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Mobile cyber-physical systems

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SEVENTH FRAMEWORK PROGRAMME

Cyber-physical systems

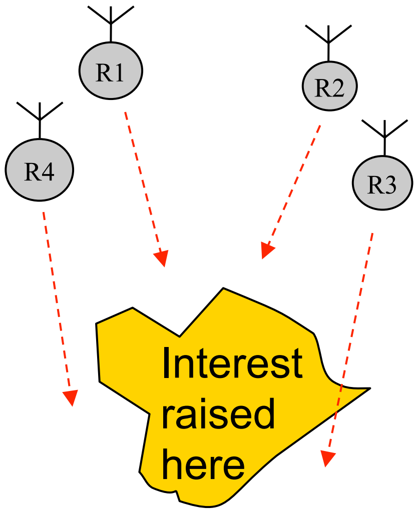
- A further step in a continuous trend since many years...
  - Ubiquitous computing, Internet of things, ambient intelligence, large-scale distributed embedded systems...
- **Cannot be characterized** deterministically
  - High heterogeneity, fuzzy frontiers, variable composition
- Yet, some cases require a minimum **quality of service**
  - Distributed sensing and control, tracking (possibly visual)...
- And **need to be robust** wrt
  - Topology changes (node crashes, reconfigurations)
  - Denial-of-service (malfunctioning nodes, malicious actions)
  - Intrusion (unauthorized accesses or actions)

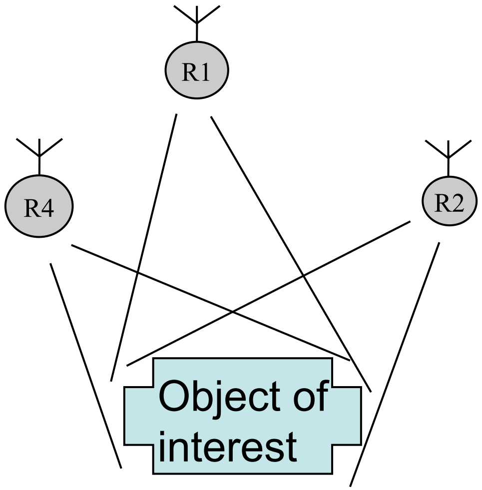
Cyber-physical systems

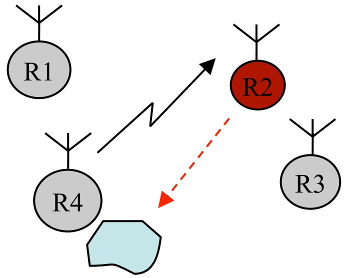
- Basic purpose
  - **Sensing and control** (in some way)
- Applications
  - Building automation, **indoor and outdoor surveillance, assisted terrestrial transportation systems**, early warning systems, **environmental monitoring, precision agriculture, search and rescue**, monitoring large assets...
- Need for **extending the reach** of sensing/actuation
  - Sensor networks (fixed)
  - **Move sensors/actuators around as needed** or exploit their independent movement (transportation systems)

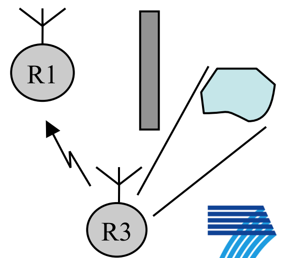
Mobile cybe‌r-physical systems

- **Moving sensors / actuators** may allow:
  - Robust sensing
  - Cooperative sensing & control
  - Efficient actuation, ...









Mobile cyber-physical systems

- Our target
  - To deploy a **team** of **heterogeneous autonomous agents,** provided with appropriate sensing and actuating capabilities, in a given operational scenario, which is capable of **cooperating towards a global goal without needing** any
    - **specific** agents **configurations**
    - previous **environment preparation**

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In the remainder of this talk

- **Architectural issues** in this kind of M-CPS
- **Wireless communication** issues
- **Team-level** issues
- Some related **open issues in wireless** communication
- Our related work
  - **Dynamic RT traffic scheduling** within a team (with Univ. Pavia)
  - Supporting a **robotic soccer** team (Univ. of Aveiro /Univ. Pittsburgh)
  - Adding **graceful degradation** to a RT protocol (with Univ Zaragoza)
  - RSS-based **relative-localization** & navigation (with U. Zhejiang)

Architectural issues in these M-CPS

- **Number of nodes:** variable, normally small (<20)
- **Network topology:** no fixed infrastructure, normally flat
  - Must be clustered for larger numbers of nodes
- **Synchronization:** none / global (/or within cluster)
- **Inter-agent information sharing:** global
- **Dynamic membership:** notion of team /(sub-team/cluster)
- **Location-awareness:** relative (no anchors) /absolute if pos.
- **Consensus:** global (/or local if clustered)
- Combination of **coordinated** with **autonomous** behaviors
- Communication medium: **wireless!**

Wireless pros & cons

- **Openness**
  - Ad-hoc connections based on proximity
  - Prone to intrusion and denial-of-service
- **Freedom** of relative **movements**
- **Bit error rate** higher than with wired comm.
- Potential for **unavailability periods**
  - Other uncontrolled traffic, interference, ...
- Common **RT-assumptions** of bounded delays, connectivity, medium availability and cooperative environment
  - Typical in wired systems
  - Have **lower coverage in wireless** systems

At the team level

- **Coordination** must be **adaptive and tolerant** to
  - **communication unavailability** (poor coverage of RT-assumptions)
  - **changes in team composition**

- Some useful techniques
  - Use **dynamic role** assignment
  - Define set of **safe autonomous behaviors**
    - Guarantee **safe switch** to such states when needed
  - Use **positioning** to control **connectivity** / **topology**
  - Improve support from the **underlying communication** protocols to **push coverage further**

Some wireless-related directions

- Network level
  - **Logical addressing:** based on capabilities / location
  - **Routing:** reactive/proactive, considering dynamic membership
- MAC level
  - **TDMA-based** protocols are efficient for **intense communication** and **energy saving**
    - Apply them to (sub-)teams – (**local/)global synchronization**
    - Make them **adaptable** to **team composition** and **medium conditions**
    - Integrate **CSMA-based** protocols to **relax transmission control**
    - **Adapt communication pace / mode** to needs
- Physical level
  - **Consider new coding / tx techniques:** network coding, cognitive radio, digital fountains...

Our related work – **MAC level**

- **Dynamic real-time traffic scheduling** within a team
  - with Univ. of Pavia
    - Tullio Facchinetti, Giorgio Buttazzo

- Target
  - **Synchronize a team** to support real-time traffic scheduling
    - Implicit EDF (replicated comm. requirements and EDF schedulers)
  - Cope with **dynamic variations** in
    - membership
    - communication requirements

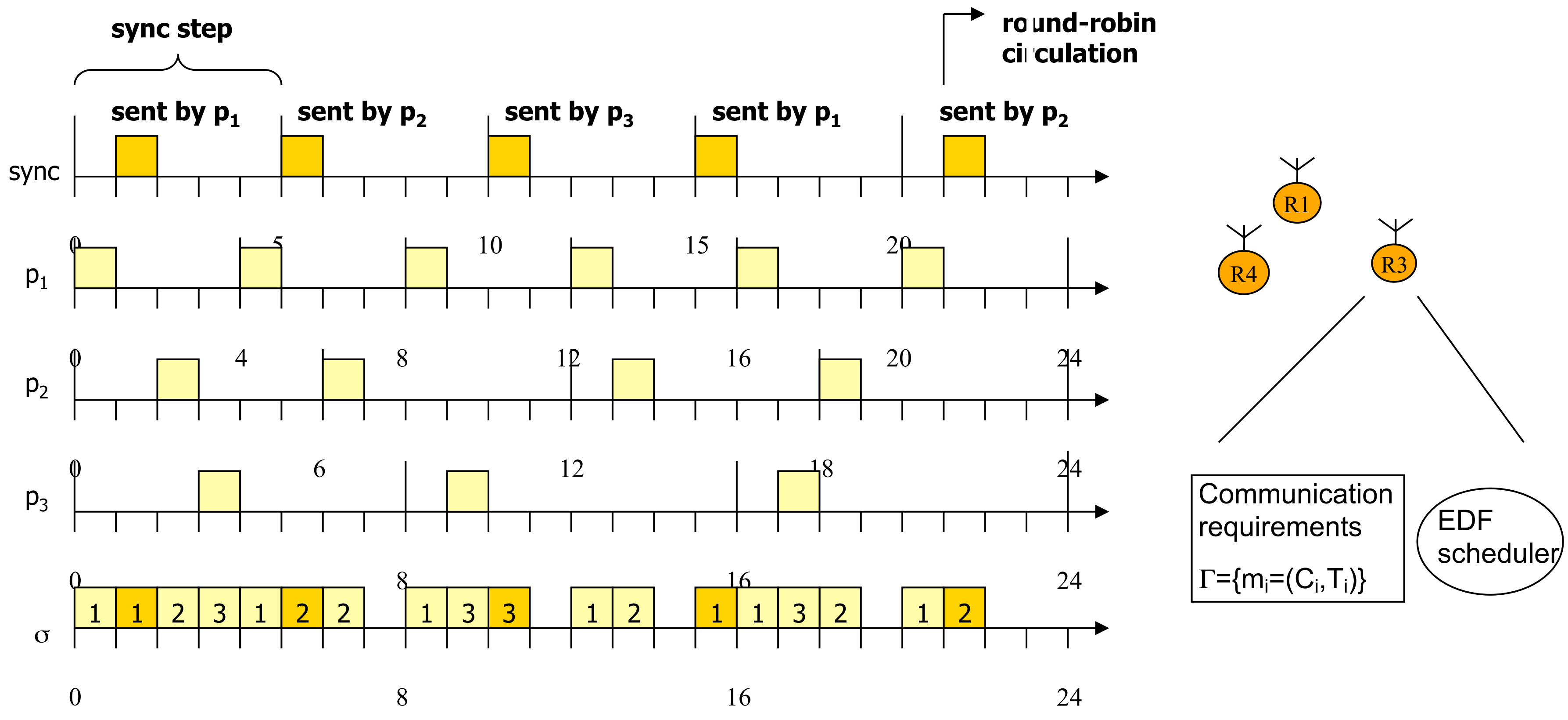
Dynamic RT traffic scheduling

- Assumption: **Team *normally* fully linked**
- Different sorts of information must be exchanged
  - Images, laser, audio, sonar, localization data, movement commands
  - Different timings requirements

    ➔ Need for **real-time traffic management**
- Proposed solution:
  - **Producer–Consumer** cooperation model
  - **Replicated** communication requirements + schedulers
  - **Synchronized EDF schedulers** operating with fixed size slots
    - Synchronization message sent by all in a round robin cycle
      - Distributed clock synchronization + Schedulers synchronization

Dynamic RT traffic scheduling

$m_1=(4,1)$ $m_2=(6,1)$ $m_3=(8,1)$ sync=(5,1)



Dynamic RT traffic scheduling

- **Adding dynamism** to the team or comm. requirements **needs global agreement** to maintain synchronization
  - Set an **agreed time in the future (t_a)** when all nodes should reconfigure
  - **Disseminate** the agreement info within the team
    - Agreement vector (binary) sent within the Sync message
    - Indicates which nodes have been notified about the change and t_a
- Defining t_a

Upper bounds on the agreement process duration

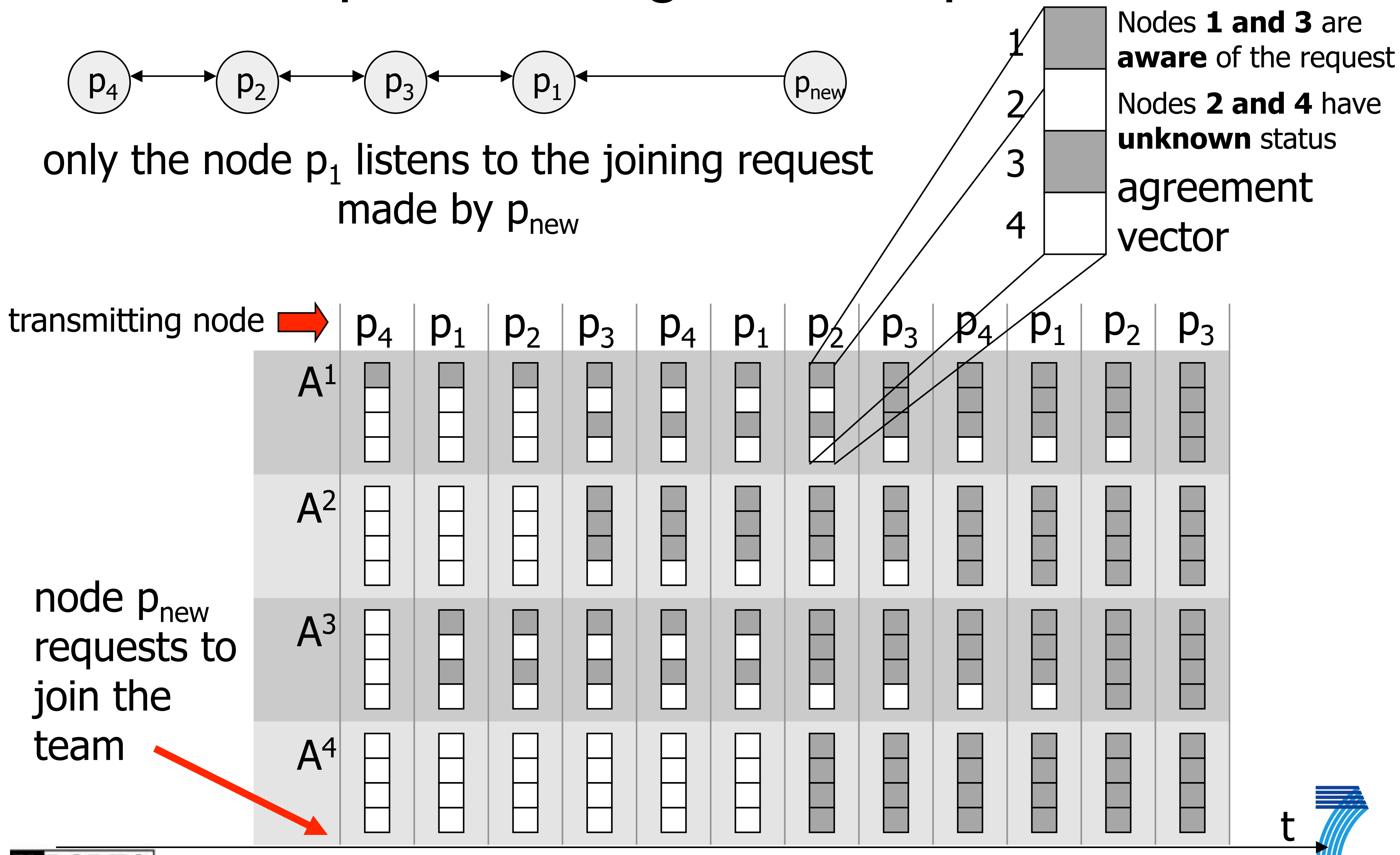
$$t_a = \min(S(n), \sigma(n,d))$$

$S(n) = n^2-n-1$ (worst-case topology with n nodes)

$\sigma(n,d) \leq 2(n-1)d$ (topology with diameter d)

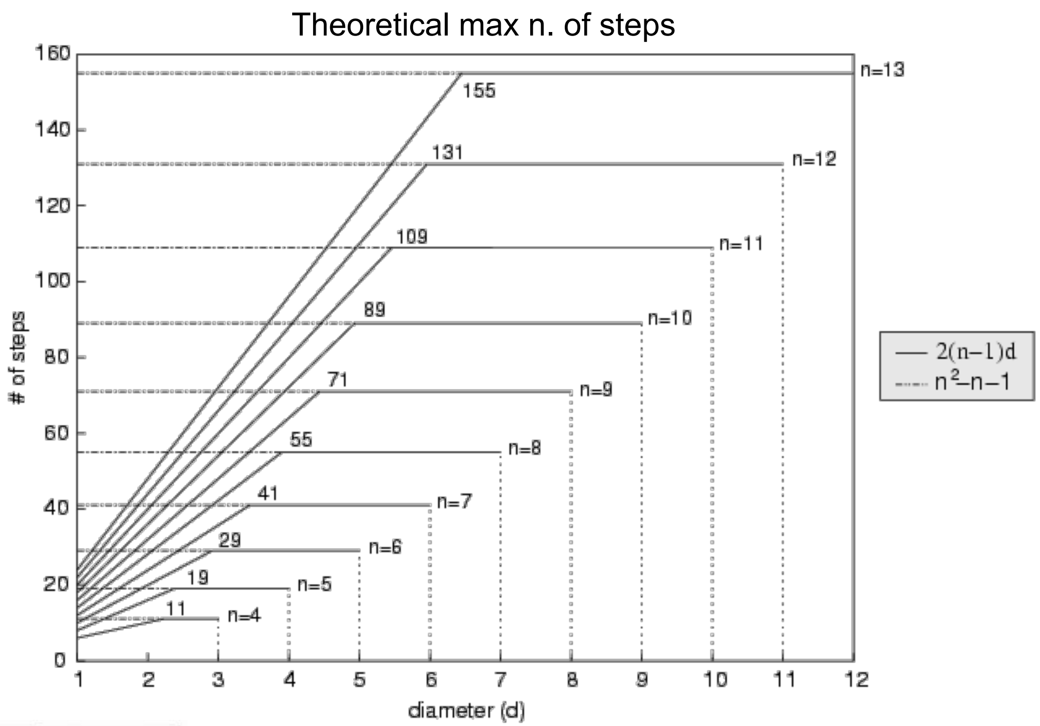
T. Facchinetti, L. Almeida, G. Buttazzo, C. Marchini. Real-Time Resource Reservation Protocol for Wireless Mobile Ad Hoc Networks. RTSS 2004, 25th IEEE Real-Time Systems Symposium,.Dec 2004.

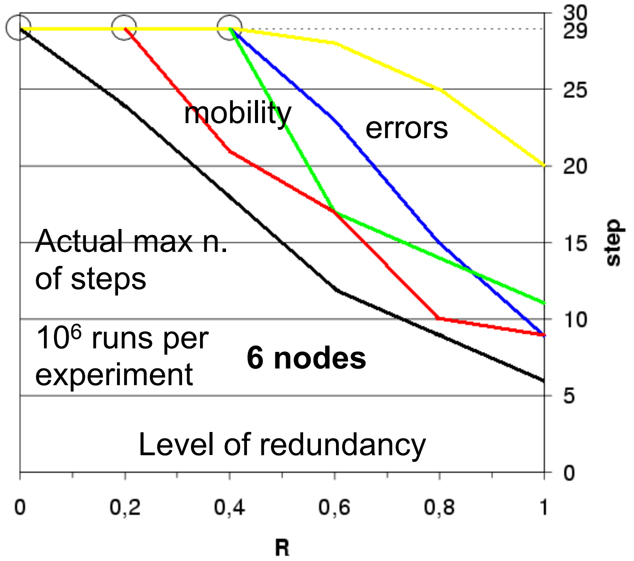
Example of an agreement process

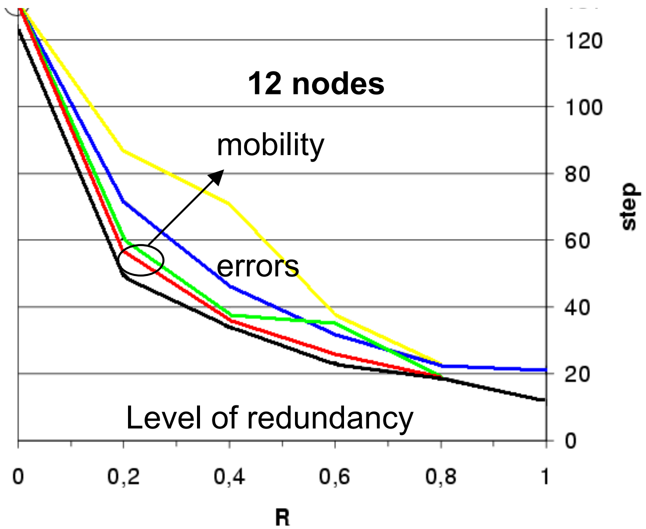


Convergence of the agreement process

- **Proved** with **any stable** topology
- **Good statistical** performance
  - with **mobility** and **errors**







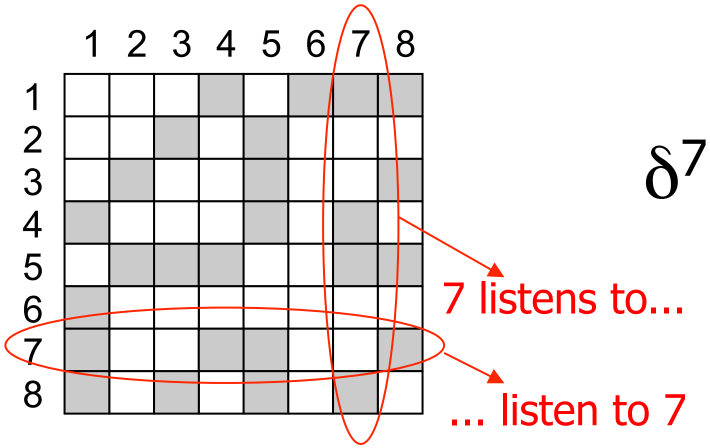
Topology tracking

- How to compute “d”, the **network diameter**?
- How to detected **absent** (e.g., crashed) **nodes**?

➔ Carry out **topology tracking**

- Achieved using
  - $M^k(t)$: a **connectivity matrix** (disseminated within the sync message)
  - $\delta^k(t)$: a **local vector** of shortest distances

$M^7(t)$



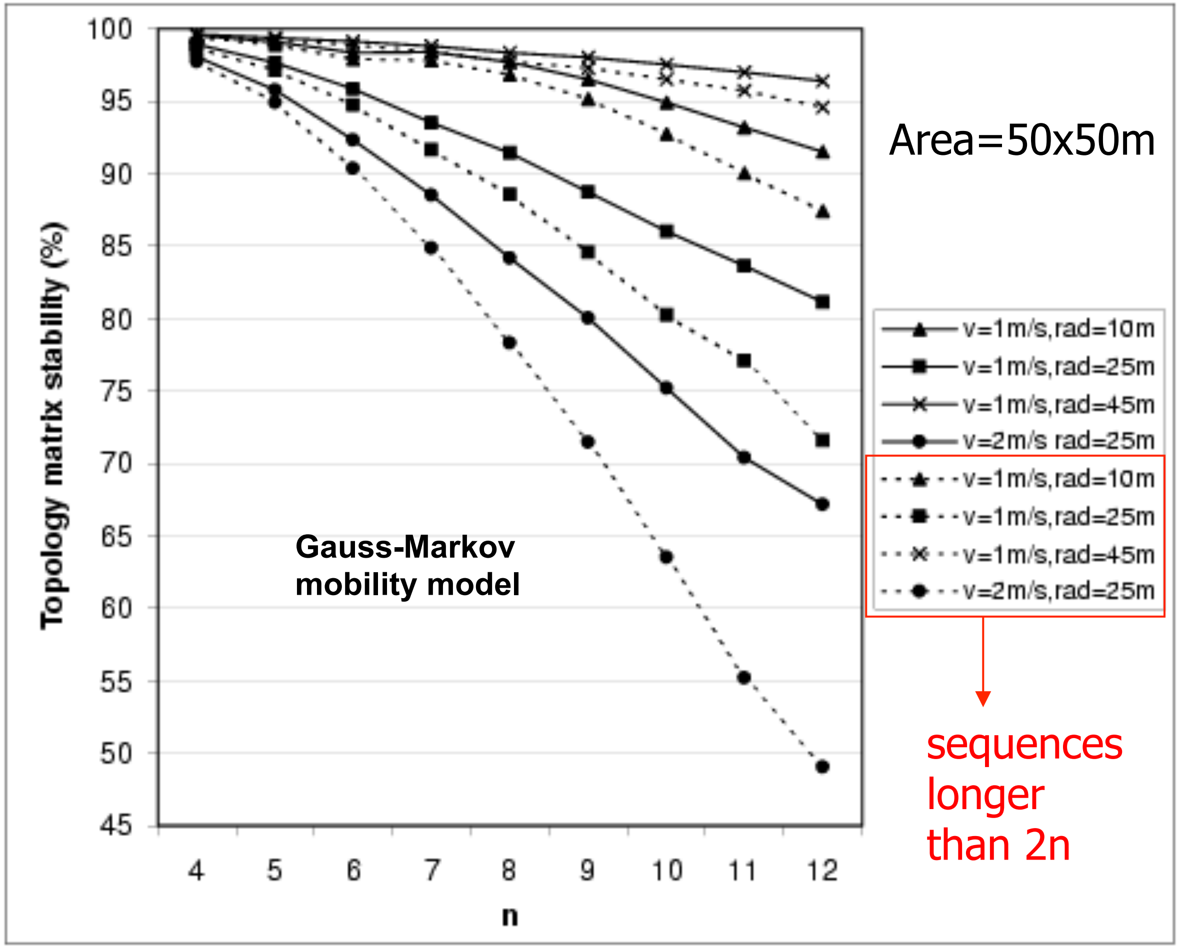
$\delta^7(t)$

node	neigh	dist
1	1	1
2	5	2
3	8	2
4	4	1
5	5	1
6	1	2
7	7	0
8	8	1

T Facchinetti, G. Buttazzo, L. Almeida. Dynamic Resource Reservation and Connectivity Tracking to Support Real-Time Communication among Mobile Units, EURASIP J.I on Wireless Comm. and Networking, 2005(5): 712-730, December 2005.

Topology tracking

- Process **proved** to converge with **stable topology**
  - Similar to the agreement case
- Shows **good stability with mobility**
- Limitations
  - Binary matrix
  - Circulation order
  - Clock sync
  - Startup
  - Overhead



Our related work – **MAC & Middleware**

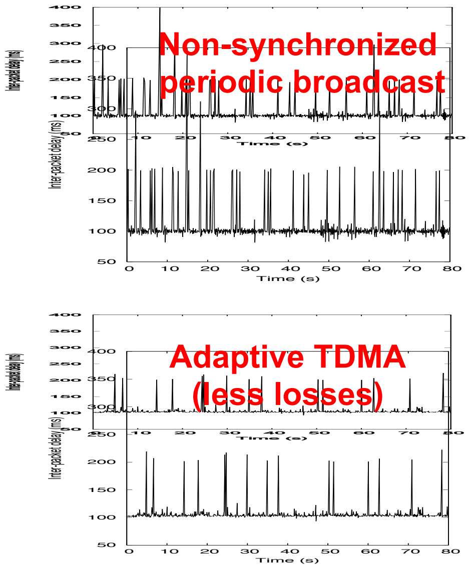
- **Real-time data dissemination** in a robotic soccer team
  - Univ. of Aveiro / Univ. of Pittsburgh
    - Frederico Santos, Luis S Lopes, Daniel Mossé

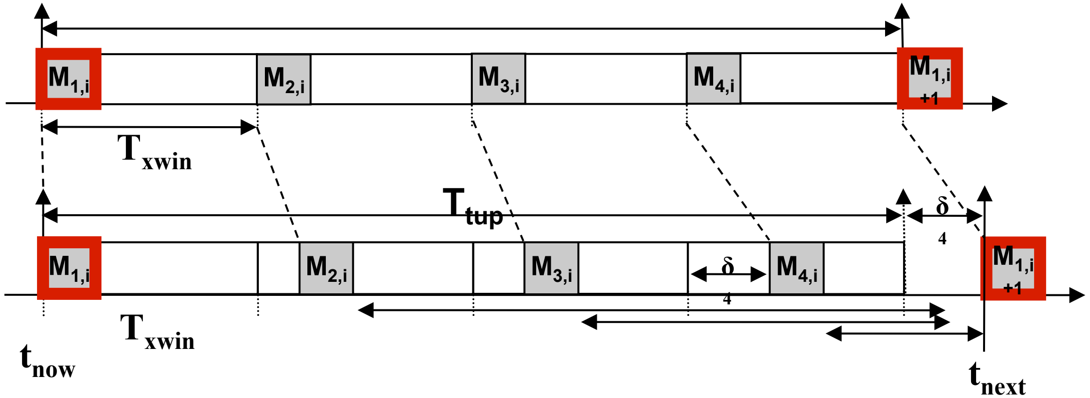
- Wireless technology:
  - **IEEE 802.11** (async mode)
- Must **tolerate *alien* traffic**
  - (wrt the team) → interference
- Team **normally fully-linked**
- **Highly dynamic** team composition
  - Use **Access-Point** to facilitate consistent view of membership

F. Santos, L. Almeida, L. S. Lopes. Self-configuration of an Adaptive TDMA wireless communication protocol for teams of mobile robots. ETFA 2008. Hamburg, Germany, 15-18 September 2008.

Adaptive (A-)TDMA

- Team members transmit in sequence
  - **TDMA set on top of CSMA-CA** of IEEE802.11
  - Virtually **eliminates collisions** among **team members**
  - **Fully distributed synchronization** based on frame receptions
  - Shifts phase of TDMA round to match periodic interference
  - **Time constraints → TDMA round period Ttup**





If $0<\delta_k<\Delta$ then $t_{next} = t_{now}+T_{tup}+max_k(\delta_k)$

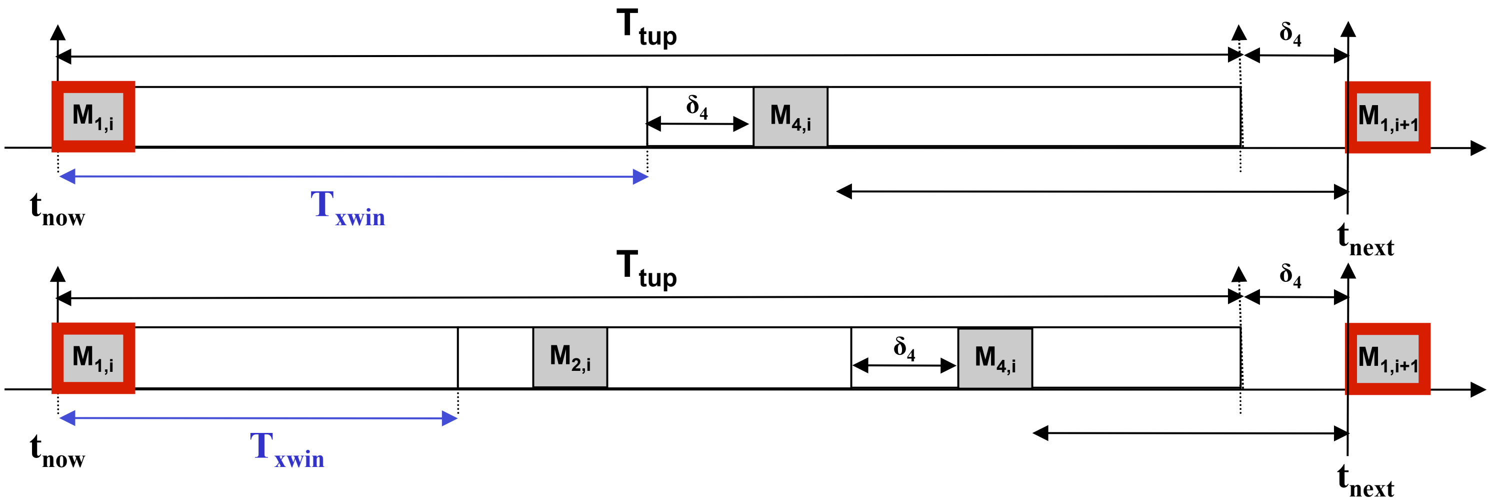
round period will be within $[\ T_{tup}\ ,\ T_{tup}+\Delta\ ]$

Reconfigurable and Adaptive (RA-)TDMA

- **Dynamic reconfiguration of the slot structure**
  - Robots join and leave dynamically
    - crash, maintenance, movements...
  - Slot structure of TDMA round need not be predefined
    - Number of slots continuously adjusted as needed
  - **Fully distributed – minimal a priori knowledge**

2 running robots:

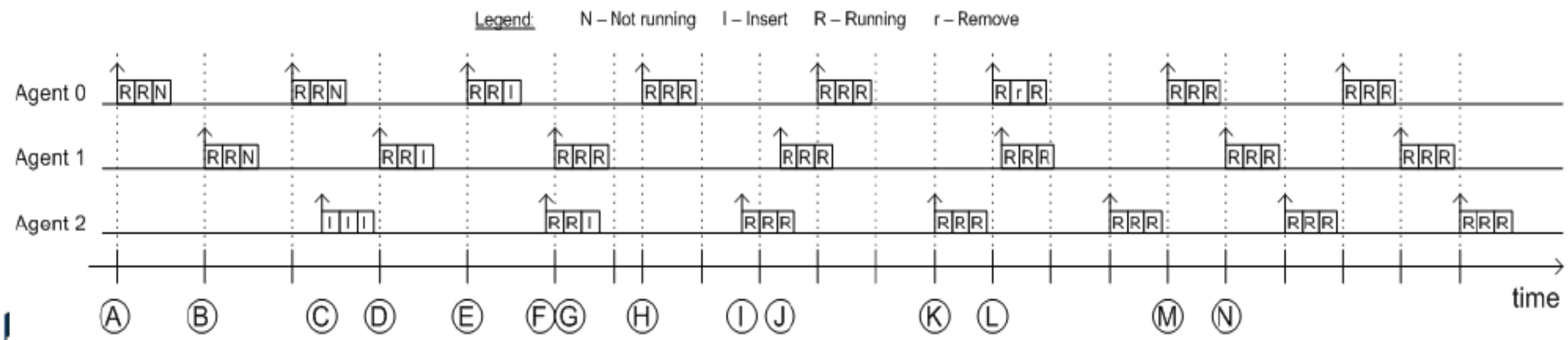
3 running robots:



SEVENTH FRAMEWORK PROGRAMME

Reconfigurable and Adaptive TDMA

- **Using an AP simplifies team membership definition** and **speeds up the agreement process** for reconfigurations
  - **Topology** becomes virtually **fixed**
  - **Agreement** takes about **one TDMA round**
    - For all nodes to reach consensus on the reconfiguration to be done
  - **Synchronization** takes a **few more** rounds (**bounded**)
    - For all nodes to synchronize with the new round structure



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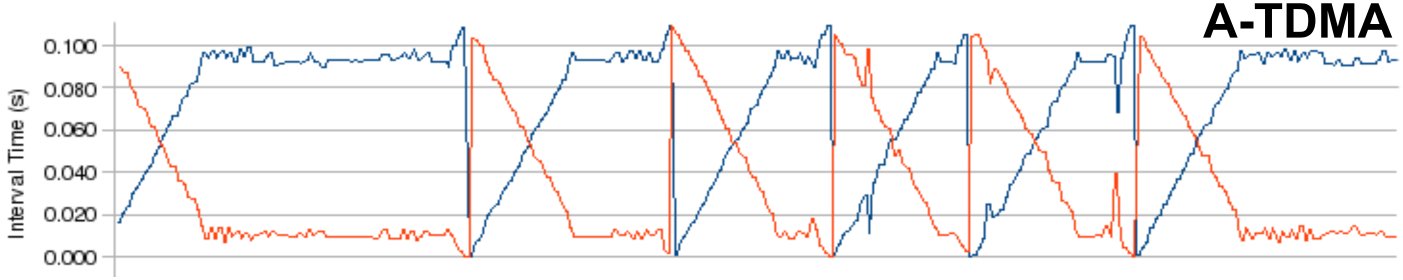
Reconfigurable and Adaptive TDMA

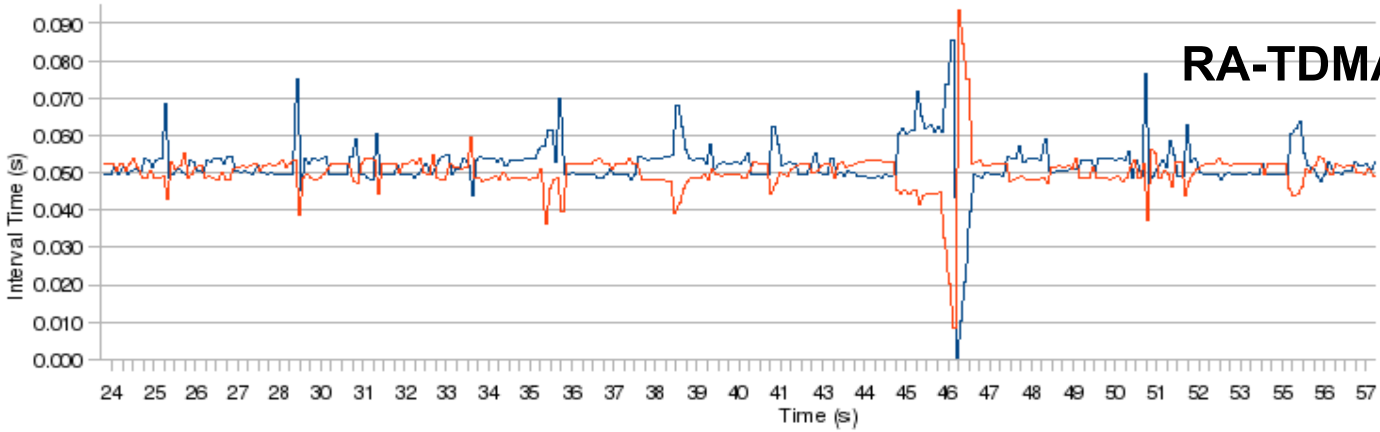
- Main advantages
  - Absence of a fixed TDMA round structure
  - Fully distributed startup procedure with minimal configuration
  - Further contribution to reduce collisions



A-TDMA (2 nodes/10 slots)

in sync: **50%**

lost packets:**1,2%**



RA-TDMA (2 nodes)

in sync: **97%**

lost packets: **0,3%**

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SEVENTH FRAMEWORK PROGRAMME

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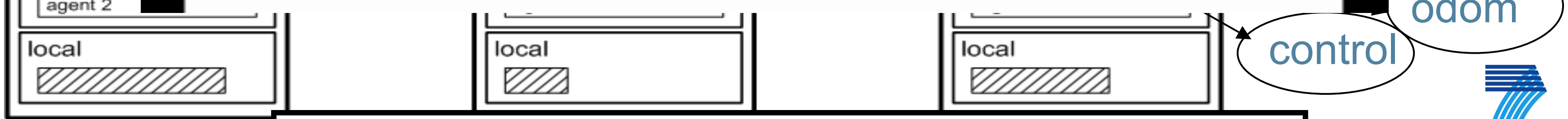
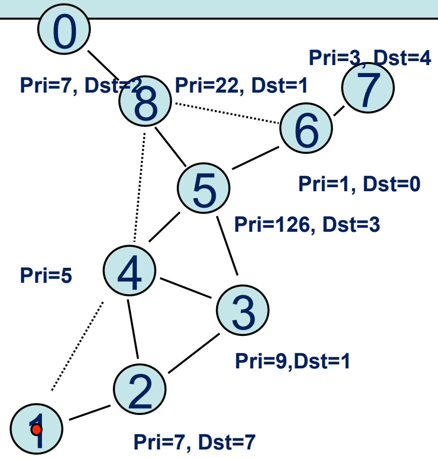


F. Santos, L. Almeida, P. Pedreiras, L. S. Lopes. A real-time distributed software infrastructure for cooperating mobile autonomous robots. ICAR 2009. Munich, Germany, 24-26 June 2009.

RT-WMP – routing on demand

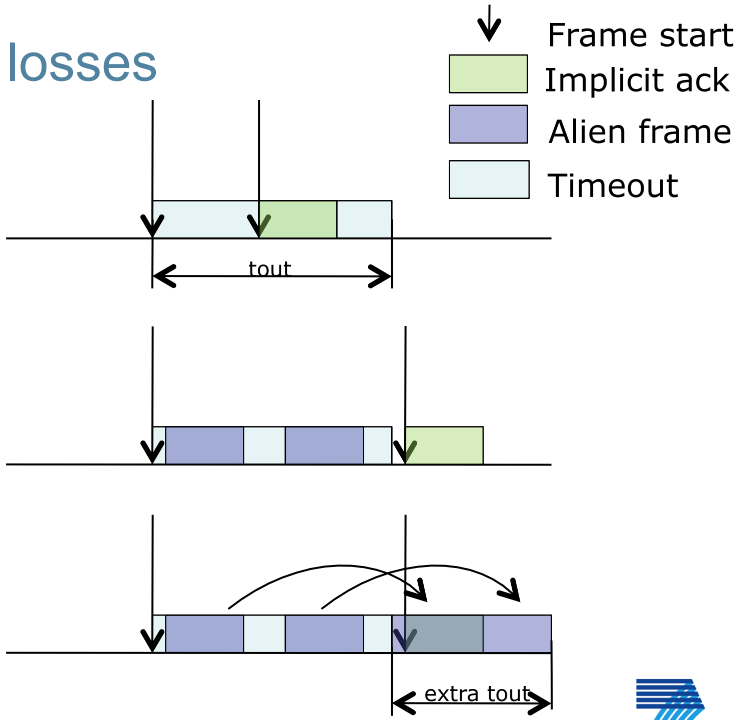
- **Real-time wireless multi-hop** protocol
  - Developed at Univ. of Zaragoza (Danilo Tardioli, José L. Villarroel)
  - Recent cooperation to allow RT-WMP to **cope with alien traffic**



- Wireless technology: **IEEE 802.11**
- **Fixed priorities**-based with **token**
- Works in 3 phases:
  - **Arbitration:** token circulated among all nodes to agree on priority
  - **Authorization:** After Arbitration, node with highest priority message is known → let it know!
  - **Transmission:** actual message transmission

RT-WMP – routing on demand

- All 3 phases are bounded
- Includes mechanisms based on **timeouts**
  - These are **not compatible with alien traffic**!
  - Thus, alien traffic causes high packet losses
- Proposal
  - **Extend all timeouts** by the time taken by alien frames
  - Increases latency but avoids extra packet losses
- Preliminary results show the **desired graceful degradation**



Our related work – **team level**

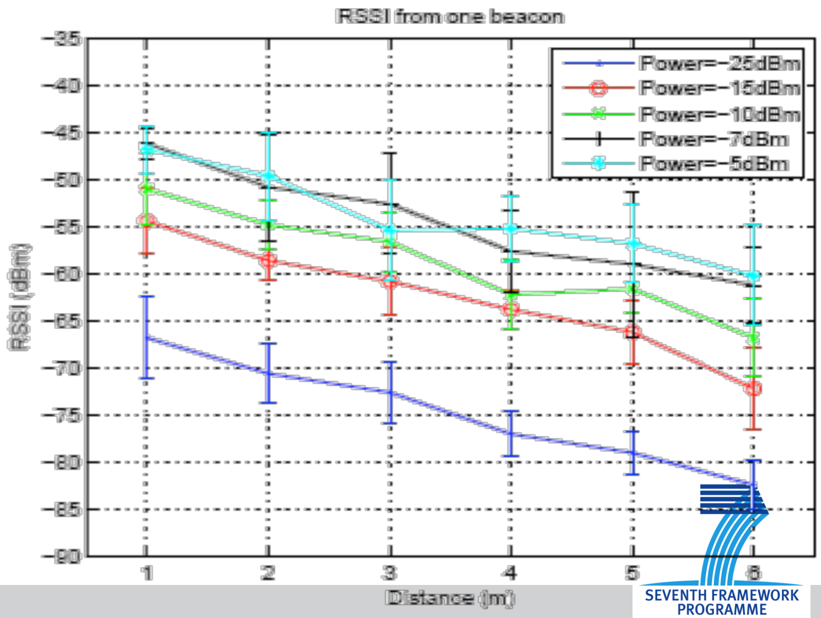
- **Topology-based relative localization and navigation**
  - with Zhejiang University / Univ. of Aveiro
    - Hongbin Li, Wang Zhi, Youxian Sun, Fausto Carramate, Luís Oliveira

- Not concerned with RT data transmission
- Relaxed sync (CSMA-CA, RA-TDMA)
- Wireless technology:
  - **IEEE 802.15.4** (async mode, beacon-less)
- **Extended connectivity matrix**
  - With analog RSS values → gives indication of link quality

Hongbin Li, Luis Almeida, Zhi Wang, Youxian Sun. Relative Positions within Small Teams of Mobile Units. MSN 2007, 3rd Int. Conf. on Mobile Ad-hoc and Sensor Networks. Beijing, China. Dec 2007.

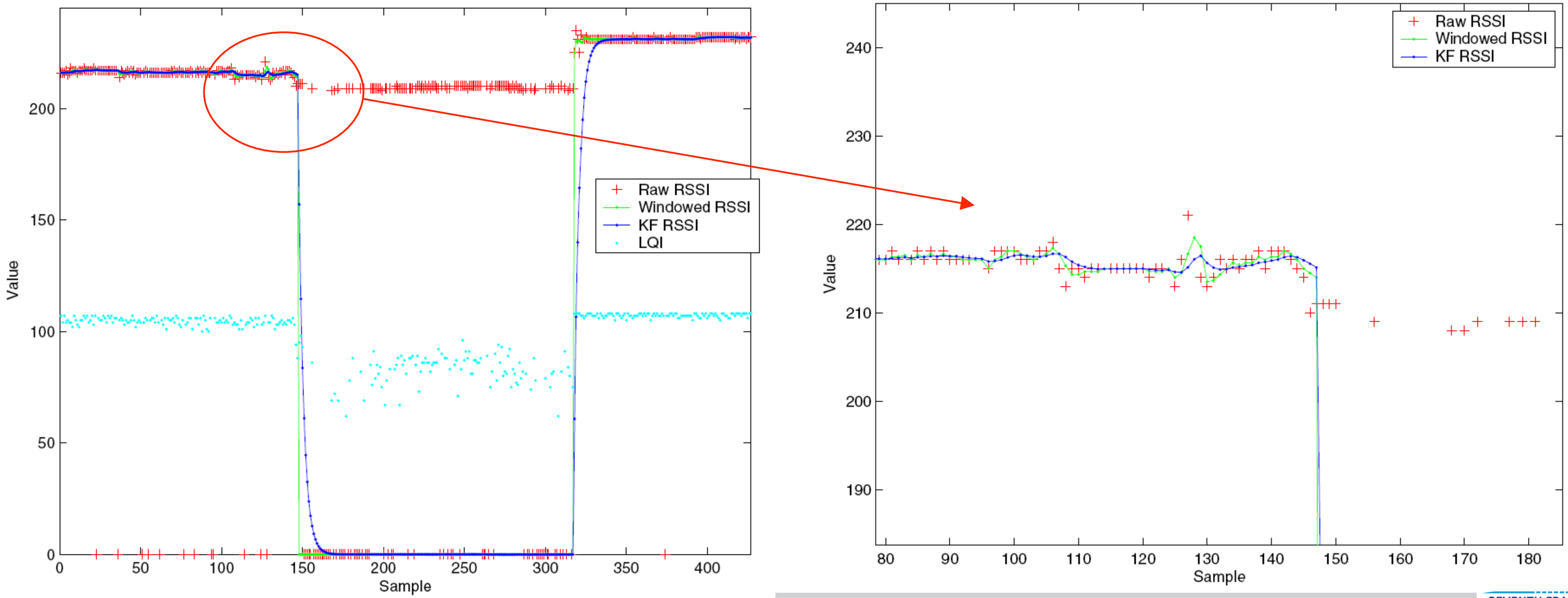
Topology-based relative localization

- For many tasks, just a gross notion of localization is enough
  - e.g., to give direction indications of movement to other robots
- We proposed using the **RSS** as an **indicator of distance**
  - **Network topology → relative localization of nodes**
    - using **Multi-Dimensional Scaling**
- But **RSSI** has **large variance**...
  - Needs filtering...



Topology-based relative localization

- Filtering the RSSI
  - **Average with sliding window** (reduces impact of packet losses)
  - **Kalman filter** (smoothes RSSI rapid fluctuations)
  - Packets with **low LQI not used** for matrix updating

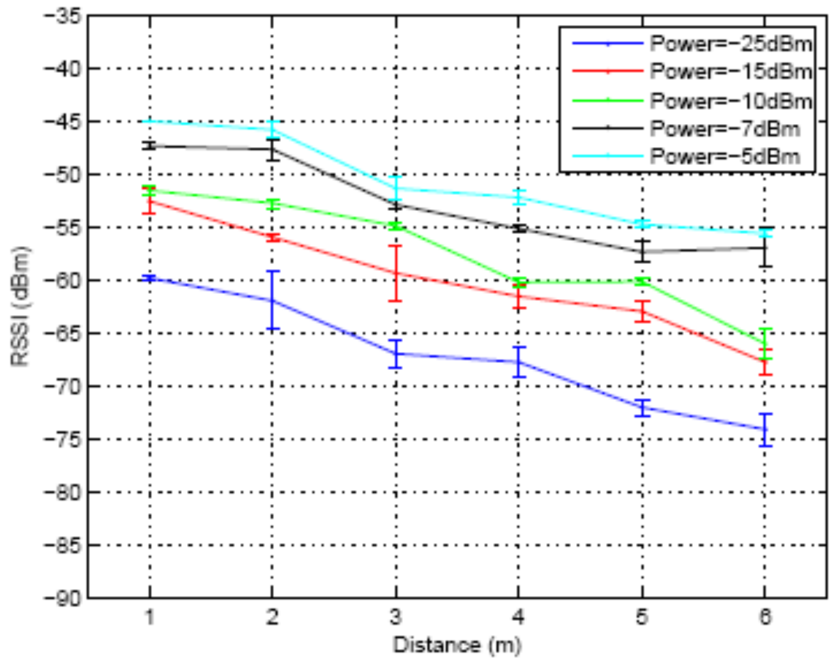


Topology-based relative localization

- **Variance** can also be **reduced** using **multiple antennas** and average the receptions

- **Filtered RSSI** is saved in the **connectivity matrix**
  - Non-existing links or with poor LQI → 0

Tx with 3 antennas



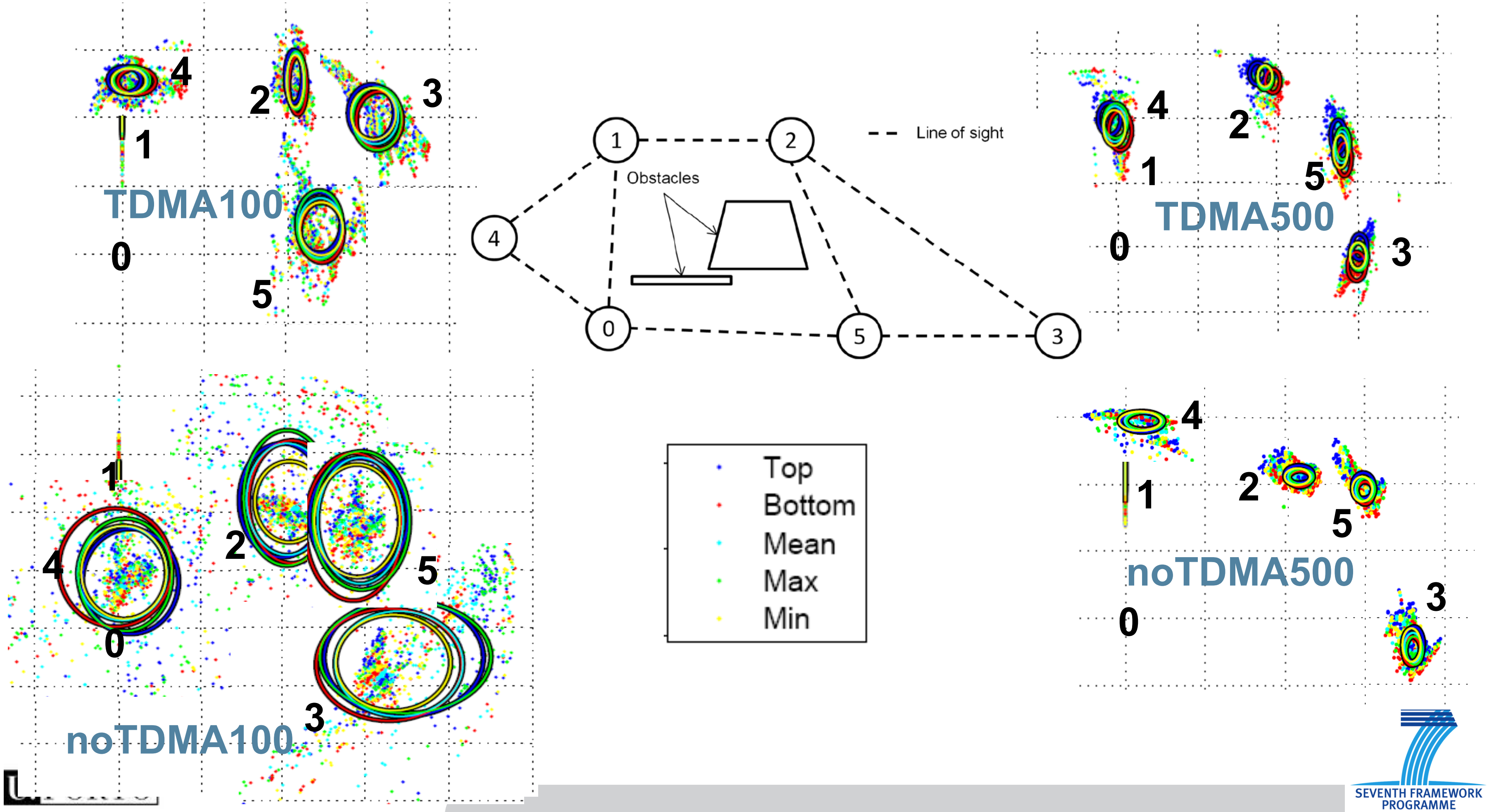
	0	1	2	3	4	5	Sending nodes
0	0	35	22	31	31	33	RSSI values received by node 0
1	38	0	35	24	52	34	RSSI values received by node 1
2	23	35	0	29	23	42	RSSI values received by node 2
3	0	23	29	0	19	36	RSSI values received by node 3
4	31	51	24	21	0	27	RSSI values received by node 4
5	31	33	43	37	26	0	RSSI values received by node 5

Topology-based relative localization

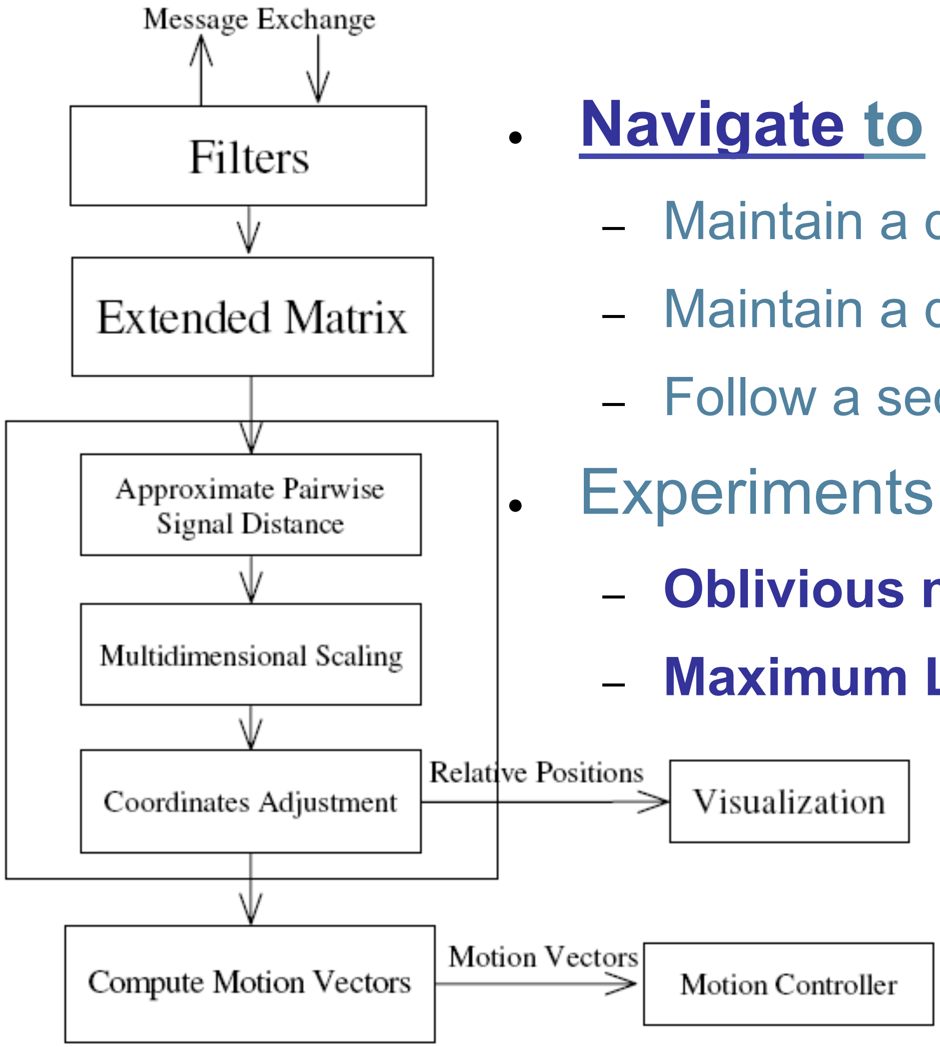
- **Multi-Dimensional Scaling**
  - Transforms **distance pairs** in **compatible positions**

Topology-based relative localization

- Impact of **synchronization** and **non-symmetry** on **MDS**



RSS-based navigation



- **Navigate to**
  - Maintain a desired RSS in a given link
  - Maintain a desired number of links with the team
  - Follow a sequence of beacons ...
- Experiments with 1 mobile and 1 static nodes
  - **Oblivious method** (random directions)
  - **Maximum Likelihood Estimator** (MLE)

(using beacon with 3 antennas)

(using omni antenna +ground plane)

Hongbin Li, Luis Almeida, Fausto Carramate, Zhi Wang, Youxian Sun. Using Low-Power Radios for Mobile Robots Navigation. FET 2009 – 8th IFAC Conference on Fieldbuses and Networks in industrial and embedded systems. Ansan, Korea. May 20-22, 2009.

RSS-based navigation

- Obliv
  - Us
    -
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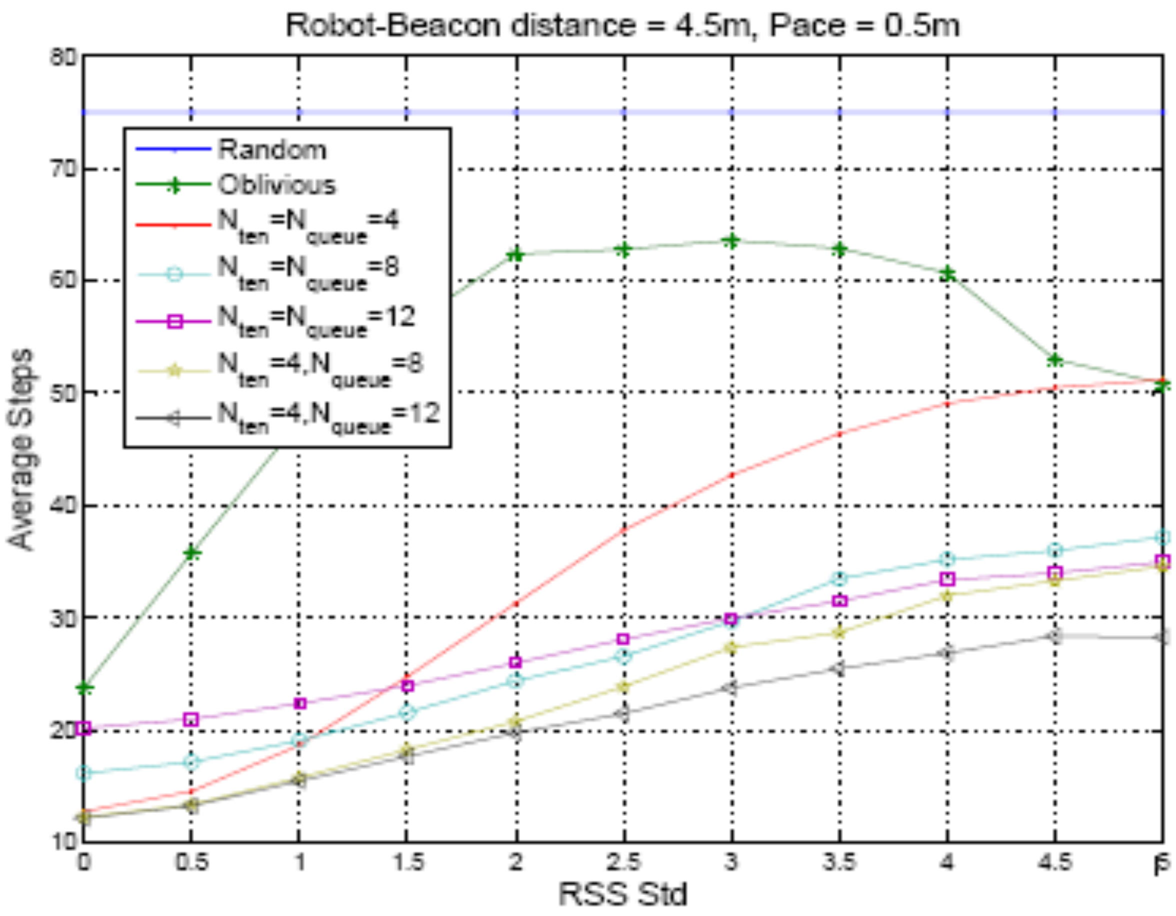

- MLE
  - Us
    -

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Video
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Dynamic targets tracking

- **Global team coordination to**
  - Maximize the **quality of the sensing** (minimum co-variances)

$$J_{Sense} = det(\mathbf{P}_{fused}) = det(\sum_{i}^{M} \mathbf{R}_i^{-1})^{-1}$$

  - Maximize the **connectivity** (max Signal-to-noise ratios ≈ k/d^2)

$$J_{Com} = \sum_{i=1, j=i+1}^{i=M-1, j=M} \frac{1}{SNR_{ij}}$$

  - Maximize **area coverage** (minimum uncovered area)

$$J_{Cov} = -\frac{A_{1-covered}}{A_{tot}}$$

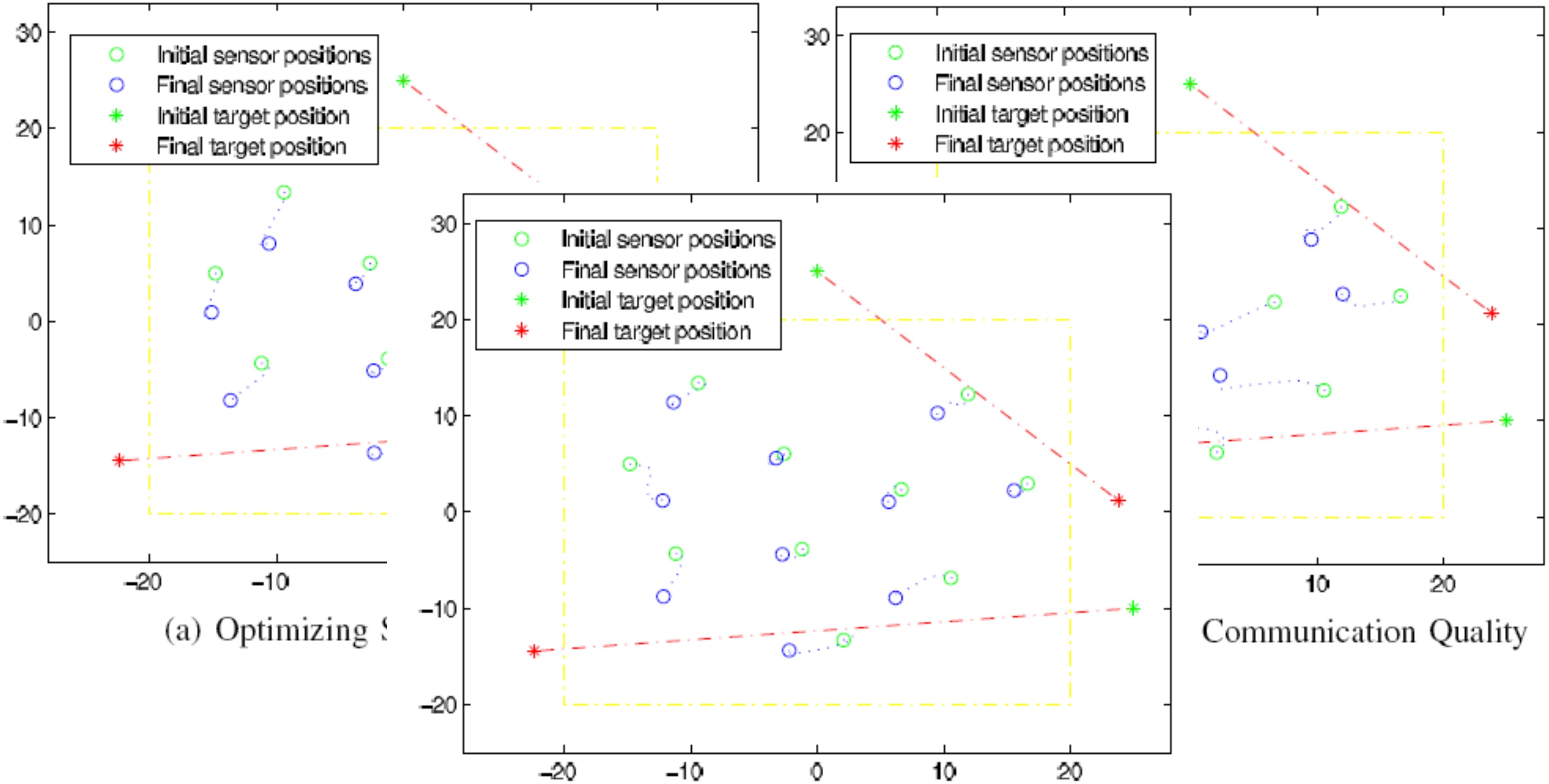
- Use **gradient descent** to find direction to move in a distributed way (motion vectors)

$$\mathbf{u}_i = \mathbf{u}_{Sense,i} + \mathbf{u}_{Com,i} + \mathbf{u}_{Cov,i}$$

- All computations based on the **nodes positions**

Hongbin Li, Luis Almeida, Youxian Sun. Dynamic Target Tracking with Integration of Communication and Coverage using Mobile Sensors. IECON 2009 – IEEE Conf. on Industrial Electronics. Porto, Portugal. Nov 3-5, 2009.

Dynamic targets tracking



(a) Optimizing S

Communication Quality

(c) Optimizing Sensing, Communication and Coverage Quality

Conclusion

- Cooperation among robots requires wireless communication
- Interference, errors, multi-path fading, attenuation lead to **poor coverage of real-time assumptions**
  - **Adaptive and reconfigurable mechanisms** are particularly suited to provide **graceful degradation**
- **Synchronization to reduce collisions** is worthwhile
  - Particularly, for **periodic traffic** and **high medium utilization**
  - combining **TDMA** as overlay protocol over **CSMA-CA** technologies **reduces the synchronization precision** requirement, helps **coping with interfering traffic** and **reduces packet losses**
- The **RSSI** can provide **support to team-level functionality**
  - Such as **relative localization** and **navigation**

Conclusion

- A few open issues ...
  - Using an **AP** (possibly mobile) versus **fully ad-hoc** mode
  - Switching **synchronization on/off** depending on **medium load**
  - Faster and efficient **topology tracking** to
    - Cope with higher mobility
    - Support a better combination of reactive and proactive routing
  - **Better processing of the RSSI** to improve its usability
  - Applicability of **new RF-ranging** devices
  - **Team coordination** methods that...
    - Cope with **limitations of the wireless** communication
    - **Manage team connectivity** (maybe not needed permanently)
      - Manage clustering in these dynamic networks
    - **Optimize the global use of the team resources**
      - energy, computing, specific subsystems, ...

Announcement

A simulation competition, you just have to write the robots program!

- **CyberRescue@RTSS2009**
  - **http://robot.unipv.it/cyberrescue-RTSS09/**
- *Control the team of 5 robots*
  with ***ad-hoc communication capabilities***
  to reach the victim in the least time