REAL-TIME NETWORKS Real-Time Wireless Industrial Networks

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Outline

- Introduction
- IEEE 802.15.4e
- Wireless HART
- 6TiSCH and IETF proposals
- Link quality issues
- Conclusion

Introduction

- Industry does not like probabilistic approaches
  - One of the main reasons is certification
  - Tendency to use periodic traffic

- A number of pure TDMA solutions have been proposed
  - To IEC: WirelessHART, ISA 100.11a, WIA/PA, WIA/FA
  - To IETF: 6TiSCH
  - In scientific papers: RT-WiFi

IEEE 802.15.4e

- Amendment to IEEE 802.15.4
- Main innovations
  - 3 pure TDMA options (LLDN, TSCH, DSME)
  - 2 low energy options
    - one similar to WiseMAC (CSL: coordinated sampled listening)
    - receiver initiated transmissions (RIT)
  - Information Elements (IEs)
    - Together with multipurpose frames and enhanced beacons

Time Synchronized Channel Hopping - TSCH

- Fixed duration time slots (value is left to implementer)
  - Enough for sending one packet and receiving ack
- No superframe, no regular beacon, general topology
  - Each node has the notion of slotframe (repetition period) for each piece of information it sends or receives

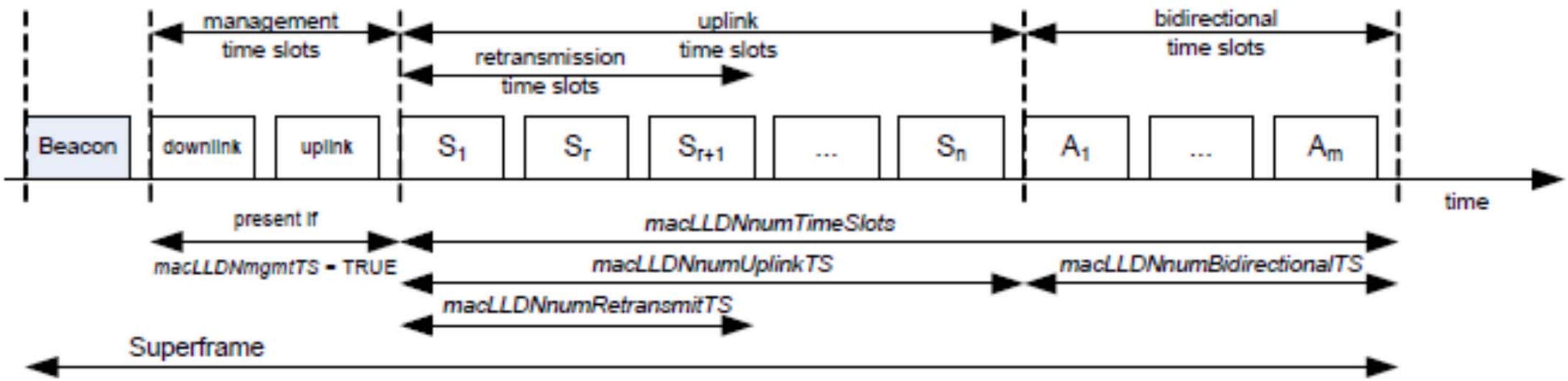
	ASN=0	ASN=1	ASN=2	ASN=3	ASN=4	ASN=5	ASN=6	ASN=7	
Slotframe 1 5 slots	TS 0	TS 1	TS 2	TS 3	TS 4	TS 0	TS 1	TS 2	...
Slotframe 2 3 slots	TS 0	TS 1	TS 2	TS 0	TS 1	TS 2	TS 0	TS 1	...

Source: IEEE 802.15.4 std

- See also [Deji Chen 2014]

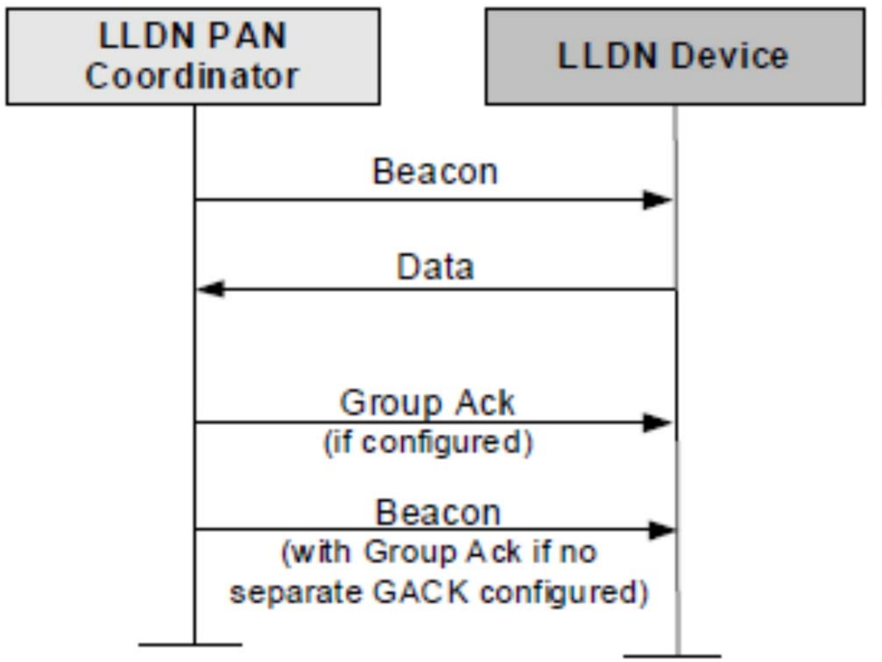
Low Latency Deterministic Networks - LLDN

- Star network with a single coordinator
  - Send the beacon in the first slot of the superframe
  - All other slots are assigned to nodes
    - Some may be assigned to multiple nodes (shared)
    - Slot type (uplink or bidir) is indicated in beacon
    - No ack in slot but in next beacon / slots reserved for retries dyn. alloc



LLDN group ack

- No immediate ack after transmission



- Slots for retransmissions allocated in a distributed manner

LLDN (cont.)

- Slot size

$$t_{TS} = (p \cdot sp + (m+n) \cdot sm + IFS) / v$$

with

- p number octets of the PHY header
- sp number of symbols per octet in PHY header
- m number octets for MAC overhead
- sm number of symbols per octet in PSDU
- n maximum number octets in data payload = Timeslot Size field value
- IFS = macSIFSPeriod symbols if m + n ≤ aMaxSIFSFrameSize octets, or macLIFSPeriod symbols if m + n > aMaxSIFSFrameSize octets
- v symbol rate

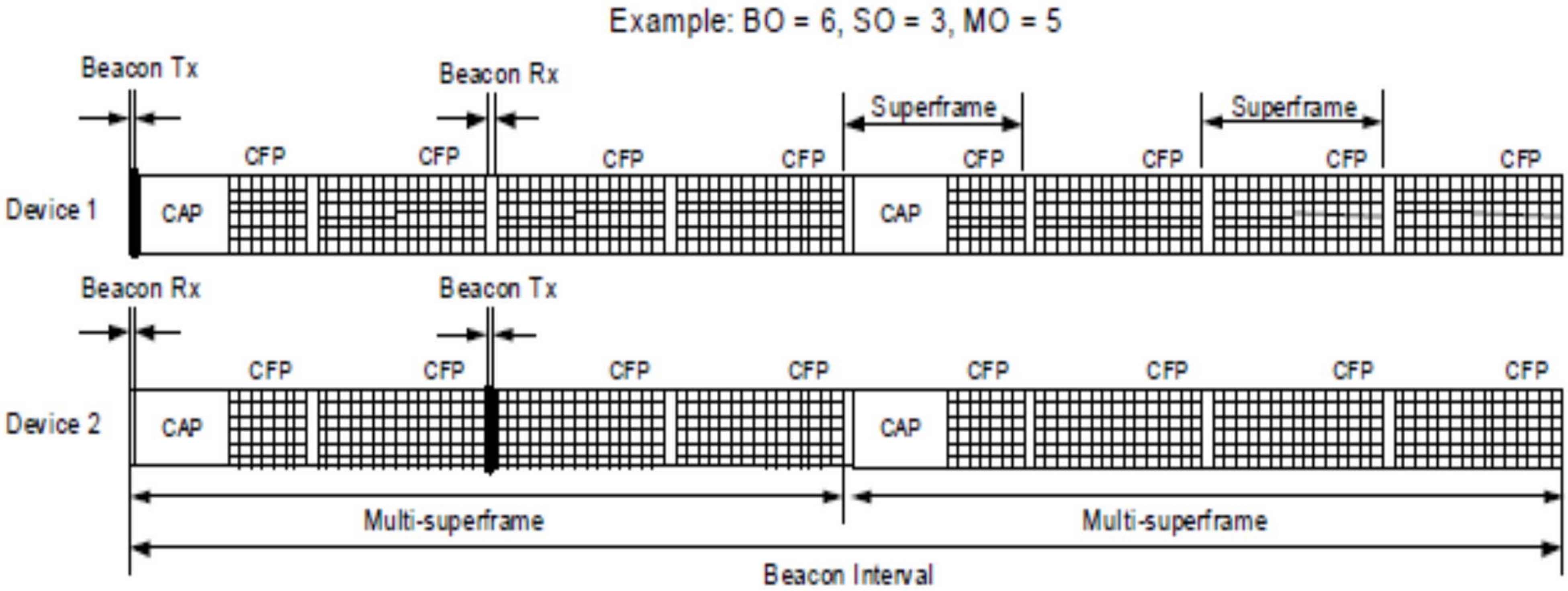
- Variable slot assignment is interesting

Deterministic and Synchronous Multi-channel Extension - DSME

- Multi-channel, multi-superframe, mesh extension to GTS for deterministic latency, flexibility & scalability
- Group acknowledgment option for high reliability and efficiency
- Distributed beacon scheduling and distributed slot allocation for robustness and scalability
  - Deferred beacon with offset indication
- Two channel diversity modes (channel adaptation and channel hopping) for robustness and high reliability even in dynamic channel conditions

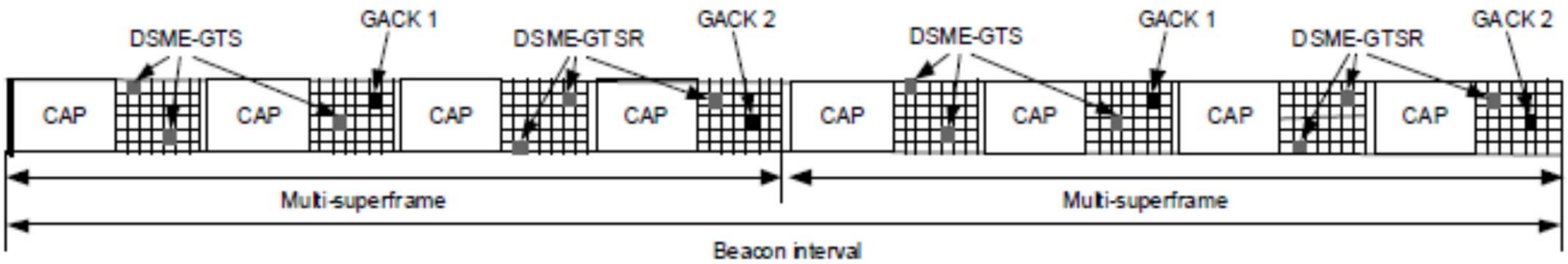
DSME (cont.)

- keeps the constraints established in 802.15.4-2011
  - 16 slots in any superframe



DSME retransmissions

- Slots may be reserved for group acks
  - GACK1 for all packets until then
  - GACK2 for all packets from GACK1 until then



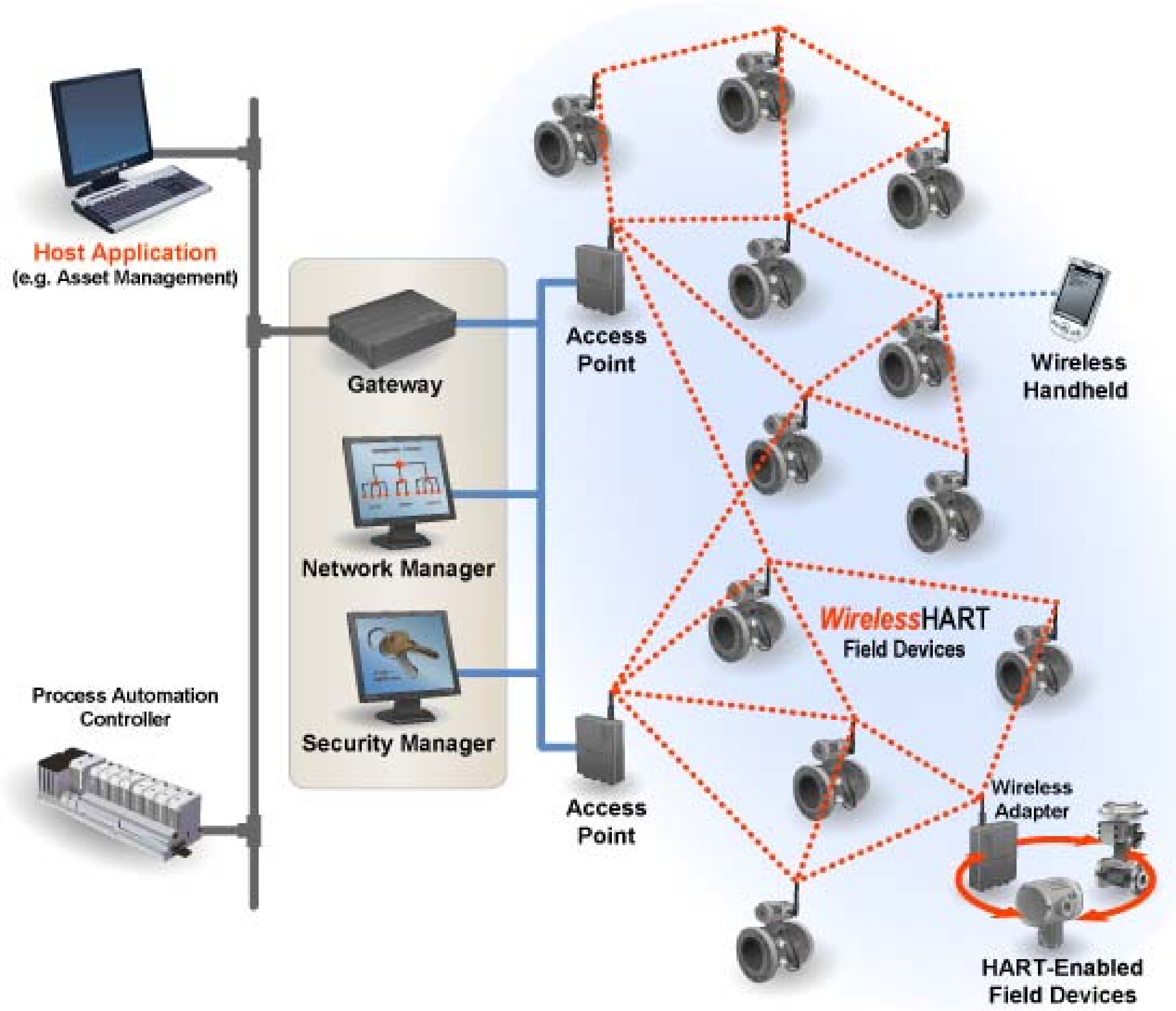
  - "The devices shall allocate an additional DSME-GTSR (i.e., GTS for Retransmission) per each allocated DSMEGTS for transmission to that coordinator"

Wireless HART

- Industry initiative (HART foundation)
- Provides a counterpart of HART using radio
- Meant for process control (rather slow)
- Now an international standard – IEC 62591
- Full solution (not only MAC)
- MAC similar to IEEE 802.15.4e TSCH
  - See [Deji Chen 2014] for the differences

Elements of a WHART network

- Field devices
  - Source
  - Sink
  - routers
- Security manager
- Network manager
  - Redundancy possible
- Gateway(s)
  - Access points



Wireless HART in short

- Uses IEEE 802.15.4 physical layer and PDUs
- TDMA MAC
  - Time and frequency diversity
  - 100 hops /s
  - Entirely configured from the network manager
- Mesh network with route redundancy
  - All field devices are possible routers
- Prioritized traffic possible
- Application layer compatible with HART
- Security based on AES-128

Physical Layer

- Physical layer: 802.15.4-2011
- Services
  - PH-CCA
  - PH-RECV-SD (start delimiter indication)
  - PH-DATA
  - PHM-SET/GET

Medium Access Control

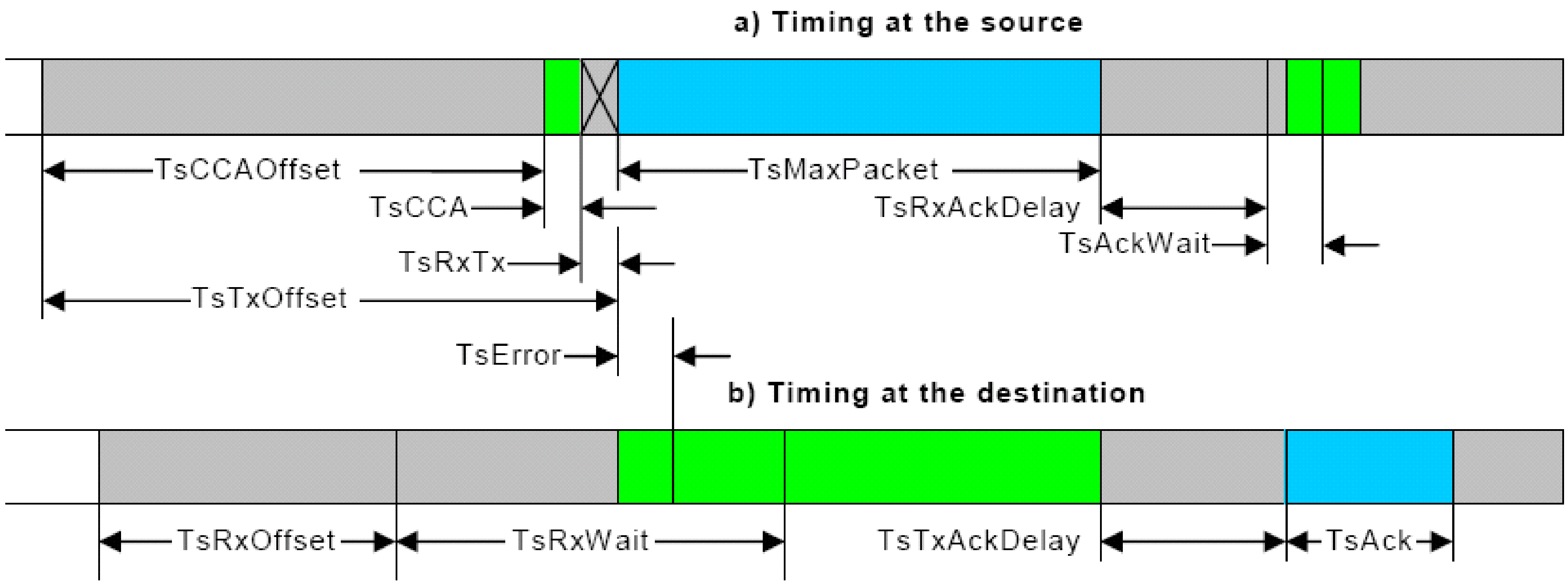
Frame 0 5 slots	TS0	TS1	TS2	TS3	TS4	TS0	TS1	TS2	TS3	TS4	TS0	TS1
Frame 1 3 slots	TS2	TS0	TS1	TS2	TS0	TS1	TS2	TS0	TS1	TS2	TS0	TS1

- TDMA
- One or more superframes of a fixed number of slots
- Channel hopping at each slot
  - There a list of used channels (same for all, some may be blacklisted)
    - 16 channels for 2.4 GHz operations
  - There is counter of the slot number since startup (ASN)
    - Active channel = (Channel-offset + Absolute Slot Nb) mod Nb_of_active_channels
- Slots (fixed size): Send / receive / shared / broadcast / join
- (superframe, slot #, channel offset) = link
  - Normal, broadcast, join, discovery
  - One or more links per device

Medium Access Control (2)

- Slot in superframe obtained by
  - SlotNb = ASN mod (Number_of_slots_in_superframe)
  - There might be more than one link in a given slot
    - Belong to different superframes
    - Transmit has priority over receive
- Rules in case more than one packet is to be sent in a given slot
- Slots may be with one source or shared
  - Shared slots are accessed using CSMA/CA
- Each device maintains a list of neighbors
  - Keep_alive and advertise PDUs

Time slot



- TsMaxPacket = 4.256 ms
- Max. 7.3ms used (43% efficiency)

Traffic specifications

- Timetables
  - For periodic transfers
    - Specifies transfer period on a connection
    - End-to-end latency is assumed not to exceed 1/3 of period
  - For sporadic (intermittent) transfers
    - Specifies maximum end-to-end latency
  - Used to filter traffic
    - Traffic that exceed what is in time table will be rejected
- Slots are assigned by NM

Traffic scheduling

- Defined in superframes
  - made of one or more slots
  - Collection of links assigned to time slots
  - One or more superframes
  - Superframe periods should follow an harmonic chain
  - Associated with a graph ID
- All superframes start at time 0+N.T (T = period)
- In case a node has to transmit (receive) on 2 or more slots at the same time, it elects the slot in the superframe with lowest ID

Traffic scheduling (2)

- A data transfer has one slot + 1 slot for retry + 1 slot on another path for 2nd retry
- There is a slot for each en-route device (router) + 2 slots for retries
- There is a management superframe (6400 slots)
  - Slots for keep_alive (3 slots each 15 minutes per node)
  - Slots for join request/resp + en-route relaying (no retry)
    - Shared with network management commands
  - Slots for ad-hoc request and response traffic (>=1 slot/min/device)
  - Special purpose slots (block transfers, hand held)
- Gateway superframe (40 slots, alternate tx/rx, shared)
  - All slots should be allocated (if no traffic then advertise)

Addressing

- Source + destination
- 8 bytes IEEE EUI 64
- Or 2 bytes unique address within a network
- 2 bytes network ID
- Broadcast address is 5 bytes long (all =0) ???

Data Link Layer

- Data receive service – DL_Receive (.ind)
- Data transfer service – DL-Transmit (.req, .ind., .cnf)
  - Includes retries / supports multicast and broadcast
  - May carry the next hop neighbors as param (graph)
  - If broadcast indicates superframe id to be used
- Event service (connect, disconnect, path failure,
- Management service (Set, Get, Action
- Security (no encryption but authentication)
- QoS
  - Priority (Command, process data, Normal, alarm)
    - Traffic below a given priority may be prohibited (Priority_Threshold)
  - timeout

DLE / NLE tables

- Superframe table
- Link table
  - Each link belongs to one and only one supeframe
- Neighbor table
  - Initialy sent by network manager, updated by the node
- Graph table
  - Next hop destinations for upward or downward traffic
  - Directed list of paths

DLL maintenance

- Discovery
  - Advertise DLPDU
    - ASN, graph ID, list of supeframes, list of links
    - Sent periodically using a random period between 0 to discovery_time
  - Keep Alive DLPDU
  - Nodes continuously listen for advertisements (in discovery links) and join requests
    - Update the neighbor list, Communicate list of neighbors to NM
- Time keeping
  - Some nodes are clock references
  - Nodes measure difference between expected receive time & effective one
    - Difference is transmitted in ack packets
    - Used by non reference nodes to adjust their clock

Network layer

- End to end security (3 keys: join, network mgr, gateway)
  - Activated by network management
  - Keys distributed by NM
- Transmit – NL-Transmit
- Management – SET/GET/Action
  - Action
    - Add/delete session, add/delete route, add/delete timetable, default route, reset

Routing

- Defined by network manager
- 4 types
  - Graph route
    - Any of the next hops indicated in the graph
    - Graph_ID selected by initial source device upper layers
  - Source route
    - Route is decided by source entity (contained in NPDU)
    - Used to test the routes
  - Broadcast
    - NL indicates superframe to be used (any broadcast slot in that superframe may then be used)
  - Proxy (joining device)

Graph routing

- Normal routing technique
- Multiple graphs in a single network
- Directed links
  - Graph is undirectionnal
- Redundant
  - Link is choosen localy for each NPDU. How ???
- NPDU conveys graph id
  - Each intermediate node must have the local view of the graph
  - This is stored in connection tables
- Superframe routing (superframe_id instead of graph_id)
  - Forwards to any neighbor that has a link in the superframe

Transport layer

- Data transfer
  - Unacknowledged – TL-DATA-Transfer
  - End-to-end acknowledged - TL-DATA-Exchange
    - No loss, duplication, reordering
    - Only one pending transaction at a time
  - There is a maximum time to complete and a maximum number of retries (TL parameter)
- Management
  - SET/GET

Acknowledged transport

- Uses pipes (optional for non ack)
  - Unicast data exchange slave with NM
  - Broadcast data exchange slave with NM
  - Unicast data exchange slave with gateway
  - Master for event notification to NM
  - Master for event notification to the Gateway

Time synchronisation

- Some nodes are time synchronisation sources
  - Used to synchronize the other devices
  - How are they synchronized ????
- Each device records the difference between the expected time of arrival and the actual one
  - This is used returned in the ack packet
  - This is used to correct local clock
- Keep_alive pdus may be used in case there is not enough traffic (max. each 30s)
  - 10 ppm clock drift per device

Application layer

- Client-server model
  - A number of services to access/modify variables and configuration
- Pre-defined basic types, structured types
- Rules for encoding variables and services
- Possibility to publish data (to client)
- Possibility for event notification (to client)

Data Types

- Fixed length
  - Integer8,16,24,32 - Unsigned8,16,24,32,40 - Float32,64
  - Data, Tim
  - Enumeration, Bit Field
  - Security Key, Unique ID, Engineering Unit
- String
  - Packet ASCII
  - ISO Latin-1
- Structure, Array
  - Nesting in allowed
- Encoding in defined in IEC 61158-6-20

Application Layer

- Virtual Field Device ASE
  - identity
- Variable ASE
  - Services to read/write variable objects + information report
- Action ASE
  - Read, write, reset, self-test,
- Device application services
  - Access and modify device attributes
- Layer management services
  - Set and read node parameters

Application relationship

- ARs are composed of a set of endpoints of compatible classes. One endpoint of each AR has to be Master class and the other end has to be Slave class.
- Each device can have only one instance of a Slave class AREP.
- A device can use more than one Master class AREP to communicate with several Slave class AREPs.
- The user at Master class AREP provides the identification of the Slave class AREP as a parameter in the request primitive.

Conclusion on Wireless HART

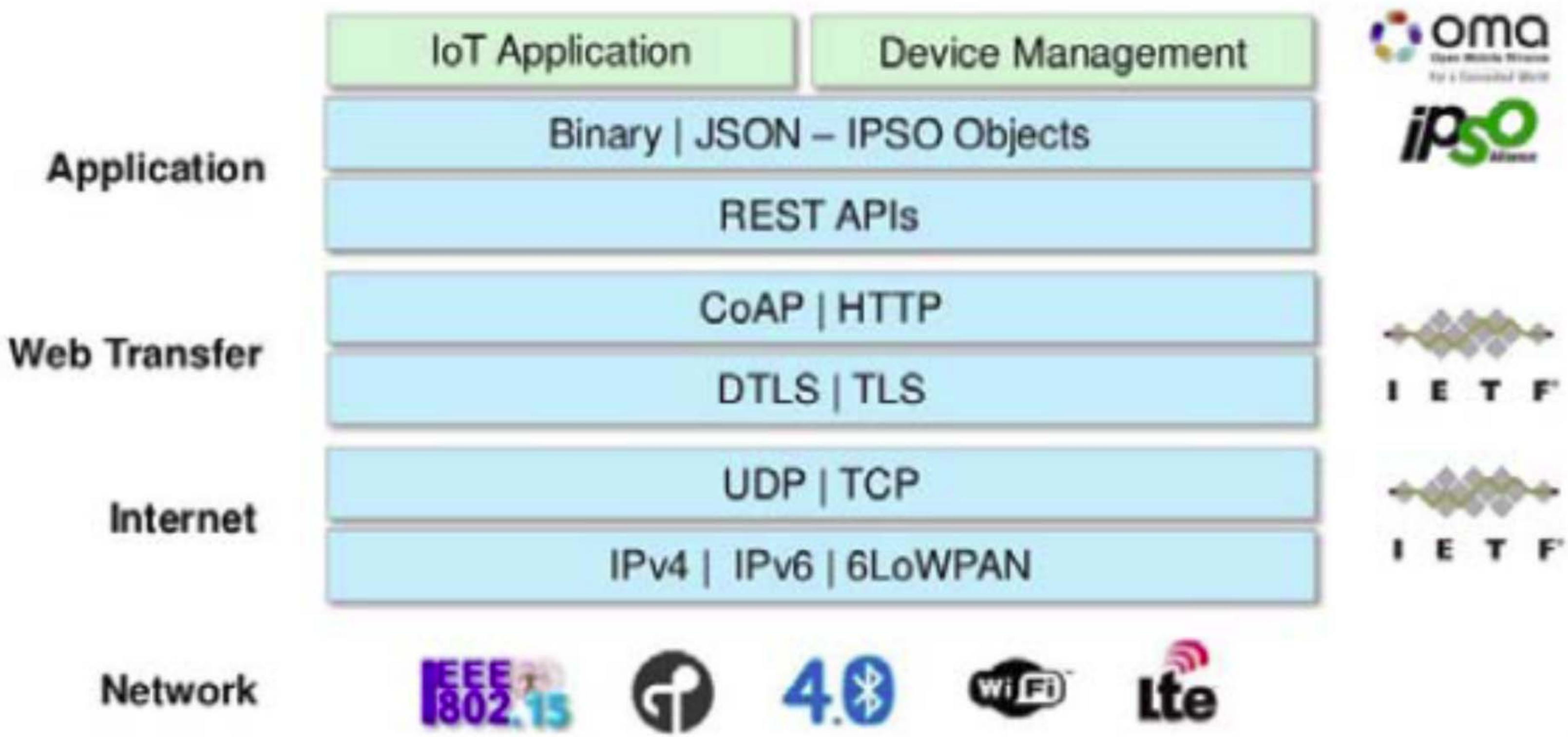
- pros
  - A complete solution
  - Good robustness to interferences and errors
    - Route diversity, retransmissions, channel hopping
- Cons
  - Complex (difficult to schedule)
  - Rather inefficient (fixed size slots, resources allocated for 2 retries)
  - Centralized (single sink)

Wireless HART References

- IEC 62591 Ed. 1.0: Industrial communication networks – Wireless communication network and communication profiles – WirelessHART™, document IEC 65C/587/FDIS
- S. Han et al, Reliable and Real-Time Communication in Industrial Wireless Mesh Networks, IEEE RTAS 2011, pp. 3-12
- Deji Chen et al. WirelessHART and IEEE 802.15.4e, IEEE ICIT, pp. 760-5, 2014.

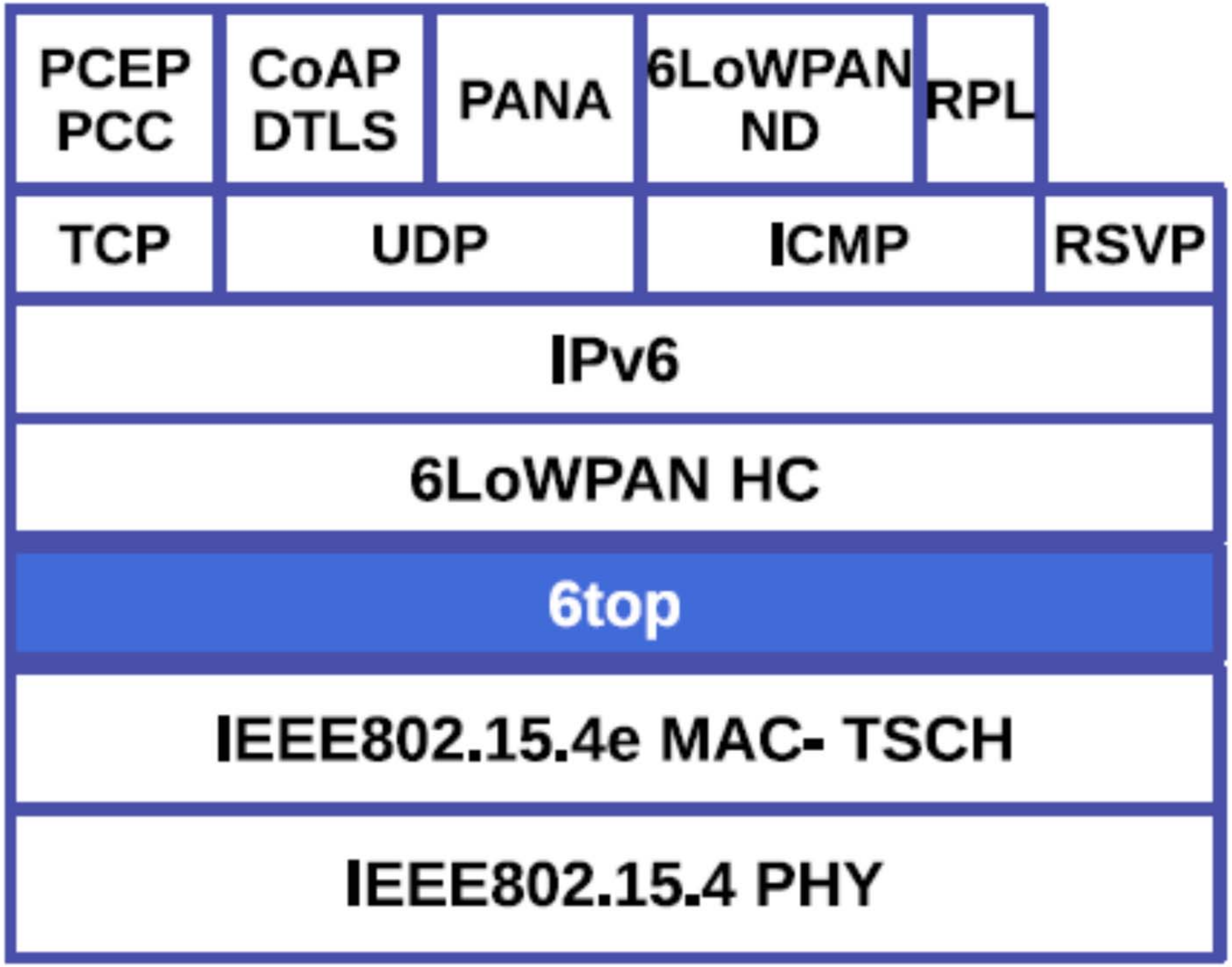
Internet Engineering Task Force

- Low-power lossy networks: CoAP, RPL, 6LoWPAN



Source: http://postscapes.com/internet-of-things-protocols#graphics

IETF & 6TiSCH



Source: Palattella, 2016

From System Engineering Guidelines IEC 62591 WirelessHART, Engineering Guidelines 00809-0100-6129, Rev AB, February 2016

- It is recommended that wireless field devices used for control and high speed monitoring have a higher path stability than general monitoring devices with updates slower than two seconds.
- Path Stability is the measure of successfully transmitted messages on any given path relative to the attempted transmissions. General requirements are 60 percent path stability, but 70 percent is recommended for control and high speed monitoring. The addition consideration provided in this text ensures higher path stability that can be confirmed once the network is deployed. Most WirelessHART vendors provide the means to verify after installation.

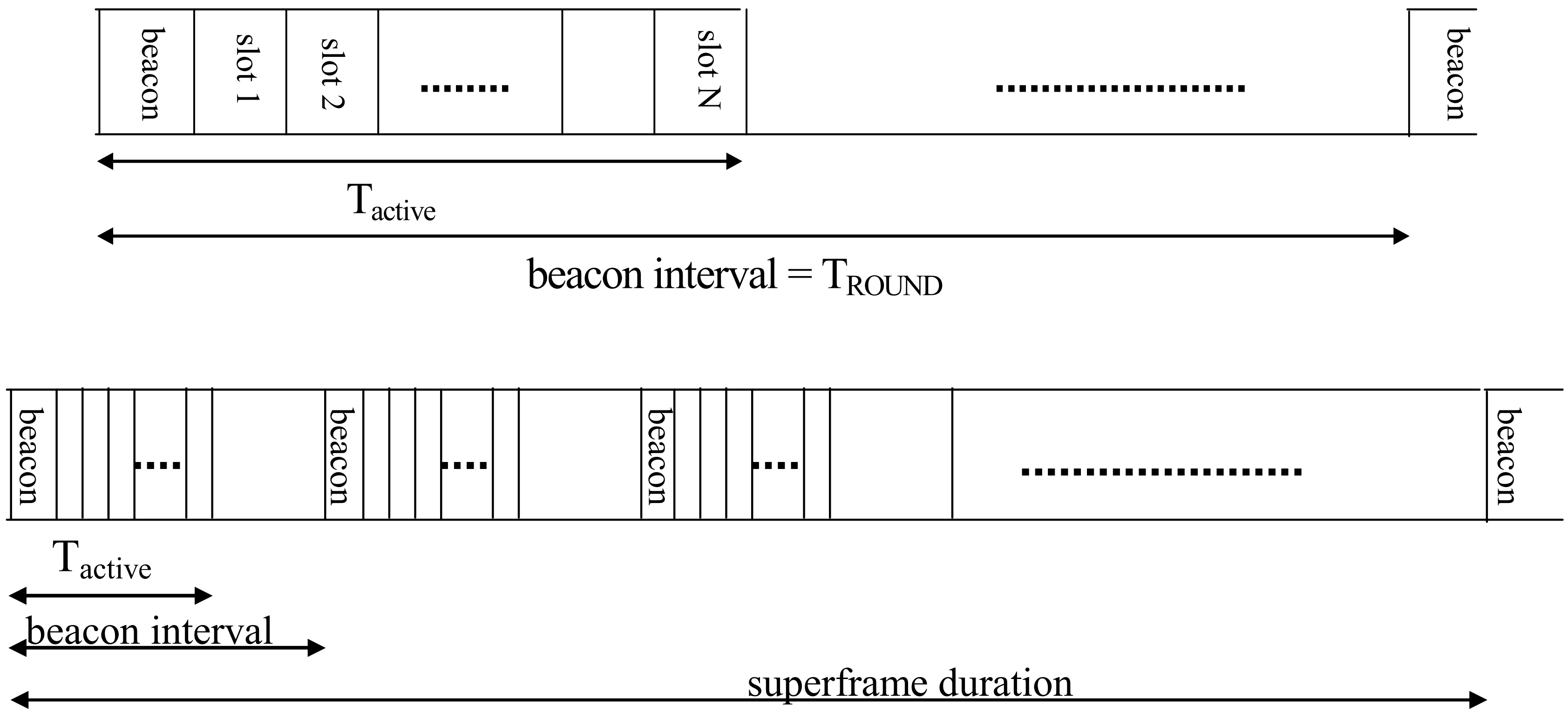
Conclusion on industrial solutions

- Having a good protocol is considered as not sufficient
- It is necessary to install the devices (or at least the antennas) so that links are good and stable

- But, what if we cannot have good links ?

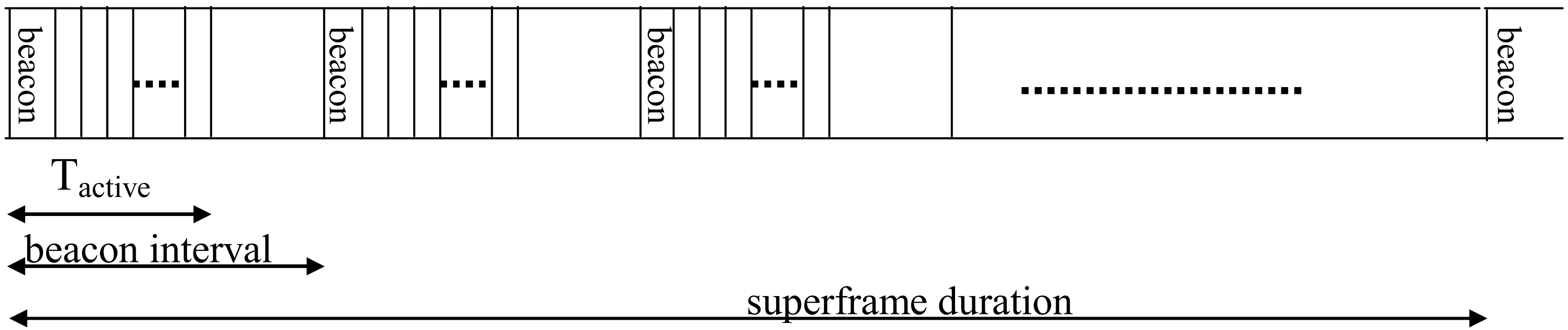
Retransmission scheme

- Wireless transmission prone to errors (e.g. BER 10-4)
- Having an efficient retransmission scheme is important



Retransmission schemes

- Assign slots for retries in a fixed manner
  - 1 slot for transmission and KR slots for retry (in KR beacon interval)

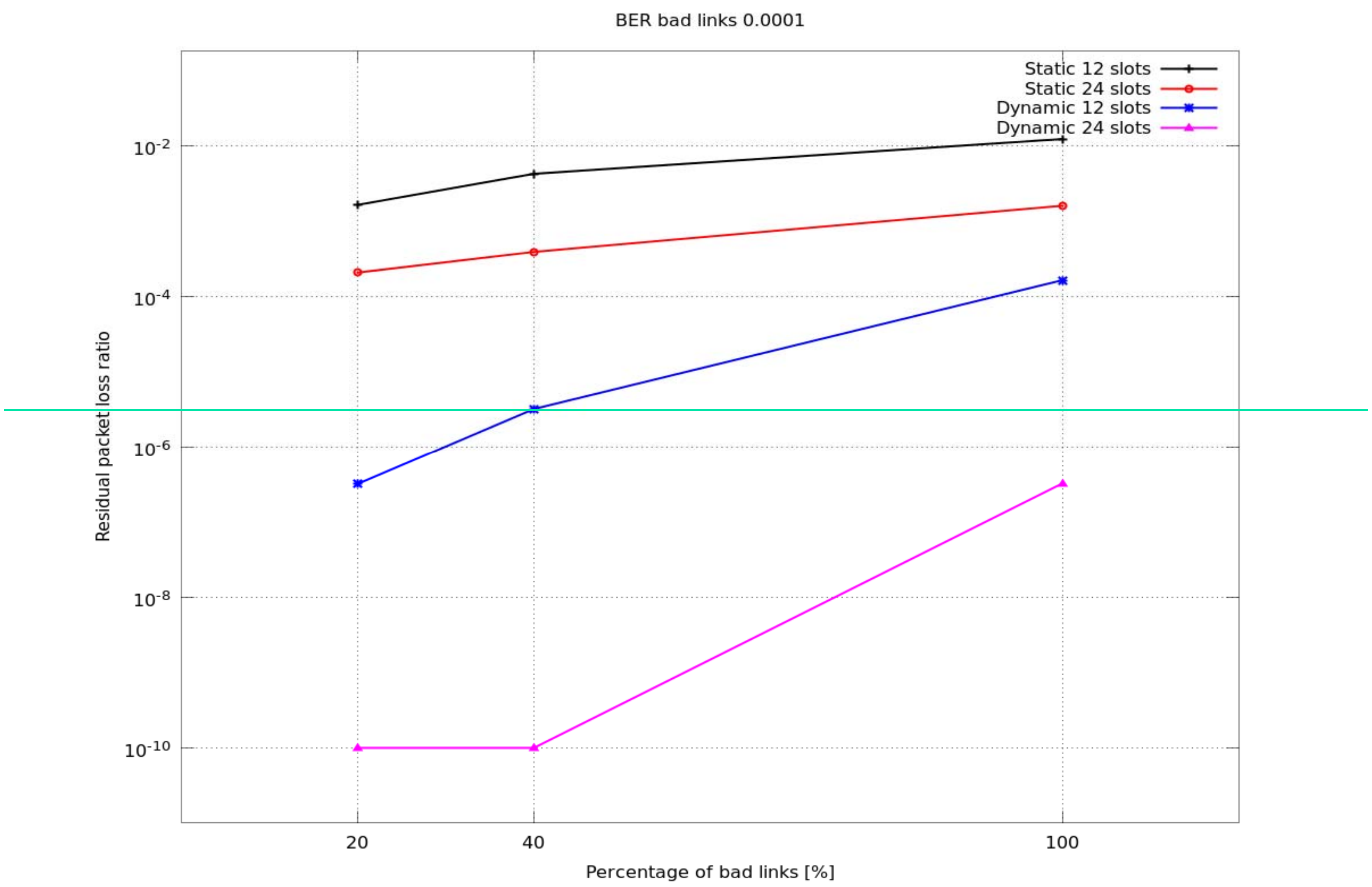


- Assign slots for retries in a dynamic manner
  - In each beacon interval, there are NSR slots for retries
  - The slots are assigned dynamically to recover from failures in previous beacon interval

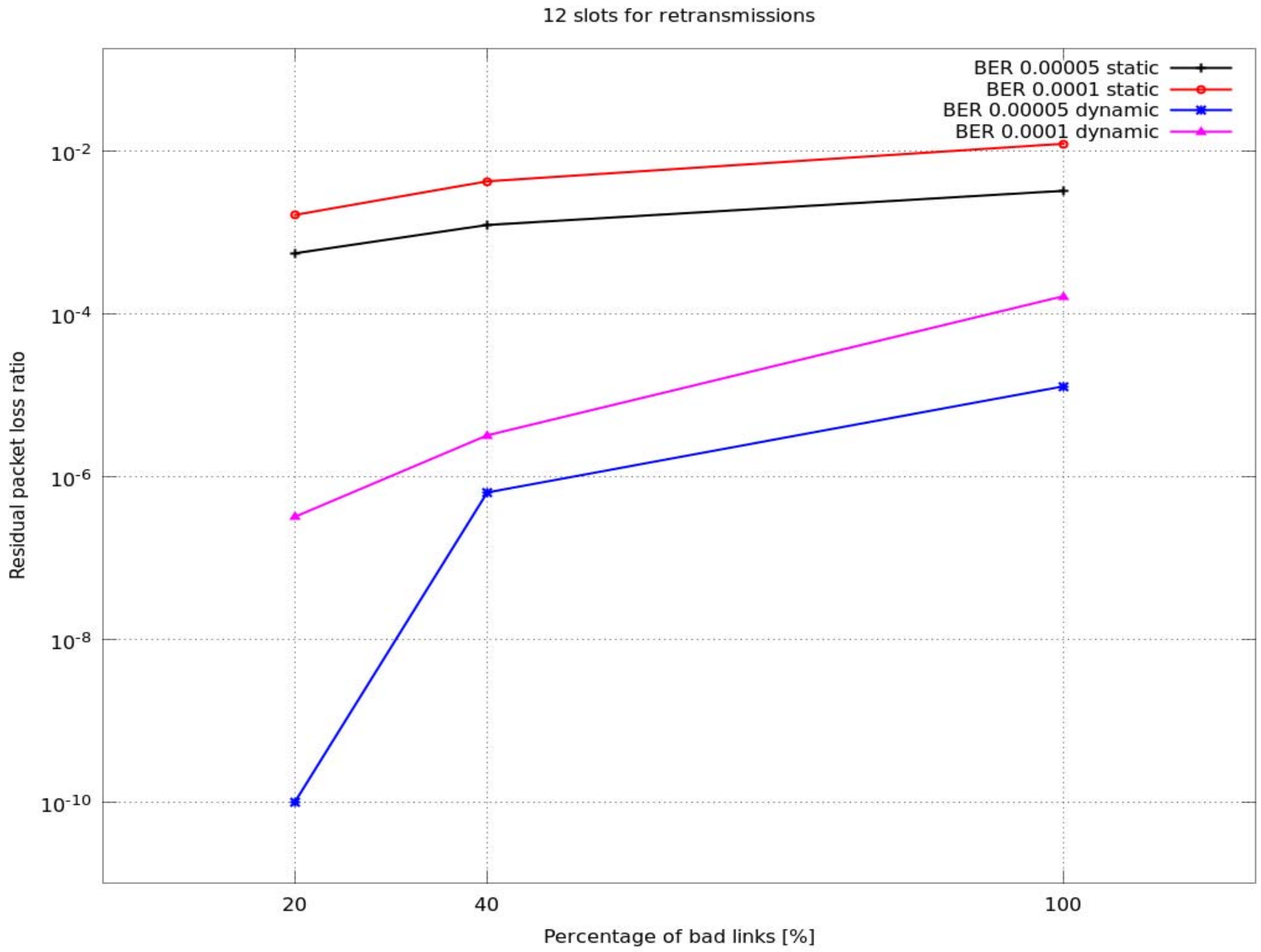
Parameters

- slot time = 150 µs, 127 Byte packet size
- Application period (superframe duration) = 12 ms
- Beacon interval: TROUND=3 ms
- Number of sensor nodes: N=12.
  - 12 slots in the 1st beacon interval in addition to the beacon.
- IR-UWB packet: PHY bitrate:
  - 1 Mb/s for the short preamble, 27 Mbit/s for the data.
- good links that have a BER of 10-6
- bad links that have a BER varying from 5.10-5 to 10-4.

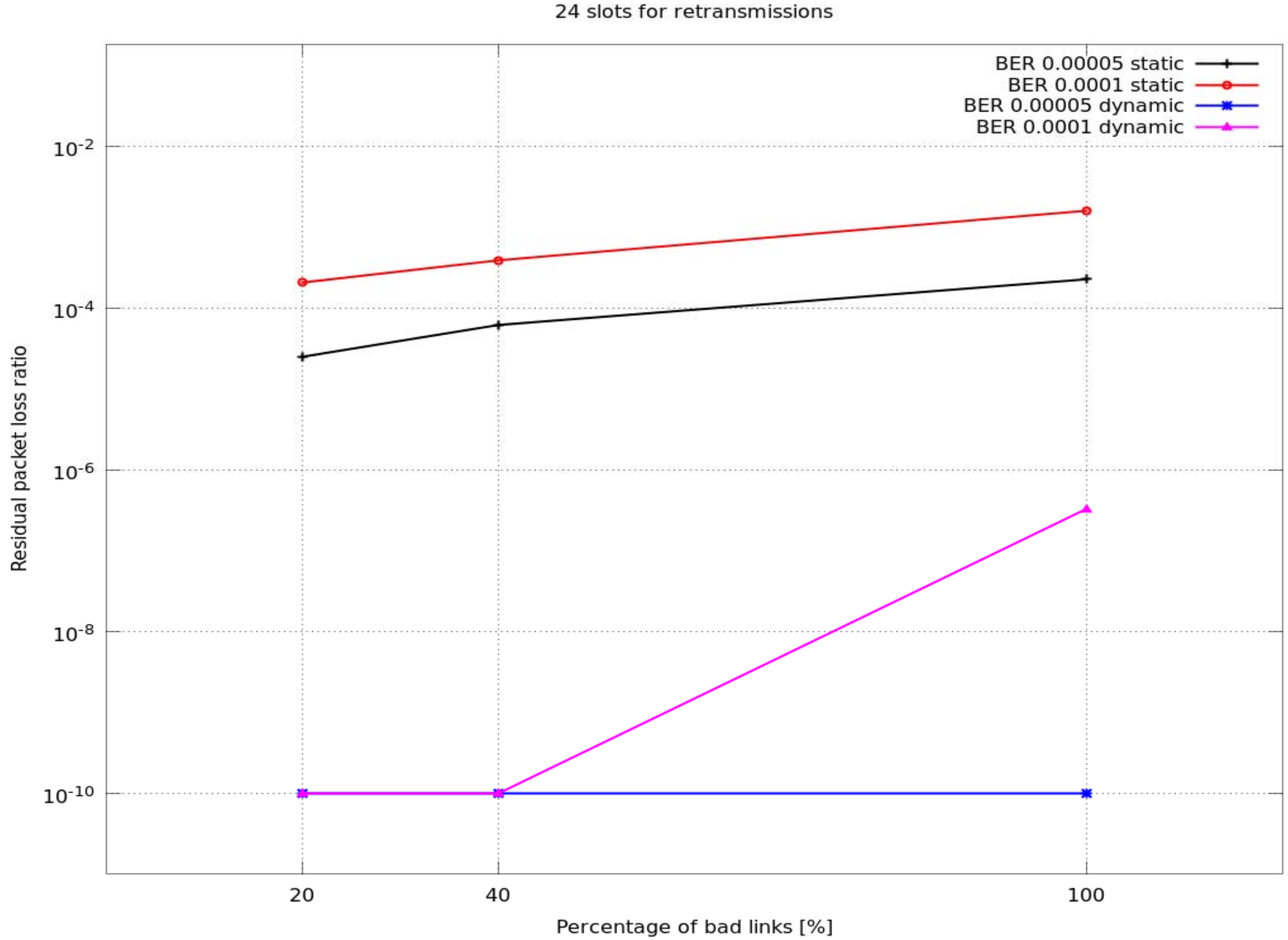
Residual PER as a function of retry policy (BER bad links = 10-4)



Residual PER as a function of BER

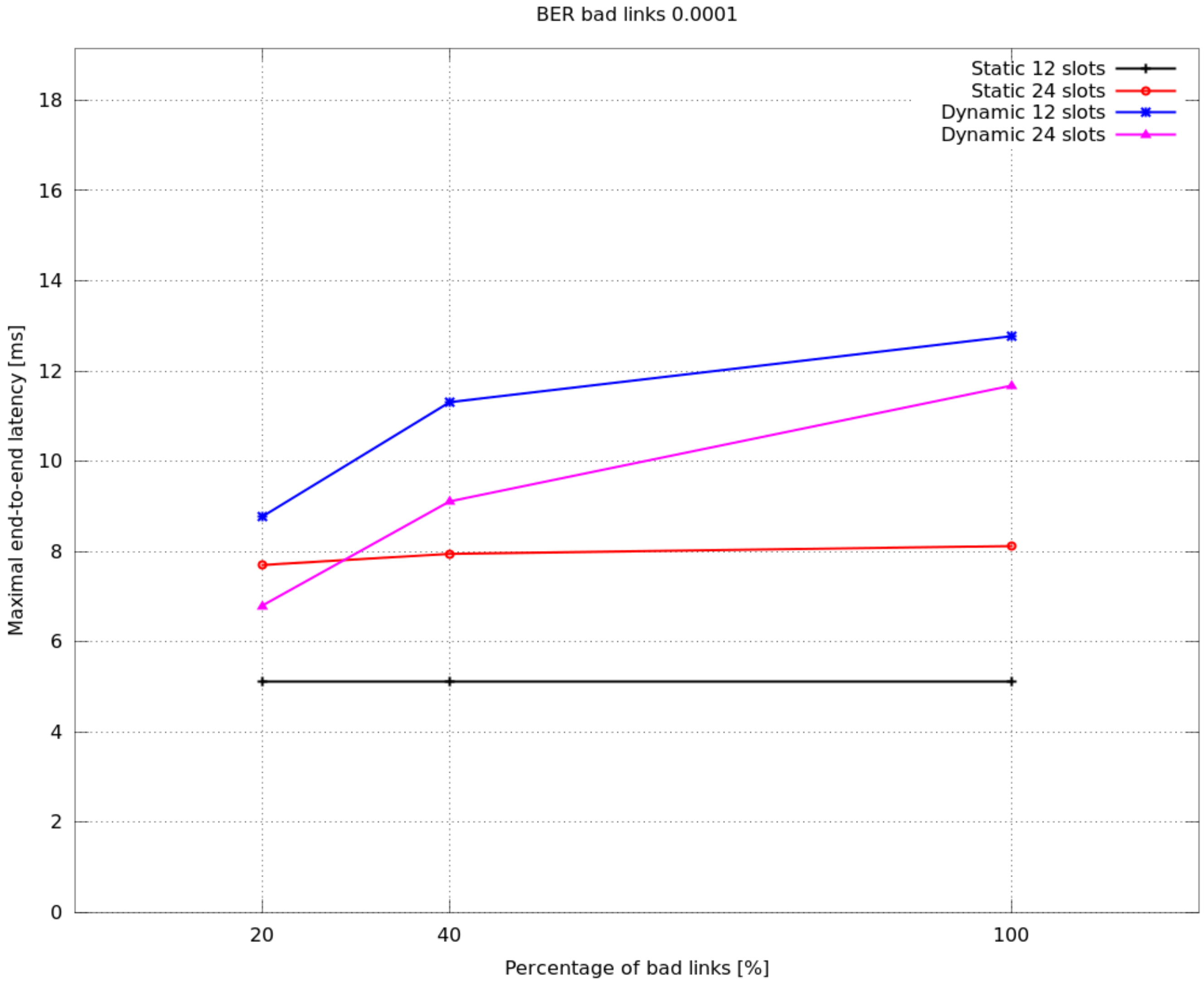


Residual PER as a function of BER



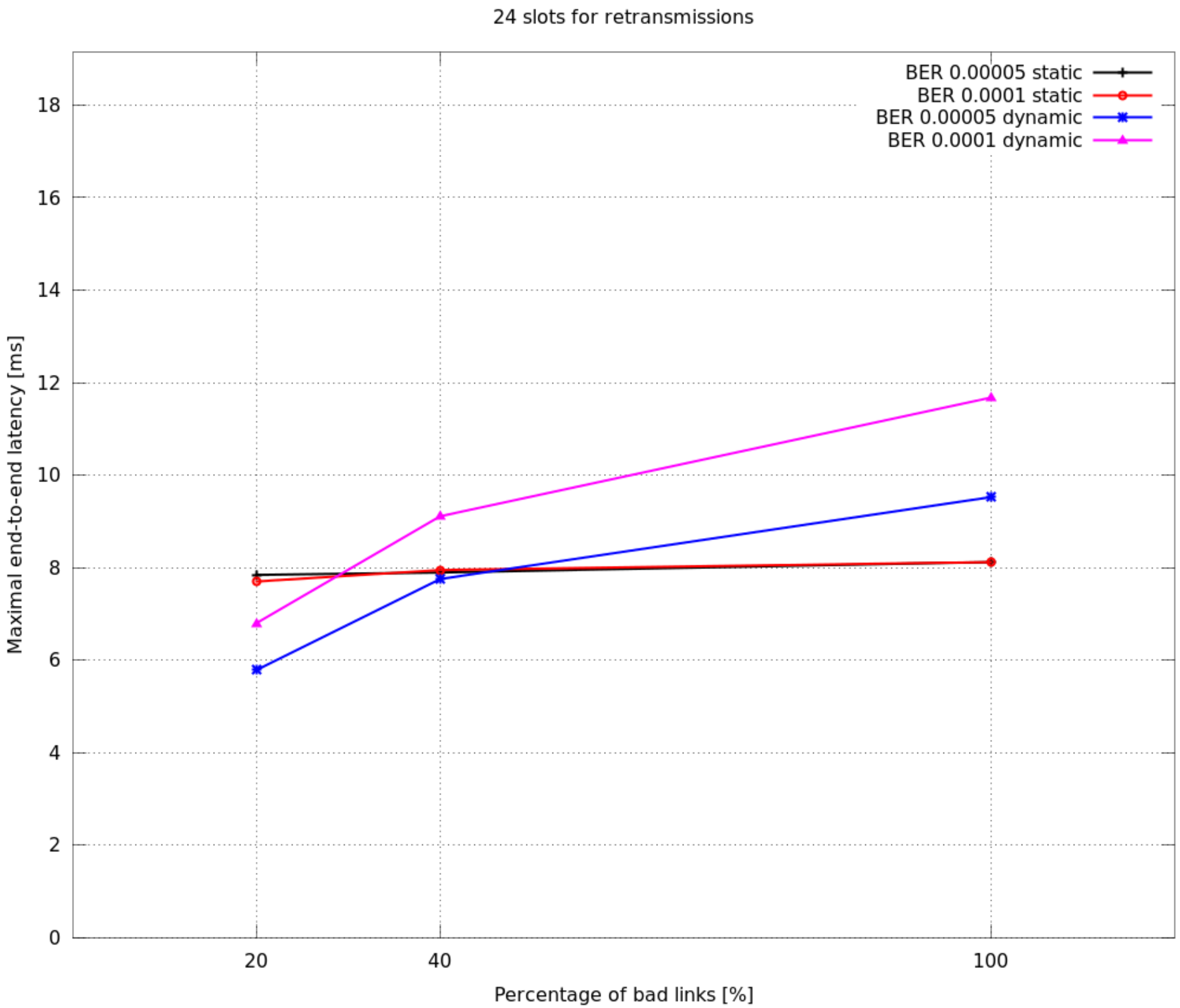
Latency as a function of retry policy

- Max ->



- Mean latency from 1.3 to 1.6ms

Maximum latency as a fct of retry policy



Conclusion

- Pure TDMA has been heavily used in industrial communications
- Different solutions with different application scopes
  - Hard to have "one size fits all"
- Most retransmission schemes are static
  - Not very efficient in particular when link reliability is uneven

References

- P. Dallemagne, J.-D. Decotignie et al., "Suitability of the IEEE 802.15.4e extensions for spacecraft and launcher communications", DASIA 2014
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- Yi-Hung Wei et al., “RT-WiFi: Real-Time High-Speed Communication Protocol for Wireless Cyber-Physical Control Applications”, RTSS 2013, pp. 140-9

References - standards

- IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011), IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer, pp. 1-225
- IEC 62591:2016, Industrial networks - Wireless communication network and communication profiles - WirelessHART™
- IEC 62601:2015, Industrial networks - Wireless communication network and communication profiles - WIA-PA
- IEC 62734:2014, Industrial networks - Wireless communication network and communication profiles - ISA 100.11a
- www.ietf.org for RPL, CoAP and 6LoWPAN