Real-Time and Wireless Sensor Network: is there a possible match ?

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Centre Suisse d'Electronique et de Microtechnique

CSEM

… is a research and development company, active in the domains of micro-, nano- and information technology

… is a private company, with mainly industrial, but also public shareholders, not-for-profit

… is under contract by the Swiss Government to perform a special mission in micro- and nanotechnology

… has revenues (2007) of 58 MCHF, today ~ 380 employees, five centers in Switzerland & international activities

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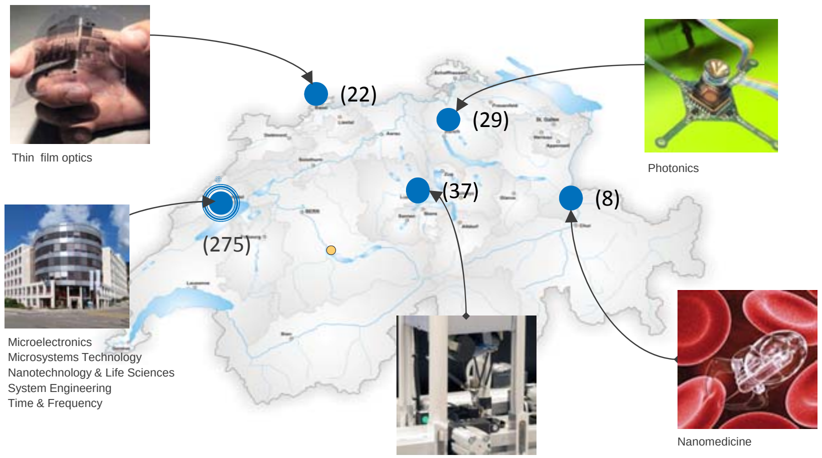
CSEM Centers in Switzerland



WSN activities

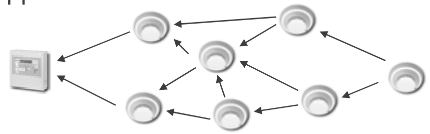
- Started in 1999
  - Combined protocol and IC design
  - Emphasis on ultra low power and ease of deployment
  - Deployments in the field since 2007
- Involved in a number of EU projects in the domain
  - eSense
  - Cruise
  - WASP
  - SCIER
  - Mobesens, ….

Fire and Flood detection at Wild Urban Interface

- Detection & prediction of fire, flood & their evolution
- network of temperature, rain, wind, humidity sensors
- Multiple sinks in urban premisses

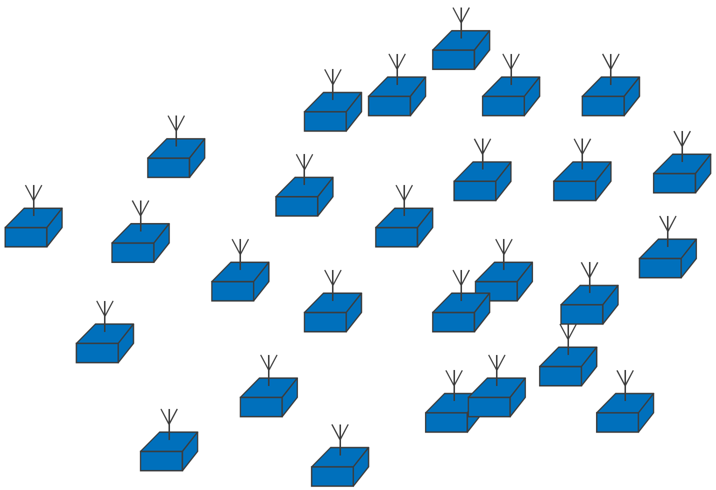
Safety Critical Sensor Networks for Building Applications

- Partners
  - ✓ SBT (Siemens Building Technology)
  - ✓ CSEM (Swiss Center for Electronics and Microtechnology)
  - ✓ ETHZ (Swiss Federal Institute of Technology)
- Project goal: Develop an ultra-low power wireless multi-hop communication system providing high reliability and low delay transmissions. Application to Wireless Fire Detection.



- Contributions from CSEM in the field of ultra-low power medium access control (MAC) for low latency mesh networking.

Wireless Communications



Real-time definitions

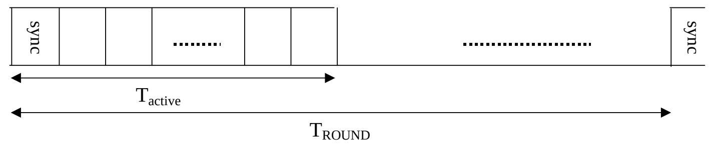
- Hard real-time
  - in case of violation of one or more temporal constraints, there is full loss of functionality
- Soft real-time
  - the functionality is not lost but its quality is degraded
  - less value is given if deadline is missed
- Firm real-time
  - same as SRT but no value is given if deadline missed

Traffic model

- Real-time periodic
  - $M_{p,i}$={T_i, D_i. C_i}
    - ✓ C_i length of message, T_i period of transfer, D_i relative deadline from beginning of period (absolute deadlines are $d_{n,i} = n\ T_i + D_i$)
- Real-time sporadic
  - $M_{s,i}$={T_i, D_i. C_i}
    - ✓ T_i min. interarrival time, D_i relative deadline from arrival time (absolute deadlines are $d_{n,i} = arr_{n,i} + D_i$)
- Best effort
  - Configuration data
  - File transfer
- Multimedia

Objectives of the talk

- show that the classical HRT paradigm is not applicable to wireless sensor networks
- Explore alternate ways
- explain why pure TDMA is not a good solution



Outline

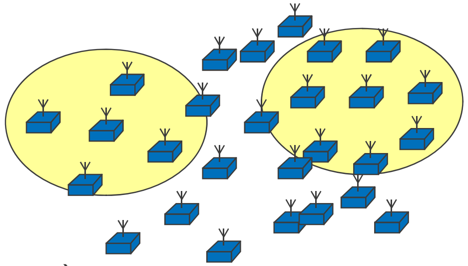
- introduction
- real-time networking research focus and results
- 7 myths about wireless communications
- truths about wireless communications
- first conclusion
- the TDMA case
- second conclusion
- where to go ?

Real-Time Network Research

- focuses on MAC layer
- often based on response time analysis
  - other metrics are throughput, delay and delay jitter
- addresses HRT constraints
- most papers do not deal with errors

- other QoS constraints are addressed in other communities (DiffServ, IntServ, TP4, XTP, RTP, queuing theory, …)

WSN features



- self organized
- multihop transmission
- battery operated (low energy)
- no infrastructure (no base station, etc.)
- small (< $1cm^3$), low cost (target <0.5$)
- low data rate (up to 10 Kbit/s/node)
- large number of nodes (0.05 to 1 nodes/m^2)
- sensor information temporal consistency

Characteristics of wireless transmission

- higher BER
- lower signalling rate
- limited possibility to detect collisions
- low spatial reuse
- prone to interference
- lower distances
- security concerns
- No remote powering

- radio transmission
  - fading
  - incompatible regulations
  - higher cost
  - longer turn on and switching times
  - hidden terminal effect
- light transmission
  - line of sight
  - sensitive to heat
  - health concerns

Wireless tx properties implications

- MAC
  - master-slave (switching time ⇒ longer timeouts)
  - bus arbiter (hidden node ⇒ limitation in broadcast, reliable detection of silence ⇒ BA redundancy)
  - tokens (hidden node ⇒ token loss, switching time ⇒ longer timeouts)
  - virtual token (reliable detection of silence ⇒ token passing)
  - CSMA (no collision detection ⇒ use timeouts)
  - TDMA (switching time ⇒ longer gaps)

Implications of wireless tx prop (2)

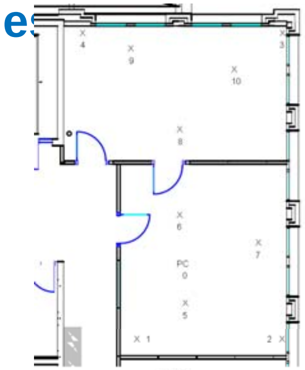
- Error recovery
  - immediate retransmission
    - ✓ lower bandwidth, impact on higher layers
  - no immediate retransmission (cyclic transmission)
    - ✓ likelihood that errors will last
  - use forward error correction codes to lower apparent FER

source: Ph. Morel, EPFL 1996

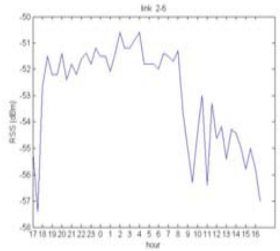
7 myths about wireless transmission

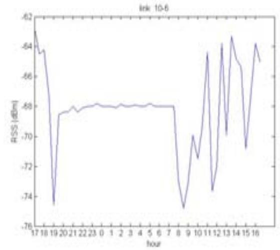
- the world is flat
- a radio transmission area is circular
- all radios have equal range
- if I can hear you, you can hear me
- if I can hear you at all, I can hear you perfectly
- signal strength is a simple function of distance
- link quality does not change

Some truths about wireless communication



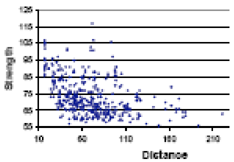
- links fall into 3 categories
    - connected, transitional, disconnected
- transitional links are often unreliable and asymmetric (even for static nodes)
- packet error does not mean collision

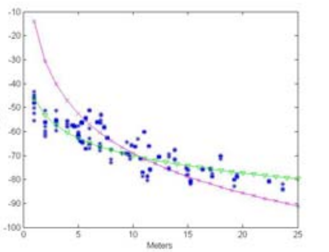


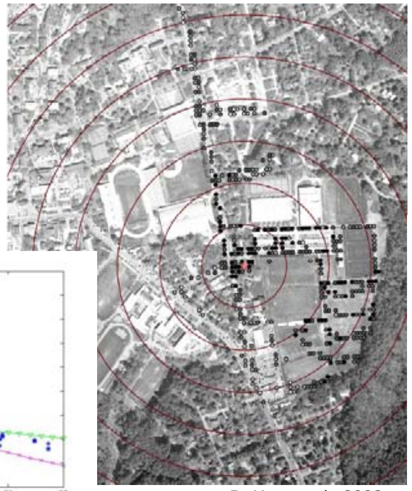


Some truths about wireless communication (cont.)

- radio coverage is not at all circular
    - obstacles, height, fading, …
- signal strength is loosely related with distance







source: D. Kotz et al., 2003

Other challenges

- severe resource constraints
    - energy, bandwidth, memory size, processing
- unbalanced traffic
    - sink nodes
- network dynamics
- scalability
- multiple traffic requirements

So what's new for RTN research ?

- not only MAC
  - mulithop must be taken into account
- impossible to ignore errors
- highly dynamic cases
- limited resources
  - energy (means good models for that)
  - memory (buffers)

Initial (old) studies

- 1992-94: ESPRIT project 7210 – Open Low-Cost Time-Critical Wireless Fieldbus Architecture (OLCHFA)
  - ✓ wireless extension to WorldFIP
- 1998-2000: ESPRIT project 27035 – Mobile Fieldbus Devices in Industry, MODFI
  - ✓ point to point wireless links based on Bluetooth for CAN networks
- 1999-2001: IST project High Performance Wireless Fieldbus in Industrial Multimedia-Related Environment, RFieldbus
  - ✓ uses IEEE 802.11 to support Profibus (Token Passing bus)
- P. Morel et al., "A wireless gateway for fieldbus", PIMRC, 1995.
  - ✓ how to add wireless nodes to an existing fieldbus (FIP)

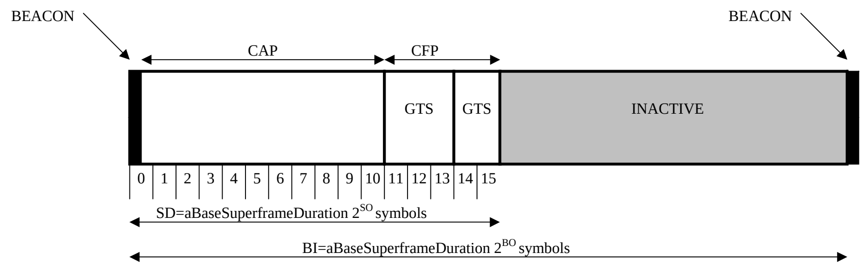
work focused on reliable physical links / ways to overcome errors

Glimpses of SOTA

- MAC
  - IEEE 802.15.4 and the GTS mechanisms
  - Implicit EDF
- routing
  - SPEED
- in-network processing (data aggregation)

802.15.4 (ZigBee)

- 2 modes: peer-to-peer and star

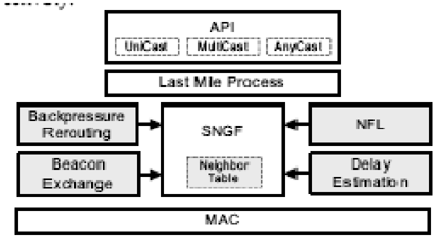


SPEED design goals

- Delay depends on distance of packet travel and hop delay
  - Support soft RT with a desired speed
    - ✓ Real-time unicast / real-time area-multicast / RT area-anycast
- Objectives
  - Stateless architecture (only knowledge of neighbors)
  - Soft real-time (end to end delay proportional to distance)
  - Minimum mac layer support (best effort sufficient)
  - QoS routing and congestion management
    - ✓ novel backpressure re-routing scheme to adapt to changing conditions
  - Traffic load balancing (use of simultaneous paths non deterministicaly)
  - Localized behaviour (all distributed operations are localized)
  - Void avoidance

SPEED principles

- Maintains desired delivery speed by
  - Diverting traffic
  - Locally regulating packets sent to MAC layer
- 5 modules
  - SNGF choose next hop
  - NFL / Backpressure reduce or divert traffic in case of congestion
  - Beacon exchange provides geographic location of neighbors



To make a long story short

there is no way to provide HRT guarantees in WSNs

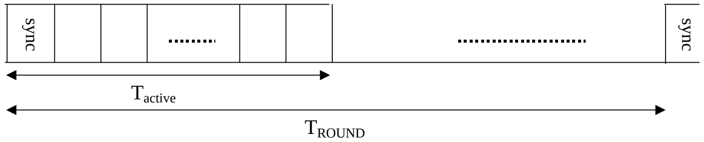
it is unlikely that pure TDMA can be efficient in WSNs

The TDMA case

- we know that pure TDMA
  - is not flexible
  - does not scale
  - does not support mobility
  - hardly supports fluctuating links (because of desynchronisation)
- but
  - it is energy efficient
    - ✓ no collisions, nodes are turned on just the necessary time
  - it is the best choice in case of high loads
- IS THAT SO ?

The TDMA case (2)

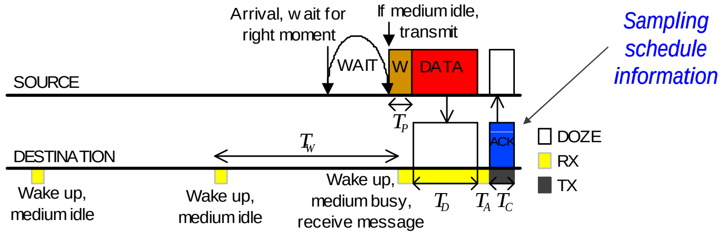
- simple case
  - all traffic has same period
    - ✓ this is the 802.15.4 star case with beacon



    - ✓ multihop network: each node receives 1 packet and transmits 1 packet per round
      - energy per round = $E_{rec} + E_{tx} + E_{rxsync} + \{E_{txsync} + 4\theta T_{ROUND} P_{tx}\} / N$
      - N number of participating nodes, θ clock drift
      - E_{txsync} (E_{rxsync}): energy to send (resp. receive) a sync. packet
      - E_{tx} (E_{rec}) : energy to send (resp. receive) a packet and receive (resp. send) ack
- adaptable case

The TDMA case (3)

- let use a non TDMA protocol, Wisemac for instance



  - ✓ assume same <u>low</u> traffic (1 msg sent and 1 msg receive per T_{round})
  - ✓ energy per round = $E_{rec} + E_{tx} + \{T_{ROUND} / T_W - 1\}E_{PS} + 4\theta T_{ROUND} P_{tx}$
  - ✓ as compared to $E_{rec} + E_{tx} + E_{rxsync} + \{E_{txsync} + 4\theta T_{ROUND} P_{tx}\} / N$

The TDMA case (4)

- adaptable case
  - TDMA rounds with slots assigned to links
  - a node need not emit at each round
  - one node sends a synchronisation message every K rounds
  - all nodes transmits 1 msg and receives 1 msg every L rounds
  - energy per L units = $E_{rec} + E_{tx} + L\, E_{rxsync}/K + \{L / T_{ROUND} - 1\}E_{PS} + 2\theta L\, P_{tx} + \{E_{txsync} + 4\theta K T_{ROUND} P_{tx}\} / N$
  - energy for Wisemac = $E_{rec} + E_{tx} + \{L / T_W - 1\}E_{PS} + 4\theta L\, P_{tx}$
  - of course, this is only valid for low traffic conditions

The TDMA case (5)

- what about high traffic conditions ?
  - we need some margin between the slots for desync.
  - we need some margin for retries
  - we need some margin to accommodate the longest packet
- asynchronous protocols are also able to avoid collisions by suppressing arbitration is some cases
  - more bit (Wisemac)
  - TXOP (IEEE 802.11)

draw your own conclusions

To make a long story short

there is no way to provide HRT guarantees in WSNs

it is unlikely that pure TDMA can be efficient in WSNs

Possible ways forward

- rethink the model
- select the right metrics
- have a clear and reasonable fault model
- Use different strategies for retransmissions
- design protocols that adapt
- use application properties
  - (TT/ET, zones, mobility, energy, …)
- Experiment in practice on sufficiently complex cases

Rethink the model

- are we sure that applications care about deadlines ?
  - ✓ what about accuracy of detection, coverage, …
- do we need end-to-end guarantees ?
  - ✓ what about other models (e.g. (m,k) firm) ?
- Are we sure we need (the same) guarantees at all place and all the time?
- what about the publish-subscribe model ?
  - ✓ WSNs are data centric not client centric
  - ✓ this is a way to uncouple the entities
    - Thomesse 1991

Fault model

- classical FT assumes crash failure
  - I am not this captures the link behaviour !
- sensing part may fail but not routing
- there is redundancy in sensing (multimodal)

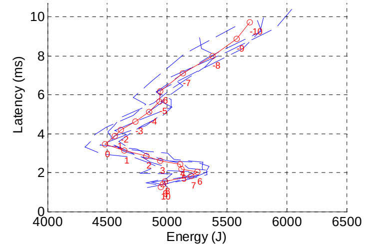
- we need to clearly state which kind of faults we tolerate
  - link / nodes / sensors
  - at which degree (link may come and go)
- which kind of mobility

The right metrics

- it is not possible to provide HRT guarantees
- what about
  - the probability that a given message reaches its destination
  - within a given deadline
    - ✓ Navet 2000, Broster 2002
  - with some energy consumption

Protocols that adapt

- Change operating parameters



- Switch from one protocol to another
  - Compatible protocols (e.g. LPL and CSMA)
    - ✓ Rousselot 2008
  - Non compatible (e.g.CSMA and TDMA)
    - ✓ Watteyne 2006, Sobral 2008

RFC 1925 Fundamental Truths of Networking

- (1) It Has To Work.
- (2) No matter how hard you push and no matter what the priority,you can't increase the speed of light.
- (2a) (corollary). No matter how hard you try, you can't make a baby in much less than 9 months. Trying to speed this up *might* make it slower, but it won't make it happen any quicker.
- (3) With sufficient thrust, pigs fly just fine. However, this is not necessarily a good idea. It is hard to be sure where they are going to land, and it could be
- dangerous sitting under them as they fly overhead.
- (4) Some things in life can never be fully appreciated nor understood unless experienced firsthand. Some things in networking can never be fully understood by someone who neither builds commercial networking equipment nor runs an operational network.
- (5) It is always possible to aglutenate multiple separate problems into a single complex interdependent solution. In most cases this is a bad idea.

RFC 1925 Fundamental Truths of Networking (2)

- (6) It is easier to move a problem around (for example, by moving the problem to a different part of the overall network architecture) than it is to solve it
- (6a) (corollary). It is always possible to add another level of indirection.
- (7) It is always something
- (7a) (corollary). Good, Fast, Cheap: Pick any two (you can't have all three).
- (8) It is more complicated than you think.
- (9) For all resources, whatever it is, you need more.
- (9a) (corollary) Every networking problem always takes longer to solve than it seems like it should.
- (10) One size never fits all.
- (11) Every old idea will be proposed again with a different name and a different presentation, regardless of whether it works.
- (11a) (corollary). See rule 6a.
- (12) In protocol design, perfection has been reached not when there is nothing left to add, but when there is nothing left to take away.

Conclusions

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