IPP Hurray!

www.hurray.isep.ipp.pt

enabling ubiquitous computing and cyber-physical systems with wireless sensor/actuator networks

what is at stake?

Mário Alves (mjf@isep.ipp.pt)

PhD School

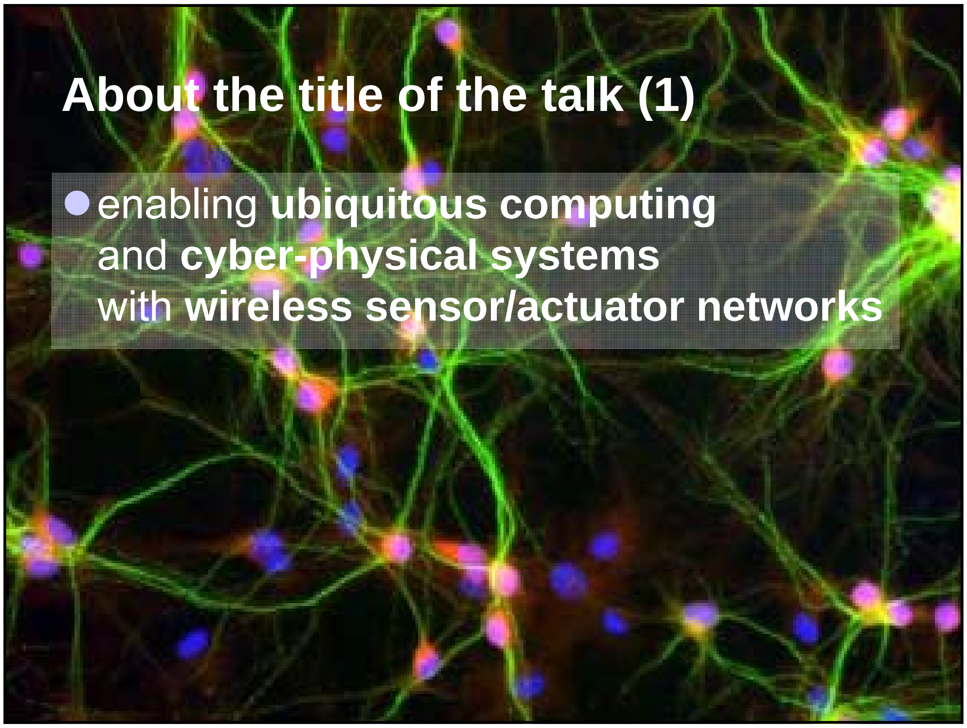
L'Aquila, Italy – 4/SEP/2008

CISTER Research Centre in Real-Time Computing Systems
FCT Research Unit 608

isep instituto superior de engenharia do porto

Who should you blame…

- I am here due to:
  - Peppe (decided to invite Eduardo)
  - Eduardo (decided to delegate to me)
  - My wife and kids (authorized me to come)
  - My parents (decided to have a third child)
- And now you have to stand me ☺
- Credits (i.e. complaint to):
  - Anis Koubaa, Nuno Pereira, Ricardo Severino, Shashi Prabh, Petr Jurcik, Bjorn Andersson



About the title of the talk (2)

- what is "**ubiquitous computing**"?
  - **"ubiquitous"**
    - from Latin ***ubique***, everywhere
    - being everywhere at once: omnipresent.
    - seeming to appear everywhere at the same time.
  - **"ubiquitous computing"**
    - is a post-desktop model of human-computer interaction in which **information processing has been thoroughly integrated into everyday objects and activities**;
    - **opposed to the desktop paradigm**, in which a single user consciously engages a single device for a specialized purpose;
    - someone "using" ubiquitous computing engages **many computational devices and systems simultaneously**, in the course of ordinary activities, and **may not necessarily even be aware to be doing so**.

4

About the title of the talk (2)

- what are “**cyber-physical systems**”?
  - cyber-physical systems (CPS) are computing systems that **do not only compute abstract quantities**; they are also **tightly integrated and interacting with their physical environment**, by taking sensor readings and acting on it.
  - integration of physical processes and computing is not new; **embedded systems** have been since a long time in place to denote systems that combine physical processes with computing.
  - **The revolution will come from massively networking embedded computing devices**

5

About the title of the talk (3)

- what are “**wireless sensor/actuator networks**”?
  - **“wireless (communication)”**
    - “wireless communication” is the transfer of information over a distance without the use of electrical conductors or "wires“ using some form of energy, e.g. radio frequency (RF), infrared light (IR), laser light, visible light, acoustic energy
  - **“sensor”**
    - a sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument, e.g. thermocouple, strain gauge;
    - sensors tend to be manufactured on a microscopic scale (MEMS technology)
  - **“actuator”**
    - devices which transform an input signal (mainly an electrical signal) into motion
    - e.g. electrical motors, pneumatic actuators, hydraulic pistons, relays, electrovalves, piezoelectric actuators, buzzers, lamps
  - **“network”**
    - a “computer network” is a group of interconnected computers

6

About the title of the talk (5)

- **"wireless sensor network"**
  - **A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions**, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations.
  - originally motivated by military applications such as battlefield surveillance; now used in many civilian application areas, including environment and habitat monitoring, healthcare applications, home automation, and traffic control
- "**sensor node**"
  - a sensor node (a.k.a. "mote"), is a node in a wireless sensor network that is capable of performing some **processing, gathering sensory information and communicating** with other connected nodes in the network
  - in addition to **one or more sensors**, each node in a sensor network is typically equipped with a **radio transceiver** or other wireless communications device, a small **microcontroller**, and an **energy source**, usually a battery.

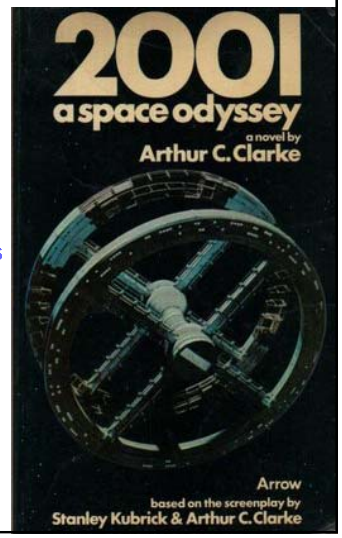
7

About the title of the talk (4)

- So,
  "wireless sensor/actuator networks"
  are
  networking infrastructures
  for
  "ubiquitous computing and **cyber-physical systems"**

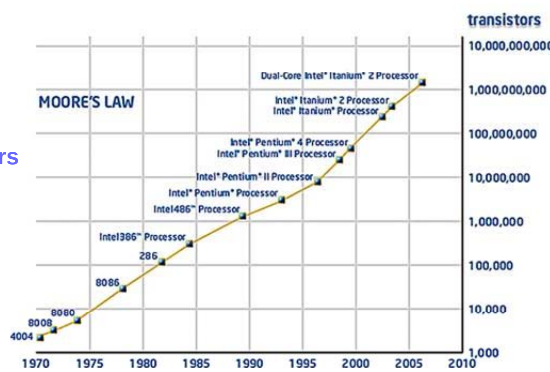
Envisioning ICTs future (1)

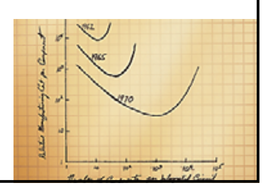
- Imagination is the limit…
  - Arthur C. Clarke's Laws (1917-2008):
    - "When a distinguished but elderly scientist states that something is possible he is almost certainly right. When he states that something is impossible, he is very probably wrong"
    - "The only way of discovering the limits of the possible is to venture a little way past them into the impossible"
    - "Any sufficiently advanced technology is indistinguishable from magic"



Envisioning ICTs future (2)

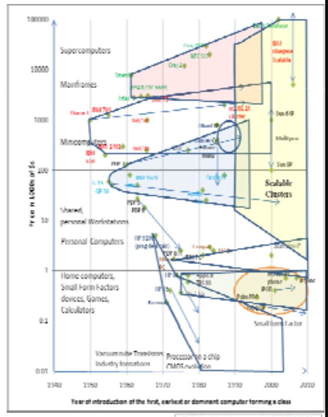
- and ICTs trend may help…
  - Gordon Moore's Law (born 1929):
    - "The number of transistors that can be inexpensively placed on an integrated circuit is increasing exponentially, doubling approximately every two years" (paper from 1965)
    - In 2005, he stated that the law cannot be sustained indefinitely and noted that transistors would eventually reach the limits of miniaturization at atomic levels

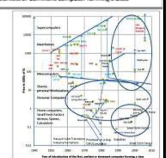




Envisioning ICTs future (3)

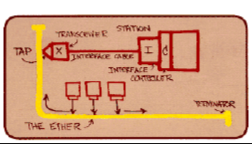
- and ICTs trend may help…
  - Gordon **Bell's Law** (born 1934)
    - "Roughly every decade a new, lower priced computer class forms based on a new programming platform, network, and interface resulting in new usage and the establishment of a new industry" (paper from 1972)
    - "**As of 2005**, the computer classes include:
      - mainframes (**1960s**)
      - minicomputers (**1970s**)
      - PCs and workstations evolving into a network enabled by Local Area Networking (**1980s**)
      - web browser client-server structures enabled by the Internet (**1990s**)
      - small form-factor devices such as cell phones and other cell phone sized devices (c. 2000)
      - wireless sensor networks, aka motes (c. **>2005**)
      - home and body area networks (**> 2010**)"

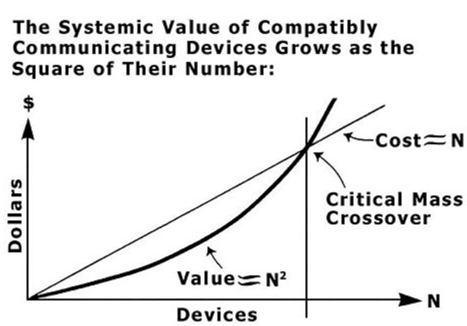




Envisioning ICTs future (4)

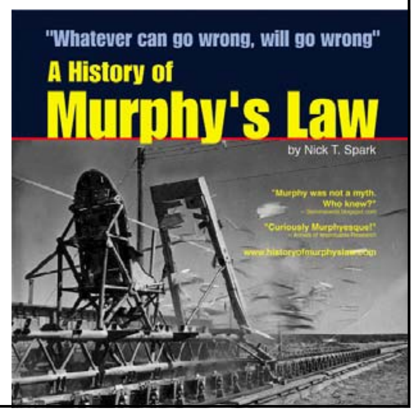
- and ICTs trend may help…
  - **Robert Metcalfe's Law** (born 1946):
    - "the value of a network grows as the square of the number of its users"





Envisioning ICTs future (5)

- but be very careful with the consequences…
  - Edward Murphy's Law (1918-1990):
    - "If there are two or more ways to do something, and one of those ways can result in a catastrophe, then someone will do it" (original version, c. 1952)

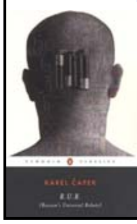


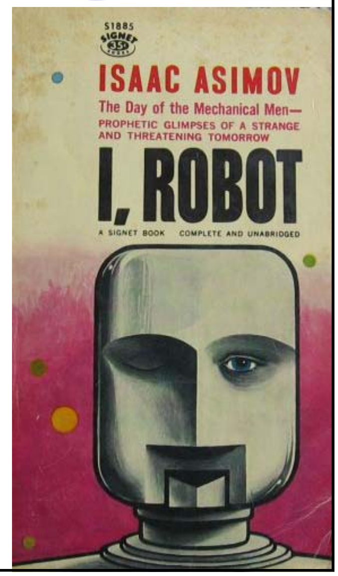
Envisioning ICTs future (6)

- but be very careful with the consequences…
  - George Orwell's "vision" (1903-1950):
    - "BIG BROTHER IS WATCHING YOU" ('1984' book, pub. 1949)
    - vision of all-knowing governments which uses pervasive and constant surveillance of the populace

Envisioning ICTs future (7)

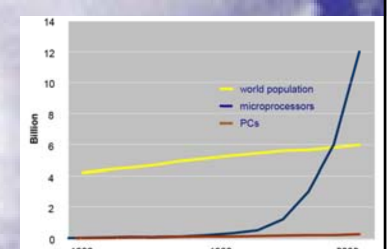
- but be very careful with the consequences…
  - **Isaac Asimov's Laws** (1920-1992):
    1. “a **robot may not injure a human** being or, through inaction, allow a human being to come to harm”
    2. “a **robot must obey orders** given to it by a human being except where such orders would conflict with the first law”
    3. “a **robot must protect its own existence** as long as such protection does not conflict with the first or second law”

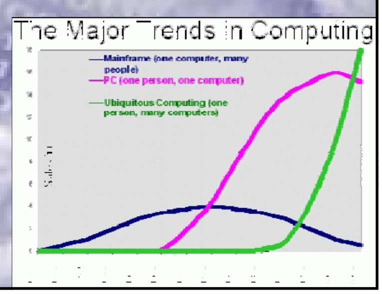




Envisioning ICTs future (8)

- **so do not forget…**
  - **Mark Weiser** (1952-1999):
    - **principles of ubiquitous computing**:
      - “the purpose of a computer is to **help you** do something else; the best computer is a quiet, **invisible servant**”
      - “the more you can do by intuition the smarter you are; **the computer should extend your unconscious**”
      - “technology should create **calm**“
    - major trends in computing
      - “ubiquitous computing names the third wave in computing, just now beginning. First were mainframes,…. Now we are in the personal computing era, …. **Next comes ubiquitous computing, or the age of calm technology, when technology recedes into the background of our lives**”





[Mark Weiser, "The Computer for the 21st Century" - Scientific American Special Issue on Communications, Computers, and Networks, September, 1991]

Are we ready for watching our world from a different angle?

now you are at the right perspective ☺

Prospective applications (1)

- “typical”:
  - environmental monitoring
  - ambient intelligence (homes, public spaces)
  - critical physical infrastructures (e.g. bridges, tunnels) monitoring
  - homeland security
  - utilities transportation systems (e.g. electrical, gas, water, oil)
  - factory automation and process control in large plants
  - domotics (home/building automation)
  - park/forest hazard monitoring
  - sports/religious/cultural events monitoring
  - disaster management (e.g. search&rescue in buildings/mines)
  - health care monitoring/management (e.g. hospitals)
  - intelligent transportation systems (e.g. highways, trains, metro)
  - the “Internet of Things”
  - games
  - participatory sensing

18

Prospective applications (2)

- Habitat Monitoring

- Infrastructure Monitoring

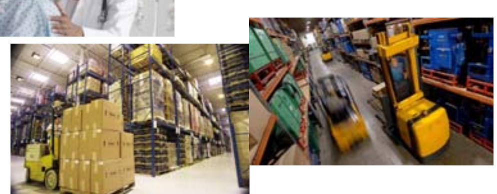
- Smart Farming and Irrigation

Prospective applications (3)

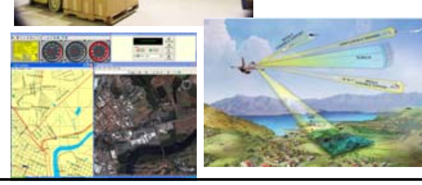
- Industrial Plant Monitoring

- Health Monitoring

- Asset Management



- Target Tracking



20

Prospective applications (4)

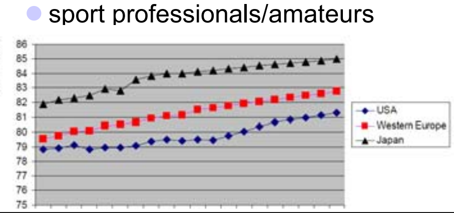
- Ex. 1: smart dust into my body?
  - to monitor (eventually to correct):
    - operation of main organs, blood, urine, muscles
    - evolution of specific diseases (cancer, infections)
    - prosthesis (namely correct absorption)
  - either in
    - punctual fashion
      - check-up, diagnosis of specific disease
      - monitoring top athletes
    - continuous fashion
      - pregnancy, pre/post-natal babies, premature babies
      - people with transient or permanent diseases
      - elderly people (trend in upcoming society)

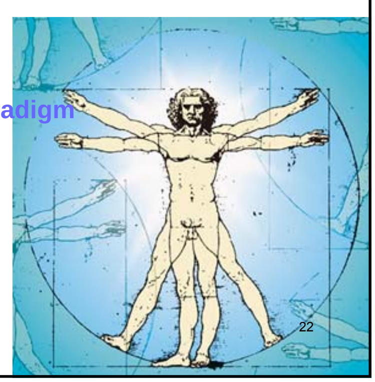
21

Prospective applications (5)

- Ex. 1: smart dust into my body? why?
  - continuous health monitoring leads to **improved quality of life**
    - “real-time” diagnosis of unknown problems
    - *pervasive* means more probability of detecting (otherwise unknown) problems
  - for people with **special needs**
    - pre and post-natal baby monitoring
    - elderly people: **the ageing society paradigm**
    - handicapped (physical/mental) people
    - sport professionals/amateurs

Figure 3-12: Average life expectancy (in years) in US, Europe, and Japan

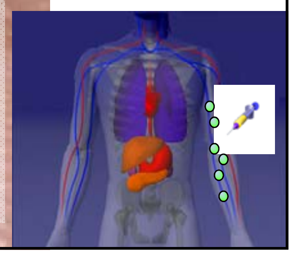




22

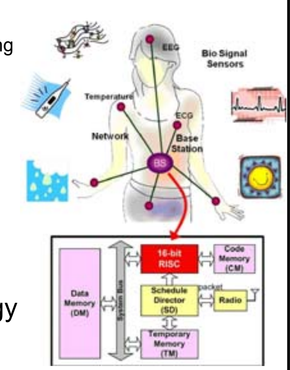
Prospective applications (6)

- Ex. 1: smart dust into my body? how?
  - sensors are (?) migrating from macro to microscopic scale
  - organic materials (as pace makers and other prosthesis)
  - introduced orally (pills), blood (injection), skin absorption
  - minimized functionality
    - minimum dedicated sensing
    - close to 0 (?) processing/memory (just info grab. and tx)
    - radically simplified communications
  - energy must be drained from human body (chemical, vibration, heat)
  - some limited corrective actions may be possible (by influencing body agents – e.g. cells)



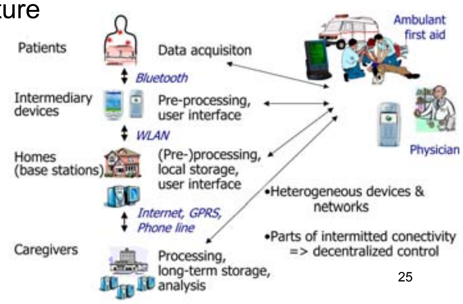
Prospective applications (7)

- Ex. 1: smart dust into my body? potential features
  - sensors can be
    - statically monitoring a specific parameter
    - sensor mobility can be useful
      - e.g. follow blood flow (for detecting arteriosclerosis drawing 3D map of channel obstruction)
  - **macroscopic nodes** may be needed due to
    - large-scale number of sensors (100s – 1000s)
    - sensor nodes huge limitations (processing, communication, energy)
  - located in strategic locations (skin, glasses, watch), forming one or more data sinks/clusters
  - more powerful processing/communication/energy capabilities



Prospective applications (8)

- Ex. 1: smart dust into my body? QoS requirements:
  - some organs/areas may be more critical than other
  - critical situations must be tackled (in real-time) according to their priority
- multi-tiered communication architecture
  - sensor/organ – cluster manager (macroscopic node) – - building/area – hospital/health care centre - …



Prospective applications (9)

- Ex. 2: big events management
  - WSN nodes embedded in participants
    - guidance/orientation/positioning/ tracking of participators
    - access control (depending on ticket price; special permissions – staff, handicapped, happy hours)
    - vital signals monitoring (due to queue waiting, riots, crowd smashing)
  - visitors to
    - exhibitions, concerts, religious events, sports events,…
  - QoS requirements
    - people in risk could be rescued
    - access violations could be punished

Some projects/deployments (1)

Great Duch Island

Observe the breeding behavior of the Leach’s Storm Petrel.

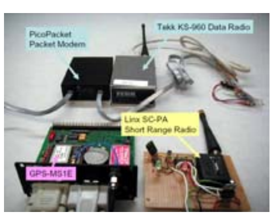
Goal: Develop a reliable and predictable sensor kit for this class of applications.

Wireless sensor networks for habitat monitoring (2002)
by Alan Mainwaring, Joseph Polastre, Robert Szewczyk, David Culler
http://www.intel-research.net/Publications/Berkeley/120520021024_43.pdf

Some projects/deployments (2)

ZebraNet

Observe the behavior of zebras, wild horses, lions, etc



Goal: Study the design tradeoffs in a mobile sensor network for this application class.

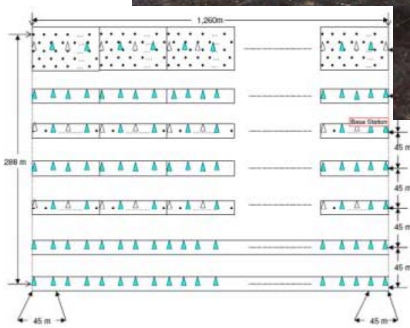
Energy-Efficient Computing for Wildlife Tracking: Design Tradeoffs and Early Experiences with ZebraNet. (2002)
by P. Juang, H. Oki, Y. Wang, M. Martonosi, L. S. Peh, and D. Rubenstein.

28

Some projects/deployments (3)

ExScal

Deployment of more than 1000 nodes.



Goal: Address the challenges in scaling to very large networks.

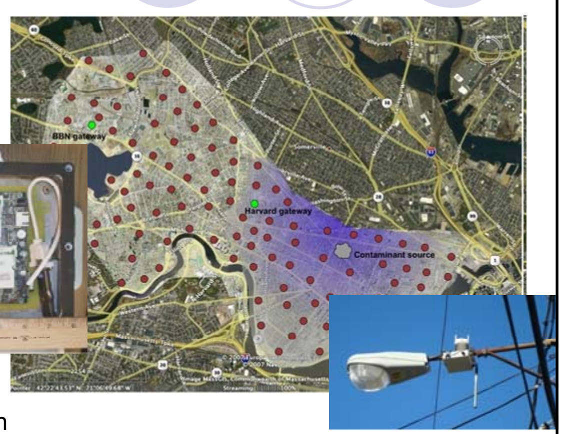
ExScal: Elements of an Extreme Scale Wireless Sensor Network (2005)
by Anish Arora, Rajiv Ramnath, Emre Ertin, Prasun Sinha, Sandip Bapat, Vinayak Naik, Vinod Kulathumani, Hongwei Zhang, Hui Cao, Mukundan Sridharan, Nick Seddon, Chris Anderson, Ted Herman, Nishank Trivedi, Chen Zhang, Romil Shah, Sandeep Kulkarni, Mahesh Aramugam, Limin Wang
http://cast.cse.ohio-state.edu/exscal/

29

Some projects/deployments (4)

CitySense

Urban-scale wireless networking testbed.



Goal: Supporting the development and evaluation of novel wireless systems that span an entire city.

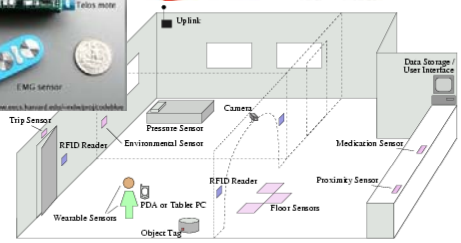
CitySense: An Urban-Scale Wireless Sensor Network and Testbed
by Rohan Murty; Geoffrey Mainland; Ian Rose; Atanu Roy Chowdhury; Abhimanyu Gosain; Josh Bers; Matt Welsh
http://www.citysense.net/

30

Some projects/deployments (5)

Alarm-Net, CodeBlue

Hardware/Software architectures for smart healthcare.



Goal: Explore the future of wireless sensor networks in medical applications.

ALARM-NET: Wireless Sensor Networks for Assisted-Living and Residential Monitoring (2006)
by A. Wood, G. Virone, T. Doan, Q. Cao, L. Selavo, Y. Wu, L. Fang, Z. He, S. Lin, J. Stankovic
http://www.cs.virginia.edu/wsn/medical/

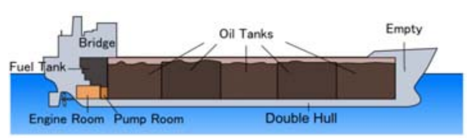
CodeBlue: An Ad Hoc Sensor Network Infrastructure for Emergency Medical Care (2004) 31
by David Malan, Thaddeus Fulford-Jones, Matt Welsh, Steve Moulton
http://fiji.eecs.harvard.edu/CodeBlue

Some projects/deployments (6)

The BP Experiment

Preventive Maintenance on an Oil Tanker in the North Sea.

Goal: test the use of sensor networks to support preventive maintenance



BP Preventive Maintenance Tanker Project
By Intel Research
http://www.intel.com/research/vert_manuf_prevmaint.htm

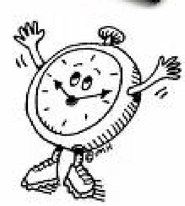
Problems and Challenges (1)

- Embedded computing systems are scaling
  - ▲ up
    - in number of nodes ($10^3 \ldots 10^6 \ldots$), and area ($10^3 \ldots 10^6 \ldots$ m^2)
  - ▼ down
    - in node size ("smart dust") and cost (<1 €/$)
- which implies
  - very low cost per node (for cost-effective deployment)
  - no maintenance (at least for most of the nodes)
  - long network/node lifetime (years)
- and stringent node resource limitations
  - processing/memory – speed, size
  - communications – radio coverage, bit rate
  - energy – battery size vs. capacity

33

Problems and Challenges (2)

- resource limitations are big impairments to
  - network/system lifetime
    - energy-efficiency
  - processing/transmitting huge amounts of information
    - data fusion/aggregation, information processing, network topologies, MAC and routing protocols
  - get tasks finished correctly and on time
    - reliable and real-time computing
  - get messages transmitted correctly and on time
    - reliable and real-time communications
- paradigm is very different from traditional WLANs (even Bluetooth)…
  - low cost/node (for large scale apps.), low comm. rate (energy), low comm. range (energy), low duty cycle (energy)



Problems and Challenges (3)

- some important challenges in WSNs: (1)
  - **energy-efficiency**
    - adequate design at all levels: energy harvesting, architecture (e.g. clustering, multiple-tiered), MAC/routing, cross-layer integration, applications, hardware optimization
  - **dependability (reliability, availability, security, safety)**
    - ability to withstand harsh environmental conditions/error prone environments, to cope with node and communication failures; privacy, authentication, encryption; unattended operation/limited or no maintenance
  - **real-time operation**
    - tasks/traffic differentiation (lower/higher priority); time-bounded computing/communications, scheduling, MAC, routing
    - node/network time synchronization
  - **network dynamics**
    - mobility of sensor nodes, cluster-heads, clusters, cluster groups,…
    - scalability/dynamic network topology (due to environmental changes, events, upgrading)
    - dynamic QoS needs (tackling events, different locations)

35

Problems and Challenges (4)

- some important challenges in WSNs: (2)
  - **heterogeneity**
    - different mote and gateway hardware,
    - different operating systems and communication protocols
    - different agents involved (ICT designers, area experts, hardware/software suppliers, end users, normalization/regulatory/fiscal entities
  - **operating systems**
    - for extremely resource-constrained embedded devices
    - energy-efficiency and real-time concerns
  - **programming**
    - simple/adequate languages/compilers/debuggers
    - over-the-air programming
  - **designing, debugging and managing large-scale systems**
    - simulators - simple/non-realistic vs. test-beds complex/realistic; somewhere in between?
    - node (OS) and network (protocol) level analysers; merging both capabilities?
    - network management

36

Problems and Challenges (5)

- some important challenges in WSNs: (3)
  - **localization**
    - GPS (proprietary solution; does not work for in-door/underground; is not scalable (uncertainty of meters)), RSS-based, …
  - **MEMS (micro-electromechanical systems)**
    - microsensors, microprocessors, RFIDs, nanonetworks,…
  - **sensor calibration**
    - large-scale brings extreme complexity
  - **node/system cost**
    - how far can industry go?
  - **radio communications**
    - improving modulation/codification techniques, antennas
    - utilization of the electromagnetic spectrum (ISM is limited)
    - hidden-node problem
  - **social/political/ethical aspects**
    - how will people face and deal with these tech.; "big brother" again…
    - computer pollution (discarding is cheaper than upgrading/maintaining)

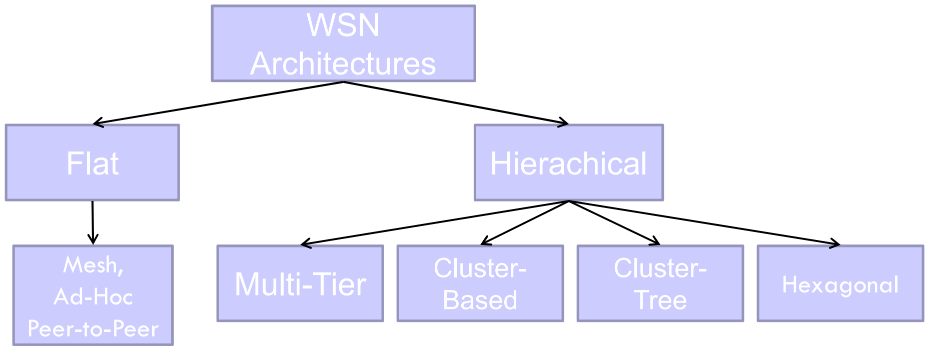
37

Problems and Challenges (6)

Body Sensor Networks might be even more challenging
[Yang, Guang-Zhong (Ed.), 2006]

Challenges	WSN	BSN
Scale	As large as the environment being monitored (metres/kilometres)	As large as human body parts (millimetres/centimetres)
Node Number	Greater number of nodes required for accurate, wide area coverage	Fewer, more accurate sensors nodes required (limited by space)
Node Function	Multiple sensors, each perform dedicated tasks	Single sensors, each perform multiple tasks
Node Accuracy	Large node number compensates for accuracy and allows result validation	Limited node number with each required to be robust and accurate
Node Size	Small size preferable but not a major limitation in many cases	Pervasive monitoring and need for miniaturisation
Dynamics	Exposed to extremes in weather, noise, and asynchrony	Exposed to more predictable environment but motion artefacts is a challenge
Event Detection	Early adverse event detection desirable; failure often reversible	Early adverse events detection vital; human tissue failure irreversible
Variability	Much more likely to have a fixed or static structure	Biological variation and complexity means a more variable structure
Data Protection	Lower level wireless data transfer security required	High level wireless data transfer security required to protect patient information
Power Supply	Accessible and likely to be changed more easily and frequently	Inaccessible and difficult to replace in implantable setting
Power Demand	Likely to be greater as power is more easily supplied	Likely to be lower as energy is more difficult to supply
Energy Scavenging	Solar, and wind power are most likely candidates	Motion (vibration) and thermal (body heat) most likely candidates
Access	Sensors more easily replaceable or even disposable	Implantable sensor replacement difficult and requires biodegradability
Biocompatibility	Not a consideration in most applications	A must for implantable and some external sensors. Likely to increase cost
Context Awareness	Not so important with static sensors where environments are well defined	Very important because body physiology is very sensitive to context change
Wireless Technology	Bluetooth, Zigbee, GPRS, and wireless LAN, and RF already offer solutions	Low power wireless required, with signal detection more challenging
Data Transfer	Loss of data during wireless transfer is likely to be compensated by number of sensors used	Loss of data more significant, and may require additional measures to ensure QoS and real-time data interrogation capabilities

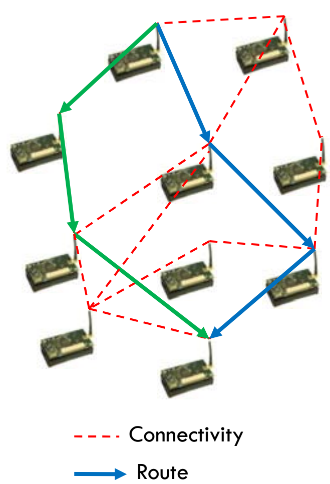
WSN architectures overview (1)



39

WSN architectures overview (2)

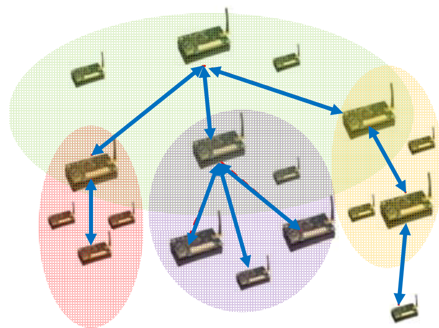
- **Flat**
  - No infrastructure
  - Peer-to-peer (flat) routing
  - Very flexible
  - Low Management Complexity
  - Limited QoS guarantees
  - All nodes have the same role
  - Basically, contention-based MAC protocols (CSMA/CA, Aloha)
  - Unsynchronized or synchronized (e.g. S-MAC)



40

WSN architectures overview (3)

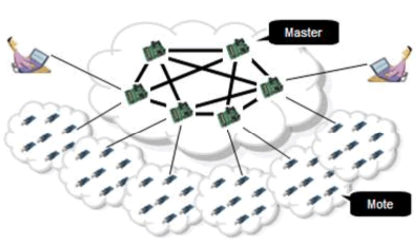
- **Cluster-Tree**
  - Network infrastructure: Backbone
  - Hierarchical routing
  - Low flexibility
  - Good QoS support
  - Complex network management
  - Basically, contention-FREE MAC protocols (TDMA)
  - Synchronized (e.g. LEACH)
  - Nodes have different roles
    - e.g. coordinator, sink, router, leaf



41

WSN architectures overview (4)

- **Multiple-Tiered**
  - Tier-1: sensor network
  - Tier-2: backbone network
  - Tier…: Internet?

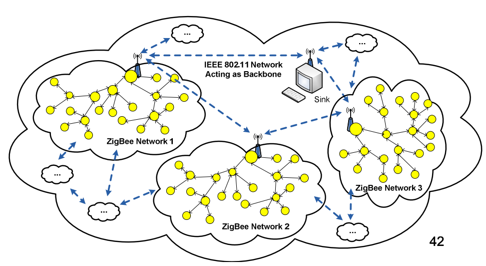


Tenet

http://research.cens.ucla.edu/projects/2007/Systems/Tenet

ART-WiSe

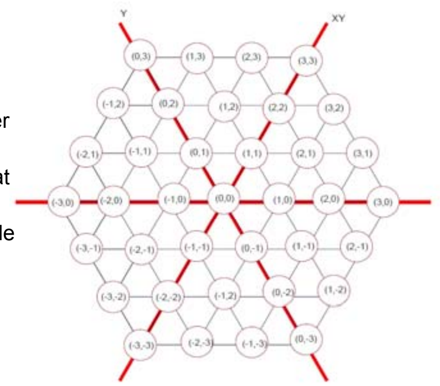
http://www.hurray.isep.ipp.pt/ART-WiSe



42

WSN architectures overview (5)

- **Hexagonal**
  - each node has six neighbors except for nodes at the edges
  - in the event of arbitrary deployments, consider a two-tier hierarchy
    - upper layer consists of nodes in hexagonal topology which are cluster heads
    - lower layer consists of the nodes that belong to one of the clusters
    - cluster heads route data over multiple hops
  - benefits of hexagonal WSN:
    - simple/low overhead MAC/network protocols
    - easy to guarantee real-time communications



S. Prabh, T. Abdelzaher

43

WSN routing overview (1)

- **Routing classification (destination)**
  - unicast
    - delivers a message to a single specified node;
  - broadcast
    - delivers a message to all nodes in the network;
  - multicast
    - delivers a message to a group of nodes that have expressed interest in receiving the message;
  - convergecast
    - disseminates and aggregates data towards a sink
- **Routing classification (determinism)**
  - probabilistic
    - routing path may vary with time (node/network status)
  - deterministic (tree routing)
    - unique routing path from any source to any destination (though nodes connectivity may be much larger)

44

WSN routing overview (2)

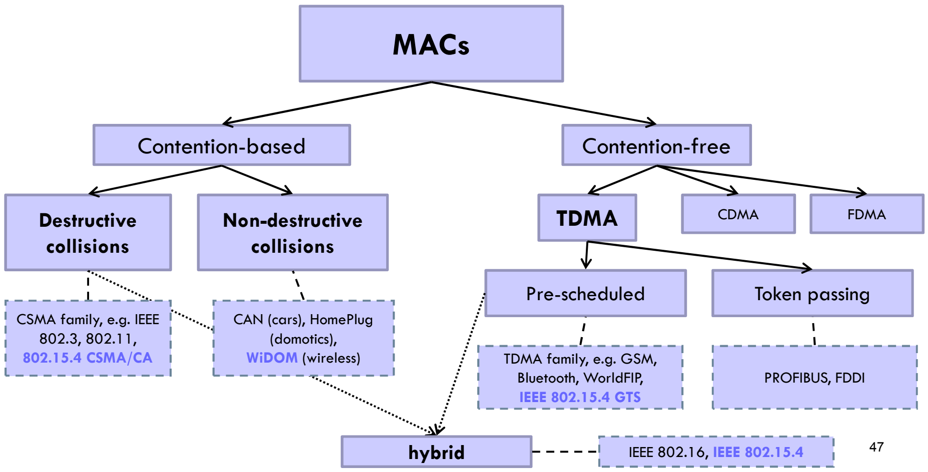
- **Routing classification (dynamics)**
  - proactive
    - First Compute all Routes; Then Route
  - reactive
    - Compute Routes On-Demand
  - hybrid
    - First Compute all Routes; then Improve While Routing
- **Routing classification (architecture)**
  - direct
    - Node and Sink Communicate Directly (Fast Drainage; Small Scale)
  - flat (equal)
    - Random Indirect Route (Fast Drainage Around Sink; Medium Scale)
  - clustering (hierarchical)
    - Route Thru Distinguished Nodes

WSN routing overview (3)

- **Routing classification (location-awareness)**
  - Location-aware
    - nodes knows where they are
  - location-less
    - nodes location is unimportant
  - mobility-aware
    - nodes may move (sources; sinks; all)
- **Routing classification (addressing)**
  - data-centric
    - the sink sends queries to certain regions and waits for data from the sensors located in the selected regions
    - data aggregation during the relaying of data
  - address-centric
    - routes are created between addressable nodes managed in the network layer of the communication stack.

WSN MAC aspects (1)

- Types of MACs



47

WSN MAC aspects (2)

1. contention-based
   - destructive collisions
     - nodes listen to the medium; if idle, transmit; if collision, backoff
     - CSMA family, e.g. IEEE 802.3, 802.11, 802.15.4 CSMA/CA
     - pros: simple, very flexible
     - cons: not energy efficient (collisions lead to retransmissions); no timing guarantees (non-deterministic); prone to hidden node problem; limited network throughput
   - non-destructive collisions
     - resolve bus conflicts by using a bitwise arbitration; each node has a unique identifier (= priority); Wire acts like a logic AND (0 is dominant, 1 is recessive); transmit identifier bit by bit and hear the medium; if a node sends a '1' but hears a '0', he loses;
     - CAN (cars), HomePlug (domotics), WiDOM (wireless)
     - pros: deterministic, time and energy-efficient
     - cons: synchronization, short tx/rx turnaround time (or 2 transceivers); multiple broadcast domains

48

WSN MAC aspects (3)

2. **contention-free**
   - transmissions are differentiated in time (**TDMA**), frequency (FDMA) or coding (CDMA)
   - **pre-scheduled access**
     - each node's transmission (which node, starting time, duration) is scheduled a priori
     - TDMA family, e.g. GSM, Bluetooth, WorldFIP, **IEEE 802.15.4 GTS**
     - **pros**: energy efficient; timing guarantees; ~100% network throughput
     - **cons**: not flexible (not adaptable to network dynamics – if scheduling is static)
   - **token passing**
     - each node transmits during its token holding time; when it expires, token is passed to the next node in a predefined sequence (e.g. logical ring)
     - e.g PROFIBUS, FDDI
     - **pros**: energy efficient; timing guarantees; ~100% network throughput
     - **cons**: not very flexible; very error-prone (token losses) in harsh environments
3. **hybrid**
   - merge both previous for more flexibility (best effort/real-time)
   - usually **CSMA+TDMA**, e.g. IEEE 802.16, **IEEE 802.15.4**
   - **pros**: best of both worlds
   - **cons**: management complexity

49

WSN MAC aspects (4)

- **Characteristics of a good MAC/DLL protocol for WSNs**
  - **energy efficiency (to prolong the network lifetime)**
    - flexible enough to adapt duty-cycles (100% → 0%)
      - dynamically
      - in a per cluster basis
    - must address some causes of energy loss:
      - collisions – due to retransmissions
      - hidden-nodes and exposed-nodes problems – lead to unnecessary extra collisions
      - overhearing – waste effort in receiving a packet destined for another node
      - idle listening – sitting idly and trying to receive when nobody is sending
  - **scalability and adaptability to changes**
    - changes in network size, node density and topology should be handled rapidly and effectively
  - **reliability**
    - error detection/correction mechanisms
  - **traffic differentiation**
    - support higher/lower priority traffic classes
    - support best effort and real-time traffic
  - **minimized frame overhead (for optimal bandwidth utilization)**
    - but still support network management, security, error detection/correction

50

Physical layer aspects (1)

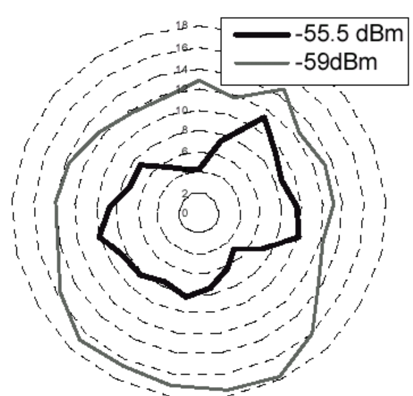
- **Radio link characteristics**
  - asymmetric links
    - node A is connected to Node B does not mean that Node B is connected to node A
  - non-isotropical connectivity
    - connectivity depends on the direction of the signal (at same distance from source)
  - non-monotonic distance decay
    - nodes geographically far away from source may get better connectivity than nodes that are geographically closer

51

*Ganesan et. al. 02; Woo et. al. 03; Zhao et. al. 03; Cerpa et. al. 03; Zhou et. al. 04

Physical layer aspects (2)

- **non-isotropy of radio links**
  - the assumption of a circular disk model does not hold for radio propagation, in practice.



52

*Zhou et. al. 04

Physical layer aspects (3)

- **propagation phenomena**
  - **reflection**
    - is the change in direction of a wave front at an interface between two different media so that the wave front returns into the medium from which it originated
  - **diffraction**
    - refer to various phenomena which occur when a wave encounters an obstacle
  - **scattering**
    - from objects that are small (when compared to the wavelength), e.g.: Rough surfaces

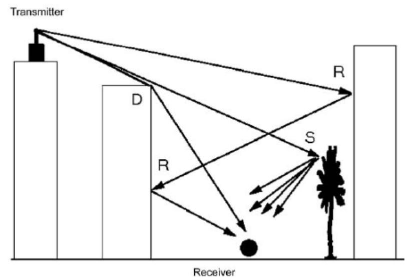


Figure 2.5 Reflection (R), diffraction (D) and scattering (S)

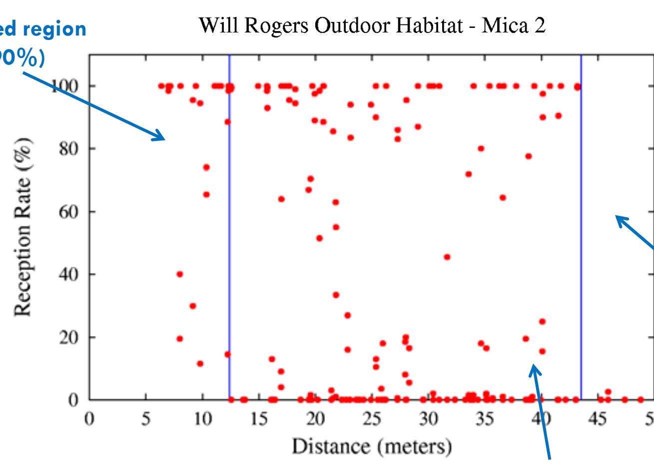
Source: **Wireless Networks,** P. Nicopolitidis, A. S. Pomportsis, G. I. Papadimitriou, M. S. Obaidat Publisher John Wiley & Sons, Inc. New York, NY, USA (2003)

53

Physical layer aspects (4)

- **Spatial characteristics**

Connected region (PRR > 90%)



Disconnected Region (PRR < 10%)

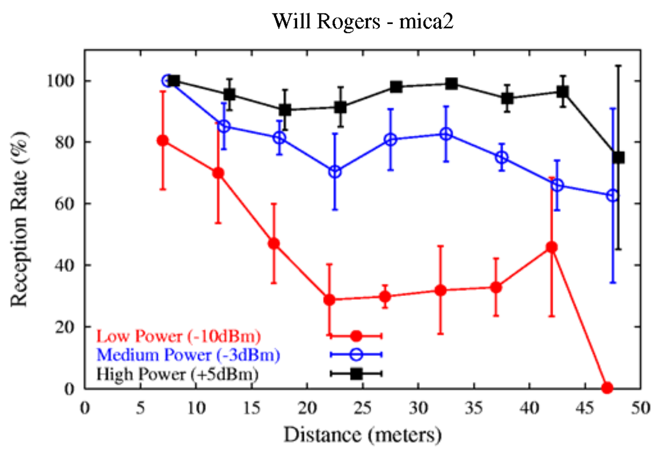
Transitional region (Gray area)

54

Cerpa et. al. 03

Physical layer aspects (5)

- **Packet Reception Rate versus Distance**



55

Cerpa et. al. 03

Technology (1) – mote examples

Node Type	Name	Typical Application
Specialized Sensing Platform	Spec	Specialized low-bandwidth sensor, or RFID tag
Generic Sensor Platform	Mica, Mica2, MicaZ, Telos, ESB, Firefly, Particle, SquidBee, SHIMMER	General purpose sensing or communication relay
High-bandwidth sensing/Gateway	iMote1, iMote2, SunSPOT, Stargate1, Stargate2, gumstix	High bandwidth sensing (video, acoustic, vibration), communication aggregation, compute node or gateway

Technology (2) – mote evolution

Mote Type / Year	WeC 1998	René 1999	René 2 2000	Dot 2000	Mica 2001	Mica2Dot 2002	Mica 2 2002	Telos 2004
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			60
RAM (KB)	0.5		1		4			2
Active Power (mW)	15		15		8		33	3
Sleep Power (μW)	45		45		75		75	6
Wakeup Time (μs)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	41
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

…

57

Technology (3) – mote common radios

	CC1000	CC1021	CC2420	TR1000	XE1205
Manufacturer	Chipcon	Chipcon	Chipcon	RFM	Semtech
Operating Frequency [MHz]	300 - 1000	402 - 470 / 804 - 940	2400	916	433 / 868 / 915
Bit Rate [kbps]	76.8	153.6	250	115.2	1.2 - 152.3
Sleep Mode [uA]	0.2 – 1	1.8	1	0.7	0.2
RX [mA]	11.8 (868 MHz)	19.9	19.7	3.8 (115.2kbps)	14
TX Min [mA]	8.6 (-20dBm)	14.5 (-20dBm)	8.5 (-25dBm)		33 (+5dBm)
TX Max [mA]	25.4 (+5dBm)	25.1 (+5dBm)	17.4 (0dBm)	12 (+1.5dBm)	62 (+15dBm

Technology (4) – RFID

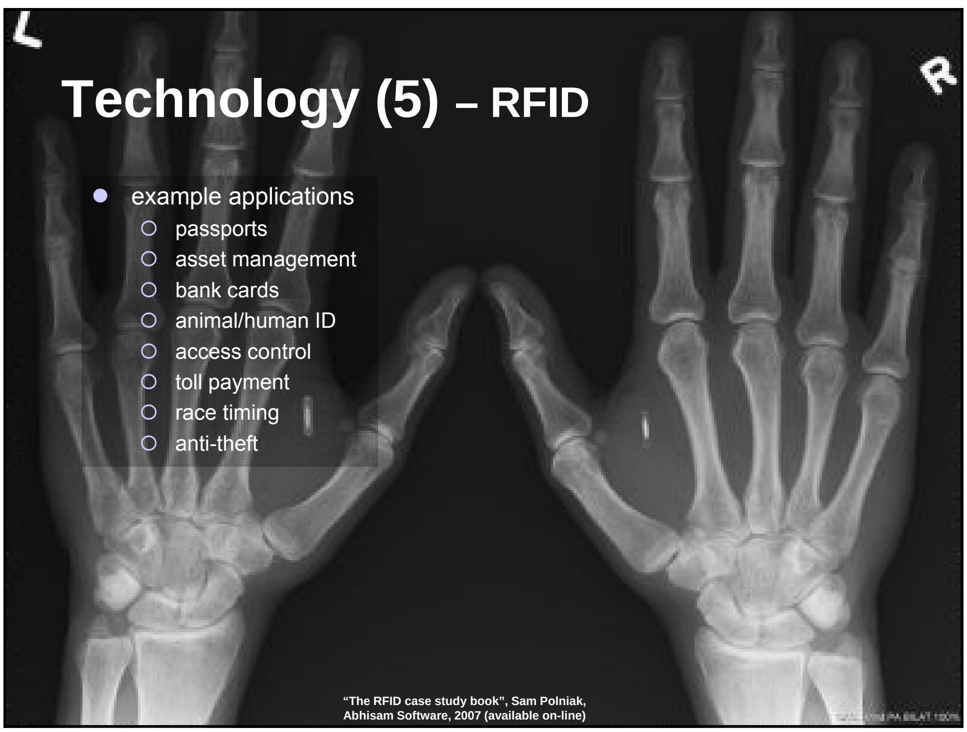
- RFID tag (or transponder)
  - is an object that can be applied to or incorporated into a product, animal, or person for the purpose of identification using radio waves
  - from centimeters to meters distance (tag-reader) with or without line-of-sight
  - composed of
    - antenna - for receiving and transmitting the signal
    - integrated circuit (optional) for storing and processing information, modulating and demodulating a (RF) signal, and other specialized functions
- Types

	Active Tag	Semi-passive Tag	Passive Tag
Power Source	Battery on tag.	Battery for chip operation. Radio wave energy from Reader for communication.	Radio wave energy from Reader for operation and communication.
Tag Signal Availability	Always on, 100 feet	Only within field of reader	Only within field of reader, less than 10 feet
Signal Strength Tag	High	Low	Very low
Required Signal Strength from Reader	Very low	Low	Very high
Typical Applications	Useful for tracking high-value goods that need to be scanned over long ranges. Example: railway cars on a track.		Useful for high-volume goods, where items can be read from short ranges. Example: retail check out.

any similarities with WSN nodes?

http://java.sun.com/developer/technicalArticles/Ecommerce/rfid/

59

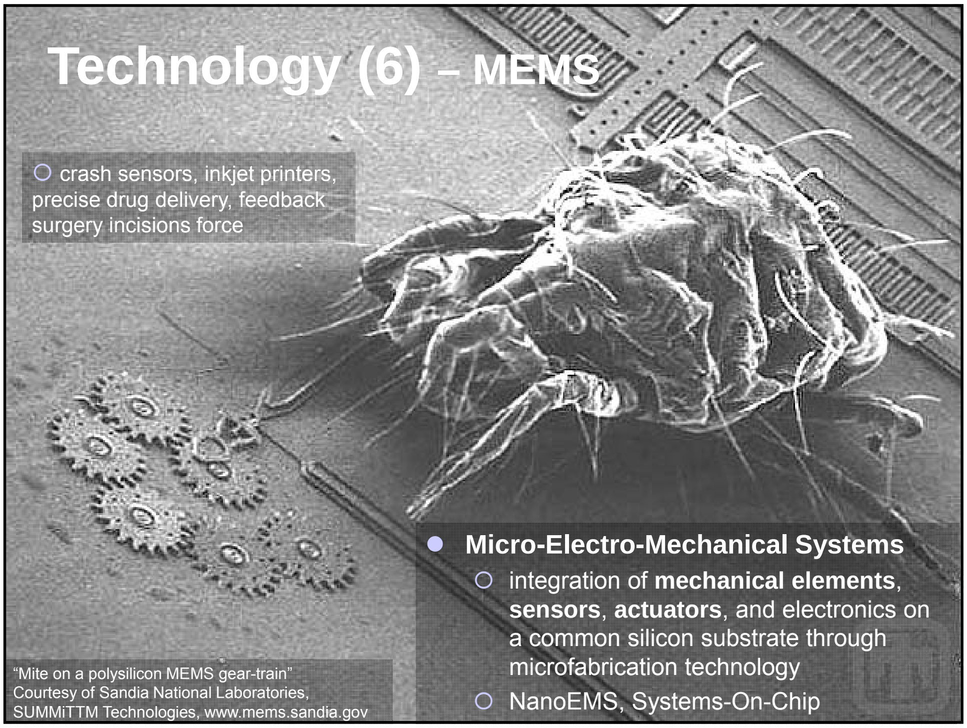


Technology (5) – RFID

- example applications
  - passports
  - asset management
  - bank cards
  - animal/human ID
  - access control
  - toll payment
  - race timing
  - anti-theft

"The RFID case study book", Sam Polniak, Abhisam Software, 2007 (available on-line)

Technology (6) – MEMS



- crash sensors, inkjet printers, precise drug delivery, feedback surgery incisions force

- **Micro-Electro-Mechanical Systems**
  - integration of **mechanical elements**, **sensors**, **actuators**, and electronics on a common silicon substrate through microfabrication technology
  - NanoEMS, Systems-On-Chip

"Mite on a polysilicon MEMS gear-train"
Courtesy of Sandia National Laboratories,
SUMMiTTM Technologies, www.mems.sandia.gov

Technology (7) – communication protocols

Distance between nodes	Nodes located in the same	Network Class (dimension)	Example protocols
x µm – x mm	Chip	NanoNetworks,NoC (Networks on Chip)	?
x mm – x m	Body	BAN (Body Area Networks)	(IEEE 802.15.6)
x m – x0 m	Room	PAN (Personal Area Networks)	USB, FireWire, 6lowpan IEEE 802.15.1/Bluetooth, IEEE 802.15.4/ZigBee, IEEE 802.15.3/UWB
x0 m – x00 m	Building, Campus	LAN (Local Area Networks)	IEEE 802.11/WiFi, IEEE 802.3/Ethernet, WirelessHART, fieldbus networks
x00 m – x0 km	City	MAN (Metropolitan Area Networks)	IEEE 802.16/WiMAX, IEEE 802.20/MBWA, ATM, FDDI
x0 km – x… km	Country – …	WAN (Wide Area Networks)	IEEE 802.22/WRAN, ATM, X.25, Frame Relay, Satellite…

WSAN can span over all of these…

Alves ☺

Tanembaum

Interprocessor distance	Processors located in same	Example
1 m	Square meter	Personal area network
10 m	Room	Local area network
100 m	Building	Local area network
1 km	Campus	Local area network
10 km	City	Metropolitan area network
100 km	Country	Wide area network
1000 km	Continent	Wide area network
10,000 km	Planet	The Internet

Technology (8) – operating systems

- some OS for resource-constrained WSN devices
  - tens of others…

Operating System	Origin	Open source	Real-time	Link
TinyOS	UCB, Intel (USA)	Yes	No	http://www.tinyos.net
Contiki	SICS (Sweden)	Yes	No	http://www.sics.se/contiki
Nano-RK	CMU (USA)	Yes	Yes	http://www.nanork.org
ERIKA	SSSUP (Italy)	Yes	Yes	http://erika.sssup.it
MANTIS	UC Boulder (USA)	Yes	No	http://mantis.cs.colorado.edu
SOS	UCLA (USA)	Yes	No	https://projects.nesl.ucla.edu/public/sos-2x/doc

Technology (7) – simulation tools

- some network simulation tools
  - tens of others…

Simulator	Origin	Open-source	WSN oriented?	Link
OPNET	OPNET Tech. Inc.	No (free for U.)	Yes	http://www.opnet.com
OMNeT++	TU Budapest (Hung)	Yes	No	http://www.omnetpp.org
Castalia (OMNet++ based)	NICTA (Australia)	Yes	Yes	http://castalia.npc.nicta.com.au
ns-2	USC (USA)	Yes	No	http://nsnam.isi.edu/nsnam
SENSORSIM (ns-2 based)	UCLA (USA)	Yes	Yes	http://nesl.ee.ucla.edu/projects/sensorsim/
GloMoSim	UCLA (USA)	Yes	No	http://pcl.cs.ucla.edu/projects/glomosim
TOSSIM	UCB (USA)	Yes	Yes	http://www.cs.berkeley.edu/~pal/research/tossim.html
SENSE 3.0	Rensselaer PI (USA)	Yes	Yes	http://www.ita.cs.rpi.edu/sense

Scientific targets – conf.&workshop

- **Wireless Sensor Networks-oriented**
  - SenSys, IPSN, MASS, SECON, EWSN, INSS, EmNets, HotEmNets, Internet of Things, Nano-Net, BSN
- **Distributed Systems-oriented**
  - ICDCS, IPDPS, DCOSS
- **Real-Time and Embedded Systems-oriented**
  - RTSS, RTCSA, ECRTS, RTAS, WPDRTS, RTNS
- **Industrial Networks-oriented**
  - FET, ETFA, WFCS
- **Networking-oriented**
  - Networking, Infocom, SIGCOMM, MobiHoc, WoWMoM, AdHoc-Now
- **Ubiquitous computing-oriented**
  - PerCom, SUTC
- **Simulation-oriented**
  - MASCOTS, MSWiM

65

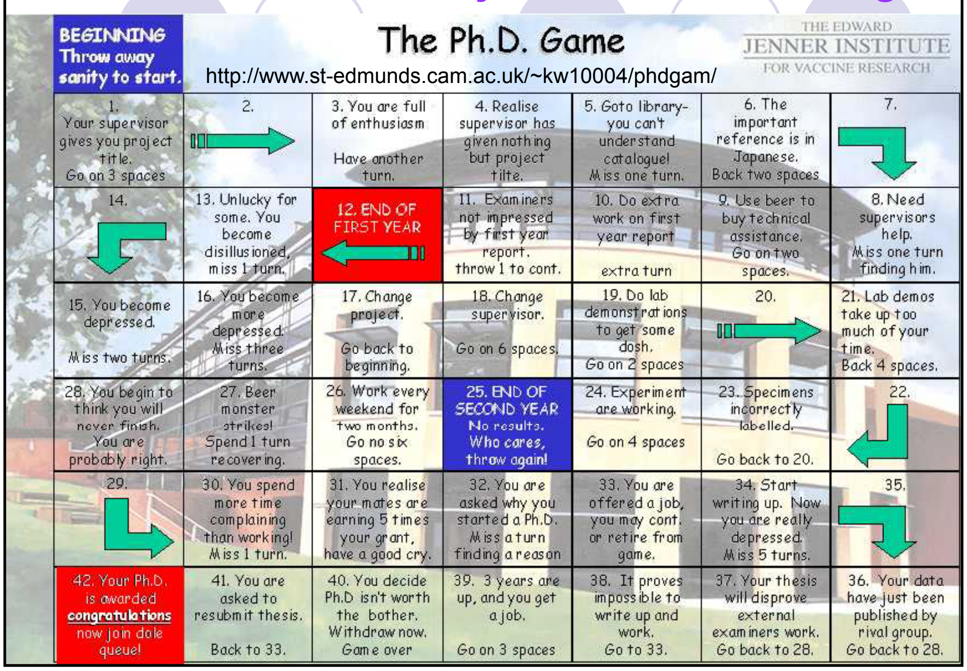
Scientific targets – journals

- **Transactions on Sensor Networks**
  - ACM
- **Ad Hoc & Sensor Wireless Networks**
  - Old City Publishing
- **Ad Hoc Networks**
  - Elsevier
- **Computer Communications**
  - Elsevier
- **Computer Networks**
  - Elsevier
- **Performance Evaluation**
  - Elsevier
- **Pervasive and Mobile Computing**
  - Elsevier
- **Real-Time Systems**
  - Springer
- **Transactions on Wireless Communications**
  - IEEE
- **Wireless Communications and Mobile Computing**
  - Wiley

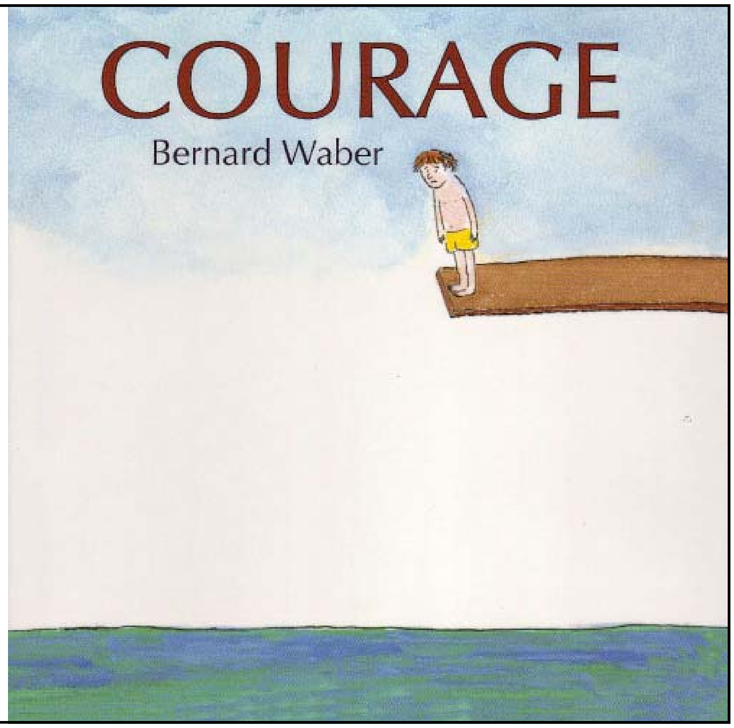
66

http://www.wsnblog.com

Now, think about what you have been doing ☺



But…



You can learn from experienced people!

- Best research practices
  - at CMU
    - http://www.cs.cmu.edu/afs/cs.cmu.edu/user/mleone/web/how-to.html
      - …
  - at UIUC
    - https://agora.cs.uiuc.edu/display/realTimeSystems/Improving+Your+Research+Skills
      - "Building a Research Career", Indranil Grupta
      - "On Conducting Research", P. R. Kumar
      - "Having Fun In Research", YuanYuan Zhao
      - "Towards Productive Research in CS", Jiawei Han
      - "Improve Research Productivity", Tarek Abdelzaher
      - "Problems Follow System", Kevin Chang
      - "Elements of Research", Lui Sha
      - "Excellence in Oral Presentation for Technical Speakers", Klara Nahrstedt
      - "Writing Good Research Papers", Mary Shaw
      - "CORE Method for Planning Research Paper Writing", Jim Frost
      - "Learning to Write", Ralph Johnson

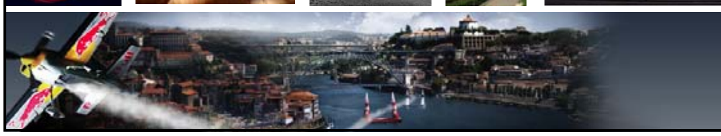
70

Where do I come from?

Somewhere around here
(Porto, Portugal)

knew about these?



CISTER/IPP-HURRAY snapshot

- FCT Research Unit 608
  - rated **Excellent** (2004-2006) (only one among 28 units in the ECE area)
  - around 25 researchers (currently 10 PhD)
  - based at the Polytechnic Institute of Porto (ISEP/IPP)
- Leading international research in:
  - **Wireless Sensor Networks for time-critical applications**
    - COTS-based sensor networks communication architecture (ART-WiSe)
    - innovative dominance-based MAC Protocols (WiDom, WiseCan)
    - innovative data aggregation, interpolation and in-network computing mechanisms
  - **Real-Time Software Infrastructure**
    - QoS-aware Middleware
    - collaborative Computing
    - real-time languages and operating systems
  - **Scheduling and Schedulability Analysis**
    - probabilistic scheduling
    - single, multicore and multiprocessor Scheduling
    - communication scheduling (TDMA/SS)
  - **Real-time Factory Communications**
    - wired/wireless real-time fieldbus communications
    - innovative communication protocols (TDMA/SS, WiseCan)

72

and don’t run away from the next talk ☺

IPP HURRAY!

www.hurray.isep.ipp.pt

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

ongoing research at IPP-HURRAY

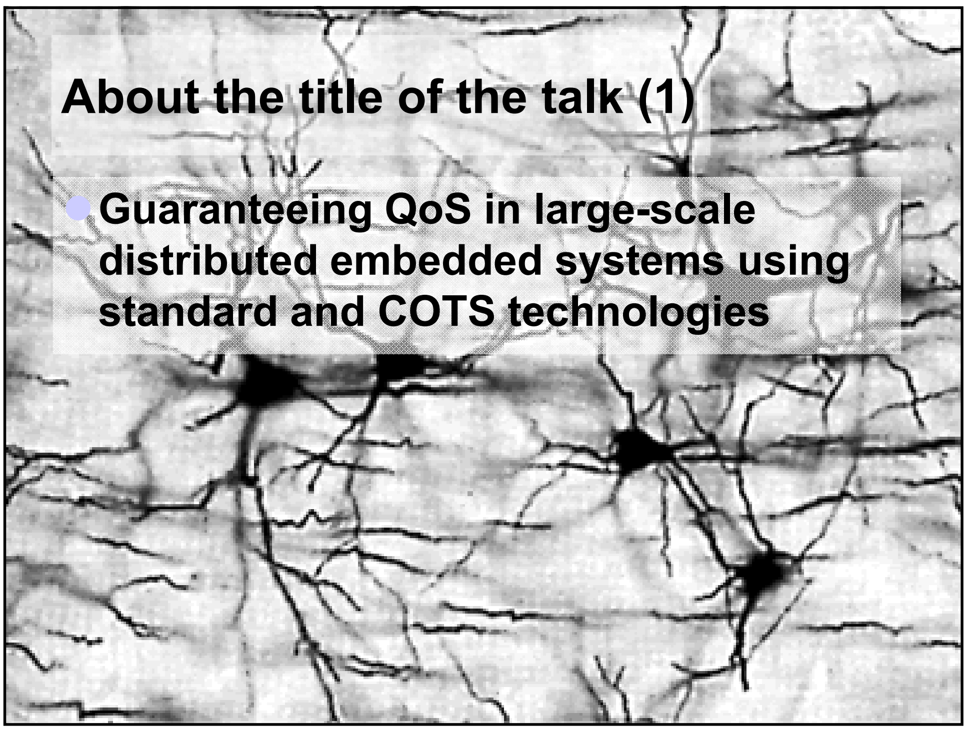
Mário Alves (mjf@isep.ipp.pt)

PhD School

L'Aquila, Italy – 4/SEP/2008

CISTER Research Centre in Real-Time Computing Systems
FCT Research Unit 608

isep instituto superior de engenharia do porto



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)

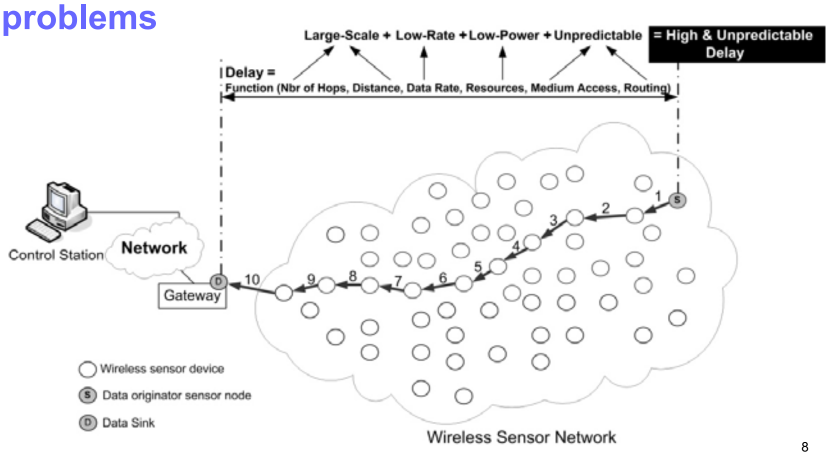
- and "**standard and COTS technologies**"?
  - "**technology**"
    - "is a broad concept that deals with a species' **usage and knowledge of tools and crafts**, and how it affects a species' ability to control and adapt to its environment. In human society, **it is a consequence of science and engineering**"
  - "**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…**

9

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

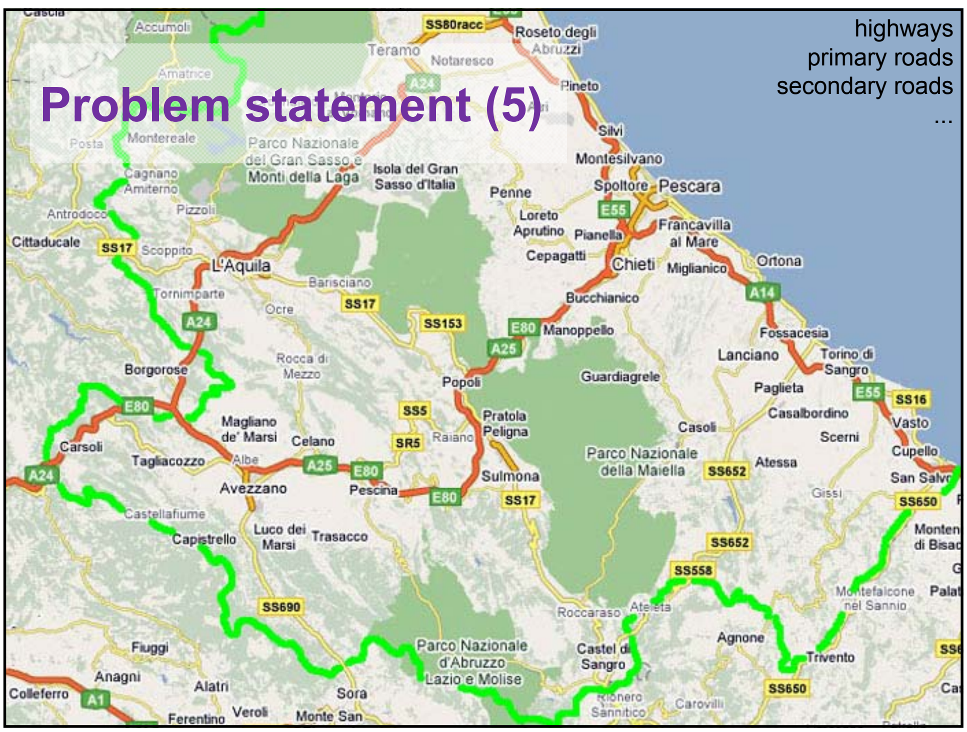
10

Problem statement (4)

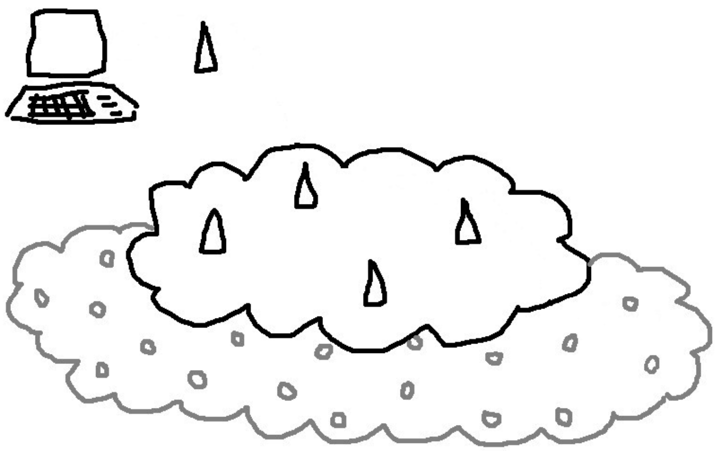
- and assumed that this would only be possible through a
  - multiple-tiered WSAN architecture

Problem statement (5)

highways
primary roads
secondary roads
...



Snapshot of the architecture (1)



13

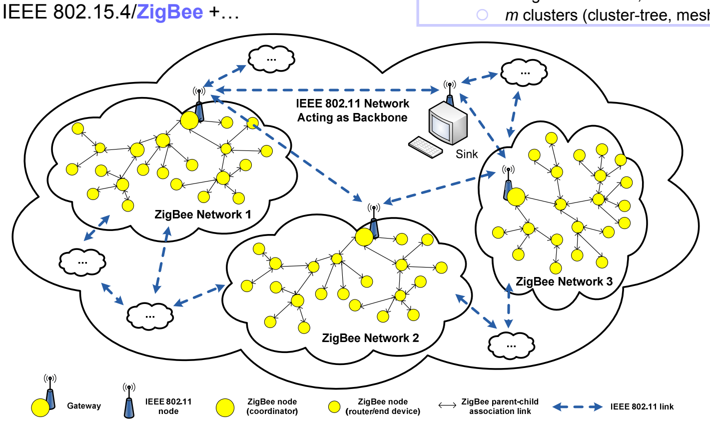
[A. Koubaa, M. Alves, "A Two-Tiered Architecture for Real-Time Communications in Large-Scale Wireless Sensor Networks: Research Challenges", ECRTS'05 (WiP)]

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

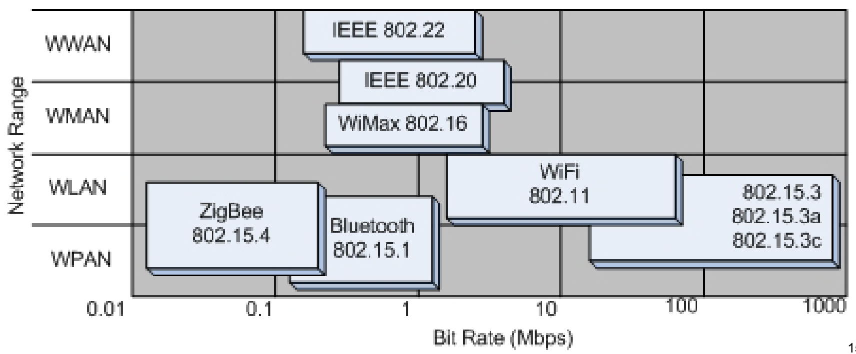
- Tier 1 is composed of
  - *n* ZigBee networks, each with
  - *m* clusters (cluster-tree, mesh)



14

Federating communication protocols (1)

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



15

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)

17

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**

18

Federating communication protocols (5)

- IEEE 802.15.4/ZigBee compared…

Market Name Standard	ZigBee® 802.15.4	--- GSM/GPRS CDMA/1xRTT	Wi-Fi™ 802.11b	Bluetooth™ 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

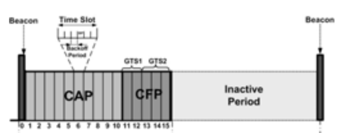
ZigBee® Alliance
Wireless Control That Simply Works

19

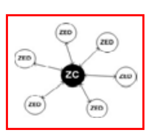
Federating communication protocols (6)

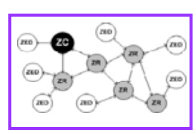
- **Why IEEE 802.15.4/ZigBee?**
  - **Energy-efficiency**
    - adaptable duty-cycles (100% → 0%)
    - low data rates (20-250 kbps)
    - low radio coverage (≈ 30 m)

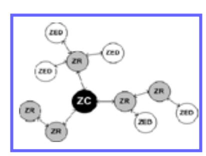
  - **Traffic differentiation**
    - Real-Time traffic
      - Guaranteed Time Slots (GTS)
    - Best-effort traffic
      - CSMA/CA mechanism



  - **Scalable network topologies**
    - star, mesh, cluster-tree
    - up to 65000 nodes per PAN







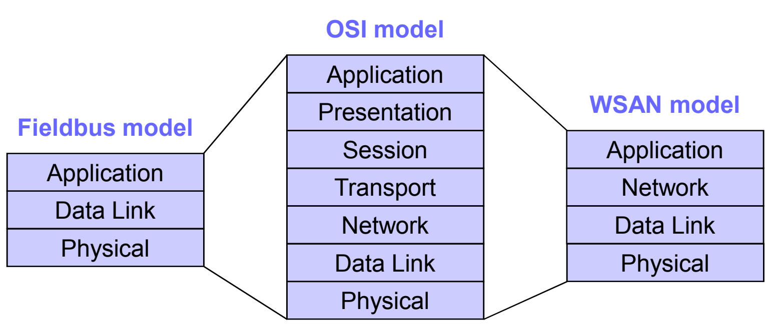
  - **COTS standard technology**
    - many different manufacturers/motes
    - fast growing market
    - simulation/debugging tools
    - OSs and prog. languages

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)

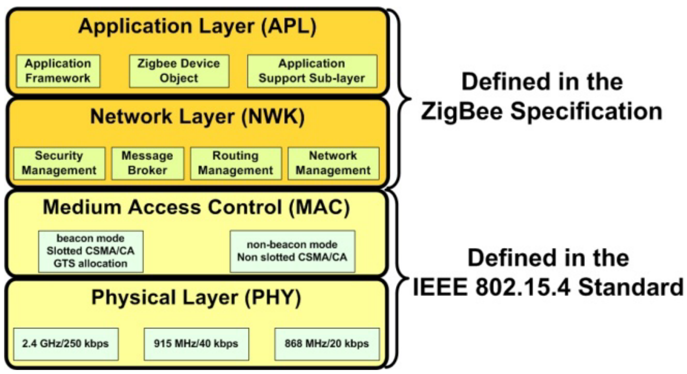
- networks for monitoring/control require
  - **simplified/collapsed version of OSI model**
    - **lighter** (< memory), **faster** (< inform. processing)



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

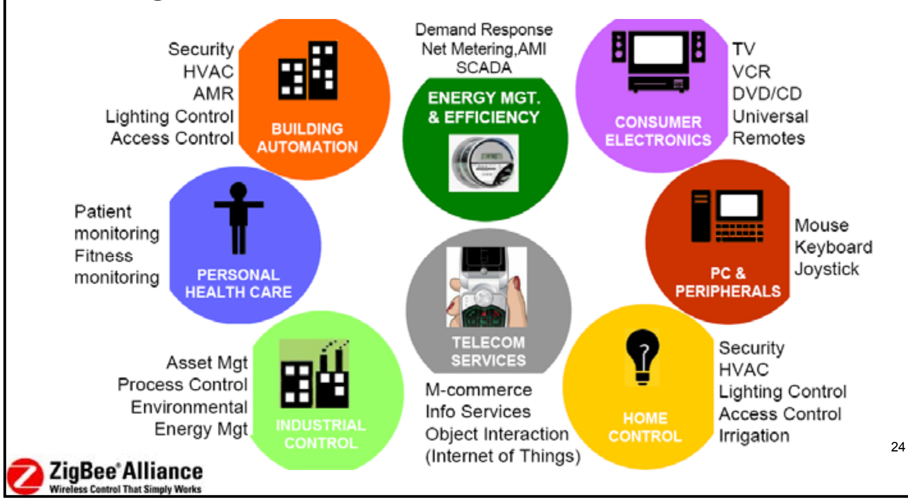


23

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

IEEE 802.15.4 and ZigBee highlights (3)

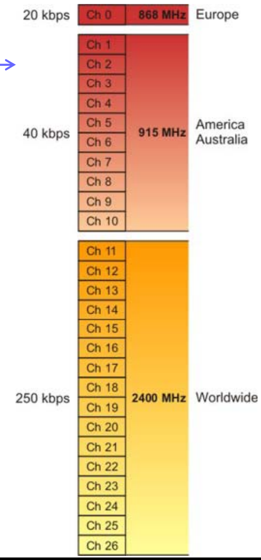
- “ZigBee Alliance” claims…



24

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**



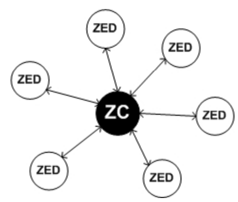
IEEE 802.15.4 and ZigBee highlights (5)

- 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**

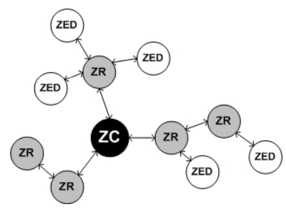
26

IEEE 802.15.4 and ZigBee highlights (6)



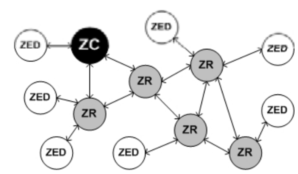
Star

- 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)

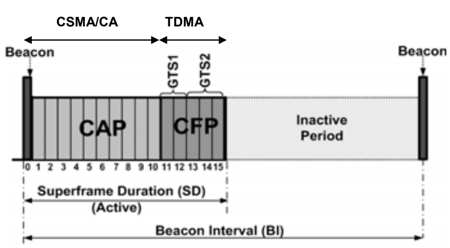


Mesh

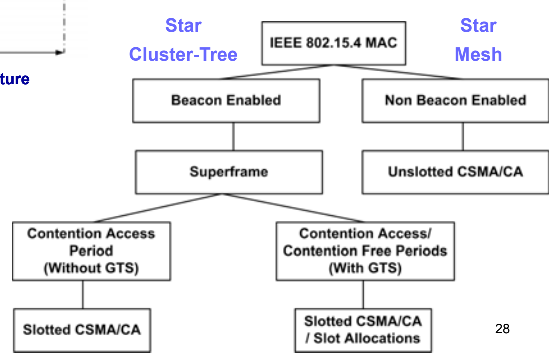
- AODV-based routing
  - not deterministic
- no synchronization (non beacon-enabled)
  - ZC and ZRs must be always on
  - no bandwidth guarantees (contention)

27

IEEE 802.15.4 and ZigBee highlights (7)



Beacon Interval and Superframe Structure



28

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**	☺

29

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

30

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

31

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**

32

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

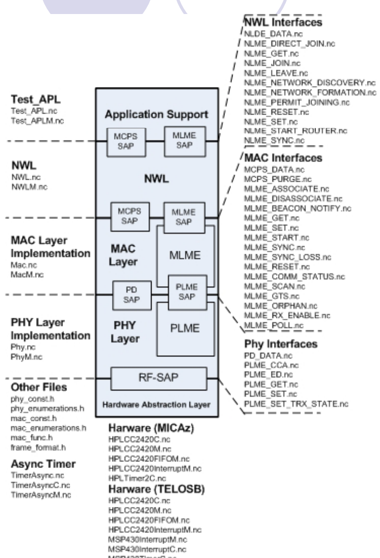
- **IEEE 802.15.4/ZigBee Protocol Analysers**
  - CC2420 Packet Sniffer for IEEE 802.15.4 v1.0
  - Daintree Networks Sensor Network Analyzer
- **TinyOS 1.1.15 and TinyOS 2.0**
  - operating system for embedded systems
  - event-driven execution model
    - concurrency model based on tasks and hardware 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

33

[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)

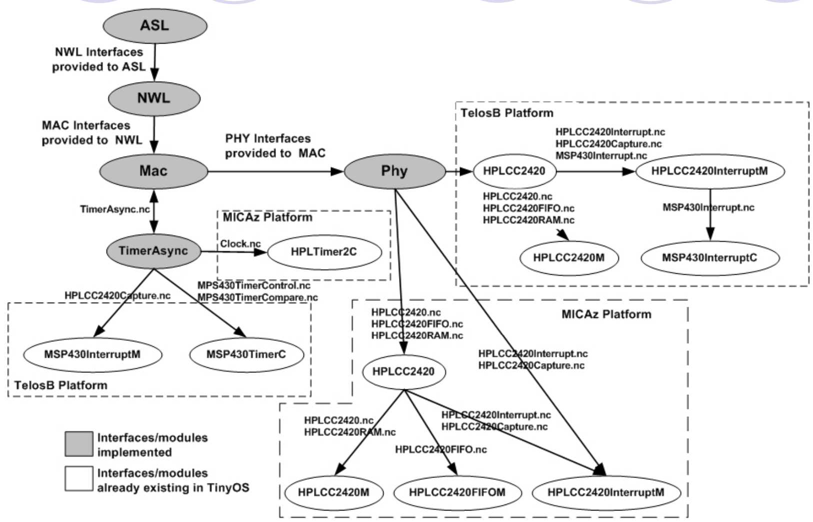


- **Phy Module (Physical Layer)**
  - Transceiver management
    - Data transmission/reception
    - Received Signal Strength Indication
    - Clear Channel Assessment
- **Mac Module (Data Link Layer)**
  - Beacon Generation
  - Synchronization
  - Association Procedures
  - CSMA/CA
  - GTS Management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

34

[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)

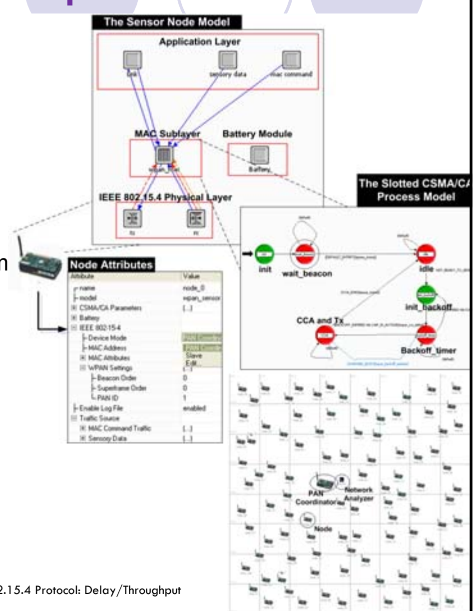


35

[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

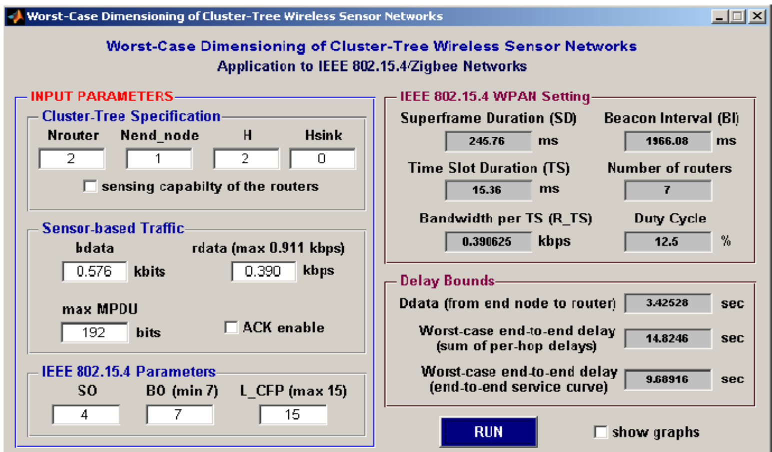
- open-source **OPNET** model
  - physical, MAC and application layers
- **supported** features
  - beacon-enabled mode
  - slotted CSMA/CA MAC protocol
  - physical layer characteristics
  - battery module (MICAz/TelosB motes)
  - Guaranteed Time Slot (GTS) mechanism
  - acknowledged **and** unacknowledged 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

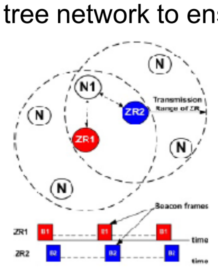
- enables worst-case network dimensioning
  - minimum duty-cycle still satisfying deadlines



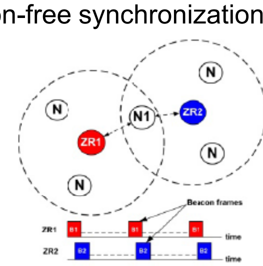
37

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



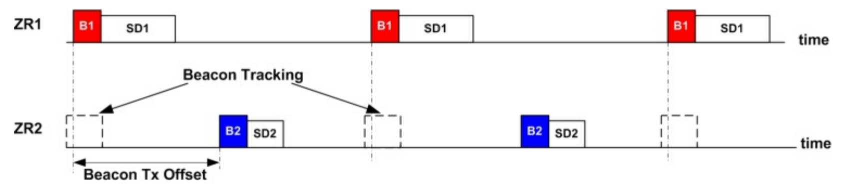
Indirect Beacon Frame Collision

38

[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



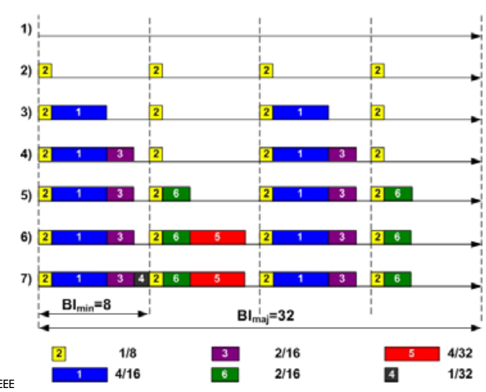
39

[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)

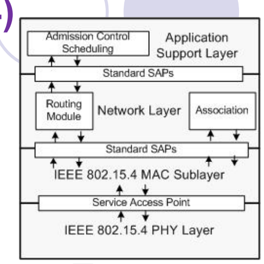
- how to **organize the beacon frames** of the different ZigBee Routers to avoid collisions with other beacons or data frames
- **sufficient to find a cyclic schedule in a hyper-period equal to BImax.**
- example:

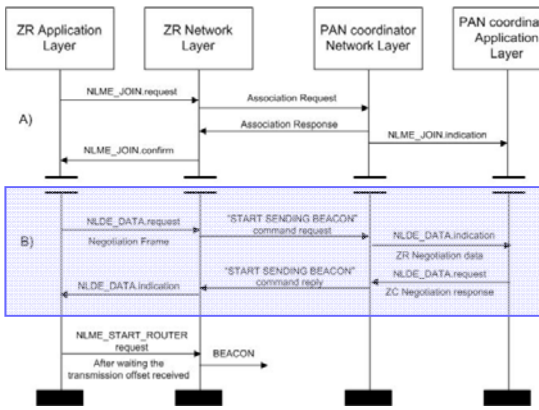
ZigBee Routers	SD	BI
ZR1	4	16
ZR2	1	8
ZR3	2	16
ZR4	1	32
ZR5	4	32
ZR6	2	16

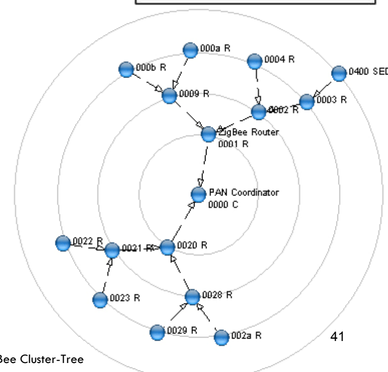


[A. Koubaa, A. Cunha, M. Alves, "A Time Division Beacon Scheduling Mechanism for IEEE 802.15.4/Zigbee Cluster-Tree Wireless Sensor Networks", ECRTS'07]

Technical achievements – TDBS (4)





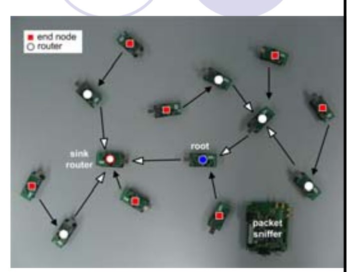


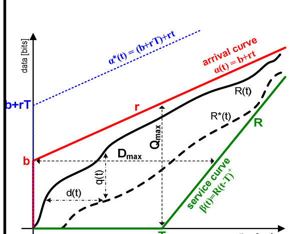
[A. Koubâa, A. Cunha, M. Alves, E. Tovar, "TDBS: A Time Division Beacon Scheduling Mechanism for ZigBee Cluster-Tree Wireless Sensor Networks", to appear in the Real-Time Systems Journal, Springer]

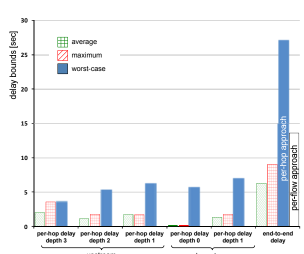
41

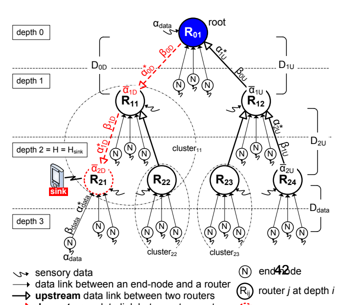
Technical achievements – analysis/dim. C-T

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









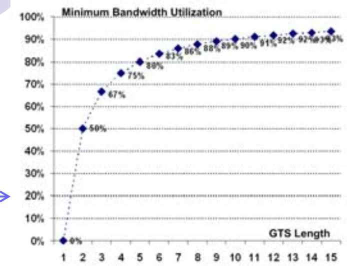
[A. Koubaa, M. Alves, E. Tovar, "Modeling and Worst-Case Dimensioning of Cluster-Tree Wireless Sensor Networks", RTSS'06]

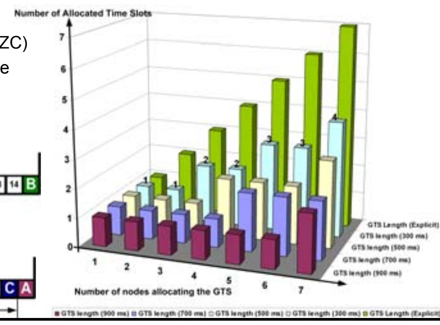
[P. Jurčík, R. Severino, A. Koubâa, M. Alves, E. Tovar, "Real-Time Communications over Cluster-Tree Sensor Networks with Mobile Sink Behaviour", RTCSA'08]

42

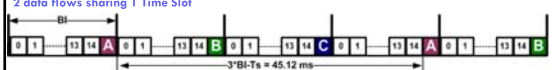
Technical achievements – i-GAME (1)

- **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)

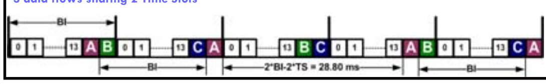




2 data flows sharing 1 Time Slot

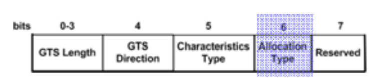


3 data flows sharing 2 Time Slots

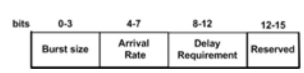


Technical achievements – i-GAME (2)

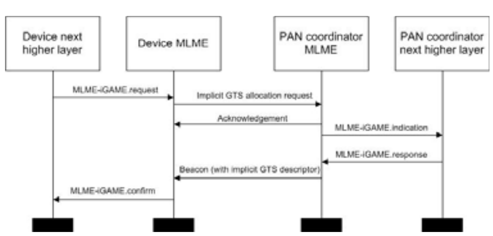
- admission control function in the ZC
  - nodes send their implicit requests including their traffic specification (b,r,D)
  - The ZC performs the admission control algorithm based on a schedulability test
- backward compatibility ensured
  - use reserved field in standard packet format – **Allocation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

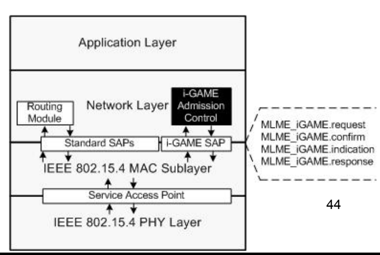


GTS Characteristics Extension Field Format for Implicit Request Allocation



Flow Specification Field Format for i-GAME





44

[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)]

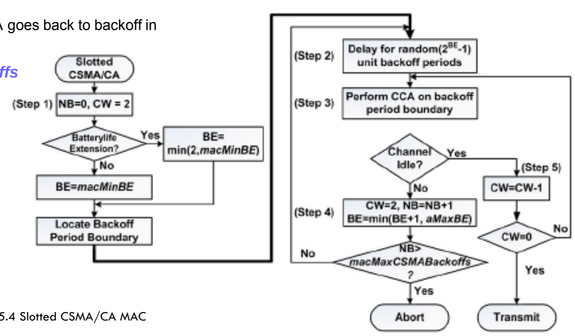
Technical achievements – CSMA/CA traffic differentiation (1)

- **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)

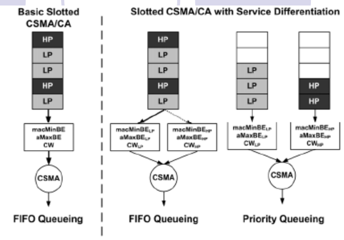
- The slotted CSMA/CA algorithm mainly depends on three variables:
  - **Backoff Exponent (BE)**: to compute random backoff delay **$[0, 2^{BE}-1]$**
    - *macMinBE ≤ BE ≤ aMaxBE*
  - **Contention Window (CW)**: nº time units that channel must be sensed idle
  - **Number of Backoffs (NB)**
    - number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

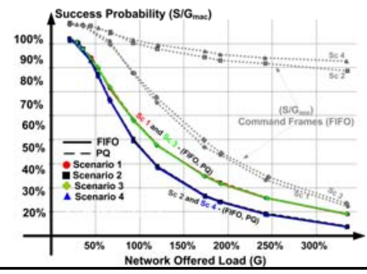
Technical achievements – CSMA/CA traffic differentiation (3)

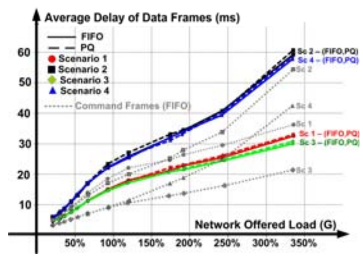
- Heuristics
  - CW_{HP} < CW_{LP}
  - $macMinBE_{HP}$ < $macMinBE_{LP}$



Scenario	[$macMinBE_{HP}$, $aMaxBE_{HP}$]	[$macMinBE_{LP}$,$aMaxBE_{LP}$]	CW_{HP}	CW_{LP}
Sc1	[2,5]	[2,5]	2	2
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

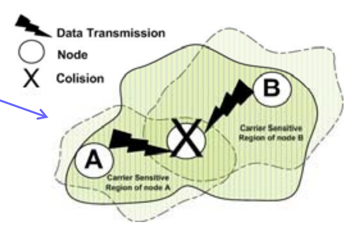


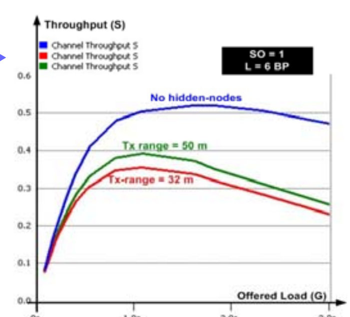


47

Technical achievements – H-NAMe (1)

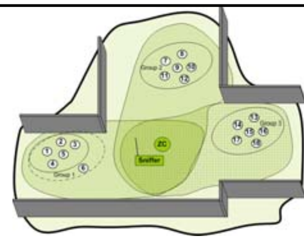
- The "**hidden-node problem**" (or "hidden-terminal problem")
  - major source of QoS degradation in WSANs due to:
    - limited communication **range** of sensor nodes,
    - radio link **asymmetry**
    - characteristics of the **physical environment**
  - degradation of the following QoS metrics.
    - **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

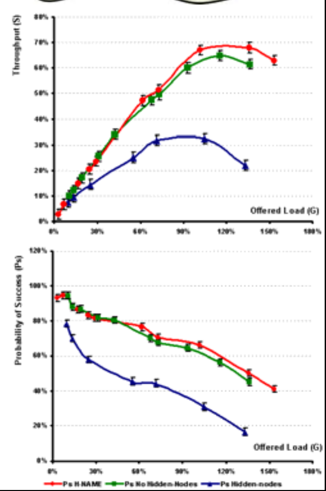


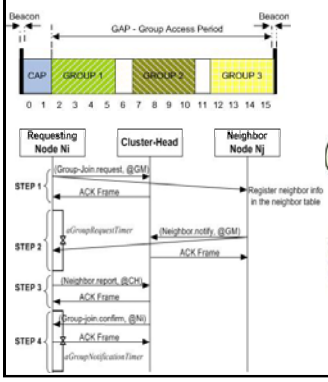


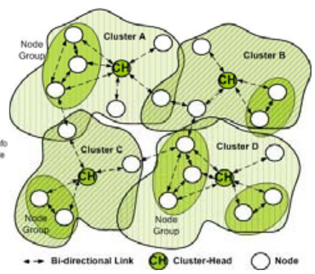
Technical achievements – H-NAMe (2)

- **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…



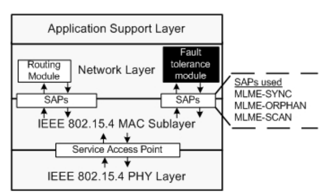


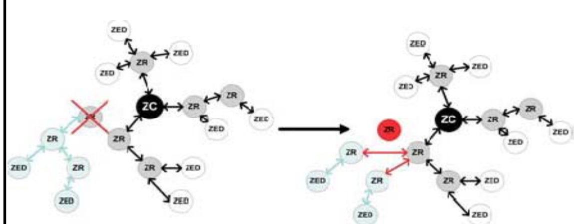




Technical achievements – fault tolerance

- **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





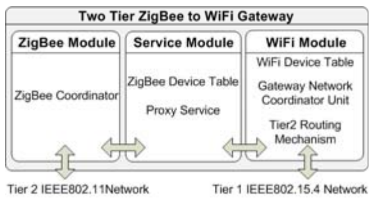
$$PAI = LQI \cdot (a \cdot Ei) \cdot \left(\frac{b}{Dp}\right) \cdot \left(\frac{c}{Tl}\right)$$

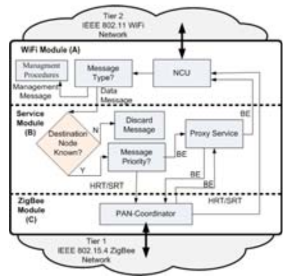
[S. Ben Attia, A. Cunha, A. Koubâa, M. Alves, “Fault-Tolerance Mechanisms for Zigbee Wireless Sensor Networks”, ECRTS’07 (WiP)]

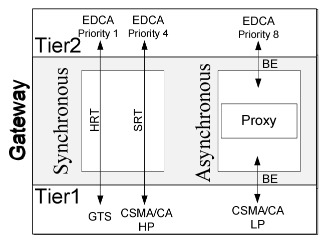
50

Technical achievements – gateway (1)

- **ART-WiSe gateway architecture**







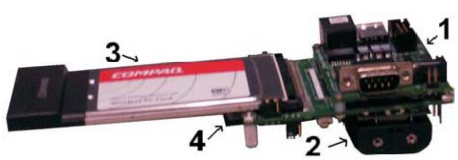
- **Gateway behavior**
  - Synchronous behavior (time critical messages)
  - Asynchronous behavior (normal messages)
- **Traffic classes**
  - HRT - Hard Real Time, for high priority
  - SRT - Soft Real Time, for medium priority
  - BE - Best Effort, for low priority

51

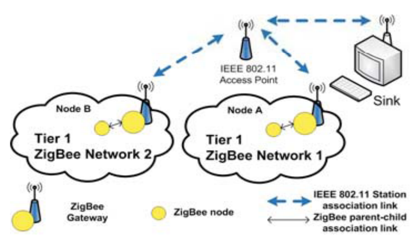
[J. Leal, A. Cunha, M. Alves, A. Koubaa, "On a IEEE 802.15.4/ZigBee to IEEE 802.11 Gateway for the ART-WiSe Architecture", ETFA'07 (WiP)]

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)

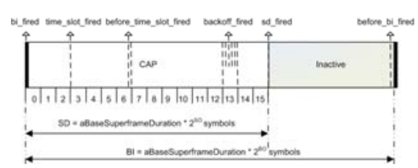
- CC2420 Transceiver Limitations
  - Transceiver turn around time

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

53

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).

54

[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)

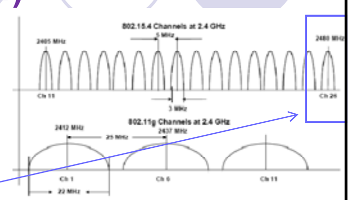
- TinyOS Task scheduler
  - **no tasks prioritization** (ongoing proposals)
  - **non pre-emptive**
- consequences
  - interrupt events are captured by event handlers that normally post a task to the FIFO task queue such that **TinyOS schedules its processing in a FIFO basis**
  - **hard to ensure the 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

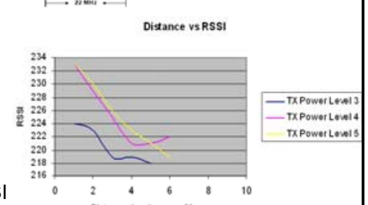
55

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

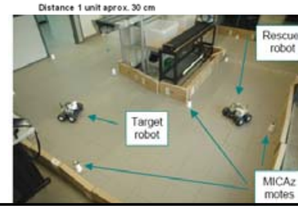
Technical achievements – Hardware, Physical Layer and Software problems (4)



- 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)

57

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

Technological Resources (2)


75 XBow MicaZ


50 XBow TelosB


10 CMU FireFly


2 Daintree IEEE 802.15.4/ZigBee Protocol Analysers


15 MICAz OEM-based


4 Scatterweb ESB

2 Scatterweb ECR


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


1 Sun SPOT Dev. Kit

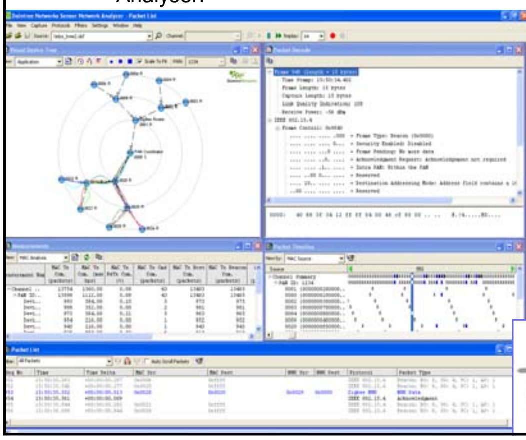

5 Serial programming boards
5 USB programming boards
2 Ethernet programming boards

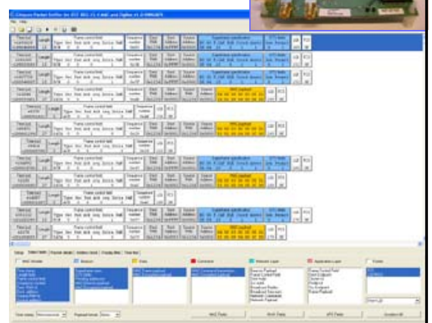

1 XBow iMote2 Builder Kit


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

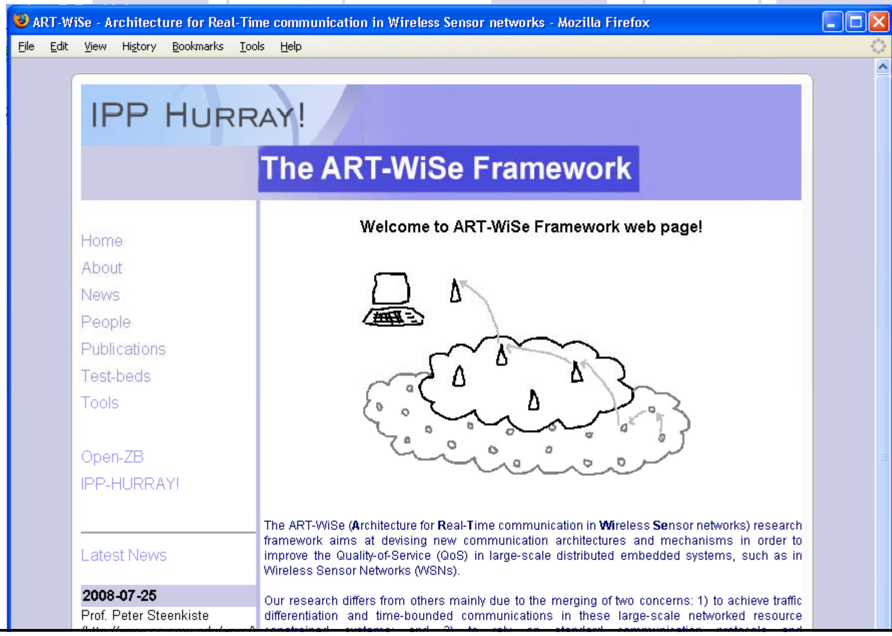
CMU | Portugal
Information and Communication Technologies Institute

Retis
Real-Time Systems Laboratory

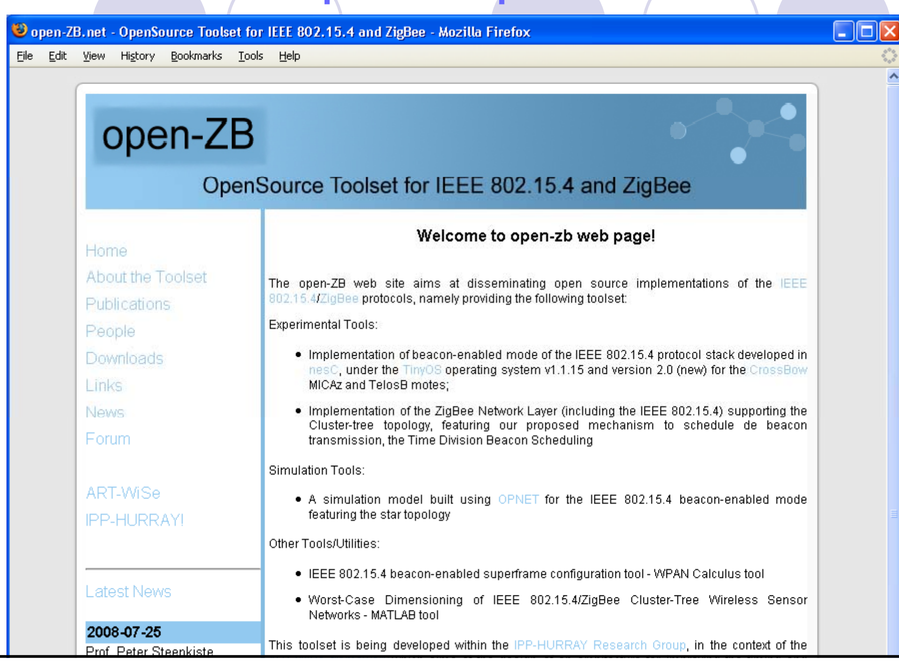
Scuola Superiore Sant'Anna
di Studi Universitari e di Perfezionamento

60

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



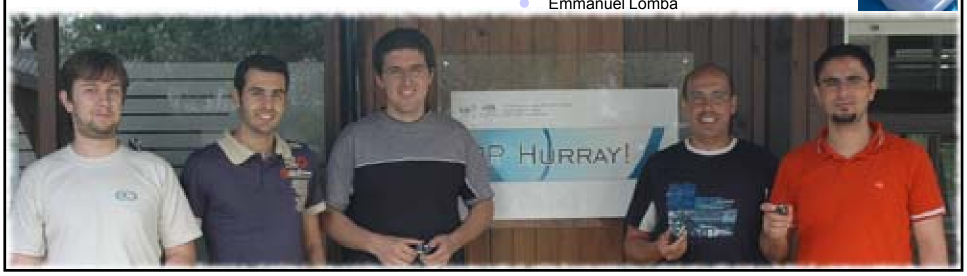
http://www.open-ZB.net



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**

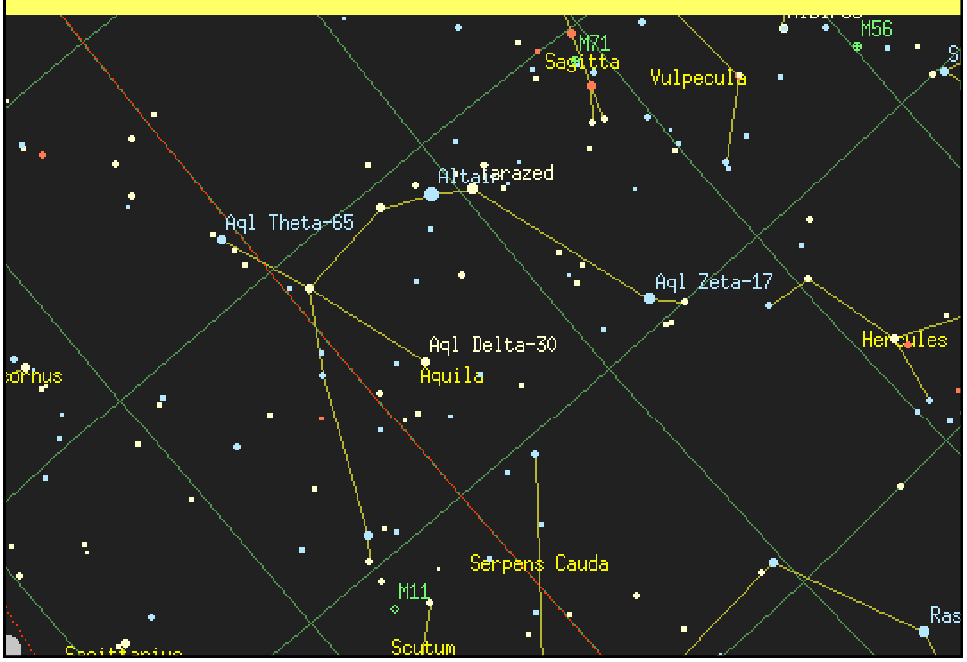
64

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**

65

THANKS ☺

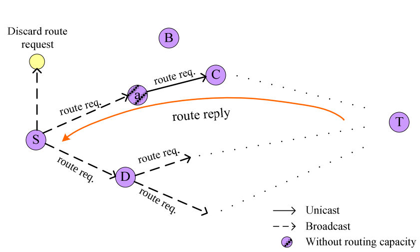


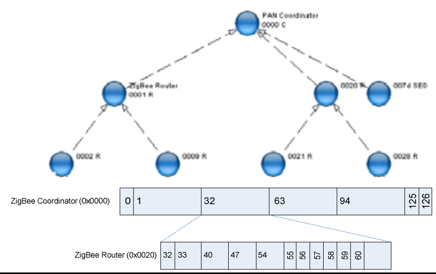
67

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

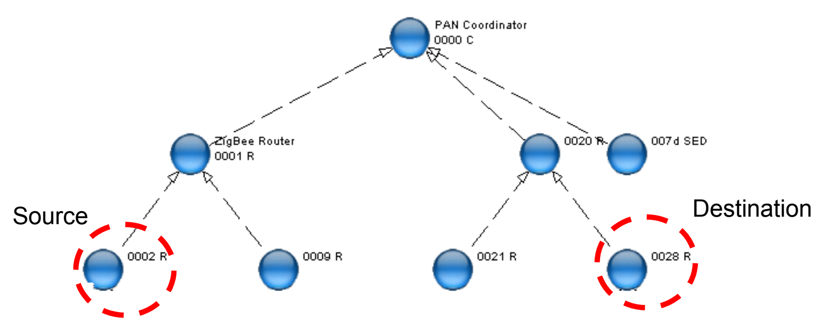
Octets: 2	2	2	1	1	Variable
Frame Control	Destination Address	Source Address	Radius[a]	Sequence Number[b]	Frame Payload
	Routing Fields				
NWK Header					NWK Payload

- 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

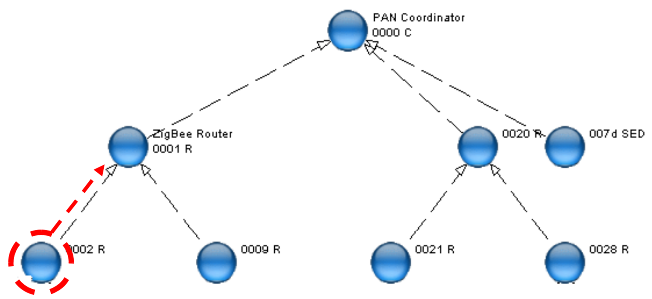


- Maximum depth (Lm): 3
- Maximum children (Cm): 6
- Maximum routers (Rm): 4

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

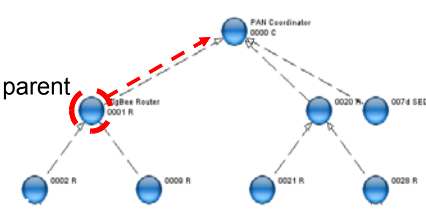
IEEE 802.15.4 and ZigBee highlights (extra) – Tree Routing – Example 4/5

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

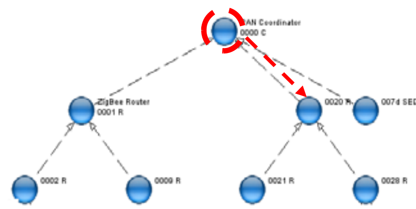
IEEE 802.15.4 and ZigBee highlights (extra) – Tree Routing – Example 5/5

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



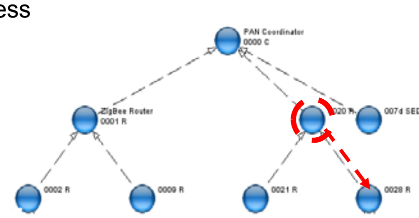
- MAC destination address – 0x0020;
- MAC source address – 0x0000;
- Network Layer Routing Destination Address – 0x0028;
- Network Layer Routing Source Address – 0x0002;

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