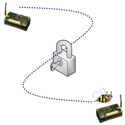
Friedrich-Alexander-Universität Erlangen-Nürnberg

SIEMENS



Improving IEEE 802.15.4 for Low-latency Energy-efficient Industrial Applications

Feng Chen[1,2]

[1]Siemens AG, Automation and Drives

[2]University of Erlangen-Nuernberg

Echtzeit 2008, Boppard am Rhein

Outline

WSNs in Industrial Applications

General requirements

- Standardization
- Coexistence, especially with WLAN
- Robust and reliable communications
- Energy-efficiency
- Security mechanism

Why choose IEEE 802.15.4

- Industrial standard for LR-WPANs
- Coexistence with WLAN due to DSSS
- Duty-cycle adjustable
- GTS for real-time applications
- Provide security mechanism

Study Case

A typical industrial application

- A star network monitors industrial processes
  - e.g.: 20 sensor nodes and 1 gateway
- Nodes send alarm messages to the gateway
  - e.g.: a short alarm message with only 1 byte payload

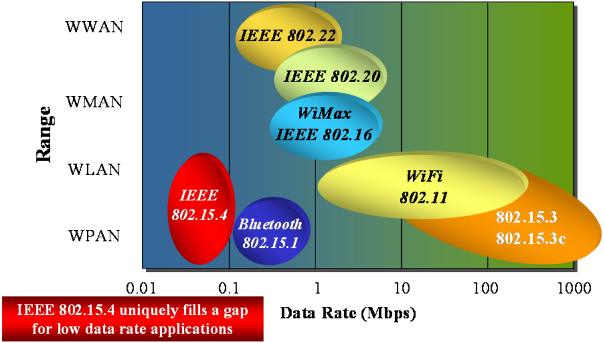
Requirements

- Real-time: guaranteed latency upper boundary
  - e.g.: $d_{GUA} < 10ms$
- Consideration of energy-efficiency
- Standardized hardwares

Overview of IEEE 802.15.4

Standard for Low-Rate WPANs

- low data rate (max. 250 kb/s)
- short distance (POS of 10m)
- ultra-low complexity
- ultra-low cost
- Long battery life



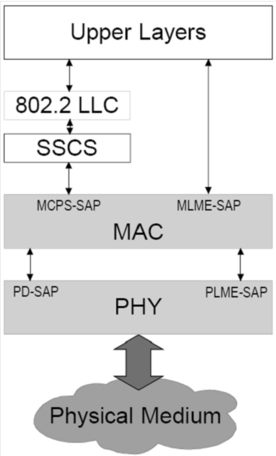
Protocol Architecture

PHY layer spec.

- 16 channels in 2.45 GHz ISM band
- max. bitrate: 250 kb/s
- max. symbol rate: 62.5 ksymbol/s

MAC layer spec.

- CSMA-CA channel access
- Optional allocation of guaranteed time slots (GTSs)
- Beaconing for sync.
- Duty-cycled superframe structure
- MAC layer security



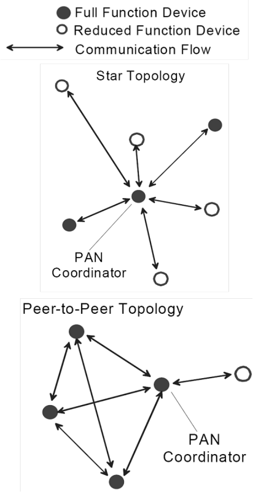
Devices and Topologies

Two device types

- Full-function device (FFD)
  - PAN coordinator, coordinator, or device
- Reduced-function device (RFD)
  - minimal resources
  - talk only to an FFD

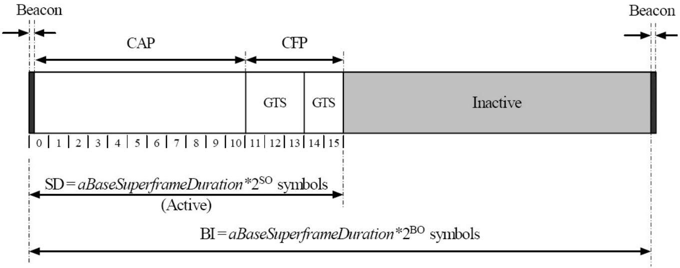
Two topologies

- Star topology
- Peer-to-peer topology (mesh)
  - Cluster-tree



Superframe Structure

- Periodical beacons sent by coordinators for sync.
- Active portion: channel access
  - Contention Access Period (CAP):
    – slotted CSMA-CA
  - Contention Free Period (CFP):
    – TDMA-like Guaranteed Time Slot (GTS)
- Inactive portion: go to sleep

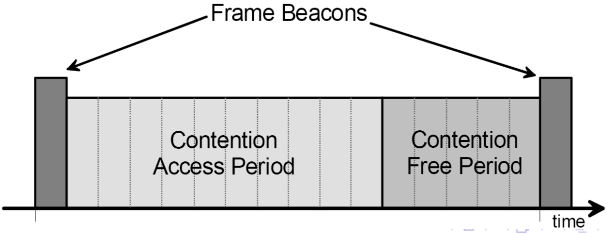


Standard Protocol Behavior

Only GTS can provide guaranteed latency boundary

Limitations in IEEE 802.15.4 GTS for studied scenario

- Maximum seven GTSs allowed – we need e.g. 20
- A minimum CAP length of 440 symbols required
  – introduce extra latency (7.04 ms/BI)
- One GTS must consist of an integer number of contiguous superframe slots
  – wast of bandwidth when transmitting e.g. 1 byte payload



Removal of Limitations

- Only GTSs in the superframe, no CAP and inactive period $\Rightarrow l_{CAP} = l_{SLP} = 0$
- Each GTS allocated with an exact bandwidth for one complete transaction $\Rightarrow l_{GTS} = l_{TR} = l_D + l_{SIFS}$

$l_{BI} = l_B + l_{SIFS} + l_{CAP} + n \times l_{GTS} + l_{SLP}$
$d_{BI} = l_{BI}/(62.5 \text{ ksymbols/s}) = 17.376ms$ (for 20 nodes)

Table: Duration Parameters

Symbol	Description	Value
l_B	length of beacon transmission	34 symbols
l_D	length of data transmission	40 symbols
l_{SIFS}	short interframe space	12 symbols
l_{TR}	length of one transaction	52 symbols

Worst Case Estimation

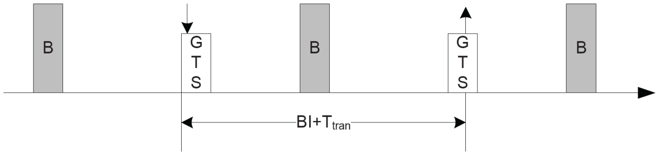
As usual means to calculate delay boundary

Assumption

Each device possesses its own GTS slot in the superframe and keeps tracking the beacon

Worst case in the studied scenario

The maximum latency occurs when a message is generated by a device during its own GTS slot slightly after the time point, at which it can be transmitted in the current GTS, and has to wait for an extra beacon interval.



Analysis Results

Guaranteed latency boundary

$$l_{GUA} = l_{BI} + l_{TR} = l_B + (n+1) \times l_{SIFS} + n \times l_D$$
$$d_{GUA} = l_{GUA}/(62.5 \text{ ksymbols/s})$$

In the case of studied scenario

$$d_{BI} = 17.376ms, d_{TR} = 0.832ms$$
$$d_{GUA} = 18.208ms > 10ms$$

Analysis

l_D and l_{SIFS} dominate the boundary value

- $l_{SIFS} = 12 symbols$
- $l_D = 40 symbols = 20 bytes$
  $\Rightarrow$Transmission of one byte payload needs 38 symbols (19 bytes) overheads added by MAC and PHY (too large)

Overview

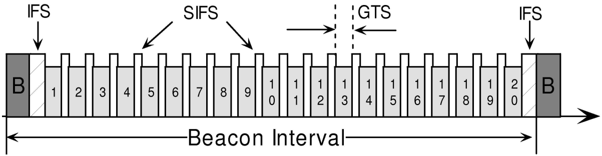
Design goals

- Guaranteed latency upper-boundary
  - 20 nodes, 1 byte payload, max. 10 ms latency
- Energy-efficiency consideration
- Hardware compatibility

General features

- Original IEEE 802.15.4 PHY
- TDMA-based superframe structure
- Largely reduced MAC overheads

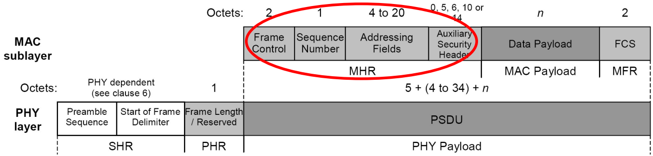
TDMA-based Superframe Structure



- Original beaconing mechanism reserved
  - Beacon tracking enabled (less latency)
  - Beacon tracking disabled (less energy)
- Pre-allocated GTS slots
- IFS (12 symbols) after or before beacon
  - time for radio switch between Rx and Tx
- SIFS (4 symbols) between GTS slots
  - no radio state switch occurs

Data Frame w/o MAC Header

- Originally 19 bytes overheads added to one byte payload



Abandon MAC header

- Pre-allocation -> implicit addressing
- No direct ACK -> SN unneeded
- Other fields dispensable

Group Acknowledgment

PAN coordinator sends a group ACK in next beacon

Parameters Recalculation

For studied scenario: 20 nodes, 1 byte payload

Table: Reduced Duration Parameters

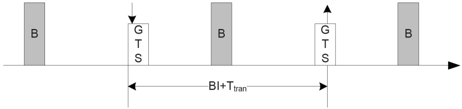
Symbol	Standard w/o limitations	Improved protocols
l_D	40 symbols	18 symbols
l_{SIFS}	12 symbols	4 symbols
l_{TR}	52 symbols	22 symbols
l_{BI}	1246 symbols	494 symbols

Beacon interval

$$l_{BI} = l_B + 2 \times l_{IFS} + n \times l_{GTS} + (n-1) \times l_{SIFS}$$
$$d_{BI} = (l_B + 2 \times l_{IFS} + 20 \times l_D + (20-1) \times l_{SIFS})/(62.5 \text{ ksymbols/s})$$

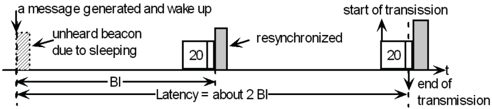
Performance Analysis

- Beacon tracking enabled



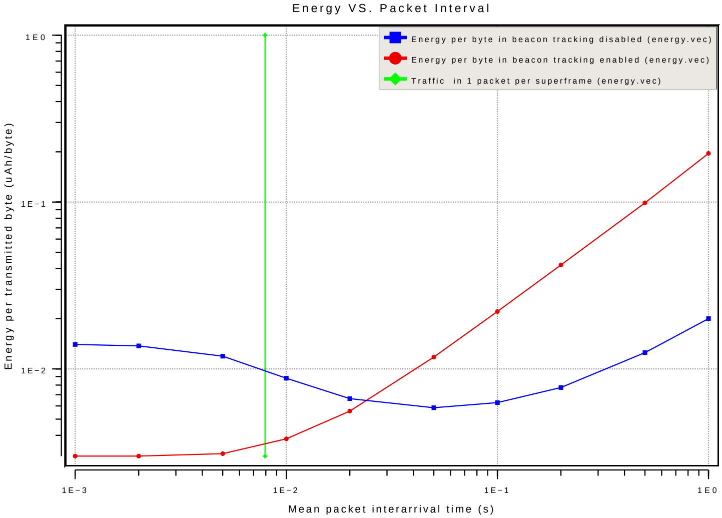
Guaranteed max latency: BI + t_{TRAN} = 8.3 ms

- Beacon tracking disabled



Guaranteed max latency: 2BI = 15.81 ms

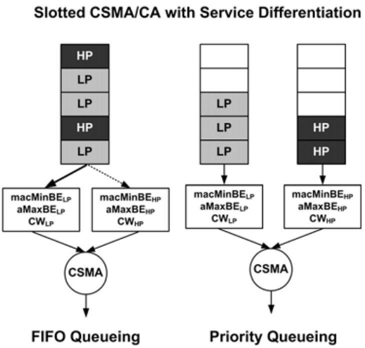
Simulation Results for Energy Consumption



Low-latency IEEE 802.15.4/CSMA

Priority-based scheme providing differentiated QoS

- Priority queue for two types of data packets
  - High priority (HP) packets
  - Low priority (LP) packets
- Differentiated CSMA/CA parameters
  - One-time CCA VS. two-times CCA
  - $CW_{HP} \leq CW_{LP}$
  - $macMinBE_{HP} \leq macMinBE_{LP}$
- Priority toning



Thank you and questions?