Body Area Networks:
RF Communication and Higher Layer Protocol Design

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Wireless Body Area Networks (BANs)

- A BAN is a self-organizing network at the human body scale which consist in a collection of smart, low-power, hardware-constrained, miniaturized and heterogeneous wireless devices attached to (or implanted into) a moving body.

- Several emerging new applications in sports, healthcare, ambient intelligence, entertainments, man-to-machine, etc.
BANs Specific Requirements

- **Heterogeneous devices**: sensor node (for data gathering), actuator node (to react according to perceived data), coordinator node (act as a gateway to external networks)

- **Variable data rates**: due to the application heterogeneity, data rates may range from a few kbit/s (ECG, etc.) to a few Mbit/s (audio/video, etc.)

- **Low energy consumption**: for sensing, radio communication and data processing.

- **QOS and reliability** (delivery ratio, latency, scalability, etc.) are critical issues for medical applications

- **Functionality and ergonomics** (size of devices, self-organizing / configuring BAN protocols, coexistence, etc.)

### Variable data-rates for medical applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Data Rate</th>
<th>Bandwidth</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG (12 leads)</td>
<td>288 kbps</td>
<td>100-1000 Hz</td>
<td>12 bits</td>
</tr>
<tr>
<td>ECG (6 leads)</td>
<td>71 kbps</td>
<td>100-500 Hz</td>
<td>12 bits</td>
</tr>
<tr>
<td>EMG</td>
<td>320 kbps</td>
<td>0-10,000 Hz</td>
<td>16 bits</td>
</tr>
<tr>
<td>ECG (12 leads)</td>
<td>43.2 kbps</td>
<td>0-150 Hz</td>
<td>12 bits</td>
</tr>
<tr>
<td>Blood saturation</td>
<td>16 bps</td>
<td>0-1 Hz</td>
<td>8 bits</td>
</tr>
<tr>
<td>Glucose monitoring</td>
<td>1600 bps</td>
<td>0-50 Hz</td>
<td>16 bits</td>
</tr>
<tr>
<td>Temperature</td>
<td>120 bps</td>
<td>0-1 Hz</td>
<td>8 bits</td>
</tr>
<tr>
<td>Motion sensor</td>
<td>35 kbps</td>
<td>0-500 Hz</td>
<td>12 bits</td>
</tr>
<tr>
<td>Cochlear implant</td>
<td>100 kbps</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Artificial retina</td>
<td>50-700 kbps</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Audio</td>
<td>1 Mbps</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Voice</td>
<td>50-100 kbps</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
BANs versus PANs

- **PANs solutions** (Bluetooth, Zigbee, B-LE) are currently adopted for the design and implementation of **basic BANs solutions**, however with **limitations** (energy consumption, size of devices, etc.)

- **PANs versus BANs:**
  - PAN devices are **too large** to fit within miniature housings (hearing aids, cochlear implants, etc.)
  - PAN devices **power consumption is high**, limiting thus network lifetime
  - PAN solutions do not address the RF **propagation aspects of BAN** (body absorption, body shadowing, moving limbs, etc.)
  - PAN protocol architecture are **not well adapted** to the BAN context
BANs Research challenges

Overview of the BANs research challenges:

- Applications
  - Navigation
  - Positioning
  - Auto- & Tracking
  - Motion Capture
  - Monitoring

- Positioning
  - Localization Schemes
  - Localization Algorithms

- Networking
  - Network Architecture
  - Routing Algorithm

- Medium Access Control
  - Beacon-Free
  - Beacon-Enabled

- Physical Layer
  - Narrow-Band
  - Ultra-Wide-Band
Networking Research activities (1/2)

- BANs Network Topology Characterization:

- Experimental investigation of the BAN topology dynamics and the performance of routing strategies using narrowband and ultra wideband time-varying channel measurements

- Several design criteria have to be carefully considered for the implementation of effective BANs architectures: placement of wireless devices on the body, the transmission power, link quality estimators, routing strategies (ANR, PDR), etc.
Networking Research activities (2/2)

- BANs Network Topology Characterization:

- Design of efficient link quality estimators (LQE) and opportunistic routing and relaying mechanisms to face the dynamic nature of the BAN radio channel and network topology.
Localization Research activities (1/2)

- Cooperative Localization for mobile groups of BANs:
  - Design of Intra/Inter cooperative BANs localization algorithms that fully exploit the spatial diversity and measurements redundancy
  - Emerging applications: group navigation, nomadic social networks, augmented reality, gaming, etc.

Range-based localization algorithms (TDOA/TOA) using N-Way cooperative ranging transactions.

- Investigate the potential issues and benefits of BANs cooperative localization schemes in terms of positioning accuracy and MAC performances
Localization Research activities (2/2)

- Simulations based on a joint realistic (biomechanical and group) mobility and radio channel modeling + IEEE 802.15.4 beacon-enabled MAC

- Cooperative localization schemes are more robust to packet loss and exhibit a higher positioning success rate (up to 96%) than NCL
- The NCL scheme can be performed in less than one SF, while cooperative approaches may require up to three MAC SFs (data acquisition delay up to 0.2s)
MAC Research activities (1/2)

- Adaptive TDMA MAC protocol for BANs ("BATMAC")
  - Beacon-based (IEEE802.15.4)
  - Flexible and adaptive superframe (SF) structure
    - Control period: beacon period (relaying), GTS request period (CAP), topology management period (hello, tree updates)
    - Data period: CAP (command and associations frames) and CFP (data and ranging frames)
  - Flexible & High QoS MAC to enable several classes of applications
    - Application scalability
    - Support of UWB and 2.4GHz
    - Path to compliance with standardized solutions
    - Ranging / location
    - Opportunistic relaying for QoS improvement mitigating the existence of timely broken links during shadowing periods

- slotted Aloha + tree topology
MAC Research activities (2/2)

- Ex. of reduced outage through adaptive relaying with no significant energy degradation

- Relays can alternatively improve the PER performance of a link through dynamic relay election as a function of the body shadowing with a high reactive MAC.
PHY Research activities

- **BAN Channel Characterization (UWB and narrowband at 2.4 GHz):**
  - TX on Hip (left)
    - Chest
    - Right Thigh
    - Right Wrist
    - Right Foot
  - TX on Left Ear
    - Right Ear
    - Hip (left)
    - Right Wrist
    - Right Foot
  - Different walking speeds

- One can distinguish a slow fading component \( S(t_n) \) and a fast one \( F(t_n) \) in the time dependent power transfer function:
\[
P(t_n) = G_0 \cdot S(t_n) \cdot F(t_n)
\]

- For a specific scenario shadowing is modeled by a log-normal distribution:
\[
S(t_n)|_{dB} \sim \mathcal{N}(0, \sigma_S)
\]

- Fast fading → Rice
Low Data Rate Needs

- **Wireless Sensor & Actuator Networks (WS&AN)**
  - Building Automation / Energy Management in a wide variety of environments and scenarios (homes, factories, airports, etc.)
  - Environmental & Physical monitoring
  - Physician / Medical monitoring
  - Internet of the Future and Internet of Things

- **Key Remaining Challenges**
  - Increase battery life or remove battery
  - Cope with low energy scavenging
  - Reconfigurability between standards
  - Enable self-calibration and self-organization
  - Enable extended functionalities (e.g. self-geolocation)
  - Add low level HW function and hybridise with sensors
Ultra-Low Power RF motivations sum-up

- **General trend**
  - Massive deployment of Wireless Sensors
  - Mandatory requirement for Low Power consumption
  - Standards refinement & WW acceptance

- **IEEE802.15.4**
  - Basis for ZigBee / industrial focus since 2003
  - Main target in the Power Management / Building Automation

- **BT low energy**
  - A ULP version of BT, alleviating protocol & PHY constraints
  - Main target in Leisure / Sport / Wellness

- **IEEE802.15.6**
  - Draft standard for BAN available at IEEE
  - Main target in the Medical area

- **IR-UWB**
  - Precise ranging / localization aspects of great interest
RF design activities

- Member: 33 analog, mixed & system RF designers
  - Senior engineers with industry background
    - Gemplus, STm, Infineon, Thomson TCS
    - Ela-Medical, Memscap, FT R&D, Atmel,....

Short range communications from RFID
To mmW in CMOS technology

- SoC RFID 13.56 MHz & UHF 2.45GHz
- SoC UWB LDR impulse modulation (3-10 GHz)
- SoC Ultra Low Power Radio Zigbee 2.45 GHz
- RF FE Millimeter 60 GHz WiHD 4Gbps
Low Power RF activity at Léti

- **Target the mW range for RF communications**
  - Full-CMOS design – high integration
  - High-level model for optimized specifications
  - Short- to Medium-range applications: BAN & PAN

- **Stick to standard-based solution**
  - ZigBee / Bluetooth low energy
  - Upcoming IEEE802.15.6 for medical app.
  - Benefit from collaborative partnerships

- **Integration of the complete solution**
  - Analog & Digital BB on the same die
  - Enhance digital blocks towards analog front-end
  - Co-design with MEMS
  - Target aggressive technology node size: 90 nm & beyond ...
System-level Models and Simulations

- **System–level approach**
  - Find the best trade-off considering: data rate / BW / standard
  - Limit power-hungry overspecified analog/digital functions

- **Impairments compensation**
  - Right balance between analog and digital
  - Mathematical tools for algorithm validations

→ **LETIBOX** to be used with Simulink®

- **Low analog complexity / digital-oriented solution**
  - Full-CMOS + highly digital → Easy technology scaling down
  - One complete RF solution → IP for the communication link
Ultra Low Power RF – IEEE802.15.4 compliant

- Letibee - ULP RF SoC Architecture
  - Zero-IF Receiver / Direct up-converter Transmitter
  - Non-linear / 3-bit ADC
  - Digital Base Band process : RX & TX
  - Full-CMOS 0.13 μm single die solution

- Letibee Analog & Digital Specifications Trade-off
  - High-level model & simulation
  - As highly digital as possible → Power Reduction

F<sub>cut-off</sub> : 50kHz to 100kHz

ΔG = 5dB

Measurement limit

1st ULP RF SoC release

- IEEE802.15.4 / ZigBee RF SoC including
  - RX & TX RF front-end – full BaseBand process
  - Frequency synthesizer
  - μ-controller 8051 and 64-kbyte memory

- Power consumption
  - TX active mode: ~ 12.5 mA
  - RX active mode: ~ 7.5 mA

- Demonstration module
  - FP7/ICT collaborative project
  - SENSEI Pan-European Testbed
  - WSN embedding localization algorithms for an industrial contract

5x3.5 cm² demonstrator

11 mm² in CMOS 130nm packaged in 40-pin QFN
Firmware structure

Applications
Localization, Physical measurements...

Validation platforms « Letibee » Node

IEEE 802.15.4 ULP Radio « Letibee » Chip
**Platform comparison**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Sensinode</th>
<th>CEA-Leti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module</td>
<td>N711</td>
<td>Letibee node</td>
</tr>
<tr>
<td>SOC/SIP chip</td>
<td>RC2301AT / TI CC2431</td>
<td>Letibee v1.6</td>
</tr>
<tr>
<td>Standard</td>
<td>IEEE 802.15.4-2006</td>
<td>IEEE 802.15.4-2006</td>
</tr>
<tr>
<td>MCU core</td>
<td>8051 8bits</td>
<td>8051 (Oregano) 8 bits</td>
</tr>
<tr>
<td>MCU clock</td>
<td>32 MHz</td>
<td>8 MHz</td>
</tr>
<tr>
<td>Paged RAM</td>
<td>256 B</td>
<td>256 B</td>
</tr>
<tr>
<td>RAM</td>
<td>8 kB</td>
<td>4 kB</td>
</tr>
<tr>
<td>ROM/EPROM/Flash</td>
<td>128 kB (Flash)</td>
<td>64 kB (internal RAM bootloaded from external EEPROM)</td>
</tr>
<tr>
<td>Antenna</td>
<td>Chip antenna (disabled)</td>
<td>Printed bended monopole</td>
</tr>
<tr>
<td></td>
<td>Whip antenna with standard SMA connector</td>
<td>Connector MMCX to external optional antenna</td>
</tr>
<tr>
<td>Battery</td>
<td>2* AA battery (total 3V)</td>
<td>Rechargeable 3.7V, 430 mAh</td>
</tr>
<tr>
<td>Sleep current (SoC only)</td>
<td>300μA, 0.9μA, 0.6μA depending on mode</td>
<td>Yet to be accurately measured</td>
</tr>
<tr>
<td>Tx current (SoC only)</td>
<td>27 mA / VCC = 2 V</td>
<td>Typically 12.5 mA / VCC = 1.2 V</td>
</tr>
<tr>
<td>Rx current (SoC only)</td>
<td>27 mA / VCC = 2 V</td>
<td>Typically 7.5 mA / VCC = 1.2 V</td>
</tr>
<tr>
<td>Max Tx Power (theoretical/at antenna connector)</td>
<td>0.6 dBm / -8 dBm</td>
<td>-8dBm ( Yet to be fine-tuned / matching issue )</td>
</tr>
<tr>
<td>Sensitivity (theoretical/measured)</td>
<td>-92 dBm / -92 dBm</td>
<td>-85 dBm</td>
</tr>
<tr>
<td>PCB Size (with/without antenna)</td>
<td>70 x 30 x 25 mm³ / 95 x 30 x 65 mm³</td>
<td>50 x 35 mm² / height ~ 7 mm</td>
</tr>
<tr>
<td>Interfaces</td>
<td>UART, proprietary serial debugging interface</td>
<td>UART, SPI Master</td>
</tr>
<tr>
<td>Sensors / converters</td>
<td>Light sensor / 8-14 bits</td>
<td>Light sensor / 12 bits</td>
</tr>
<tr>
<td></td>
<td>Temperature sensor / 8-14 bits</td>
<td>Temperature sensor / 12 bits</td>
</tr>
<tr>
<td>Actuators</td>
<td>2 buttons</td>
<td>2 buttons</td>
</tr>
<tr>
<td></td>
<td>2 red LEDs</td>
<td>2 green LEDs</td>
</tr>
</tbody>
</table>
Further ULP RF releases

- Standard-based low power PHY
  - Still full-CMOS – 90 nm, 65 nm ….
  - Addressed band: 2.4 GHz and its medical extensions
  - IEEE 802.15.4 & 15.6, Bluetooth low energy
  - Power consumption reduction is still relevant target
    ➔ between some 100s µW and some mW

- Versatility / reconfigurability
  - Adaptable RF front-ends for power consumption reduction
  - Multiple data rates / modulation schemes / bandwidths
  - Improved performance thanks to versatility
  - Reduce power consumption

- Co-design with antenna / MEMS / digital
  - Mix of simulation tools / system-level model
  - Use high Q resonators
  - Adapt the matching of the IC with the antenna impedance
On-going works on ULP RF SoC

- **Band-Pass Sampling architecture**
  - Sub-sampling process applied to IF domain
  - High level of versatility
  - Very well adapted to advanced CMOS technology (65nm and beyond)

- **Benefits**
  - Filtering constraints split over the RX chain
  - Tuneable power consumption versus required performance
  - Easy multi-standard co-integration / digital oriented front-end
  - Reconfiguration / management by higher layers
Normative situation: IEEE 802.15 standards

IEEE 802 LAN/MAN Standards Committee (wireless areas)

WLAN IEEE 802.11
WPAN IEEE 802.15
WMAN IEEE 802.16
MBWA IEEE 802.20
Regulatory TAG IEEE 802.18
Coexistence TAG IEEE 802.19
WRAN IEEE 802.22

802.15.1 "Bluetooth"
802.15.2 Coexistence
802.15.3 High data rate 2.4GHz
802.15.4 "ZigBee" PHY/MAC
802.15.5 Mesh Networking
802.15.6 Body area networks
802.15.7 Visible Light Comm.

MB-OFDM ECMA-368
TG3a Alt PHY (UWB)
TG3b Enhanced MAC
TG3c 60 GHz
TG4a Alt PHY (UWB)
TG4b Alt PHY + Enhanced MAC
TG4c Adaptation for China
TG4d Japanese sub-GHz band
TG4e Enhanced MAC
TG4f Active Tag
TG4g Smart grid
Architectures for IEEE 802.15.4a

- Non coherent energy detection

  WSN, 1Mbps, medium range 40m, Low Power

- Coherent analog I&Q

  Localization, 50 Mbps, high range 80m
TCR Design – Rx Principle and Architecture

**Rx Principle:**
- Analog saturation on 2 parallel & decorrelated Rx amplification chains
- 1.5-bit sampling of saturated signals @ fixed 1Gsps
- Simple XNOR logical operation on collected samples
- Energy integration in Baseband over variable temporal windows
- Polarity handling
TCR chip layout

- **ST CMOS 130nm**
  - 8mm² area
  - 50% RF & DRF
  - 50% BB
Coherent detection: principles for fine ranging

Pulse energy $\alpha$ and pulse position $\tau$ extractions methodology.

\[ \alpha = \sqrt{(R \text{int } II)^2 + (R \text{int } IQ)^2 + (R \text{int } QI)^2 + (R \text{int } QQ)^2} \]

\[ \tau = \arctan \left( \frac{R \text{int } IQ}{R \text{int } II} \right) \times \frac{\Delta T}{2\pi} \]
Architecture overview of coherent detection

- **Architecture Classification:**
  - Coherent (phase detection) energy detection with orthogonal sinusoidal correlation (OSCR).

- **Realization:**
  - 4GHz center frequency I&Q down-conversion
  - Orthogonal Sinusoidal Correlation: 400MHz I/Q multiplication and integration in 2.5ns window
  - 4 x 5-bits/50Mhz A-to-D conversion.
  - Frequency Synthesis: 8GHz VCO and internal PLL.

- **Key characteristics:**
  - S-Rake (select rake) - maximum 4 fingers representing 50% of minimum PRP (20ns).
  - Fine ranging capabilities: OSC process for fine part
  - High rejection above 25dB over WLAN 5.15GHz interferers
    - 4th order low-pass filter behind 4GHz down-conversion
    - 2.5ns integration window: structural cut-off frequency at 5.2GHz
  - Highest data rate 50 Mbps: 20ns minimum PRP with 5-bits 50MHz A-to-D conversion.
  - Lowest data rate: depending on Xtal accuracy, PLL final tracking jitter and DBB
  - Power consumption < 60mW (1.2nJ/b): LNA + Front-end + ADC + Frequency Synthesis
IR-UWB solutions in LETI

Coherent detection
I&Q down-conversion

- **Objectives**
  - Long Range (50 to 200 m)
  - Sensitivity @ -104dBm for 130kbps
  - High Robustness to blockers (ISM bands)
  - High Ranging Precision (10 cm)
  - Reduce constraints on power (50-100 mW)
  - FCC compliance in low band

- **Architecture choice**
  - Coherent I,Q down-conversion receiver
  - Original architecture with 4 paths analog high resolution tracking
  - 50 MHz ADCs

- **Plus**
  - Design objectives suited to long range application in harsh environment
  - Synthesizer performance
  - Front end performance
  - High resolution ranging engine

- **Minus**
  - Receiver only
  - Still a lot of work to be done for baseband

TCR – direct sampling

- **Objectives**
  - Medium Range (20 to 30 m)
  - Sensitivity @ -90 dBm for 130 kbps
  - Medium Robustness to blockers (ISM bands)
  - Std ranging Precision (30 cm)
  - Low power (10-30 mW)
  - IEEE 802.15.4a compliance in low band (RF)

- **Architecture choice**
  - Non Coherent 1-bit sampling receiver
  - Differential 1.5-bit subsampling receiver
  - Massively digital (1 GHz sampling)

- **Plus**
  - Embedded and functional transmitter (FCC limit)
  - Lightweight and already integrated with the BB
  - Proven in a real system

- **Minus**
  - PLL not suitable for pure coherent detection
  - Sensitivity too low for the some applications
  - Resistance to blockers too low for some applications
Thanks for paying attention!

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