Communications for teams of cooperating robots

Luis Almeida

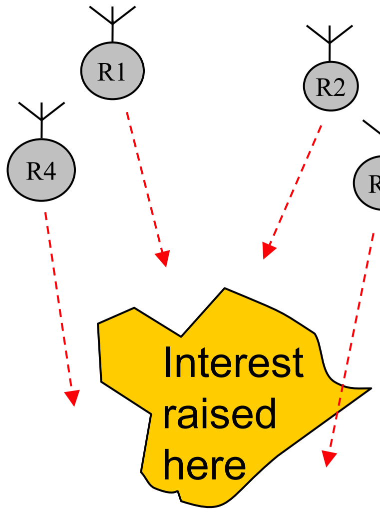
lda@fe.up.pt
www.fe.up.pt/~lda

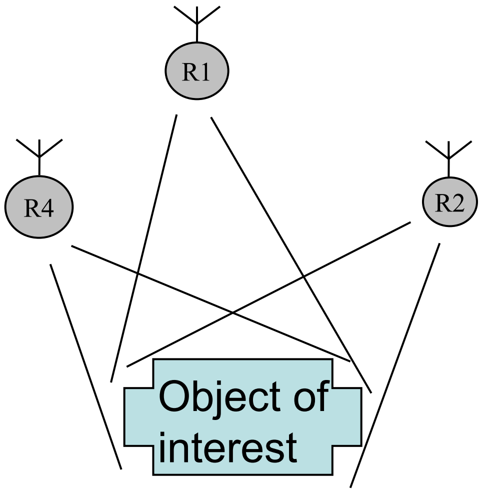
(IT) **Telecommunications Institute** – Porto
(FEUP) Faculty of Engineering – **University of Porto**, Portugal

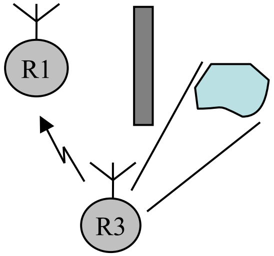
U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

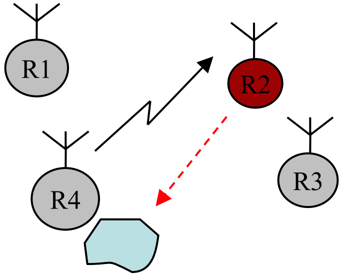
Teams of collaborating autonomous agents

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

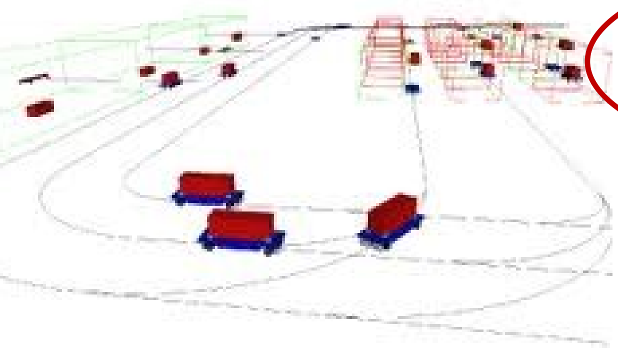






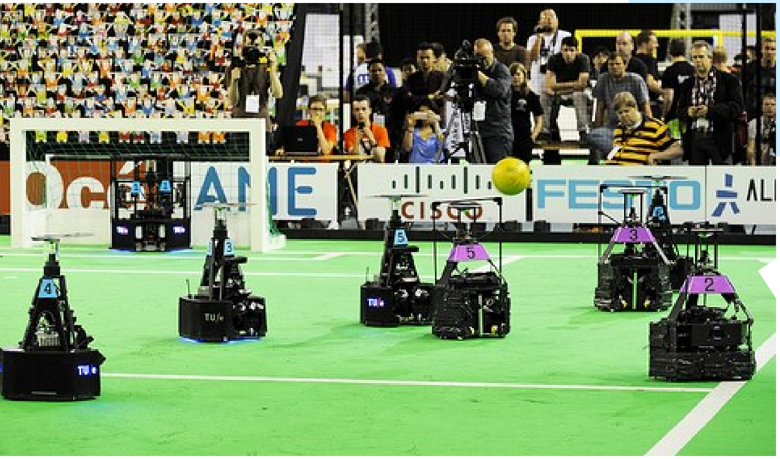


Collaboration requires communication

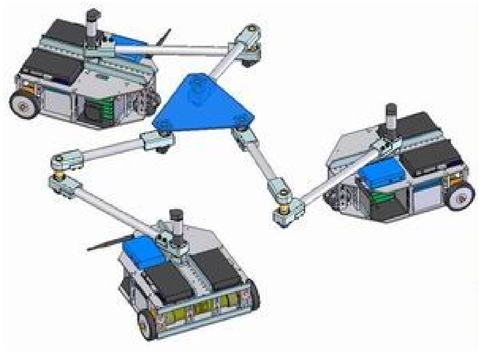


- **Sharing state + sensing**
  - Periodic short/medium size data
- **Communicating events**
  - Aperiodic short data
- **Streaming multimedi**
  - Periodic medi g data

Communication has to be wireless!



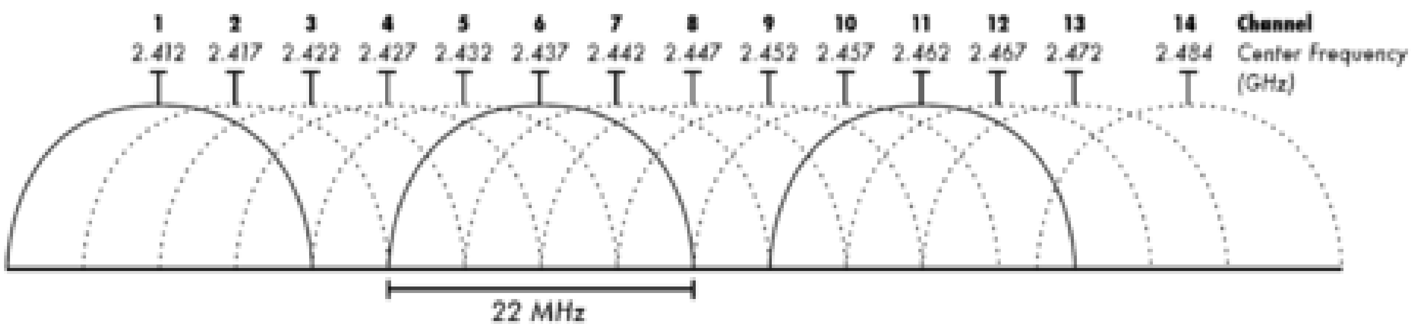
RoboCup 2013, Eindhoven, Netherlands



WiFi (802.11)

standards.ieee.org/getieee802/802.11.html

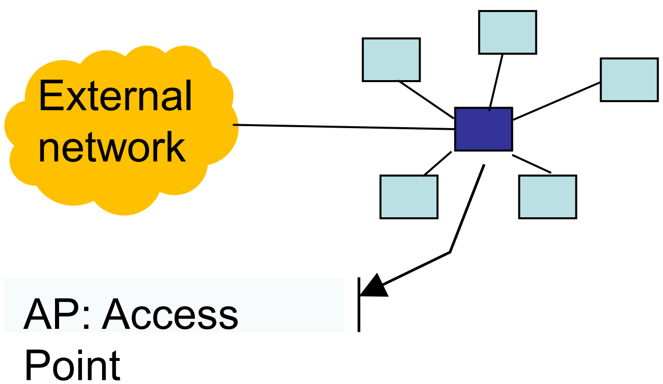
- **Created in the 90s as a general purpose WLAN**
  - Very popular technology within **teams of robots**
- **3 modes over 2 bands:**
  - 802.11**b/g** (ISM-2.4GHz), **few non-overlapping** channels
  - 802.11**a** (5GHz), **several non-overlapping** channels



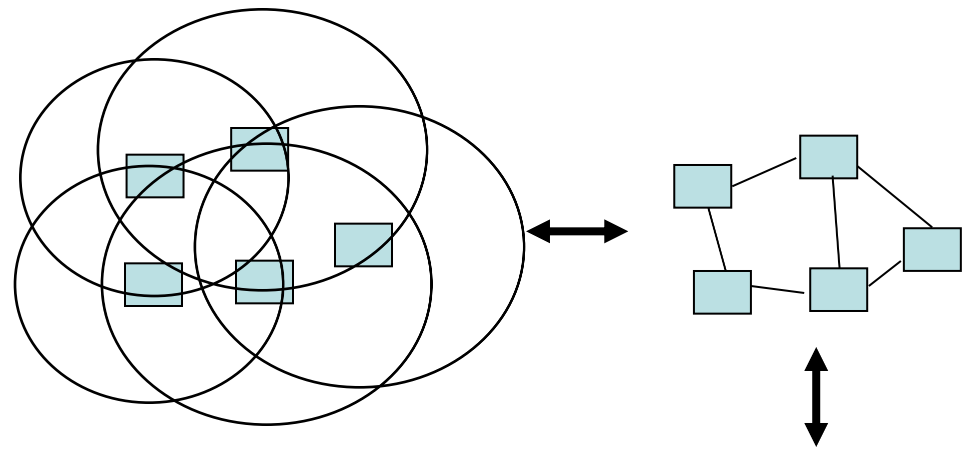
Frequency spectrum in 802.11b

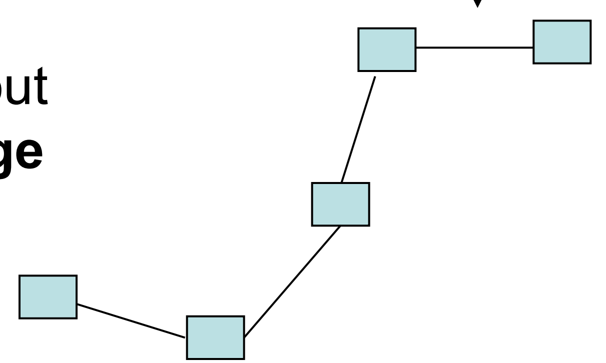
WiFi (802.11)

- **Infra-structured (star) or ad-hoc (mesh) architectures**



Easy to know
who is **in** and **out**

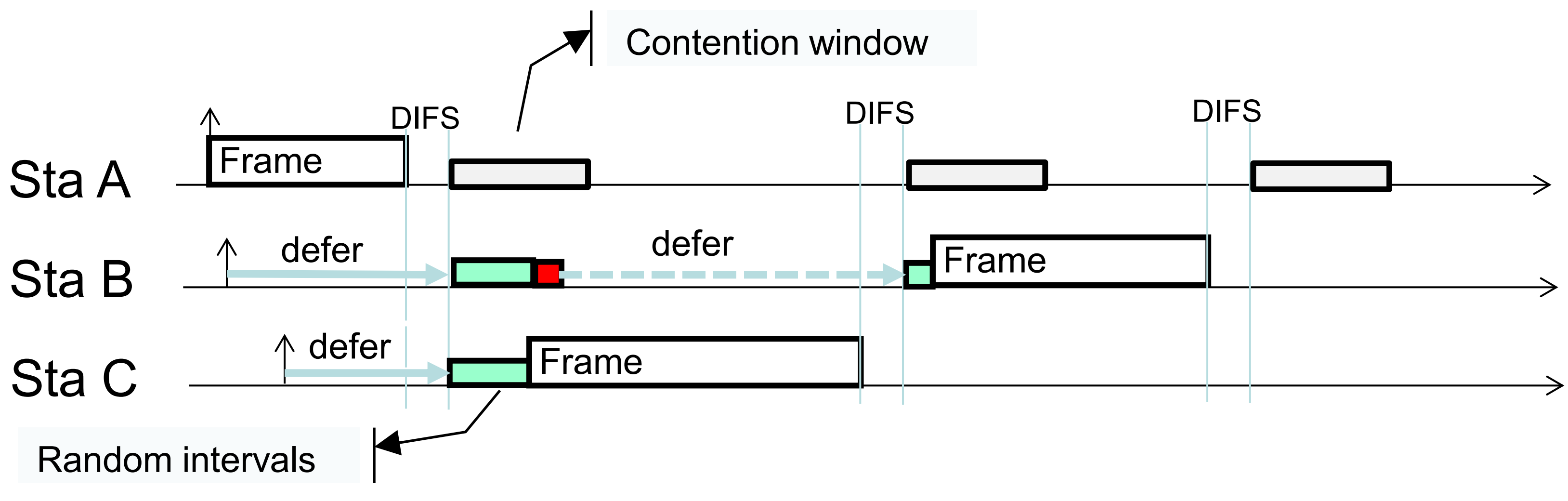




Flexible layout
and **coverage**

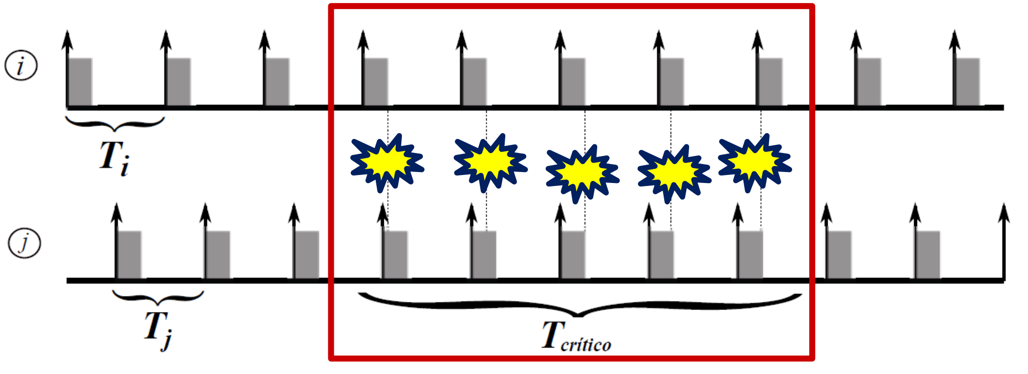
WiFi (802.11)

- **Essentially uses a contention-based MAC with mechanisms to reduce collisions and hidden-nodes**
  - **Carrier-Sense** Multiple Access w/ **Collision Avoidance** (CSMA-CA)



A few observations

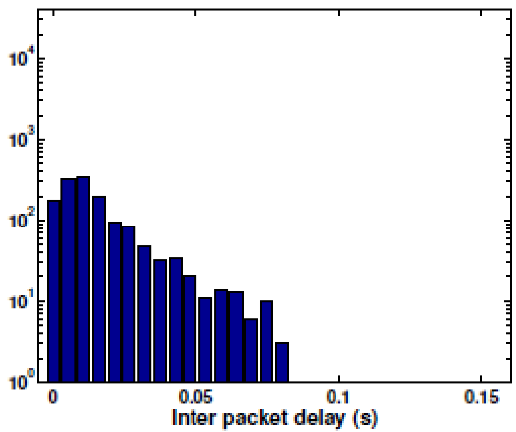
- **Use of the channel is similar to "talking in a meeting"**
- **Abuse leads to global communication degradation**
  - Saturation and thrashing
- **Under high traffic, access rules (e.g. TDMA) improve effectiveness of channel use**
- **Periodic interference can generate degradation even with light load**
  - Critical periods



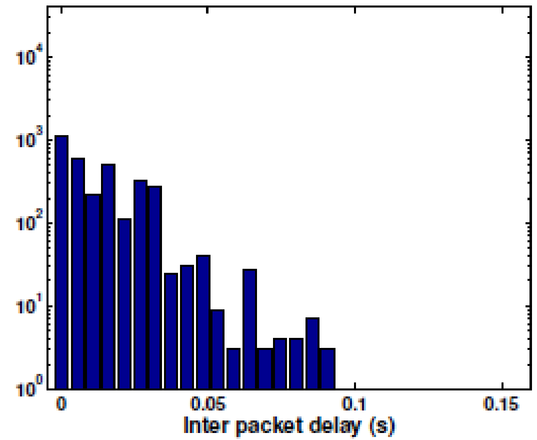
MSL logs from RoboCup 2008 – Suzhou, China

- **Log station:**
  - Laptop with built in wireless network card in monitor mode
  - IEEE802.11a
  - *Wireshark* software
- **Random games from the 3th round-robin**
  - 6 teams monitored
- **Logs duration ≈1minute**
  - Inter packet delays from the same team
  - Packet size

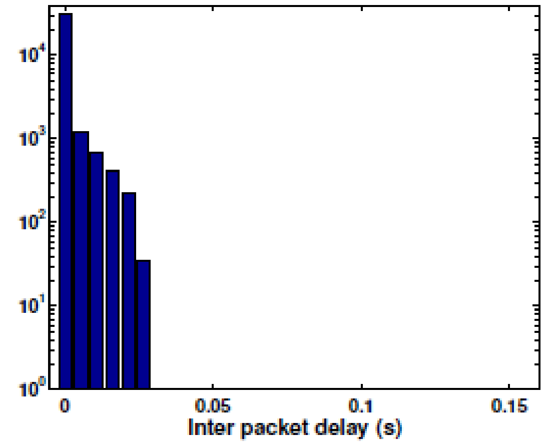
Inter-packet delays



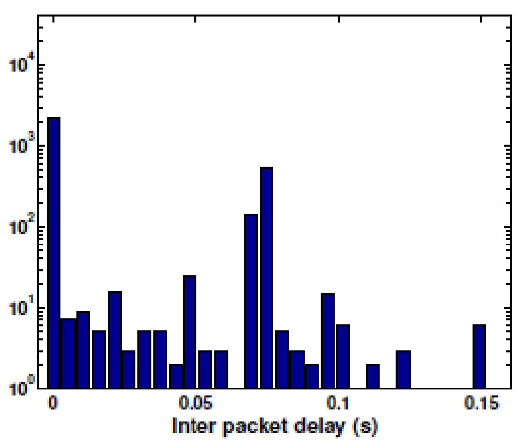
a) Team 1



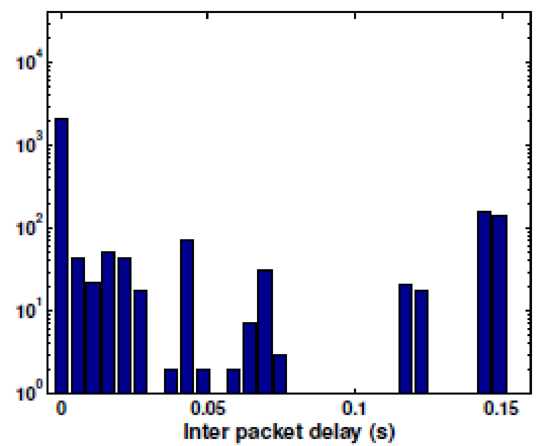
b) Team 2



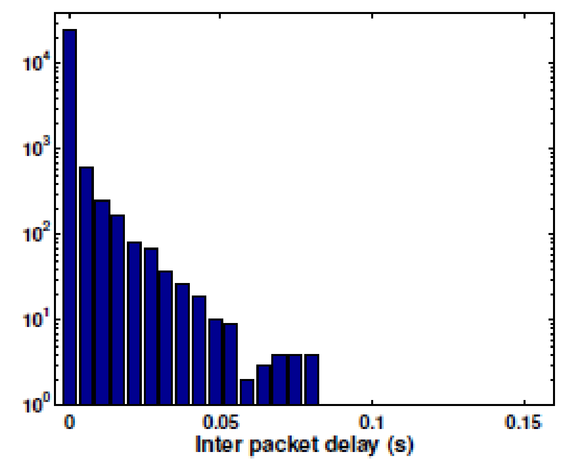
e) Team 5



c) Team 3

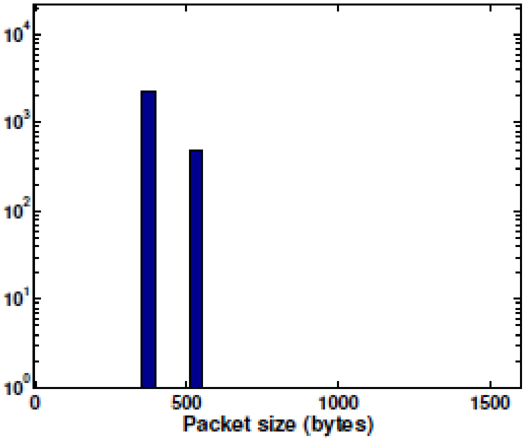


d) Team 4

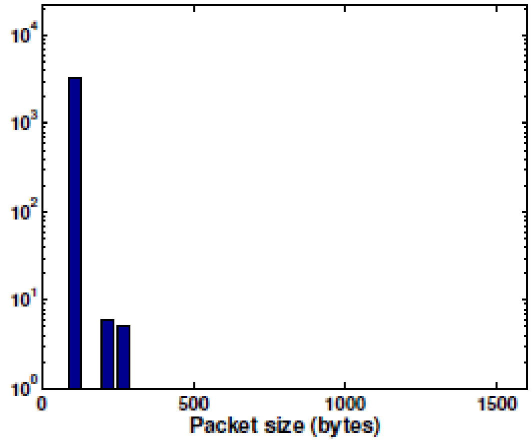


f) Team 6

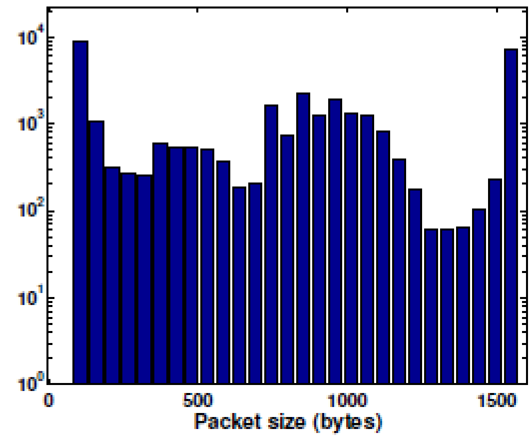
Packet sizes



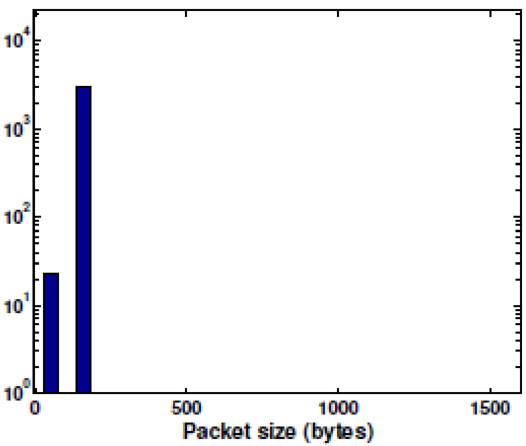
a) Team 1



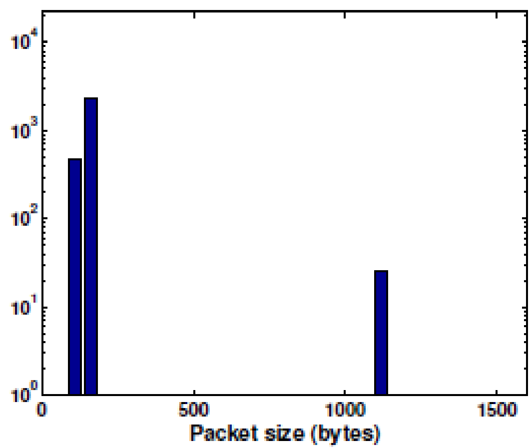
b) Team 2



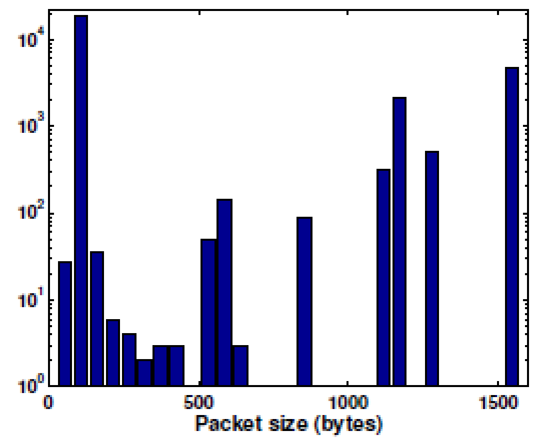
e) Team 5



c) Team 3



d) Team 4



f) Team 6

Summary of measurements

		Team 1	Team 2	Team 3	Team 4	Team 5	Team 6
Inter Packet (ms)	*avr*	17.74	15.20	20.03	21.72	1.74	1.90
	std	17.63	14.65	33.23	48.16	3.62	4.44
Packet Size (Bytes)	*avr*	412.87	139.68	160.51	187.67	787.40	497.81
	std	73.66	8.03	5.59	93.77	549.09	598.36
Burst Size (# 1.5kB pk)		–	–	–	–	6	12
Total kBytes		1158	460	480	517	26154	13072
% of max		4.43	1.75	1.84	1.98	100.00	49.98
Bandwidth utilization	802.11a	1.1%	0.4%	0.5%	0.6%	25%	13%
	802.11b	5.5%	2.0%	2.5%	3.0%	125%	65%

Summary of measurements

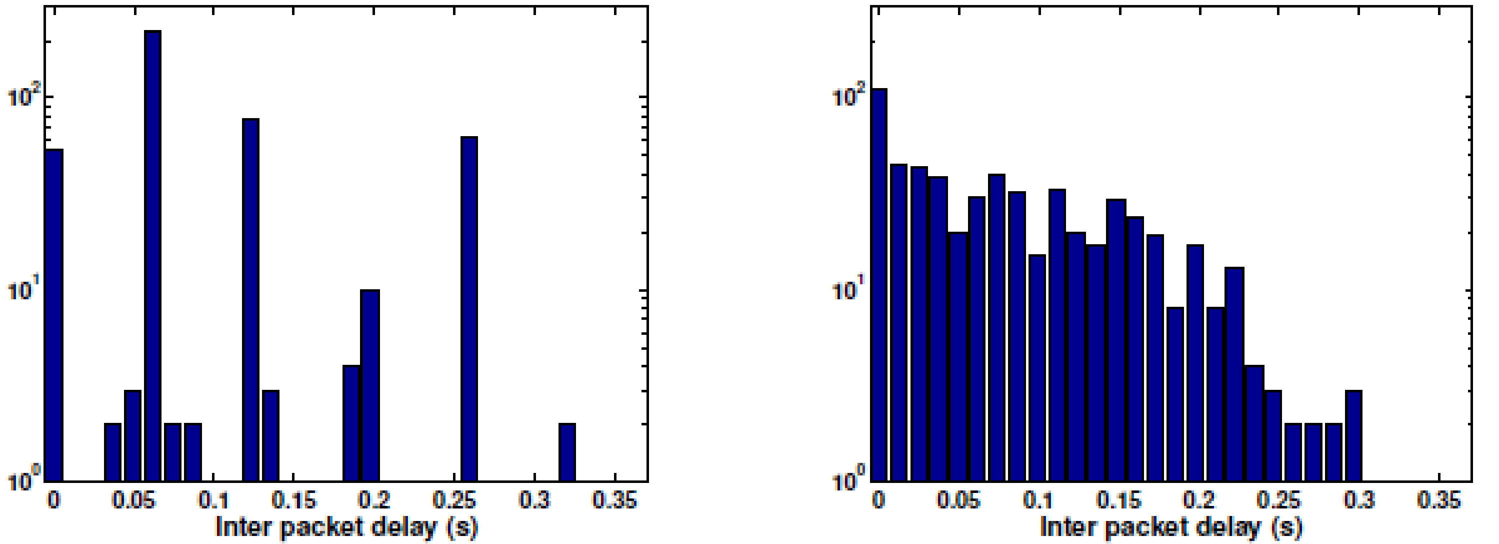
- **Wide** variability of **packet sizes**
- Some **long bursts** were observed in some teams
- **Large use** of the **bandwidth**
  - That would strongly overload the 802.11b mode
- **Very short inter-packet** intervals
- **Two of the observed teams would not comply with the rule of limiting bandwidth**
- **Limiting bandwidth is not enough**
  - Beyond bandwidth is it important to restrict **consecutive channel use**

Problems

- **Infrastructure configuration**
  - Regular wireless Internet access network in the venue
- **Team communications configuration**
  - Teams using own AP or connections in Ad-Hoc mode
  - Bursts or non-IP traffic (sometimes, even malformed frames)
- **Lack of policing**
  - No one verifies the correct application of rules
- **Channel overuse by teams**
  - High bandwidth utilization means:
    - Large packet transmission delays
    - Increase of packet losses due to collisions and channel saturation

Impact of different communications patterns

- **Pattern of team 2 (periodic transmissions in a round) is destroyed by interference of team 6**



a) Robot 1 of team 2 against team 1 b) Robot 1 of team 2 against team 6

Misconceptions

- ***No need for restricting teams transmissions***
  - But bandwidth is limited !
- ***Larger bandwidth solves the problem***
  - Only for a while, since teams will then transmit more
- ***Use technology with QoS support***
  - Which team would you give higher priority?
- ***No need for technical verifications***
  - Non-compliance will only be detected in the games !

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Best practices for the teams

- **Low bandwidth** cooperation approaches that can work with the exchange of **small amounts of data**
- Use **periodic transmission** pattern in general
- Verify the **compliance of wireless** communications with the **rules before** the actual **competitions**
- **Do not use APs** that are **not from the organization**
- **Do not transmit wireless** traffic during competitions while in the neighborhood of the fields

Best practices for the organization

- Adequate **planning of APs** and **channels**
- **Switch off** any **pre-installed WLAN** for general Internet access in the venue
- Enforce **technical verifications** of the wireless communications
- **Traffic policing** using a network monitor
- Use a specific **network analyzer**, capable of providing information on the physical channel status

Our focus and approach

- **Share state** in periods of **high team interaction**
  - **Low overhead** (computations and communications)
  - Improved data **timeliness**
    - **Quick access + Age information**
- Separate **data access** from **data transmission**
  - **Computations** *versus* **communications**
- Case study: **RoboCup Middle Size League (MSL)**

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

A couple of contributions

- **The Real–Time Data Base (RTDB)**
  - Simple **shared-memory** kind of middleware
    - Read/write semantics
  - **Temporal decoupling** between application and communications
    - **Age** information

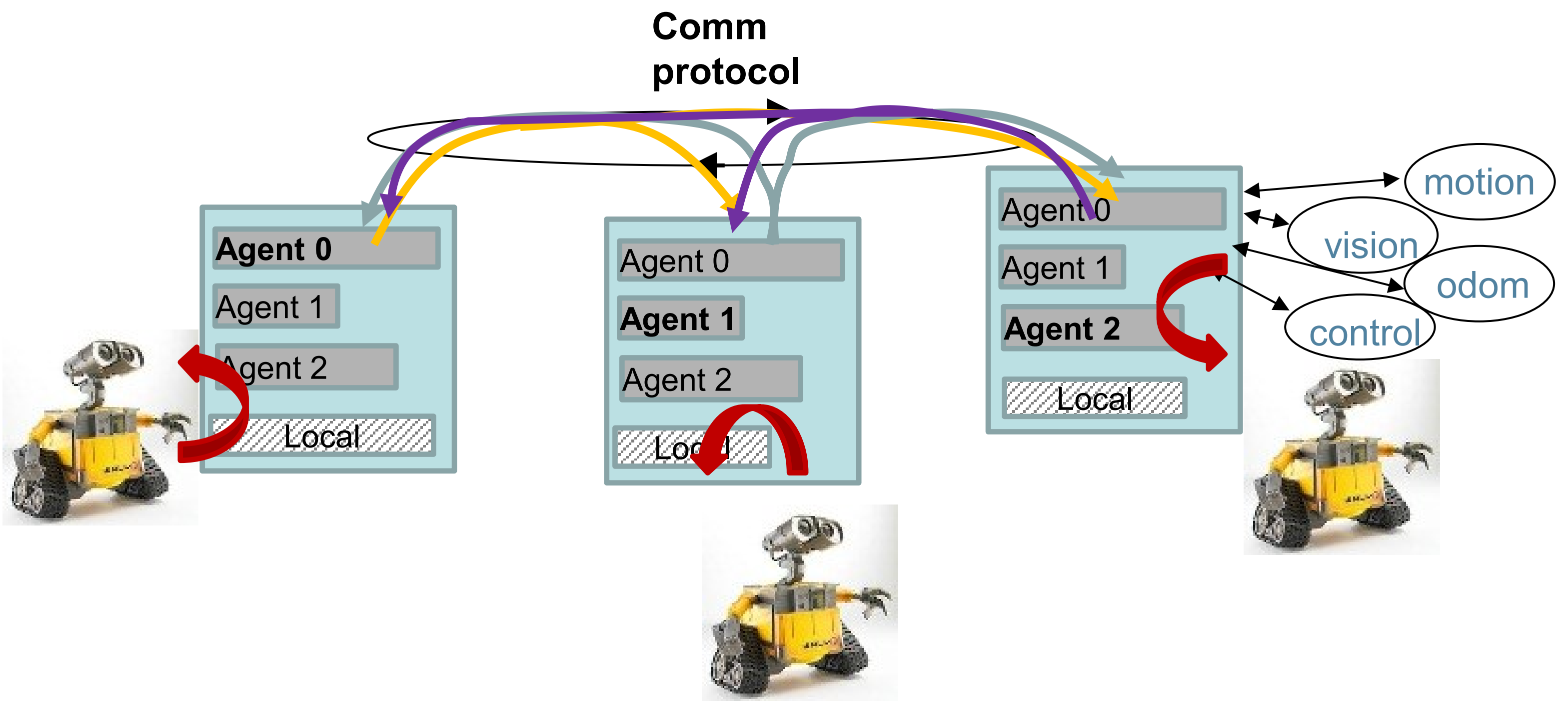
Data access

- **Reconfigurable and Adaptive TDMA protocol**
  - **Coordinated transmissions** within the team
    - Self-synchronization
    - Team broadcast dissemination
  - Copes with **external (alien) traffic**

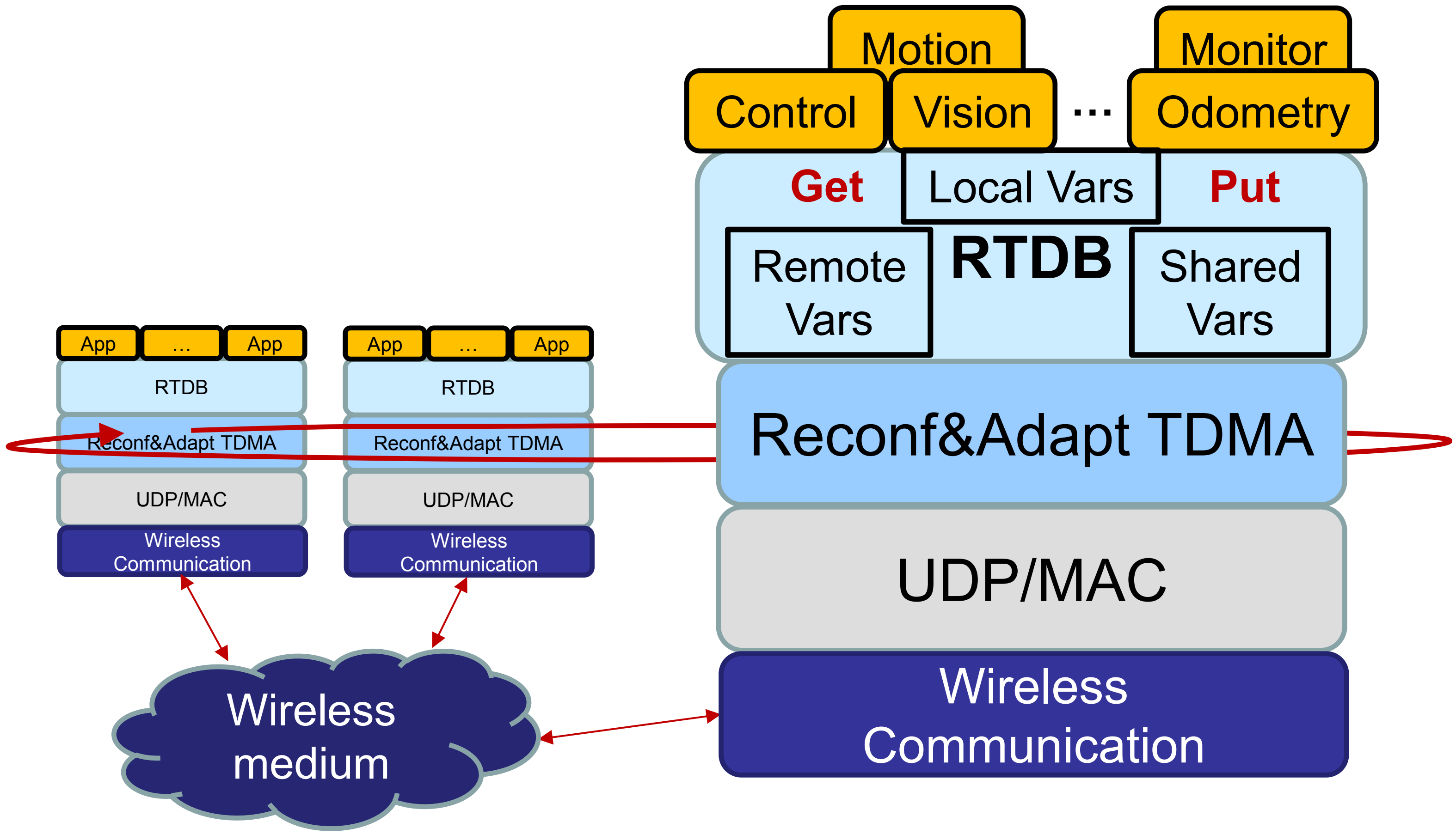
Data dissemination

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

The Real-Time Data Base (RTDB)

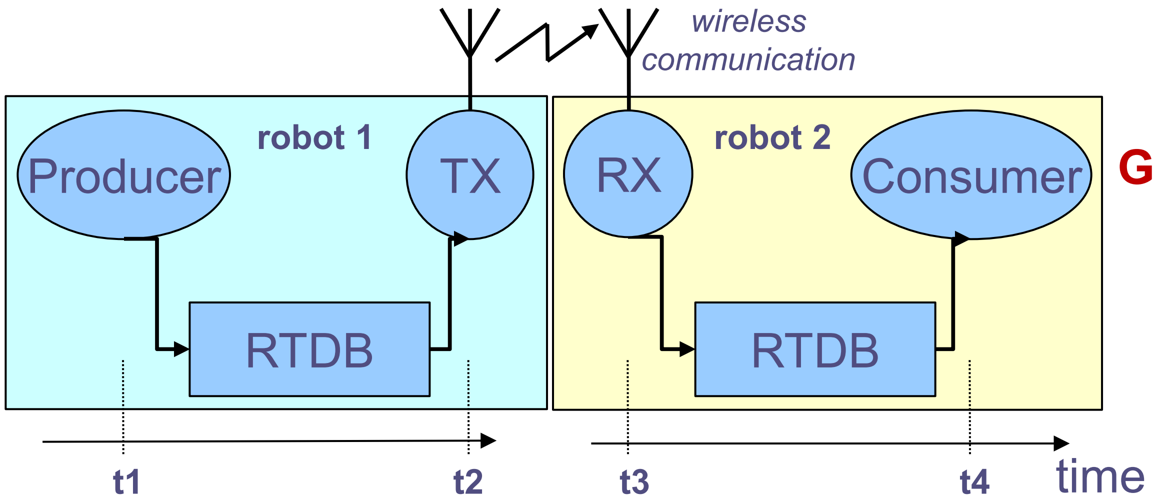


RTDB communications stack



RTDB accounting for data age

data → Put()



Get() { **data age** }

(tx – local timestamps)

age = (t4 – t3) + (t2 – t1) + wireless_communication_delay

(enhances the **safety** of using the RTDB)

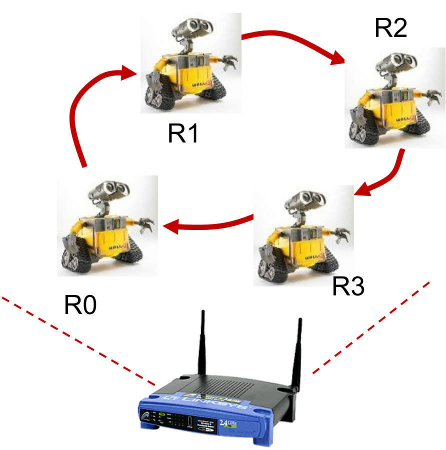
U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Adaptive TDMA

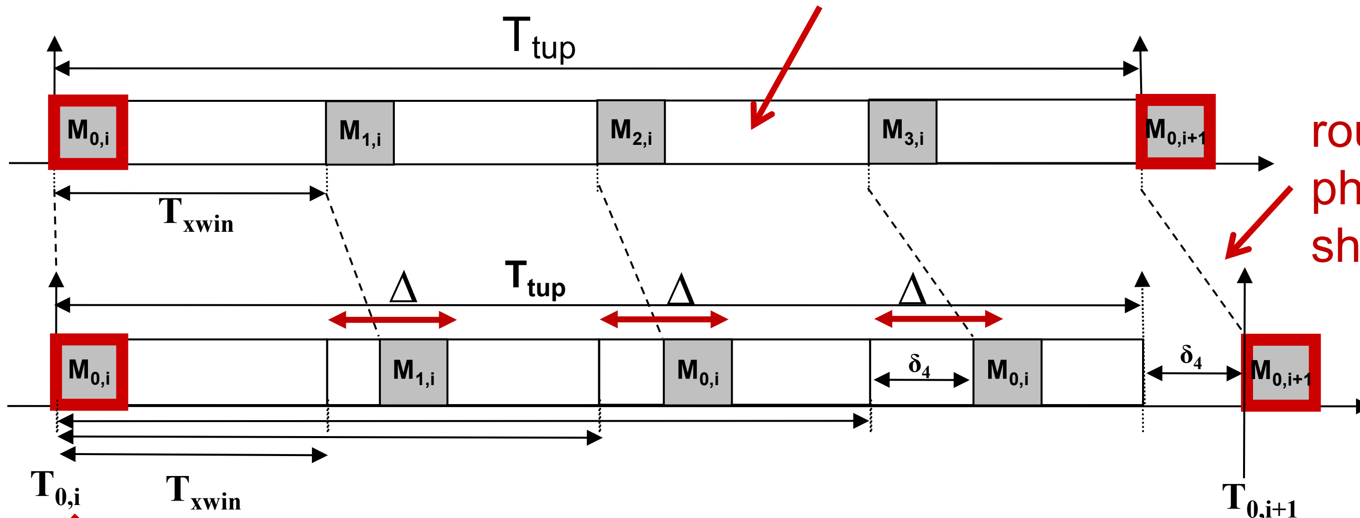
- **Time Division Multiple Access**
  - One **slot** per node - **reservation**
  - Dynamic **reference** election (lowest ID)

Maximizes separation between team transmissions

round phase shift



Infrastructured

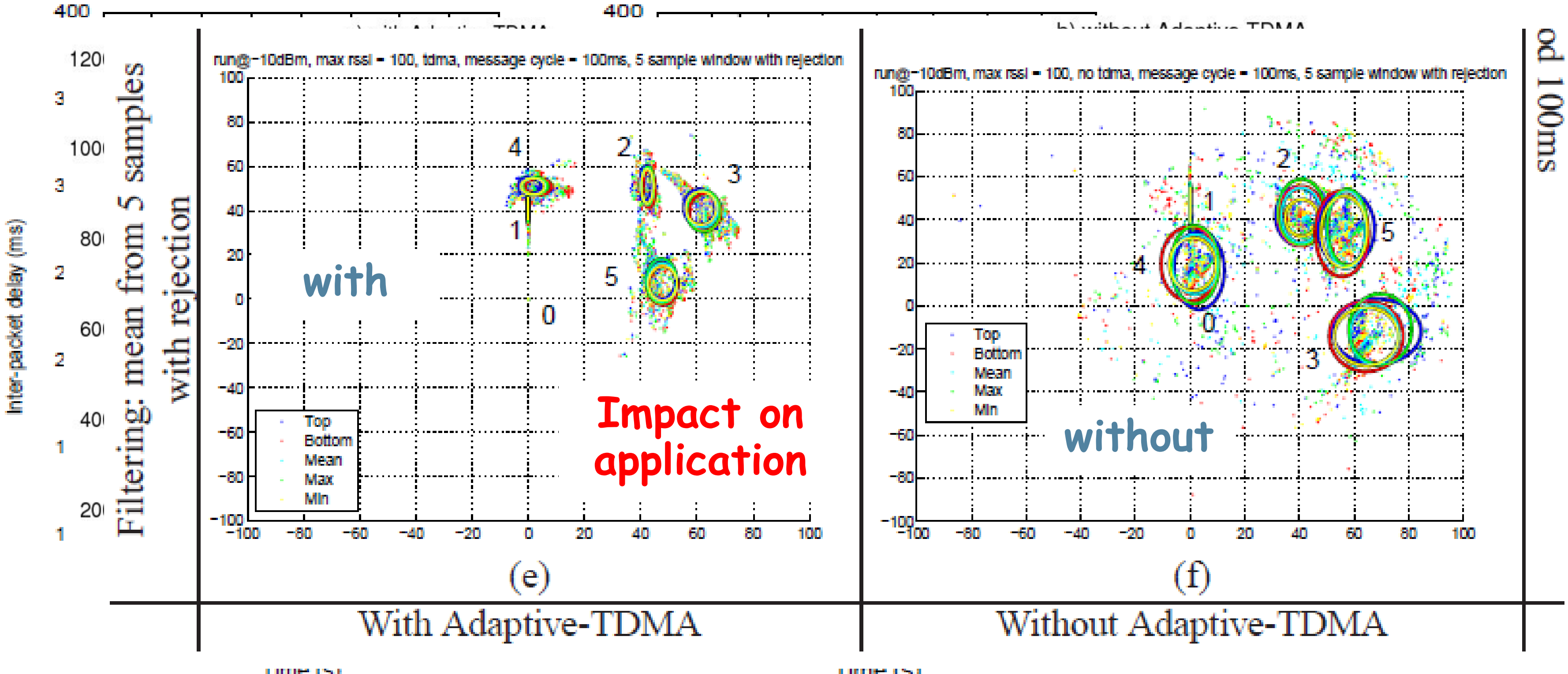


Reference $$T_{0,i+1} = T_{0,i} + T_{tup} + \max_{k=1..N-1, \delta_k < \Delta} \delta_k$$

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

Adaptive TDMA

- Effective on **reducing packet losses** and **improving application** performance under **intense communications**

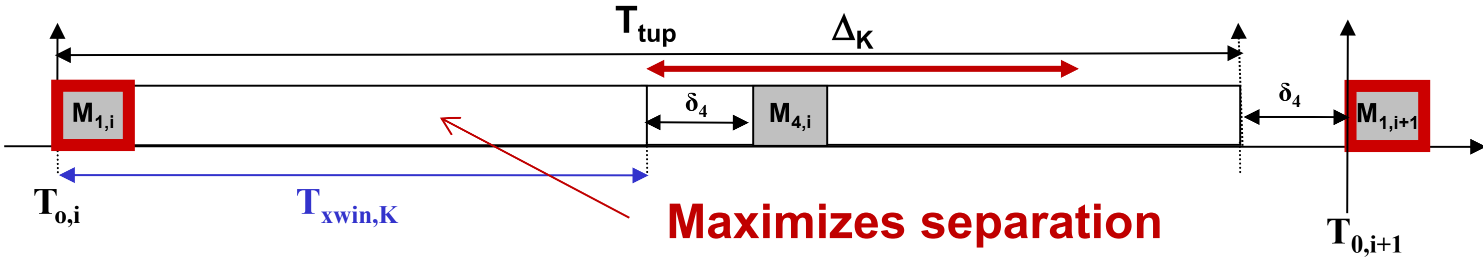


Reconfigurable & Adaptive TDMA

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

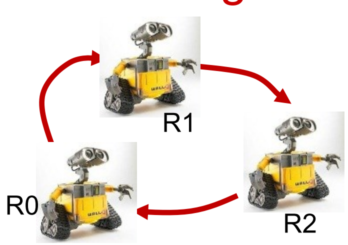
Round is kept

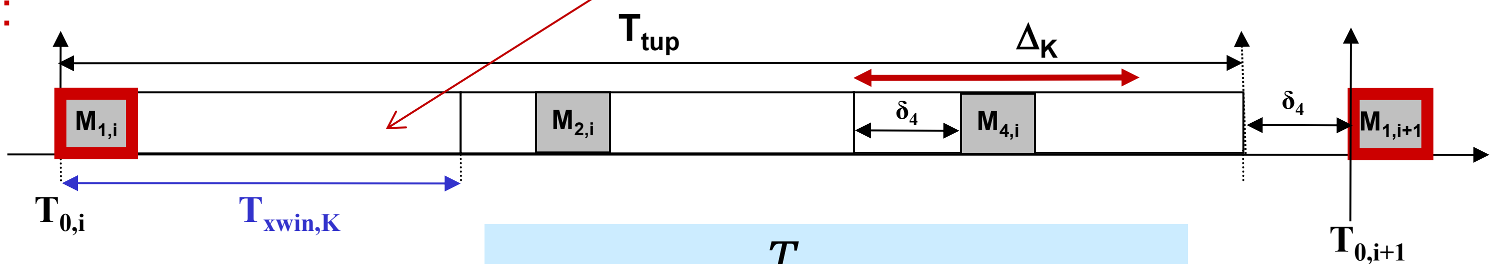
2 running robots:



Maximizes separation
between team transmissions

3 running robots:





$$T_{xwin,K} = \frac{T_{tup}}{K} \qquad K \leq N$$

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

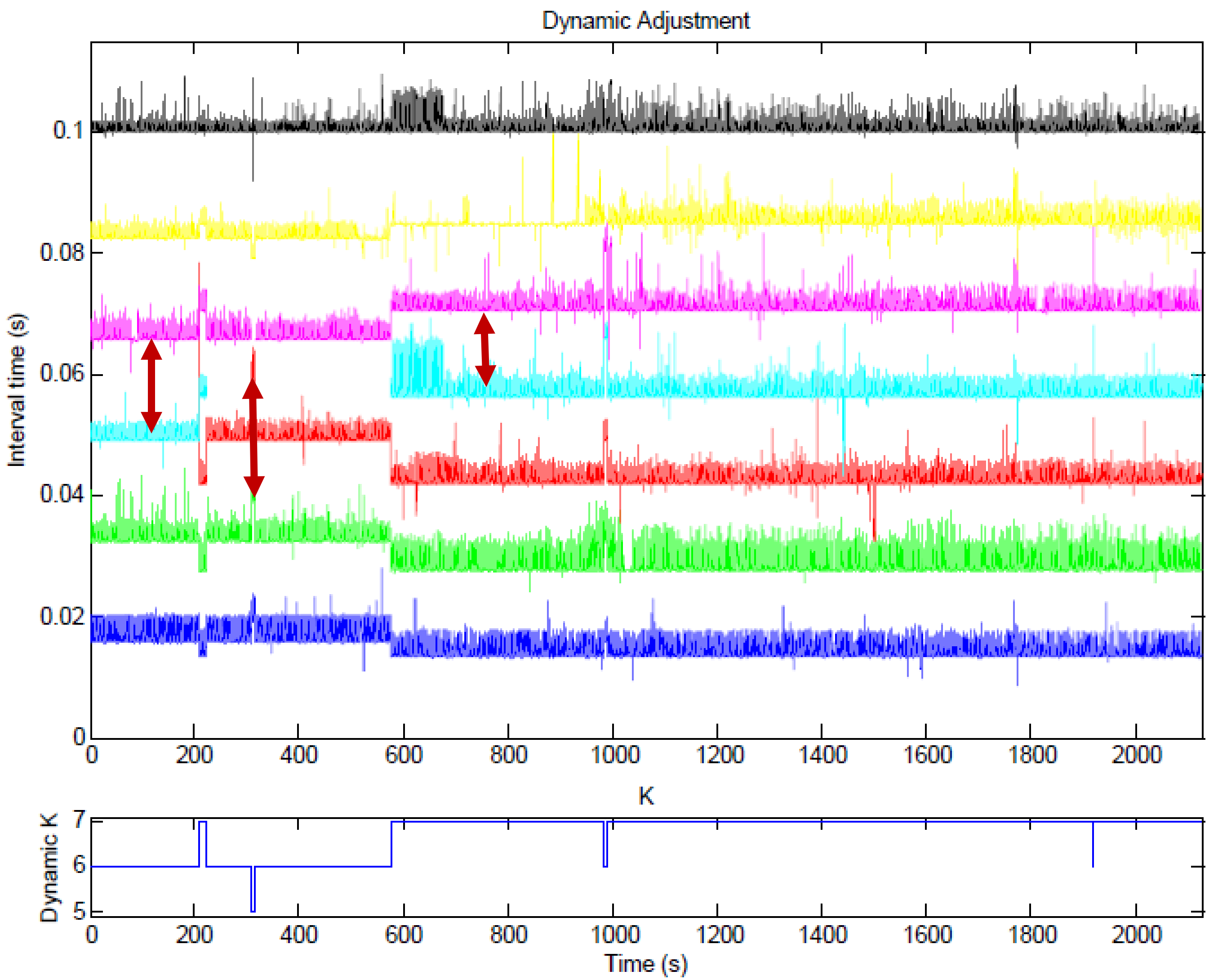
Actual team size

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Membership and round structure

Offset of Tx in the round

Team members

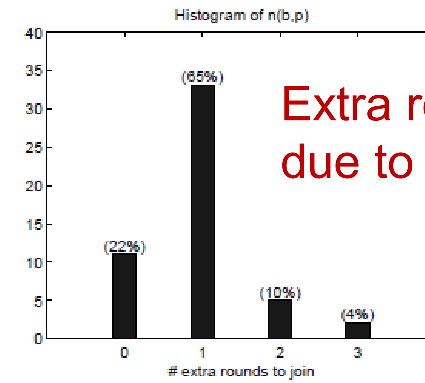


U.PORTO

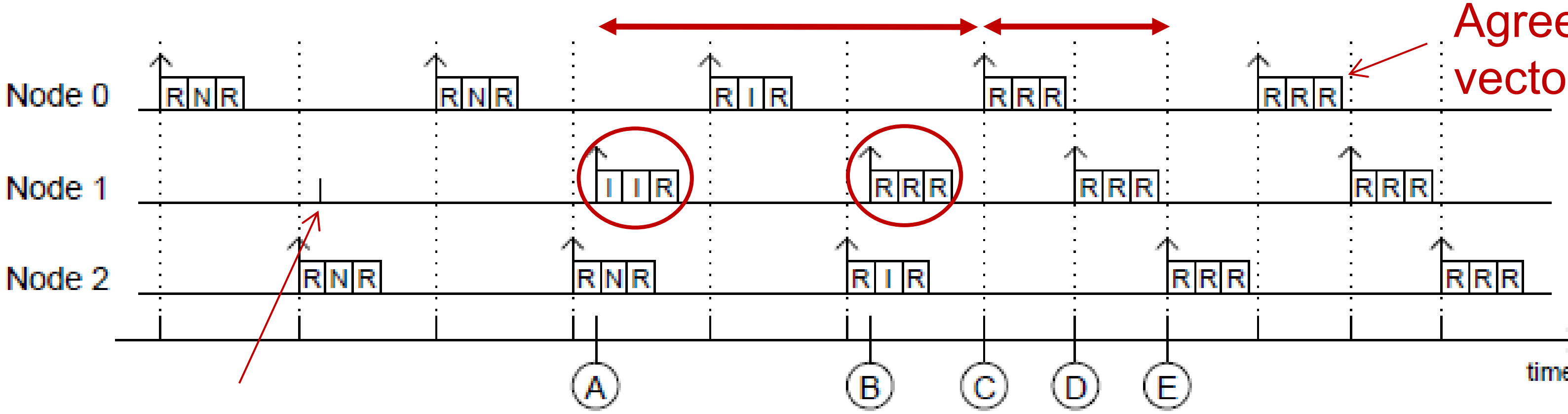
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

The joining process

- **Using an AP** simplifies **team membership** definition and speeds up the agreement process **for reconfigurations**
  - **Topology** becomes virtually **fixed**
  - **Agreement** (A-C) takes **[1 2] rounds**
  - **Resynchronization** (C-E) takes **[0 1] rounds**



Extra rounds due to errors



Agreement vector

Node 1 restarted

Announces itself

Integrated

1st reconfigured round

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/

Conclusion

- **Collaboration among autonomous agents requires**
  - **wireless communication** (interference, errors, multi-path fading, attenuation…)
  - way of **sharing information** (middleware)
- **Synchronization (TDMA) is worthwhile to reduce collisions**
  - Particularly, for **periodic (interfering) traffic** and **high load**
  - Leads to **reducing network delays & packet losses**
- **Effective RTDB shared memory middleware**
  - **Separation of** computations and communications
  - **Data age information** (enhances safety)
- **Future work: cooperating vehicles**
  - Pending issues related with **team management**

Acknowledgments

- Frederico Santos
  - **Infra-structured version** (used in MSL)
    - RTDB + RATDMA
- Luis Oliveira
  - **Ad-hoc version**
    - Adaptation of RATDMA / consensus in a mesh,
    - Point-to-point communication / routing,
    - Relative RF-based localization
- Cambada team
  - Actual case study
  - Many collaborations mainly with Frederico

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Main references

- **Structuring Communications for Mobile Cyber-Physical Systems.**
  - Luis Almeida, Frederico Santos, Luis Oliveira.
    In *Management of Cyber Physical Objects in the Future Internet of Things: Methods, Architectures and Applications*. A. Guerrieri, V. Loscri, A. Rovella, G. Fortino (Eds), Springer, Series on Internet of Things, Vol. 1: ISBN 978-3-319-26867-5, 2016. (to appear soon)
- **Design of adequate computing and communication architectures to support the realtime coordination of multiple autonomous robots.**
  - Frederico Santos. PhD Thesis, University of Aveiro, Portugal, June 2014.
- **Communicating among robots in the Robocup Middle-Size League.**
  - Frederico Santos, Luis Almeida, Luis S. Lopes, Jose L. Azevedo, M. Bernardo Cunha.
    Robocup Symposium 2009, Graz, Austria, june 2009.
- **A real-time distributed software infrastructure for cooperating mobile autonomous robots.**
  - Frederico Santos, Luis Almeida, Paulo Pedreiras, Luis S. Lopes.
    ICAR 2009 – 14th Int. Conf. on Advanced Robotics. Munich, Germany. June 22-26, 2009.
- **Self-configuration of an Adaptive TDMA wireless communication protocol for teams of mobile robots.**
  - Frederico Santos, Luis Almeida, Luis S. Lopes.
    ETFA 2008. Hamburg, Germany. 15-18 September 2008.