Engineering IEEE 802.15.4/ZigBee Wireless Sensor networks

Lecture 12

Anis Koubaa

Al-Imam University(Saudi Arabia)/CISTER Research Unit (Portugal)

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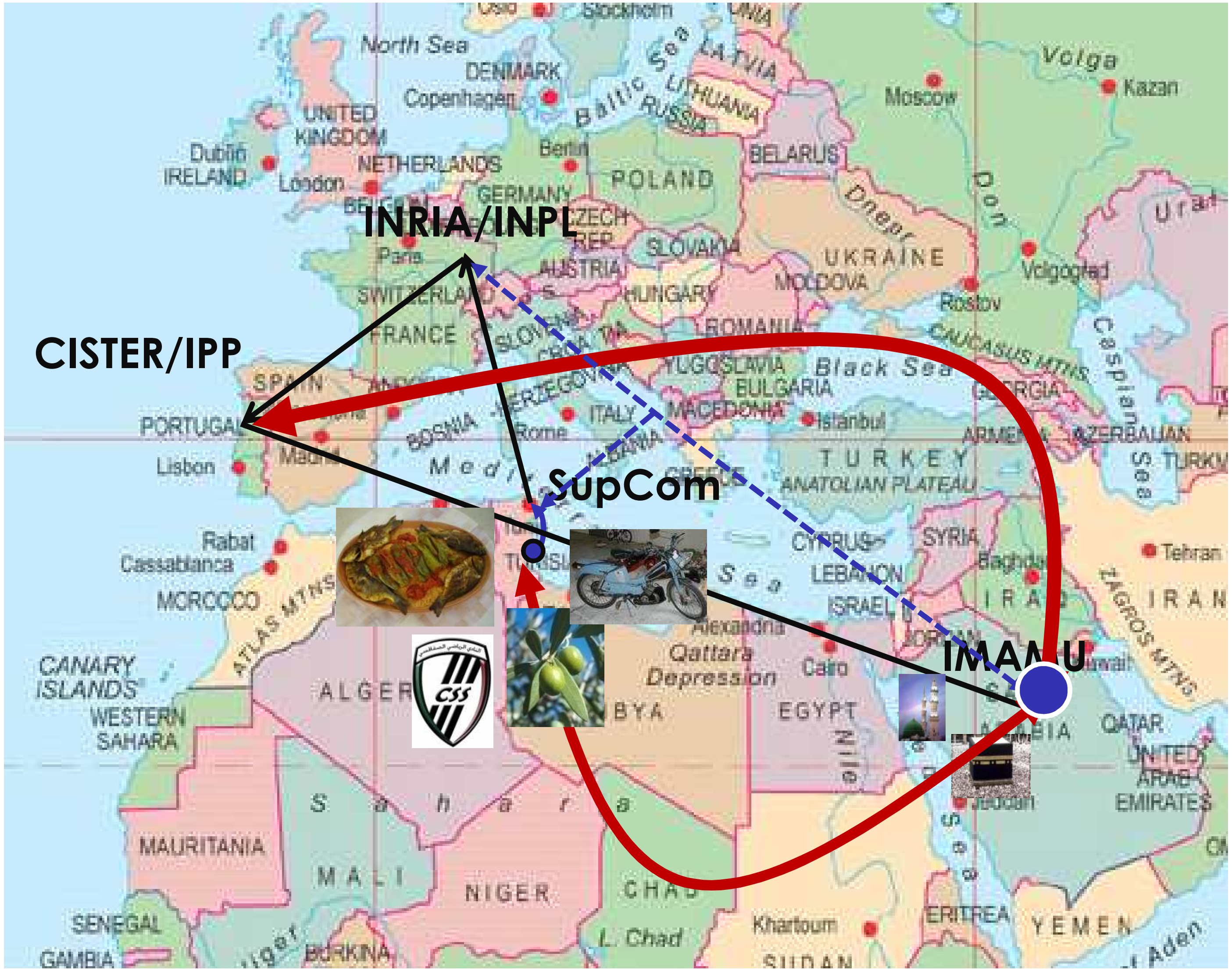
Speaker Biography

- **Anis Koubâa, Ph.D.**
- Assistant Professor @ Al-Imam University (Saudi Arabia)
- Associate Researcher @ CISTER Research Unit (Portugal)
- Chair of TinyOS ZigBee WG
- Areas: Wireless Sensor Networks, IEEE 802.15.4, ZigBee, 6LowPan, Dimensioning and Network Planning.

http://www.dei.isep.ipp.pt/~akoubaa

Speaker Biography



Where I Come From …

Goals of the talk

- Learn about IEEE 802.15.4/ZigBee
- A snapshot on its performance
- Shortcomings and amendments proposed to the standard protocol stack
- Tools for planning, testing and demonstrating applications/protocols with the standard stack

Ackowledgements

- **ARTi-Wise and open-ZB Teams**
  - Mario Alves
  - Ricardo Severino
  - Petr Jurcik
  - Nouha Baccour
  - Maissa ben Jemâa (collaborator)
  - André Cunha (ex-member)
- Credits to Mario Alves for helping out making this presentation

Related Projects

- CONET Network of Excellence
  - http://www.cooperating-objects.eu/
- ARTi-Wise Framework
  - http://artwise.cister-isep.info/
- open-ZB project
  - http://www.open-zb.net/

Outline

- **Part I. Introduction to IEEE 802.15.4/ZigBee**
- **Part II. Performance Evaluation**
  - Performance Evaluation of the IEEE 802.15 GTS Worst-Case
  - Performance Evaluation of CSMA/CA
  - Dimensioning of IEEE 802.15/ZigBee Cluster-Tree Networks
- **Part III. Amendments to the standard**
  - Enhanced GTS Mechanism for the IEEE 802.15.4
  - Hidden Node Avoidance Mechanism for IEEE 802.15.4 Networks
  - Synchronization Mechanism of the IEEE 802.15.4/ZigBee Cluster-Tree Wireless Sensor Networks
- **Part VI. Tools and Experimental Testbeds**
  - Implementations
  - OPNET Simulation Model of IEEE 802.15.4/ZigBee

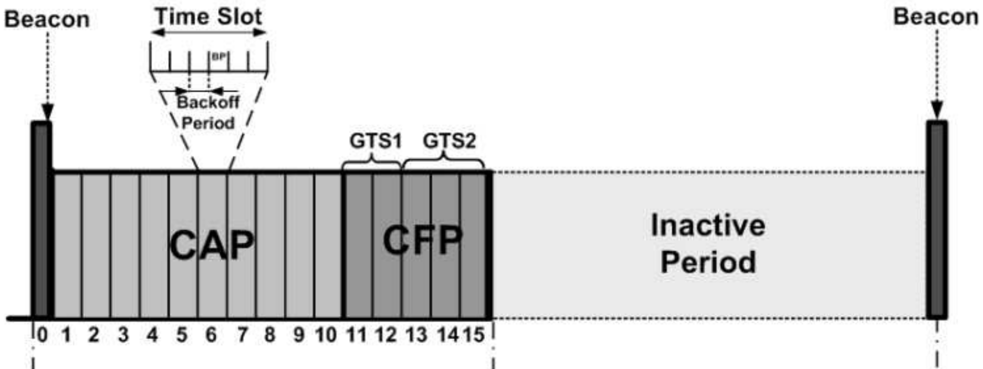
Part. I.
Introduction to the IEEE 802.15.4/ZigBee standard

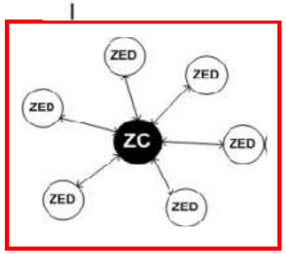
A bit of history …

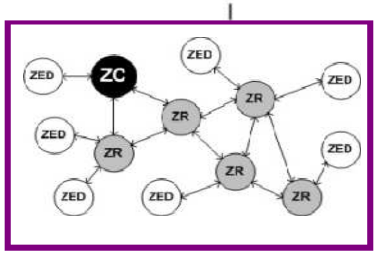
- **Why IEEE 802.15.4 standard?**
  - First release in 2003, amendment in 2006 (WG15.4b)
  - Need for Standard for PHY and MAC Layers for WPANs (e.g. WSNs)
  - Low power + low rate = Energy efficiency
  - Interoperability was not a big issue
- **Why ZigBee?**
  - First release in 2006, ZigBeePro in 2007.
  - Complement the IEEE 802.15.4 Stack with same objectives
  - Ultra low power consumption
  - Enable large-scale networks

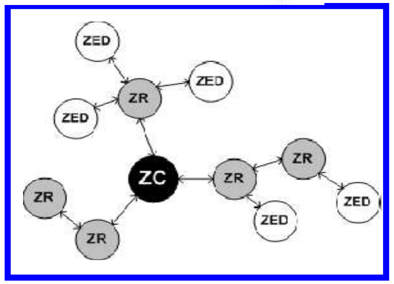
IEEE 802.15.4/ZigBee Features

- **Why IEEE 802.15.4/ZigBee?**
  - **Energy-efficiency**
    - adaptable duty-cycles (100% → 0%)
    - low data rates (20-250 kbps)
    - low radio coverage (≈ 30 m)
  - **Traffic differentiation**
    - Real-Time traffic
      - Guaranteed Time Slots (GTS)
    - Best-effort traffic
      - CSMA/CA mechanism
  - **Scalable network topologies**
    - star, **mesh**, **cluster-tree**
    - up to 65000 nodes per PAN
  - **COTS standard technology**
    - many different manufacturers/motes
    - fast growing market
    - simulation/debugging tools
    - OSs and prog. languages



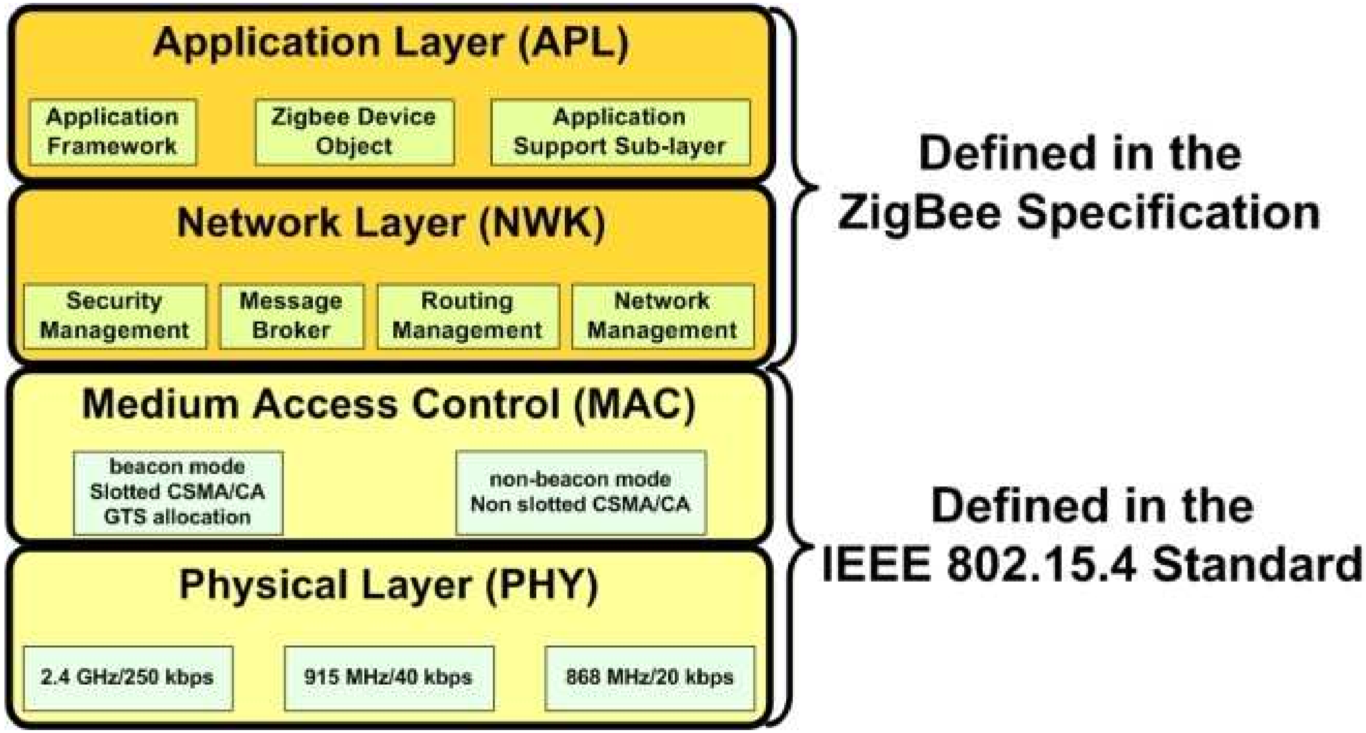






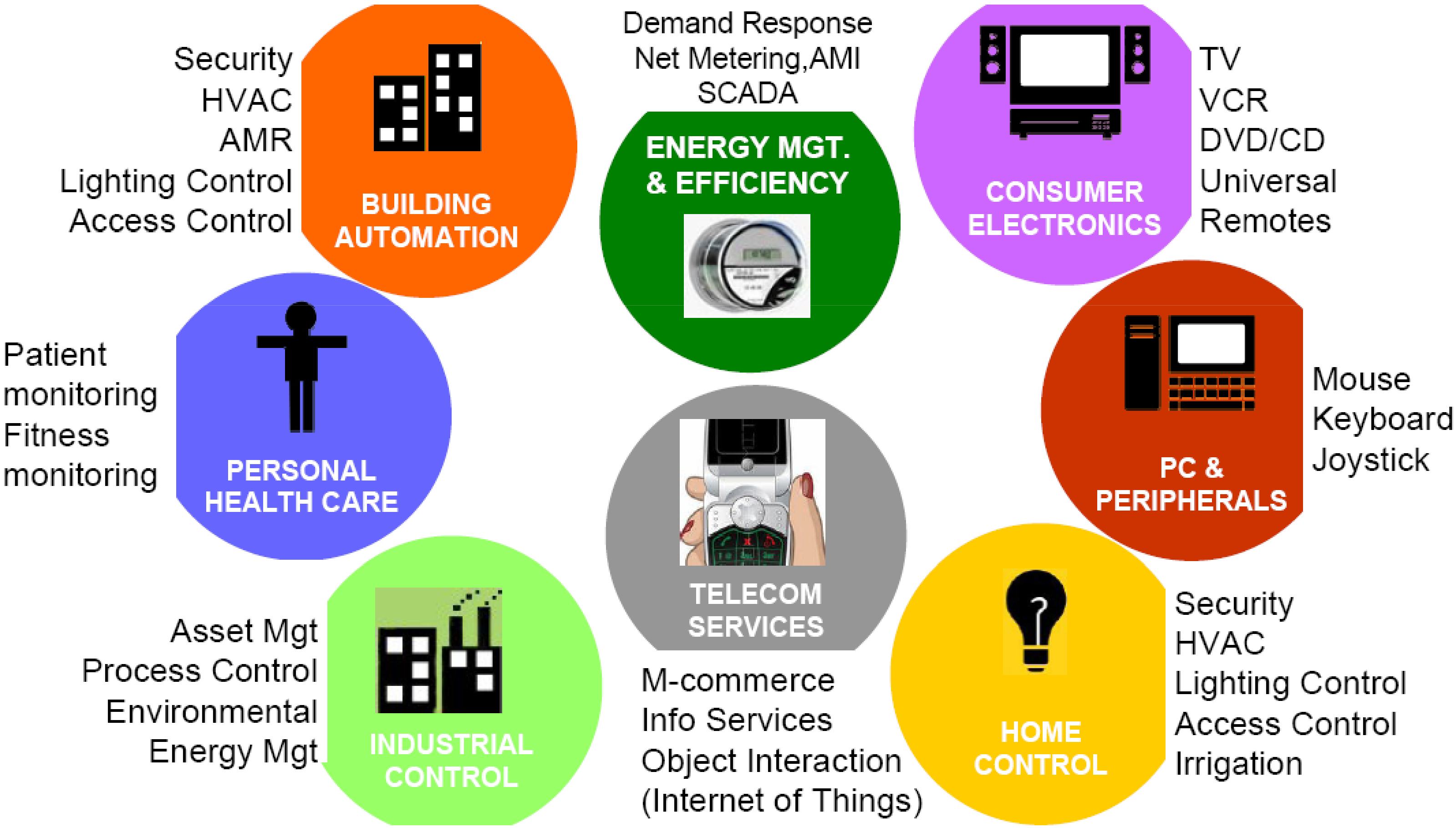
IEEE 802.15.4/ZigBee Features

IEEE 802.15.4 ≠ ZigBee



Target Applications

ZigBee® Alliance
Wireless Control That Simply Works



Target Applications

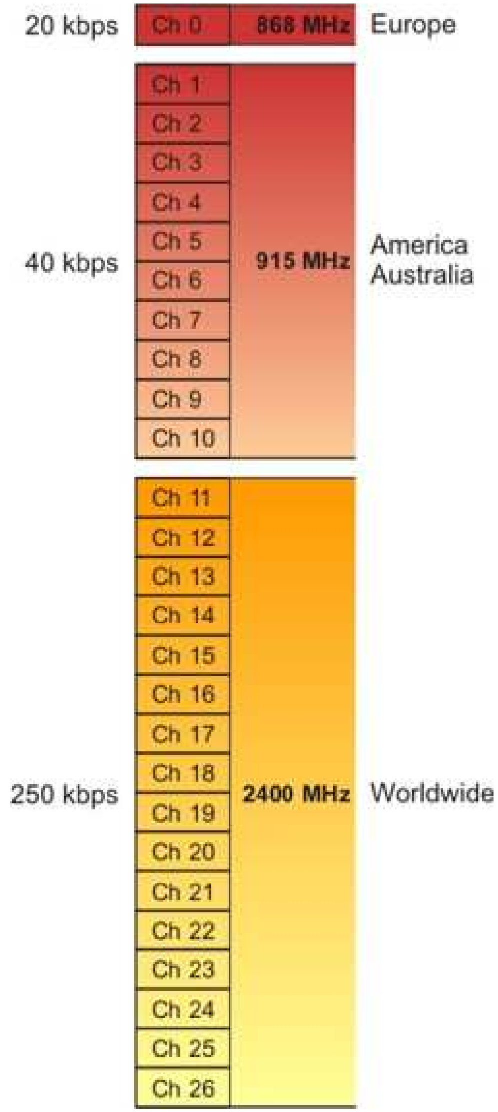
ZigBee® Alliance
Wireless Control That Simply Works

Application profile Name	Marketing documents	Technical Requirements	Specification	Testing Documents	Certified devices	Spec availability	Logos
Smart energy	Completed	Completed	Completed	Completed	YES	YES	
Home Automation	Completed	Completed	Completed	Completed	YES	YES	
Telecom Applications	Completed	Completed	Testing Phase	In progress	-	-	
Commercial buildings	Completed	Completed	Testing Phase	In progress	-	-	
Health	Completed	Completed	Testing Phase	In progress	-	-	

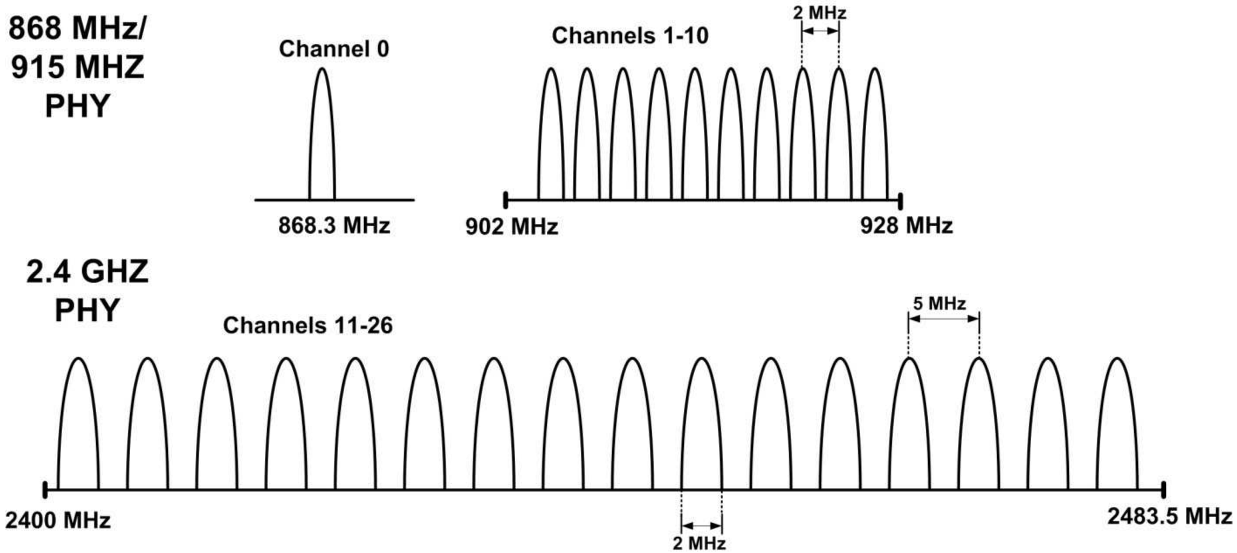
CONET Roadmap, June 2009

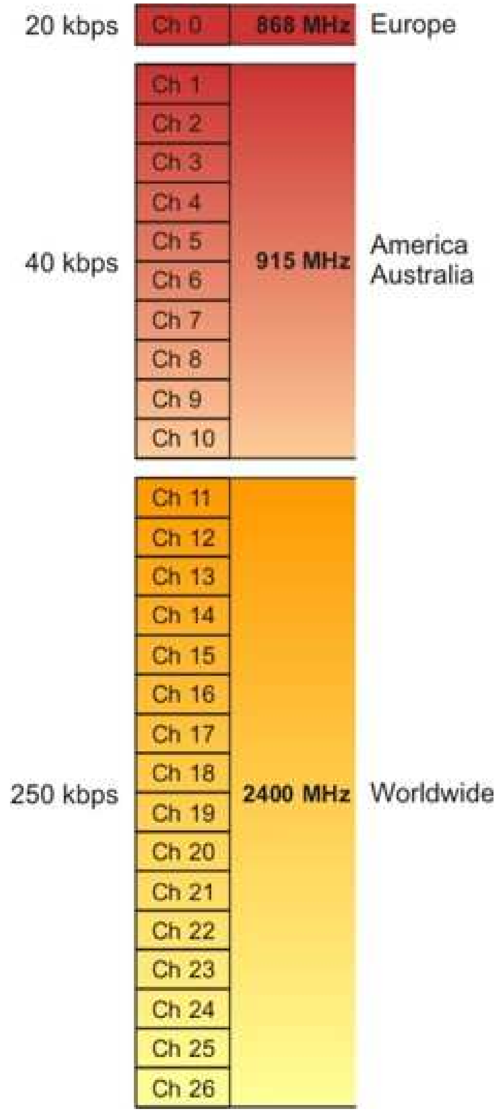
Physical Channels

- **original** (IEEE 802.15.4 – 2003)
  - 27 (1+10+16) radio channels
- **IEEE 802.15.4b** (pub. SEP/2006)
  - higher bit rates for 868/915 MHz bands, bringing them up to support 100 and 250 kbit/s as well,…
- **IEEE 802.15.4a** (pub. AUG/2007)
  - 2 new PHY
    - **UWB** – higher bit rate, precision ranging and robustness
    - **CSS** - higher mobility speeds and coverage
- **IEEE802.15.4c**
  - is considering the newly opened 314-316 MHz, 430-434 MHz, and 779-787 MHz bands in **China**
- **IEEE 802.15.4d**
  - is defining an amendment to the existing standard 802.15.4-2006 to support the new 950MHz-956MHz band in **Japan**
- **IEEE 802.15.4e**
  - ongoing WG effort e.g. to **increase QoS**
  - **http://www.ieee802.org/15/pub/TG4e.html**



Physical Layer





Frequency Band (MHz)	Spreading Parameters		Data Parameters		
	Chip rate (kchip/s)	Modulation	Bit rate (kbps)	Symbol rate (ksymbol/s)	Symbols
868	300	BPSK	20	20	Binary
915	600	BPSK	40	40	Binary
2400	2000	O-QPSK	250	62.5	16-ary

Physical Layer Functionalities

Activation and deactivation of the radio transceiver

- Three states: transmitting, receiving or sleeping.
- the radio is turned ON or OFF (the *turnaround time* from send/receive and vice versa should be no more than 12 symbol periods)

Receiver Energy Detection (ED).

- Estimation of the received signal power in an 802.15.4 channel.
- No signal identification or decoding on the channel.

Link Quality Indication (LQI).

- characterizes the Strength/Quality of a received signal on a link.
- LQI can be implemented using the receiver ED technique, a signal to noise estimation or a combination of both techniques.

Physical Layer Functionalities

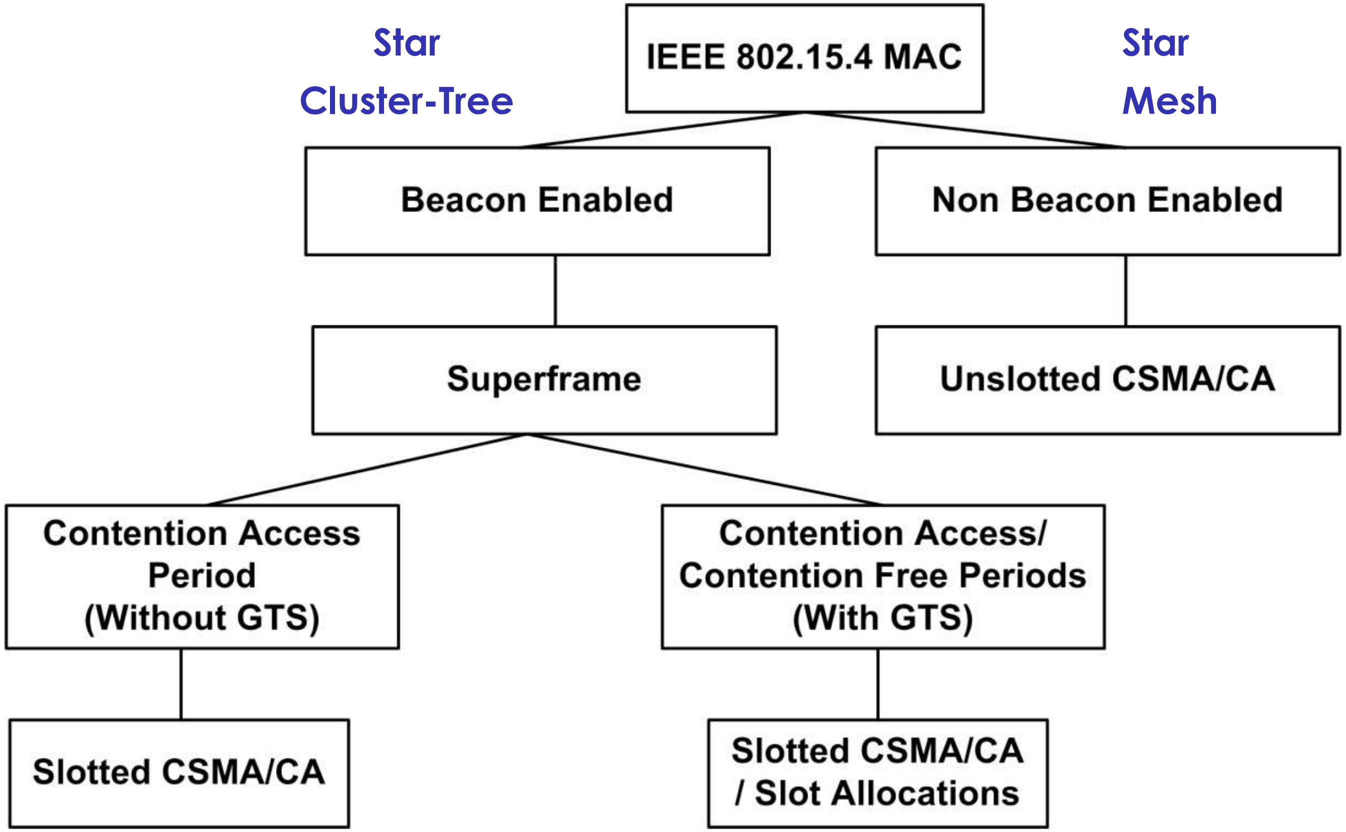
Clear Channel Assessment (CCA).

- Reporting medium state: busy or idle.
- Three operational modes:
  - **Energy Detection mode.** busy if received energy is above a given threshold.
  - **Carrier Sense mode.** busy only if it detects a signal with the modulation and the spreading characteristics of IEEE 802.15.4 and which may be higher or lower than ED threshold.
  - **Carrier Sense with Energy Detection mode.** busy only if it detects a signal with the modulation and the spreading characteristics of IEEE 802.15.4 and with received energy above the ED threshold.

Channel Frequency Selection.

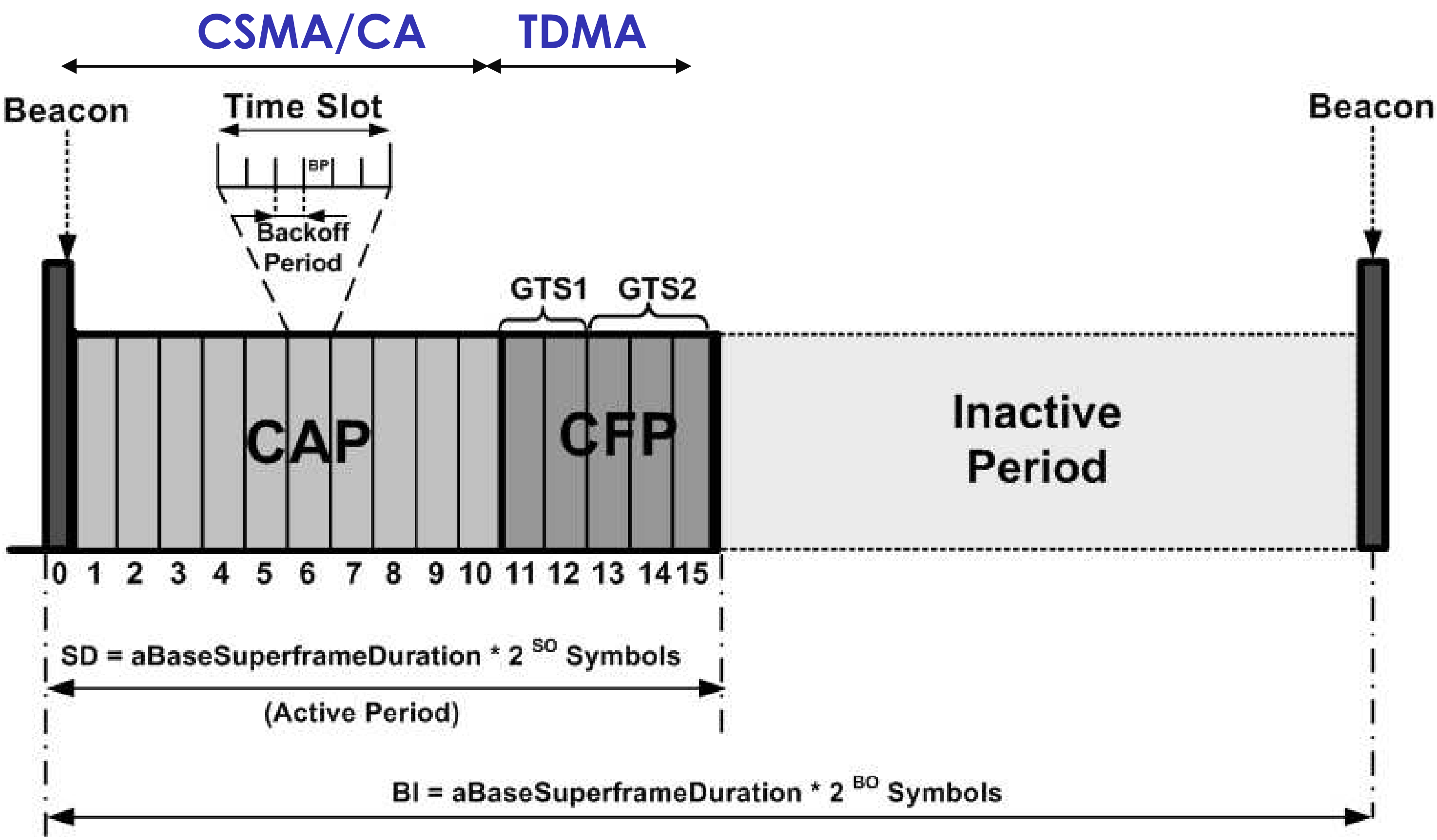
- tune its transceiver into a specific channel upon the reception of a request from a Higher Layer.

MAC Layer



Star
Cluster-Tree
IEEE 802.15.4 MAC
Star
Mesh
Beacon Enabled
Non Beacon Enabled
Superframe
Unslotted CSMA/CA
Contention Access Period (Without GTS)
Contention Access/ Contention Free Periods (With GTS)
Slotted CSMA/CA
Slotted CSMA/CA / Slot Allocations

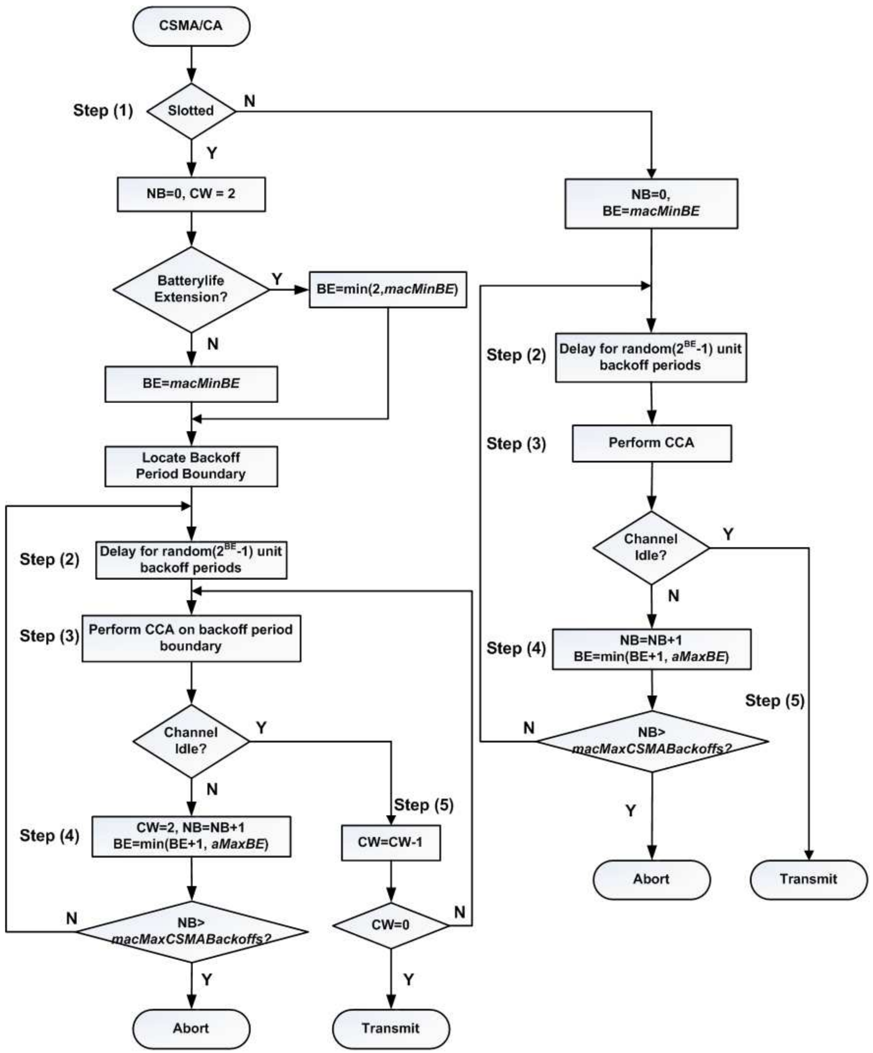
MAC Layer



$$BI = aBaseSuperframeDuration \cdot 2^{BO}$$
$$for \;\; 0 \le BO \le 14$$

$$SD = aBaseSuperframeDuration \cdot 2^{SO}$$
$$for \;\; 0 \le SO \le BO \le 14$$

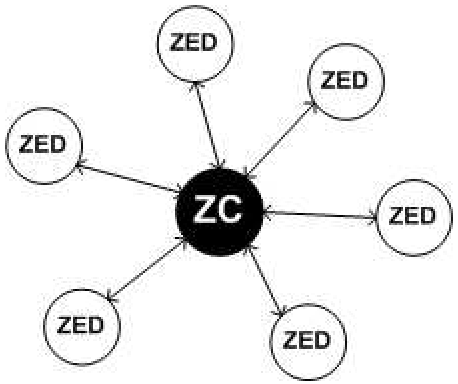
MAC Layer: CSMA/CA

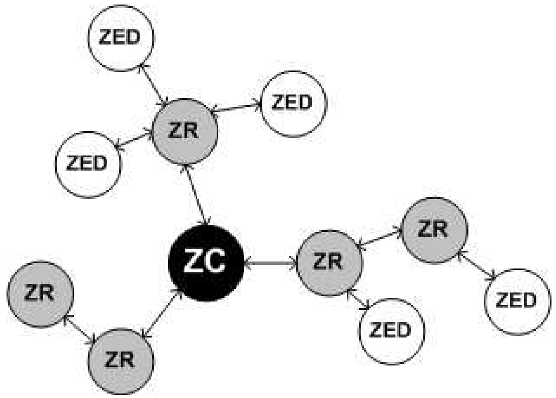


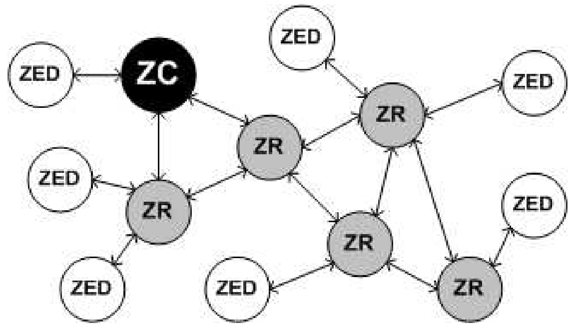
ZigBee Device Types

ZigBee Coordinator (ZC)	ZigBee Router (ZR)	ZigBee End Device (ZED)
• one and only one required per network • initiates network formation • Called PAN Coordinator in 802.15.4 • may act as router once network is formed	• optional network component • may associate with ZC or with previously associated ZR • Called Coordinator in 802.15.4 • participates in multi-hop routing	• optional network component • does not allow association • does not participate in routing

Network Topologies







Star

- No ZigBee Routers
- Communication via ZC
- Synchronization?
  - Yes (beacon-enabled mode)
  - No (non beacon-enabled mode
- Not scalable
- Real-Time

Cluster-Tree

- 1 path between any pair of nodes – tree routing
  - Deterministic
- Distributed synchronization mechanism (beacon-en.)
  - Periodic beacon frames
  - Dynamic duty-cycle adaptation per cluster
  - Enables guaranteed bandwidth (GTS)

Mesh

- AODV-based routing
  - Not deterministic
- No synchronization (non beacon-enabled)
  - ZC and ZRs must be always on
  - No bandwidth guarantees (contention)

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Part. II.
Performance Evaluation of the IEEE 802.15.4/ZigBee standard

Performance Evaluation

Guaranteed Time Slot (GTS)

CSMA/CA MAC protocol

Capacity of Cluster-Tree WSNs

GTS MODELING

Related references

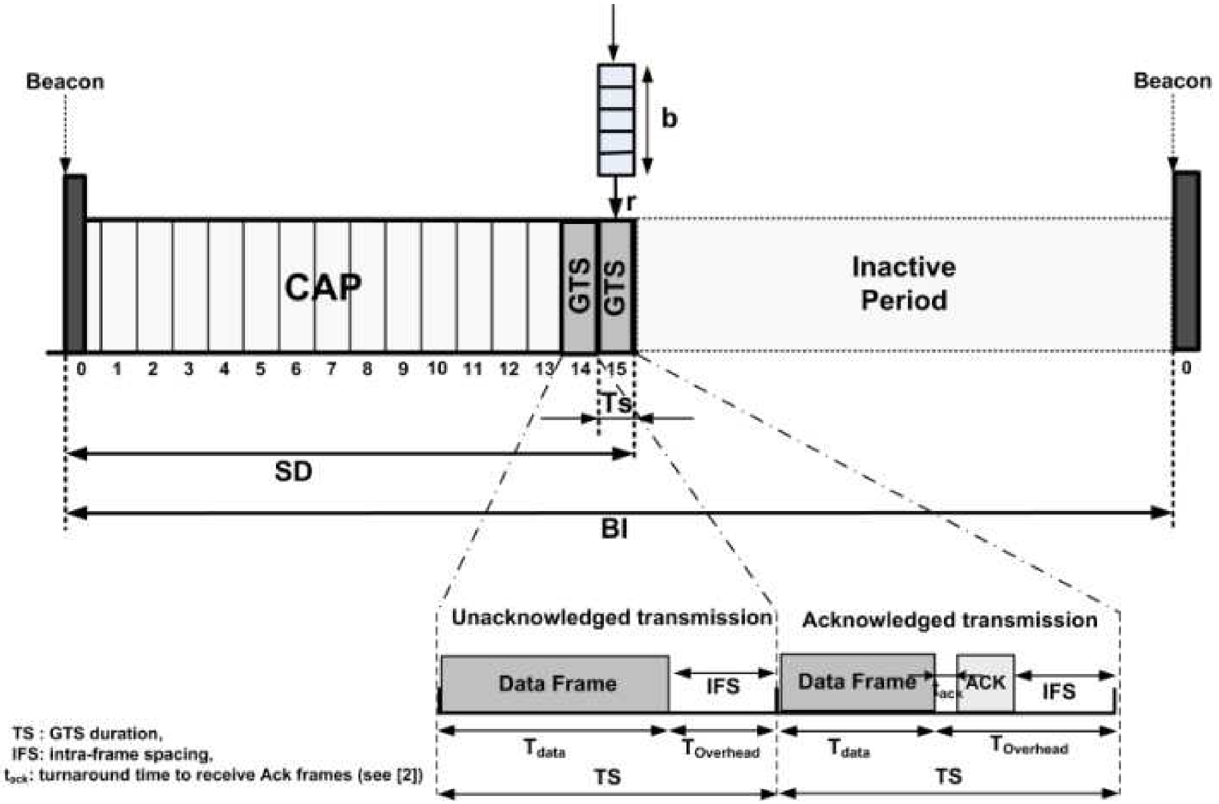
A. Koubâa, M. Alves, E. Tovar
Energy/Delay Trade-off of the GTS Allocation Mechanism in IEEE 802.15.4 for Wireless Sensor Networks
in *Wiley Journal of Communication Systems,* special issue on Energy-Efficient Network Protocols and Algorithms for Wireless Sensor Networks, 2006.

A. Koubâa, M. Alves, E. Tovar ,
"**GTS Allocation Analysis in IEEE 802.15.4 for Real-Time Wireless Sensor Networks**",
in 14th International Workshop on Parallel and Distributed Real-Time Systems (WPDRTS 2006), *invited paper* in special track on Wireless Sensor Networks, 25-26 April 2006.

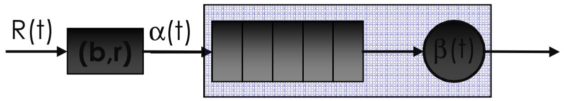
GTS Modeling

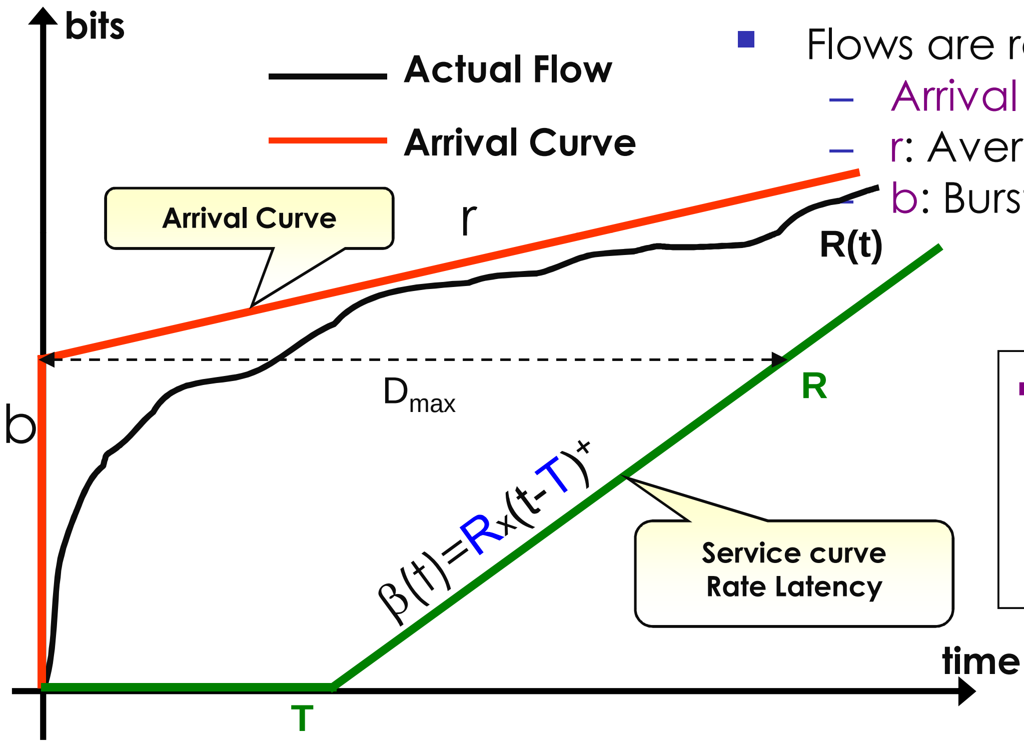
- **Summary of results**
  - Performance of the GTS mechanism
    - Modeling with Network Calculus
    - Performance Metrics: Delay and Throughput
  - Energy-delay trade-off using GTS
    - Lowest duty cycle that satisfies a delay constraint

GTS Modeling



Network Calculus





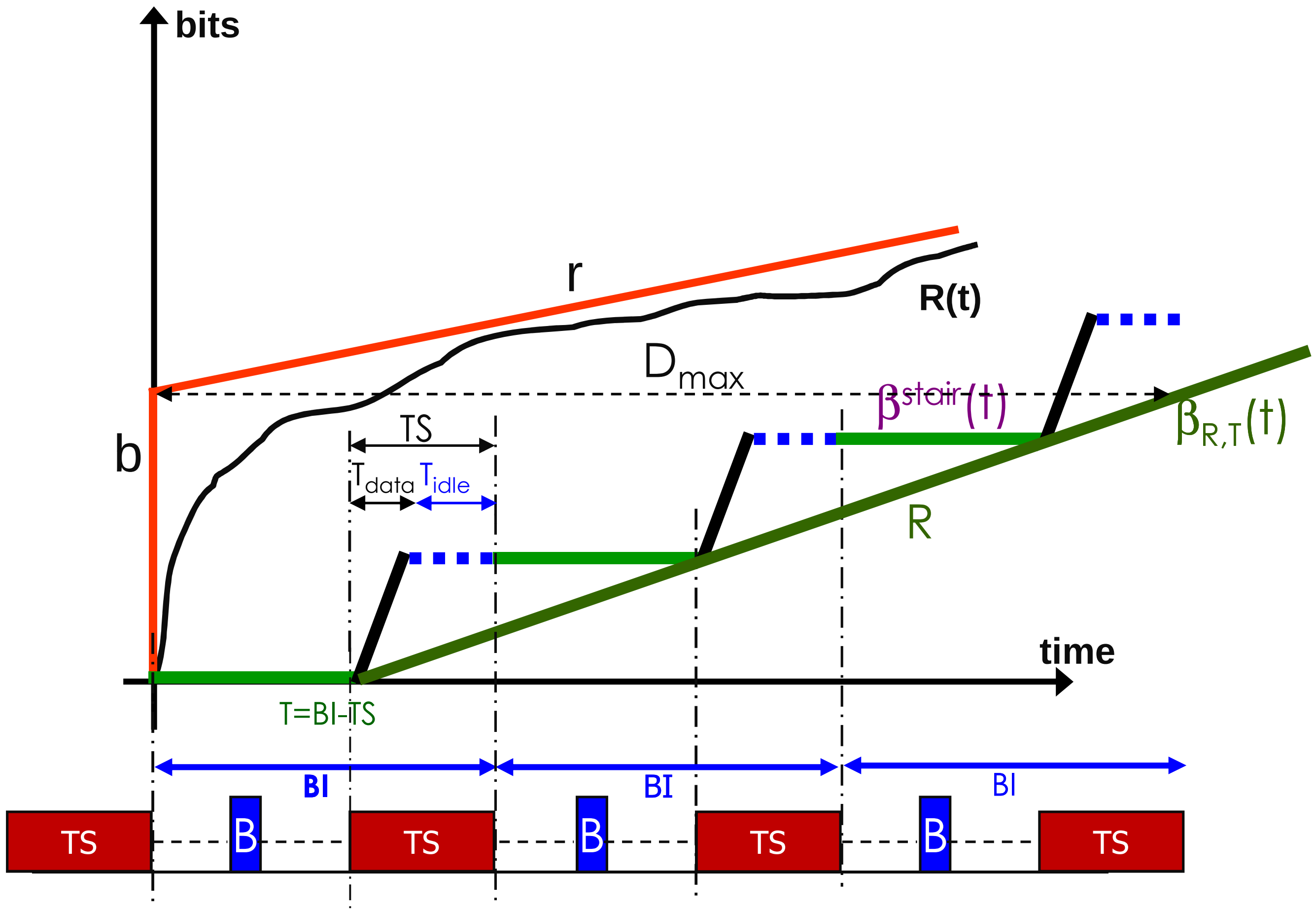
- Flows are represented by
  - Arrival Curve: $\alpha(t)=\beta+r\times t$
  - r: Average Rate
  - b: Burst Size

- The delay guaranteed to a flow with an arrival curve $\alpha(t)$ by a rate latency service curve $\beta(t)$ is:

$$D_{max} = \frac{b}{R} + T$$

$$\textbf{for } 0 \leq \mathbf{s} \leq \mathbf{t},\ \mathbf{R}(\mathbf{t}) - \mathbf{R}(\mathbf{s}) \leq \mathbf{b} + \mathbf{r}(\mathbf{t} - \mathbf{s})$$

GTS Modeling – 1 Time Slot



GTS Modeling – 1 Time Slot

Delay for Linear Service Curve

$$\beta_{R,T}(t) = R(t - T)^{+}$$

$$R = \frac{T_{data} \cdot C}{BI} = \left(\frac{Ts - T_{idle}}{BI}\right) \cdot C$$

$$T = BI - Ts$$

$$D_{\max} = \frac{b}{R} + (BI - Ts)$$

Delay for Stair Service Curve

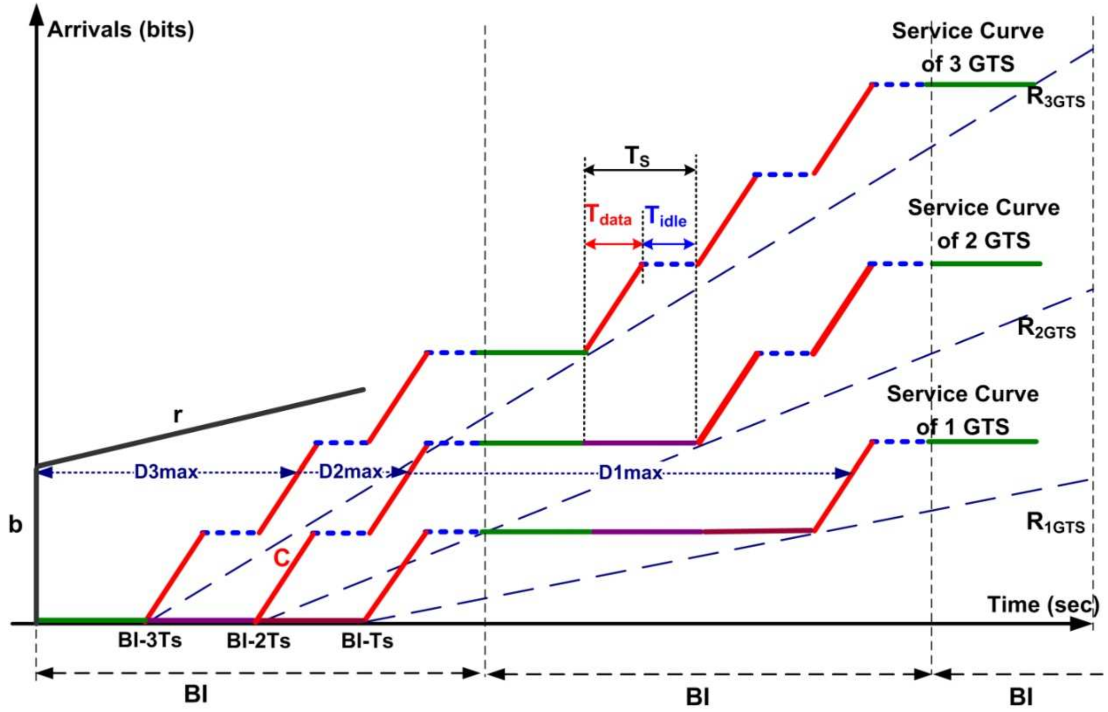
$$\beta_{C,T}^{stair}(t) = \sum_{k} \beta_{C,T}^{k}(t) \quad \forall t$$

$$\beta_{C,T}^{k}(t) = \begin{cases} (k-1) \cdot C \cdot T_{data} + C\left(t - (k \cdot BI - Ts)\right)^{+} \\ \quad \forall t,\ (k-1) \cdot BI \le t \le k \cdot BI - T_{idle} \\ 0 \qquad \text{Otherwise} \end{cases}$$

$$D_{\max}^{stair} = \frac{b}{C} + (k+1) \cdot BI - Ts - k \cdot T_{data}$$

$$\text{if } k \cdot C \cdot T_{data} < b \le (k+1) \cdot C \cdot T_{data}$$

GTS Modeling – *n* Time Slot



Rate Latency Service Curve

$$R_n = n \cdot \frac{T_{data} \cdot C}{BI} = n \cdot \left(\frac{Ts - T_{idle}}{BI} \right) \cdot C$$

$$T_n = BI - n \cdot TS$$

Delay Bound with Stair Service Curve

$$D_{n,\max}^{stair} = \left(\frac{b}{C} + (k+1) \cdot BI - n \cdot (Ts + k \cdot T_{data}) + m \cdot T_{idle} \right)$$

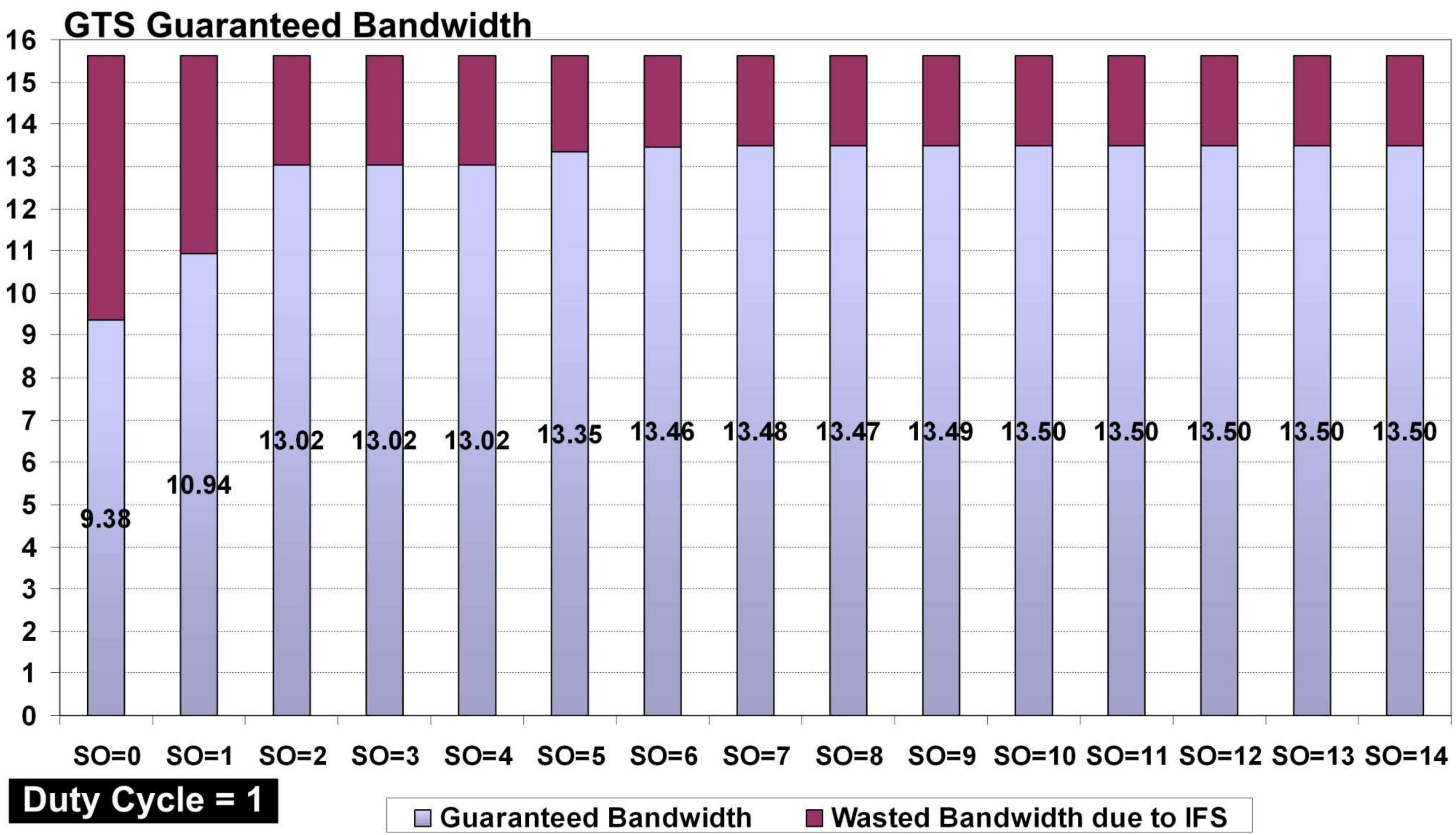
$$where \ m = \left\lfloor \frac{b - k \cdot (n \cdot T_{data}) \cdot C}{T_{data} \cdot C} \right\rfloor$$

$$\text{if } k \cdot C \cdot (n \cdot T_{data}) < b \leq (k+1) \cdot C \cdot (n \cdot T_{data})$$

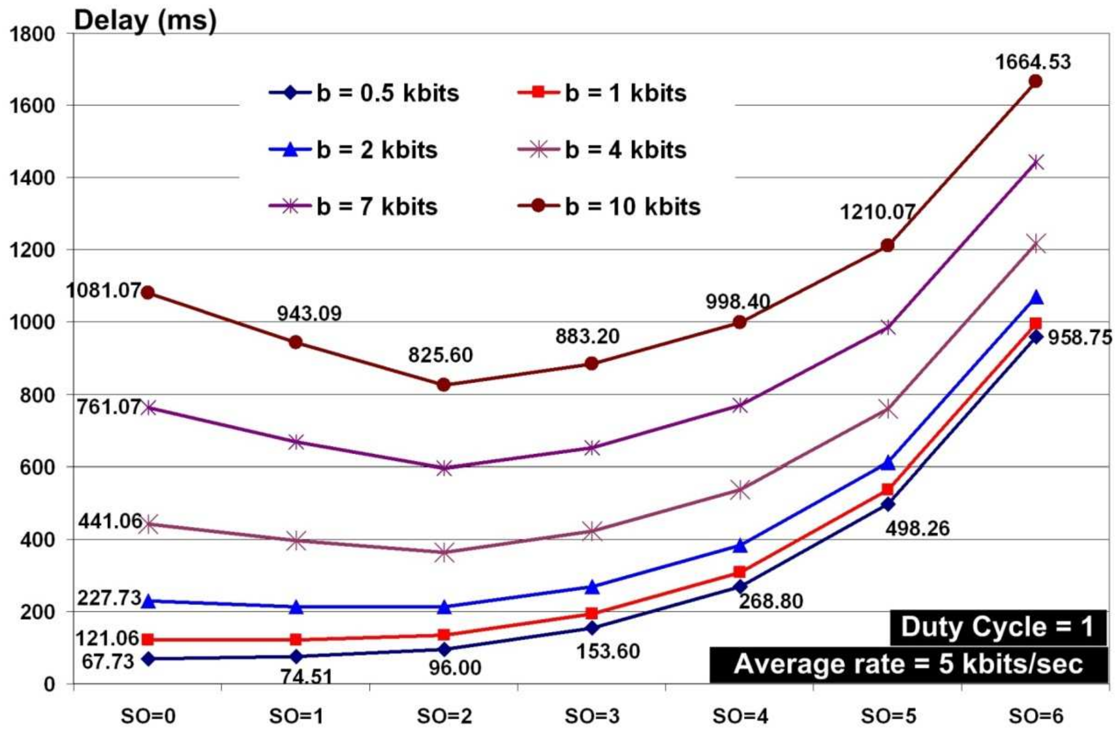
Delay Bound with $\beta_{Rn,Tn}(t)$

$$D_{n,\max} = \frac{b}{R_n} + (BI - n \cdot Ts)$$

GTS Performance: Throughput



GTS Performance: Delay



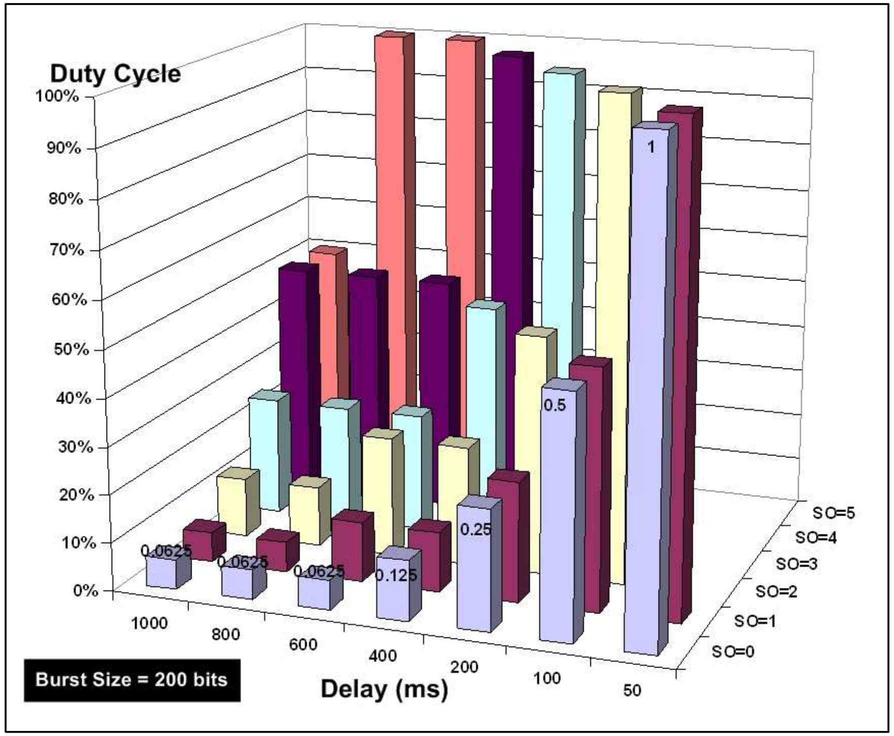
Problem

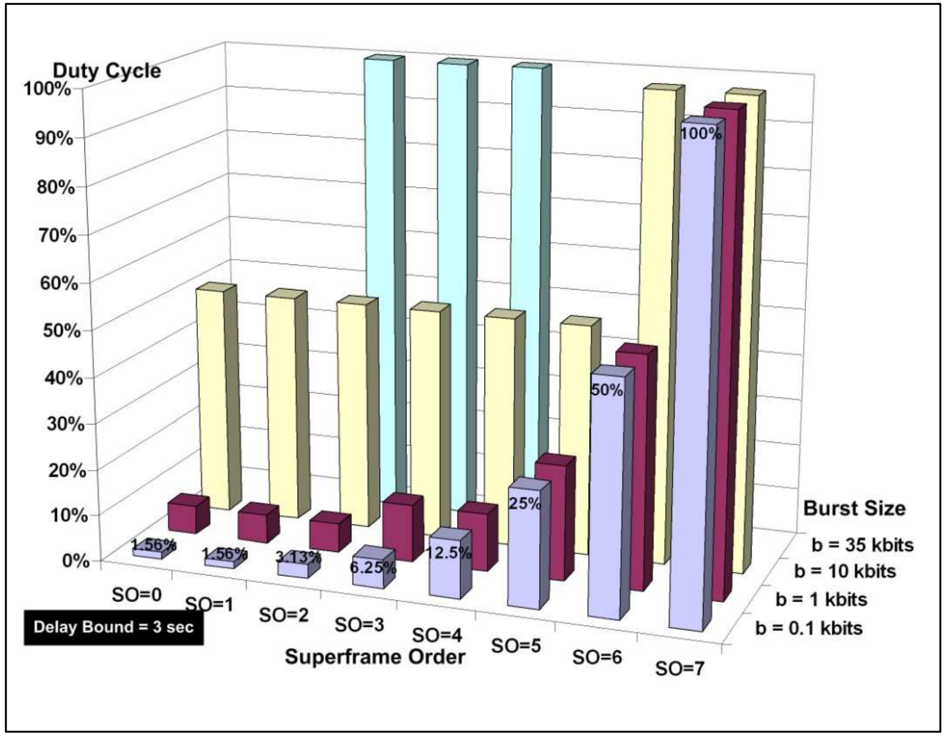
- Determine the best superframe structure (SO) that reduces the delay bounds

Lessons

- Superframe Order configuration depends on the burst size
- For low burst sizes, the delay is an increasing function with SO (SO = 0)
- For high burst sizes, SO>0

GTS Performance: Energy/Delay Trade-Off





Problem

- Determine the best superframe structure (SO) that satisfies the delay bound and reduces the energy consumption

Lessons

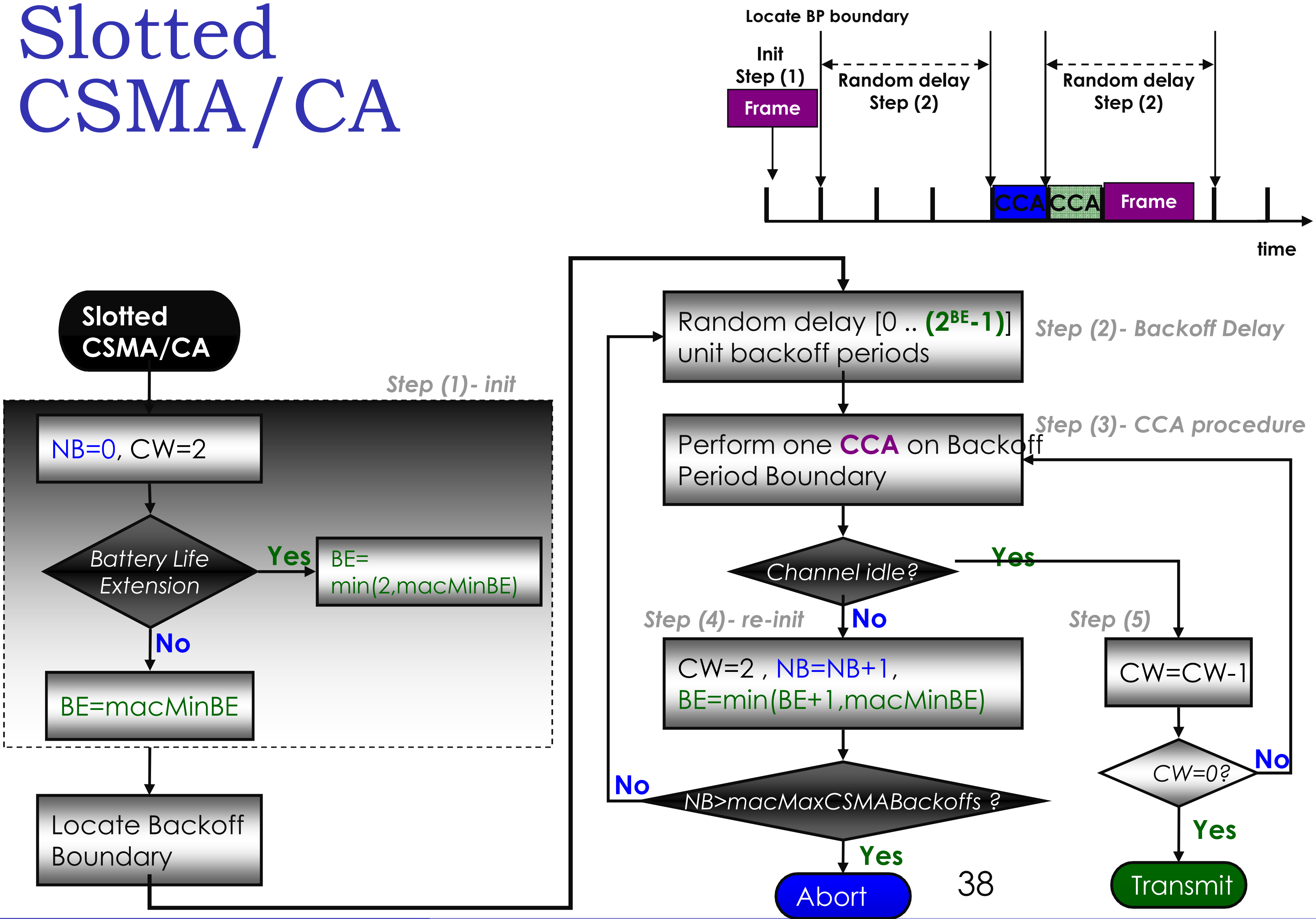
- Low Superframe Orders are more suitable for a best energy/latency trade-off
- Exception for high burst sizes

PERFORMANCE OF CSMA/CA

Related references

A. Koubâa, M. Alves, E. Tovar
A Comprehensive Simulation Study of Slotted CSMA/CA for IEEE 802.15.4 Wireless Sensor Networks
In IEEE WFCS 2006, Torino (Italy), June 2006.

Slotted CSMA/CA



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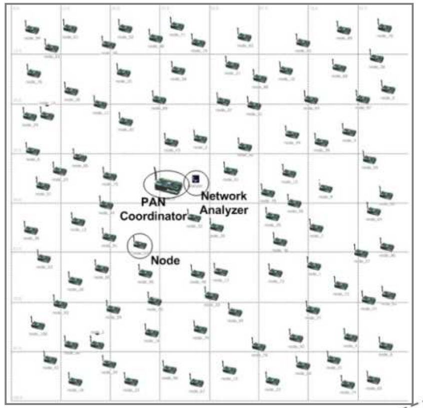
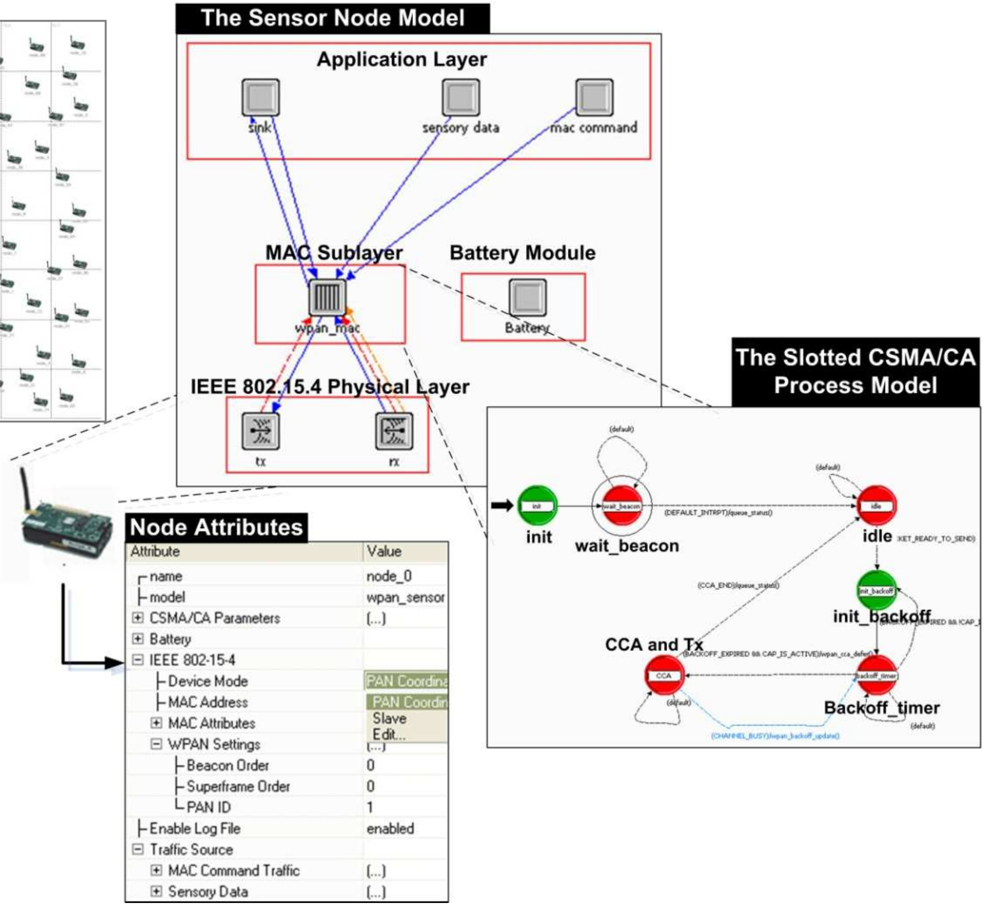
CMSA/CA Performance

Simulation Set-up

- **Topology**
  - 100 nodes in a surface: (100 m * 100 m)
- **PAN Coordinator**
  - default (BO = SO = 3)
  - duty cycle = 100%
- **Slotted CSMA/CA**
  - CW = 2,
  - macMinBE = 2,
  - macMaxCSMABackoff = 5
- **Default frame size: 404 bits**
  - 300 bits data payload
  - 104 bits MAC header
- **Physical layer**
  - Transmission power: 1 mW
  - All nodes hear each other: no hidden-node problem



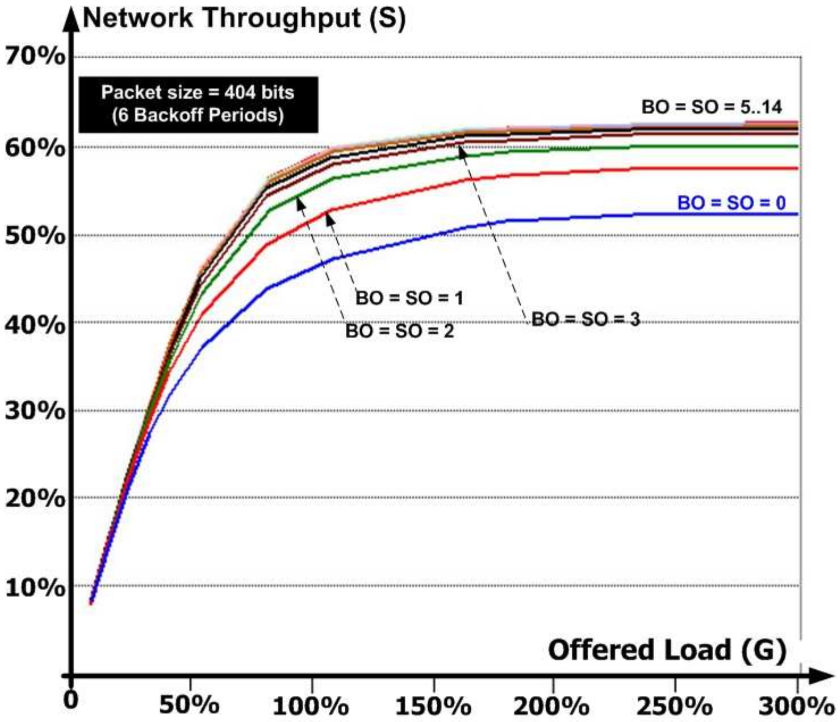
Version 01 open-ZB
OPNET Simulation Model
http://www.open-zb.net/



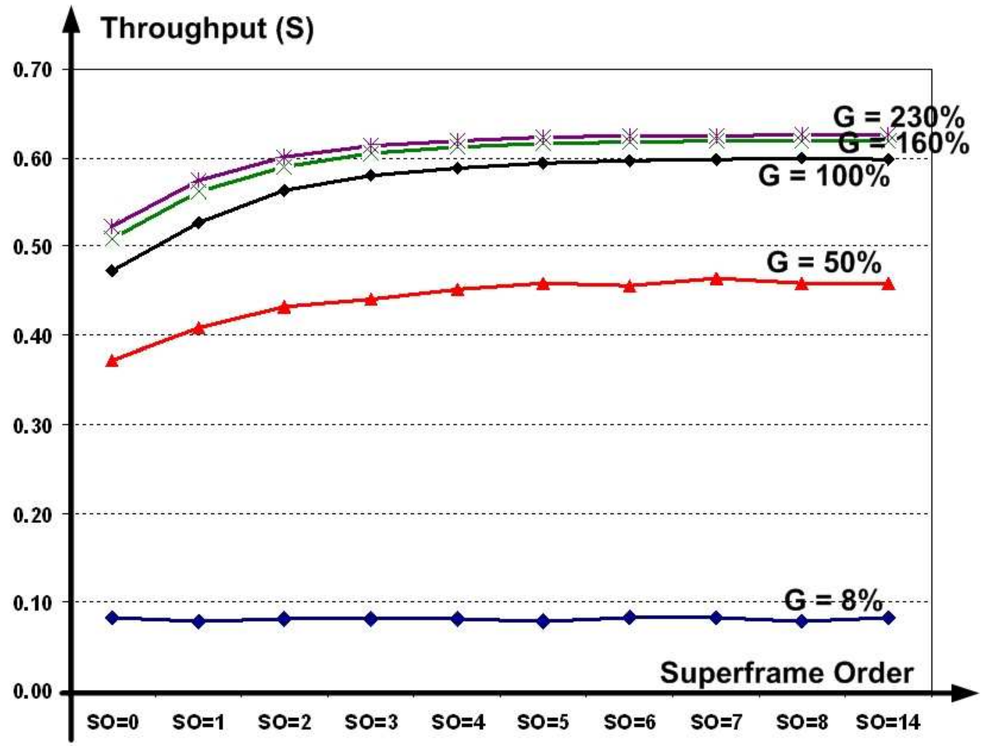
CMSA/CA Performance

- **Summary of results**
  - BO and SO have an impact on the throughput (and success probability)
  - Lower SO decreases the throughput due to CCA deference effect
  - Delay increases with BO for high load and decreases with BO for low load
  - macMinBE does not have an impact of throughput for large-scale nets and do have for low-scale.
  - Delay increases with macMinBE

Impact of BO and SO



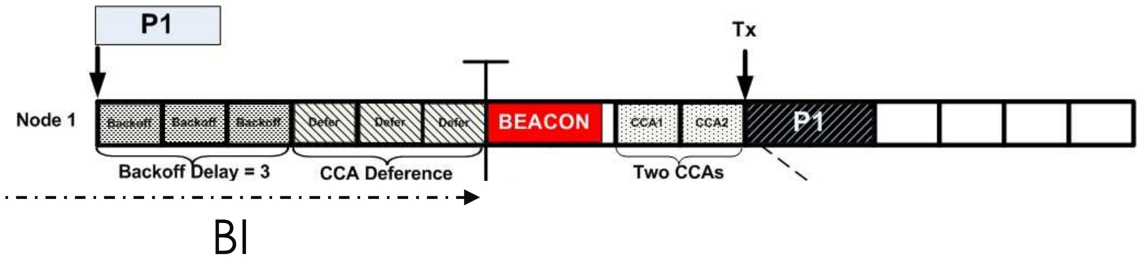
Throughput (S) as a function of the offered load (G)



Throughput (S) as a function of Superframe Order (SO)

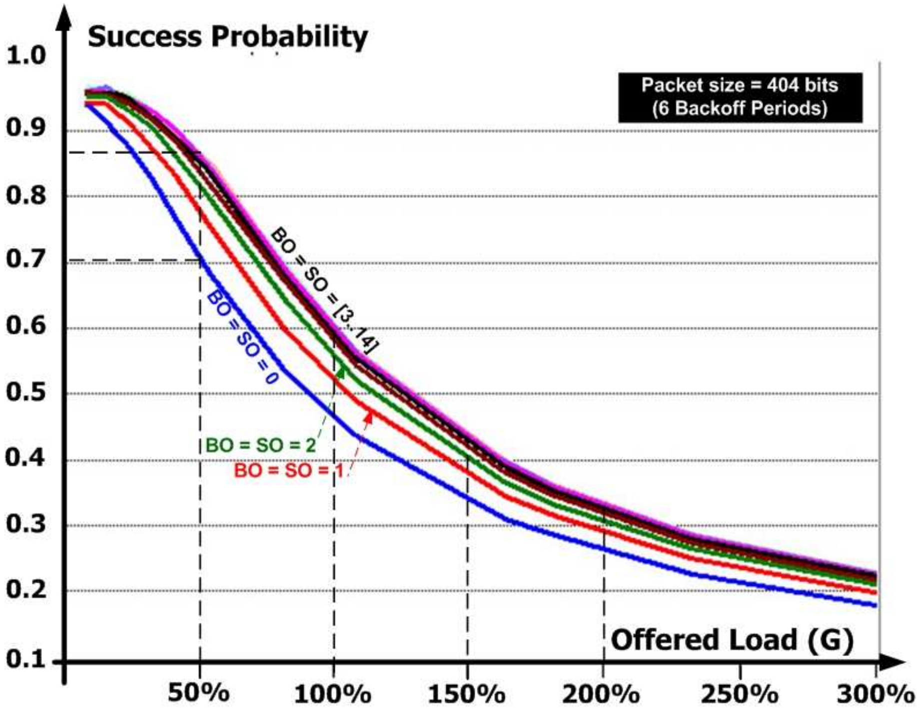
Impact of BO and SO

Problem of the CCA Deference (Spec. 2003)

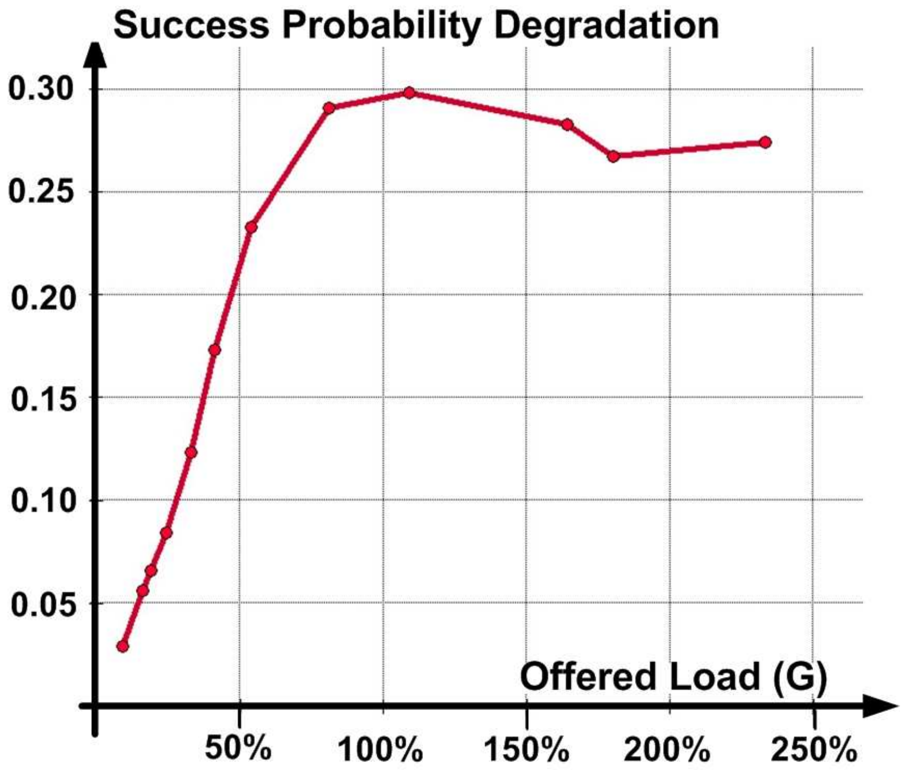


Based on simulation results, the CCA deference with SO = 0 degrades the throughput performance from 20% to 25% as compared to throughput with SO = 14.

Impact of BO and SO



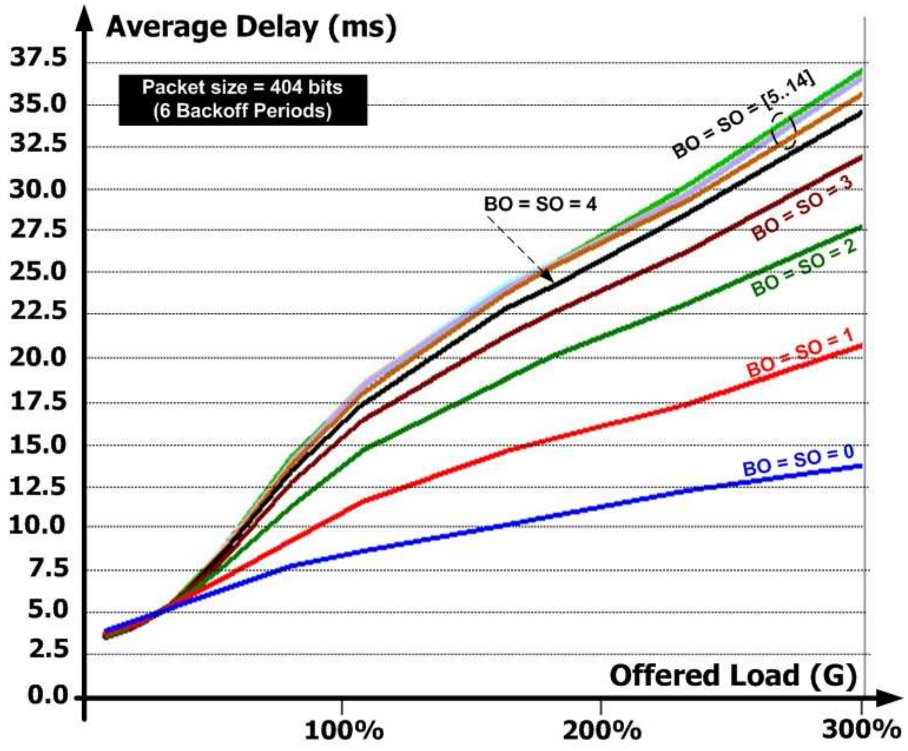
Success Probability as a function of the offered load (G)



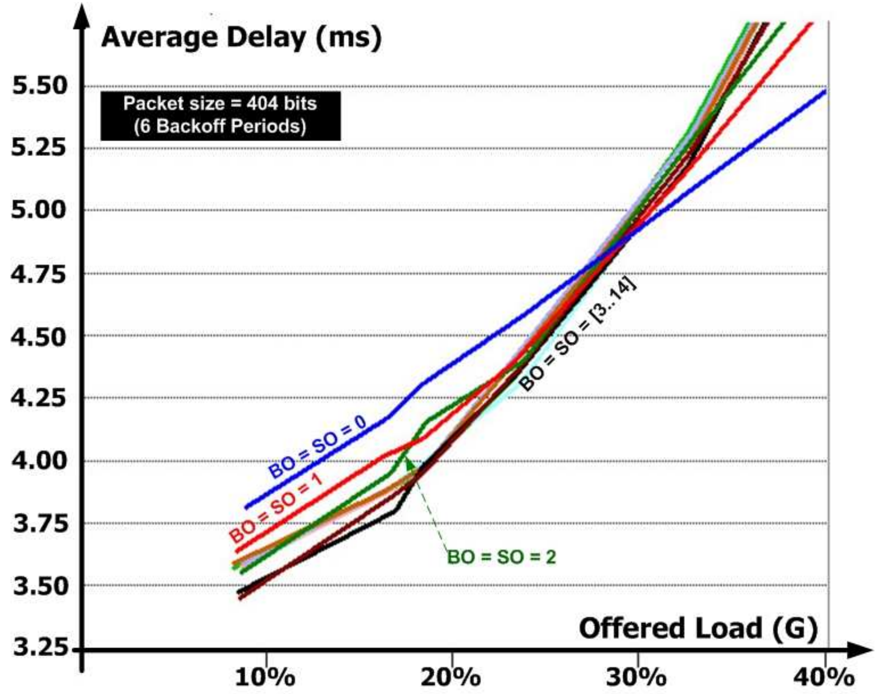
Success Probability Degradation
for SO = 0 as compared to SO = 14

Up to 30% of success probability degradation

Impact of BO and SO on Delay

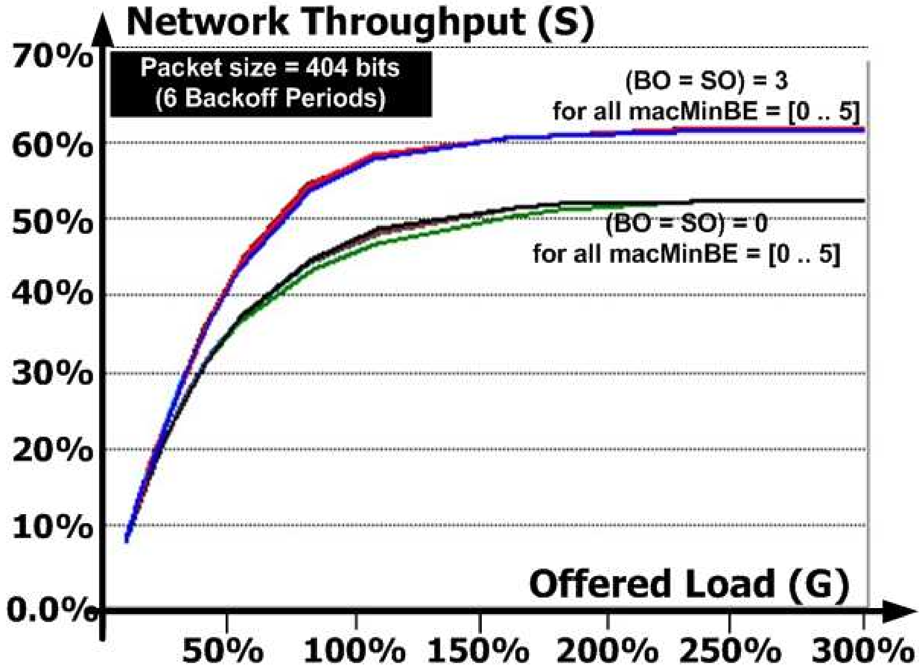


Average delay as a function of the offered load (G)

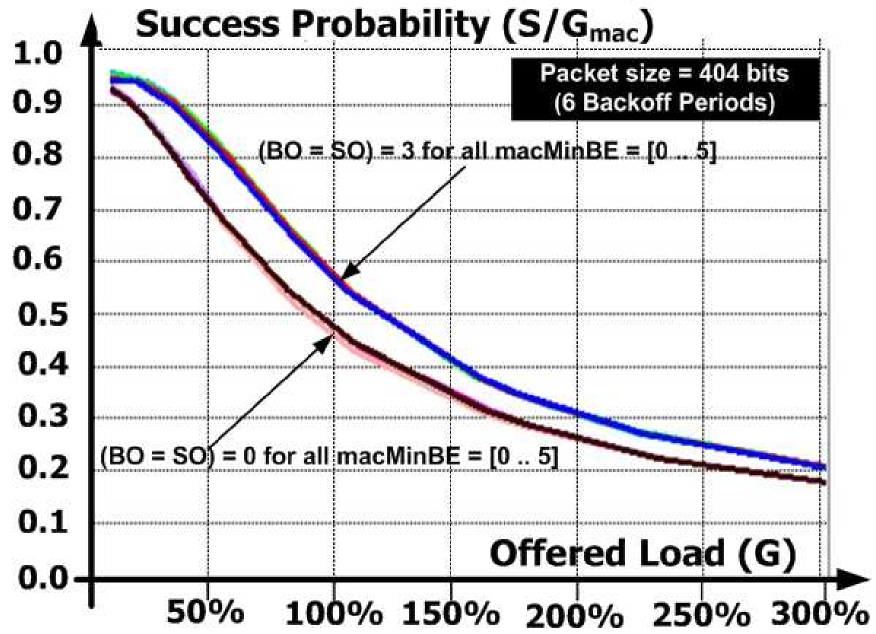


Average delay as a function of the offered load (G) at low load conditions

Impact of *macMinBE*



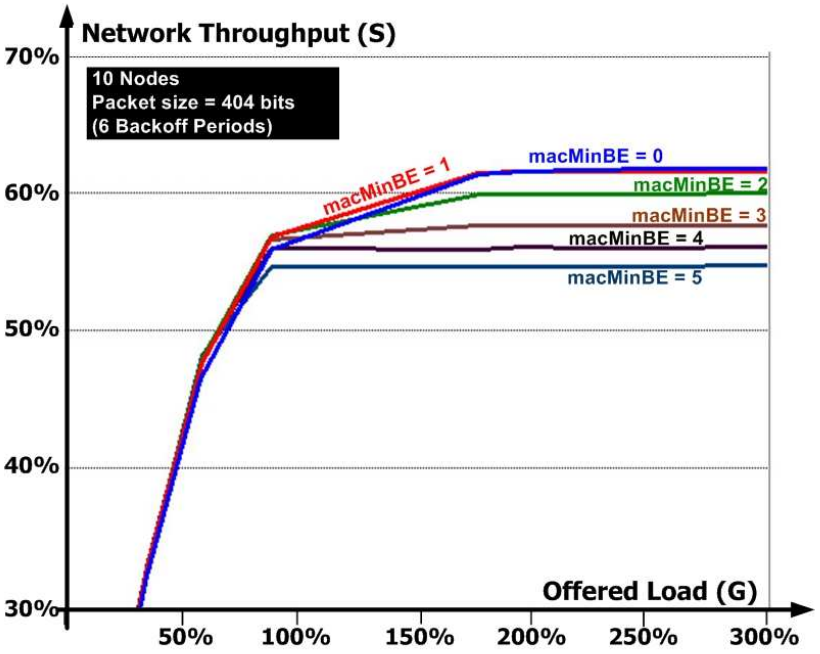
Throughput as a function of the offered load (G)



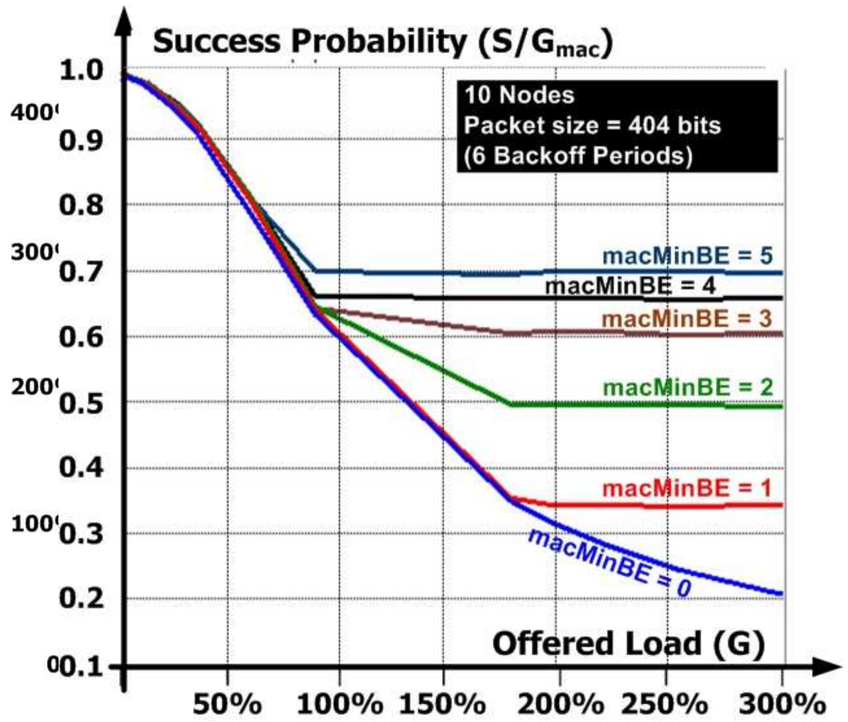
Success Probability as a function of the offered load (G)

No impact of macMinBE on the throughput in large scale WSNs

Impact of *macMinBE*: Case of 10 Nodes



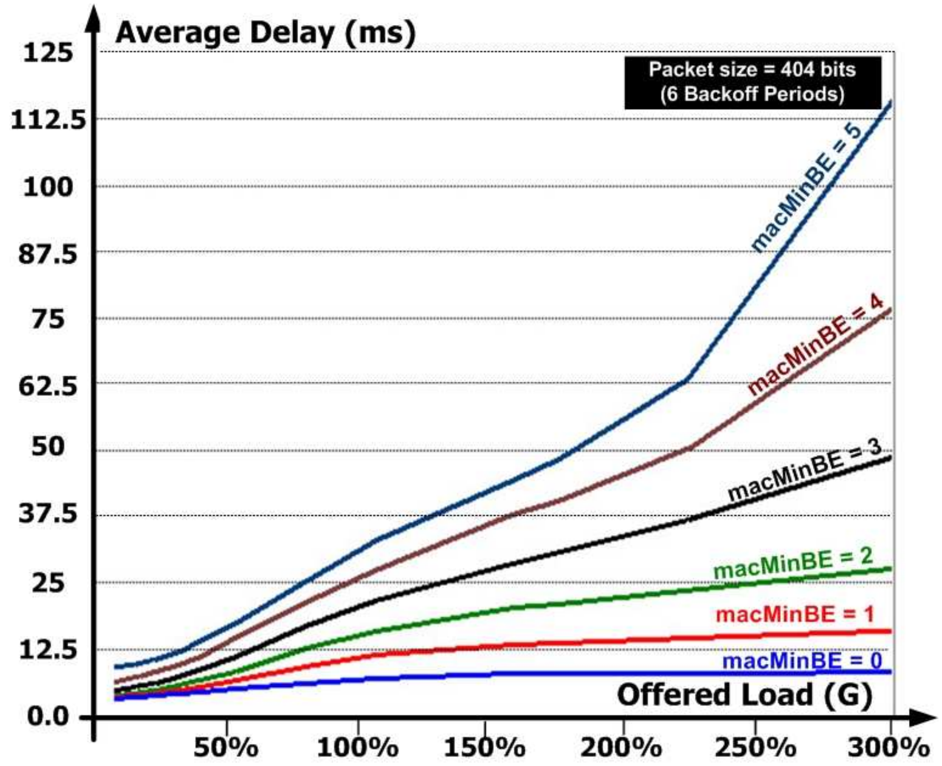
Throughput as a function of the offered load (G) with 10 nodes



Success Probability as a function of the offered load (G)

Higher *macMinBEs* improve the reliability of broadcasts in small scale WSNs

Impact of *macMinBE*: Case of 100 Nodes



Average delays as a function of the offered load (G) with 100 nodes

Higher macMinBEs increase the average delays

CAPACITY OF ZIGBEE CLUSTER-TREE SENSOR NETWORKS

Related references

Petr Jurčík, Anis Koubâa, Mário Alves
On the Capacity of Cluster-tree ZigBee Networks
COGnitive systems with Interactive Sensors, Paris, 2009.

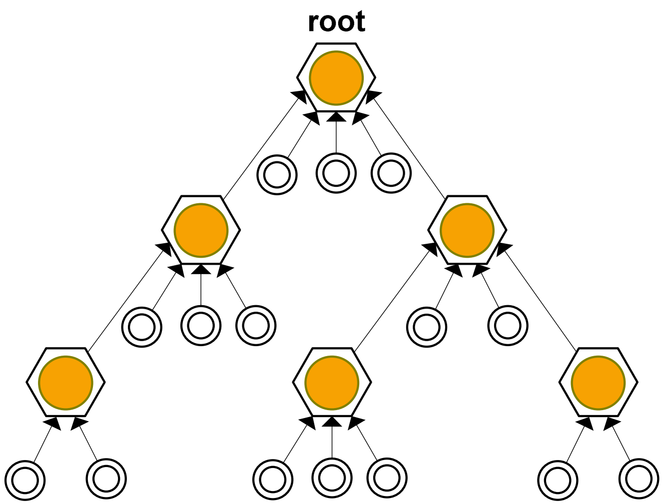
Petr Jurčík, Ricardo Severino, Anis Koubâa, Mário Alves
Real-Time Communications over Cluster-Tree Sensor Networks with Mobile Sink Behaviour
the 14th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA 2008), Kaohsiung, Taiwan , 25 - 27 August 2008

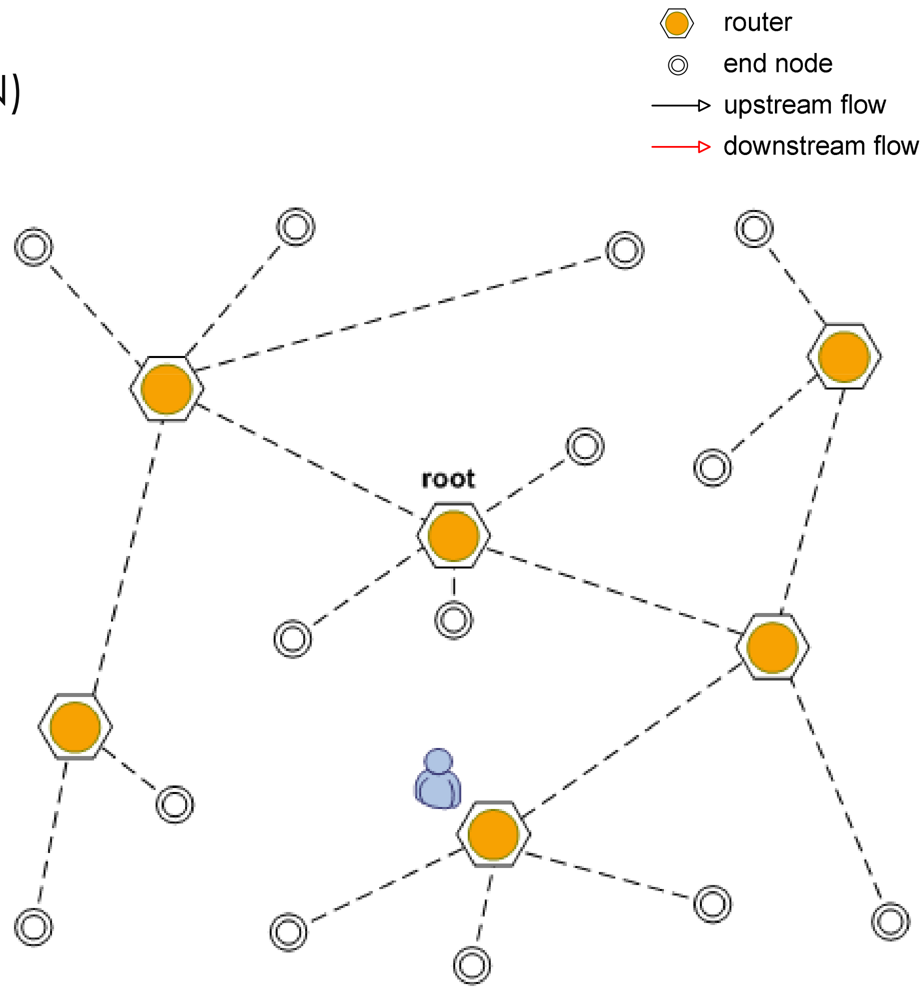
A. Koubâa, M. Alves, E. Tovar
Worst-Case Dimensioning of Cluster-Tree Wireless Sensor Networks
IEEE Real-Time System Symposium (RTSS'06), Rio di Janeiro (Brazil), Dec. 2006.

Problem

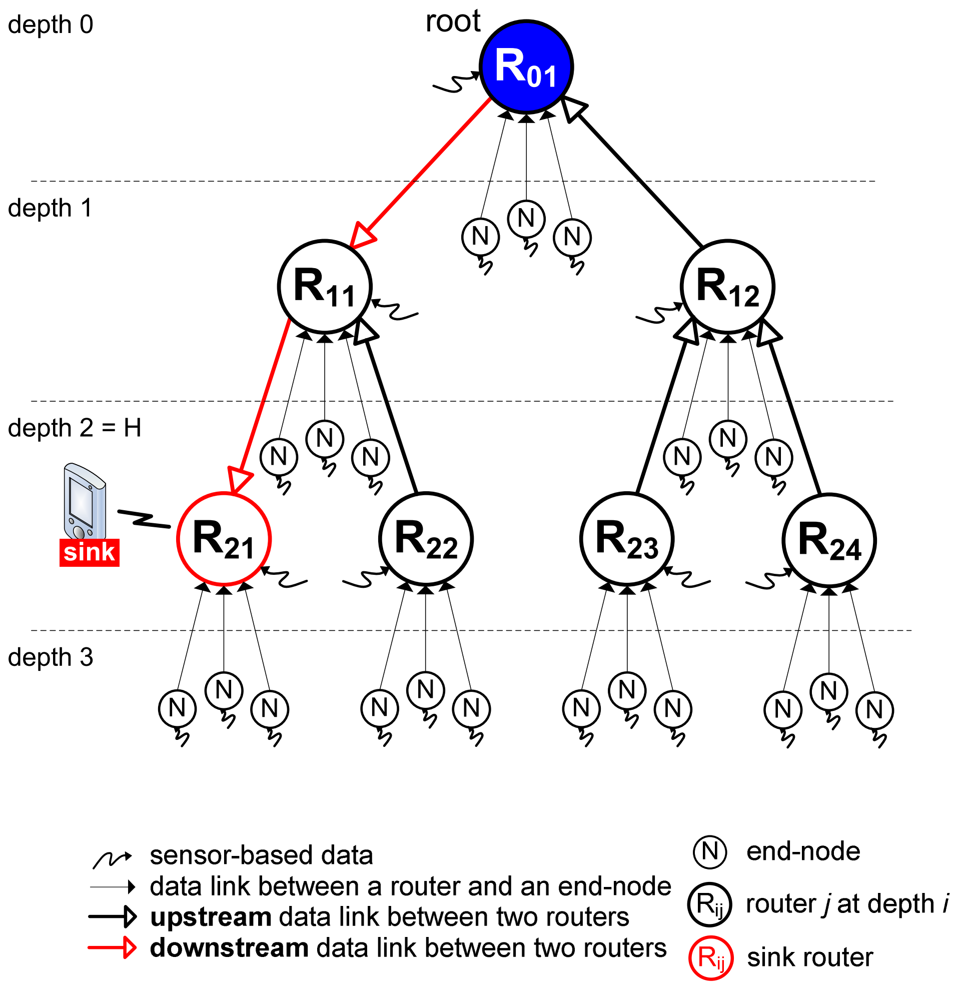
- Static/dynamically changing WSNs
  - worst-case cluster-tree topology
- Sink oriented data communication (WSN)
- Support for autonomous sink mobility
  - upstream and downstream flows
- Worst-case dimensioning

  and analysis of cluster-tree WSN





Cluster-Tree Topology Model



- $H = 2$
- $N_{router}^{MAX} = 2$
- $N_{end\text{-}node}^{MAX} = 3$
- $H_{sink} = 2$

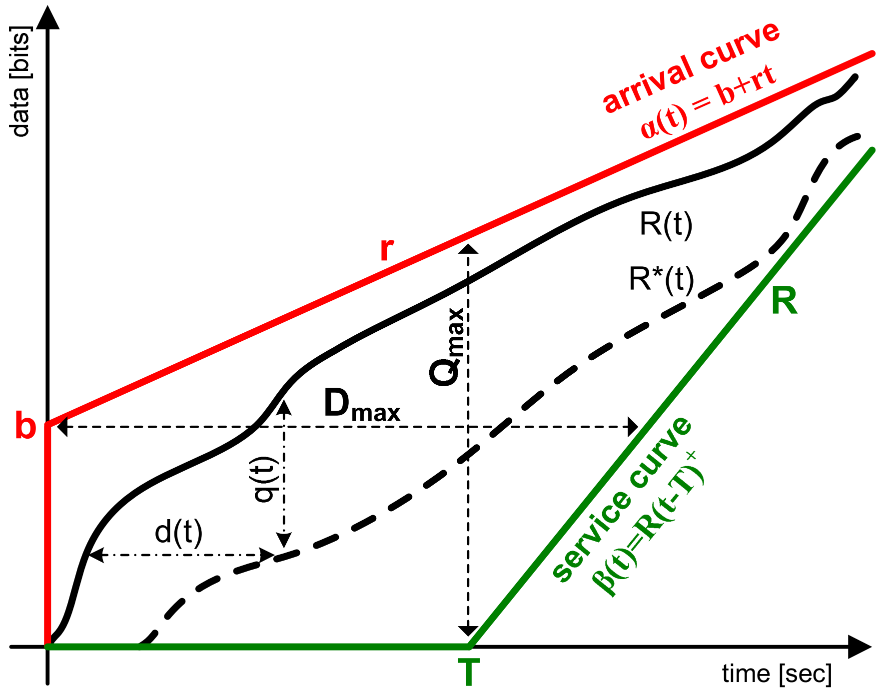
worst-case topology

- balanced tree
- balanced load

mobile sink

- upstream flows
- downstream flows

Data Flow Model – Network Calculus

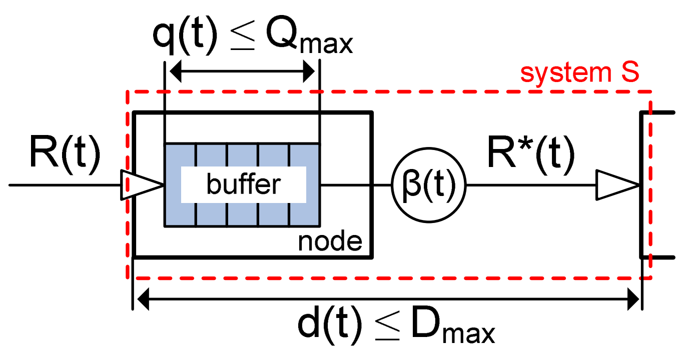


- backlog bound

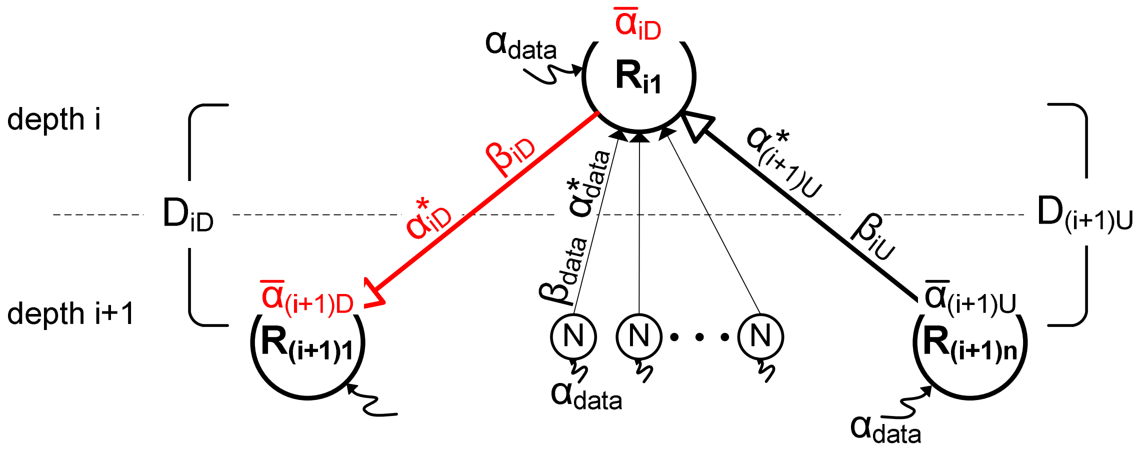
$$Q_{max} = b + r \cdot T$$

- delay bound

$$D_{max} = \frac{b}{R} + T$$



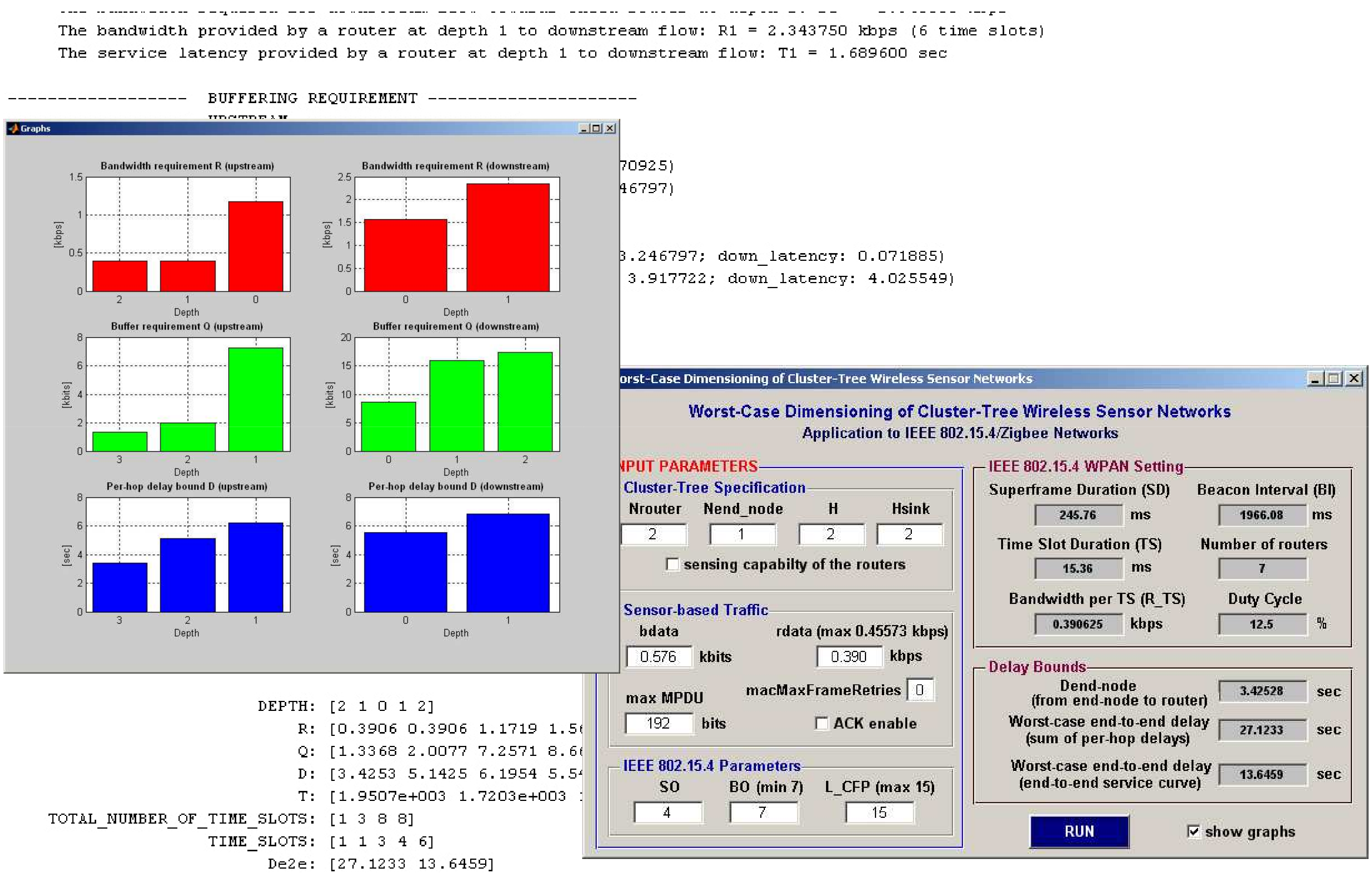
Network Flow Analysis



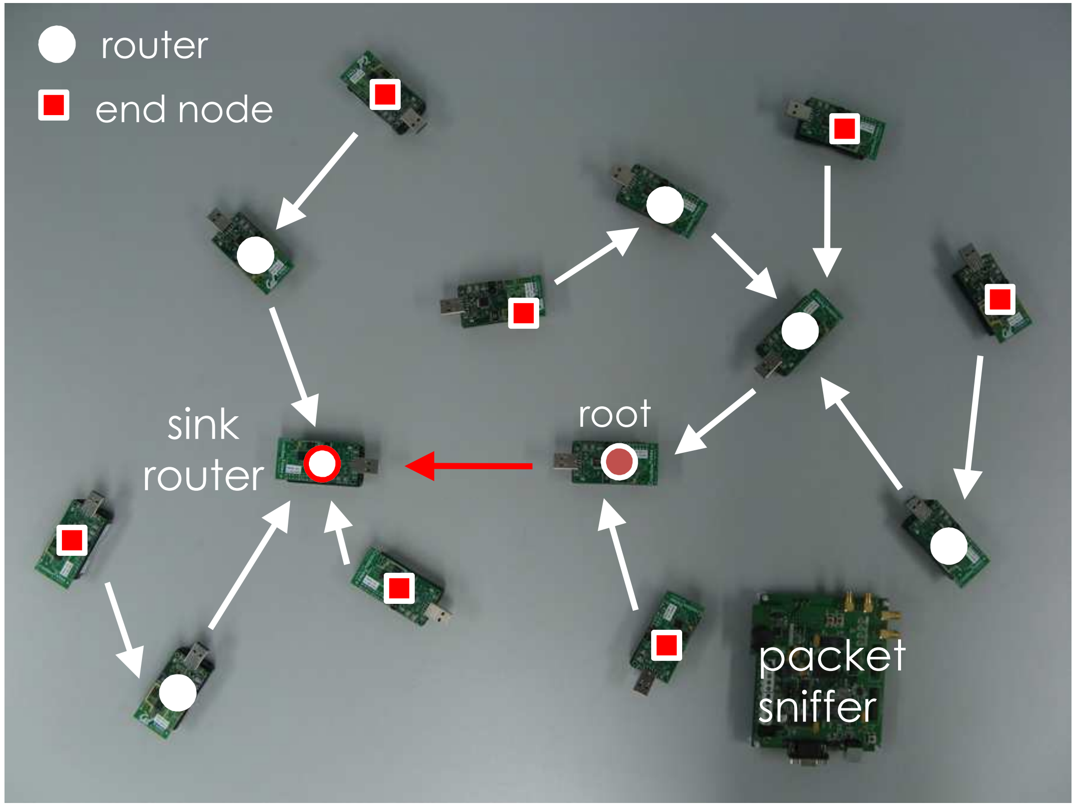
- **per-hop analysis**
  - arrival curve constraining the total input flow of any router at depth *i*
  - upper bound of outgoing flow from a router at depth *i*
  - bandwidth requirement by a router at depth *i*
  - buffer requirement by a router at depth *i*
  - delay between routers

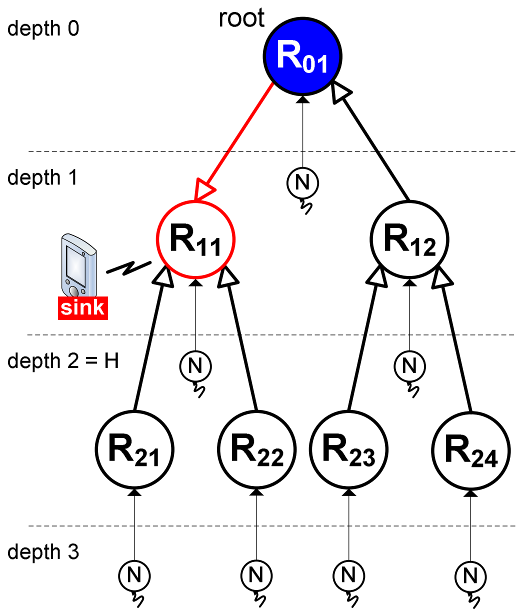
- **maximum end-to-end delay D_{e2e}^{MAX} [sec]**
  - sum of per-hop delays
  - network-wide service curve for individual flows

Matlab Model – Analytical Model



Experimental Setup – Test Bed Deployment





- $H = 2$
- $N_{router}^{MAX} = 2$
- $N_{end\text{-}node}^{MAX} = 1$
- $H_{sink} = 1$

- TelosB motes
  - IEEE 802.15.4/ZigBee protocol stack (TinyOS)
- Chipcon cc2420 packet sniffer

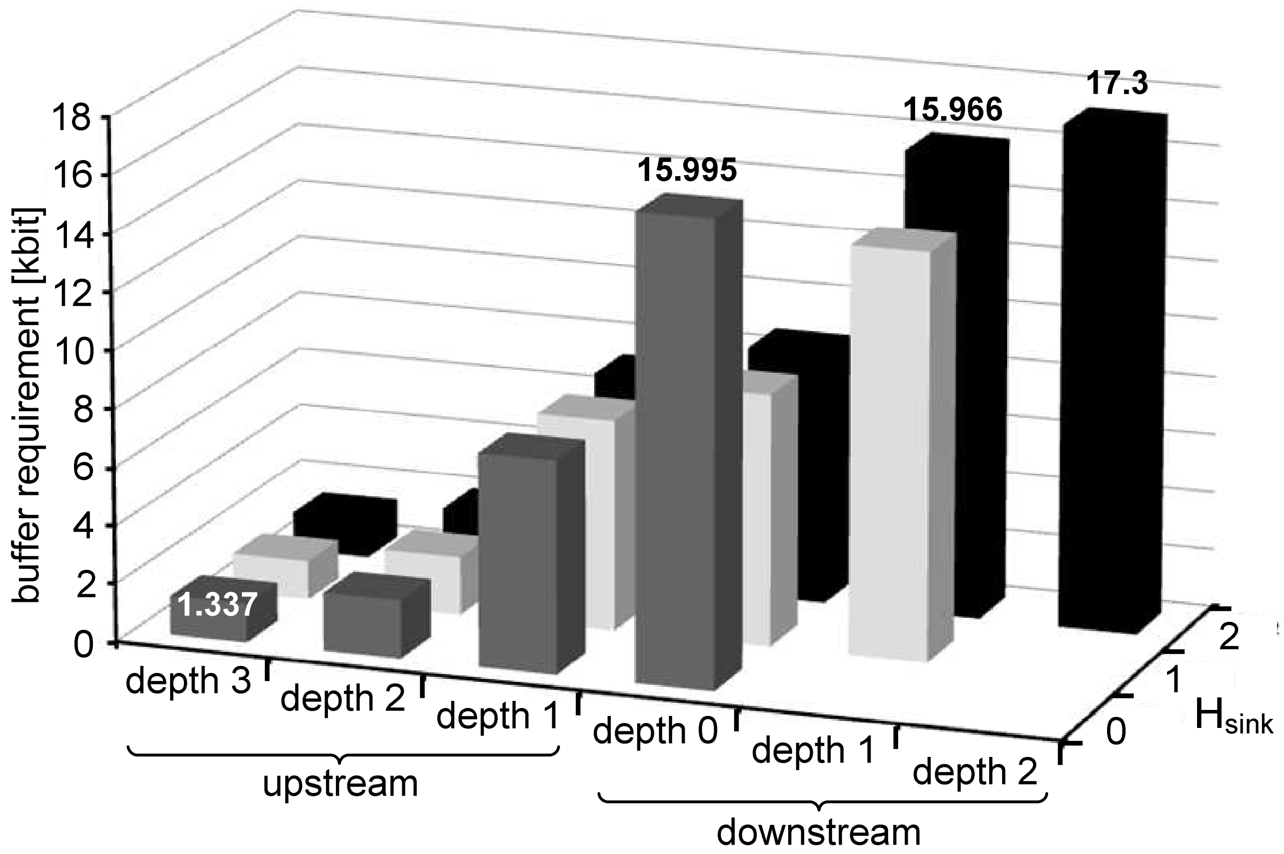
Performance Evaluation

worst-case dimensioning of WSNs

- the **maximum** resource requirements (e.g. buffer, delay) per depth for an aggregate flow along the longest path in WSN
- the average resource requirement per depth

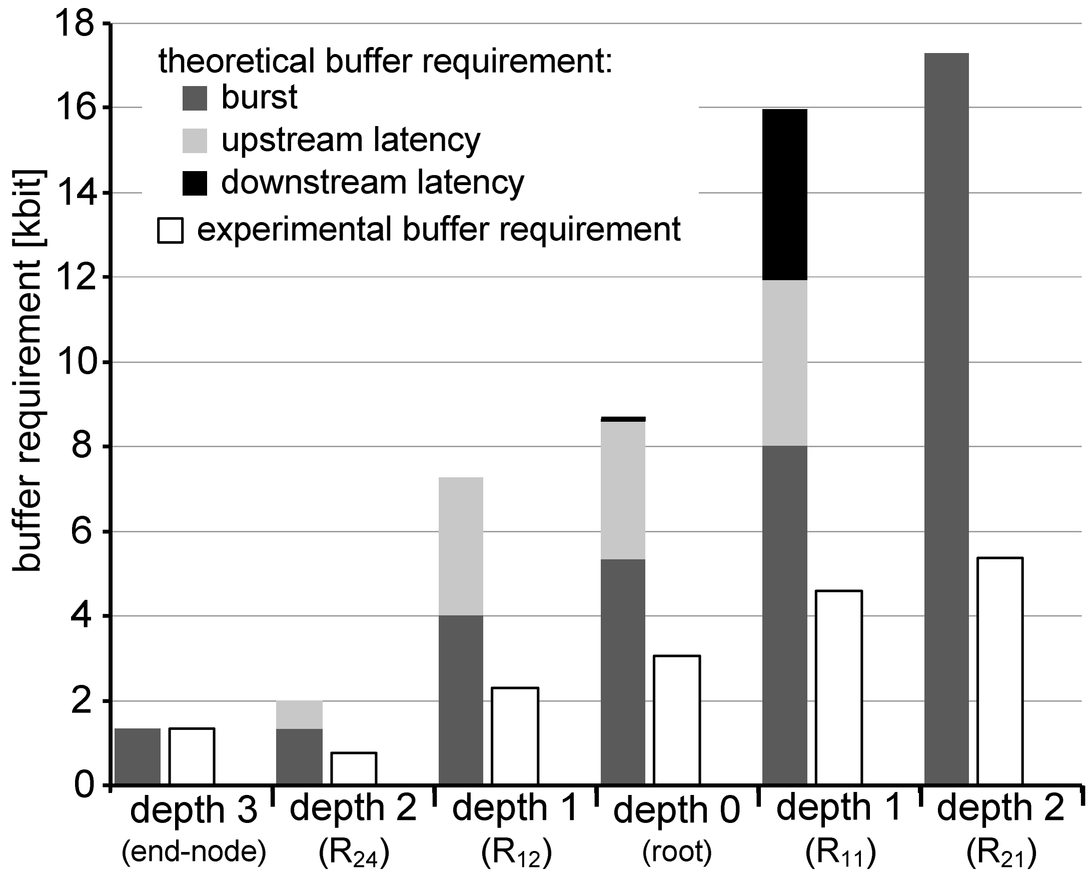
Buffer Requirements

the theoretical worst-case buffer requirements per router as a function of the depth and sink position



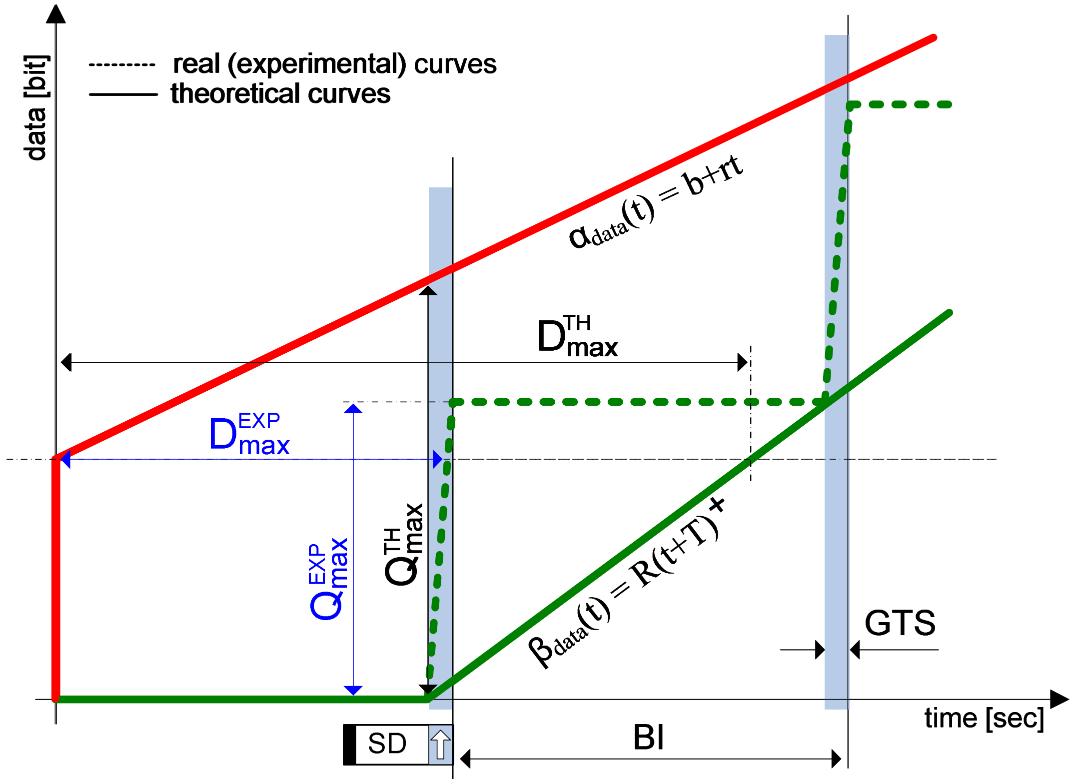
Buffer Requirements

the theoretical worst-case vs. experimental maximum buffer requirements for $H_{sink} = 2$



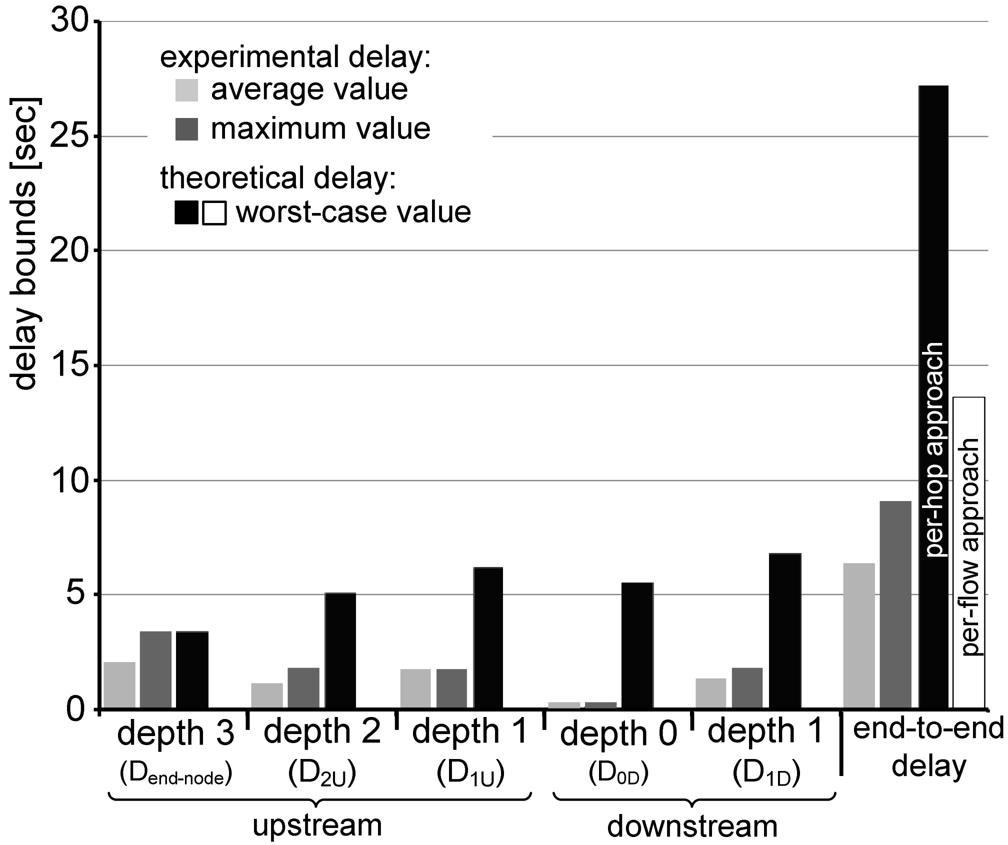
Theoretical vs. Experimental Data Traffic

- in practice, data is transmitting only during the GTS
- the gap between theoretical and experimental grow with depth (cumulative flow effect)
- rate-latency service curve → trade-off between complexity and pessimism



Delay Bounds

the theoretical worst-case vs. experimental maximum and average delay bounds

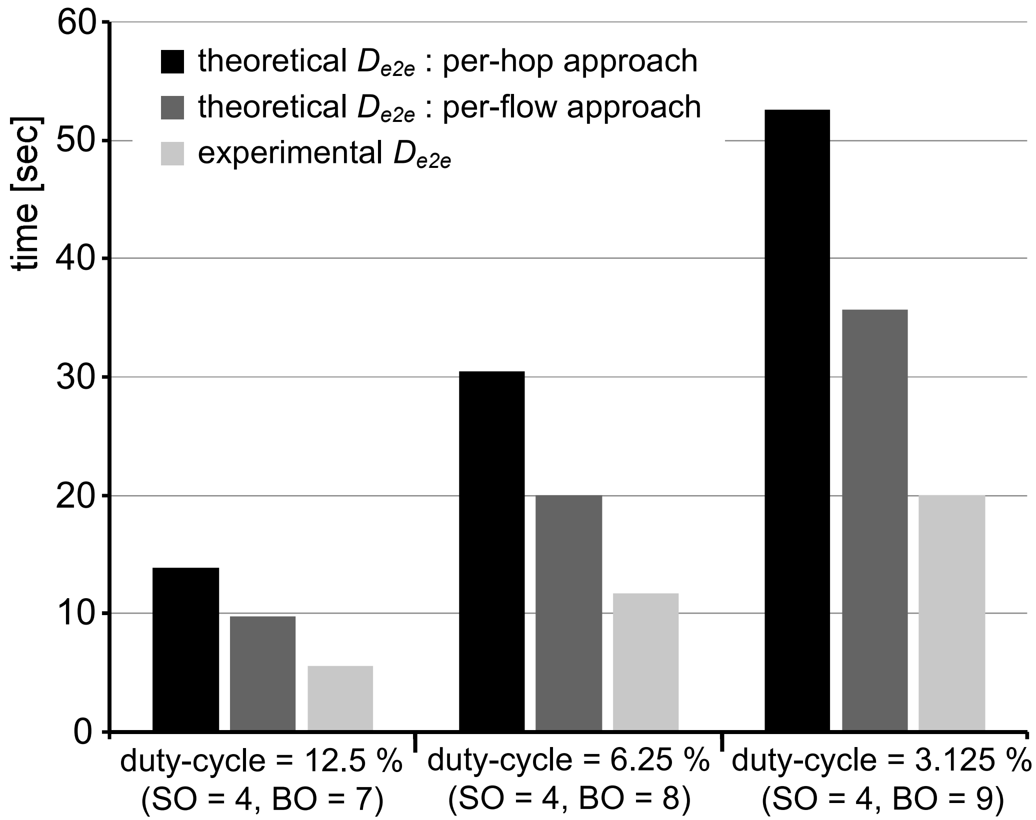


end-to-end delay

- per-hop approach
- per-flow approach
  - network wide curve

Duty-cycle vs. Timing Performance

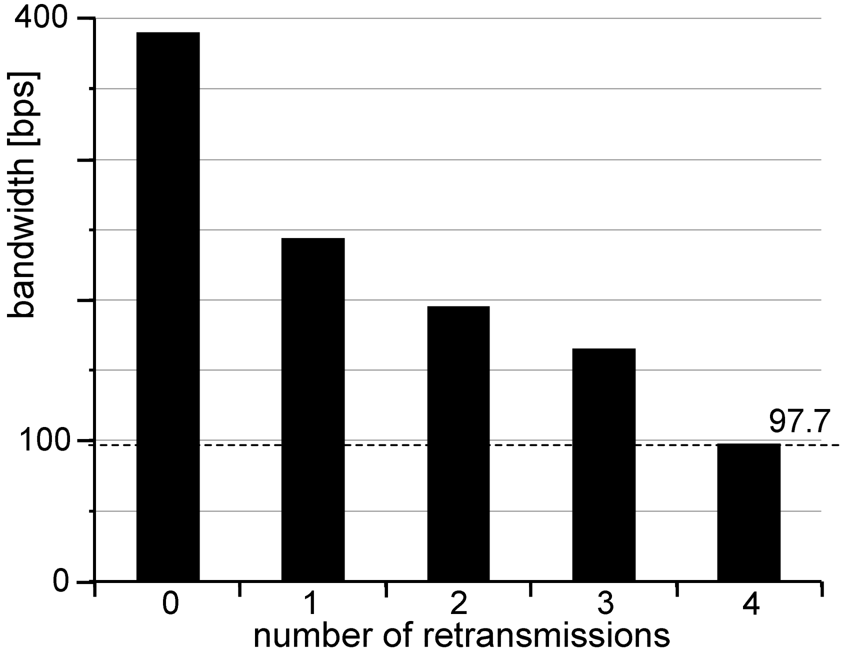
the theoretical worst-case and experimental maximum end-to-end delay as a function of duty cycle for $H_{sink} = 0$ (lifetime of WSNs)

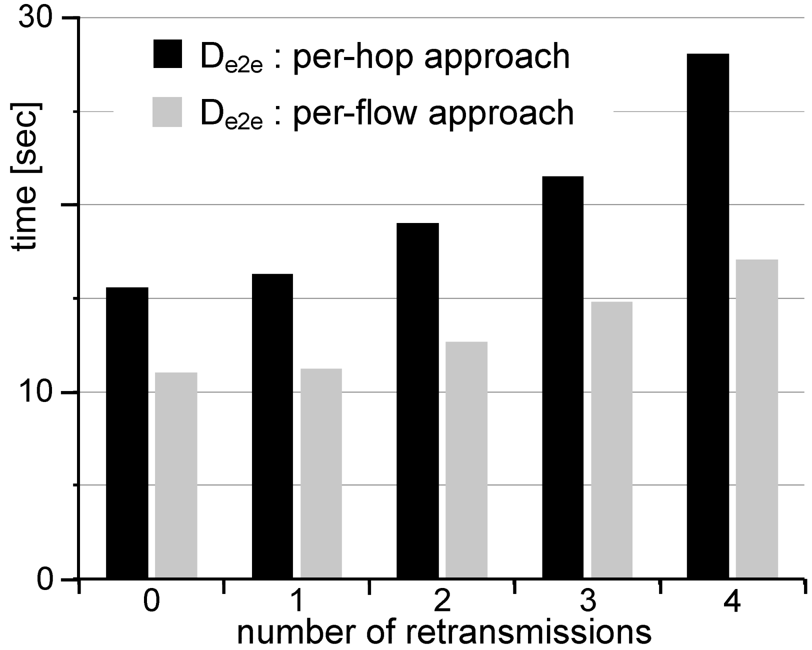


$$\text{duty-cycle} = \frac{SD}{BI} = \frac{2^{SO}}{2^{BO}}$$

Number of Retransmissions vs. Timing Performance

unreliable and time-varying characteristics of wireless channels can be minimized using the retransmission mechanisms

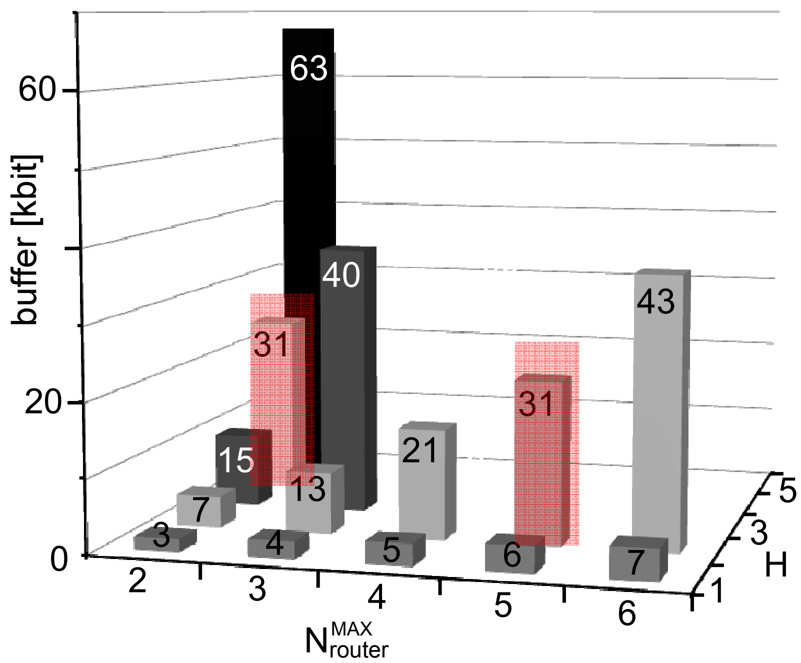


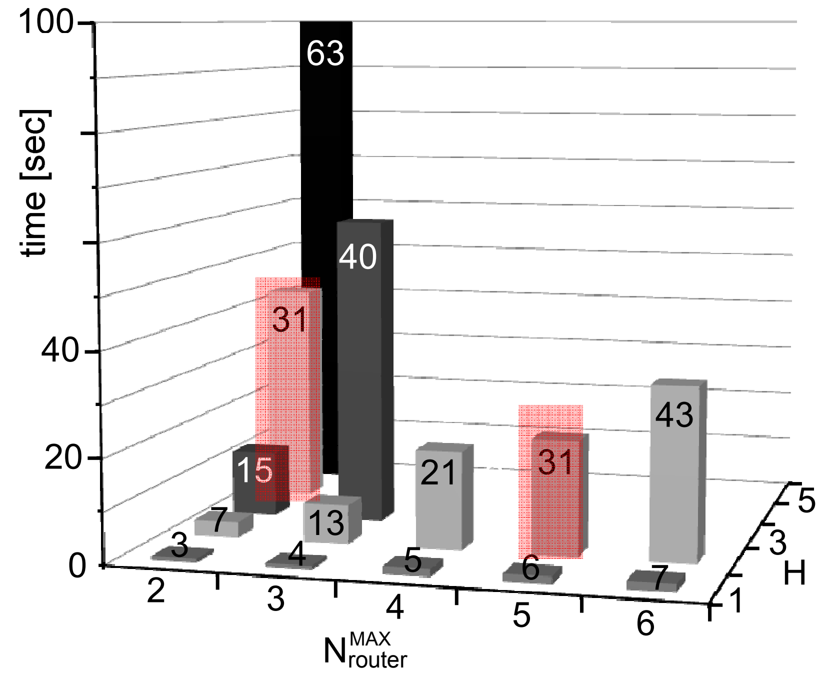


guaranteed bandwidth of one time slot and the theoretical worst-case end-to-end delay as a function of the maximum number of retransmissions

Network Planning –
Feasible Configurations

buffer requirement of the sink router (H_{sink}=0) and the worst-case end-to-end delay as a function of the height of the tree and the maximum number of child routers





Outline

- **Part I. Introduction to IEEE 802.15.4/ZigBee**
- **Part II. Performance Evaluation**
  - Performance Evaluation of the IEEE 802.15 GTS Worst-Case
  - Performance Evaluation of CSMA/CA
  - Dimensioning of IEEE 802.15/ZigBee Cluster-Tree Networks
- **Part III. Amendments to the standard**
  - Enhanced GTS Mechanism for the IEEE 802.15.4
  - Hidden Node Avoidance Mechanism for IEEE 802.15.4 Networks
  - Synchronization Mechanism of the IEEE 802.15.4/ZigBee Cluster-Tree Wireless Sensor Networks
- **Part VI. Tools and Experimental Testbeds**
  - Implementations
  - OPNET Simulation Model of IEEE 802.15.4/ZigBee

Part. III.
Amendment to the IEEE 802.15.4/ZigBee standard

AMENDMENTS FOR THE GTS MECHANISM

Related references

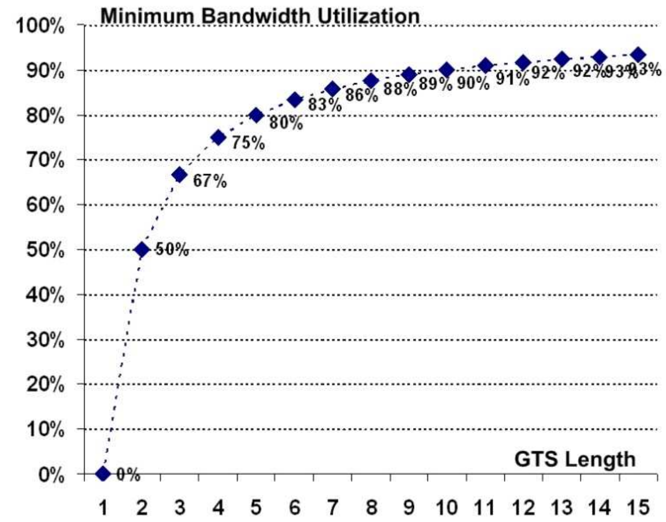
Anis Koubâa, Andre Cunha, Mario Alves, Eduardo Tovar
i-GAME: An Implicit GTS Allocation Mechanism in IEEE 802.15.4, theory and practice
in Springer Real-Time Systems Journal, Volume 39, Numbers 1-3, pp 169 - 204, Springer, August 2008.

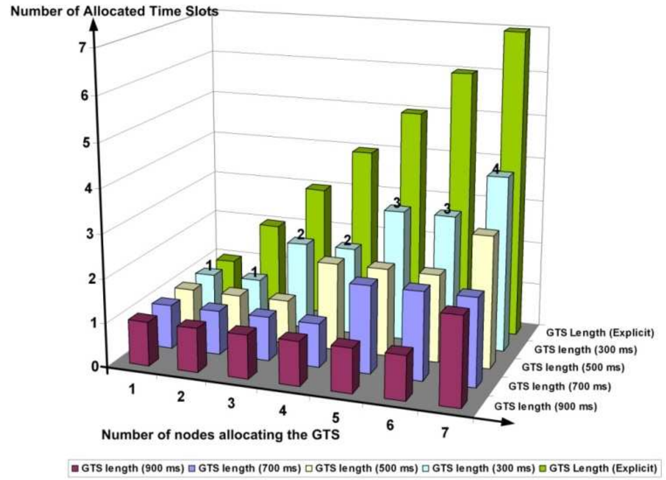
Andre Cunha
On the use of IEEE 802.15.4/ZigBee as federating communication protocols for Wireless Sensor Networks
MSc Thesis, University of Porto, Faculty of Engineering, September 2007.

A. Koubâa, M. Alves, E. Tovar
i-GAME: An Implicit GTS Allocation Mechanism in IEEE 802.15.4
In Euromicro Conference on Real-Time Systems (ECRTS 2006), Dresden (Germany), July 2006. (~*25% acceptance*)

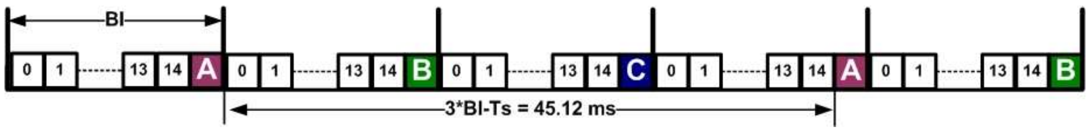
i-GAME: Implicit Allocation of GTS

- **Problem**
  - Each Superframe supports a **maximum of 7 GTS** allocations
  - **Each GTS** is exclusively assigned to **one node** (upstream or downstream)
  - **GTS may be underutilized**
- The implicit GTS Allocation Mechanism (**i-GAME**) overcomes these limitations
  - **same GTS used by more than 1 node**
    - guaranteeing the nodes delay and bandwidth requirements (negotiated between nodes and ZC)
    - dynamically allocating GTS in each Superframe (scheduled by ZC in round-robin)

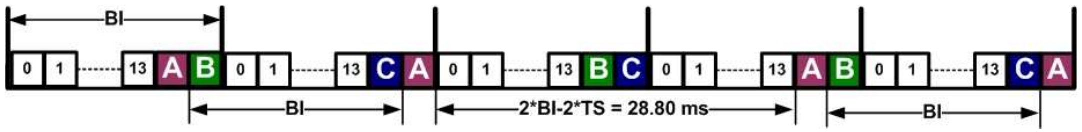




2 data flows sharing 1 Time Slot



3 data flows sharing 2 Time Slots



i-GAME: Implicit Allocation of GTS

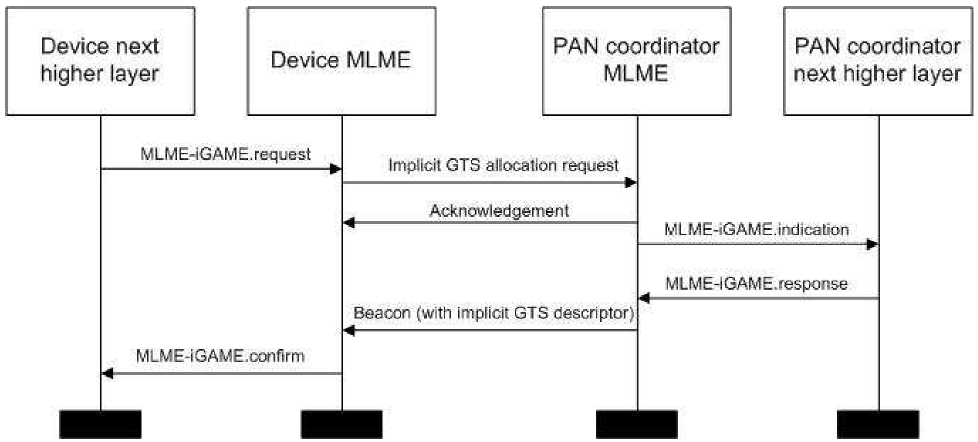
- admission control function in the ZC
  - nodes send their implicit requests including their traffic specification (b,r,D)
  - The ZC performs the admission control algorithm based on a schedulability test
- backward compatibility ensured
  - use reserved field in standard packet format
    – **Allocation Type**

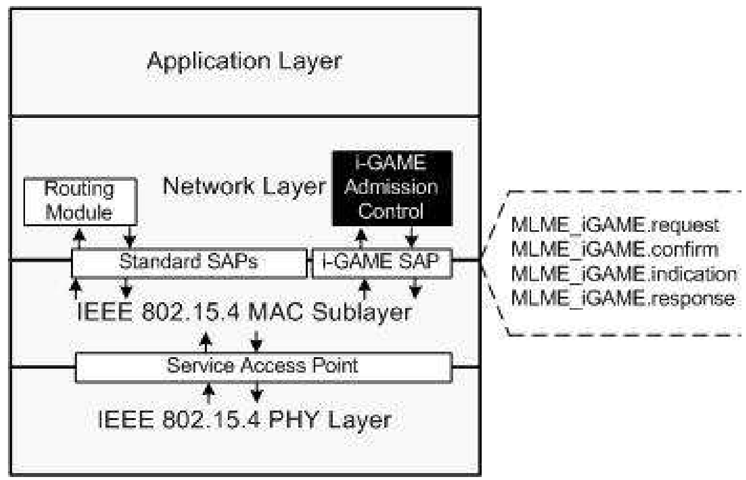
bits	0-3	4	5	6	7
	GTS Length	GTS Direction	Characteristics Type	Allocation Type	Reserved

GTS Characteristics Extension Field Format for Implicit Request Allocation

bits	0-3	4-7	8-12	12-15
	Burst size	Arrival Rate	Delay Requirement	Reserved

Flow Specification Field Format for i-GAME





TDBS FOR ZIGBEE SYCHRONIZATION

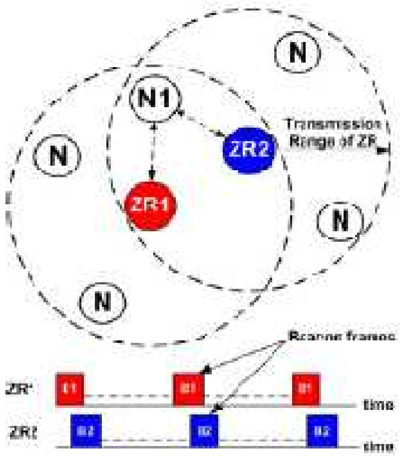
Related references

Anis Koubâa, Andre Cunha, Mario Alves, Eduardo Tovar
TDBS: a time division beacon scheduling mechanism for ZigBee cluster-tree wireless sensor networks
in Springer Real-Time Systems Journal, Volume 40, Number 3, pp 321 - 354, Springer, October 2008.

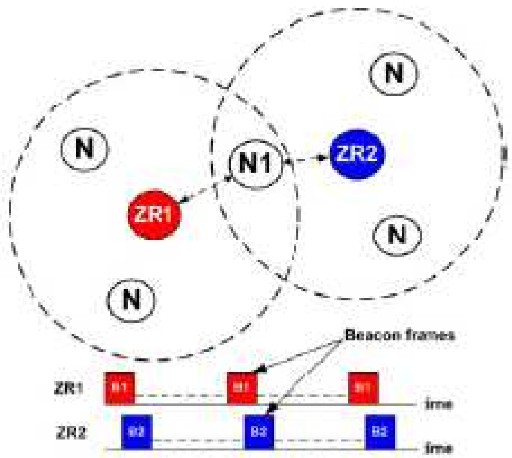
Anis Koubaa, Andre Cunha, Mário Alves,
A Time Division Beacon Scheduling Mechanism for IEEE 802.15.4/Zigbee Cluster-Tree Wireless Sensor Networks
19th Euromicro Conference on Real-Time Systems (ECRTS 2007), Pisa(Italy), July 2007.
Won the"Best Paper Award" (~25% acceptance)

TDBS: Time Division Beacon Scheduling

- **Problem Statement**
  - synchronization in ZigBee cluster-tree networks is based on beacon frames, to avoid inter-cluster collisions
  - the IEEE 802.15.4/Zigbee specifications do not provide any practical solution to synchronize a cluster-tree network
- **Challenge**
  - how to coordinate the generation of beacon frames in a cluster-tree network to ensure a collision-free synchronization?



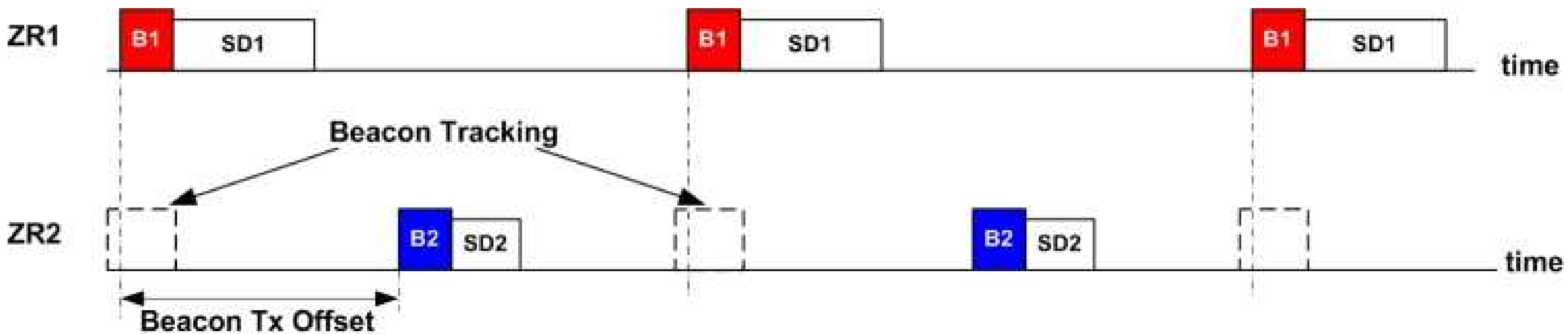
Direct Beacon Frame Collision



Indirect Beacon Frame Collision

TDBS: Time Division Beacon Scheduling

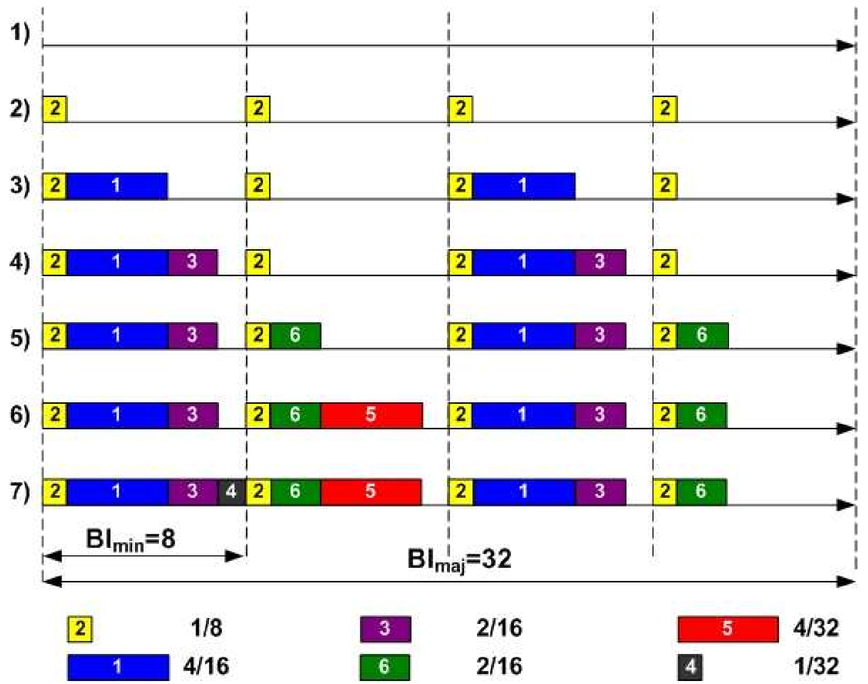
- **Solution**
  - **Time Division Beacon/Superframe Scheduling (TDBS)**
    - **pros**
      - simple
      - no changes to the standard specifications
    - **cons**
      - high cluster density $\Rightarrow$ low duty-cycle
      - direct communication between neighbors is impossible



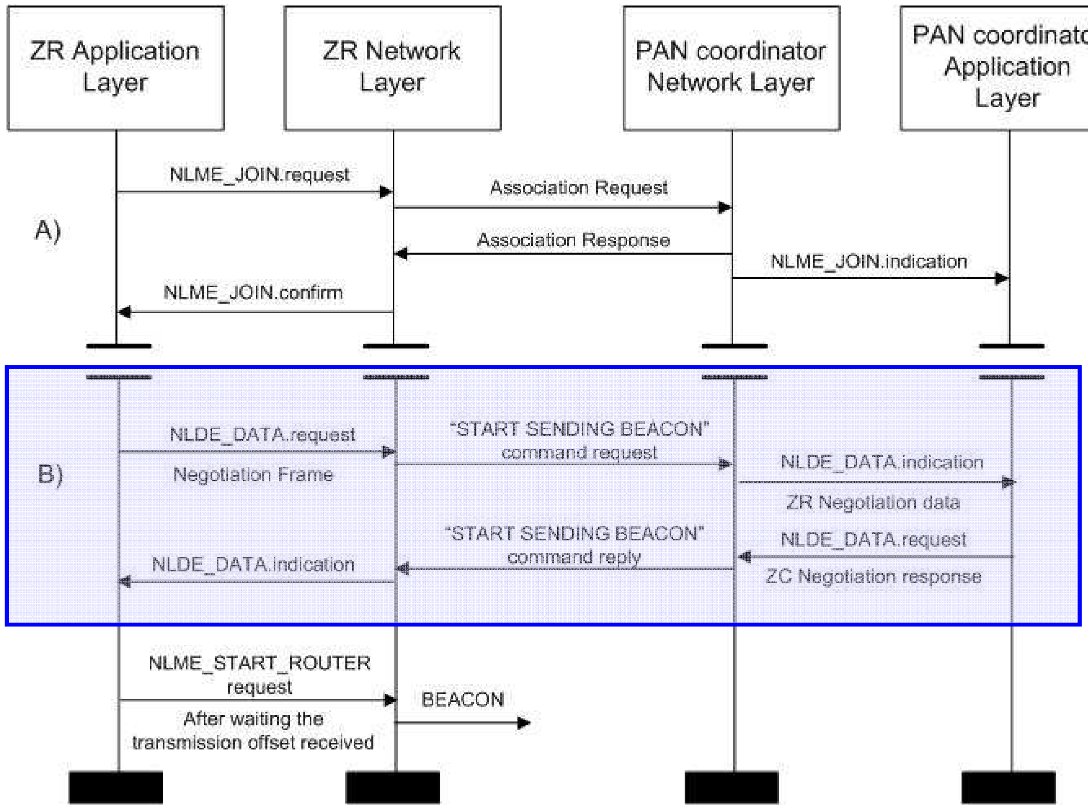
TDBS: Time Division Beacon Scheduling

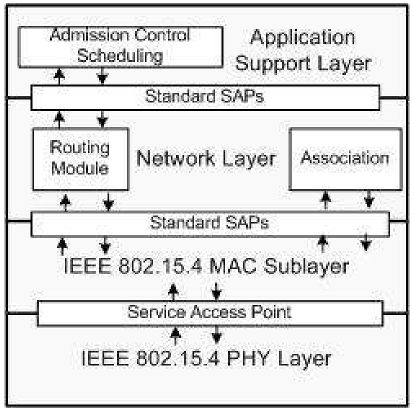
- how to **organize the beacon frames** of the different ZigBee Routers to avoid collisions with other beacons or data frames
- **sufficient to find a cyclic schedule in a hyper-period equal to BImax**

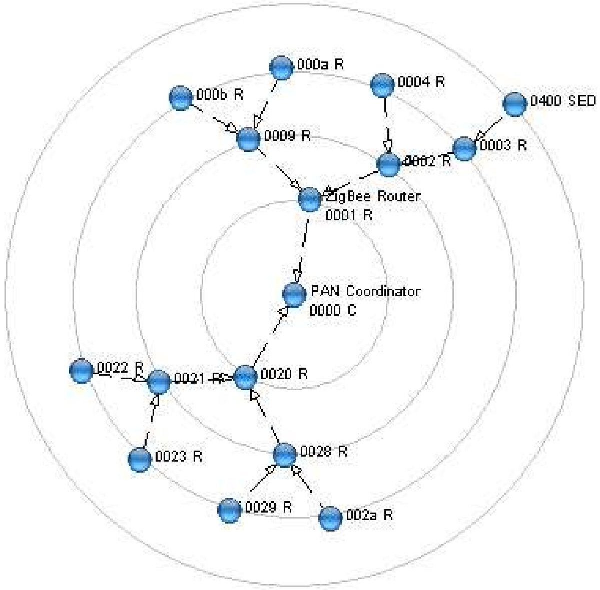
ZigBee Routers	SD	BI
ZR1	4	16
ZR2	1	8
ZR3	2	16
ZR4	1	32
ZR5	4	32
ZR6	2	16



TDBS: Time Division Beacon Scheduling







IMPROVED SCHEMES FOR CSMA/CA MECHANISM

Related references

A. Koubâa, R. Severino, M. Alves, E. Tovar
Improving Quality-of-Service in Wireless Sensor Networks by mitigating hidden-node collisions
IEEE Transactions on Industrial Informatics, Special Issue on Real-Time and Embedded Networked Systems, Volume 5, Number 3, August 2009.

Ricardo Severino
On the use of IEEE 802.15.4/ZigBee for Time-Sensitive Wireless Sensor Network Applications
MSc Thesis, Polytechnic Institute of Porto, School of Engineering, October 2008. BEST EWSN/CONET MSc THESIS AWARD, 2009.

Anis Koubâa, Ricardo Severino, Mario Alves, Eduardo Tovar
H-NAMe: A Hidden-Node Avoidance Mechanism for Wireless Sensor Networks
8th IFAC International Conference on Fieldbuses and Networks in Industrial and Embedded Systems (FET'09), Ansan, Republic of Korea, May 2009.

A. Koubâa, M. Alves, B. Nefzi, Y. Q. Song
Improving the IEEE 802.15.4 Slotted CSMA/CA MAC for Time-Critical Events in Wireless Sensor Networks
In Proc. of the Workshop of Real-Time Networks (RTN 2006), *Satellite Workshop to* (ECRTS 2006), July 2006.

First Approach

Traffic Differentiation

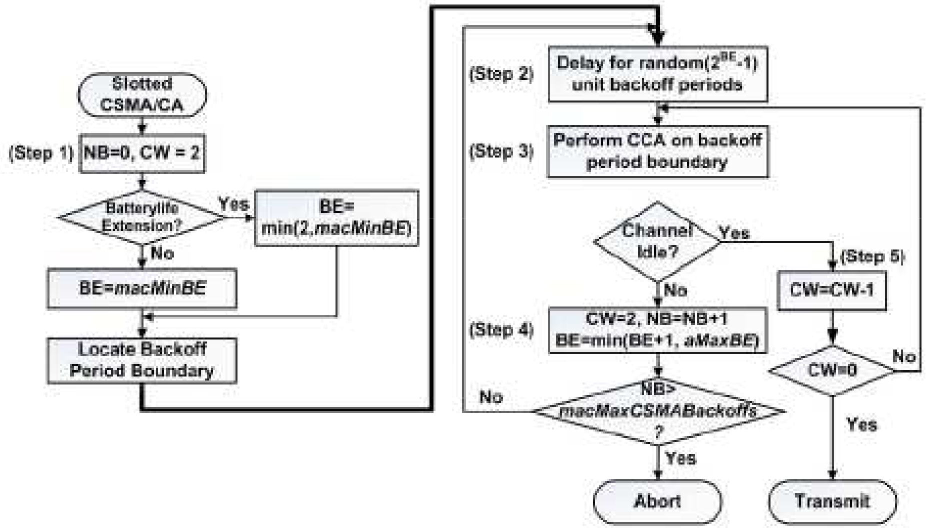
CSMA/CA traffic differentiation

- **Problem Statement**
  - CFP provides bandwidth guarantees
    - but requires GTS allocations/de-allocations in the CAP (CSMA/CA MAC)
  - slotted CSMA/CA mechanism supports **no traffic differentiation**, which would be important to tackle
    - sporadic critical messages, e.g.: events (alarms), network management, GTS allocation/deallocation
- **Challenges**
  - improving the Slotted CSMA/CA MAC to enable differentiating between **high and low priority traffic**
  - not modifying the standard protocol to keep **backward compatibility**

A. Koubaa, M. Alves, B. Nefzi, Y.-Q. Song, "Improving the IEEE 802.15.4 Slotted CSMA/CA MAC for Time-Critical Events in Wireless Sensor Networks" (RTN'06)

CSMA/CA traffic differentiation

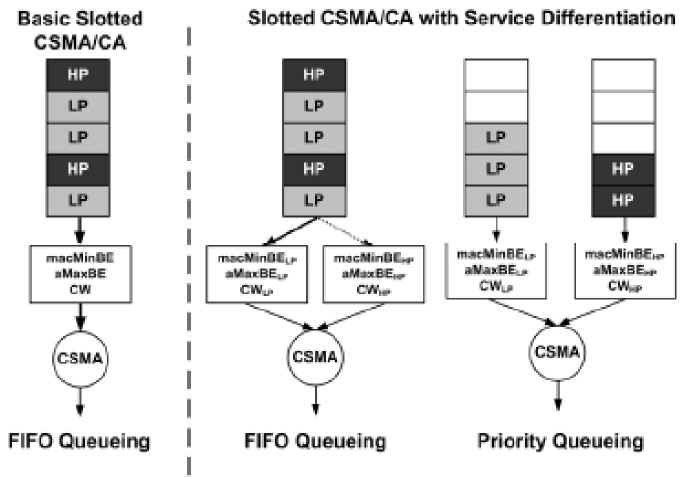
- The slotted CSMA/CA algorithm mainly depends on three variables:
  - **Back-off Exponent (BE):** to compute random back-off delay **[0,2^{BE}-1]**
    - ***macMinBE ≤ BE ≤ aMaxBE***
  - **Contention Window (CW)**: n° time units that channel must be sensed idle
  - **Number of Back-offs (NB)**
    - number of time units CSMA/CA goes back to back-off in case of busy channel
    - ***NB ≤ macMaxCSMABackoffs***



A. Koubaa, M. Alves, B. Nefzi, Y.-Q. Song, “Improving the IEEE 802.15.4 Slotted CSMA/CA MAC for Time-Critical Events in Wireless Sensor Networks” (RTN'06)

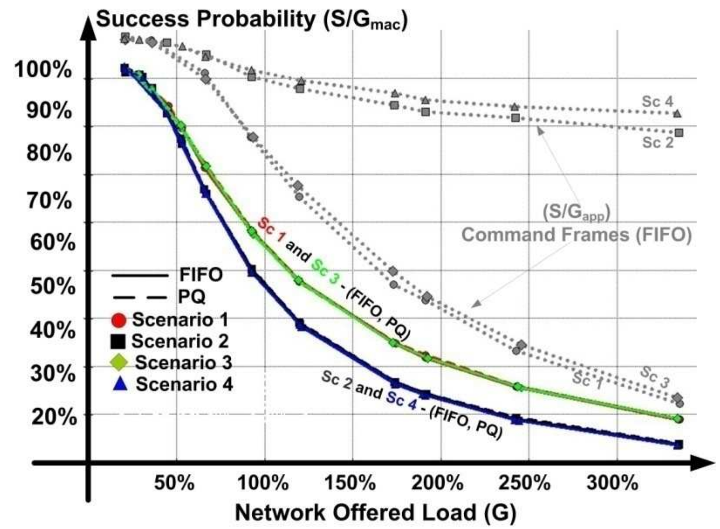
CSMA/CA traffic differentiation

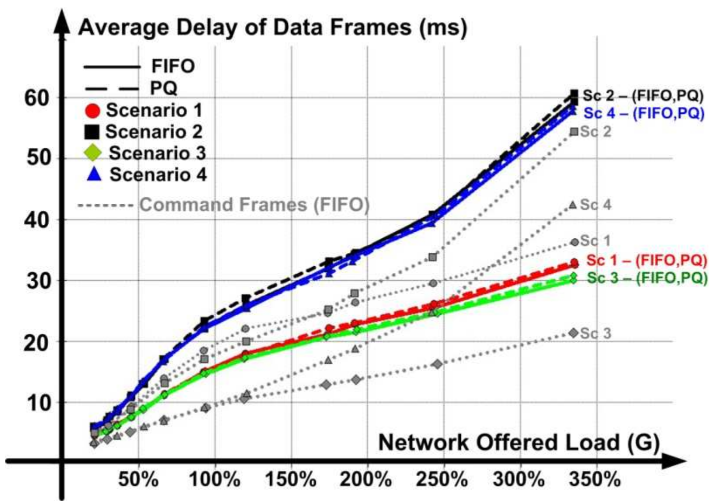
- Heuristics
  - $CW_{HP} < CW_{LP}$
  - $macMinBE_{HP} < macMinBE_{LP}$



Scenario	[macMinBE$_{HP}$, aMaxBE$_{HP}$]	[macMinBE$_{LP}$,aMaxBE$_{LP}$]	CW$_{HP}$	CW$_{LP}$
Sc1	[2,5]	[2,5]	2	2
Sc2	[2,5]	[2,5]	2	3
Sc3	[0,5]	[2,5]	2	2
Sc4	[0,5]	[2,5]	2	3

No differentiation
CW differentiation
macMinBE differentiation
CW and macMinBE differentiation



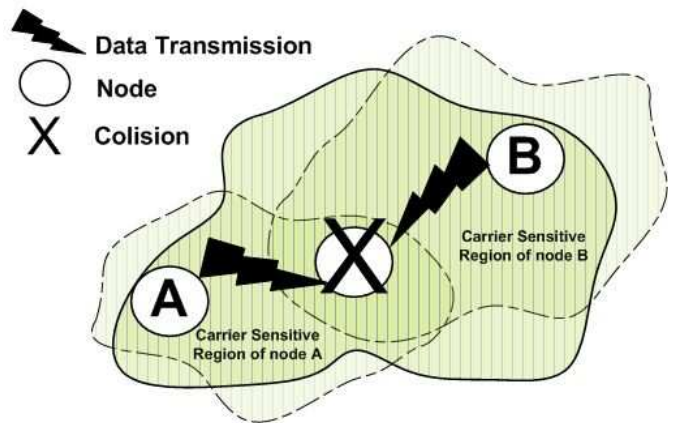


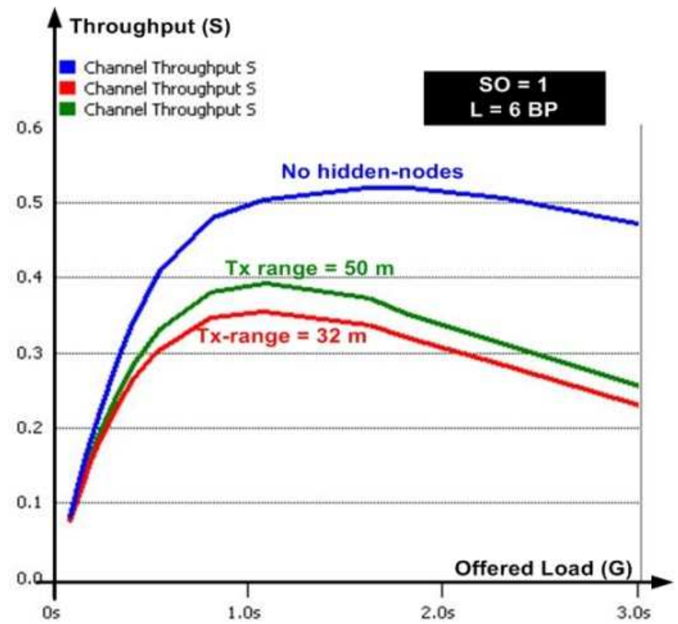
Second Approach

Hidden-Node Avoidance Mechanism

H-NAMe: Hidden-Node Avoidance Mechanism

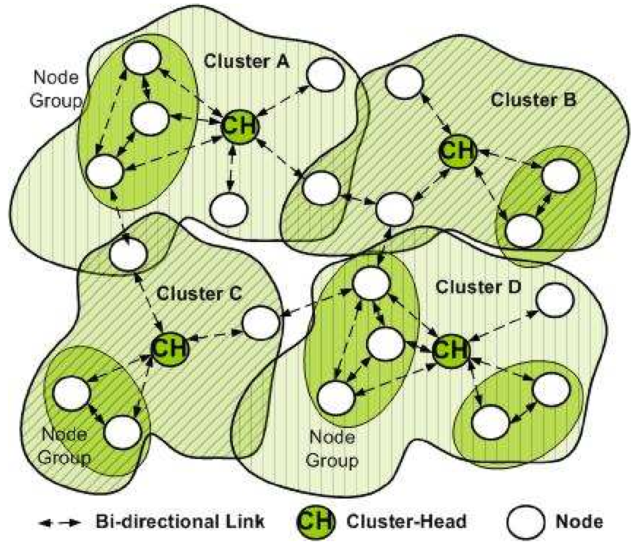
- The "**hidden-node problem**"
(or "hidden-terminal problem")
  - major source of QoS degradation in WSANs due to:
    - Limited communication **range** of sensor nodes,
    - Radio link **asymmetry**
    - Characteristics of the **physical environment**
  - Degradation of the following QoS metrics.
    - **Throughput**
      - decreases due to additional blind collisions.
    - **energy-efficiency**
      - that decreases since each collision causes a new retransmission.
    - **message delay**
      - becomes higher due to the multiple retransmissions of a collided message

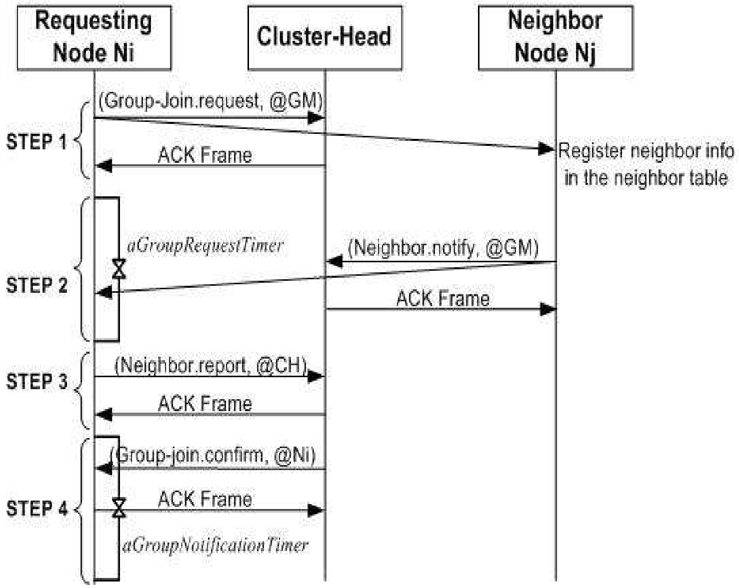


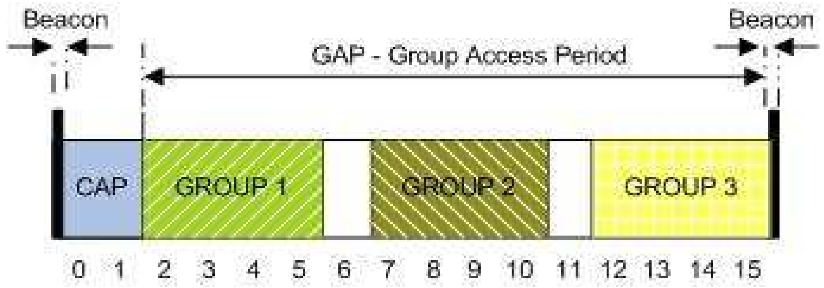


H-NAMe: Hidden-Node Avoidance Mechanism The Protocol.

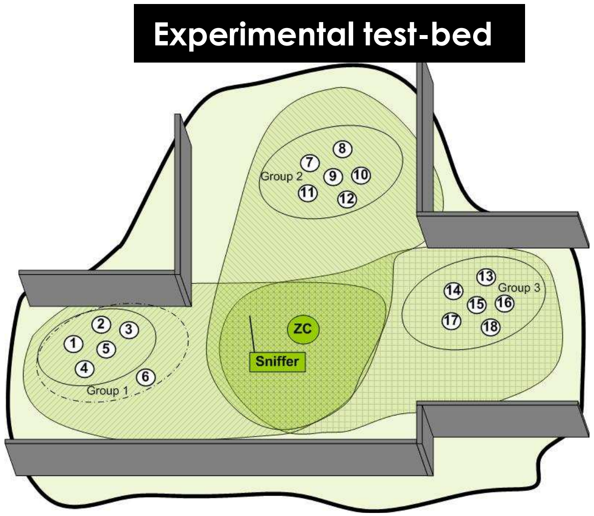
- **Hidden-Node Avoidance Mechanism (H-NAMe)**
  - **proactive** rather than reactive
  - groups of "all-visible" nodes are formed
    - each group uses a part of the CAP – **GAP**
  - cluster groups must also be formed…

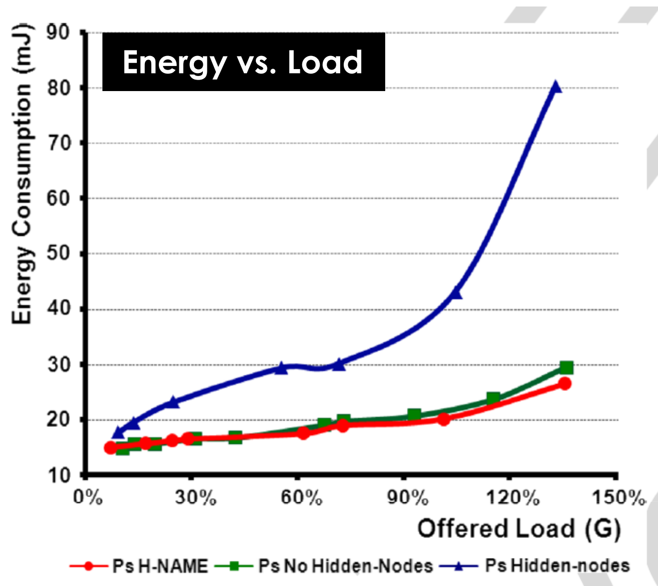


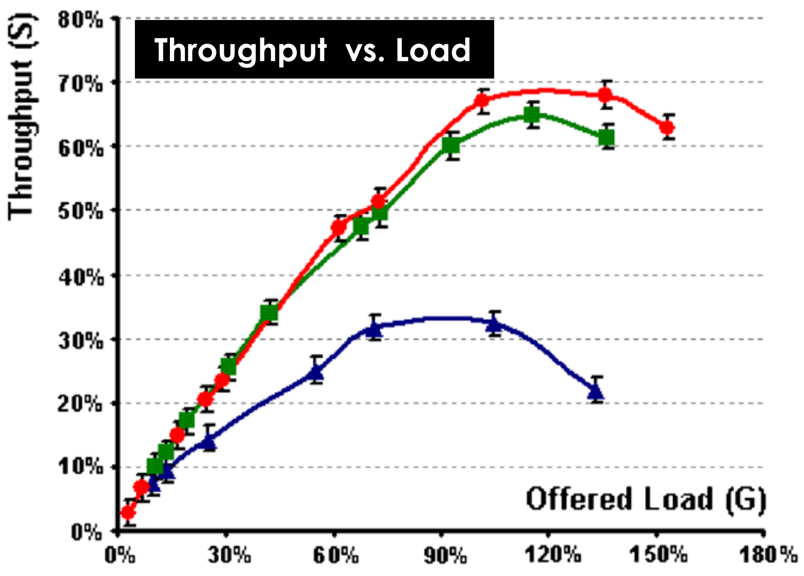


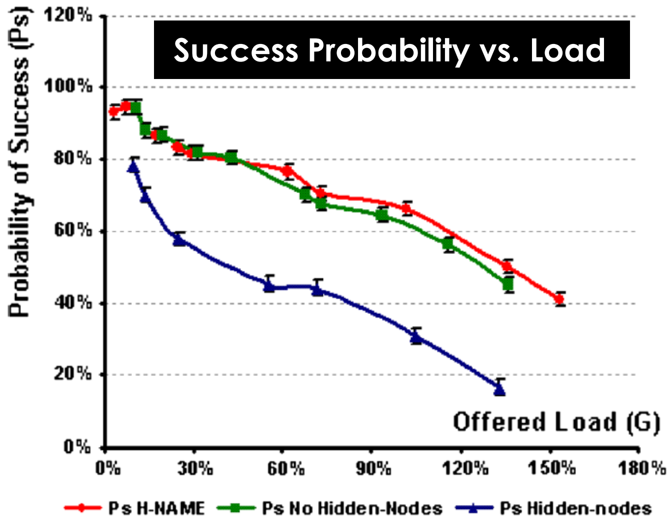


H-NAMe: Hidden-Node Avoidance Mechanism
The Performance.



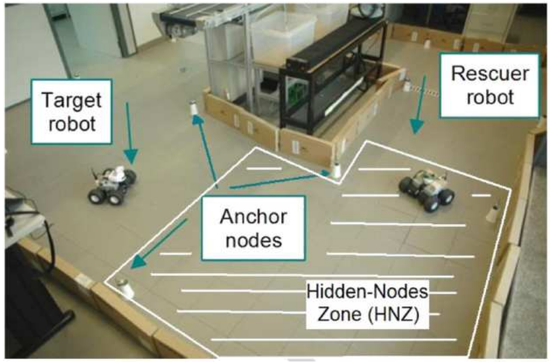




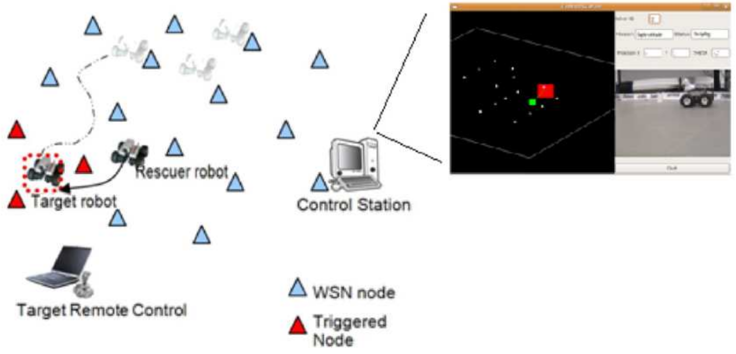


H-NAMe: Hidden-Node Avoidance Mechanism
The Performance.

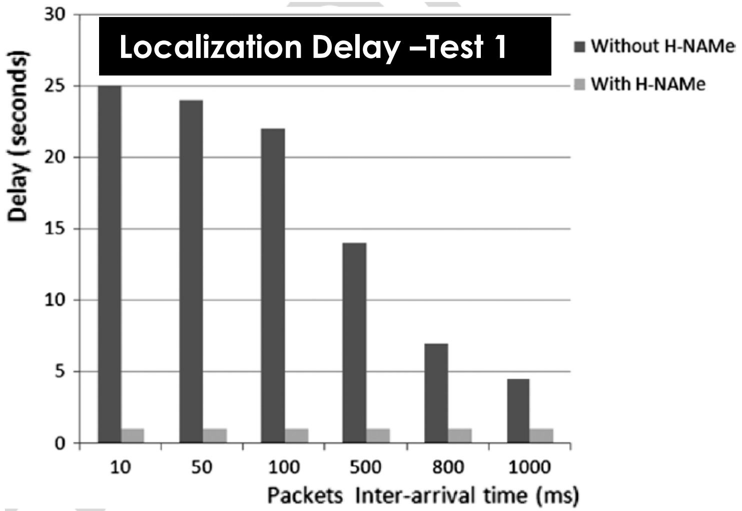
Experimental Environment



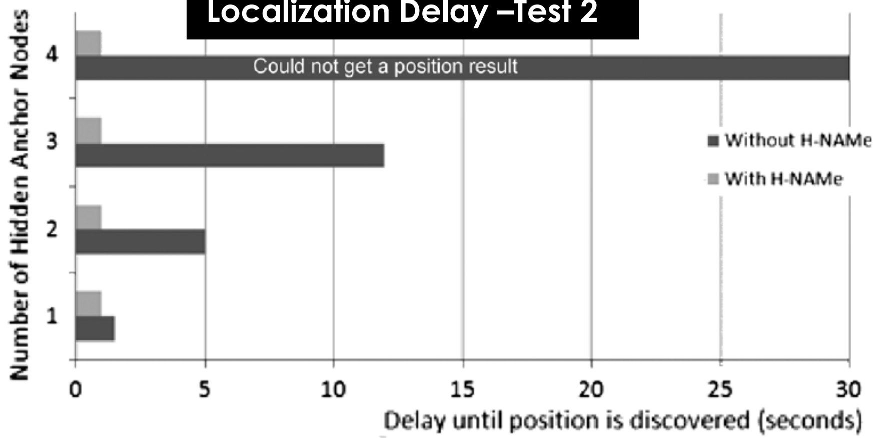
Tracking Application



Localization Delay –Test 1



Localization Delay –Test 2



Outline

- **Part I. Introduction to IEEE 802.15.4/ZigBee**
- **Part II. Performance Evaluation**
  - Performance Evaluation of the IEEE 802.15 GTS Worst-Case
  - Performance Evaluation of CSMA/CA
  - Dimensioning of IEEE 802.15/ZigBee Cluster-Tree Networks
- **Part III. Amendments to the standard**
  - Enhanced GTS Mechanism for the IEEE 802.15.4
  - Hidden Node Avoidance Mechanism for IEEE 802.15.4 Networks
  - Synchronization Mechanism of the IEEE 802.15.4/ZigBee Cluster-Tree Wireless Sensor Networks
- **Part VI. Tools and Experimental Testbeds**
  - Implementations
  - OPNET Simulation Model of IEEE 802.15.4/ZigBee

Part. IV.
Tools and Experimental Testbeds

OPEN-ZB IMPLEMENTATION

Related references

Ricardo Severino
On the use of IEEE 802.15.4/ZigBee for Time-Sensitive Wireless Sensor Network Applications
MSc Thesis, Polytechnic Institute of Porto, School of Engineering, October 2008.
BEST EWSN/CONET MSc THESIS AWARD, 2009.

A. Cunha, R. Severino, N. Pereira, A. Koubâa, M. Alves,
ZigBee over TinyOS: implementation and experimental challenges
CONTROLO'2008

A. Cunha, A. Koubaa, R. Severino, M. Alves
Open-ZB: an open-source implementation of the IEEE 802.15.4/ZigBee protocol stack on TinyOS
4th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS´07), Pisa, Italy, October 2007, pp.1-12

Andre Cunha
On the use of IEEE 802.15.4/ZigBee as federating communication protocols for Wireless Sensor Networks
MSc Thesis, University of Porto, Faculty of Engineering, September 2007.

open-ZB stack

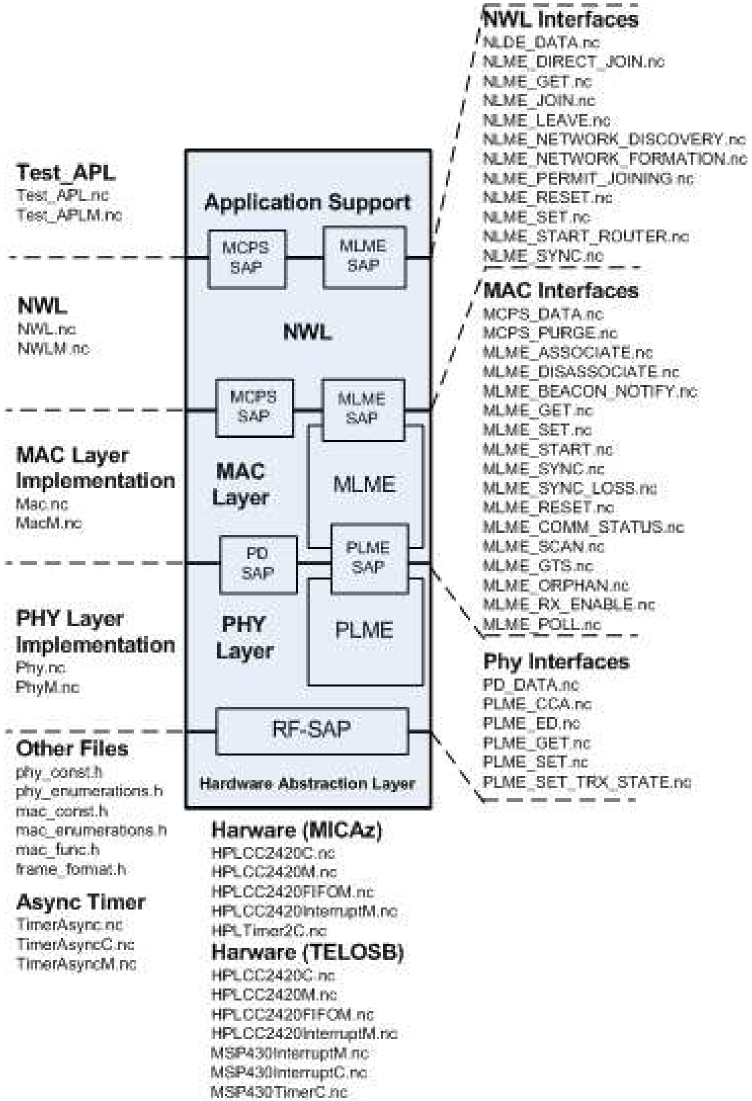
- **IEEE 802.15.4/ZigBee protocol stack www.open-zb.net**
  - nesC/TinyOS
  - Crossbow MICAz and TelosB
  - IEEE 802.15.4
  - ZigBee Network Layer

- **IEEE 802.15.4/ZigBee Protocol Analysers**
  - CC2420 Packet Sniffer for IEEE 802.15.4 v1.0
  - Daintree Networks Sensor Network Analyzer

- **TinyOS 1.1.15 and TinyOS 2.0**
  - operating system for embedded systems
  - event-driven execution model
    - concurrency model based on tasks and hardware event handlers/interrupts
  - developed in nesC - C-like syntax
  - TinyOS applications are built out of components wired by interfaces

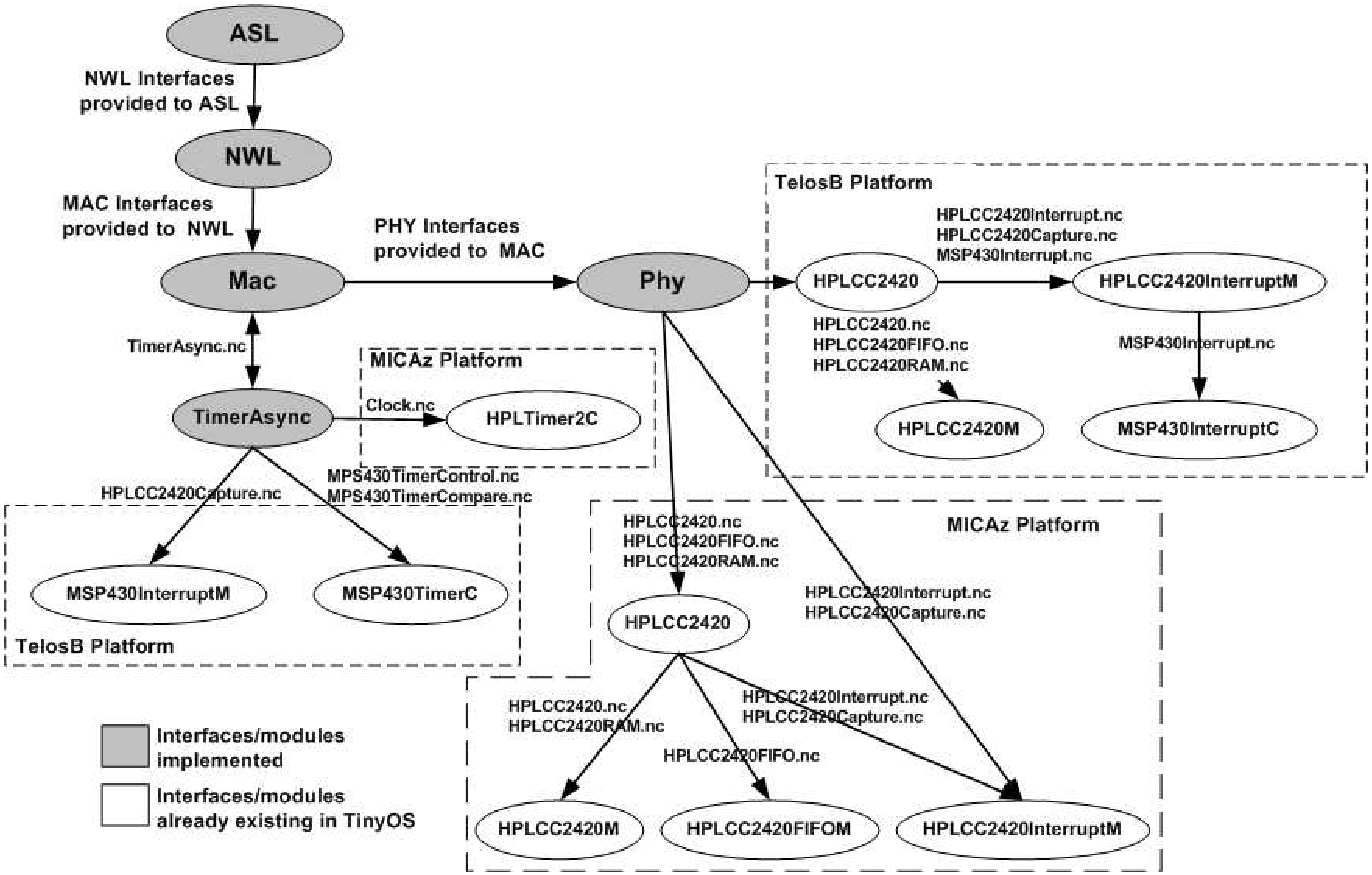
Ported to TinyOS 2.x as result from our collaboration with the TinyOS Network Protocol Working Group

open-ZB stack



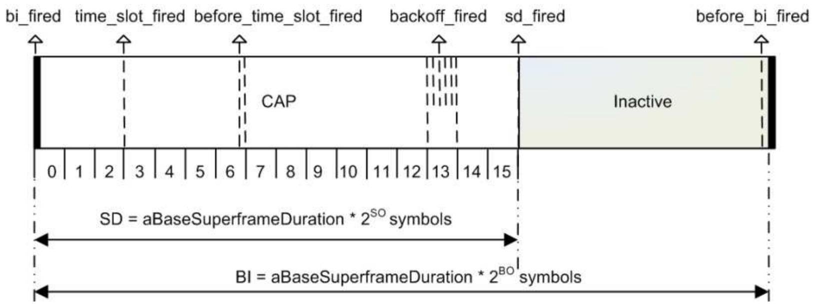
- **Phy Module (Physical Layer)**
  - Transceiver management
    - Data transmission/reception
    - Received Signal Strength Indication
    - Clear Channel Assessment
- **Mac Module (Data Link Layer)**
  - Beacon Generation
  - Synchronization
  - Association Procedures
  - CSMA/CA
  - GTS Management
- **NWL Module (Network Layer)**
  - Network topology
  - Addressing schemes
  - Neighbour tables
  - Tree-Routing

open-ZB Stack



ZigBee over TinyOS: Problems and Challenges

- Timing and synchronization
  - IEEE 802.15.4 is very demanding
    - each backoff period corresponds to 20 symbols (320 µs)
    - motes timer granularity does not allow having the exact value
      - higher BO error
      - use equal mote platforms



- As experienced, the loss of synchronization can be caused by multiple factors:
  - the processing time of the beacon frame for low *BO/SO* configurations;
  - the mote stack overflow that results in a block or a hard reset;
  - the unpredictable delay of the wireless communications;
  - The non-real time behaviour of TinyOS;
  - the reduced processing capability of the microcontroller in conducting some of the protocol maintenance tasks (e.g. creating the beacon frame, the maintenance of GTS expiration and indirect transmissions).

ZigBee over TinyOS: Problems and Challenges

- TinyOS Task scheduler
  - **no tasks prioritization** (ongoing proposals)
  - **non pre-emptive**
- consequences
  - interrupt events are captured by event handlers that normally post a task to the FIFO task queue such that **TinyOS schedules its processing in a FIFO basis**
  - **hard to ensure the stability of the network** when the nodes are generating packets with very low inter-arrival times
- to overcome this problem
  - use a real-time operating system (e.g. ERIKA, nano-RK)

OPEN-ZB SIMULATION MODEL WITH OPNET

Related references

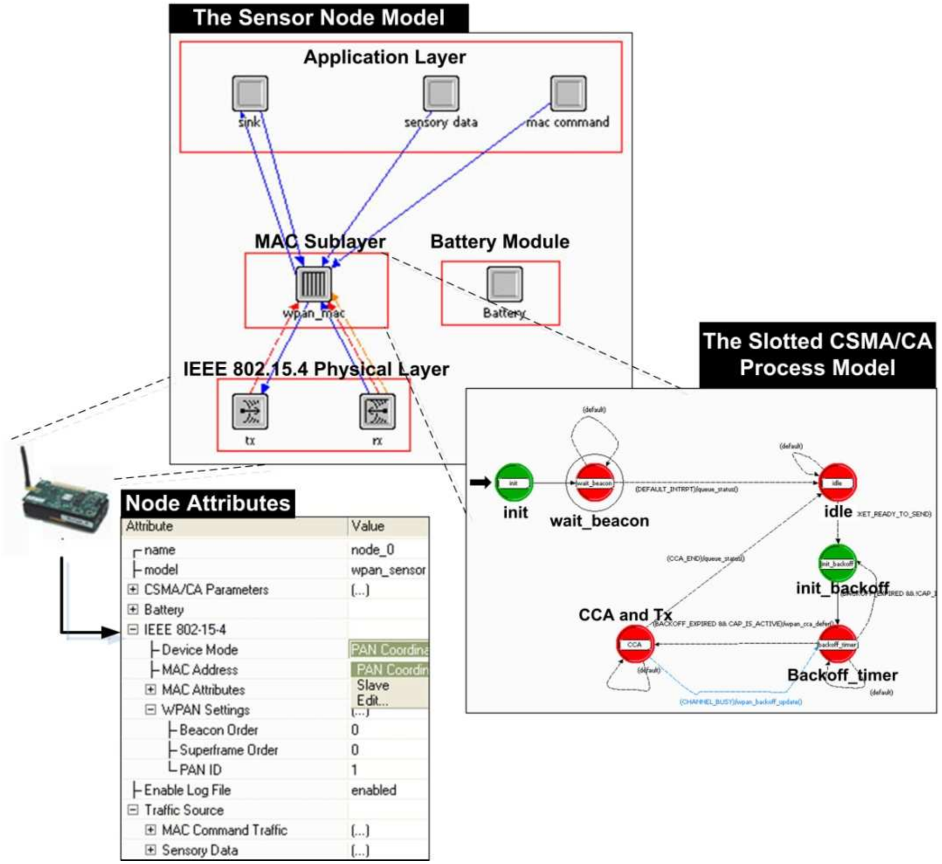
P.Jurcik, A. Koubaa, M. Alves, E. Tovar, Z. Hanzalek,
A Simulation Model for the IEEE 802.15.4 Protocol: Delay/Throughput Evaluation of the GTS Mechanism
IEEE MASCOTS´07, Turkey, 2007.

A. Koubaa, M.Alves, E.Tovar,
A Comprehensive Simulation Study of Slotted CSMA/CA for IEEE 802.15.4 Wireless Sensor Networks
In IEEE IEEE WFCS 2006, Torino (Italy), June 2006.

Petr Jurcik, Anis Koubaa
The IEEE 802.15.4 OPNET Simulation Model: Reference Guide v2.0
IPP-HURRAY Technical Report, HURRAY-TR-070509, May 2007

open-ZB Simulation Model with OPNET

- open-source **OPNET** model
  - physical, MAC and application layers
- **Supported** features
  - beacon-enabled mode
  - slotted CSMA/CA MAC protocol
  - physical layer characteristics
  - battery module (MICAz/TelosB motes)
  - Guaranteed Time Slot (GTS) mechanism
  - acknowledged **and** unacknowledged application data generator for CAP
  - acknowledged **or** unacknowledged application data generator for CFP
  - **Cluster-Tree (new) – Sept 2009.**
- **non-supported** features
  - Non beacon-enabled mode
  - Un-slotted CSMA/CA MAC protocol
  - PAN management (association/disassociation)



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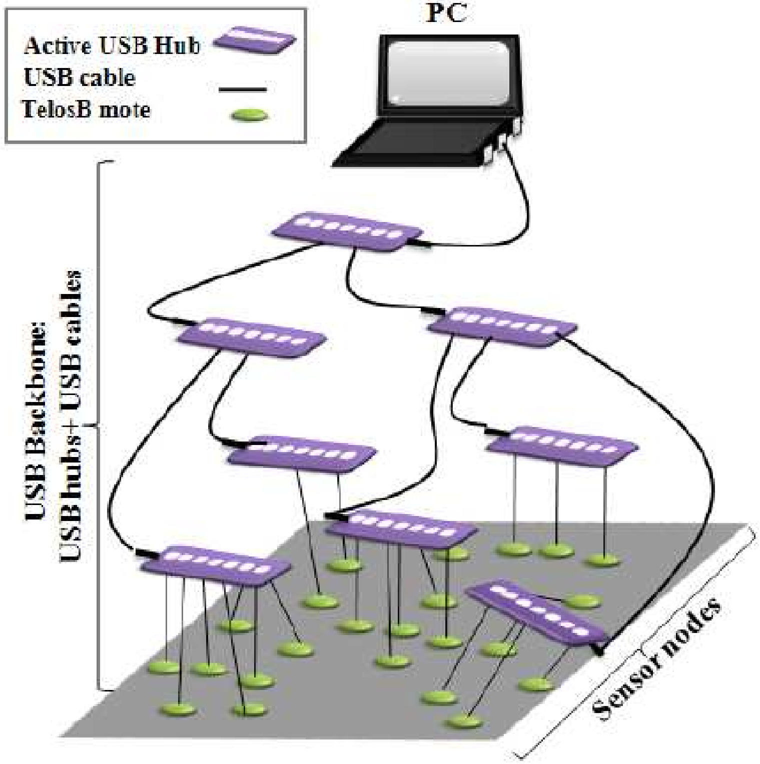
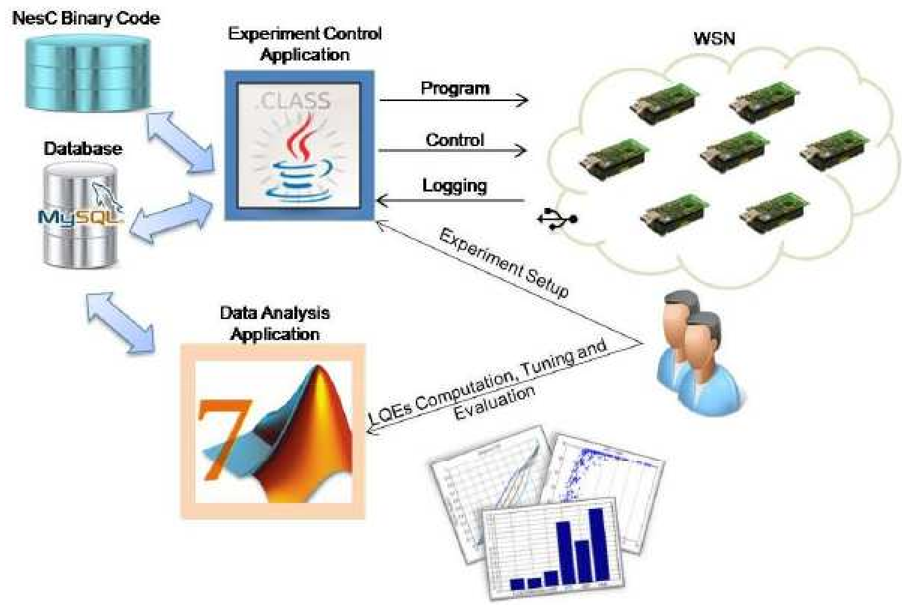
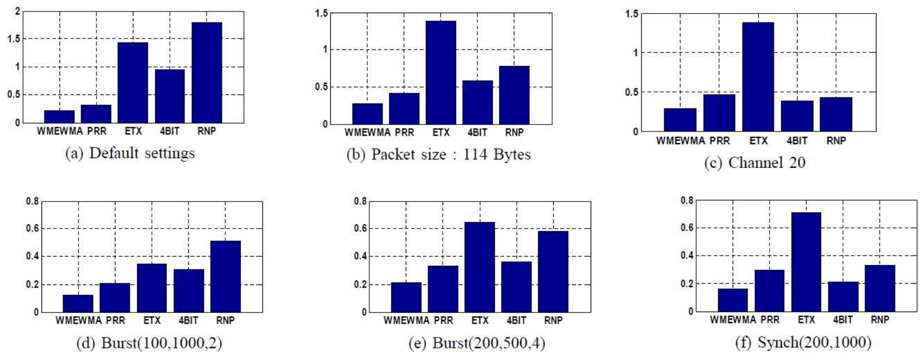
EXPERIMENTAL TESTBED FOR LINK QUALITY ESTIMATION

LQE-TB: Testbed for Link Quality Evaluation







LQE-TB: Testbed for Link Quality Evaluation

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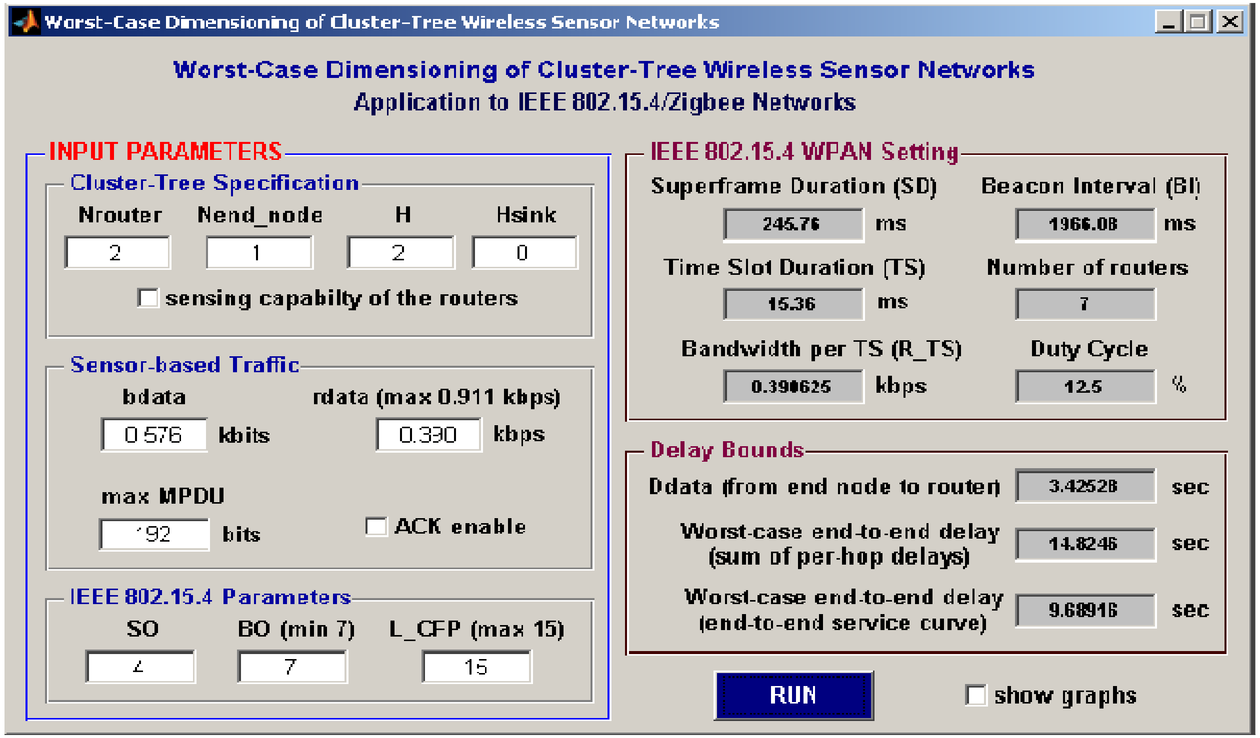
CLUSTER-TREE DIMENSIONING TOOL WITH MATLAB

Cluster-Tree Dimensioning Tool with MATLAB

- **Enables worst-case network analysis & dimensioning**
  - minimum duty-cycle still satisfying deadlines



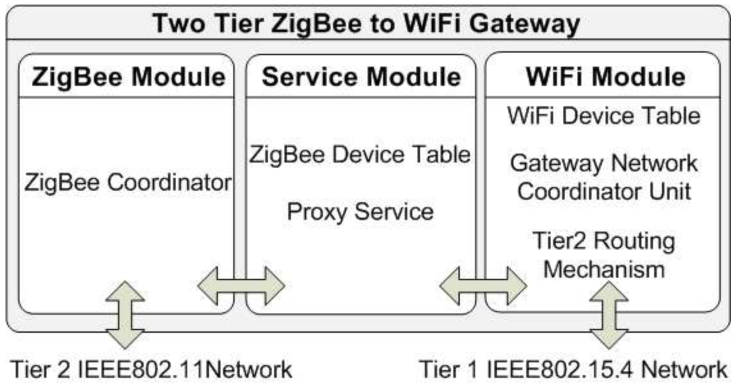
WIFI/15.4 GATEWAY

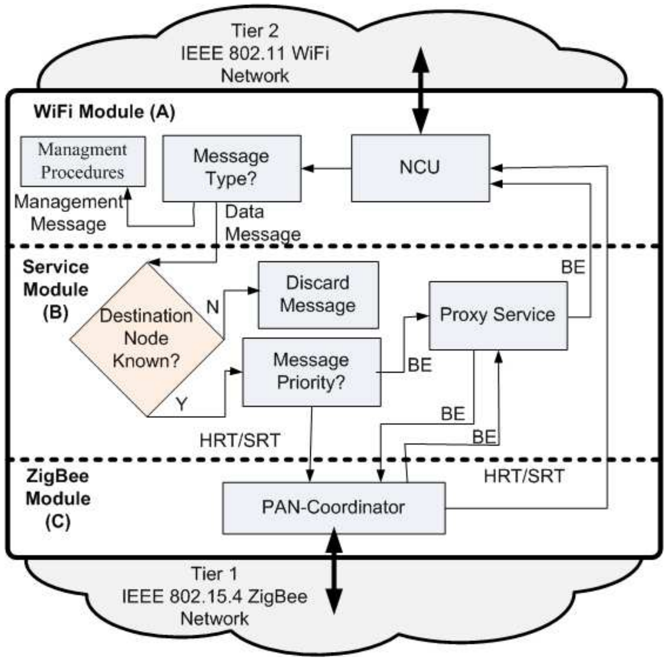
Related references

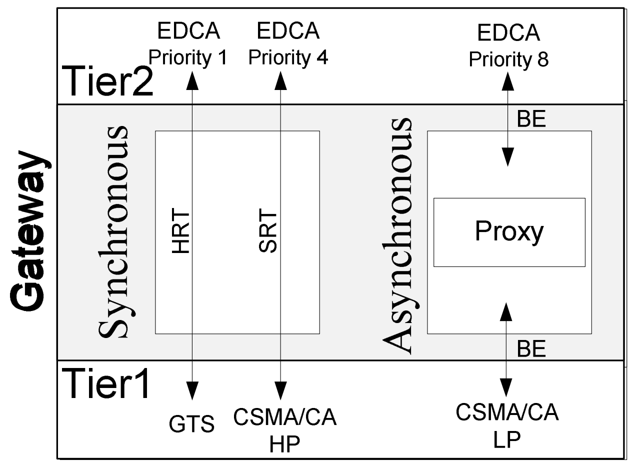
J. Leal, A. Cunha, M. Alves, A. Koubaa,
On a IEEE 802.15.4/ZigBee to IEEE 802.11 Gateway for the ART-WiSe Architecture
ETFA'07 (WiP)

WiFi/15.4 Gateway

- **ART-WiSe gateway architecture**





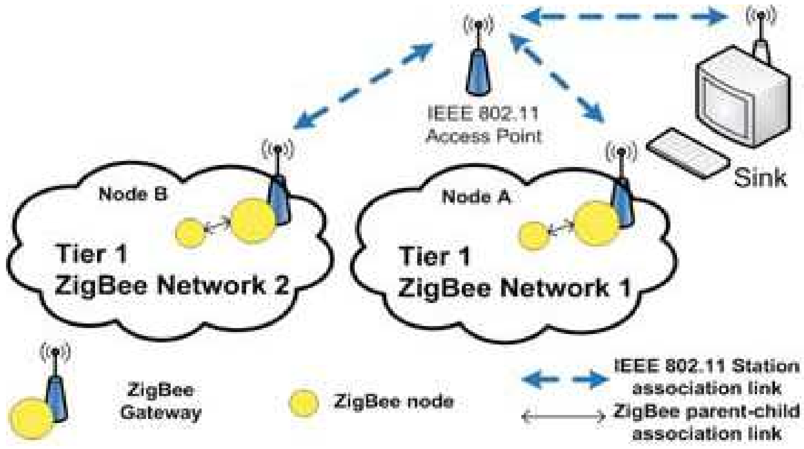


- **Gateway behavior**
  - **Synchronous** behavior (time-critical messages)
  - **Asynchronous** behavior (normal messages)
- **Traffic classes**
  - **HRT** - Hard Real Time, for high priority
  - **SRT** - Soft Real Time, for medium priority
  - **BE** - Best Effort, for low priority

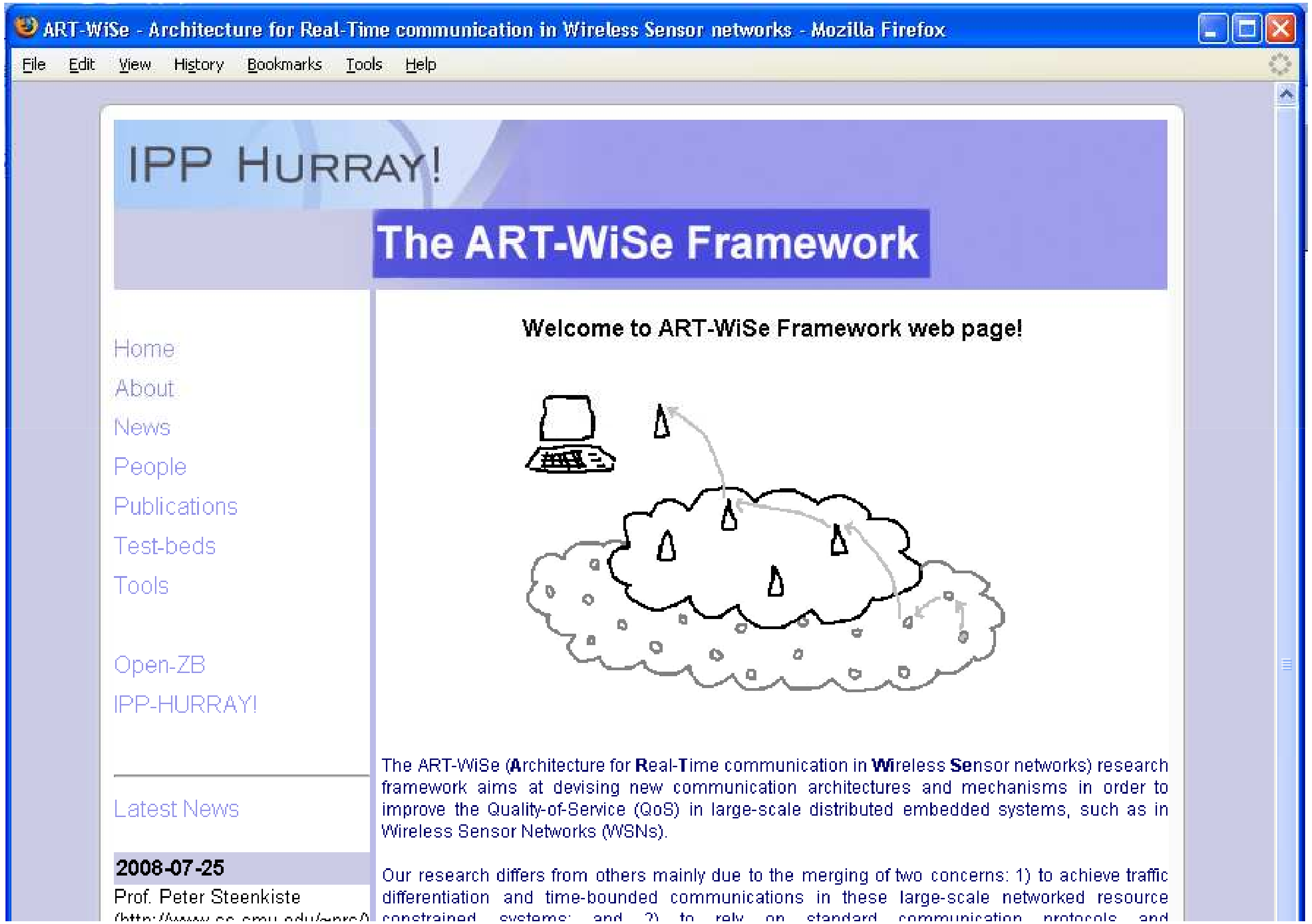
WiFi/15.4 Gateway

- First **experimental prototype** of the ART-WiSe gateway

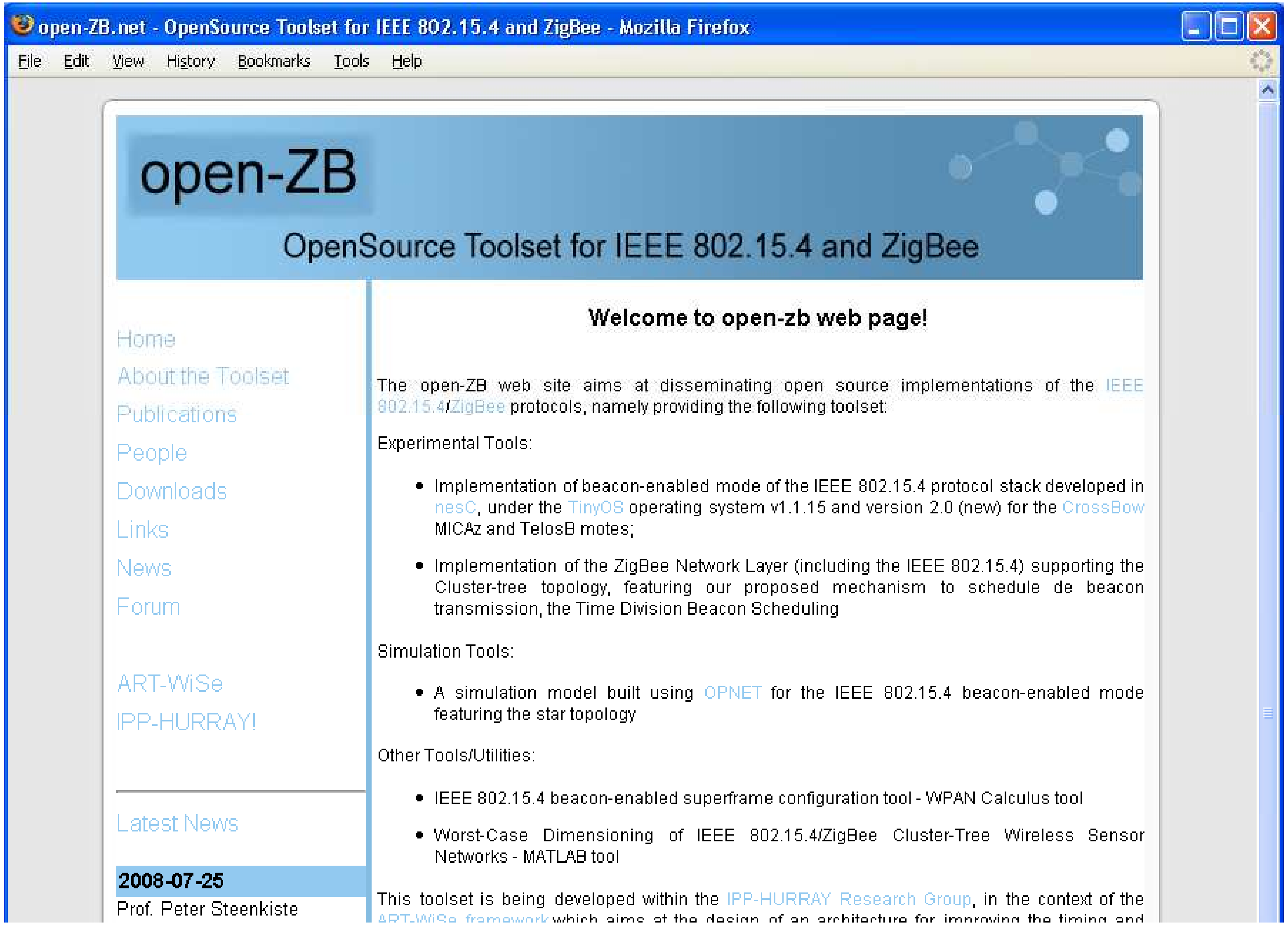
1. Stargate Single Board Computer
2. MICAz mote - IEEE 802.15.4/ZigBee coordinator
3. IEEE 802.11 board
4. Memory card



http://www.hurray.isep.ipp.pt/ART-WiSe



http://www.open-ZB.net



Conclusions

- The war of standard protocols: Who wins?
  - IEEE 802.15.4/ZigBee, 6lowpan, WirelessHart, ISA100
- Interoperability becomes a main issue for CPS
  - IP is main component in the design of Large-Scale and Interoperable CPS