Long-term deployments of communicating mobile sensors for wildlife monitoring*

*Works extracted from: PhD thesis of R. Kuntz, ongoing PhD preparation of J. Beaudaux

Antoine Gallais

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Research and Development of Ad-hoc- and Wireless Sensor Networks for Environmental and Animal Behavioural Monitoring
Crossed Seasons France / South Africa
Associate professor at University of Strasbourg

- Teaching duty
  - Networking classes
  - Computer networks and embedded systems Master

- Research activities
  - Image Sciences, Computer Sciences and Remote Sensing Lab
    - University of Strasbourg and CNRS Research Unit
    - Network research group, led by Prof. Thomas Noël
  - Ad hoc and WSN, activity scheduling, routing/MAC
  - IP over WSN, SensLAB/FIT platform, wildlife monitoring

STRASBOURG: SELECTED FIGURES
- Founded in 12 B.C.
- 276,063 residents in Strasbourg
- 474,524 residents in the Strasbourg urban Community
- 500 km of cycle paths
- 2hrs20 to Paris by train
- More than 4 million visitors every year
Motivations and research focus

• Many existing projects (e.g. zebranet, habitat monitoring, badgers, turtles)
  • No multi-hop communications
  • No (or limited) mobility
  • No geolocation (without GPS)

• Our research interests in wildlife monitoring
  • Expertise on networking new kinds of wireless mobile sensors
    • Routing and MAC layers
  • Collecting data for further modelling
    • Mobility
    • Radio topologies
Wildlife monitoring projects

- **ARGOS**: high costs, hard to adapt to specific requirements
- **GPS-based sensors**
  - “Simple” dataloggers, no radio communications
  - High energy-consumption still
  - Long-term deployments? Limited geographic areas (fewer GPS readings)
  - e.g. Electronic Shepherd, UC Davis’s Puma Project
- **GPS-free sensors**
  - Radio communications, large areas
  - Need for adapted devices (size and weight especially)
  - Direct communications to fixed infrastructure
  - e.g. Falcons tracking, salmons tracking
Wildlife monitoring projects

- **Zebra Net (Kenya, 2003): Study zebras at night**
  - Battery for 1 year: if solar array then 200g, else 1kg
  - Communications every 2 hours (for 5 mn, radio range: 1 to 5 km)
  - Routing: None
  - MAC: GPS receiver -> time-slotted transmissions

- **Issues:**
  - 2 hours is too long a period
  - time-synchronization is possible thanks to GPS
  - Large size and weight for many animals (e.g. penguins, storks)
Nilgai tracking

- **WildCENSE project**: Monitoring Indian Nilgai and its habitat
  - Sensing and storing every 3 hours...
  - Routing/MAC: XBee-PRO (time-slotted on-the-shelf protocol)
  - Impossible to use on smaller animals
Wildlife monitoring projects

- The Badger Project (Wytham Woods, Oxfordshire, UK, 2010)
  - “Regular” data -> RFID storage (tag) and upload (reader)
  - Low-volume data -> multihop communications to 3G gateway
    - Communications every 30mn
    - Routing: Simple tree-based (gradient-like) protocol
    - MAC: Preamble-sampling X-MAC protocol
Ongoing work: Penguin tracking

- **Currently**
  - Animals equipped at time $T$ and captured again at time $T + X$ months
- **Make such biologgers communicate**
  - Eased download of data, data redundancy
- **Monitoring of the ongoing experiment**
Long-term deployments for wildlife monitoring

Requirements

- **Hardware**
  - Antenna: Depends on the monitored animal (i.e. body full of water)
  - Size and attachment: e.g. penguins can not wear collars
  - Packaging: e.g. waterproof, temperature/pressure variations

- **Data collect**
  - Time-stamped: strict/relaxed time synchronization
  - Various sampling periods: primary or complex data
  - Fault-tolerant: e.g. logger-to-logger communications for data redundancy

- **Software**
  - Efficiency: Memory write/read actions
  - Long-term: Communication protocol stack, sensing and radio activity mainly
Designing protocols for wireless communications

Medium access control (MAC)

- **Air is a shared resource:** e.g. People willing to discuss in a common area
  - **Diffusion:** all sensors within the communication area of a sending node receive
  - **Solution:** Only one single transmitting node in a given communication area
Designing protocols for wireless communications

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Long-term deployments of communicating mobile sensors for wildlife monitoring


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Designing protocols for wireless communications

Medium access control (MAC)

- AT86RF231 chip (consumption with a transmission power of 3dBm)
Duty-cycling: MAC layer

- Active/Passive: At which layer? Application? Routing? MAC?
  - Controlling medium access (MAC) for a better radio usage
  - Main assumption: each node works its own MAC, using local information only
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  - **Main idea:** having the radio off most of the time

- **Connectivity** between loggers must be ensured + fairness regarding **latency** and **scalability**
  - 2 main types of MAC protocols: synchronized, **preamble-sampling**
Preamble-sampling MAC protocols

- **Low Power Listening (LPL): no time-synchronization (B-MAC)**
  - **Sampling** periods
  - Use of a **preamble** before any data transmission

Preamble-sampling MAC protocols

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  - Includes **destination** related information

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  - Includes destination related information

⇒ **Scalable and robust to topological modifications** (e.g. faults, mobility)

Preamble-sampling MAC protocols: Challenges

• **Goal:** Having routing paths composed of energy-efficient links only
  • Short LPL (100 ms): frequent wake-ups and short preambles
    • Cost for receivers (sampling): OK if most of nodes are transmitting
  • Long LPL (500 ms): less frequent wake-ups but longer preambles
    • Cost for senders: OK if most nodes are not transmitting

• **Problems**
  • How to set LPL mechanisms based on energy/delay compromises?
  • How to deal with opposite traffic patterns?

➡ **Goal:** Automatically tune LPL for nodes involved in communications
Communications among mobile biologgers

- **Last requirement:** Detailed information for accurate design of protocols

<table>
<thead>
<tr>
<th>Scenario</th>
<th>#loggers</th>
<th>#sink stations</th>
<th>Contact duration with sinks</th>
<th>Contacts with other loggers</th>
<th>Primary data to be stored</th>
<th>Complex data to be stored</th>
<th>Deployment duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storks</td>
<td>50</td>
<td>1 per nest</td>
<td>7h / day</td>
<td>10 / days (15s each)</td>
<td>275kb / day</td>
<td>125Mb / day</td>
<td>1 year</td>
</tr>
<tr>
<td>Penguins</td>
<td>100</td>
<td>1 to several per area</td>
<td>&gt; 1h / day</td>
<td>50 / day (10s-10h each)</td>
<td>1.2Mb / day</td>
<td>125Mb / day</td>
<td>3 months</td>
</tr>
</tbody>
</table>

Protocols to be designed: **MAC** and routing layers
MAC: Adapting LPL configuration

- **Proactive approaches**
  - Using
    - Routing information
    - Application criteria

- **Reactive approaches**
  - Induced traffic
MAC: Adapting LPL configuration

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Proactive approach

• **Using routing information**
  • Root of the tree-based routing structure -> sink station
  • Leafs: sending their own data only
  • Remaining nodes:
    • Sending their own data
    • Relaying data of associated nodes (e.g. sons, grand-sons)

• **Using application criteria**
  • e.g. Coverage, connectivity, density control
Using routing information

- **Leaf nodes become sensing-only**
  - Only sensing and sending their own data
  - Not relaying data packets
  - Configured with long LPL

- **Usable with several routing protocols**
  - RPL (IETF)
  - Gradient-based approaches

---


Using application criteria

- Possible criteria
  - e.g. Target tracking, Border coverage, Point of interest / Area coverage, Density control
  - Network connectivity

- **Active nodes**: Short/reactive LPL

- **Passive nodes**: Long/energy-efficient LPL
Using application criteria

- **Sleep depth**: Partitioning the network into disjoint subsets
  - One subset = One sleep depth = One LPL configuration
  - The lower the layer, the deeper the sleep
  - Nodes of layer $n$ can communicate with nodes of any layer $i$ while $i < n$
  - Density control: If $x$ neighbors on layer $i$, then layer $i$-- (timeout)
Energy consumption

- Construction layers/gradient structure
- Consumption under “idle” and relaying states (traffic induced)
Energy consumption

- Construction layers/gradient structure
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Energy consumption

- **Construction layers/gradient structure**
- **Consumption under “idle” and relaying states (traffic induced)**

![Graph showing energy consumption](image)

- **Radio consumption**
- **Processor consumption**

- **Construction of the routing structure**
- **Traffic-free period**
Energy consumption

- Construction layers/gradient structure
- Consumption under “idle” and relaying states (traffic induced)
MAC: Adapting LPL configuration

- **Proactive approaches**
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    - Routing information
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MAC: Adapting LPL configuration

• Proactive approaches
  • Using
    • Routing information
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• Reactive approaches
  • Induced traffic
Reactive approach

- Default: Nodes fully asleep (long sampling periods and long preambles)
- Problem: Cost of the preamble before each TX along the routing path
- Idea: split LPL in 2 distinct values
  - Using longer sleep periods on passive sensors (Tmax)
  - Using short preamble along routing path (Tmin): EE links along the way
- Constraint: Preserving network connectivity by preventing node isolation
Reactive approach

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- Reminder: On-the-fly adaptation may isolate
  ➔ Most propositions assume homogeneous LPL configurations...
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![Diagram showing Preamble = LPL 1 and Sleep period = LPL 2]

Avoid

LPL 1 < LPL 2
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Routing path: A-B-C

Sender

Receiver

A
B
C

Z
Tmax
Z
Tmax
P
Tmax
P
Tmax
P
Tmax

Time

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Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Sender  Relay  Receiver

Routing path: A-B-C

A
B
C

Time

Time

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Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Routing path: A-B-C

Sender

Relay

Receiver

Tmax

A

B

C

P

Z

Tmax

Tmax

Tmax

Tmax

Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Routing path: A-B-C

Sender

Relay

Receiver

Tmax

A

B

C

P

Z

Tmax

Tmax

Tmax

Tmax
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Reactive approach
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Routing path: A-B-C

Sender

Relay

Receiver

EE Link

P
Tmin
Z
Tmax

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

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Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link

Tmax

Time

A

B

C

EE Link
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Routing path: A-B-C

Sender

Relay

Receiver

P  Tmin

Tmax

P  Tmin

Tmin

P  Tmax

Tmin

P  Tmin

Tmin

Tmax

ACKs stand for agreements to EE links
no overhead with our solution
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Sender

Relay

Receiver

A

B

C

EE Link

EE Link

P Tmin

Z Tmax

P Tmin

Z Tmin

P Tmin

Z Tmin

P Tmax

Time

Time

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Long-term deployments of communicating mobile sensors for wildlife monitoring
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Sender  
 Relay  
 Receiver

Time

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Long-term deployments of communicating mobile sensors for wildlife monitoring
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Sender | EE Link | Relay | EE Link | Receiver

\[\text{P} \quad \text{Tmin} \quad \text{Z} \quad \text{Tmax}\]

\[\text{P} \quad \text{Tmin} \quad \text{Z} \quad \text{Tmin}\]

\[\text{P} \quad \text{Tmax} \quad \text{Z} \quad \text{Tmin}\]

A \quad \text{Time} \quad B \quad \text{Time} \quad C \quad \text{Time}
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement

Sender

Relay

Receiver

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BOX-MAC: Burst-Oriented X-MAC enhancement

Sender

Relay

Receiver

\[ P \quad T_{\text{min}} \]

\[ Z \quad T_{\text{max}} \]

\[ P \quad T_{\text{min}} \]

\[ Z \quad T_{\text{min}} \]

\[ P \quad T_{\text{max}} \]

\[ Z \quad T_{\text{min}} \]

\[ T_{\text{max}} \quad T_{\text{max}} \]

\[ T_{\text{min}} \quad T_{\text{min}} \quad T_{\text{min}} \quad T_{\text{min}} \]

\[ \text{Timeout} \]

\[ T_{\text{min}} \quad T_{\text{min}} \quad T_{\text{min}} \quad T_{\text{min}} \]

\[ \text{Timeout} \]

\[ T_{\text{max}} \quad T_{\text{max}} \]

\[ Time \]

\[ Time \]

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\[ Time \]
Reactive approach
BOX-MAC: Burst-Oriented X-MAC enhancement
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Reactive approach
Performance Evaluation

- Grid topology consisting of **100 sensors**
- Simulations performed with **WSNet**

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<td>BOX-MAC</td>
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| Data          | Event / time-driven
(1 s. during 10 s.) |
| Routing       | Random geographic                                      |
| Radio model   | Friis, throughput 15 ko/s                              |
| Energy model  | CC1100
(TX, RX, idle, init)                                   |
Reactive approach
Performance Evaluation: Overall energy consumption
Reactive approach
Performance Evaluation: Overall energy consumption

Total energy consumption (Joule)

LPL 100 ms
LPL 250 ms
LPL 500 ms

Receiving
Sending
Idle
Radio init

77%
Reactive approach
Performance Evaluation: Overall energy consumption

2.3%
Reactive approach
Performance Evaluation: Overall energy consumption

![Graph showing energy consumption over distance for LPL 100 ms, LPL 250 ms, and LPL 500 ms.](image)

**Energie totale consommée (Joules)**

- LPL 500 ms
  - 35% decrease in energy consumption compared to LPL 100 ms.
Reactive approach
Performance Evaluation: Overall energy consumption

![Graph showing energy consumption](image)

- LPL 100 ms
- LPL 250 ms
- LPL 500 ms

30% savings in energy consumption.
Reactive approach
Performance Evaluation: Overall energy consumption

Long-term deployments of communicating mobile sensors for wildlife monitoring
Reactive approach
Performance Evaluation: Delay to access the medium

![Graph showing the delay to access the medium for different MAC protocols and LPL values.](image-url)
Reactive approach

Performance Evaluation: Delay to access the medium

4 hops = 4 s.
Reactive approach
Performance Evaluation: Delay to access the medium

4 hops = 4 s.
Reactive approach
Performance Evaluation: Delay to access the medium

- X-MAC (LPL 500 ms)
- X-MAC (LPL 250 ms)
- X-MAC (LPL 100 ms)
- BOX-MAC

LPL 250 < BOX-MAC < LPL 100
Reactive approach: Conclusion

- **Configuring LPL** prior to deployments poorly efficient against dynamic situations
  - Auto-adaptation is required

- **BOX-MAC** skips LPL in 2 *values*: Preamble length and sampling period
  - **EE links**: Connectivity ensured between sensors
  - **Bonus**: No control message overhead
    - Energy-efficient
    - shortened delays and less losses due to improved resource utilization

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R. Kuntz, A. Gallais and T. Noel.
*From Versatility to Auto-Adaptation of the Medium Access Control in Wireless Sensor Networks.*
Conclusion

• Communicating biologgers require finer energy-efficient mechanisms

• Energy-efficiency: Radio usage -> MAC layer, LPL configuration
  • Reactive and proactive approaches
    • Induced traffic, routing information, application criteria
    • Strong needs for prior detailed information (e.g. expected traffic)

• Mobility
  • Several solutions already investigated
    • e.g. medium stealing, dynamic time slot allocation
  • Very much remains to be done
Future works

- **Experimentations before real deployment**
  - Multi-chip boards -> select the best on-the-shelf hardware components
  - Mobile robots and FIT equipex project -> emulating expected situations

- **Communication protocols**
  - Other L2 solutions
    - Receiver-Initiated MACs?
    - Standards (IEEE 802.15.4)
  - MAC/Routing interactions
    - Increased energy-efficiency
    - Fault tolerance (using passive nodes)
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Research and Development of Ad-hoc- and Wireless Sensor Networks for Environmental and Animal Behavioural Monitoring
Crossed Seasons France / South Africa
Turtle tracking

- For some climate change models
  - More and more jellyfishes while less and less fish and fishers
  - Problem: Hard to study jellyfishes
- MIRETTE project (2008-[]): Study impact of global change on jellyfish?
  - Through the monitoring of its main predator: the luth turtle
Reactive approach
Performance Evaluation: Overall energy consumption

![Graph showing message losses (%) vs. X-MAC with two bars: Losses at sink and Losses due to MAC layer. The graph indicates that losses increase with X-MAC, particularly for the Losses due to MAC layer. The y-axis represents message losses in percentage, and the x-axis represents X-MAC values from 0 to 500.]
Reactive approach

Performance Evaluation: Overall energy consumption

![Graph showing message losses due to MAC layer and loss at sink]
Reactive approach
Performance Evaluation: Overall energy consumption

![Bar chart showing message losses (%) across different X-MAC and BOX-MAC levels with losses at sink and losses due to MAC layer. The chart indicates that the message losses are below 5% in the X-MAC and BOX-MAC categories.]

- Losses at sink
- Losses due to MAC layer

- Reactive approach
- Performance Evaluation: Overall energy consumption
Reactive approach

Performance Evaluation: Overall energy consumption

- **BOX-MAC** more sensitive to hidden node problem:
  - Several short preambles may collide with a long one.
Reactive approach
Performance Evaluation: Overall energy consumption

- **BOX-MAC** more sensitive to **hidden node problem**:
  - Several short preambles may collide with a long one.

→ Need to reduce the **number of long preambles** that are used (51%)
Future Work

- Several optimizations
  - e.g. suggesting next hops to routing layer
- Large-scale experiment with SensLAB testbed

More information
www.senslab.info

SensLAB: Very Large Scale Open Wireless Sensor Network Testbed.
ICST TRIDENTCOM’11 - Shanghai, China, April 2011.

Using SensLAB as a First Class Scientific Tool for Large Scale Wireless Sensor Network Experiments.
IFIP Networking’11 - Valencia, Spain, May 2011.