Grenoble INP Ensimag

Wireless Sensor Networks

Prof. Andrzej Duda
duda@imag.fr

http://duda.imag.fr

1

Contents

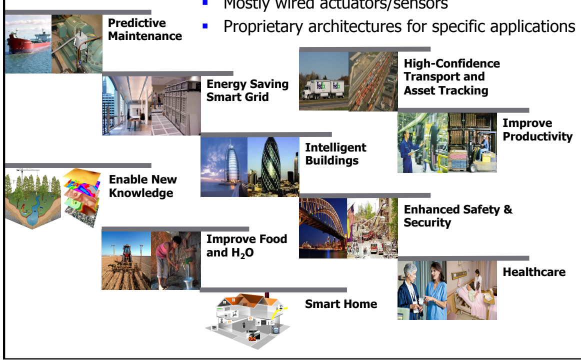
2

Wireless Sensor Networks

3

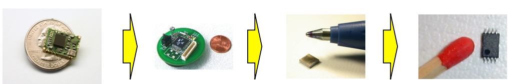
A World of Sensors

- Mostly wired actuators/sensors
- Proprietary architectures for specific applications

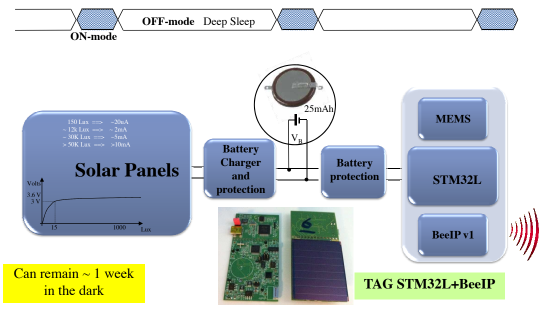


What is a WSN or Low Power Lossy Network (LLN)?

- Sensor node – a highly constrained small device
  - sensor that can measure physical data (e.g., temperature, humidity, light, vibration, CO_2)
  - actuator capable of performing a task (e.g., switch on, change traffic lights, rotate a mirror)
  - radio device to receive commands, send measured data or control information
  - energy supply – battery or energy harvesting
  - processor – run protocols and applications
  - memory (RAM, flash) – usually limited
- Low cost, low energy



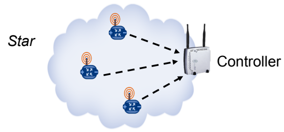
GreenNet node – STM32



6

Network of sensors

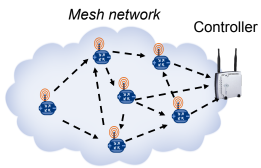
- Connect nodes to a controller
  - star topology
  - all nodes within the radio range



7

Network of sensors

- Connect nodes to a controller
  - mesh network
  - larger coverage



8

Requirements

- Desired properties
  - unrestricted placement (get rid of wires)
  - reliable collection of data (over variable quality radio channel, possible multi-hop)
  - low latency (for some applications)
  - long lifetime (no battery change)
- Traffic types
  - small data sent to the sink (measurements)
  - some data sent to nodes (control, update)
  - possibly large number of nodes

Radio technologies

- Licensed bands, cellular networks
  - GSM, GPRS, EDGE
  - UMTS, LTE, *LTE-A M2M (Machine-to-Machine, future)*
- Long range, low rate, cellular, proprietary
  - SigFox (169, 868 MHz, 1kb/s, 30km)
- Public bands, standards
  - Low Power 802.11 (2.4 GHz, ~20 Mb/s)
  - *802.11ah (future, 868 MHz, > 100kb/s, < 1km)*
  - Bluetooth 4.0, BLE (2.4 GHz, 1Mb/s)
  - IEEE 802.15.4 (868/915 MHz, 2.4 GHz, 256 kb/s)
- Public bands, proprietary
  - Wavenis, EnOcean, Z-Wave, ANTS

Security, coverage, but live days

Mainly upload

Star

Mesh

Challenges

- Saving energy
  - nodes will mostly sleep, but need to communicate
  - energy harvesting
- Standardization
  - interoperable devices
  - connected to the Internet – Internet of Things
- Reliable communication in a mesh network
  - plug-in operation
  - discover, join, operate
  - adapt to changes (nodes with no energy, failed)
- Programming support
  - popular platforms: TinyOS, Contiki
  - no isolation between applications and system
  - tricky development
- Security
  - key management

Saving Energy

12

Energy Efficiency

- Energy consumption
  - usual operations (sensing, transmitting, forwarding results, routing maintenance)
- Energy waste
  - idle listening (wait for a reception)
    - bursty traffic in sensor-net apps
    - idle listening consumes 50—100% of the power for receiving
  - collisions and retransmissions
  - overhearing unnecessary traffic (not sent to me)
  - protocol overhead (e.g. headers, beacons, RTS/CTS)

13

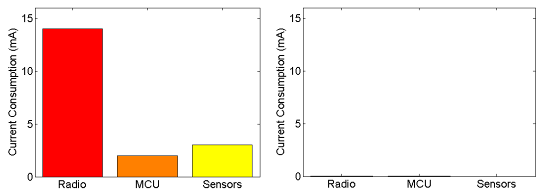
"Idle Listening" Problem

- The power consumption is roughly the same whether the radio is transmitting, receiving, or simply ON, "listening" for potential reception
- Radio must be ON (listening) in order receive anything
  - transmission is infrequent
  - listening (potentially) happens all the time
- Total energy consumption dominated by idle listening

14

PHY Layer

- Energy consumption
  - most energy spent for radio transmission and reception, but the proportions change



15

Current consumption

- Coronis
  - 10μA average operating current
  - 17mA RX
  - 45mA TX (25mW output power)
  - 2μA STANDBY

TABLE II
MEASURED CURRENT CONSUMPTION OF CC2500

Radio (sleep)	900 nA
Radio (idle)	1.5 mA
Radio (transmit)	22 mA
Radio (receive)	14 mA
Microcontroller (active)	8 mA
Microcontroller (idle)	2 mA

16

Current consumption

Mote	#bits	RAM [kB]	CPU ON [mA/MHz]	CPU sleep [μA]	TX 0dBm [mA]	RX [mA]	Har-vested	Batt. size/type [mAh]
GreenNet	32	32	0.185	0.44	4.9	4.5	Y	25
Hikob [54]	32	16	0.180	0.6	13.8	11.8	Y	2000
SmartMeshIP [52]	32	72	0.176	0.8	5.4	4.5	OPT	2AA
M3OpenNode [55]	32	64	1.138	25	11.6	10.3	N	650
OpenMote [56]	32	32	0.438	0.4	24	20	N	2AAA
WisMote [57]	16	16	0.312	1.69	25.8	18.5	N	2AAA
TelosB [58]	16	10	1.8	5.1	19.5	21.8	N	2AA
Waspmote15.4 [59]	8	8	1.07	7.5	45	50	OPT	N/A
MICAz [60]	8	4	1.0	<15	17.4	19.7	N	2AA

17

Energy Efficient Techniques

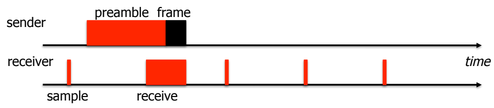
- Reduce idle listening
  - sleep most of the time
- But avoid deafness
  - detect/know about transmissions of other nodes
- Two main approaches
  - send a long preamble
  - synchronize on a common schedule (wake up schedules or TDMA slots)

18

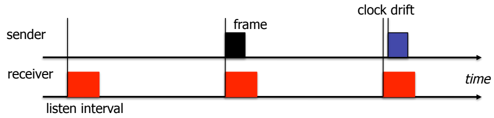
MAC access methods

Communicating Sleeping Devices

- Preamble Sampling (e.g. ContikiMAC)



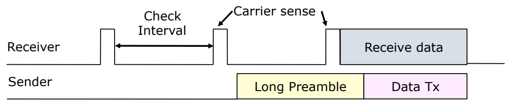
- Scheduled Listening (e.g. 802.15.4)



MAC proposals

- Preamble Sampling
  - LPL (1984, 1999), B-MAC (2004), Wise-MAC (2004), CSMA-MPS (2004), MFP (2006), X-MAC (2006)
- Scheduled Listening
  - S-MAC (2002), T-MAC (2004)
- Hybrid methods
  - SCP-MAC (2006), ContikiMAC
- TDMA-based
  - 802.15.4

LPL - Low Power Listening



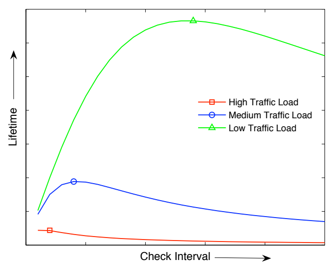
- Long preamble sampling
  - wake up every Check-Interval
  - sample channel using CCA (Clear Channel Assess.)
  - if no activity, go back to sleep for Check-Interval
  - Else start receiving packet
- If long Check-Intervals
  - message delays and collision rate may increase

LPL - Low Power Listening

- Shifts cost of coping with Idle Listening from receiver to transmitter
- Highly beneficial for infrequent transmissions
- Unsuitable for higher load due to collisions and retransmissions

LPL - Low Power Listening

- Optimal Check-Interval



WiseMAC – Shorter Preambles

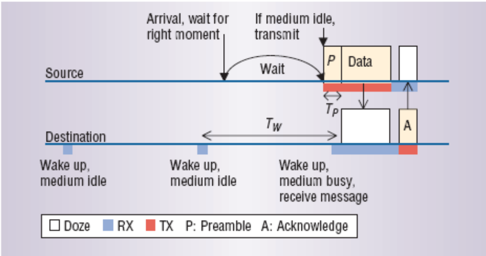


Figure 1. *WiseMAC preamble minimization. A low-power, media access control protocol, WiseMAC uses a scheme that learns the sampling schedule of direct neighbors and exploits this knowledge to minimize the wake-up preamble length.*

25

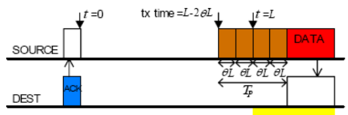
Preamble duration

- Know neighbor wake up times
  - piggybacked onto ACK frames
- Problem – clock drift
  - T_p must compensate for drift between the clock at the AP and the sensor node
  - Preamble duration must be $4\theta L$ if both quartz have a frequency tolerance of $\pm\theta$ and L is the interval between communications (*θL is clock difference)*

26

Drift Compensation

- AP may be late, while node may be early, start the preamble $2\theta L$ in advance
- Because the sensor node may be late while the AP is early the duration of preamble must be $4\theta L$



27

WiseMAC

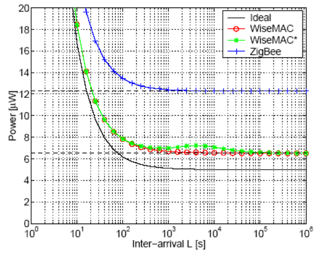
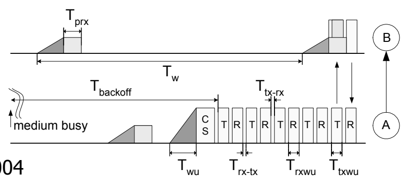


Figure 7. Power consumption of WiseMAC and ZigBee as a function of the inter-arrival L (T_W = 1 s).

28

CSMA-MPS
Minimum Preamble Sampling



Sept. 2004

- Preamble - alternating short Transmit (wake up message) and Receive slots
- Receiver sends an ACK during a Receive slot
- Requires sampling longer than Recv. slot

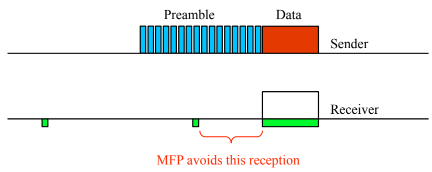
29

Micro Frame Preamble

- Preamble is a sequence of microframes
- Microframe contains
  - instant of the start of the transmission
  - destination address
- Avoid overhearing
  - of the preamble
  - of data frames
- ICC, June 2006

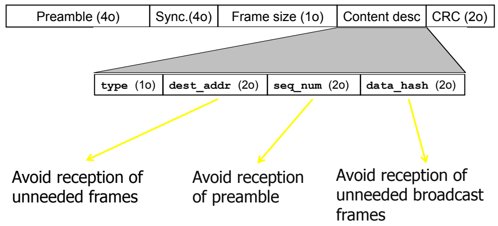
30

Micro Frame Preamble

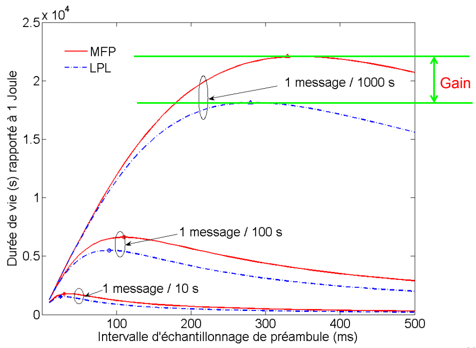


- Short samples
- Avoids idle listening during a part of the preamble and when receiving a frame not sent to our address

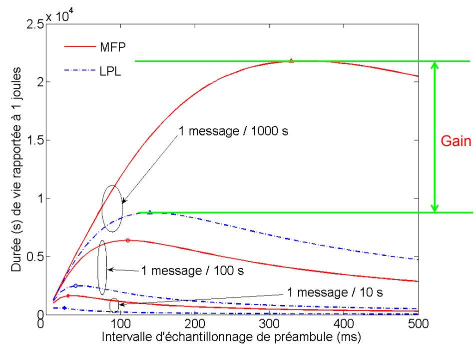
Microframe structure



Performance – 1 neighbor

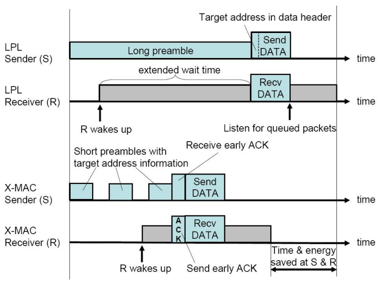


Performance – 10 neighbors

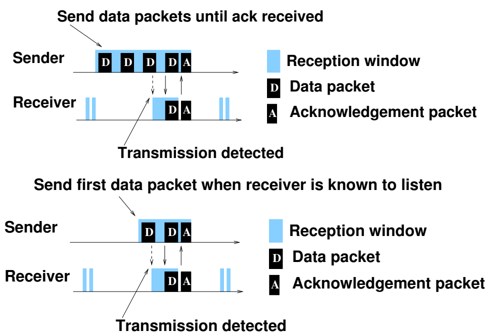


X-MAC

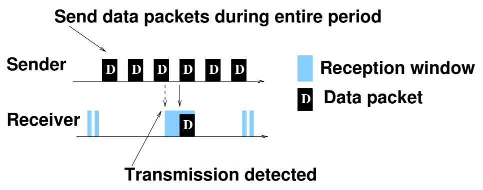
- Same as CSMA-MPS
- SenSys Oct. 2006



ContikiMAC – X-MAC

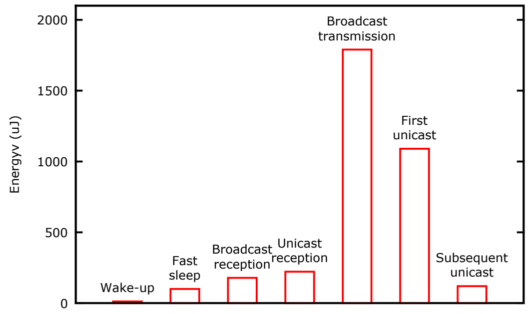


ContikiMAC - broadcast



37

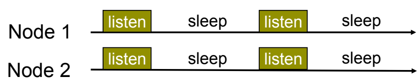
ContikiMAC - broadcast



38

S-MAC - Sensor MAC

- Nodes periodically sleep
  - Turn off radio when sleeping
  - Reduce duty cycle to ~ 10%
- Trades energy efficiency for lower throughput and higher latency
- S-MAC = lite-802.11 + scheduling



39

S-MAC - Common Schedules

- Deafness
  - common active periods, low duty cycle
- Active periods
  - SYNC exchange – accept a schedule, no schedule received, create a new one
  - data exchange
  - 802.11 DCF alike contention in each sub-period
  - strong contention in active periods

40

Scheduled Channel Polling (SCP-MAC) When WiseMAC meets S-MAC

- By synchronizing channel polling times of all neighbors, long preambles are eliminated and ultra-low duty cycles (below the LPL 1-2% limits) are possible
- Know my neighbors' schedule
  - broadcast SYNC messages
  - piggyback schedule info on data frames

41

SCP-MAC

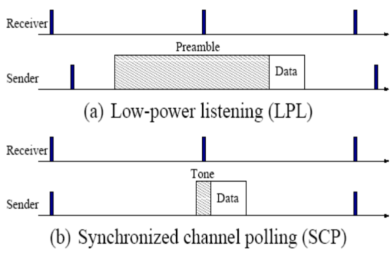
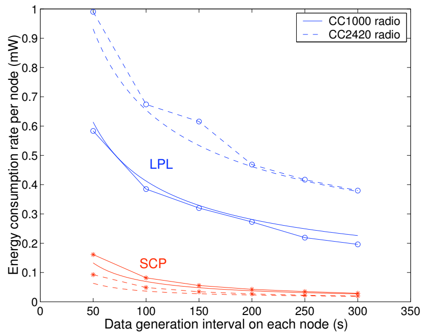


Figure 1. Sender and receiver synchronization schemes.

42

SCP – Energy consumption



43

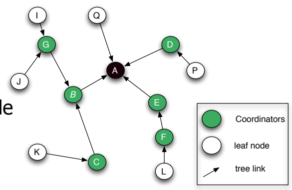
802.15.4

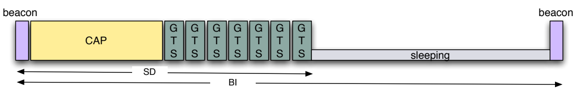
- TDMA controlled by a PAN Coordinator
  - **Beacons** – common time base
  - define Superframe structure
- Devices may sleep for extended periods over multiple beacons
- Slotted CSMA in beaconed PANs
- Unslotted CSMA in non-beaconed PANs
- Low duty cycle requires **beaconed enabled mode** and **slotted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

44

Overview of IEEE 802.15.4

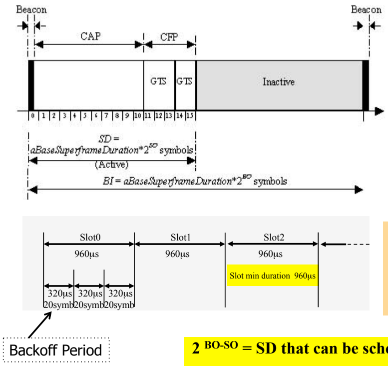
- MAC: two modes
  - Beacon-Enabled mode
    - Star & Cluster-Tree
  - Non Beacon-Enabled mode
    - Peer-to-Peer





45

Superframe



BO Beacon Order
BI Beacon Interval

SO Superframe Order
SD Superframe Duration

1 Symbol = 4bits = 16 µs

0 <= SO <= BO <= 14

BI = (960µs * 16) 2^{BO}
SD = (960µs * 16) 2^{SO}

2^{BO-SO} = SD that can be scheduled in BI=2^{BO}

46

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

47

Superframe

- CAP – Contention Access Period
  - Slotted CSMA/CA
- CFP – Contention Free Period
  - GTS – Guaranteed Time Slot (may span several slots)
- In a beacon sent in the first slot of the superframe:
  - Beacon Order (BO) - describes the interval at which the coordinator shall transmit its beacon frames
  - if BO = 15, superframe is ignored
  - Superframe Order (SO) - describes the length of the active portion of the superframe
  - if SO = 15, superframe should not remain active after the beacon

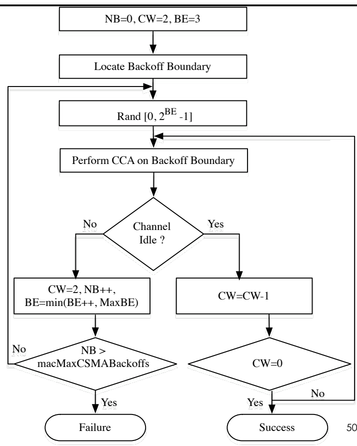
48

CSMA/CA

- Backoff period: time unit=20 symbols
- BE: Backoff Exponent (size of Contention Window)
- Backoff: random interval in [0, 2^{BE}-1]* Backoff period
- CW
  - the number of units to perform CCA (Clear Channel Assessment) after random backoff (default CW=2)
- NB: Number of Backoffs (initial 0)
- A node drops a frame either
  - when there is no ACK received after *MaxFrameRetries* or
  - when the node performed *MaxCSMABackoffs* without finding the channel free
- Default values:
  - *minBE*=3, *maxBE*=5, *MaxFrameRetries*=4, *MaxCSMABackoffs*=4

49

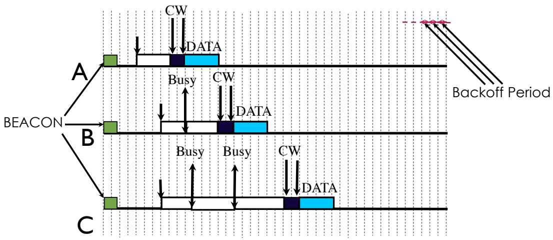
Slotted CSMA/CA



50

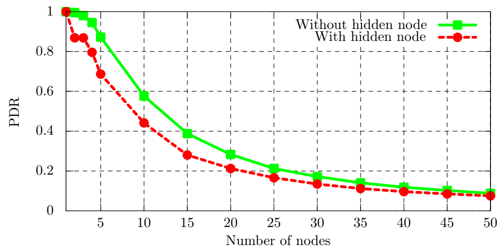
Slotted CSMA/CA

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



51

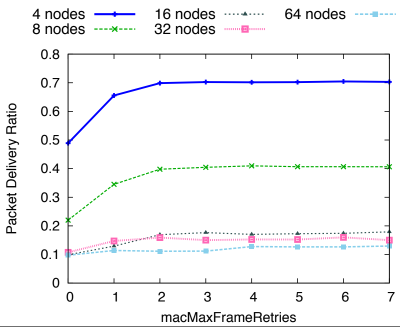
Contention in 802.15.4



52

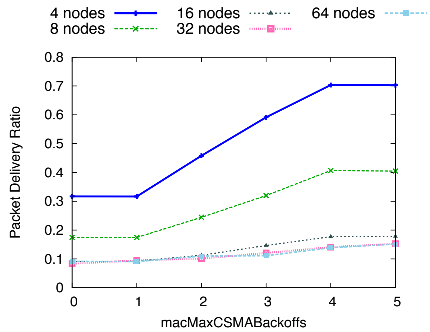
Slotted CSMA/CA
Max. number of retransmissions

(no ACK received)



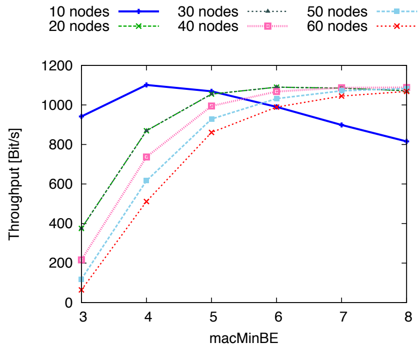
53

Slotted CSMA/CA
Max. clear channel assessments



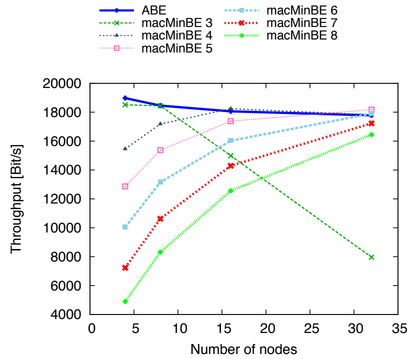
54

Slotted CSMA/CA
Initial random backoff window size



55

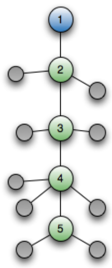
ABE – parameter adaptation



56

Topology in 802.15.4

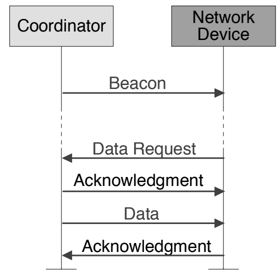
- Cluster Tree
  - nodes associate with a coordinator
  - coordinator sends beacons
- Multi-hop forwarding
- Complex topology at L2 required for synchronized operation



57

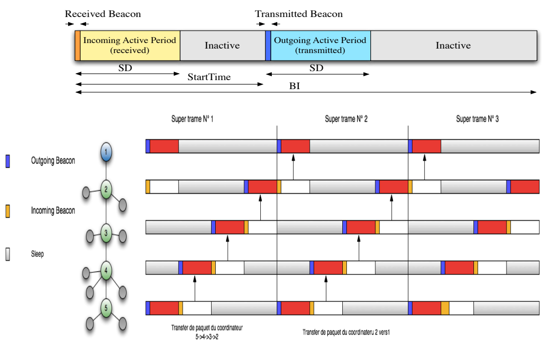
Data pull in 802.15.4

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



58

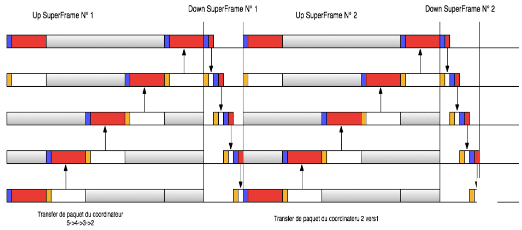
Beacon Scheduling in 802.15.4



59

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

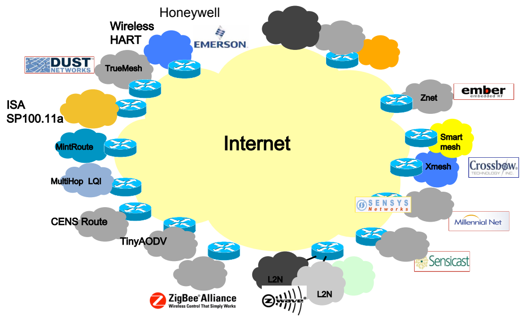


60

Standardization and Internet of Things

61

A World of Proprietary Protocols

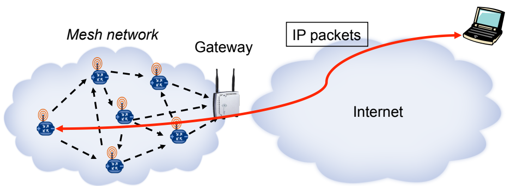


courtesy of JP Vasseur

62

WSN connected to Internet

- IP connectivity to nodes
  - use the Internet protocol stack end-to-end



63

Internet of Things

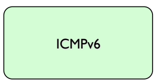
- Application (HTTP like)
  - CoAP (Constrained Application Protocol)
- Transport
  - lightweight, chosen functions
- Network – Routing
  - adaptation (header compression)
- MAC
  - Low Radio Duty Cycle
- PHY
  - 802.15.4, others

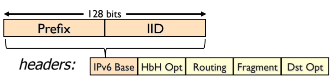
CoAP
TCP/UDP
IPv6 - RPL
6LoWPAN
802.15.4 MAC/PHY

64

Key IPv6 Contributions

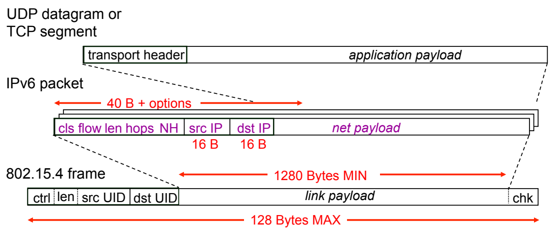
- Large simple address (128 bits, 16 bytes)
  - Network ID + Interface ID
  - Plenty of addresses, good for Things!
  - subnetwork has to carry at least 1280 bytes
- Autoconfiguration and Management
  - ICMPv6:
    - Neighbor Solicitation (NS)
    - Neighbor Advertisement (NA)
- Protocol options framework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





65

IPv6 over 802.15.4?

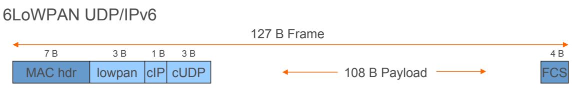


- Large IP Address & Header => 16 bit short address / 64 bit EUID
- Minimum Transfer Unit => Fragmentation
- Short range & Embedded => Multiple Hops

66

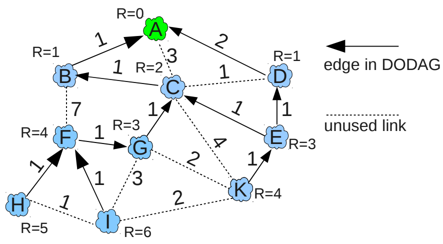
6LoWPAN

- IPv6 packets over 802.15.4 networks
  - 802.15.4 frame - 127 bytes, IPv6 - 1280 bytes -> fragmentation
  - compress headers (derive addresses from 802/15.4)



67

RPL (IPv6 Routing Protocol for Low power and Lossy Networks)

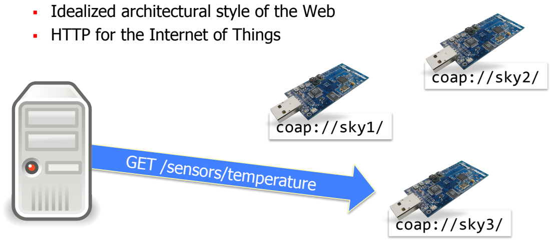


- Distance vector
- Metrics: hops, ETX (number of retransmissions)

68

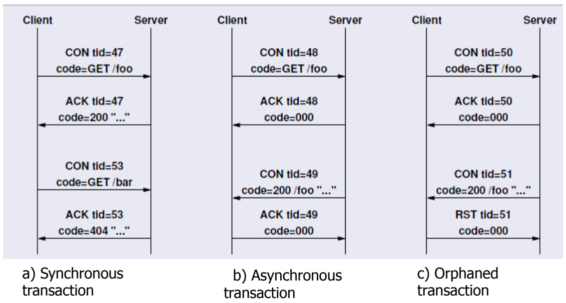
Constrained Application Protocol (CoAP)

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

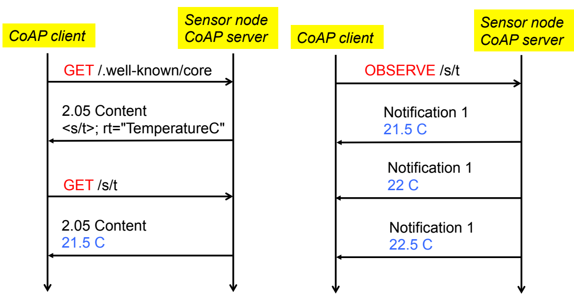


69

REST - Representational State Transfer



CoAP



- Example exchanges

71

Facts to remember

- Future Internet of Things
  - relies on IP networking
  - promising approach to unifying sensor networks
- Still many issues to address
  - low power MAC methods – reduce all sources of energy waste
  - topology construction: how to choose a parent and associate at L2? Topology at L2 vs. L3
- Upper layer issues
  - transport (TCP) over duty cycled networks

72