IEEE 802.15.4e Standard
A Building Block for the Internet of (Relevant) Things

Giuseppe Anastasi
Pervasive Computing & Networking Lab (PerLab)
Dept. of Information Engineering, University of Pisa
Website: www.iet.unipi.it/~anastasi/

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Smart Cities & Communities

PerLab

Missouri University of Science & Technology| Rolla, MO, May 17, 2016

Overview

- Introduction
- IEEE 802.15.4 standard
  - limitations
- IEEE 802.15.4e
  - Improvements wrt 802.15.4
- 802.15.4e TSCH mode
  - literature survey
  - open issues
- IoT with 802.15.4e TSCH
  - The 6TiSCH initiative
- Conclusions

Internet of Things

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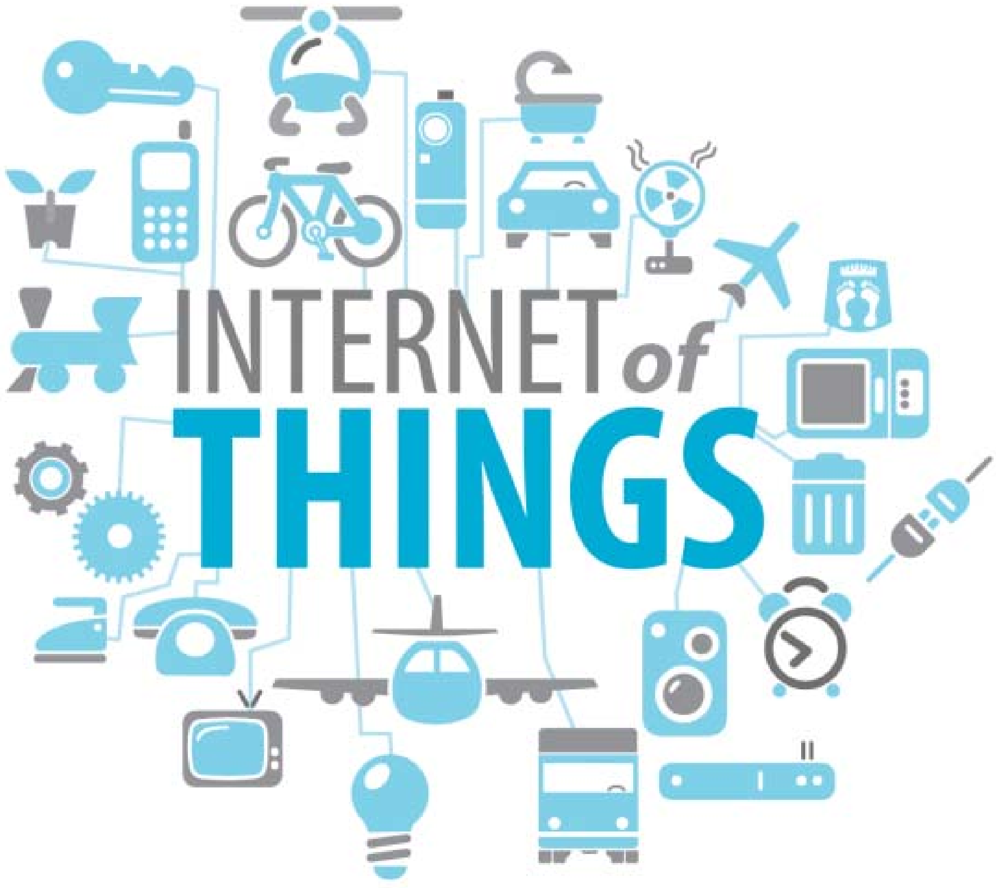
"The next logical step in the technological revolution connecting people anytime, anywhere is to connect inanimate objects. This is the vision underlying the **Internet of things: anytime, anywhere, by anyone and anything"**
(ITU, Nov. 2005)

More than 26 billion devices will be wirelessly connected to the Internet of Things by 2020

- computers and communication devices
- cars, robots, machine tools
- persons, animals, and plants
- garments, food, drugs, etc.



Wireless Sensor & Actuator Networks (WSANs)

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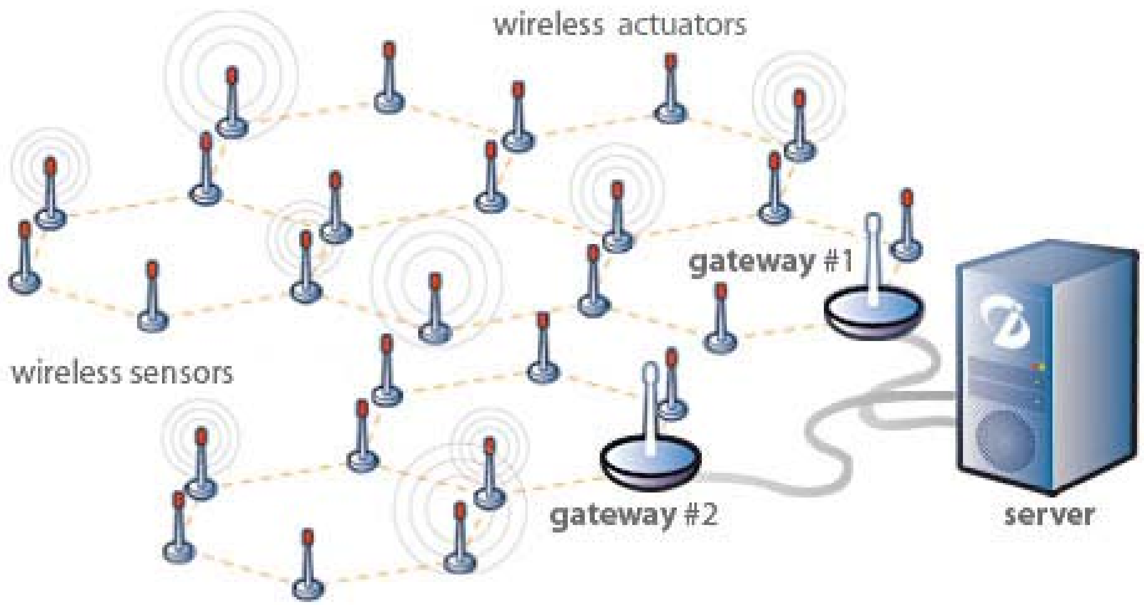
“WSANs will behave as a digital skin for the IoT

providing a virtual layer through which any computational system can interact with the physical world”



C. Alcaraz, P. Najera, J. Lopez, R. Roman, **Wireless Sensor Networks and the Internet of Things: Do we need a Complete Integration?** Proc. *International workshop on the Security of The internet of Things (SecIoT 2010)*, Tokyo, Japan, 2010.

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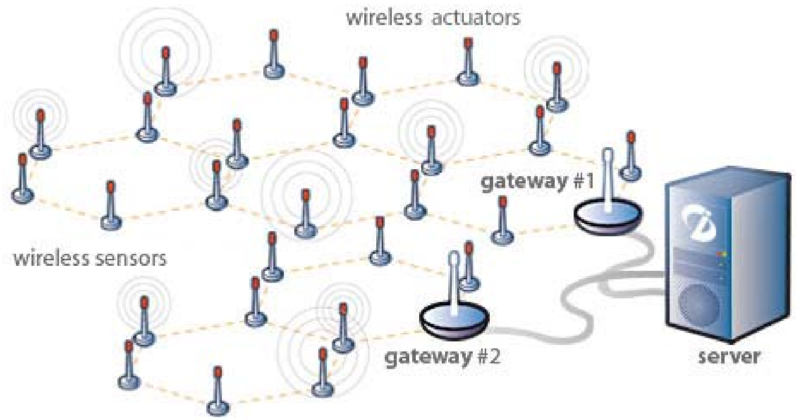
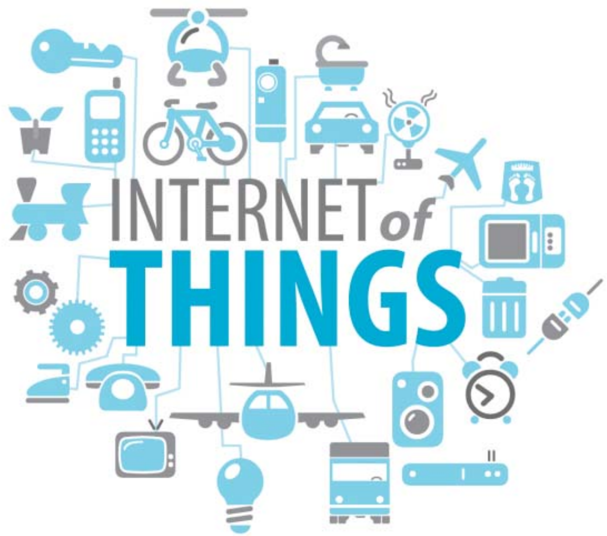
Standards for WSANs

- IEEE 802.15.4/802.15.4e
- ZigBee
- Bluetooth
- WirelessHART
- ISA-100.11a



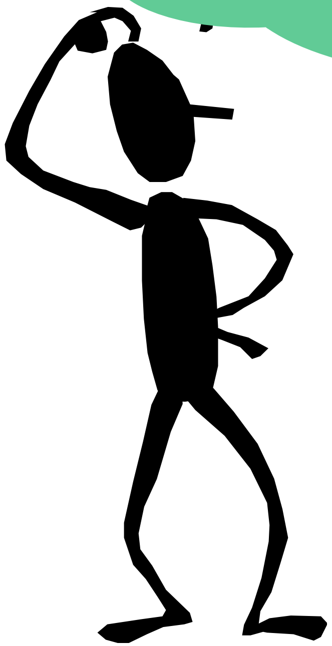
- 6LoWPAN
  - *IPv6 over Low power WPAN*
- RPL
  - *Routing Protocol for Low power and Lossy networks*
- CoAP
  - *Constrained Application Protocol*



IEEE 802.15.4 Standard

Reference technology for WSANs

Expected to be a major enabling technology also for IoT



IEEE 802.15.4 standard

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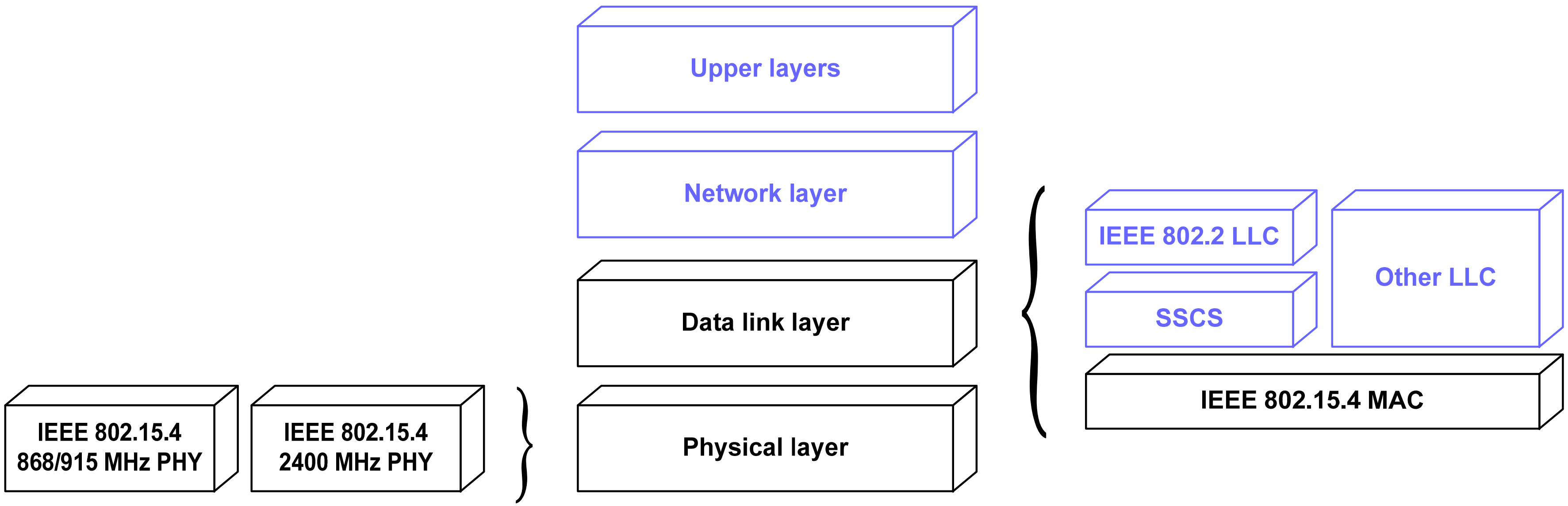
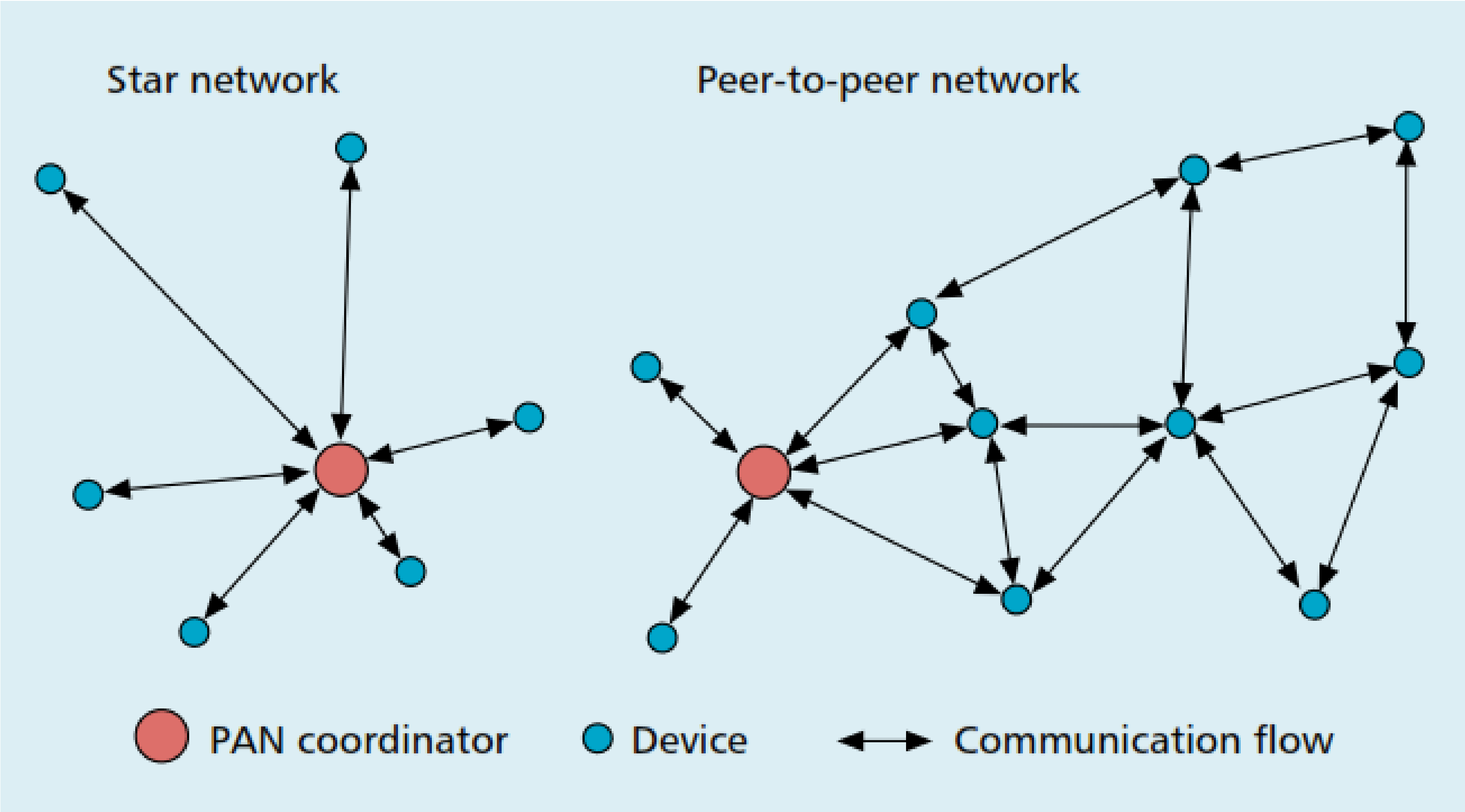


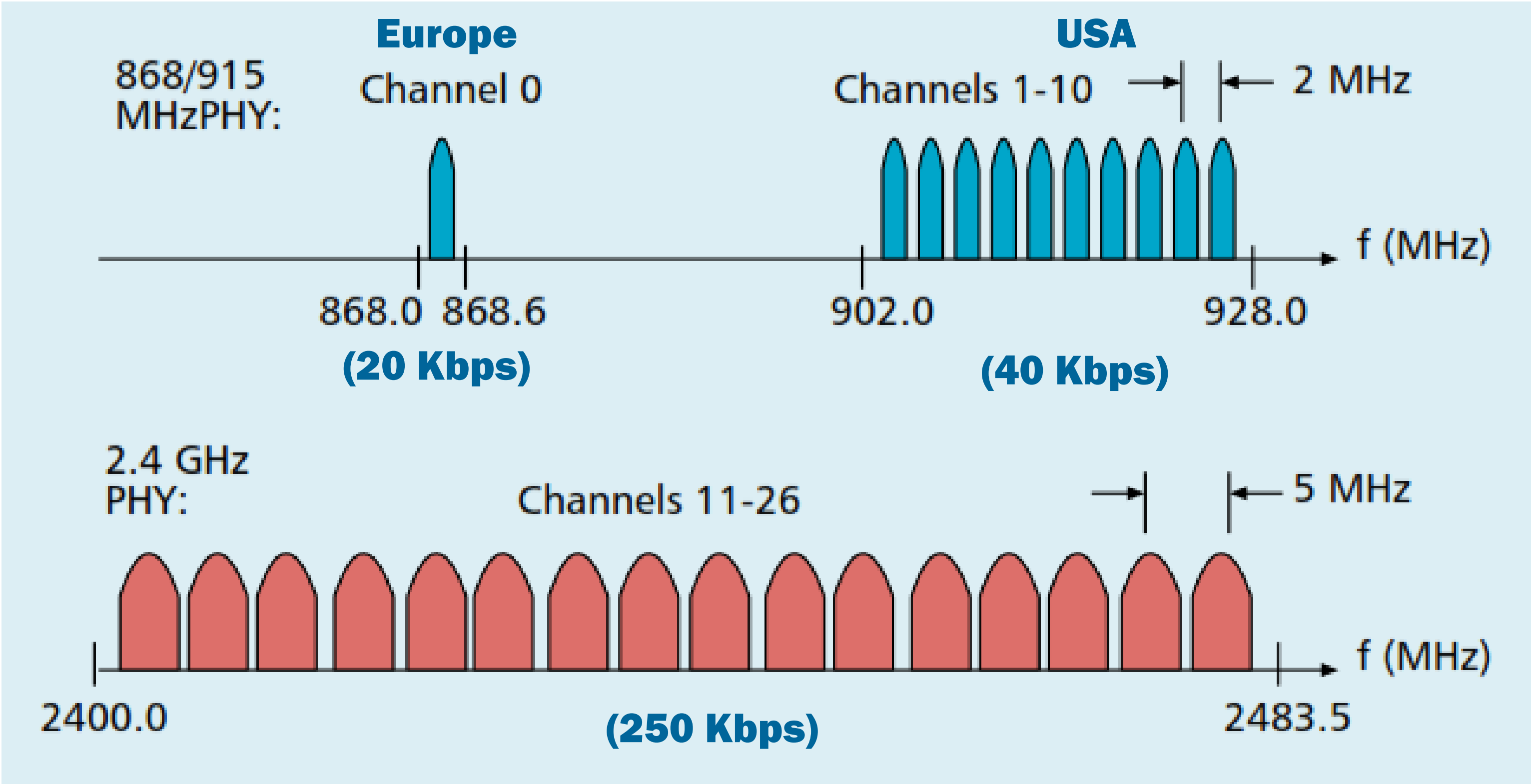
- Standard for Personal Area Networks (PANs)
  - low-rate and low-power
  - PHY and MAC layers
- Main features
  - transceiver management
  - channel access
  - PAN management

802.15.4 Network Topologies



Ed Callaway, Paul Gorday, Lance Hester, Jose A. Gutierrez, Marco Naeve, Bob Heile, **Home Networking with IEEE 802.15.4: Developing Standard for Low-Rate Wireless Personal Area Networks,** *IEEE Communications Magazine*, August 2002.

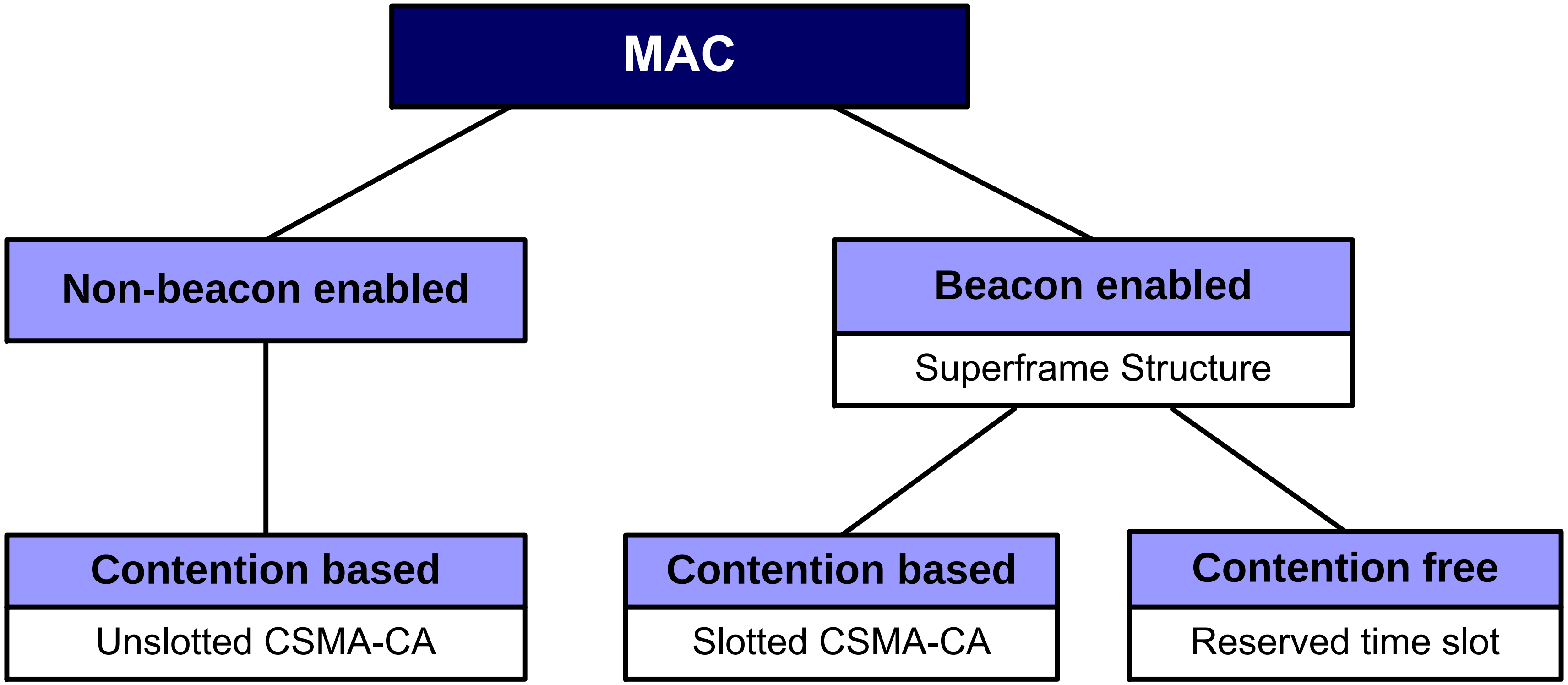
Channel frequencies



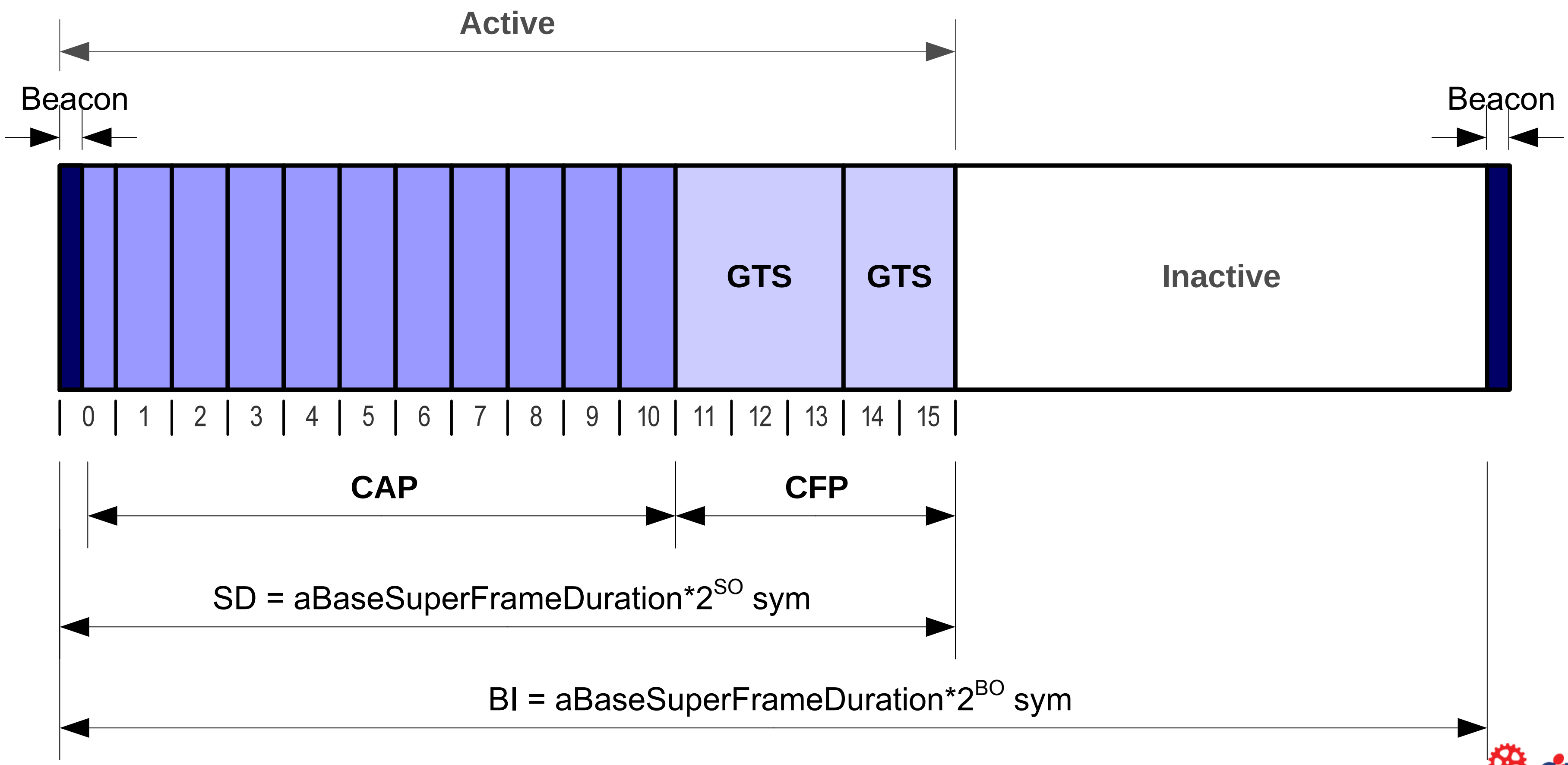
Ed Callaway, Paul Gorday, Lance Hester, Jose A. Gutierrez, Marco Naeve, Bob Heile, **Home Networking with IEEE 802.15.4: Developing Standard for Low-Rate Wireless Personal Area Networks,** *IEEE Communications Magazine*, August 2002.

802.15.4 MAC protocols

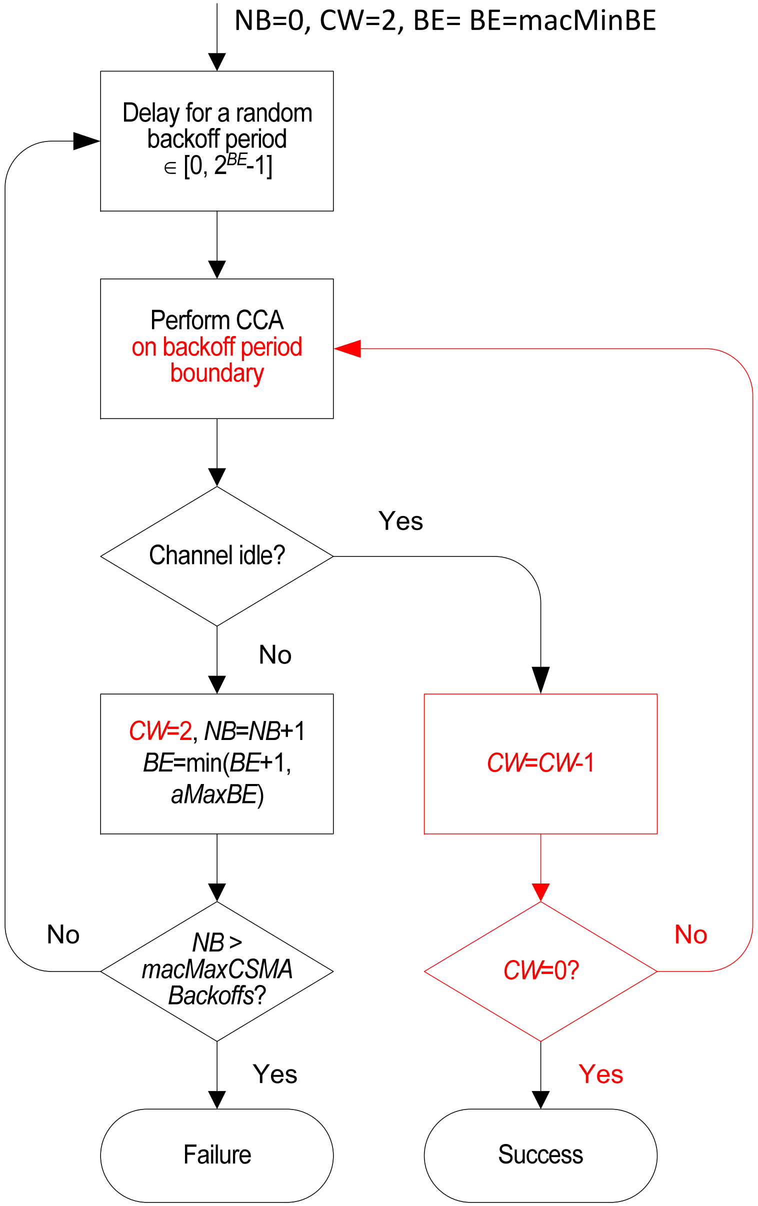
- Two different channel access methods
  - Beacon-Enabled duty-cycled mode
  - Non-Beacon Enabled mode (aka Beacon Disabled mode)



802.15.4 Beacon Enabled mode



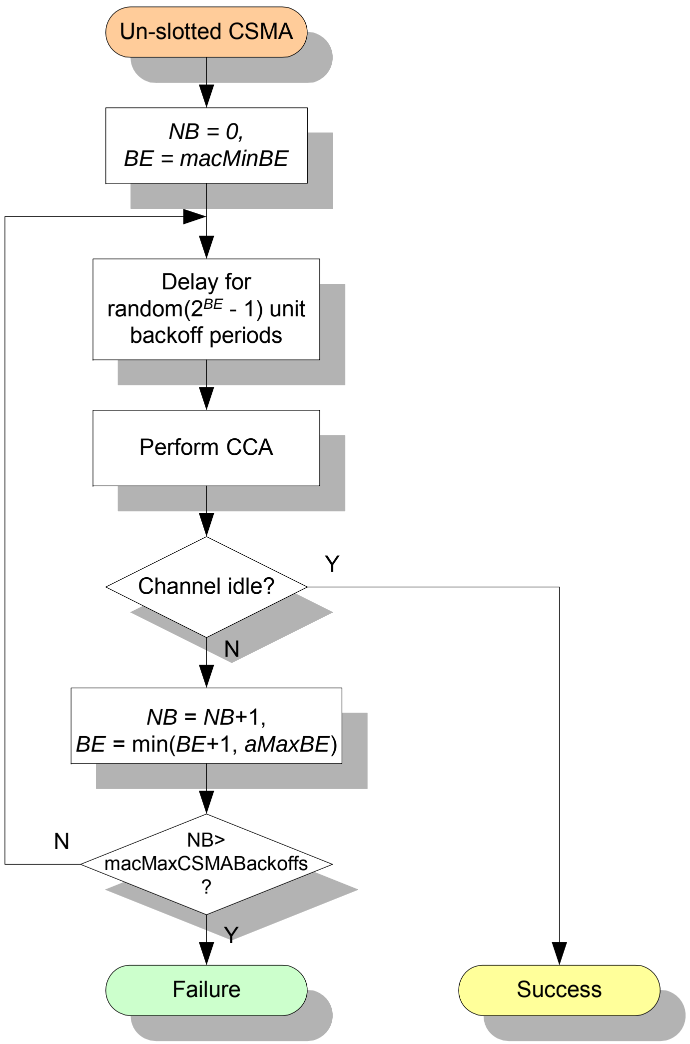
CSMA-CA: Beacon-Enabled mode



At each trial the backoff-window size is doubled

Only a limited number of attempts is permitted (***macMaxCSMABackoffs***)

CSMA-CA: Non-Beacon Enabled mode



At each trial the backoff-window size is doubled

Only a limited number of attempts is permitted (***macMaxCSMABackoffs***)

Acknowledgement Mechanism

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- Optional mechanism
- Destination Side
  - ACK sent upon successful reception of a data frame
- Sender side
  - Retransmission if ACK not (correctly) received within the timeout
  - At each retransmission attempt the backoff window size is re-initialized
  - Only a maximum number of retransmissions allowed (*macMaxFrameRetries)*

Limits of IEEE 802.15.4 MAC

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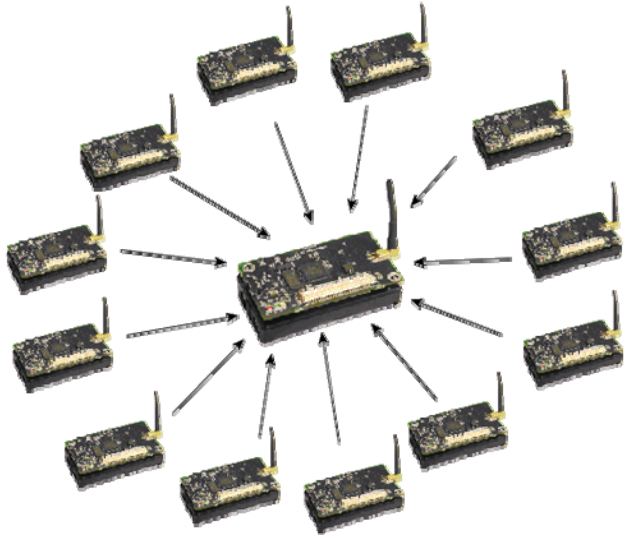
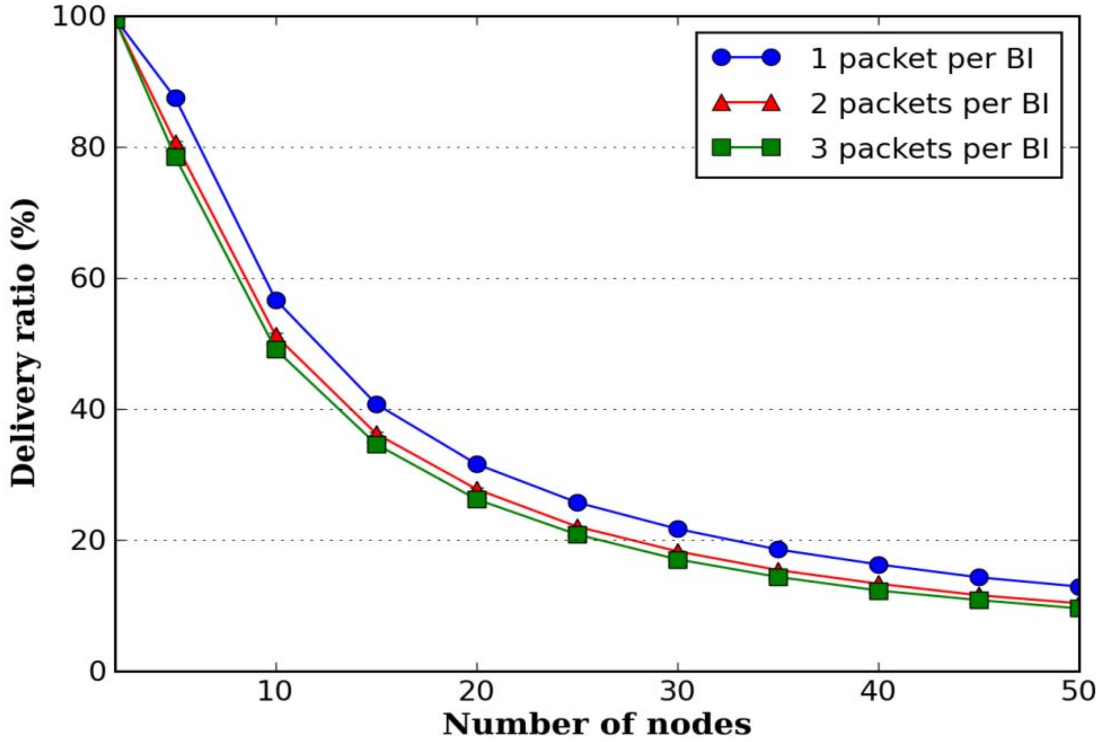
- Reliability and scalability issues
- Unbounded latency
  - Due to contention-based CSMA-CA algorithm
- No guaranteed bandwidth
  - Unless GTS is used
  - GTS only provides a limited service (7 slots)
- No built-in frequency hopping technique
  - Prone to failures due to interferences and multi-path fading

G. Anastasi, D. De Guglielmo, A Seghetti, **From IEEE 802.15.4 to IEEE 802.15.4e: a Step towards the Internet of Things**, Chapter 10 in *Advances onto the Internet of Things (*S. Gaglio, G. Lo Re, Editors), pp. 135-152. January 2014. Springer

Performance of CSMA-CA in BE mode





G. Anastasi, M. Conti, M. Di Francesco, **The MAC Unreliability Problem in IEEE 802.15.4 Wireless Sensor Networks**, Proceedings *ACM MSWIM 2009*, Tenerife, Spain, October 26-30, 2009

G. Anastasi, M. Conti, M. Di Francesco, **A Comprehensive Analysis of the MAC Unreliability Problem in IEEE 802.15.4 Wireless Sensor Networks**, *IEEE Transactions in Industrial Informatics,* Vol. 7, N. 1, Feb 2011.

Limits of IEEE 802.15.4 MAC

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Limits of IEEE 802.15.4 MAC

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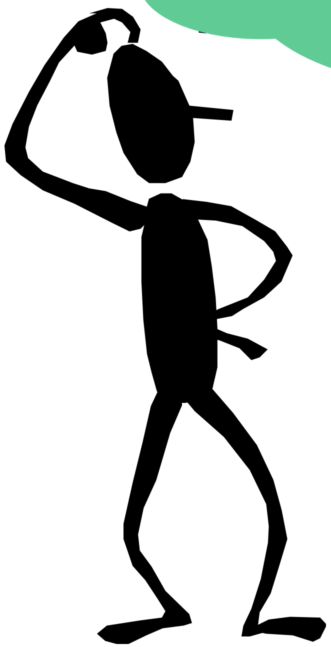
Key Question

How to do in real-life critical scenarios?



Some Real-life Scenarios

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- Smart Cities
- Smart Buildings
- Smart Homes
- Industrial Settings
- ....

Requirements

- M. Dohler, T. Watteyne, T. Winter, and D. Barthel, *Routing Requirements for Urban Low-Power and Lossy Networks*, IETF ROLL Std. RFC5548, May 2009.
- J. Martocci, P. De Mil, N. Riou, andW. Vermeylen, *Building Automation Routing Requirements in Low-Power and Lossy Networks*, IETF ROLL Std. RFC5867, June 2010.
- A. Brandt, J. Buron, G. Porcu, Home Automation Routing Requirements in Low-Power and Lossy Networks, IETF ROLL Std. RFC5826, April 2010
- K. Pister, P. Thubert, S. Dwars, and T. Phinney, *Industrial Routing Requirements in Low-Power and Lossy Networks*, IETF ROLL Std. RFC5673, Octobert 2009.

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Requirements

- Energy Efficiency
  - Target battery lifetime: 5 years, or more
- Scalability
  - Large network sizes
- Timeliness
  - Alert applications, process monitoring, ...
- Reliability
  - Wire-like reliability may be required, e.g., 99.9% or better

IEEE 802.15.4e

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- **IEEE 802.15 Task Group 4e**
  - chartered to define a MAC amendment to the existing standard 802.15.4-2006.
  - The intent of this amendment was to enhance and add functionalities to the 802.15.4-2006 MAC
    - ⇨ better support the industrial markets
    - ⇨ increase robustness against external interference
  - On February 6, 2012 the IEEE Standards Association Board approved the IEEE 802.15.4e MAC Enhancement Standard document for publication.
    - ⇨ http://www.ieee802.org/15/pub/TG4e.html

Major Changes

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- General functional improvements
  - not tied to any specific application domain
- MAC Behavior Modes
  - support of specific application domains

Remarks:

Many ideas borrowed from previous industrial standards

⇨ WirelessHART and ISA 100.11.a

⇨ *slotted access*, *shared and dedicated slots*, *multi-channel* communication, and *frequency hopping*.

General Functional Improvements

- Low Energy (LE)
- Information Elements (IE)
- Enhanced Beacons (EB)
- Multipurpose Frame
- MAC Performance Metrics
- Fast Association (FastA)

MAC Behavior Modes

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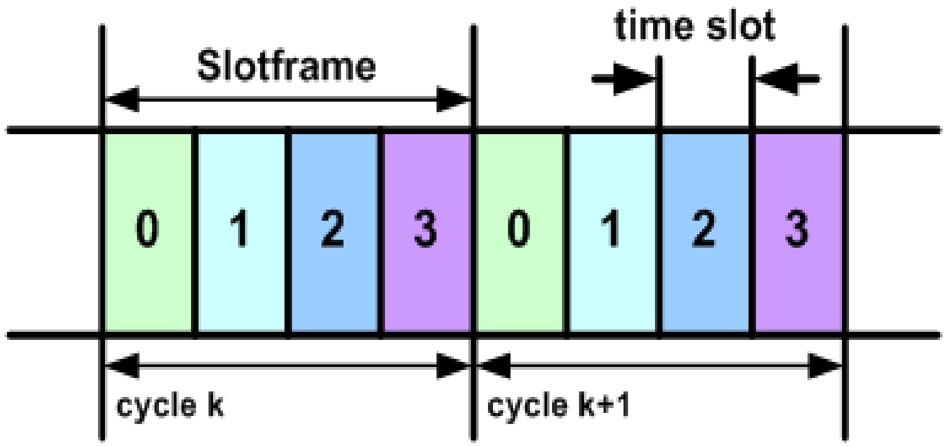
- **Radio Frequency Identification Blink (BLINK)**
  - item and people identification, location, and tracking
- **Asynchronous Multi-Channel Adaptation (AMCA)**
  - application domains where large deployments are required (e.g., process automation/control, infrastructure monitoring, etc.)
- **Deterministic & Synchronous Multi-channel Extension (DSME)**
  - industrial and commercial applications with stringent timeliness and reliability requirements
- **Low Latency Deterministic Network (LLDN)**
  - applications requiring very low latency requirement (e.g., factory automation, robot control)
- **Time Slotted Channel Hopping (TSCH)**
  - application domains such as process automation

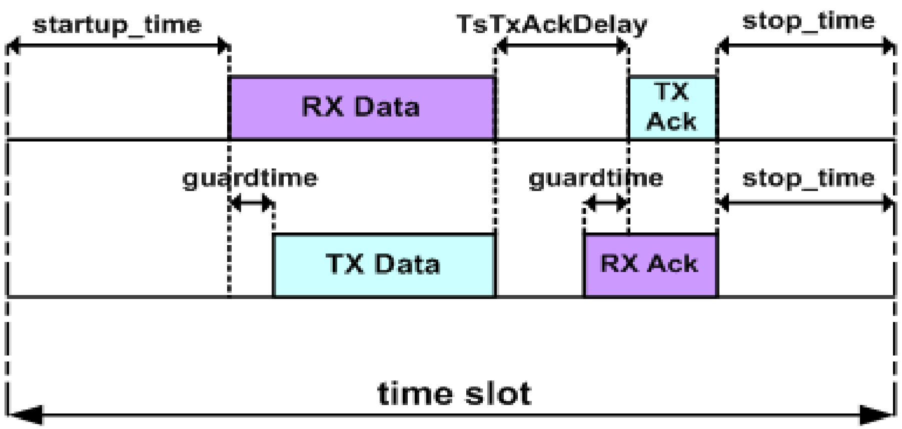
IEEE 802.15.4e TSCH

Time Slotted Channel Hopping (TSCH)

- *Time slotted* access, *multi-channel* communication and *channel hopping*
  - Particularly suitable for multi-hop mesh networks
- Time-slotted access
  - Predictable and bounded latency
  - Guaranteed bandwidth
- Multi-channel communication
  - More nodes can communicate at the same time (i.e., same slot) using different channels (identified by different channel offsets)
    - ⇨ increased network capacity
- Channel hopping
  - mitigates the effects of interferences and multipath fading
  - improves reliability

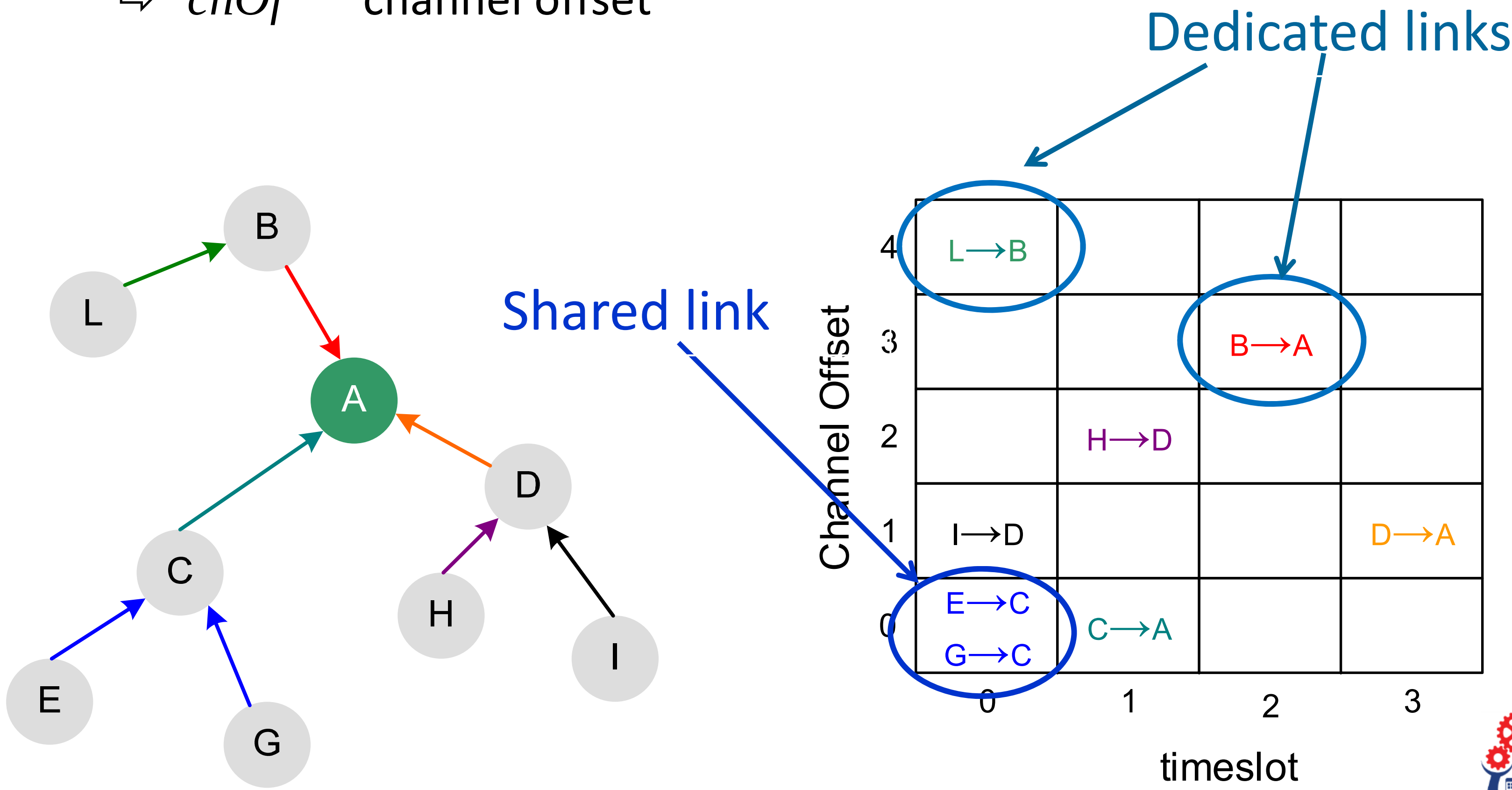
Periodic Slotframe





TSCH Link

- *Link* = Pairwise assignment of a directed communication between devices in a specific slot, with a given channel offset
  - ⇨ *t* slot in the slotframe
  - ⇨ *chOf* channel offset



Dedicated vs. Shared Links

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- **Dedicated links**
  - Deterministic traffic
  - Periodic transmissions
  - One transmitter – One receiver
  - Direct access
- **Shared links**
  - Sporadic, unpredictable traffic
  - Discovery and routing messages
  - Multiple transmitters/receivers
  - TSCH CSMA-CA protocol
    - ⇨ For avoiding repeated collisions

D. De Guglielmo, B. Al Nahas, S. Duquennoy, T. Voigt, G. Anastasi, **Analysis and Experimental Evaluation of IEEE 802.15.4e TSCH CSMA-CA Algorithm**, *IEEE Transactions on Vehicular Technology*, to appear.

TSCH Link

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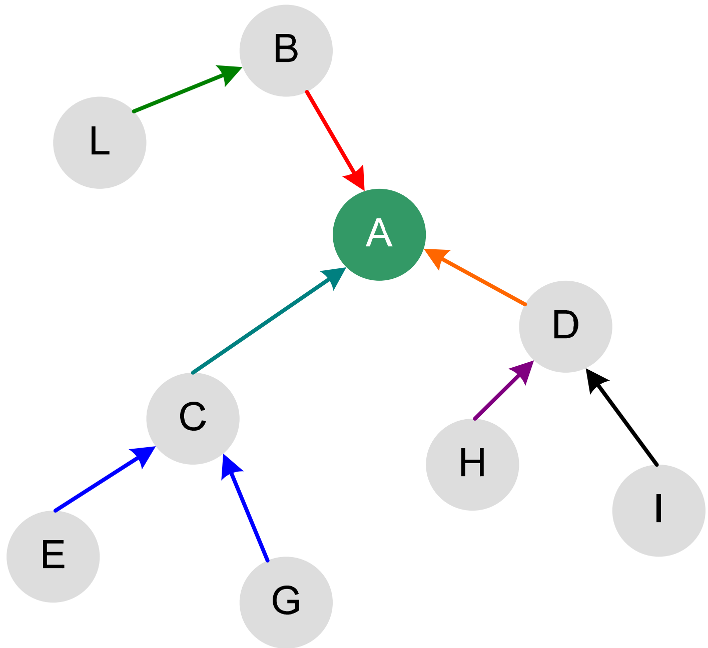

Channel Offset	0	1	2	3
4	L⟶B			
3			B⟶A	
2		H⟶D		
1	I⟶D			D⟶A
0	E⟶C G⟶C	C⟶A		

timeslot

Frequency Translation - Channel Hopping

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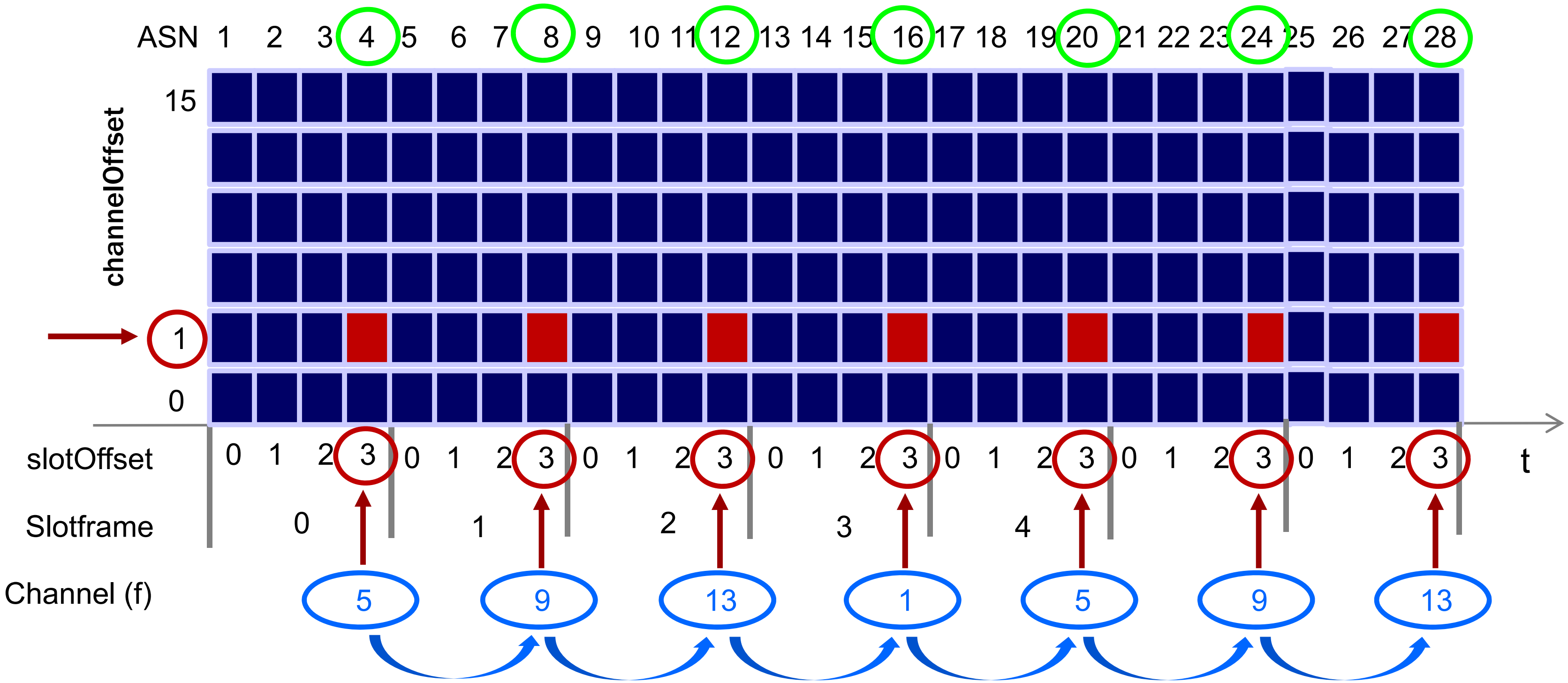
The channel offset of a Link = (t, $chOf$) is translated in an operating frequency f

$$f = F\left\{(\mathrm{ASN} + chOf) \mod n_{ch}\right\}$$

- ASN: total # of slots elapsed since the network was deployed
- n_{ch}: number of used physical channels
- F is implemented as a look-up-table containing the set of available channels

TSCH: Multi-channel + Frequency Hopping

$$f = F\{(ASN + chOf) \mod n_{ch}\}$$



Slotframe size and n_{ch} should be relatively prime

Each link rotates through the n_{ch} available channels over n_{ch} slotframes.

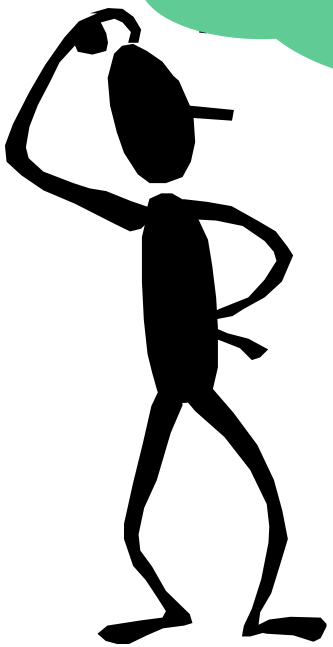
Literature Review

A lot of attention by the research community

- Researches mainly focused on:
  - Performance Evaluation of TSCH mode
  - Network formation
  - Link scheduling
  - Network synchronization
- IETF 6TiSCH Initiative
  - Integration of TSCH with IoT protocols
    - ⇨ Use of IPv6 on top of 802.15.4e TSCH

IEEE 802.15.4e TSCH

Performance Evaluation



Performance Evaluation of TSCH Mode

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- S. Zats, R. Su, T. Watteyne, K. Pister, **Scalability of Time Synchronized Wireless Sensor Networking**, Proceedings of *Annual Conference on IEEE Industrial Electronics Society* (*IECON 2011)*, November 7-10, 2011.
- S. Chen, T. Sun, J. Yuan, X. Geng, C. Li, U. Sana, M. Abdullah Alnuem, **Performance Analysis of IEEE 802.15.4e Time Slotted Channel Hopping for Low-Rate Wireless Networks**, *KSII Transactions on Internet and Information Systems*, Vol. 7, N. 1, 2013.
- D. De Guglielmo, G. Anastasi, and A. Seghetti, **From IEEE 802.15.4 to IEEE 802.15.4e: A Step Towards the Internet of Things**, Chapter in *Advances onto the Internet of Things,* pp. 135–152, 2014. Springer.
- X. Vilajosana, Q. Wang, F. Chraim, T. Watteyne, C. Tengfei, K. Pister, **A Realistic Energy Consumption Model for TSCH Networks**, IEEE *Sensors Journal,* 14 (2), 482-489, Feb. 2014.
- T. Watteyne, J. Weiss, L. Doherty, J. Simon, **Industrial IEEE802.15.4e Networks: Performance and Trade-offs**, Proceedings of *IEEE International Conference on Communications (ICC 2015),* June 8-12, 2015.
- ....

Scalability

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- Network composed of 10,000 nodes
  - deployed in an area of 0.1 km^2
    - ⇨ E.g., oil refinery where miles of piping are equipped with 100-1000 temperature, pressure, level and corrosion sensors, deployed in a relatively small geographical area
  - 50 Access Points
    - ⇨ i.e., special nodes that collect data generated by sensor nodes
    - ⇨ Multi-hop communication towards the AP
      - – routes are constructed using the upstream algorithm of RPL
      - – with a metric which introduces load-balancing between APs
  - Periodic data generation
    - ⇨ 1 packet every 10s

S. Zats, R. Su, T. Watteyne, K. Pister, **Scalability of Time Synchronized Wireless Sensor Networking**, Proceedings of *Annual Conference on IEEE Industrial Electronics Society* (*IECON 2011)*, November 7-10, 2011.

Scalability

- Results
  - delivery ratio above 99.9%
  - end-to-end latency of 2.25 s
  - network lifetime of 8.4 years
    - ⇨ if 2200mAh AA batteries are used

- Conclusions
  - By tiling 100 of these networks, the same results hold for a network with
    - ⇨ 1 million nodes
    - ⇨ deployed in 10 km^2
    - ⇨ using 5,000 APs.

S. Zats, R. Su, T. Watteyne, K. Pister, **Scalability of Time Synchronized Wireless Sensor Networking**, Proceedings of *Annual Conference on IEEE Industrial Electronics Society* (*IECON 2011)*, November 7-10, 2011.

Suitability to Real-life Applications

Goal

- exploring the capabilities and performance of a TSCH network under different conditions
  - ⇨ trade-off between throughput, latency, reliability, and power consumption for different scenarios

Use Cases

- Smart City
- Smart Building
- Industrial Setting

➡

T. Watteyne, J. Weiss, L. Doherty, J. Simon, **Industrial IEEE802.15.4e Networks: Performance and Trade-offs**, Proceedings of *IEEE International Conference on Communications (ICC 2015),* June 8-12, 2015.

Suitability to Real-life Applications

Smart City

- 10-100 thousands node with moderate density
- Low data rate (data reporting period often in the order of hours)
- Delay tolerant (a fraction of the reporting period)
- 99% reliability
- Target battery lifetime: 10 years (or more)

Smart Building

- Large networks, but broken in application-specific networks
- Moderate data rate (e.g., 1 packet every 1-30 s)
- Maximum delay less than 1s for security or fire applications
- Higher reliability than in urban networks, e.g., 99.9% reliability
- Target battery lifetime: 5 years (or more)

T. Watteyne, J. Weiss, L. Doherty, J. Simon, **Industrial IEEE802.15.4e Networks: Performance and Trade-offs**, Proceedings of *IEEE International Conference on Communications (ICC 2015),* June 8-12, 2015.

Suitability to Real-life Applications

Industrial Setting

- Process monitoring and control applications
- Harsh environment
- Network size typically smaller than in urban/building environments, but with larger radius (i.e., # of hops)
- Low-to-moderate data rate
  - ⇨ 1 data packet every 1-60 s
- Delay tolerant for some monitoring applications, stringent requirements for control applications
- 99.9% (or better) reliability
- Target battery lifetime: 5 years (or more)
  - ⇨ Larger batteries can be used because of lower cost sensitivity

T. Watteyne, J. Weiss, L. Doherty, J. Simon, **Industrial IEEE802.15.4e Networks: Performance and Trade-offs**, Proceedings of *IEEE International Conference on Communications (ICC 2015),* June 8-12, 2015.

Suitability to Real-life Applications

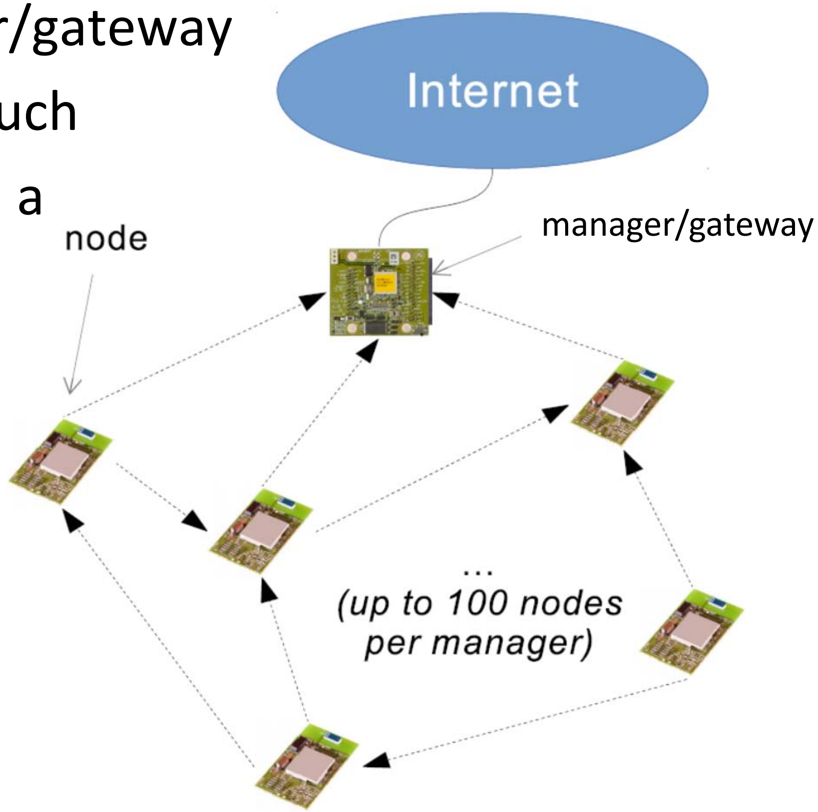
- Performance Estimator for TSCH networks
  - Advanced model providing latency, power consumption and throughput achieved by nodes
  - assumes that topology, quality of wireless links, and traffic demands are known

- Validation through experimental measurements
  - based on SmartMesh IP

T. Watteyne, J. Weiss, L. Doherty, J. Simon, **Industrial IEEE802.15.4e Networks: Performance and Trade-offs**, Proceedings of *IEEE International Conference on Communications (ICC 2015),* June 8-12, 2015.

Suitability to Real-life Applications

- Topology
  - Multi-hop mesh topology
    - ⇨ Up to 100 nodes per manager/gateway
    - ⇨ In a real environment many such networks can be tiled to form a large network



- Common Parameters
  - Packet size: 90 bytes

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Suitability to Real-life Applications

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Parameters

- Nodes: 100
- Network Radius: 8 hops
- Similar # of nodes at each hop
- Data report period: 3600 s
- No peer-to-peer traffic
- P_{loss}=20%
- Slotframe=1024
- 10000 mAh battery

Performance

- Lifetime: 51 years
  - ⇨ Larger than 10-year requirement
- Latency
  - ⇨ 1-hop nodes: 1.50 s
  - ⇨ Deep nodes: 12.0 s

T. Watteyne, J. Weiss, L. Doherty, J. Simon, **Industrial IEEE802.15.4e Networks: Performance and Trade-offs**, Proceedings of *IEEE International Conference on Communications (ICC 2015),* June 8-12, 2015.

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Suitability to Real-life Applications

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Parameters

- Nodes: 100
- Network Radius: 4 hops
- 40, 30, 20, 10 nodes per hop
- Data report period: 15 s
- Peer-to-peer traffic and downstream control
- P_{loss}=30%
- Slotframe=256
- 2000 mAh battery (a pair of AA batteries)

Performance

- Lifetime: 5.3 years
  - ⇨ Larger than 5-year requirement
- Latency
  - ⇨ 1-hop nodes: 0.92 s
  - ⇨ Deep nodes: 3.7 s

T. Watteyne, J. Weiss, L. Doherty, J. Simon, **Industrial IEEE802.15.4e Networks: Performance and Trade-offs**, Proceedings of *IEEE International Conference on Communications (ICC 2015),* June 8-12, 2015.

Industrial Setting

Parameters

- Nodes: 100
- Network Radius: 20 hops
- 5 nodes for each hop
- Data report period: 30 s
- P_{loss}=30%
- Slotframe=256
- 10000 mAh battery

Performance

- Latency
  - ⇨ 1-hop nodes: 0.46 s
  - ⇨ Deep nodes: 9.2 s

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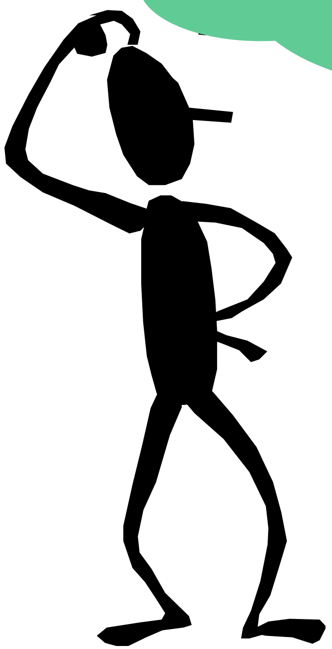
IEEE 802.15.4e TSCH

TSCH
Network Formation



Network Formation

- Based on *Enhanced Beacons* (EBs)
  - Regularly emitted by the PAN Coordinator and other nodes

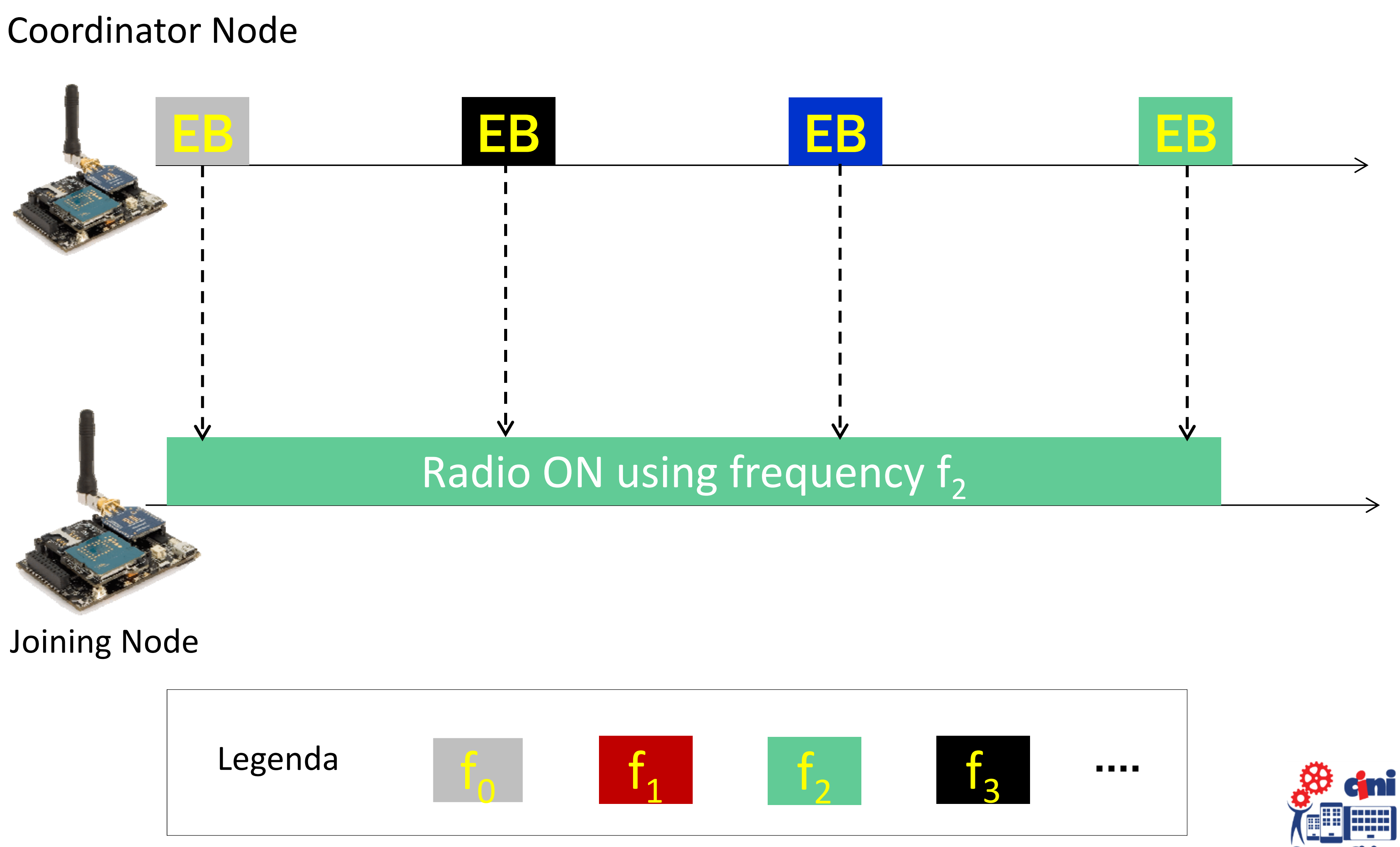
- EBs are special frames containing
  - *Synchronization information*
    - ⇨ allows new devices to synchronize to the network
  - *Channel hopping information*
    - ⇨ allows new devices to learn the channel hopping sequence
  - *Timeslot information*
    - ⇨ describes when to expect a frame transmission and when to send an acknowledgment
  - *Initial link and slotframe information*
    - ⇨ allows new devices to know:
      - when to listen for transmissions from the advertising device
      - when to transmit to the advertising device

The EB advertising policy is not part of the 802.15.4e standard

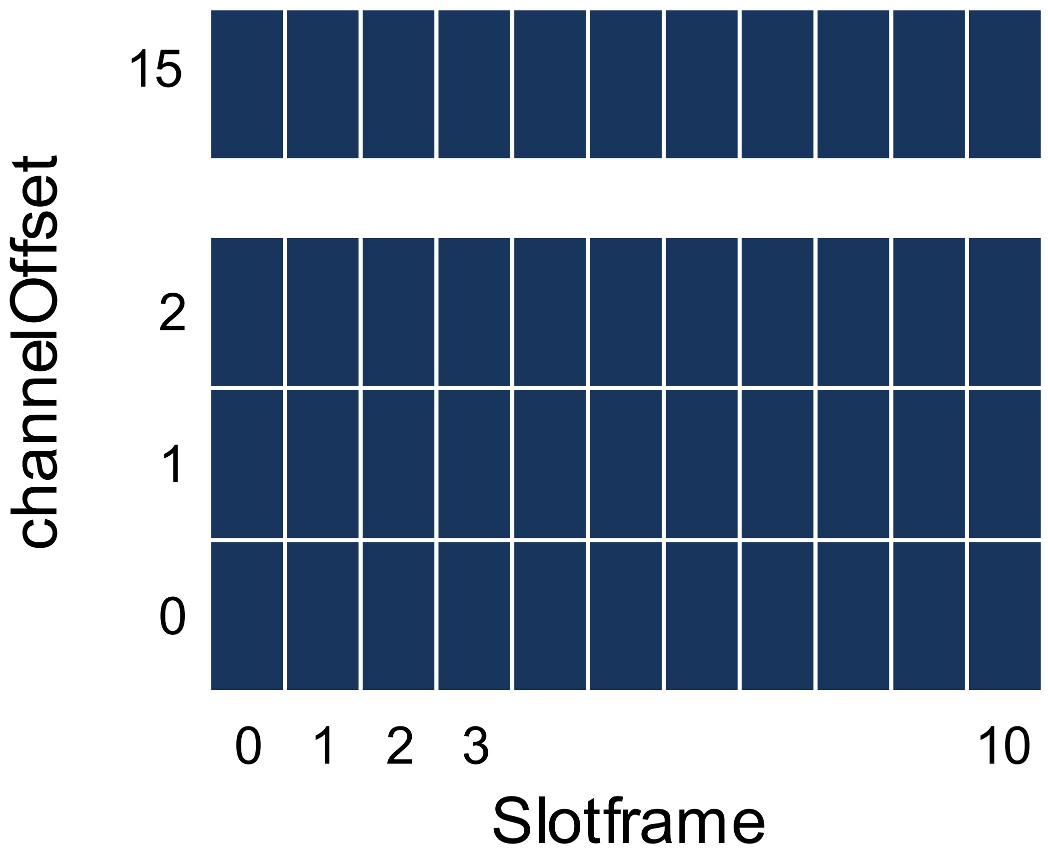
Network Formation

- A joining device starts listening for possible EBs
  - on a certain frequency
- Upon receiving an EB
  - The MAC layer notifies the higher layer
  - The higher layer initializes the slotframe and links
    - ⇨ Using information in the received EB message
  - and switches the device into TSCH mode
    - ⇨ At this point the device is connected to the network
  - Then, the device allocates communication resources
    - ⇨ (i.e., slotframes and links)
  - and starts advertising, on its turn

Network Formation



When to transmit EBs?



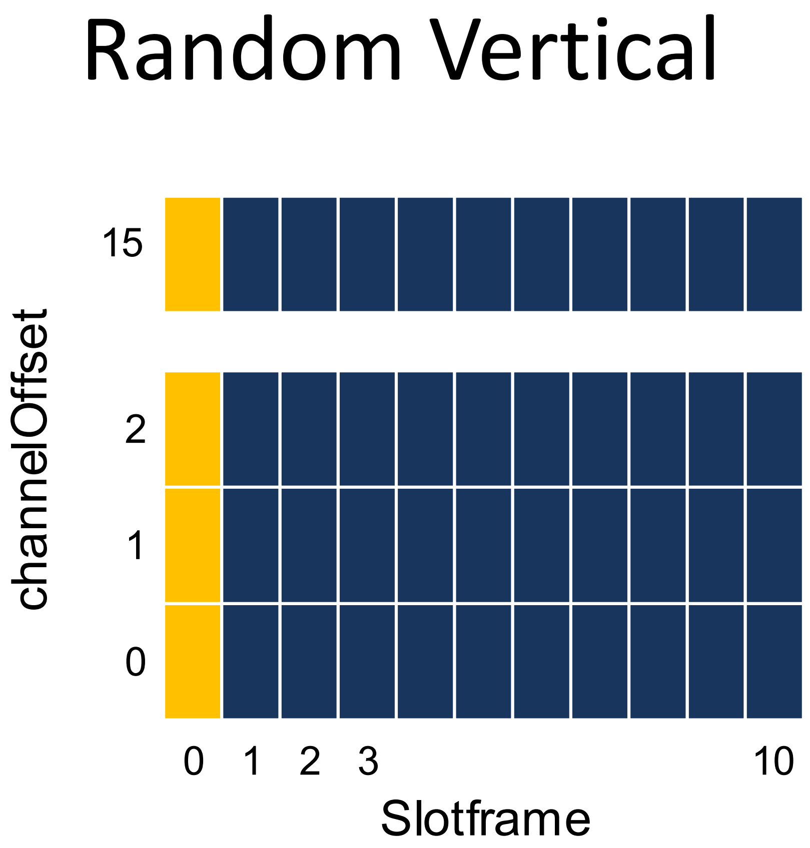
Goals

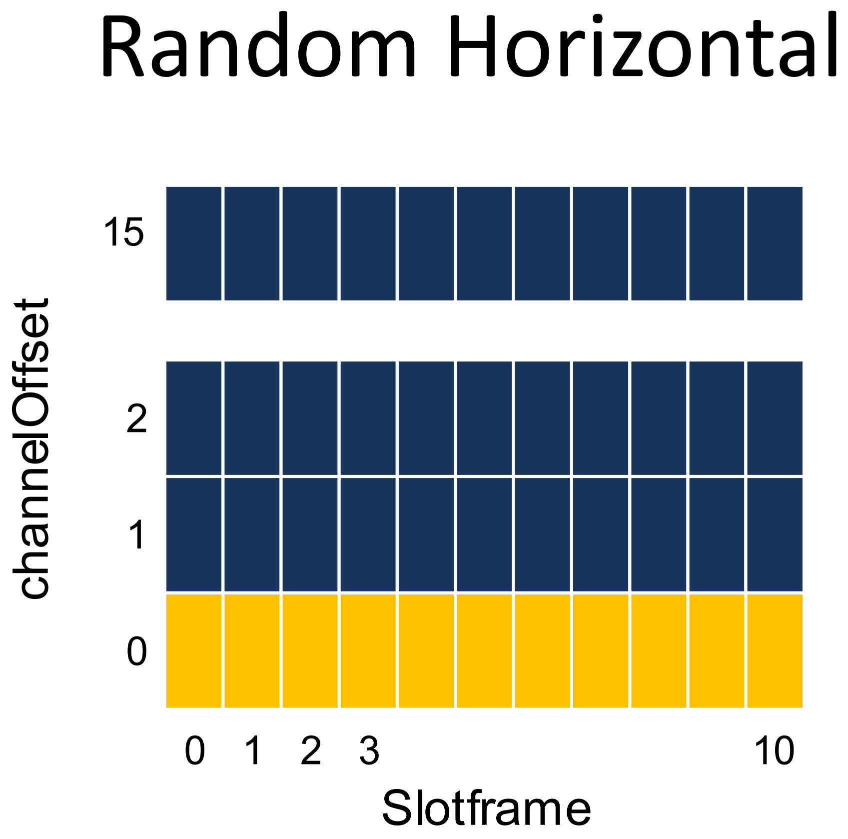
PerLab

- Minimum Joining time
  - Devices must keep the radio ON during the joining phase
  - EBs should be sent frequently

- Frequent EB transmissions
  - Reduce communication resources
  - Increase energy consumption at network nodes

When to transmit EBs?

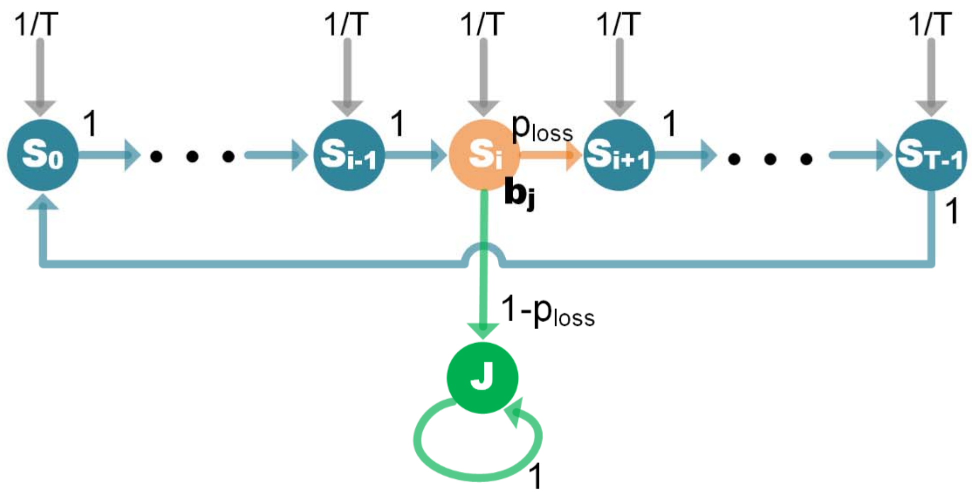




E.Vogli, G.Ribezzo, L.A.Grieco, and G.Boggia, **Fast Join and Synchronization Schema in the IEEE 802.15.4e MAC**, *Proc. IEEE Wireless Communications and Networking Conference Workshops (WCNCW 2015)*, 2015.

Model of the Joining Phase

- Based on DTMC
- Analytical expression of *joining time* τ_{join}
  - ⇨ Avg. joining time depends on the EB transmission strategy



$$
P = \begin{array}{cc}
 & \begin{array}{cccccccc} s_0 & \cdots & s_{i-1} & s_i & s_{i+1} & \cdots & s_{T-1} & J \end{array} \\
\begin{array}{c} s_0 \\ \vdots \\ s_{i-1} \\ s_i \\ s_{i+1} \\ \vdots \\ s_{T-1} \\ J \end{array} &
\left[\begin{array}{cccccccc}
0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \\
0 & \cdots & 0 & 1 & 0 & \cdots & 0 & 0 \\
0 & \cdots & 0 & 0 & p_{loss} & \cdots & 0 & 1-p_{loss} \\
0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
1 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\
0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 1
\end{array}\right]
\end{array}
$$

D. De Guglielmo, S. Brienza, G. Anastasi, **A Model-based Beacon Scheduling Algorithm for IEEE 802.15.4e TSCH Networks**, Proc. *IEEE Int'l Symposium on a World of Wireless, Mobile, and Multimedia Networks* (*WoWMoM 2016*), Coimbra, Portugal, June 21-24, 2016.

Model-based Approach

PerLab

Model of the Joining Phase

- Based on DTMC
- Analytical expression of *joining time* τ_{join}
  - ⇨ Avg. joining time depends on the EB transmission strategy

$$\tau_{join} = \frac{\sum_{i=0}^{N_b-1}\left(\left(1-p_{loss}^{N_b}\right)\frac{d(b_i,b_{i+1})(d(b_i,b_{i+1})-1)}{2} + d(b_{i-1},b_i)\left(1-p_{loss}^{N_b}+\sum_{j=0}^{N_b-1}\left(d\left(b_{i+j+1},b_{i+j+2}\right)p_{loss}^{i+j}\right)\right)\right)}{(N_c N_s)\left(1-p_{loss}^{N_b}\right)}$$

$$b_{N_b} \equiv b_0$$

D. De Guglielmo, S. Brienza, G. Anastasi, **A Model-based Beacon Scheduling Algorithm for IEEE 802.15.4e TSCH Networks**, Proc. *IEEE Int'l Symposium on a World of Wireless, Mobile, and Multimedia Networks* (*WoWMoM 2016*), Coimbra, Portugal, June 21-24, 2016.

Model-based Approach

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Optimization Problem

$$\begin{cases} \min_{d_j} \tau_{join} \\ \sum_{j=0}^{N_b} d_j = T \\ d_j \in N \ \forall j \end{cases}$$

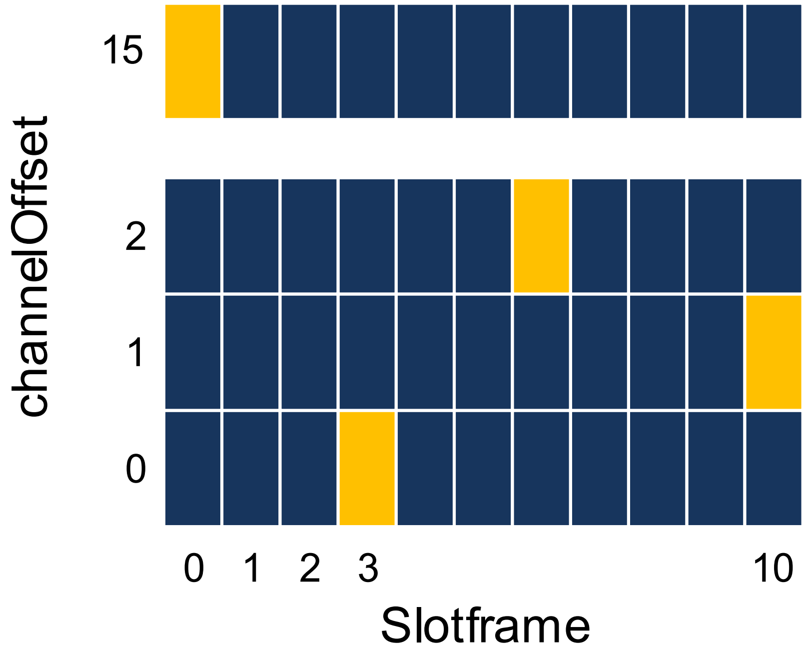
- $d_0 \ldots d_{N_b-1}$ are the unknowns
  - distances, in terms of timeslots, between successive EBs
- T: slotframe duration

D. De Guglielmo, S. Brienza, G. Anastasi, **A Model-based Beacon Scheduling Algorithm for IEEE 802.15.4e TSCH Networks**, Proc. *IEEE Int'l Symposium on a World of Wireless, Mobile, and Multimedia Networks* (*WoWMoM 2016*), Coimbra, Portugal, June 21-24, 2016.

Model-based Approach

PerLab

- Model-based Sheduling Algorithm
  - Given the total number of EBs to allocate
  - provides the EB allocation strategy that minimizes the joining time



Performance Comparison

PerLab

- Model-based Scheduling (MBS)
- Random (RD)
- Extended Random Vertical (ERV)
- Extended Random Horizontal (ERH)

$\mathbf{N_b}$ (# of EBs advertised per superframe) equal for all the considered options

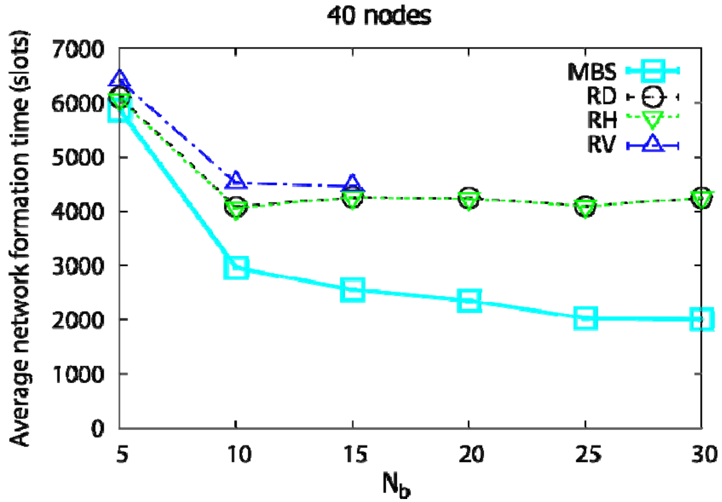
Performance Index: Avg. Network Formation Time

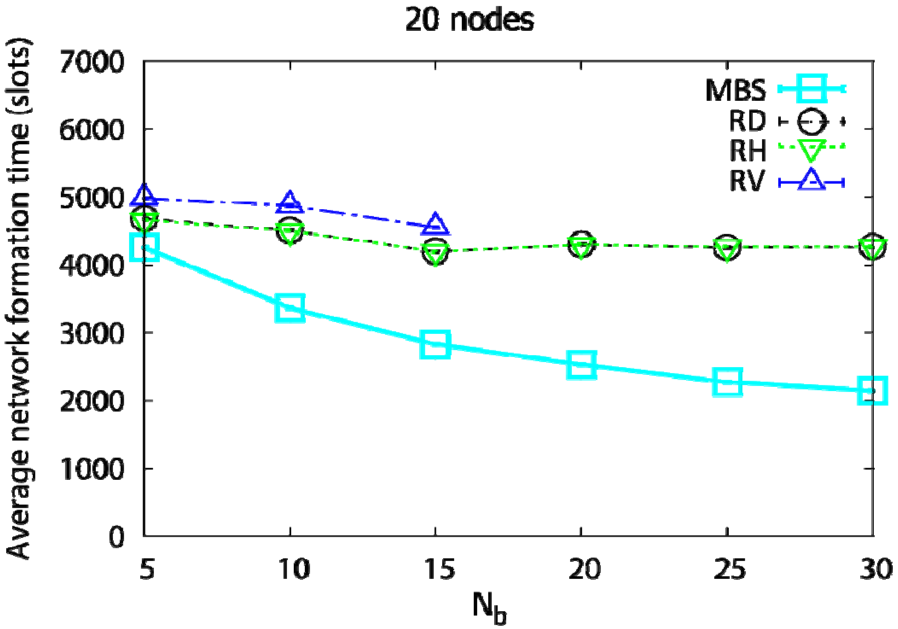
average time (in # of timeslots) from when the PAN coordinator transmits the first EB to when the last node in the group joins the network

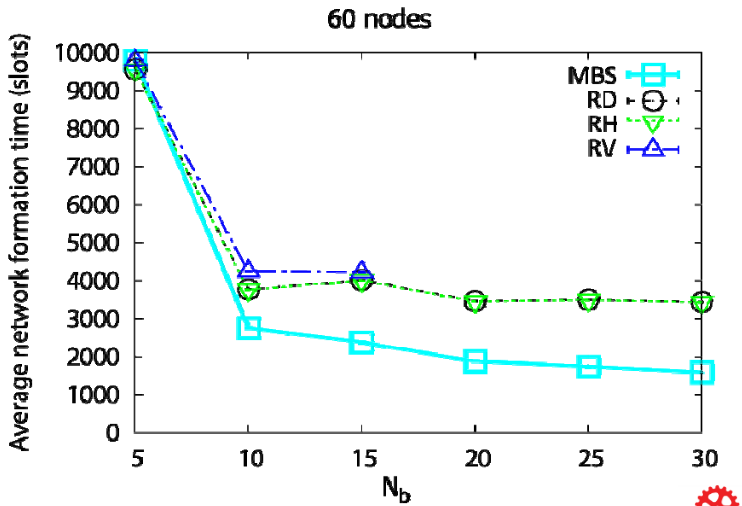
PerLab

Scenario

- N nodes willing to set up a network
- Random deployment over an area of 80×80 m^2
- P_{loss} = 0%

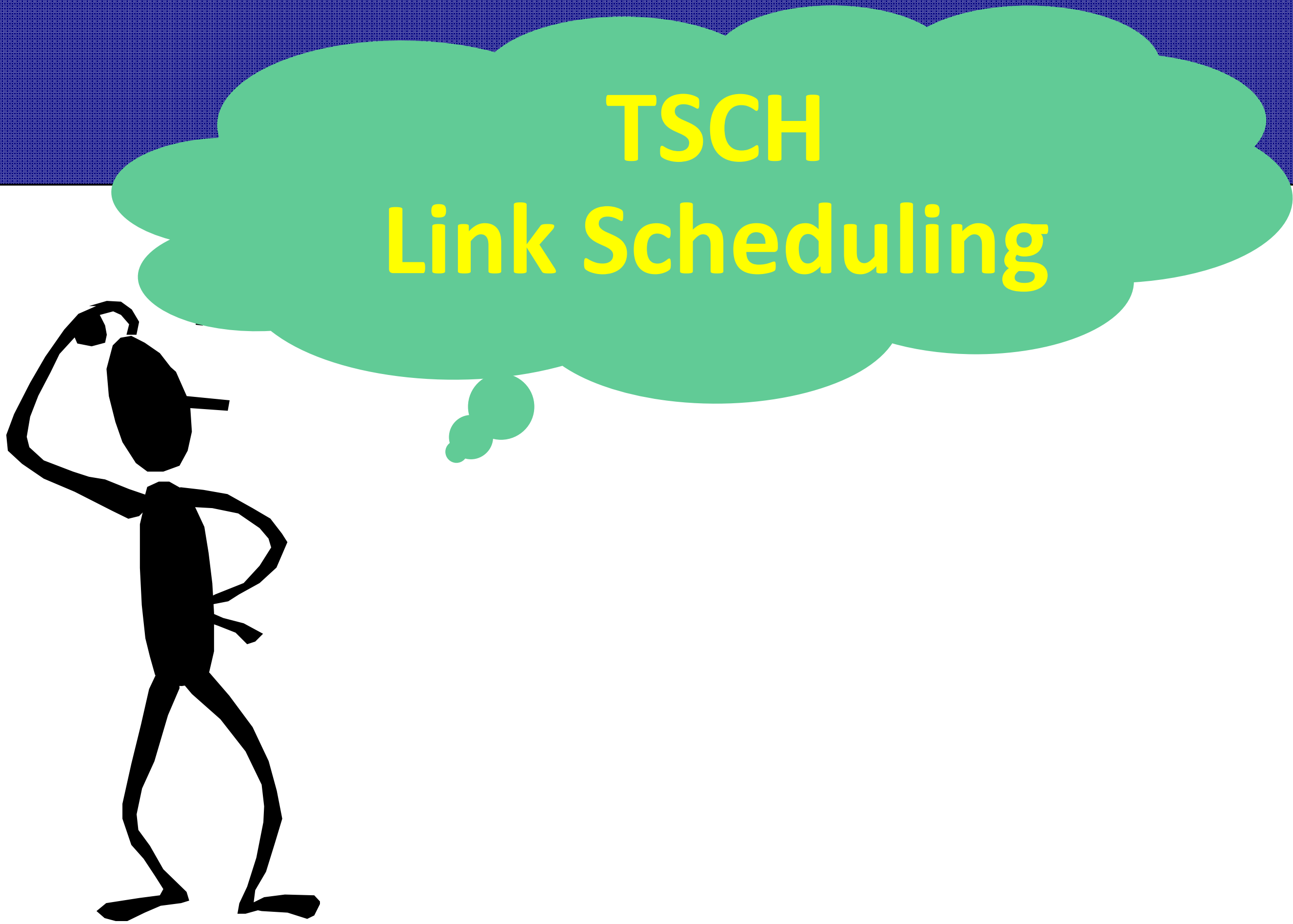






D. De Guglielmo, S. Brienza, G. Anastasi, **A Model-based Beacon Scheduling Algorithm for IEEE 802.15.4e TSCH Networks**, Proc. *IEEE Int'l Symposium on a World of Wireless, Mobile, and Multimedia Networks* (*WoWMoM 2016*), Coimbra, Portugal, June 21-24, 2016.

IEEE 802.15.4e TSCH



Link Scheduling

PerLab

- Assignment of links to nodes for data transmissions
  - *Duplex-conflict free*
    - ⇨ A node cannot receive simultaneously from many senders
    - ⇨ A node cannot transmit and receive at the same time
  - *Interference-conflict free*
    - ⇨ neighboring nodes should not transmit in the same timeslot and with the same channel offset
- Multi-channel comm. makes link scheduling easier
  - Optimal schedule is hard to find
    - ⇨ large networks with multi-hop topology
    - ⇨ dynamic networks (mobility, power management, …)

IEEE 802.15.4e does NOT specify how to derive an appropriate link schedule

TDMA Scheduling

- TDMA scheduling algorithms typically address single-channel networks
  - recently, multi-channel TDMA scheduling solutions have been proposed
- Most existing multi-channel scheduling schemes are not suitable for TSCH networks
  - do not allow per-packet channel hopping
  - do not address resource-constrained nodes
    - ⇨ e.g., they are not memory efficient
  - do not consider the spatial reuse of channels

TSCH Scheduling

PerLab

- Centralized Scheduling
- Distributed Scheduling

TSCH Scheduling

Centralized Scheduling

- Link schedule computed and distributed by a special node
  - Coordinator (Manager) node
  - Based on information received by all the nodes of the network
    - ⇨ network topology
    - ⇨ traffic pattern
- Re-computed dynamically
  - Whenever a change in the operating conditions occurs
- Not appealing for
  - *dynamic* networks (mobile nodes, power management)
  - *large-scale* networks

TSCH Scheduling

Distributed Scheduling

- No central entity
  - Link schedule computed autonomously by each node
    - ⇨ based on local, partial information exchanged with its neighbors.
- The overall schedule is typically *non optimal*
- Limited Overhead
  - Suitable for energy-constrained nodes

TSCH Centralized Scheduling

- TASA (Traffic Aware Scheduling Algorithm) [1] [2]
  - Tree network topology
  - Converge-cast communication model
  - The coordinator has a single radio interface
  - Heterogeneous traffic conditions

- MODESA (Multi-channel Optimized Delay Slot Assignment) [3]
  - Tree network topology
  - Converge-cast communication model
  - The coordinator has multiple radio interfaces
  - Homogeneous traffic conditions (heterogeneous conditions in [4])

[1] M.R. Palattella, N. Accettura, M. Dohler, L.A. Grieco, G. Boggia, **Traffic Aware Scheduling Algorithm for reliable low-power multi-hop IEEE 802.15.4e networks**, Proc. *IEEE Int'l Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2012),* Sept. 12, 2012

[2] M.R. Palattella, N. Accettura, L.A. Grieco, G. Boggia, M. Dohler, T. Engel. **On Optimal Scheduling in Duty-Cycled Industrial IoT Applications Using IEEE802.15.4e TSCH**, *IEEE Sensors Journal, Vol.* 13, N. 10, pp. 3655-3666, October 2013

[3] R. Soua, P. Minet, E. Livolant, **MODESA: An optimized multichannel slot assignment for raw data convergecast in wireless sensor networks**, Proc. *IEEE International Performance Computing and Communications Conference (IPCCC 2012),* Dec. 1-3, 2012

[4] RSoua, E. Livolant, P. Minet, **MUSIKA: A multichannel multi-sink data gathering algorithm in wireless sensor networks**, *Proc. International Wireless Communications and Mobile Computing Conference (IWCMC 2013*), July 1-5, 2013

TSCH Centralized Scheduling --TASA

PerLab

- Every node regularly updates the Manager with
  - the list of other nodes it can hear
  - the amount of data it generates
- The Manager
  - draws the *connectivity graph …*
    - ⇨ Based on information received from nodes
  - *assigns* slots *to* different links in the graph …
    - ⇨ Conflict-free schedule taking an *iterative* approach
    - ⇨ Based on a combination of matching and vertex coloring techniques
  - *informs* each node about links it is involved in
- If the connectivity graph changes
  - the manager updates its schedule and informs affected nodes

Palattella, M. R., Accettura, N., Dohler, M., Grieco, L. A., & Boggia, G., **Traffic Aware Scheduling Algorithm for reliable low-power multi-hop IEEE 802.15. 4e networks**, *Proc. IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2012)*, pp. 327-332, 2012

TSCH Centralized Scheduling

PerLab

- TASA (Traffic Aware Scheduling Algorithm) [1] [2]
  - Tree network topology
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  - The coordinator has a single radio interface
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- MODESA (Multi-channel Optimized DElay Slot Assignment) [3]
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[2] M.R. Palattella, N. Accettura, L.A. Grieco, G. Boggia, M. Dohler, T. Engel. **On Optimal Scheduling in Duty-Cycled Industrial IoT Applications Using IEEE802.15.4e TSCH**, *IEEE Sensors Journal, Vol.* 13, N. 10, pp. 3655-3666, October 2013

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TSCH Centralized Scheduling --MODESA

PerLab

- Basic idea
  - selecting one node at each iteration …
  - … and choosing a link to accommodate one of its required transmissions
  - The execution terminates when the transmissions of *all* nodes in the network have been accommodated
- Node selection
  - based on dynamic priority
  - depending on the number of packets still to transmit

R. Soua, P. Minet, E. Livolant, **MODESA: An optimized multichannel slot assignment for raw data convergecast in wireless sensor networks**, Proc. *IEEE International Performance Computing and Communications Conference (IPCCC 2012),* Dec. 1-3, 2012

TSCH Centralized Scheduling --MODESA

PerLab

MODESA Algorithm

Iterates over the set of nodes with data to transmit

- and having an available interface with their parent in that slot
- Sorted according to their priorities

- Picks the node with the highest priority
- Schedules its first transmission
  - on that timeslot
  - on the first channel offset
- Then, selects another node
  - If the node is in conflict with a previously scheduled node its transmission is allocated on a different channel offset
  - otherwise, the same channel offset is used
- Continues until transmissions of all nodes have been scheduled

R. Soua, P. Minet, E. Livolant, **MODESA: An optimized multichannel slot assignment for raw data convergecast in wireless sensor networks**, Proc. *IEEE International Performance Computing and Communications Conference (IPCCC 2012),* Dec. 1-3, 2012

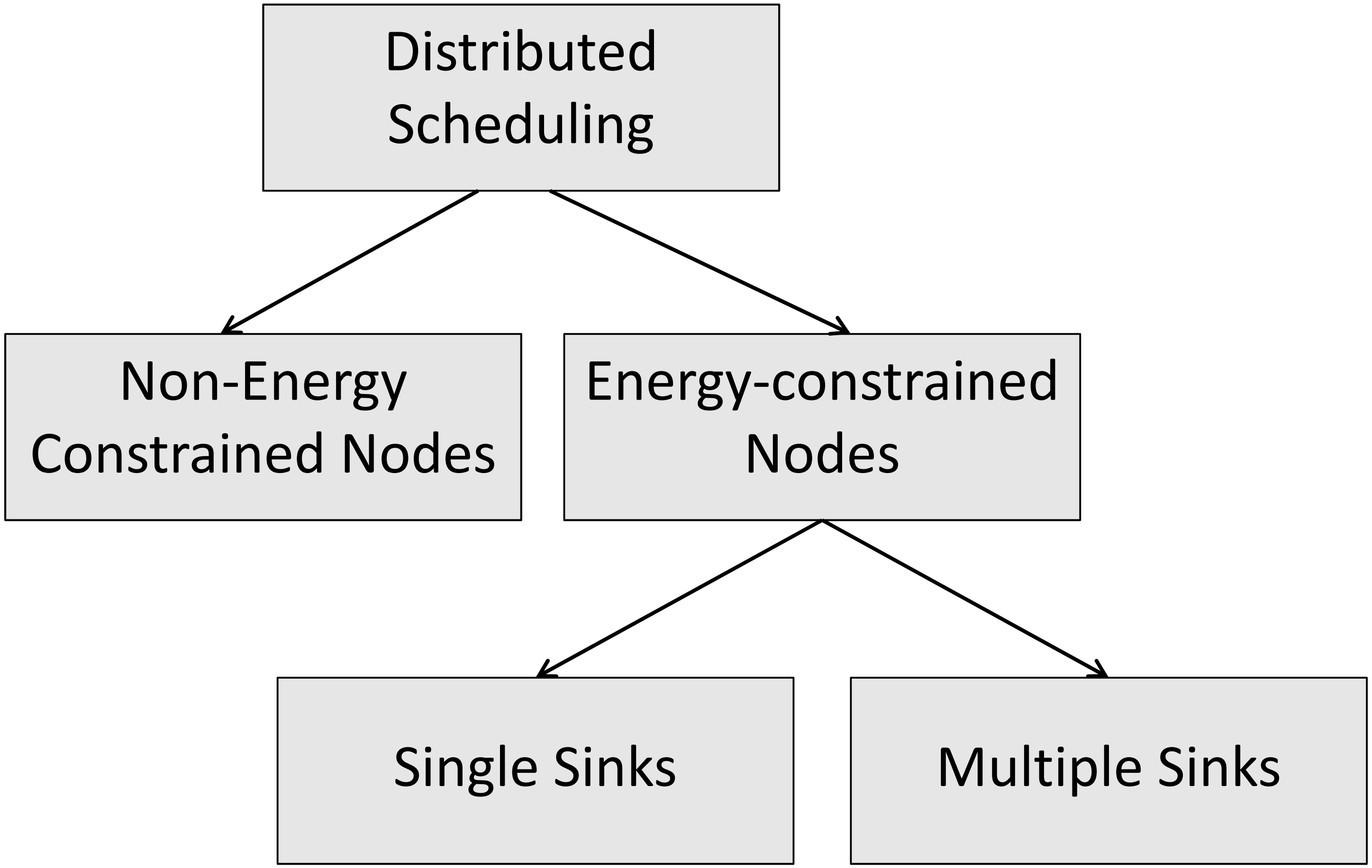
TSCH Centralized Scheduling --MODESA

PerLab

- MODESA has been shown to be optimal
  - For linear and balanced-tree topologies
- Performance is close to that of an optimal algorithm
  - Also for random network topologies
- Impact of # of communication channels
  - Drastically reduce the schedule length
  - Similar trend when increasing the # of interfaces at the coordinator
- Guidelines
  - It is useless to equip the coordinator with a number of interfaces greater than the number of its children
  - It is pointless to use a number of channels higher than the number of coordinator interfaces.

R. Soua, P. Minet, E. Livolant, **MODESA: An optimized multichannel slot assignment for raw data convergecast in wireless sensor networks**, Proc. *IEEE International Performance Computing and Communications Conference (IPCCC 2012),* Dec. 1-3, 2012

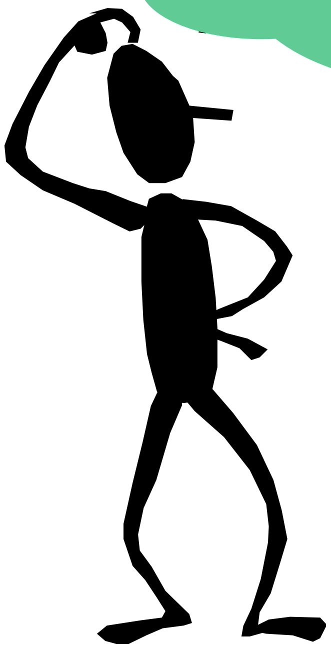
TSCH Distributed Scheduling



D. De Guglielmo, S. Brienza, G. Anastasi, **IEEE 802.15.4e: a Survey**, *Computer Communications,* Accepted with minor revision.

IEEE 802.15.4e TSCH

Summary & Open Issues



Summary

TSCH combines

- Time-slotted access
- multi-channel communication
- frequency hopping

- Energy efficiency
- Reliability
- Guaranteed bandwidth
- Limited and predictable delay
- Scalability (high aggregate throughput)
- Support for multi-hop mesh communication

Open Issues

PerLab

- Communication Model
  - Most of the previous studies have considered a convergecast scenario
  - Node-to-node communication needs to be investigated
    - ⇨ In the perspective of the Internet of Things
    - ⇨ Lightweight scheduling and routing solutions for quickly establishing node-to-node paths
- Network Formation
  - Currently available solutions may be inefficient for
    - ⇨ Mobile Objects → Frequent joins and leaves
    - ⇨ Nodes operating on a duty cycle

Open Issues

- Security
  - TDMA networks are typically prone to *Selective Jamming (*SJ*)* attacks
    - ⇨ An attacker can easily identify slots assigned to victim node
    - ⇨ and destroy all communications by that node
  - Frequency Hopping and Secure Beacons should make TSCH networks more secure
  - How robust is a TSCH network against SJ attacks?

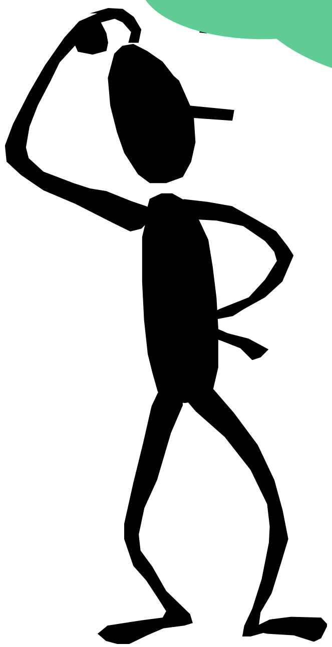
Open Issues

- TSCH and IoT integration
  - IoT protocols rely on a flexible and dynamic paradigm
    - ⇨ E.g., the IPV6 Routing Protocol for Low-Power and Lossy Networks (RPL)
  - They assume that smart objects
    - ⇨ are always active
    - ⇨ can be added and removed dynamically

Combining a dynamic and flexible routing mechanism (e.g., RPL) with 802.15.4e TSCH introduces a number of challenges

IEEE 802.15.4e TSCH

TSCH and
the Internet of Things



The 6TiSCH Initiative

- Working Group set up by IETF
  - Name: IPv6 over the TSCH mode of IEEE 802.15.4e
  - Acronym: 6TiSCH
- Goal
  - defining mechanisms to combine the high reliability and low-energy consumption of IEEE 802.15.4e TSCH with the ease of interoperability and integration offered by the IP protocol

https://datatracker.ietf.org/wg/6tisch/

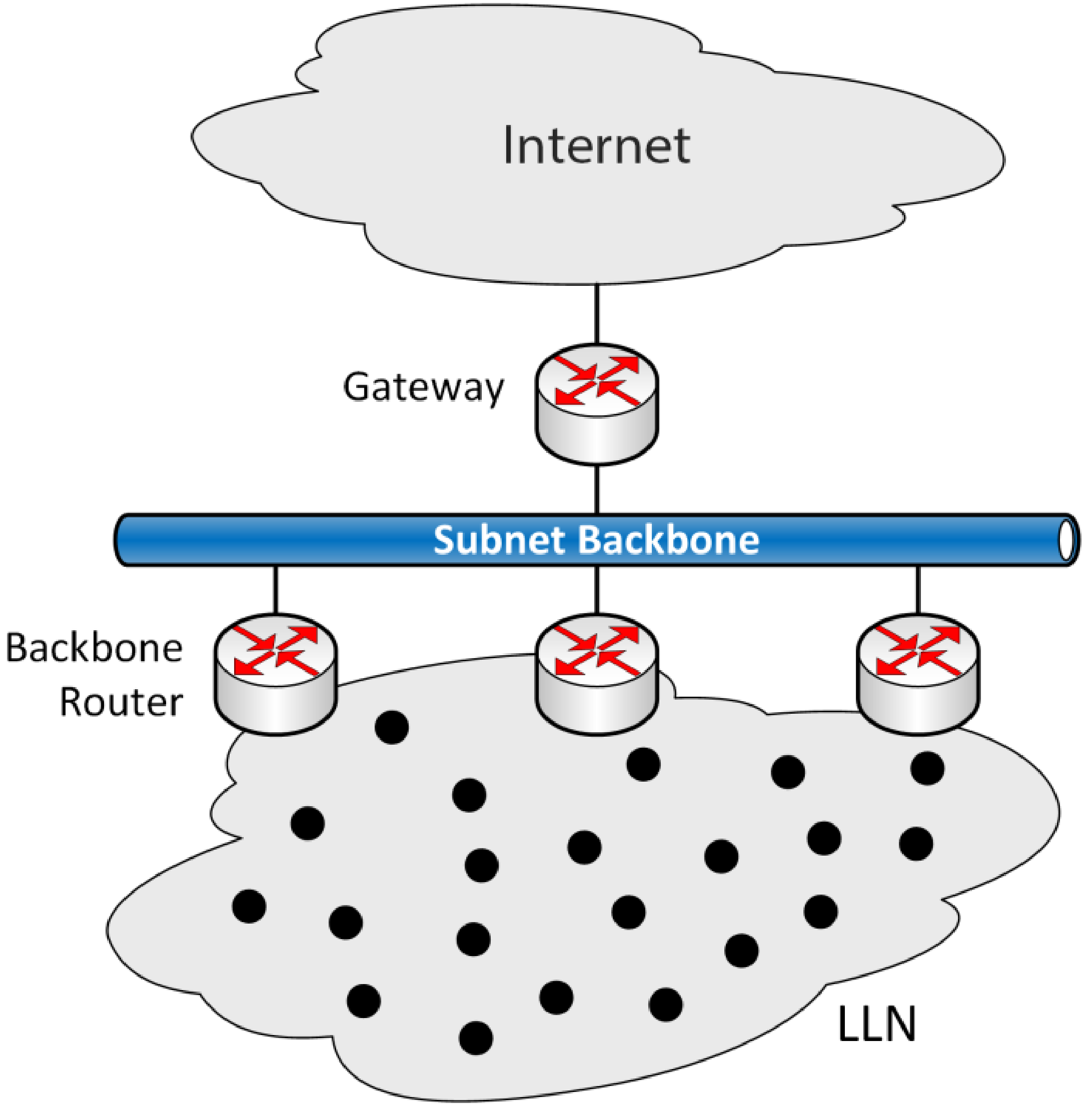
6TiSCH: Problem

PerLab

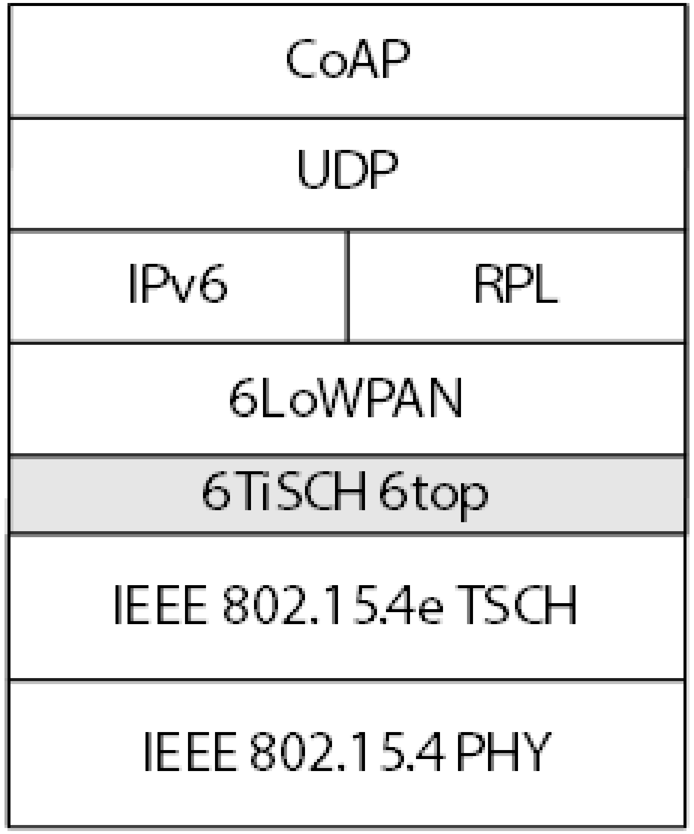
TSCH does not define

- policies to build and maintain the communication schedule
- mechanisms to match the schedule to the multi-hop paths maintained by RPL
- mechanisms to adapt the resources allocated between neighbor nodes to the data traffic flows
- techniques to allow differentiated treatment of packets
  - data packets generated at the application layer
  - signaling messages needed by 6LoWPAN and RPL to discover neighbors and react to topology changes

6TiSCH Reference Architecture



6TiSCH Protocol Stack

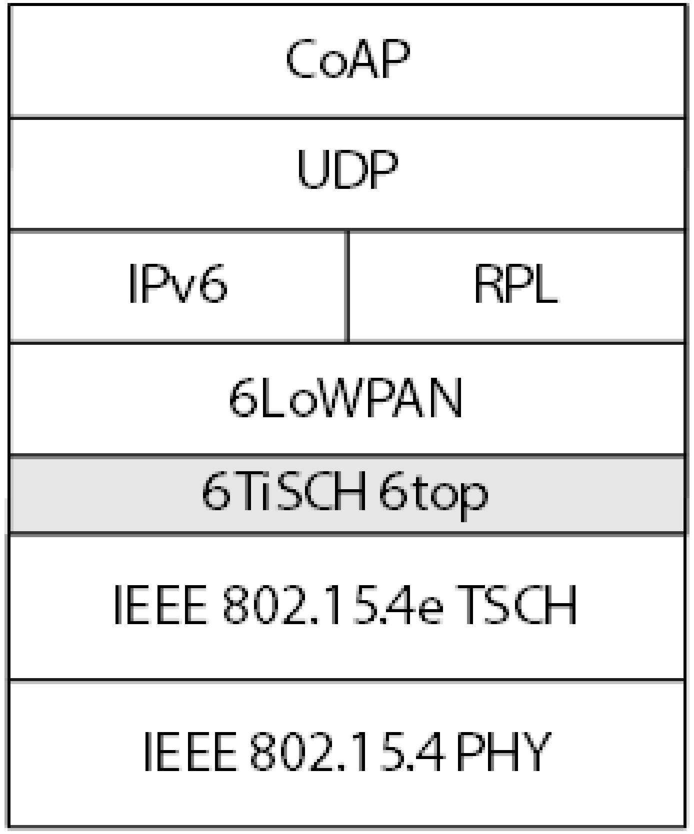


Protocol stack for deterministic IPv6-enabled wireless mesh networks

New sub-layer for integrating higher IETF layers with IEEE 802.15.4e TSCH

Under definition by the 6TiSCH WG

6Top Sub-layer



- Controls the TSCH schedule
  - Through a *Management Entity* (ME)
  - Adds/removes links (cells)
- Collects connectivity information
  - useful for upper layers (e.g., RPL)
- Monitors the performance of links (cells)
  - reschedules them if performance is not as expected
  - Both centralized and distributed scheduling supported

6TiSCH Scheduling

- **Minimal Scheduling**
  - used during network bootstrap or
  - when a better schedule is not available
- **Centralized Scheduling**
  - Based on a central entity
  - *Path Computation Element (PCE)*
- **Distributed Scheduling**
  - distributed multi-hop scheduling protocols
  - neighbor-to-neighbor scheduling negotiation

Minimal scheduling

PerLab

- Static scheduling
  - Pre-configured
  - Learnt by the node at joining time
- Minimal 6Tisch configuration

  X. Vilajosana and K. Pister, “Minimal 6TiSCH Configuration, draft-ietf-6tisch-minimal-00”, IETF, Fremont, CA, USA, 2013

Centralized Scheduling

PerLab

Path Computation Element (PCE)

- Collects
  - ⇨ network state information
  - ⇨ traffic requirements from all nodes
- Builds
  - ⇨ Communication schedule
  - ⇨ Making sure that QoS requirements of all flows are met
- Installs
  - ⇨ The schedule on the network

6TiSCH will define the protocol to be used for message exchange between PCE and network nodes

Distributed Scheduling

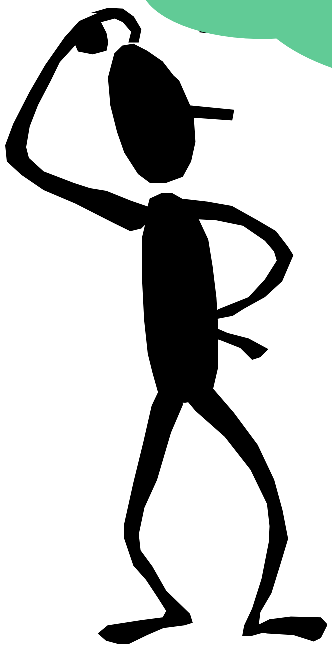
PerLab

- Nodes agree on a common schedule
  - distributed multi-hop scheduling protocol
  - neighbor-to-neighbor scheduling negotiation
- Reservation protocol
  - to transport QoS requirements along a certain path
- Negotiation phase
  - at each hop, 6top starts a negotiation with the next hop
    - ⇨ which and how many cells allocate to satisfy the QoS requirements of the path

6TiSCH WG is currently identifying protocols to be used for QoS requirements.
Strategies for cells allocation are also under definition

IEEE 802.15.4e

Summary and Conclusions



References

- D. De Guglielmo, S. Brienza, G. Anastasi, **IEEE 802.15.4e: a Tutorial and Survey**, *Computer Communications*, to appear.

- G. Anastasi, D. De Guglielmo, A Seghetti, **From IEEE 802.15.4 to IEEE 802.15.4e: a Step towards the Internet of Things**, Chapter 10 in *Advances onto the Internet of Things*, pp. 135-152, January 2014. Springer

Questions