Enabling IPv6 in constrained networks

Enzo Mingozzi
Associate Professor @ DII – University of Pisa
enzo.mingozzi@unipi.it

Outline

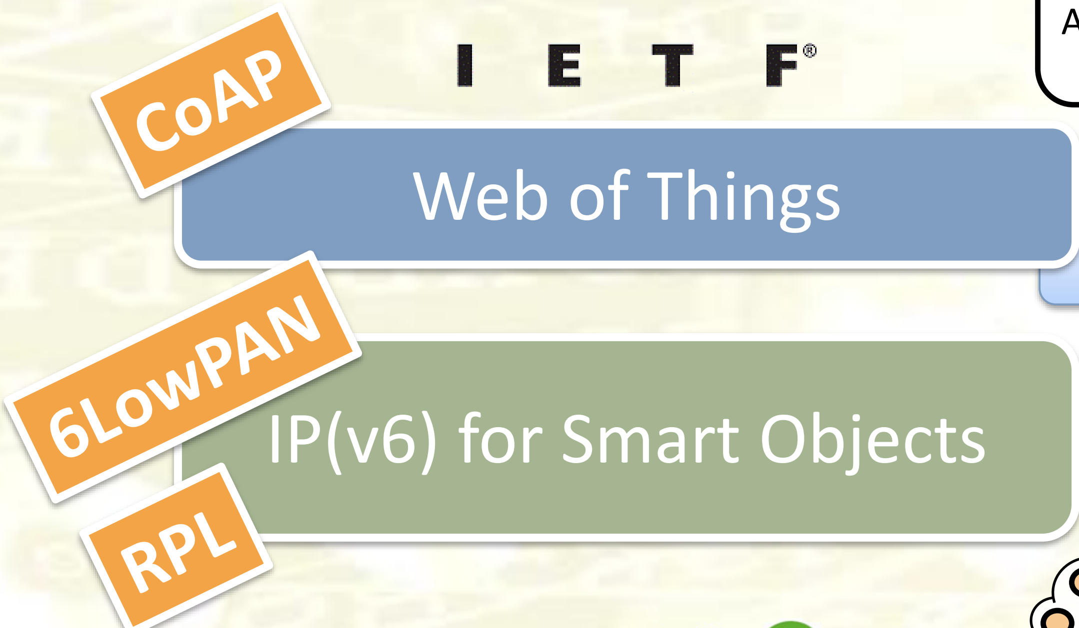
- **Intro**
  - the IETF vision about Low Power and Lossy Networks
- **6LowPAN/6lo**
  - Motivation and (brief) overview
- **The RPL routing protocol**
  - Motivation and protocol overview
  - The Trickle algorithm
  - Link Quality Estimation
- **The Constrained Application Protocol (CoAP)**
  - Motivation and protocol overview
  - QoS support with asynchronous communication

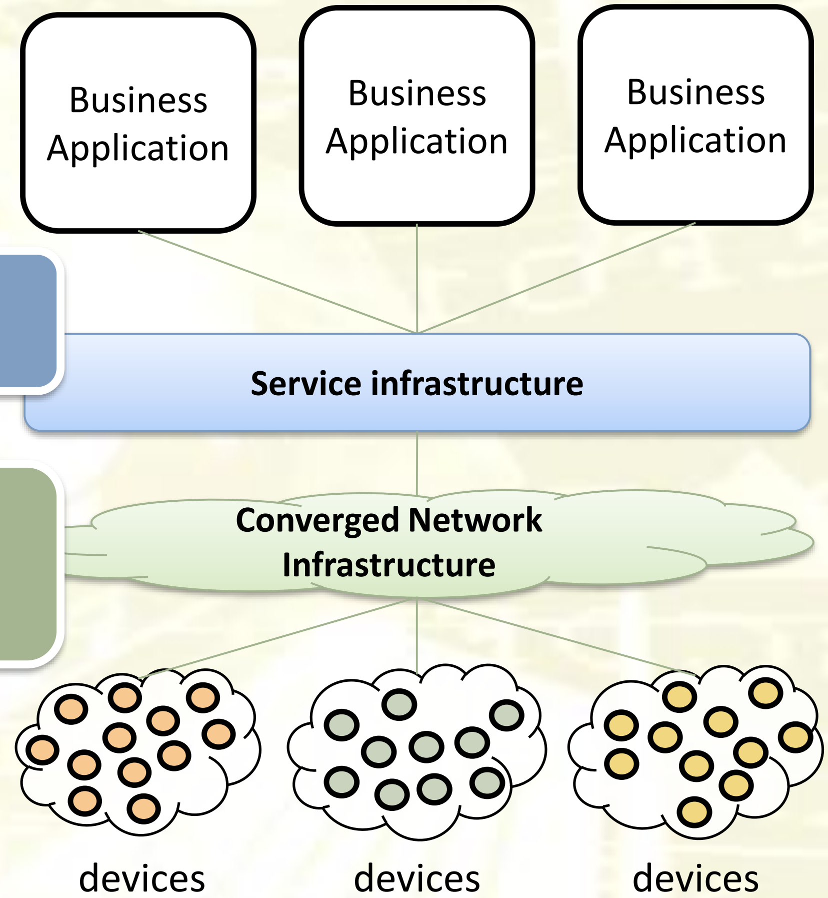
IoT: new opportunities …

… but also new challenges

- Scalability
  - Number of nodes in the system
  - Amount of data generated by each node
- Diversity of applications
- Diversity of communication technologies
  - Potentially lossy if wireless
- Interoperability
- Low-power consumption
- Lifetime
- Context-awareness
- Security, trust
- …

How to achieve? The IETF vision





- **IP for Smart Objects**
  - Set of IPv6-based solutions have been defined by IETF (6LowPAN, ROLL, COAP)
  - Supported by the IPSO Alliance

Distributed intelligence & actions across standardized networks & interfaces

IP(v6) for IoT – Why?

Inter-operability

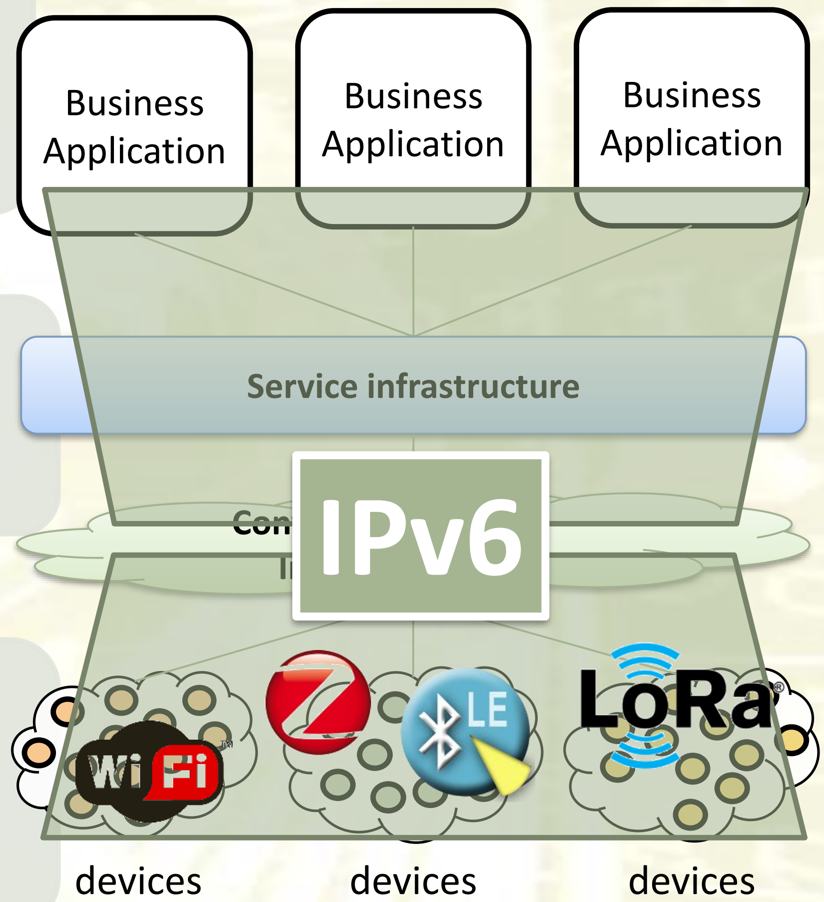
- **Layered** approach to allow independence of underlying technologies

Scalability

- Survived the Internet **evolution**
- Unique (IPv6) **addressing**
- Direct support for **self-configuration** and management

End-to-end

- **No multi-protocol** intermediate gateways
  - Expensive/difficult to manage
  - Lack of QoS end-to-end
  - Security holes



IPv6 for IoT – What?

- Packet **adaptation**
- Network **auto-configuration** procedures (neighbor discovery)
- **Routing** protocols accounting for specific constraints
  - Energy-efficiency
  - Limited resources on each node (memory, computation)
  - Lossyness of the communication media
- Application protocols enabling **RESTful** architectures

Outline

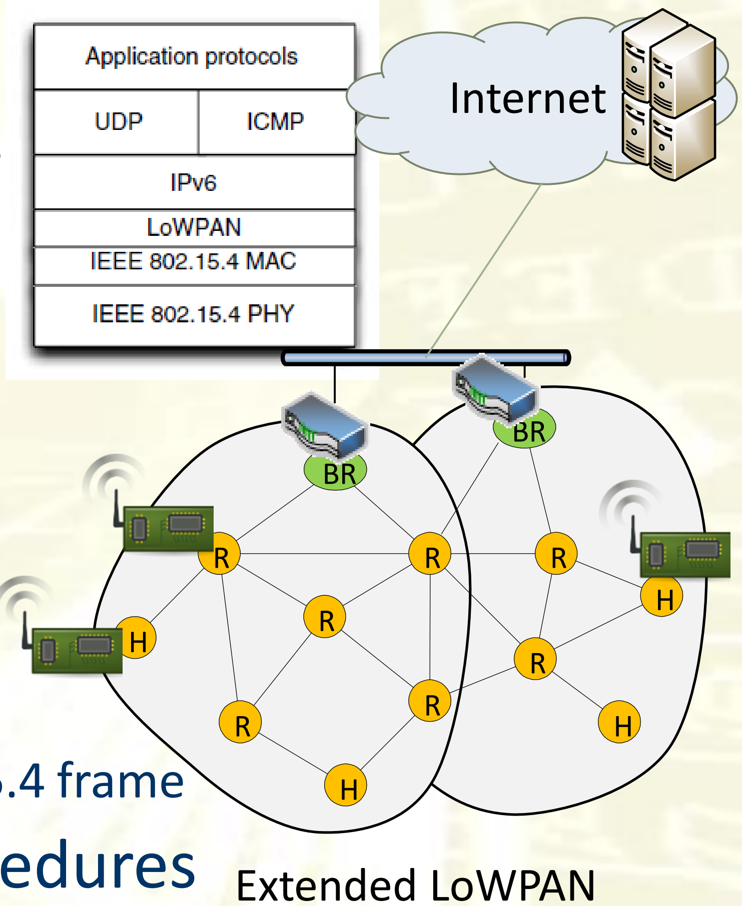
- **Intro**
  - the IETF vision about Low Power and Lossy Networks
- **6LowPAN/6lo**
  - Motivation and (brief) overview
- **The RPL routing protocol**
  - Motivation and protocol overview
  - The Trickle algorithm
  - Link Quality Estimation
- **The Constrained Application Protocol (CoAP)**
  - Motivation and protocol overview
  - QoS support with asynchronous communication

Target link-layer technologies

- **Low power and Lossy Networks (LLN)**
  - consist of constrained nodes (with limited processing power, memory, and sometimes energy when they are battery operated or energy scavenging)
  - lossy links, typically supporting only low data rates, that are usually unstable with relatively low packet delivery rates
  - may potentially comprise up to thousands of nodes
- Wireless
  - Wireless Personal Area Networks (IEEE 802.15.4, ZigBee, Bluetooth LE, ITU-T G.9959, DECT LE)
  - Low-power WiFi (GainSpan, IEEE 802.11ah (WiFi Halow))
  - Low-power WANs (LoRaWAN, Sigfox)
- Wired
  - Power Line Communication (PLC)

IETF 6LoWPAN WG

- **IPv6 over Low-power Wireless Personal Area Networks**
  - started 2005, concluded 2014
  - rfc4919, rfc4944, rfc6282, rfc6775, …
- General architecture for 6LoWPANs
- **Adaptation** layer for devices connected by IEEE 802.15.4
  - Efficient header **compression**
    - IPv6 base and extension headers, UDP header
  - **Fragmentation**
    - 1280-byte IPv6 MTU → 127-byte 802.15.4 frame
- Optimized **neighbor discovery** procedures



IETF 6lo WG

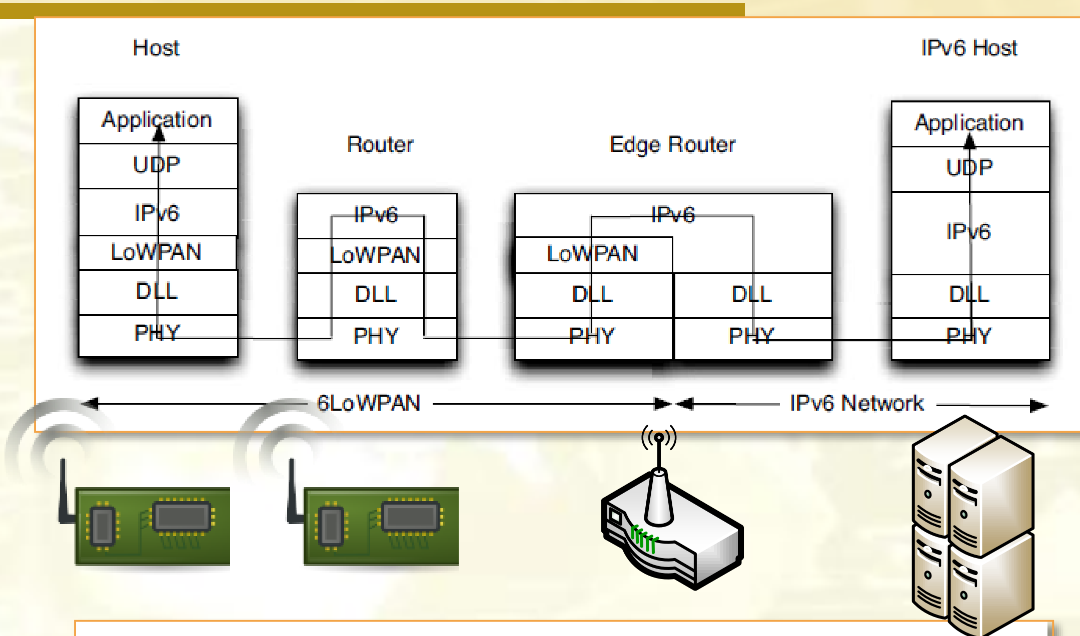
- **IPv6 over Networks of Resource-constrained Nodes**
  - started 2013, ongoing
  - to facilitate **IPv6 connectivity over constrained node networks** with the characteristics of
    - limited power, memory and processing resources
    - hard upper bounds on state, code space and processing cycles
    - optimization of energy and network bandwidth usage
    - lack of some layer 2 services like complete device connectivity and broadcast/multicast
- **rfc7668**: **IPv6 over BLUETOOTH(R) Low Energy**

Outline

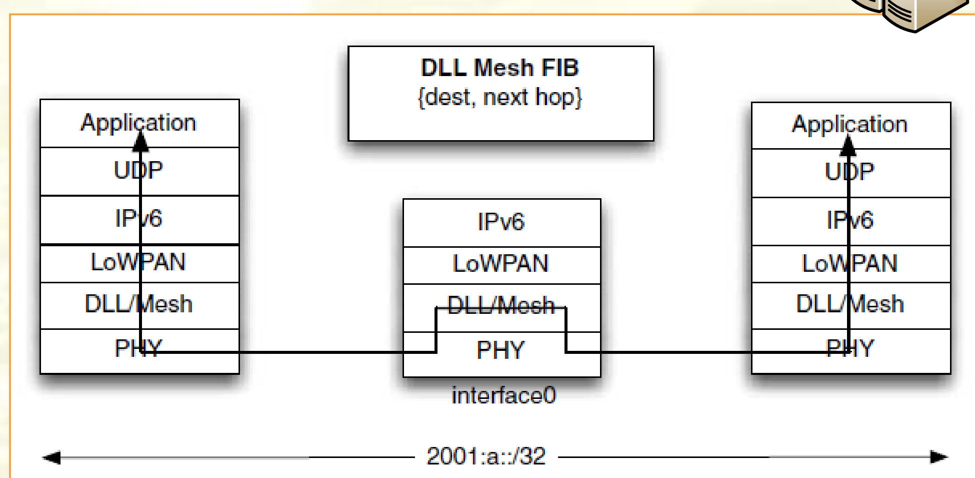
- **Intro**
  - the IETF vision about Low Power and Lossy Networks
- **6LowPAN/6lo**
  - Motivation and (brief) overview
- **The RPL routing protocol**
  - Motivation and protocol overview
  - The Trickle algorithm
  - Link Quality Estimation
- **The Constrained Application Protocol (CoAP)**
  - Motivation and protocol overview
  - QoS support with asynchronous communication

Multi-hop forwarding in LLNs

- Route-Over



- Mesh-Under



ROLL WG

- RPL (Routing Protocol for Low-power and Lossy Networks)
- Distance Vector algorithm
  - Destination–oriented DAG formation
  - Constrained routing based on multiple metrics
- A Layer-3 routing protocol!

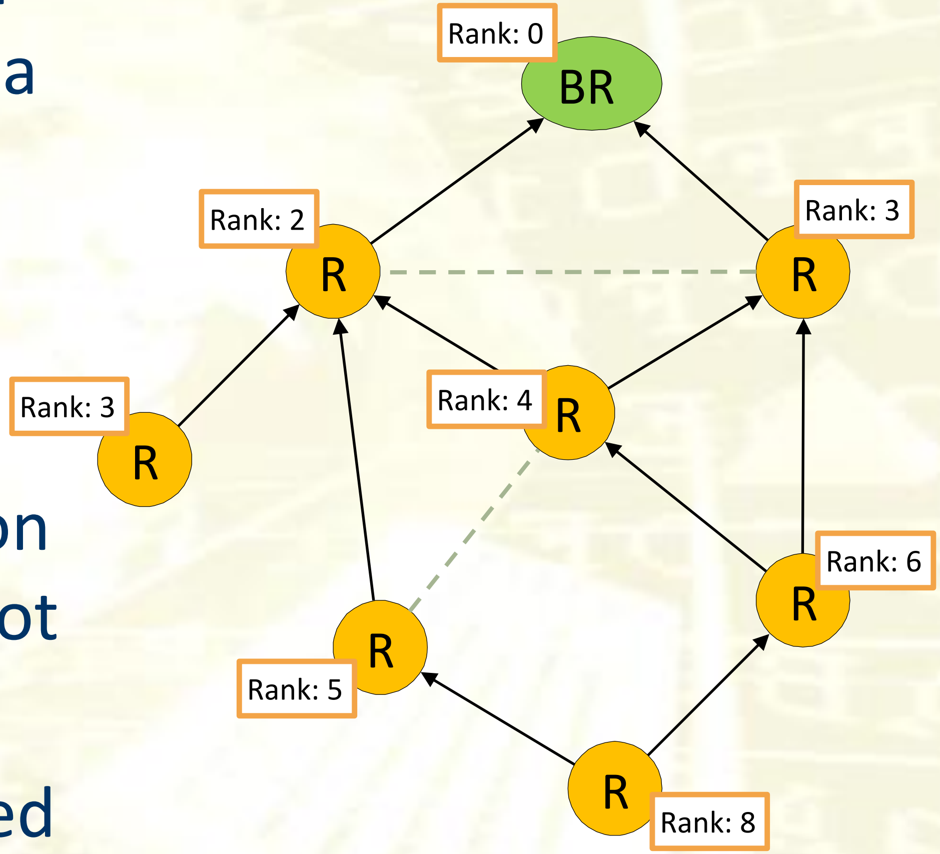
6LowPAN and RPL adopted by ZigBee/IP

Routing principles

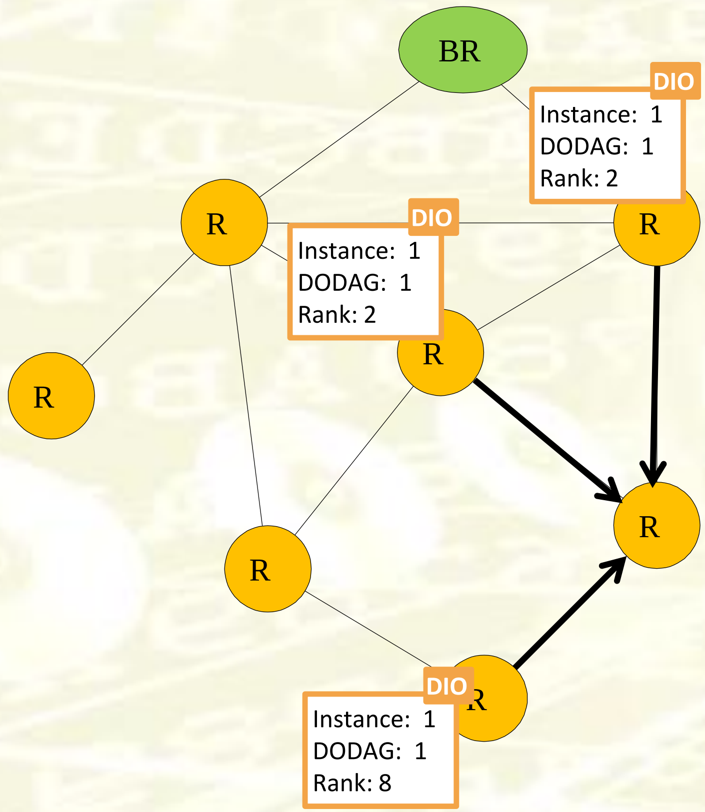
- Routes are optimized for data delivery to a selected number of destinations (**MultiPoint-to-Point forwarding**)
  - RPL builds a ***Destination-Oriented Directed Acyclic Graph*** *(DODAG)* on top of the multiple L2 broadcast domains
  - Routes are then computed based on a **distance vector** routing protocol

Node rank

- A scalar representation of the **node location** within a DODAG instance
  - Not meant to represent a path cost
- The rank **must** monotonically decrease on each path towards the root
- Computed based on routing metrics established by an **Objective Function**

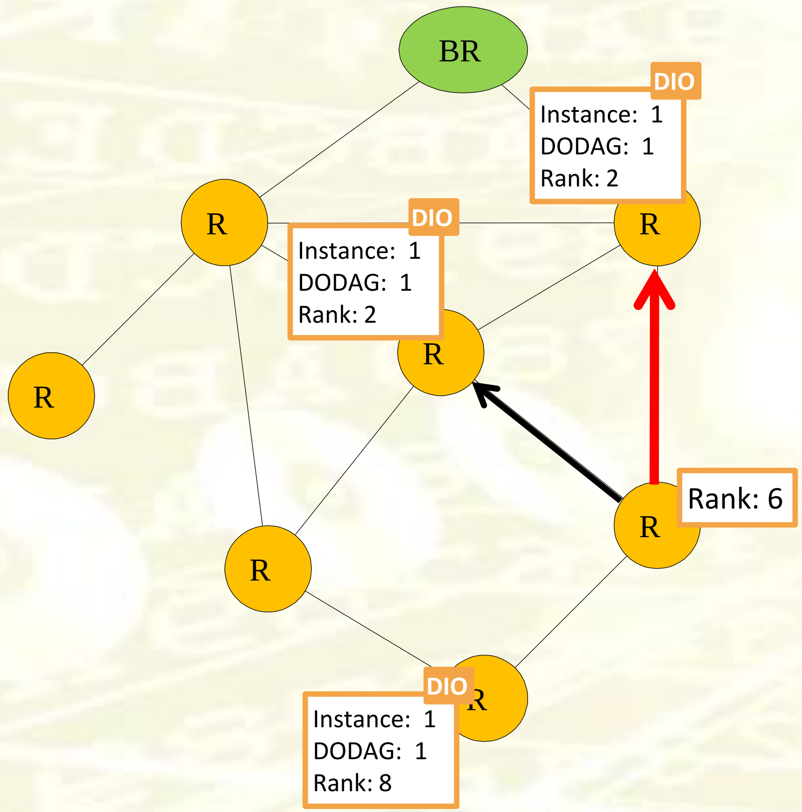


DODAG formation



- Presence is advertised by broadcasting **DIO** (**DODAG Information Object**) messages
  - Including the rank of the sender
- DIO advertising is started by the DODAG **root**
- RPL nodes listen to DIO messages to learn the set of nodes in the one-hop neighborhood

DODAG formation (cont.)



- As soon as the first DIO message is received, the node **joins** the DODAG
  - It computes its own rank based on received information
  - It start transmitting its own DIO messages
- The process is **dynamic**
  - A **set of parents** is maintained dynamically while receiving DIO messages
  - A **preferred parent** is selected

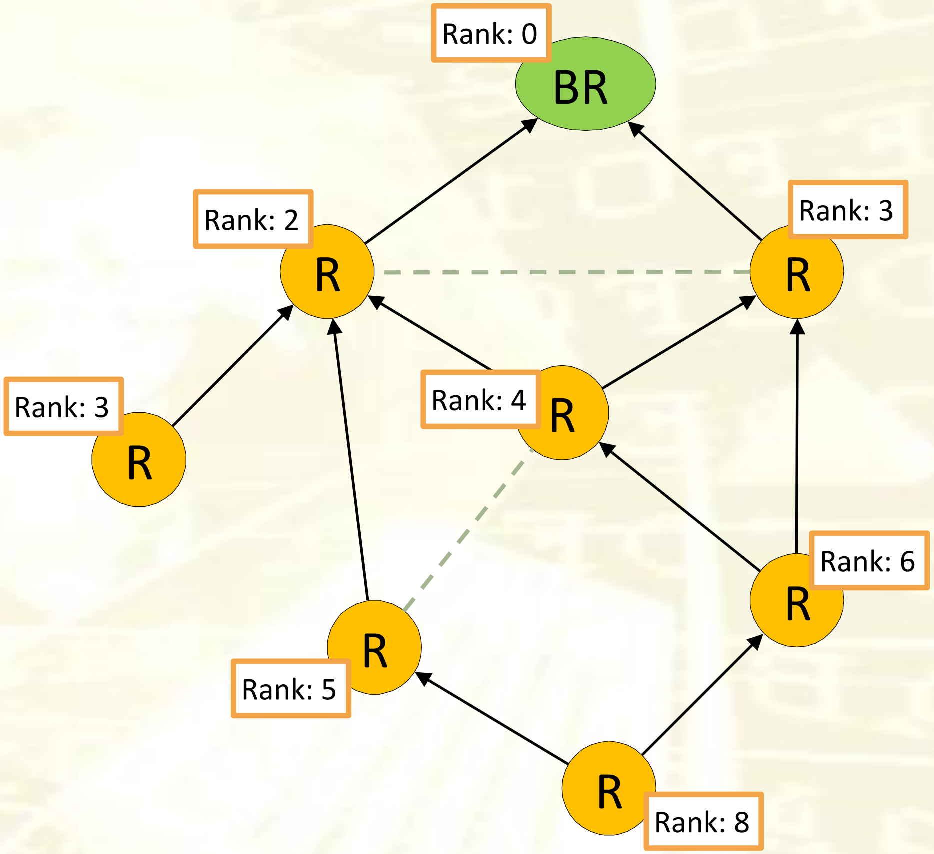
Objective Functions

- The **Objective Function** (OF) defines what **metrics/constraints** to use for finding minimum cost paths in a given RPL instance

- More in general, the OF defines
  - How to **compute the path cost**
  - How to **select parents** (when, who, how many)
  - How to **compute the rank**
  - How to **advertise the path cost**

Routing Metrics/Constraints

- **Node** metric/constraints
  - Node state and attributes
  - Node energy (power mode, remaining lifetime)
  - Hop count
- **Link** metrics/constraints
  - Throughput
  - Latency
  - Link reliability
  - Link colors



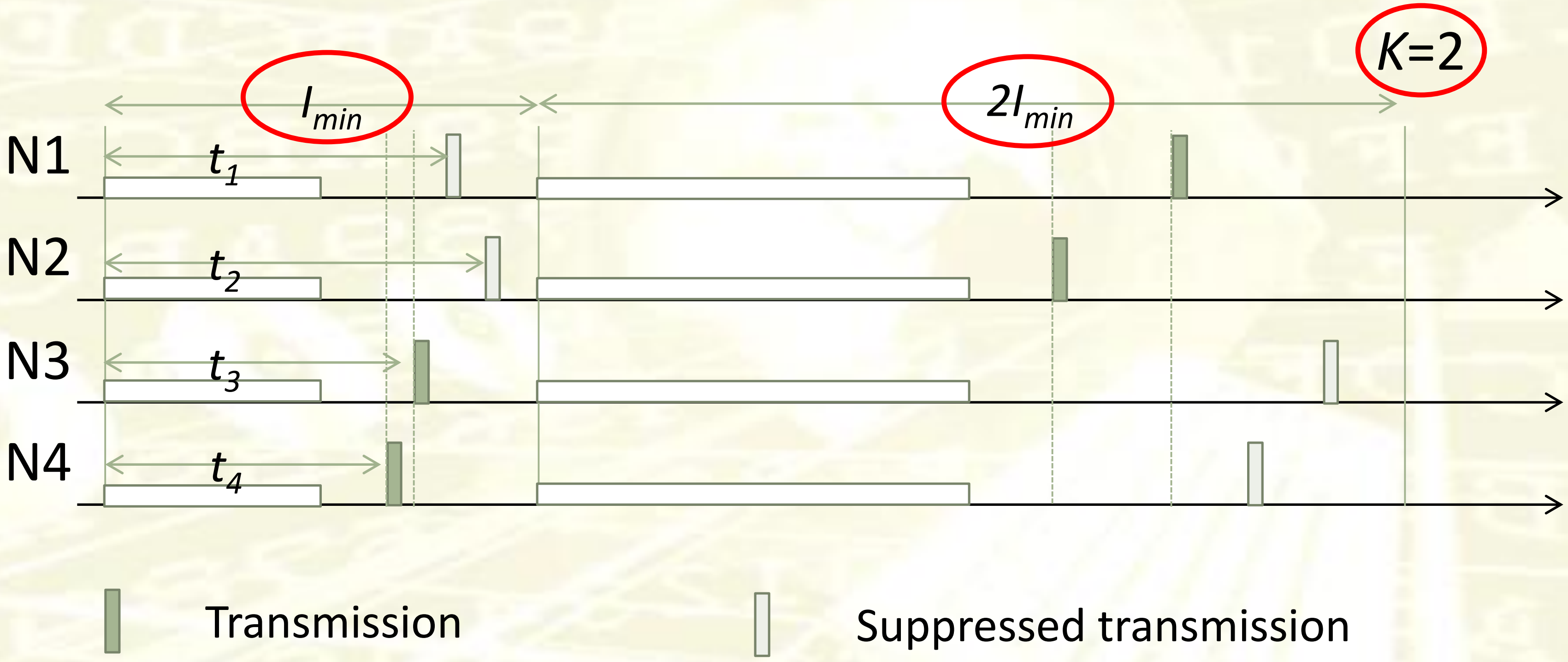
DIO message broadcasting

- DIO messages are periodically re-broadcast to maintain routing information up to date
  - **Control flooding**, but
  - **Fast propagation when needed** (e.g., routing loops)

- DIO broadcasting is regulated by the ***Trickle* algorithm** (rfc6206)
  - Broadcast suppression
  - Adaptive periodicity

DIO message broadcasting

- DIO broadcasting is regulated by the *Trickle* algorithm (rfc6206)



Performance evaluation

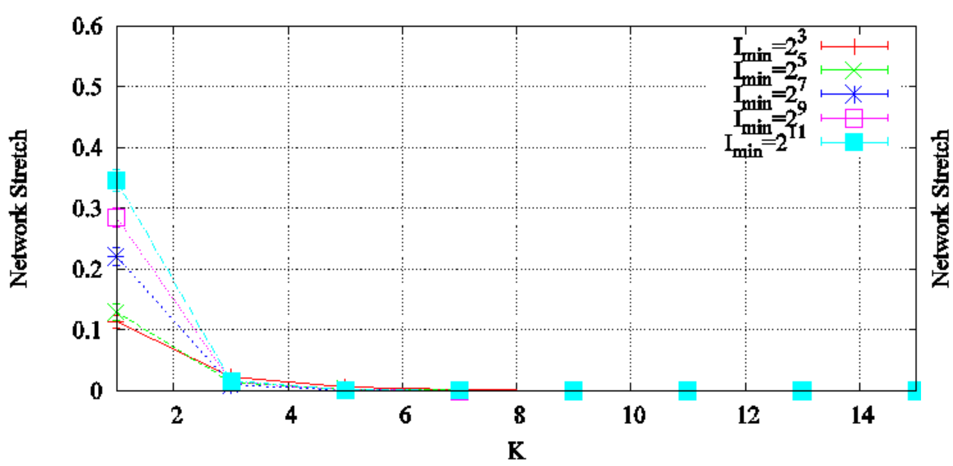
- Scenario
  - Topology: 20x20 grid (10m node distance)
  - One instance, one DODAG
  - **ETX** routing metric (ideal)
  - I_{min} and k variable
- Computer simulation
  - 200 replicated experiments

C. Vallati, E. Mingozzi, **Trickle-F: fair broadcast suppression to improve energy-efficient route formation with the RPL routing protocol,** *Proceedings of the 3rd IFIP Conference on Sustainable Internet and ICT for Sustainability (SustainIT 2013)*, Palermo, Italy, October 30-31, 2013.

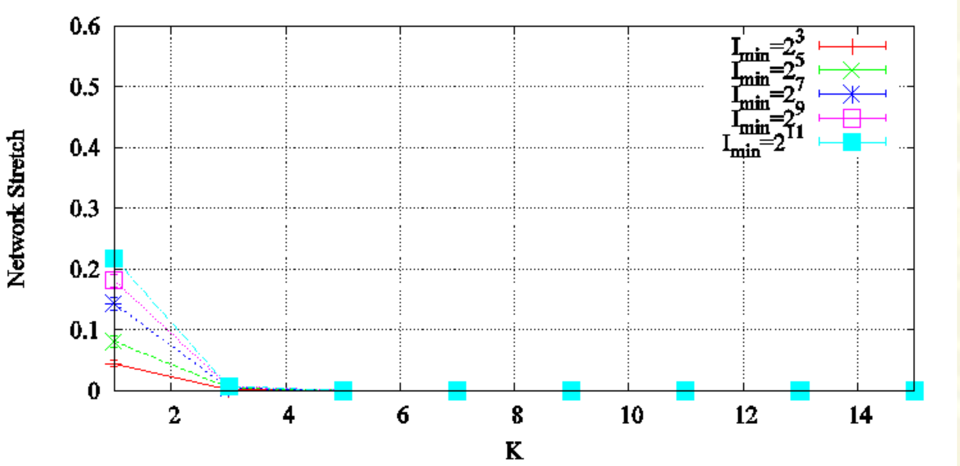
Performance evaluation

- How much good are paths to the BR?
  - *Path stretch*: Path actual cost *minus* Best path cost
  - *Network stretch*: Fraction of nodes whose path stretch is greater than 1

~17 min

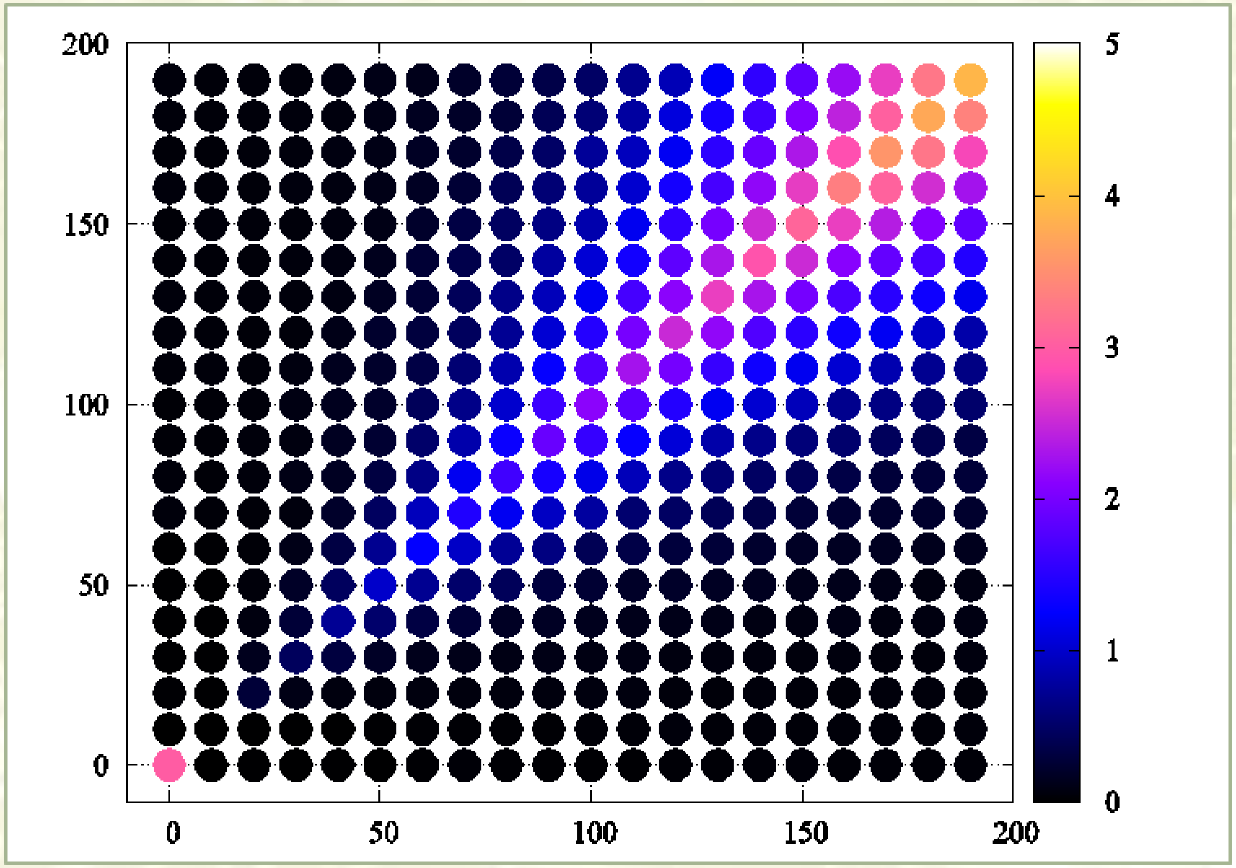


~1677 min



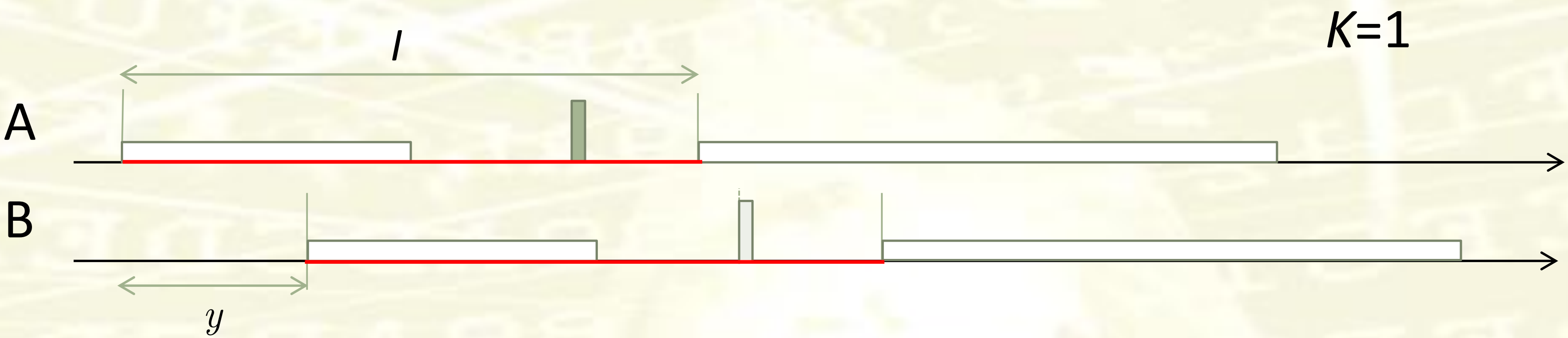
Performance evaluation

- Distribution of path stretch values among nodes



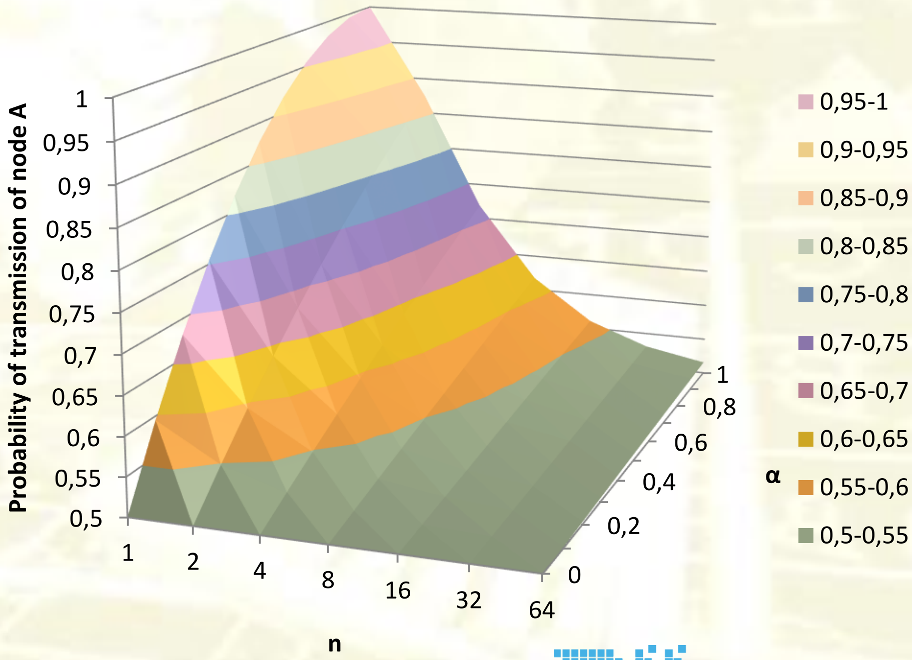
Trickle – analysis

K=1



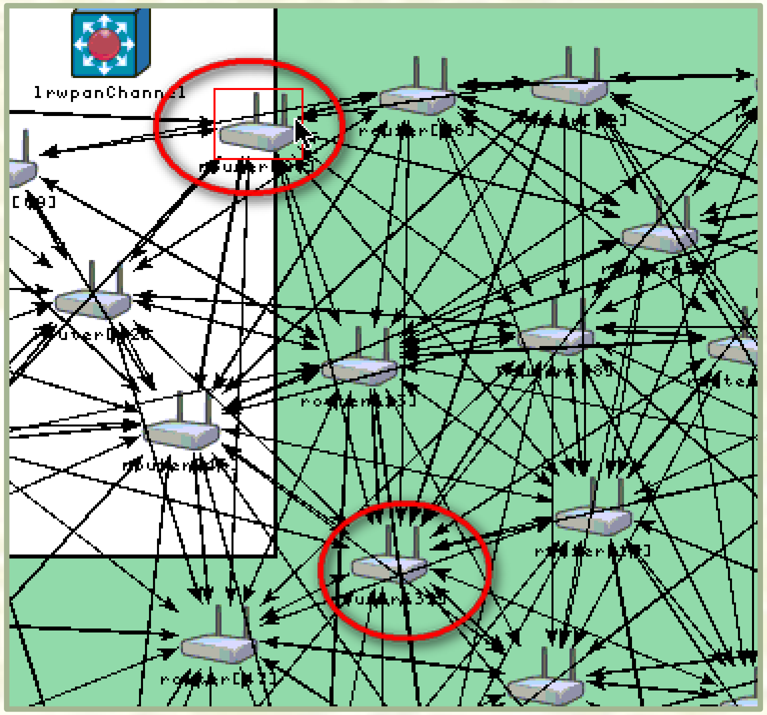
$$\alpha = \frac{y}{I/2}, 0 \le \alpha \le 1$$

$$P\left(A\, tranmits\right) = 1 - \frac{1}{2}\left(1 - \frac{\alpha}{n}\right)^2, n = 1, 2, 4, 8, 16, \ldots$$



Affected scenarios

- The impact is higher on route optimization
  - Who is transmitting matters more!

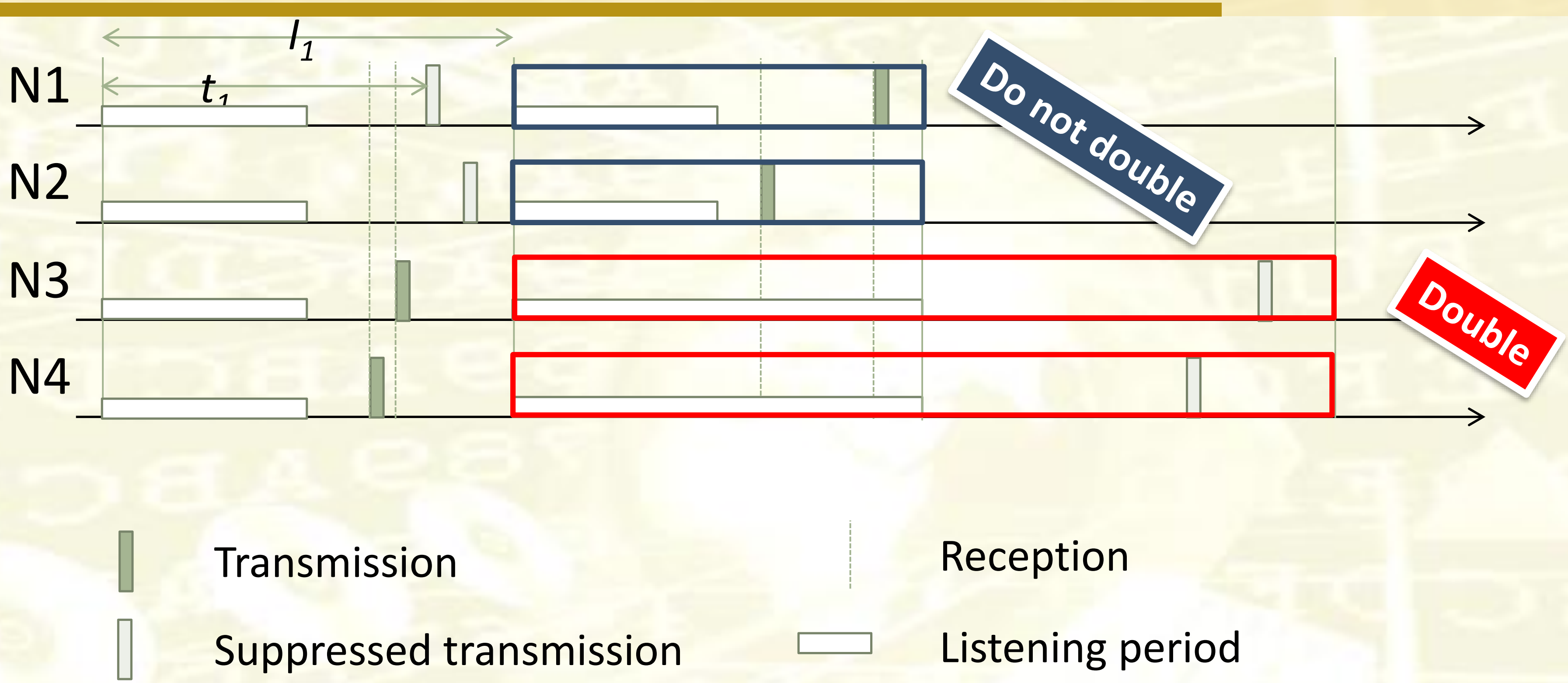


- I = 7, K = 5

- Router 31 (bottom) only sends 3 DIO messages in 6000 s

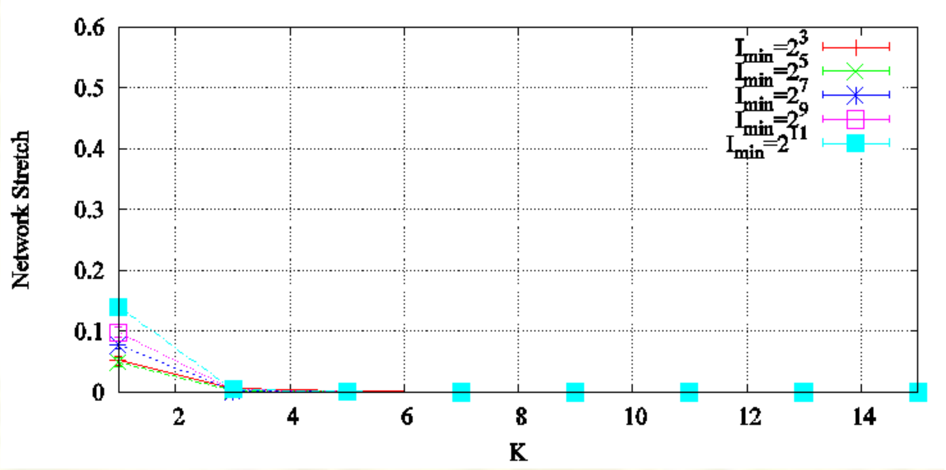
- Only the third DIO arrives correctly to router 28 (up), which then changes its own preferred parent

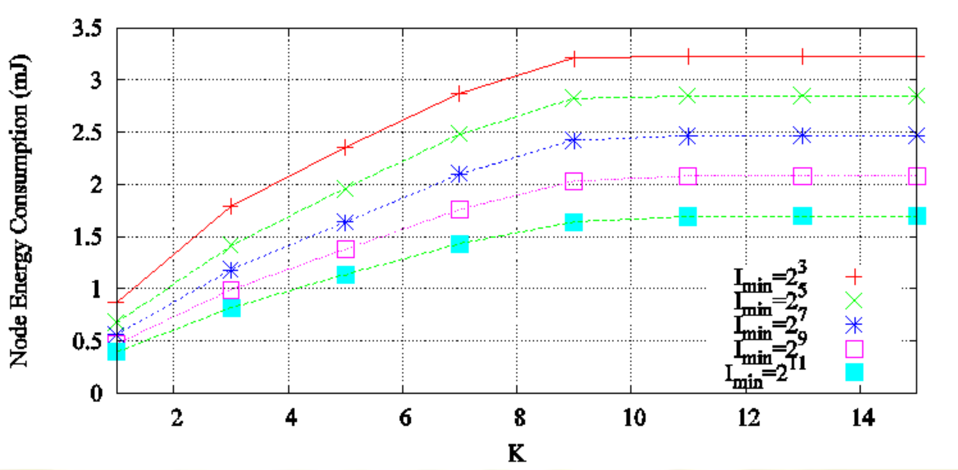
Countermeasures? Trickle-F



Performance evaluation

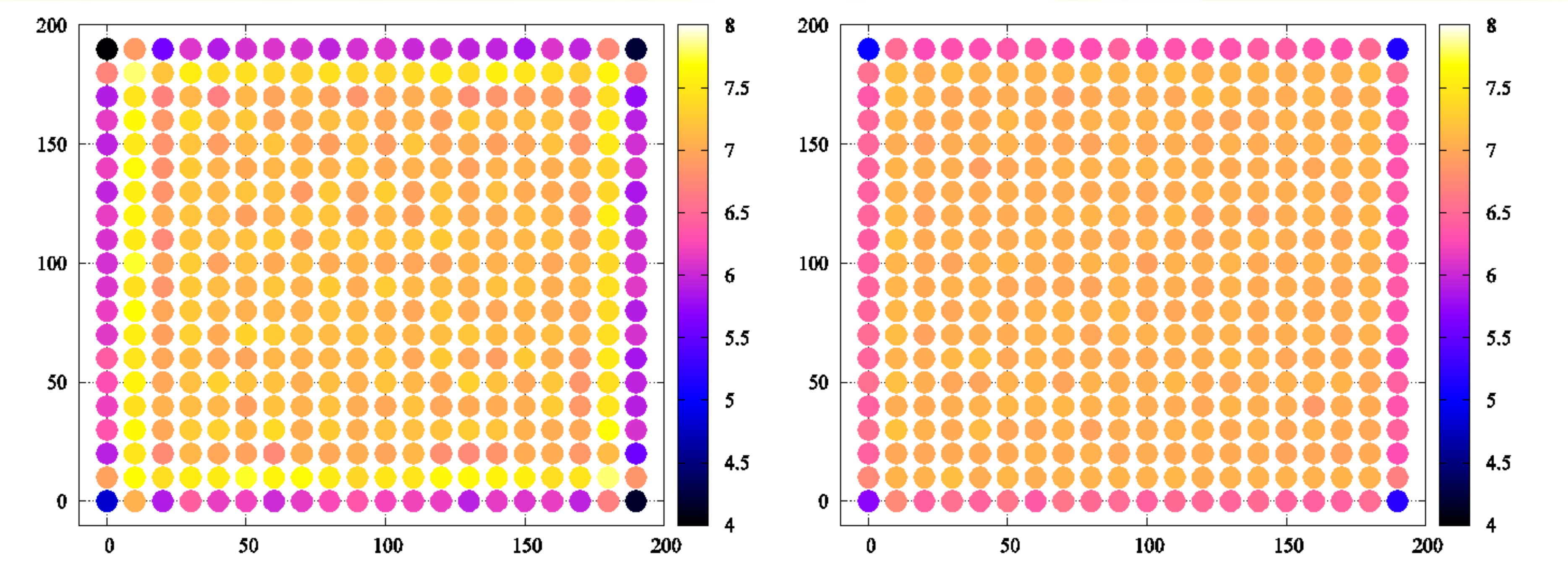
- Better routes on average at the same energy cost





Performance evaluation

- More fair distribution of suppressed transmissions (apart from border effects)



Routing metrics in RPL

- Rank computation may be based on dynamic metrics
  - Objective Function Zero (OF0) [rfc6552] recommends the use of dynamic link properties such as **ETX (Expected Transmission Count)**
- **Topology stability** is highly dependent on the **accuracy of Link Quality Estimation (LQE)**

Link monitoring for LQE

- **Link monitoring** defines a strategy to have traffic over the link allowing for link measurements
  - **Passive monitoring** exploits existing data traffic without incurring additional communication overhead
    - monitoring idle links is not possible without generating additional traffic
  - **Active monitoring** requires nodes to monitor links to their neighbours by sending probe packets
    - Probe packets are generally sent periodically but event-based approaches are also possible
    - The lower the probing rate, the higher the energy efficiency but the lower the accuracy, especially for links with frequent link-quality fluctuations

	Pros	**Cons**
Unicast probing	• accurate link measurements	• overhead increases with the number of neighbours • slow reaction to topology changes
Broadcast probing	• simple to implement • less overhead • multiple measurements	• no link-level acknowledgments • differences between unicast and broadcast link properties

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

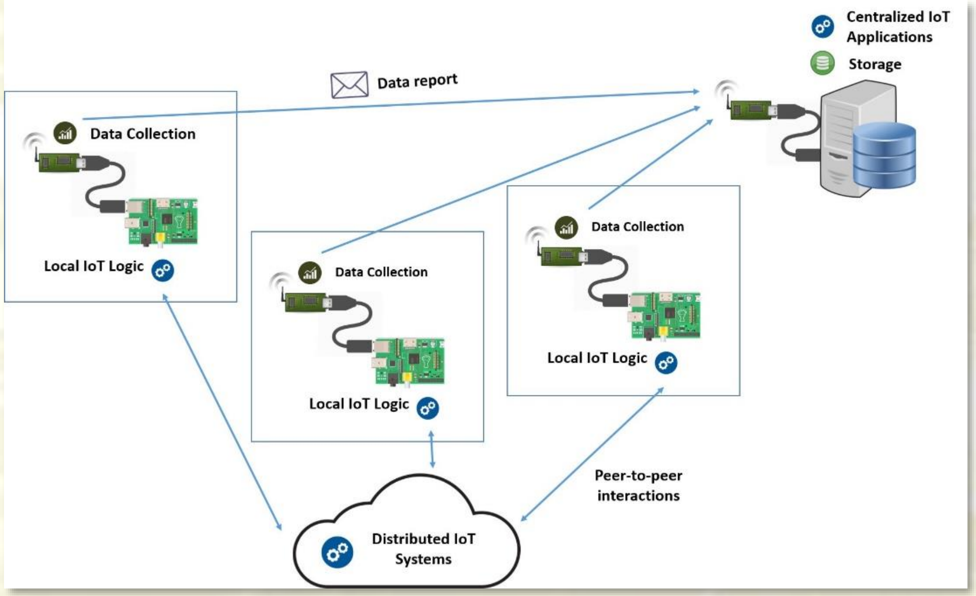
LQE in RPL?

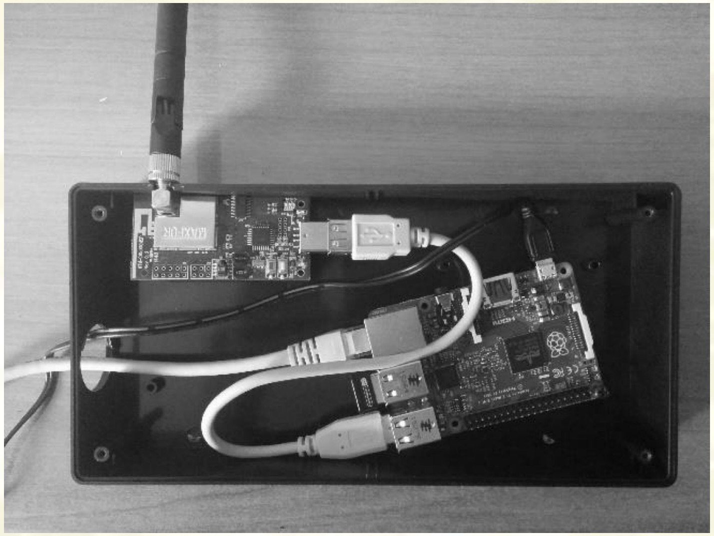
- RPL DIOs are **not transmitted on a regular basis** (Trickle), hence they cannot be exploited for link monitoring
- Alternatively, **use <u>data</u> traffic** to measure link quality

- Example: LQE in **Contiki OS v3.0** RPL implementation
  - (default) passive monitoring with optimistic link estimation
    - A node can only assess the quality towards the current preferred parent
    - To test all potentially good neighbours, optimistic link estimation is used (i.e., prefer recent discovered neighbours) -> implies that the next hop frequently changes
  - (optional) active monitoring with periodic unicast probes (DIOs) to the nodes in the parent set

Experimental testbed @DII

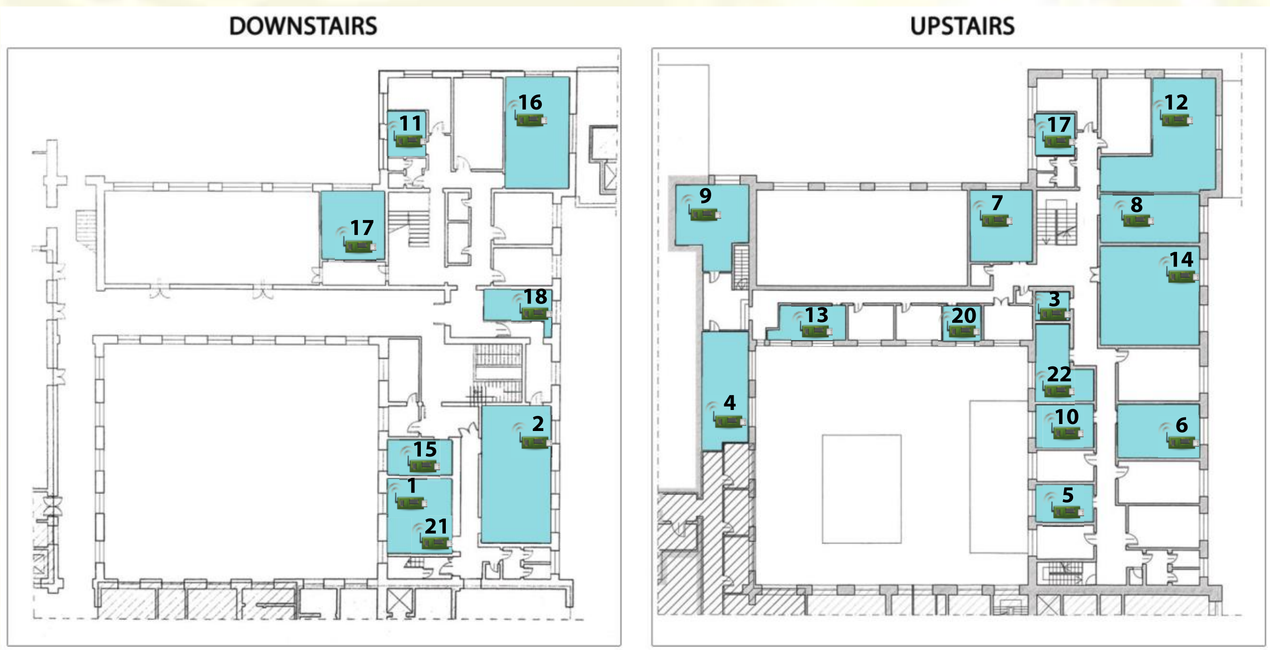
- For troubleshooting and data collection, all the nodes are connected to a dedicated backbone network using the Raspberry PI Ethernet adapter
  - **TelosB** (MSP430 microcontroller, Texas CC2420 IEEE 802.15.4 wireless transceiver, 5dBi external antenna
  - **Raspberry Pi 2** Model B (ARM Cortex-A7 CPU)

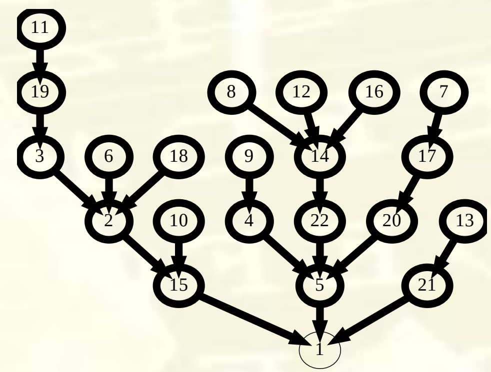




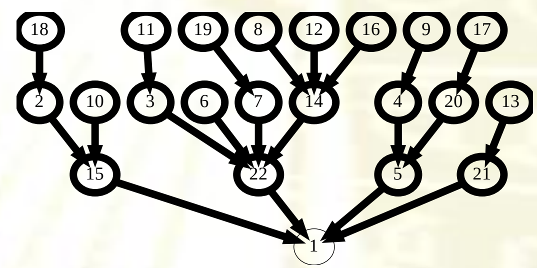
Experimental testbed @DII

- 22 nodes installed in offices and laboratories at DII (two-floor) premises
- Two topologies for different transmission powers (and ranges)





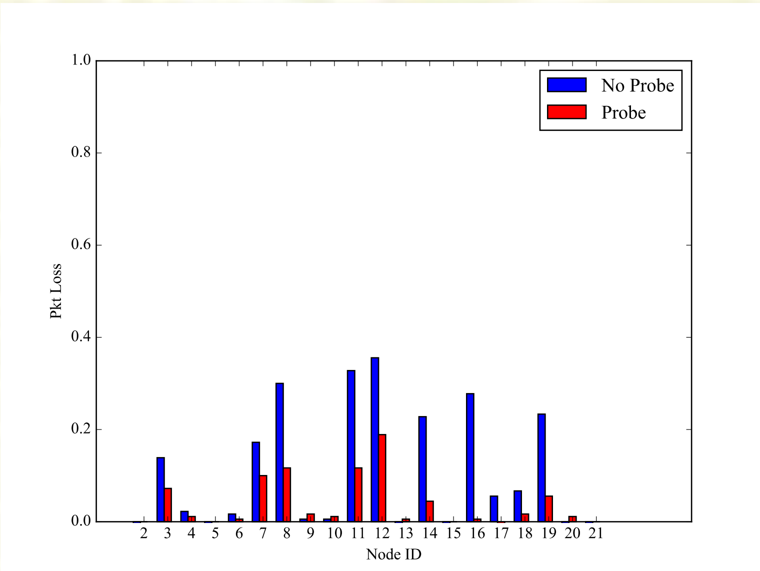
P_{tx}= -7 dBm

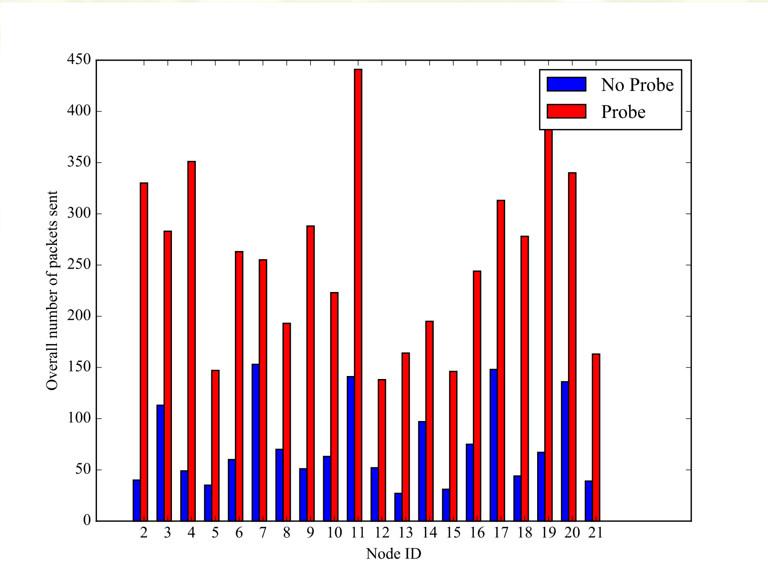


P_{tx}= 0 dBm

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Passive vs. Active LQE in RPL





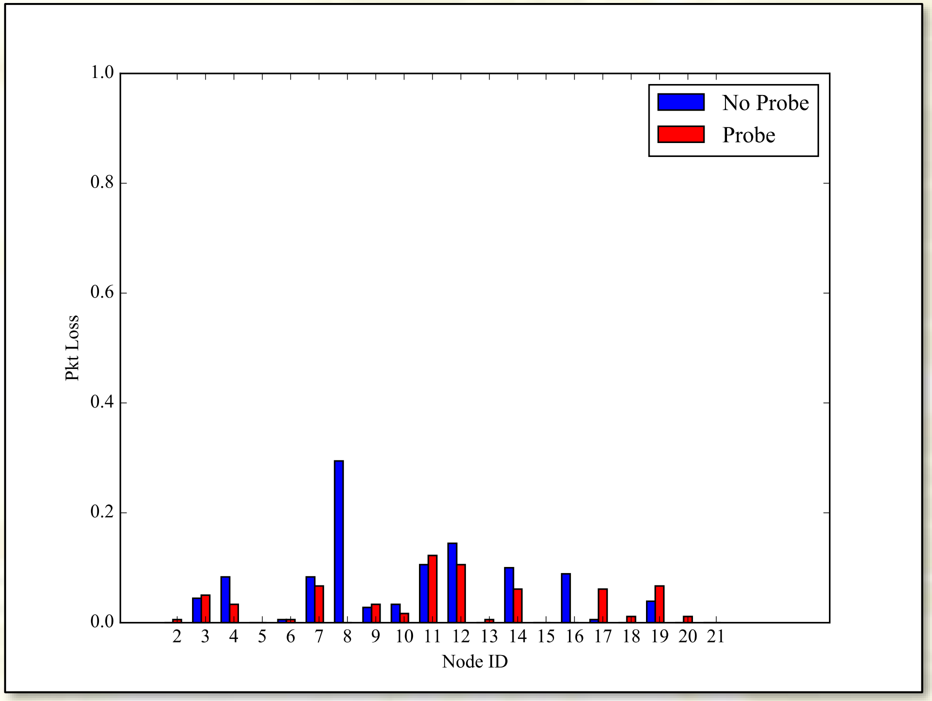
- Active probe mechanism can help many nodes in significantly mitigating the packet loss ratio
- Benefit is dependent on the topology (central nodes benefit more)
- Active probe allows a node to:
  - discover all the neighbours
  - rapidly detect variations in the channel quality

- With active probing more packets are sent by each node

C. Vallati, E. Ancillotti, R. Bruno, E. Mingozzi, G. Anastasi, **Interplay of Link Quality Estimation and RPL performance: an Experimental Study**, Proc. of the 13th ACM Int. Symp. on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (ACM PE-WASUN 2016), Valletta, Malta, November 13-17, 2016.

Passive vs. Active LQE in RPL

- Efficiency of active probing is topology-dependent
- A lower transmission power reduces the number of neighbours for each node, thus reducing the number of potential preferred parent
- There is less margin of improvement



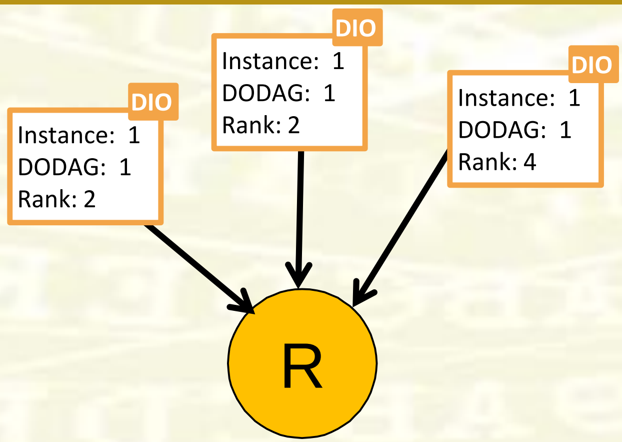
LQE at DODAG formation

- At network formation time, there is **no available estimate** for just discovered links
  - That is, long convergence time before stability while improving the accuracy of link quality estimation

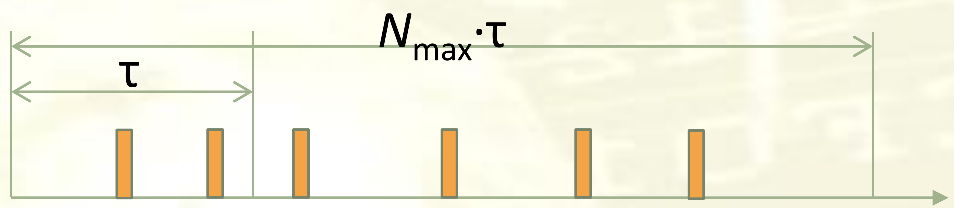
1. Delay joining the DODAG until (at least) one link with minimum quality is found
   - Eventually bounded by a maximum time
2. Introduce a **fast** link quality estimation mechanism at DODAG formation time
   - Possibly, at no or negligible cost from an implementation point of view

E. Ancillotti, R. Bruno, M. Conti, C. Vallati, E. Mingozzi, **Trickle-L^2: Lightweight Link Quality Estimation through Trickle in RPL networks,** *Proceedings of the 15th IEEE Conference on a World of Wireless Mobile and Multimedia Networks (WoWMoM 2014)*, Sydney, AU, June 16-19, 2014.

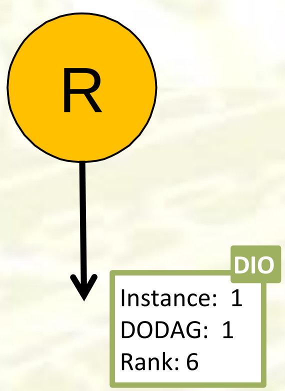
Trickle-L^2

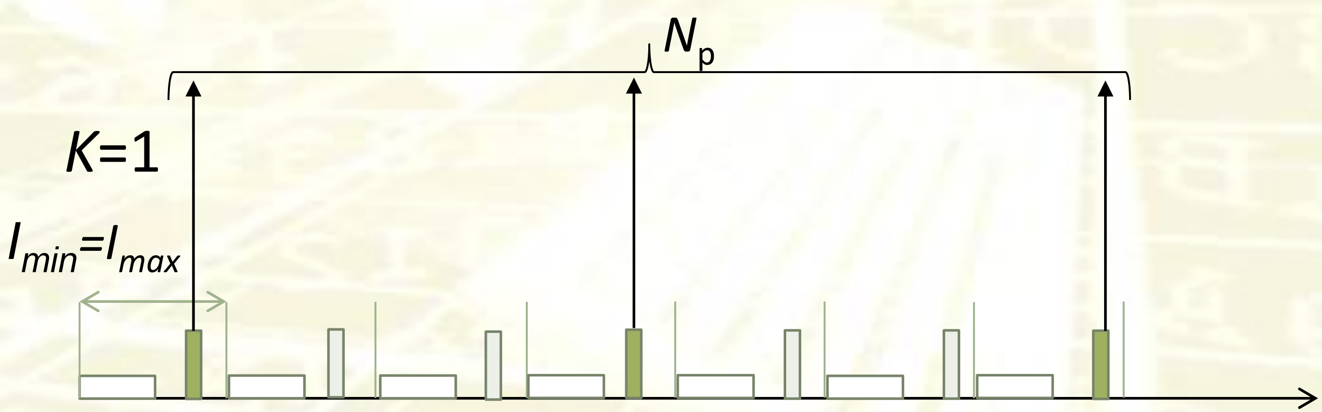


Bootstrap: collect DIO messages and do estimate ETX



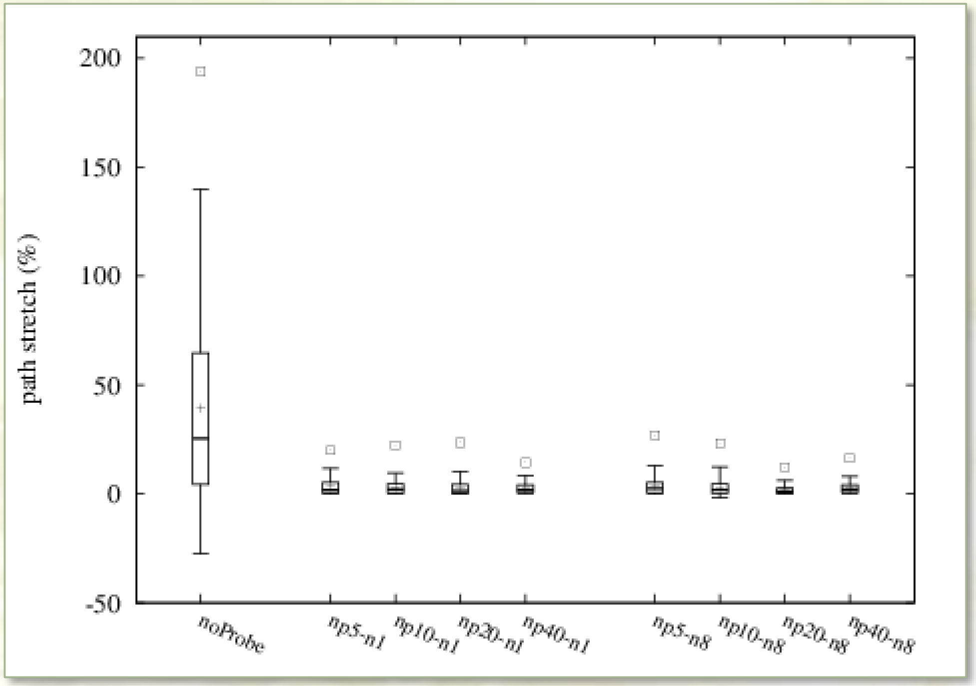
Limited active probing: send DIO messages with sequence numbers





Numerical results

- N_{max} = 1, 8; N_p = 5, 10, 20, 40
- Path ETX stretch over the entire simulation (two hours)



Hybrid approach – RL-Probe

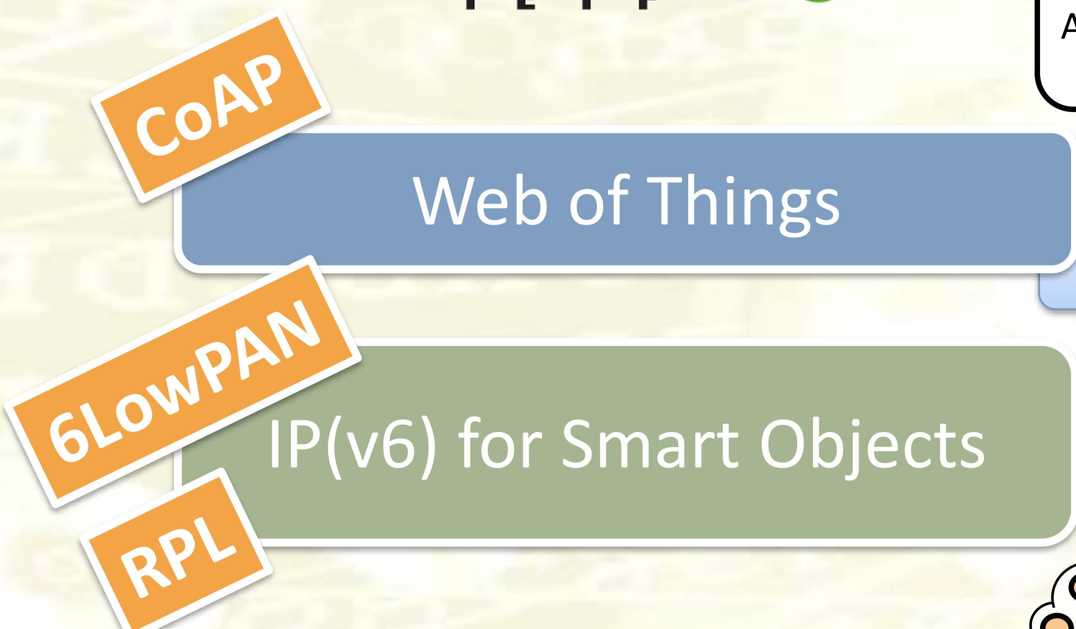
- **Synchronous** active probing
  - Unicast probes with **adaptive frequency** (selected as a result of a Multi-Armed Bandit problem)
  - And different **probing priority** (per neighbour **cluster**), which depends on RPL route maintenance
- **Asynchronous** active probing
  - Broadcast probes for rapid LQE assessment adaptively triggered
    - Isolation of faulty nodes, preferred parent unavailability

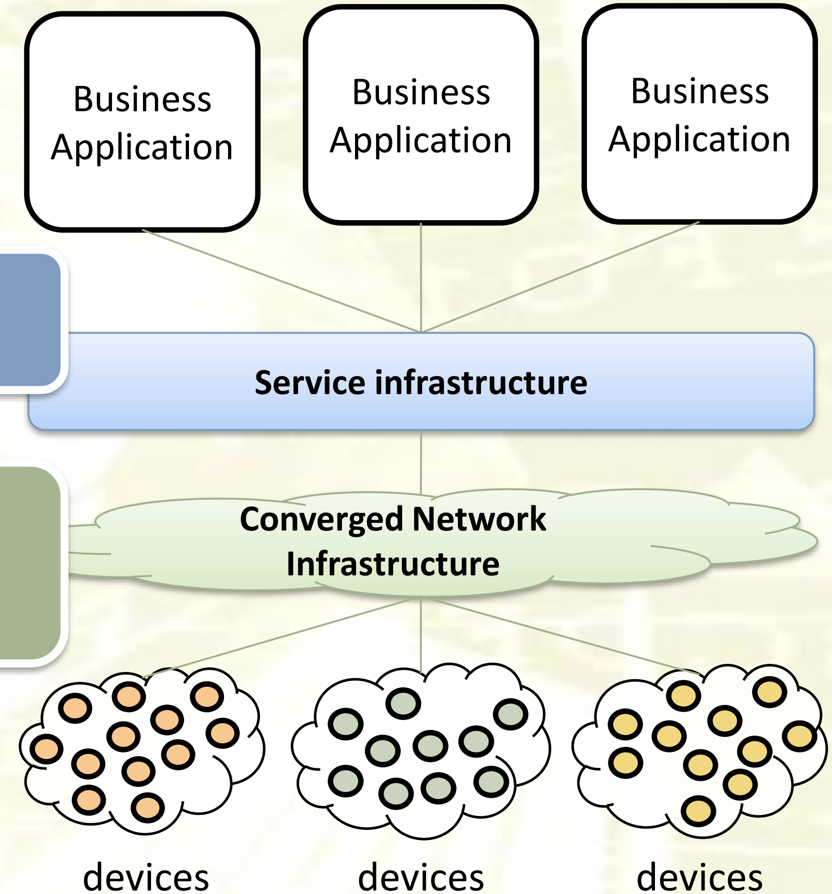
E. Ancillotti, C. Vallati, R. Bruno, E. Mingozzi, **A Reinforcement Learning-based Link Quality Estimation Strategy for RPL and its Impact on Topology Management**, *under review*, 2017.

Outline

- **Intro**
  - the IETF vision about Low Power and Lossy Networks
- **6LowPAN/6lo**
  - Motivation and (brief) overview
- **The RPL routing protocol**
  - Motivation and protocol overview
  - The Trickle algorithm
  - Link Quality Estimation
- **The Constrained Application Protocol (CoAP)**
  - Motivation and protocol overview
  - QoS support with asynchronous communication

How to achieve? The IETF vision



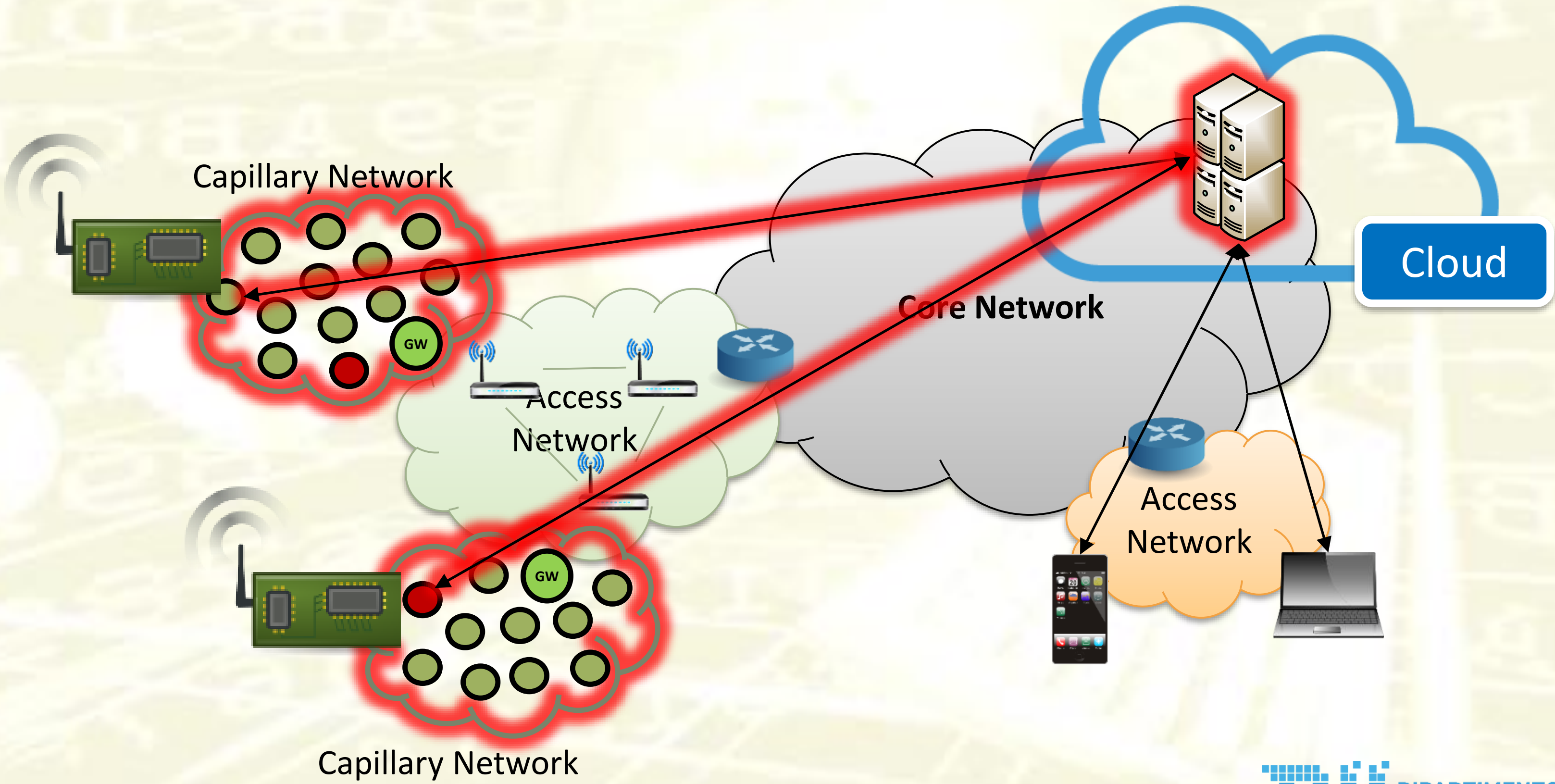


- IP for Smart Objects
  - Set of IPv6-based solutions have been defined by IETF (6LowPAN, ROLL, COAP)
  - Supported by the IPSO Alliance

Distributed intelligence & actions across standardized networks & interfaces

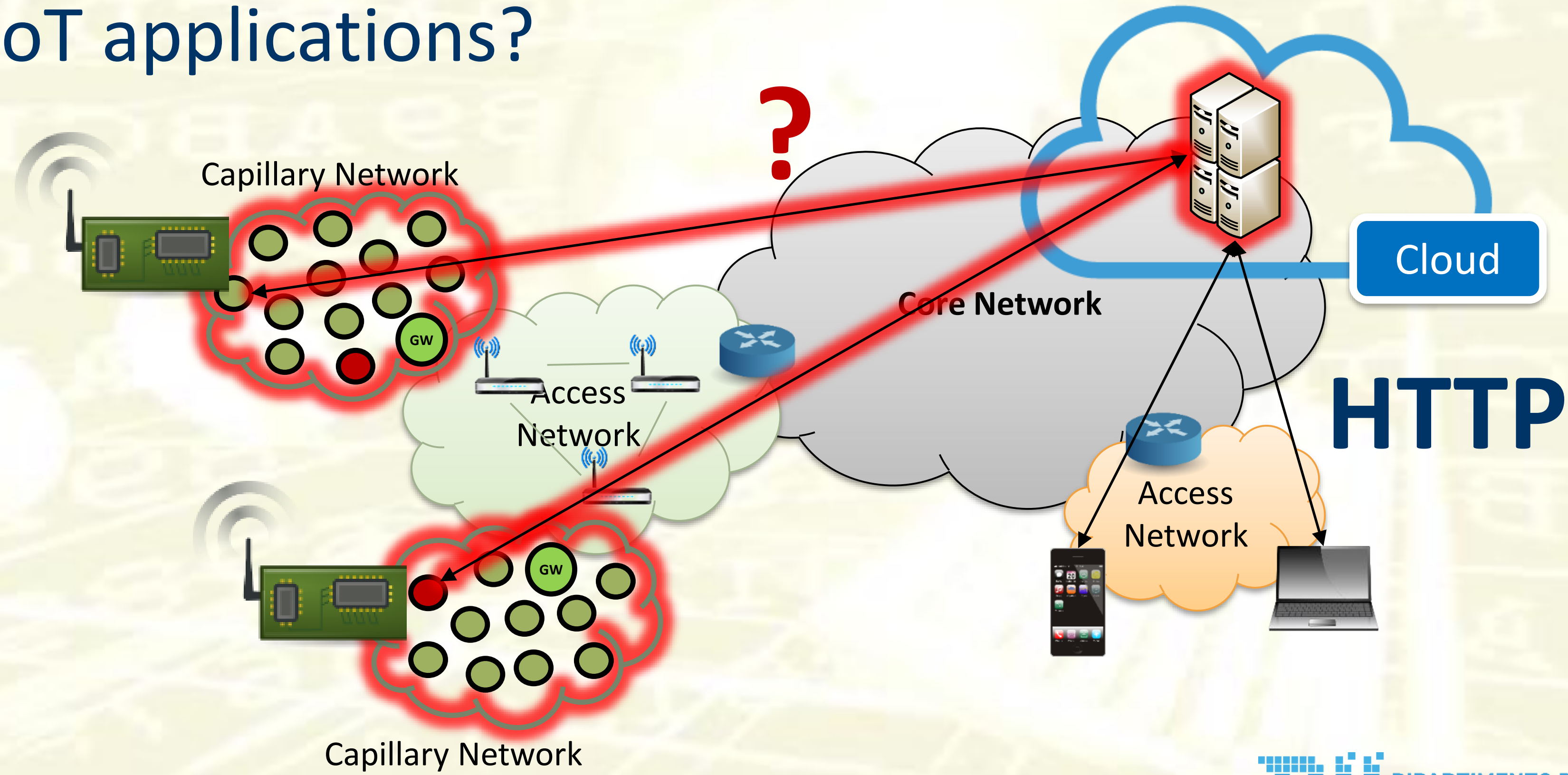
Web for IoT – Why?

- Integration between IoT and Cloud Computing



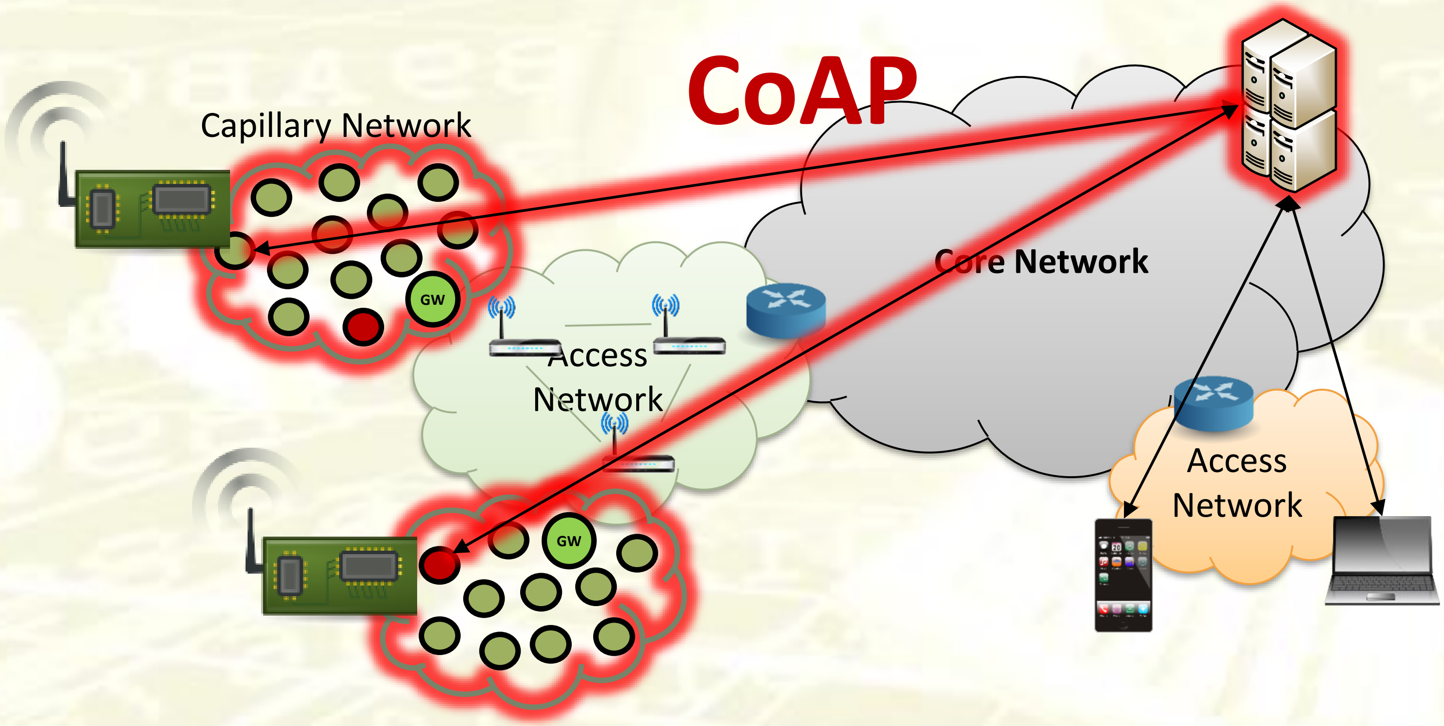
Web for IoT – Why?

- What protocol to use at the application-layer to integrate device components into (cloud-based) IoT applications?



IoT applications

- Constrained Application Protocol
  - – IETF CoRE WG – **RFC 7252** (June 2014)



Constrained Application Protocol

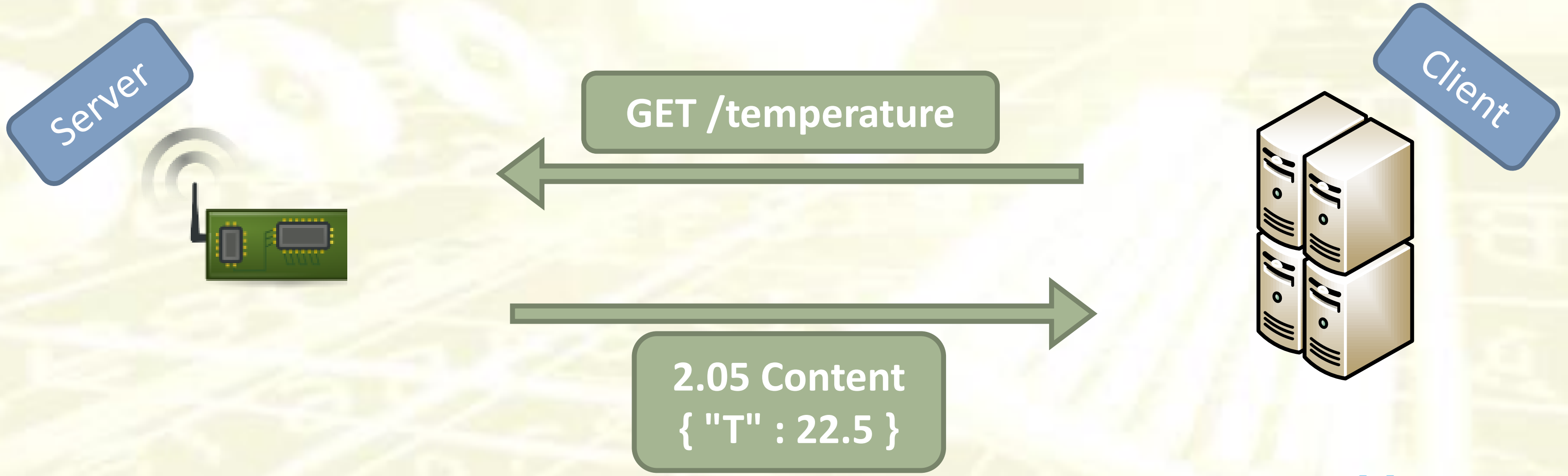
- Generic **web protocol** for the special requirements of **constrained environment** (LLNs), especially considering **Machine-to-Machine** (M2M) applications

- Binding to **UDP** transport protocol
- **Request/response communication (RESTful)**
- support for asynchronous message exchanges
- **Low** header **overhead** and parsing **complexity**
- Simple **proxy** and **caching** capabilities
- Support for **discovery** of resources

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

CoAP interaction model

- Request/Response communication, on top of
- Asynchronous Messages (w/ optional reliability)
  - *Confirmable* (CON), *Non-confirmable* (NON)
  - *Acknowledgement* (ACK), *Reset* (RST)



Request Method definitions

- **GET**: retrieves a representation of the state of the resource (safe and idempotent)
- **POST**: requests that the representation enclosed be processed (neither safe nor idempotent)
  - It usually results in a new resource being created or the target resource being updated
- **DELETE**: requests the resource to be deleted (not safe but idempotent)
- **PUT**: requests that the resource be created or updated with the enclosed representation (not safe but idempotent)

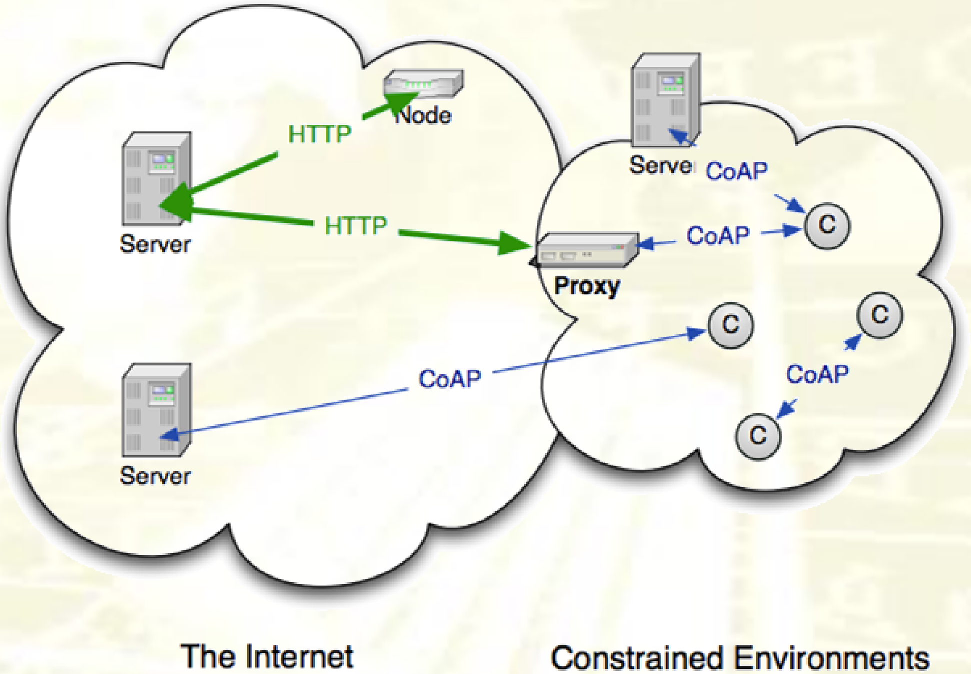
Message format

- Binary format
- Fixed-size four bytes header

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Ver| T |  TKL  |      Code     |          Message ID           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Token (if any, TKL bytes) ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Options (if any) ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 1 1 1 1 1 1|    Payload (if any) ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

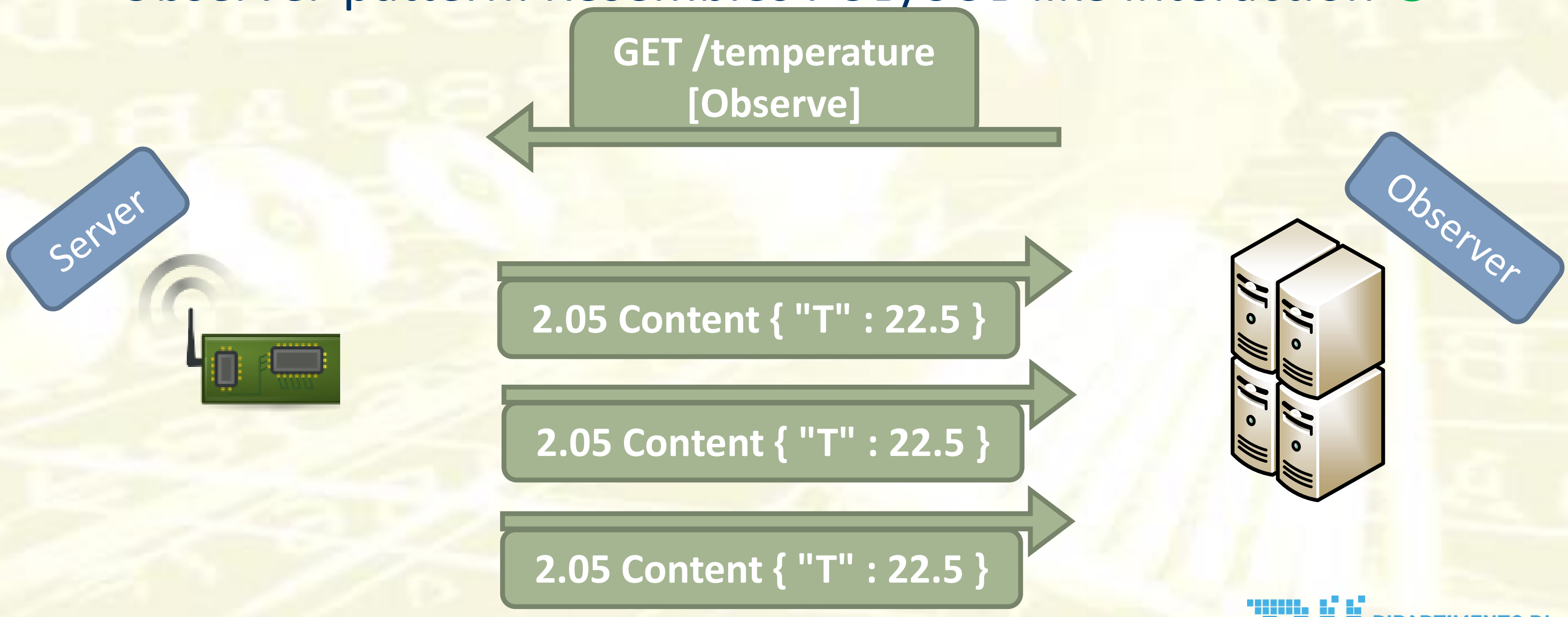
Proxy translation

- Cross-protocol proxy (Cross-Proxy): a proxy that translates between different protocols
  - CoAP-to-HTTP proxy
  - HTTP-to-CoAP proxy



CoAP resource observing

- What if a client is interested in being *indefinitely* updated about a resource?
  - Continuous polling: Period? Overhead? ☹
  - *Observer* pattern: Resembles PUB/SUB like interaction ☺

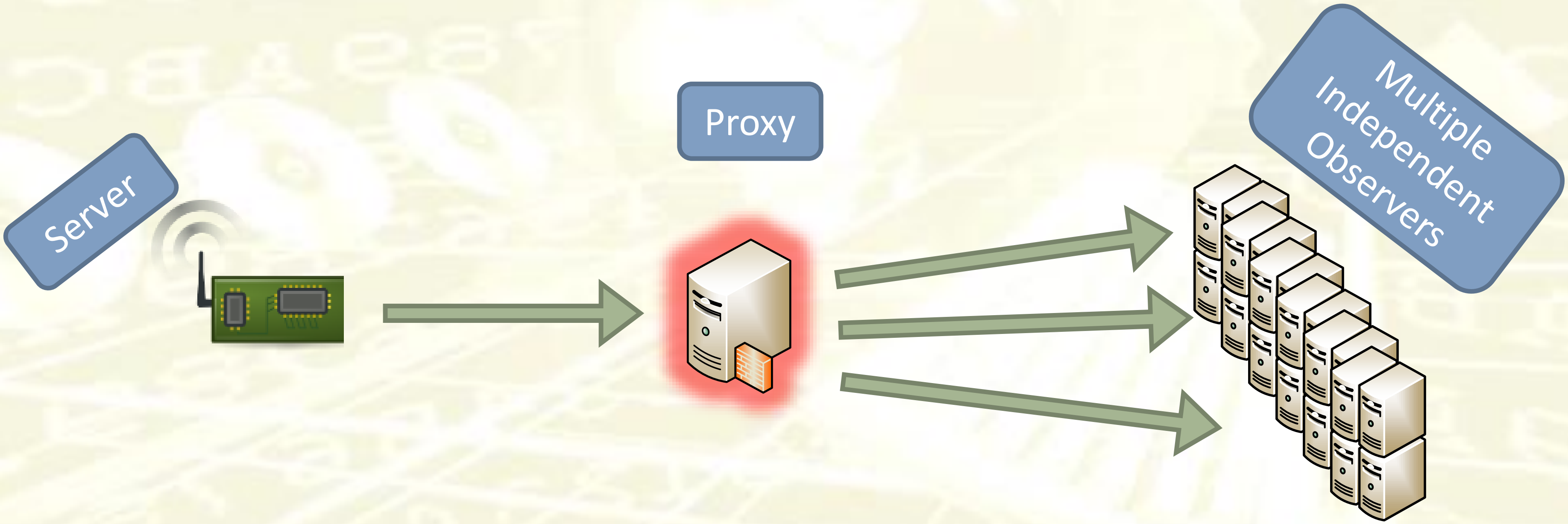


CoAP observing

- **Problem**: a constrained endpoint may manage a **limited** number of **simple** (i.e., **periodic**) observe relationships, but
  - Clients are potentially unlimited
  - Client requirements are different

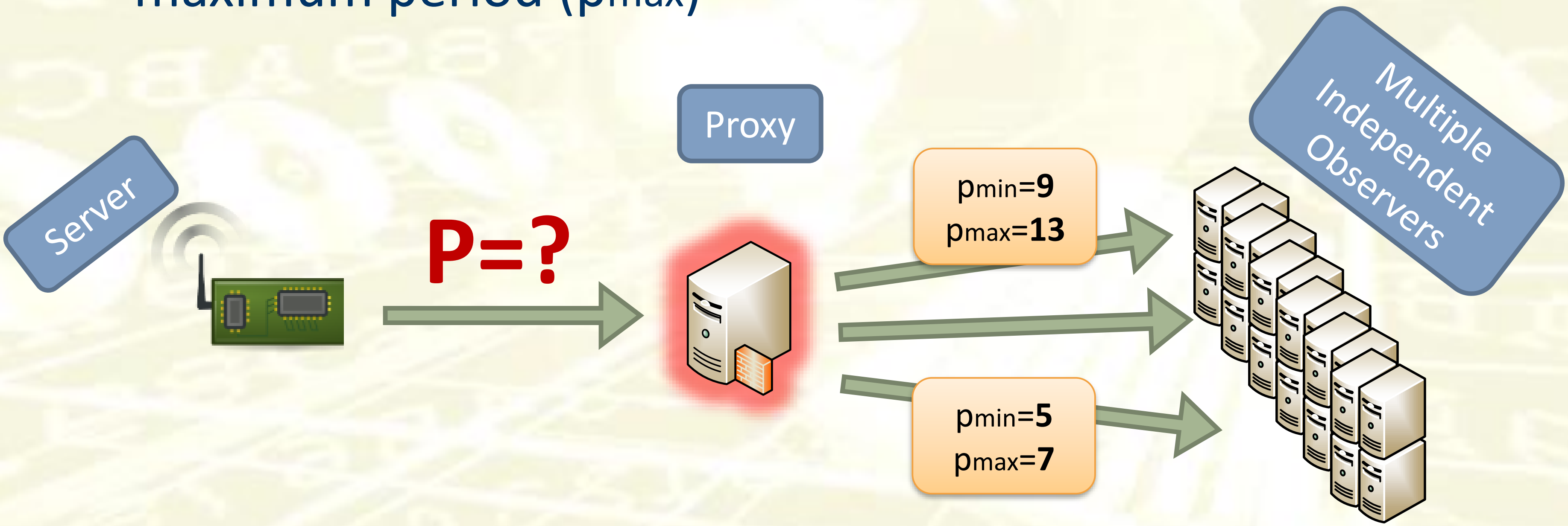
CoAP observing

- Multiple clients: use a **Proxy** as an intermediary
  - Establish observe relationships with as **many** clients
  - Establish **one** observe relationship per device
  - One-to-Many notifications



CoAP observing

- Not all client requirements are equal: **???**
  - State-related parameters: change step, greater then, less then
  - Time-related parameters: minimum period (p_{min}), maximum period (p_{max})

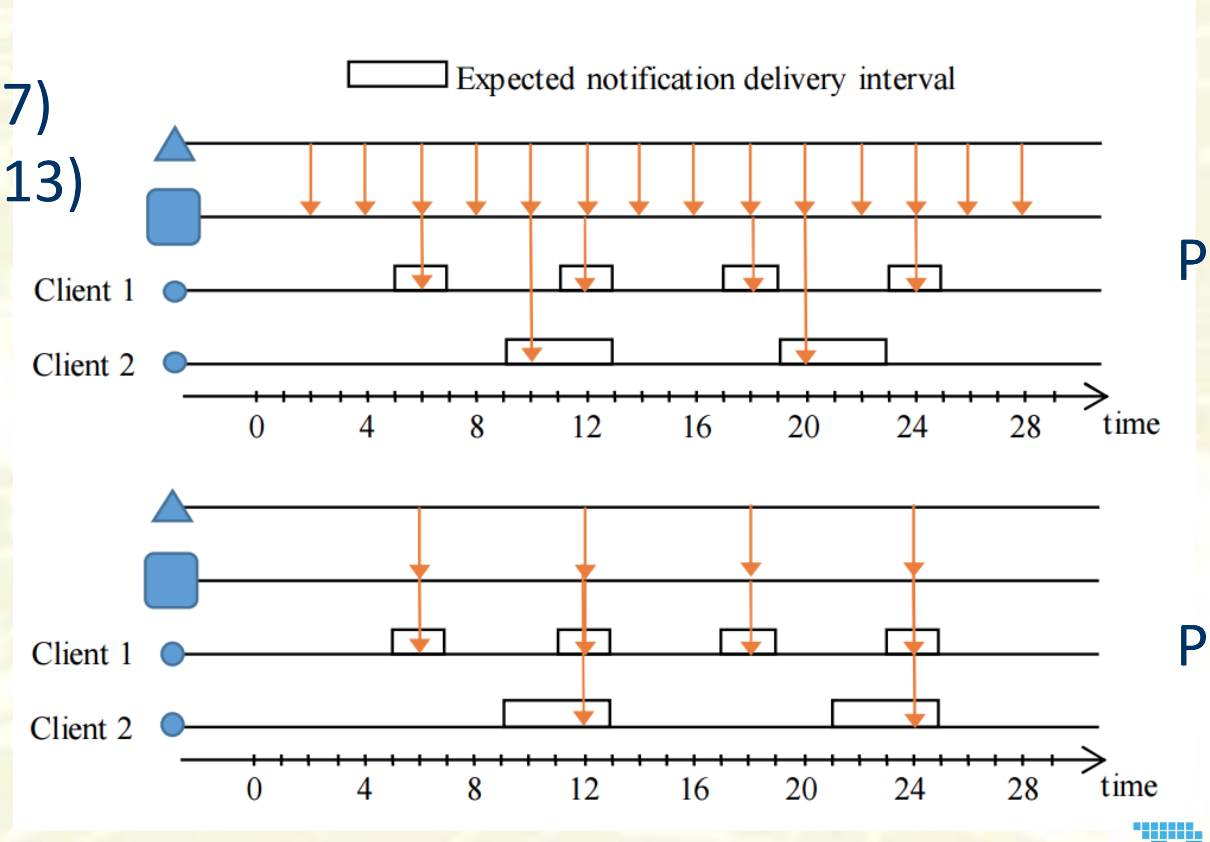


Capillary Network

CoAP observing – QoS

- **Optimization problem**: minimize the period P while satisfying all observers' requirements

Client 1: (5,7)
Client 2: (9,13)



P = 2

P = 6

Observation Period Selection

$$\max P$$

$$\left\lceil \frac{p^i_{min}}{P} \right\rceil P \leq p^i_{max} \;\forall i$$

[there is at least a multiple of P in between p_{min} and p_{max}]

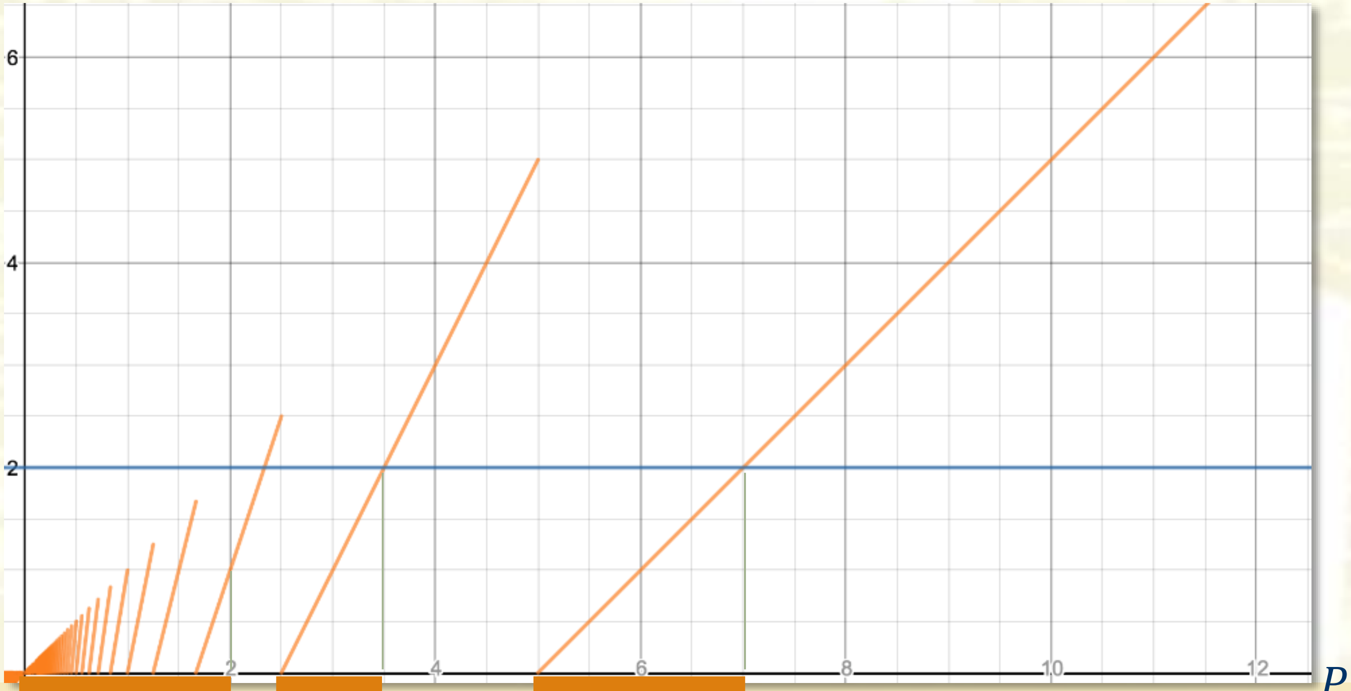
G. Tanganelli, E. Mingozzi, C. Vallati, M. Kovatsch, **Efficient Proxying of CoAP Observe with Quality of Service Support**, Proceedings of the IEEE 3rd World Forum on Internet of Things (IEEE WF-IoT 2016), Reston (VA), USA, December 12-14, 2016.

Observation Period Selection

$$\max P$$

$$\left\lceil \frac{p^i_{min}}{P} \right\rceil P \le p^i_{max} \; \forall i$$

[there is at least a multiple of P in between p_{min} and p_{max}]



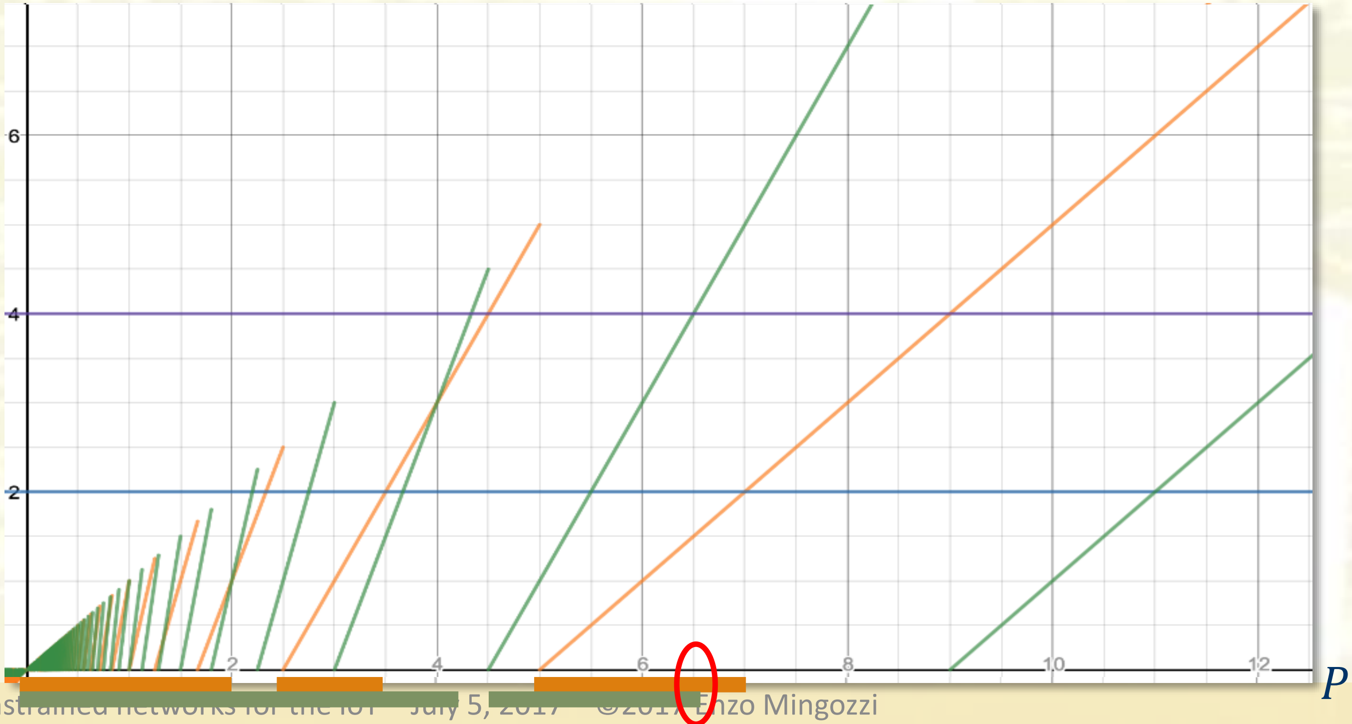
p_{min}=**5**
p_{max}=**7**

Observation Period Selection

$$\max P$$

$$\left\lceil \frac{p_{min}^i}{P} \right\rceil P \leq p_{max}^i \;\forall i$$

[there is at least a multiple of P in between p_{min} and p_{max}]



$p$min=**5**
$p$max=**7**

$p$min=**9**
$p$max=**13**

Observation Period Selection

$$\max P$$

$$\left\lfloor \frac{p_{min}^{i}}{P} \right\rfloor P \leq p_{max}^{i} \; \forall i$$

[there is at least a multiple of P in between p_{min} and p_{max}]

- There is always a solution (Worst Case Period)

$$P = \min_{i}\{p_{max}^{i} - p_{min}^{i}\}$$

- Simple and elegant iterative procedure that finds the optimum solution

Thanks!

Enzo Mingozzi
DII – University of Pisa
enzo.mingozzi@unipi.it