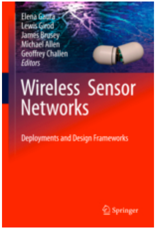
# Sensors KTN WiSIG
# Wireless Sensor Networks
# Designing for Deployment

James Brusey

Cogent Computing Applied Research Centre,
Coventry University

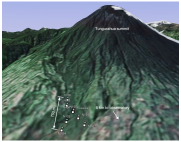
NEC, September 28, 2010

# This talk is based on



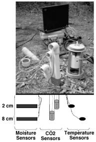

Elena Gaura, Lewis Girod, James Brusey, Michael Allen, and Geoffrey Werner Challen, editors. *Wireless Sensor Networks: Deployments and design frameworks.* Springer, 2010.

# and draws from seven seminal real-life WSN projects



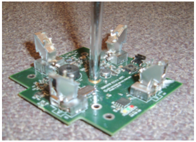

Lance (Werner Challen)

VoxNet (Allen)

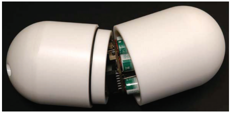



Vigilance (Schoellhammer)

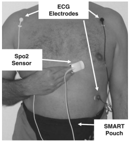
Cane Toad (Hu)



ExScal (Naik)



GlacsWeb (Martinez)




SMART (Curtis)

# About Cogent Computing

We have a great team ... that work on some cool projects like this one in Singapore ...

# About Cogent Computing

... we like to *engage* with the real world

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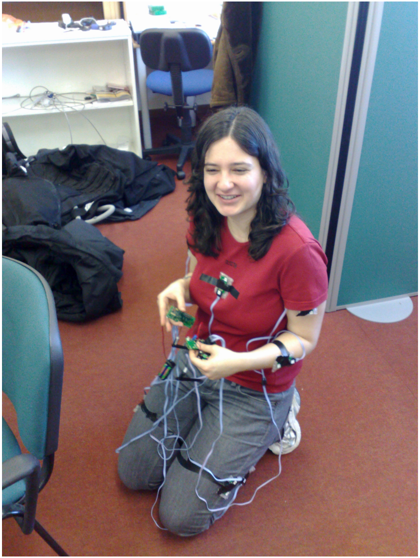

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... and to work with *real* systems

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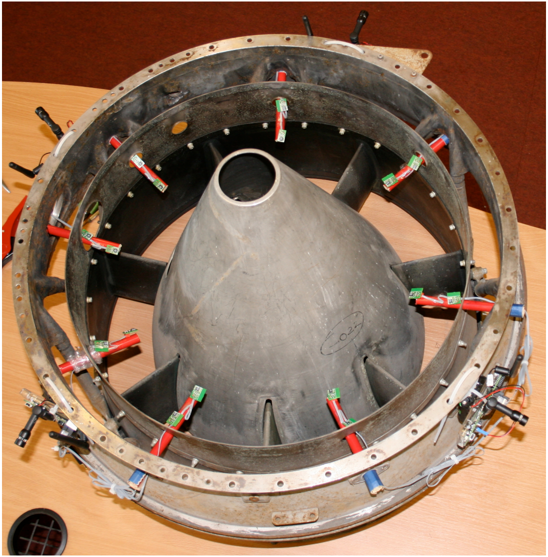

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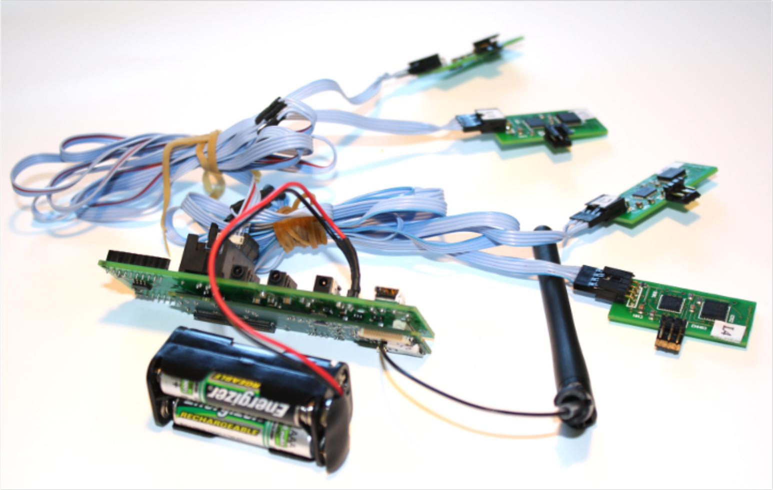


# Wireless Sensor Networks—Where are we?

- Better products are making their way to the market
- Some potential killer application for WSNs are emerging
- Progress is helped by frequent and sustained deployment of research products

... real-life WSN apps will prove they can really work in practice ...

... *reliable* mesh networking and *long-life, robust* WSN systems will help cut costs and make wireless sensing viable for more apps

# Environmental monitoring could be a killer WSN application

Why?

- Economies of scale
  - natural requirement for geographically distributed deployments with hundreds (millions?) of instances
- Political drive
  - global warming and climate change
  - U.S 2009 incentive package for smart energy monitoring
- End-user scale
  - nearly 70% of average household utility bill could be influenced by WSN-based energy monitoring

# So the future looks bright

- Likely consequences of killer apps:
  - drive down hardware *cost* and encourage emergence of *standards*

**Leading to**

...increased reliability systems with easy-to-use functionality

- Research / commercial opportunities:
  - simple low data rate sense-and-send solutions—rapid *productisation*
  - sophisticated high data rate systems—future *technology transfer*
  - long life systems—energy harvesting technologies & integration—*research / technological adoption*
  - user-driven information extraction strategies
  - cheaper, higher accuracy MEMS sensors/actuators/harvesters and on-chip packages
  - more reliable, scalable communications
  - web integration and integration into existing IP infrastructures

# … but it's not been an easy road …

- Experimental applications have been proposed to address virtually every aspect of society from scientific research to health care and industrial monitoring
- These have motivated WSN systems and theory development
- Yet few have passed successfully into the commercial domain
- Why? Due to challenges for which computer science (CS) researchers are poorly prepared—e.g.
  - managing deployment logistics
  - gaining deep understanding of the target domain
- Such challenges are just as critical to success as more traditional, CS ones

Non-CS challenges are equally critical impediments to defining, developing, deploying and commercialising WSN applications.

## … we must remember where we came from …

The Smart Dust vision assumed that:

- large deployment scale and redundancy would compensate for low quality measurements
- nodes would be extremely low-power and resource limited
- deployment would be easy (scatter them from the air)

Thus research focused on such things as:

- scalability
- software design for resource constrained nodes
- small footprint operating systems
- efficient multi-hop protocols

## … and what lessons real deployment taught

- The developer must be concerned with the fidelity of the data that the nodes are sensing, and must develop a means of fulfilling the application even when this data is simply not continuously available
- For high data rate applications, larger, more powerful platforms are needed
- To ensure low system cost, focus on design and architecture
- Harsh deployment environments can hinder even small scale, carefully planned deployments
- Working with the end user and complying with procedures and regulations in sensitive environments severely limits the WSN technological choices
- Acquiring enough accurate data to gain insight into the researched phenomena is often surprisingly difficult to achieve

# Lessons from Deployment Experience—Bangladesh Groundwater Monitoring, 2006

- Reported by Nithya Ramanathan, CENS/UCLA and Lorax Analytics
- Project run by MIT/CENS/Bangladesh University of Engineering and Technology
- A few facts
  - rice paddy deployment to help scientists evaluate the relationship between irrigation and arsenic contamination
  - motivation—risk of massive environmental poisoning (2 million cancer cases/year)
  - 50 sensors connected over a low-power wireless network to monitor a variety of soil chemistry and hydrological parameters in 9 different locations
  - 26,000 measurements collected at base station over 12 days.

# Lessons from Deployment Experience—Bangladesh Groundwater Monitoring, 2006

Original images used with permission of Charlie Harvey, MIT Civil and Environmental Engineering.

# Lessons from Deployment Experience—Bangladesh Groundwater Monitoring, 2006

Unexpected events

- base-station theft over night
  - solution: robust system design, delay-tolerant networking layer—91% of the data received with 50% active base-station

> Without a networking layer that cached data locally until it was successfully received at the base-station, our system would have missed the key diurnal activity

# Lessons from Deployment Experience—Bangladesh Groundwater Monitoring, 2006

- Identifying sensor faults in the field
  - phenomena is an unknown
  - faulty sensor vs unexpected data: throw away or fix up?

> … in one instance, a nitrate sensor reporting out-of-range values was miscalibrated, in another instance, it was reporting an accurate, but unexpectedly low, concentration

# Lessons from Deployment Experience—Bangladesh Groundwater Monitoring, 2006

- solution
  - time and effort in the field
  - detailed contextual analysis to to diagnose faults

> ... painstaking human actions and observations were necessary to interpret much of the data we collected in Bangladesh

# Lessons from Deployment Experience—Bangladesh Groundwater Monitoring, 2006

Desirable elements

- Real-time feedback on the system health—aids focus resources on data problems that require in-field validation and action
- Integrative design of the WSN as a human-machine system—maximise information return with limited burden on the user

> … the final system uses an automated model designed in advance but which *also* incorporates feedback from the user at run-time in order to adapt to new environments gracefully

# Essentials for successful deployments—Overview

1. What makes developing WSN systems different?
2. Choosing an appropriate design view and hardware base
3. Don't start off without ...
4. The design process
   - Prototyping and iteration
   - Key design space parameters
5. Lessons from the field
6. Concluding remarks

# What makes developing WSN systems different from other system projects?

- Application specifics have a large impact on eventual design,
- Designs tend to require optimisation across many layers, but this is not practical for prototyping
- Many applications are breaking new ground, compared with more mature areas such as IT, web services
- Significant impact from environmental complexity—compared with "virtual world" of IT and Web services
- Requires teams with an unusual blend of hardware and software expertise—specialised hardware—includes developing device drivers as well as applications

# Why do many project fail short of full blown in-situ deployment?

- time and budgetary restrictions limiting practical implementation and deployment;
- difficulty in translating the theoretical ideas into a deployable prototype;
- taking an inflexible approach to design and development that leaves little scope for dynamic adjustment;
- lack of certain, important experience in development teams (common examples are systems and hardware development experience and concrete application motivation and expertise);
- ignoring the deployment process and target environment during the design process; and
- expecting complete success in a first-time deployment rather than planning for iteration.

# Design Views

Three views on the WSN design space

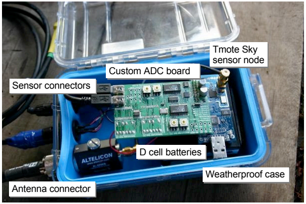
- application-centric
- network-centric
- device-centric

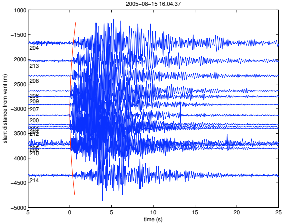
# Application Centric

## Definition

Application Centric View: The application's requirements dictate the software and hardware functionality that should be developed

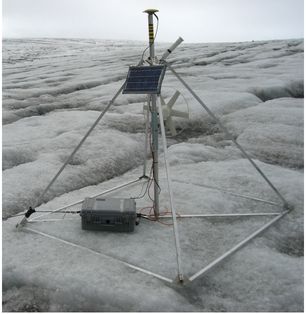
# Application Centric Examples

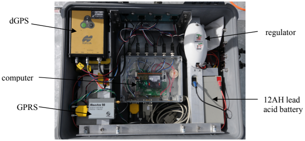


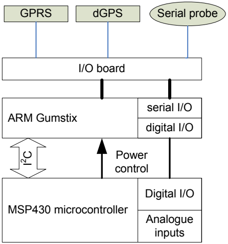

- iterative development and deployment of a Volcano monitoring project [WALJ$^{+}$06, WADHW08]
- led to development of LANCE architecture
- summary mechanism + "pull"
- relatively short-life <13 days on D-cells

# Application Centric Example





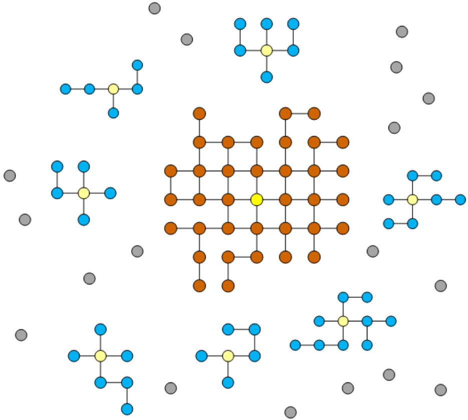

- development of a WSN to monitor glaciers [MHO09b, PDMJ06, MPE$^+$06]



# Network centric

## Definition

The *network-centric* view focuses on directly designing generic components for building sensor networks as a first principle, so that arbitrary applications at arbitrary scales can be accommodated



# Network centric examples

- MAC protocols such as SMAC, BMAC ([YHE02, PHC04]),
- multi-hop routing protocols (LEACH [HCB00], Directed Diffusion [IGE00]),
- localisation algorithms[NSB03, LR03],
- data collection (Collection Tree Protocol [GFJ+09]) and
- dissemination protocols (Trickle [LPCS04])

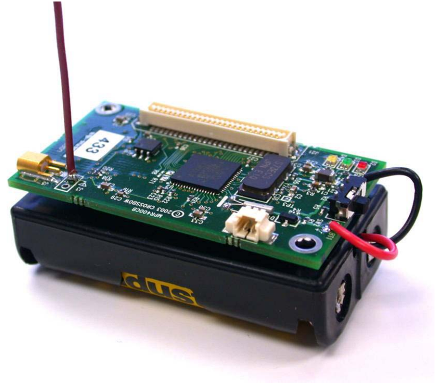
# Problems with Network Centric

- Network centric work forms the bulk of research from late 90s to early 00s
- Much of the work is simulation-based
- Proliferation of minor incremental improvements to protocols and algorithms based on simulation only
- Many common simulation assumptions (radio signal strength models, communication range / variability) have been disproved empirically [WKW+05, LLS06]
- If algorithms and protocols are to be used successfully in practise, they must be tested under realistic conditions (or at least with more realistic simulation) (e.g. as opposed to, say, LEACH – tested only in Matlab)

# Device Centric

## Definition

The *device-centric* view builds WSN design choices around an existing hardware platform, meaning the platform dictates the extent to which the application goals can be met as well as the type of protocols which can be implemented on the device



# Device centric examples

- Several efforts using the Mica2 for acoustic ranging and self-localisation have had to work around the limited platform capabilities [Whi02, WC06, SBM+04, ZYSS07, KMS+05]
- Highly accurate range estimation solutions using marginally more processing power or memory [GE01, PSZ+07, LLP06]
- The platform constraint has lead to a novel set of self-localisation techniques using interferometry [MVD+05, KLK07, KSB+07]

# 'centric summary

- The device centric view forces optimisation before application is realised
- The network centric view produces generic solutions without understanding the difference between real applications
- The overriding priority for the application centric view are the real-world requirements
  - test of system is a realistic one, without simulation assumptions
  - tends to produce simpler, more robust designs
  - considers time/budget, environmental, hardware availability, processor power constraints along with unforeseen system failures

# Choosing the hardware base

- Wide choice with varying capability / price / footprint / genericity / maturity
  - End-to-end WSN solutions
  - Generic/OEM solutions
  - Research platforms

# End-to-end WSN solutions

| Company | Wireless Technology | Application driver | DevKit? |
|---|---|---|---|
| ArchRock | 6LowPan (IPv6) | Intelligent energy analytics | Y |
| Sentilla | 802.15.4 | Intelligent energy analytics | Y |
| Grape Networks | Custom/433MHz | Microclimate monitoring | N |
| PPM Technology | ZigBee | Indoor air-quality | N |
| MicroStrain | 802.15.4/FDMA | High data rate sensing (up to 4KHz) | N |
| Soil Instruments | 2.4GHz | Structural monitoring (using sensors in SI range) | N |
| SynapSense | 802.15.4 | Data centre monitoring / cooling control | N |
| OnSet | 802.15.4 | Temperature and Soil moisture monitoring | N |

End-to-end, application-specific WSN solutions, showing the company, wireless technology and application driver for the products

# End-to-end WSN solutions

- Most solutions transmit in the 2.4GHz ISM band (only Grape Networks' solution does not), although they use different solutions.
- Many are custom based protocols compatible with 802.15.4 MAC and PHY standards, whilst others employ high level standards for communication (which sit on top of 802.15.4), such as ZigBee, 6LowPan or WirelessHART.

# Generic/OEM WSN solutions

| Company | Wireless Technology | Application driver |
|---|---|---|
| Dust Networks | WirelessHart | Multiple industry (WirelessHART) |
| Sensinode | 6LowPan (IPv6) | Multiple industry (MBUS focus) |
| Millenial Net | 2.4GHz | Multiple industry |
| Jennic | ZigBee PRO | Multiple industry/home |
| Ember | ZigBee | Multiple industry |
| TI/Labview | 802.15.4 | Embedded control systems |
| EnOcean | 868MHz/315MHz | Multiple industry/home (energy harvesting) |

OEM WSN solutions, showing the company, wireless technology and application driver for the products.

# Research platforms

| Platform | MCU/CPU | Comms | Node cost | Target apps |
|---|---|---|---|---|
| AmbioMote | MCU | custom 2.4GHz | $200 | SHM type |
| Arduino | MCU/8-bit | ZigBee or Bluetooth | €45-95 | hobby/gadget |
| BTnode | MCU/8-bit | 800MHz and Bluetooth | €165 | research |
| Cricket | MCU/8-bit | 868MHz | $195 | localisation |
| Iris | MCU/8-bit | 802.15.4 | $115 | research |
| MicaZ | MCU/8-bit | 802.15.4 | $99 | research |
| Mica2 | MCU/8-bit | 433 or 868MHz | $99-125 | research |
| SquidBee | MCU/8-bit | ZigBee | €130-150 | hobby/gadget |
| TNode/KeyNode | MCU/8-bit | 315 to 868MHz | €65-99 | research |
| Mulle | MCU/16-bit | 802.15.4 or Bluetooth | €139-149 | research |
| Pioneer | MCU/16-bit | 802.15.4 | $499 | industrial |
| Shimmer | MCU/16-bit | 802.15.4 and Bluetooth | €199 | medical monitoring |
| TelosB/TMote | MCU/16-bit | 802.15.4 | $99 | research |
| Gumstix Verdex/Overo | CPU/32-bit | Bluetooth | $129-219 | hobby/gadget |
| IMote2 | CPU/32-bit | 802.15.4 | $299 | research |
| SunSPOT | CPU/32-bit | 802.15.4 | $750 / 2 | hobby/gadget |

# Don't start off without ...

- ... awareness that
  - push-pull tensions exist between a variety of facets of WSN design and development
  - the tenets of the Smart Dust often contrast with the requirements of real-life clearly defined applications

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  2. Involve end-users throughout the development cycle, demonstrating end-to-end results at intermediate stages, and
  3. Maintain a clear motivation for development, ideally based on a realistic business model.

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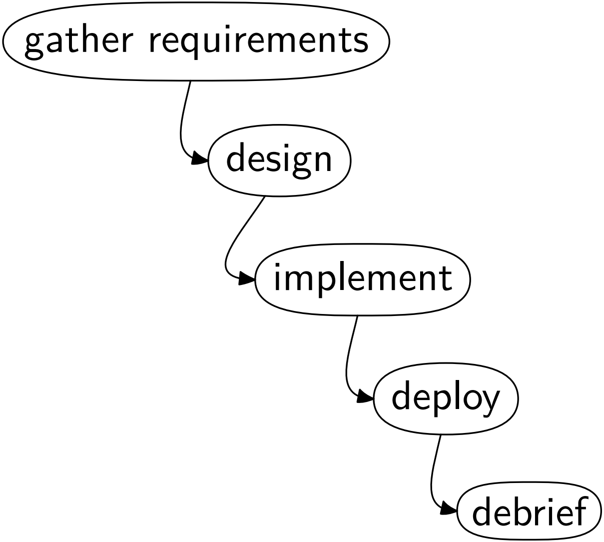
- ... considering an *application centric* approach to system design

# The WSN Development Life Cycle



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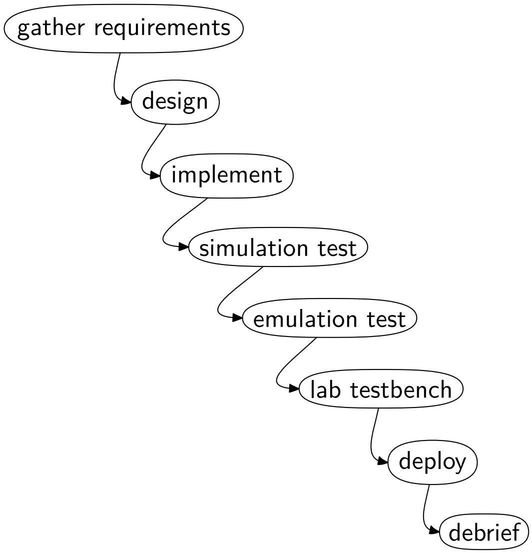

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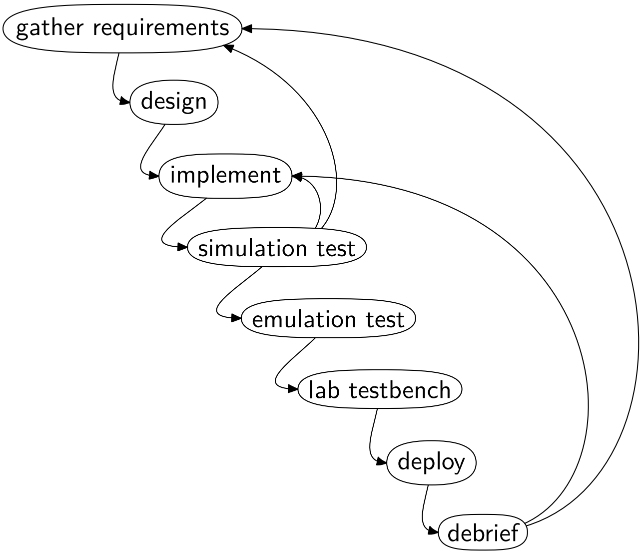

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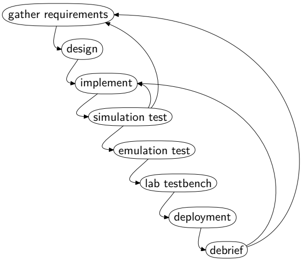



- The ExScal [DGA+05] project made use of this staged testing approach
  - Some problems were not discovered in emulation and only found in the lab test bench.
  - Typical problems: memory leaks, protected memory exceptions
- Thus:
  - Stage deployment as well if possible.
  - Feedback unexpected problems into the emulation / simulation

# Why do we need so many testing stages?

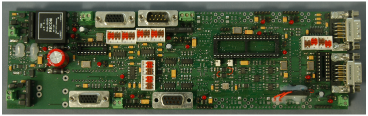
- The piece of lab equipment that you leave behind (multi-meter, soldering iron, etc) will be the one that you need
- Devices and software that were working fine in the lab will be found to malfunction in the field (where it is harder and more costly to diagnose) (GlacsWeb [MHO09a])
- What's going to happen when things go wrong?
  - You turn everything on but nothing happens
  - (I'm alive LEDs, config status LEDs, etc)
- Services such as time synchronisation are fundamental
- Write extensive logs—these will help diagnose problems that you didn't anticipate.

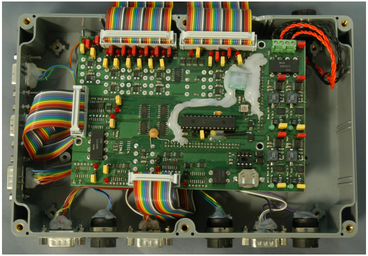
# Iterative Deployment—Cane Toad Monitoring Example

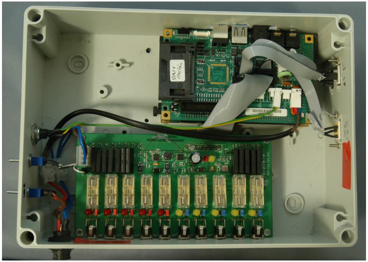
| Versions | Pilot | Second | Final [1] |
|---|---|---|---|
| **Goal** | Automated acoustic census of amphibian populations | Miniaturisation | Miniaturisation |
| **Challenges** | Remote, hostile environment, significant external noise | Data reduction | Data reduction |
| **Contributions** | Weather-proof operation, robust classification algorithm | Signal capture on motes, hybrid architecture | Lightweight classification |

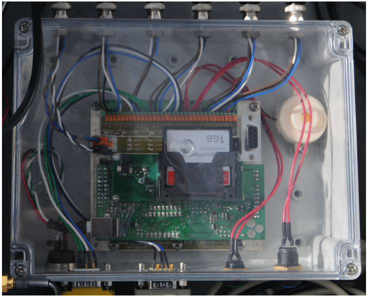
[1] Reproduced from [GGB$^+$10, ch.7]

# Iterative Deployment—Glacier Monitoring









# Iterative Deployment

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Although lab testing was useful in the early stages of development, it was the deployment at remote sites that forced us to think about what tools and features were still lacking in Hyper's design. (Schoellhammer)

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Starting with more powerful computing platforms allowed the development of robust detection and classification systems that were immediately useful to ...[the domain scientists]..., and then allowed us to focus on how to migrate such functionality into cost-effective low-power computing platforms. (W. Hu)

# The design space—Key parameters

- Sampling rate and data rate
- Cost
- Network size and density
- Deployment environment
- Deployment duration
- Target audience and interaction model

# Sampling rate and data rate

Some applications have either (or both)

- High sample rate (e.g. accels, audio, video)
- Low event rate (e.g. door opening, earthquake)

How to deal with it

- *Event detection*, where transmissions are only made when something interesting occurs (e.g. VoxNet)
- *Data compression*, where the data is compressed before transmitting (e.g., Cane Toad Monitoring); and
- *Filtering*, where data is reduced to a summary before transmitting (e.g., Lance).

# Cost

- Consider the whole lifetime costs including purchase, development, deployment, and maintenance
- Design choices may change where costs are incurred in the lifecycle
  - COTS mean higher upfront cost
    - but perhaps less development / deployment / maintenance
  - Might avoid COTS if number of nodes is large (e.g. Cane Toad)
- Deployment costs are often high (e.g. deploying on volcano or glacier)
  - Avoid by spending more time on testing and developing deployment tools
- Ultimately weigh the costs against the value of the data gathered

# Network size and density

- Large dense networks allow for *spatial redundancy*
  - also allow low-power radio and multi-hop protocols
- Sensor range is a key related factor
  - higher power, long-range sensors can help reduce the need for too great a density of nodes
- Network range is another key related factor
  - some networks (e.g. VoxNet) require each node to see two neighbours to maintain highly accurate clock synch.

# Deployment environment

- Wireless communication is heavily affected by environmental factors at the deployment site
  - e.g. glacier deployment (transmitting through ice, seasonal changes)
  - urban environment (competing with other WiFi)
- Installation is critical
  - can the node be installed?
  - will it be stolen?
- Packaging is often critical in ensuring that electronic components are kept dry and within operating temperature ranges
  - maintenance and debugging should be considered here

# Deployment duration

- Not all systems need to be deployed for months at a time.
  - short lived deployments can operate continuously and sample data at $>$10kHz
- For long-lived systems,
  - consider priority schemes such as Lance
  - reduce the sampling rate
  - aggregate transmissions

# Target audience and interaction model

- Many deployed systems are aimed at use by domain scientists
  - focus tends to be on data quality rather than usability
- As WSN hits the mainstream, better visualisation / interaction will be needed of
  - the data being gathered
  - the state and functioning of the system

# Lessons from the field—Development

- Try not to re-invent the wheel—use existing software and hardware where possible
- Simulate first
- Build in support, to ease the deployment process
- Instrument the system with logging for debugging and optimising system performance

# Lessons from the field—Deployment

- Allocate adequate time for deployment and actual system operation
- Prepare an equipment checklist and include spares
- Focus on data quality

# Lessons from the field—Deployment Experience

- Optimise last and only optimise as needed
- Let the application requirements drive the iteration process

# Concluding remarks

1. No WSN development team is complete without the application domain specialist as the first user of the technology (of course before the technology becomes pervasive enough to enable pervasive use...)
2. No WSN application should be considered resolved without repeated, in-situ evaluation
3. The end-user has the last word on requirements and is only through realistic, informed and revised requirements that the work progresses—hence iterative design cycles are needed
4. The experimental scientist needs to learn early that not all which has been developed theoretically will work, or at least it will not at the level of performance predicted by the simulation
5. The wireless technologies are still flaky, rarely work out of the box and the deployment environment heavily affects performance
6. Integration is not merely the last thing to be done but must be a serious concern from the word GO in the development cycle

# That's your lot!

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