Towards the Internet of Relevant Things

The IEEE 802.15.4e Standard

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Smart Cities & Communities

PerLab

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Overview

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

References

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

Internet of Things

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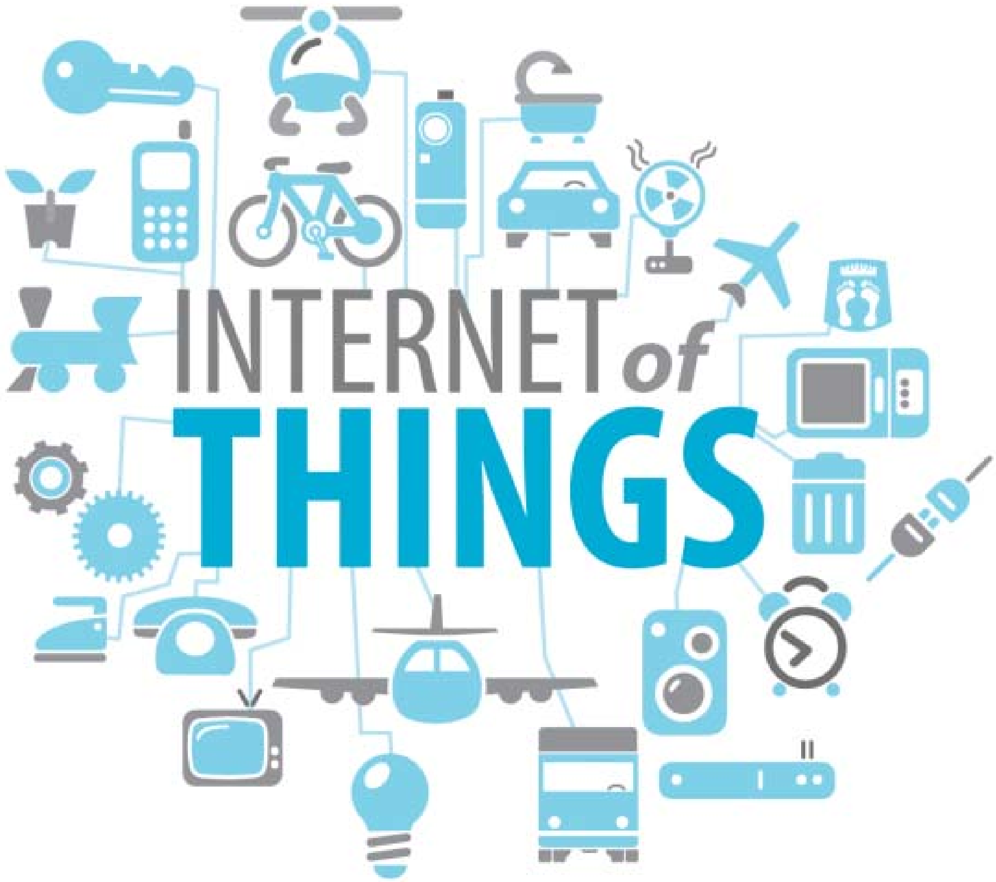
“The next logical step in the technological revolution connecting people anytime, anywhere is to connect inanimate objects. This is the vision underlying the **Internet of things: anytime, anywhere, by anyone and anything”**
(ITU, Nov. 2005)

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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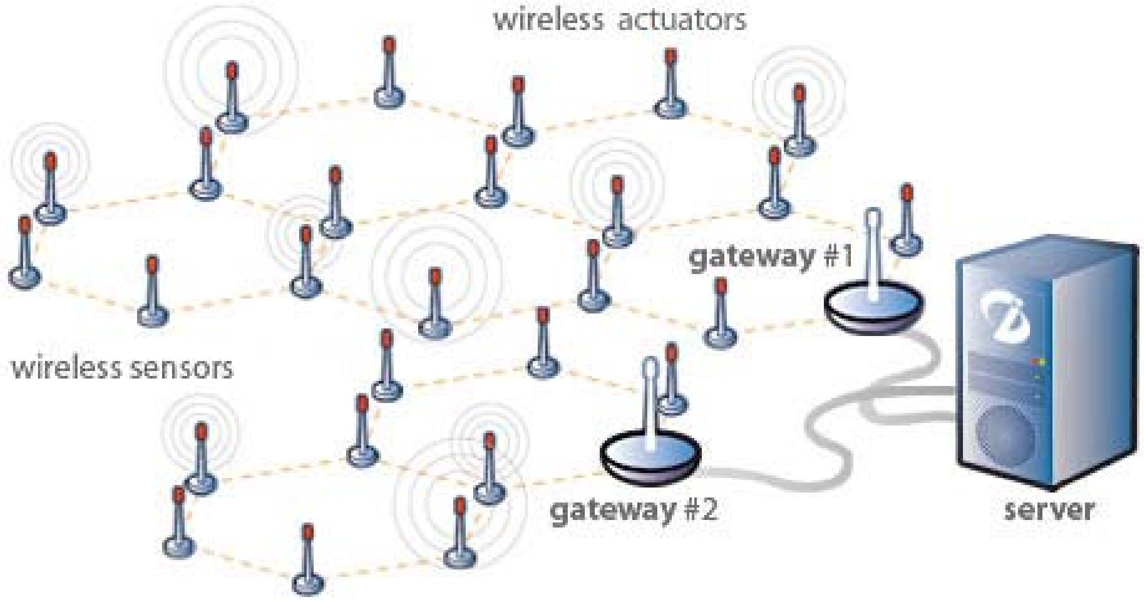
"WSANs will behave as a digital skin for the IoT

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.

Standards for WSANs

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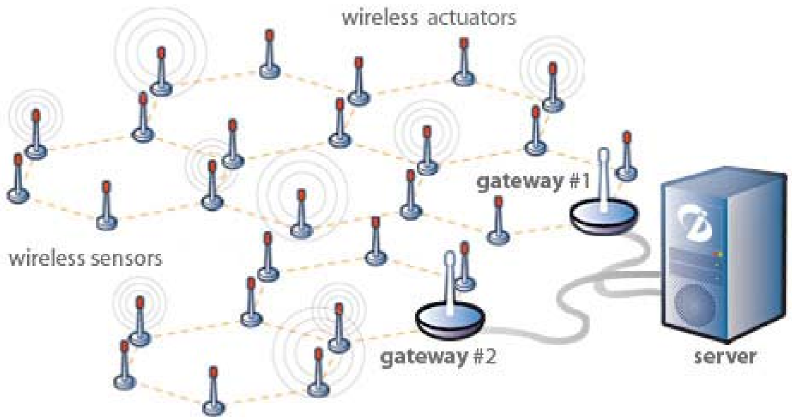
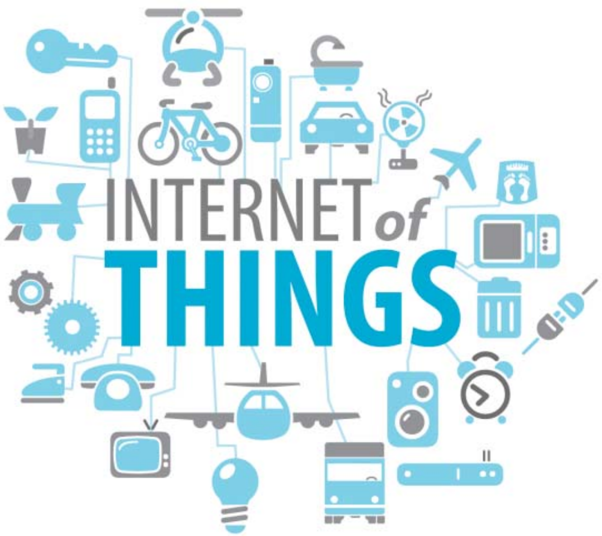
- IEEE 802.15.4/802.15.4e
- ZigBee
- Bluetooth
- WirelessHART
- ISA-100.11a



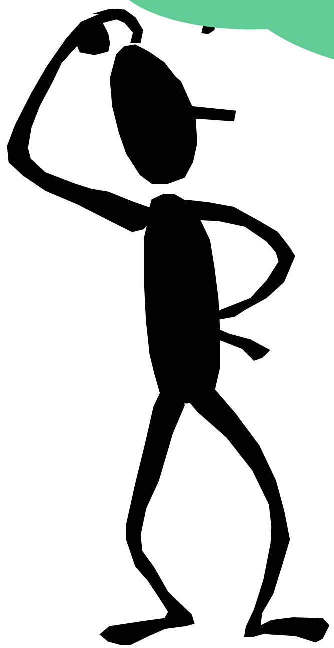
- 6LoWPAN
  - *IPv6 over Low power WPAN*
- RPL
  - *Routing Protocol for Low power and Lossy networks*
- CoAP
  - *Constrained Application Protocol*



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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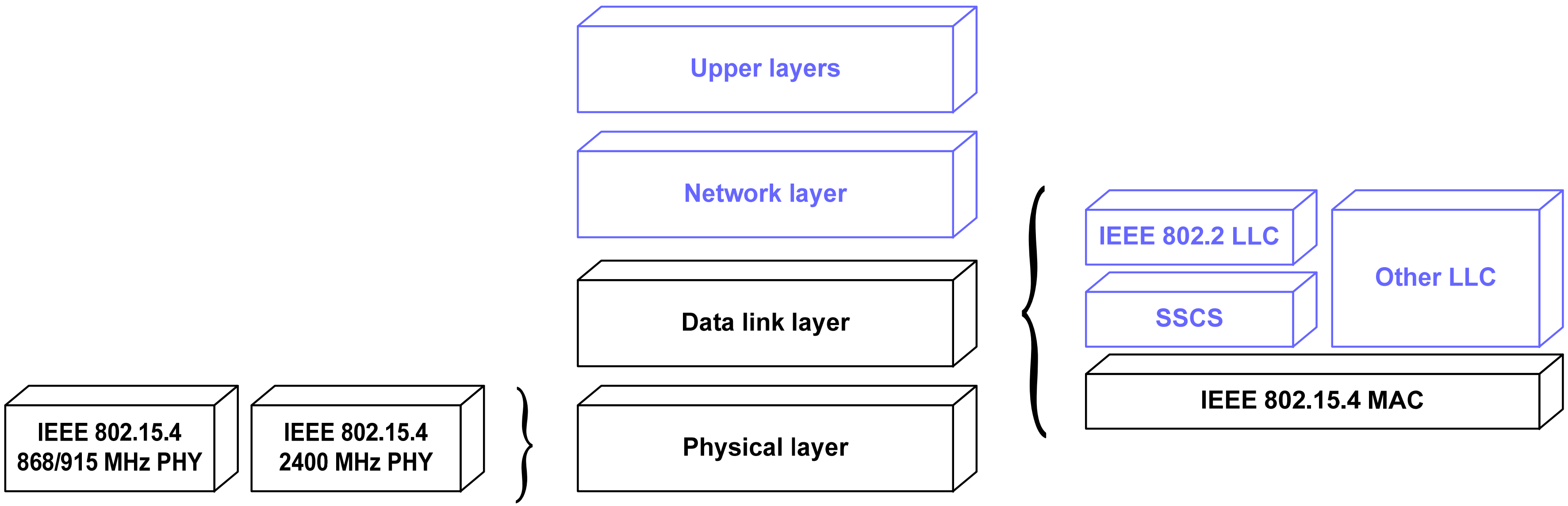

- Standard for Personal Area Networks (PANs)
  - low-rate and low-power
  - PHY and MAC layers
- Main features
  - transceiver management
  - channel access
  - PAN management

802.15.4 Network Topologies

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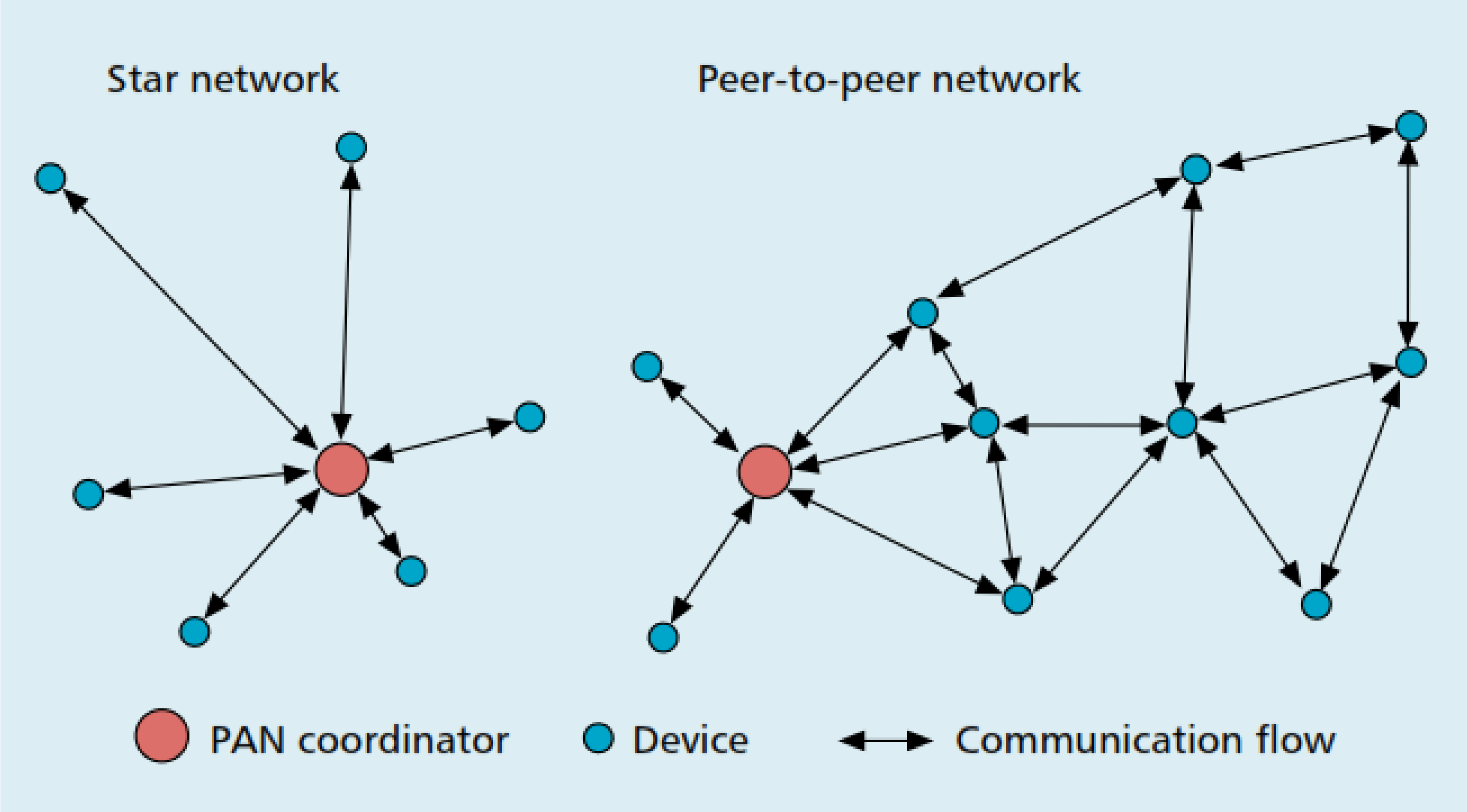
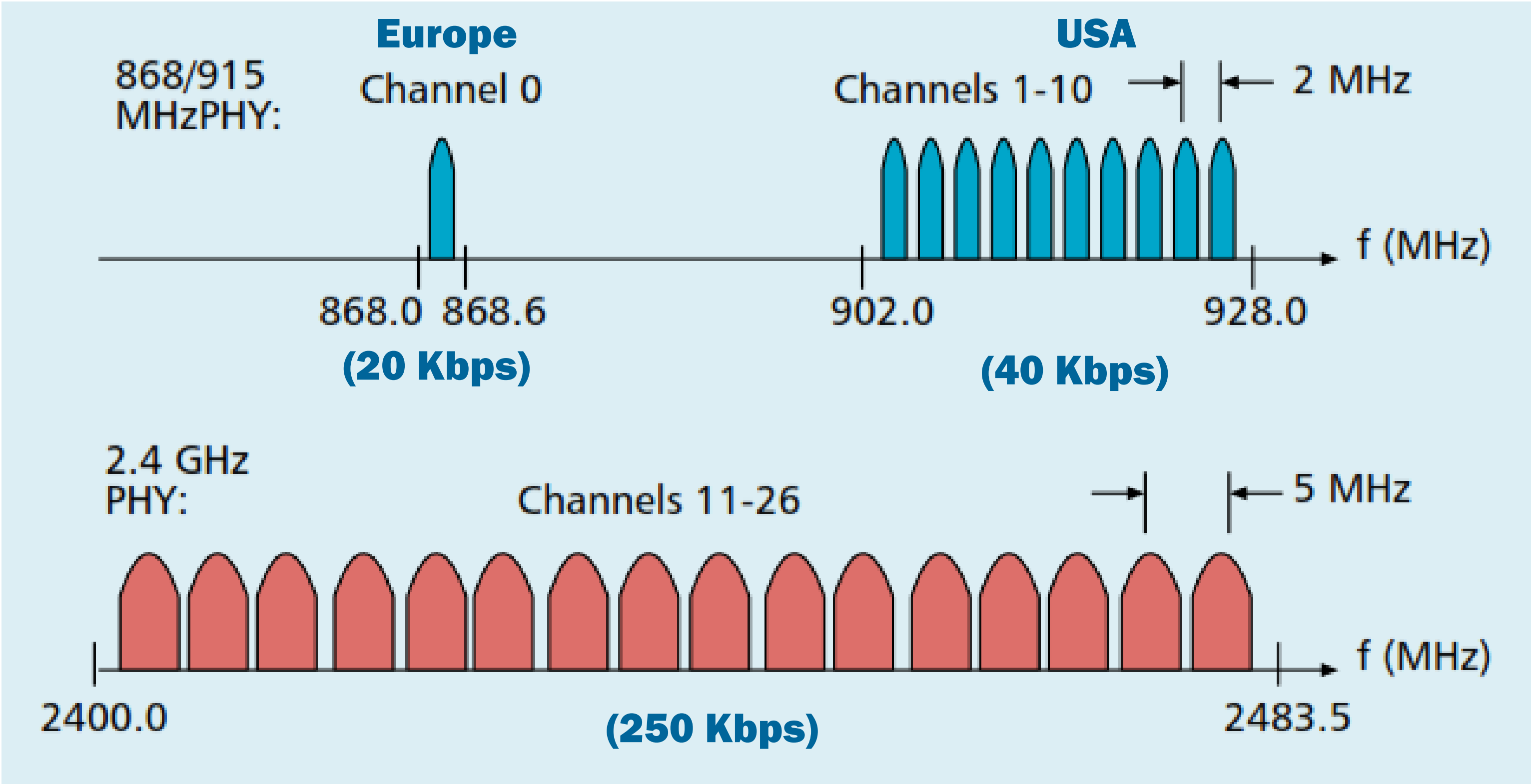


Ed Callaway, Paul Gorday, Lance Hester, Jose A. Gutierrez, Marco Naeve, Bob Heile, **Home Networking with IEEE 802.15.4: Developing Standard for Low-Rate Wireless Personal Area Networks,** *IEEE Communications Magazine*, August 2002.

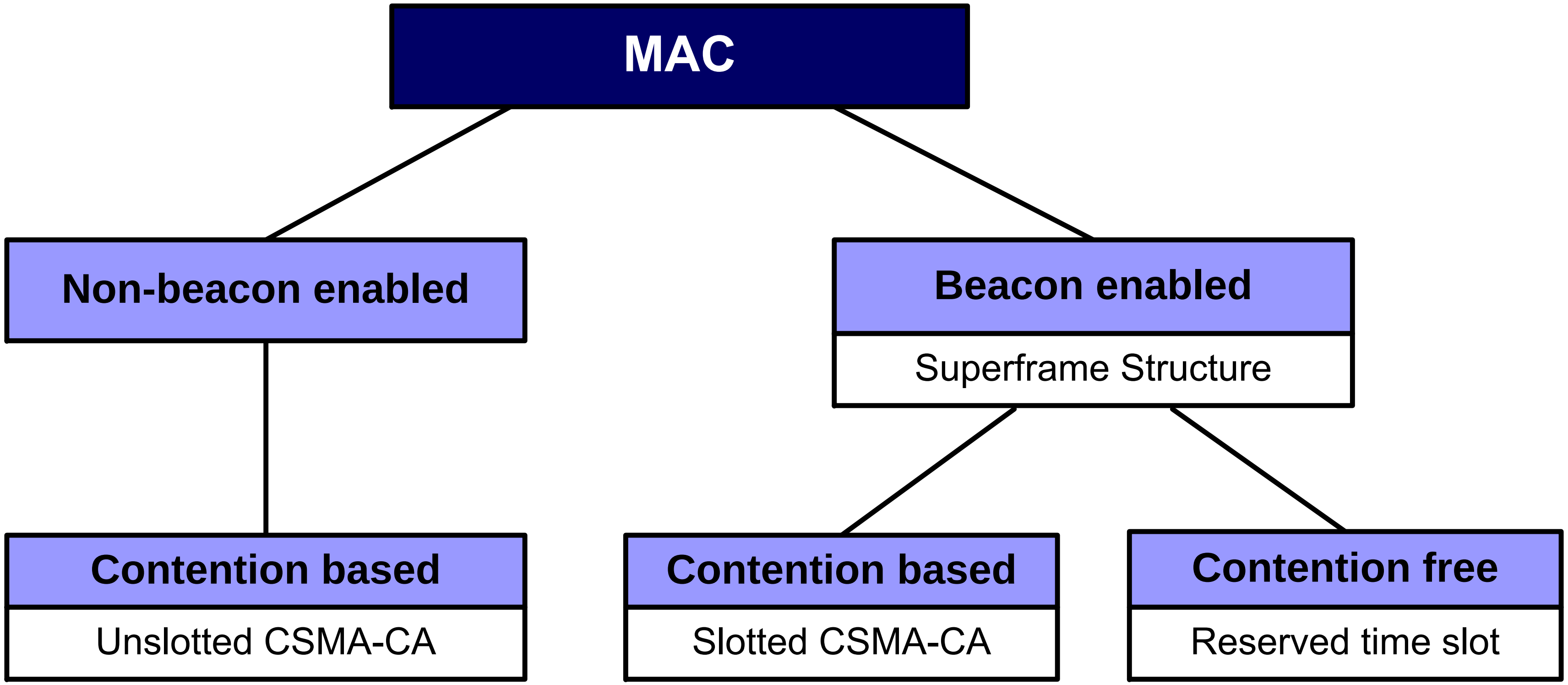
Channel frequencies



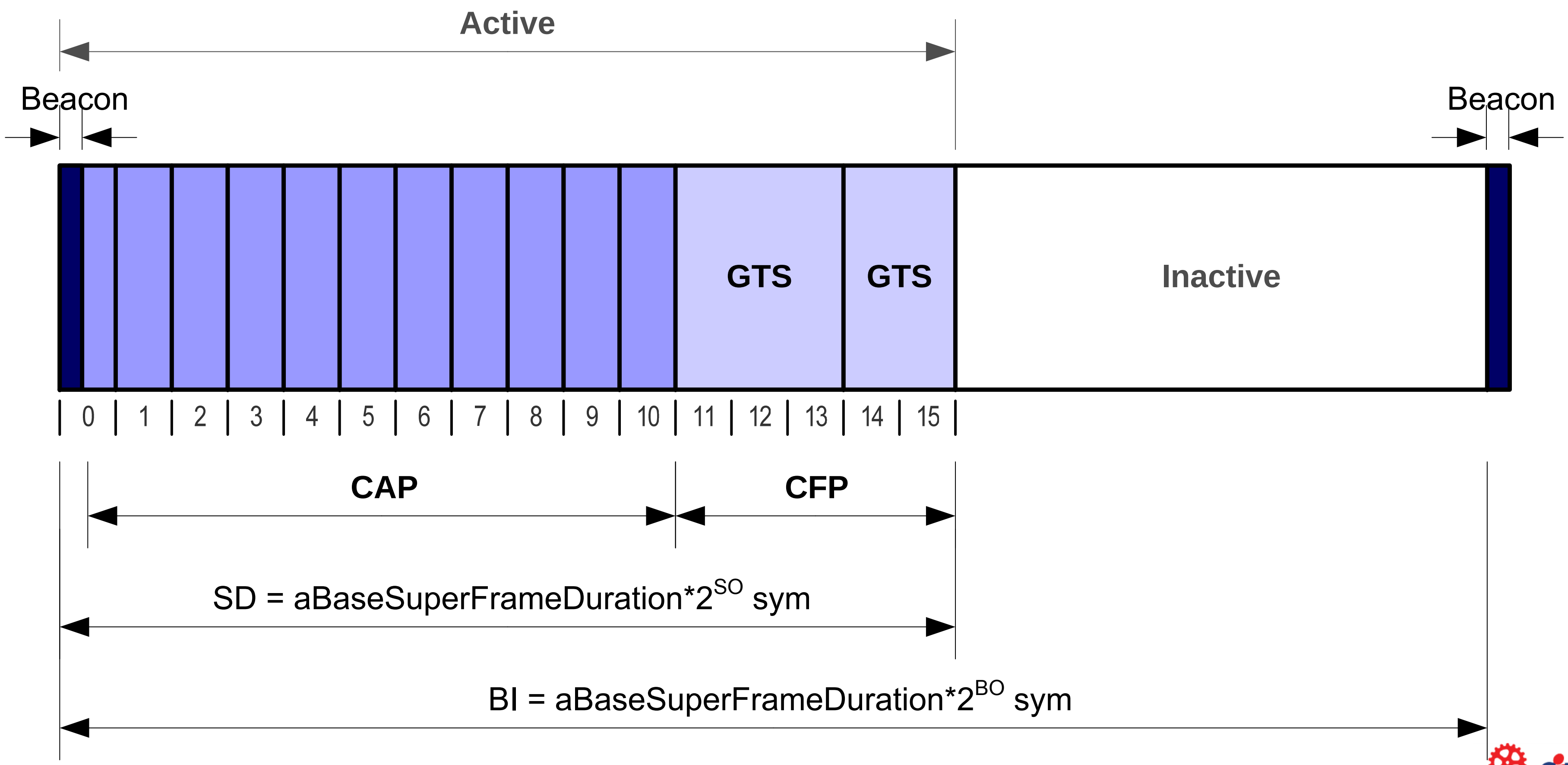
Ed Callaway, Paul Gorday, Lance Hester, Jose A. Gutierrez, Marco Naeve, Bob Heile, **Home Networking with IEEE 802.15.4: Developing Standard for Low-Rate Wireless Personal Area Networks,** *IEEE Communications Magazine*, August 2002.

802.15.4 MAC protocols

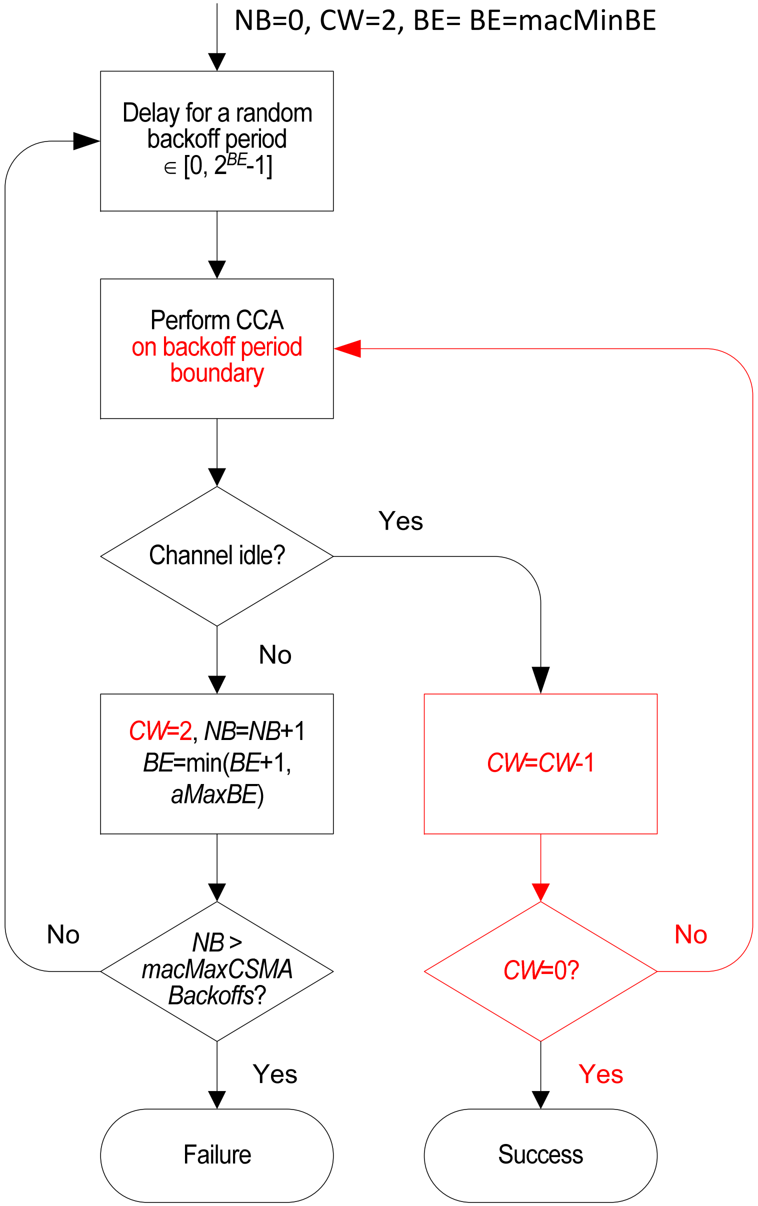
- Two different channel access methods
  - Beacon-Enabled duty-cycled mode
  - Non-Beacon Enabled mode (aka Beacon Disabled mode)



802.15.4 Beacon Enabled mode



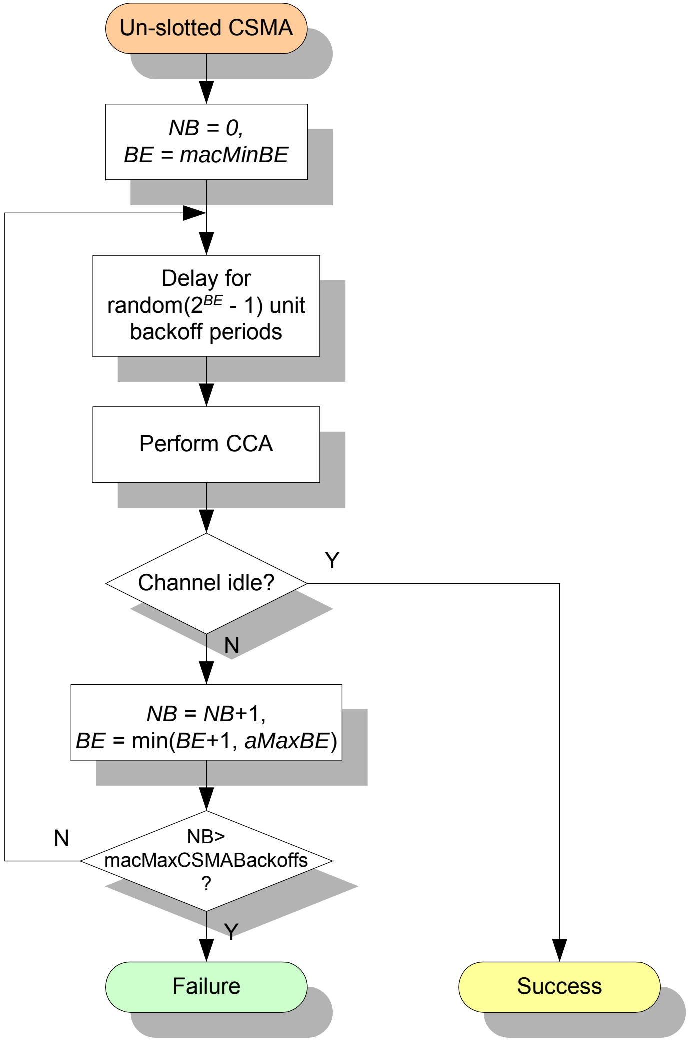
CSMA-CA: Beacon-Enabled mode



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

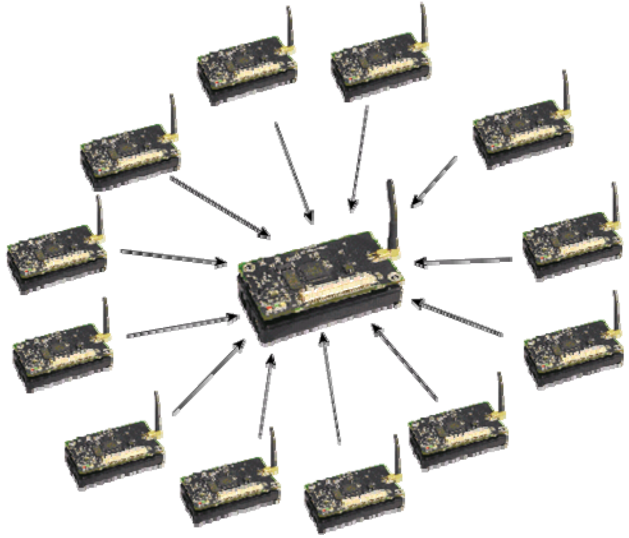
- Optional mechanism
- Destination Side
  - ACK sent upon successful reception of a data frame
- Sender side
  - Retransmission if ACK not (correctly) received within the timeout
  - At each retransmission attempt the backoff window size is re-initialized
  - Only a maximum number of retransmissions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

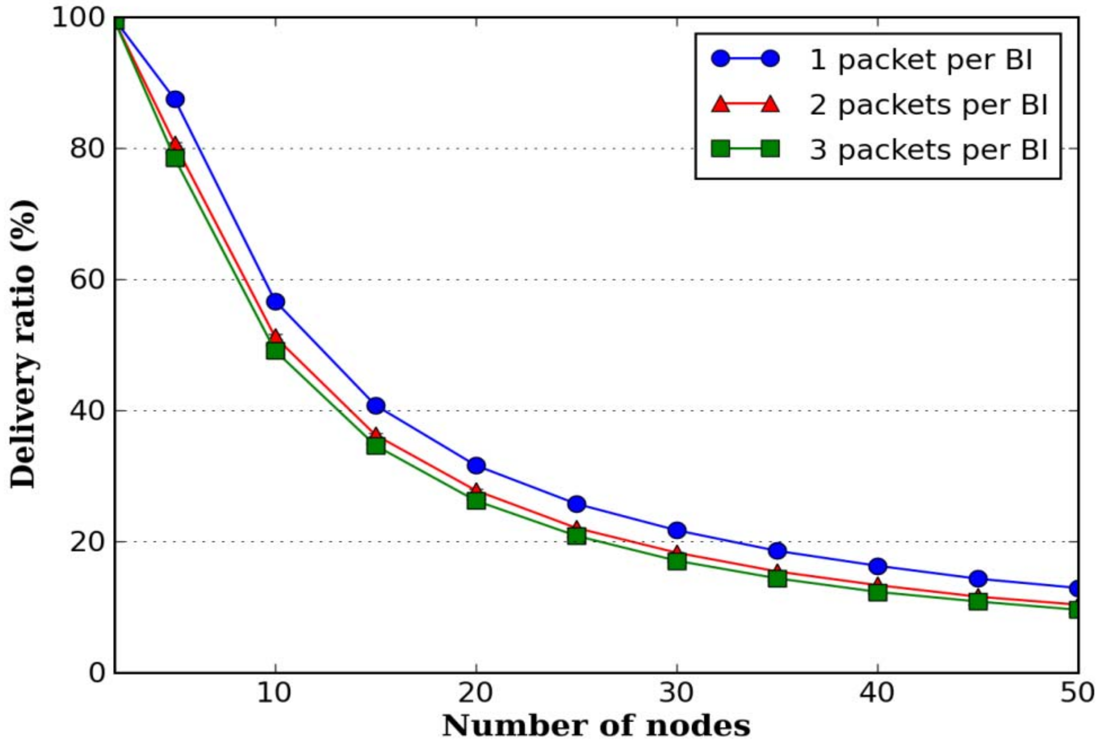
Limits of IEEE 802.15.4 MAC

- 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, **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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Channel Hopping

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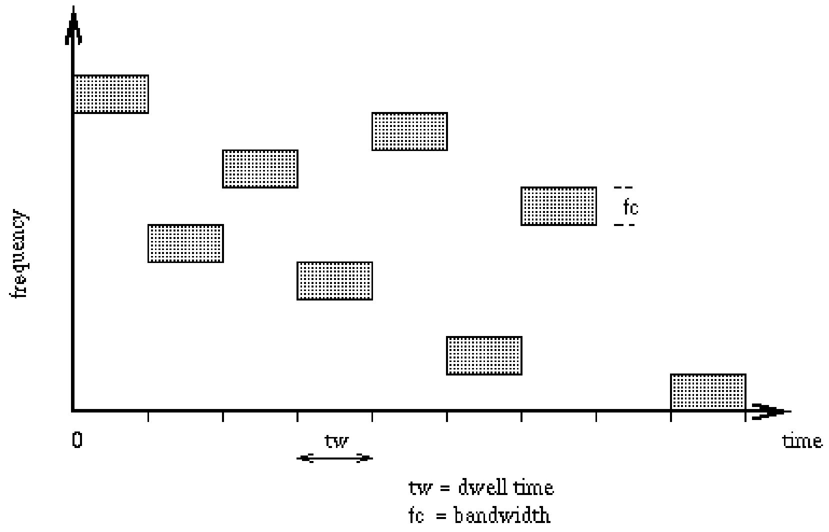
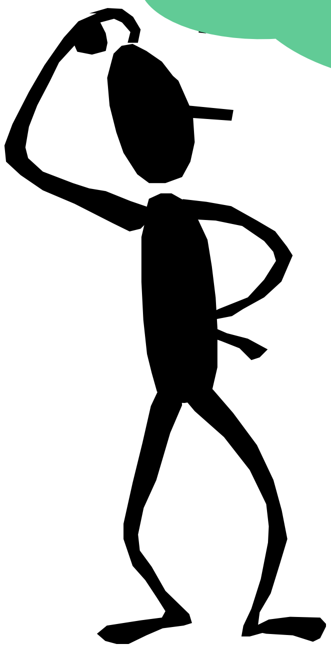
- Subsequent packets are sent at a different frequency
  - following a **pseudo-random hopping** pattern
- If a transmission fails
  - retransmission will happen on a **different frequency**
- Greater chance of successful transmission
  - than if the retransmission happened on the same channel
  - Since a different frequency means different effects of multi-path fading and interference
- Increased security
  - Against *Selective Jamming* attack
- Channel Hopping used in
  - Bluetooth
  - WirelessHart



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

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- 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

- **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

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

MAC Behavior Modes

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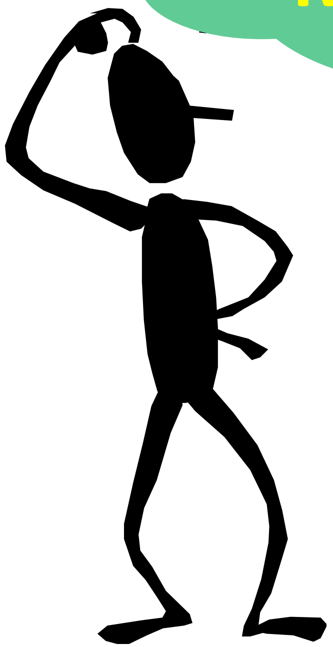
- **Radio Frequency Identification Blink (BLINK)**
  - item and people identification, location, and tracking
- **Asynchronous Multi-Channel Adaptation (AMCA)**
  - application domains where large deployments are required (e.g., process automation/control, infrastructure monitoring, etc.)
- **Deterministic & 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 DSME

Deterministic &
Synchronous
Multichannel Extension

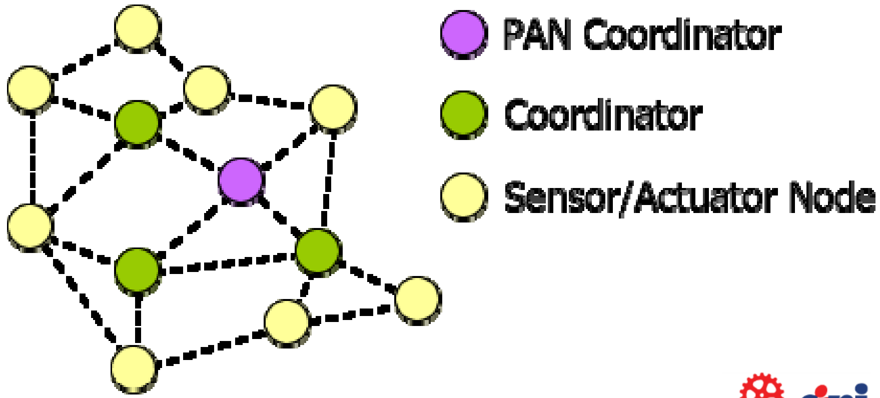


IEEE 802.15.4e DSME

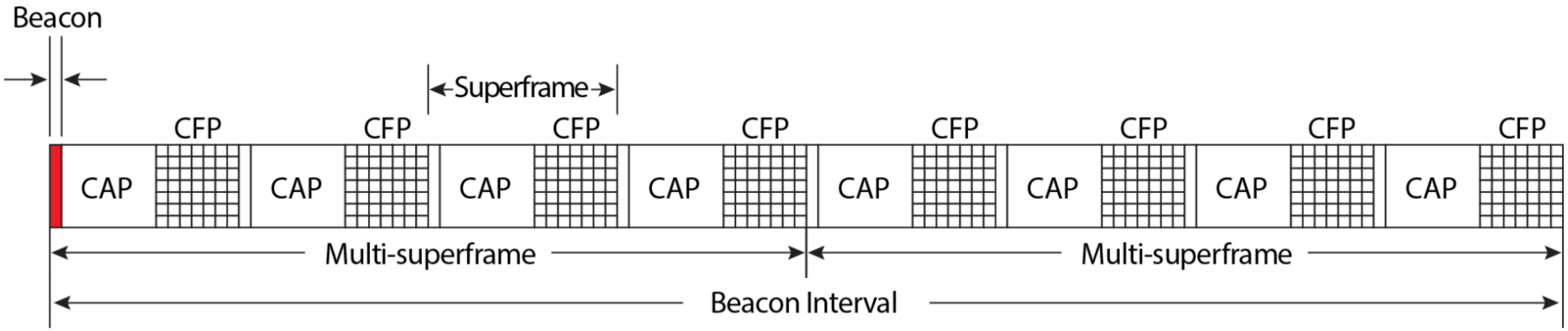
- Target Application Domains
  - Industrial applications
  - Commercial applications
  - Healthcare applications
- Provides
  - Flexibility
  - Robustness
  - High reliability
  - Deterministic latency
  - Scalability
  - Efficiency

Main Features

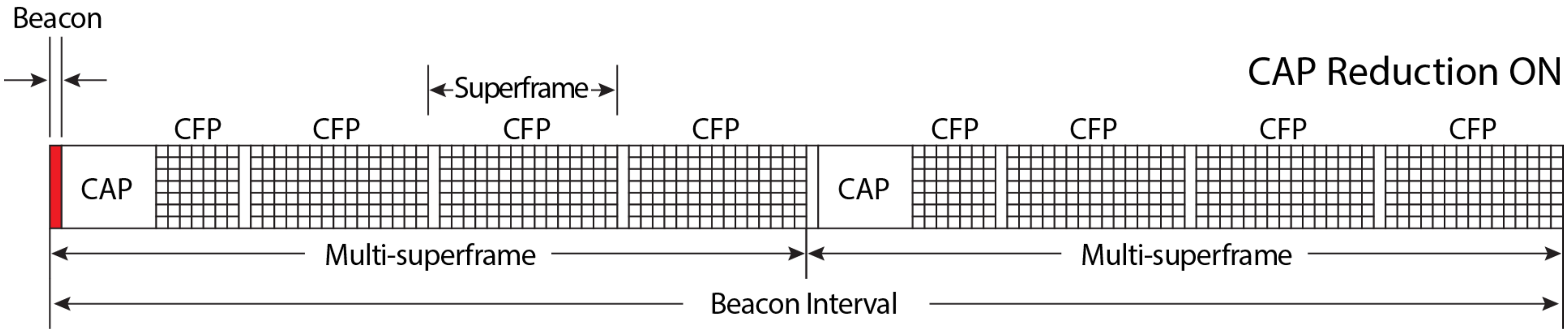
- Multi-channel, multi-superframe
- Mesh extension to GTS
- Two channel diversity modes
  - channel adaptation
  - channel hopping
- Distributed beacon scheduling
- Distributed slot allocation
- Group acknowledgments
- Many topologies
  - Star, cluster-tree and peer-to-peer



Multi superframe structure



When **CAP reduction** is **enabled**, only the first superframe in the multi-superframe has the CAP



Enhanced Beacons (EBs)

- Sent by each coordinator at regular intervals
  - At the beginning of superframes
- Contains parameters
  - To regulate the multi-superframe structure
- Indicates the enabled options
- Used for global time synchronization
  - Each node associates with a coordinator (i.e., its *time synchronization parent*) and tracks its EBs
  - In order to join the network, a node performs a *passive channel scan* over a given list of channels

Beacon Scheduling

Each coordinator transmits its EBs during a superframe

- Distributed scheduling algorithm
- Beacon schedule information shared through EBs
  - ⇨ A bitmap sequence indicates the usage of beacon slots by its one-hop neighbors
  - ⇨ A bit in the bitmap is set to one if the corresponding beacon slot is already used for EB transmission
- A prospective coordinator searches for a vacant slot in the bitmaps of all the received EBs
- Once the new device finds a vacant beacon slot, it uses the slot as its own beacon slot

Channel Diversity

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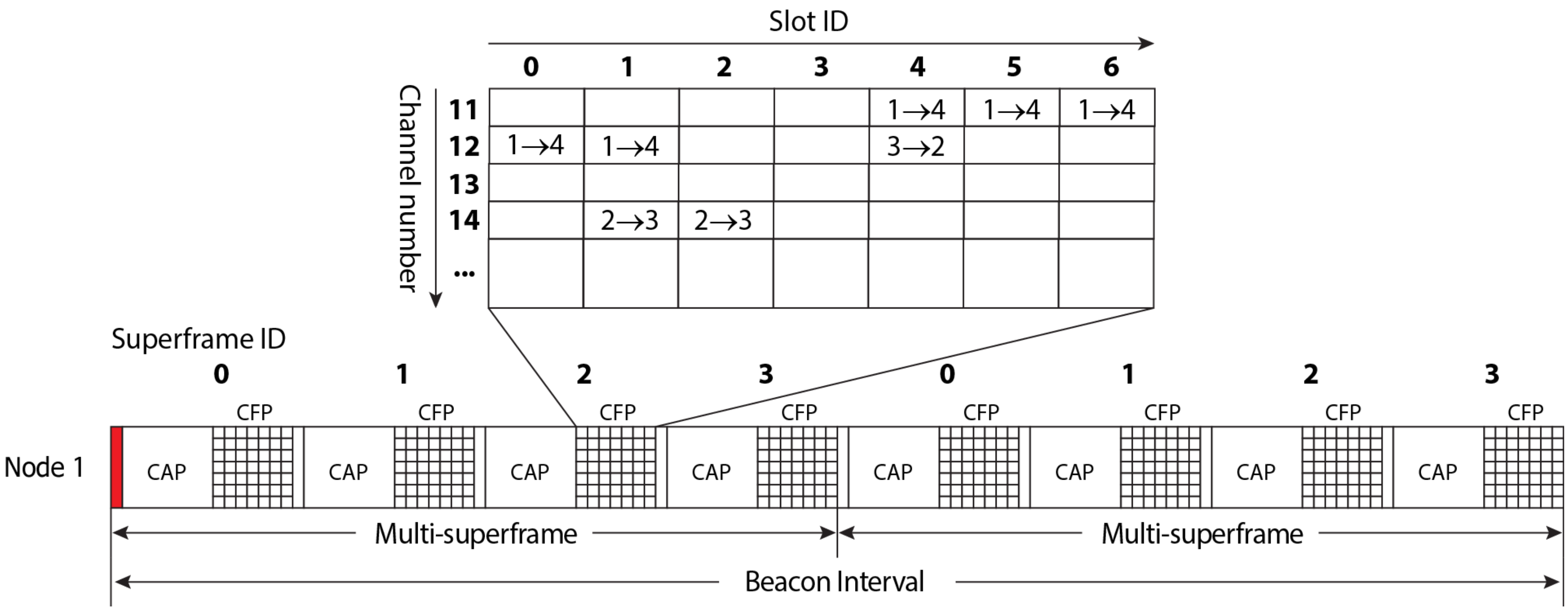
- Channel Adaptation
  - Two neighboring nodes can communicate using *any* of the free available channels
  - The channel is decided basing on the quality estimated by nodes
  - The channel used in a DSME-GTS does not change over time
    - ⇨ unless its quality degrades
- Channel Hopping
  - Nodes change the communication channel at each DSME-GTS
  - The series of channels used is referred to as *Hopping Sequence*
  - Each node has a *Channel Offset*
    - ⇨ an integer indicating the starting position in the Hopping Sequence
  - A transmitting node has to switch to the channel used by the receiver

Channel Adaptation



Channel Hopping

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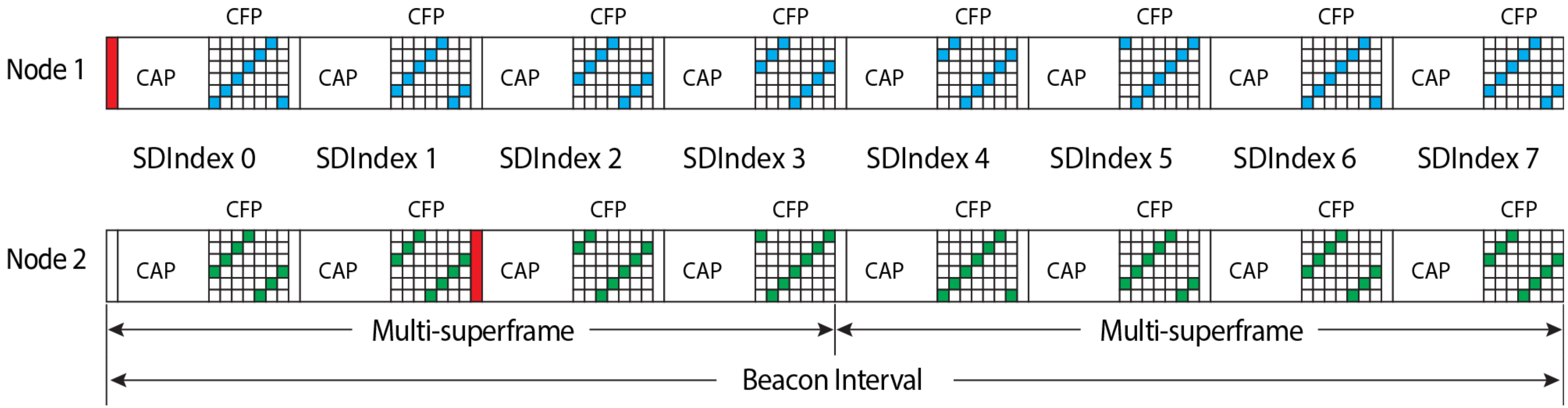

Channel number *C* at the given DSME-GTS Slot ID *i* in SDIndex *j*, shall be determined as follows:

$$C(i) = macHoppingSequenceList[(j \times l + i + macChannelOffset + macPANCoordinatorBSN) \% macHoppingSequenceLength]$$

Data Structures (1/2)

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ALLOCATION COUNTER TABLE (ACT)

- A table containing an entry for each Guaranteed TimeSlot allocated *to the node*
- Each entry stores the following information:
  - Superframe ID
  - Slot ID
  - Channel ID
  - Direction
  - Address

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Data Structures (2/2)

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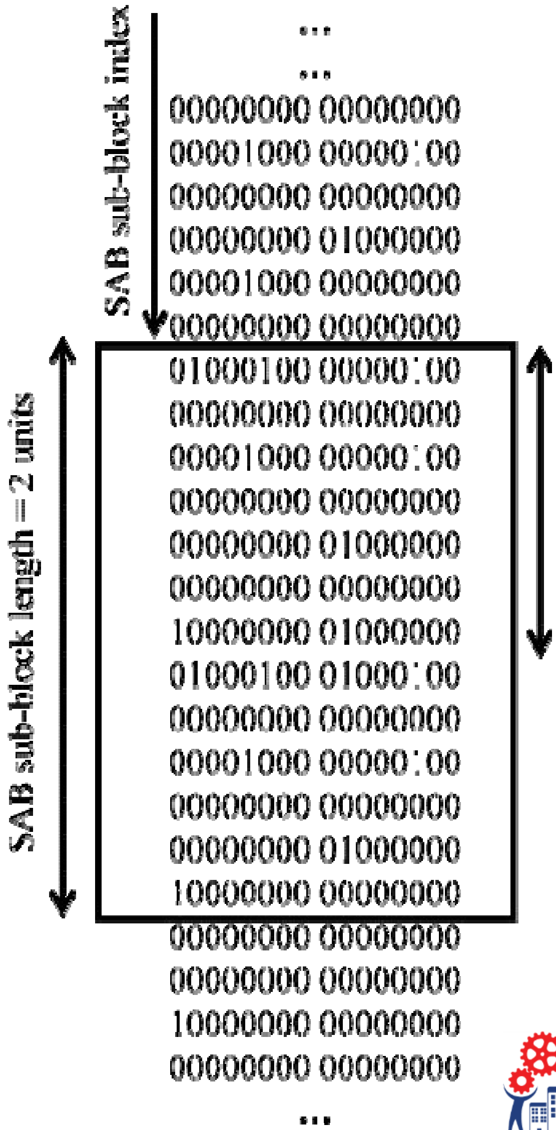
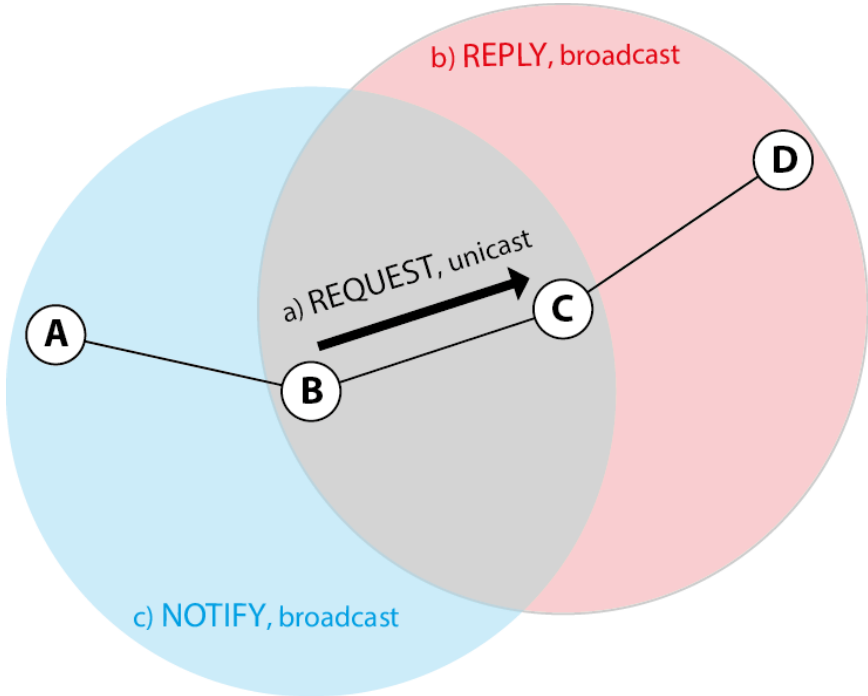
SLOT ALLOCATION BITMAP (SAB)

- A bitmap used to store which GTSs in the multi-superframe are allocated *to the node and its neighbors*
- The SAB contains a bit for each possible pair **[*ch, ts*]**, indicating whether the channel *ch*, during timeslot *ts*, is used (1) or not (0).



DSME-GTSs

- A DSME-GTS is used for communication between a specific source device and a specific destination device.
- A DSME-GTS is allocated by the destination device, basing on
  - requirements specified by the source node in the request
  - current slot availability
- DSME-GTSs are allocated on a FCFS basis
- Three-step allocation (during CAP)

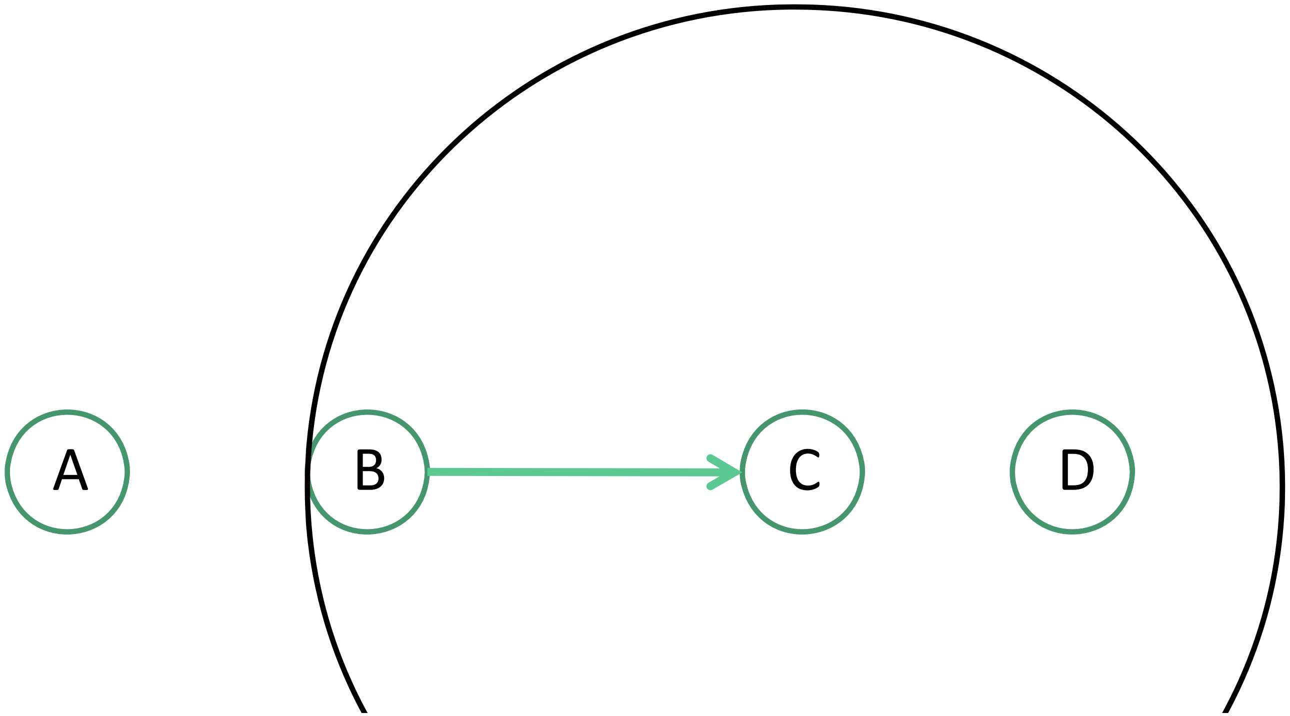


DSME-GTSs: Allocation (1/3)

- In this example, B wants to allocate a DSME-GTS with C

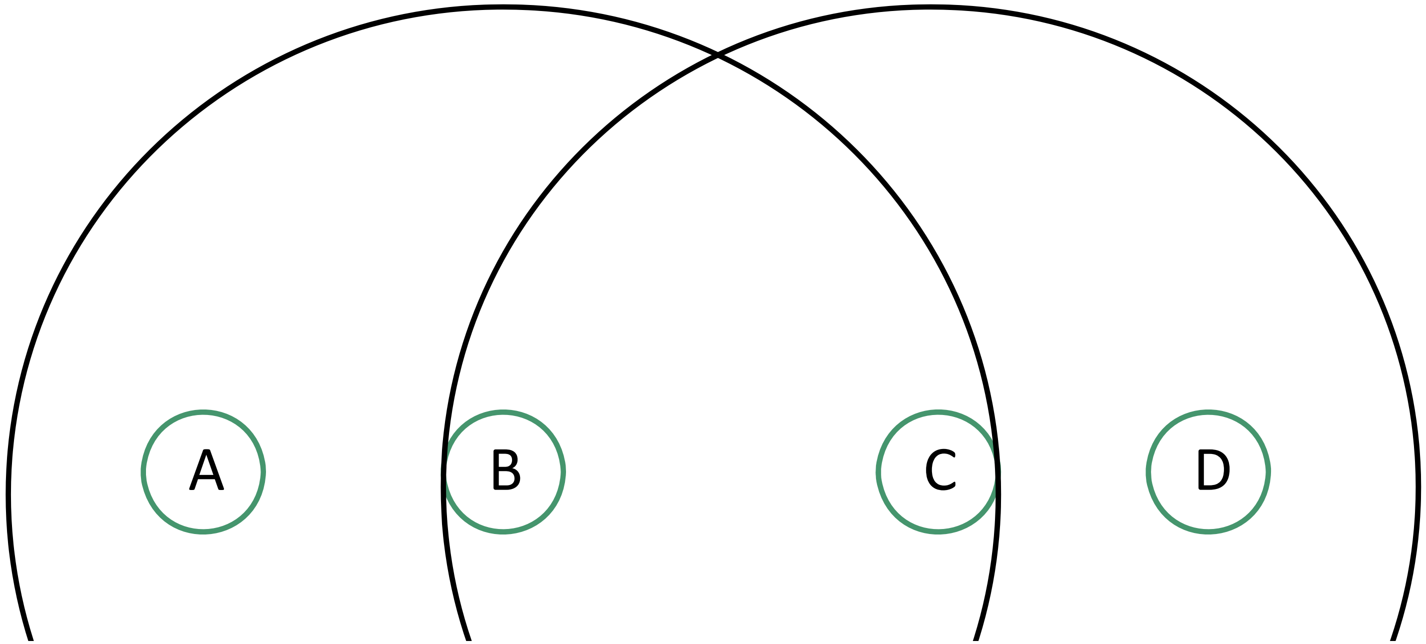
- B sends a REQUEST in unicast to C
- The REQUEST indicates the available slots for allocation
- After transmission, node B waits for a REPLY from node C
- If the REPLY frame is not received in time, the allocation is assumed to be failed (i.e., a Timeout occured)

DSME-GTSs: Allocation (2/3)



- Once the REQUEST has been received, C search in its bitmap for free GTSs in common with B
- If they are found, C updates its own data structures
- C sends a REPLY in Broadcast, indicating the newly allocated GTSs

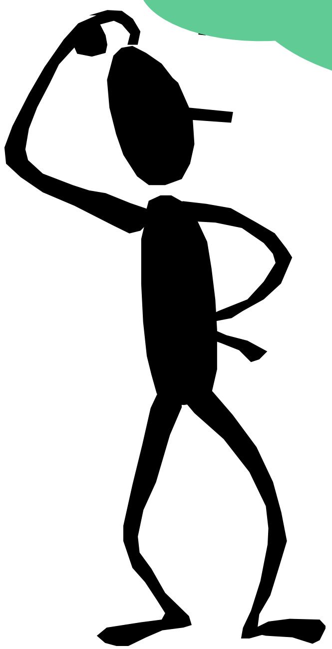
DSME-GTSs: Allocation (3/3)



- Upon receiving the REPLY, B updates its data structures
- B broadcasts a NOTIFY message to inform its neighbors
- When receiving a REPLY/NOTIFY, A and D check if they already use the just allocated GTS:
  - If not, they update their SAB
  - Otherwise, they send a error message to the sender

IEEE 802.15.4e DSME

Literature Review



Performance Evaluation

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- W.C. Jeong, J. Lee, **Performance evaluation of IEEE 802.15. 4e DSME MAC protocol for wireless sensor networks**, In Proceedings of the *first IEEE Workshop on Enabling Technologies for Smartphone and Internet of Things (ETSIoT)*, Seoul, South Korea, 18 June 2012.
- T. Paso, J. Haapola, J. Iinatti, **Feasibility study of IEEE 802.15.4e DSME utilizing IR-UWB and S-Aloha**, In Proceedings of the *24th IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, London, United Kingdom, 8-11 September 2013.
- J. Lee, W.C. Jeong, **Performance analysis of IEEE 802.15.4e DSME MAC protocol under WLAN interference**, In Proceedings of the *IEEE International Conference on ICT Convergence (ICTC)*, Jeju Island, South Korea, 15-17 October 2012.
- G. Alderisi, G. Patti, O. Mirabella, L. Lo Bello, **Simulative assessments of the IEEE 802.15.4e DSME and TSCH in realistic process automation scenarios**, In Proceedings of the *13th IEEE International Conference on Industrial Informatics (INDIN)*, Cambridge, United Kingdom, 22-24 July 2015.

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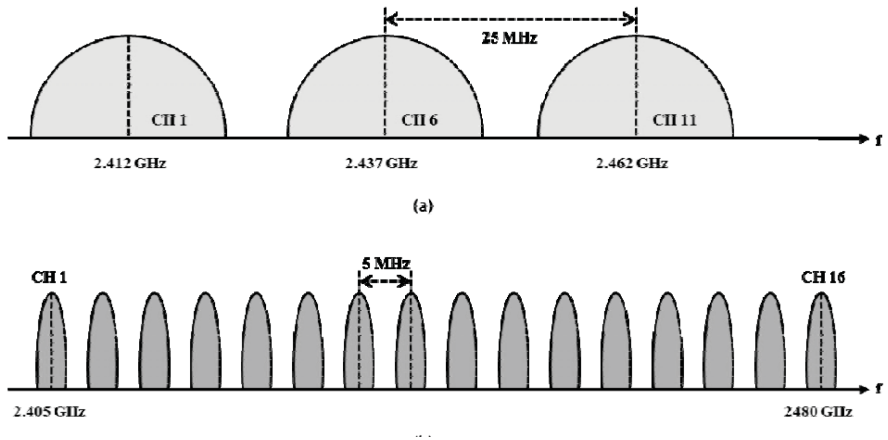
802.15.4e DSME vs. 802.15.4 BE

- DSME always offers a minimum throughput
  - only limited by the number of available DSME-GTSs
- In 802.15.4 BE the delivery ratio decreases when the # of nodes increases
- DSME guarantees a deterministic delay
  - it is unpredictable in 802.15.4 CSMA-CA (or S-Aloha)
- DSME shows a significant lower consumption
  - as collisions cannot happen and CCA are not needed
- DSME is much more resistant to external interferences,
  - thanks to its channel diversity mechanisms



802.15.4e DSME vs. TSCH

- Both are robust against channel noise
  - assuring high reliability
- TSCH offers lower delays
  - when the number of nodes is limited
  - the DSME multi-superframe structure does not adapt to the network size
- TSCH needs larger timeslots
  - to accommodate ACKs
  - DSME can benefit from the Group ACK option
- DSME exhibits lower delays
  - when the number of nodes grows
  - more DSME-GTSs in the multi-superframe are used.

G. Alderisi, G. Patti, O. Mirabella, L. Lo Bello, **Simulative assessments of the IEEE 802.15.4e DSME and TSCH in realistic process automation scenarios**, Proc. *IEEE International Conference on Industrial Informatics (INDIN 2015)*, Cambridge, UK, July 2015

General Enhancements (1/2)

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- ELPIDA (Enhancements for Low-Power Instrumentation DSME Applications)
  - Aims at making DSME more energy efficient in cluster-tree networks
  - Limits the time spent by leaf nodes radio in RX state (e.g. during CAP)
  - Introduces three main changes to DSME:
    - ⇨ CAP Wake-up
    - ⇨ DSME-GTS Wake-up
    - ⇨ Beacon Look-up
  - ELPIDA decreases the energy consumption of end devices
    - ⇨ up to a factor 7, if compared with standard DSME

S. Capone, R. Brama, F. Ricciato, G. Boggia, and A. Malvasi, **Modeling and Simulation of Energy Efficient Enhancements for IEEE 802.15.4e DSME**, Proceedings of *Wireless Telecommunications Symposium (WTS)*, Washington, DC, USA, 9-11 April 2014.

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General Enhancements (2/2)

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- EFastA (Enhanced Fast Association)
  - Addresses the association phase
    - ⇨ Many collisions may occur with the association procedure described in the standard
    - ⇨ Many Beacon Intervals can be necessary to associate all the nodes to the network
  - In EFastA, nodes do not sent association requests immediately after the EB reception
  - Nodes wait for a randomly selected superframe inside the multi-superframe
  - Simulations show that EFastA reduces association time
    - ⇨ up to about 90%, with respect to FastA

X. Liu, X. Li, S. Su, Z. Fan, G. Wang, **Enhanced Fast Association for 802.15.4e-2012 DSME MAC Protocol,** Proceedings of the *2nd International Conference on Computer Science and Electronics Engineering (ICCSEE)*, Hangzhou, China, 22-23 March 2013.

Beacon Scheduling (1/3)

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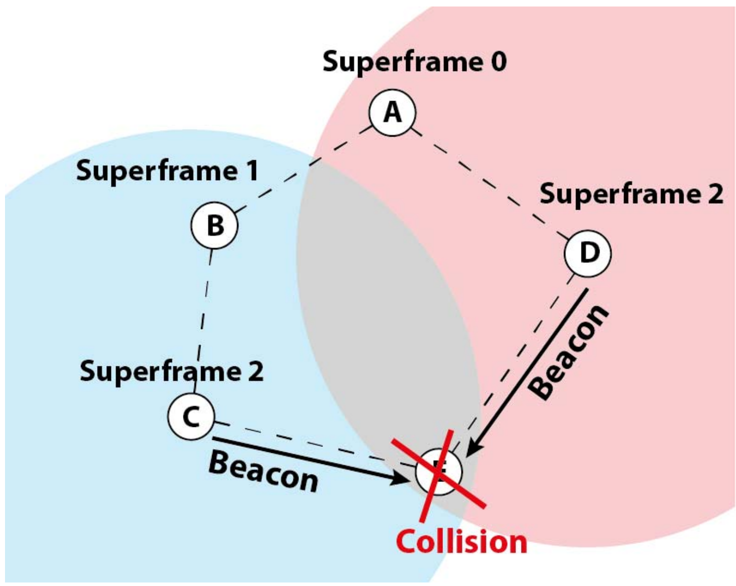
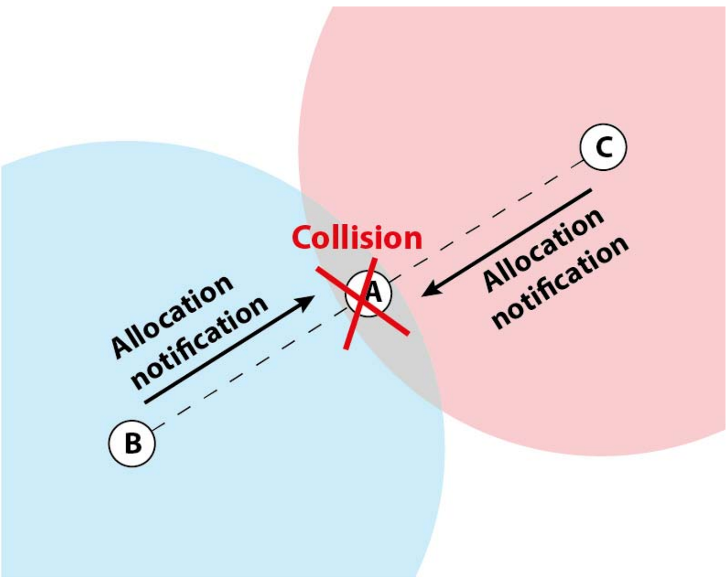
- The DSME Beacon Scheduling algorithm presents a number of limitations
  - long waiting time for network construction
  - storage wastage
  - variable and growing length of EB frame size
  - potential beacon collision issues





Beacon Scheduling (2/3)

- E-DSME (Enhanced DSME)
  - Exploits a distributed permission notification mechanism
    - ⇨ A node waits for a *Permission Notification* to complete the allocation
    - ⇨ Only the coordinator that has transmitted the latest beacon can send permission notifications
  - CAP is divided into *Allocation Contention Periods* (*ACP*) and *Permission Notification Periods* (*PNP*)
  - Simulation results show that E-DSME allows
    - ⇨ to achieve very high success ratio (near to 100%)
    - ⇨ to avoid beacon collisions even in complex networks

K. Hwang, S. Nam, **Analysis and Enhancement of IEEE 802.15.4e DSME Beacon Scheduling Model,** *Journal of Applied Mathematics*.

Beacon Scheduling (3/3)

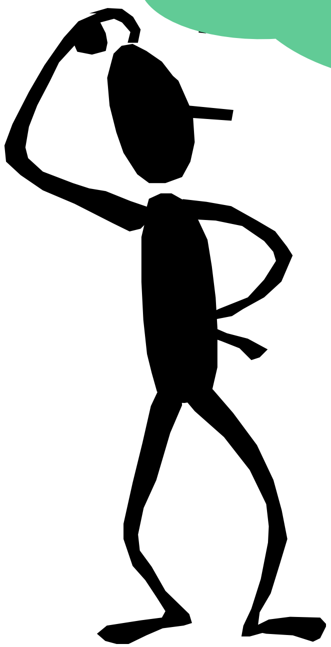
PerLab

- DFBS (Distributed Fast Beacon Scheduling)
  - many problems are caused by the use of a bitmap to represent slot allocation data
  - The bitmap is replaced by a single integer, namely RINSD (Representative Indicator of Neighbor Superframe Duration)
    - ⇨ It represents the index of the superframe to be used to send EBs
    - ⇨ Each node maintains its own RINSD
  - To join the network, a node performs an *Active Association*
  - Simulation results show that
    - ⇨ allows to solve the highlighted beacon collision problems
    - ⇨ reduces the network construction time (up to 75% with 25 nodes)

W. Lee, K. Hwang, Y.A. Jeon, S.S. Choi, **Distributed Fast Beacon Scheduling for Mesh Networks**, Proceedings of the *8th IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS)*, Valencia, Spain, 17-22 October 2011.

IEEE 802.15.4e DSME

Open Issues



Open Issues (1/2)

PerLab

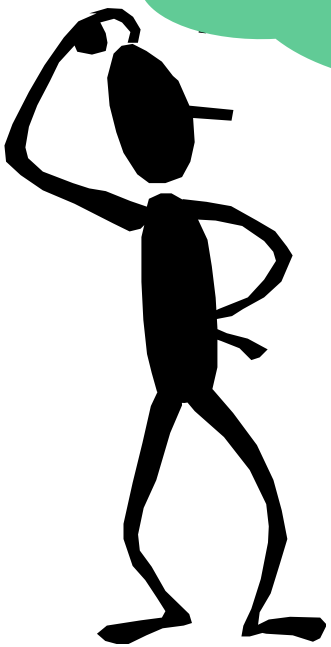
- A complete implementation of DSME is still missing
- Current works do not consider mesh topologies
- Many aspects are left to implementers
  - How to choose the DSME-GTSs to be allocated
  - How to accommodate traffic in GTSs
  - How to select the communication channel when using channel adaptation
  - The beacon scheduling algorithm is presented without any concrete outline and implementation details
  - …

Open Issues (2/2)

- More attention should be devoted to the energy topic
- DSME conceals a number of security issues
  - The distributed DSME-GTS allocation mechanism assumes that all nodes are trustworthy
- Feasibility of the integration with the upper layers of the network stack should be investigated
  - with reference to the Internet of Things protocols, such as *6LoWPAN, RPL, and CoAP*.

IEEE 802.15.4e TSCH

Time Slotted
Channel Hopping

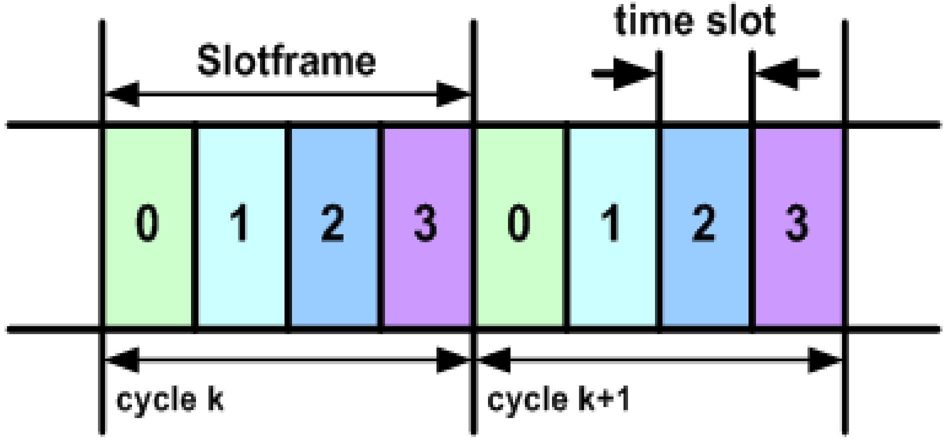


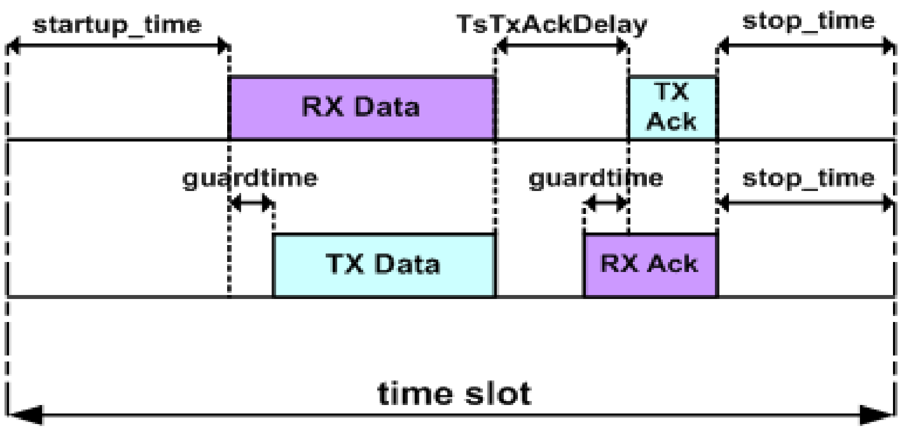
Time Slotted Channel Hopping (TSCH)

PerLab

- *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
- No CAP in TSCH

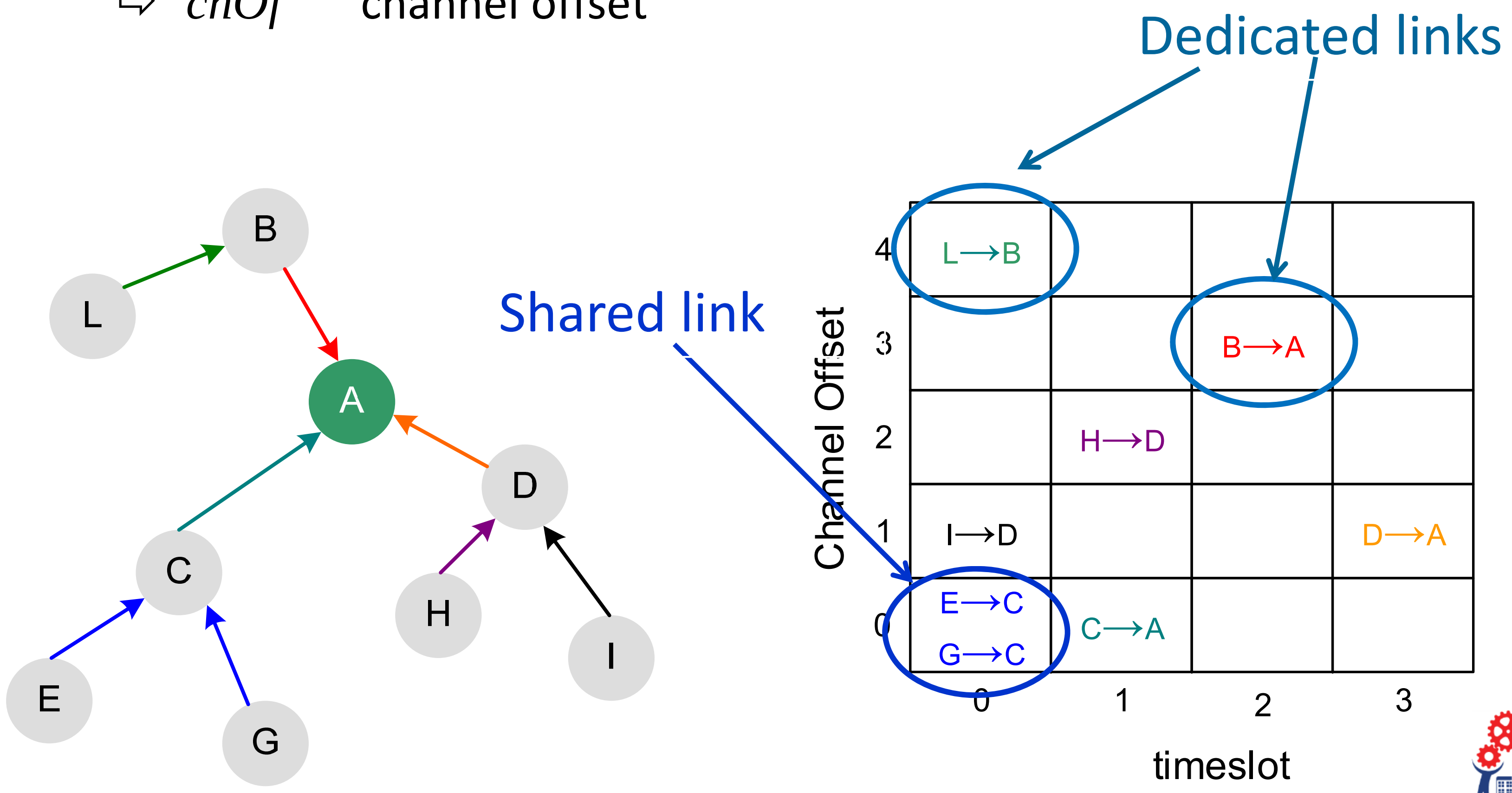
Periodic Slotframe





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

PerLab

- **Dedicated links**
  - Deterministic traffic
  - Periodic transmissions
  - One transmitter – One receiver
  - Direct access
- **Shared links**
  - Sporadic, unpredictable traffic
  - Discovery and routing messages
  - Multiple transmitters/receivers
  - CSMA-CA based access

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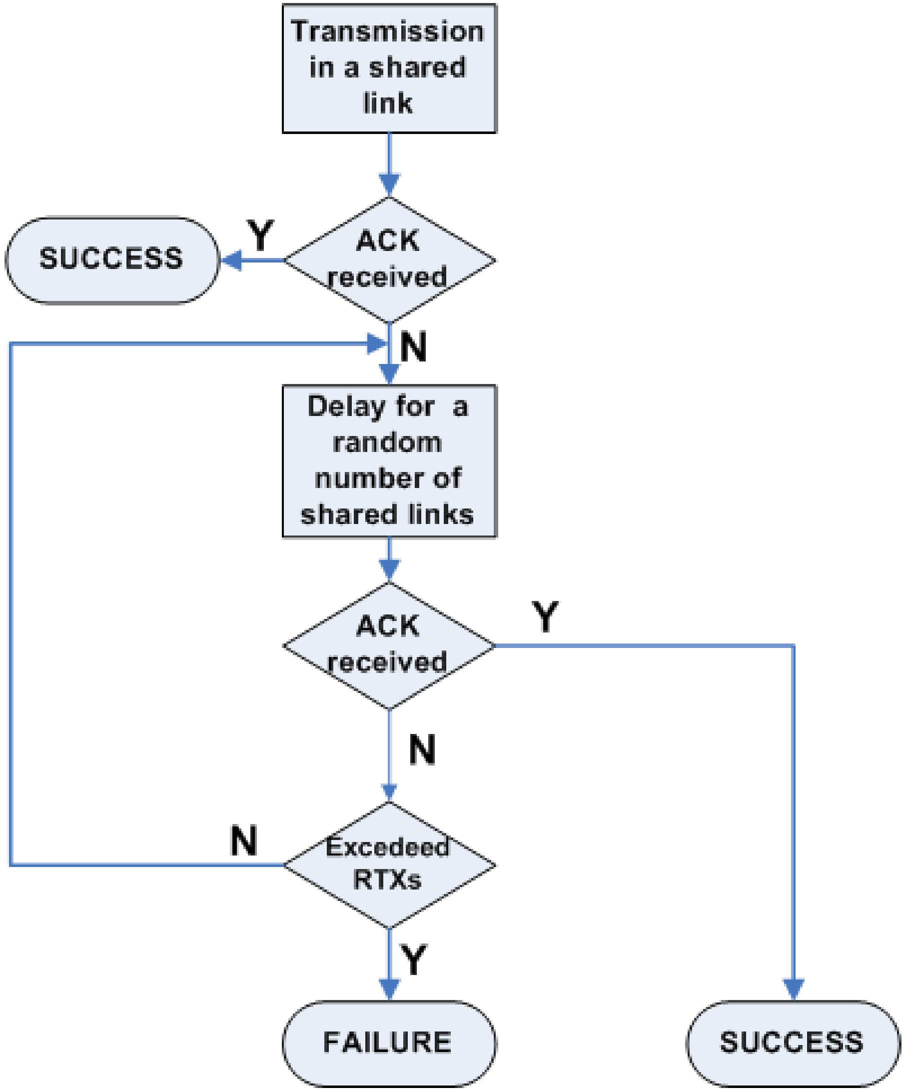
TSCH CSMA-CA for Shared Links



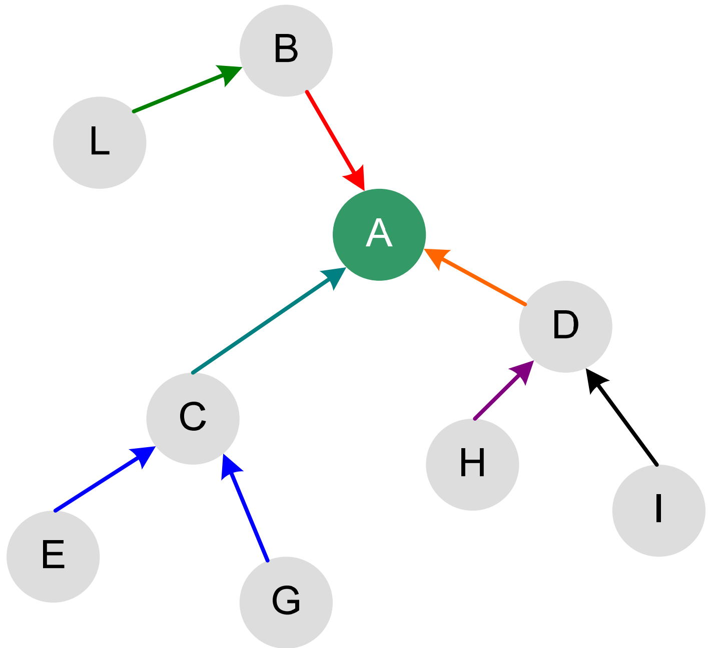
TSCH CSMA-CA vs. 802.15.4 CSMA-CA

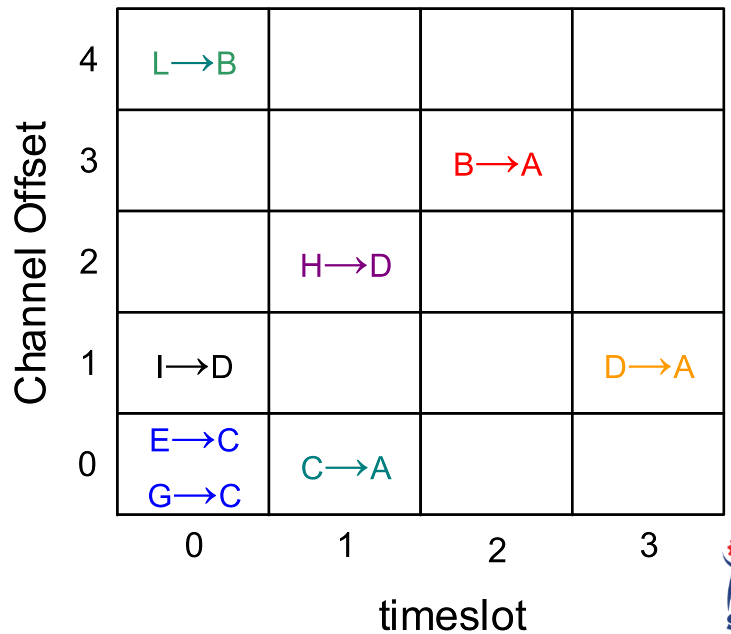
- **Backoff mechanism**
  - is activated only after the node has experienced a collision (to avoid repeated collisions)
- **Backoff unit duration**
  - TSCH: a shared slot
  - 802.15.4: 320 μsec
- **Clear Channel Assessment (CCA)**
  - CCAs are not used to prevent collisions among nodes, but to avoid transmitting a packet if a strong external interference is detected
- **Packet dropping**
  - a packet is dropped only if it reaches the maximum number of retransmissions

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

- *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





Frequency Translation - Channel Hopping

PerLab

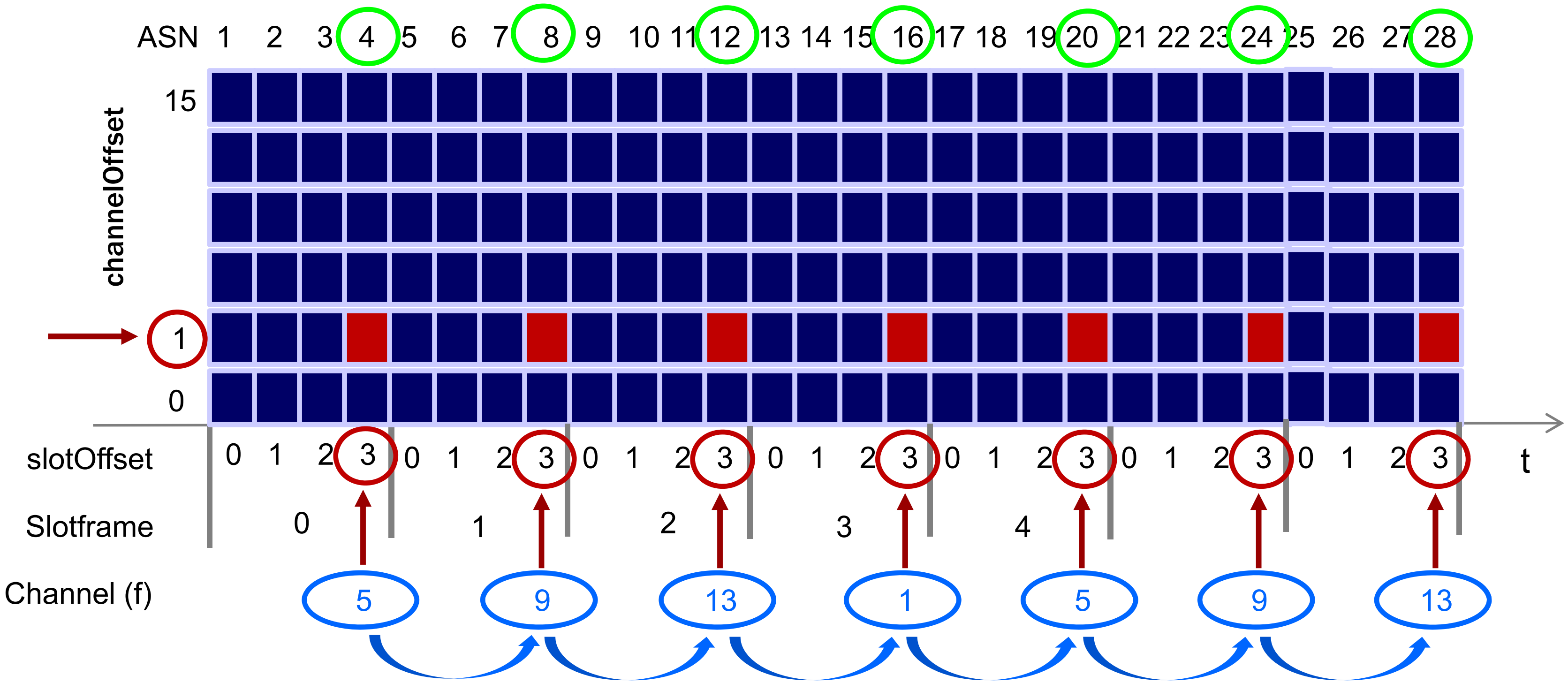
The channel offset of a Link = (*t*, *chOf*) is translated in an operating frequency *f*

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

- 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

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



Slotframe size and n_{ch} should be relatively prime

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

Literature Review

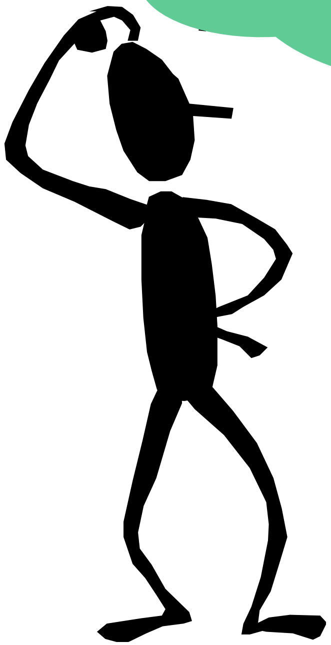
PerLab

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



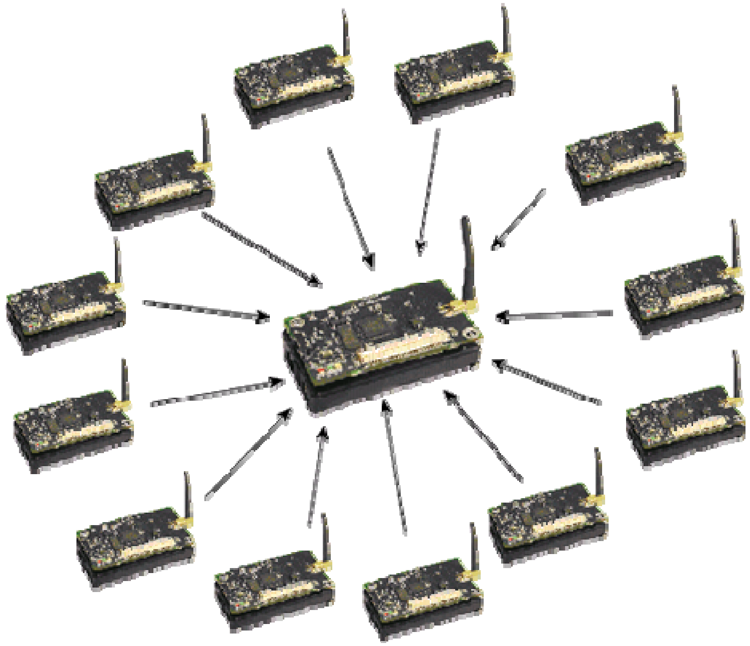
Performance Evaluation of TSCH Mode

PerLab

- 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.
- ....

802.15.4e TSCH vs. 802.15.4 CSMA-CA

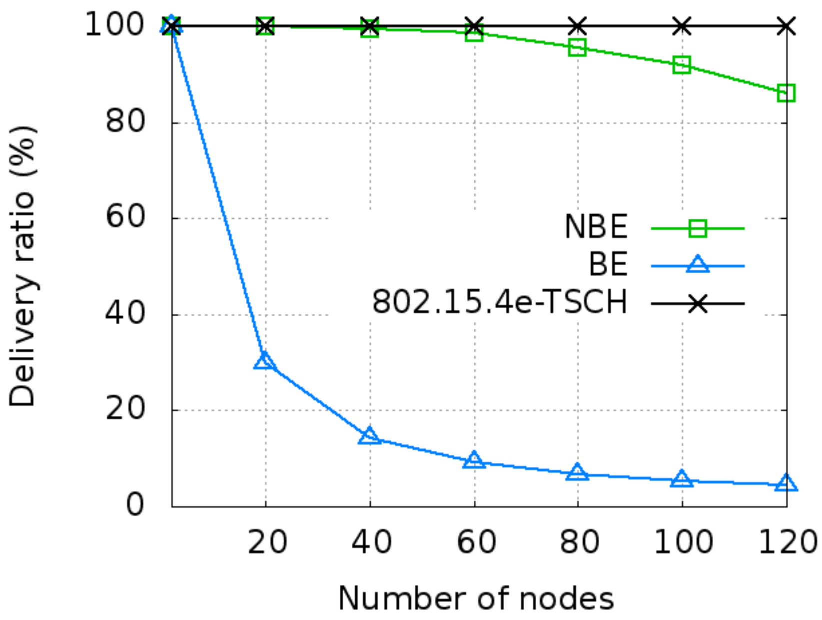
- Comparison
  - 802.15.4 CSMA-CA in BE and NBE mode
  - 802.15.4e in TSCH mode
- Star Network
- Periodic Reporting
  - 1 packet every T (BI in BE mode)
  - TSCH: single channel used
- Performance Metrics
  - Delivery Ratio
  - Average Latency
  - Energy per Delivered Packet

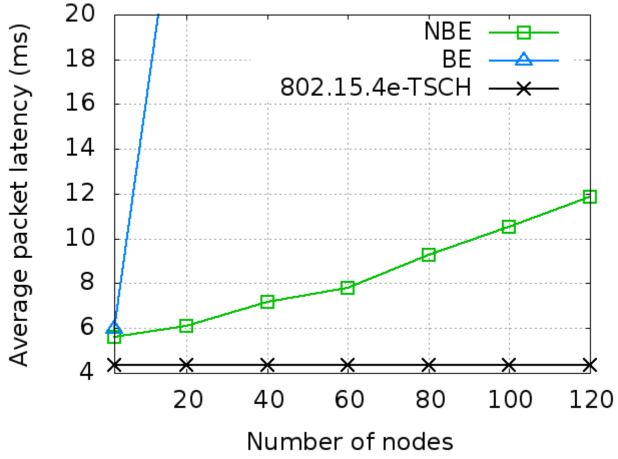


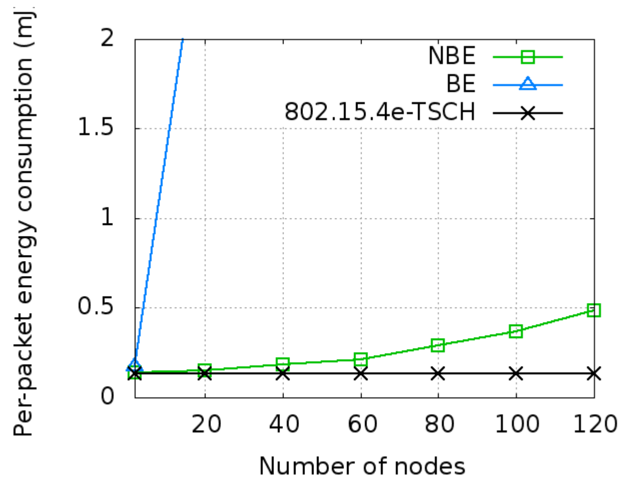
G. Anastasi, D. De Guglielmo, A Seghetti, **From IEEE 802.15.4 to IEEE 802.15.4e: a Step towards the Internet of Things**, Chapter 10 in *Advances onto the Internet of Things* (S. Gaglio, G. Lo Re, Editors), pp. 135-152. January 2014. Springer

PerLab

Simulation Results







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

Scalability

PerLab

- 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

PerLab

- 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

PerLab

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.

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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.

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Suitability to Real-life Applications

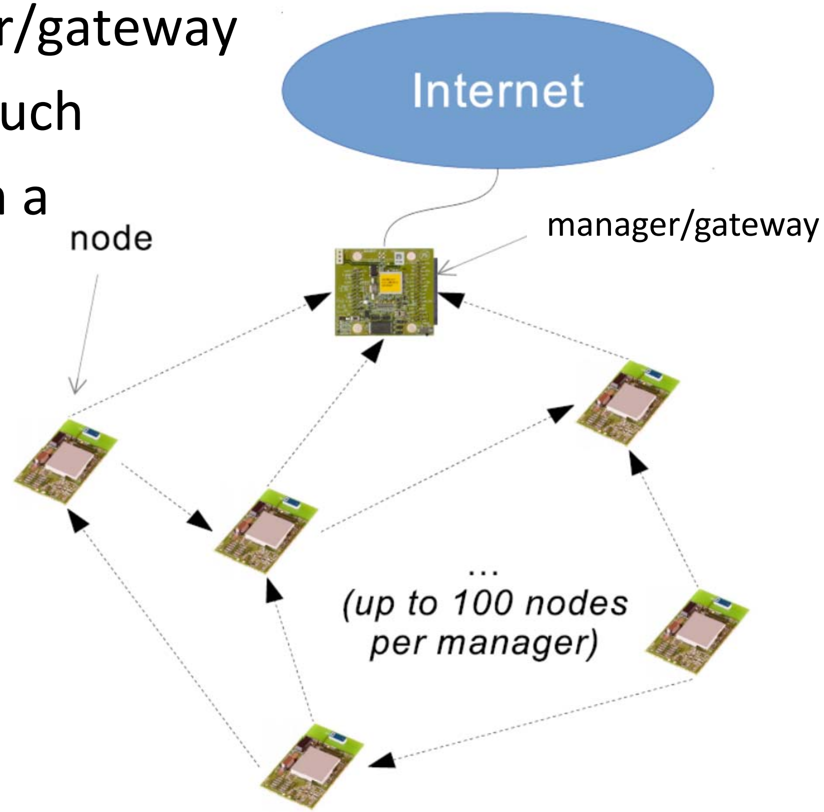
PerLab

- 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

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

PerLab

Smart City

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.

Smart Building

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.

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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

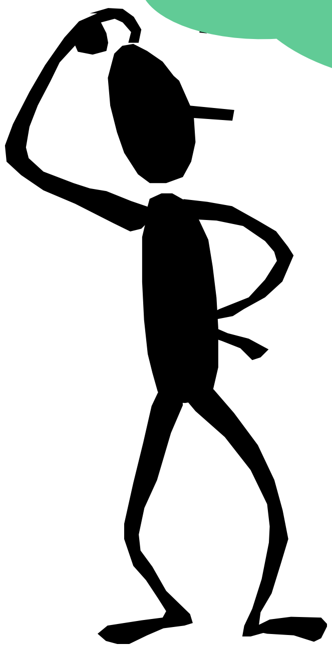
Performance

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

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.

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

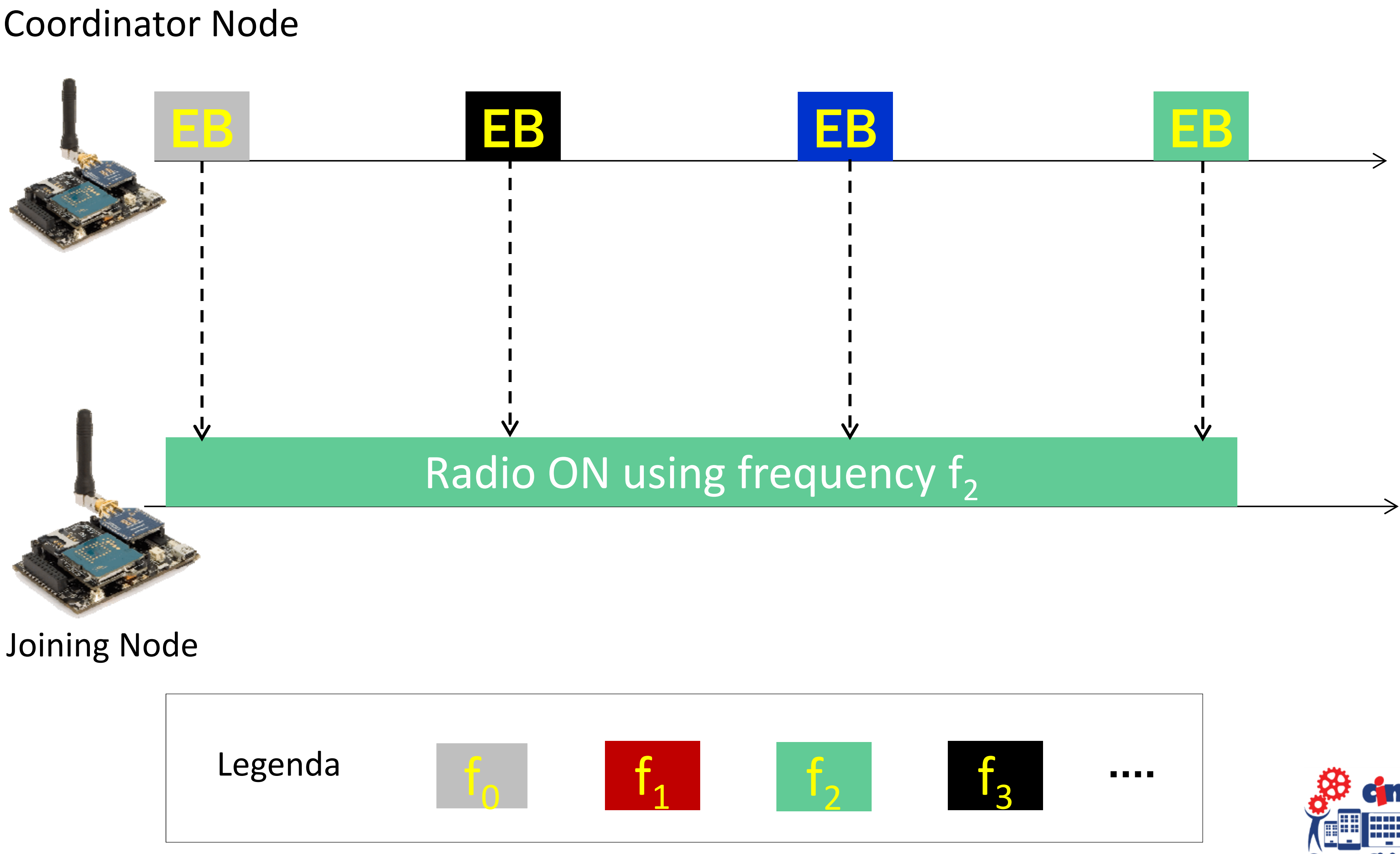
The EB advertising policy is not part of the 802.15.4e standard

Network Formation

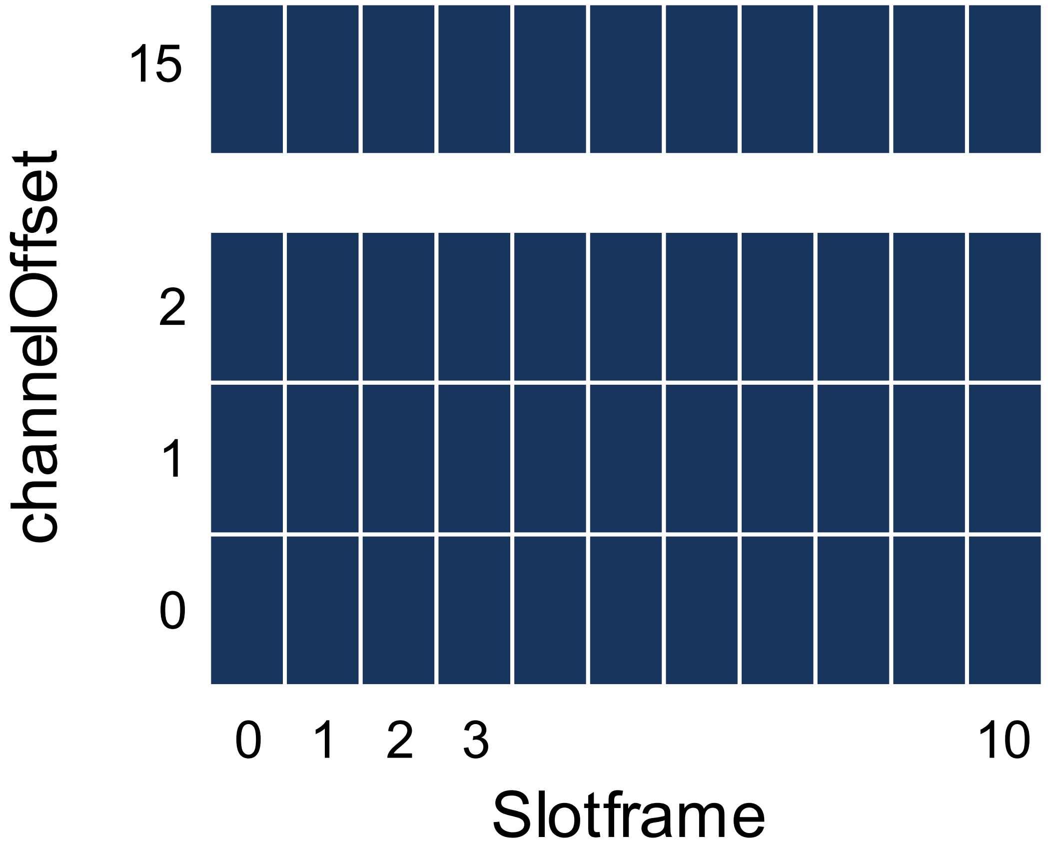
PerLab

- 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

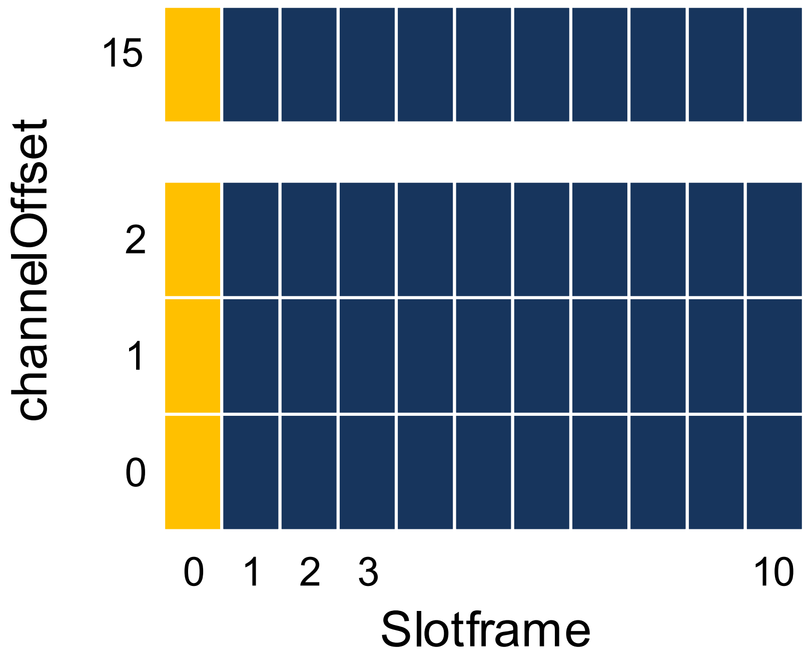
- Minimum Joining time
  - Devices must keep the radio ON during the joining phase
  - EBs should be sent frequently

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

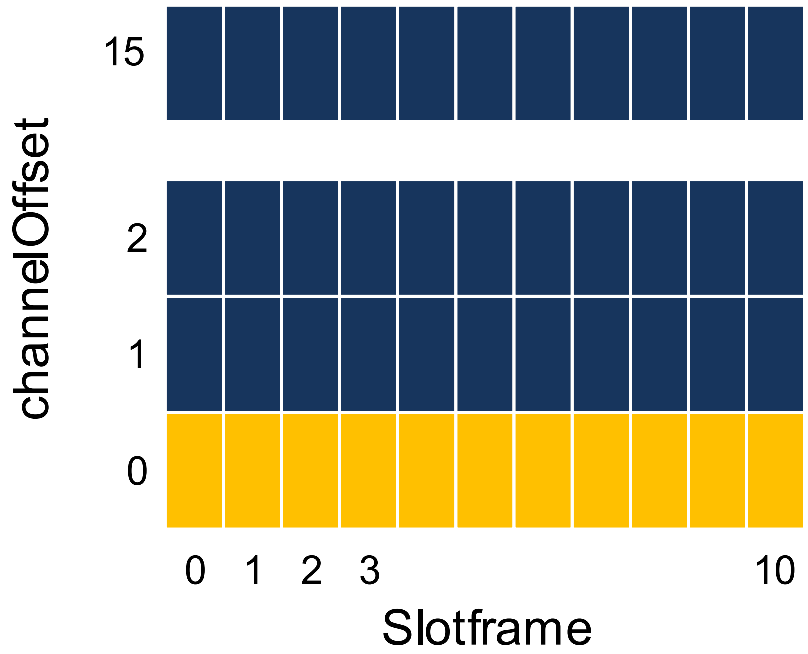
When to transmit EBs?

PerLab

Random Vertical



Random Horizontal

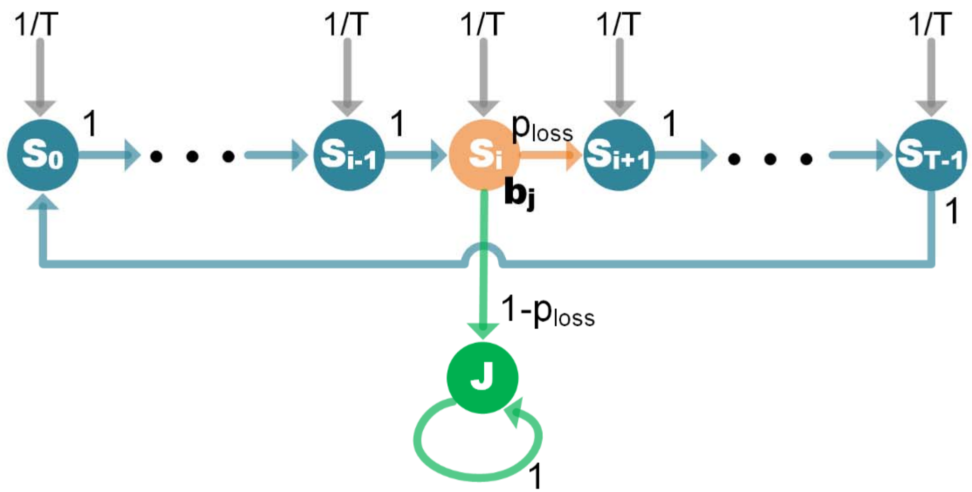


E.Vogli, G.Ribezzo, L.A.Grieco, and G.Boggia, **Fast Join and Synchronization Schema in the IEEE 802.15.4e MAC**, *Proc. IEEE Wireless Communications and Networking Conference Workshops (WCNCW 2015)*, 2015.

Model-based Approach

Model of the Joining Phase

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



$$P = \begin{array}{c} \\ S_0 \\ \vdots \\ S_{i-1} \\ S_i \\ S_{i+1} \\ \vdots \\ S_{T-1} \\ J \end{array} \begin{array}{c} \begin{array}{cccccccc} S_0 & \cdots & S_{i-1} & S_i & S_{i+1} & \cdots & S_{T-1} & J \end{array} \\ \begin{bmatrix} 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \\ 0 & \cdots & 0 & 1 & 0 & \cdots & 0 & 0 \\ 0 & \cdots & 0 & 0 & p_{loss} & \cdots & 0 & 1-p_{loss} \\ 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 1 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \end{array}$$

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.

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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.

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Model-based Approach

PerLab

Optimization Problem

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

- $d_0 \dots d_{N_b-1}$ 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.

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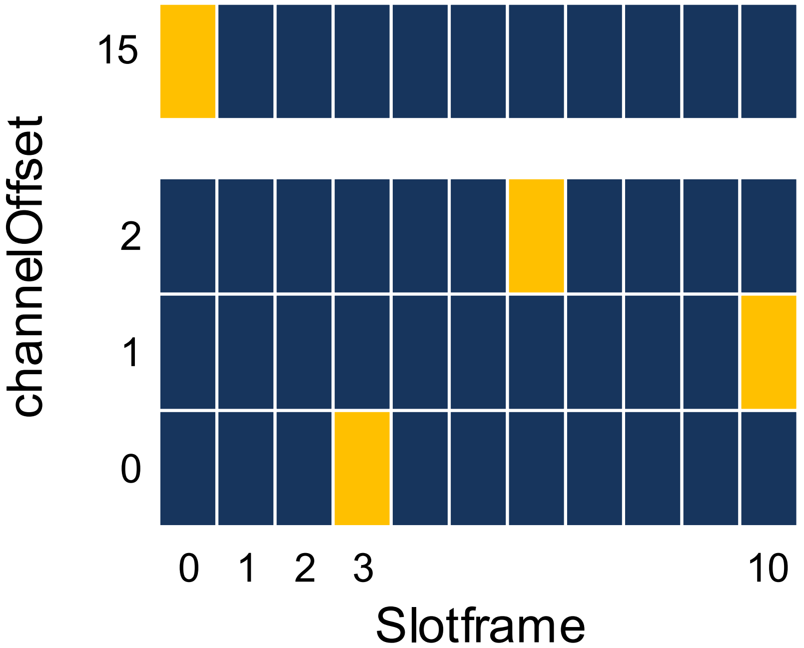
Model-based Approach

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



Performance Comparison

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- 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

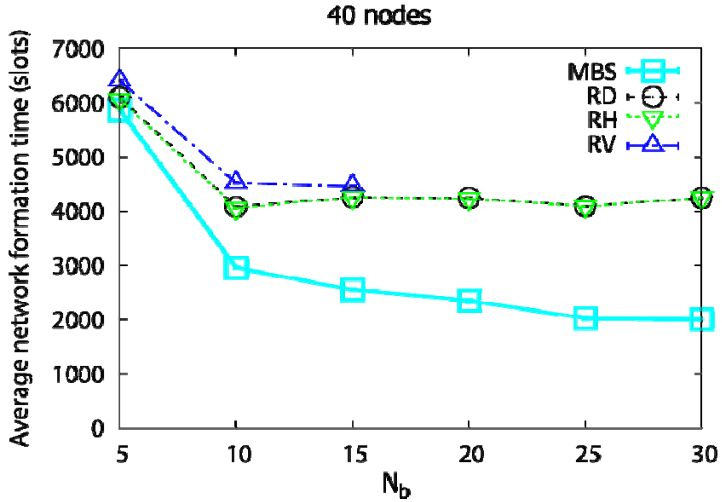
Performance Index: Avg. Network Formation Time

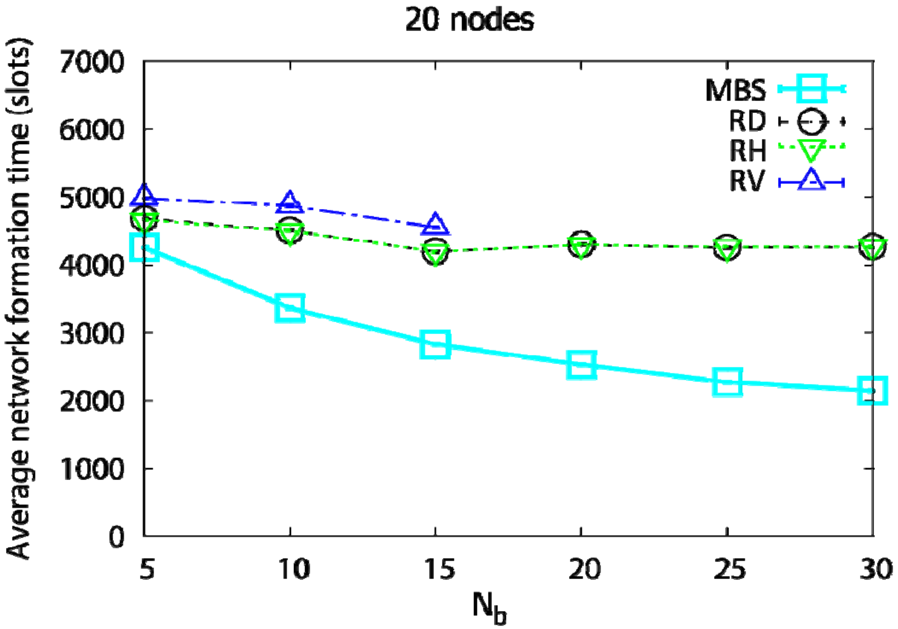
average time (in # of timeslots) from when the PAN coordinator transmits the first EB to when the last node in the group joins the network

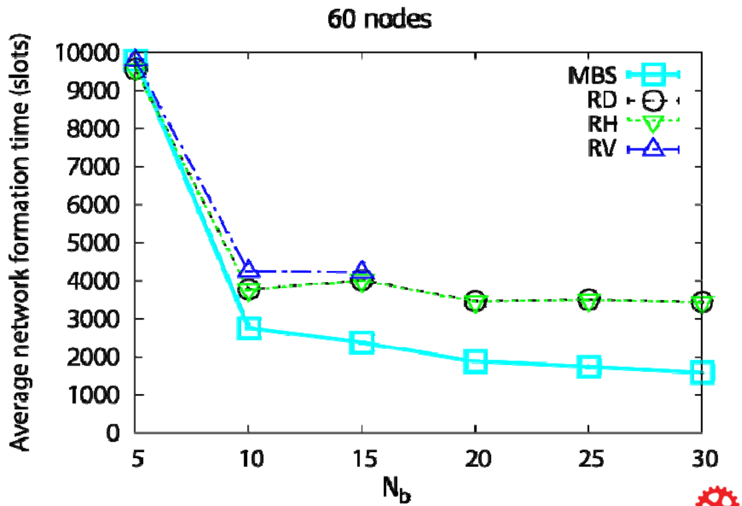
PerLab

Scenario

- N nodes willing to set up a network
- Random deployment over an area of 80×80 m²
- 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.

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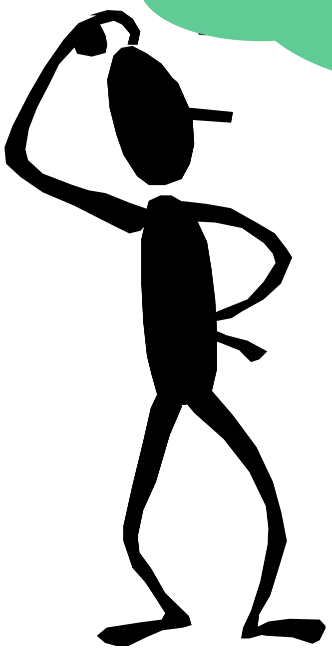
IEEE 802.15.4e TSCH

TSCH
Link Scheduling



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

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

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

- 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]
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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

- 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

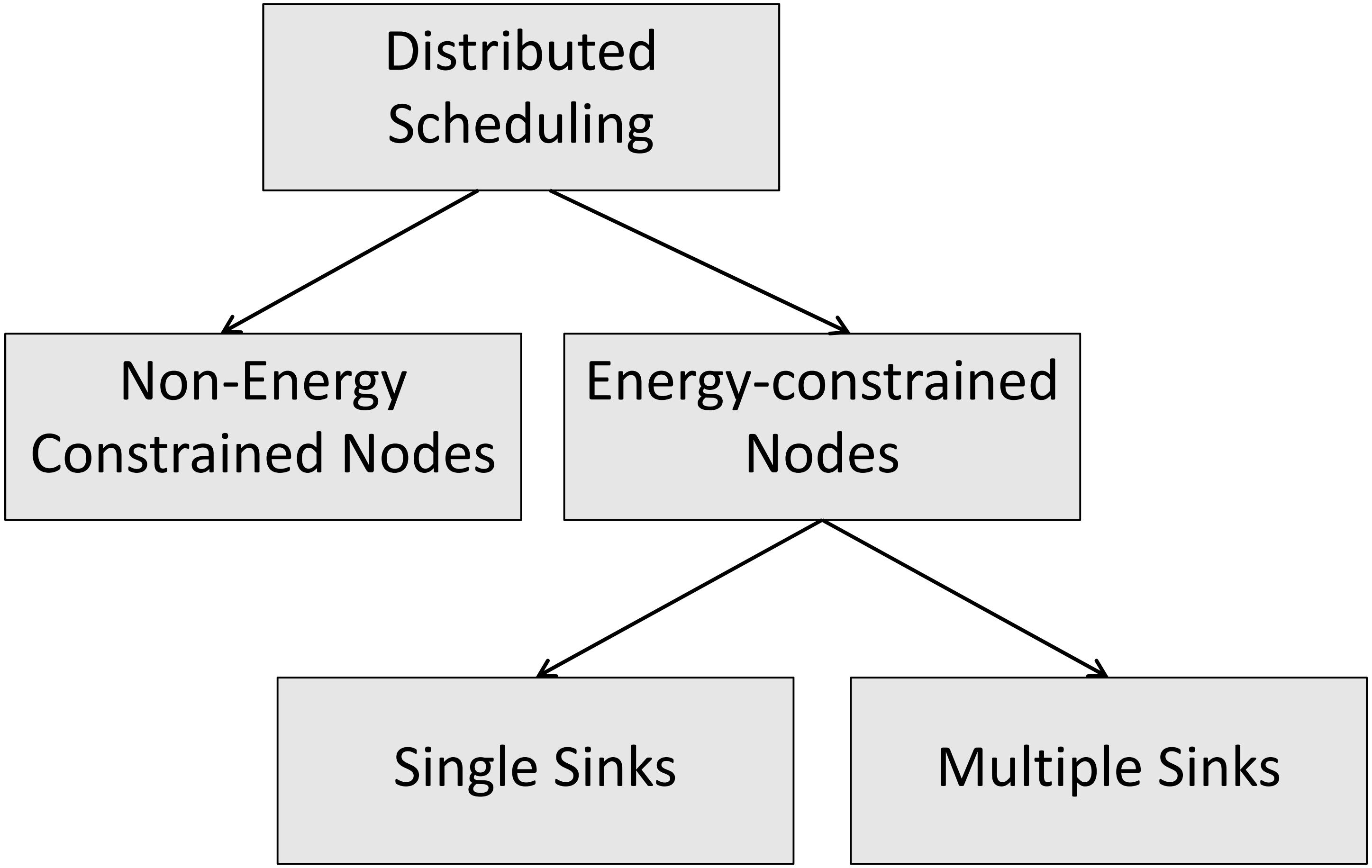
TSCH Centralized Scheduling --MODESA

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

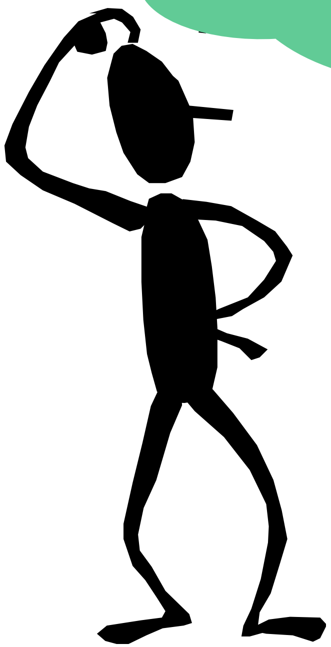
TSCH Distributed Scheduling



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

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- 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?

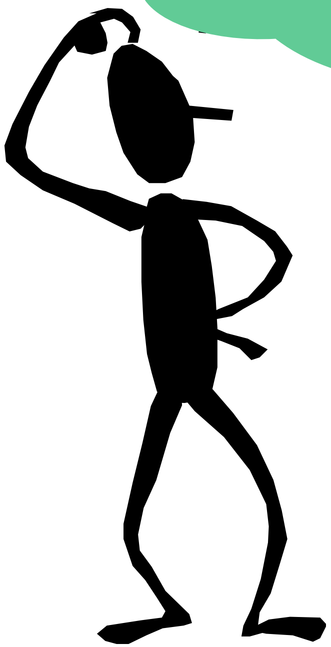
Open Issues

- 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

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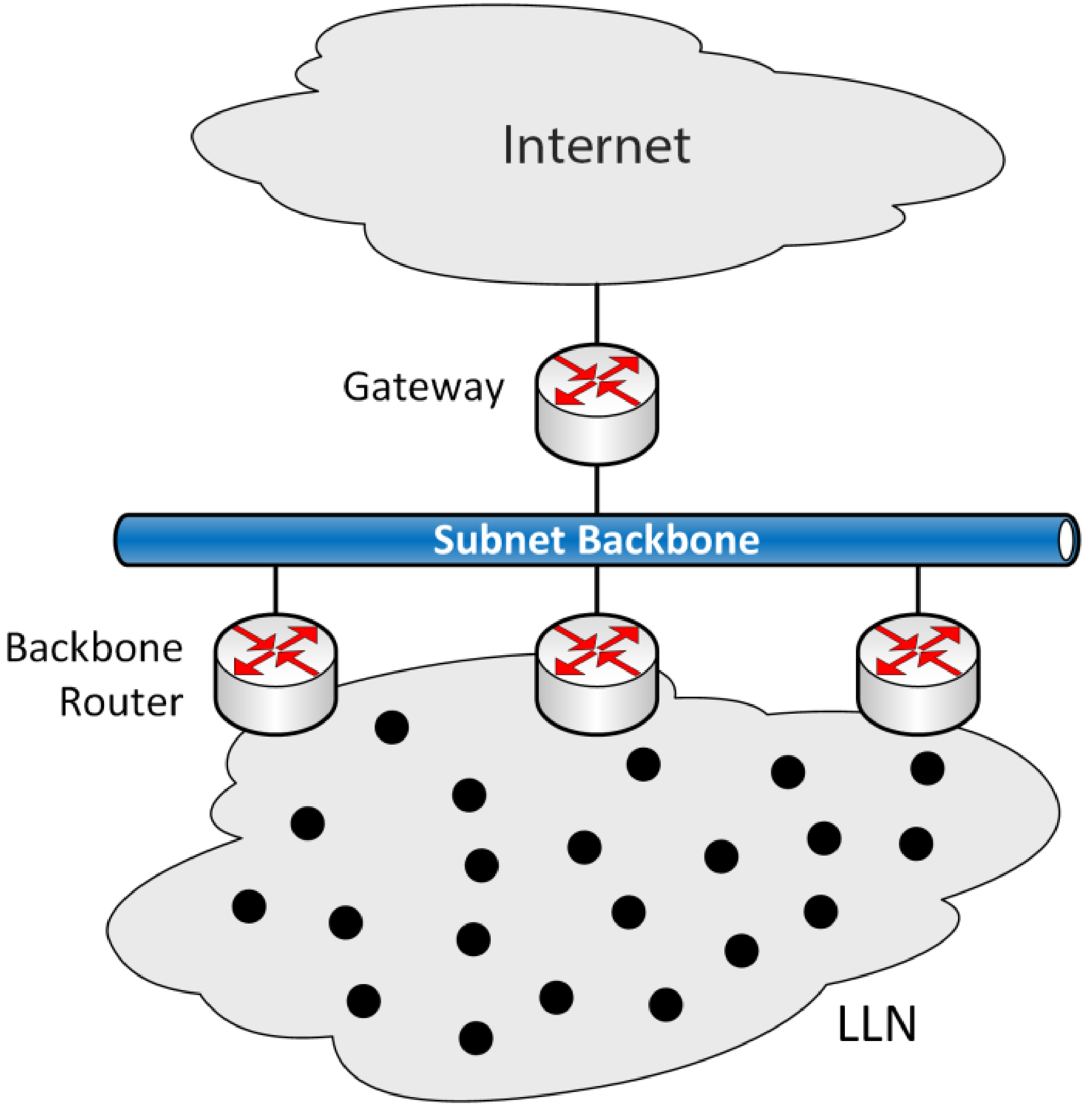
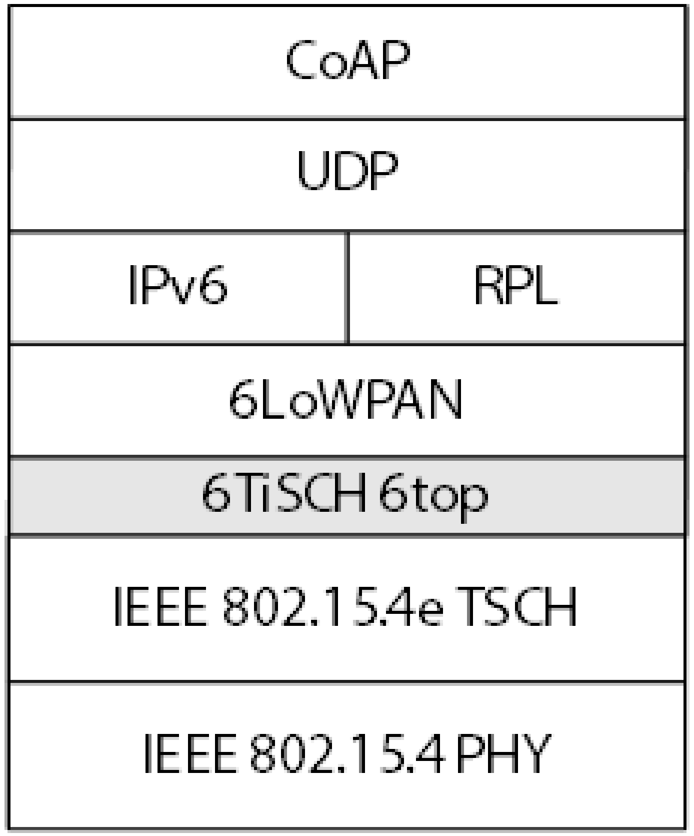
TSCH does not define

- 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

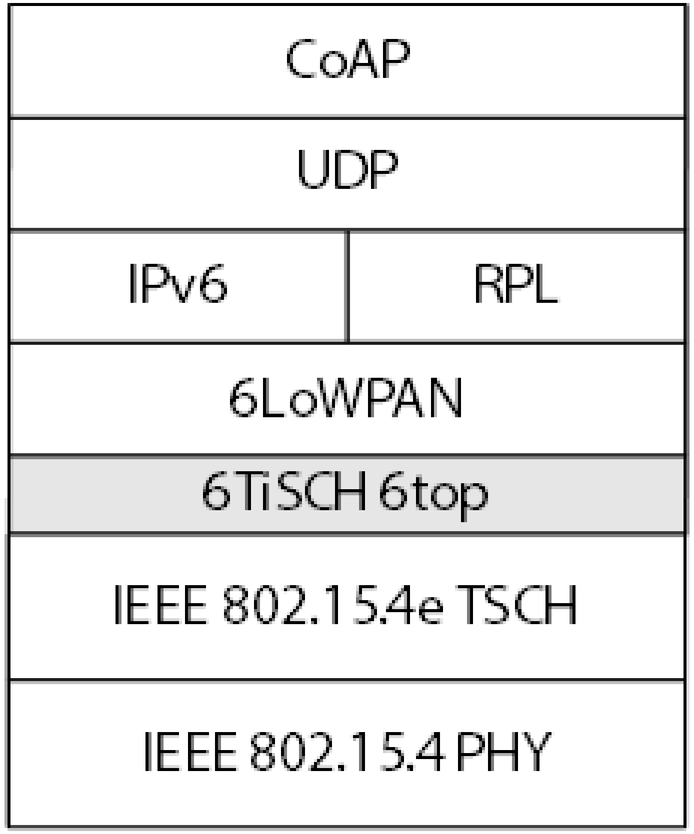


Protocol stack for deterministic IPv6-enabled wireless mesh networks

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

PerLab

- **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

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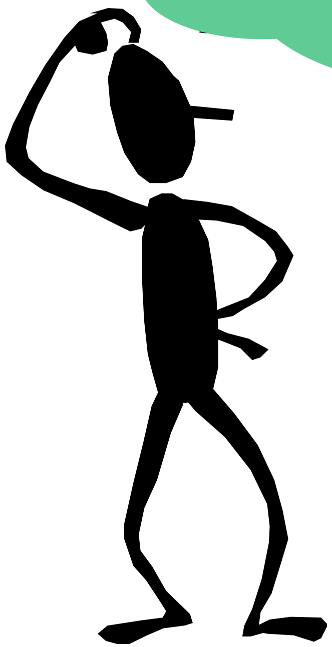
Distributed Scheduling

- 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



Summary

- IEEE 802.1.5.4 standard
  - limitations
- IEEE 802.15.4e
- 802.15.4e DSME mode
  - literature survey
  - open issues
- 802.15.4e TSCH mode
  - literature survey
  - open issues
- IoT with 802.15.4e TSCH
  - The 6TiSCH initiative

Conclusions

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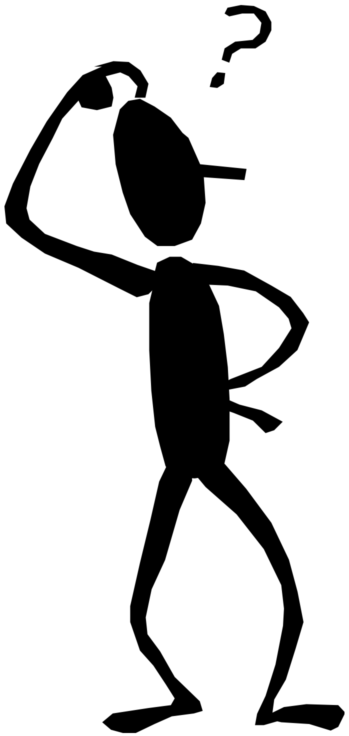
- 802.15.4e DSME mode
  - Only partially investigated
  - A lot of open issues
- 802.15.4e TSCH mode
  - A lot of work has been done
  - Many open issues still remains
    - ⇨ Network Formation
    - ⇨ Security
- IoT with 802.15.4e TSCH
  - Still a completely open issue

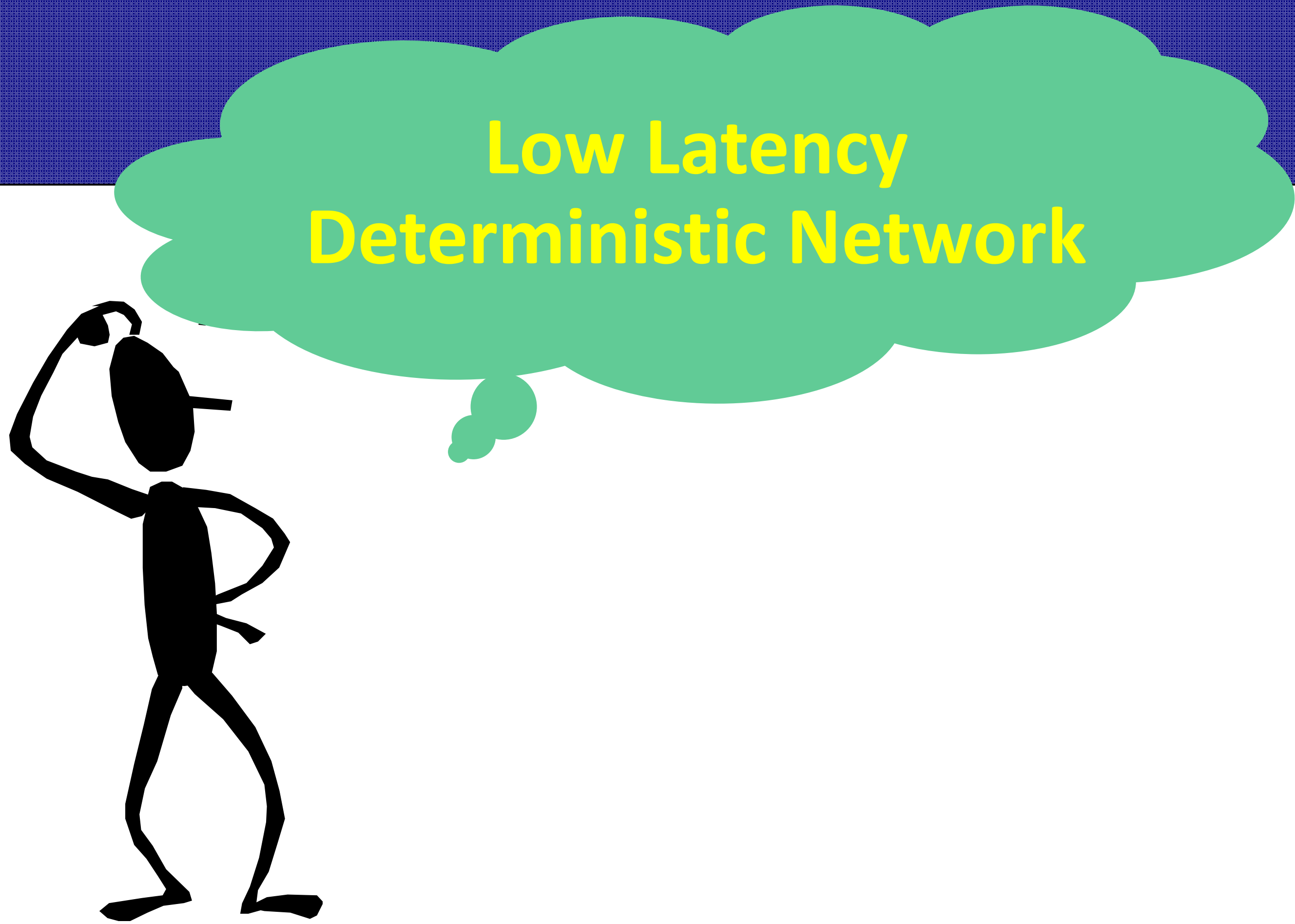
References

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



IEEE 802.15.4e LLDN



Main Characteristics

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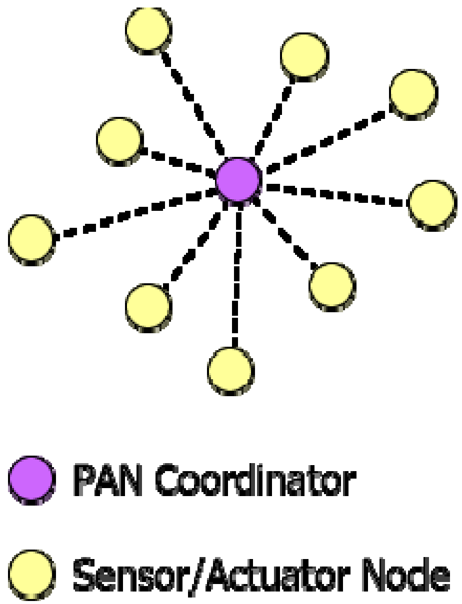
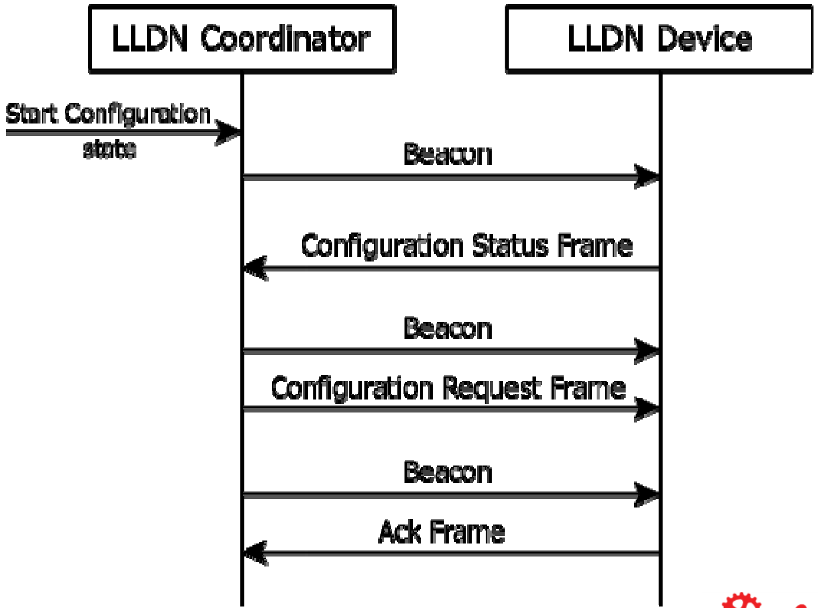
- LLDN Addresses the industrial automation application domain
  - LLDN devices can be located on robots, cranes, and portable tools in the automotive industry, …
- Common requirements are low latency and high cyclic determinism
  - LLDN shall allow to transmit data from 20 different sensor nodes every 10 ms
- Designed for star topologies and periodic traffic
- Nodes use just one frequency channel
- Time is divided into superframes
  - Nodes can access the medium in dedicated timeslots of the superframe, according to a time division (TDMA) approach.
  - Shared group timeslots can also be configured, to allow multiple access for groups of nodes (using a CSMA protocol).



Transmission States

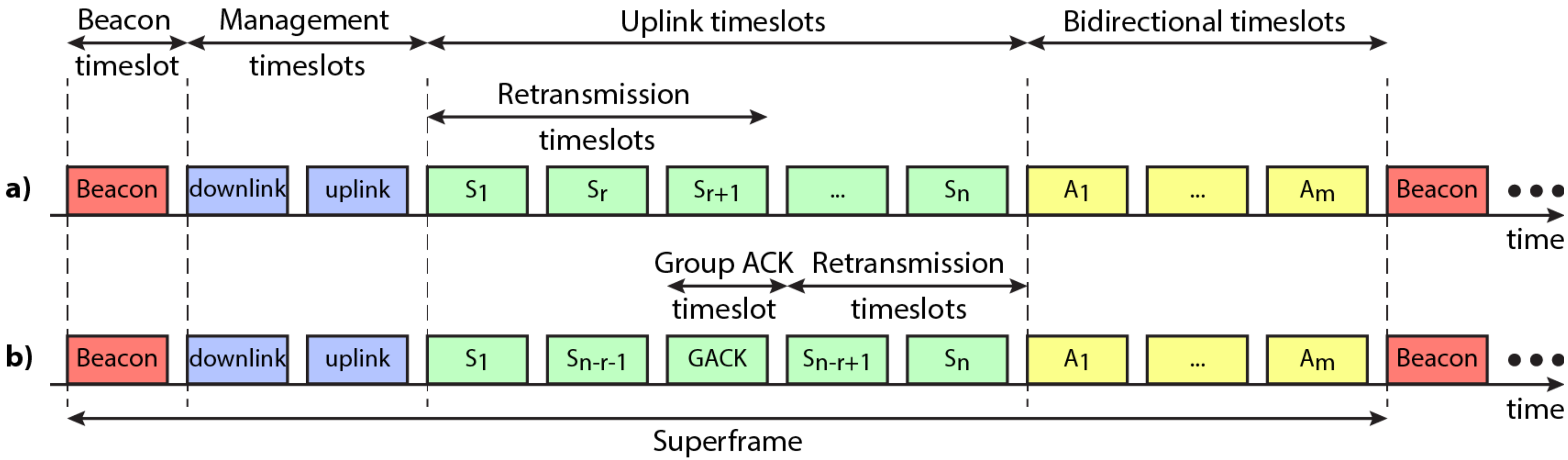
- An LLDN network passes through three states in order to become operative (current state is announced through beacons).

1. DISCOVERY
   - ⇨ Devices scan channels to detect a beacon
2. CONFIGURATION
   - ⇨ Each node sends a frame to the PAN coordinator, containing the node's requirements
   - ⇨ The PAN coordinator replies with the configurations the node must use (e.g., the timeslots that have been assigned to the node).



3. ONLINE
   - ⇨ Nodes can transmit data and readings to the PAN coordinator

Superframe Structure



- Superframes have a fixed duration and are divided into timeslots:
  - Beacon timeslots
  - Management timeslots
  - Uplink timeslots
  - Bidirectional timeslots

Literature Review

PerLab

- ## Improving communication reliability through Relay nodes

1. Berger, M. Pichler, A. Springer and W. Haslmayr, **Energy Efficient and Reliable Wireless Sensor Networks – An Extension to IEEE 802.15.4e**, *EURASIP Journal on Wireless Communications and Networking*, 9 August 2014.
2. H. Kapil and C. S. R. Murthy, **Rainbow product ranking based relay placement and adaptive retransmission scheme for a reliable 802.15.4e LLDN**, In Proceedings of *IEEE International Conference on Industrial Technology (ICIT)*, Seville, Spain, 17-19 March 2015.
3. A. Berger, A. Entinger, A. Potsch, and A. Springer, **Improving IEEE 802.15.4e LLDN Performance by Relaying and Extension of Combinatorial Testing**, In Proceedings of *IEEE Emerging Technology and Factory Automation (ETFA)*, Barcelona, Spain, 16-19 September 2014.

- ## Extending the network coverage through Relay nodes

4. G. Patti, G. Alderisi, and L. Lo Bello, **Introducing multi-level communication in the IEEE 802.15.4e protocol: The MultiChannel-LLDN**, In Proceedings of *IEEE Emerging Technology and Factory Automation (ETFA)*, Barcelona, Spain, 16-19 September 2014.

- ## Tackling node mobility

5. Y. Al-Nidawi, H. Yahya, and A. H. Kemp, **Impact of mobility on the IoT MAC infrastructure: IEEE 802.15. 4e TSCH and LLDN platform**, in Proceedings of the *2nd IEEE World Forum on Internet of Things (WF-IoT)*, December 2015.
6. Y. Al-Nidawi and H. Yahya and A. H. Kemp, **Tackling Mobility in Low Latency Deterministic Multihop IEEE 802.15.4e Sensor Network**, *IEEE Sensors Journal*, 16 (5), March 2016.

- ## Analytical model for shared timeslots

7. C. Ouanteur, D. Aïssani, L. Bouallouche-Medjkoune, M. Yazid, and H. Castel-Taleb, **Modeling and performance evaluation of the IEEE 802.15.4e LLDN mechanism designed for industrial applications in WSNs,** *Wireless Networks*, 2016.