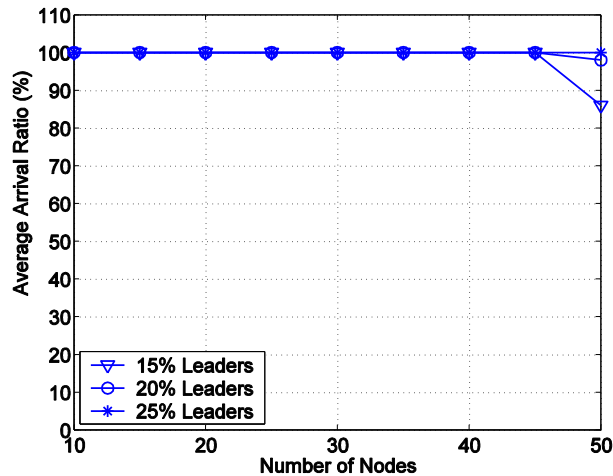
Simulation Results

$$\tilde{d}_i^k = \beta \vec{d}_i^k + (1 - \beta) \vec{g}$$

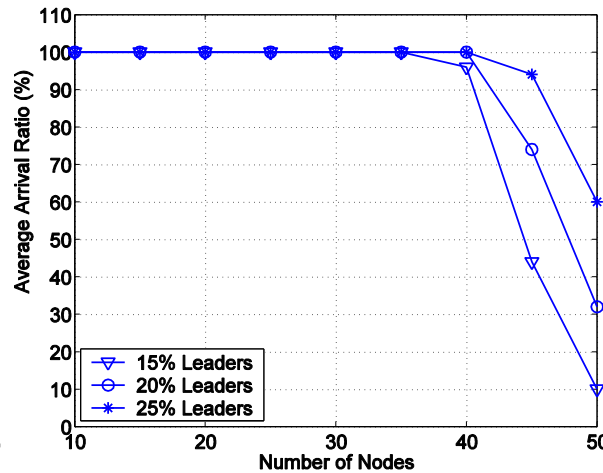
- Each leader computes a convex hull covering all of its 1-hop neighbors
- Each leader decides its β value depending on its distance to the center of its convex hull
 1. smaller value when closer to the center
 2. larger value otherwise

Simulation Result

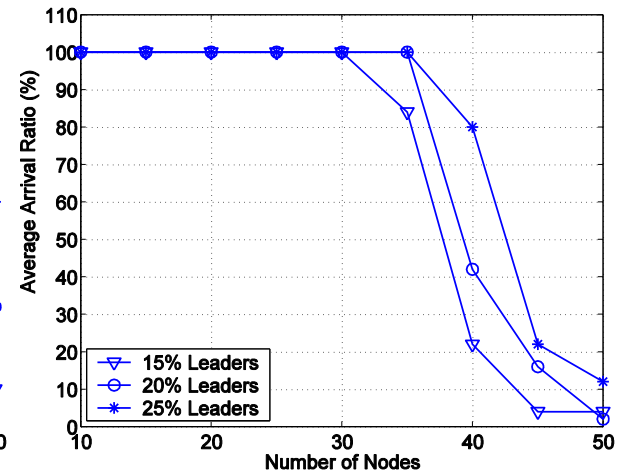
◆ Number of Robots – Arrival Ratio



moving speed = 3



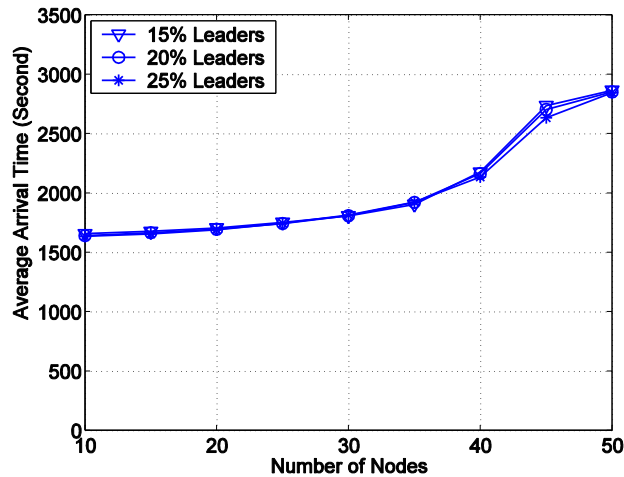
moving speed = 6



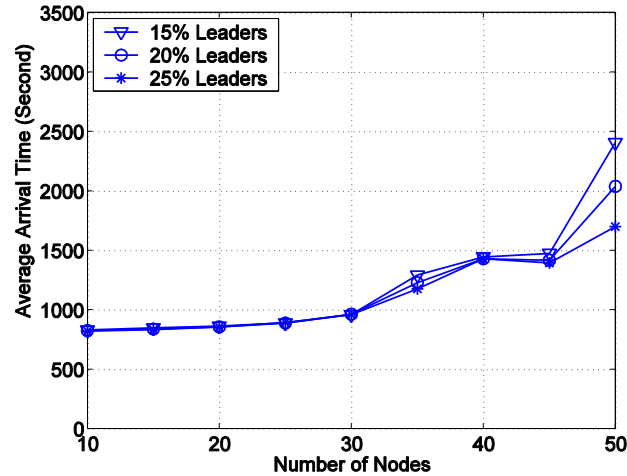
moving speed = 9

Simulation Result

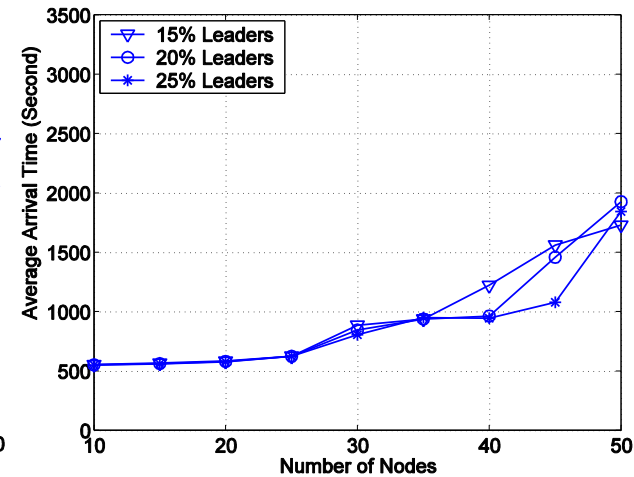
◆ Number of Robots – Arrival Time



moving speed = 3



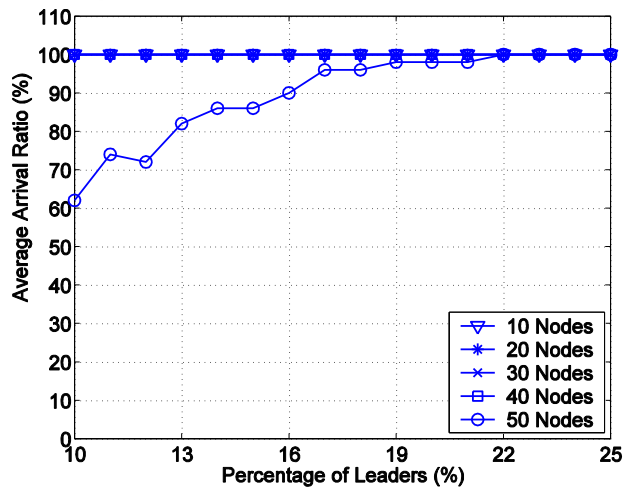
moving speed = 6



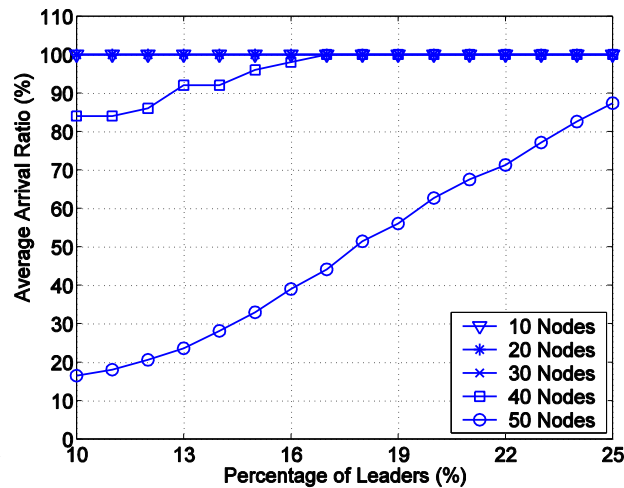
moving speed = 9

Simulation Result

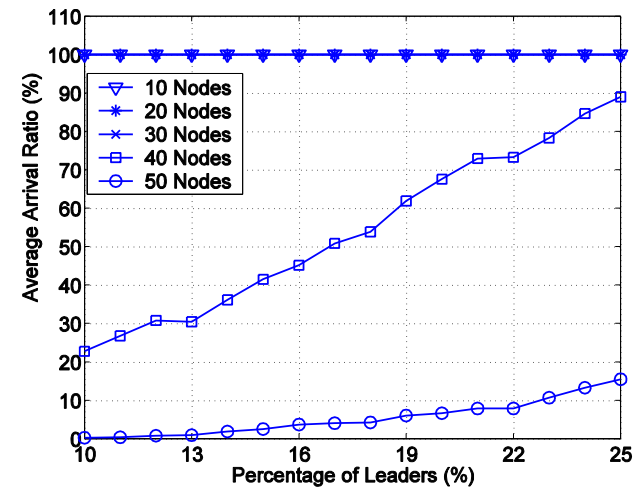
◆ Percentage of Leaders – Arrival Ratio



moving speed = 3



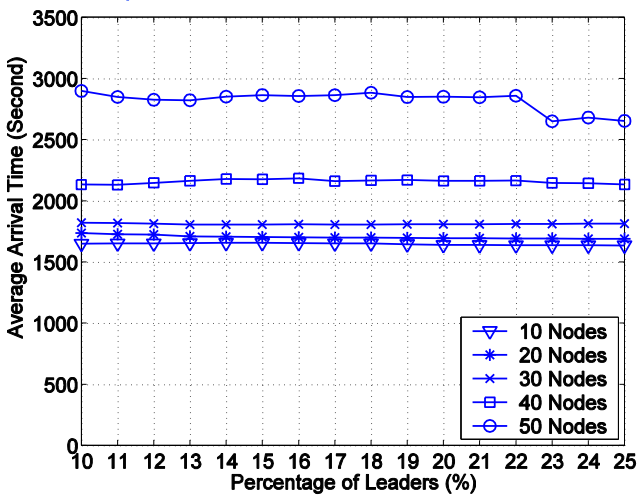
moving speed = 6



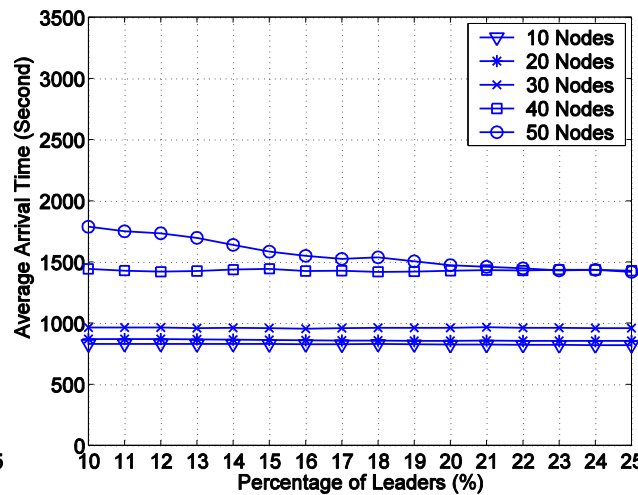
moving speed = 9

Simulation Result

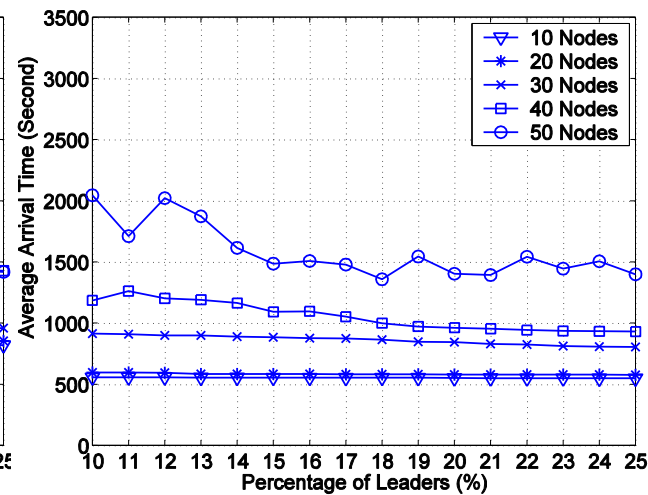
◆ Percentage of Leaders – Arrival Time



moving speed = 3



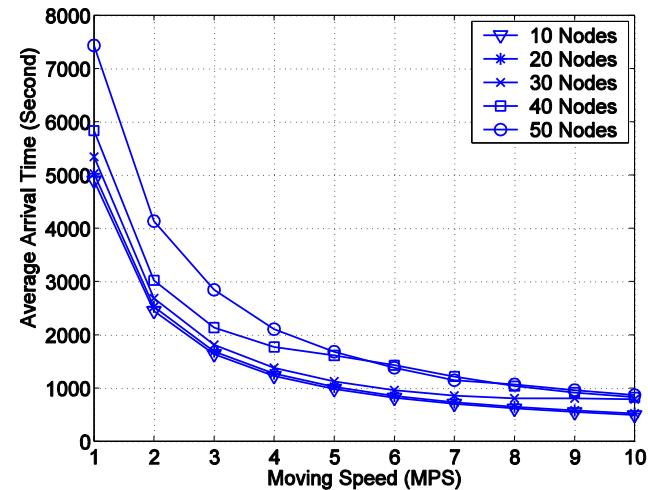
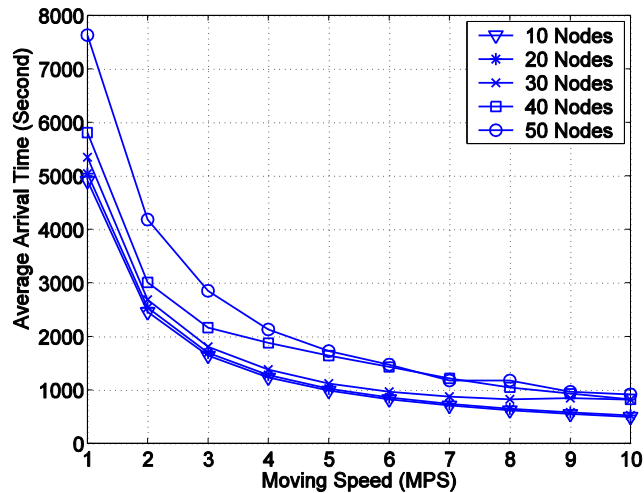
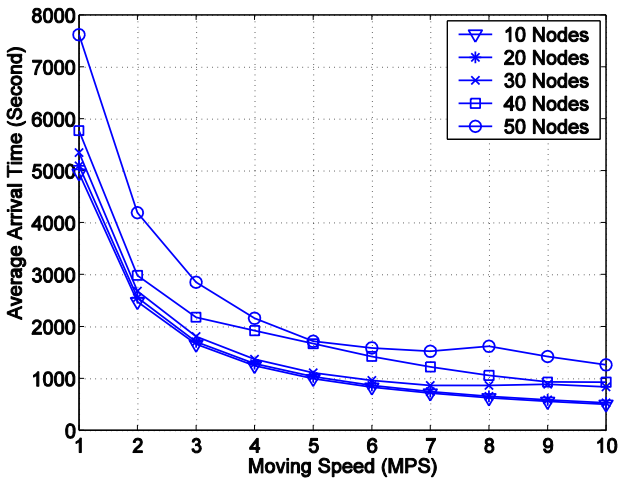
moving speed = 6



moving speed = 9

Simulation Result

◆ Moving Speed – Arrival Time



Leader Percentage = 15%

Leader Percentage = 20%

Leader Percentage = 25%

Anticipated conclusions

- ◆ Relatively small numbers of covert robots can provide leadership to the swarm.
- ◆ High speeds (infrequent updates) disrupt the swarm and lead to unstable behavior...

Conclusions (unanticipated)

- ◆ ...this instability is a function of leadership density, not swarm density.
- ◆ Critical leadership size scales with swarm size.
- ◆ Leaders tend toward the front of the swarm.
- ◆ Large ZOOs yield better coordination.

Other Issues

- ◆ Derivation of a balance between ZOO size (multihop communications) and update interval instabilities
- ◆ Dynamic zones
- ◆ Obstacle avoidance
- ◆ Kinetic constraints
- ◆ Background flows (ocean current)

Conclusions

- ◆ Undersea Distributed Networked Systems enables Next-Generation Undersea Warfare
- ◆ Paradigm shifts to **sensor rich** and **autonomy rich**
- ◆ New networking and swarming protocols