Pulse-Coupled Synchronization for Cooperating Agents

towards Mobile Cyber-Physical Systems

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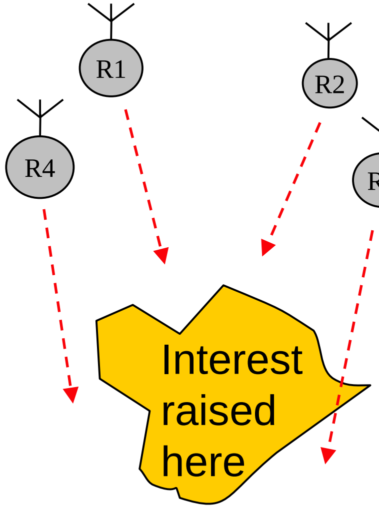
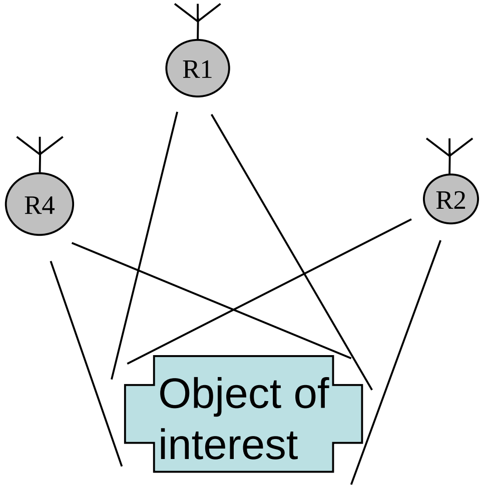
DaRTES Distributed and Real-Time Embedded Systems Lab

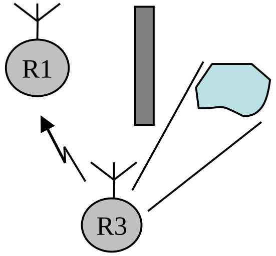
CISTER - Research Centre in Real-Time & Embedded Computing Systems

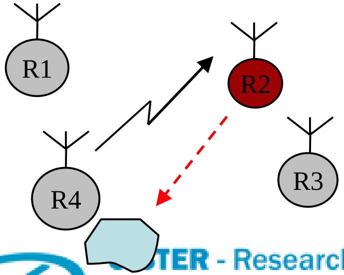
Teams of cooperating agents

- **What for?**
  - Robust & wider sensing
  - Cooperative sensing & control
  - Efficient actuation, ...









Requirements for effective collaboration

- **Synchronization**
  - Coordination in **time**
- **Information dissemination**
  - Sharing **state**, **events**…
- **Dynamic membership**
  - **Who** is in the team
- **Location-awareness**
  - **Where** are the team-mates
- **Combination of behaviors**
  - **Collaborative** versus **autonomous**

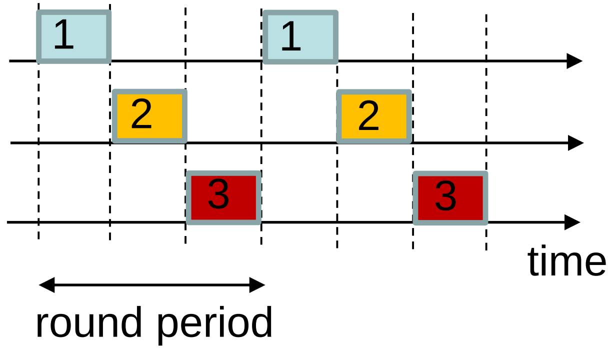
Communication requirements

- **Sharing state + sensing**
  - Periodic short/medium size d
- **Streaming multimedi**
  - Periodic medium/ ata
- **Communic events**
  - Ape hort data

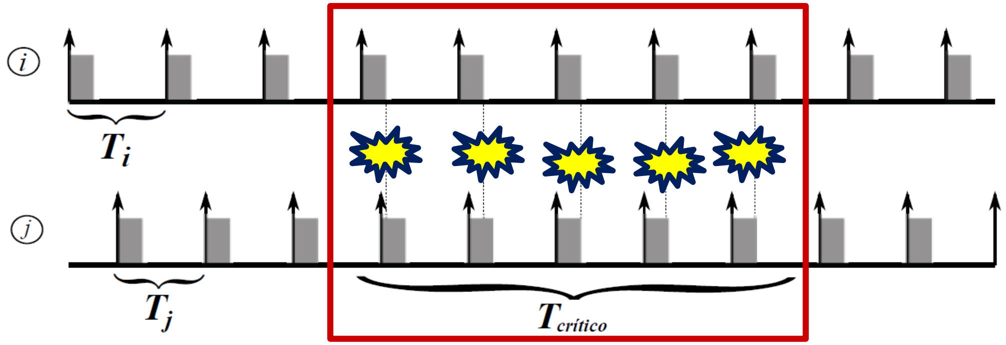
Communication has to be wireless!

A few observations on wireless communication

- **Common CSMA MACs are similar to "talking in a meeting"**
- **Abuse leads to global communication degradation**
  - Saturation, starvation, thrashing…
- **Under high traffic, access rules improve effectiveness of channel use**
  - Example: **TDMA** – Time Division Multiple Access



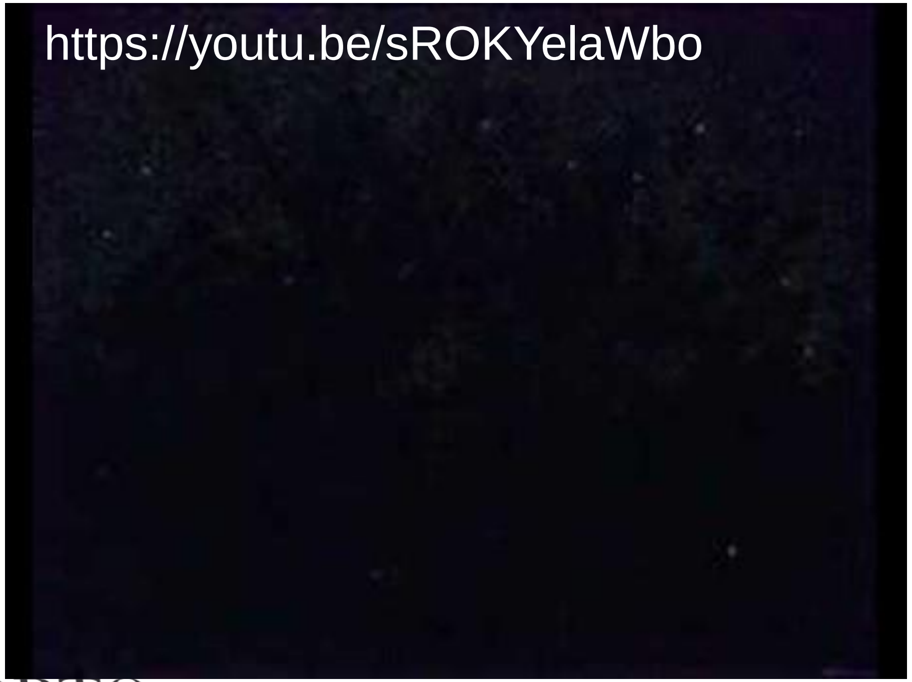
- **Periodic interference can generate degradation even with light load**
  - Critical periods



Pulse-coupled synchronization, an inspiration

- Synchronization is important for effective and efficient communications
- Pulse-coupled synchronization is a natural mechanism that is
  - **Infrastructure-free, distributed**, **scalable** and **robust**

(videos from youtube)



Initial case study – RoboCup MSL (Middle Size League)

- **Requirements**
  - **WiFi** communication
  - Need to **share state** and events within the team
  - Need to **cope with external (alien) traffic**
- **Coordination of transmissions**
  - State sharing → ***periodic pulses***
    - broadcast medium → ***coupling mechanism***
- **Reconfigurable and Adaptive TDMA protocol (RA-TDMA)**
  - **Coordinates transmissions** within the team
    - Internal synchronization, broadcast dissemination
  - Escapes from **critical periods** and copes with **external traffic**

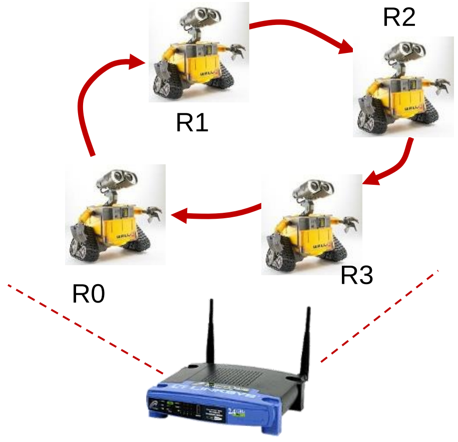
Adaptive TDMA

Time Division Multiple Access

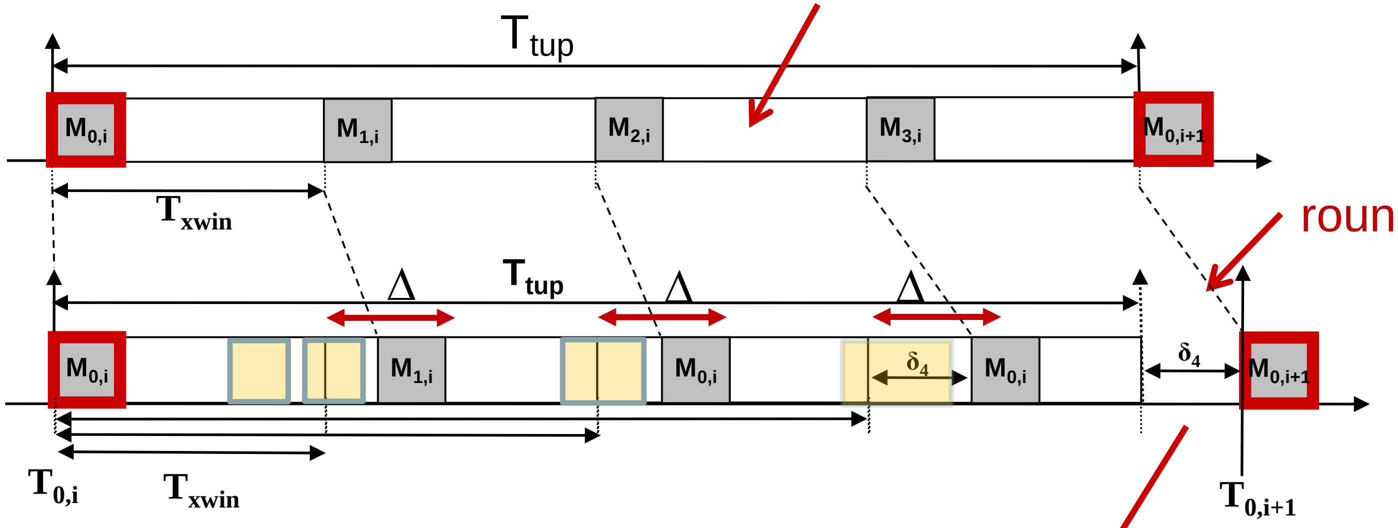
- One **slot** per node - **reservation**
- Dynamic **reference** election (lowest ID)

Maximizes separation between team transmissions

round phase shift



Infrastructured



Reference $t_{0,k+1} = t_{0,k} + T_{tup} + \min\left(\max_{i=1..N-1} \delta_i , \Delta\right)$

Other nodes $t_{i,k} = \hat{t}_{0,k} + i * T_{xwin}, \quad i = 1..N-1$

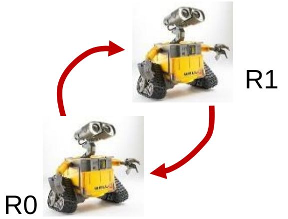
round *k*
agent *i*

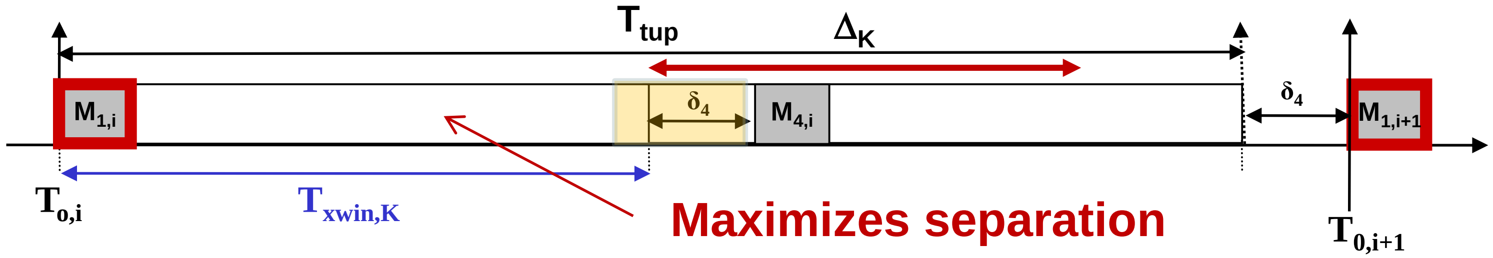
Reconfigurable & Adaptive TDMA

- **Robots join and leave dynamically**
  - crash, maintenance, moving in and out of range…
  - Slots are **created / destroyed** dynamically

Round is kept

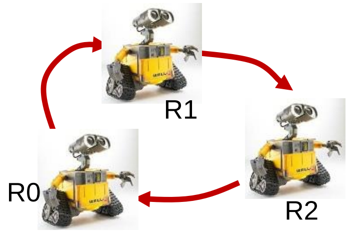
2 running robots:

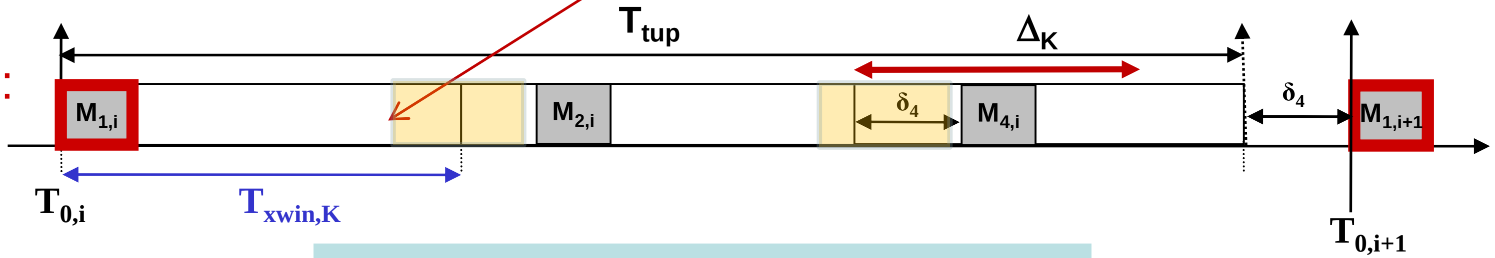




Maximizes separation
between team transmissions

3 running robots:





$$T_{xwin,K} = \frac{T_{tup}}{K} \qquad K \leq N$$ → Actual team size

$$\Delta_K = T_{xwin,K} * \varepsilon \qquad 0 < \varepsilon \leq 1$$ → Stretchability coefficient

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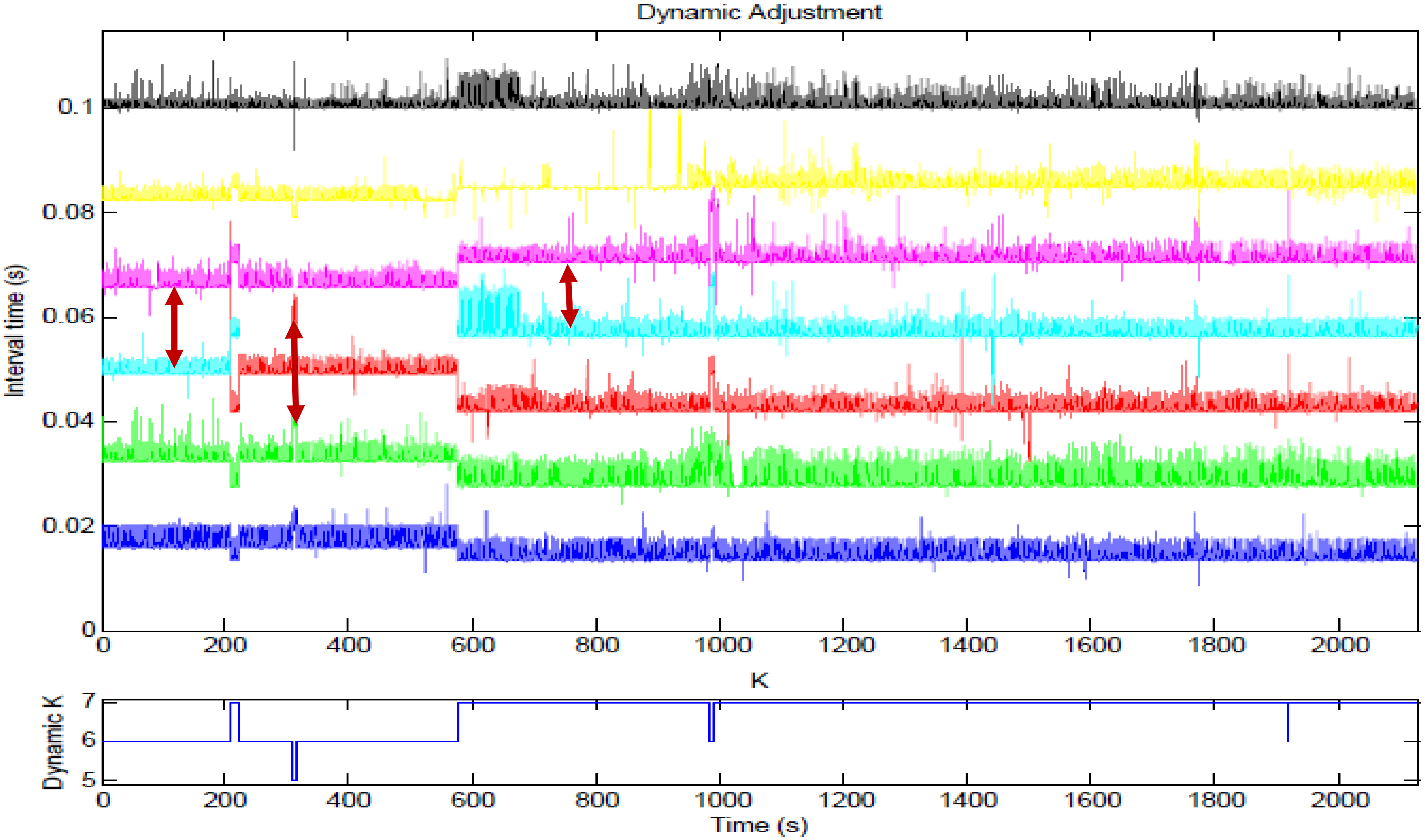
Membership and round structure

Offset of Tx in the round

Team members



On the use of the protocol

- Adequate to disseminate state information
  - On the contrary, implies extra delays on event transmission
  - **Events** should be sent as **external traffic**, outside the protocol control
- Typical behaviors
  - Collaborative **ball tracking**
  - **Formation** control
    - Team entrance in and departure from field
    - Set-plays (tactics) enforcement
  - Collaborative **sensing** for strategic reasoning
    - At the coach level

Source code available at:
www.bitbucket.org/fredericosantos/rtdb/

RA-TDMA at work

Search and Rescue scenarios

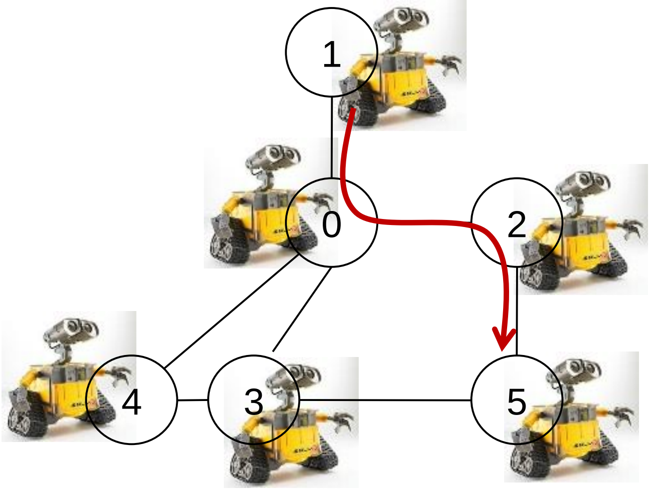
- **Multi-hop mesh topology is more favorable**
  - Higher flexibility in area coverage and formation control
- **but**
  - New agents can **join in a "corner"** of the network
  - There can be **localized noise** affecting a few agents, only

Ad-hoc
Reconfigurable and Adaptive
TDMA protocol
(RA-TDMA+)

(WiFi and IEEE 802.15.4)

Membership? Topology tracking?

- **Build and maintain an adjacency matrix**
  - Sense **neighborhood** and disseminate in a **periodic message**
  - **Merge matrices** with neighbors (**flooding**)
  - Enables on the fly **(proactive) routing**



	0	1	2	3	4	5
0	0	1	1	1	1	0
1	1	0	0	0	0	0
2	1	0	0	0	0	1
3	1	0	0	0	1	1
4	1	0	0	1	0	0
5	0	0	1	1	0	0

Vision of node 0

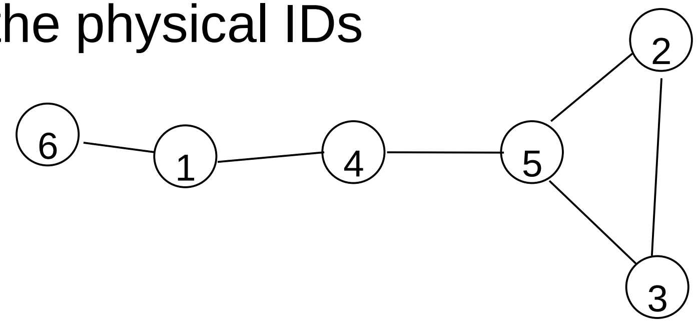
Neighbor

Not neighbor

Who receives from node 0

Converging to a global adjacency matrix

- **Detecting omissions**
  - The **corresponding bit** in the local vision (its line) in the receiver matrix is **reset**
  - A column with all 0s means that **node is disconnected** from the team
- **Uses sequence numbers per line**
  - **Update** the lines with **higher sequence number** (seq. number included)
  - **Increment** just before transmission and send together
  - **Erase lines** that have not been updated for some time
- **Slot allocation**
  - Based on the order of the physical IDs



$S^3(t)$

1	5
2	2
3	3
4	5
5	5
6	5

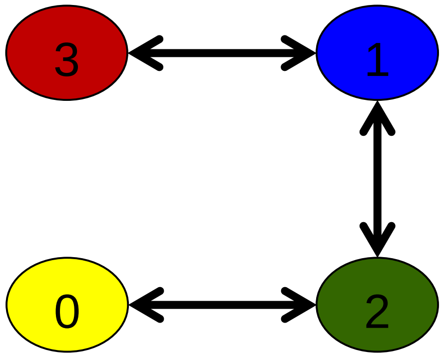
$M^3(t)$

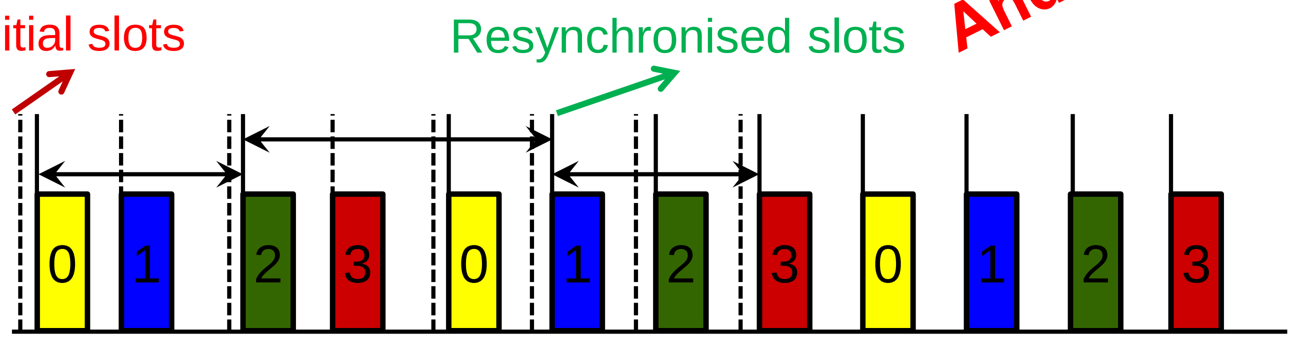
	1	2	3	4	5	6
1	0	0	0	1	0	1
2	0	0	1	0	1	0
3	0	1	0	0	1	0
4	1	0	0	0	1	0
5	0	1	1	1	0	0
6	1	0	0	0	0	0

Ad-hoc synchronization

- **Slot synchronization is localized**
  - Agents synchronize directly with their **neighbours** using their **periodic messages**
- **Synchronization is propagated through the network**
  - Even if agents do **not communicate directly** they eventually synchronize
  - Time necessary to reach **synchronization depends** on **link density**

And does it converge?

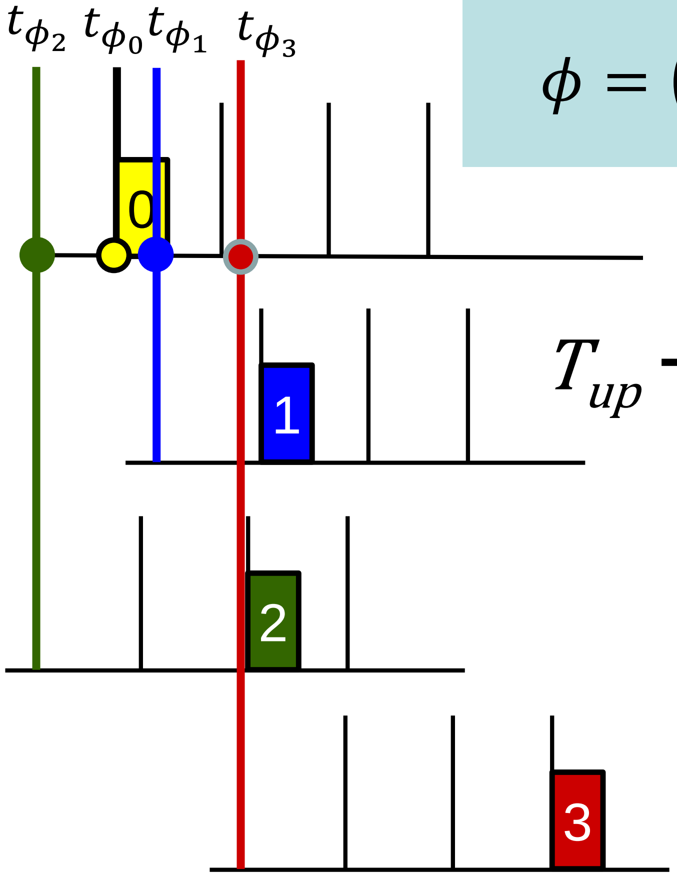




$$t_{i,k+1} = t_{i,k} + T_{tup} + \min\left(\max_{j \in \aleph_i} \delta_j \,, \Delta\right)$$

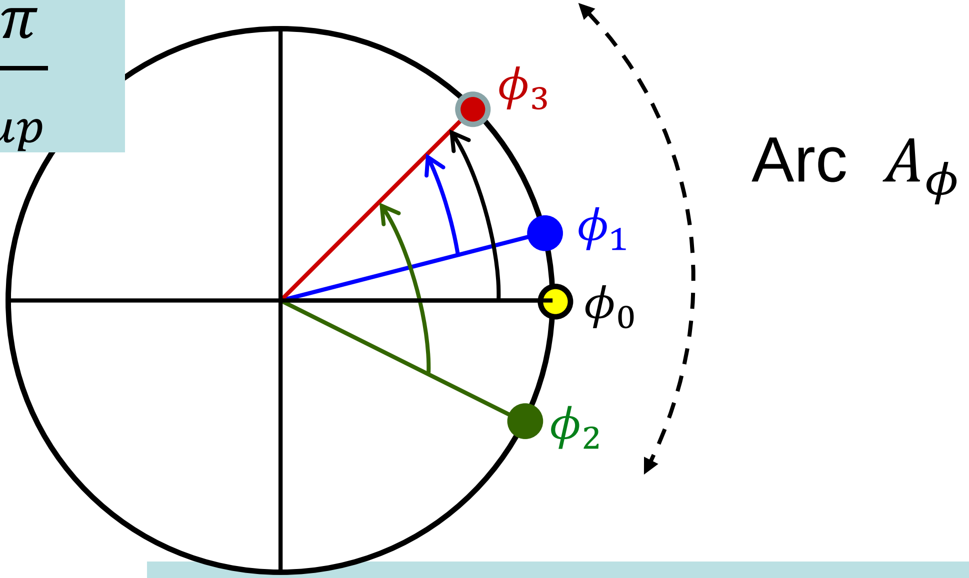
round k
agent i
neighbour j

Expressing delays as angles → phases



$$\phi = (t_\phi + k * T_{up})\frac{2\pi}{T_{up}}$$

T_{up} → 360º (2π)



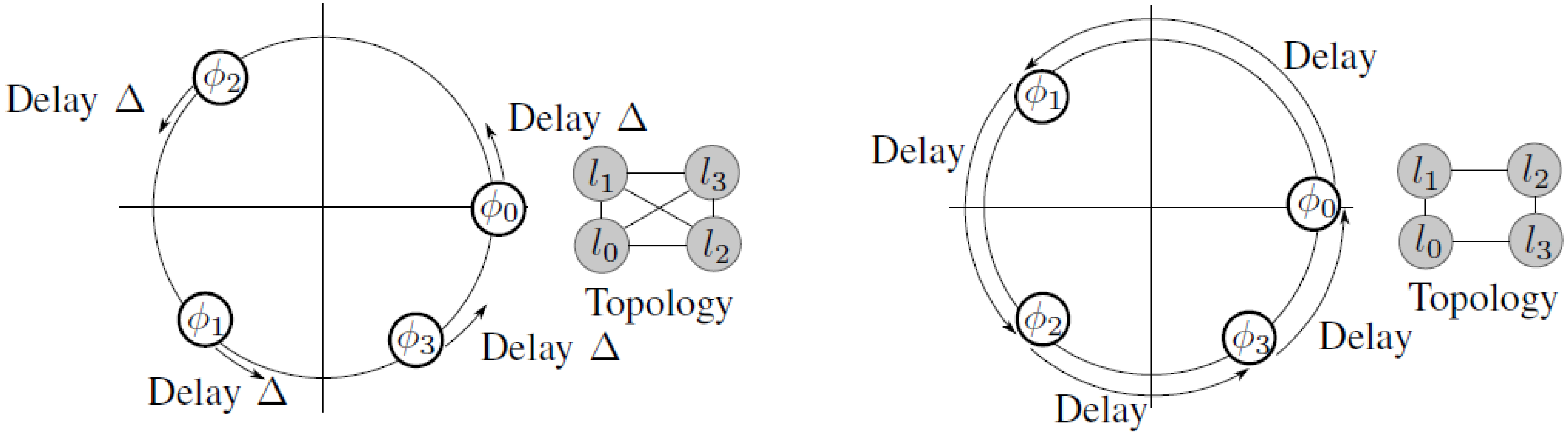
$$\phi_i \leftarrow \phi_i + \min\left(\max_{j \epsilon \aleph_i}(\delta_j), \Delta\right)\frac{2\pi}{T_{up}}$$

Synchronization $\Leftrightarrow$ A_ϕ → **0**

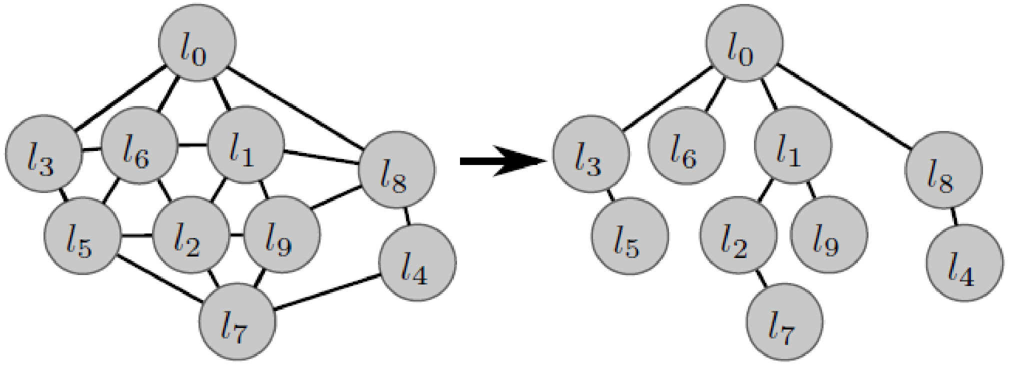
Guaranteed for $\boldsymbol{A_\phi < \pi}$ with $\boldsymbol{\phi_i} \in [-\boldsymbol{\pi}, \boldsymbol{\pi}[$

Anomalies when $A_\phi \geq \pi$

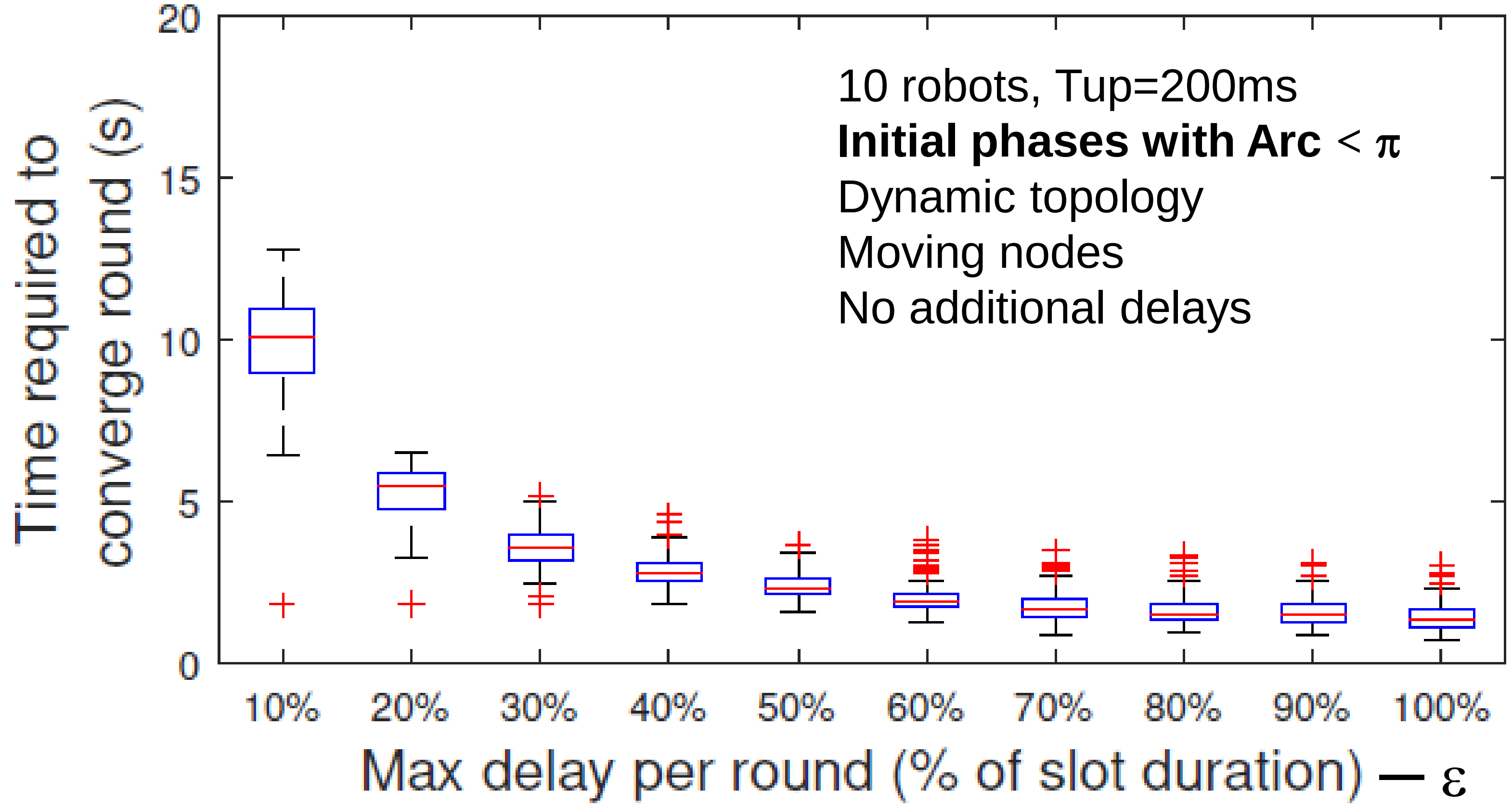
- **Unclear reference**
  - Different agents see **different maximum phase** !



- **Solution:**
  - **Spanning-tree** (+ random Δ)



Impact of Δ in the convergence time

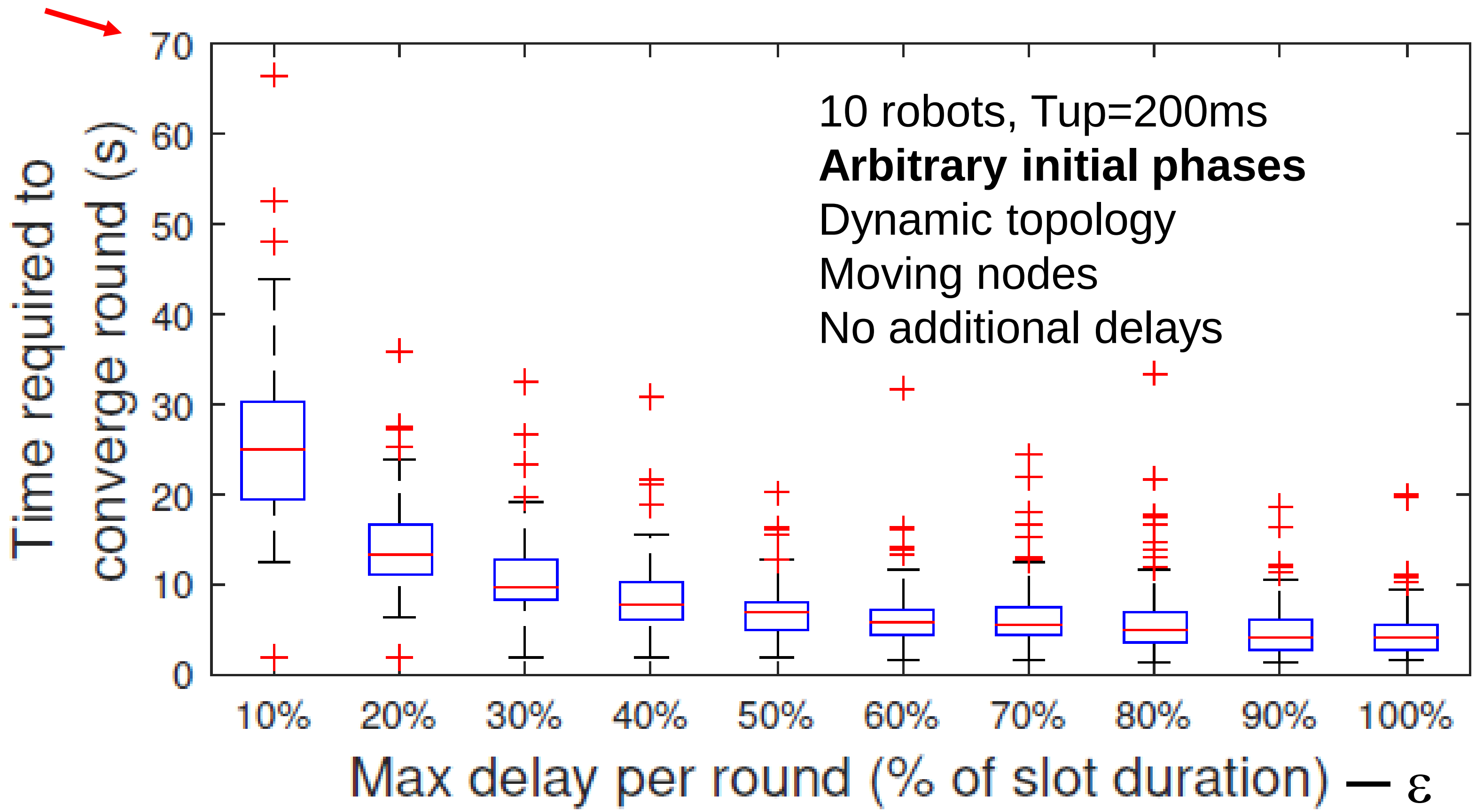


Synchronization always achieved

<u>Smaller Δ (ε)</u>
Smaller phase adjustments
Slower convergence

<u>Larger Δ (ε)</u>
Larger phase adjustments
Faster convergence

Impact of Δ in the convergence time



Synchronization always achieved

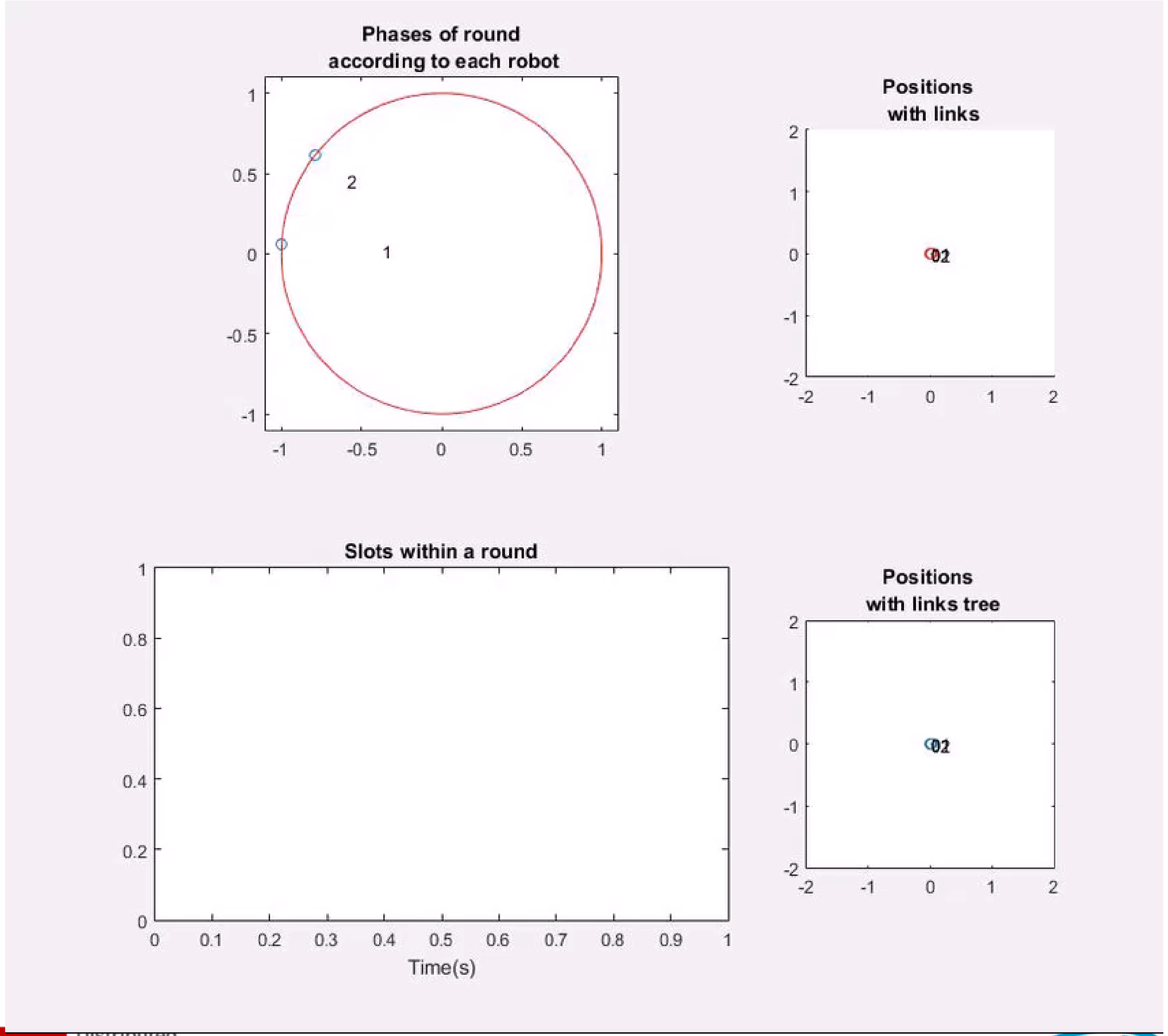
Smaller Δ (ε)
Smaller phase adjustments
Slower convergence

Larger Δ (ε)
Larger phase adjustments
Faster convergence

Synchronization in phase and time

Random topologies
Random initial phases
No external delays

https://cutt.ly/sbcZZKS



Physical topology with moving agents

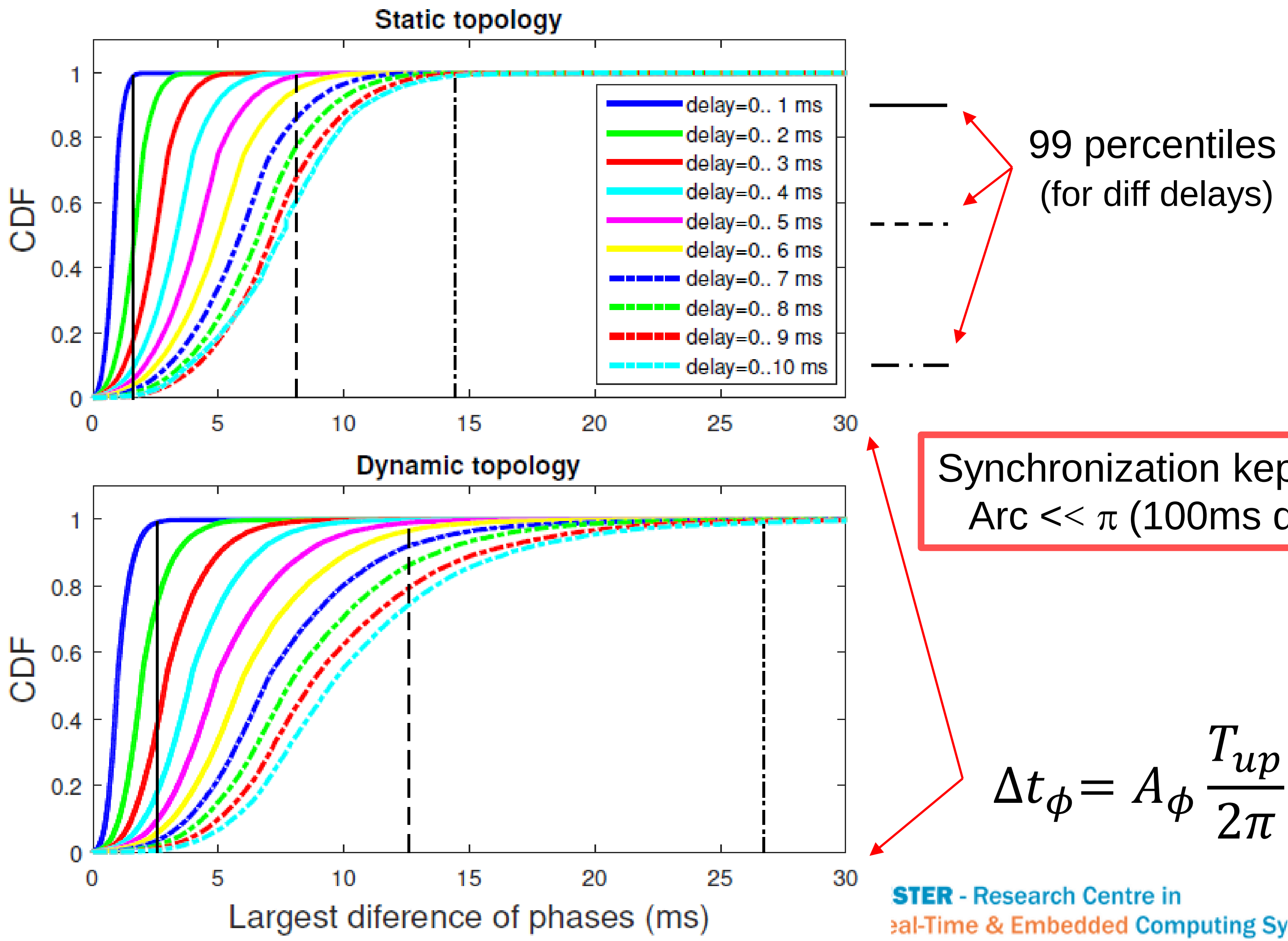
Forced spanning-tree topology

Impact of mobility and network delays

10 robots, **initially in phase**
Tup=200ms
Δ=8ms (ε=40%)

Impact of **network delays**:
Different levels of interference

Impact of **network delays** plus **dynamic topology**:
Dynamic topology increases Arc



Synchronization kept
Arc << π (100ms diff)

$$\Delta t_{\phi} = A_{\phi} \frac{T_{up}}{2\pi}$$

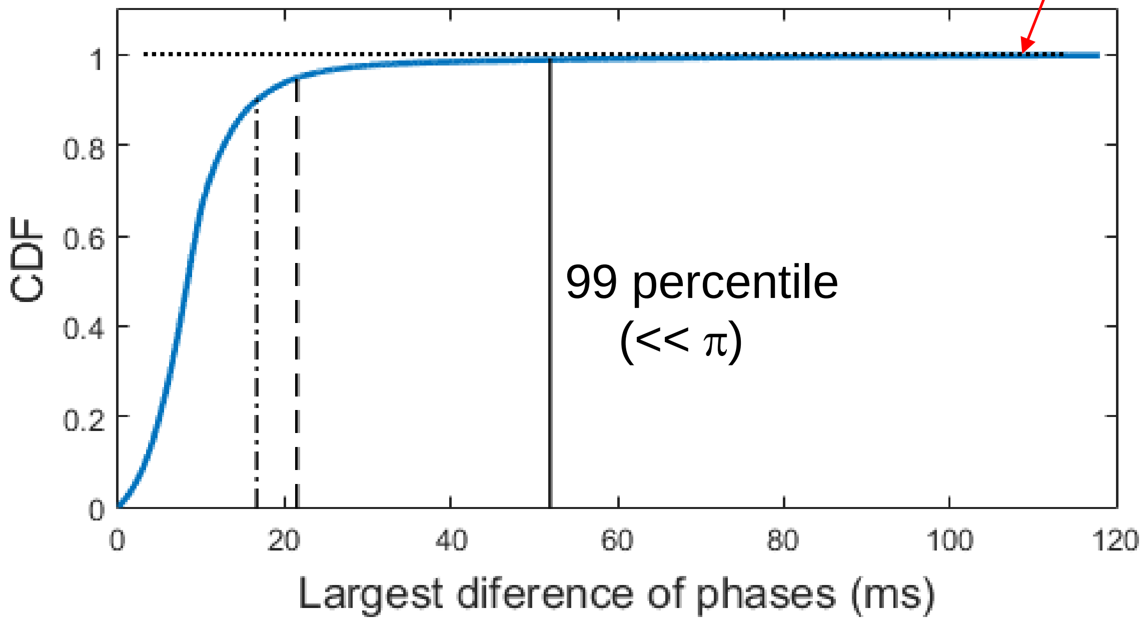
Impact of membership

Rare cases (> π) due
to membership changes

Tup=200ms
Δ=8ms (ε=40%)
Max level interference (0..10ms)

Impact of **network delays**
plus **dynamic topology**
plus **dynamic membership**:

Agents in the team: 3 → 10 → 3 → 10…
1 **added /removed every 50s** for 10000s



Δt_{ϕ}

Synchronization kept → Arc << π (100ms diff)
Except when adding/removing agents

Synchronization in phase and time

External delays + losses
Dynamic topologies
Dynamic membership

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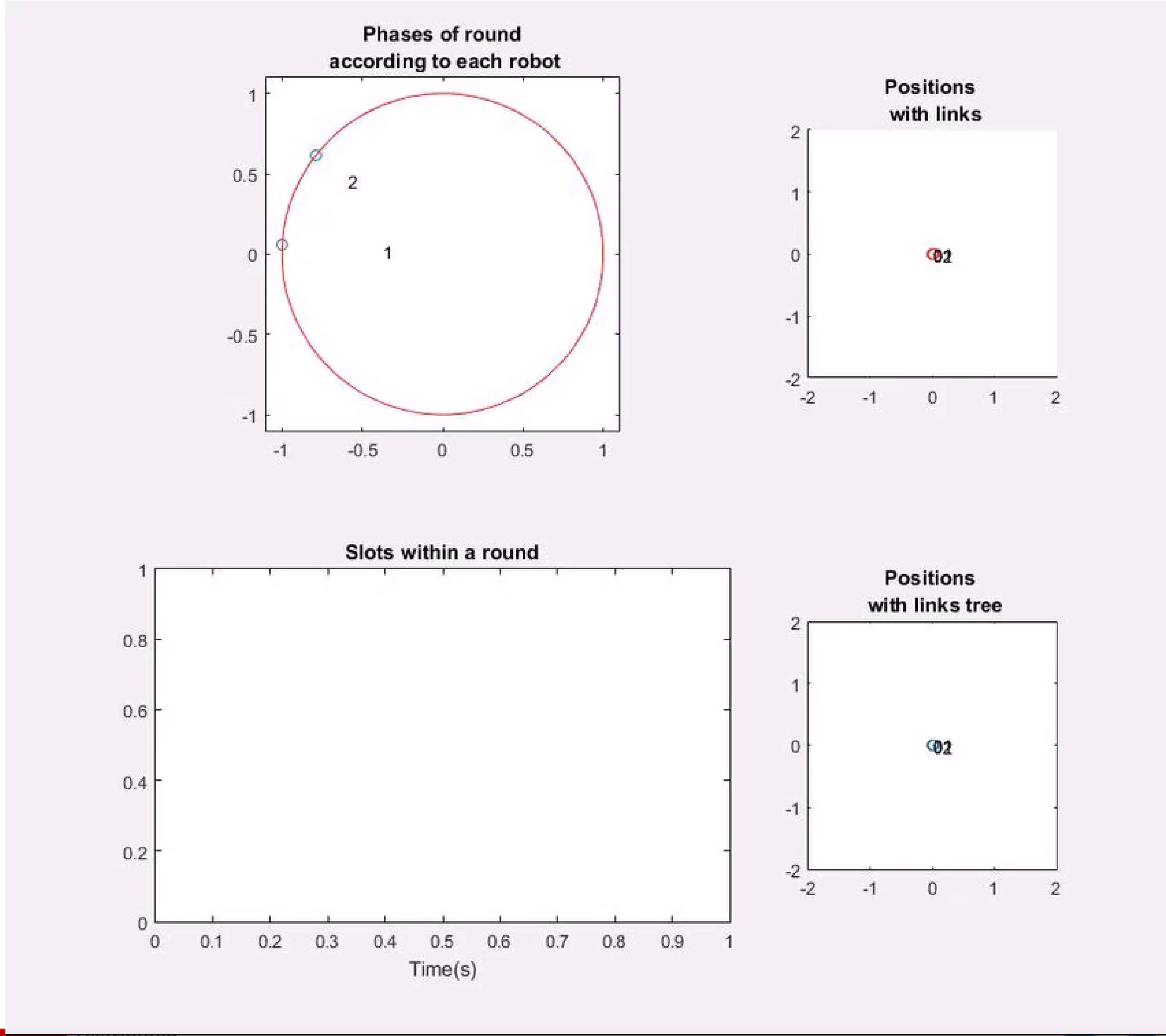


Physical topology with moving agents

Forced spanning-tree topology

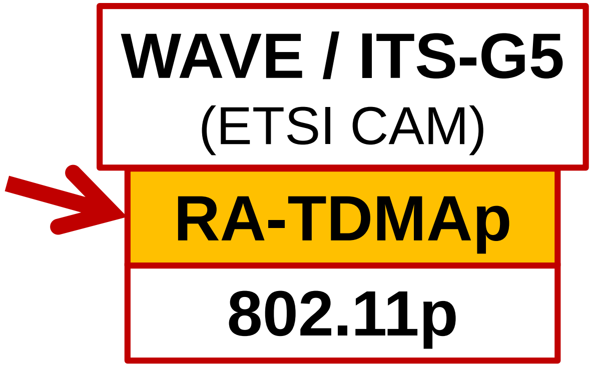
Vehicular networks - platooning

- Line topology to connect the platoon
  - Vehicles broadcast **periodic beacons** (CAM – Cooperative Awareness Messages)
  - Potentially **multi-hop**
- Must be highly scalable
  - Potentially many vehicles within reach
  - How to reduce collisions and improve channel use

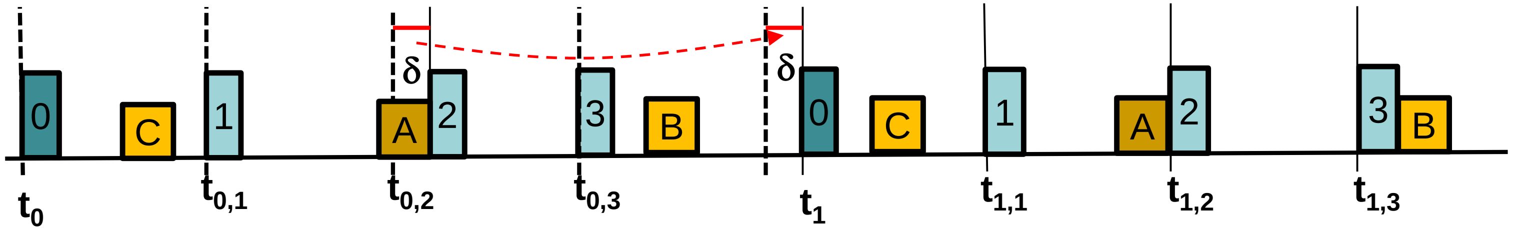
Reconfigurable and Adaptive TDMA for platooning protocol (RA-TDMAp)

(IEEE 802.11p)

RA-TDMAp for platooning



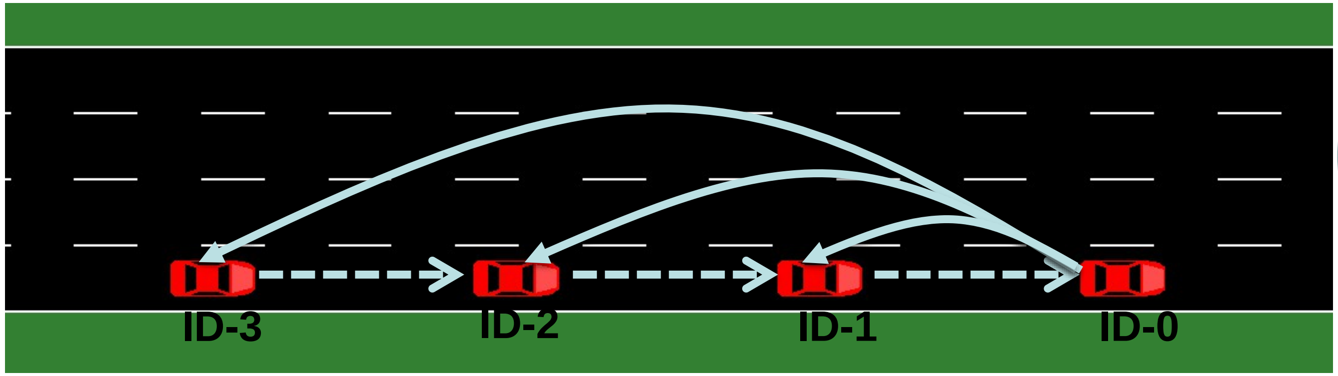
- **Synchronization**
  - CAMs in a platoon with **offsets** (slots) with respect to leader
- **Adaptivity**
  - Leader, only, **adjusts tx time** to bring its platoon **out of phase** wrt other platoons or single cars (**unaware synchronization**)

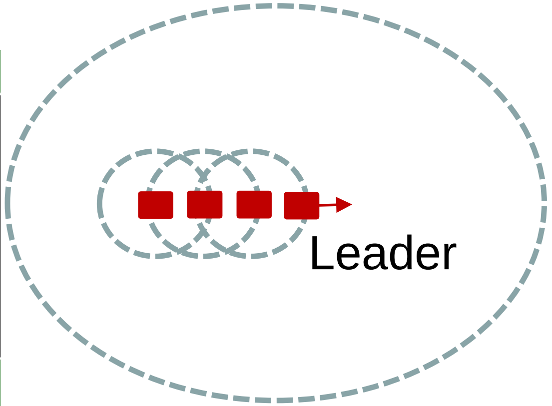


- **Reconfigurability**
  - **Admission control**, offsets adjustment simultaneously with platoon control

Tx power in RA-TDMAp

- **Transmission power control**
  - **Leader** → **Higher power** to synchronize the whole platoon
  - **Follower** → **Lower power** to interact with car ahead
    - **Reduces interference** caused to other vehicles
    - Improves **spatial reusability** of the channel
    - **Requires multi-hop** communication to propagate delays to the leader

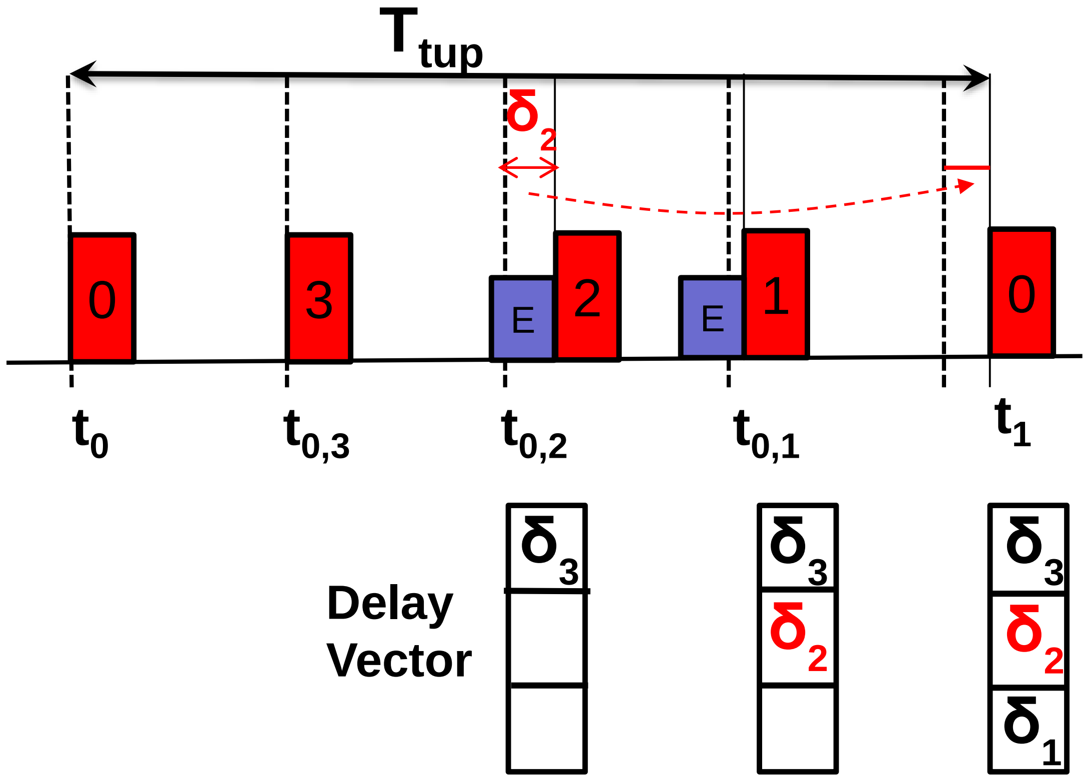




[Segata etal, 2014]

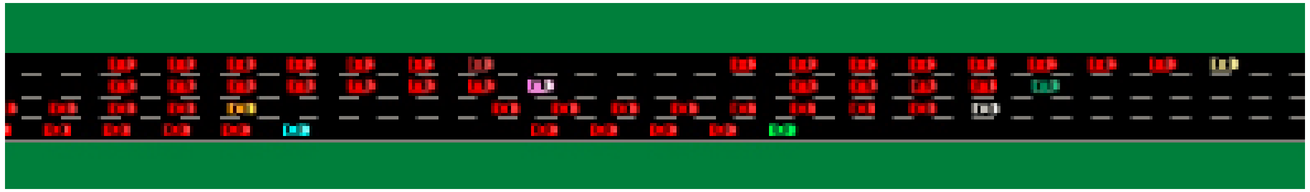
Propagating delays in RA-TDMAp

Following car **observes delay** when **receiving** message, writes it to a **Delay Vector** and piggybacks this vector to its **next transmission**



Simulation framework

- **PLEXE → Platooning Extension for Veins**
  - **platooning simulator**
  - Highway scenario
  - Autonomous vehicles

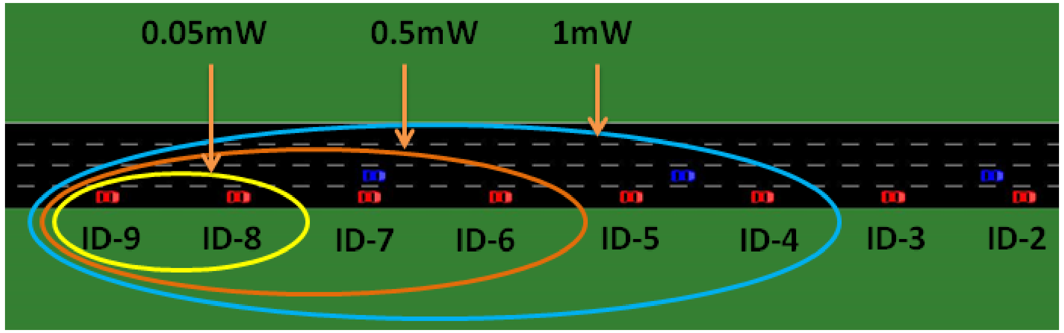


- **Veins → Open source vehicular network simulation**
  - Real environment scenario, considering high mobility
  - Full stack of **IEEE802.11p / IEEE 1609.4** standards

  - **SUMO → Road traffic simulation**
  - **OMNET++ → Event-based simulator**
    - Runs Veins and PLEXE, plus the RA-TDMAp logic
    - Allows collecting operational data

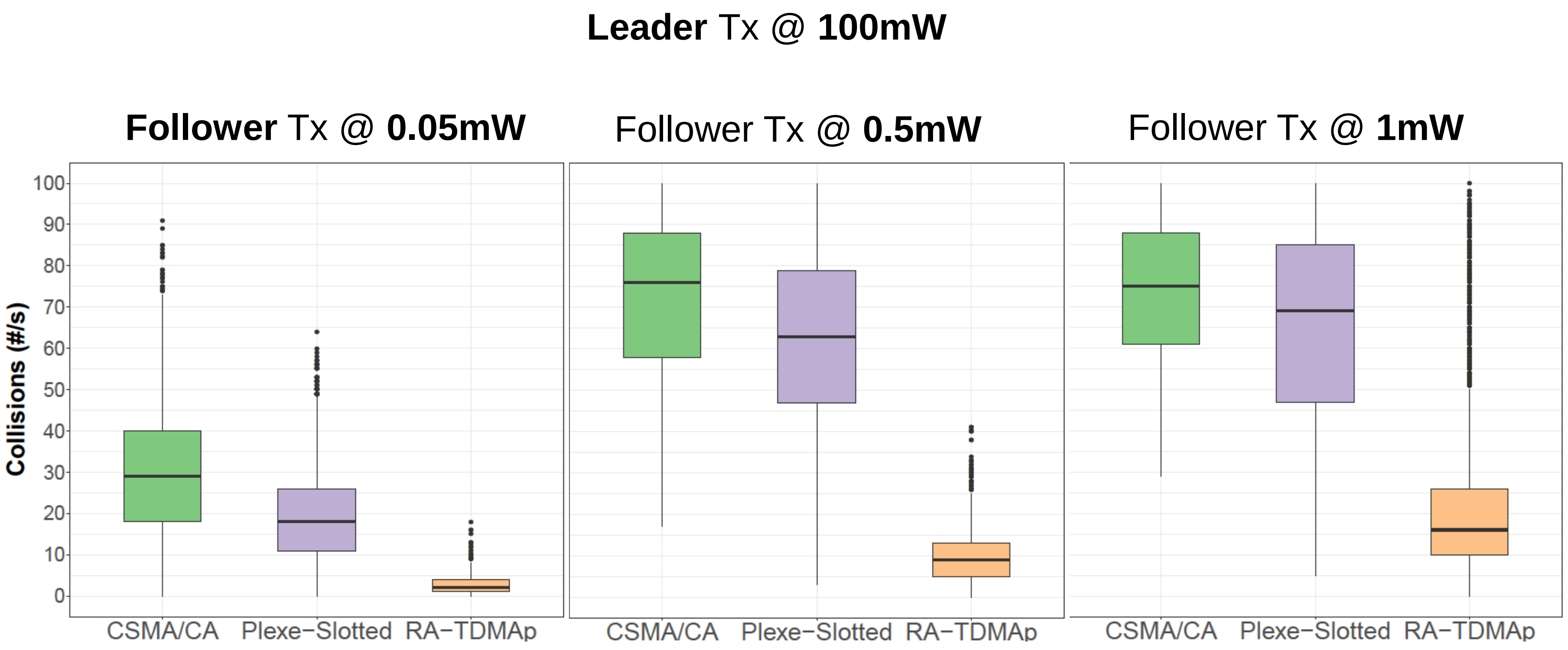
Simulation experiments

- **Scenario**
  - **4** lanes, **16** platoons with **10** vehicles each
  - **5m** vehicles gap, **CACC** controller
- **Comparison with related protocols**
  - **Plexe_Slotted** (fixed offsets inside the platoon) and **CSMA/CA** (random offsets and drift)
  - **Three** different followers' transmission **power levels**

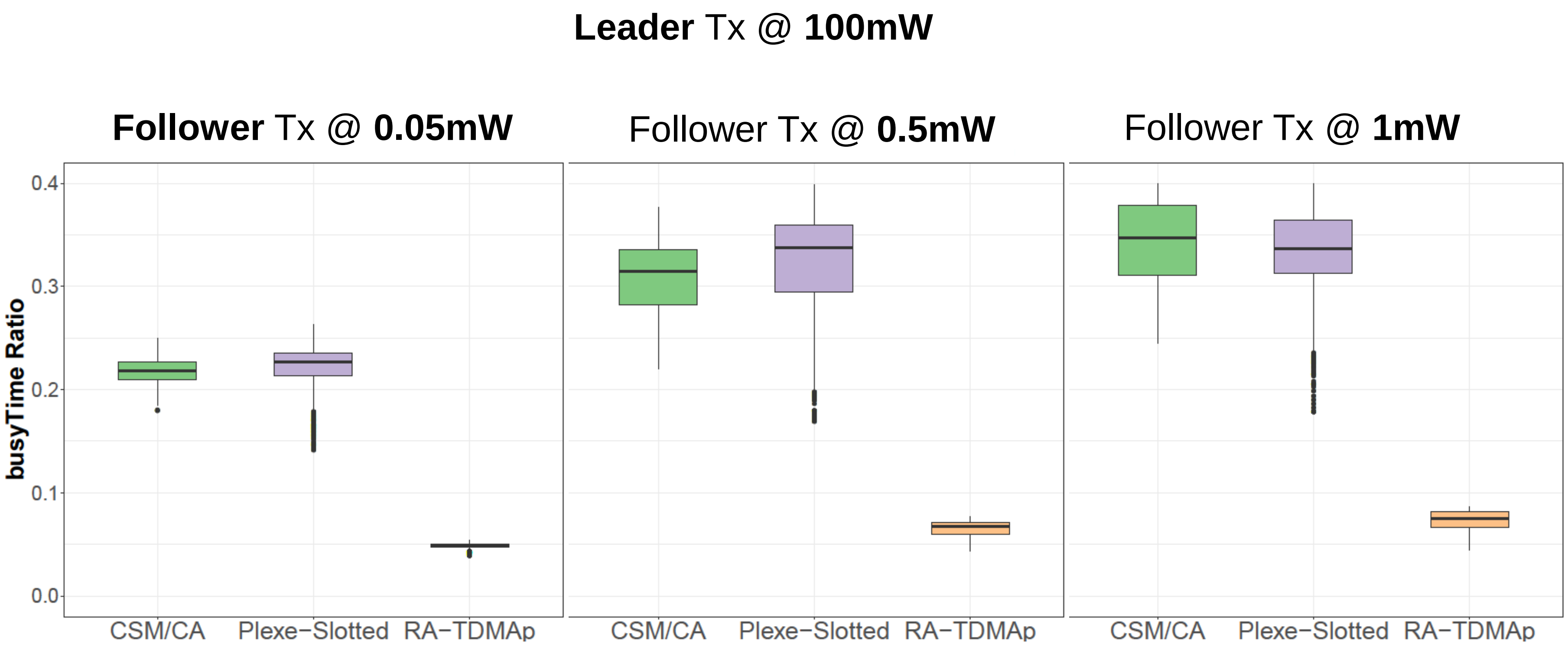


- **Network metrics**
  - **Collisions rate** and **Channel busy ratio**
- **Application layer metric**
  - **Safe-time ratio**

Collisions rate

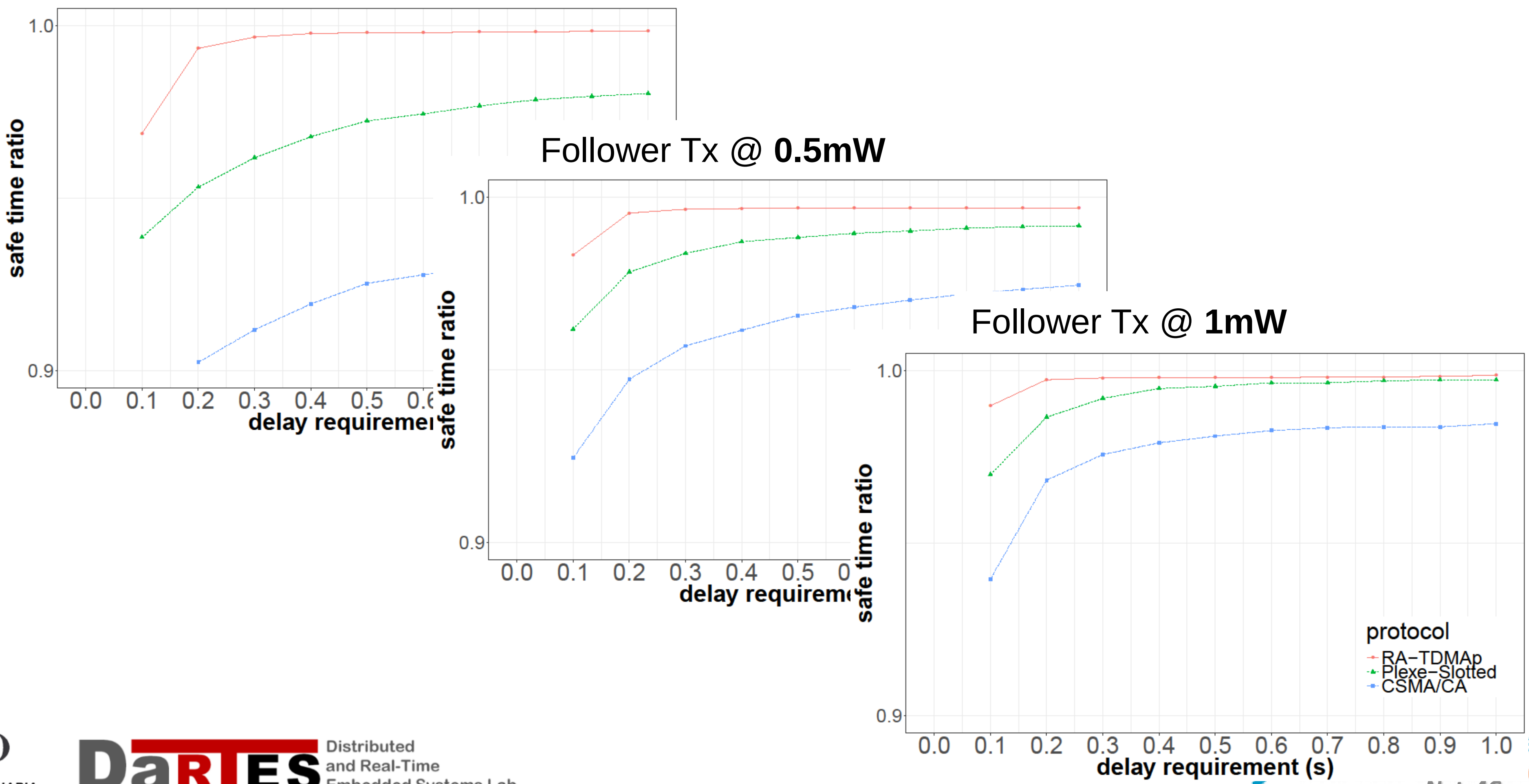


Channel busy ratio



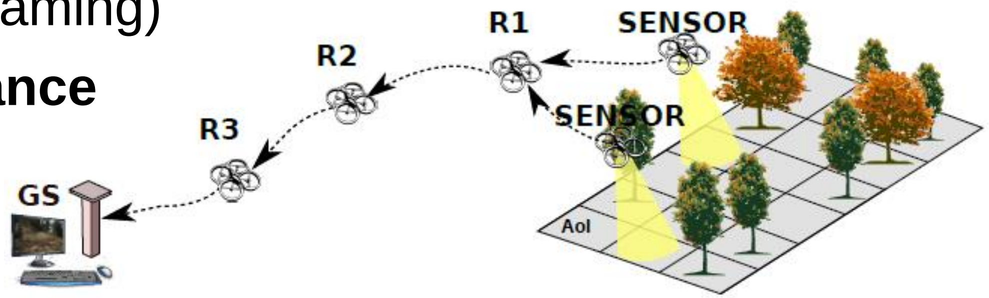
Safe-time ratio

Leader Tx @ **100mW**



Online monitoring with aerial networks

- **Line topology needed to extend reach**
  - Intermediate agents **relay** to a ground station
  - **High bandwidth** requirements (e.g., live video streaming)
  - Compromise between **bandwidth, delay** and **distance**
- **Uses confirmed unicast transmissions**
  - More **robust** to losses but more **variable** delays

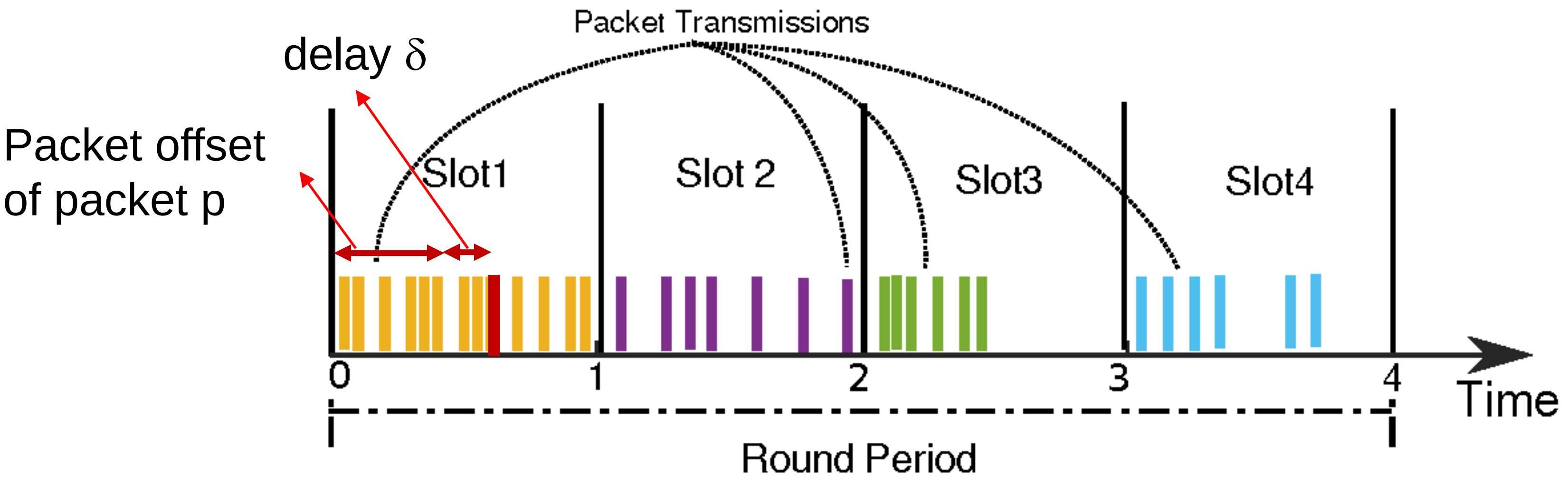


Reconfigurable and Adaptive TDMA streaming protocol (RA-TDMAs)

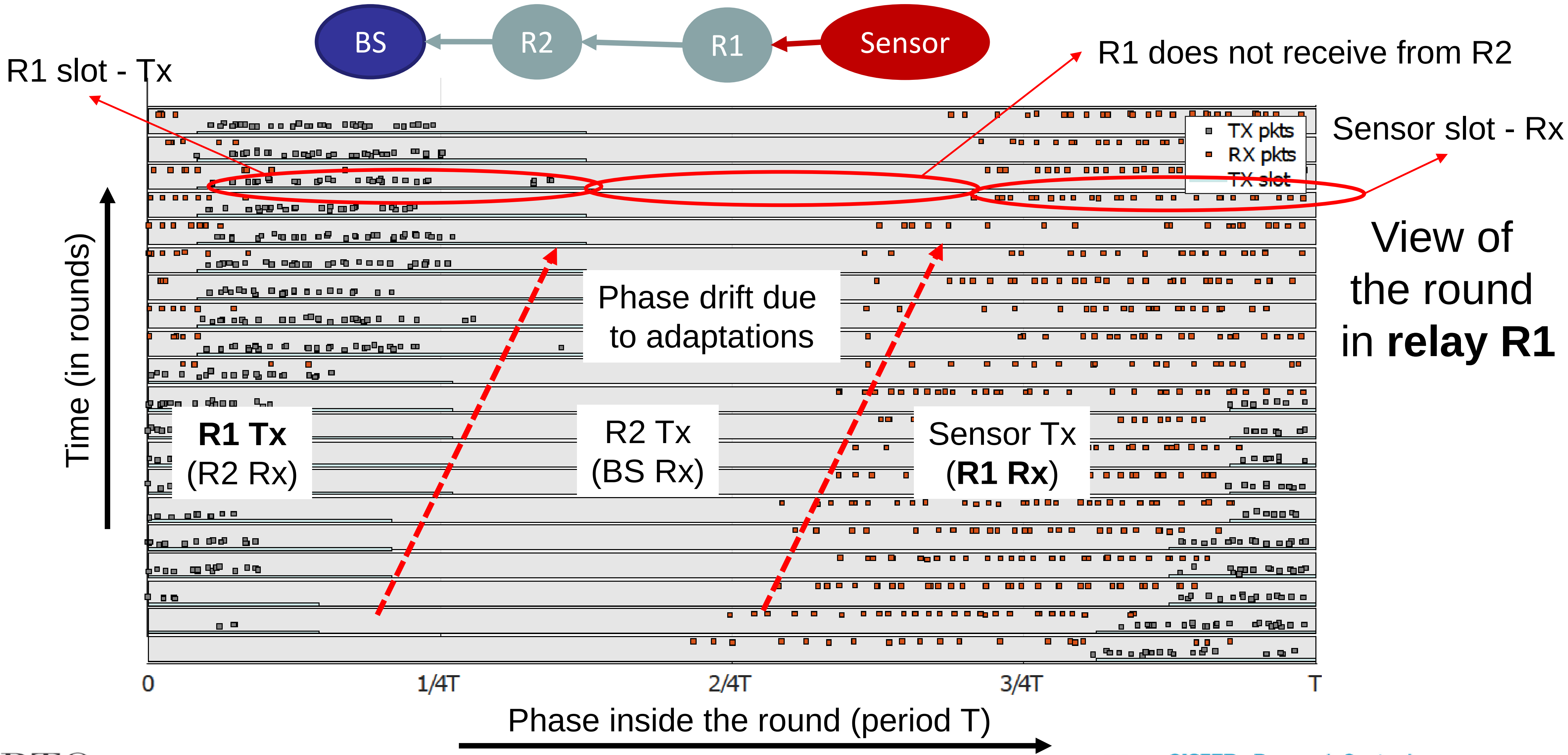
(WiFi)

Synchronizing from many packets

- **Many packets, different delays**
  - Each packet carries its **packet offset** → enables use for synchronization
- **Estimation of network delay needed**
  - Packets **transmitted if** there is reasonable confidence, they are **received in that slot**



Using RA-TDMAs



Using RA-TDMAs

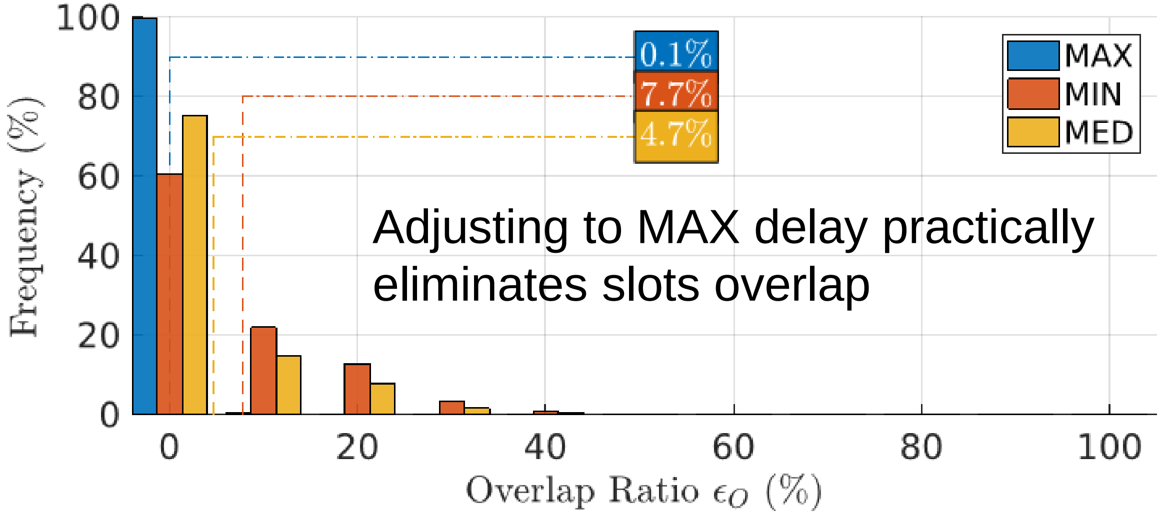
- **Estimating the round offset**
  - How to **combine** the delays of all packets in each slot ?
  - How do simple aggregation functions (**MIN, MAX, MED)** perform ?

- **Experiments**
  - **Platform:** AR Drone 2.0
    - ARM 700MHz
    - 802.11g@24Mb/s, MAC retries = 2

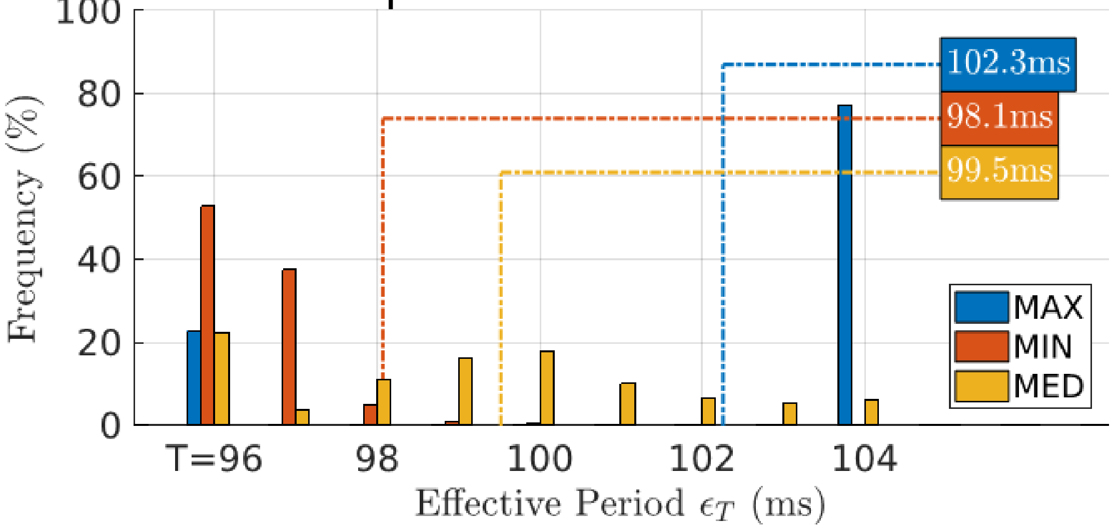
  - **Topology**
    - Physically fully connected network
    - Logical line enforced with static routing
  - **RA-TDMAs**
    - T = 96ms, slot = 32ms, Δ = 8ms (25% of slot)
    - Slot IDs – ascending from source to BS
  - **Data Flow**
    - Sensor tx 1 frame every ~130ms = 7.5FPS
    - 1 frame = 11KB in 73 UDP (154B) packets

Results

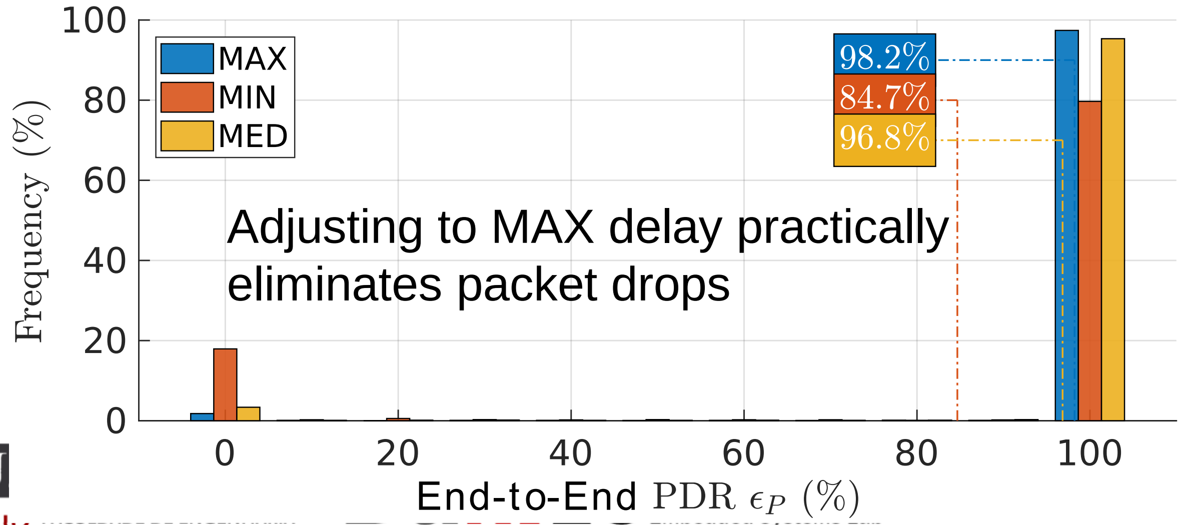
Adjusting to MAX delay practically eliminates slots overlap



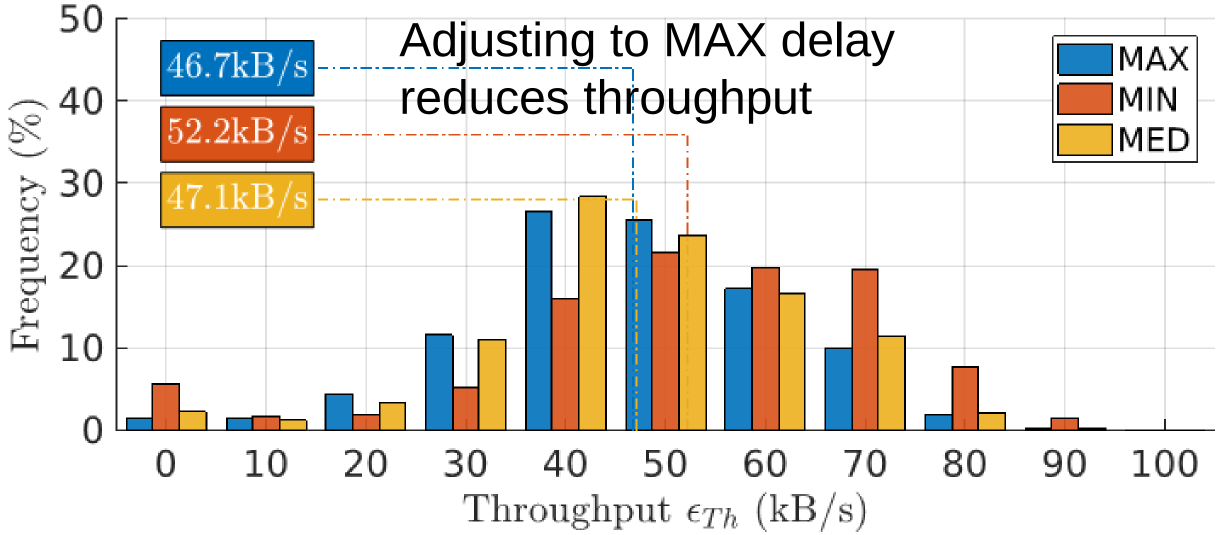
Adjusting to MAX delay increases effective period



Adjusting to MAX delay practically eliminates packet drops



Adjusting to MAX delay reduces throughput



Conclusion

- Collaboration among autonomous agents requires
  - **wireless communication** (interference, errors, multi-path fading, attenuation…)
- Synchronization (TDMA) improves the channel
  - Particularly, for **periodic (interfering) traffic** and **high load**
  - Leads to **reducing network delays & packet losses**
- RA-TDMA approaches provide robust sync in a multitude of scenarios
  - Follow **pulse-coupled synchronization** principle
  - Tolerate **interferences** and adapt to **delays** of any source
  - Tolerate **loss** of packets
  - Improve **channel usage** by **multiple teams** unaware of each other

A few open issues

- **Manage nodes positions**
  - (infrastructure) Continuously relocate the AP to maximize team coverage
  - (line of relays) Manage relays positions to equalize link parameters
  - (ad-hoc) Ensure multiple links, e.g. bi-connectivity
- **Improve online estimation of link parameters and delay pattern**
  - Throughput, PDR, delay
- **Optimize the global use of the team resources**
  - Bandwidth, energy, computing, specific subsystems, ...

Acknowledgments

- **This is essentially the work of four concluded PhD thesis**
  - Frederico Santos
    - **Infra-structured version:** RA-TDMA (plus RTDB, used in RoboCup-MSL)
  - Luis Oliveira
    - **Ad-hoc version**: RA-TDMA+ / consensus in a mesh (plus RT routing and localization)
  - Luis Pinto
    - **Line relaying version**: RA-TDMAs (plus online streaming, slots adaptation, relay positioning)
  - Aqsa Aslam
    - **Platoon version:** RA-TDMAp (scalability and admission control)

Some pointers to our work in this line

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