From IEEE 802.15.4 to IEEE 802.15.4e
Another Step towards the Internet of (Important) Things

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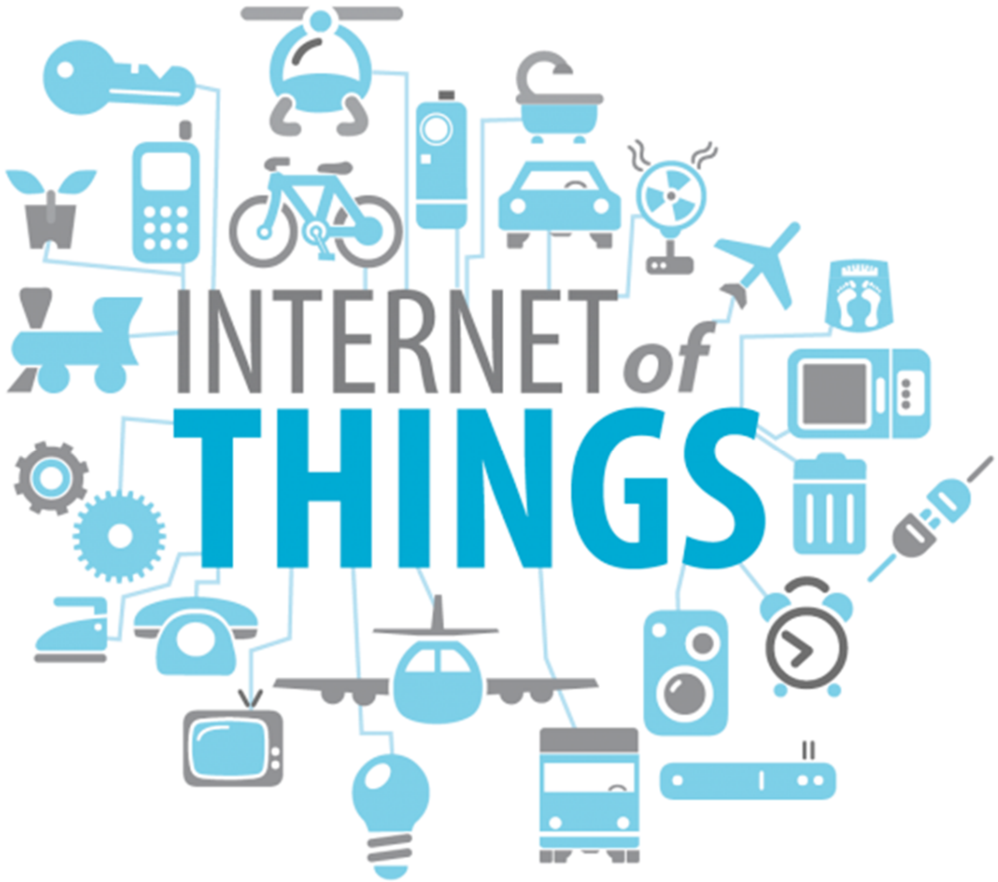
Sun Yat-Sen University
Guangzhou, China, May 16, 2014

Internet of Things

"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)

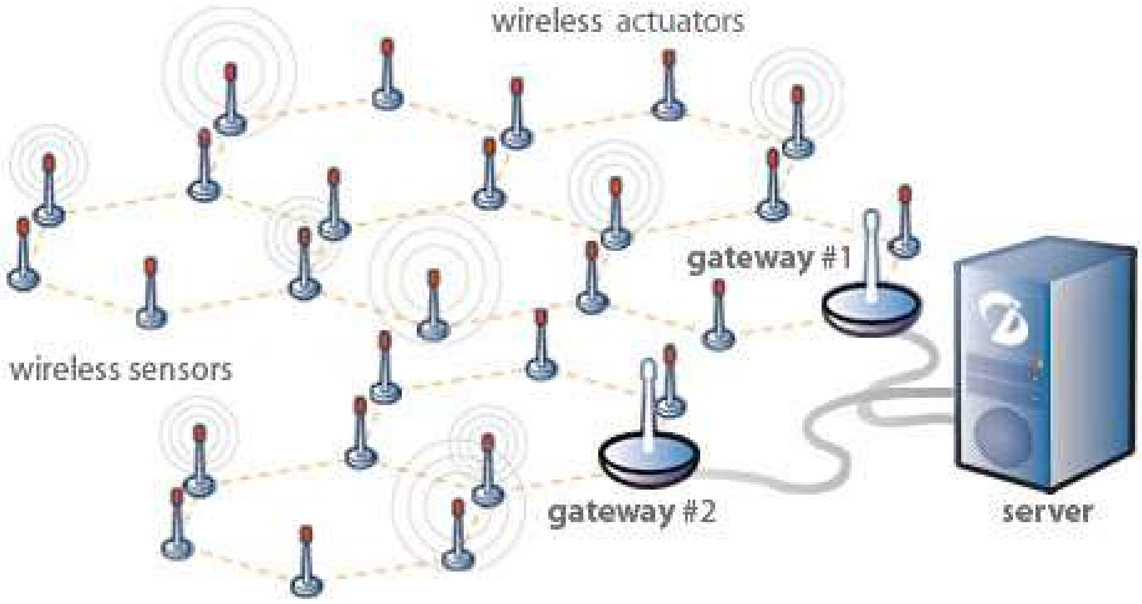
More than 26 billions devices will be wirelessly connected to the Internet of Things by 2020

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



Wireless Sensor & Actuator Networks (WSANS)

- 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



Standards for WSANs

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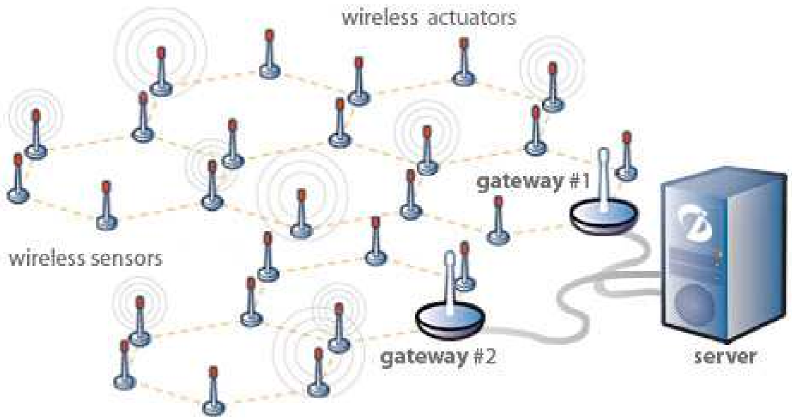
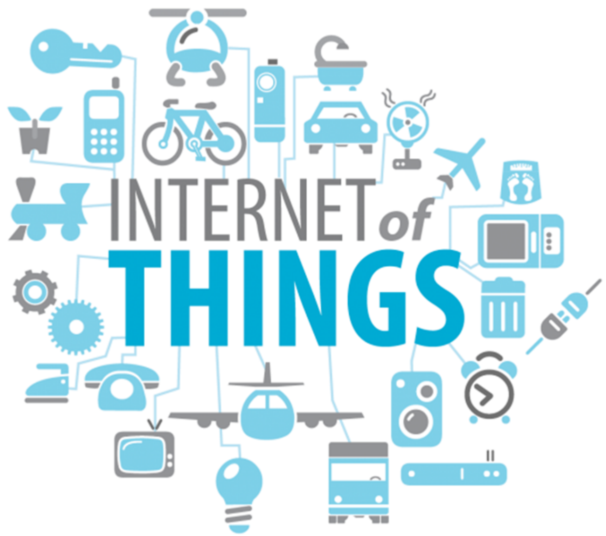
- IEEE 802.15.4/802.15.4e
- ZigBee
- Bluetooth
- WirelessHART
- ISA-100.11a



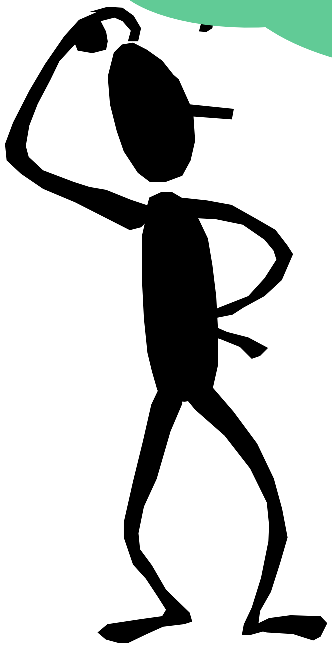
- 6LoWPAN
  - *IPv6 over Low power WPAN*
- RPL
  - *Routing Protocol for Low power and Lossy networks*
- CoAP
  - *Constrained Application Protocol*



IEEE 802.15.4 Standard

Reference technology for WSANs

Expected to be a major enabling technology also for IoT



Overview

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- IEEE 802.15.4
  - MAC protocols
- Limits of IEEE 802.15.4 MAC
  - Performance and reliability
- Possible enhancements
- IEEE 802.15.4e
  - *Time-Slotted Channel Hopping (TSCH)* mode
- Open Issues

IEEE 802.15.4 standard

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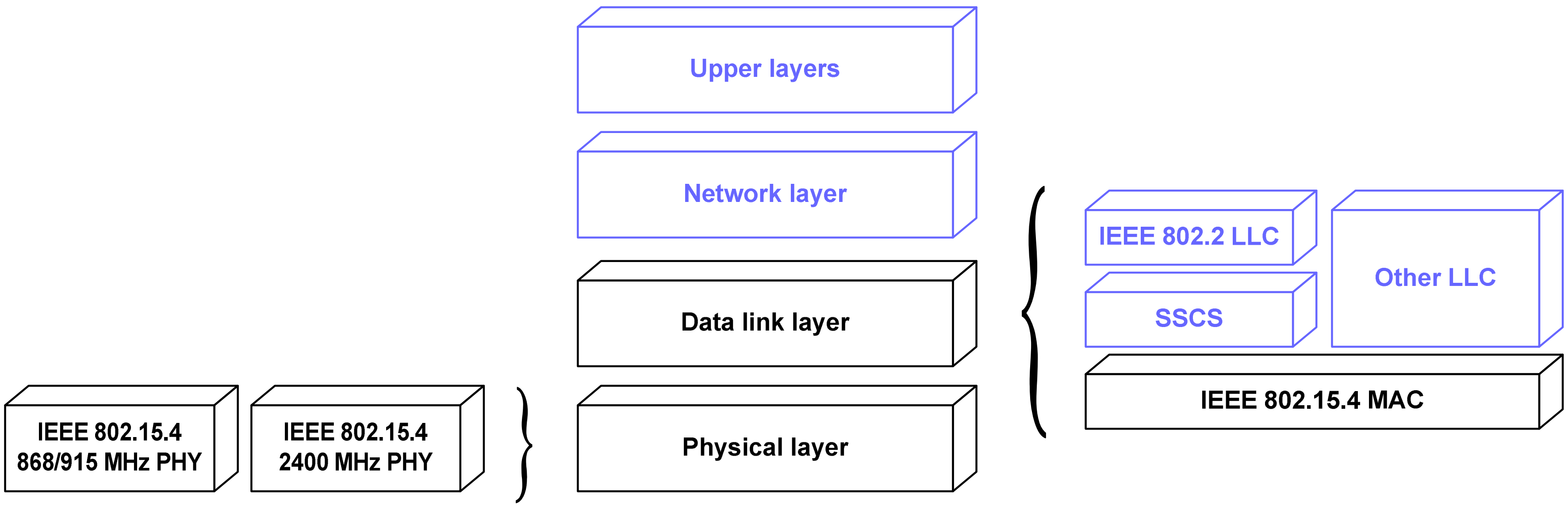

- Standard for Personal Area Networks (PANs)
  - low-rate and low-power
  - PHY and MAC layers
- Main features
  - transceiver management
  - channel access
  - PAN management

802.15.4 Network Topologies

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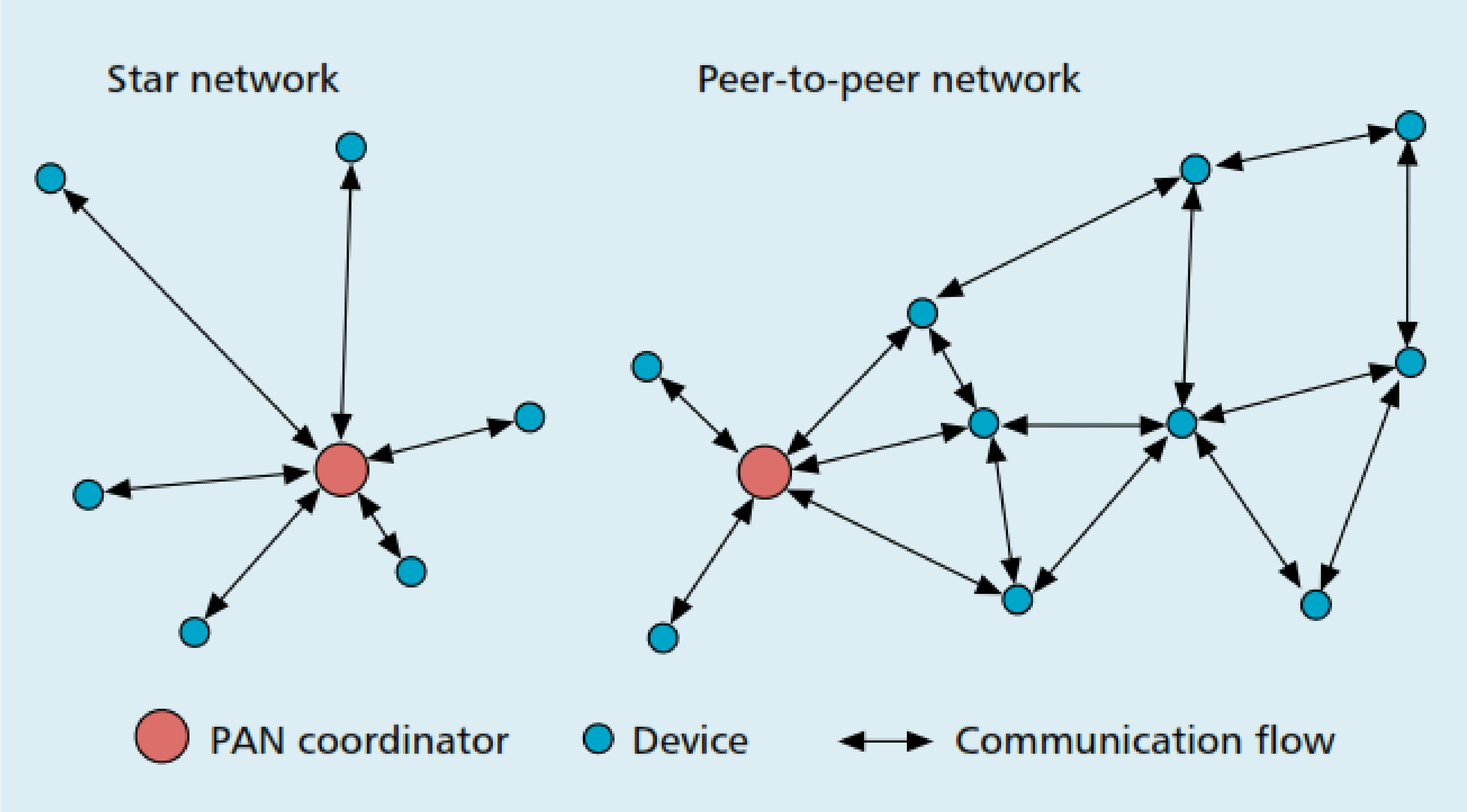

Ed Callaway, Paul Gorday, Lance Hester, Jose A. Gutierrez, Marco Naeve, Bob Heile, **Home Networking with IEEE 802.15.4: Developing Standard for Low-Rate Wireless Personal Area Networks,** *IEEE Communications Magazine*, August 2002.

Channel frequencies

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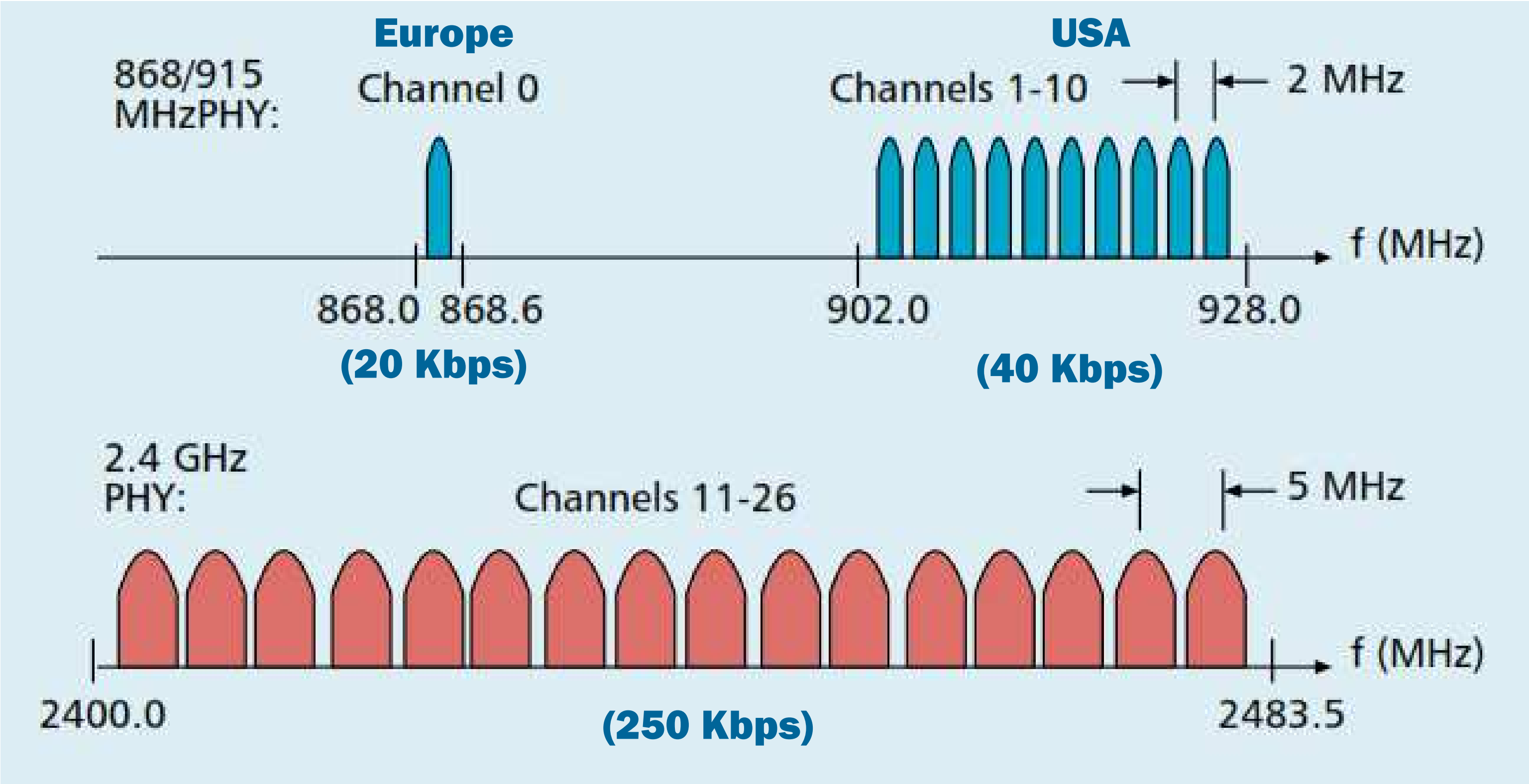
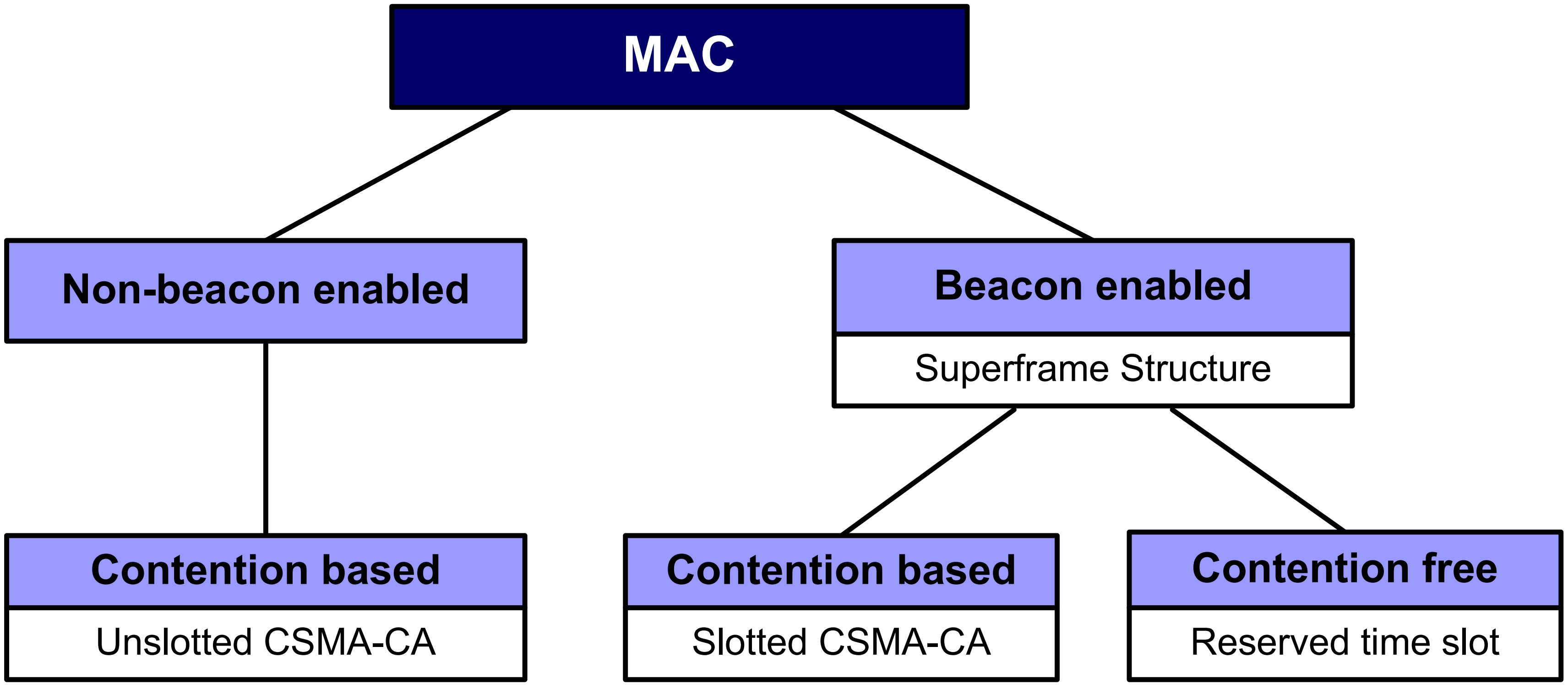


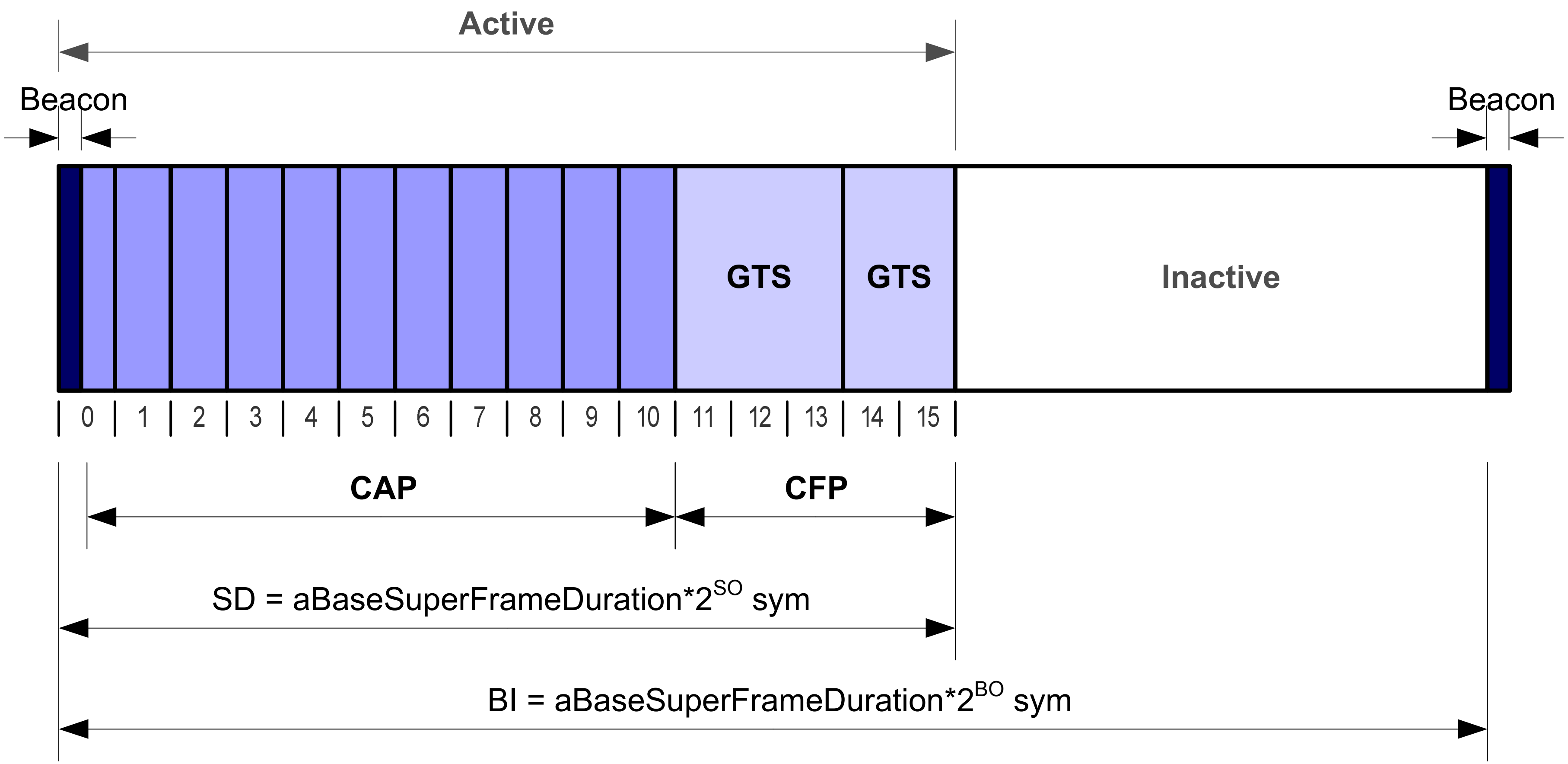
Ed Callaway, Paul Gorday, Lance Hester, Jose A. Gutierrez, Marco Naeve, Bob Heile, **Home Networking with IEEE 802.15.4: Developing Standard for Low-Rate Wireless Personal Area Networks,** *IEEE Communications Magazine*, August 2002.

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

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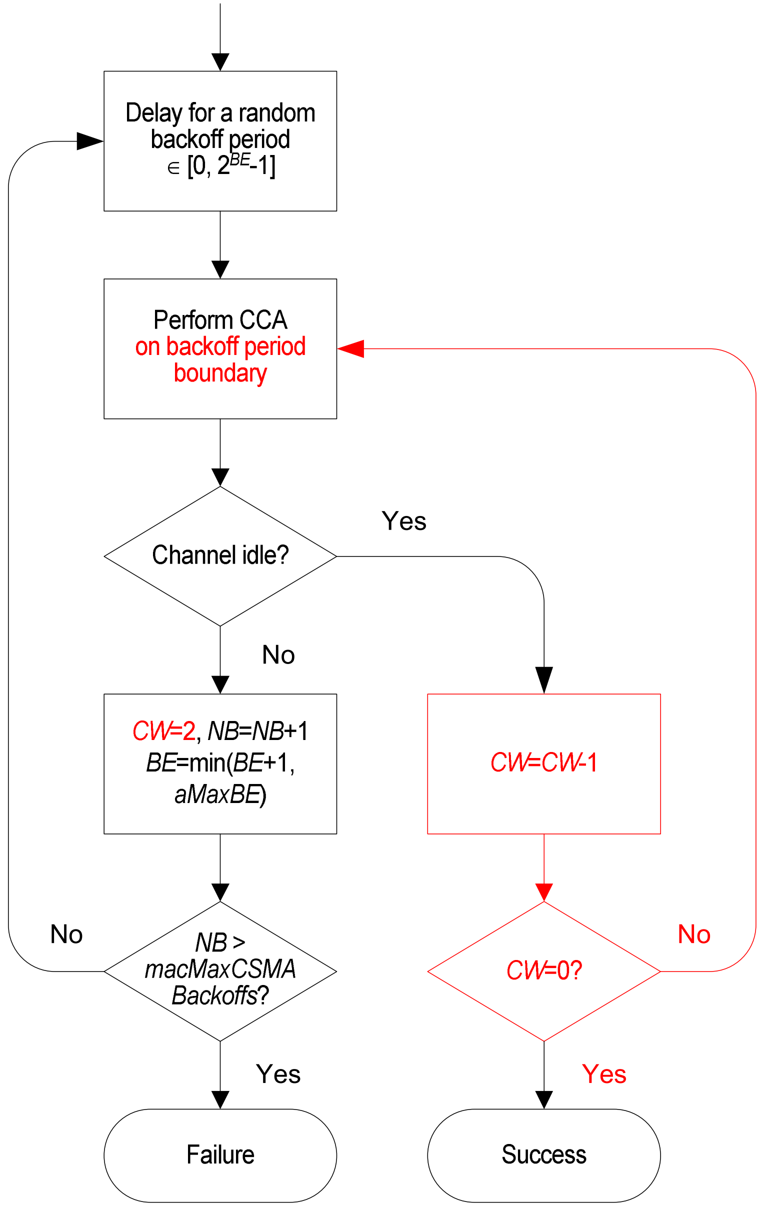
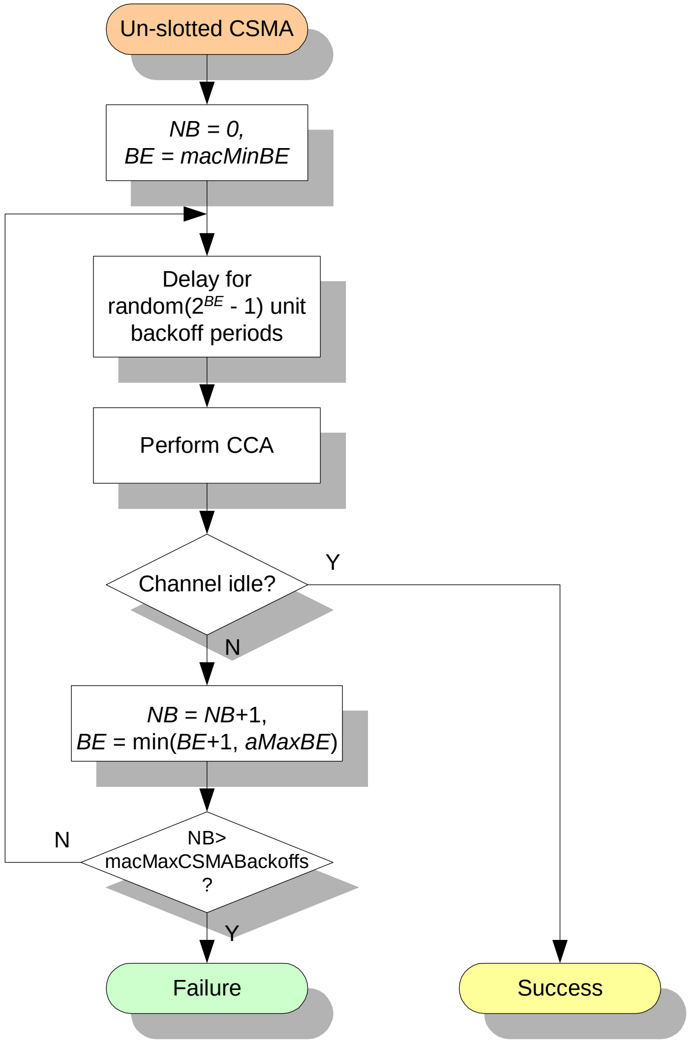


At each trial the backoff-window size is doubled

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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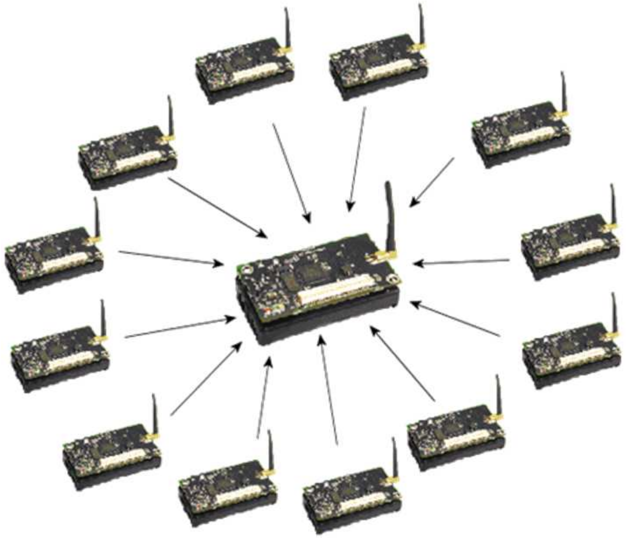
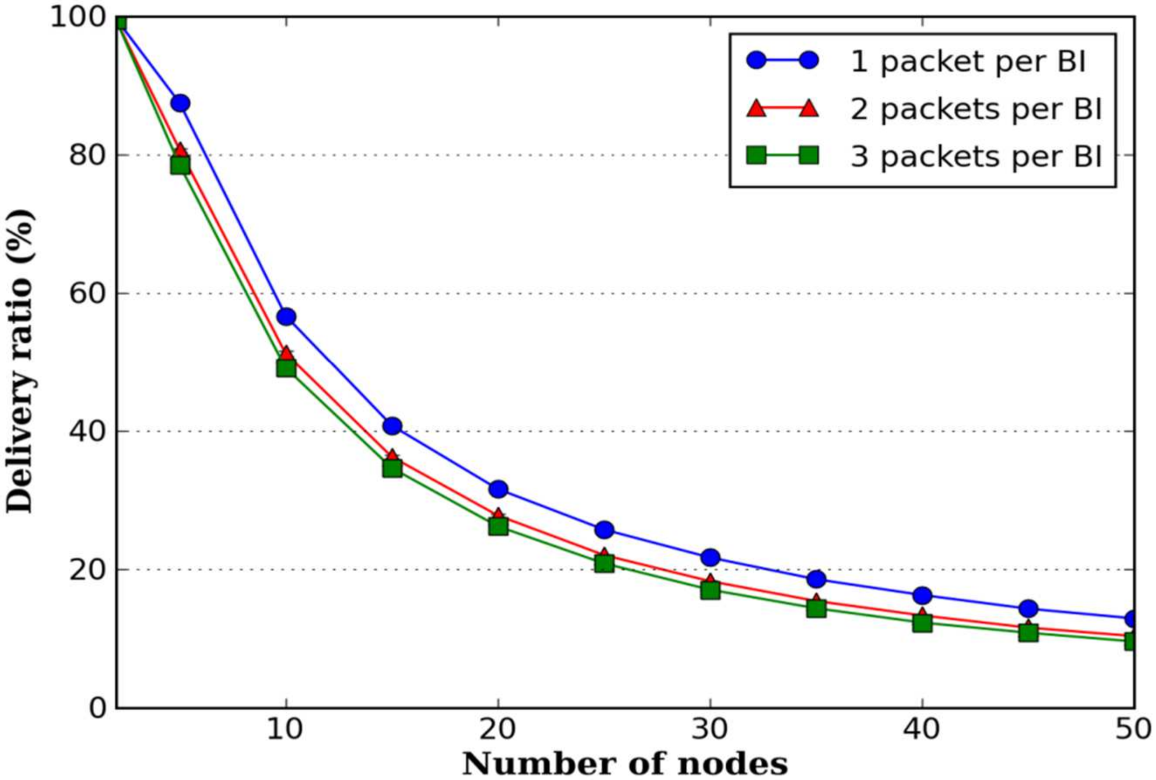
- MAC Unreliability
- Unbounded latency
- No guaranteed bandwidth
  - Unless GTS is used
  - GTS only provides a limited service (7 slots)
- No built-in frequency hopping technique
  - Prone to failures due to interferences and multi-path fading

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

802.15.4 CSMA/CA Performance

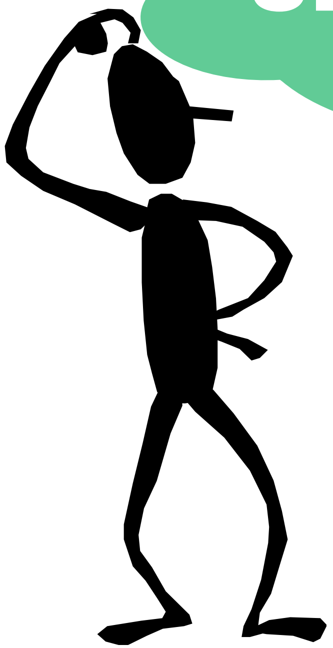




G. Anastasi, M. Conti, M. Di Francesco, **A Comprehensive Analysis of the MAC Unreliability Problem in IEEE 802.15.4 Wireless Sensor Networks**, *IEEE Transactions in Industrial Informatics,* Vol. 7, N. 1, Feb 2011.

Key Question

Why the 802.15.4 MAC Unreliability Problem?



Possible Answers

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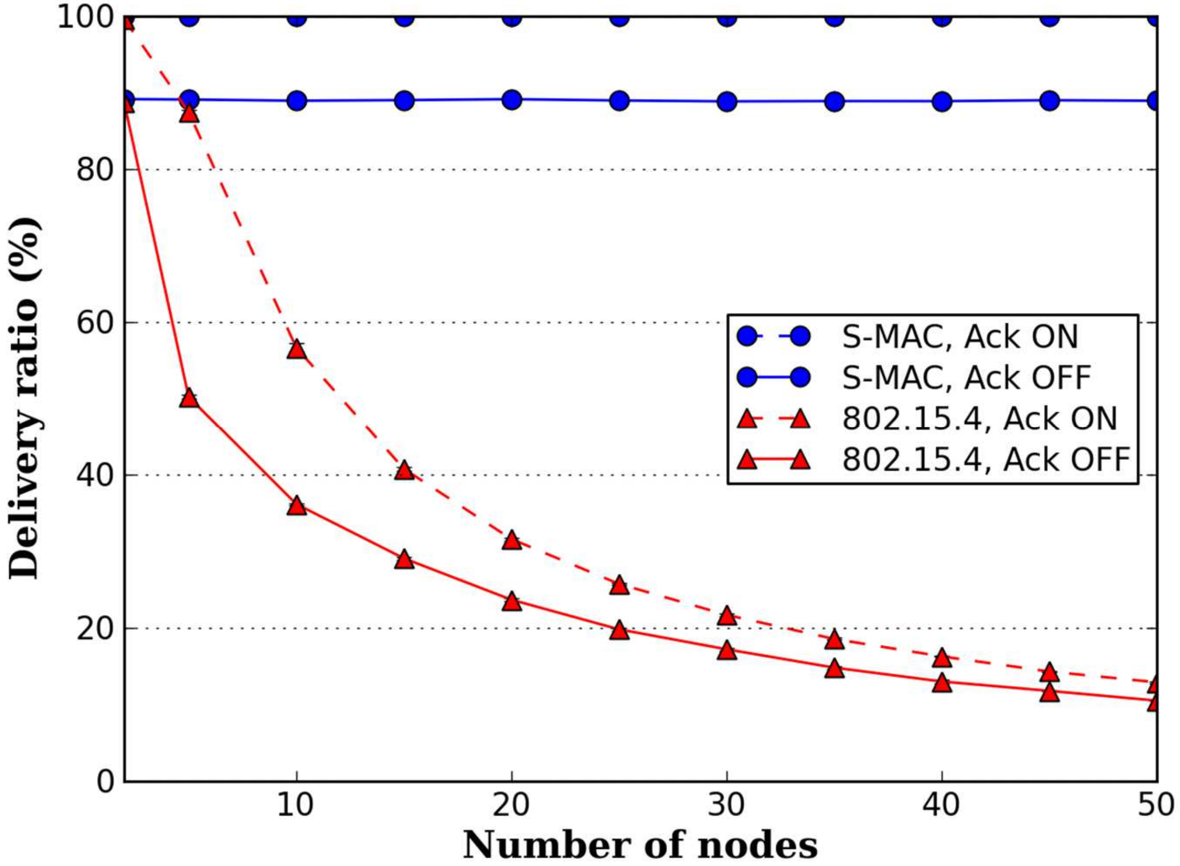
- The access method is CSMA-CA
  - Contention increases with the # of active nodes
- The periodic Beacon synchronizes nodes' accesses
  - *All* sensor nodes contend for channel access upon receiving a beacon

How about other CSMA-based MAC protocols operating in same conditions?

802.15.4 MAC vs. S-MAC



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CSMA/CA parameters

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Parameter	2003 release	2006 release	Notes
macMaxFrameRetries	3 (*aMaxFrameRetries*)	**0÷7** **Default: 3**	Max number of re-transmissions
macMaxCSMABackoff	**0÷5** **Default: 4**	**0÷5** **Default: 4**	Max number of backoff stages
macMaxBE	**5** (***aMaxBE***)	**3÷8** **Default: 5**	Maximum Backoff Window Exp.
macMinBE	**0÷3** **Default: 3**	**0÷7** **Default: 3**	Minimum Backoff Window Exp.

CSMA parameter values

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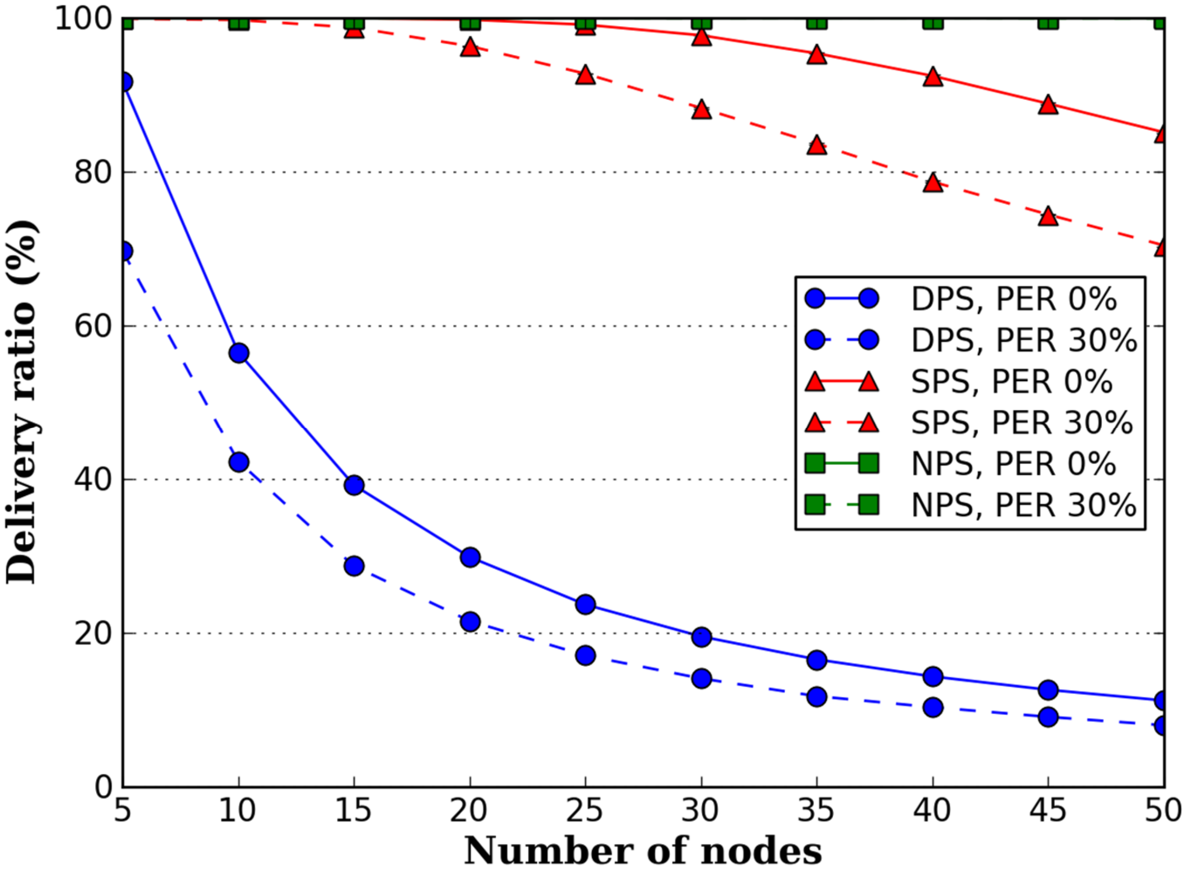
- *DPS (Default Parameter Set)*
  - Default parameter values defined in the standard
- *SPS (Standard Parameter Set)*
  - Larger parameter values allowed by the standard
- *NPS (Non-standard Parameter Set)*:
  - Larger parameter values not allowed by the standard

	macMinBE	macMaxBE	macMaxCSMABackoff	macMaxFrameRetries
DPS	3	5	4	3
SPS	7	8	5	7
NPS	8	10	10	10

Delivery Ratio vs. Packet Error Rate



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.

Latency and Energy vs. Packet Error Rate

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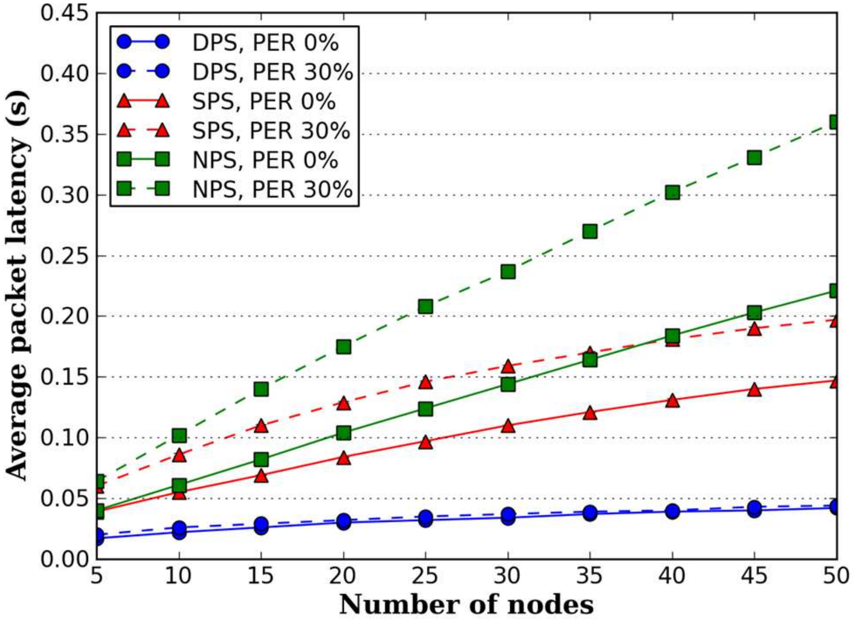
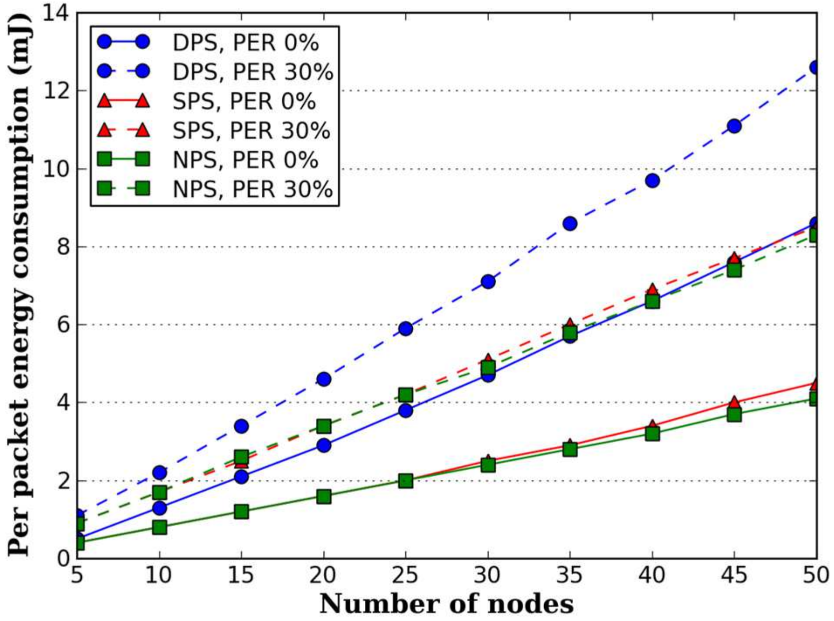
Avg. Latency



Energy/msg



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.

Learned Lesson

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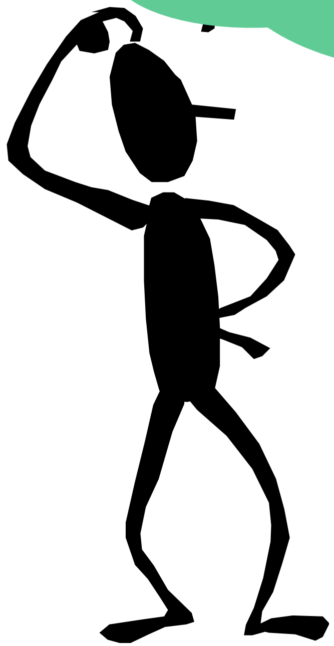
- MAC unreliability mainly due to CSMA/CA
- Periodic Beacons synchronize channel accesses
  - thus maximizing contention and increasing the collision probability
- Default MAC parameter values not appropriate
  - More appropriate settings can alleviate the problem
  - However the optimal setting depends on
    - ⇨ Applications requirements
    - ⇨ Operating conditions
    - ⇨ …

Enhancements

How to achieve the desired reliability level (e.g., 80%) with the minimum energy expenditure?



Strategies for Optimal Settings

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- Model-based offline computation [1]
- Model-based online adaptation [2]
- Measurement-based adaptation [3]
- Learning-based adaptation [4]

[1] P. Park, P. Di Marco, P. Soldati, C. Fischione, K. H. Johansson, **A Generalized Markov Chain Model for Effective Analysis of Slotted IEEE 802.15.4**, Proc. *IEEE International Conference on Mobile Ad Hoc and Sensor Systems* (*MASS 2009*). Macao, China, October 2009

[2] P. Park, P. Di Marco, C. Fischione, K. H. Johansson, **Modeling and Optimization of the IEEE 802.15.4 Protocol for Reliable and Timely Communications**, *IEEE Transactions on Parallel and Distributed Systems*, 2012.

[3] M. Di Francesco, G. Anastasi, M. Conti, S. K. Das, V. Neri, **Reliability and Energy-efficiency in IEEE 802.15.4/ZigBee Sensor Networks: An Adaptive and Cross-layer Approach**, *IEEE Journal on Selected Areas in Communications*, 2011.

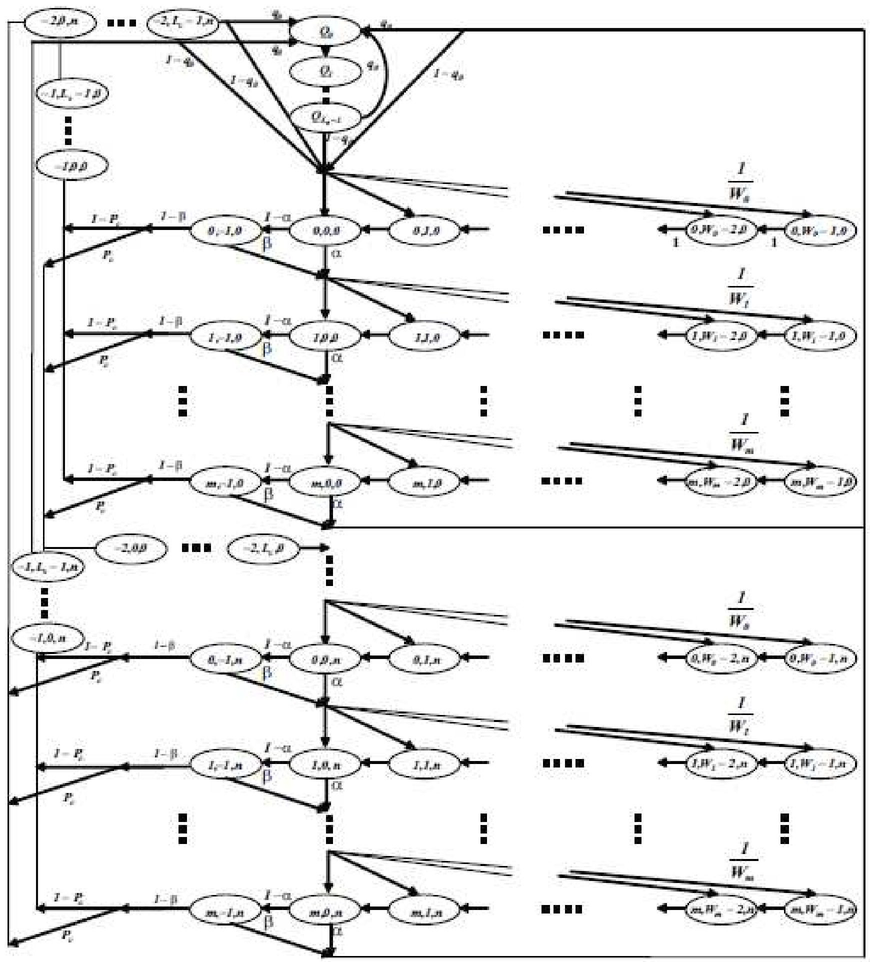
[4] S. Brienza, D. De Guglielmo, C. Alippi, G. Anastasi, G. Anastasi, M. Roveri, **A Learning-based Algorithm for Optimal MAC Parameters Setting in IEEE 802.15.4 Wireless Sensor Networks**, *Proc. ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN 2013),* Barcelona, Spain, November 3-7, 2013

Park's Model

Markov Chain Model

- **Assumptions**
  - Star network
  - Ideal channel
  - Fixed and known # of nodes
  - …
- **Reliability (*R*)**
- **Latency (*D*)**
- **Energy per packet (E_{tot})**

As functions of the 802.15.4 MAC parameters



P. Park, P. Di Marco, P. Soldati, C. Fischione, and K. Johansson, **A Generalized Markov Chain Model for Effective Analysis of Slotted IEEE 802.15.4**, *Proc. IEEE International Conference on Mobile Ad hoc and Sensor Systems (MASS 2009)*, October 2009, pp. 130 –139.

Model-based Offline Computation

Algorithm 1: Optimal MAC parameters

```
Input: Feasible range of MAC parameters (m0, m, n)
Output: m0*, m*, n*
begin
    currentObj ← ∞ ;
    V* ← V0 ;
    /* V* = [m0* m* n*], Current best                  */
    for m0 ← 3 to 8 do
        for m ← 2 to 5 do
            n ← f(m0, m) ;
            V ← [m0, m, n] ;
            if R(V) ≥ Rmin and D(V) ≤ Dmax and isrg(n)
            then
                /* isrg(n): Check validity of n.
                   */

                if currentObj > Etot(V) then
                    currentObj ← Etot(V);
                    V* ← V;
                    /* else; Solution is not
                       optimal.                          */

                /* else; Solution is not
                   feasible.                             */
end
```

Offline Algorithm

Provides the MAC parameters set that guarantees

- $(R \geq R_{min})$ & $(D \leq D_{max})$

while minimizing

- E_{tot}

Limits of Model-based Computation

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- Offline approach
- Requires to know the operating conditions of the sensor network
  - unsuitable for real environments
- Requires a significant amount of time
  - to solve the Park's model and derive the optimal MAC parameter setting
  - About 400s (i.e., around 7 minutes) with a quad-core PC

Model-based Adaptation

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Online Algorithm

- Estimates α, β, and τ through direct measurements
  - α: probability to find the channel busy during the first CCA
  - β: probability to find the channel busy during the second CCA
  - τ: probability that the node will attempt the first CCA in a generic backoff slot
- Introduces α, β, and τ in the Park's model
- Derives R, D and E_{tot}
  - for any MAC parameters set
- Selects the optimal parameter setting

P. Park, P. Di Marco, C. Fischione, K. H. Johansson, **Modeling and Optimization of the IEEE 802.15.4 Protocol for Reliable and Timely Communications**, *IEEE Transactions on Parallel and Distributed Systems*, 2012.

Limits of model-based algorithms

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- Effectiveness bounds to the model accuracy
  - Assumptions on packet arrival process typically does not fit real scenarios
  - The communication channel is never ideal
- Requires to know configuration parameters
  - They may change over time (e.g., # of sensor nodes)
- Unsuitable for multi-hop WSNs

Measurement-based Adaptation

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ADAPT: Adaptive Access Parameters Tuning

- Completely heuristic approach
- Provides the desired reliability with minimum energy consumption (and latency)
- Based on local measurements of unreliability
- No a-priori knowledge about operating conditions
  - Suitable for real-life scenarios

M. Di Francesco, G. Anastasi, M. Conti, S. K. Das, V. Neri, **Reliability and Energy-efficiency in IEEE 802.15.4/ZigBee Sensor Networks: An Adaptive and Cross-layer Approach**, *IEEE Journal on Selected Areas in Communications*, 2011.

AdAPT: Unreliability Measurements

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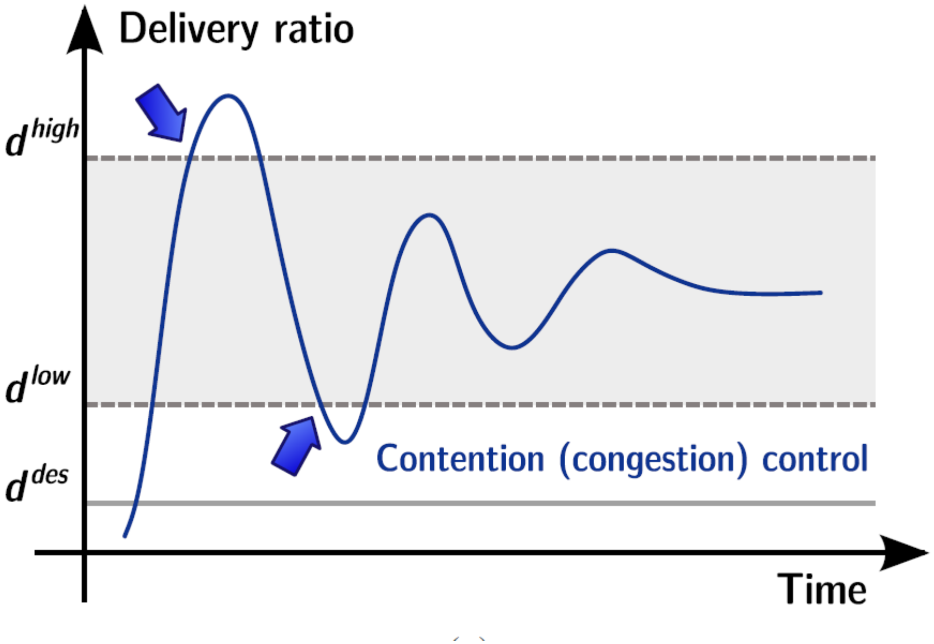
- Sources of message loss
  - Congestion (Contention)
  - Noisy channel (fading, interferences, …)

- Unreliability Measurements
  - Messages discarded due to exceeded # of backoffs
    - ⇨ congestion
  - Messages discarded due to exceeded # of rtx
    - ⇨ Channel errors
    - ⇨ Collisions (can be neglected in the considered scenario)

AdAPT: Adaptation Strategy



$$\hat{d}_i = \delta \cdot \hat{d}_{i-1} + (1 - \delta) \cdot d_i$$

Algorithm 1: Contention control scheme

if $\hat{d}_i < d^{low}$ **then**
  if macMinBE $<$ macMinBE^{max} **then**
    macMinBE++
  else if macMaxCSMABackoffs $<$ macMaxCSMABackoffs^{max} **then**
    macMaxCSMABackoffs++
else if $\hat{d}_i > d^{high}$ **then**
  if macMaxCSMABackoffs $>$ macMaxCSMABackoffs^{min} **then**
    macMaxCSMABackoffs−−
  else if macMinBE $>$ macMinBE^{min} **then**
    macMinBE−−

Limits of ADAPT

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- Oscillations
  - ADAPT tends to oscillate between adjacent sets
  - Thus consuming more energy than necessary
- Memory-less
  - ADAPT does not take advantage of a recurrent states

LEAP

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LEAP: *LEarning-based Adaptive Parameter* Tuning

- based on local measurements, like ADAPT
- does not require any input parameter
  - ⇨ it can be used in a real scenario
- learns the past history
  - ⇨ it can take advantage of recurrent states in the system
- behaves very close to an ideal algorithm

S. Brienza, D. De Guglielmo, C. Alippi, G. Anastasi, M. Roveri, **A Learning-based Algorithm for Optimal MAC Parameters Setting in IEEE 802.15.4 Wireless Sensor Networks**, Proceedings of *ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN 2013),* Barcelona, Spain, November 3-7, 2013.

LEAP Algorithm

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- LEAP selects the optimal parameters setting
  - using the knowledge learned in the past history.

- LEAP algorithm
  - Exploration Phase
    - ⇨ An adaptive approach is used to set CSMA-CA parameters
    - ⇨ Sensor node builds a Learning Table using the knowledge learned during the Exploration phase.
    - ⇨ Then it enters the Exploitation phase
  - Exploitation Phase
    - ⇨ Sensor node checks the Learning Table to derive the optimal setting, given the current operating conditions.

Performance Comparison

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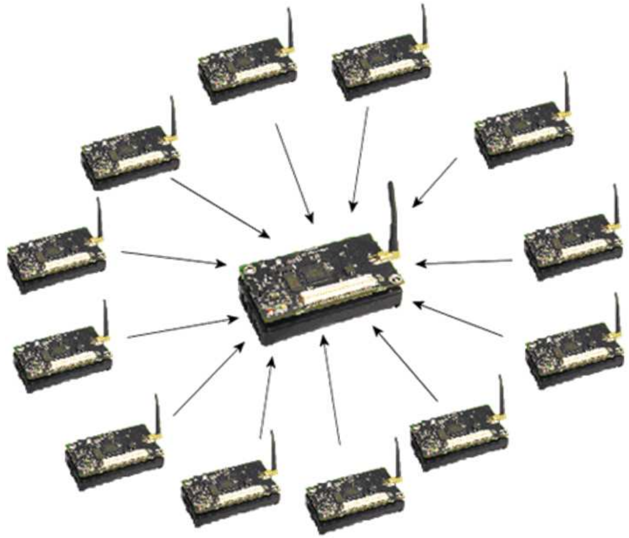

PHY layer	2.4 GHz
Bit Rate	250 Kbps
Sensor nodes	from 1 to 50
Distance from Coordinator Node	10m
CS range	30m
RX range	15m
Traffic Generation	Periodic
Message Size	100 bytes
Messages per Period	10
Message Loss Rate	0-%
Coordinator always ON	

Performance Measures

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- **Packet Delivery Ratio**

  ratio between # of packets correctly received by the sink, and the total # of packets generated by all sensor nodes.

- **Miss ratio**

  fraction of times when the packet delivery probability – calculated over the current Beacon Interval – drops below the threshold required by the application

- **Average Energy per Packet**

  total energy consumed by each sensor node divided by the # of data packets correctly delivered to the sink.

- **Average Latency**

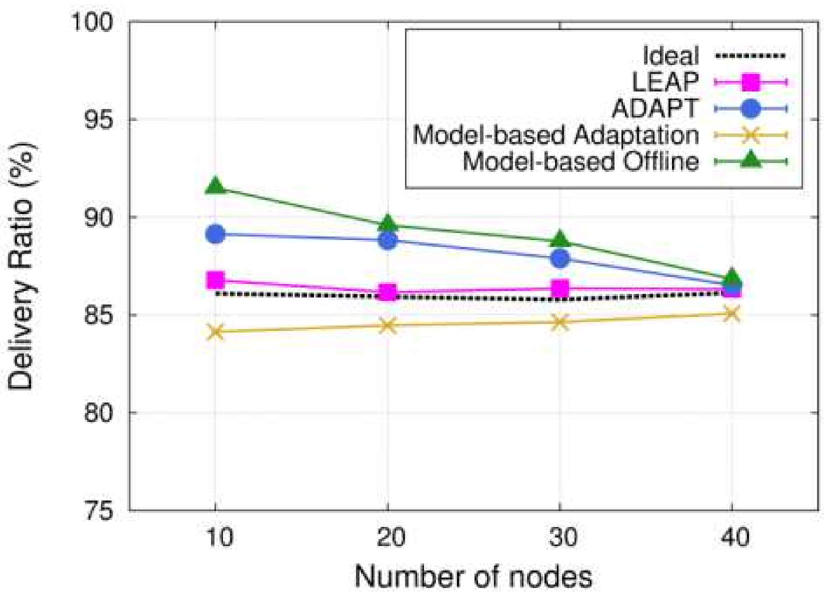
  average time from when the packet transmission starts at the source node to when the packet is correctly received by the sink

Performance in Stationary Conditions

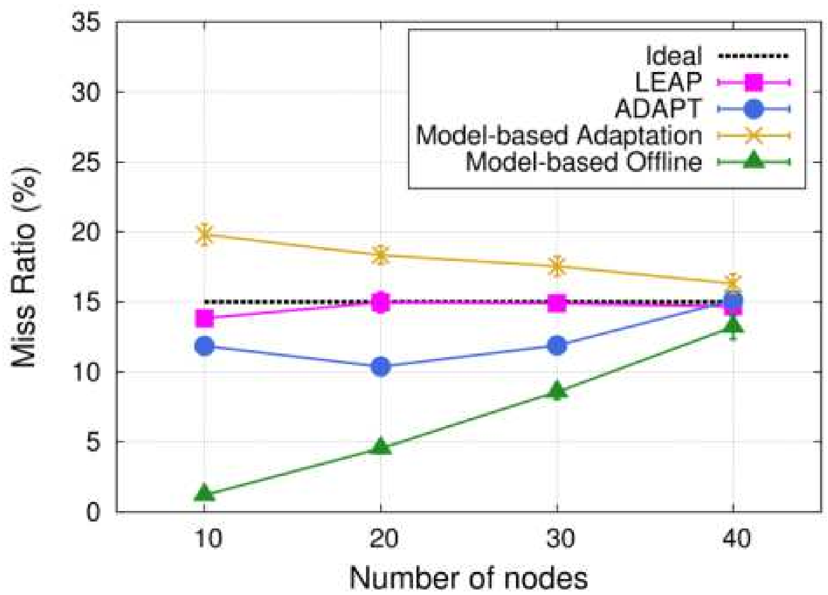
Requirements

- Delivery Ratio: > 80%
- Miss Ratio: < 15%

Delivery ratio (%)

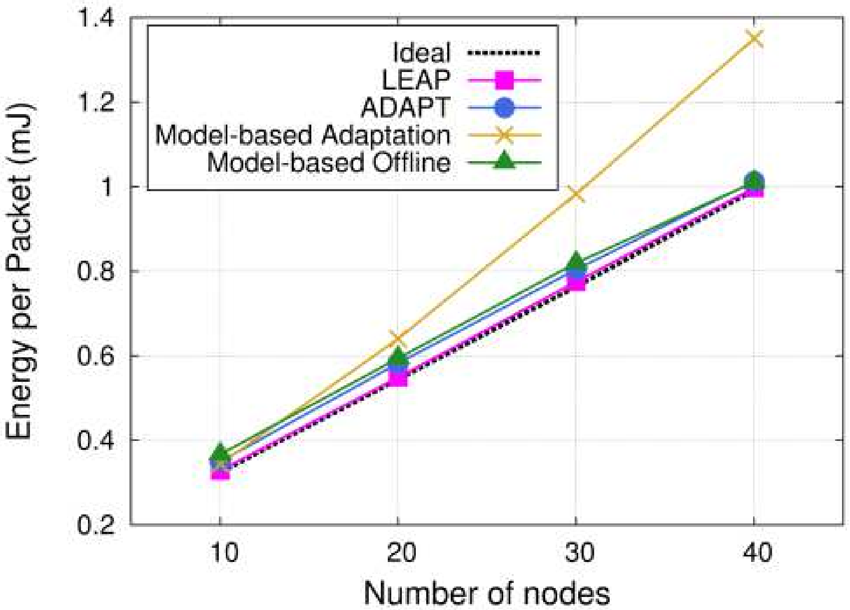


Miss Ratio (%)

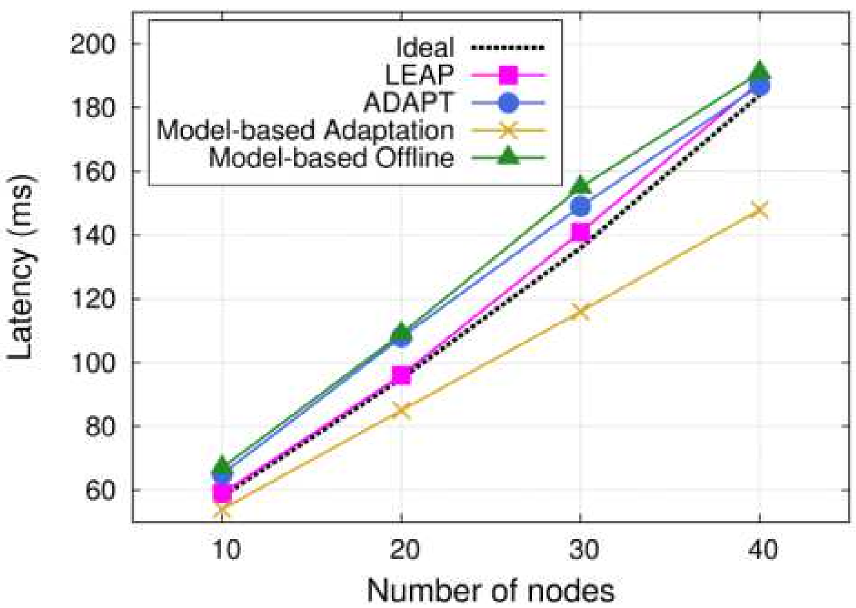


Performance in Stationary Conditions

Energy per packet (mJ)



Latency (ms)



Summary

- The desired reliability can be achieved
  - Through an appropriate CSMA/CA parameter setting
- At the cost of
  - Increased energy consumption
  - Increased latency

Other limits of 802.15.4

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- 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 failure due to interferences and multi-path fading

Limits of 802.15.4/ZigBee

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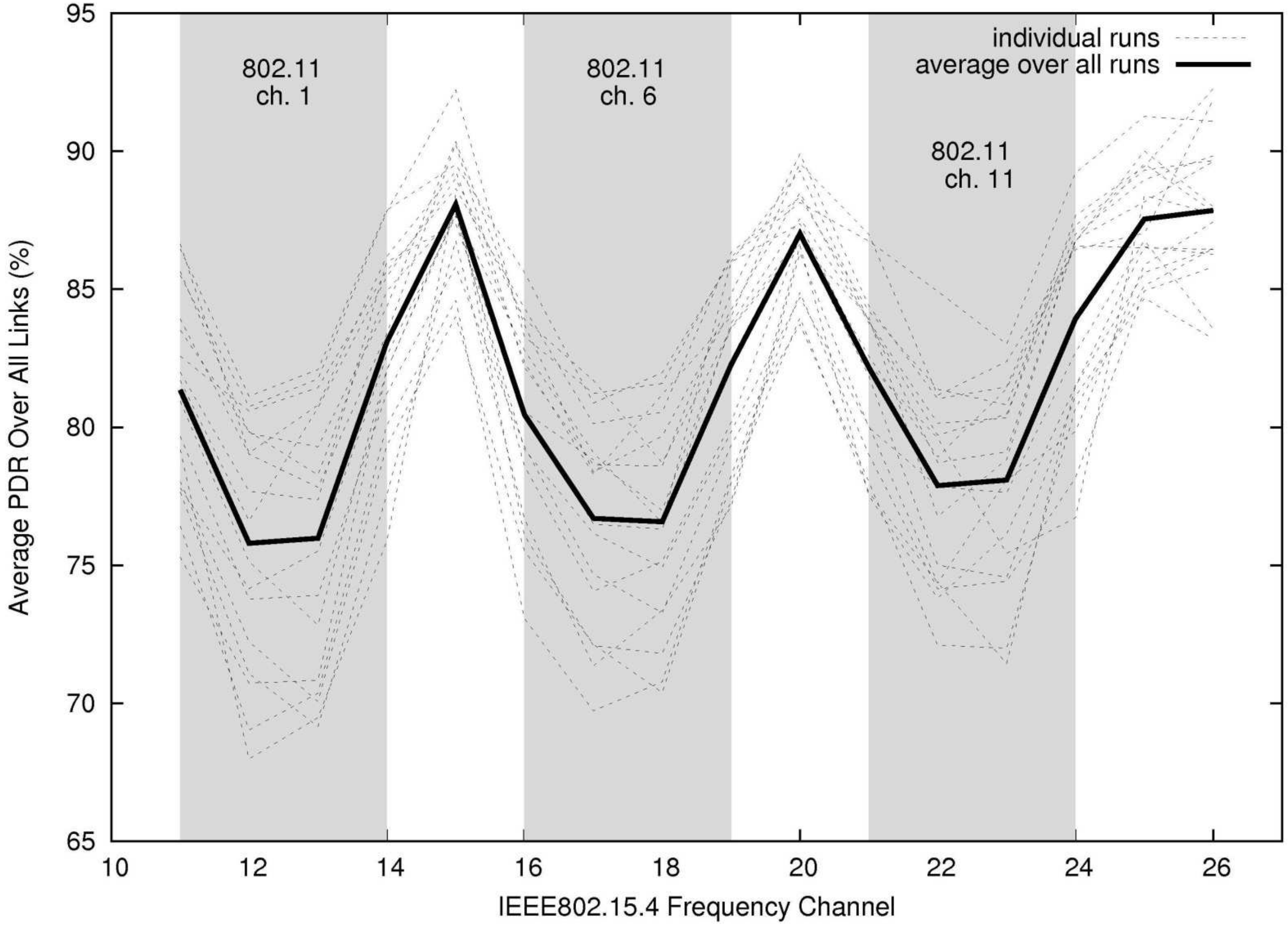
- Unbounded latency
  - Due to contention-based CSMA/CA algorithm
- No guaranteed bandwidth
  - Unless GTS is used
  - GTS only provides a limited service (7 slots)
- No built-in frequency hopping technique
  - Prone to failure due to interferences and multi-path fading

Link Reliability vs. Channel



Connectivity traces were collected by J. Ortiz and D. Culler in a UC Berkeley office space (traces are made available at http://wsn.eecs.berkeley.edu/connectivity/). 46 IEEE802.15.4-compliant TelosB motes are deployed in a 50m by 50m indoor environment, and are constantly listening for packets. One after the other, each mote transmits a burst of 100 packets, with a 20ms inter-packet time and a transmission power of 0dBm, on each of the 16 frequency channels which span the 2.4-2.485GHz band.

Channel Hopping

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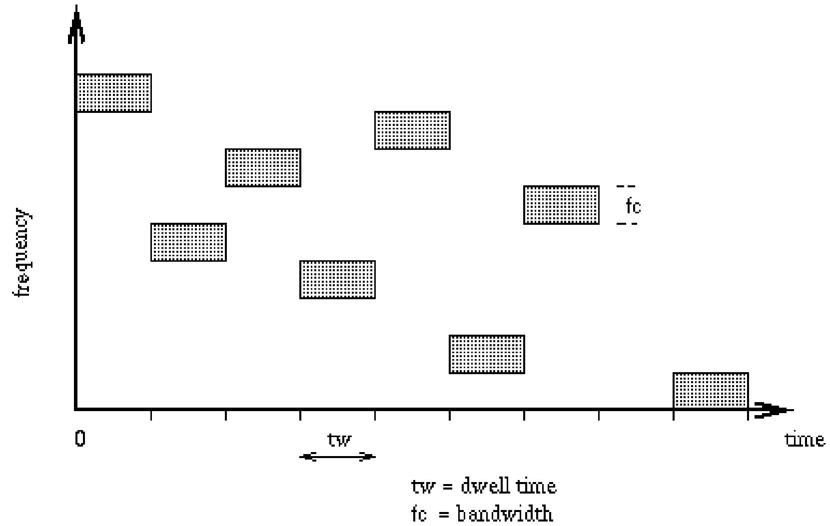
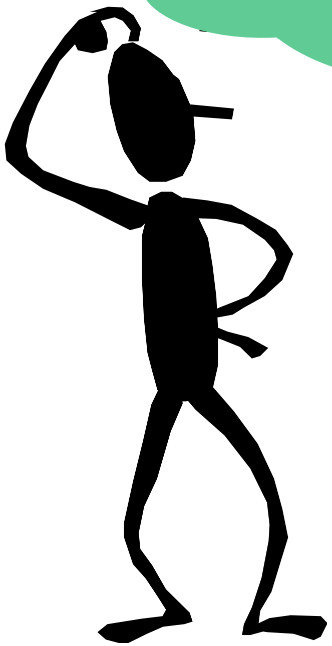
- Subsequent packets are sent at a different frequency
  - following a pseudo-random hopping pattern.
- If a transmission fails, retransmission will happen on a different frequency
- Greater chance of successful transmission
  - that if the retransmission happened on the same channel
  - Since a different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



Key Question

What to do in critical scenarios?



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 functionality to the 802.15.4-2006 MAC
    - ⇨ better support the industrial markets
    - ⇨ permit compatibility with modifications being proposed within the Chinese WPAN.
  - 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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- MAC Behavior Modes
  - support of specific application domains
- General functional improvements
  - not tied to any specific application domain.

Comment:

Many ideas taken 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

PerLab

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

MAC Behavior Modes

PerLab

- *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

Deterministic & Synchronous Multi-channel Extension (DSME)

PerLab

- DSME networks run on Beacon-enabled PAN
- All devices synchronize to multi-superframe via beacon frames
- Multi-superframe enhances GTS in 802.15.4
  - By grouping multiple superframes
  - and extending single channel operation to multi-channel operation
    - ⇨ either by adapting (switching) channels or by hopping channels.
- A pair of peer devices wakes up at a reserved GTS slot to exchange a data frame and an ACK frame.

Low Latency Deterministic Network (LLDN)

PerLab

- Target: factory and process automation
  - automotive robots, machine tools, milling/turning/ robot
  - Very low and deterministic latency (e.g., 5-50 ms)
- Designed for small networks and small frames
  - Operates in *star* topology
- LLDN MAC uses a *superframe,* based on time slots, to provide determinism
  - beacon timeslot
  - management timeslots (if present)
  - base transmission timeslots (of equal length)
    - ⇨ The base timeslots include uplink timeslots and bidirectional timeslots.

Low Latency Deterministic Network (LLDN)

PerLab

- Group Acknowledgement (GACK) slots
  - Configured to promote the retransmission of failed tx in uplink timeslots.
- Two categories of base timeslots
  - Dedicated timeslots
    - ⇨ The slot owner has access privileges in dedicated timeslots
  - Shared timeslots
    - ⇨ devices assigned to a shared timeslot use the contention-based access method.

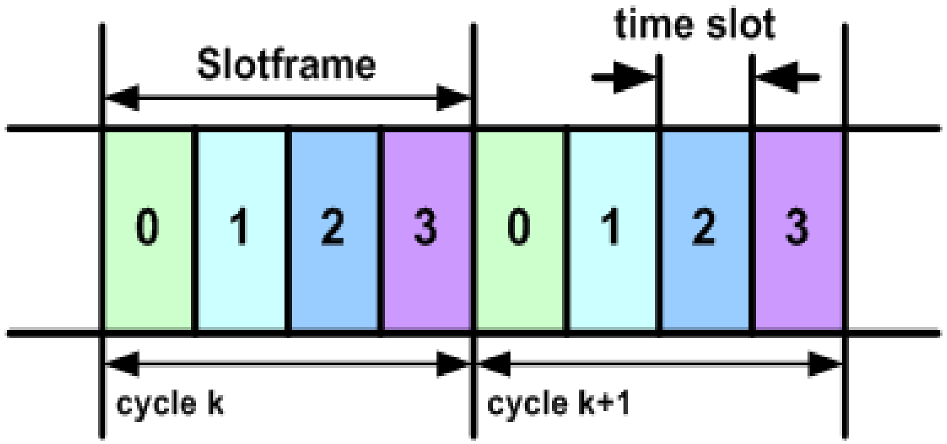
Time Slotted Channel Hopping (TSCH)

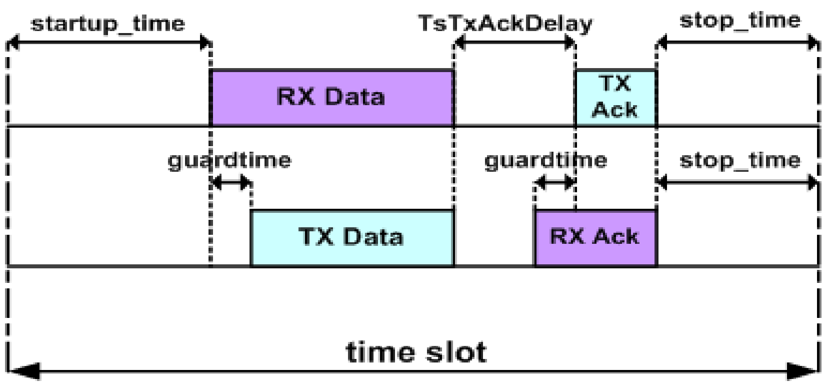
PerLab

- Combines *time slotted* access, *multi-channel* communication and *channel hopping*
  - Particularly suitable for multi-hop 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 interference and multipath fading
  - improves reliability

Periodic Slotframe

During a timeslot, one node typically sends a frame, and another sends back an acknowledgement if it successfully receives that frame. If an acknowledgement is not received within the timeout period, retransmission of the frame waits until the next assigned transmit timeslot (in any active slotframe) to that address occurs.





Frequency Translation

PerLab

- The channel offset is translated in an operating frequency f

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

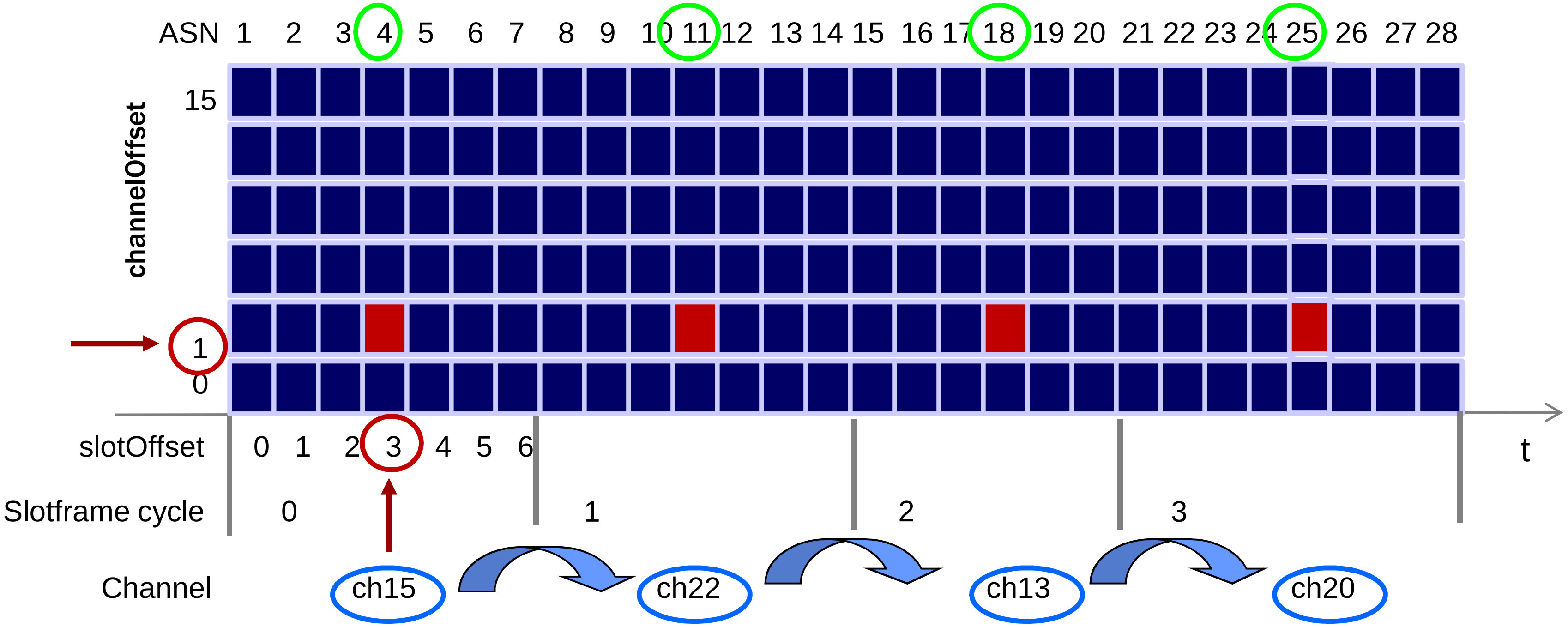
  - ASN: total # of slots that elapsed since the network was deployed
    - ⇨ $ASN=(k \cdot S+t)$ *where* S *is the slotframe size,* k *the slotframe cycle*
  - n_{ch} : *number of used channels*
  - F is implemented as a look-up-table containing the sets of available channels

Frequency Translation

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

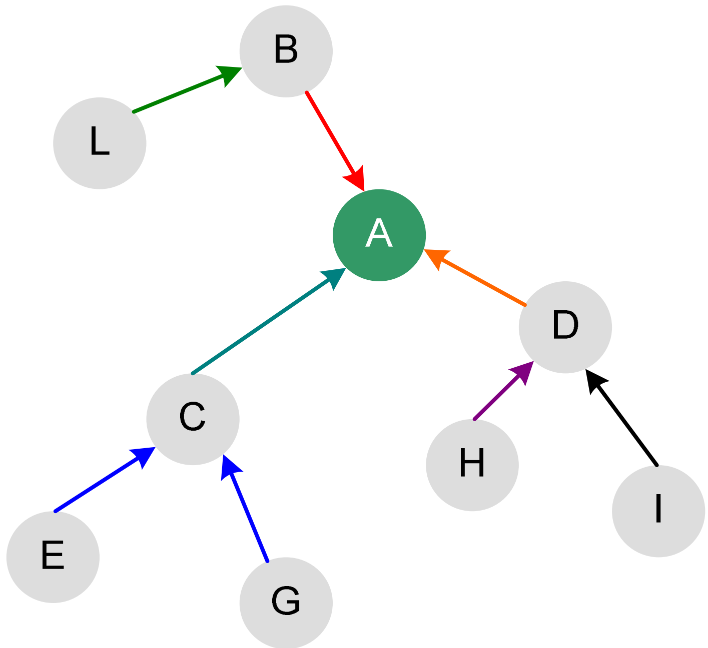
Table I. FrequencyTranslation

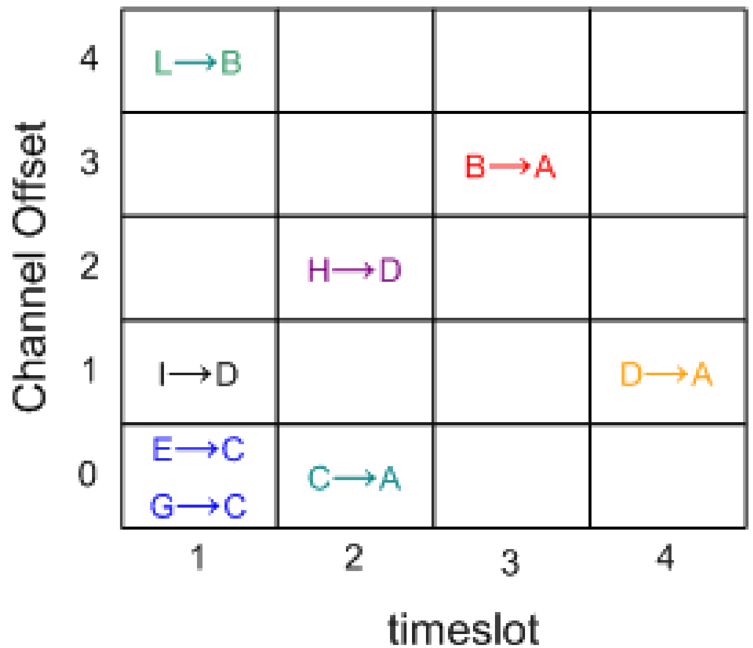
k	ASN	$chOf$	f
0	4	1	5
1	11	1	12
2	18	1	3
3	25	1	10



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





TSCH Scheduling

- The standard only explains how the MAC layer executes a schedule
  - it does not specify how such a schedule is built
- Centralized Scheduling
  - a *manager node* is responsible for building and maintaining the network schedule
- Distributed Scheduling
  - No central entity
  - Each node decides autonomously

Centralized Scheduling

PerLab

- Every node regularly updates the manager with
  - the list of other nodes it can hear
  - the amount of data it is generating
- The manager draws the *connectivity graph*,
- *assigns* slots *to* different links in the graph
  - Based on data generation demands
- and *informs* each node about links in the schedule it is participating in.
  - ⇨ If the connectivity graph changes (i.e., a node lost a neighbor), *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**. *IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2012)*, pp. 327-332, 2012

Distributed Scheduling

PerLab

- Each node decides locally on which links to schedule with which neighbors.
- Suitable for highly dynamic networks
  - e.g., networks with mobile nodes
  - or when the network has many gateway nodes
  - centralized schedules are known to be superior to distributed ones for fairly static networks

P. Zand, A. Dilo, and P. Havinga, **D-MSR: A distributed network management scheme for real-time monitoring and process control applications in wireless industrial automation**, Sensors, vol. 13, no. 7, pp. 8239–8284, 2013.

Accettura, N., Palattella, M. R., Boggia, G., Grieco, L. A., & Dohler, M., **Decentralized Traffic Aware Scheduling for multi-hop Low power Lossy Networks in the Internet of Things"**. In *IEEE International Symposium and Workshops on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2013)*, 2013.

Tinka, A., Watteyne, T., & Pister, K., **A decentralized scheduling algorithm for time synchronized channel hopping**. *Ad Hoc Networks*, pp. 201-216, Springer Berlin Heidelberg (2010)

Network Formation Protocol

PerLab

- Advertiser nodes emits *Enhanced Beacons* (EBs) at regular times
- EBs are special TSCH frame 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

Network Formation Protocol

PerLab

- A joining device starts scanning for possible EBs.
- Upon receiving an EB from an advertiser node
  - 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 can start advertising, on its turn

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

Advertising Policy

PerLab

Random Advertisement Protocol

- Each node is assigned a link $[timeslot, channelOffset]$ for EB advertisement
- Timeslots devoted to EB advertisement repeat periodically
  - with period T_{EB} (T_{EB} and N_c are assumed to be relatively prime)
  - All nodes use the same slot, possibly with different channel offset
- Each advertiser node transmits its EB, using the scheduled link, with a probability p_{EB}
- p_{EB} is derived autonomously by each node
  - so as to minimize the collision probability
  - $p_{EB} = 1/N_{neighbors}\,(channelOffset)$

D. De Guglielmo, A. Seghetti, G. Anastasi, M. Conti, **A Performance Analysis of the Network Formation Process in IEEE 802.15.4e TSCH Wireless Sensor/Actuator Networks**, Proc. *IEEE International Symposium on Computers and Communications (ISCC 2014),* Madeira, Portugal, June 23-26, 2014.

Some results

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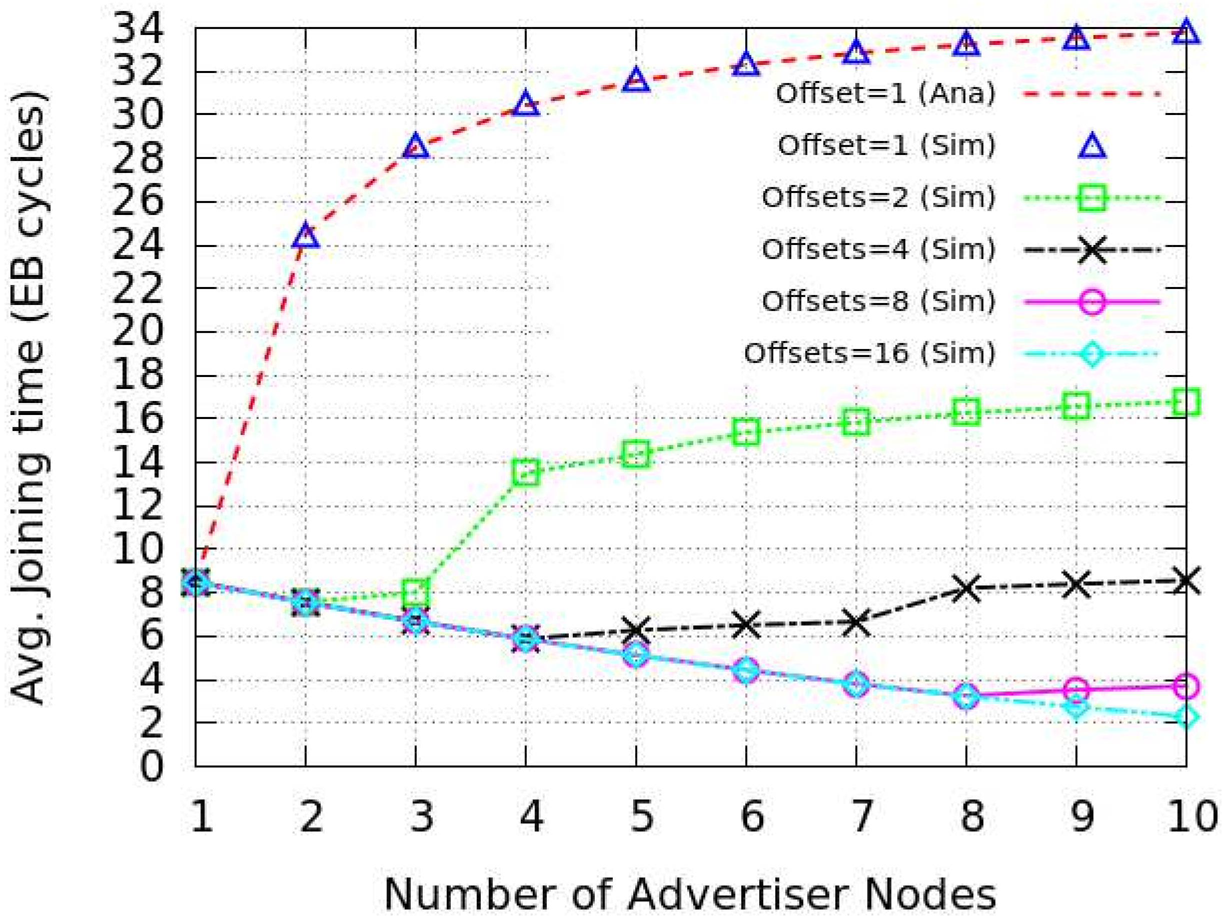
Average Joining Time vs. Number of Links used for EBs



Conclusions

PerLab

- IEEE 802.15.4 suffers many performance limitations ...
  - in terms of both delay and packet dropping probability
  - due to the CSMA-CA access method and default parameter values
- ... and is vulnerable to fading and interferences
- IEEE 802.15.4e overcomes the previous limitations
  - To meet the requirements of industrial and time-constrained applications
  - TSCH combines
    - ⇨ Time-slotted access
    - ⇨ Multi-channel communication
    - ⇨ Frequency hopping

Open Research Issues

- Link Scheduling Algorithm
  - Centralized vs. distributed
- EB Advertisement protocol
  - for network formation
- Interaction between TSCH and IoT protocols
  - Interactions between TSCH and RPL
  - IETF 6TiSCH standardizes mechanisms for running an IPv6-enabled protocol stack on top of TSCH.

Additional Info on IEEE 802.15.4e and 6TiSCH

PerLab

- IEEE 802.15 WPAN™ Task Group 4e (TG4e), [Online], http://www.ieee802.org/15/pub/TG4e.html

- http://datatracker.ietf.org/wg/6tisch/charter/

- 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. Pages 135-152. January 2014. Springer. Also available at: http://info.iet.unipi.it/~anastasi/papers/book-lo-re-10.pdf

Questions