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guaranteeing QoS in large-scale distributed embedded systems using standard and COTS technologies

ongoing research at IPP-HURRAY

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L'Aquila, Italy – 4/SEP/2008

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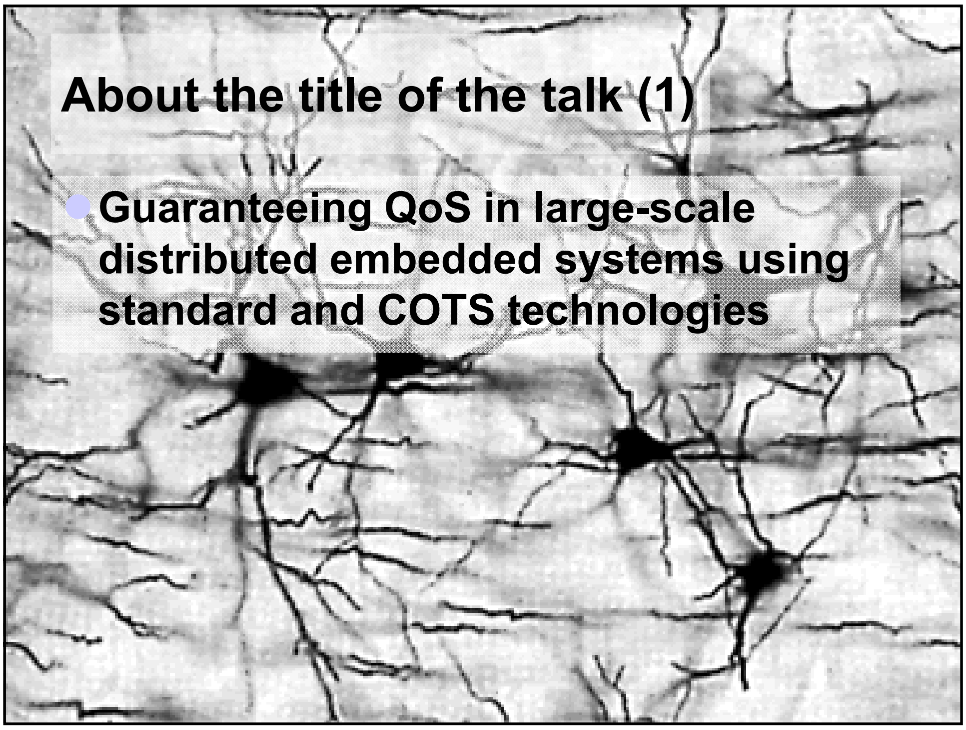


About the title of the talk (1)

- Guaranteeing QoS in large-scale distributed embedded systems using standard and COTS technologies

About the title of the talk (2)

- what is "**Quality-of-Service (QoS)**"?
  - **"QoS is the ability to provide different priority to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow. …"**
    - **"… For example., a required bit rate, delay, jitter, packet dropping probability and/or bit error rate may be guaranteed…"**
    - **"…QoS guarantees are important if the network capacity is a limited resource…" (isn't it always?)**
    - **"e.g. voice over IP, online games and IP-TV"**
  - basically, **QoS must be considered for**
    - **any application with critical requirements (e.g. factory automation, automotive, medical, surveillance)**

About the title of the talk (3)

- what are "**distributed embedded systems**"?
  - no result from Wikipedia ☹, but…
- an "**embedded system**" is
  - "a **special-purpose computer system** designed to perform one or a few dedicated functions, **often with real-time computing constraints**. …"
  - "… It is usually **embedded as part of a complete device including hardware and mechanical parts**. …"
- "Embedded systems control many of the common devices in use **today**.…"
  - mobile phones, automotive systems, household appliances,…
  - and in the **future**…
    - **ubiquitous computing**, **cyber-physical systems**

About the title of the talk (4)

- and "**distributed system**"?
  - Wikipedia redirects to… "**distributed computing**":
    - "Distributed computing deals with **hardware and software systems containing more than one processing element or storage element, concurrent processes, or multiple programs**, running under a loosely or tightly controlled regime."
    - "In distributed computing **a program is split up into parts that run simultaneously on multiple computers communicating over a network**."

- so, a "**distributed embedded system**" is
  - "**a system composed of several (eventually distinct) embedded computing devices that interoperate via a communication network**" (this definition is mine ☺)
- and "**large-scale distributed embedded system**"?
  - just substitute 'several' by '**many**' in the last phrase ☺

About the title of the talk (5)

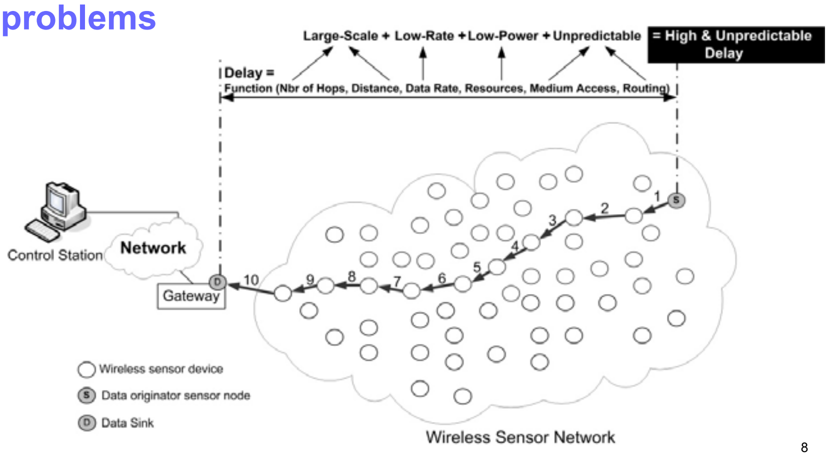
- and "**standard and COTS technologies**"?
  - "**technology**"
    - "is a broad concept that deals with a species' **usage and knowledge of tools and crafts**, and how it affects a species' ability to control and adapt to its environment. In human society, **it is a consequence of science and engineering**"
  - "**standard**"
    - "A technical standard is an **established norm or requirement**. It is usually a formal document that establishes uniform engineering or technical criteria, methods, processes and practices."
  - "**COTS**"
    - "Commercial, off-the-shelf (COTS) is a term for software or hardware, generally technology or computer **products, that are ready-made and available for sale, lease, or license to the general public**."

About the title of the talk (6)

- but why using "**standard and COTS technologies**"?
  - for reducing the development and maintenance costs
    - we can buy them (or get them for free – open-source)
  - for increasing interoperability
    - with what other people (industry/academia) is doing
  - for speeding up their utilization and deployment in real world applications
    - by system developers (love COTS)
    - by end-users (hate new/immature things)

Problem statement (1)

- **WSAN multi-hop communications lead to QoS problems**



[A. Koubaa, M. Alves, "A Two-Tiered Architecture for Real-Time Communications in Large-Scale Wireless Sensor Networks: Research Challenges", ECRTS'05 (WiP)]

Problem statement (2)

- actually, the “problem” is reflected by the title of this talk:
  - “Guaranteeing QoS in large-scale distributed embedded systems using standard and COTS technologies”
- we believed that
  - it would be possible to devise a **WSAN communication architecture with the appropriate QoS levels, using standard and COTS technologies…**

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Problem statement (3)

- we privileged the following QoS axis:
  - **reliability**
    - tasks must be completed correctly
    - messages must arrive correctly
  - **timeliness**
    - tasks must be completed on time
    - messages must arrive on time
  - **scalability**
    - architecture must adapt to changes in network scale
  - **mobility**
    - architecture must adapt to mobility of nodes or node groups
  - **system lifetime**
    - architecture must provide adequate energy-efficiency
  - **cost-effectiveness**
    - overall system must be economically feasible

difficulty is fulfilling ALL of them

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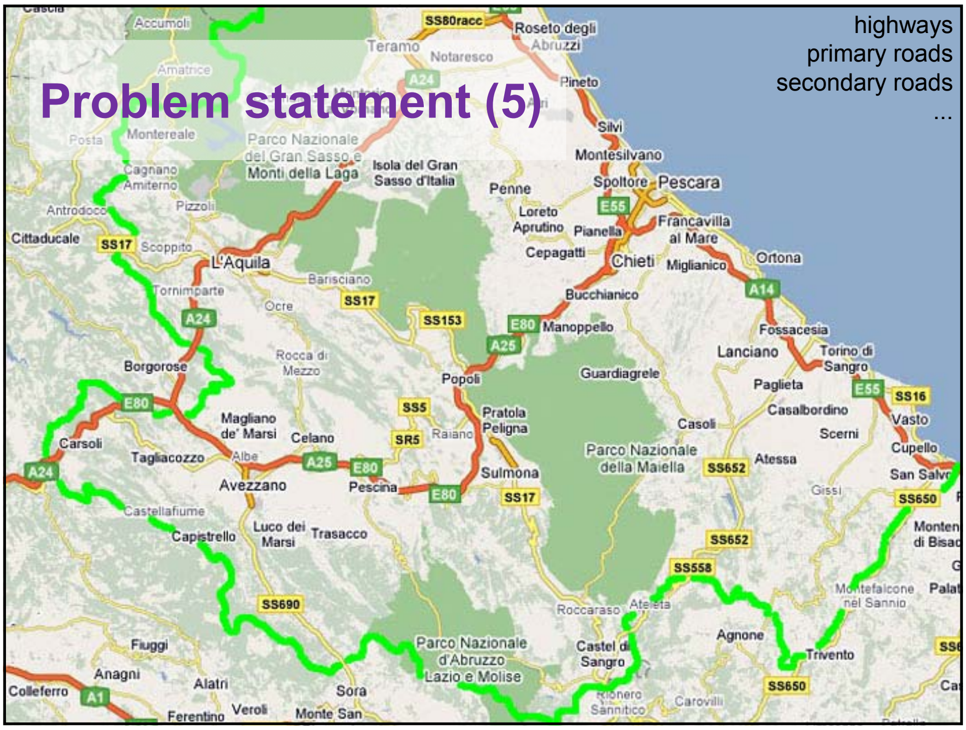
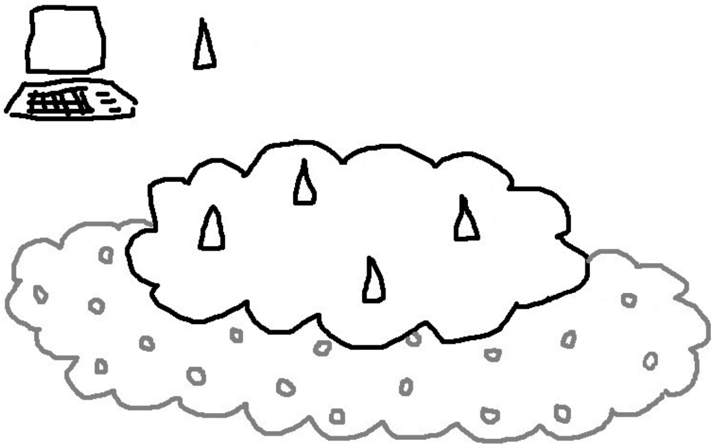
Problem statement (4)

- and assumed that this would only be possible through a
  - multiple-tiered WSAN architecture

Problem statement (5)



Snapshot of the architecture (1)



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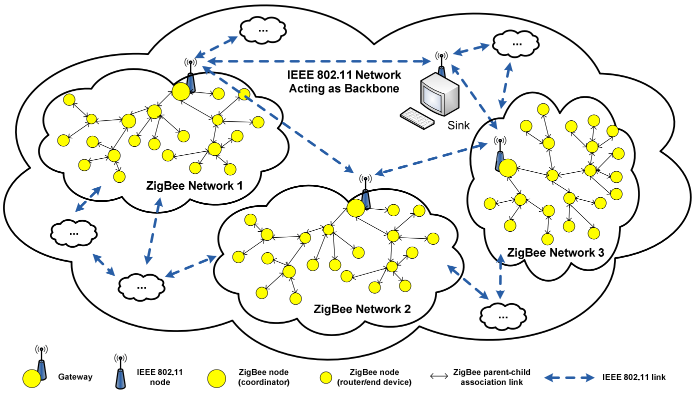
[A. Koubaa, M. Alves, "A Two-Tiered Architecture for Real-Time Communications in Large-Scale Wireless Sensor Networks: Research Challenges", ECRTS'05 (WiP)]

Snapshot of the architecture (2)

- **Multiple Tiered Arch.**
  - Tier 2: backbone
    - IEEE 802.11 (WiFi) +… or
    - IEEE 802.16 (WiMAX) +… or
  - Tier 1: sensor network
    - IEEE 802.15.4/**ZigBee** +…

- Tier 2 is composed of
  - *n* WiFi nodes, each including a
  - gateway to a Tier 1 ZigBee network

- Tier 1 is composed of
  - *n* ZigBee networks, each with
  - *m* clusters (cluster-tree, mesh)



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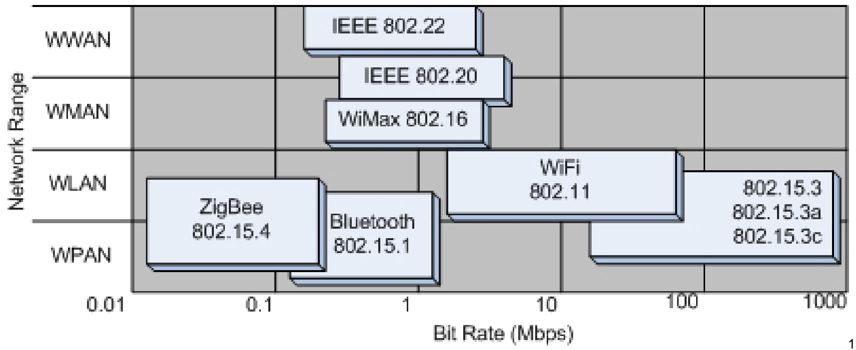
Federating communication protocols (1)

- landscape of standard wireless communication protocols (see Part 1)



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Federating communication protocols (2)

- standard wireless communication protocols
  - higher communication tiers (backbone network)
    - IEEE 802.11/WiFi
    - IEEE 802.16/WiMAX
    - IEEE 802.15.3/UWB
    - GSM/GPRS
    - wired: switched Ethernet, ATM,FDDI,…
  - lower communication tiers (sensor network)
    - (IEEE 802.15.1/Bluetooth)
    - (IEEE 802.15.6 (just formed NOV/2007) – BAN)
    - IEEE 802.15.4 (Physical and Data Link Layers) – PAN
    - ZigBee (Network and Application Layers over IEEE 802.15.4)
    - Wireless HART (over IEEE 802.15.4)
    - ISA100 (over IEEE 802.15.4)
    - 6lowPAN (Network Layer over IEEE 802.15.4)
    - wired: EIB/KNX, HomePlug, HART, ASi, PROFIBUS, Foundation Fieldbus, P-Net, DeviceNet, ModBus,…

Federating communication protocols (3)

- lower tier protocol (WSAN) requirements
  - wireless
  - standard and COTS
  - adequate QoS guarantees
    - e.g. low energy consumption
- higher tier protocol (backbone) requirements
  - wireless
  - standard and COTS
  - adequate QoS guarantees
    - e.g. > radio coverage, bit rate, robustness
- inter-tier requirements
  - smooth interoperability
    - e.g. addressing, dissemination, traffic classes
  - end-to-end (cross-tier) QoS guarantees
    - (see slide #10)

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Federating communication protocols (4)

- higher tier protocol (backbone) candidates
  - we did not address this yet (seriously)
  - but
    - **IEEE 802.11/WiFi (inappropriate QoS)**
    - IEEE 802.16/WiMAX (COTS not mature yet)
    - IEEE 802.15.3/UWB (COTS not mature yet)
  - are prominent candidates
- lower tier protocol (WSAN)
  - we opted (back in 2005) for
    - **IEEE 802.15.4 and ZigBee**

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Federating communication protocols (5)

- IEEE 802.15.4/ZigBee compared…

Market Name	ZigBee®	---	Wi-Fi™	Bluetooth™
Standard	802.15.4	GSM/GPRS CDMA/1xRTT	802.11b	802.15.1
Application Focus	Monitoring & Control	Wide Area Voice & Data	Web, Email, Video	Cable Replacement
System Resources	4KB - 32KB	16MB+	1MB+	250KB+
Battery Life (days)	100 - 1,000+	1-7	.5 - 5	1 - 7
Network Size	Unlimited (2^{64})	1	32	7
Maximum Data Rate (KB/s)	20 - 250	64 - 128+	11,000+	720
Transmission Range (meters)	1 - 100+	1,000+	1 - 100	1 - 10+
Success Metrics	Reliability, Power, Cost	Reach, Quality	Speed, Flexibility	Cost, Convenience

ZigBee Alliance
Wireless Control That Simply Works

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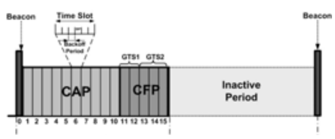
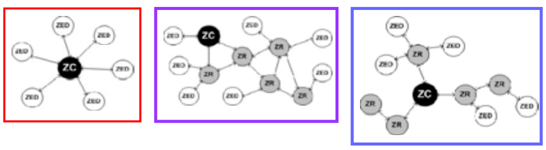
Federating communication protocols (6)

- **Why IEEE 802.15.4/ZigBee?**
  - **Energy-efficiency**
    - adaptable duty-cycles (100% → 0%)
    - low data rates (20-250 kbps)
    - low radio coverage (≈ 30 m)

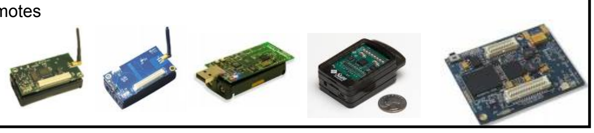
  - **Traffic differentiation**
    - Real-Time traffic
      - Guaranteed Time Slots (GTS)
    - Best-effort traffic
      - CSMA/CA mechanism



  - **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

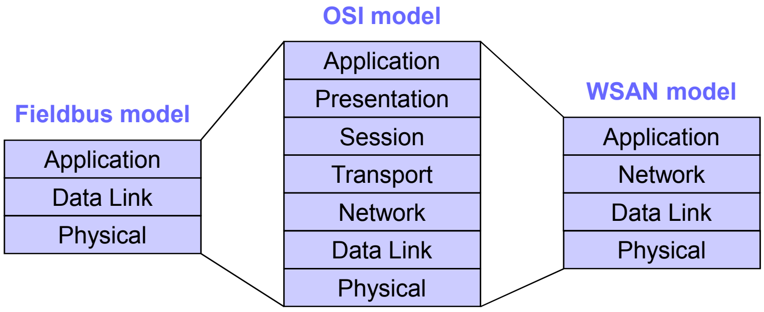


Federating communication protocols (7)

- why IEEE 802.15.4 and ZigBee?
  - to be really, really honest… ☺
  - because…
    - in 2005, **these were emerging & “hot” technologies**
  - and…
    - **we were quite curious to learn about them and to know if it was possible to use them in WSAN with more demanding QoS requirements**

IEEE 802.15.4 and ZigBee highlights (1)

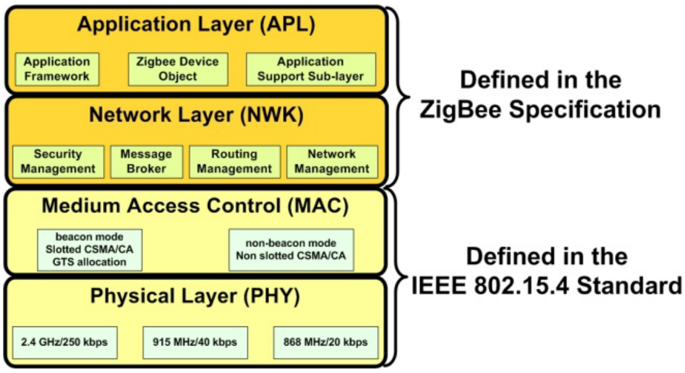
- networks for monitoring/control require
  - **simplified/collapsed version of OSI model**
    - **lighter** (< memory), **faster** (< inform. processing)



note: single bus segment are single hop networks – no need for Network Layer

IEEE 802.15.4 and ZigBee highlights (2)

- IEEE 802.15.4 ≠ ZigBee



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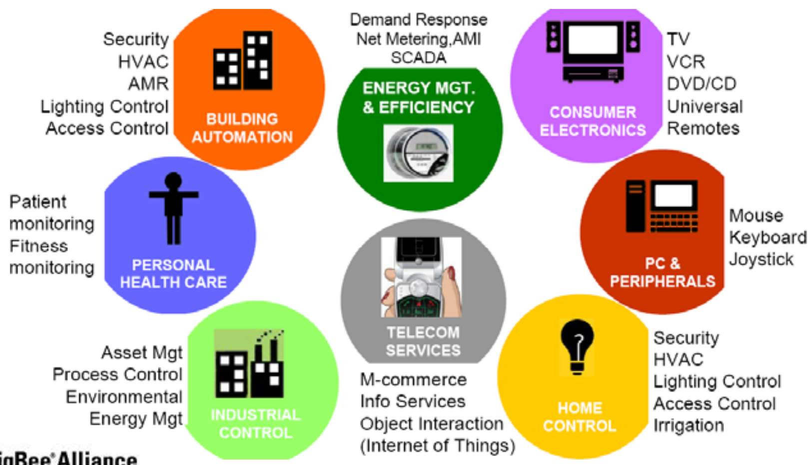
note: IEEE 802.15.4 Physical Layer is being used by WirelessHART, ISA100, 6loWPAN

IEEE 802.15.4 and ZigBee highlights (3)

- “ZigBee Alliance” claims…



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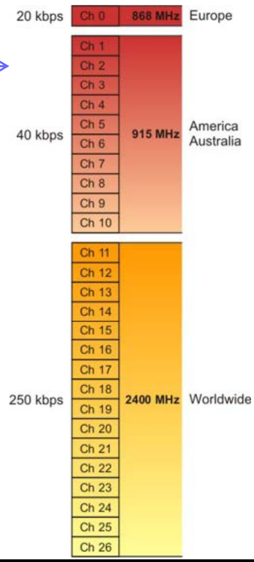
ZigBee Alliance
Wireless Control That Simply Works

IEEE 802.15.4 and ZigBee highlights (4)

- Physical Layer 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 802.15.4 and ZigBee highlights (5)

- device types
  - ZC **ZigBee Coordinator** (**ZC**)
    - one and only one required per network
    - initiates network formation
    - acts as 802.15.4 2003 PAN coordinator (FFD)
    - may act as router once network is formed
  - ZR **ZigBee Router** (**ZR**)
    - optional network component
    - may associate with ZC or with previously associated ZR
    - acts as 802.15.4 2003 coordinator (FFD)
    - participates in multihop routing
  - ZED **ZigBee End Device** (**ZED**)
    - optional network component
    - does not allow association
    - does not participate in routing

- device types
  - Full Function device (FFD)
    - Implements the **full protocol**
    - **ZC**, **ZR**, **ZED**
  - Reduced Function Device (RFD)
    - Implements a **subset** of the protocol
    - **ZED**

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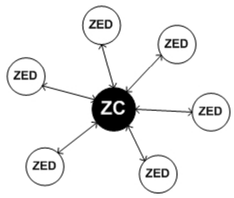
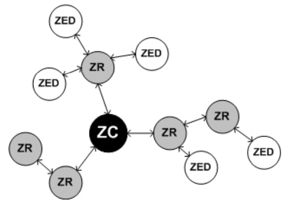
IEEE 802.15.4 and ZigBee highlights (6)



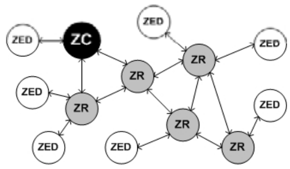
Star

- no ZR
- communication via ZC
- synchronization?
  - yes (beacon-enabled mode)
  - no (non beacon-enabled mode
- not scalable



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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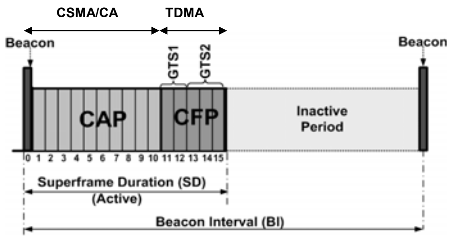
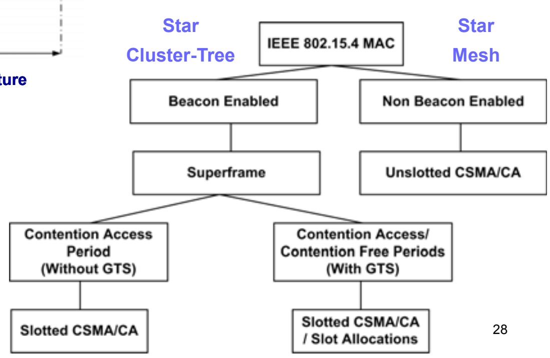
IEEE 802.15.4 and ZigBee highlights (7)



Beacon Interval and Superframe Structure



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Why research on ZigBee Cluster-Tree? (1)

	Star	Mesh	Cluster-Tree	Interesting within our research?
Scalability	No	Yes	**Yes**	☺
Synchronization	Yes (no)	No	**Yes**	☺
Inactive Periods	All nodes	ZEDs	**All nodes**	☺
Guaranteed bandwidth	Yes (GTS)	No	**Yes (GTS)**	☺
Redundant Paths	N/A	Yes	**No**	☺
Routing Protocol Overhead	N/A	Yes	**No**	☺
Commercially Available	Yes	Yes	**No**	☺

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

Why research on ZigBee Cluster-Tree? (2)

- Some of these factors lead us to investigate the use of
  - beacon-enabled mode in
  - star and **cluster-tree network topologies**
- for
  - **WSANs with QoS requirements**
- because
  - interesting "base" functionalities
    - already supported in the standard specifications
  - interesting "open" functionalities
    - not supported in the standard specifications

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Why research on ZigBee Cluster-Tree? (3)

- some **open issues** (that we have been addressing)
  - **no beacon/superframe scheduling mechanism**
    - to engineer ZigBee Cluster-Tree networks avoiding inter-cluster collisions
    - to resynchronize/reschedule clusters' duty-cycles upon clusters joining/leaving
  - **no open-source stack implementation**
    - for developing cooperative research
    - complete, including beacon-enabled mode and GTS management
  - **no accurate/complete simulation model**
    - for developing cooperative research
    - complete, including beacon-enabled mode and GTS management
  - **no timing analysis models/tools**
    - for computing worst-case end-to-end delays
    - for network dimensioning (optimize cluster duty-cycles for minimum acceptable guaranteed bandwidth)
  - **no router fault-tolerance mechanism**
    - to overcome the single-point-of-failure problem in ZigBee cluster-tree networks
  - **no hidden-node avoidance mechanism**
    - to improve network throughput and energy-efficiency
  - **no mobility management mechanism**
    - to support the mobility of nodes or clusters

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Technical achievements – summary

- Developed a **complete open source toolset** to analyse, simulate, dimension and test IEEE 802.15.4/ZigBee networks
  - **Star** & **Cluster-Tree** (operating in beacon-enabled mode)
  - analytical models (MATLAB)
  - simulation models (OPNET)
  - protocol stack (nesC/TinyOS over MICAz/TelosB motes)
- Proposed and validated **novel methodologies** to
  - optimize guaranteed bandwidth vs. energy consumption
  - increase bandwidth utilization by multiple nodes sharing time slots
  - dimension and engineer cluster-tree networks
  - efficiently schedule cluster (beacon/superframe) active periods
  - mitigate the hidden-terminal problem
  - tolerate router failure/degradation via proactive re-association
  - differentiate between low/high priority traffic in CSMA/CA
    - **respecting backward compatibility with the standard specifications**

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Technical achievements – open-ZB stack (1)

- **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

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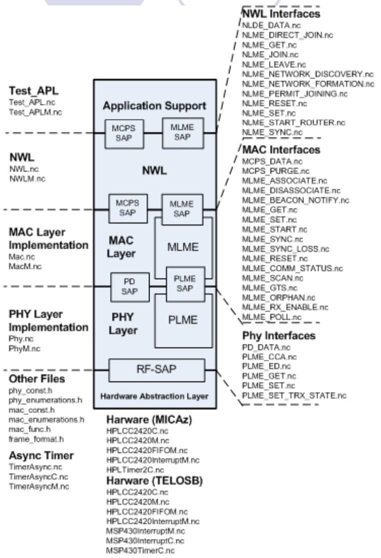
[A. Cunha, A. Koubaa, R. Severino, M. Alves, "Open-ZB: an open-source implementation of the IEEE 802.15.4/ZigBee protocol stack on TinyOS", 4th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS´07), Pisa, Italy, October 2007, pp.1-12]

Technical achievements – open-ZB stack (2)



- **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

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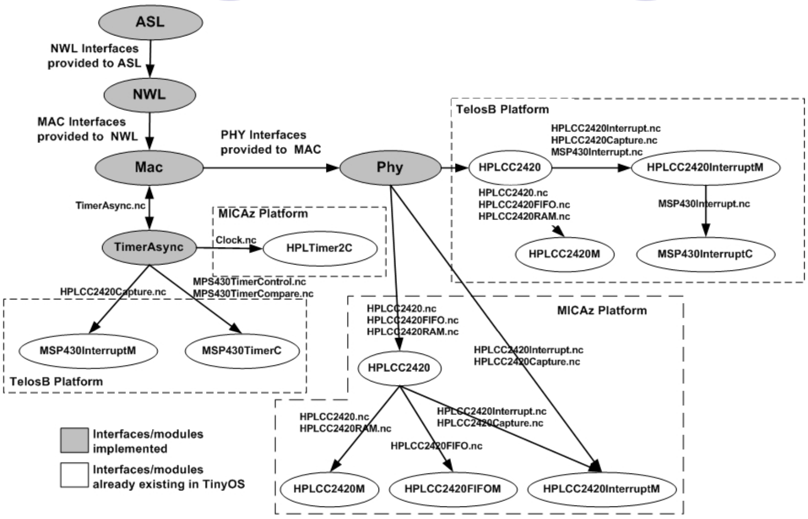
[A. Cunha, A. Koubaa, R. Severino, M. Alves, "Open-ZB: an open-source implementation of the IEEE 802.15.4/ZigBee protocol stack on TinyOS", 4th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS´07), Pisa, Italy, October 2007, pp.1-12]

Technical achievements – open-ZB stack (3)



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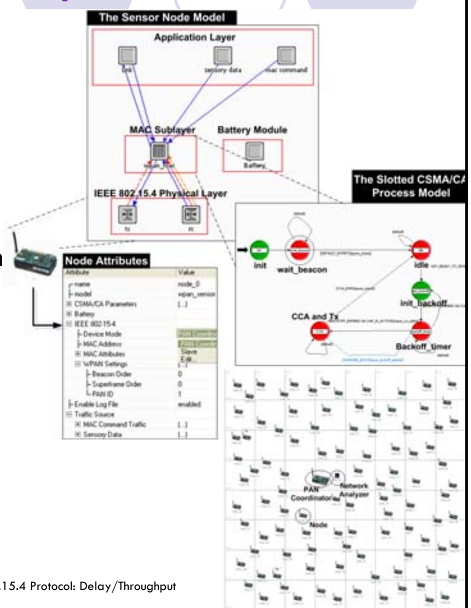
[A. Cunha, A. Koubaa, R. Severino, M. Alves, "Open-ZB: an open-source implementation of the IEEE 802.15.4/ZigBee protocol stack on TinyOS", 4th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS´07), Pisa, Italy, October 2007, pp.1-12]

Technical achievements – open-ZB simulation

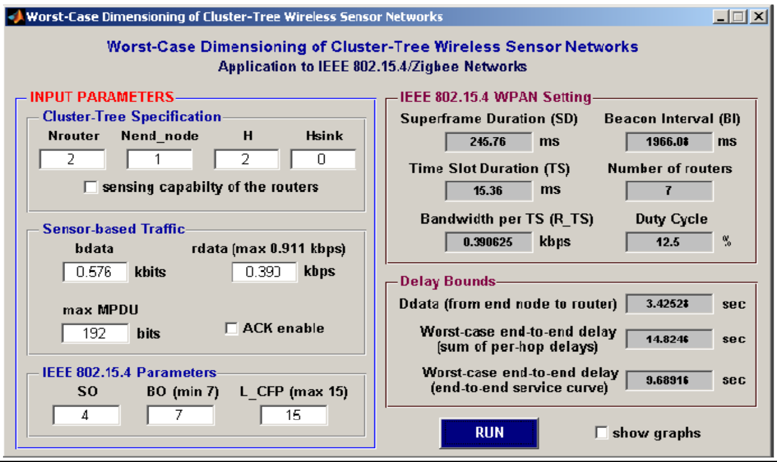
- open-source OPNET model
  - physical, MAC and application layers
- supported features
  - beacon-enabled mode
  - slotted CSMA/CA MAC protocol
  - physical layer characteristics
  - battery module (MICAz/TelosB motes)
  - Guaranteed Time Slot (GTS) mechanism
  - acknowledged **and** unacknowledged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



[A. Koubaa, M.Alves, E.Tovar, A Comprehensive Simulation Study of Slotted CSMA/CA for IEEE 802.15.4 Wireless Sensor Networks, WFCS'06]
[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", MASCOTS´07]

Technical achievements – open-ZB MATLAB

- enables worst-case network dimensioning
  - minimum duty-cycle still satisfying deadlines



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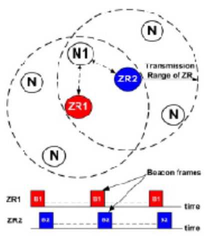
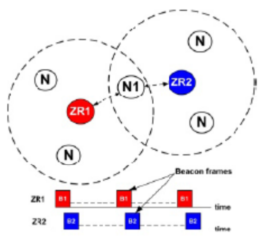
Technical achievements – TDBS (1)

- **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

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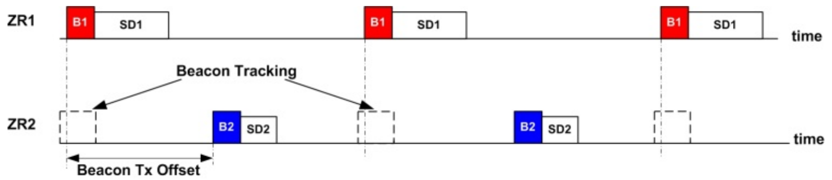
[A. Koubaa, A. Cunha, M. Alves, "A Time Division Beacon Scheduling Mechanism for IEEE 802.15.4/Zigbee Cluster-Tree Wireless Sensor Networks", ECRTS 2007]

Technical achievements – TDBS (2)

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



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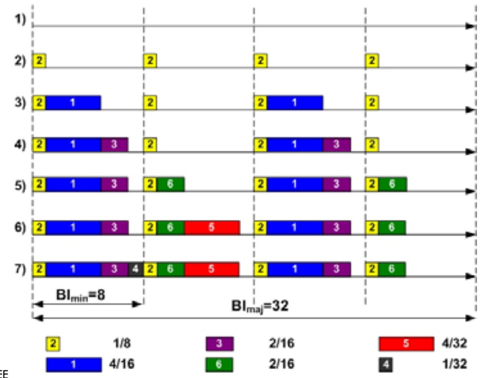
[A. Koubaa, A. Cunha, M. Alves, "A Time Division Beacon Scheduling Mechanism for IEEE 802.15.4/Zigbee Cluster-Tree Wireless Sensor Networks", ECRTS 2007]

Technical achievements – TDBS (3)

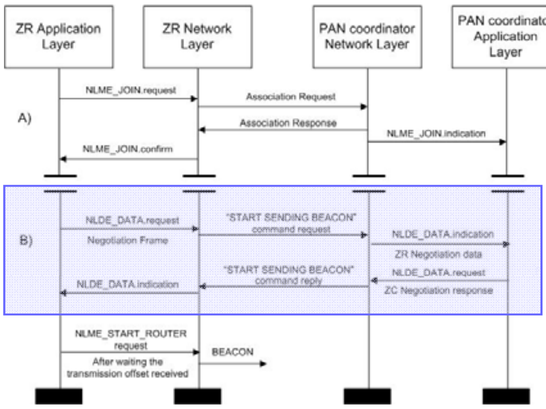
- how to **organize the beacon frames** of the different ZigBee Routers to avoid collisions with other beacons or data frames
- **sufficient to find a cyclic schedule in a hyper-period equal to BImax.**
- example:

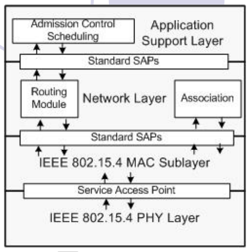
ZigBee Routers	SD	BI
ZR1	4	16
ZR2	1	8
ZR3	2	16
ZR4	1	32
ZR5	4	32
ZR6	2	16

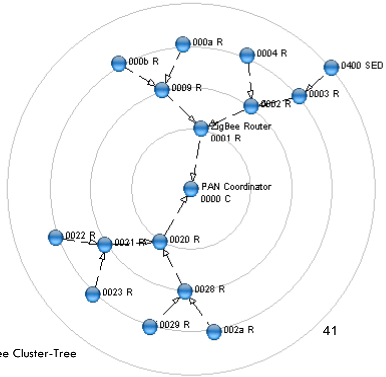


[A. Koubaa, A. Cunha, M. Alves, "A Time Division Beacon Scheduling Mechanism for IEEE 802.15.4/Zigbee Cluster-Tree Wireless Sensor Networks", ECRTS'07]

Technical achievements – TDBS (4)







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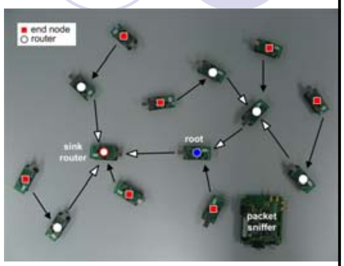
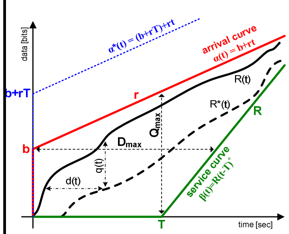
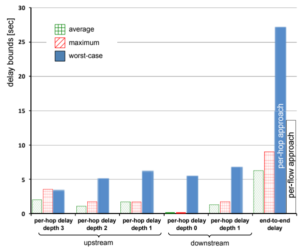
[A. Koubâa, A. Cunha, M. Alves, E. Tovar, "TDBS: A Time Division Beacon Scheduling Mechanism for ZigBee Cluster-Tree Wireless Sensor Networks", to appear in the Real-Time Systems Journal, Springer]

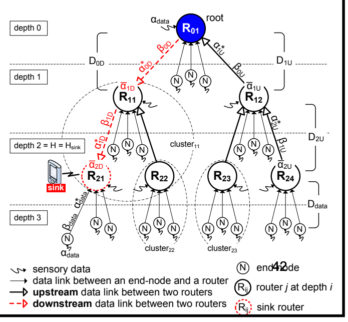
Technical achievements – analysis/dim. C-T

- New **mechanisms/methodologies for**
  - worst-case timing analysis and network dimensioning
    - energy/bandwidth tradeoff
    - real-time and energy-efficient communications









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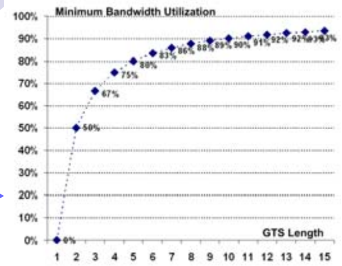
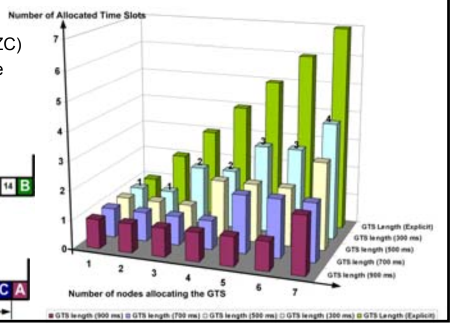
[A. Koubaa, M. Alves, E. Tovar, "Modeling and Worst-Case Dimensioning of Cluster-Tree Wireless Sensor Networks", RTSS'06]

[P. Jurčík, R. Severino, A. Koubâa, M. Alves, E. Tovar, "Real-Time Communications over Cluster-Tree Sensor Networks with Mobile Sink Behaviour", RTCSA'08]

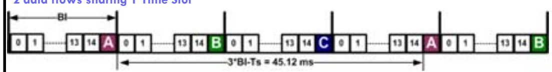
Technical achievements – i-GAME (1)

- **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)

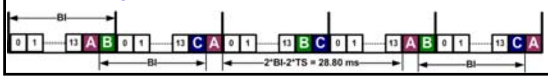




2 data flows sharing 1 Time Slot

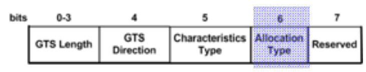


3 data flows sharing 2 Time Slots

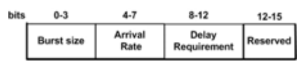


Technical achievements – i-GAME (2)

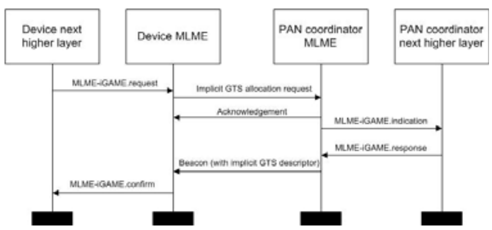
- admission control function in the ZC
  - nodes send their implicit requests including their traffic specification (b,r,D)
  - The ZC performs the admission control algorithm based on a schedulability test
- backward compatibility ensured
  - use reserved field in standard packet format – **Allocation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

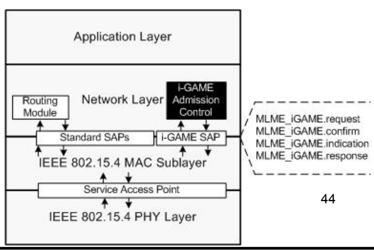


GTS Characteristics Extension Field Format for Implicit Request Allocation



Flow Specification Field Format for i-GAME





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[A. Koubaa, M. Alves, E. Tovar, "i-GAME: An Implicit GTS Allocation Mechanism in IEEE 802.15.4", 18th Euromicro Conference on Real-Time Systems (ECRTS´06)]

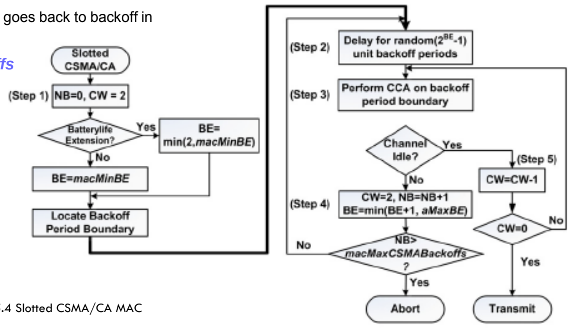
Technical achievements – CSMA/CA traffic differentiation (1)

- **Problem Statement**
  - CFP provides bandwidth guarantees
    - but requires GTS allocations/deallocations 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)

Technical achievements – CSMA/CA traffic differentiation (2)

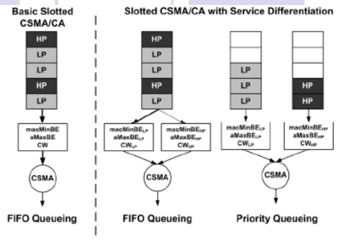
- The slotted CSMA/CA algorithm mainly depends on three variables:
  - **Backoff Exponent (BE)**: to compute random backoff delay **[0,2^{BE}-1]**
    - ***macMinBE ≤ BE ≤ aMaxBE***
  - **Contention Window (CW)**: nº time units that channel must be sensed idle
  - **Number of Backoffs (NB)**
    - number of time units CSMA/CA goes back to backoff in case of busy channel
    - ***NB ≤ macMaxCSMABackoffs***



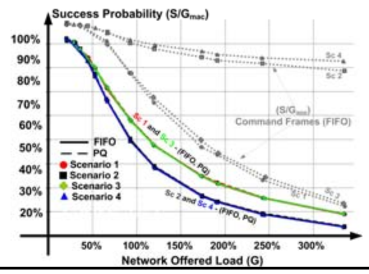
A. Koubaa, M. Alves, B. Nefzi, Y.-Q. Song, "Improving the IEEE 802.15.4 Slotted CSMA/CA MAC for Time-Critical Events in Wireless Sensor Networks" (RTN'06)

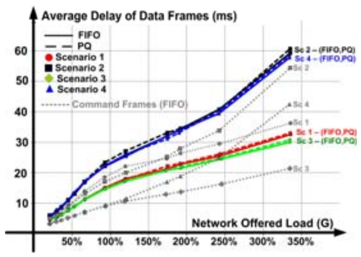
Technical achievements – CSMA/CA traffic differentiation (3)

- 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	No differentiation
Sc2	[2,5]	[2,5]	2	3	CW differentiation
Sc3	[0,5]	[2,5]	2	2	macMinBE differentiation
Sc4	[0,5]	[2,5]	2	3	CW and macMinBE differentiation





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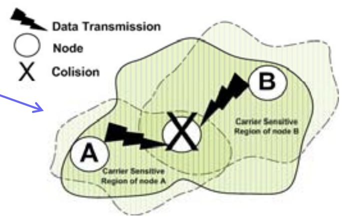
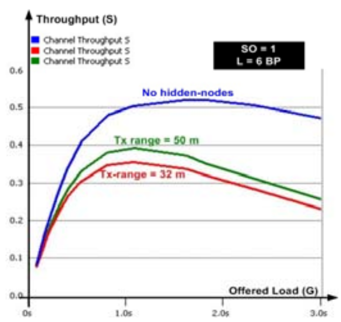
Technical achievements – H-NAMe (1)

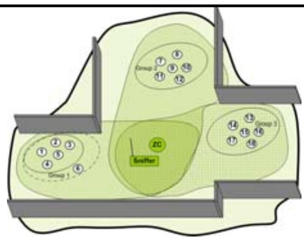
- The "**hidden-node problem**" (or "hidden-terminal problem")
  - major source of QoS degradation in WSANs due to:
    - limited communication **range** of sensor nodes,
    - radio link **asymmetry**
    - characteristics of the **physical environment**
  - degradation of the following QoS metrics.
    - **throughput**
      - the amount of traffic successfully received by a destination node
      - decreases due to additional blind collisions.
    - **energy-efficiency**
      - that decreases since each collision causes a new retransmission.
    - **message delay**
      - the time duration from the generation of a message until its correct reception by the destination node
      - becomes higher due to the multiple retransmissions of a collided message

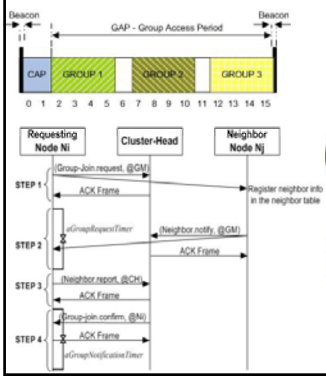


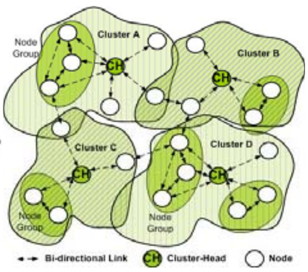


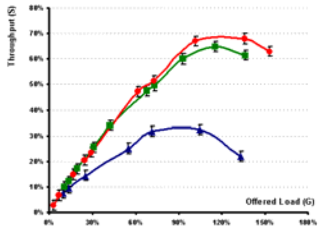
Technical achievements – H-NAMe (2)

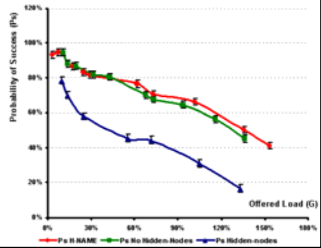
- **Hidden-Node Avoidance Mechanism (H-NAMe)**
  - **proactive** rather than reactive
  - groups of “all-visible” nodes are formed
    - each group uses a part of the CAP – **GAP**
  - cluster groups must also be formed…





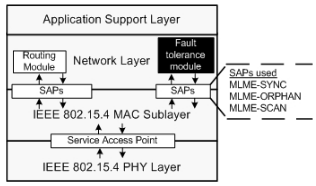


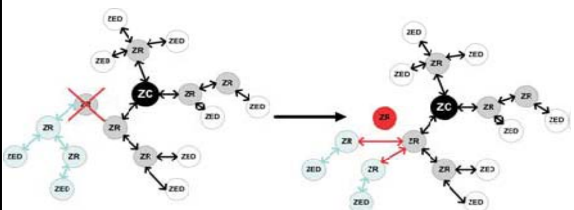




Technical achievements – fault tolerance

- **ZRs are single-points-of-failure**
  - We are investigating mechanisms for
    - tolerating routers failure/link quality degradation
      - **proactive** re-association mechanism
      - respecting **backward compatibility** with standard





$$PAI = LQI \cdot (a \cdot Ei) \cdot \left(\frac{b}{Dp}\right) \cdot \left(\frac{c}{Tl}\right)$$

[S. Ben Attia, A. Cunha, A. Koubâa, M. Alves, “Fault-Tolerance Mechanisms for Zigbee Wireless Sensor Networks”, ECRTS'07 (WiP)]

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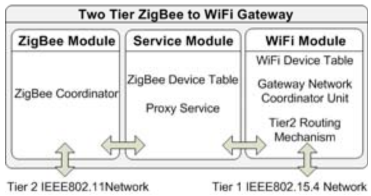
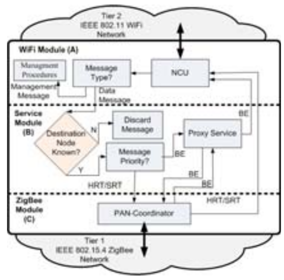
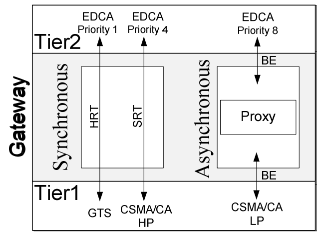
Technical achievements – gateway (1)

- **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

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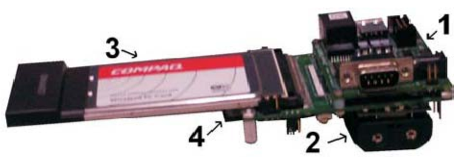
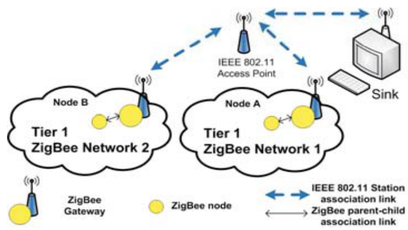
[J. Leal, A. Cunha, M. Alves, A. Koubaa, "On a IEEE 802.15.4/ZigBee to IEEE 802.11 Gateway for the ART-WiSe Architecture", ETFA'07 (WiP)]

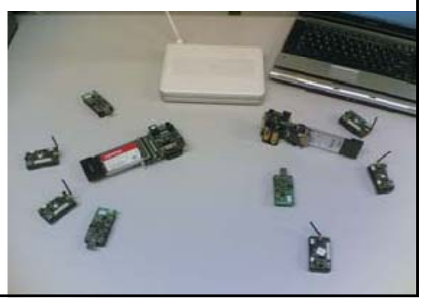
Technical achievements – gateway (2)

- 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





[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)]

Technical achievements – Hardware, Physical Layer and Software problems (1)

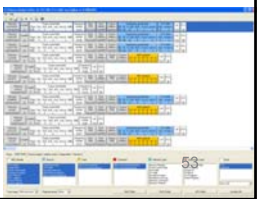
- WSN **mote constraints** – MICAz and TelosB
  - too limited to comply with the most demanding IEEE 802.15.4 timing constrains, especially for small Beacon orders (*BO < 3, 122 ms for BO=3*)

    This turns these configurations impossible to deploy, considering that the motes must also have availability for processing other tasks.

  - difficult to get a consistent behaviour of the Throughput - cannot get high offered loads

  - Available RAM memory MICAz – 4KB and TelosB – 10KB
    - Blink 55 bytes
    - MultihopOscilloscopeApp 3348 bytes
    - Open-ZB 802.15.4 2678 bytes ZigBee 3224 bytes
  - Debugging – Using serial port is not a good idea
    - causes desynchronization of the network

  Must use sniffer hardware instead! (e.g CC2420DK or Daintree)



- CC2420 Transceiver Limitations
  - Transceiver turn around time

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

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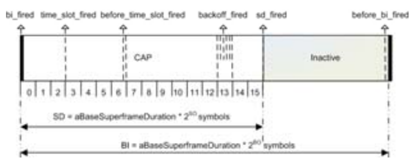
Technical achievements – Hardware, Physical Layer and Software problems (2)

- 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:
  1. the processing time of the beacon frame for low *BO/SO* configurations;
  2. the mote stack overflow that results in a block or a hard reset;
  3. the unpredictable delay of the wireless communications;
  4. The non-real time behaviour of TinyOS;
  5. 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).

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

Technical achievements – Hardware, Physical Layer and Software problems (3)

- 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)

Nano-RK

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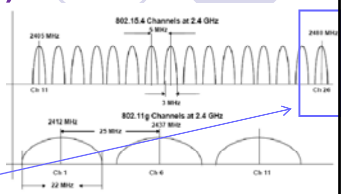
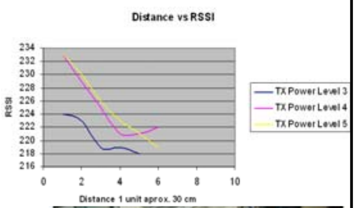
[A. Cunha, R. Severino, N. Pereira, A. Koubâa, M. Alves, "ZigBee over TinyOS: implementation and experimental challenges", CONTROLO'2008]

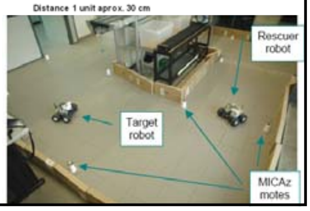
Technical achievements – Hardware, Physical Layer and Software problems (4)

- Interference with IEEE 802.11 networks
  - during CCA, channel is sensed **busy** very often
    - **reduced network throughput**
    - collision with beacon frames leads to **network desynchronization**
  - basic solution
    - use IEEE 802.15.4 **channel 26**



- RSSI based localization inaccuracy
  - measurements highly sensitive to ambient conditions.
    - proximity to metal and walls highly increased the number of reflections leading to non-consistent RSSI readings
    - RSSI value is not linear with the distance and varies with different mote antenna orientations
    - probable to find several different RSSI readings for the same distance
  - location **uncertainty of around 0,7 meter**
    - may be adequate for many WSAN applications





[R. Severino, M. Alves, "Engineering a Search and Rescue Application with a Wireless Sensor Network-based Localization Mechanism", WoWMoM'07 (poster session)]

Technological Resources (1)

- **Hands-On Lab**



- **Technological Resources**
  - WSN motes (different platforms)
  - sensor and interface boards
  - single board computers
  - network/protocol analysers
  - mobile platforms (robotics and others)

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http://www.hurray.isep.ipp.pt/activities/WSN/Technologies.ashx

Technological Resources (2)


75 XBow MicaZ


50 XBow TelosB


2 Daintree IEEE 802.15.4/ZigBee Protocol Analysers


15 MICAz OEM-based


10 CMU FireFly


4 Scatterweb ESB


2 Scatterweb ECR


2 Chipcon Dev. Boards
(Typically used as a network sniffers)


1 Sun SPOT Dev. Kit

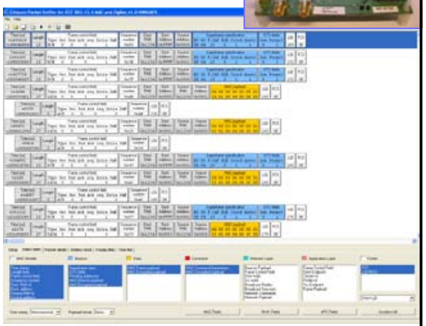

5 Serial programming boards
5 USB programming boards
2 Ethernet programming boards

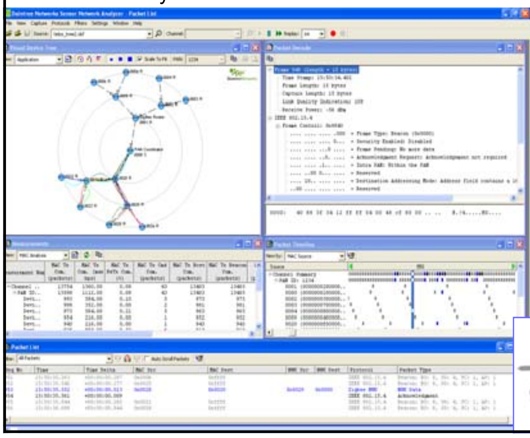

1 XBow iMote2 Builder Kit


2 Stargate XScale SBC

Technological Resources (3)

- work supported by two network protocol analysers (packet sniffers):
  - Chipcon CC2420 Packet Sniffer for IEEE 802.15.4 v1.0
  - Daintree IEEE 802.15.4/ZigBee Network Analyser.





Ongoing collaborations

- **TinyOS WG**
  - IEEE 802.15.4/ZigBee implementations for TinyOS
  - only non-US partner, with UBerkeley, USC, UHarvard, UStanford, MIT
- ARTISTDesign and **CONET** NoEs
  - 16 partners, e.g. SICS, ETH Zurich, TUDelft, UCLondon, SAP, Schneider Electric, Boeing R&T Europe, Telecom Italy
- **PT-CMU** (Carnegie Mellon University)
  - long term programme: research projects and dual PhD in ECE
  - SensorAndrew pilot
- **SSSUP** (Pisa, Italy)
  - open-ZB stack implementation over ERIKA – real-time operating system

TinyOS

COOPERATING OBJECTS NETWORK OF EXCELLENCE

CMU | Portugal
Information and Communication Technologies Institute

Retis
Real-Time Systems Laboratory

Scuola Superiore Sant'Anna
di Studi Universitari e di Perfezionamento

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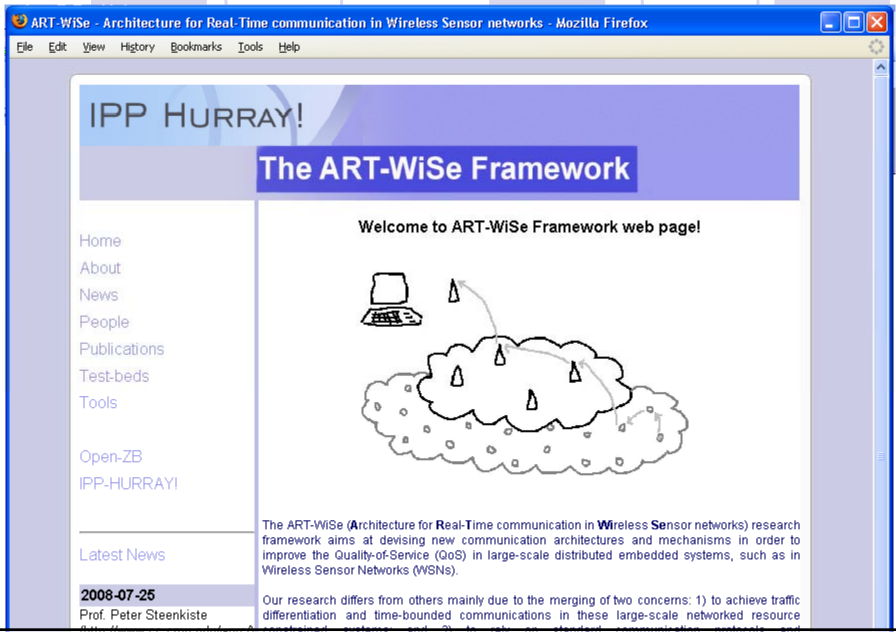
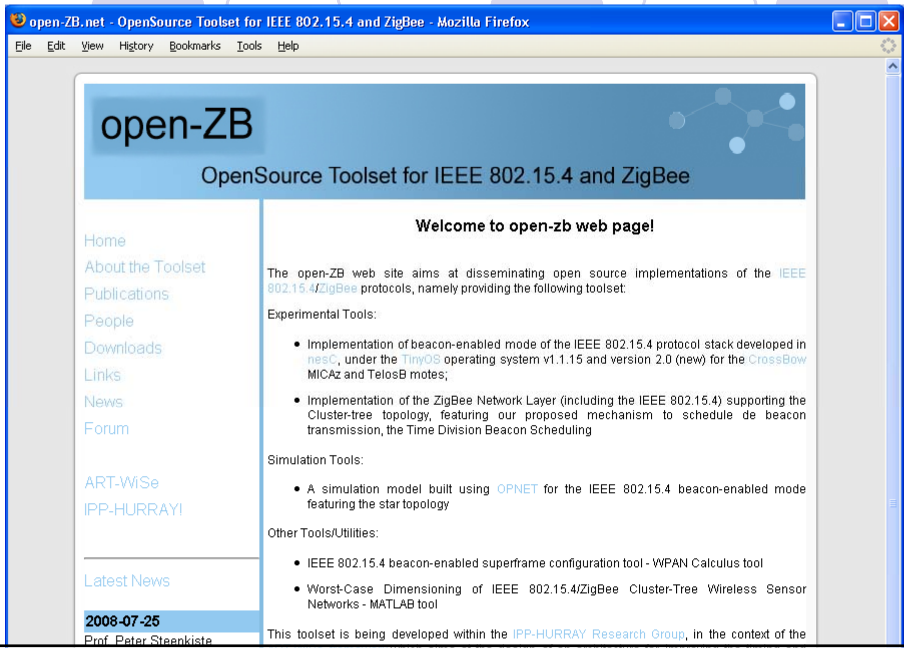
http://www.hurray.isep.ipp.pt/ART-WiSe



http://www.open-ZB.net



ART-WiSe team

- Senior Researchers
  - Mário Alves (PhD)
  - Anis Koubâa (PhD)
  - Eduardo Tovar (PhD)
- PhD researchers
  - Petr Jürcik (MSc)
  - Nouha Baccour (MSc)
- MSc researchers
  - Ricardo Severino
  - Manish Batsa
- Former collaborators
  - Skender Ben Attia
  - Melek Attia
  - Anneleen Van Nieuwenhuyse
  - Bilel Znefi
  - Y-Q Song
  - André Cunha (MSc)
  - Emmanuel Lomba

Ongoing/future research

- at the sensor network level
  - **link quality estimation and characterization** (new approach)
  - supporting **mobility** (with RT and energy-efficiency)
  - supporting **fault-tolerance** (with RT and energy-efficiency)
- at the backbone level
  - assessing **candidate technologies for Tier 2** (WiFi, WiMAX, UWB)
  - designing the **gateway architecture** (and the overall architecture)
- on system engineering
  - developing **system/network planning/management** tools
  - optimizing **deployment strategies** (logical over physical)
- on implementation and experimental work
  - migrating the open-ZB protocol stack to **other OSs and platforms**
  - applying ART-WiSe architecture to **target applications**

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Opportunities at HURRAY

- We welcome
  - PhD students
    - **short, medium and long-term (sandwich PhD)**
    - including a **dual PhD in ECE with the CMU**
  - **Post-docs**
    - several research areas

- See available jobs at
  - **http://www.hurray.isep.ipp.pt/asp/list_jobs2.asp**

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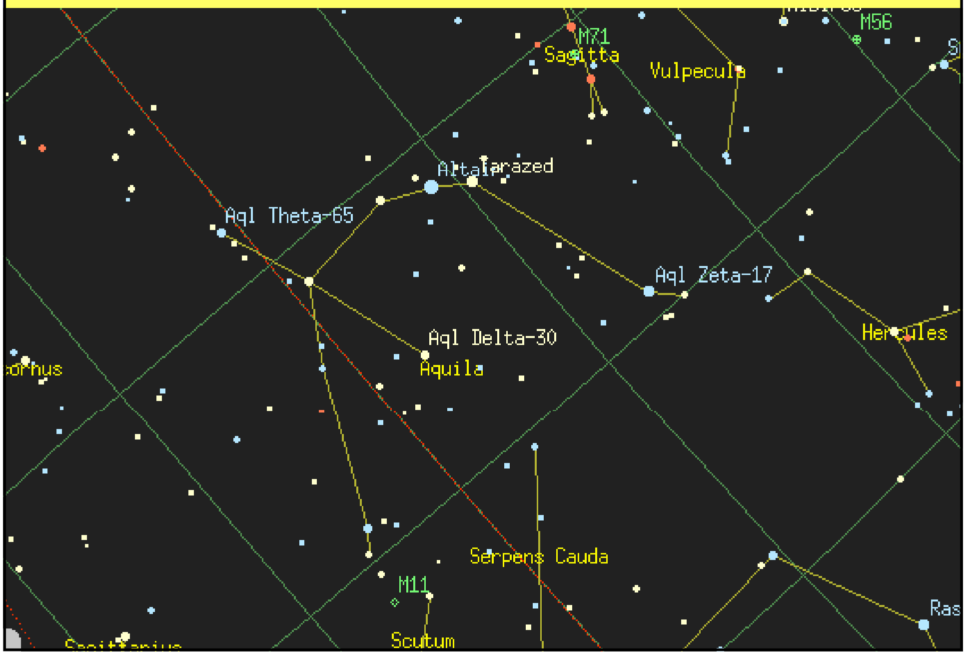
THANKS ☺



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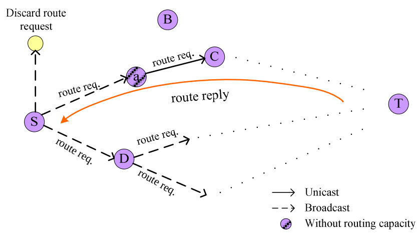
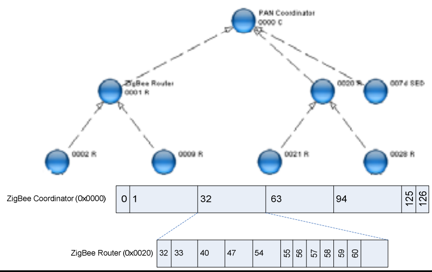
Extra slides

IEEE 802.15.4 and ZigBee highlights (extra)

- Network Layer
  - Device Configuration – ZigBee Coordinator/Router/End Device
  - Starting a Network – establish the network parameters
  - Address Assignment – ZigBee Coordinator/Routers
  - Neighbour Table – devices one-hop away
  - Routing
    - Mesh (AODV-like)

Cluster-Tree (Tree-Routing)





IEEE 802.15.4 and ZigBee highlights (extra)

- ZigBee Coordinators and Routers support 3 types of routing:
  - **Neighbour Routing**
    - based on the neighbour table
    - If the target device is physically in range it can send the message directly
  - **Table Routing**
    - AODV – Ad-hoc On Demand Distance Vector
      - based on routing tables
      - path cost metrics
  - **Tree-Routing**
    - based on the address assignment schemes
    - hierarchical routing along the tree

IEEE 802.15.4 and ZigBee highlights (extra) – Tree Routing – Example 1/5

- If the destination is a descendant of the router device if
  - ***A < D < A + Cskip*(*d*−1)**
    - A – router short address
    - D – destination address
    - d – router depth in the network
  - otherwise route to parent

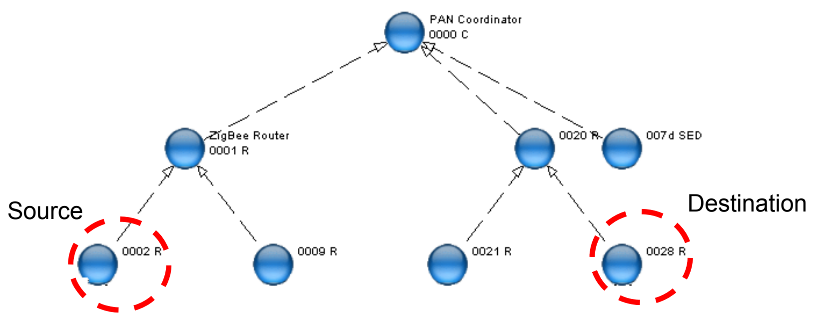
Octets: 2	2	2	1	1	Variable
Frame Control	Destination Address	Source Address	Radius[a]	Sequence Number[b]	Frame Payload
	Routing Fields				
NWK Header					NWK Payload

- If the destination is a child of the router device (neighbour table check), the address **N** (next hop) is given by
  - **N = D** , where **D** is the device short address present in the neighbour table
- Otherwise the address **N** (next hop) is given by

$$N = A + 1 + \left\lfloor \frac{D-(A+1)}{Cskip(d)} \right\rfloor \times Cskip(d)$$

IEEE 802.15.4 and ZigBee highlights (extra) – Tree Routing – Example 2/5

ZR 0x0002 wants to transmit a message to ZR 0x0028

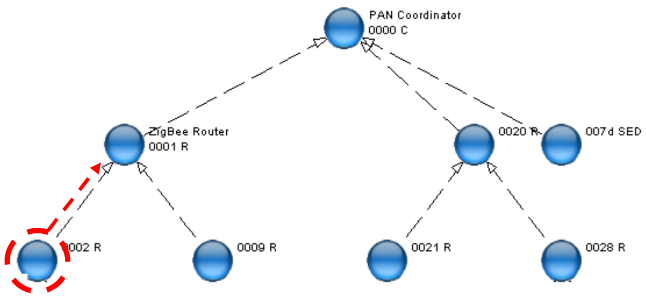


- Maximum depth (Lm): 3
- Maximum children (Cm): 6
- Maximum routers (Rm): 4

Depth	Cskip(Depth)
0	31
1	7
2	1

IEEE 802.15.4 and ZigBee highlights (extra) – Tree Routing – Example 3/5

- ZR 0x0002 creates the data frame and sends it to it parent (0x0001).



Depth	Cskip(Depth)
0	31
1	7
2	1

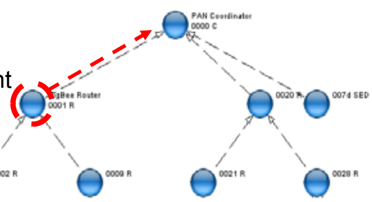
IEEE 802.15.4 and ZigBee highlights (extra) – Tree Routing – Example 4/5

1. ZR 0x0001 receives the data frame
2. realizes that the message in not for him and has to be relayed
3. tries to find the if destination is one of its child devices
4. checks if the routing destination address is a descendant

A < D < A + Cskip(d-1)

0x0001 < 0x0028 < 0x0001 + 7

5. the destination is not a descendant route to parent



- MAC destination address – 0x0000;
- MAC source address – 0x0001;
- Network Layer Routing Destination Address – 0x0028;
- Network Layer Routing Source Address – 0x0002;

Depth	Cskip(Depth)
0	31
1	7
2	1

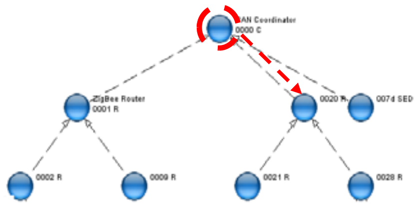
IEEE 802.15.4 and ZigBee highlights (extra) – Tree Routing – Example 5/5

1. ZC 0x0000 receives the data frame
2. realizes that the message in not for him and has to be relayed
3. tries to find if the destination is one of its child devices
4. routes down by calculating the next hop

$$N = A + 1 + \left\lfloor \frac{D - (A+1)}{Cskip(d)} \right\rfloor \times Cskip(d)$$

$$N = 0x0000 + 1 + \left\lfloor \frac{0x0028 - (0x0000 + 1)}{31} \right\rfloor \times 31$$

N = 32 (decimal) = 0x0020



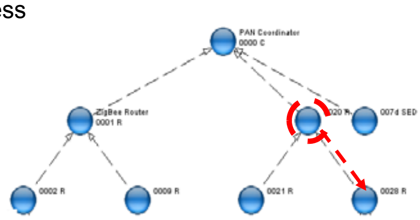
- MAC destination address – 0x0020;
- MAC source address – 0x0000;
- Network Layer Routing Destination Address – 0x0028;
- Network Layer Routing Source Address – 0x0002;

Depth	Cskip(Depth)
0	31
1	7
2	1

IEEE 802.15.4 and ZigBee highlights (extra)

1. ZR 0x0020 receives the data frame
2. realizes that the message in not for him and has to be relayed
3. tries to find if the destination is one of its child devices
4. the destination address is a neighbour
5. the next hop is assigned with the short address

present in the selected neighbour table entry



- MAC destination address – 0x0028;
- MAC source address – 0x0020;
- Network Layer Routing Destination Address – 0x0028;
- Network Layer Routing Source Address – 0x0002;

Depth	Cskip(Depth)
0	31
1	7
2	1