Cooperating Objects NETwork of Excellence

7th Framework Programme

FP7-224053

Quality of Service in Wireless Sensor Networks: towards the eQualiSer…

SensorNets School, Monastir, Tunisia, 20DEC2009

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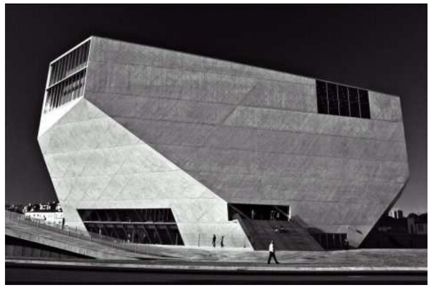
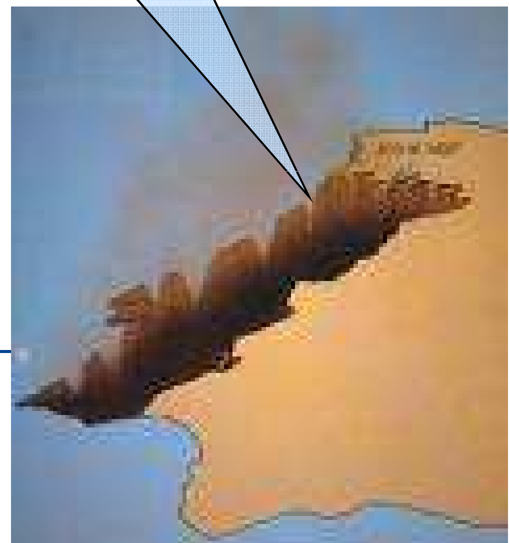
Where do I come from...

Somewhere around here
(Porto, Portugal)

knew about these?





About my research unit – CISTER

CISTER

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

http://www.cister.isep.ipp.pt

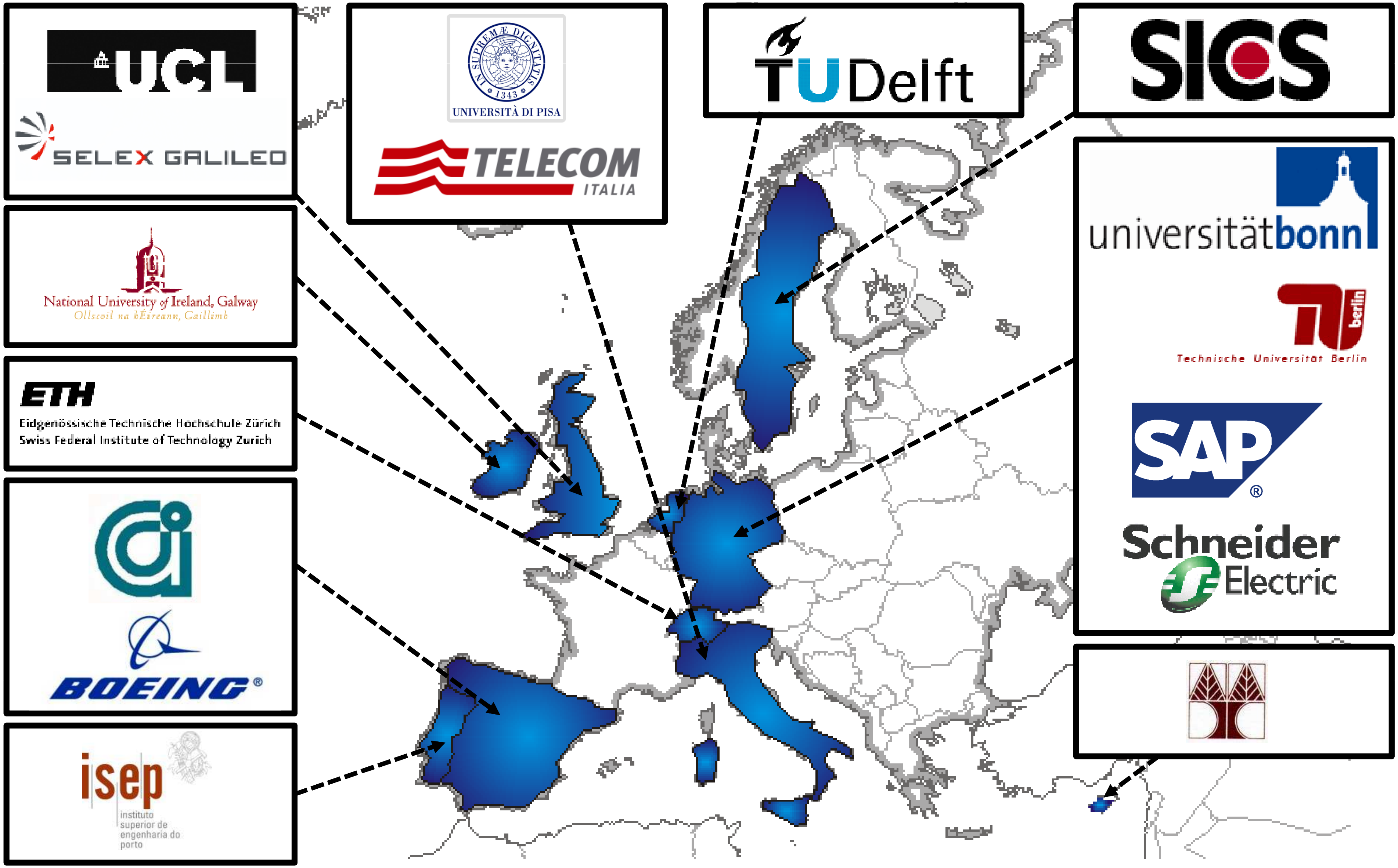
About my research unit – CISTER

- Main scientific area
  - **Real-time and embedded computing systems**
- Research areas:
  - **Wireless Sensor Networks**
    - **http://www.cister.isep.ipp.pt/research/sensor+networks**
  - Cyber-Physical Systems
    - http://www.cister.isep.ipp.pt/research/cyber-physical+systems
  - Multicore/multiprocessor Systems
    - http://www.cister.isep.ipp.pt/research/multicore+systems
  - Adaptive Real-Time Systems
    - http://www.cister.isep.ipp.pt/research/adaptive+rt+systems
  - Real-Time Software
    - http://www.cister.isep.ipp.pt/research/rt+software

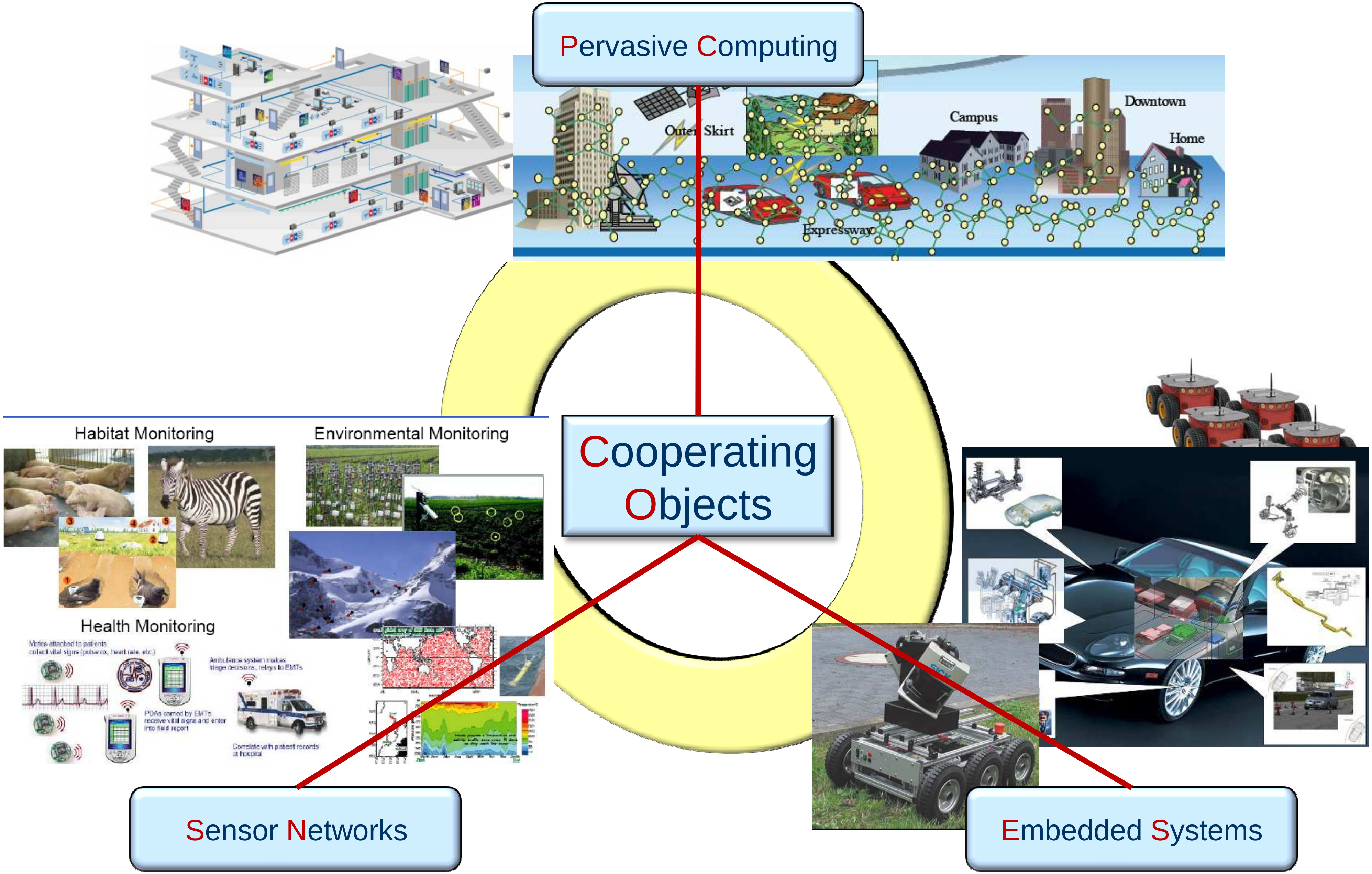
About CONET – Cooperating Objects NoE

- Network of Excellence funded in FP7 (INFSO-ICT-224053)
  - **1/JUN/2008 – 31/MAY/2012** (48 months)
  - EC funding: **4 MEuro** | Total Budget: **10.4 Meuro**
  - **16 core** partners: key **academic** and **industrial** players
  - strong **Industrial and External Advisory Boards**
  - more information: http://www.cooperating-objects.eu
- Definition of "Cooperating Objects"
  - ***Cooperating Objects consist of embedded computing devices*** *equipped with communication as well as sensing or actuation capabilities that are* ***able to cooperate and organize themselves autonomously into networks to achieve a common task****.*

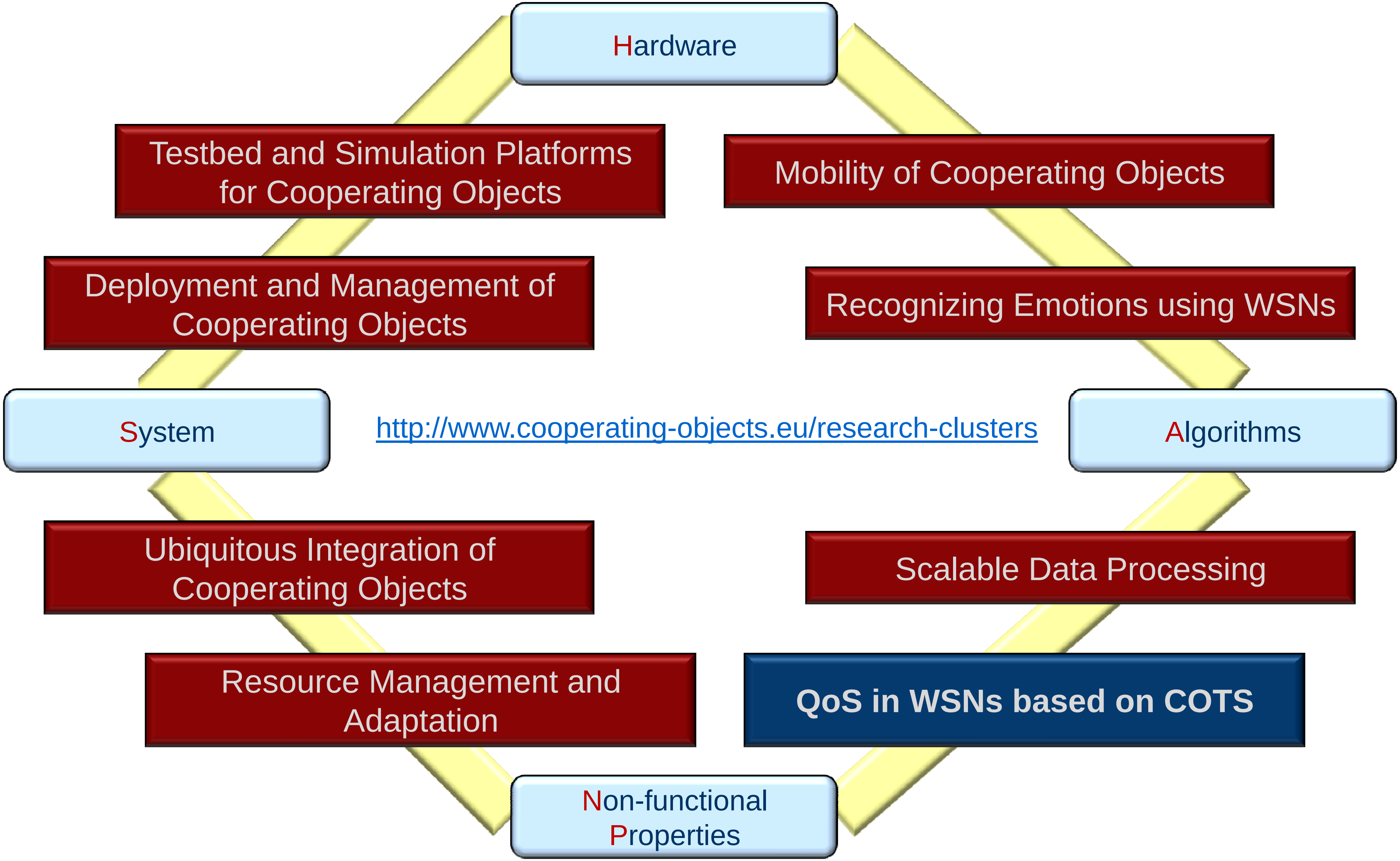
About CONET – core partners



About CONET – areas



About CONET – research clusters



CISTER – related projects

- EMMON (ARTEMIS programme) http://www.artemis-emmon.eu/
  - large-scale embedded monitoring using WSNs
  - MAR/2009 – FEB/2012
  - 8 partners: Critical Software (PT), Intesys (UK), Trinity College Dublin (IR)…
  - target – WSN application with 10000 nodes
- ARTISTDesign (EC NoE) http://www.artist-embedded.org
  - embedded systems design
  - JAN/2008 – JAN/2012 (4 years)
  - 30 partners: OFFIS (D), a PAREDES (I), Centre de Énergie Atomique (F), U. Uppsala (S), U. York (UK), U. Lund (S), U. Bolonha (I), U. Lausanne (CH), …
  - coordinated by Prof. Joseph Sifakis, 2007 ACM Turing Award
- PT-CMU (Carnegie Mellon University) http://www.cmuportugal.org
  - WSN for monitoring critical physical infrastructures
  - JAN/2007 – FEB/2012 (5 years)
- TinyOS Alliance http://www.tinyos.net
  - leading IEEE 802.15.4/ZigBee protocol stack – http://www.open-ZB.net
  - since 2006 (in Net2 WG), since 2009 (in 15.4 and ZigBee WGs)
  - http://tinyos.stanford.edu:8000/15.4_WG | http://www.cister.isep.ipp.pt/activities/ZigBee_WG/

References

- „**Cooperating Objects Roadmap**“, 2009, this talk is in synergy with several sections (e.g. 3.3, 6.1.3 and 6.2.3)
- M. Alves et. al, „**Quality-of-Service in Wireless Sensor Networks: state-of-the-art and future directions**“, HURRAY-TR-091108, available at http://www.cister.isep.ipp.pt/docs

About the title of the talk (1)

- **Quality of Service in Wireless Sensor Networks: towards the eQualiSer…**

About the title of the talk (2)

- What are “wireless sensor/actuator networks”?
  - **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

WIKIPEDIA
The Free Encyclopedia

SEVENTH FRAMEWORK

About the title of the talk (3)

- What is "**Quality-of-Service (QoS)**"?
  - traditionally, **"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…"
    - "…e.g. voice over IP, online games and IP-TV…"
  - **but we can argue against this concept/definition**

Wikipedia
The Free Encyclopedia

- so we will look at **QoS in a different perspective...**

SEVENTH FRAMEWORK

Outline

- **A holistic perspective on QoS**
  - an integrated perspective over different QoS properties
- **SOTA, gaps and trends**
  - state-of-the-art and roadmap for each QoS property
- **Multilateral impacts**
  - how each property influences the other properties
- **Relevance and Timeline**
  - according to CONET survey – relevance of each property and when are mature solutions expected
- **Final highlights**

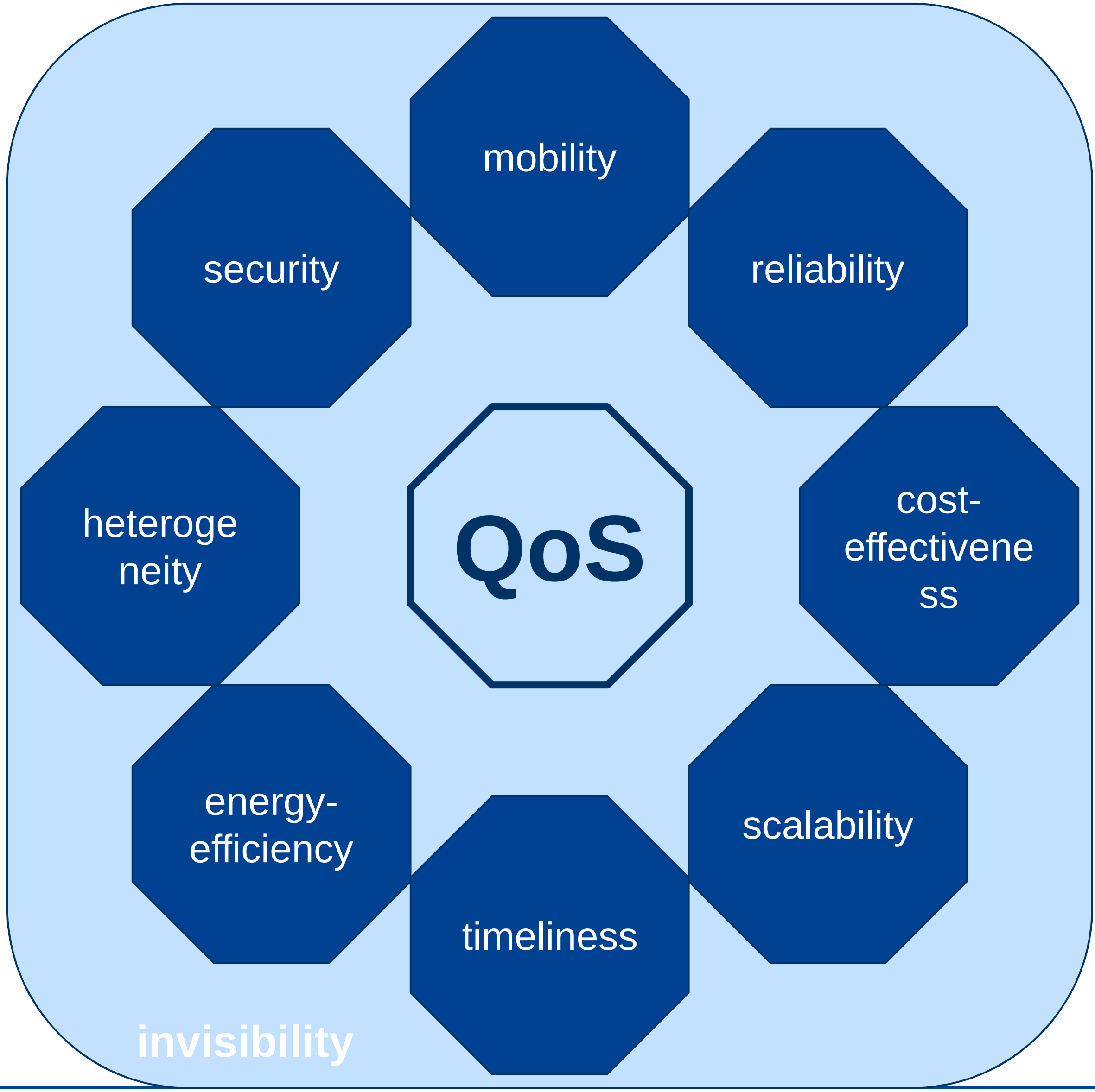
A holistic perspective on QoS

- Recalling Slide #12 (Wikipedia definition of 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. …"
- QoS is thus traditionally associated to:
  - **bit rate, network throughput, delay, bit/packet error rate**
  - which reflect the "**performance**" properties (timing & error rate)
- **In this talk, I advocate that**
  - these properties **alone** **DO NOT** reflect the **overall quality** of the **service** provided to the **user/application**

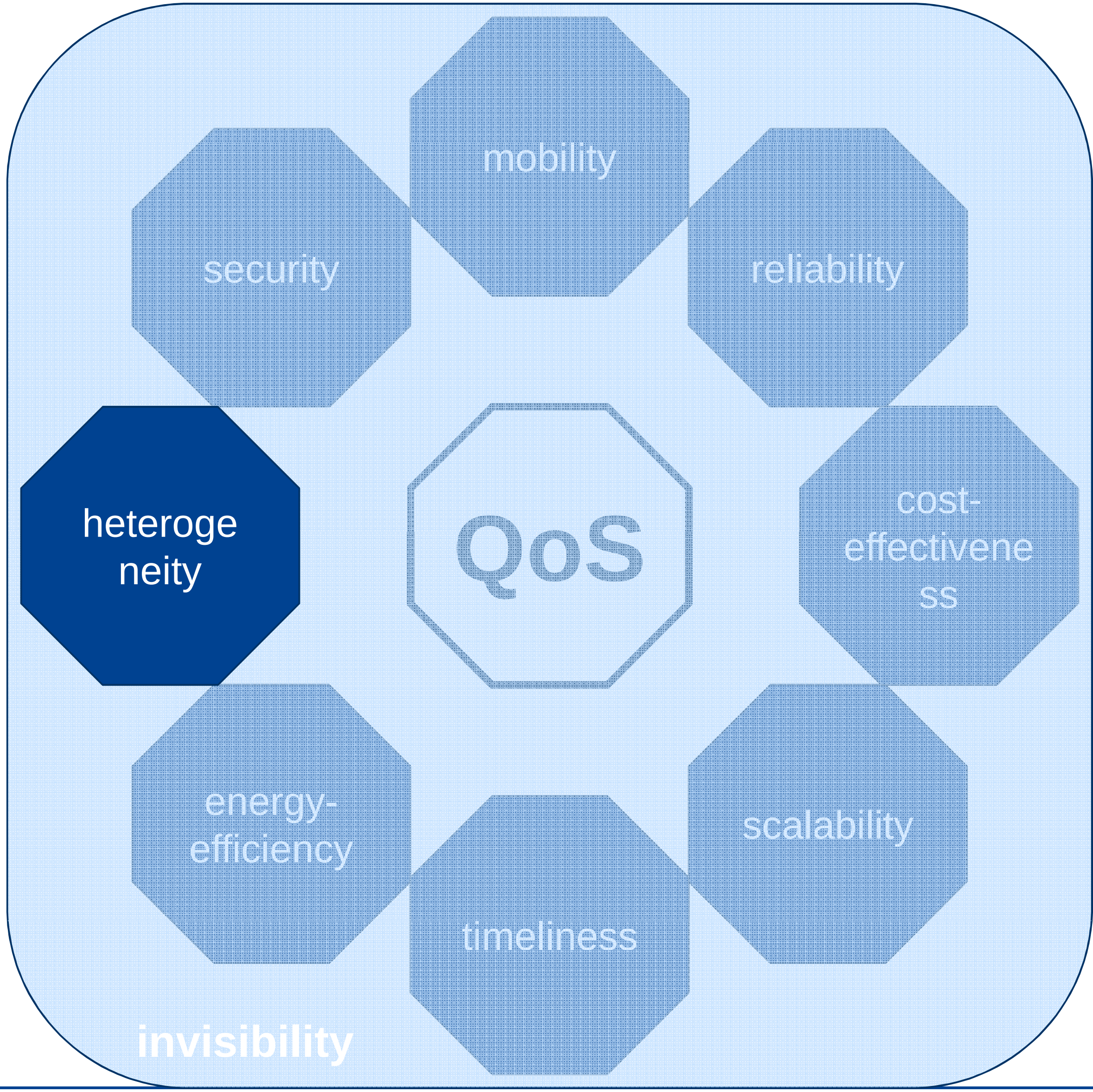
A holistic perspective on QoS

- We consider that **this concept of QoS is too strict**
  - especially when considering **the complexity and scale** of emerging computing systems
    - e.g. **Cooperating Objects** and **Cyber-Physical Systems**
- Computing systems and particularly WSN applications should be designed taking into consideration **other NFP properties**
  - **Non-Functional Properties** are defined as the properties of a system that **do not affect their functionality**, but their behavior/performance
  - e.g. energy-sustainability, dependability (reliability, robustness, availability, maintainability, security, safety,…), timeliness (throughput, delay, traffic differentiation), scalability, mobility, heterogeneity, cost-effectiveness
- thus, **we extend the QoS concept to a holistic perspective**
  - encompassing several NFPs, as ellaborated next...

A holistic perspective on QoS



Quality-of-Service – heterogeneity



Quality-of-Service – heterogeneity

- **Heterogeneity emerges from:**
  - **≠ networking hardware & software**
    - ≠ sensor/actuator-level communication protocols (wired/wireless)
    - ≠ higher-level nodes (e.g. gateways, data processing sinks)
    - ≠ higher-level communication protocols
    - ≠ network planning/management tools
  - **≠ embedded system nodes hardware/software architectures**
    - ≠ sensors and sensor boards, design diversity, calibration
    - ≠ operating systems (for resource-constrained net. embedded systems)
    - ≠ programming languages & simulation/modelling tools ("idem")
    - ≠ middleware (e.g. security and fault-tolerance mechanisms)

Quality-of-Service – heterogeneity

- **Heterogeneity emerges from (cont.):**
  - **≠ cyber/pervasive/host computing devices**
    - HMIs (in general), wearable computing (e.g. mobile phones, PDAs, handheld terminals, HMDs, RFID readers)
    - industrial computers (e.g. PLCs, NCs, RCs) and machinery, mobile robots, transportation vehicles, data-base servers
  - **≠ applications/services/users in the same system**
    - same network infrastructure may support several applications/services
    - potentially several/many human users, eventually playing at ≠ levels and with ≠ cultures, ≠ technical skills,...

Quality-of-Service – heterogeneity

- Research challenges
  - **new classes** of resource-constrained embedded system nodes **must be identified**
    - Eliminating/reducing (or not?) the existing **fuzzy frontiers between nodes with ≠ characteristics and ≠ capabilities**
      - MEMS, active/passive RFID, “general-purpose” motes (e.g. Mica, Telos, Firefly), powerful motes (e.g. iMote, SunSPOT, Stargate)
    - trend for **miniaturization will turn this task harder** (or easier?)...

Quality-of-Service – heterogeneity

- Research challenges (cont.)
  - **interoperability btw sensor/actuator-level comm. protocols**
    - experience: there will be **no "single" standard protocol for WSNs**
      - **≠ wireless protocols will have to coexist**
        - e.g. IEEE 802.15.4, IEEE 802.15.6, ZigBee, 6loWPAN, IEEE 802.15.1 & Bluetooth Low Power, ISA100 or WirelessHART
      - **WSN protocols will have to coexist wih wired protocols**
        - such as for domotics (e.g. KNX, LonWorks), process control (ASi, DeviceNet, HART), industrial automation (PROFIBUS, FF) and automotive (e.g. FlexRay, CAN, LIN, MOST) systems

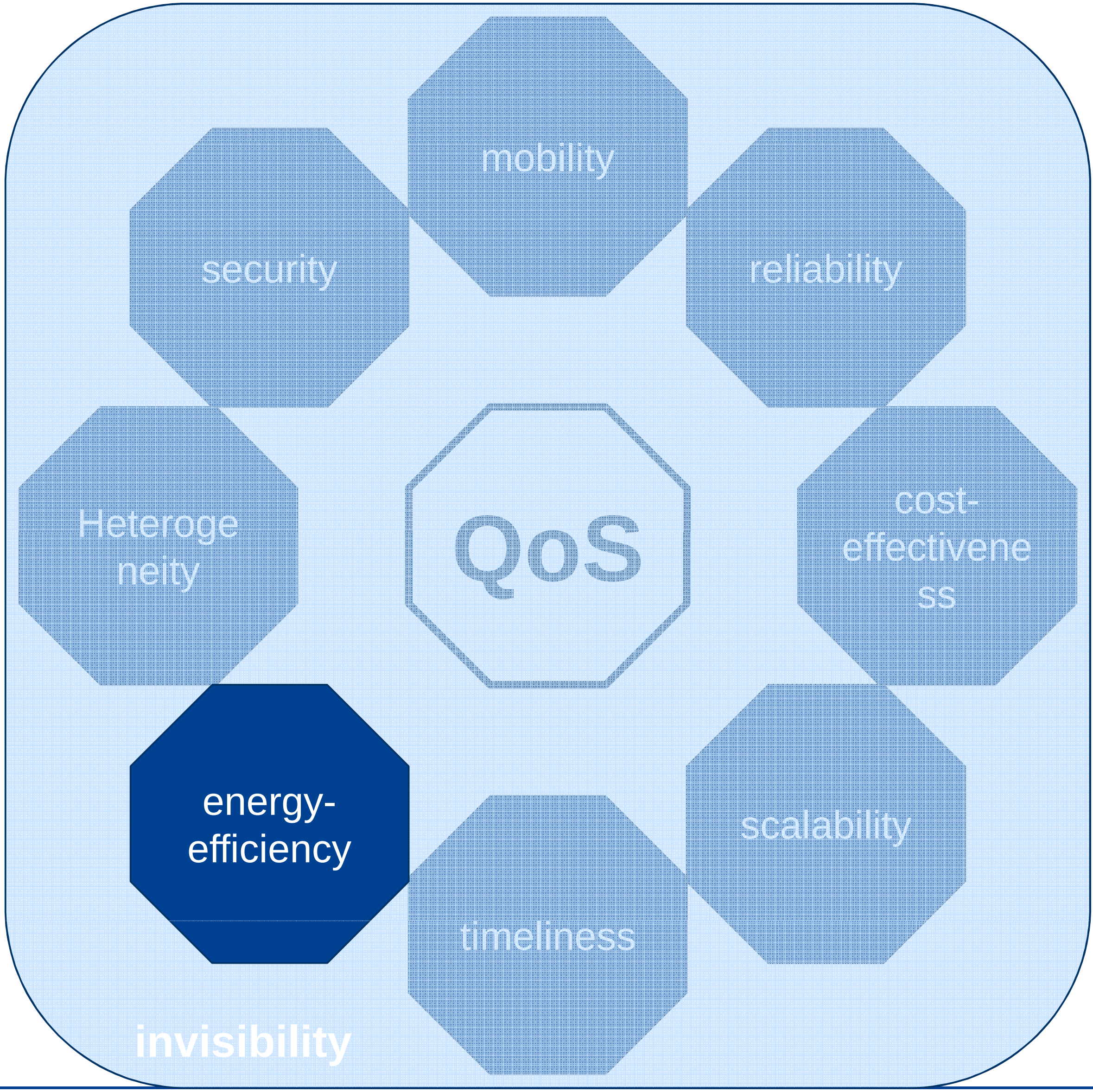
Quality-of-Service – heterogeneity

- Research challenges (cont.)
  - **interoperability btw sensor/actuator-level and higher-level protocols**
    - wireless: IEEE 802.11/WiFi, IEEE 802.16/WiMAX, IEEE 802.15.3/UWB
    - wired: Switched/Industrial Ethernet, ATM
    - guaranteeing end-to-end QoS is even more complex!
  - **dealing with ≠ embedded system nodes hardware/software**
    - **≠ sensor technology**
      - for measuring different physical quantities
      - same physical parameter measured by n sensor nodes
        - = type: redundancy, accuracy, functional (e.g. MAX) needs
        - ≠ types: “design diversity” needs
    - **≠ operating systems** (e.g. TinyOS, Contiki)
      - ≠ programming languages (e.g. nesC, C, JAVA)
      - ≠ simulation/programming environments/tools

Quality-of-Service – heterogeneity

- Research challenges (cont.)
  - **≠ applications/services/users in the same system**
    - same network infrastructure may support several applications/services
      - **≠ applications/services will impose ≠ QoS requirements**
        - will dynamically change depending on **spatiotemporal** issues
      - system designers must adequately **devise mechanisms** such as MAC/routing, admission control and scheduling, security, fault-tolerance, data aggregation/processing
        - **to encompass such applications/services coexistence**
    - **several/many human users, playing at ≠ levels and with ≠ cultures, ≠ technical skills,...**
      - further research on Human-Computer Interaction, HMIs, ergonomics, psychology and **semantics** is required

Quality-of-Service – energy-efficiency



Quality-of-Service – energy-efficiency

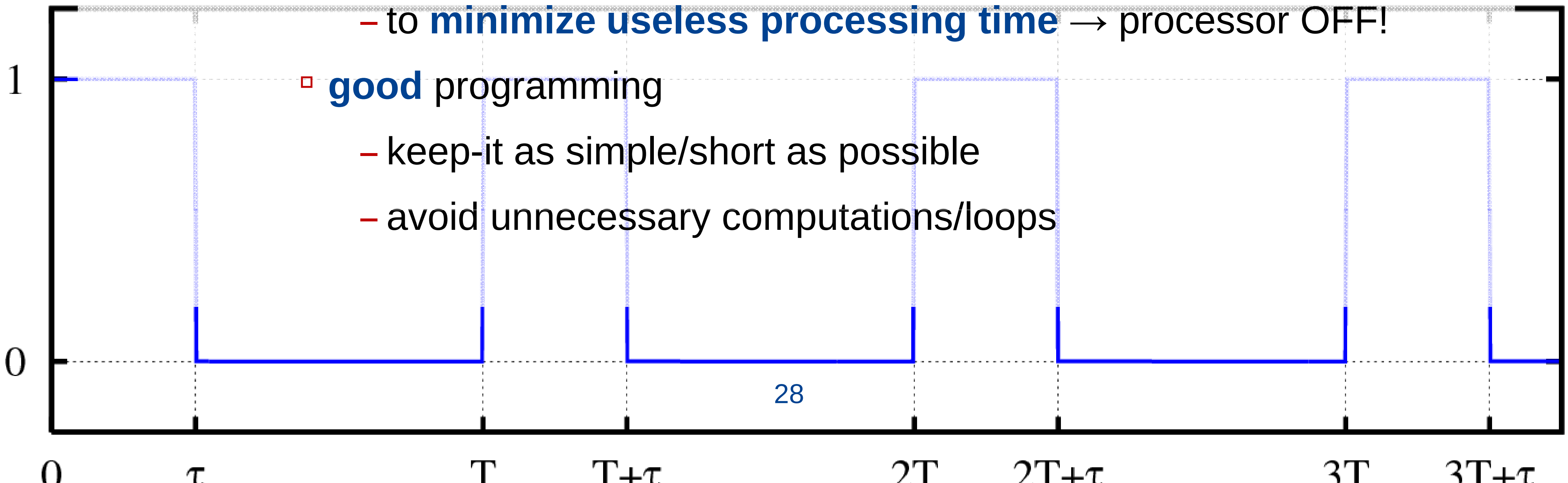
- Energy concerns must always be present
  - WSNs = embedded devices at large-scale
    - most will be **communicating through air** (wirelessly)
    - some will be **mobile**
    - additional energy **cables are a real burden** of even impossible
  - therefore
    - most of the devices must be **self-sustainable** (energetically)
  - but this does **<u>not</u>** mean that all devices need to be autonomous in terms of energy
    - **some devices** can (must) be **powered by the electrical grid**
      - due to special duties (e.g. routers/gateways, data processing)
    - **some devices** can (must) be **powered by special energy sources** (micro-generators or high capacity batteries/fuel cells/supercapacitors)
      - due to innaccessible location, mobility features, etc.

Quality-of-Service – energy-efficiency

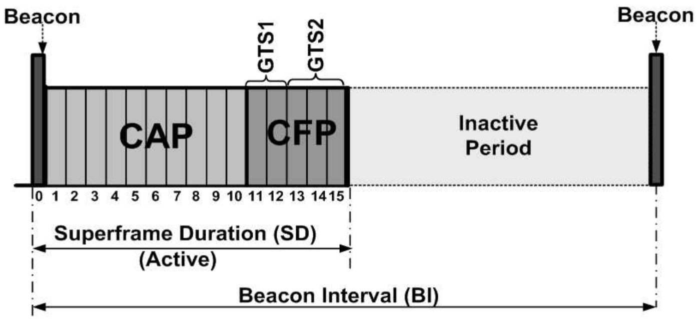
- Research challenges
  - **hardware design**
    - **reduce hardware's energy consumption**
      - microprocessors, microcontrollers, DSPs
      - memories, ADC/DAC
    - **reduce energy losses**
      - mechanical (e.g. friction), electrical (Joule's), magnetic (Foucault's)
      - trend for MEMS (when appropriate)
    - **favouring active sensors** (vs. passive)
      - active sensors produce their own energy
      - thermocouple, piezoelectric, photocell

Quality-of-Service – energy-efficiency

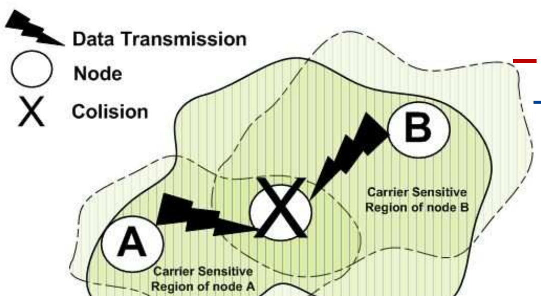
- Research challenges (cont.)
  - **resources utilization**
    - **sleep** as much as possible
      - low duty-cycle computations and communications
    - **efficient** computations
      - try to reach **100%** CPU(s) utilization
        - optimal scheduling algorithms; reduce task switching
        - to **minimize useless processing time** → processor OFF!
      - **good** programming
        - keep-it as simple/short as possible
        - avoid unnecessary computations/loops



Quality-of-Service – energy-efficiency



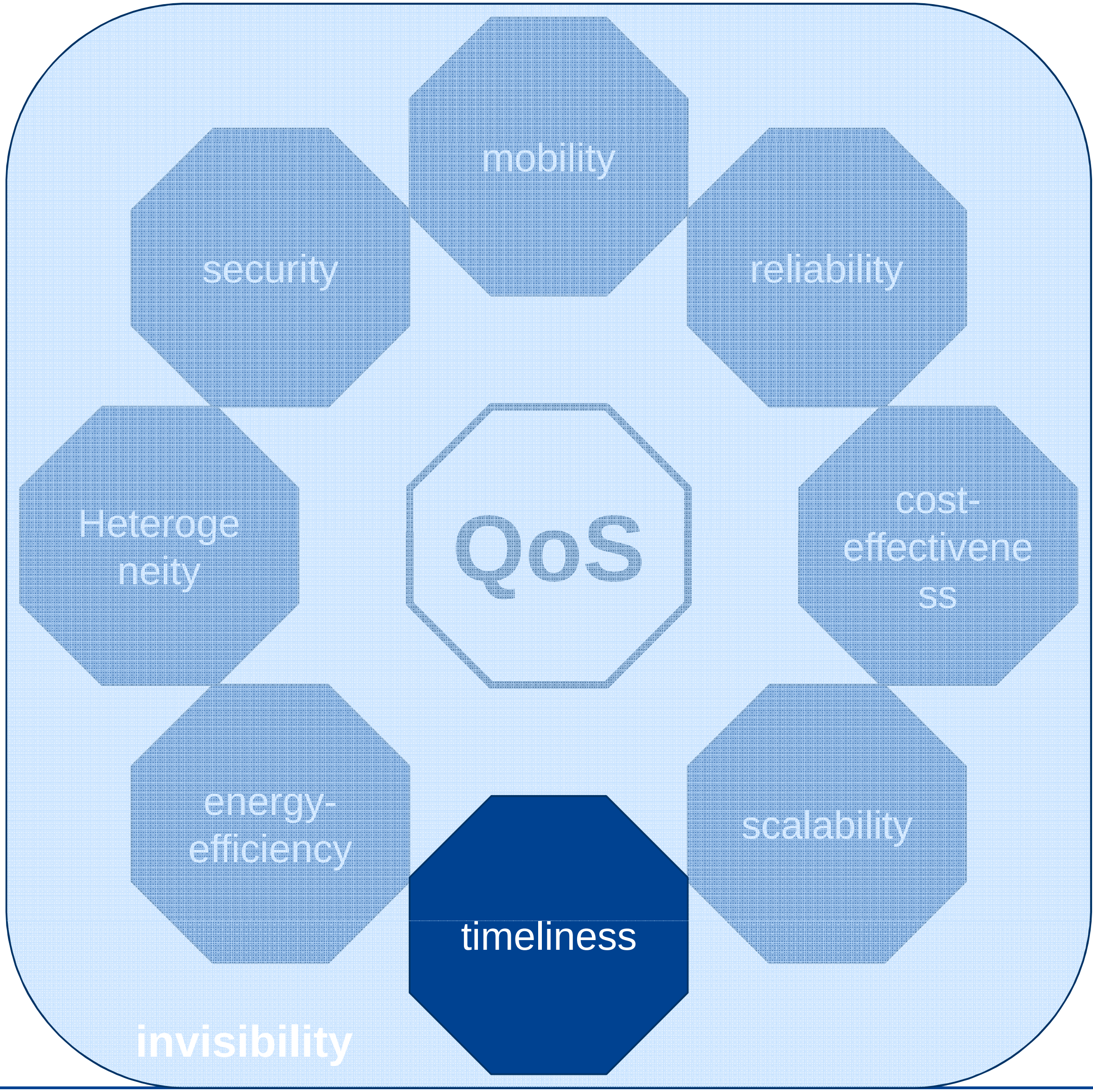
- Research challenges (cont.)
  - resources utilization (cont.)
    - **efficient** communications
      - **minimize communication time** → tranceiver OFF!
        - **data aggregation & distributed data processing** (if possible)
        - efficient **MAC/routing scheduling schemes**
          - do **not waste bandwidth** (specially in TDM-like MACs)
        - operate at **low duty cycles** (requires synchronization)
      - **energy-aware PhL/MAC/routing protocols**
        - use **optimal TX/RX power level** (→ location-awareness)
        - avoid **idle listenning & hidden/exposed terminal** problems
        - use **optimal routes**, the shorter the better (not always)
        - avoid **collisions** (group nodes in CSMA, contention-free MACs)



Quality-of-Service – energy-efficiency

- Research challenges (cont.)
  - resources utilization (cont.)
    - **efficient** communications (cont.)
      - **reduce overheads**
        - < memory footprint, < proc. delays
        - **lighter** protocol stacks
          - OSI layer headers/overheads
          - network management messages
          - **cross-layer design**
  - **energy harvesting**/scavenging
    - grab energy **from environment**
      - (e.g. thermal, vibration, **light**, humidity, wind, waves, EMI)

Quality-of-Service – timeliness



Quality-of-Service – timeliness

- Timeliness **= timing behaviour** of a system
  - is reflected in properties such as
    - network **throughput**
      - effective bit rate
    - message **delays**
      - how long does it take for a message to be transmitted from a source to be received by the destination
    - traffic **differentiation**
      - assign traffic classes/priorities, e.g. real-time/best effort traffic
  - these must be **balanced with other QoS properties**
    - e.g. to increase throughput it might be necessary to increase the “hardware” bit rate or nodes duty cycle
      - leading to more energy consumption

Quality-of-Service – timeliness

- Timeliness is **of increasing importance**
  - in a **cyber-physical world**, computing entities closely interact with their physical environment, thus their **timing behaviour is of paramount importance**
  - In some applications, some tasks are imposed to finish within a certain **deadline** – dubbed as “**real-time applications**”
    - need **RT computation**
      - requiring RT operating systems and programming languages
    - need **RT communication**
      - requiring RT communication protocols
    - usually require **over-allocation of resources**
      - resulting of the inherent pessimism of the analysis (e.g. WCET)
      - a problem for dynamic and energy-efficient systems

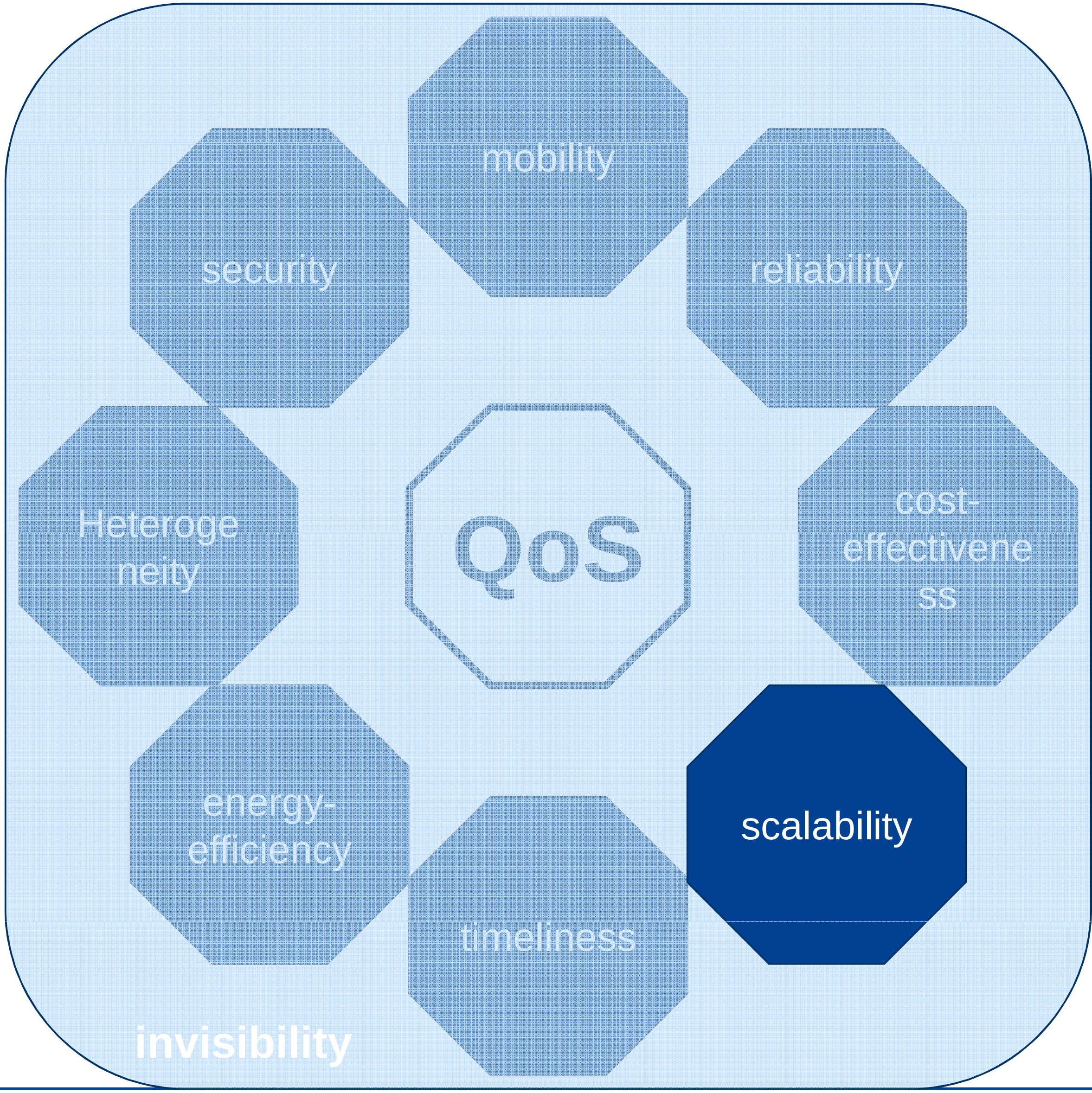
Quality-of-Service – timeliness

- Network **resources must be predicted in advance** (pre-run-time)
  - to support the applications with a predefined timeliness
  - to guarantee that the system will behave as expected
- **Network dimensioning methodologies/tools**, for computing
  - performance limits (throughput)
  - worst-case **message delays** (end-to-end or per-hop)
  - worst-case routers' **buffers size**
- Real-time communications require
  - **deterministic** MAC and routing protocols
  - **hierarchical** network models (hexagonal, grid or cluster-tree)

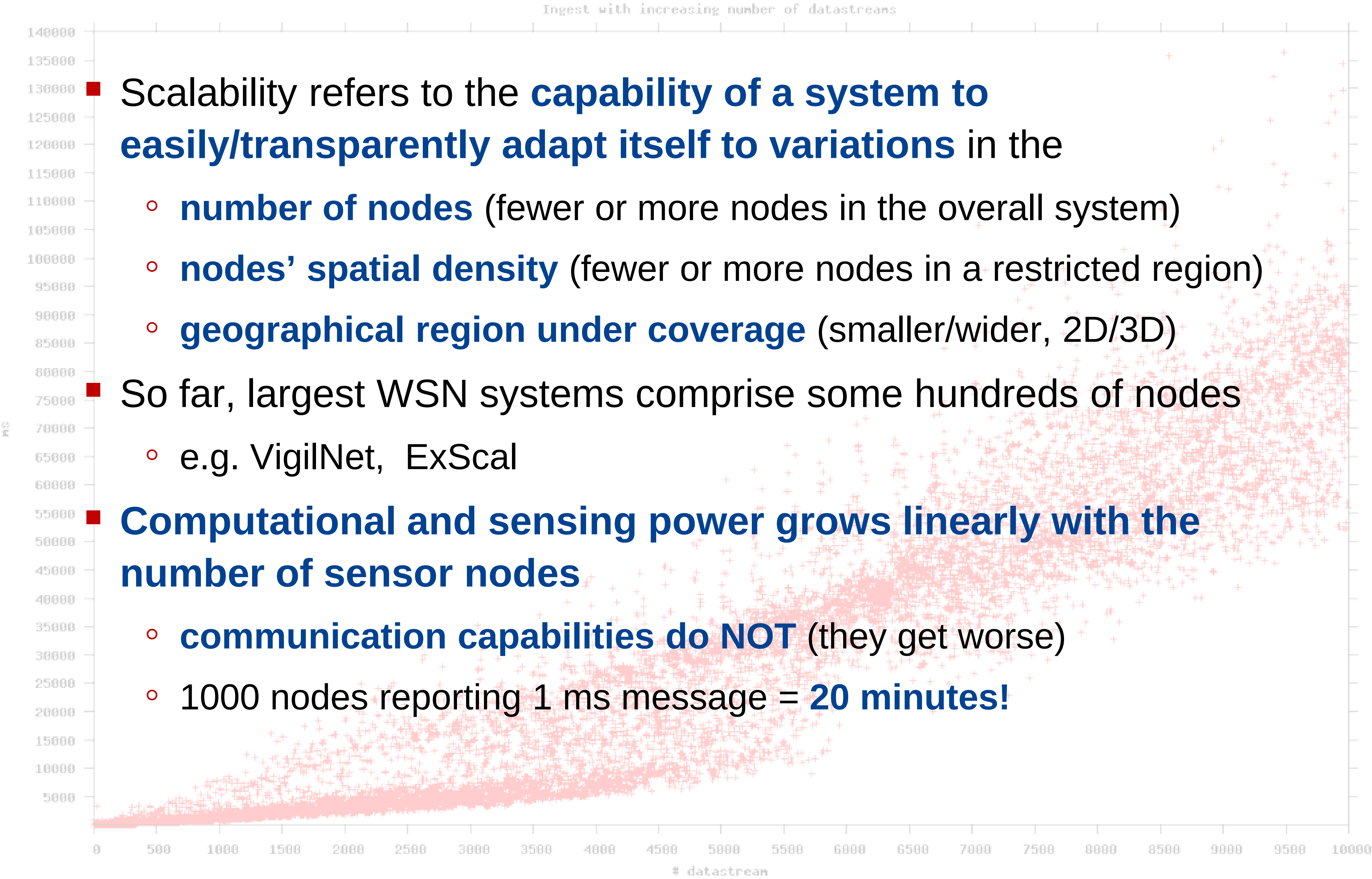
Quality-of-Service – timeliness

- Research challenges
  - **biggest challenge is to balance all contradictory QoS properties**
  - explore hierarchical network architectures (already referred)
  - investigate how **aggregate computations** can be used to achieve a **time complexity that is independent of the number of nodes**
  - design algorithms and protocols in a **cross-layer approach**; bad thing is that software gets more difficult to maintain and update
  - **consider timeliness both at the network and node levels**; nodes hardware design, OS, prog. language and style impact timeliness
  - investigate **existing OSs** (particularly TinyOS and Contiki) **to incorporate real-time features** (e.g. preemption, priority-inheritance)
  - find **innovative MAC and routing schemes** (e.g. to reduce collisions, increase throughput and bandwidth utilization,...)

Quality-of-Service – scalability



Quality-of-Service – scalability

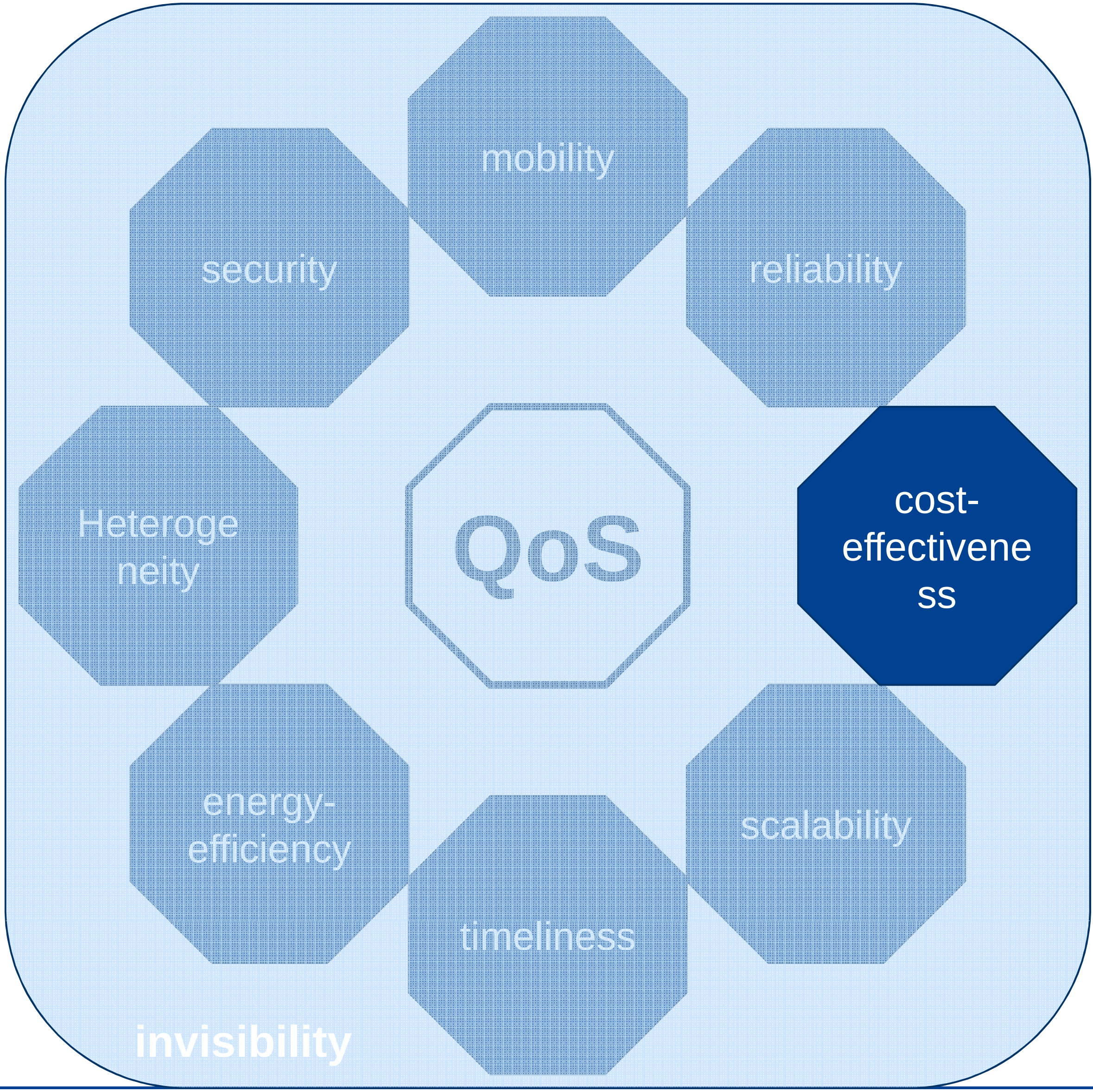


- Scalability refers to the **capability of a system to easily/transparently adapt itself to variations** in the
  - **number of nodes** (fewer or more nodes in the overall system)
  - **nodes' spatial density** (fewer or more nodes in a restricted region)
  - **geographical region under coverage** (smaller/wider, 2D/3D)
- So far, largest WSN systems comprise some hundreds of nodes
  - e.g. VigilNet, ExScal
- **Computational and sensing power grows linearly with the number of sensor nodes**
  - **communication capabilities do NOT** (they get worse)
  - 1000 nodes reporting 1 ms message = **20 minutes!**

Quality-of-Service – scalability

- Research challenges
  - efficient **scale-aware MAC/routing mechanisms** (e.g. **WiDOM**)
  - efficient **data processing, aggregation, storage and querying**
  - explore hierarchical (tiered) network architectures
  - support **multiple data sinks** (need or load balancing)
  - investigate **how standard and COTS technologies can be used** and interoperate to support scalable systems

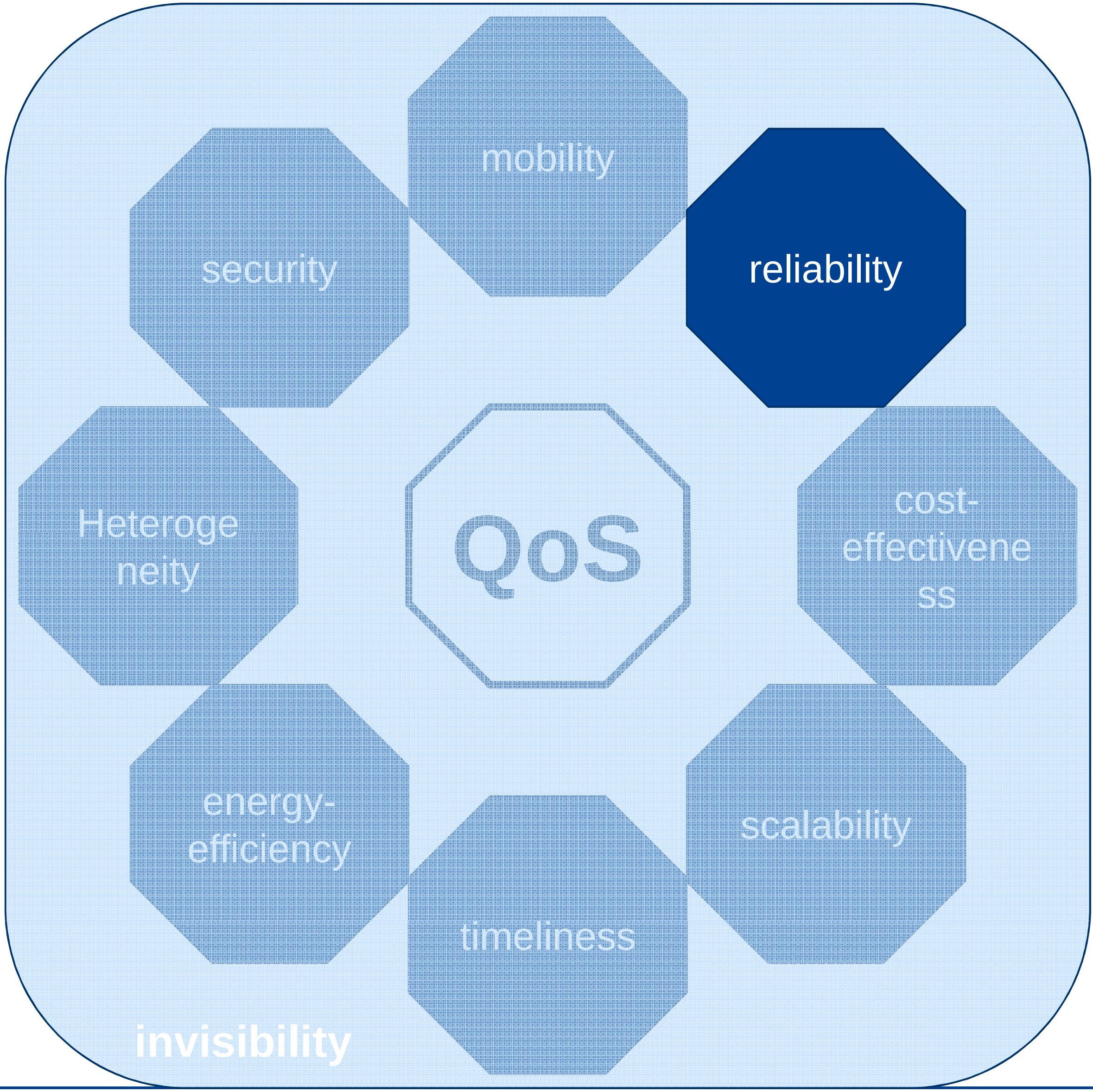
Quality-of-Service – cost-effectiveness



Quality-of-Service – cost-effectiveness

- **System cost** usually includes issues such as
  - system design/development
  - hardware cost
  - deployment and commissioning
  - exploration and maintenance
- Research challenges
  - cost/node target **< $1 threshold** (current cost €10-€50)
  - go for **mass production** (demand-supply snowball)
  - bet on **cheaper designs/materials/production processes**
  - bet on **components reduction/miniaturization** (e.g. MEMS)

Quality-of-Service – reliability



Quality-of-Service – reliability

- In WSN applications, **operational and environmental conditions may be unfavourable**
  - vibration/mechanical impacts
  - extreme (high/low) temperatures
  - extreme (high/low) pressures
  - water, humidity, moisture, dust
  - other RF sources, EMI
- Data delivery in WSN is inherently faulty and unpredictable (much more than in wired networks or even in other wireless networks)
  - sensor nodes are fragile and have weak resources
  - radio links are error-prone (EMI, obstacles, environment, mobility)
  - network congestion (event data bursts) may lead to packet loss
  - multi-hop nature of WSNs

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Quality-of-Service – reliability

- WSN equipment must be **robust** and **reliable**
  - to overcome all these harsh conditions
  - to reduce or eliminate maintenance actions
  - to have a lifetime of years
- **Robustness** (hardware/software) refers to
  - a component or a system that performs well not only under ordinary conditions but also under abnormal conditions that stress
- **Reliability** is
  - the ability of a component or system to perform its required functions under stated conditions for a specified period of time
    - requires the use of robust hardware/software
    - requires the support for fault-tolerance mechanisms

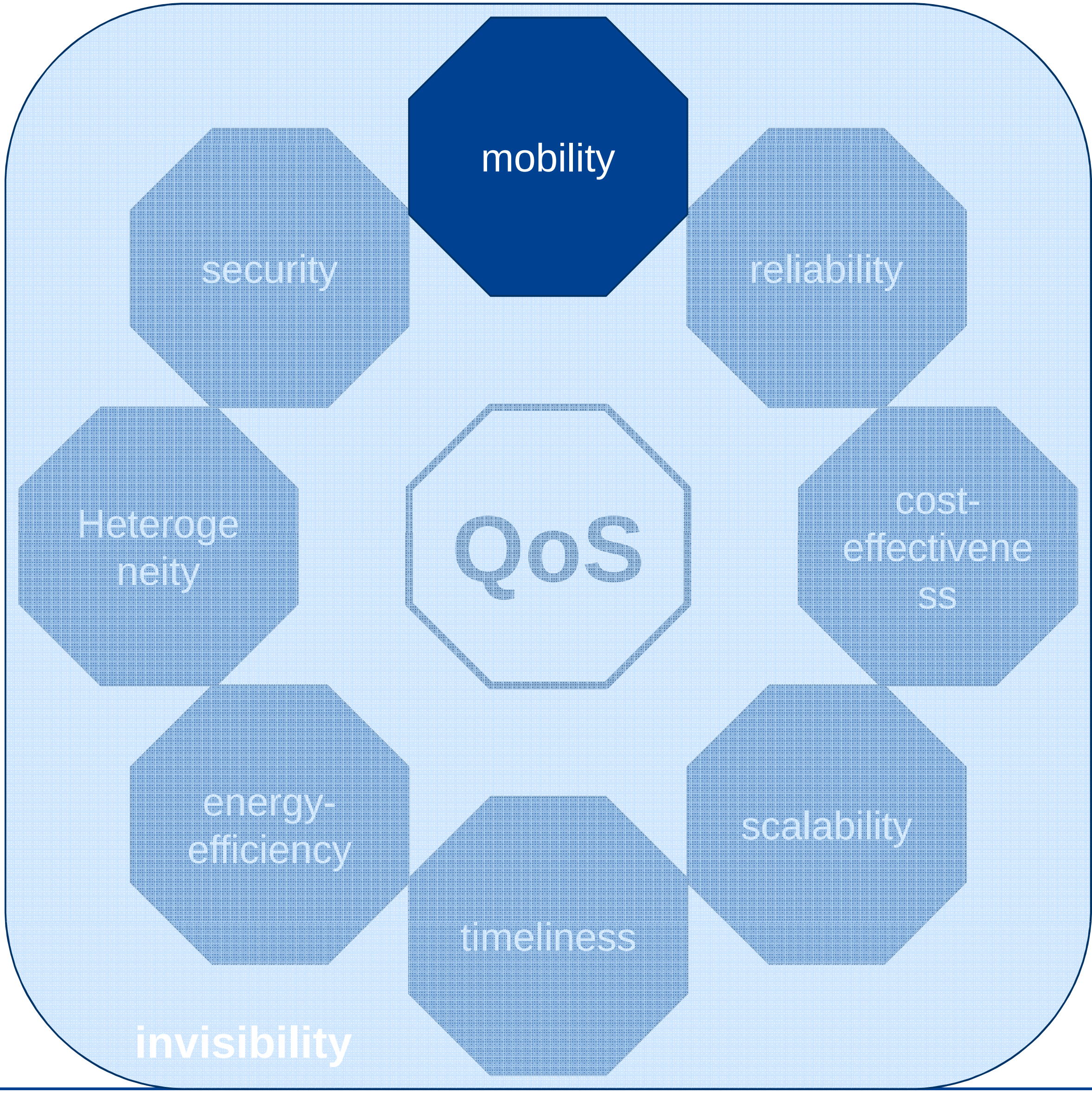
Quality-of-Service – reliability

- Research challenges
  - hardware robustness
    - investigate on robust, cheap, ecological materials/components
    - miniaturization & cost/node should not prejudice hardware robustness
  - robust software/algorithms
    - write “generic” code, to accommodate wide range of situations and thereby avoid having to insert extra code just to handle special cases
    - using formal techniques, e.g. fuzz testing, to test algorithms
    - providing each application with its own memory area (avoiding interference with the memory areas of other applications and kernel)
    - explore advanced programming paradigms (e.g. collaborative computing, reflection mechanisms)

Quality-of-Service – reliability

- Research challenges (cont.)
  - fault-tolerance
    - generically, investigate F-T mechanisms that are scalable, energy/time-efficient, adaptable to dynamic changes
    - F-T mechanisms must spread along different layers (DLL, NL, AL), in a cross-layer approach (exploring the interactions btw layers)
    - find more robust TL solutions that can recover from node/link failures and network congestion
  - measurement accuracy
    - related to accuracy of sensor/signal conditioning, ADC,...
    - note sensor density **vs.** data fusion/aggregation

Quality-of-Service – mobility



Quality-of-Service – mobility

- WSN applications may involve a diverse set of **mobile entities**
  - vehicles, equipment, animals, humans, fluids,…
- instantiated in
  - **nodes**' mobility
    - isolated or in groups, sensor nodes or gateways
  - **data sinks**' mobility
    - on purpose (e.g. data mules) or due to user/application requirements
  - **event** mobility
    - kind of mobility, e.g. event tracking (e.g. tsunami, gas leak, herd, fire)
- mobility **speed**
  - fast: > 20 km/h
  - slow: < 20 km/h

Quality-of-Service – mobility

- Radio-cell/cluster boundaries
  - **intra-cell** (or intra-cluster) mobility
    - mobile node moves without losing connectivity with base station (structured network) or peers (ad-hoc network)
    - requires no mobility management
  - **inter-cell** (or inter-cluster) mobility
    - mobile node moves outside the radio coverage of a certain cell/cluster into another cell/cluster
    - hand-off (or hand-over) management mechanism is required

Quality-of-Service – mobility

- Mobility support can be very helpful, e.g.
  - to maintain and repair network connectivity (self-configuration)
  - to improve network coverage
  - to balance energy consumption (e.g. rotating cluster-heads/routers)
  - to adapt to dynamic stimulus changes (collect data upon event)
  - to collect data (data mules), extending WSN lifetime
  - to **increase QoS in critical regions**, upon events
  - to encompass **new applications** or extend “current” applications’ boundaries with extra capabilities
  - ultimately, to increase **users’ satisfaction** ☺

Quality-of-Service – mobility

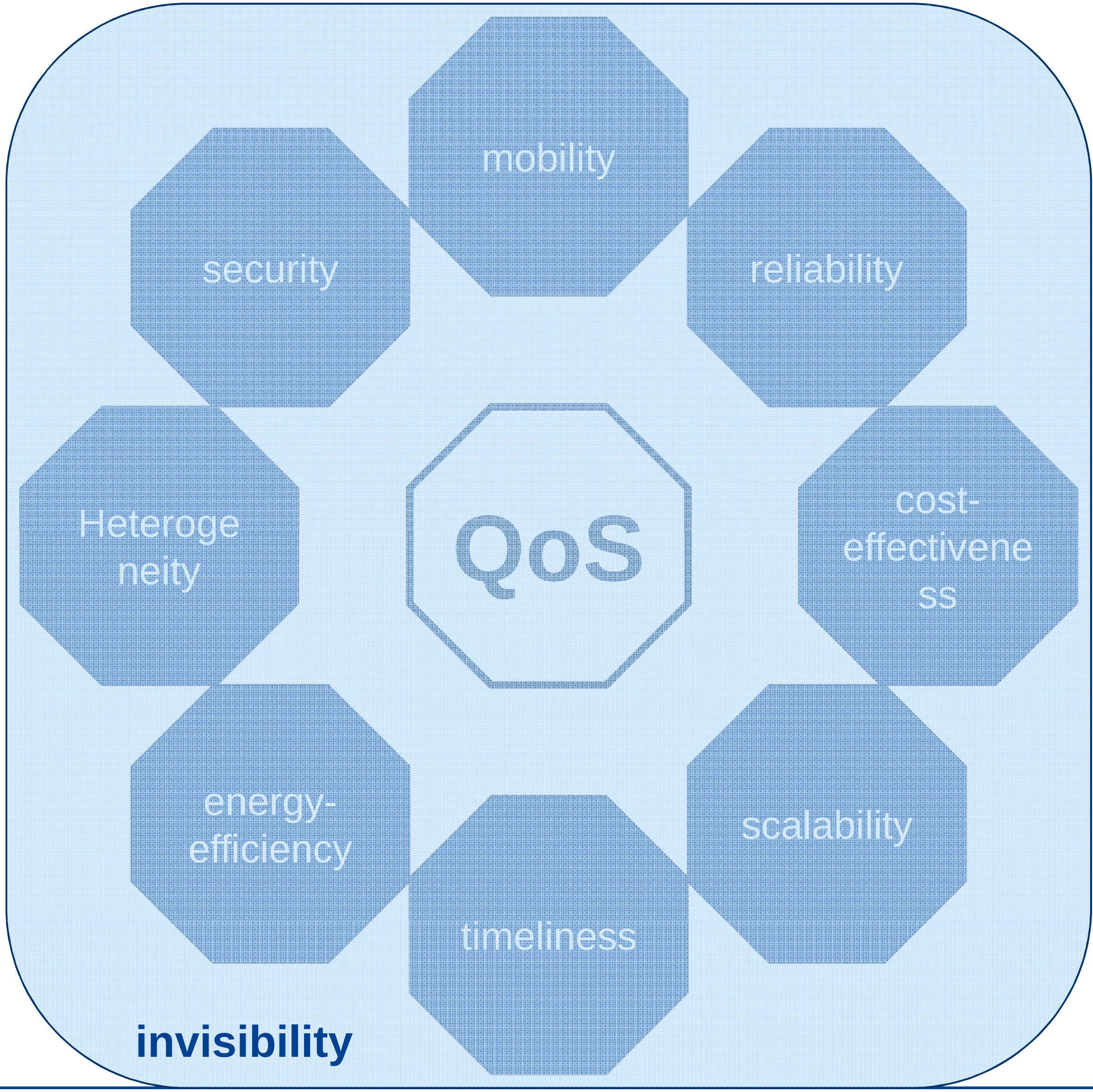
- Research challenges
  - mobility support in WSNs is still in its infancy
  - investigate on mechanisms for **transparent, energy-efficient and reliable mobility support** with **no network inaccessibility times**
    - usually, protocols (e.g. ZigBee) only support joining/leaving of nodes
  - analyse how **fast mobility** can be supported (even harder to tackle)
  - investigate new **MAC and routing** mechanisms that are **adaptive to dynamical changes** (traffic load, topology) caused by mobility
  - develop WSN **simulation tools/models encompassing mobility**
  - find **new localization mechanisms** that are energy/cost-efficient
  - propose **accurate radio link quality estimators**
    - a basic building block for mobility, for hand-off decisions

Quality-of-Service – security

Quality-of-Service – security

- Nothing to add to
  - Gianluca Dini talk ☺
- Just note that there is the need to
  - balance security **with other QoS properties**
    - implementing security may imply additional hardware, additional computations, additional communications, longer messages,…

Quality-of-Service – invisibility

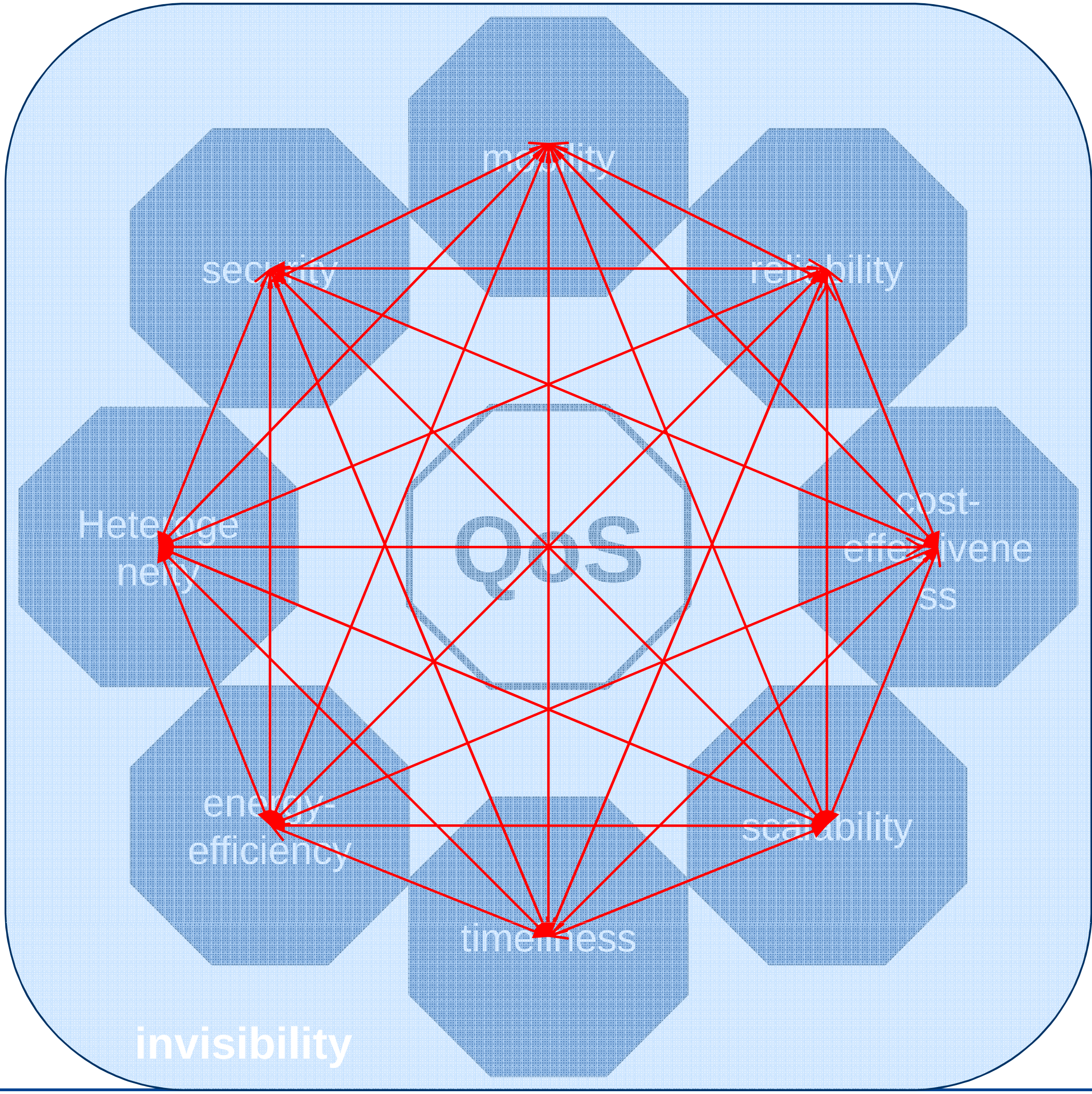


Quality-of-Service - invisibility

- Invisibility
  - Mark Weiser's vision
    - "**the best computer is a quiet, invisible servant**"
  - embed system/components in the environment:
    - **invisible** (to the human eye)
    - **inaudible** (to the human ear)
    - ...
  - environmental impact
    - avoiding "buying new is cheaper than maintaining/repairing/recharging"
    - **recyclable** materials, **sustainable** systems
    - **ecologically friendly** (fauna, flora, land, sea, air)

if we get "calm technology", we can just relax ☺

Quality-of-Service – multilateral impacts

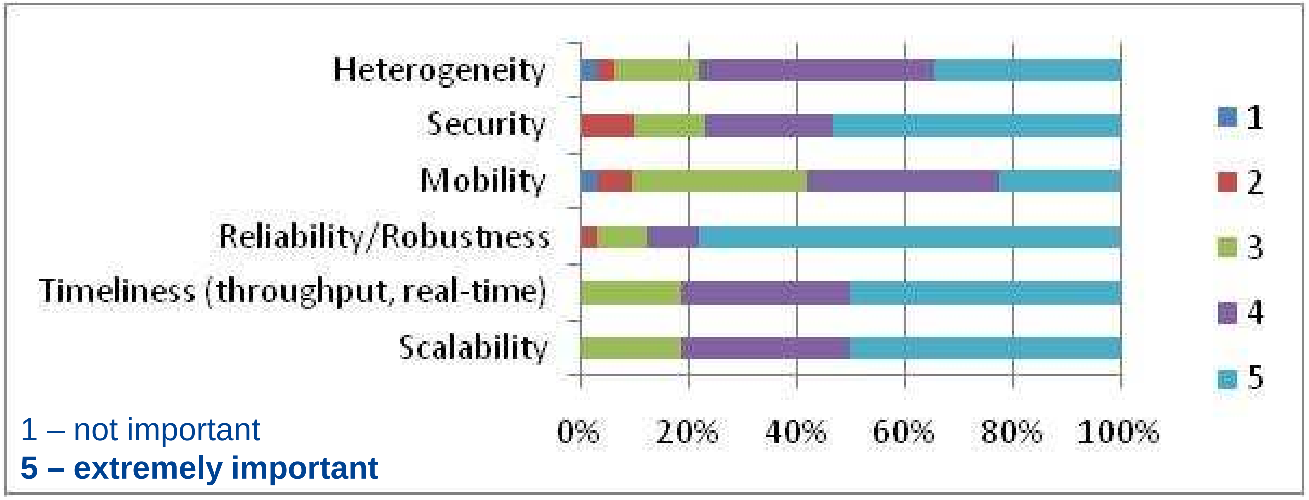


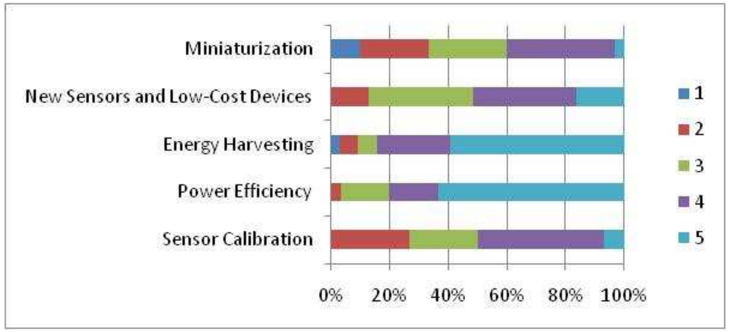
Quality-of-Service – multilateral impacts

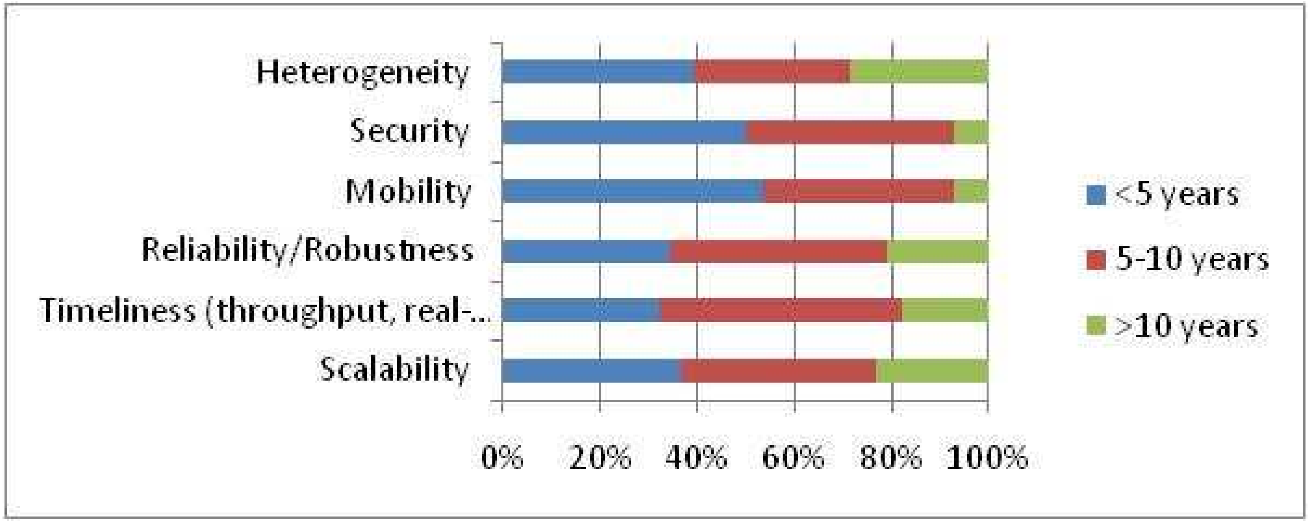
- just one example:
  - providing **timeliness** guarantees (e.g. throughput, deadlines) may **impact** on:
    - **Scalability** – the WSN may not be able to grow
    - **Security** – lighter algorithms and message overheads
    - **Reliability** – timing/information redundancy may not be feasible
    - **Cost-effectiveness** – powerful hardware is more expensive
    - **Mobility** – network inaccessibility times not tolerated
    - **Energy-efficiency** – increasing bit-rate and duty-cycles costs energy
    - **Heterogeneity** – network dimensioning/planning may be harder
- you can easily think about other implications...

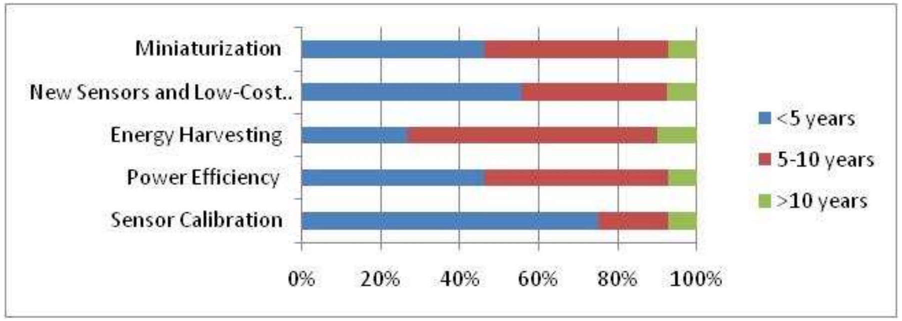
Quality-of-Service – relevance+timeline

- CONET survey (perfomed 1st quarter 2009)





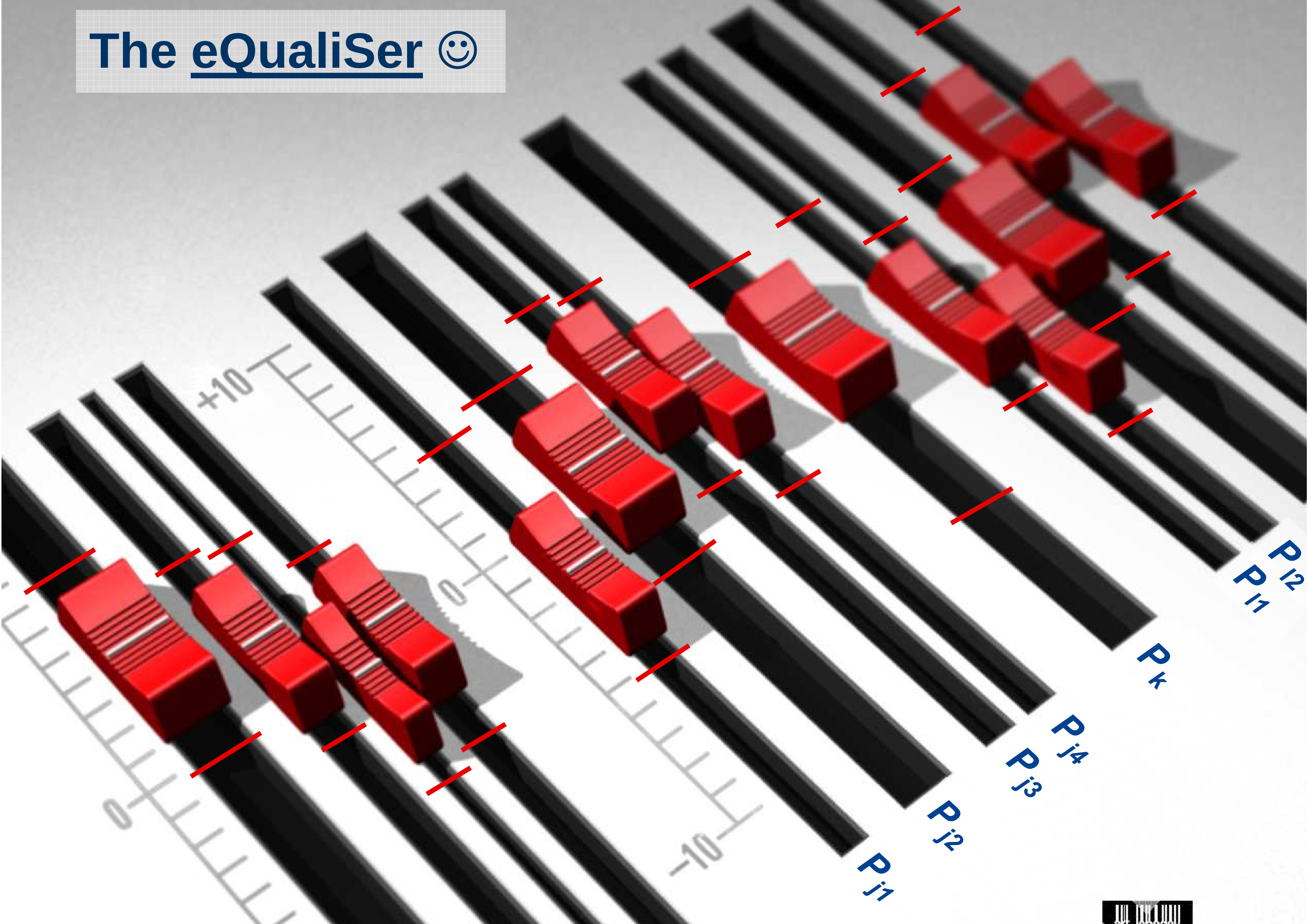




Concluding remarks

- QoS is of growing importance in WSN applications
  - e.g. Cooperating Objects, Cyber-Physical Systems
- But the provision of QoS in WSNs is very challenging due to
  - (usually) severe limitations of WSN nodes
  - (usually) harsh nature of the WSN environments
  - large-scale nature of (most) WSNs
  - high interdependency btw QoS properties – often contradictory
- Approach
  - reach maturity (real/effective solutions) for every property
  - design network/system planning/dimensioning models, methodologies and tools for achieving optimal trade-offs

The eQualiSer ☺



Final highlights

- **“Cooperating Objects Roadmap 2009”**
  - a book on **SOTA and future directions** in the CO/WSN area
  - download at http://www.cooperating-objects.eu/roadmap/download/
  - new (updated/refined) version to appear in 2010
- CONET **newsletter**
  - monthly releases; free subscription!
  - http://www.cooperating-objects.eu/newsletter
- **check job opportunities at CISTER (PhD or post-doc)**
  - go to http://www.cister.isep.ipp.pt/jobs/
  - several areas, including **WSN** and **CPS**
  - engage on a thrilling experience ☺