ARCHITETTURE IPV6 PER SMART ENERGY SYSTEMS: LO STANDARD RPL

Speaker: Raffaele Bruno

IIT - CNR

Energy@Home Workshop, Rome
December 11, 2012

IIT-CNR

IIT-CNR

- **CNR** is a network of public research institutes, operating in several sectors, such as medicine, biology, ICT, chemistry, socio-economic sciences, etc.
- **Ubiquitous Internet group** (UI) is within IIT- CNR institute and its activities focuses on the Future Internet design and evaluation, which special emphasis on
  - Opportunistic networking and computing
  - Content-centric network architectures
  - Mobile social networking
  - *Internet of Things*
  - *Smart grid communications*

OUTLINE

- ICT in Smart Energy Systems
- Interoperability problem: the case for IPv6
- Pros and Cons of IPv6 in Low-Power and Lossy Networks (LLNs)
- IPv6 stack for LLNs: standards, implementations, industrial initiatives
- Open problems for IPv6 routing in LLNs (RPL)
- Outlook on possible RPL enhancements

Smart Energy Systems: Drivers

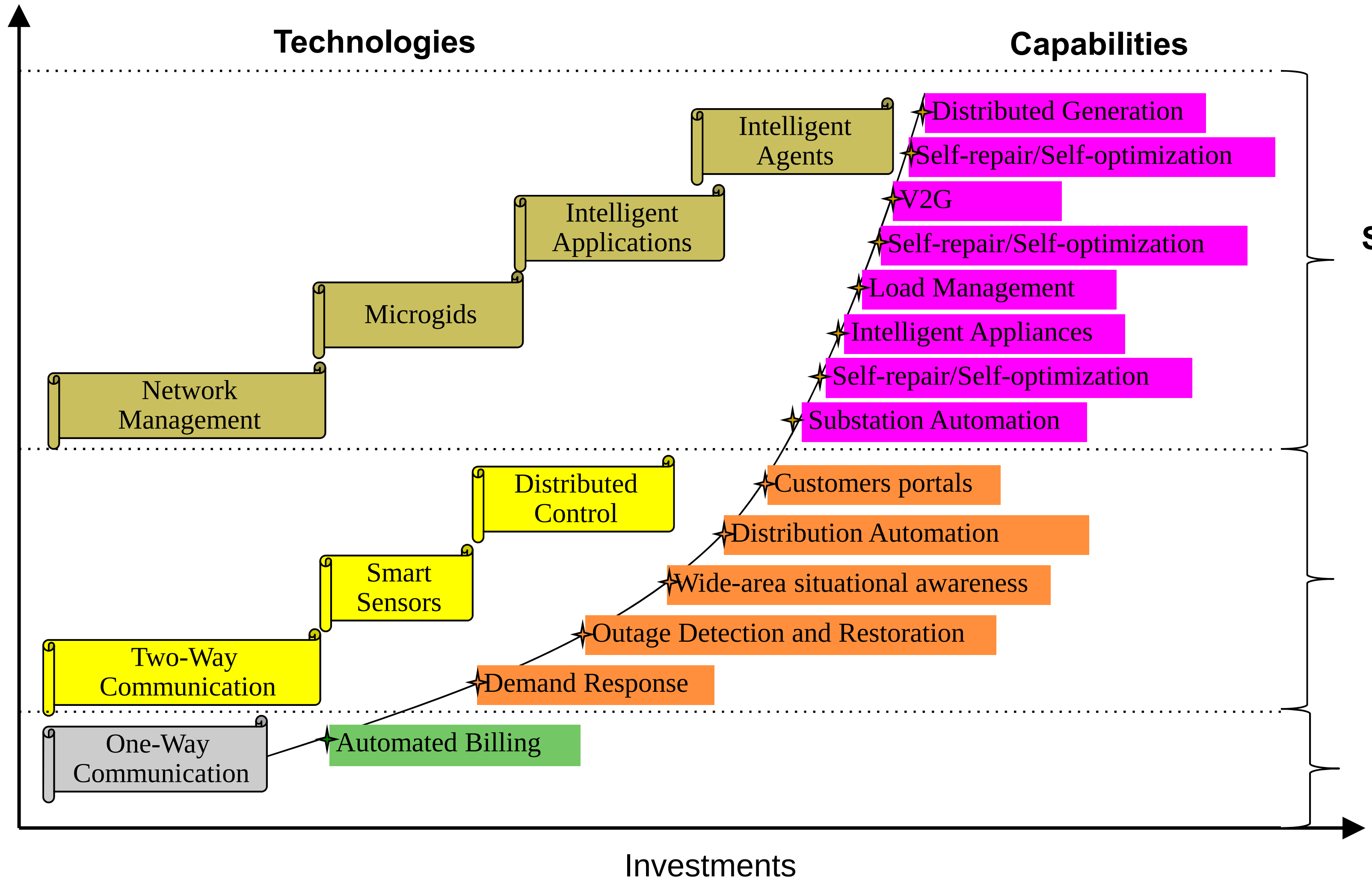
- Conventional hierarchical, unidirectional, and **centralized model** for electricity **production**, **distribution** and **control** adopted in the past is **not suitable** to meet the increasing demand for higher resiliency, efficiency, adaptability, and sustainability

- Trends that are driving the evolution of the next-generation electricity grid towards a “**smarter**” **system**:
  - The proliferation of residential-scale dispersed distributed energy sources based on **renewable resources**, which must be seamlessly integrated into the main grid, leading to **distribution of energy production**
  - Electricity **market deregulation** and the growing importance of **prosumers** present power flow scenarios and uncertainties electric systems were not designed to handle
  - **Bidirectional load management** to balance the supply of electricity with electrical loads
  - A new generation of power transport and control technologies are providing new levels of controllability in the grid.
  - The large-scale integration of mobile loads and resources, i.e., **plug-in electric vehicle**s (EVs)
  - The proliferation of widely dispersed **energy storage** systems

SMART ENERGY SYSTEMS: ICT ENABLERS

- **Smart Appliances** and **Intelligent Electronic Devices** (**IEDs**):
  - Residential **appliances** will no longer consist of dumb devices but will form interactive and **intelligent** on the smart grid with **communication, computing and storage capabilities**
  - **Sensors** will be massively deployed to continuously collect energy quality and consumption data, as well as equipment condition and operational status.
- **Advanced Metering Infrastructure**:
  - A **two-way communication system** needed to interconnect smart meters and IEDs with data aggregators and remote control centers
  - It will enable remote monitoring and control, new interactions between utility companies and customers, additional services
- **Real-Time Distributed Intelligence**:
  - **Protection**, **control** and **optimization** technologies will adopt a more **decentralized** and **autonomic** model in which multiple autonomous and independent energy management systems (EMSs) cooperate to dynamically balance load and resources to maximize energy delivery efficiency and security in real time

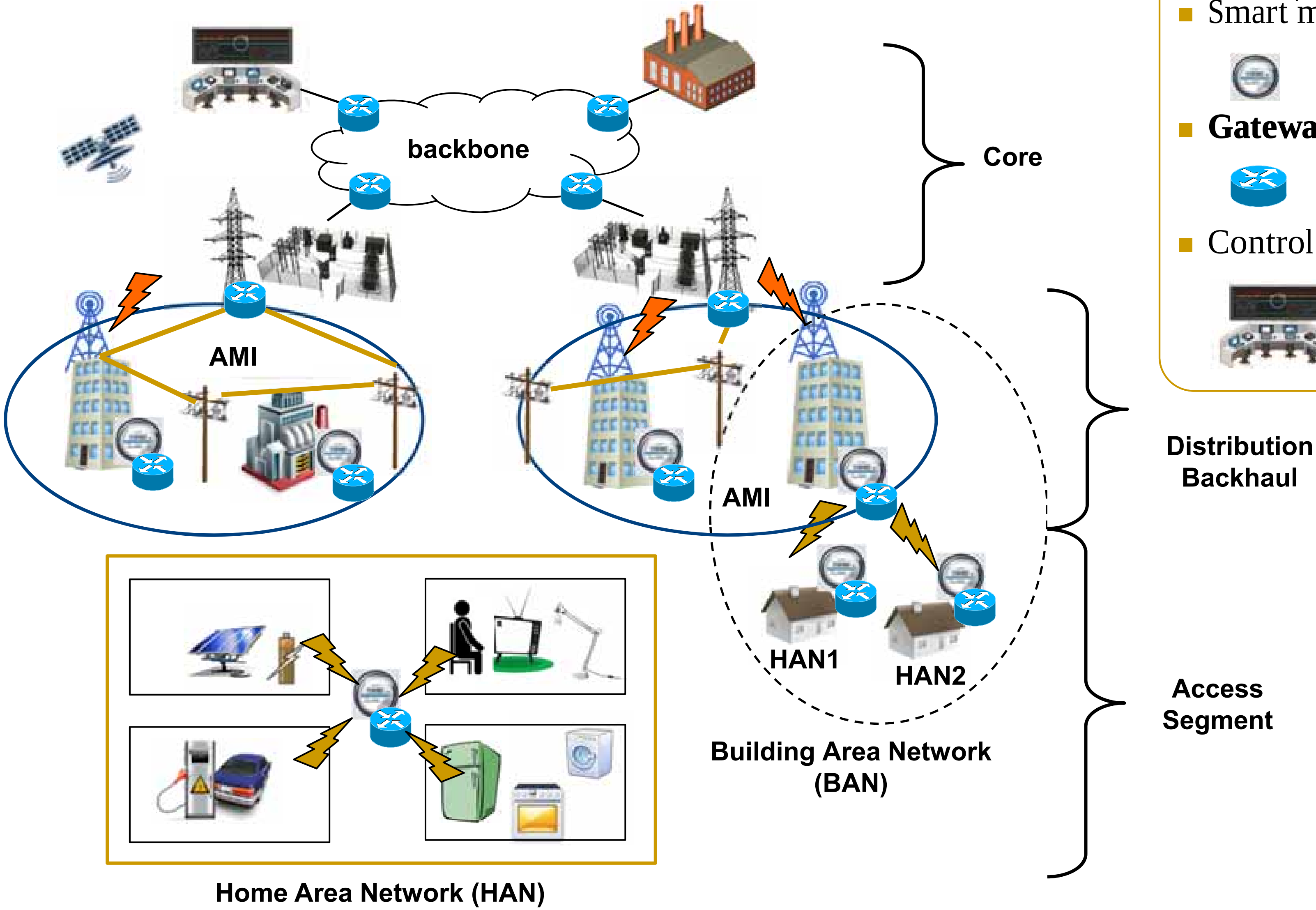
EVOLUTION PATH TOWARDS SMART ENERGY SYSTEMS



Source: H. Farhangi, "The path of the smart grid", IEEE Power & Energy Magazine, vol. 8, no. 1, pp. 18-28, 2010

A (Simplified) Model of the SG Communication Infrastructure

- Communication Links
- Smart meter
- **Gateway**
- Control center

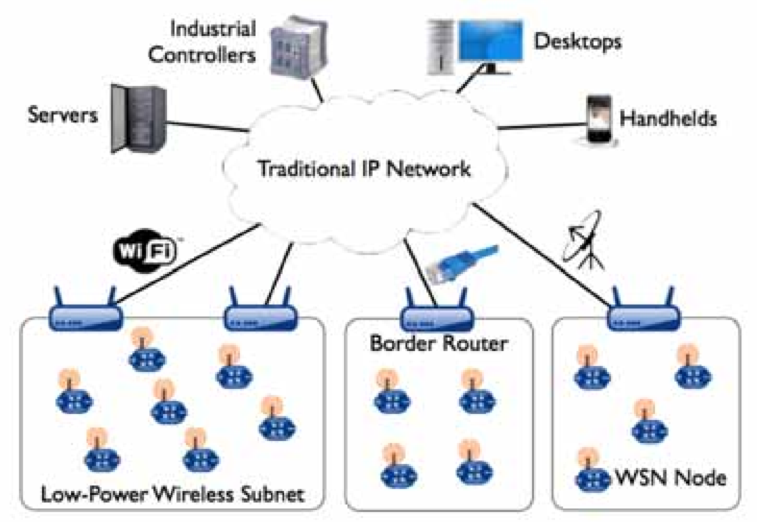


What type of Networking Technologies for the SG Access Segment?

- *What type of applications?*
  - **Data acquisition** (e.g., monitoring power quality, or how much electricity is produced/stored by DER units and consumed by households appliances)
  - **Command & Control** (e.g., distribution of configuration variables or commands to modulate electricity usage or to react to failure conditions and anomalies)
- *What type of communication technologies?*
  - **Communication technology diversity** because no communication technology can provide 100% coverage at reasonable cost, e.g.
    - Power Line Communication (Insteon, X10, G3- PLC, PRIME, HomePlug, LonWorks)
    - Wired technologies (DSL, GPON, EPON)
    - Mobile Communication (WiMAX, UMTS, LTE)
    - LAN/PAN technologies (ZigBee, WirelessHART, WiFi)
- *What type of devices and operating conditions?*
  - **Small embedded devices** that operate with constraints on processing power, memory, and, sometimes, energy
  - Environments are harsh, thus links can be characterized by **high loss rates**, **low data rates**, and **instability**

RESOURCE CONSTRAINED NETWORKS

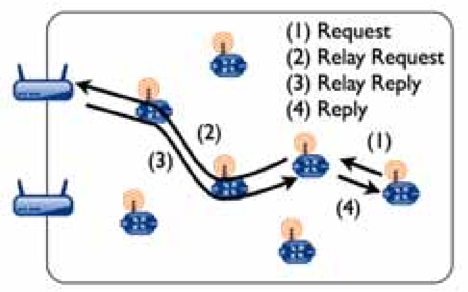
WHY INTERNET (IPV6) TECHNOLOGIES?



- The Internet Protocol (IP) has proven its **interoperability** and **extensibility** as the protocol underlying the global Internet
- The **large address space** of IPv6 provides for a huge number of devices, it eliminated many of the artificial naming constraints.
- Communicating natively with IP, **nodes can communicate end-to-end** with each other and any arbitrary IP device over the wide-area at the network layer.
- Internet already provides solutions for layering, **addressing**, header formats, **configuration**, management, **routing**, and **forwarding**
- **Gateways** are agnostic to the set of applications deployed in the network.

Source: Jonathan W. Hui, David E. Culler, "IP is Dead, Long Live IP for Wireless Sensor Networks", Proc. of ACM SenSys'08.

WHY IPV6 AND NOT IPV4?



- Various layer-two protocols (e.g., ARP and DHCP) have been pulled into the IPv6 framework to provide **native support for autoconfiguration**
- IPv6 also supports a richer set of communication paradigms, including a scoped addressing architecture and multicast into the core design
- IPv6 allows more **efficient implementations** than IPv4 (e.g., the structure of IPv6 addresses are more amenable to cross-layer compression)
- Autoconf and ICMPv6 were designed to address **scalability**, **neighbor discovery**, and **unattended operation**, all features necessary in production WSNs

IPV6 IS REGARDED AS THE REFERENCE ARCHITECTURE OF THE INTERNET OF THINGS

CRITICISMS FOR USING IP STACK IN RESOURCE-CONSTRAINED NETWORKS

- RFC-complaint IP stack is **too heavyweight** for small embedded devices with severe resource constraints and application-specific optimizations are necessary
- Internet protocols have been designed to support communications on **reliable link-layer technologies**.
- The **sheer number of devices** will preclude reliance on a broadcast communication or the configuration currently needed to deploy and operate networked devices in Internet
- Traditional networks are designed to accommodate a **wide range of applications**, while SG networks will be tailored for monitoring and control applications
- Unlike traditional networks, sensor nodes many not need an identity (e.g., an address) because naming can be data-centric

IETF Efforts towards IPv6 Adaptations for Resource-constrained Networks

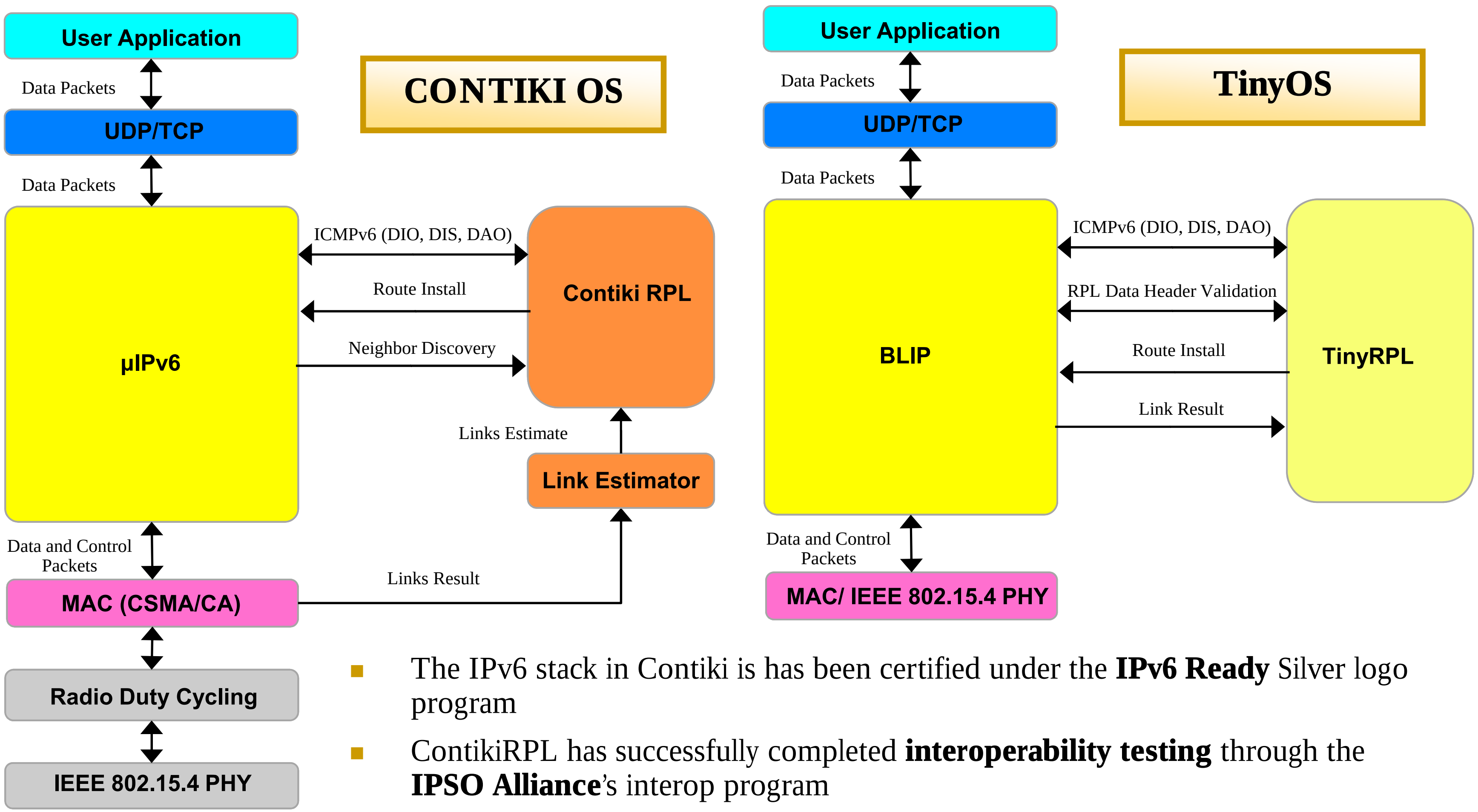
- In IETF the class of resource constrained networks is called Low-Power and Lossy Networks (LLNs) applicable to Building Automation, Home Automation, Industrial, and Urban application scenarios.

- The **IETF 6LoWPAN** working group has defined a
  - **Header compression** scheme for IPv6 over IEEE 802.15.4
  - link-layer **fragmentation** and **reassembly** mechanism
  - 6LoWPAN has been subsequently used for other link layers such as **PLC**

- The **IETF ROLL** working group has defined a
  - **IPv6-based routing protocol** optimized for data collection applications (gradient-based routing and default routes)
  - It is designed to **minimize memory requirements** (e.g., storage space for routing information and routing tables)
  - It is designed for networks with **high loss rates** and using low data rates communication technologies
  - It distributes **compact routing information** to support link-layer technologies with restricted frame sizes

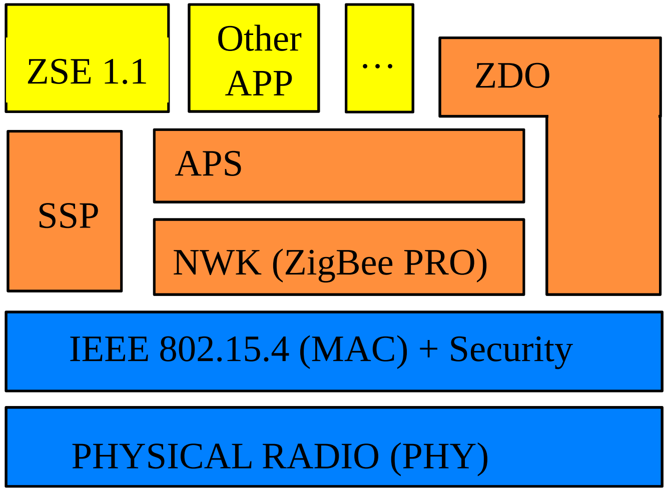
- The **IETF CoRE** working group is defining a
  - Constrained web protocol fulfilling M2M (**CoAP**)

IMPLEMENTATIONS OF THE IPV6 LLN STACK



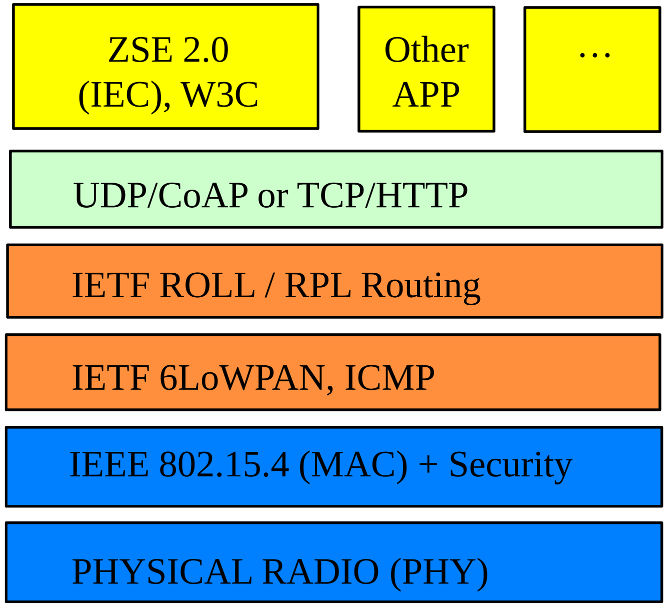
- The IPv6 stack in Contiki is has been certified under the **IPv6 Ready** Silver logo program
- ContikiRPL has successfully completed **interoperability testing** through the **IPSO Alliance**'s interop program
- Contiki includes implementations of the Point-to-Point Protocol (PPP) for tunneling packets over serial links., Serial Line IP (SLIP) and Ethernet adaptation

Protocol Stack for ZigBee Smart Energy

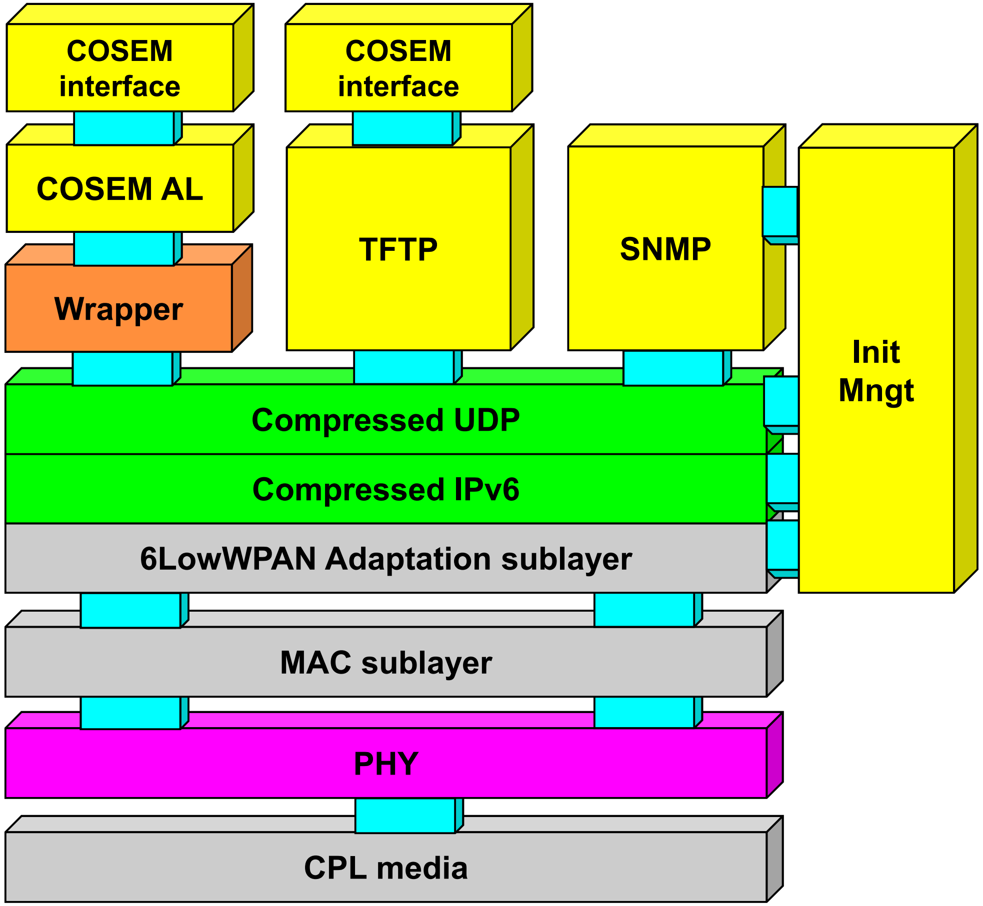


- The **Smart Energy Profile (SEP) 1.0/1.1** was developed to allow ZigBee to support communication between smart meters and products that that monitor, control, and automate the delivery and consumption of electricity and other utilities.
- Define a *Function Set* of application-specific features and commands

- **Smart Energy 2.0 Profile** is under development in response to the need for a single protocol to communicate with the growing universe of energy-aware devices and systems.
- Function Sets currently defined under SEP2.0 were expanded to include: DR & LC, Public Messaging, PHEV, DER Management, Billing



PROTOCOL STACK FOR PLC G3



- G3-PLC is a global, open **powerline communication** protocol specifically designed for smart grid communications
- G3-PLC relies on a robust high-performance PHY layer based on **OFDM** modulation
- Adoption of the IEEE 802.15.4 MAC layer, because it is regarded as perfectly suited to **handle noisy and heavily disturbed environments**
- Supports IPv6 to allow Internet-based energy management systems and applications.
- **Mesh routing protocol** to determine the best path between remote network nodes.
- IEC 62056-61/62 for object identification (COSEM AP)
- IEC 62056-53 as application layer (COSEM AL)

WHAT ABOUT **RELIABILITY**, **EFFICIENCY**, AND **SCALABILITY** IN RPL?

Experiments

- Network setup times are small but this is achieved at the expense of high protocol overheads, which can be a significant portion of the overall traffic **[1]** ☐
- RPL provides quick repair of local link failures and path quality fairly close to the one of shortest paths **[2]** ☐
- With proper RPL parameter tuning protocol overheads can be reduced without affecting RPL ability to quickly discover routes **[3]** ☑

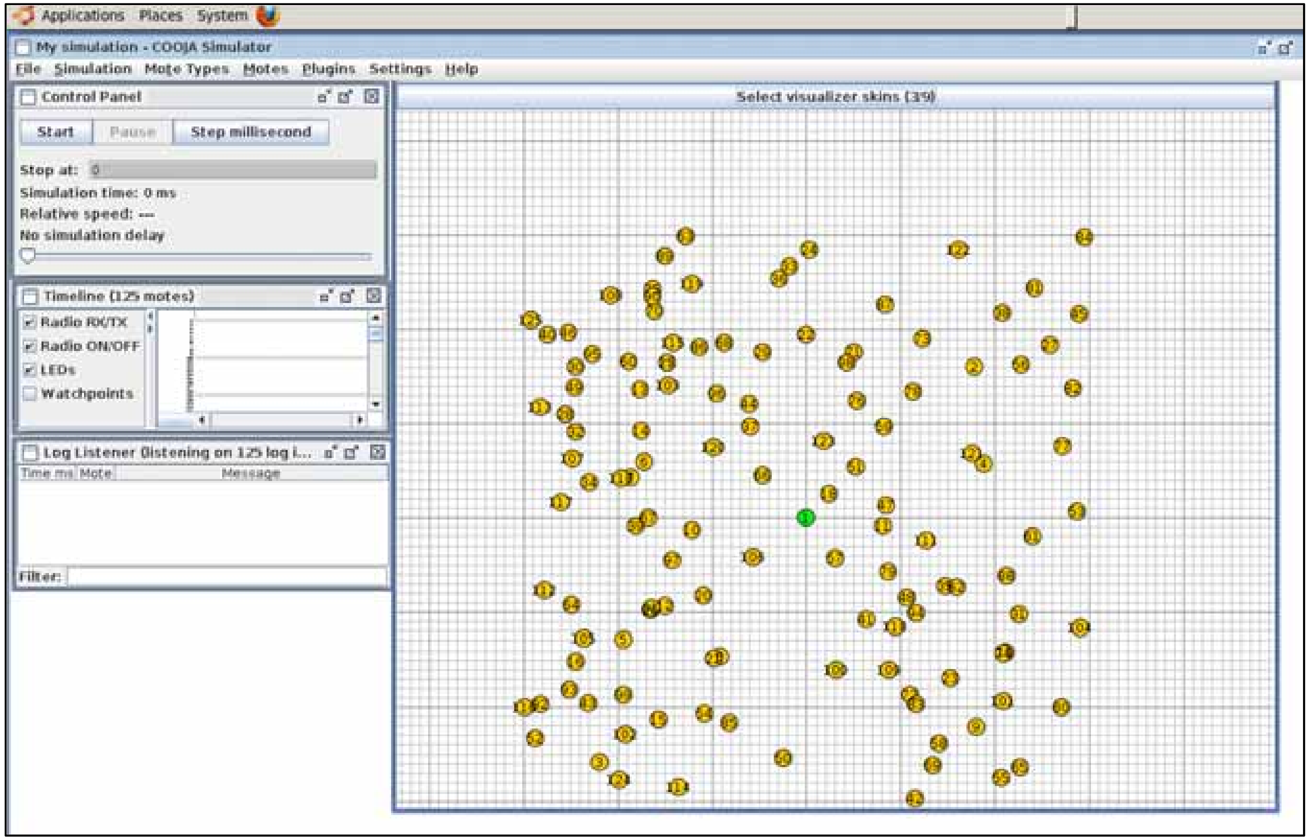
Open problems

- Is RPL able to provide **reliable communications** to applications?
- Is RPL design really **optimized** for devices with **limited data storage**, which can keep status information only for a limited set of links?
- Which is the efficiency or RPL mechanisms for **discovering and maintaining** information on **network topology** and link properties?
- Which is the **interplay** between RPL **routing** and **addressing**?

[1] N. Accettura, L. Grieco, G. Boggia, and P. Camarda, "Performance analysis of the RPL routing protocol," in *Proc. of IEEE ICM'11*, 2011
[2] J. Tripathi, J. de Oliveira, and J. Vasseur, "Applicability Study of RPL with Local Repair in Smart Grid Substation Networks," in *Proc. of IEEE SmartGridComm'10*, 2010
[3] N. Bressan, L. Bazzaco, N. Bui, P. Casari, L. Vangelista, and M. Zorzi, "The deployment of a smart monitoring system using wireless sensor and actuator networks," in *Proc. of IEEE SmartGridComm'10*, 2010

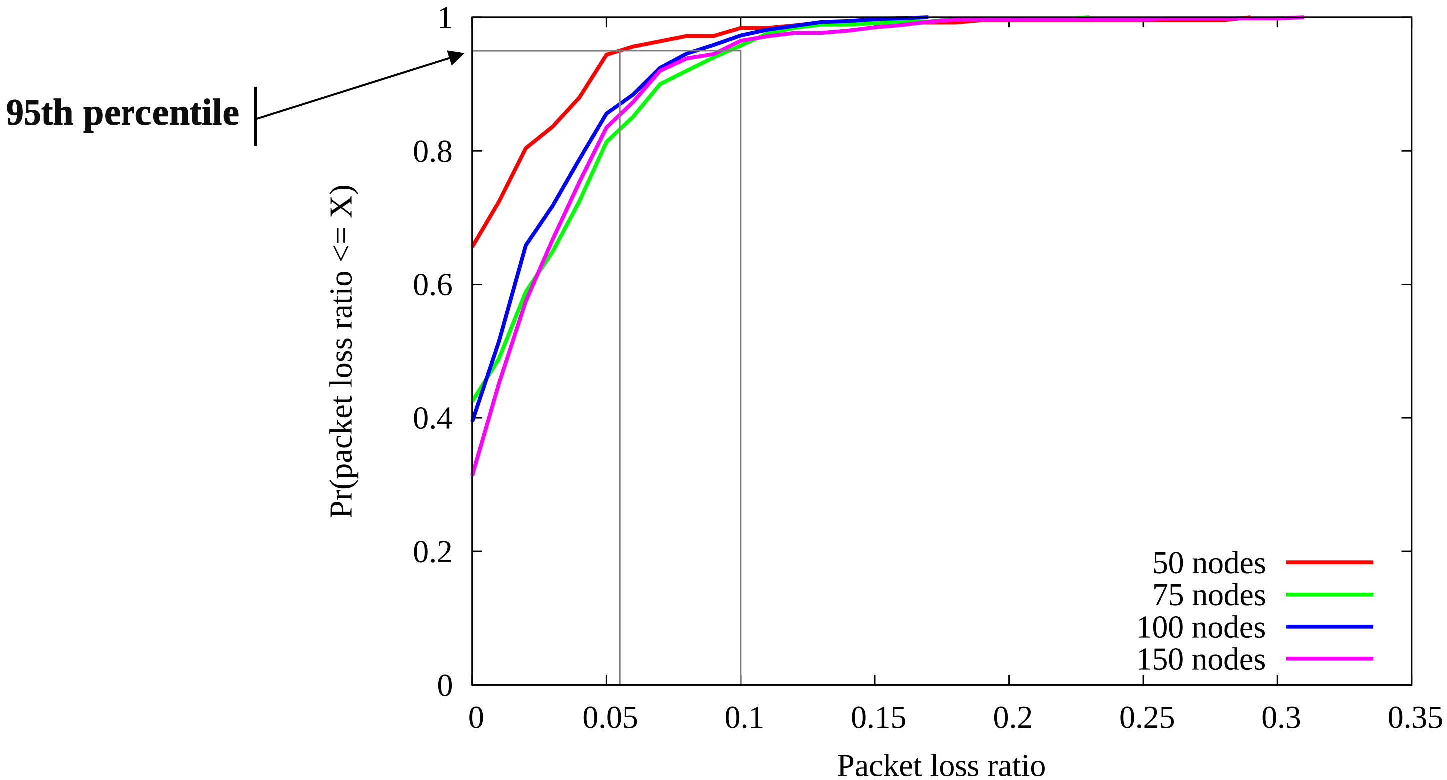
EMULATION SETUP - COOJA

COOJA is a **cross-level simulation platform** that combines low-level simulation of device hardware with execution of CONTIKI software



- Network Size **= 800m x 800m**
- *Tmote Sky* platform (10KB RAM, 48KB flash)
- 802.15.4-compatible CC2420 radio chip (250kbps,MTU=127B)
- *MAC protocol*: CSMA/CA shipped with Contiki
- *Channel model*: Multi-path Ray-tracer Medium (MRM)
- Traffic: **CBR**, *30-byte long packets every minute*

CDF OF PACKET LOSS RATIOS



- **95th percentile** of packet loss ratios is around **10%**
- Packet loss ratios can be **up to 30%**
- **Every smart meter** should be able to **reliably deliver its metering data** to the network data aggregator to provide reliable smart grid services to individual end customers

RPL ENHANCEMENTS UNDER INVESTIGATION (AT CNR)

- To investigate lightweight **channel probing techniques** that could improve the efficacy of RPL procedures for topology construction but avoid using costly periodic probing (e.g., coordinated policies to manage RPL and IP neighborhood tables, which enable a probabilistic exploration of the links with neighbors)
- To explore techniques for **discovering link properties** in order to reduce the probability that RPL uses inconsistent or outdated link information (e.g., to maintain more precise information for the nodes that are most useful for the RPL routing)
- To investigate mechanisms to remove links/network paths that cannot meet the (stringent) **reliability** requirements demanded by the application, while preserving the global **network connectivity**
- To investigate hierarchical addressing scheme that can preserve the scalability of the routing state maintained by RPL

THANKS

BACKUP SLIDES

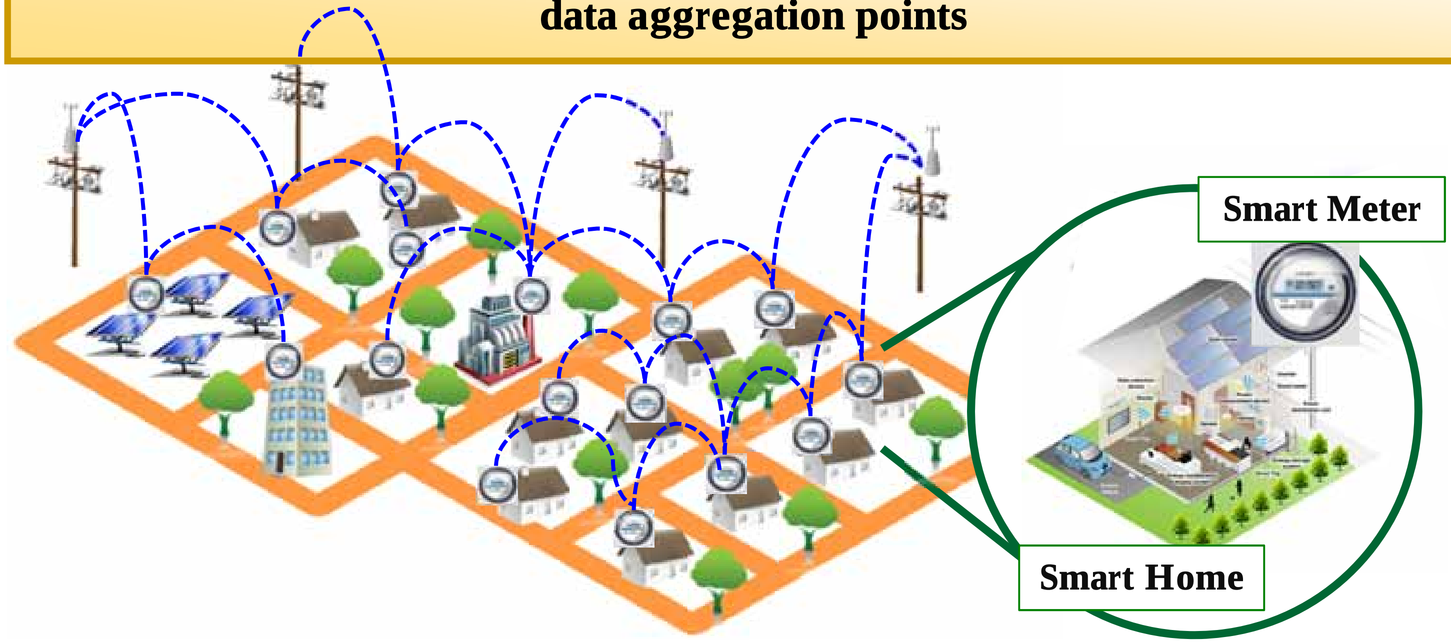
SMART HOUSES AND BUILDINGS

- End-user energy management systems will monitor the energy consumption situation in residences, office buildings, and shop-ping malls.
- They will know the consumption patterns and preferences of the occupants, as well as real-time conditions (e.g., market prices, grid stress).
- They will use the collected information to autonomously interact with the grid to determine the charging and discharging cycles of plug-in electric vehicles, schedule washer and dryer cycles, and optimize HVAC operations without sacrificing occupants' comfort.
- Appliances will continuously monitor voltages and frequencies.
- When the system experiences distress due to unforeseen disturbances, the appliances will modulate the power consumed to reduce the stress on the system and help prevent service disruptions.

Source: www.nec.com

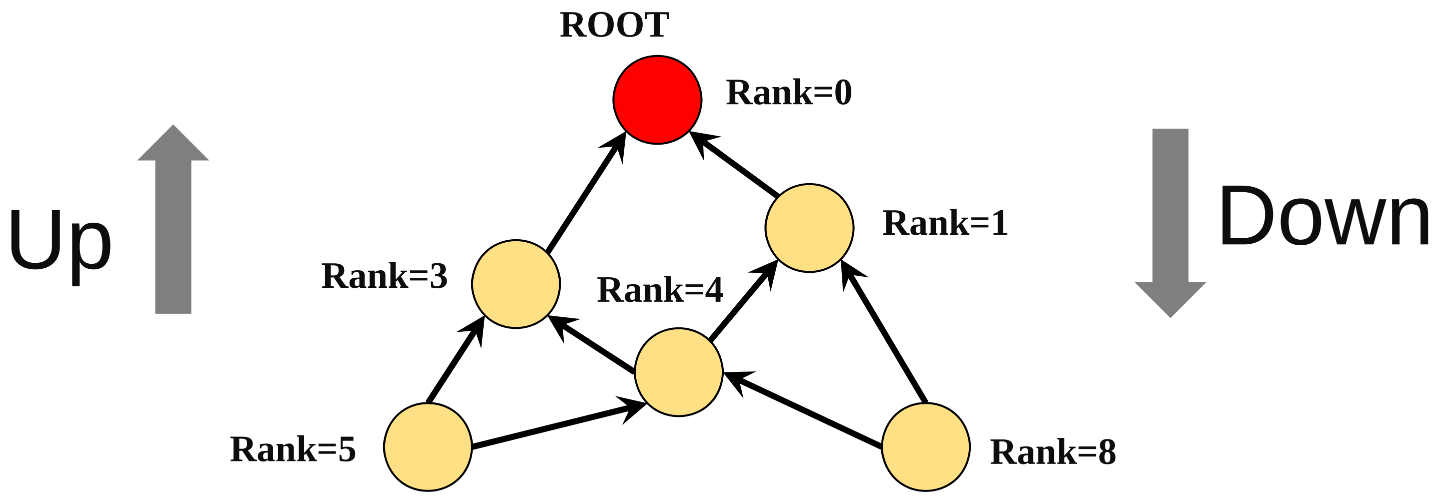
ADVANCE METERING INFRASTRUCTURE (AMI)

An **AMI** is a **two-way communication network** interconnecting **smart meters** (installed at end customers' premises) and intelligent electric devices (**IEDs**) with **data aggregation points**



- AMI are needed in smart grids:
  - To enable large-scale and pervasive **data acquisition** (e.g., to monitor power quality, DER and energy usage of home appliances)
  - To **send configuration variables** and **commands** to smart meters and IEDs
  - To support new smart grid services (e.g., demand response through dynamic pricing or direct load control, etc.)

TOPOLOGY CONTROL IN RPL



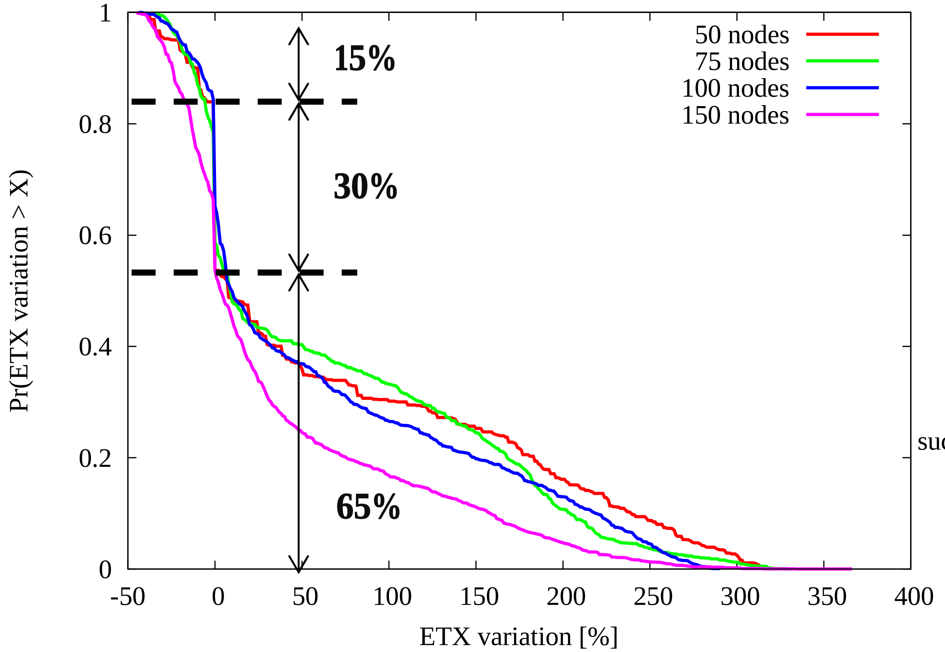
- RPL network topology is a directed acyclic graph routed at a single destination (**DODAG**)
- RPL assigns to each node a **rank value**, which is a scalar representation of the location of that node within the DODAG (e.g., distance from the root)
- Rank values form a **routing gradient**, i.e., the rank of the nodes must monotonically decrease as the DODAG is followed towards the root
- The **Objective Function** specifies how:
  - Nodes compute rank values from link and path metrics
  - Nodes select preferred parents in the DODAG

LESSONS LEARNED

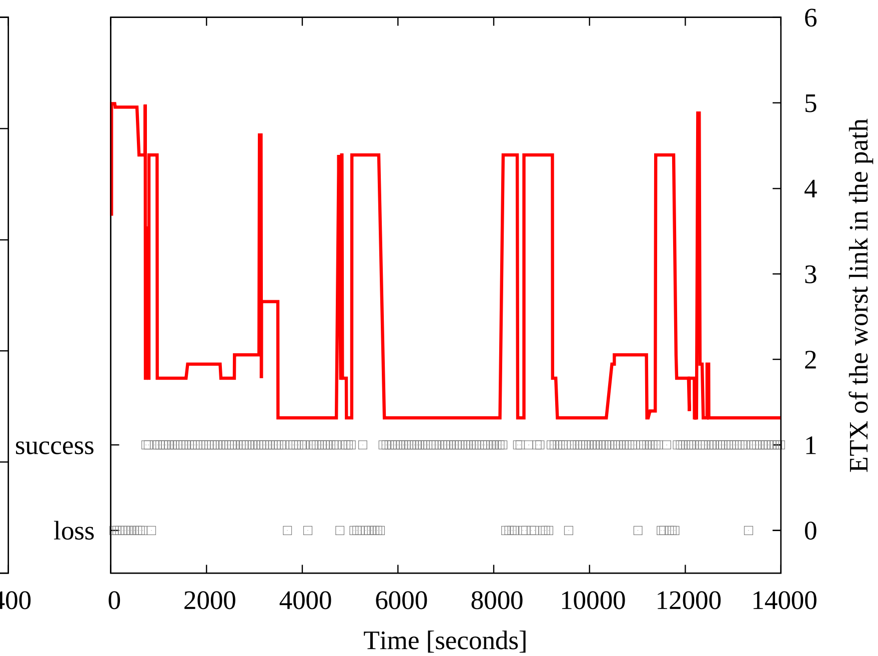
- RPL procedures for route selection create **dominant routes that are significantly persistent**
- RPL has a very **partial knowledge** of the link qualities because the neighbor attribute cache has a limited size, and RPL collects **estimates only for the links on which data traffic is transmitted**.
- **Data-driven techniques** for link estimation **do not appear the best choice** during DODAG construction because they do not allow exploration of nodes' neighborhoods
- RPL procedures for DODAG construction ensure short setup times but are **scarcely adaptive** (trial-and-error approach)
- RPL nodes may sometimes use network paths with **many long and unreliable links**
- Losses are not due to congestion, indeed **end-to-end delays are small**

UNDERSTANDING THE CAUSES OF PACKET LOSSES

CCDF – route flaps



Node with avg. packet loss ratios = 0.2



- **15%** of route flaps offer an **improvement of the worst link**
- **30%** of route flaps **maintain an equivalent worst link**
- **65%** of route flaps cause a **significant degradation** of the quality of the worst link
- Most of the **packet losses occur on low-quality links** that may be selected by RPL even if alternative high-quality links are available.