Cross-Layer Interactions in IP Wireless Sensor Networks

Andrzej Duda

Grenoble INP - Ensimag

Grenoble Informatics Laboratory

duda@imag.fr

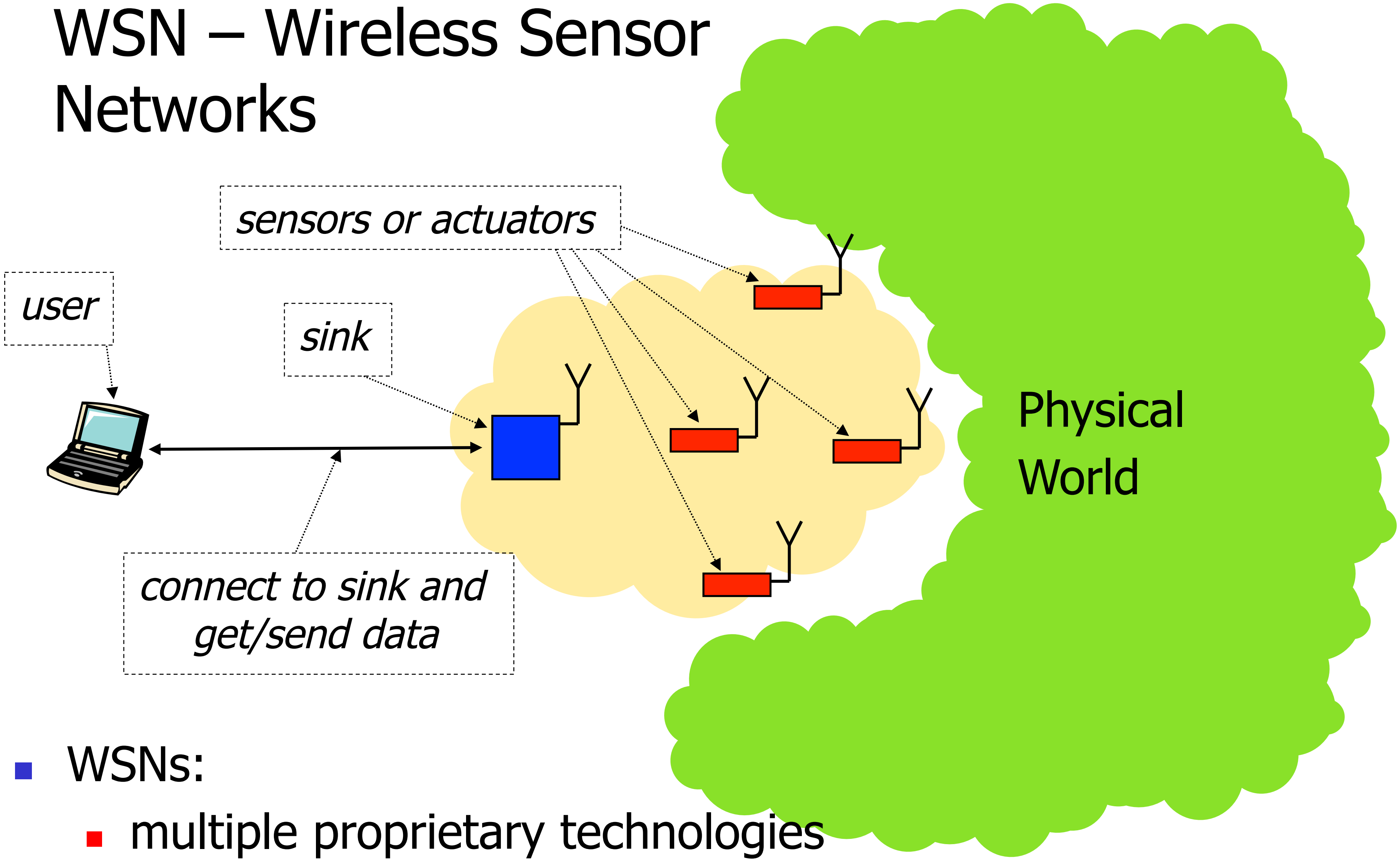
http://duda.imag.fr

Overview

- Wireless Sensor Networks and Internet of Things
- IP protocol stack
- L2 - MAC issues: saving energy
- L3 - IP and routing
- L2 - L3 Layer interactions
- Conclusions

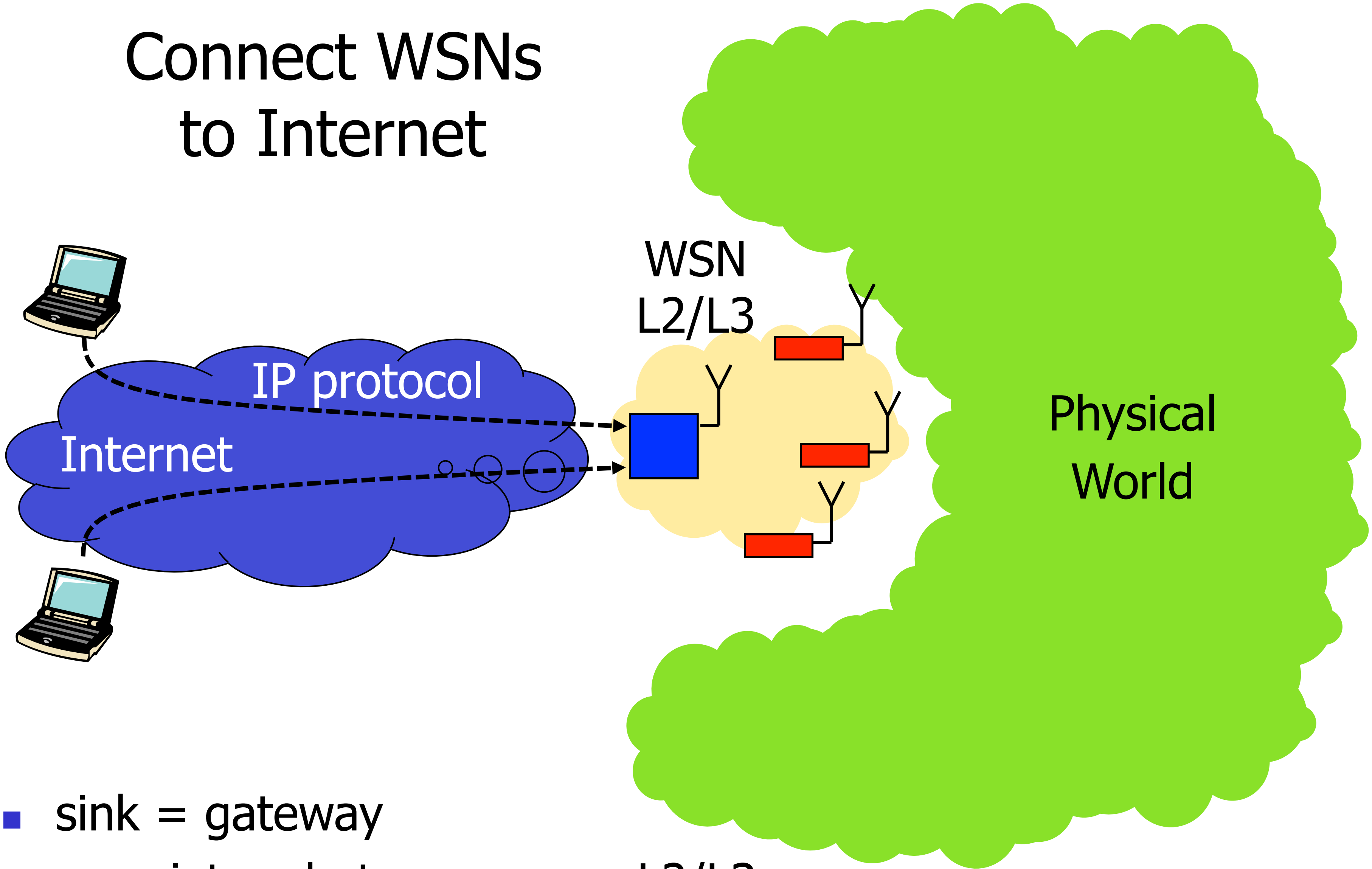
Wireless Sensor Networks and Internet of Things

WSN – Wireless Sensor Networks



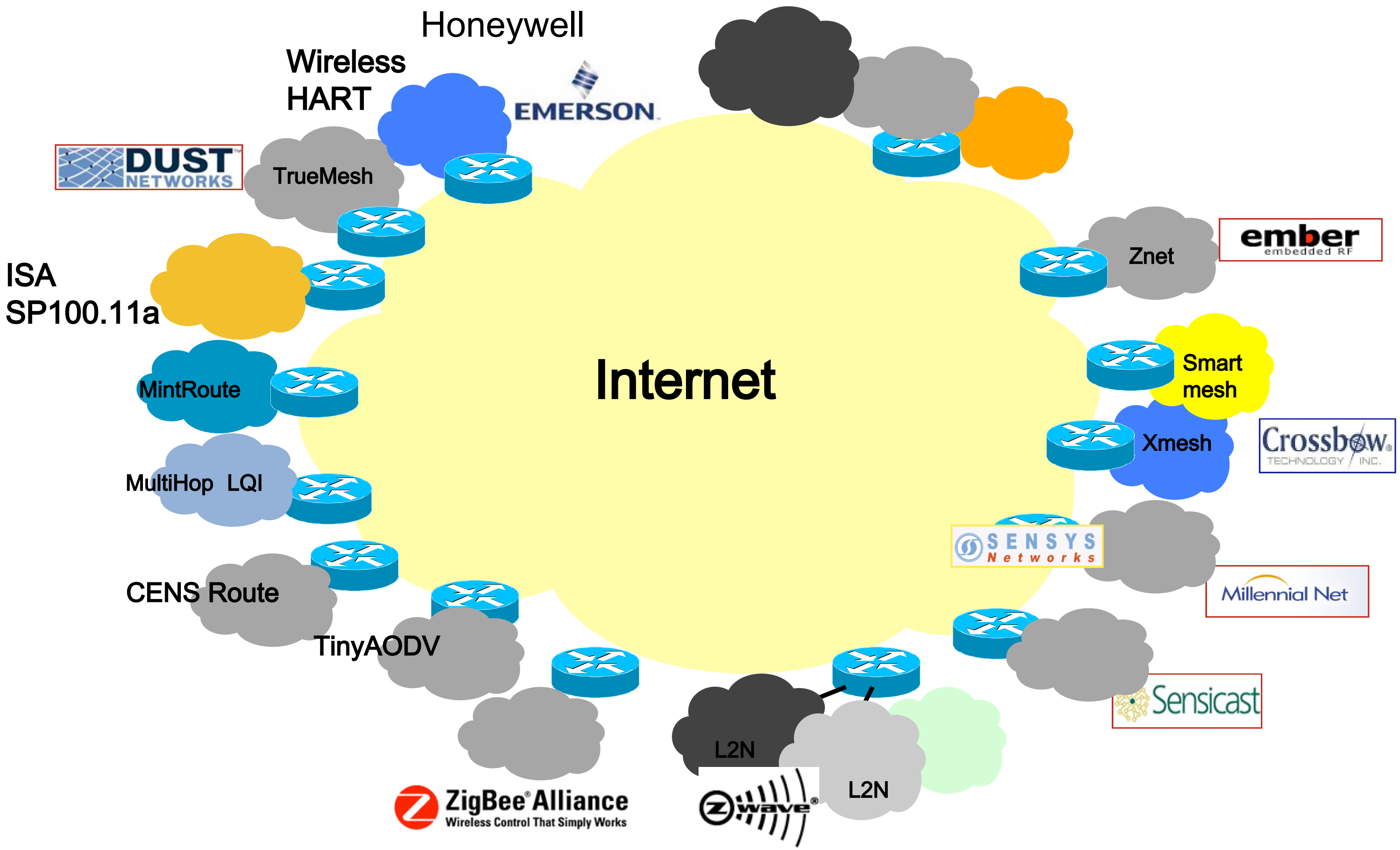
- WSNs:
  - multiple proprietary technologies (Wavenis, DUST, EMBER, Z-WAVE, Crossbow, many others…)

Connect WSNs to Internet



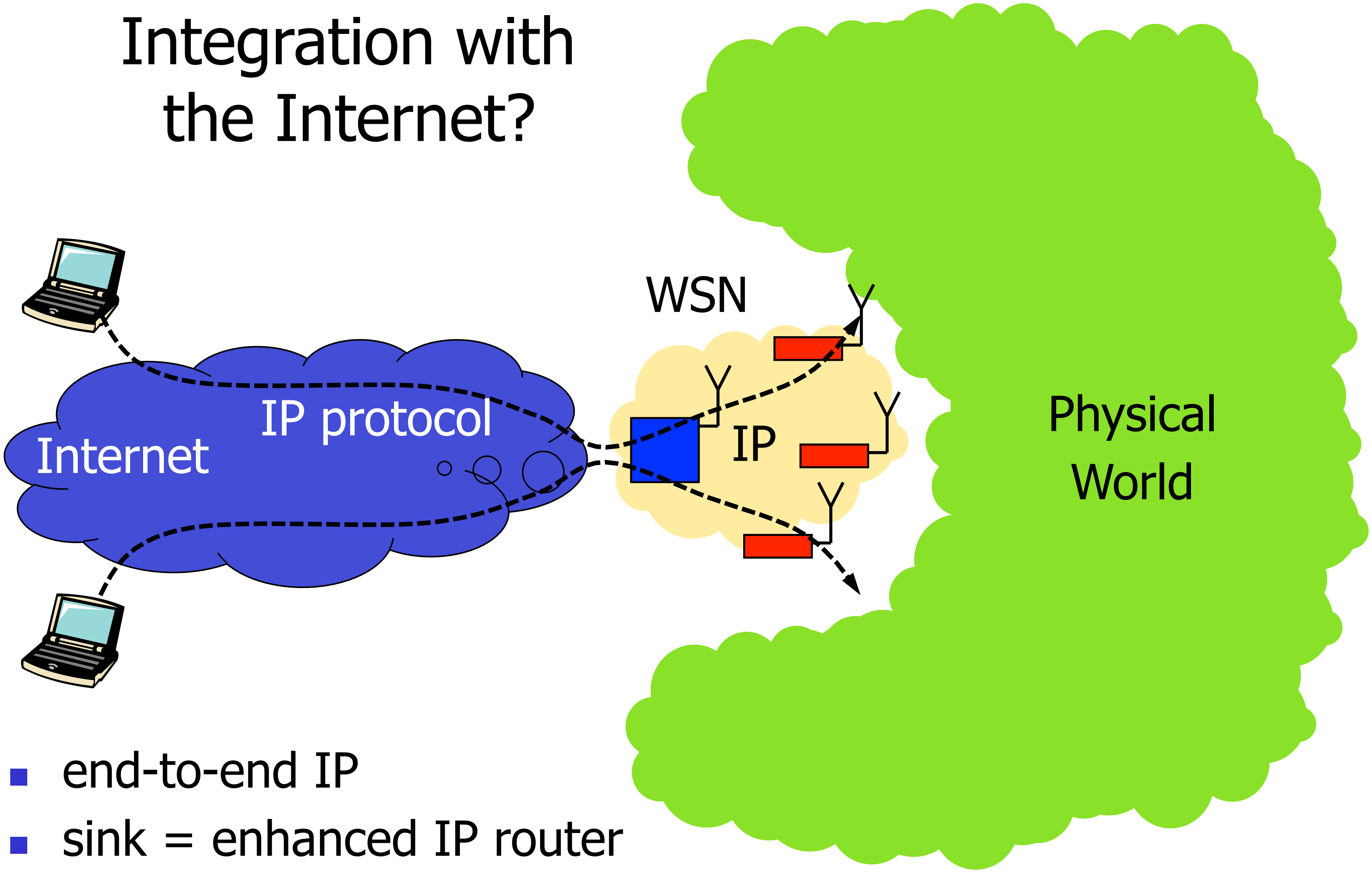
- sink = gateway
- proprietary heterogeneous L2/L3
- many gateways for each L2/L3

IETF July 2007



courtesy of JP Vasseur

Integration with the Internet?



- end-to-end IP
- sink = enhanced IP router
  - header compression, data aggregation, security
- nodes are IP enabled, endpoints with IP addresses

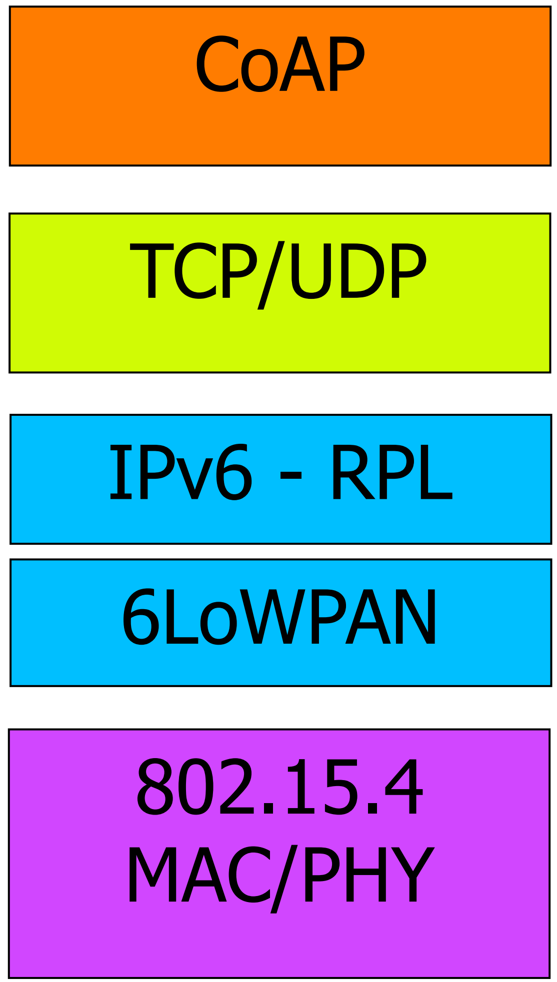
Target Applications

- Smart Grid
  - precise metering of electricity distribution
  - monitoring of energy consumption
  - acting upon devices
- Urban/Environmental Sensing
  - generic platform for sensing applications
- Environmental Sensing
  - low cost wireless communications
- Home and building automation
  - heating/air conditioning, light control

Internet of Things and IP protocol stack

Internet of Things

- Application (HTTP like)
  - CoAP (Constrained Application Protocol)
- Transport
  - lightweight, chosen functions
- Network – Routing
  - adaptation (header compression)
- MAC
  - Low Radio Duty Cycle
- PHY
  - 802.15.4, LP 802.11, Wavenis



Internet of Things

- CoAP:
  - simplified HTTP, RESTful (no state, asynchronous request/response)
  - point-to-point, client initiated
  - on top of UDP
- RPL:
  - Distance Vector routing protocol
  - builds Directed Acyclic Graph (multiple parents)
- 6LoWPAN:
  - adaptation layer for IPv6 over IEEE 802.15.4
  - fragmentation/header compression

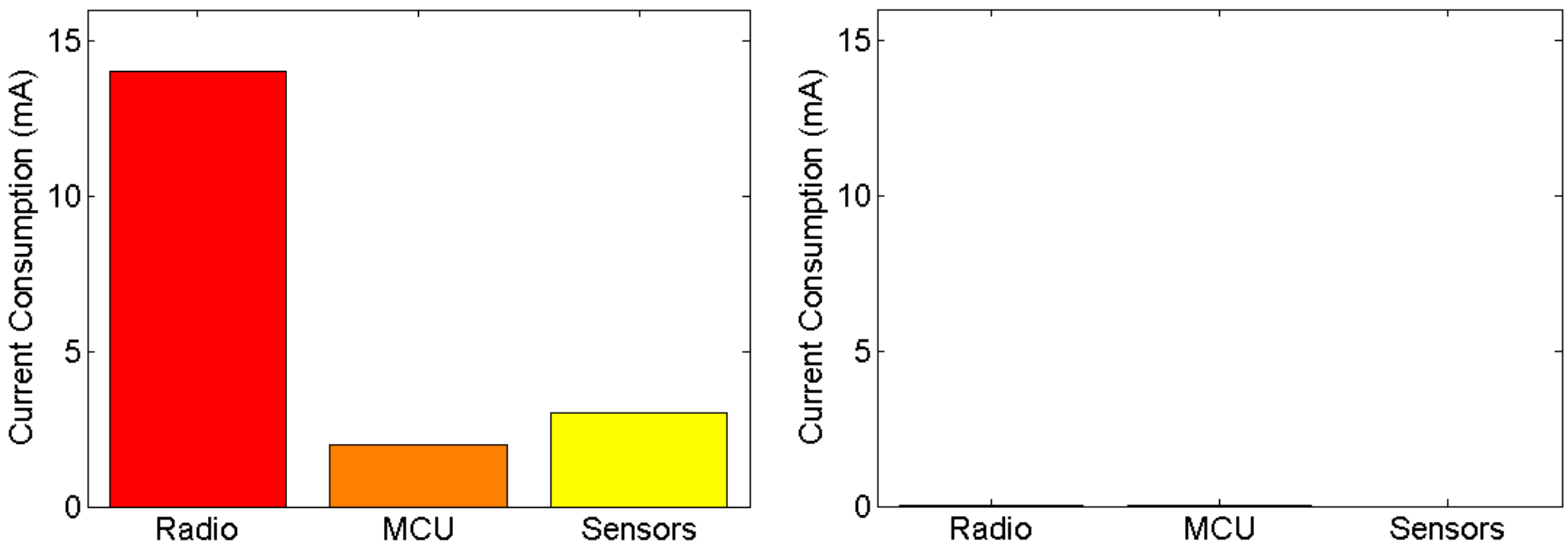
Contiki (SICS)

Transport UDP / TCP	End–to–end reliability, application addressing
Network (IPv6, RPL)	Host addressing, routing
Adaptation (6lowpan, ...)	Header compression, fragmentation
Medium Access Control (CSMA/CA, ...)	Medium access control
Radio Duty Cycling (ContikiMAC, X–MAC, ...)	Low–power operation
Link (802.15.4, 802.11, ...)	Radio connectivity

L2 - MAC Issues: Saving Energy

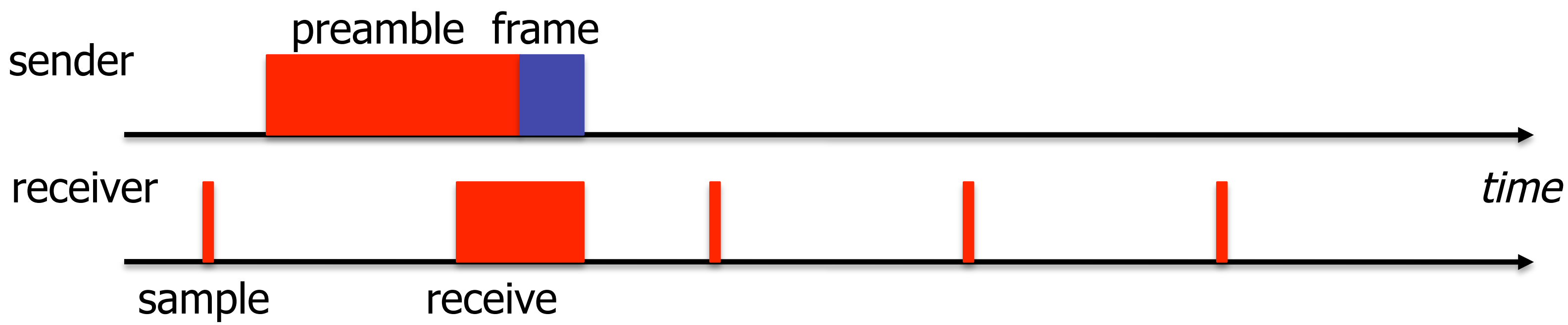
PHY Layer

- Energy consumption
  - most energy spent for radio transmission and reception!

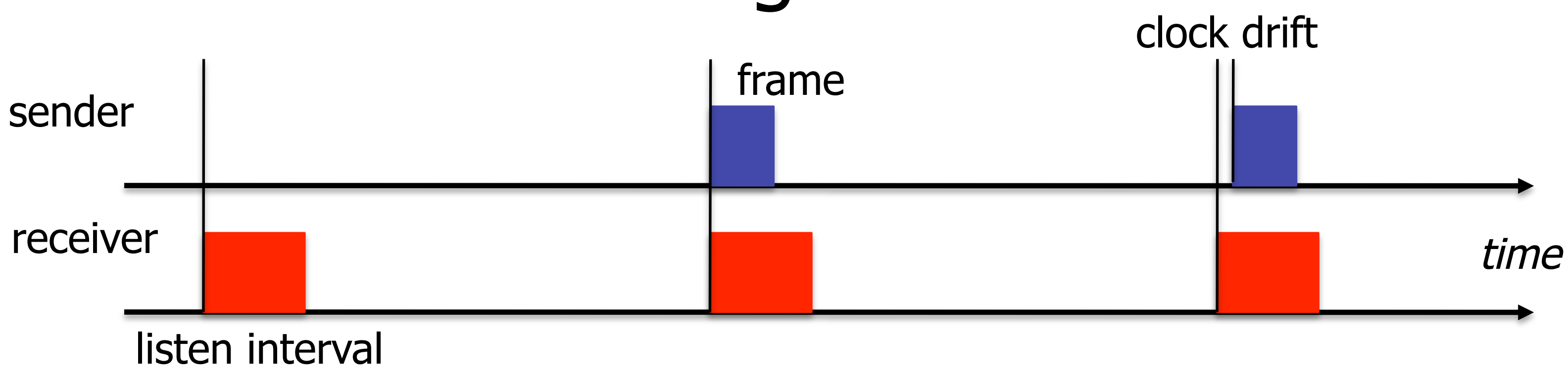


Basic MAC access methods

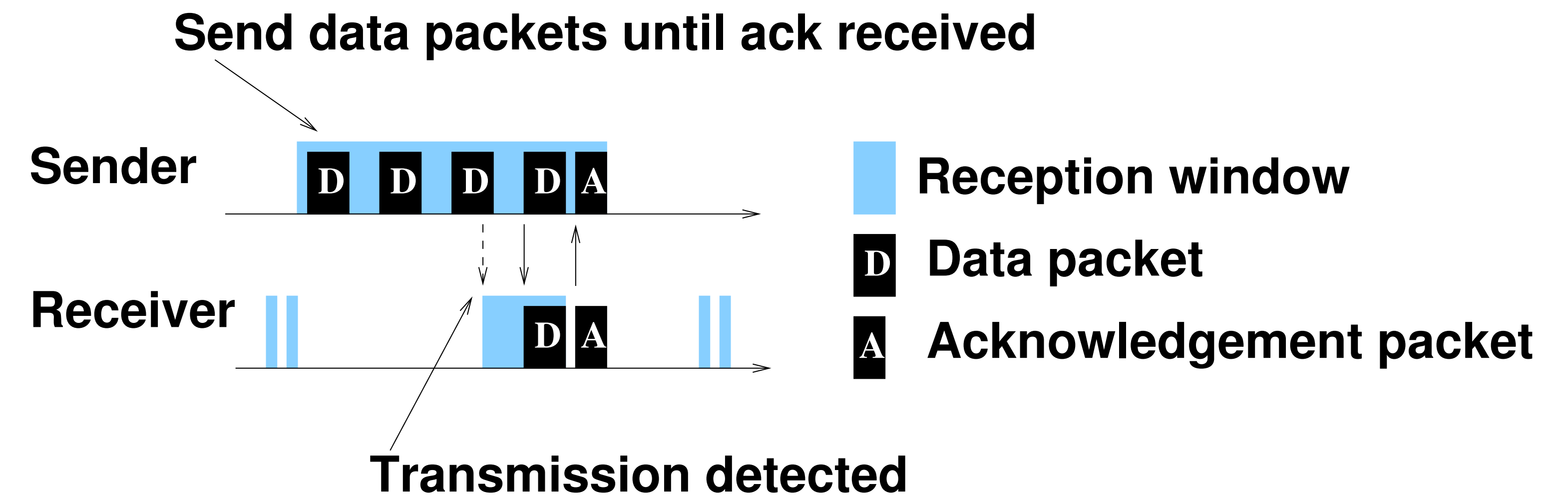
- Preamble Sampling

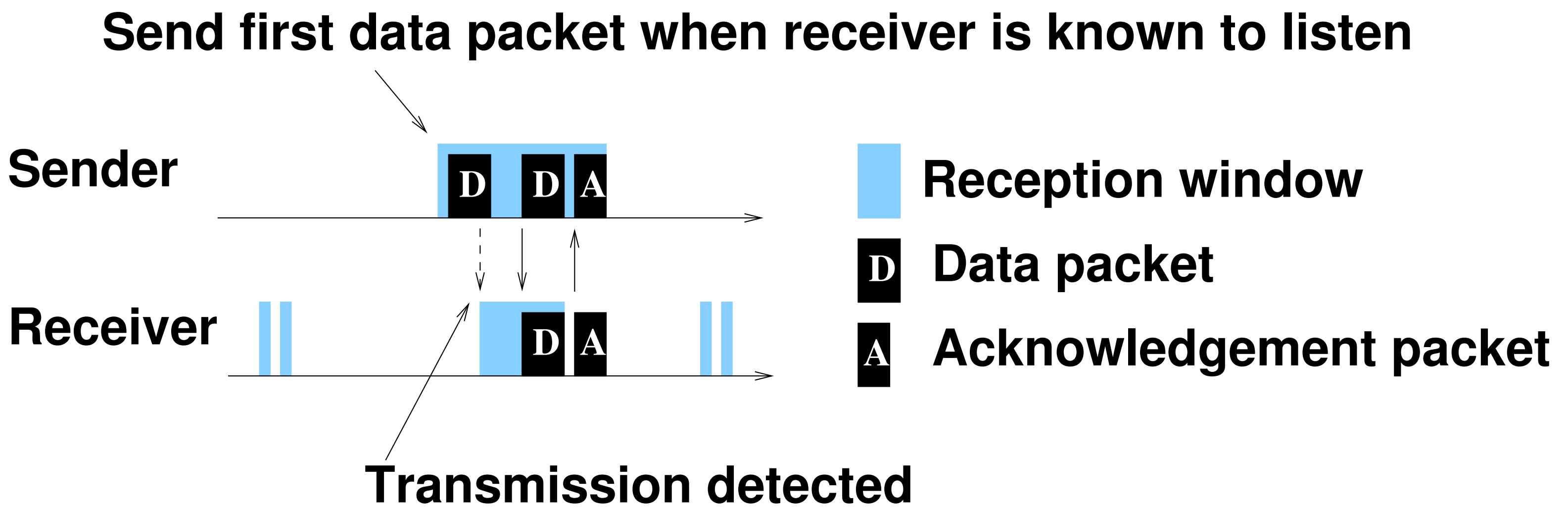


- Scheduled Listening

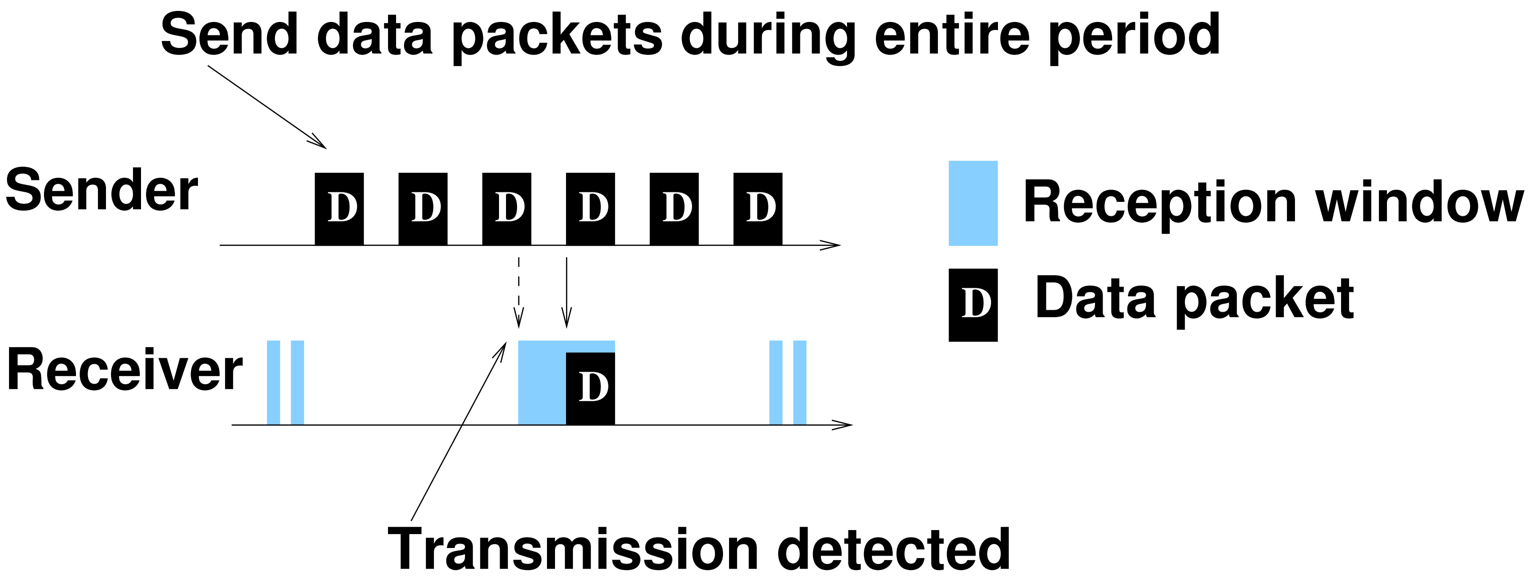


ContikiMAC – X-MAC

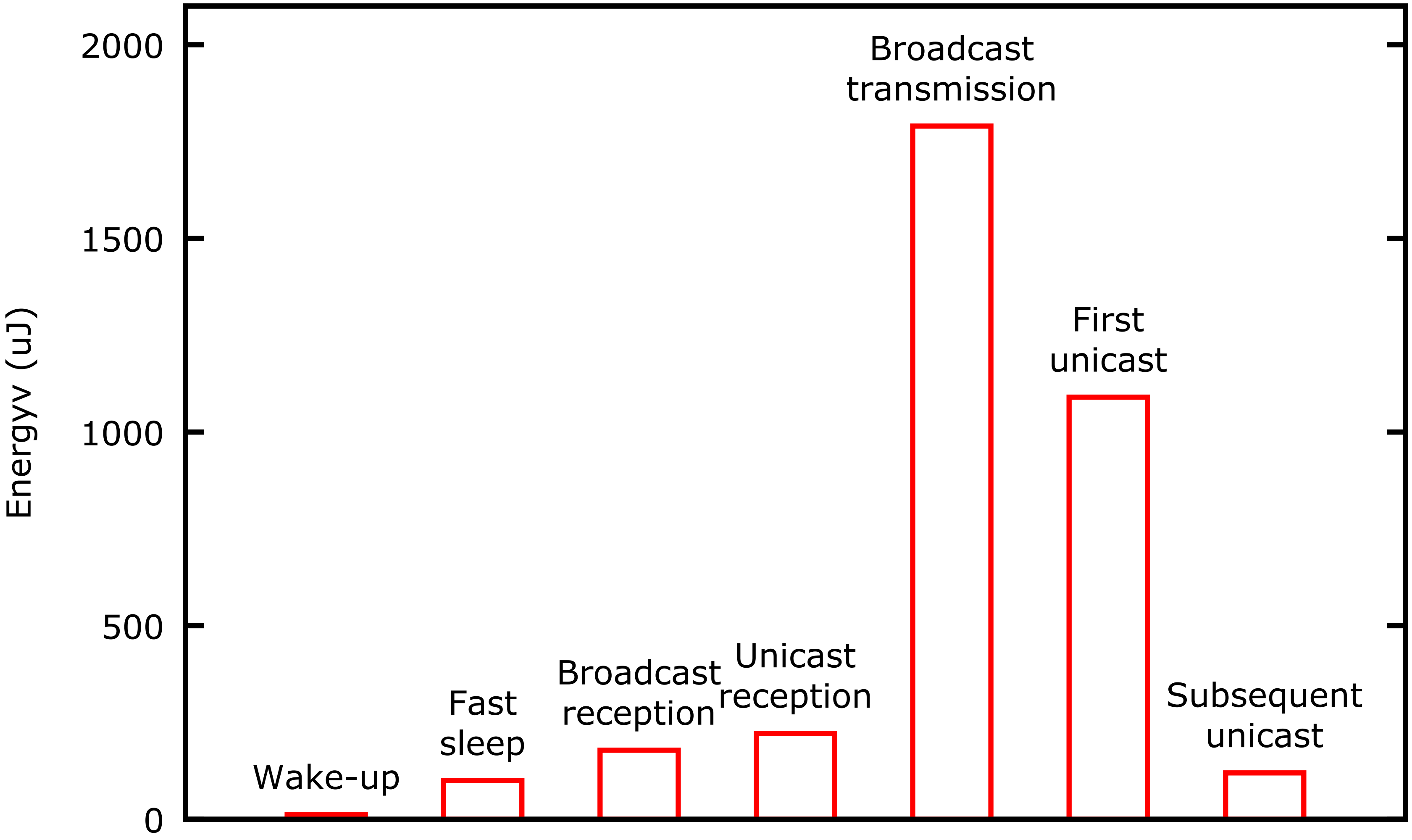




ContikiMAC - broadcast



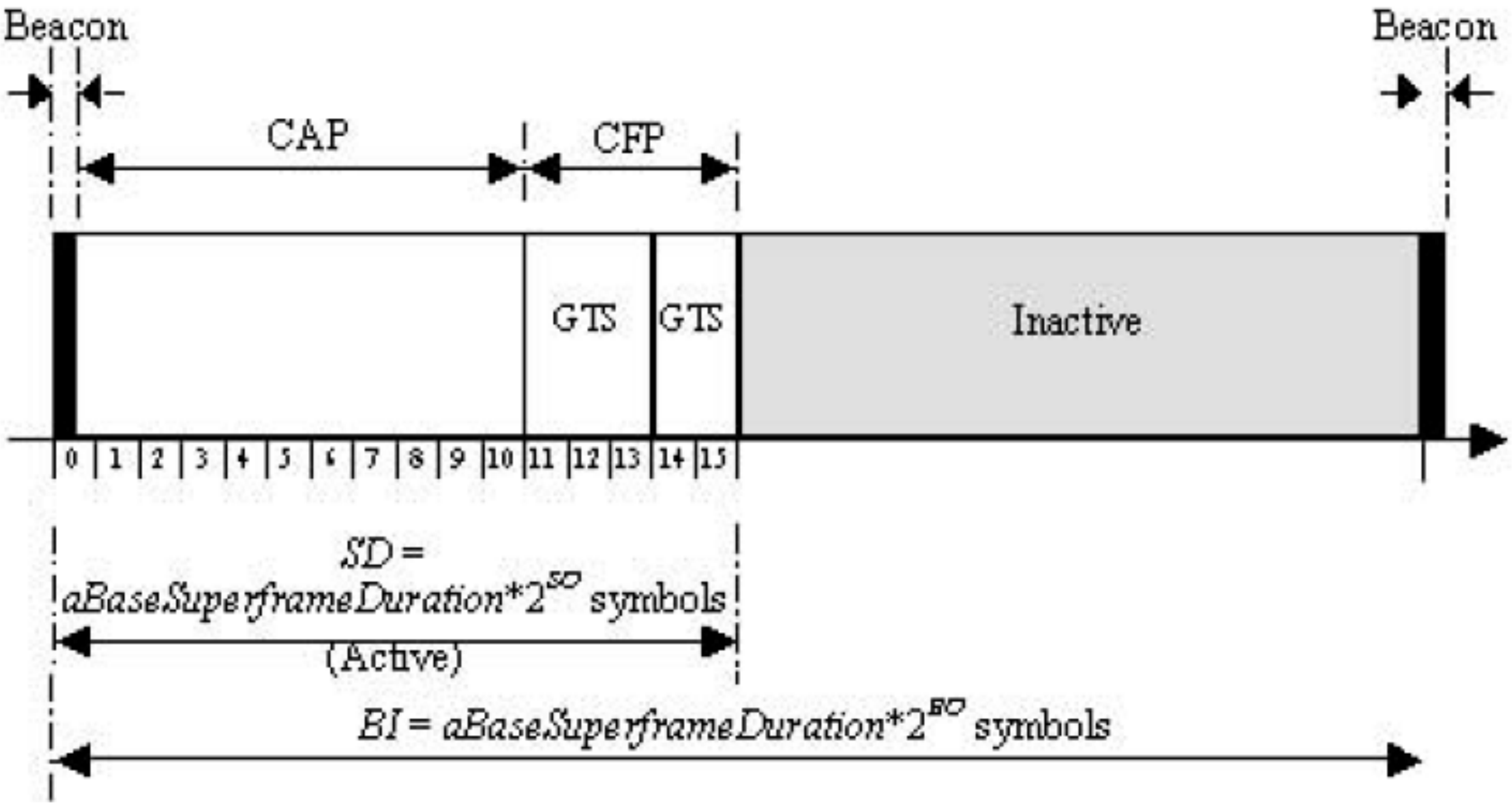
ContikiMAC - broadcast



802.15.4

- TDMA controlled by a PAN Coordinator
  - **Beacons** – common time base
  - define Superframe structure
- Devices may sleep for extended periods over multiple beacons
- Slotted CSMA in beaconed PANs
- Unslotted CSMA in non-beaconed PANs
- Low duty cycle requires **beaconed enabled mode** and **slotted CSMA**

Superframe



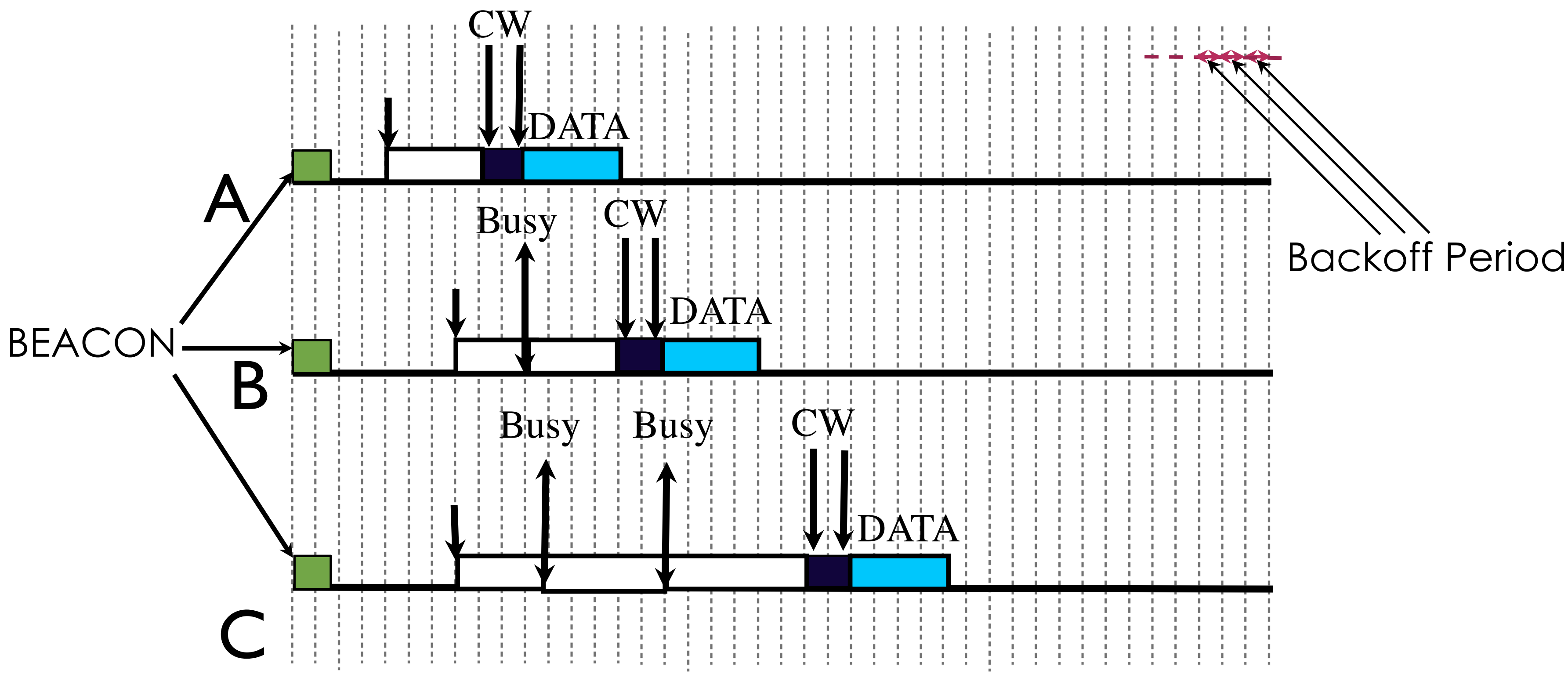
Beacon
Beacon
CAP
CFP
GTS
GTS
Inactive
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
SD = aBaseSuperframeDuration*2^SO symbols
(Active)
BI = aBaseSuperframeDuration*2^BO symbols

CSMA/CA

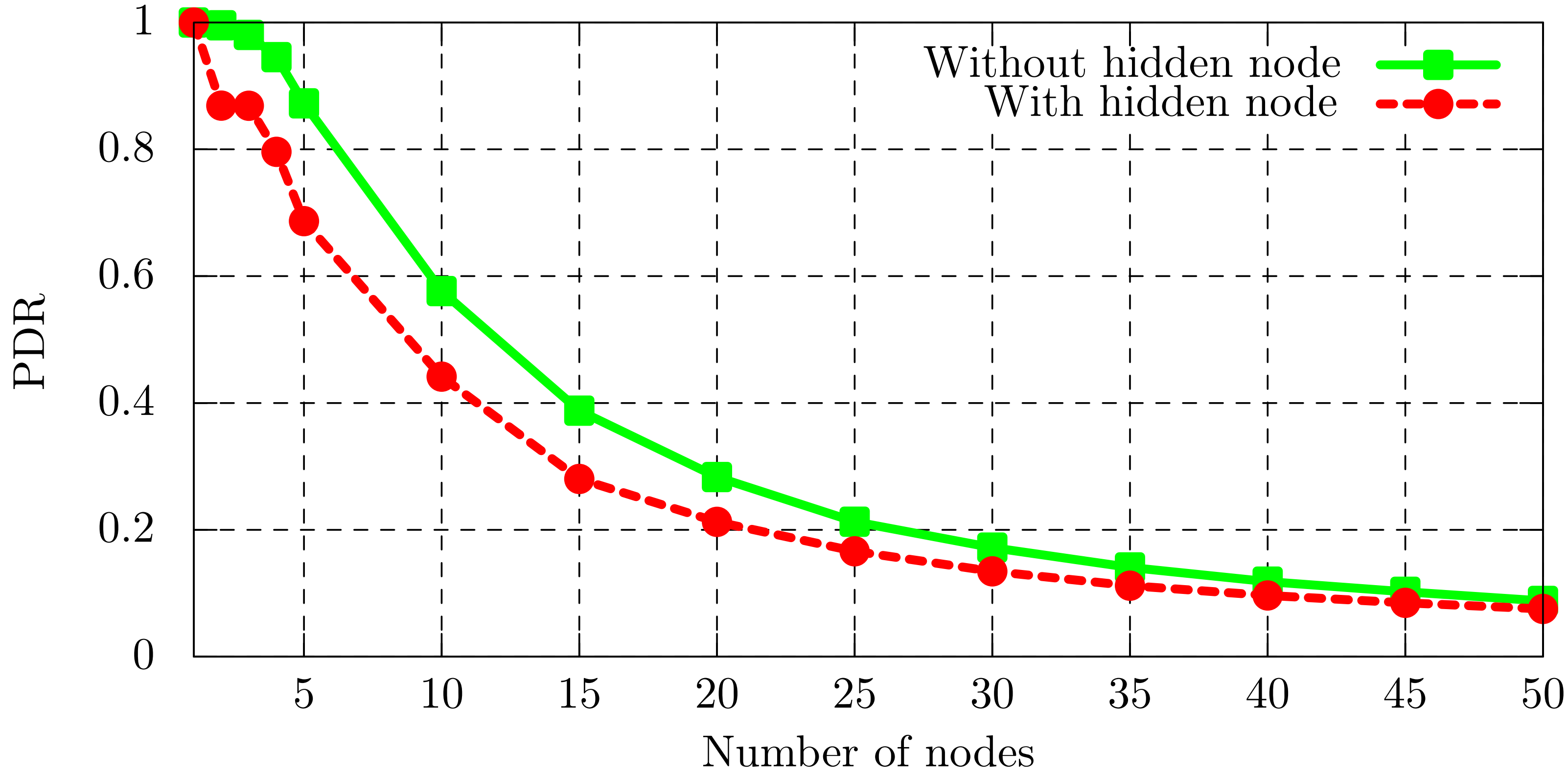
- Backoff period: time unit=20 symboles
- BE: Backoff Exponent
- Backoff: random interval in $[0, 2^{BE}-1]$* Backoff period
- CW: Contention Window – the number of units to perform CCA (Clear Channel Assessment) after random backoff
- NB: Number of Backoffs (initial 0)
- Default values: minBE=3, maxBE=5, limit=4

Slotted CSMA/CA

- Initialization: NB=0, CW=2, Backoff=[0 , 2 ^{BE} -1]
- Busy: NB=NB+1, CW=2, BE=min[BE+1, MaxBE]

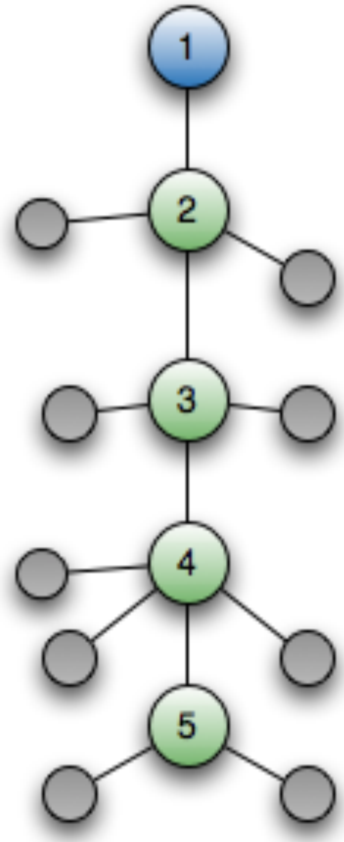


Contention in 802.15.4



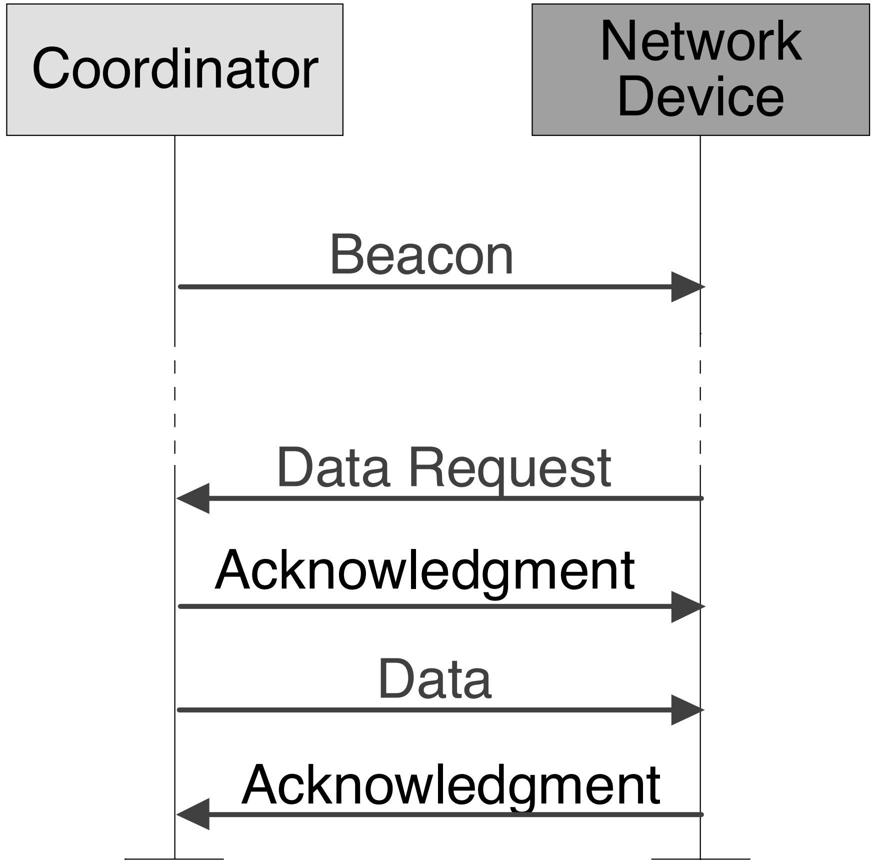
Topology in 802.15.4

- Cluster Tree
  - nodes associate with a coordinator
  - coordinator sends beacons
- Multi-hop forwarding
- Complex topology at L2 required for synchronized operation

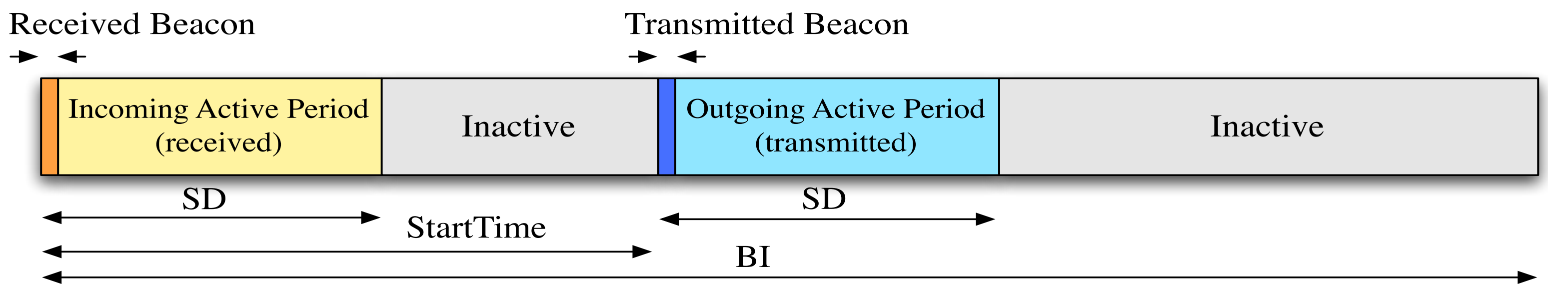


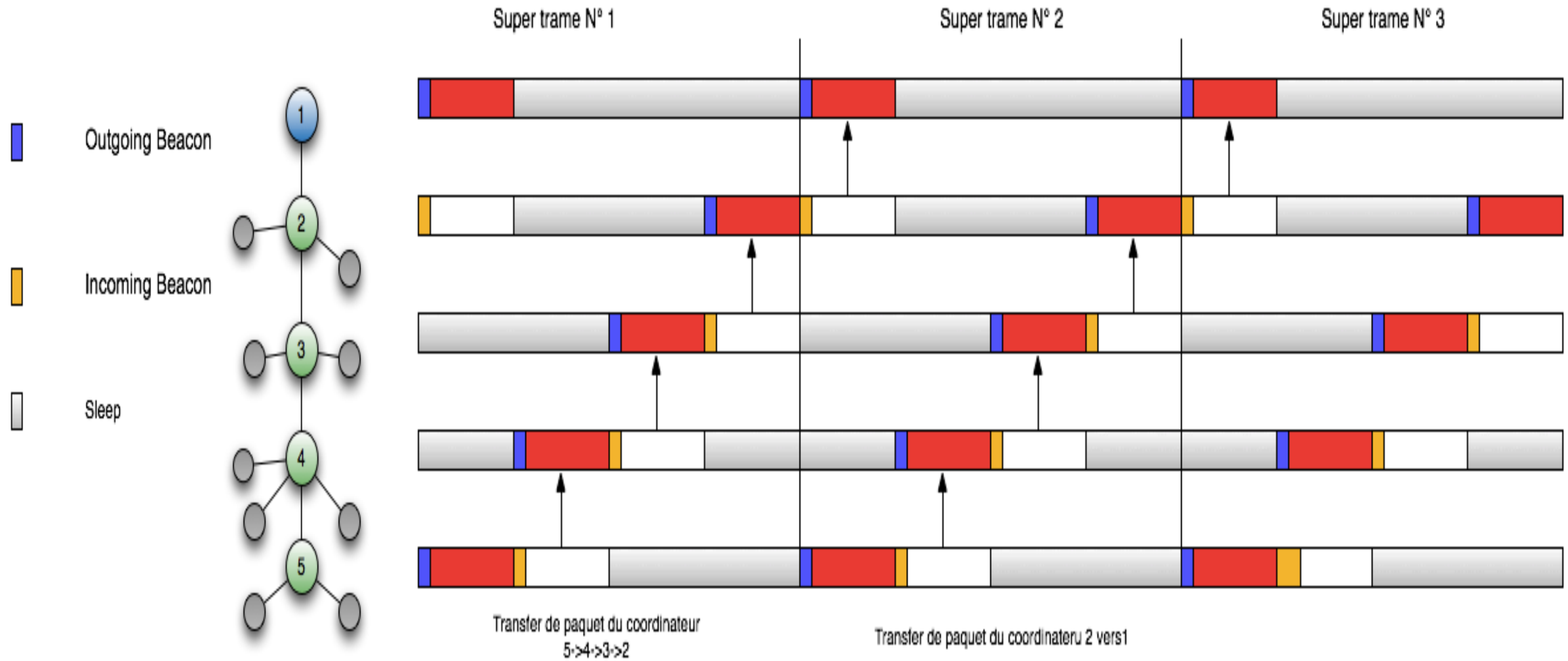
Data pull in 802.15.4

- Data pending flag in a beacon
- Broadcast flag
  - coordinator to devices
- No broadcast from devices



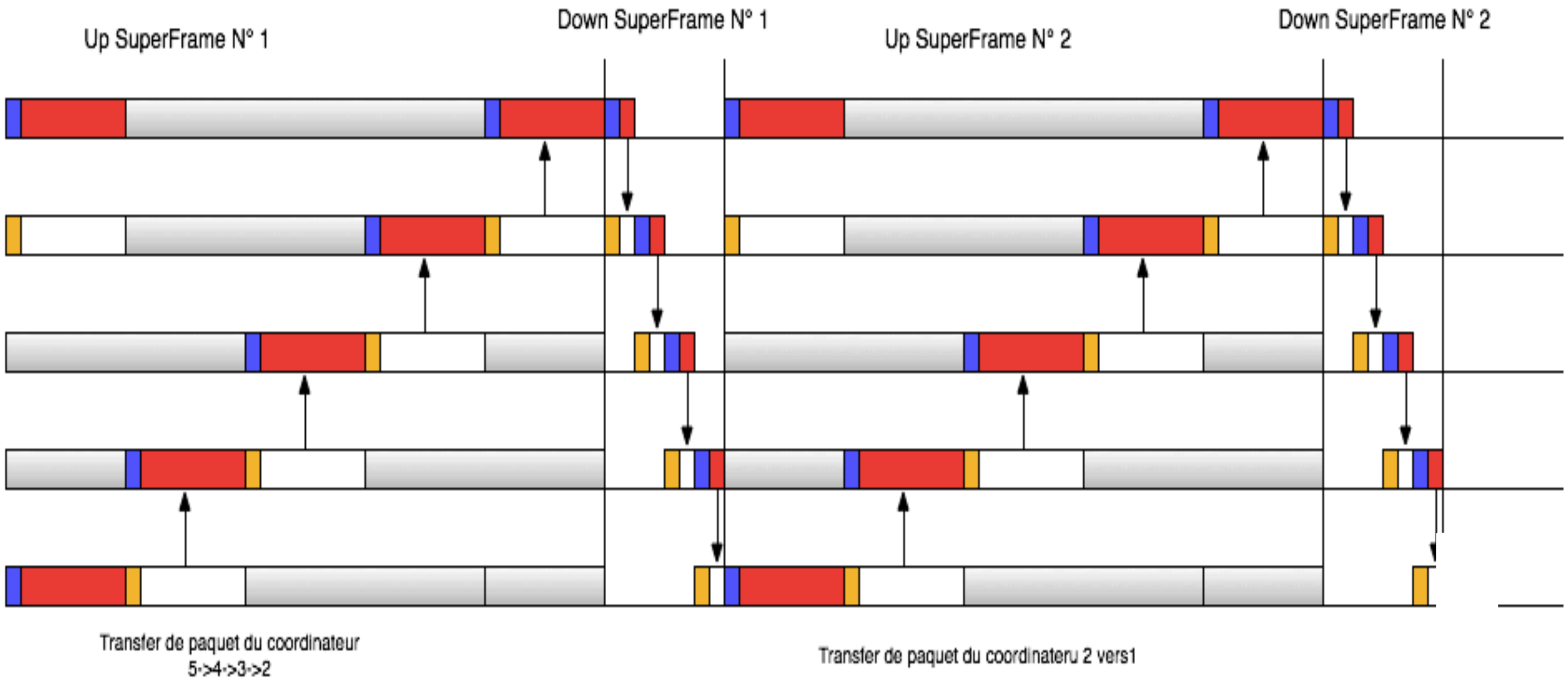
Beacon Scheduling in 802.15.4





No optimization for Upward and Downward Traffic!

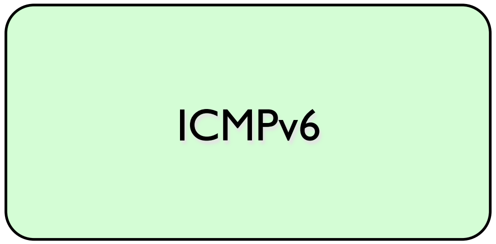
- Previous slide:
  - One BO for all nodes (standard)
  - Upward Latency : BI (1 Superframe)
  - Downward Latency : N-hops * BI



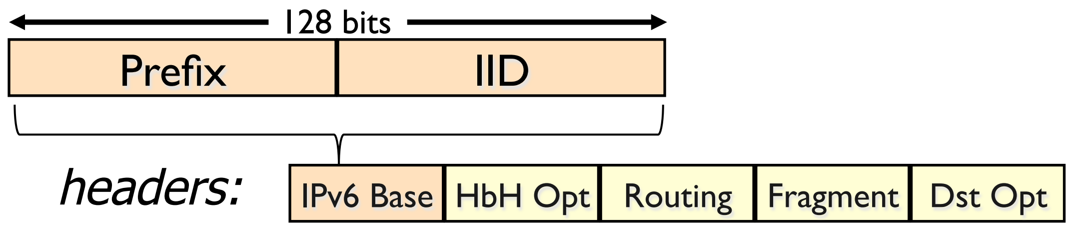
IP and routing

Key IPv6 Contributions

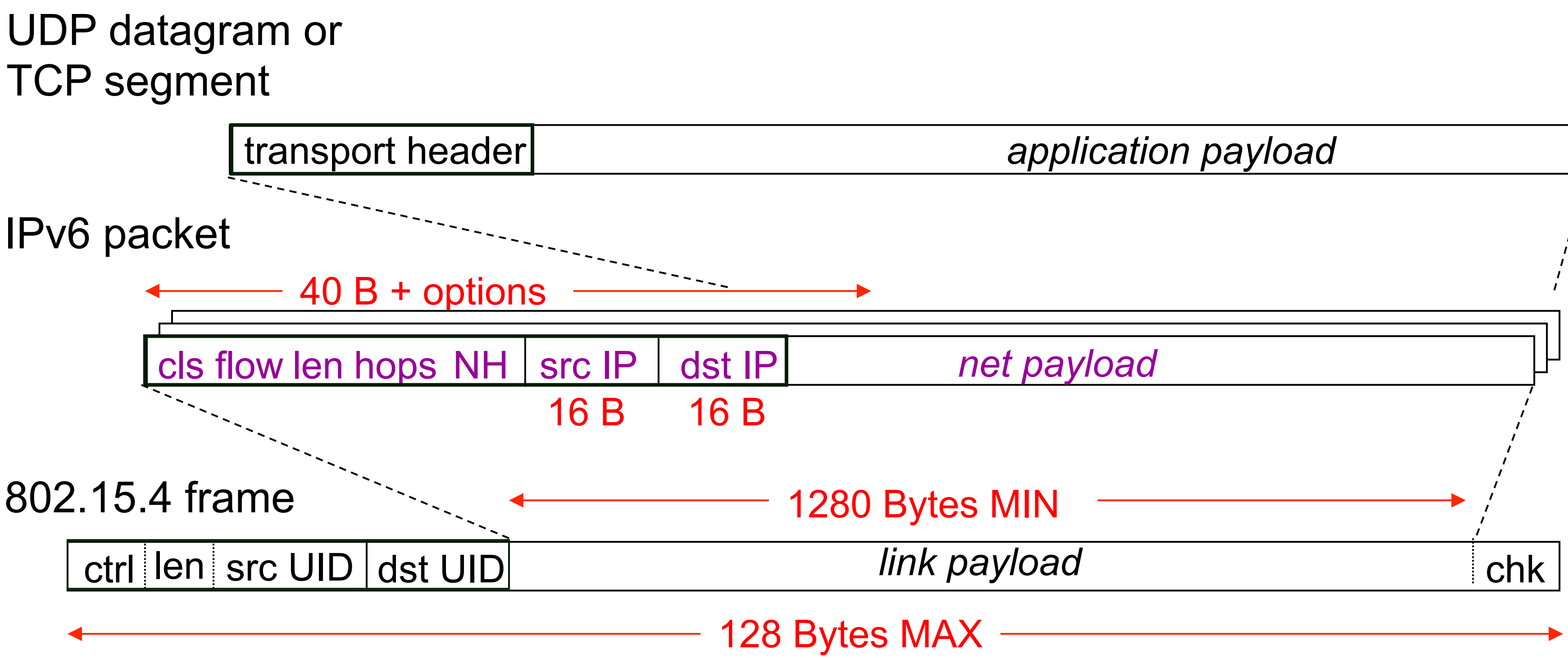
- Large simple address (128 bits, 16 bytes)
  - Network ID + Interface ID
  - Plenty of addresses, good for Things!
  - subnetwork has to carry at least 1280 bytes
- Autoconfiguration and Management
  - ICMPv6:
    - Neighbor Solicitation (NS)
    - Neighbor Advertisement (NA)



- Protocol options framework
  - Header extensions



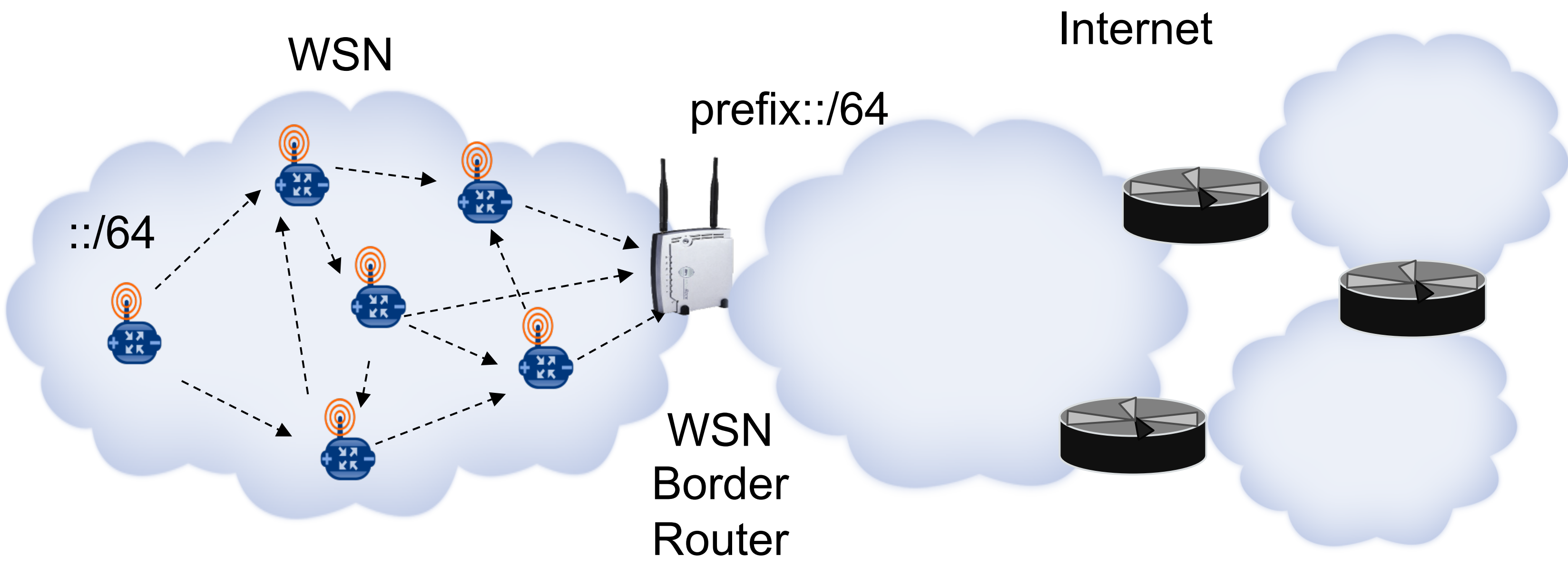
IPv6 over 802.15.4?



- Large IP Address & Header => 16 bit short address / 64 bit EUID
- Minimum Transfer Unit => Fragmentation
- Short range & Embedded => Multiple Hops

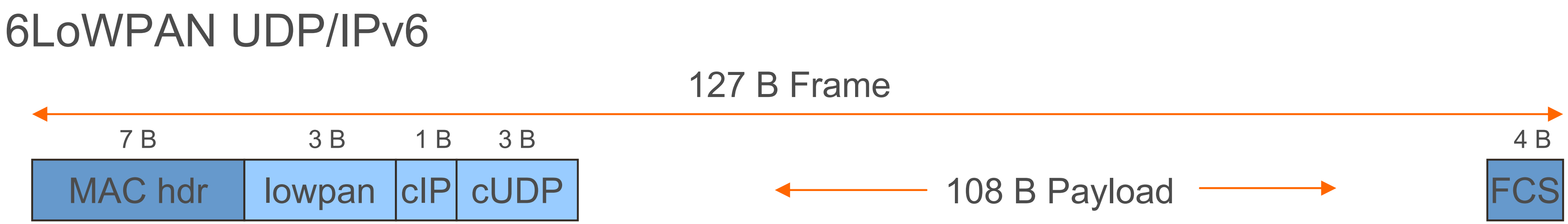
IPv6 and WSN

- Addresses in WSN
  - same subnet, 0 prefix (::/64)
  - Border Router adds prefix



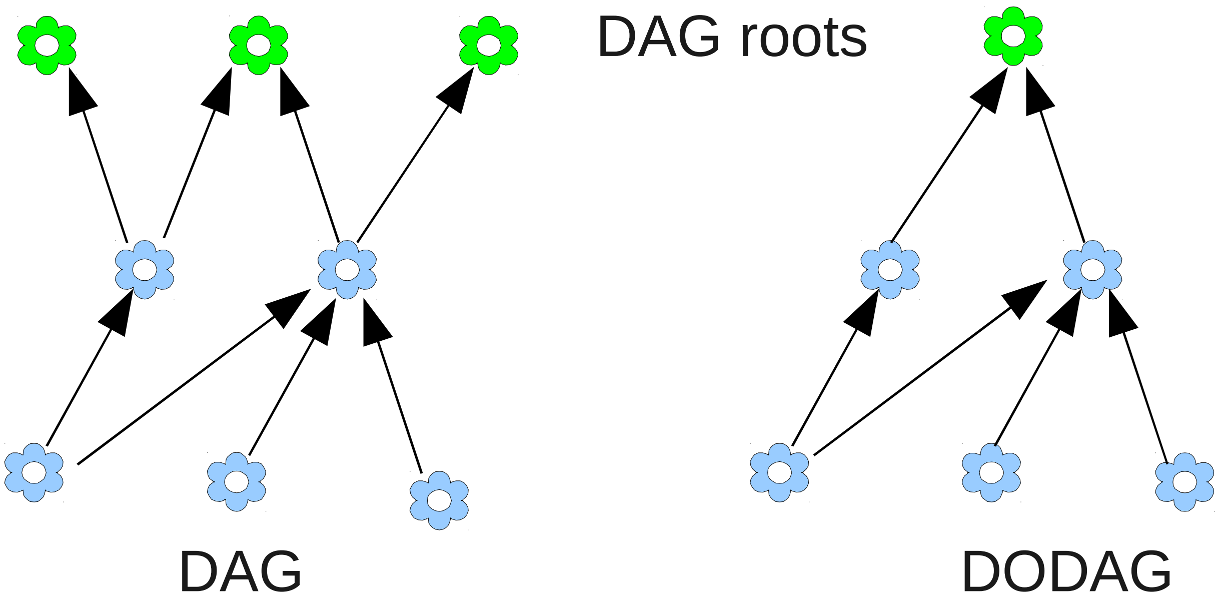
6LoWPAN

- IPv6 packets over 802.15.4 networks
  - 802.15.4 frame - 127 bytes, fragmentation
  - compress headers (derive addresses from L2)
  - Neighbor Discovery



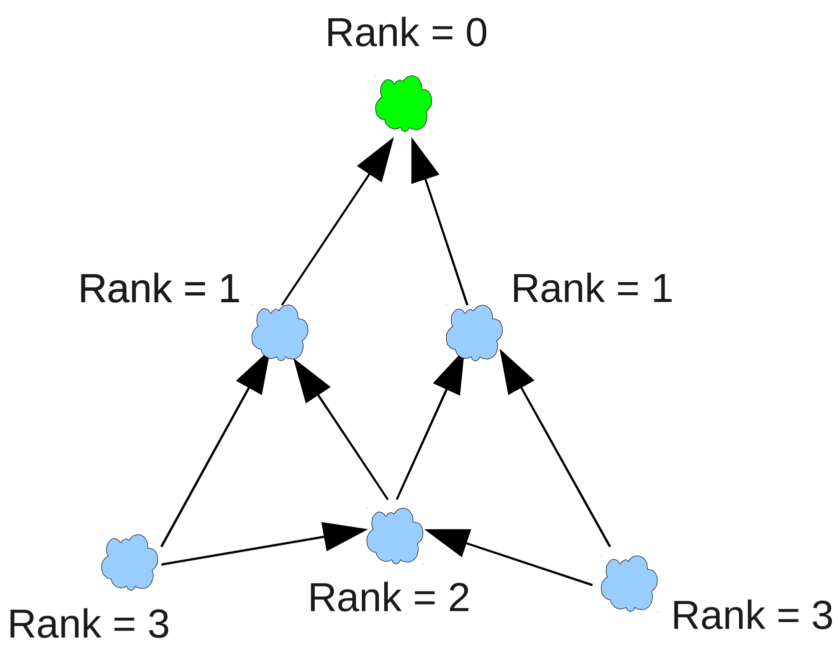
RPL (IPv6 Routing Protocol for Low power and Lossy Networks

- Directed Acyclic Graph (DAG) - a directed graph with no cycles exist.
- Destination Oriented DAG (DODAG) - a DAG rooted at a single destination.



Rank

Defines a node's relative position within a DODAG with respect to the DODAG root.

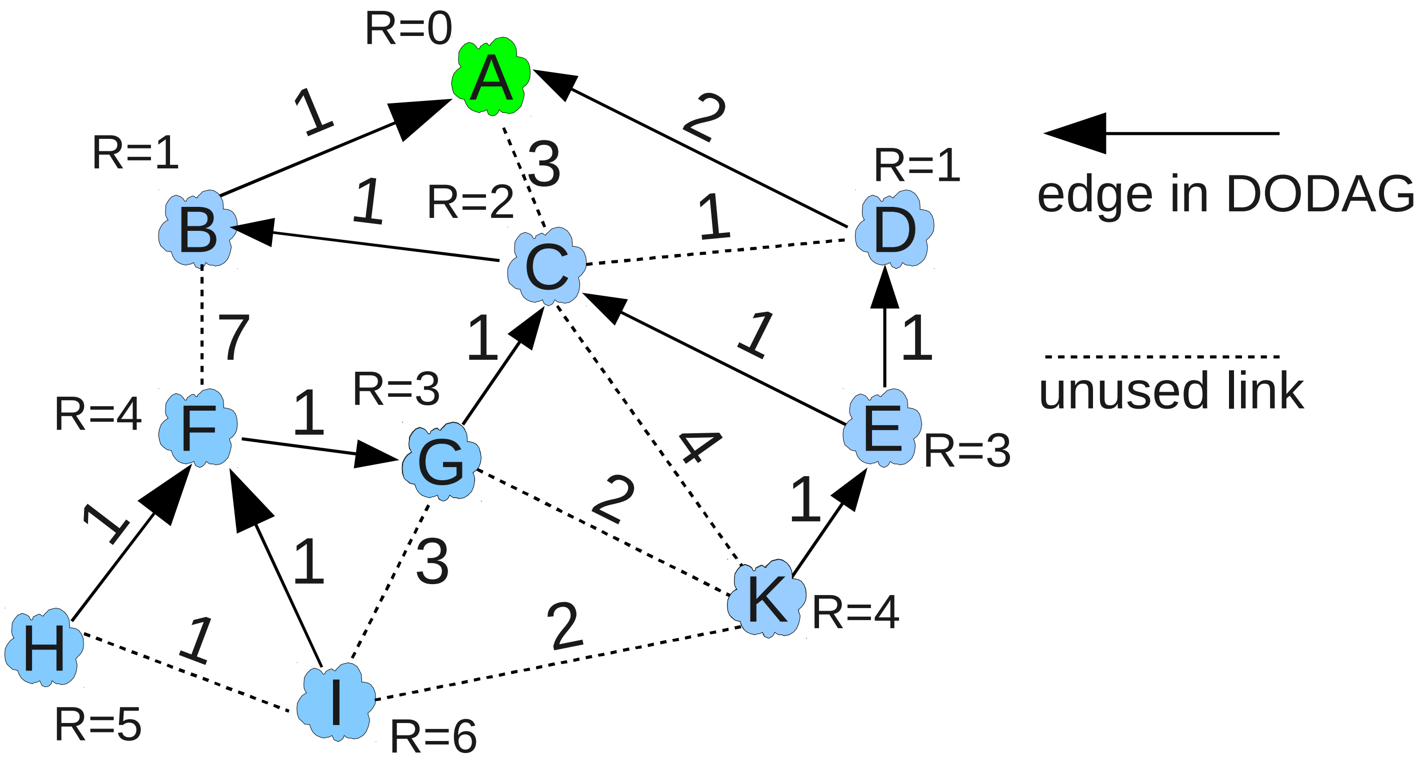


Routing messages

RPL defines a new ICMPv6 message with three possible types:

- DAG Information Object (DIO) - carries information that allows a node to discover an RPL Instance, learn its configuration parameters and select DODAG parents
- DAG Information Solicitation (DIS) - solicit a DODAG Information Object from a RPL node
- Destination Advertisement Object (DAO) - used to propagate destination information upwards along the DODAG.

DODAG construction



- Metrics
  - hops
  - ETX (number of retransmissions)

Trickle Timer

- Periodically send link-local multicast DIO messages, nodes listen to DIOs (overhearing)
- Routing inconsistencies influence the rate of DIO messages:
  - either every node that hears the message finds its data is consistent with their own state → double the timer
  - a recipient detects an inconsistency → reset the timer
- Consequence:
  - expects always-on nodes!
  - decoupled from beacon period!
  - link quality changes result in trickle reset

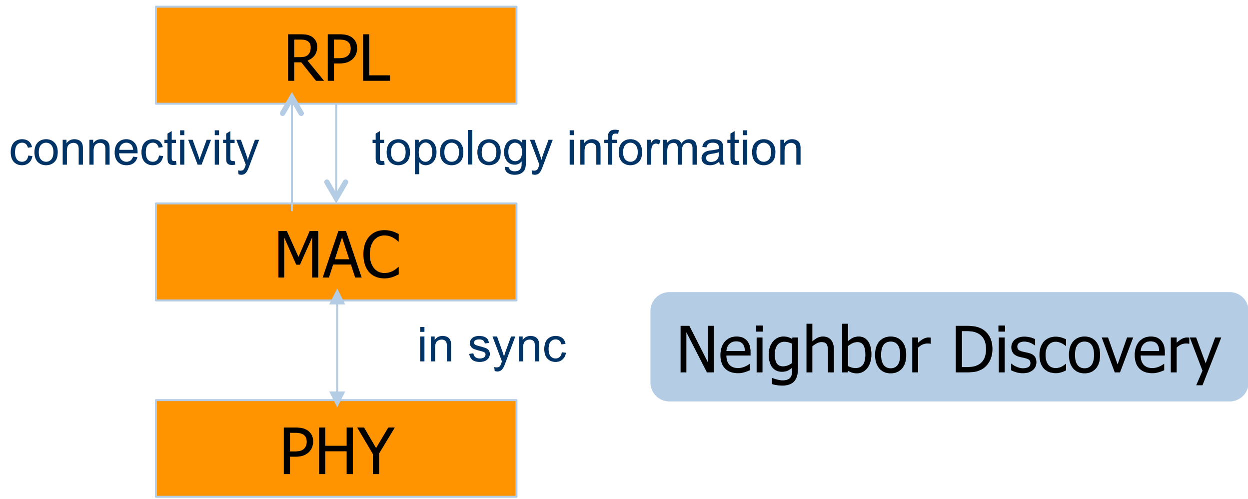
L2 – L3 layer interactions

RPL on top of 802.15.4?

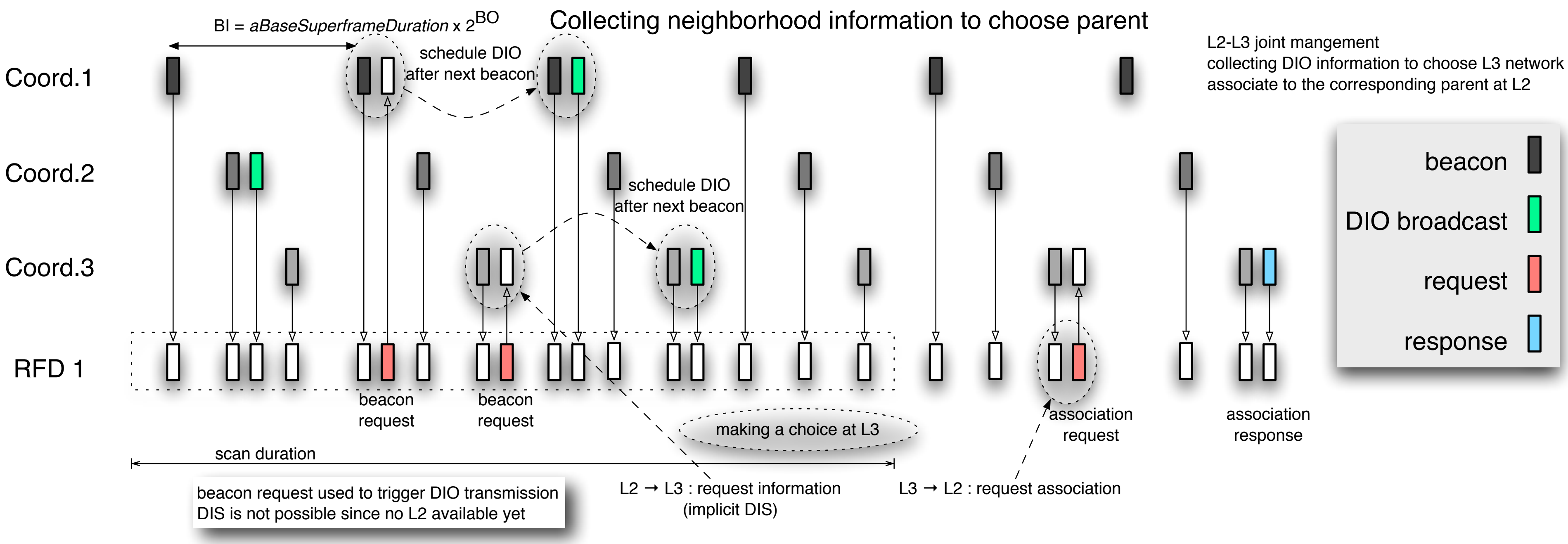
- DODAG construction requires L2 connectivity for sending DIO
  - DIO provides the information about parents
  - association with a parent at L2 should be done before!
  - tree constructed before at L2
- DODAG construction on a Tree = Tree
- Parent choice based on DIO reception – L3 metric (no check for a symmetric link)
- DIO message may exceed the available 79 octets causing fragmentation
- Trickle ineffective because of beaconed mode

Need for cross-layer

- Node needs to associate with a coordinator at L2
  - it cannot send any data frame before association
- Node waits for beacons, but it may only make the association decision based on the L3 information coming from RPL

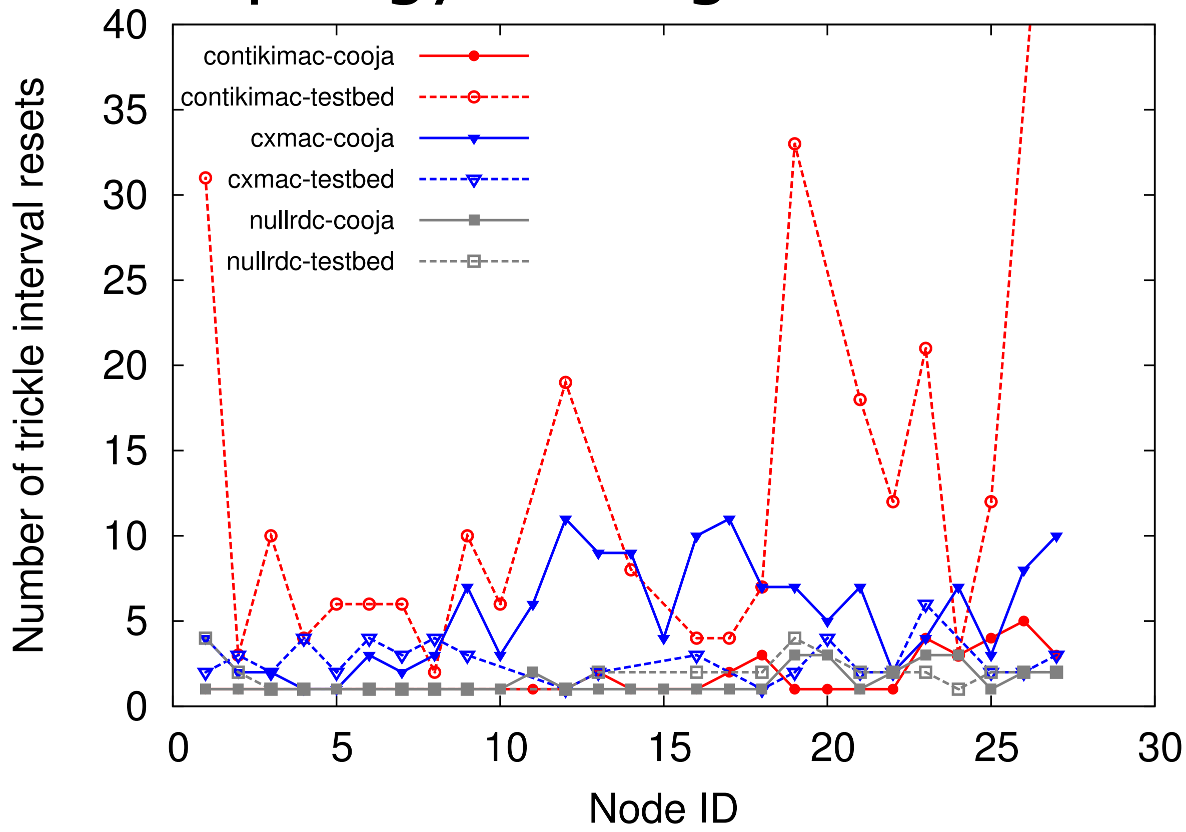


Possible scheme for topology construction



RPL on top of ContikiMAC?

- Expensive broadcasts, needs data to keep sync
- Convergence to low Duty Cycle based on Trickle
  - works if no dynamic changes (not realistic)
- Good - no topology binding at L2



RPL on top of 6LoWPAN?

- Neighbor Discovery? – Link Maintenance already done at MAC/PHY layer
- Neighbor Solicitation/Advertisement
  - needed for mapping L2 addresses to L3
  - are NS/NA really necessary?
    - timeouts before next beacon and active period?
    - DAD not mandatory as addresses are based on EUI-64
    - L2 address already known from L3

- No need for using IPv6 Neighbor Discovery (no NS/NA)

Conclusions

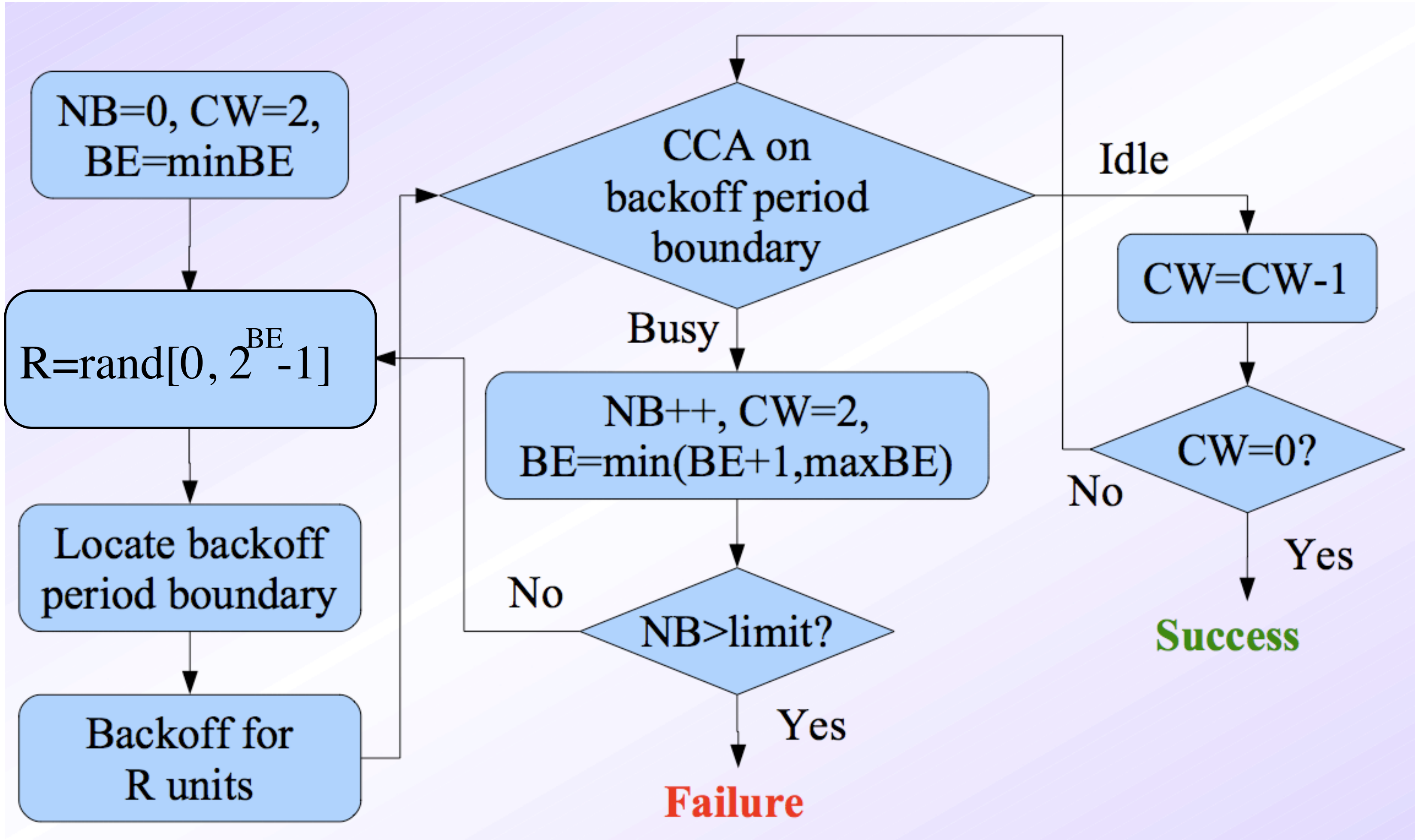
- Future Internet of Things
  - relies on IP networking
  - promising approach to unifying sensor networks
- Still many issues to address
  - topology construction: how to choose a parent and associate at L2? Topology at L2 vs. L3
  - better link metric estimation (take into account asymmetric links)
  - neighborhood maintenance coupled with duty cycled L2
- Upper layer issues
  - transport (TCP) over duty cycled networks

Questions?

Size of Super Frame

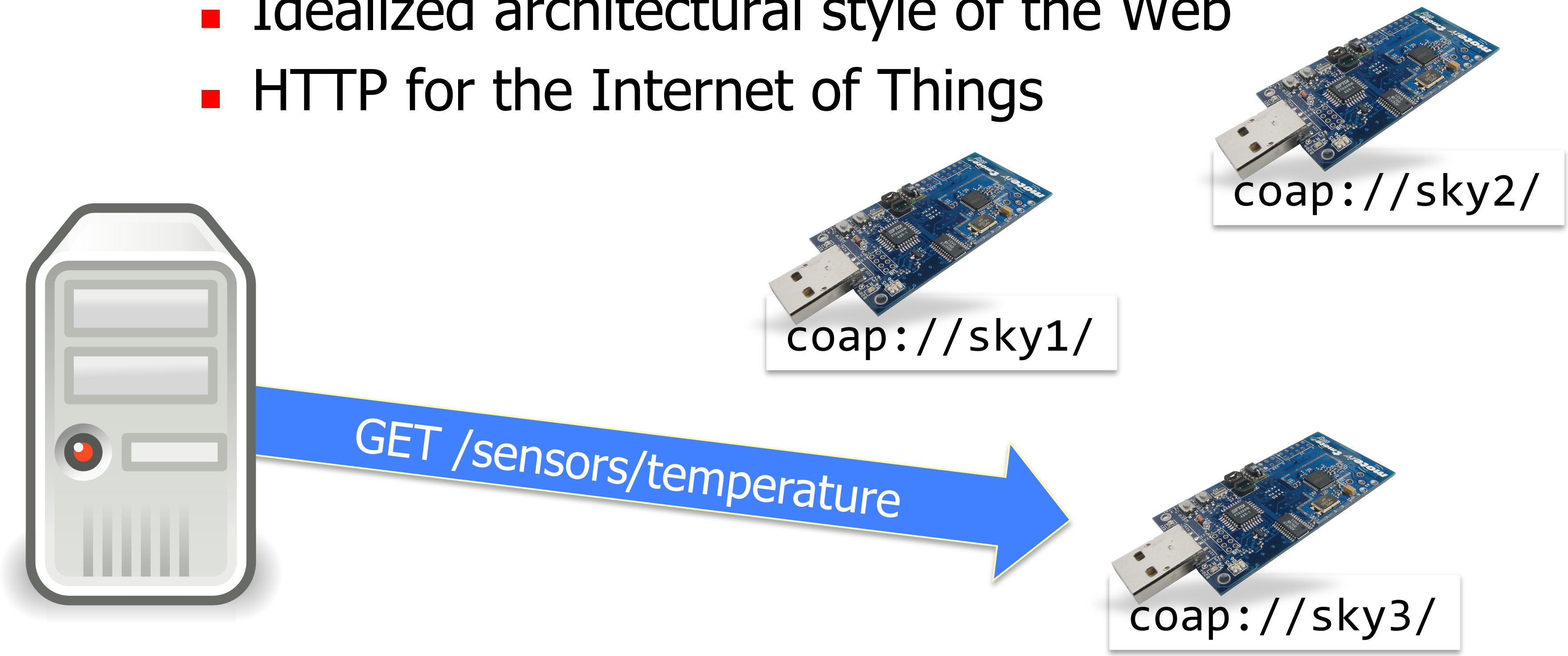
SO	Size of Slot (symbols)	SD duration 2,4/2,485 GHz	SD duration 902/928 MHz	SD duration 868/868,6 MHz
0	60	15,36 ms	24 ms	48 ms
1	120	30,72 ms	48 ms	96 ms
2	240	61,44 ms	96 ms	192 ms
3	480	122.88 ms	192 ms	384 ms
4	960	245.76 ms	384 ms	768 ms
¦	¦	¦	¦	¦
14	983040	251,6 s	393,2 s	786,4 s

Slotted CSMA/CA



Constrained Application Protocol (CoAP)

- RESTful Web services for networked embedded devices
  - Idealized architectural style of the Web
  - HTTP for the Internet of Things



CoAP on top of RPL?

- Needs Downward routes
  - DAO from leaves to sink
  - standard does not specify when to send DAO
- Storing nodes
  - routing table – one entry per IP address (ad hoc)
- Multiple sinks?
  - multi-homing problem for a sensor node