Routing over Low Power and Lossy Networks

Analysis and possible enhancements of the IETF RPL routing protocol

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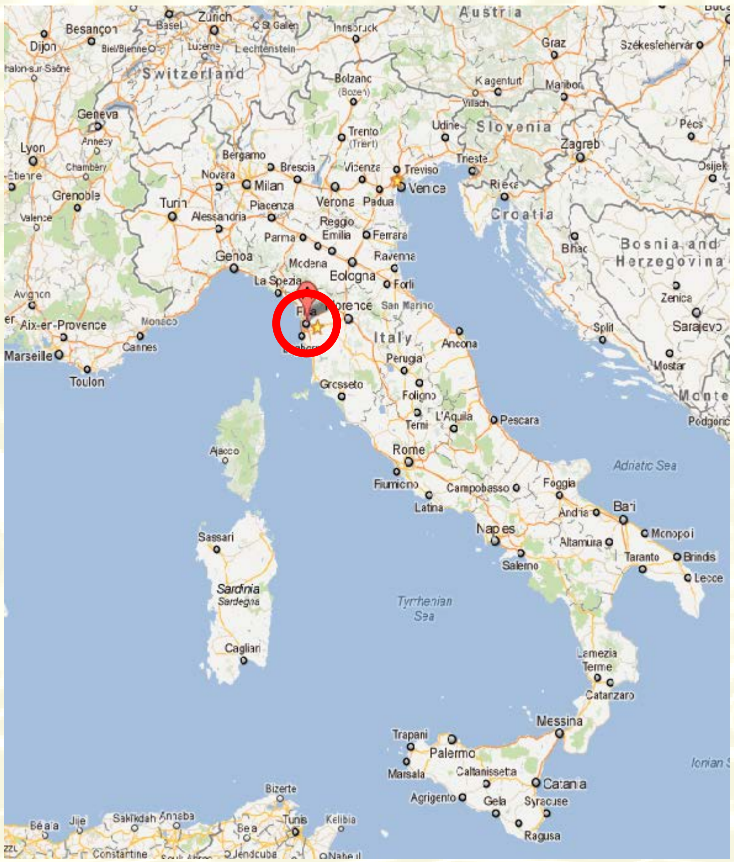
Where am I from?

- Pisa, Italy



Founded in 1343
~50,000 students
> 150 courses

yes, the tower is still up … and leaning

Outline

- Introduction
  - IETF activities around LLNs
- The RPL routing protocol
  - Overview of basic concepts and operation
- RPL message dissemination: the Trickle algorithm
  - Issue 1: unfairness -> Trickle-F
  - Issue 2: link quality estimation -> Trickle-L^2
- Conclusions

IoT: new opportunities …

… but also new challenges

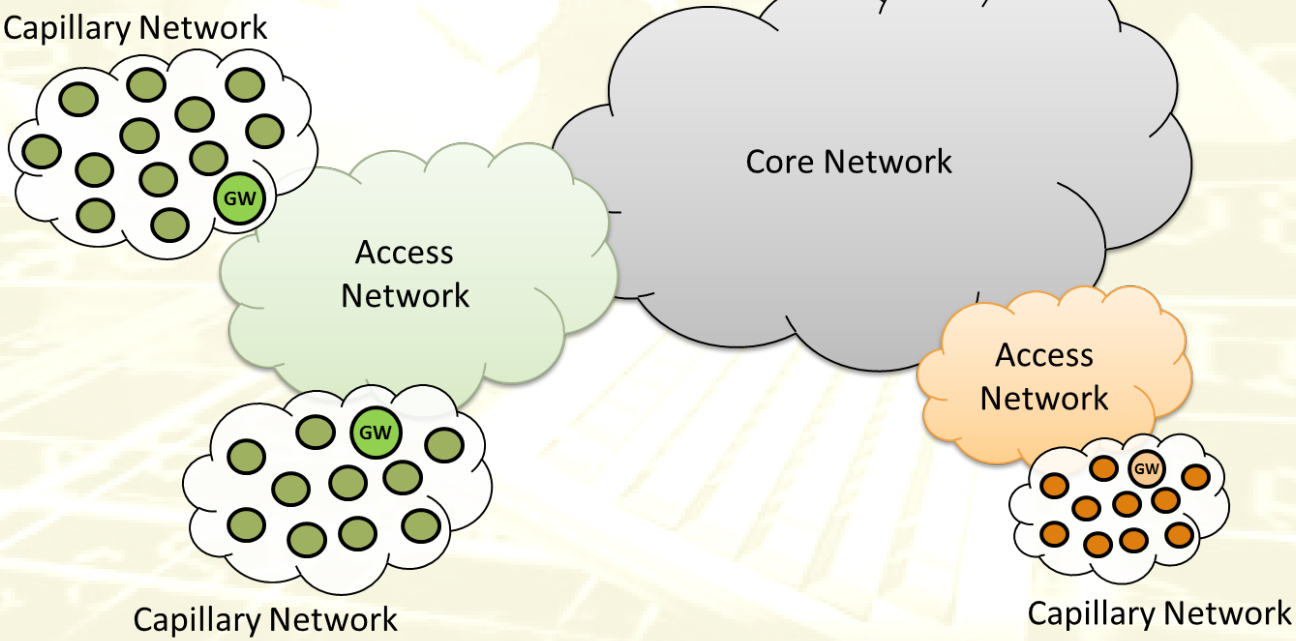
- Scalability
  - Number of nodes in the system
  - Amount of data generated by each node
- Diversity of applications
- Diversity of communication technologies
  - Potentially lossy if wireless
- Interoperability
- Low-power consumption
- Lifetime
- Context-awareness
- Security, trust
- …

IP for Smart Objects

- IP for Smart Objects
  - Set of IPv6-based solutions being defined by IETF
  - Supported by the IPSO alliance (http://www.ipso-alliance.org/)

I E T F

ipso Alliance



IP(v6) for Smart Objects

Inter-operability

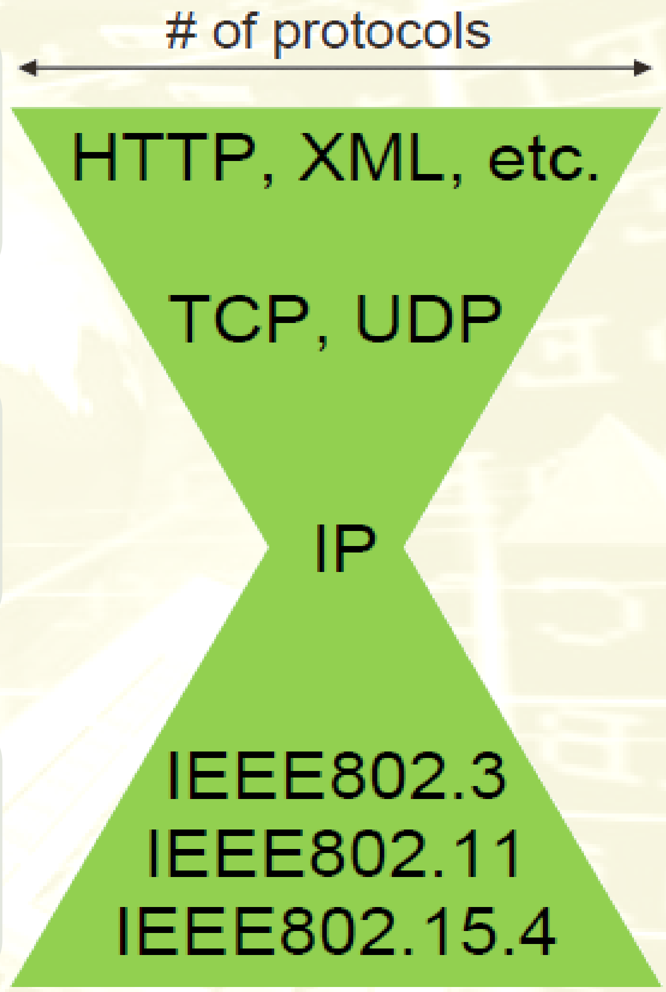
- Layered approach for independence of underlying technologies

Scalability

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

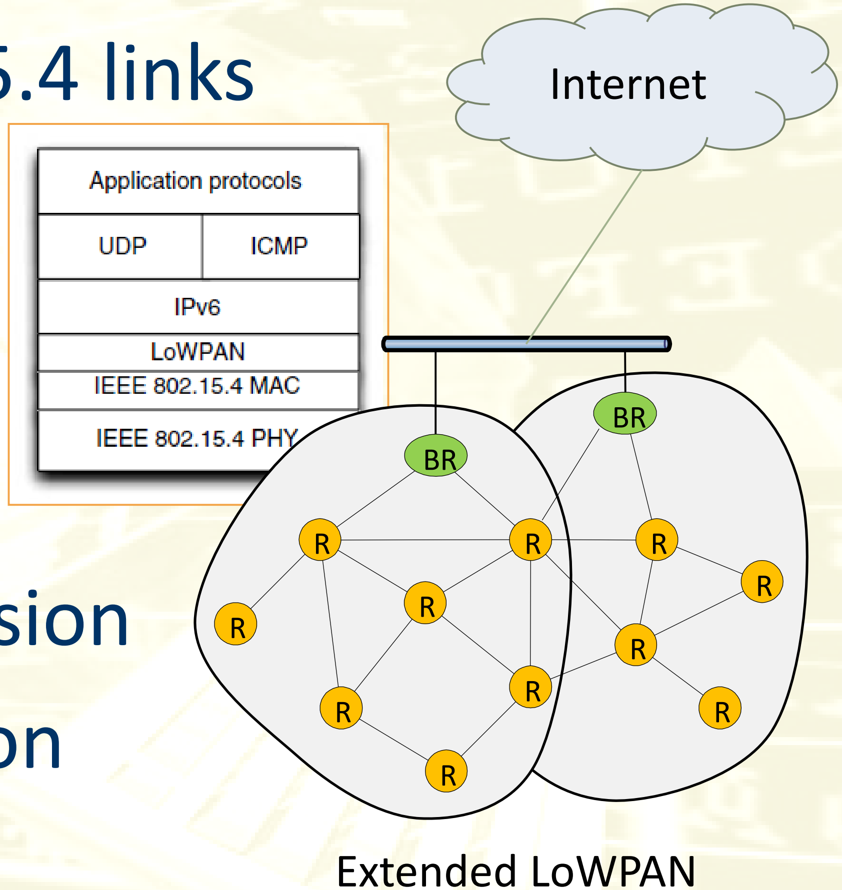
End-to-end

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



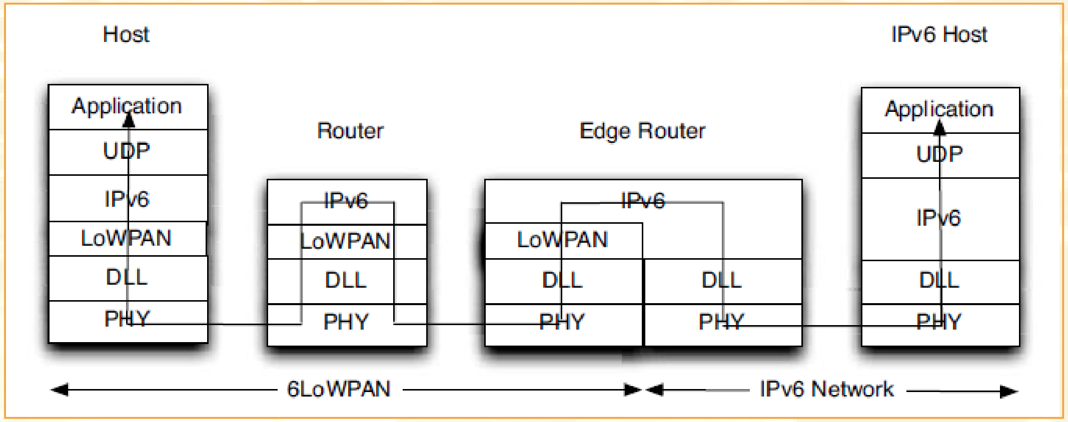
6LowPAN WG

- Adaptation layer for devices connected by IEEE 802.15.4 links [rfc4919, rfc4944]
- Fragmentation
  - 1280 byte IPv6 MTU -> 127 byte 802.15.4 frames
- Efficient header compression
- Network autoconfiguration using neighbor discovery

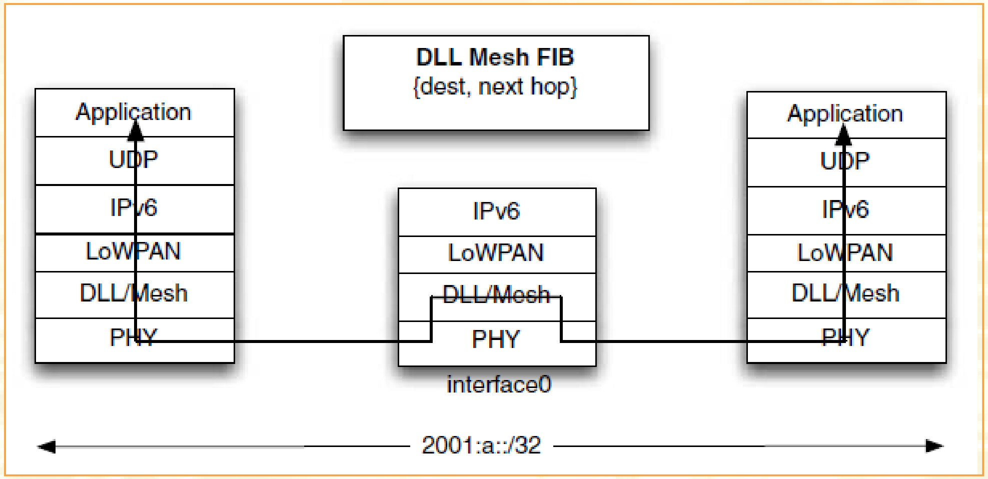


Multi-hop forwarding in LLNs

- Route-Over



- Mesh-Under



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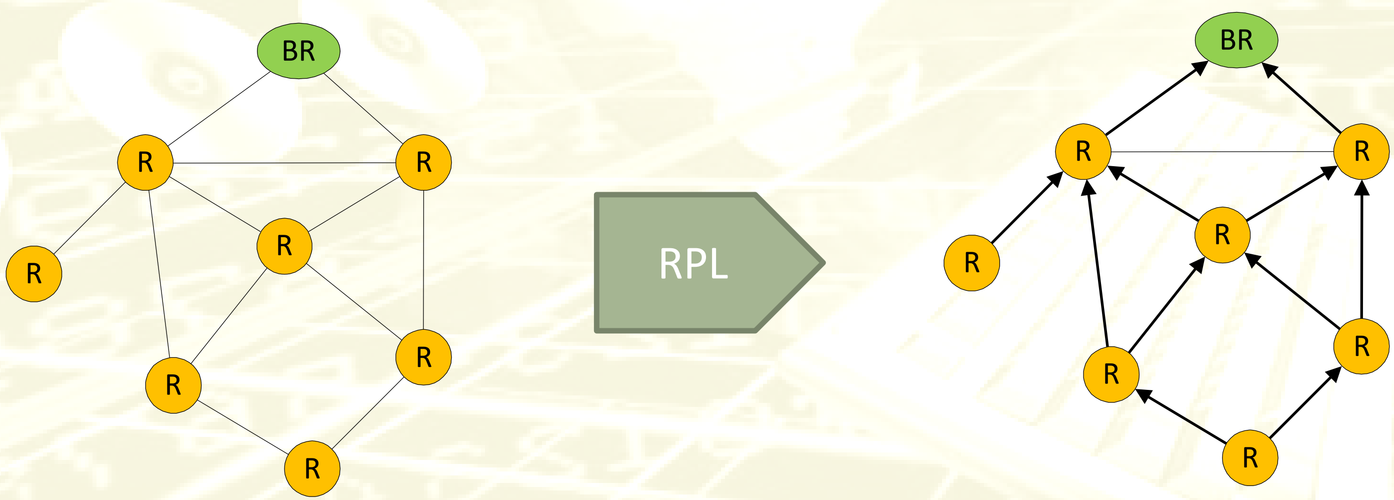
ROLL WG

- 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

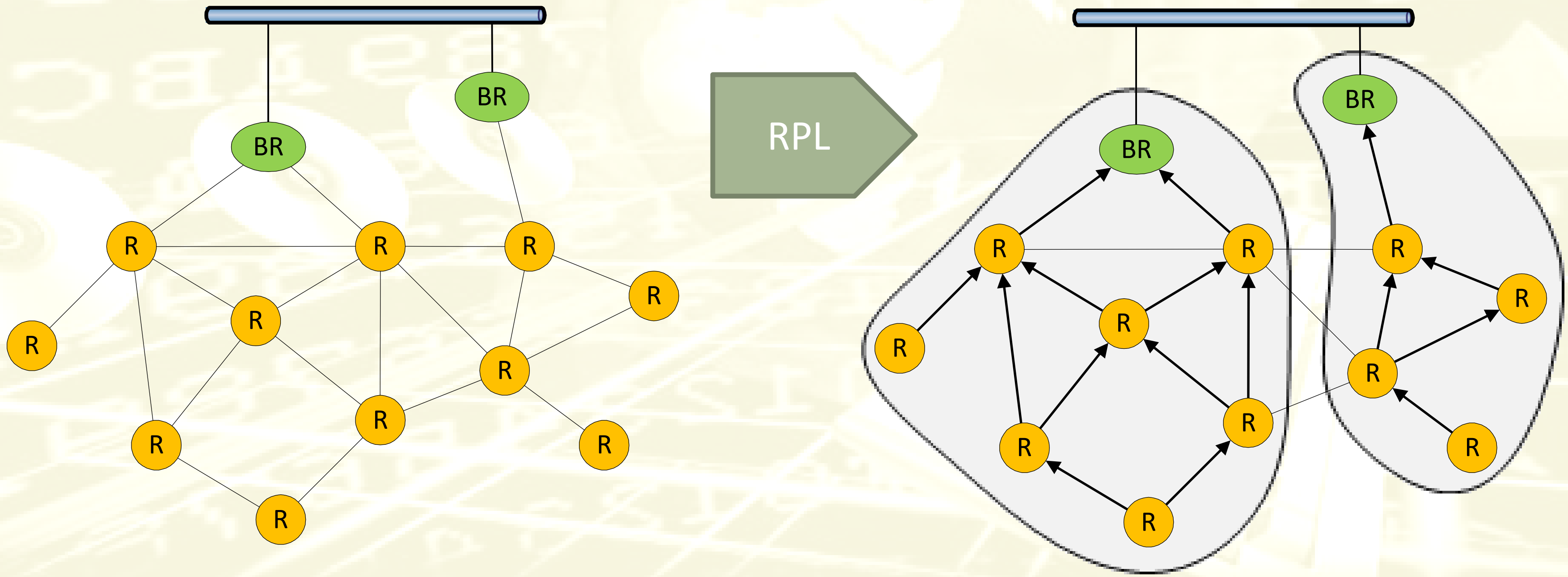
Routing principles

- 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 protocol



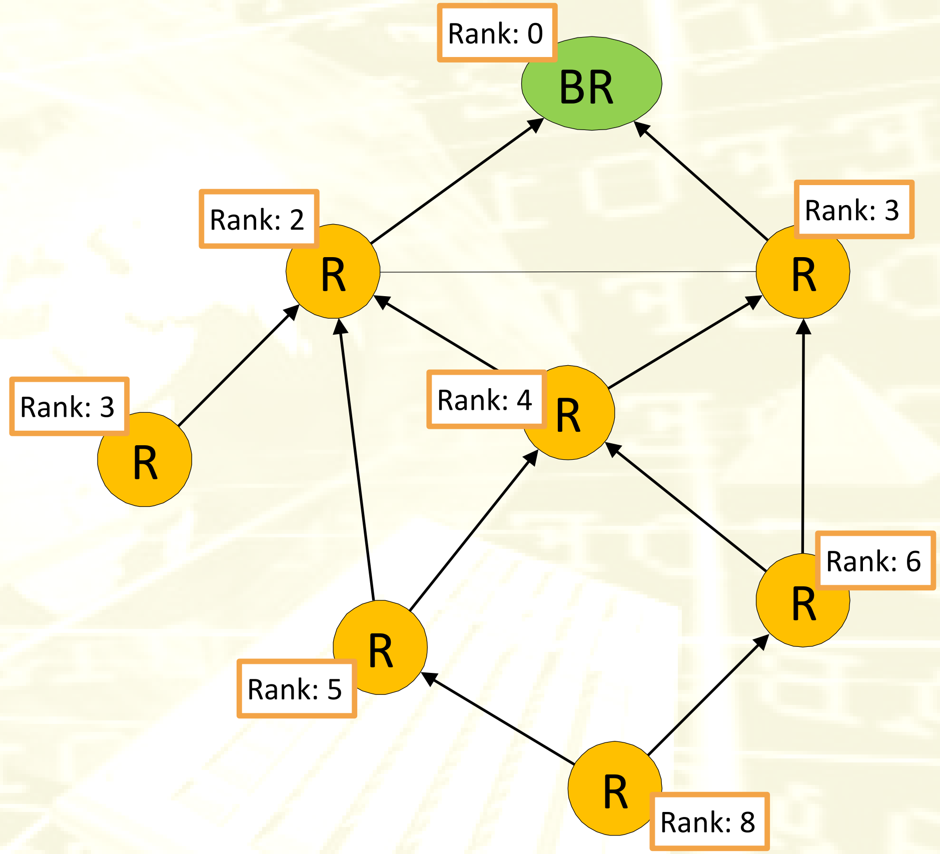
Routing principles (cont.)

- In case of multiple sinks, one DODAG per sink
- RPL nodes may belong to one and only one DODAG (per RPL instance)

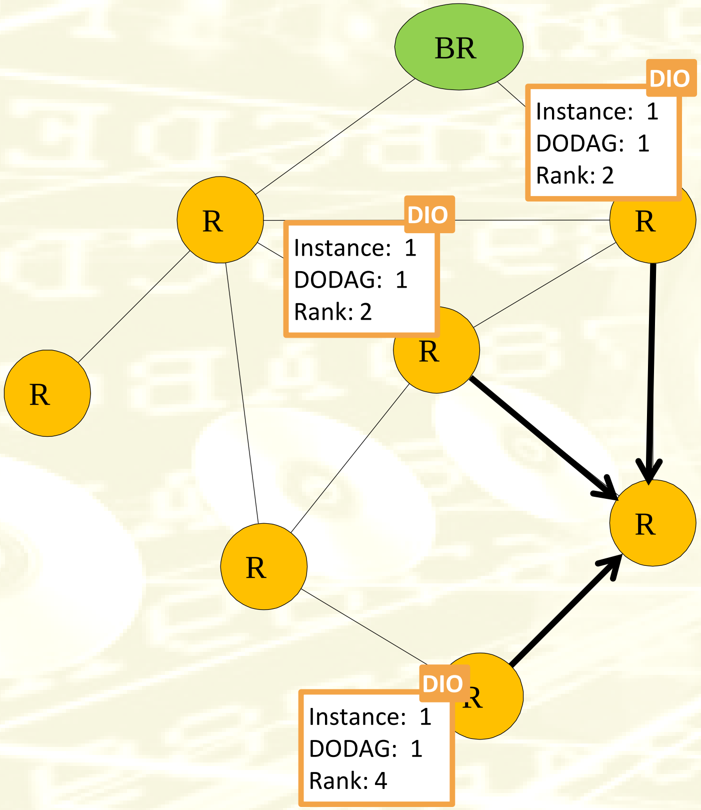


Node rank

- A scalar representation of the node location within a DODAG instance
- The rank <u>MUST</u> monotonically decrease on each path towards the root
- Computed based on routing metrics established by an **Objective Function**

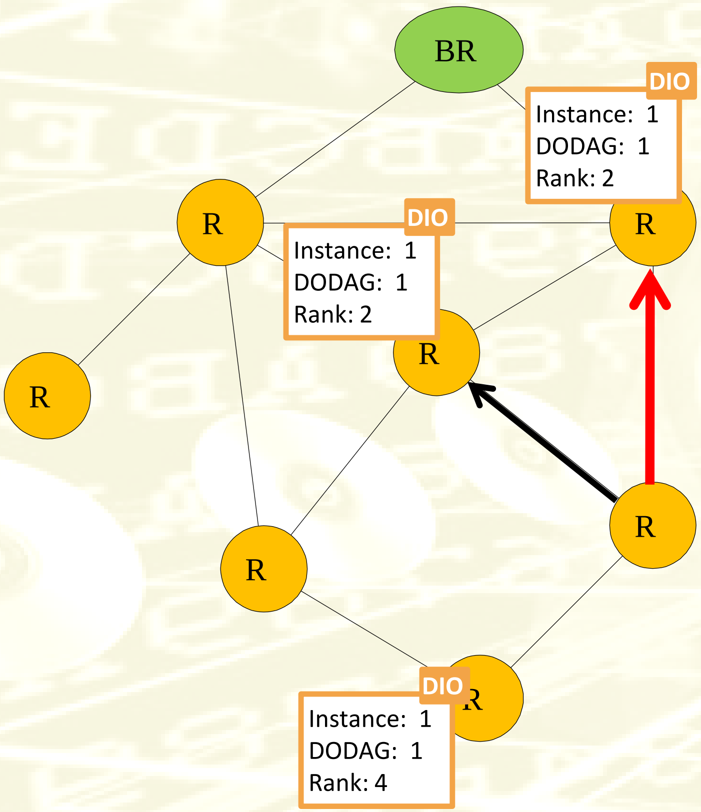


DODAG formation



- 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

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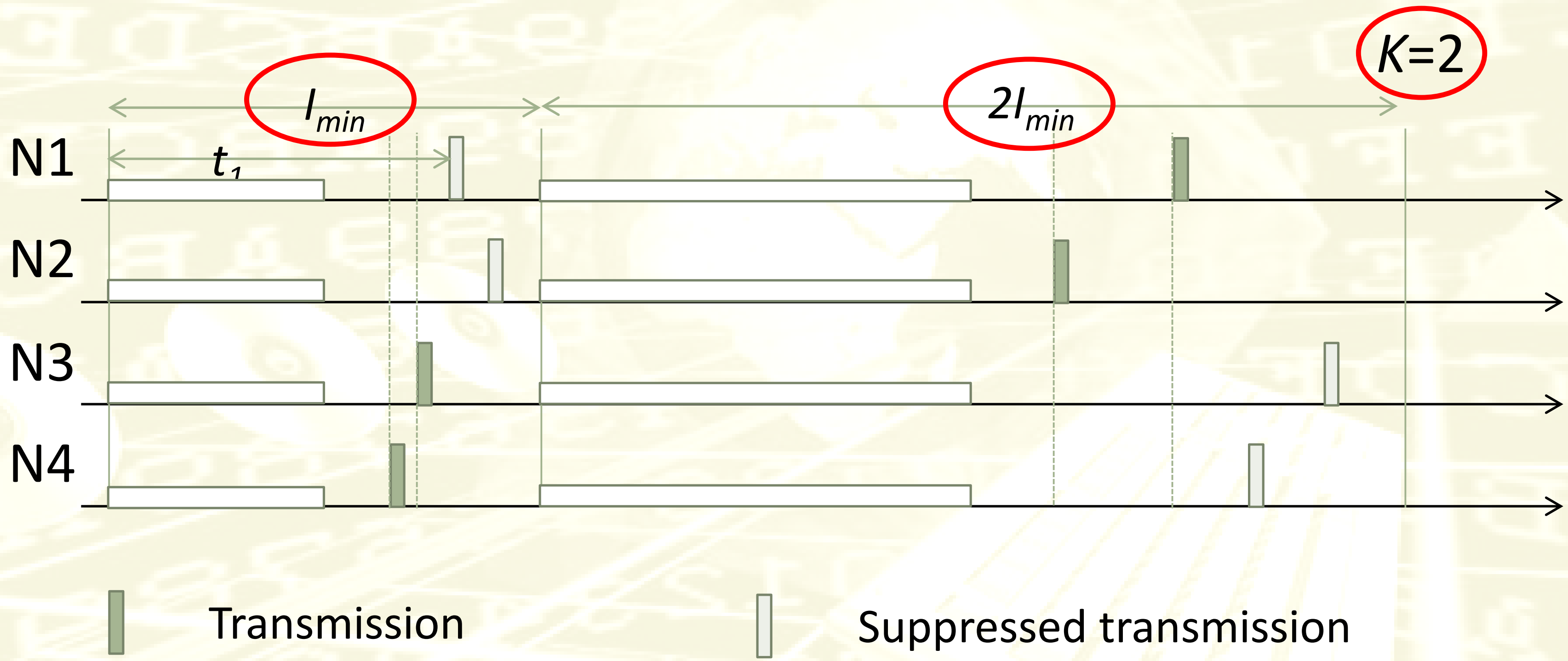
DIO message broadcasting

- 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)



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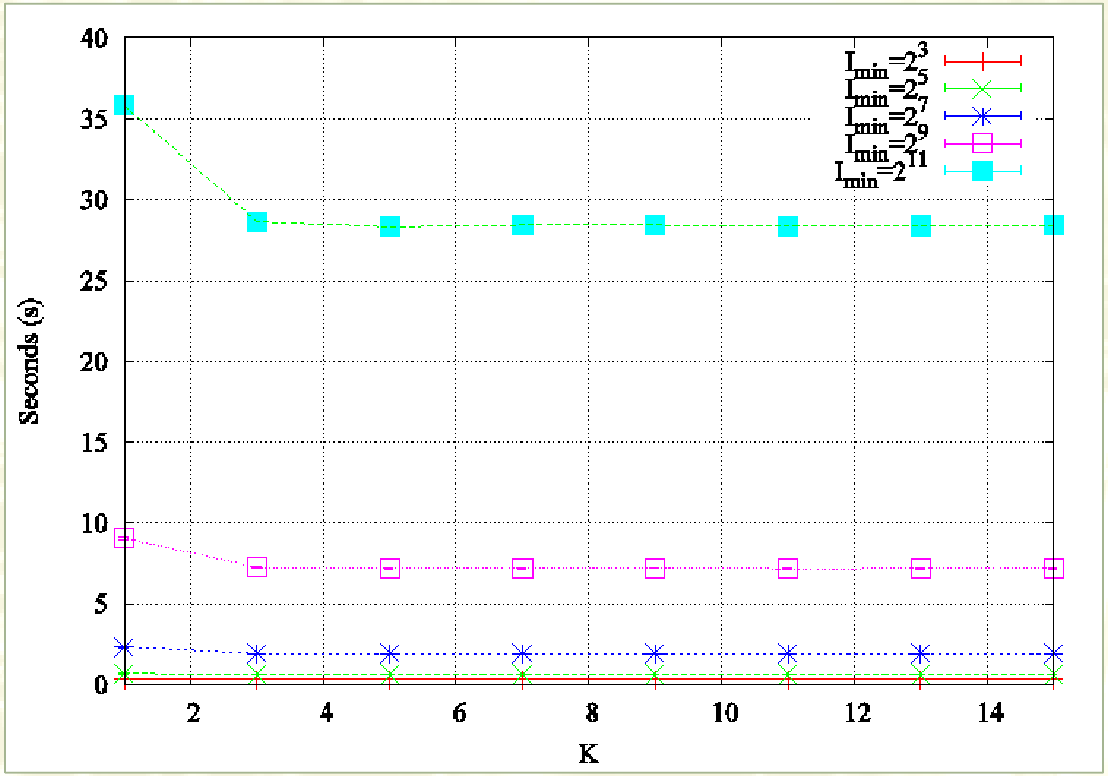
Performance evaluation

- 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

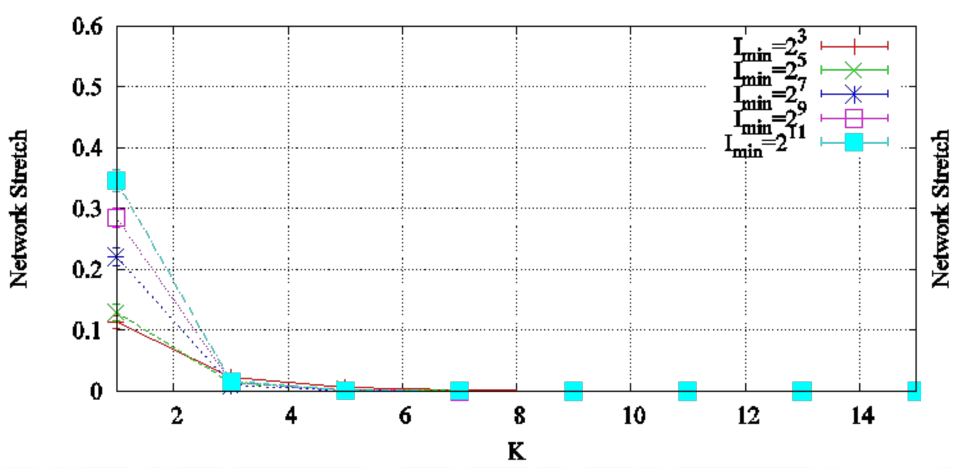
- How much time it takes to form the first DODAG (i.e., the network is fully connected)?



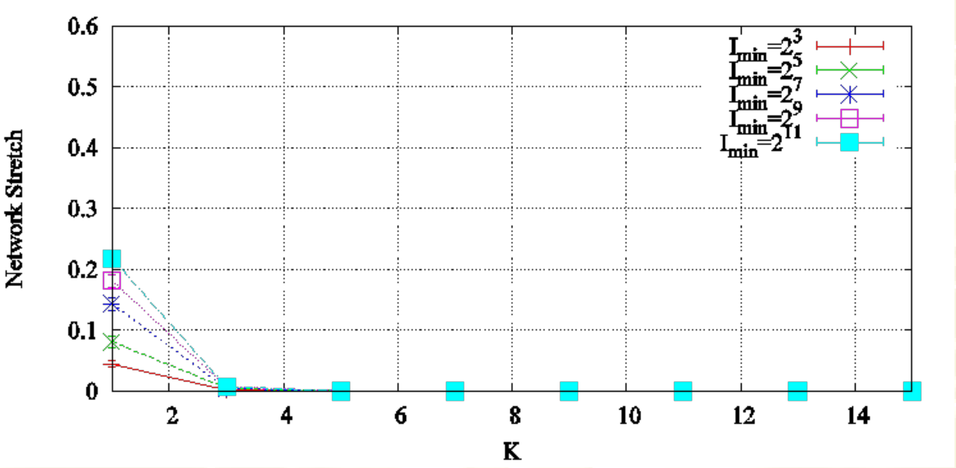
Performance evaluation

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

~17 min

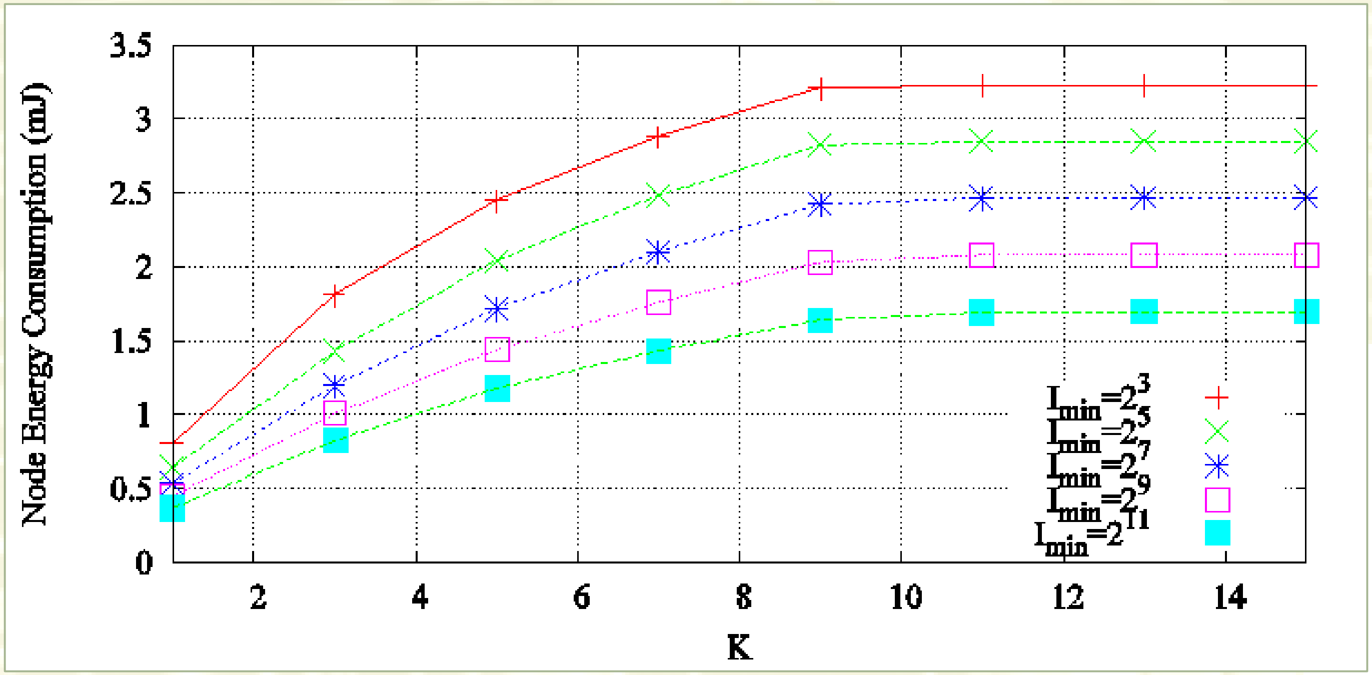


~1677 min



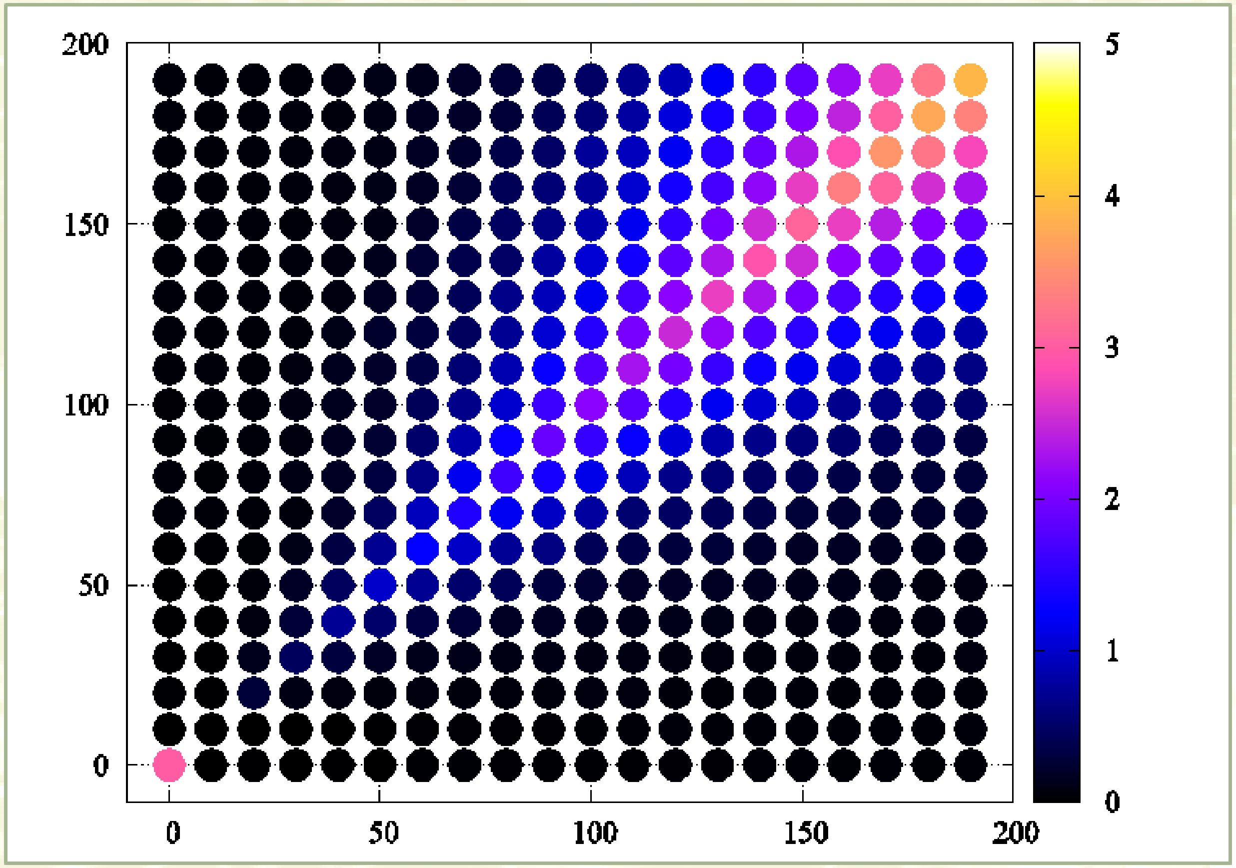
Performance evaluation

- How much energy is consumed?
  - Constant base + variable part proportional to the number of transmissions

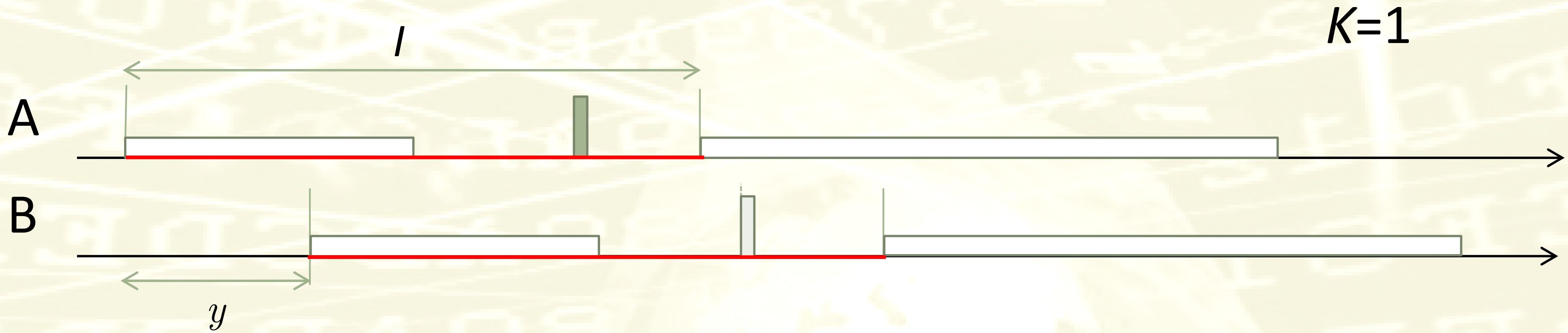


Performance evaluation

- Distribution of path stretch values among nodes



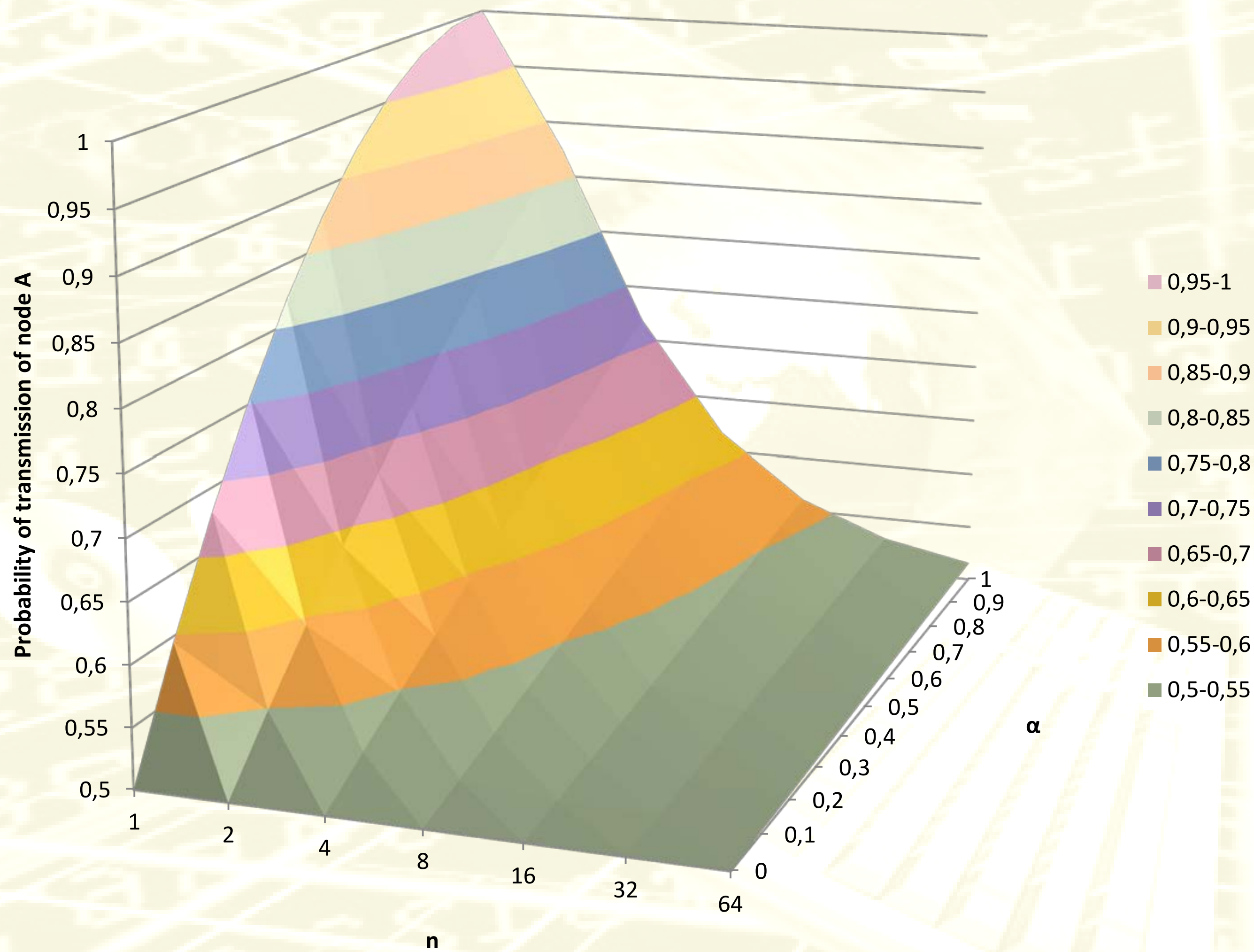
Trickle – analysis



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

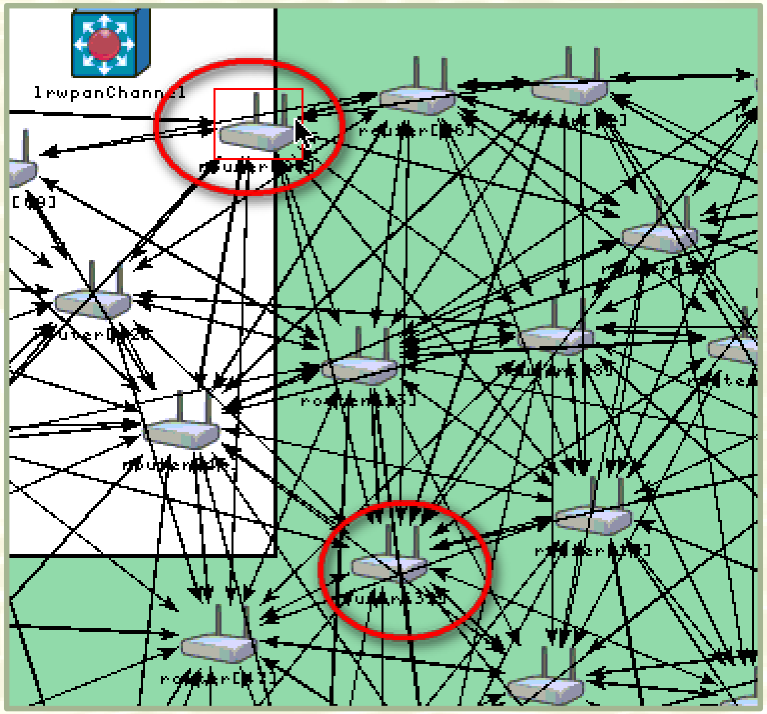
$$P\left\{A\,tranmits\right\} = 1 - \frac{1}{2}\left(1 - \frac{\alpha}{n}\right)^2, n = 1,2,4,8,16,\ldots$$

Trickle – analysis



Affected scenarios

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

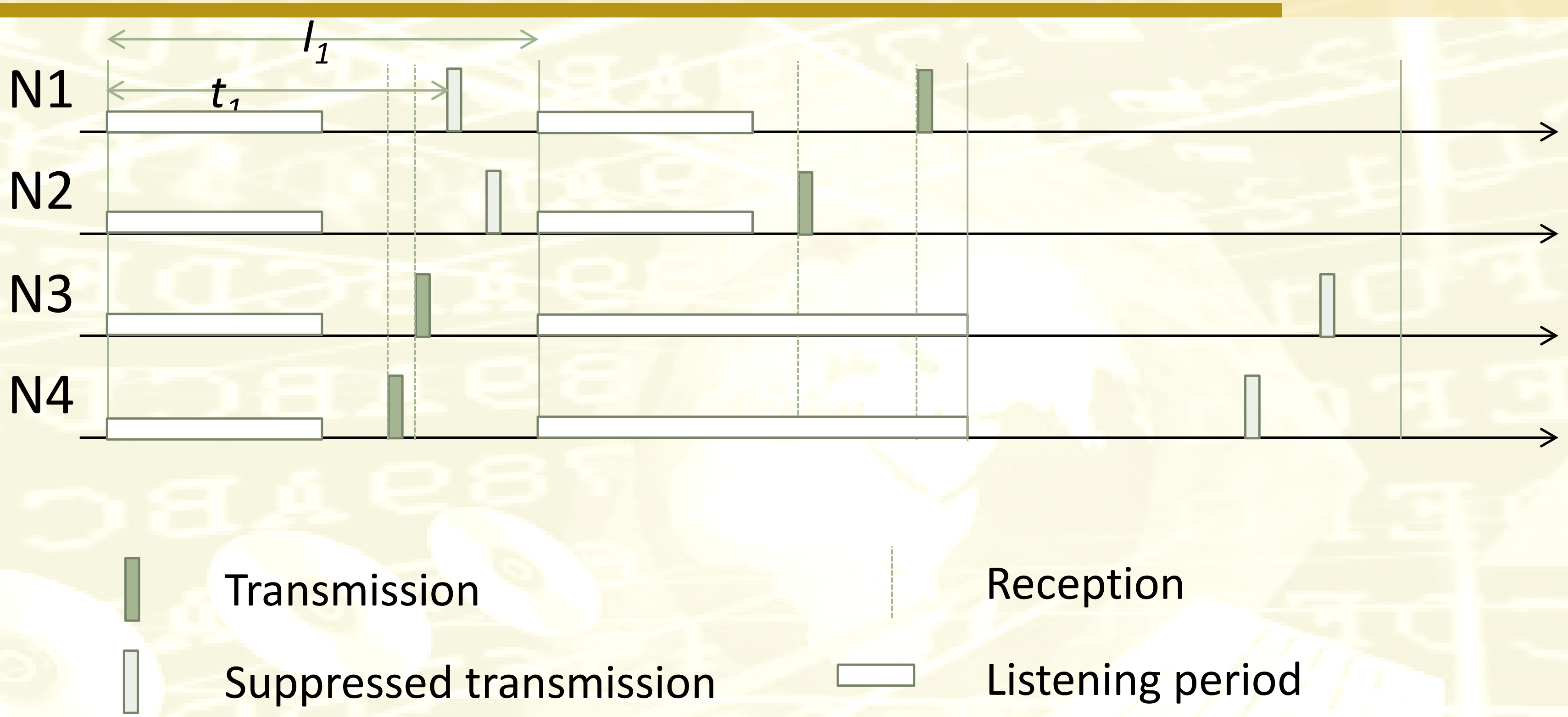


- I = 7, K = 5

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

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

Countermeasures?



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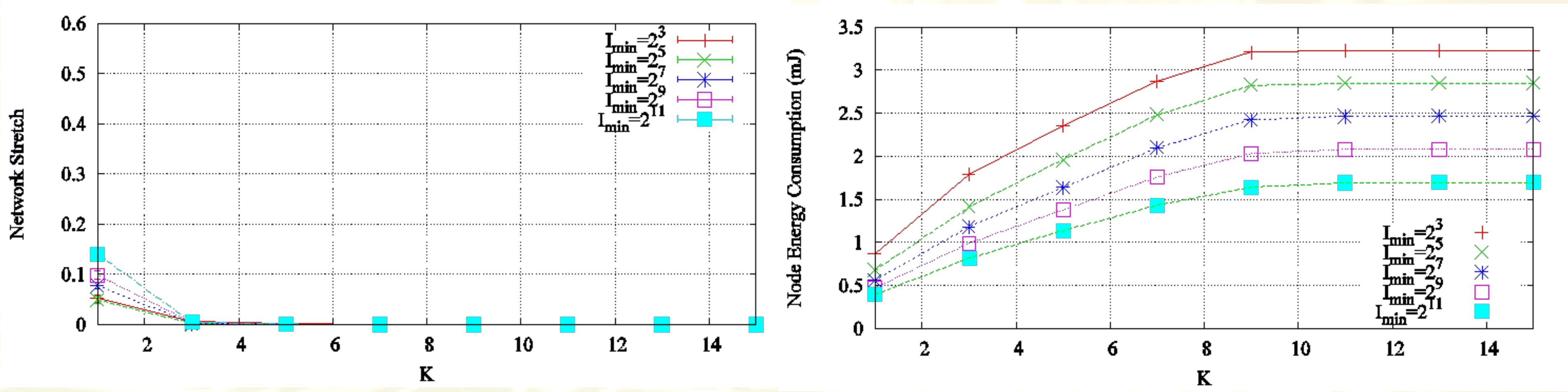
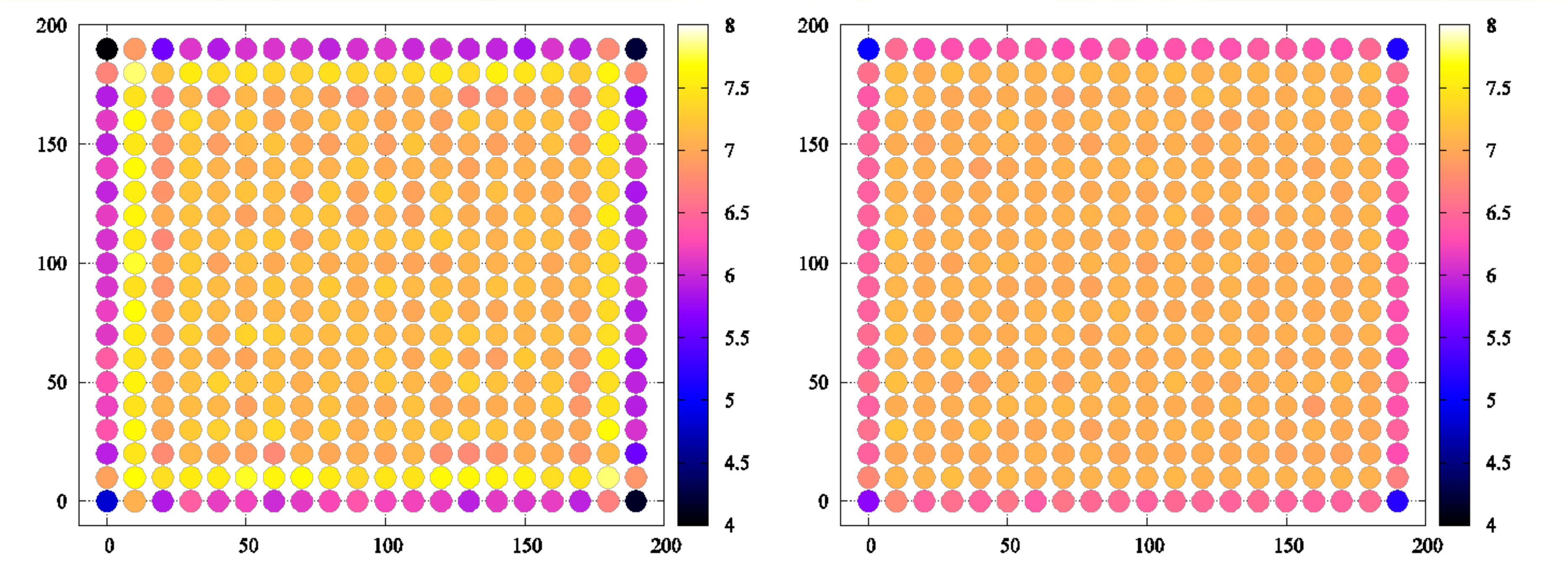
Performance evaluation

- Better routes on average at the same energy cost



Performance evaluation

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



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Link quality estimation

- Rank computation may be based on dynamic metrics
  - Objective Function Zero (rfc6552) recommends the use of dynamic link properties such as **ETX (Expected transmission Count)**
- Topology stability is highly dependent on the accuracy of link metric estimation
- But, at network formation time, there is no available estimate for just discovered links
  - Contiki's RPL implementation adopts a conservative choice: any previously unknown link is **bad**
- That is, long convergence time before stability while improving the accuracy of link quality estimation

Link quality estimation

- Link quality estimation and RPL
  - Routing protocol control messages
    - Not transmitted on a regular basis because of Trickle DIO message suppression
  - Active probing through unicast messages
    - Adds complexity and overhead
    - Adds much latency exp. at network formation
  - Passive monitoring through data packets transmission
    - Only applies to links in use → does not cover the full DODAG

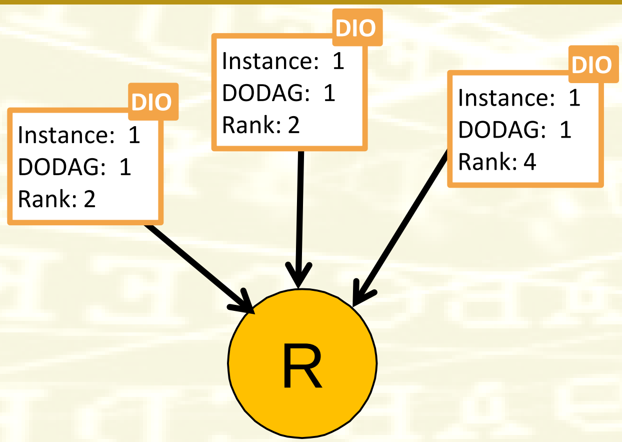
Proposal: Trickle-L^2

1. Delay joining the DODAG until (at least) one link with minimum quality is found
   – Eventually bounded by a maximum time

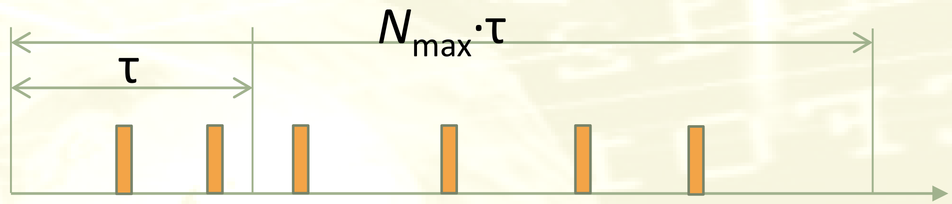
2. Introduce a **fast** link quality estimation mechanism at DODAG formation time
   – Possibly, at no or negligible cost from an implementation point of view

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.

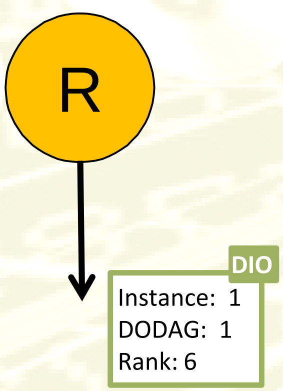
Trickle-L^2

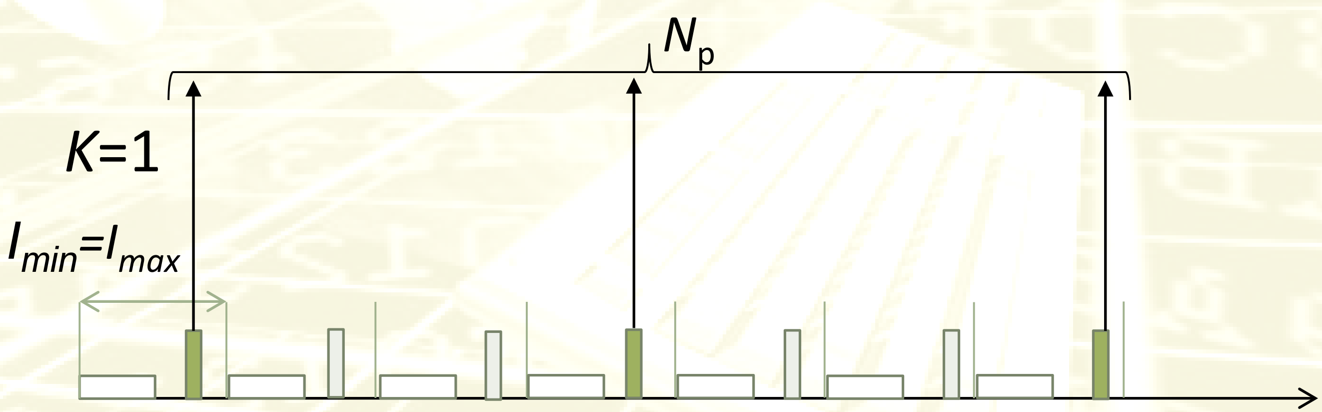


Bootstrap: collect DIO messages and do estimate ETX



Limited active probing: send DIO messages with <u>sequence numbers</u>



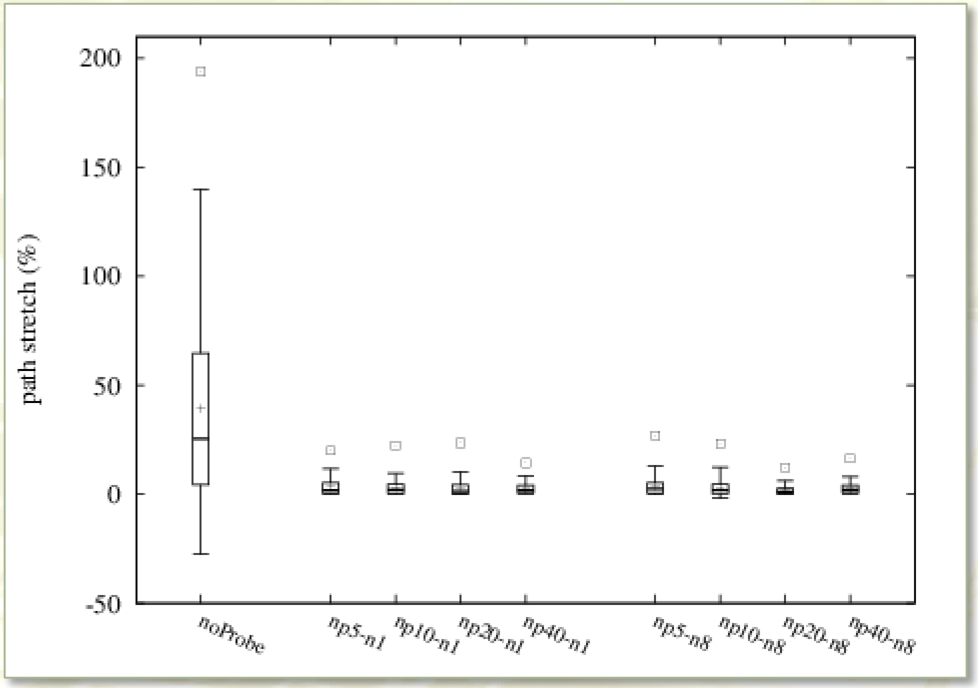


Performance evaluation

- Trickle-L^2 implemented in ContikiRPL
- Scenario
  - 100 nodes, uniformly distributed in 600x600sqm area
  - 1 sink
  - CBR traffic, 1 Pkt/minute/node
  - OF Zero with ETX, I_{min}=I_{max}= 64ms @probing phase
- Cooja emulator (actual implementation tested)
  - Tmote Sky platform
  - MRM interference model
  - 5 runs per experiment, 2 hours of simulated time per run

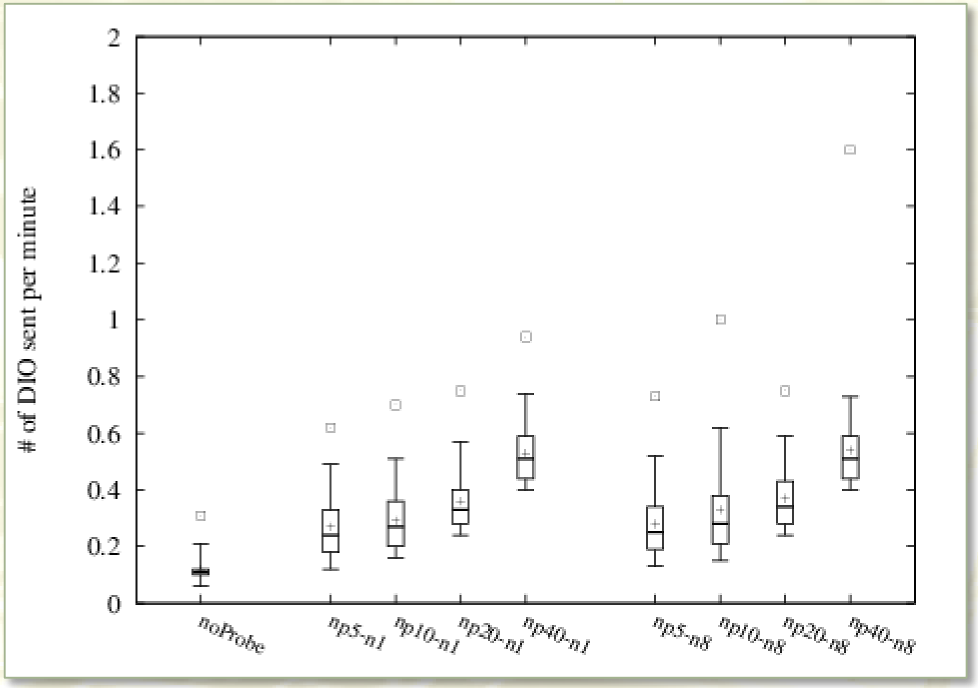
Numerical results

- N_{max} = 1, 8; N_p = 5, 10, 20, 40
- Path ETX stretch over the entire simulation (2 hours)



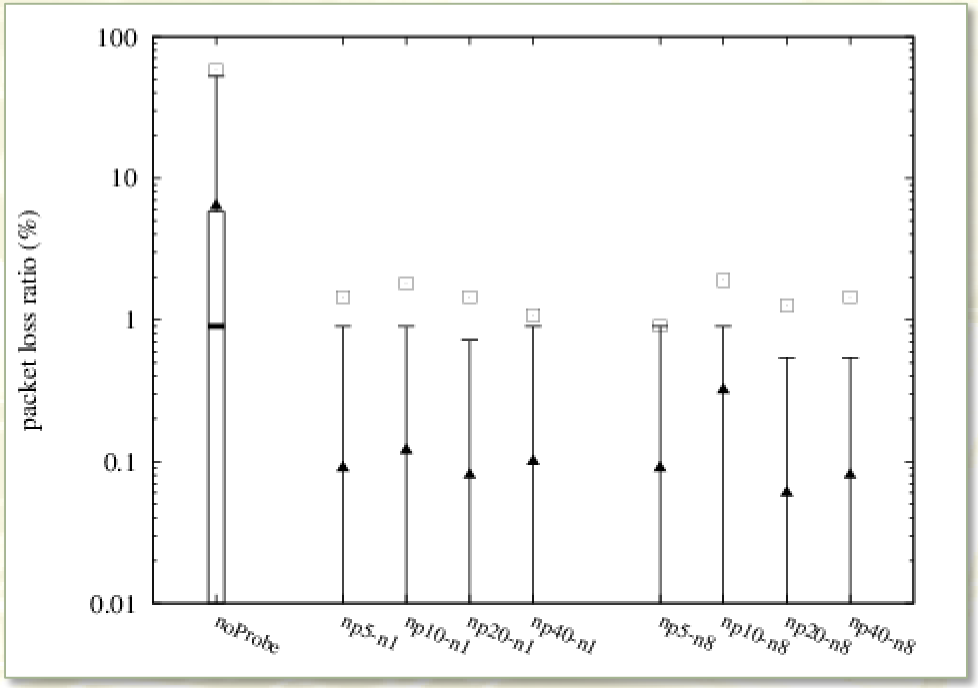
Numerical results

- Average number of DIOs sent per minute



Numerical results

- Packet loss rate per node



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Conclusions

- RPL is by now the most promising candidate for IPv6 routing in future LLNs (i.e., the access part of the IoT)
- Good performance vs. energy efficiency trade-off is key to the operation of the protocol
  - Trickle-*F* improves fairness of message suppression to improve routing information dissemination
  - Trickle-L^2 exploits Trickle operation to enable fast active probing at network formation
- Future work
  - Impact of duty-cycling
  - Performance analysis in more dynamic scenarios

References

- RFC 6206, **The Trickle Algorithm**, March 2011
- RFC 6550, **RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks**, March 2012
- RFC 6551, **Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks**, March 2012
- RFC 6552, **Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)**, March 2012
- RFC 6719, **The Minimum Rank with Hysteresis Objective Function**, September 2012

- J.-P. Vasseur, A. Dunkels. *Interconnecting Smart Objects with IP: The Next Internet*. Morgan Kaufmann, 2010

Thanks!

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