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Long-term Wireless Sensor Networks

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Autonomous Systems Laboratory

CSIRO

ICT Centre Research Laboratories

- **Autonomous Systems** – ICT for the physical world
- **Information Engineering -** Flexible information solutions to solve unpredicted problems
- **Networking Technologies** – Connecting the future
- **Wireless Technologies** – Creating a wireless world

Autonomous Systems Lab - ICT Centre

- Based in Brisbane and Sydney
- Focus areas of:
    - Robotics
    - Sensor Networks
    - Adaptive Systems

Overview

- Background of CSIRO’s work in WSN
- Current application drivers
- Adaptive energy management
- Audio/video processing in WSN

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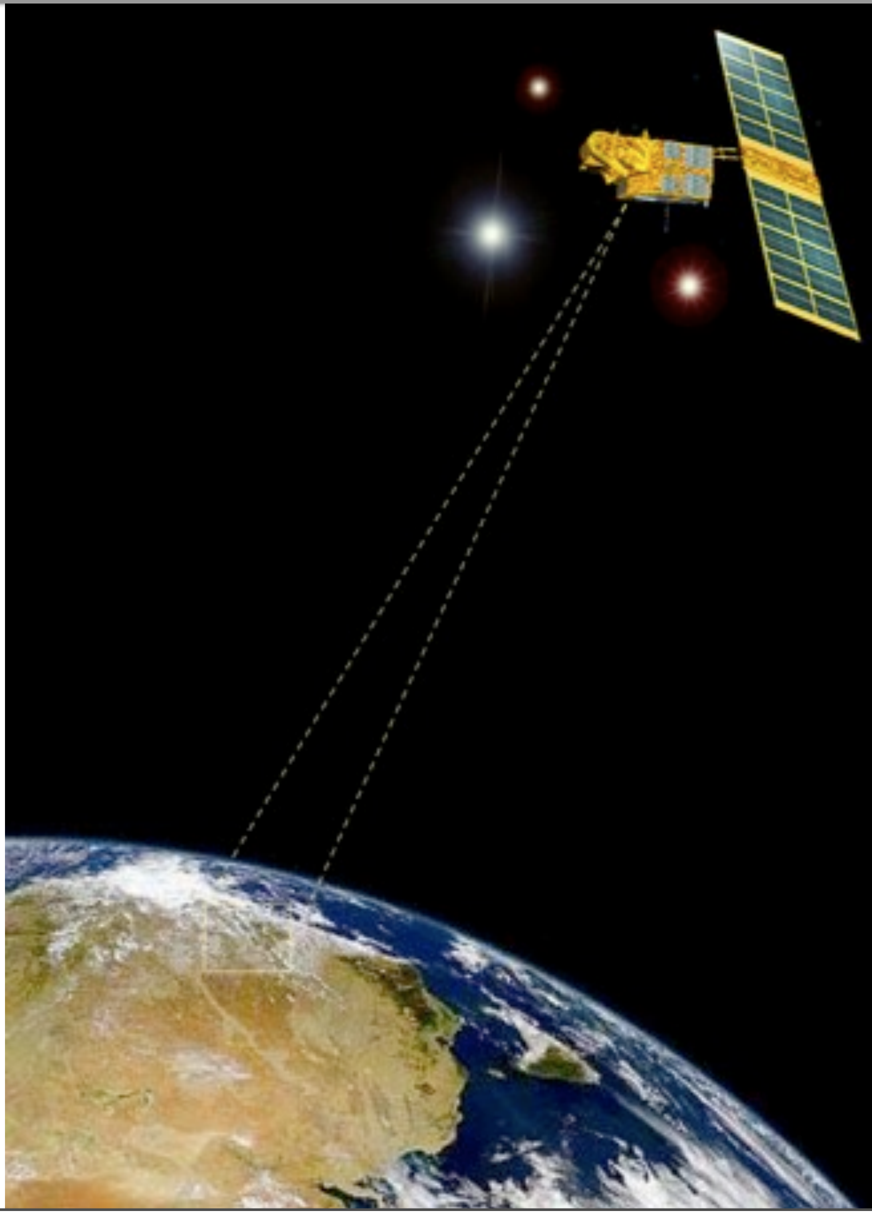
Watching our World

- **Measurement** is a key to a better understanding of the environment around us
- Satellite imagery has brought about huge advances in understanding our planet
- Limited in the resolution of information and what we can infer
- **Sensor networks** have the potential to change the way we measure.

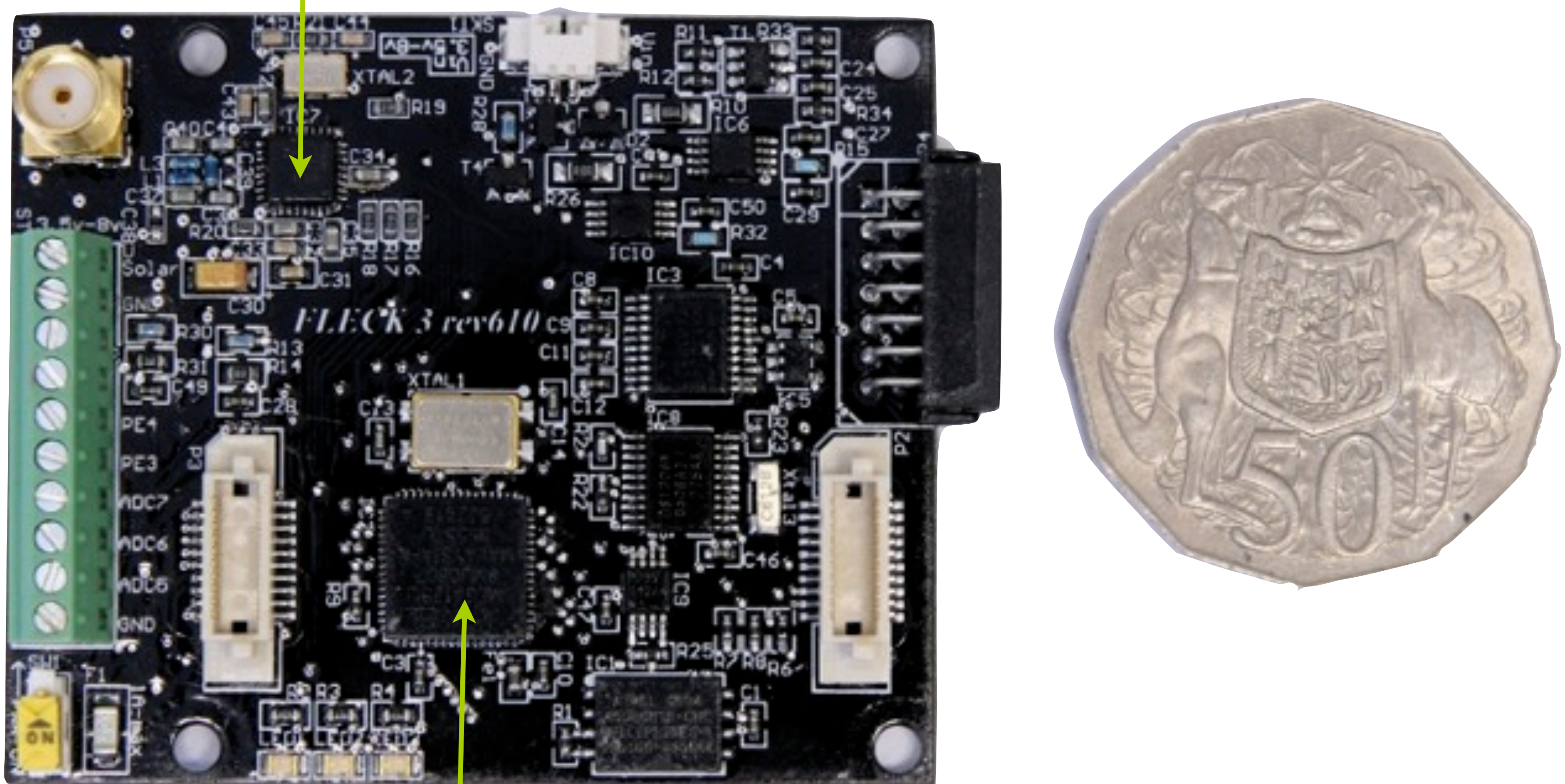


Test-bed at CSIRO (QCAT)

- Initial outdoor testbed, 2005
- 433 MHz Radios
- Sensors:
  - Temperature
  - Soil Moisture
  - Humidity
  - Water Quality

Hardware Platform - Fleck

Nordic Radio (915MHz)

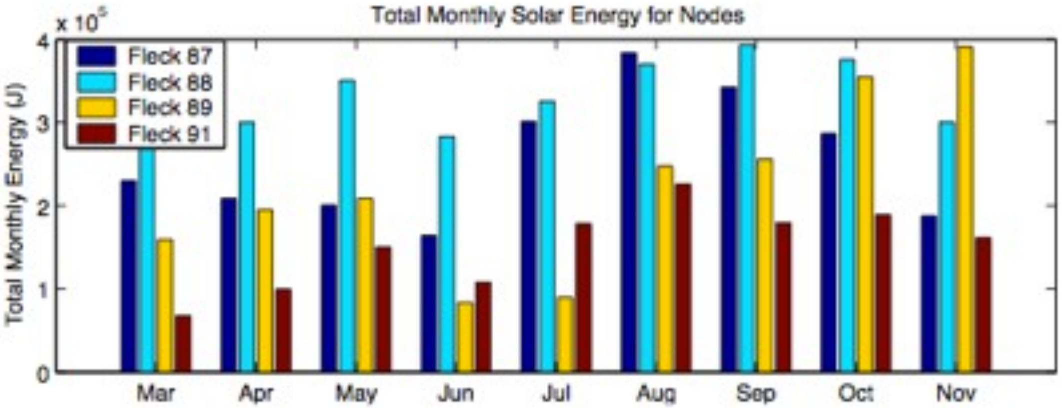


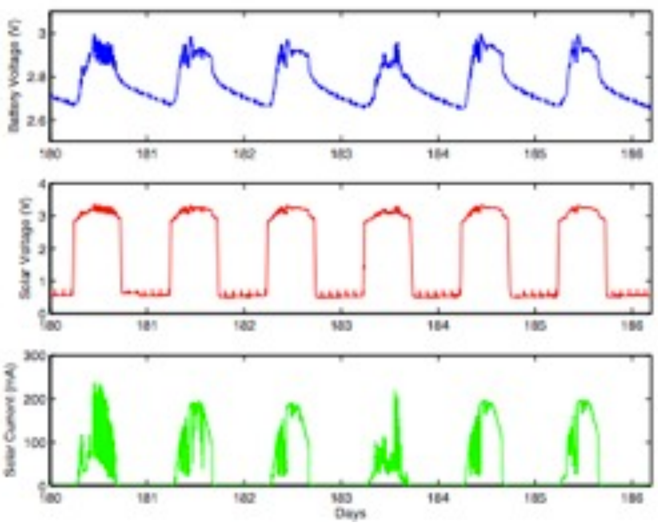
Atmega 1281 Processor (8KB RAM)

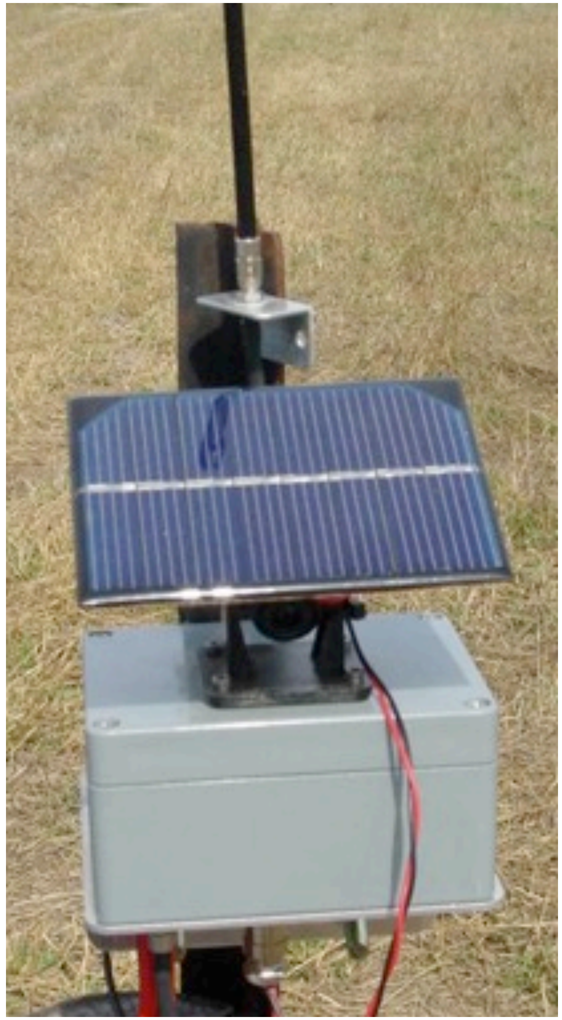
Sensor boards

- Light, Temp
- Water Quality: pH, Redox, Temp, Conductivity
- Soil Moisture
- Motion: GPS, Accel,Gyro, Magnetometer
- Strain Gauges
- DSP: Audio, Video

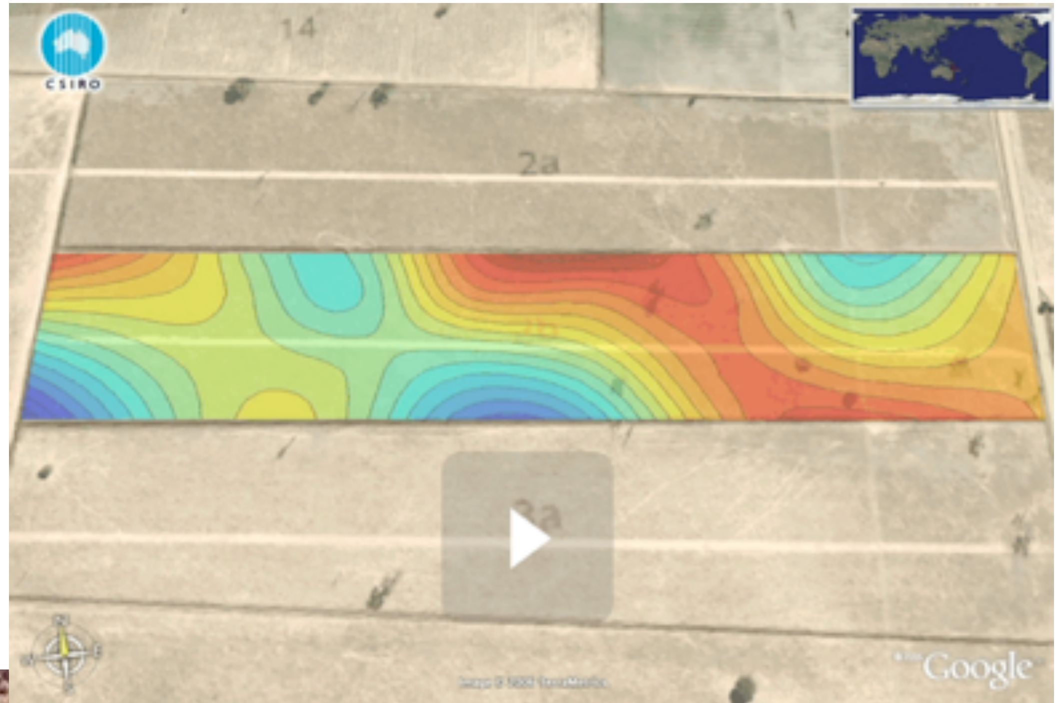
Solar Energy



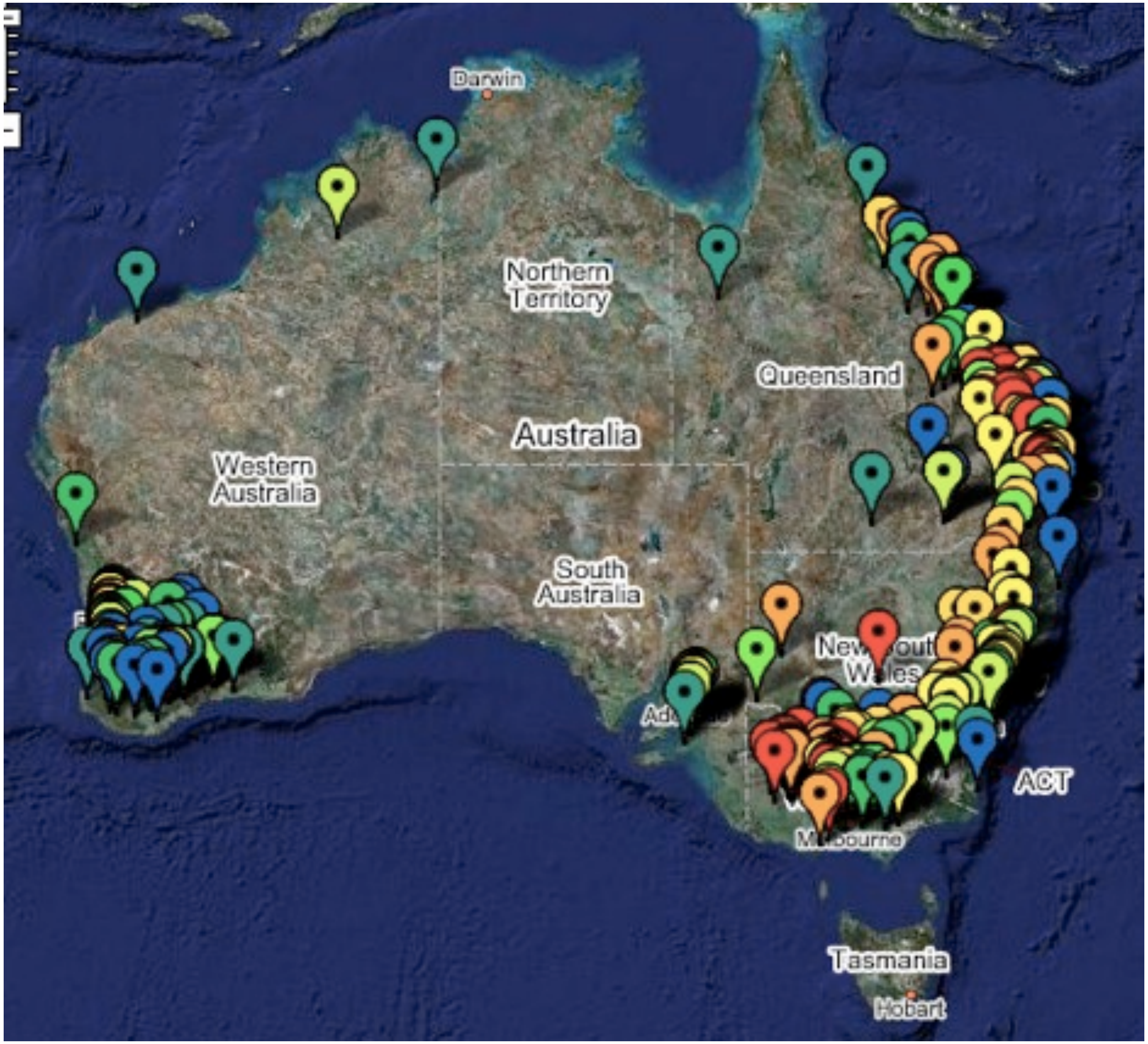




Farm testbed - Belmont QLD



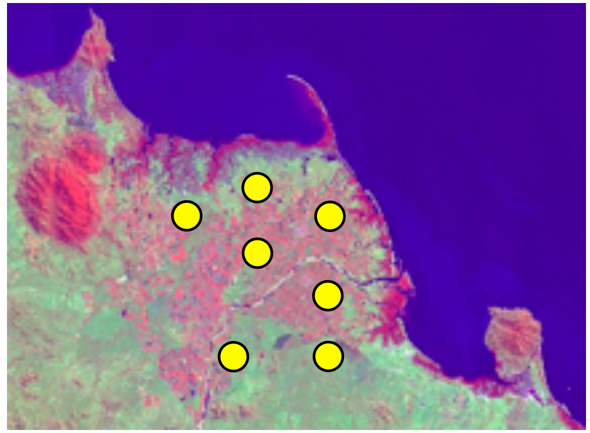
Water Resources Observation Network

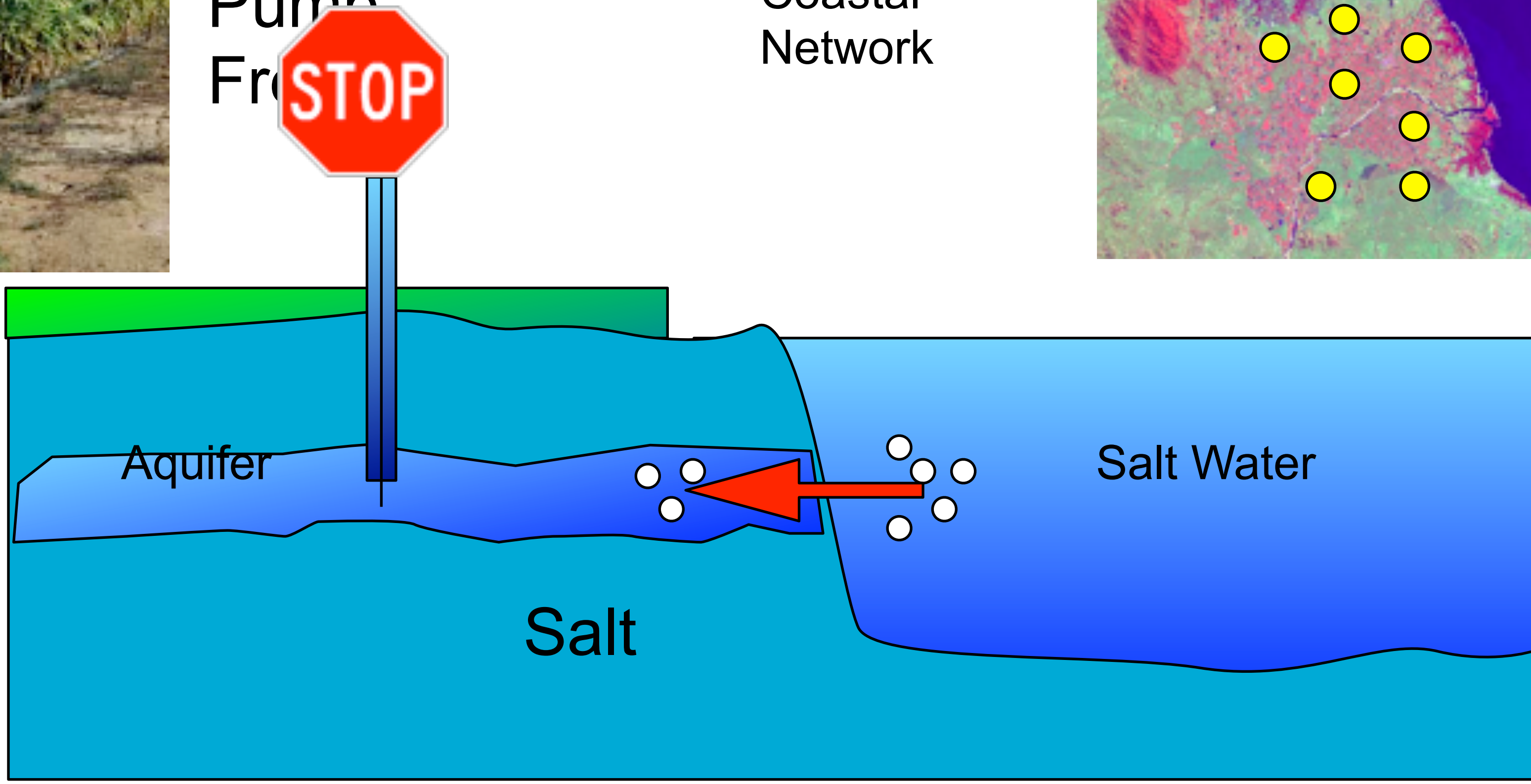


Burdekin Delta

Detect Salinity &
Stop Pumping

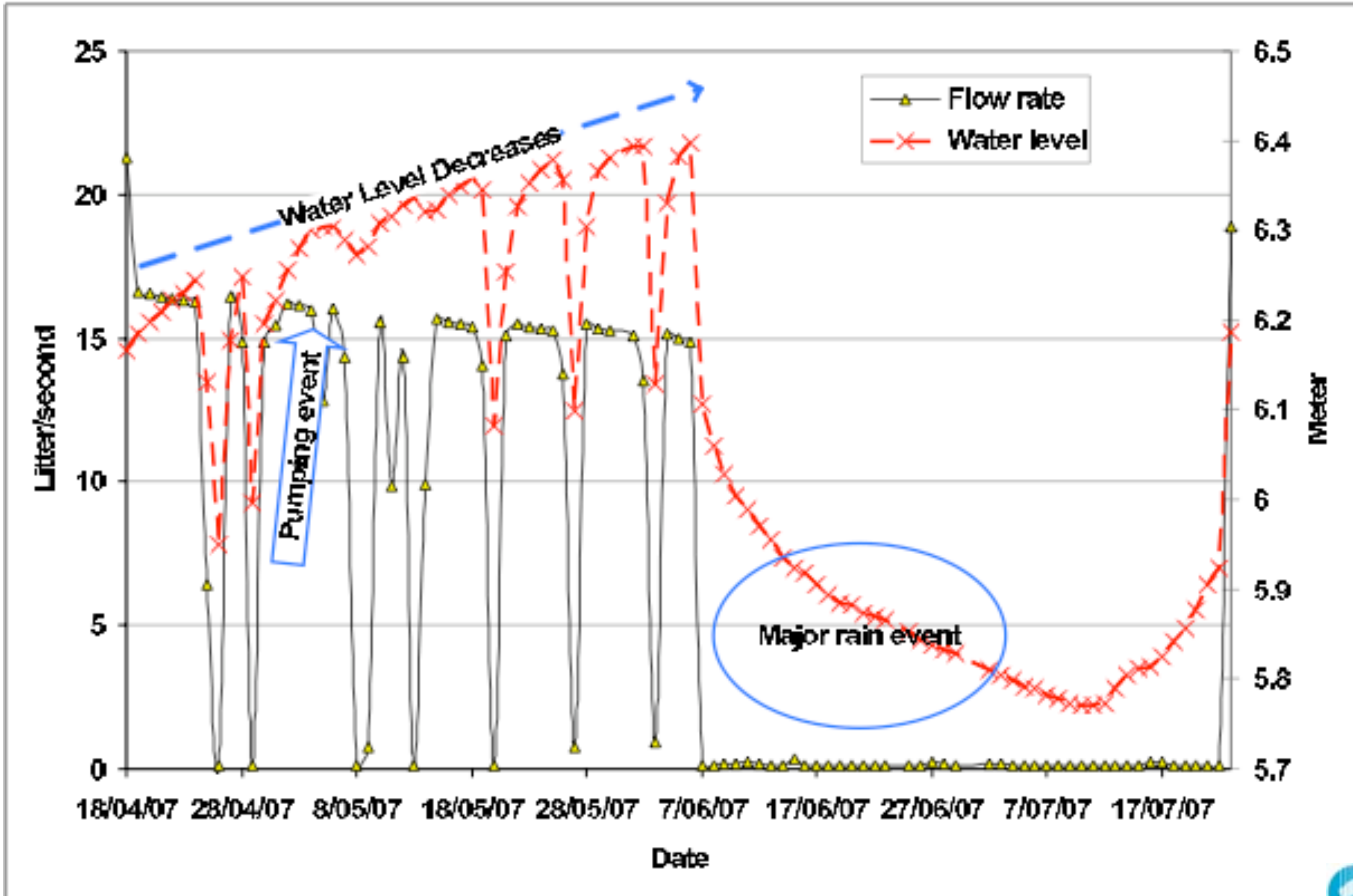
Coastal
Network





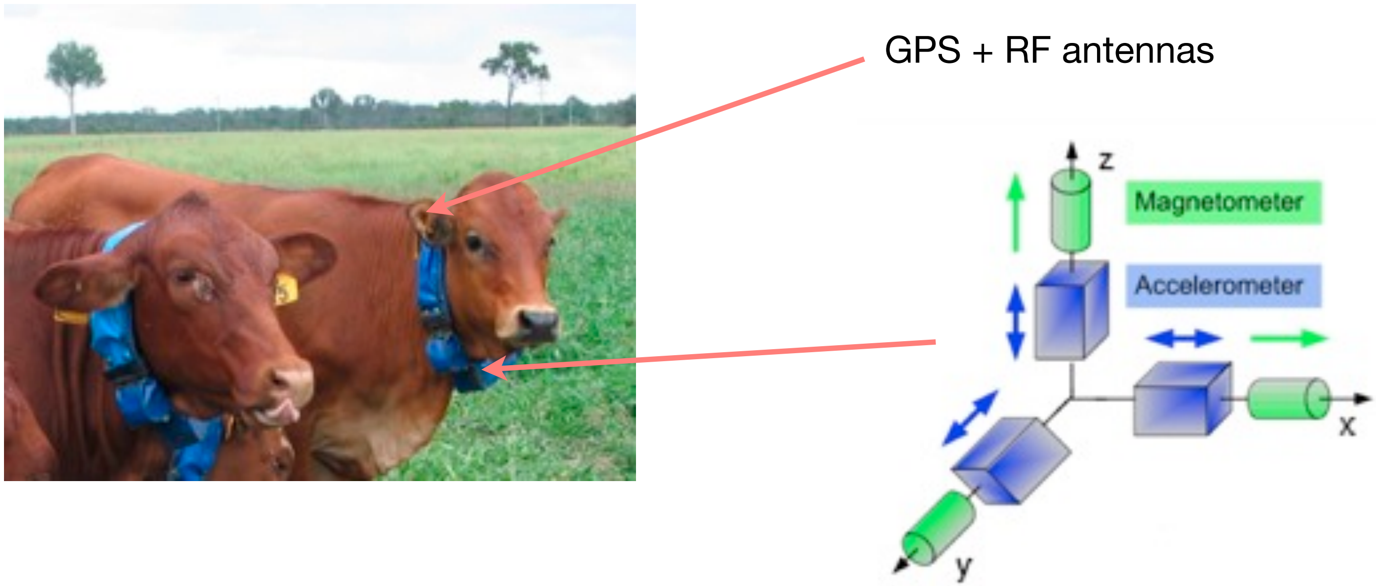
Burdekin Delta

Water table level

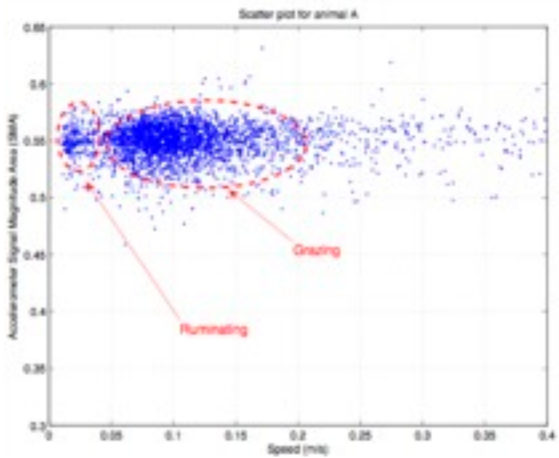


Cattle sensor networks

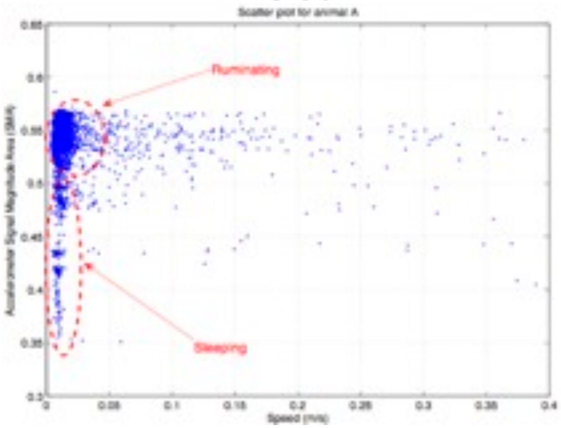
- Key driver has been current research into cattle behaviour
  - Partner: CSIRO Livestock Industries
- Domain problems:
  - Herd behaviour, grazing patterns, better understanding social interaction



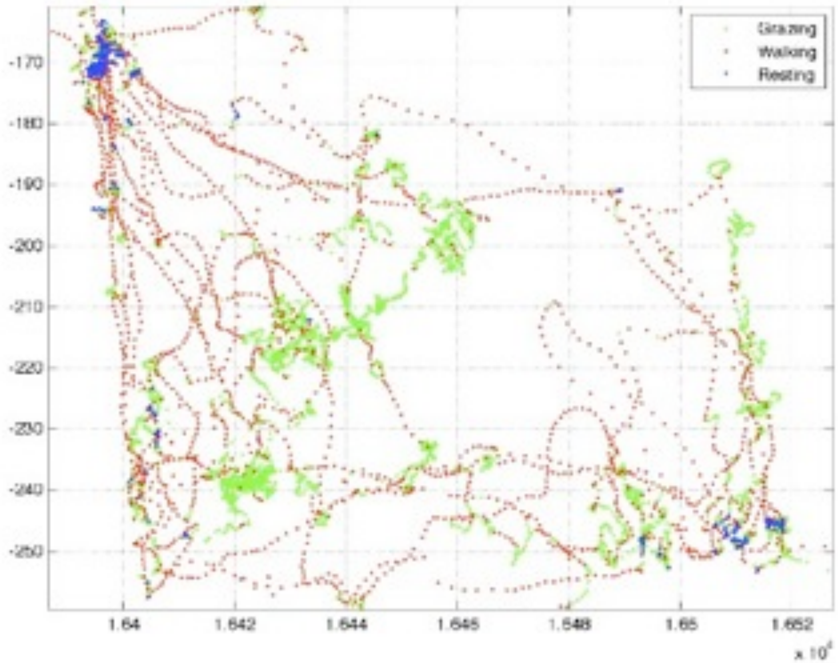
Mobile nodes: Machine learning



Day



Night

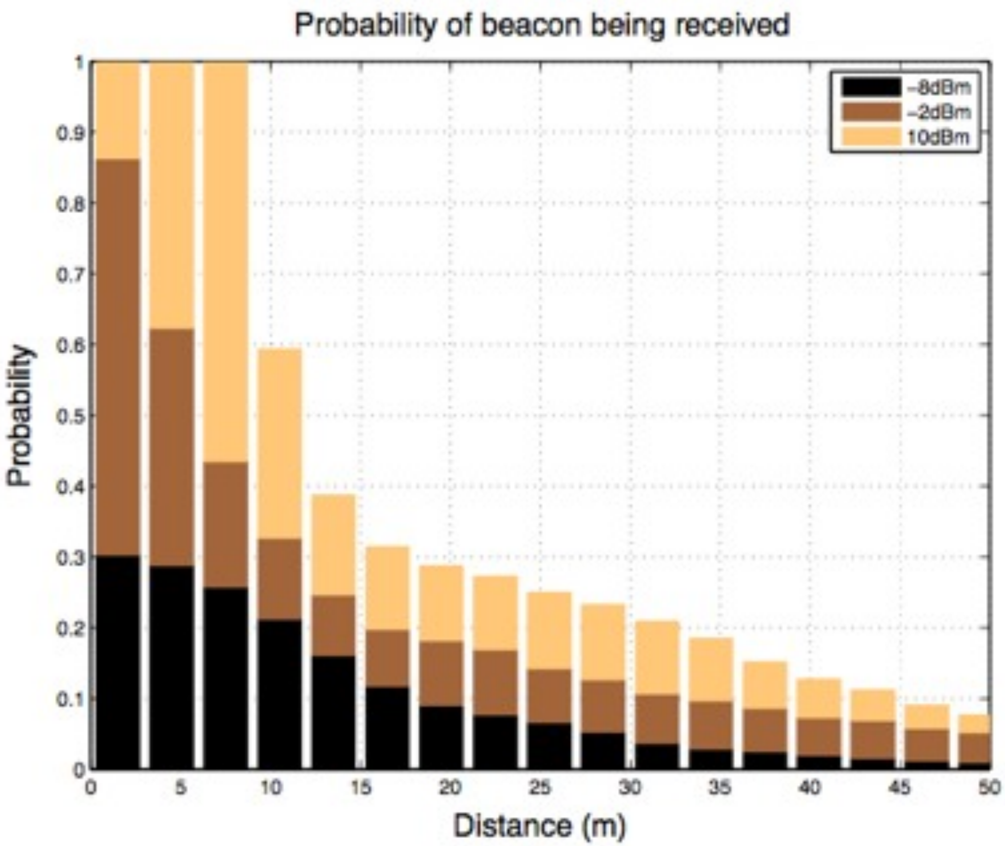


Summarised information can now hop onto surround sensor network and come back to base.

Heli-mustering

Heli-Mustering

- Animal-heli connectivity was then determined to show the potential for radio-proximity bases mustering



$$P(\varphi_{rx}|d_1 < \kappa \leq d_2) = \frac{P(\varphi_{rx}) \int_{d_1}^{d_2} p(\kappa|\varphi_{rx}) d\kappa}{\int_{d_1}^{d_2} p(\kappa) d\kappa}$$

Virtual Fencing: Environmental protection

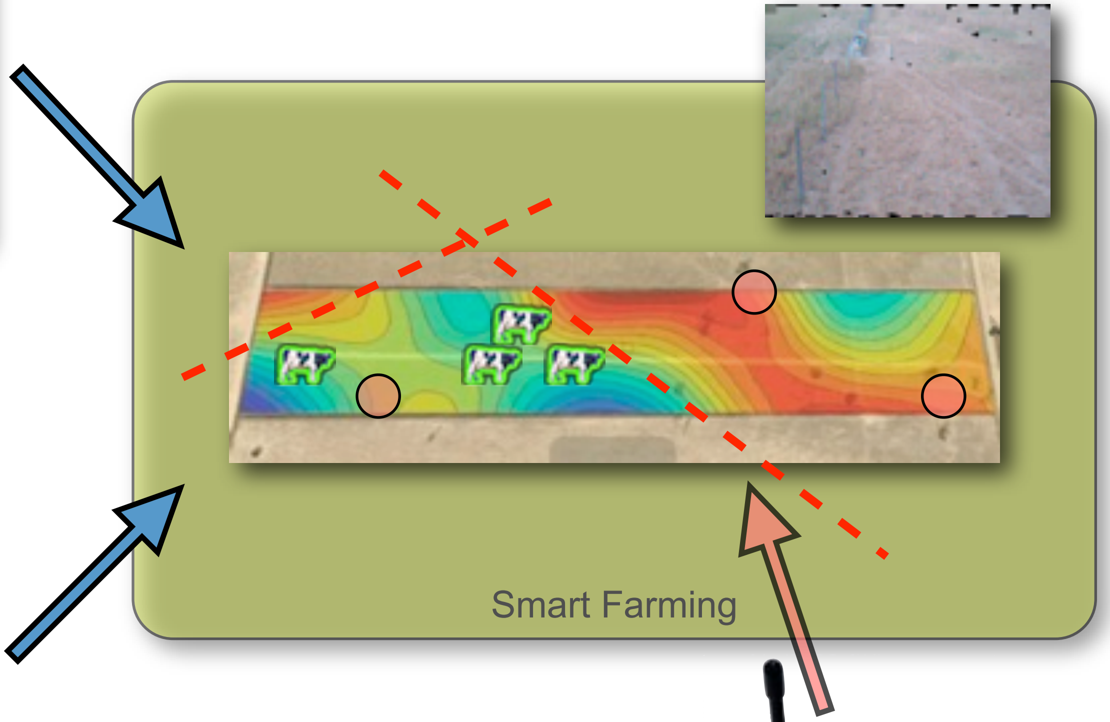
QuickTime™ and a decompressor are needed to see this picture.

Example area: Sustainable Agriculture

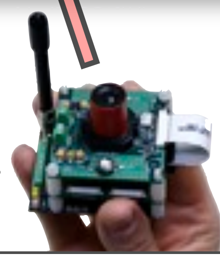
- Increased focus on in-network decision making provides a means to bring together many technologies in agriculture

Virtual Fencing

Remote Sensing + WSN



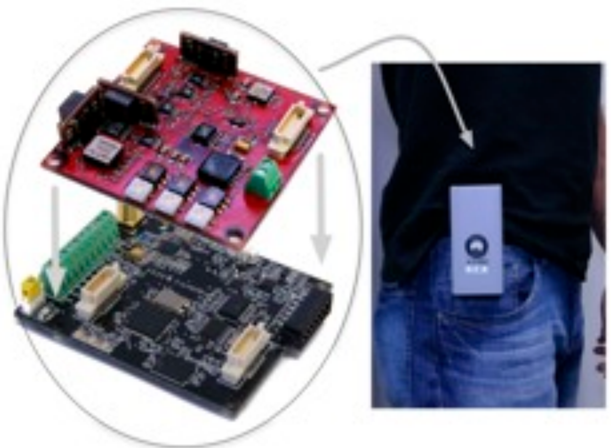
Miniature Cameras



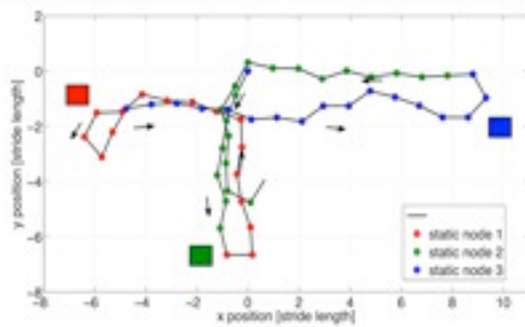
Indoor Localisation - Health Domain

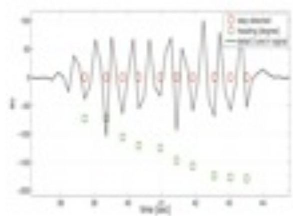
- Mobile device
  - 3-axis magnetometer
  - 3-axis gyroscope
  - 3-axis accelerometer
- Mobility model
  - **Heading:** Magnetometer + Gyroscope (Complementary Filter)
  - **Stride:** Accelerometer used for step detection / stride length

Mobility model



Mobility model

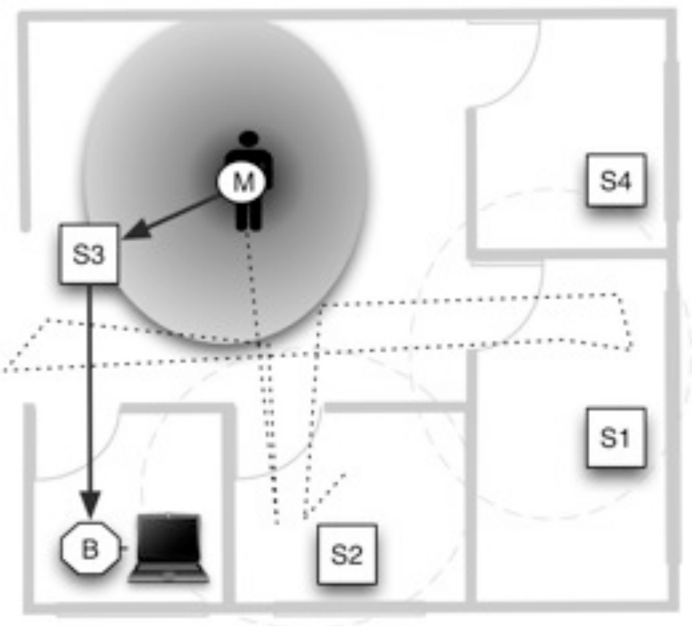




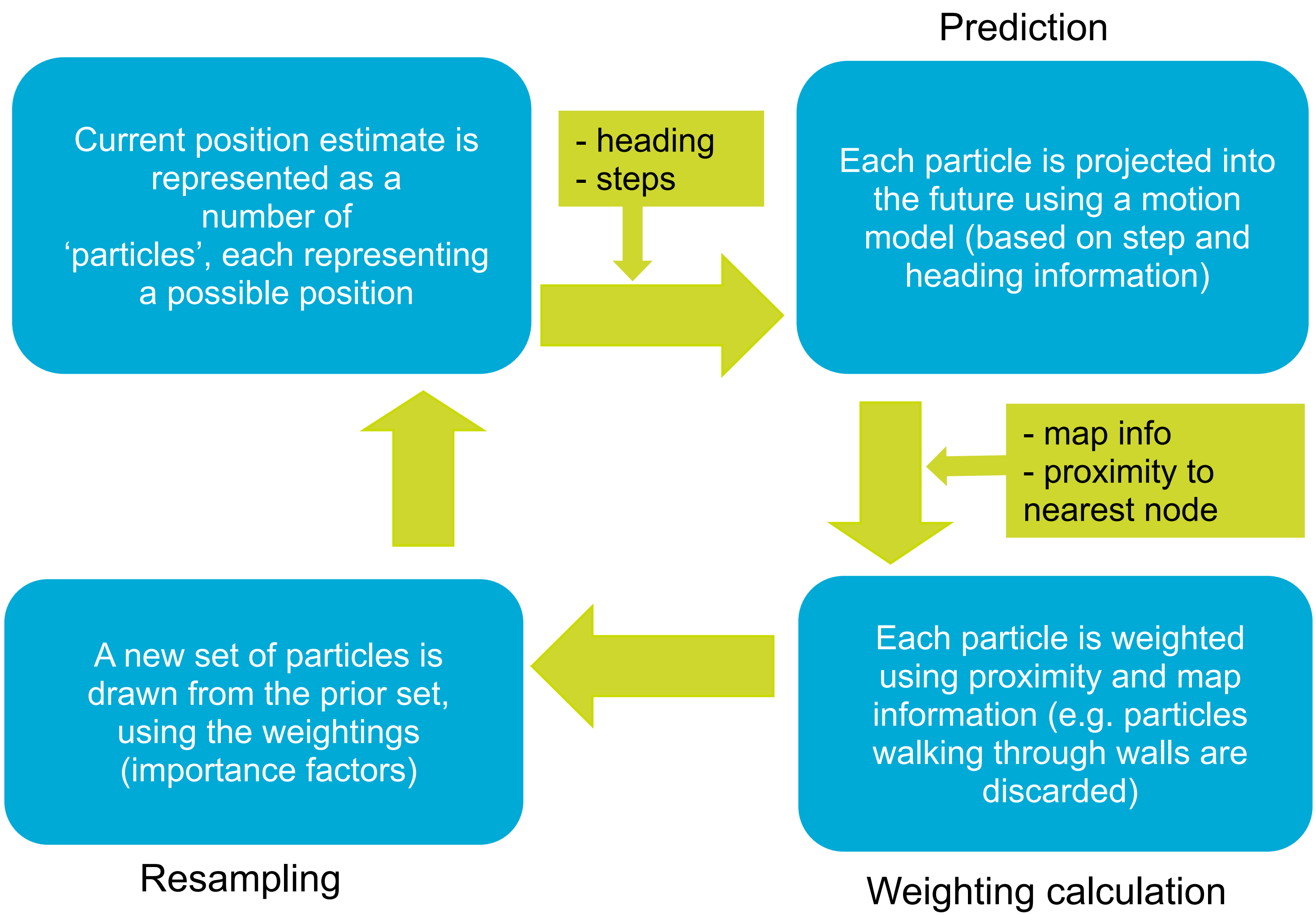
Indoor Localisation - Health Domain

- Static sensor network
  - Connectivity information from static nodes with known locations can update position estimates
  - Provides the infrastructure to relay real-time data back to base (single-hop or multi-hop)

Static sensor network



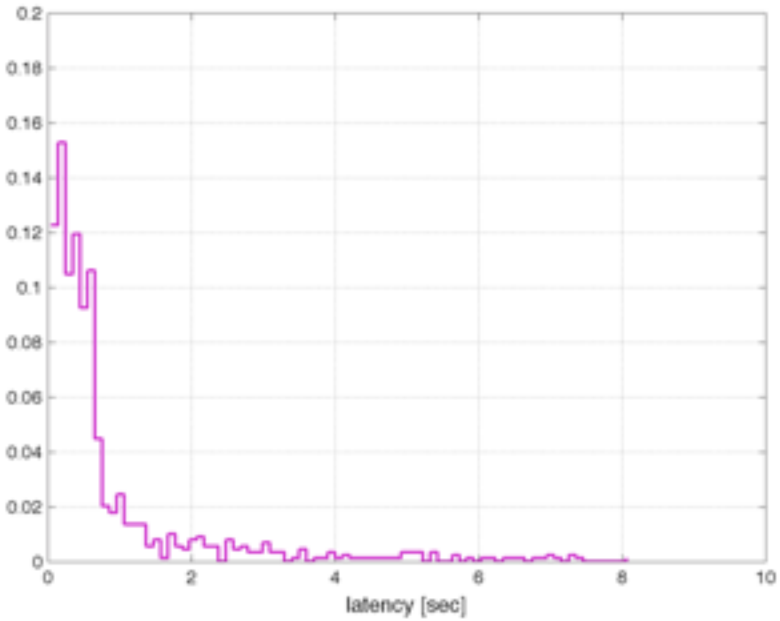
Monte Carlo Based Estimation - Particle Filter

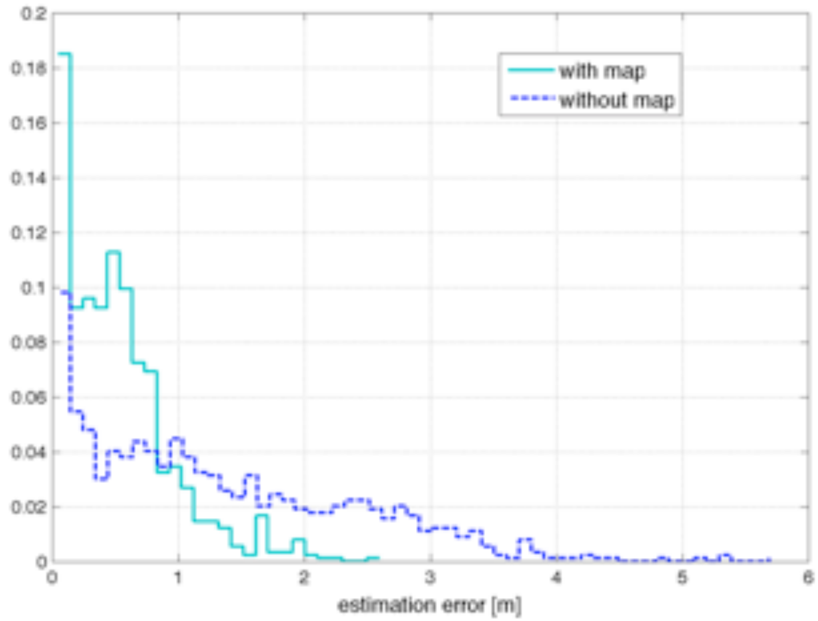


Indoor Localisation - Health Domain

Experimental Results

- Latency and estimation error



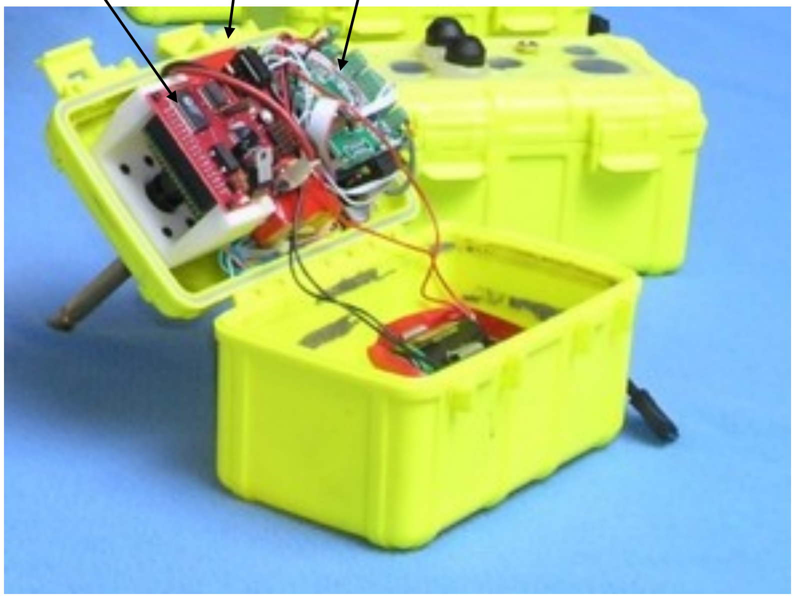


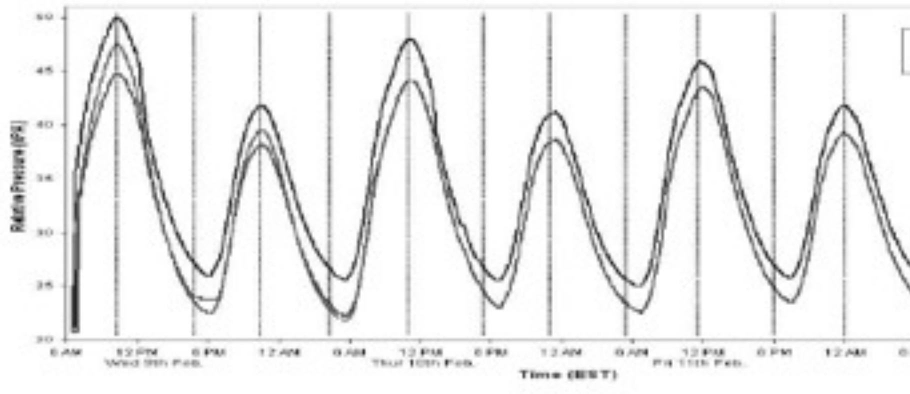
The underwater sensor node

Pressure/Temperature Sensing

Camera

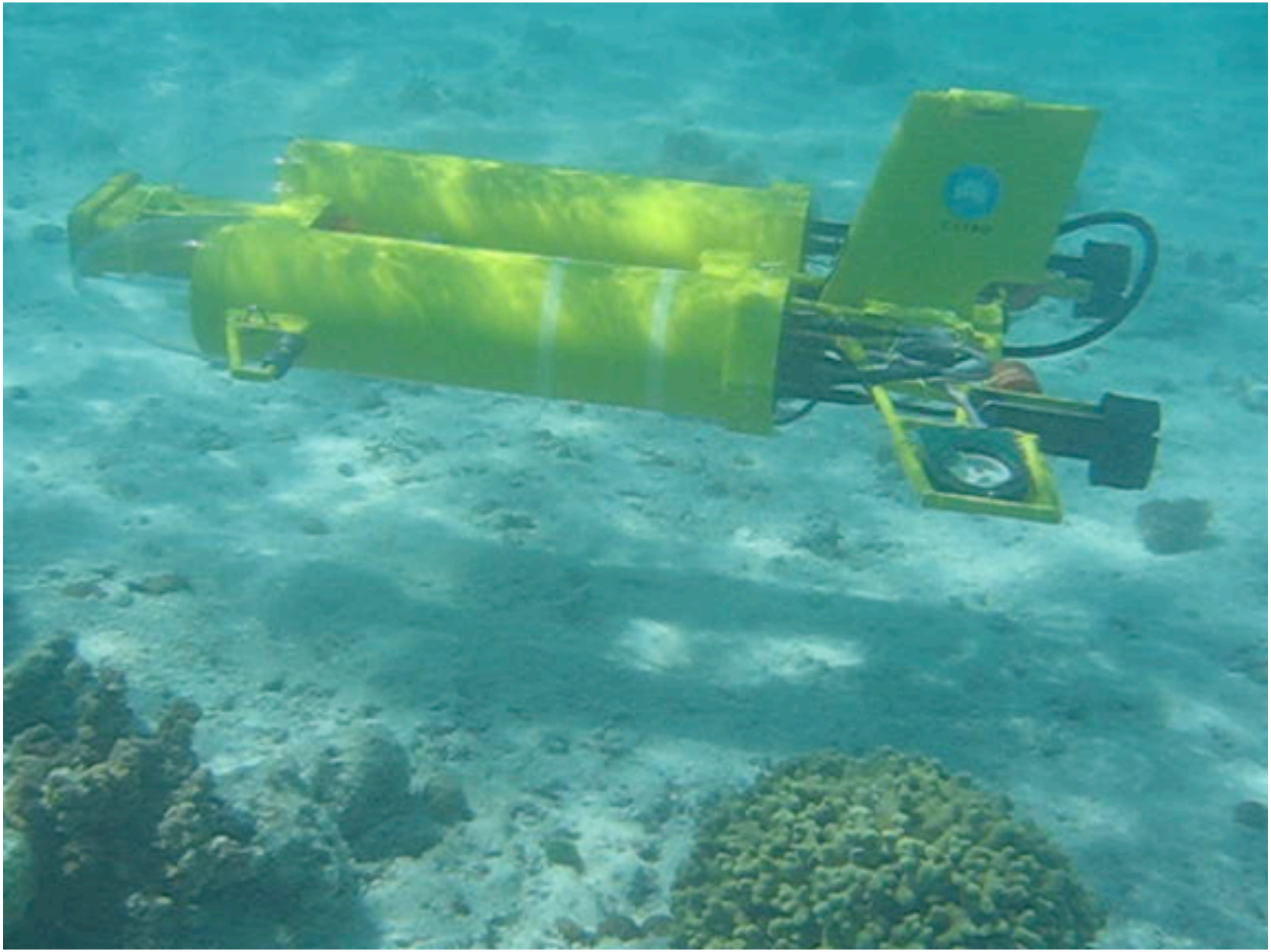
Fleck + Optical module





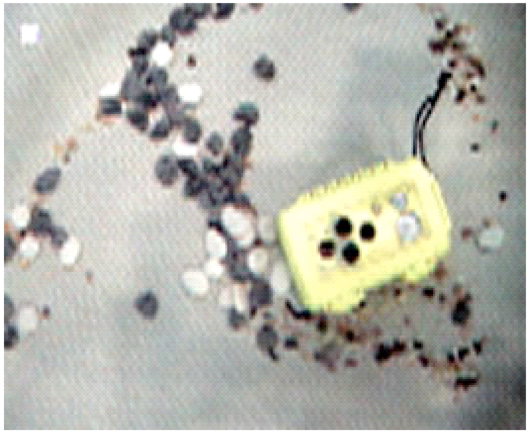
8 bit / 4K Ram 128K Program / 512K Data
36 Wh Battery (3 C cells)

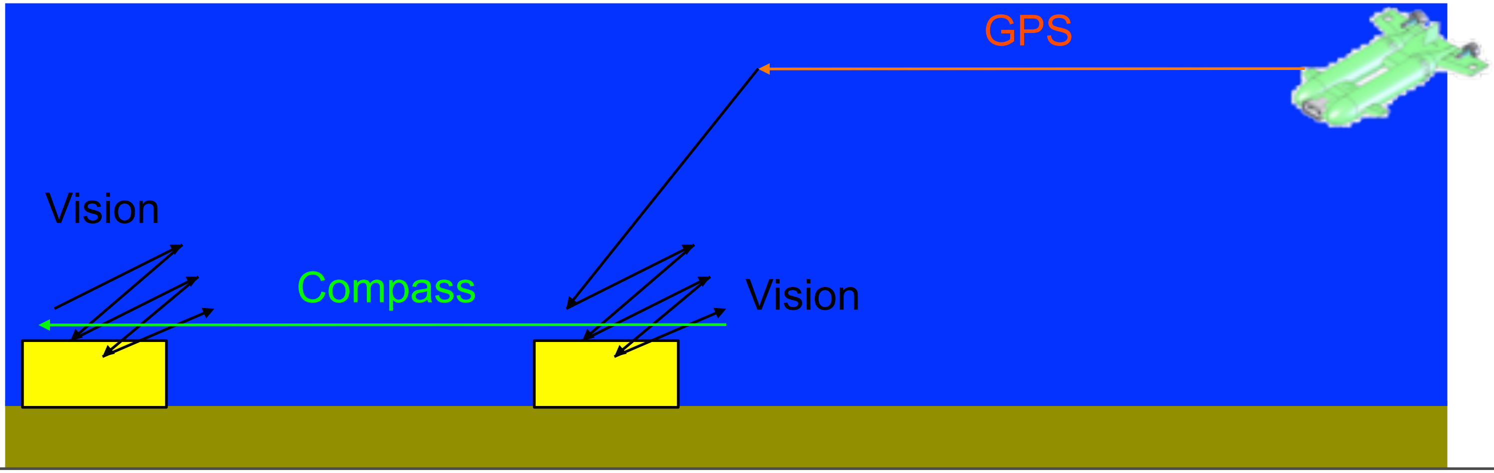
Underwater robotics - Terrain following



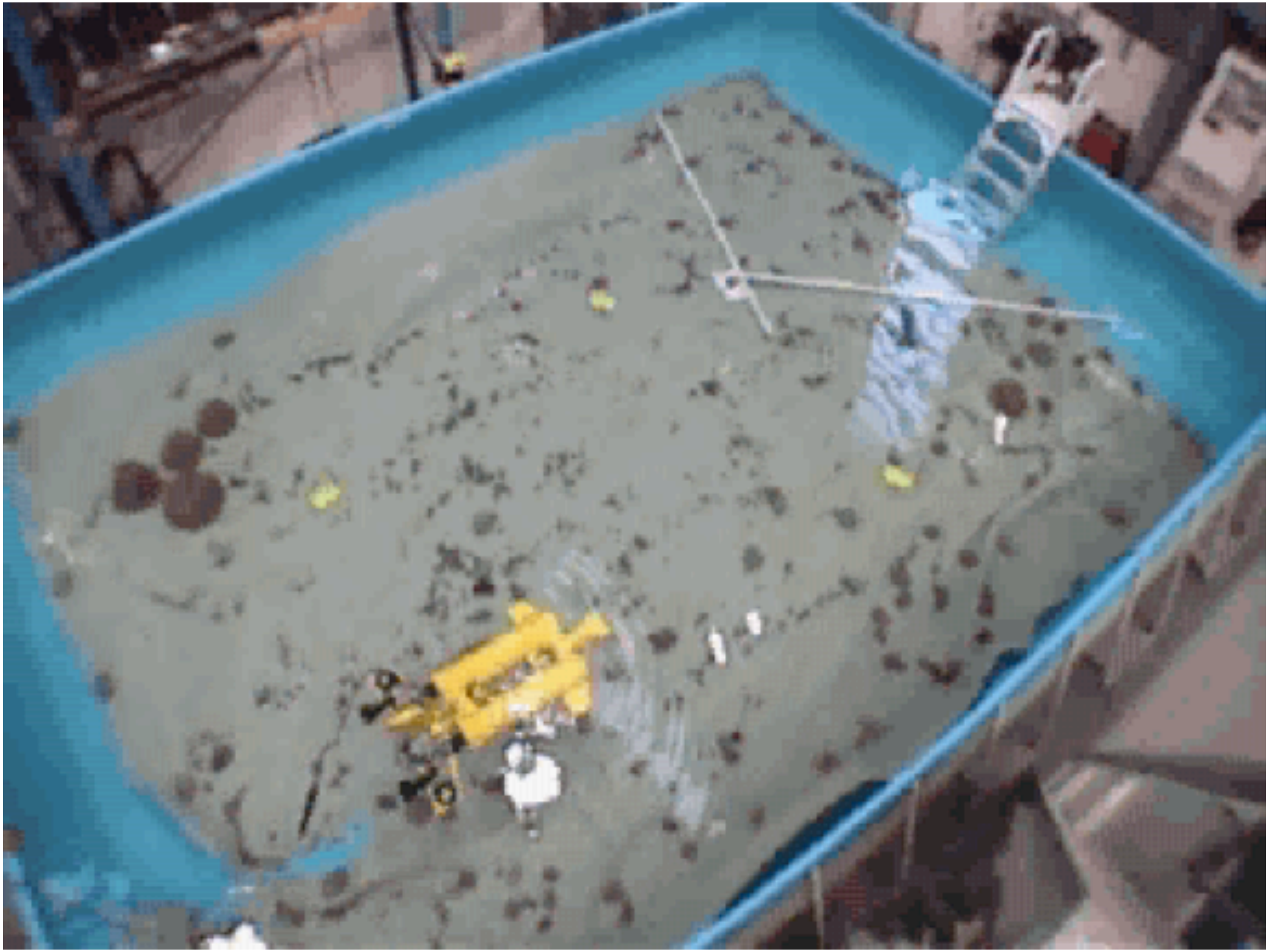
Data retrieval - algorithm

- GPS navigation to first node (known location)
- Descend and search
- Establish transmission protocol (query, stateless)
- Hover while getting data
- Move to the next node





Data Retrieval



Overview

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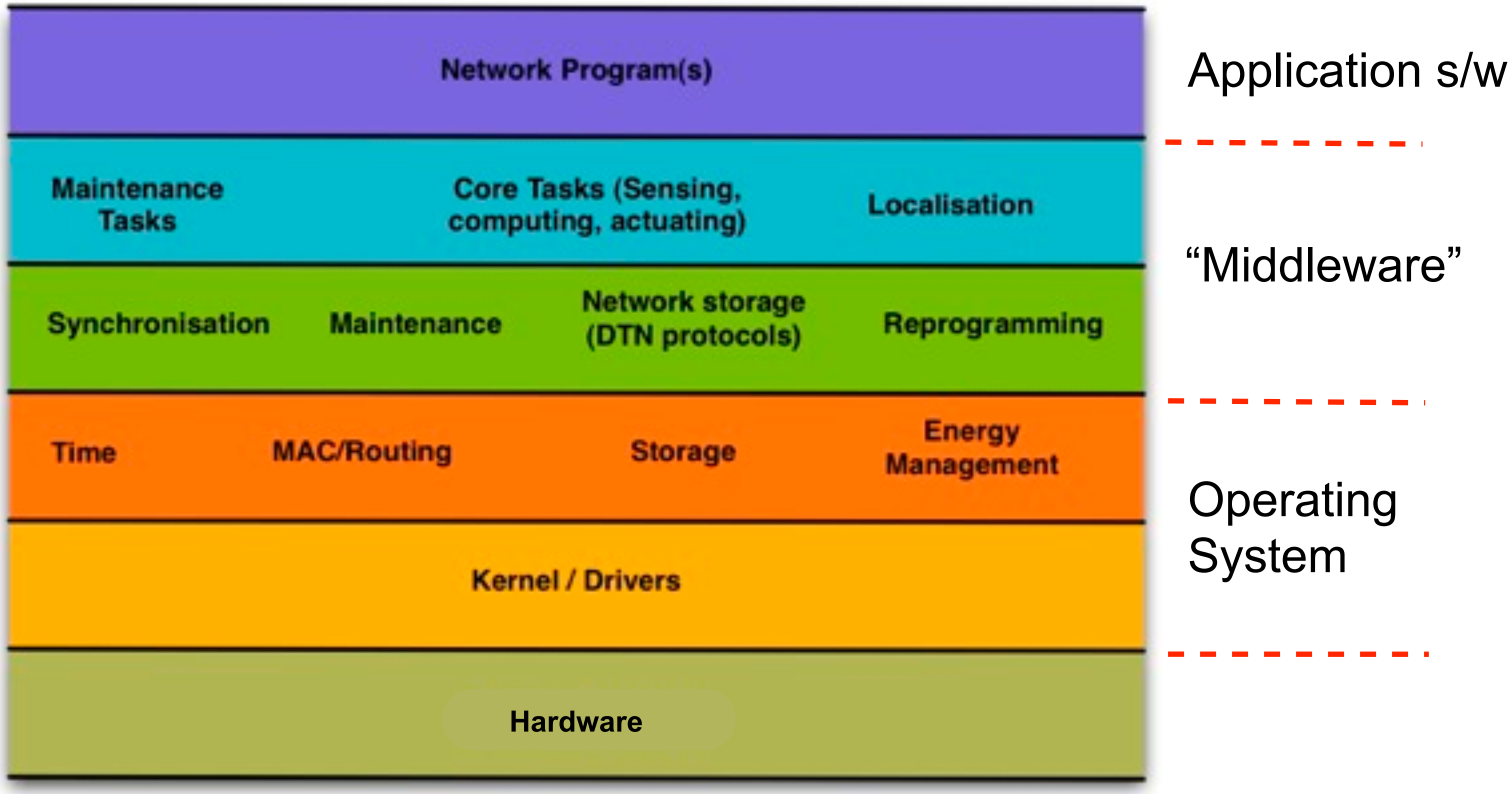
- **Current application drivers**
- Adaptive energy management
- Audio/video processing in WSN

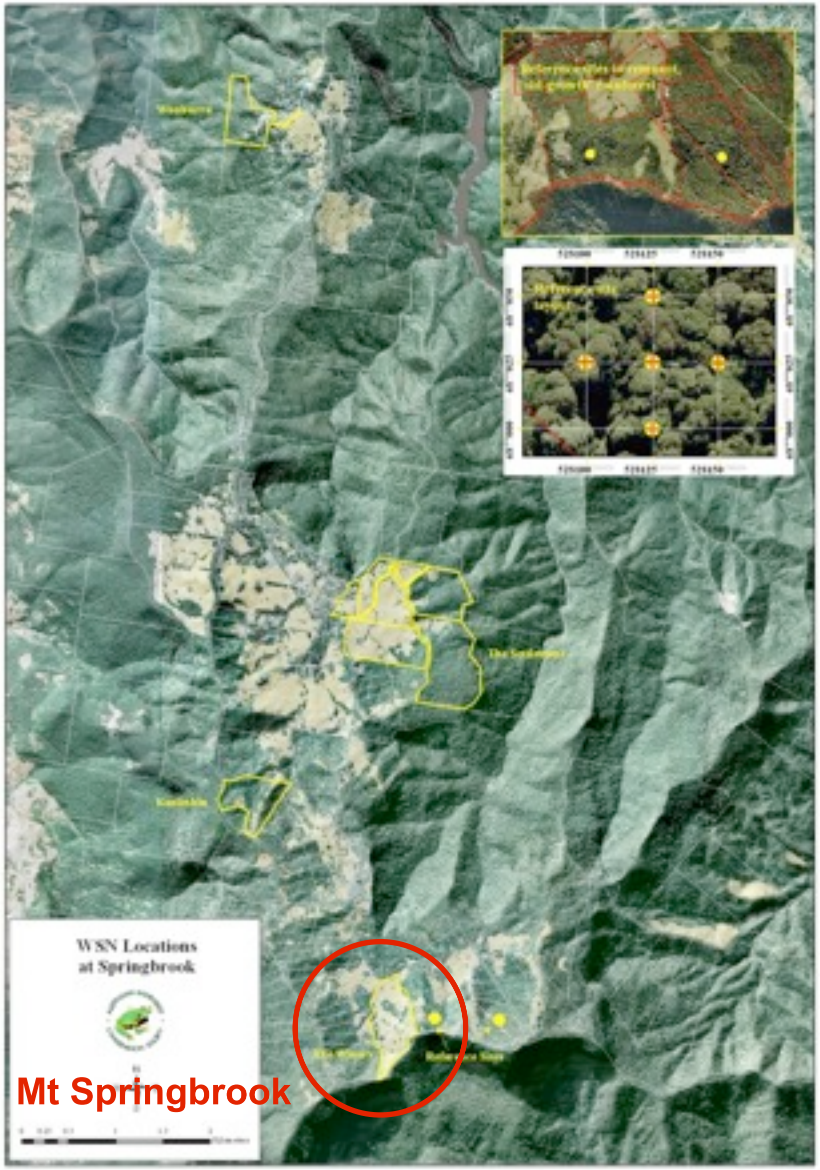
Current Research Challenges



- What protocols do we need for environmental sensor networks deployments to last for years?
- What are the next-stage capabilities for sensor networks beyond simple sample and send?

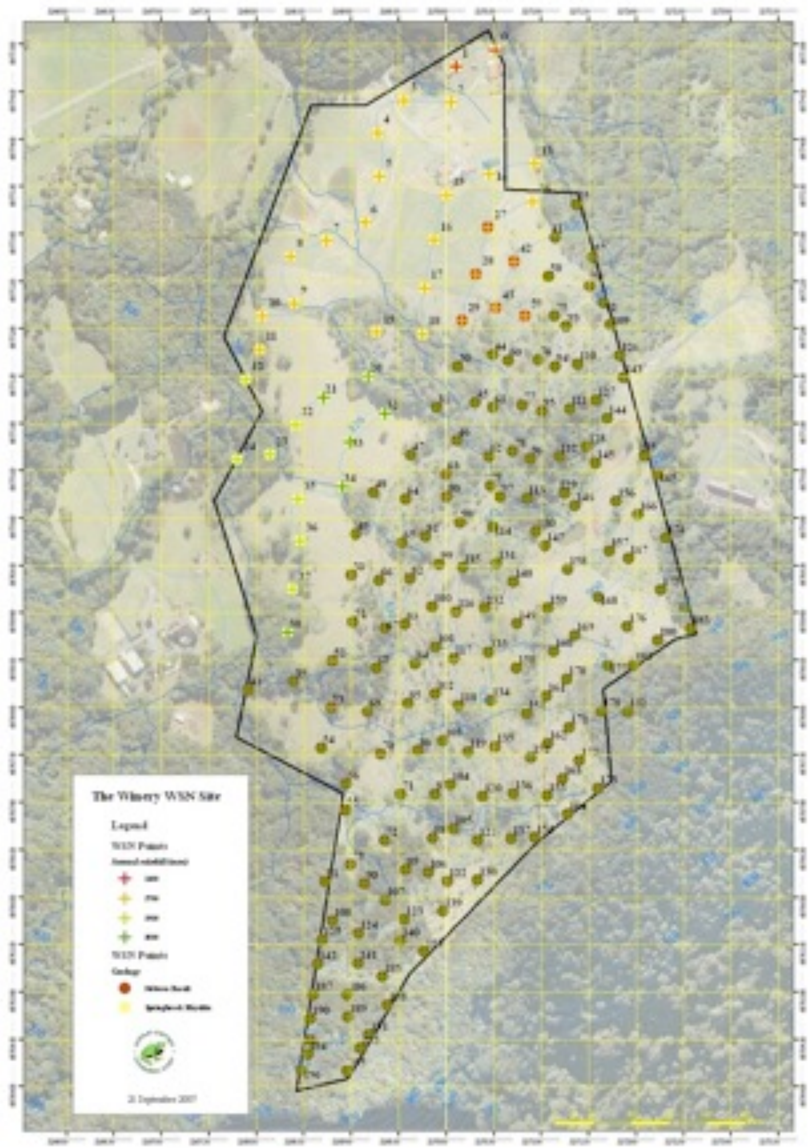
Springbrook Rainforest Deployment

- Co-investment with Queensland EPA
- Part of TREON (The Rainforest Ecological Observation Network) being driven by Australian Rainforest Conservation Society (ARCS)
- Aim:
  - Measure, model and understand the effects of climate change, land use and species invasion on rainforest regeneration
  - Gain better understanding of biodiversity and ecological functioning of rainforests



Springbrook Rainforest Deployment

- Mt Springbrook Network
  - Network of 200 nodes distributed through remnant and regenerating rainforest areas
  - **Phase 1: (complete)**
    - Small testbed to quantify factors such as amount of solar energy available and communication link quality throughout rainforest
  - **Phase 2:**
    - Expansion of network to 200 microclimate nodes
    - Inclusion of new types of biodiversity sensors such as audio/video based



Rainforest nodes

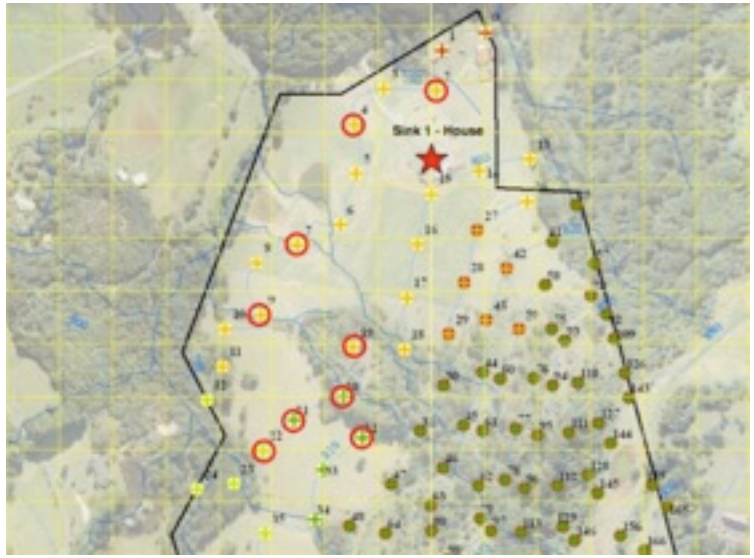
- Phase 1 Micro-climate nodes
  - temperature, humidity
  - wind speed, direction
  - soil moisture
  - leaf wetness

Table 1: Sensors provided at each node.

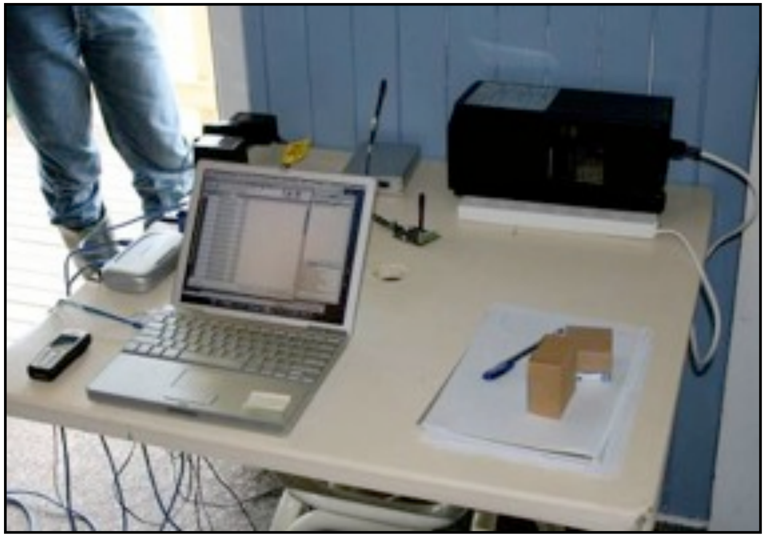
Sensor	Manufacturer
Wind speed	Met One Instruments
Wind direction	Met One Instruments
Soil moisture	Decagon
Leaf wetness	Decagon
Temperature	Sensirion
Humidity	Sensirion

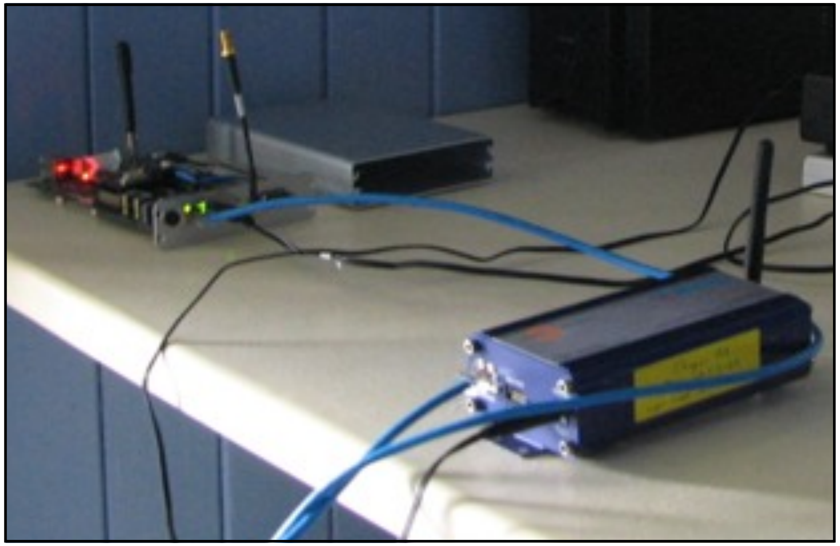
Phase 1 - Network protocols

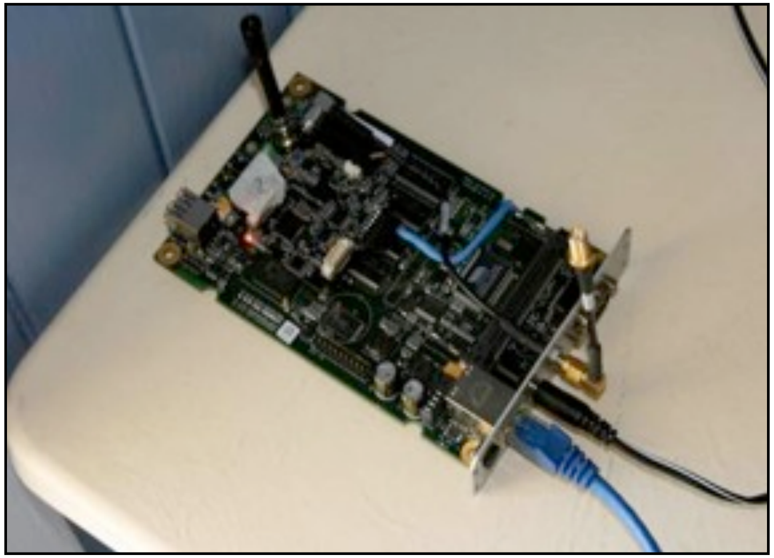
- Multi-hop network protocol
  - Nodes are typically 1-4 hops from base
- MAC protocol is based around Low-Power Listening (LPL) MAC
  - The transmitting node sends long preamble
  - Ideally suited to low-traffic networks
- Routing protocol is based around link-qualities of nodes
  - Well suited where radio environment is very dynamic
  - Packet sequence numbers coming from each node are used to estimate upstream and downstream link qualities



Network gateway / basestation







Wireless Sensor Gateway

- Manages incoming data
- Collates, buffers and delivers data to database server via internet
- Mini Linux-based computer
  - *500MHz AMD processor*
  - *256MB RAM*
  - *CompactFlash socket*
  - *Ethernet, dual USB & serial ports*

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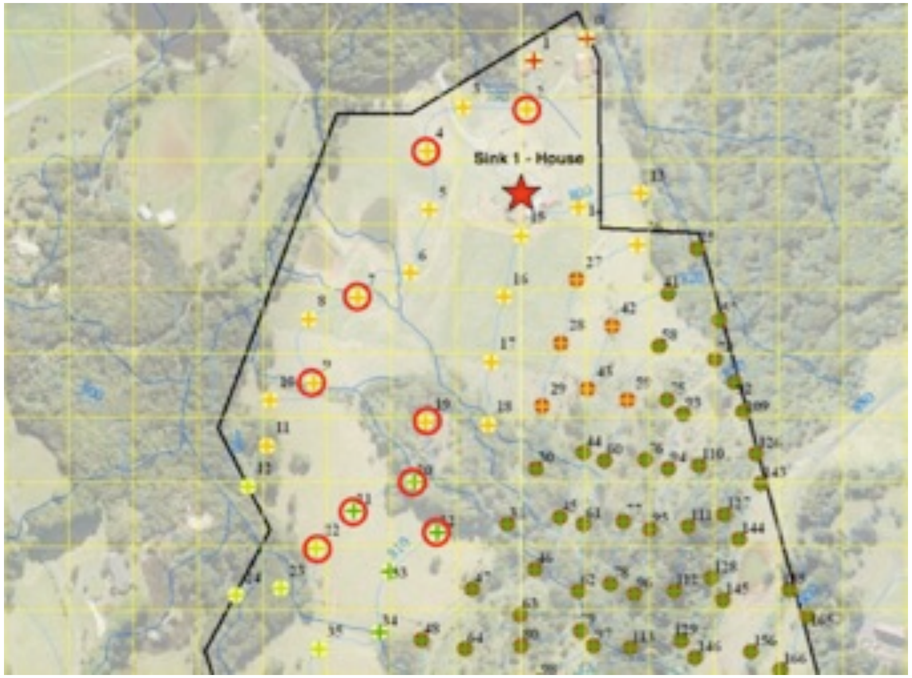
Network Visualisation

- Data is returned to a remote Oracle database server
- Web interface used for querying and plotting of time-series data

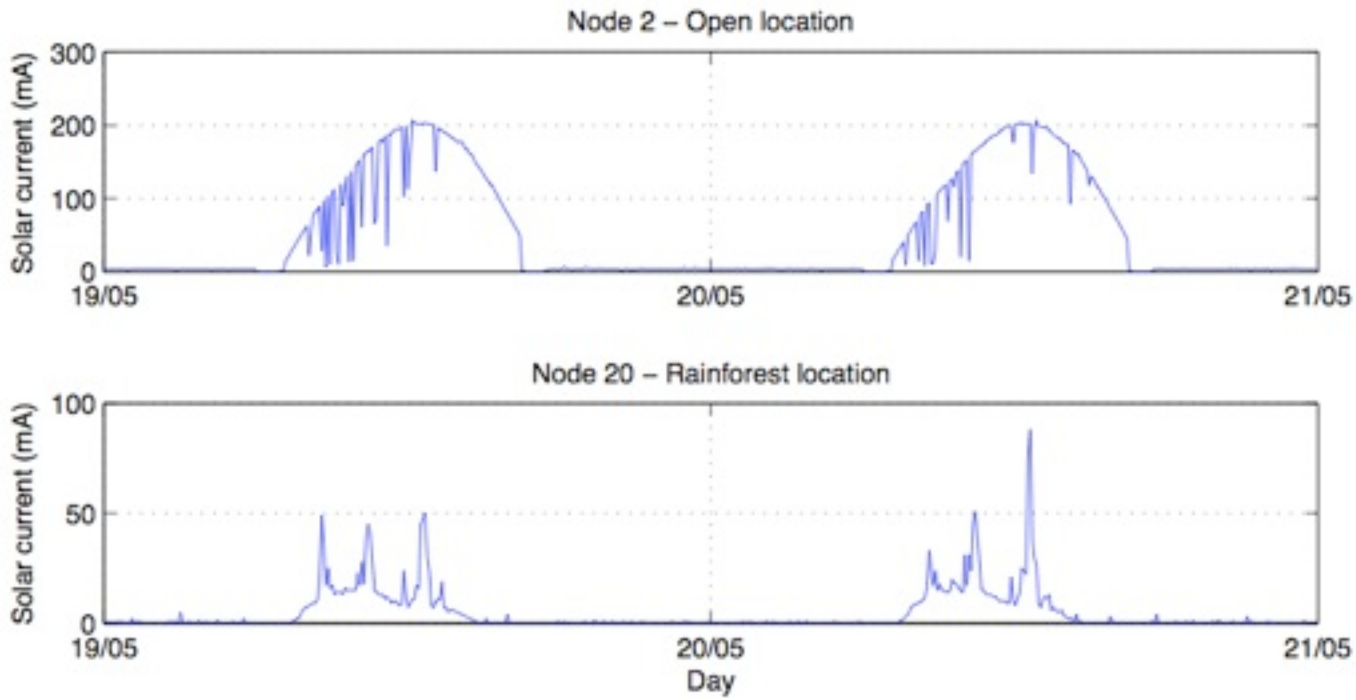
Evaluation

- Aim was to quantify the level of network performance given the challenging environmental conditions
- Areas of focus:
  - Energy
  - Network communication



Evaluation

- Energy
  - Daily solar energy budget is highly variable in between open and covered areas



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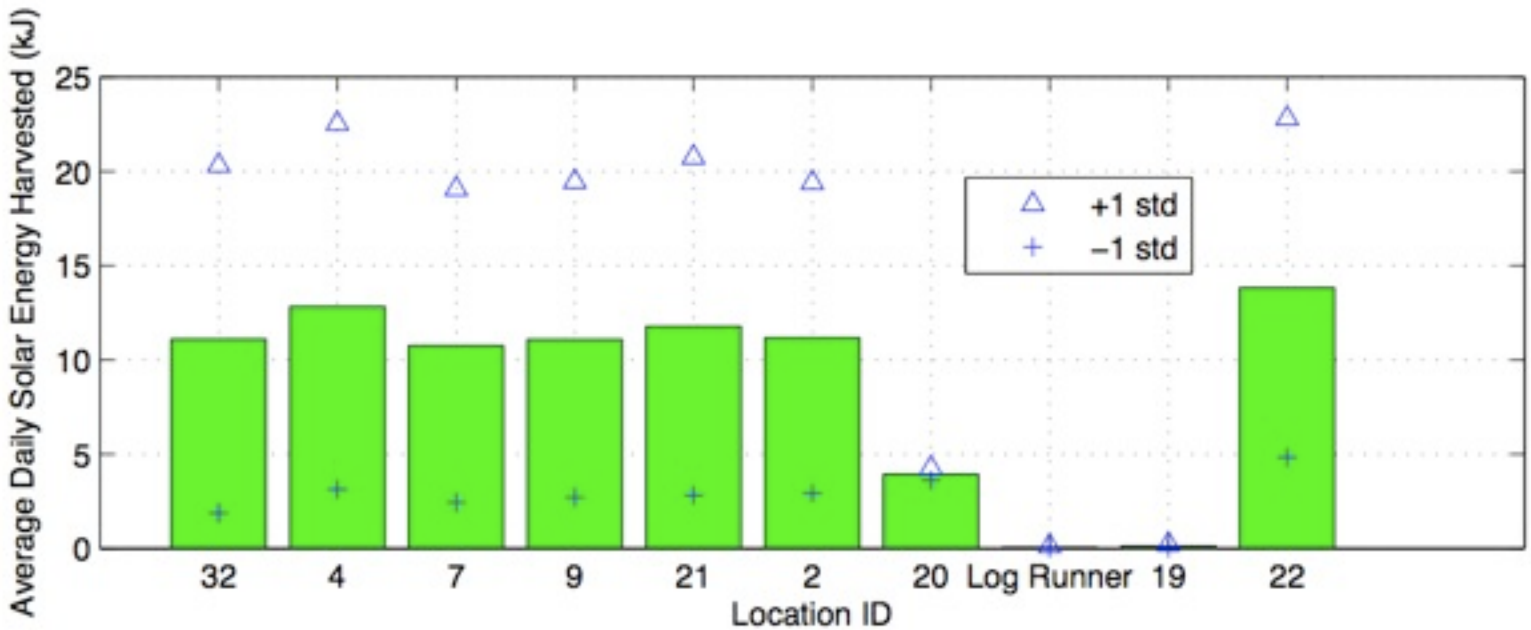
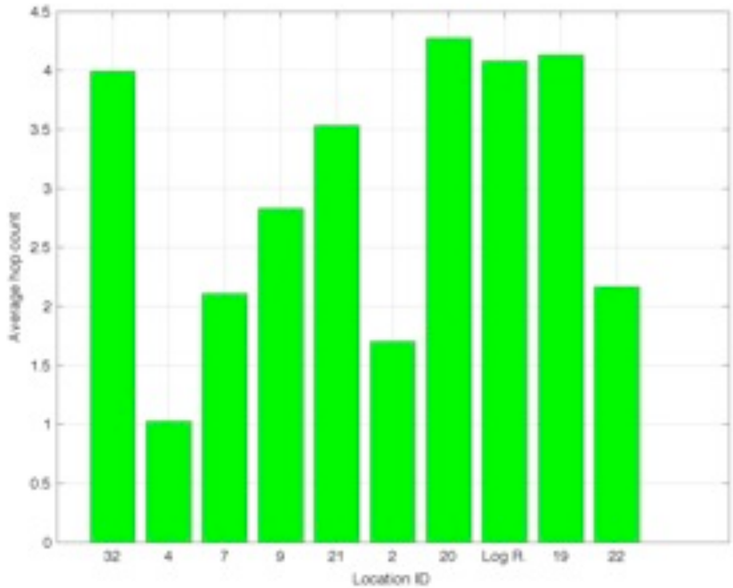


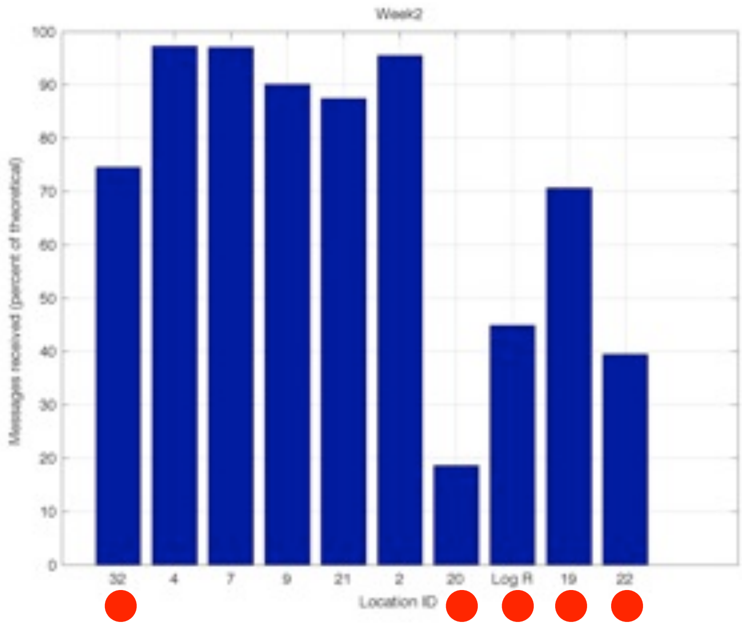
Evaluation

- Network performance

Average hop count

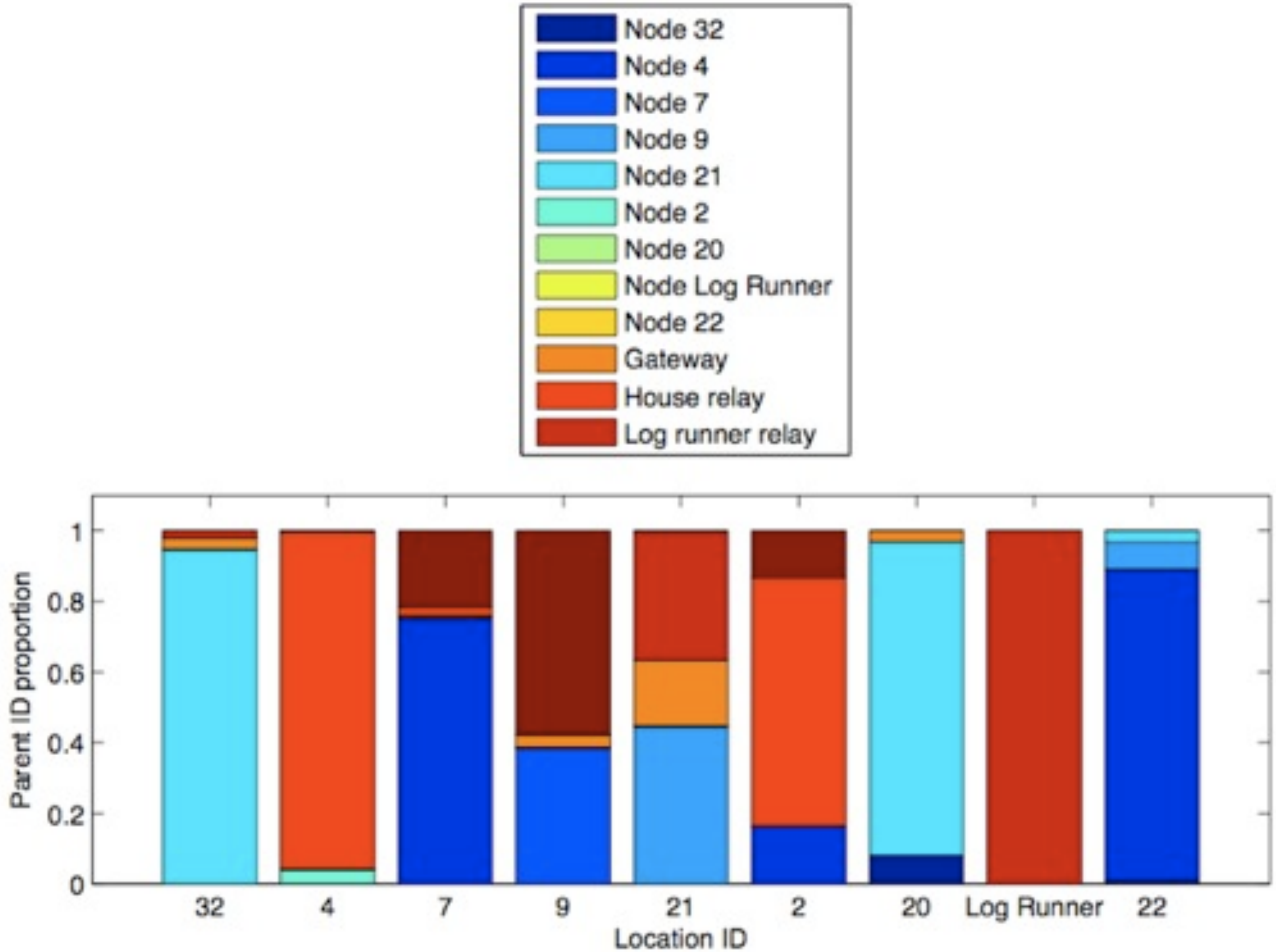


Delivery ratio



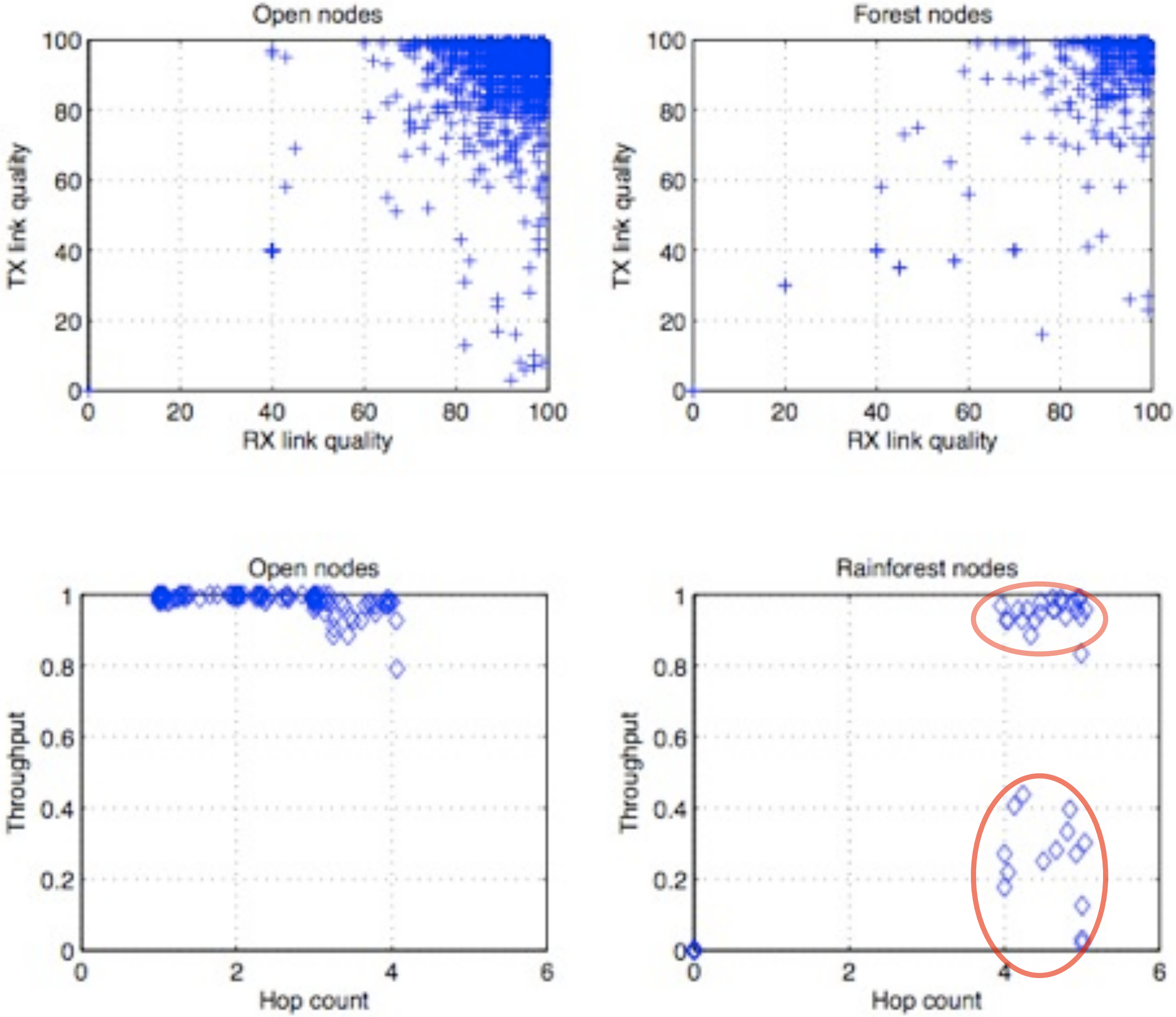
Evaluation

- Network characteristics - variation in parent node

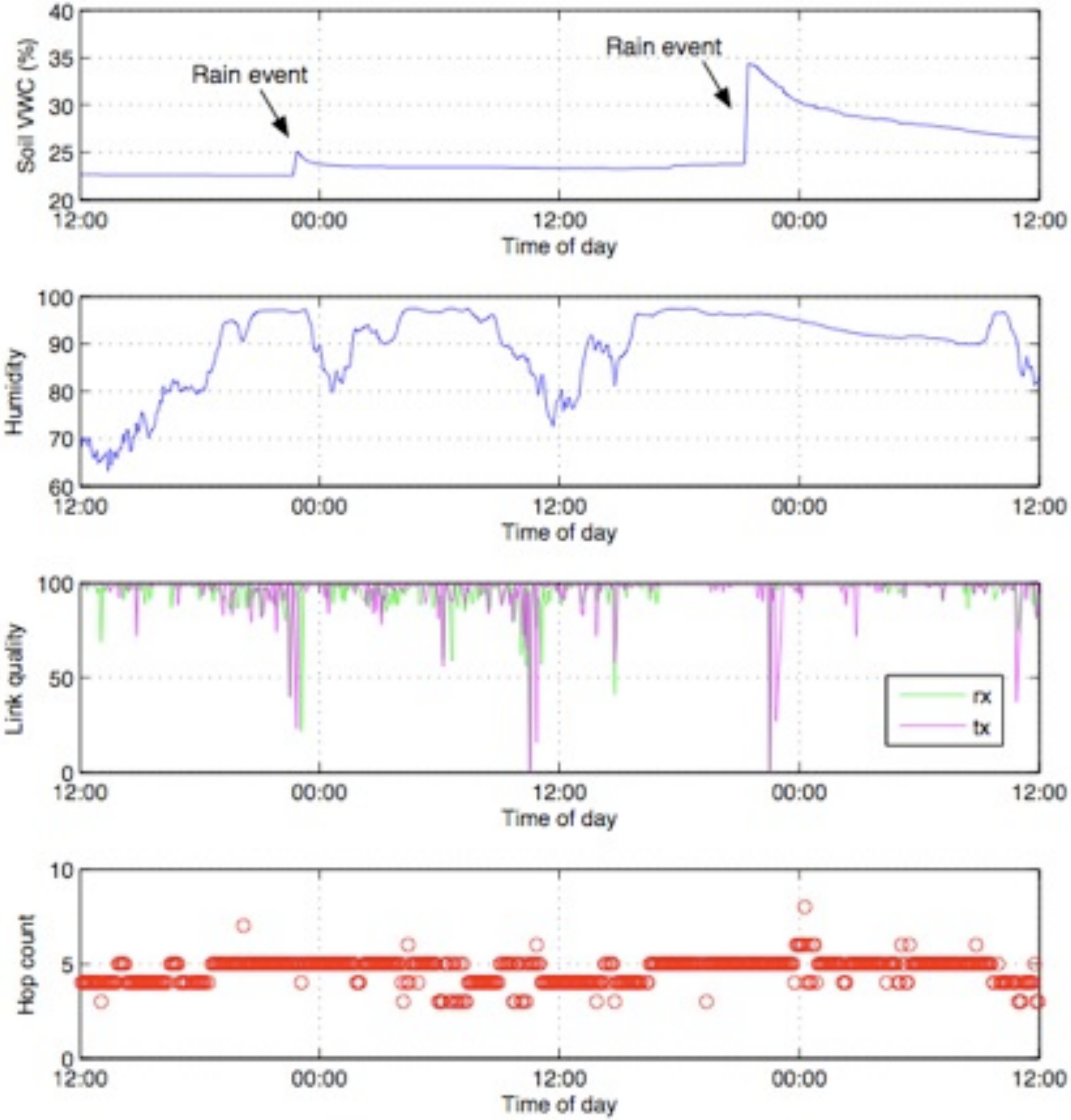


Evaluation

- Link quality, throughput, hop-count

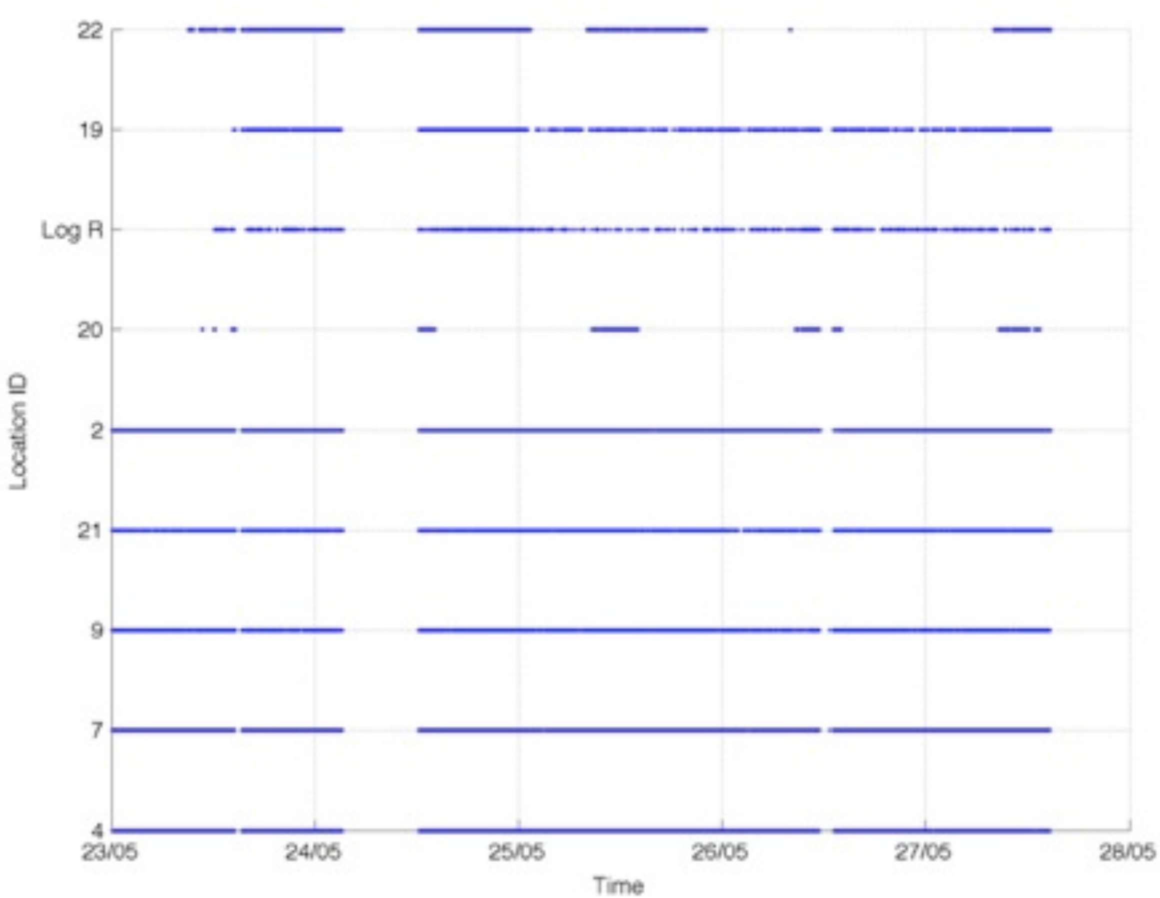


Evaluation


Soil VWC (%)
Rain event
Rain event
Time of day
Humidity
Time of day
Link quality
rx
tx
Time of day
Hop count
Time of day
12:00
00:00
12:00
00:00
12:00

Evaluation - Gateway

- 3G connection reliability



Design Specifications for Phase 2 - 200 nodes

- Node battery lifetime
  - All rechargeable batteries have a finite number of charge cycles
  - Design for node batteries to last >= 2 years before being changed
- Latency
  - In general aim for latency in the order of minutes, except in cases where we need to conserve energy at one or more nodes
- Reliability / Data quality
  - Criteria will be in that the **information** in the samples returned is sufficient to describe the phenomena being measured
  - Should return as **much** information as possible, rather than the minimum

CSIRO

Overview

- Background of CSIRO's work in WSN
- Current application drivers
- **Adaptive energy management**
- Audio/video processing in WSN

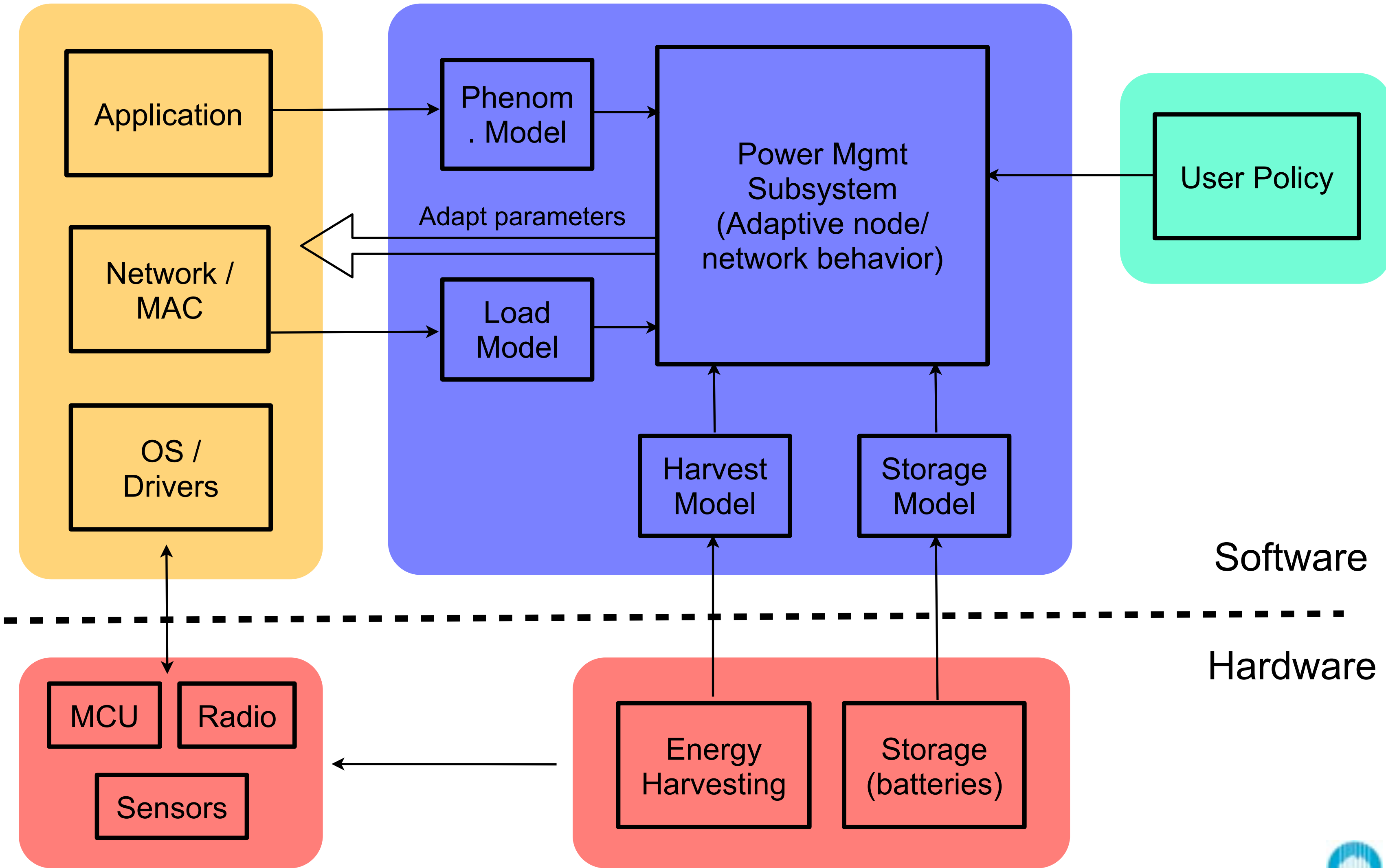
Current paradigms for environmental WSN

- Non-harvesting
  - Calculate energy **consumption** costs for typical usage patterns
    - Radio listen / TX / forward, network overheads, sampling
  - Provide necessary energy storage to meet required lifetime and operating point of network
- Harvesting (e.g. solar)
  - Calculate energy **consumption** costs for typical usage patterns
    - Radio listen / TX / forward, network overheads, sampling
  - Estimate total energy we can **harvest** (and store) over lifetime of network
  - Supplement with additional stored energy
- Key point:
  - Any energy available for harvesting which is not stored is **wasted** energy!

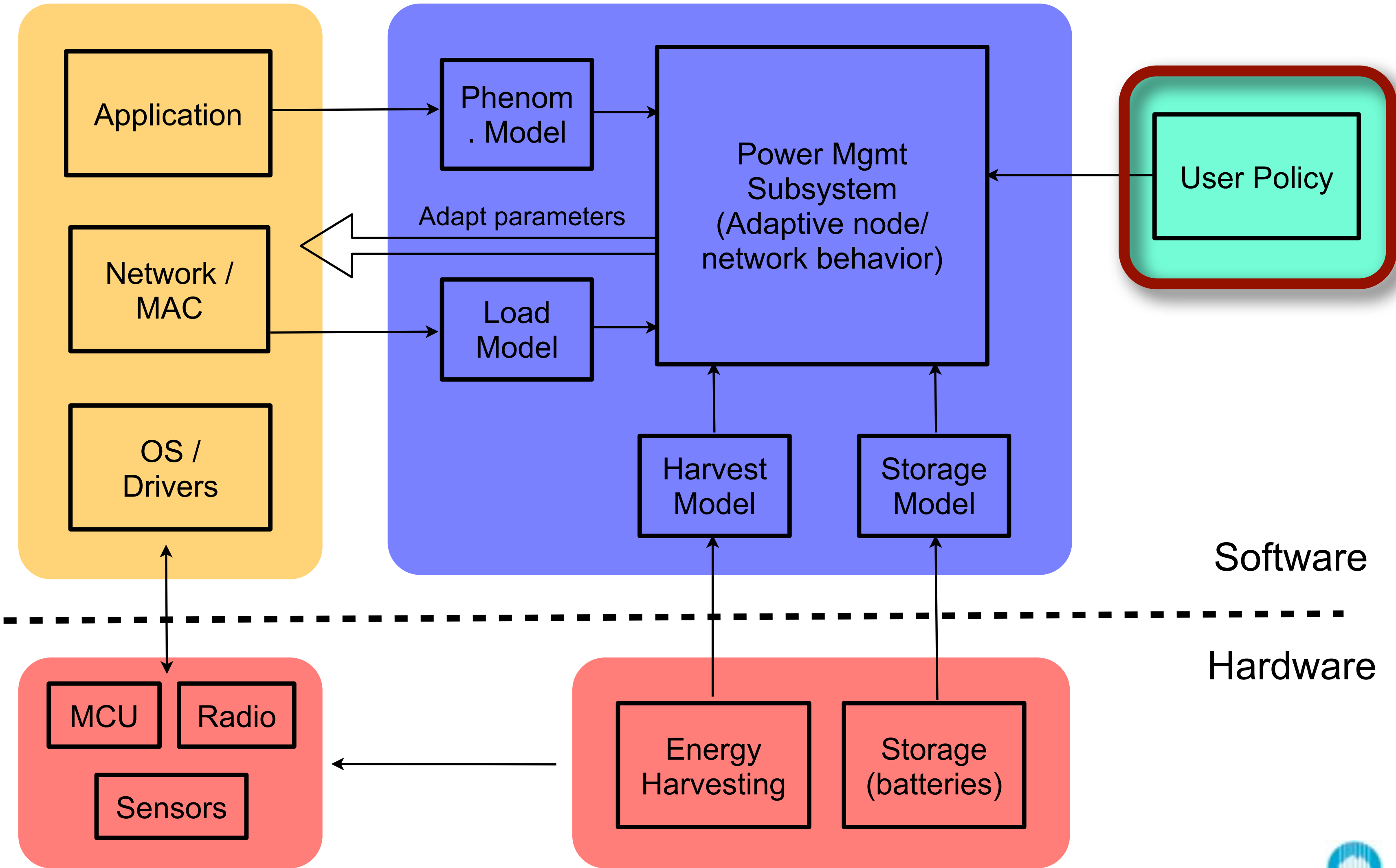
What's our current aim?

- Given a long-term, solar harvesting network - how can we **maximize** the amount of energy consumption dedicated to returning **information** - while still ensuring system can meet lifetime goals?

System Architecture



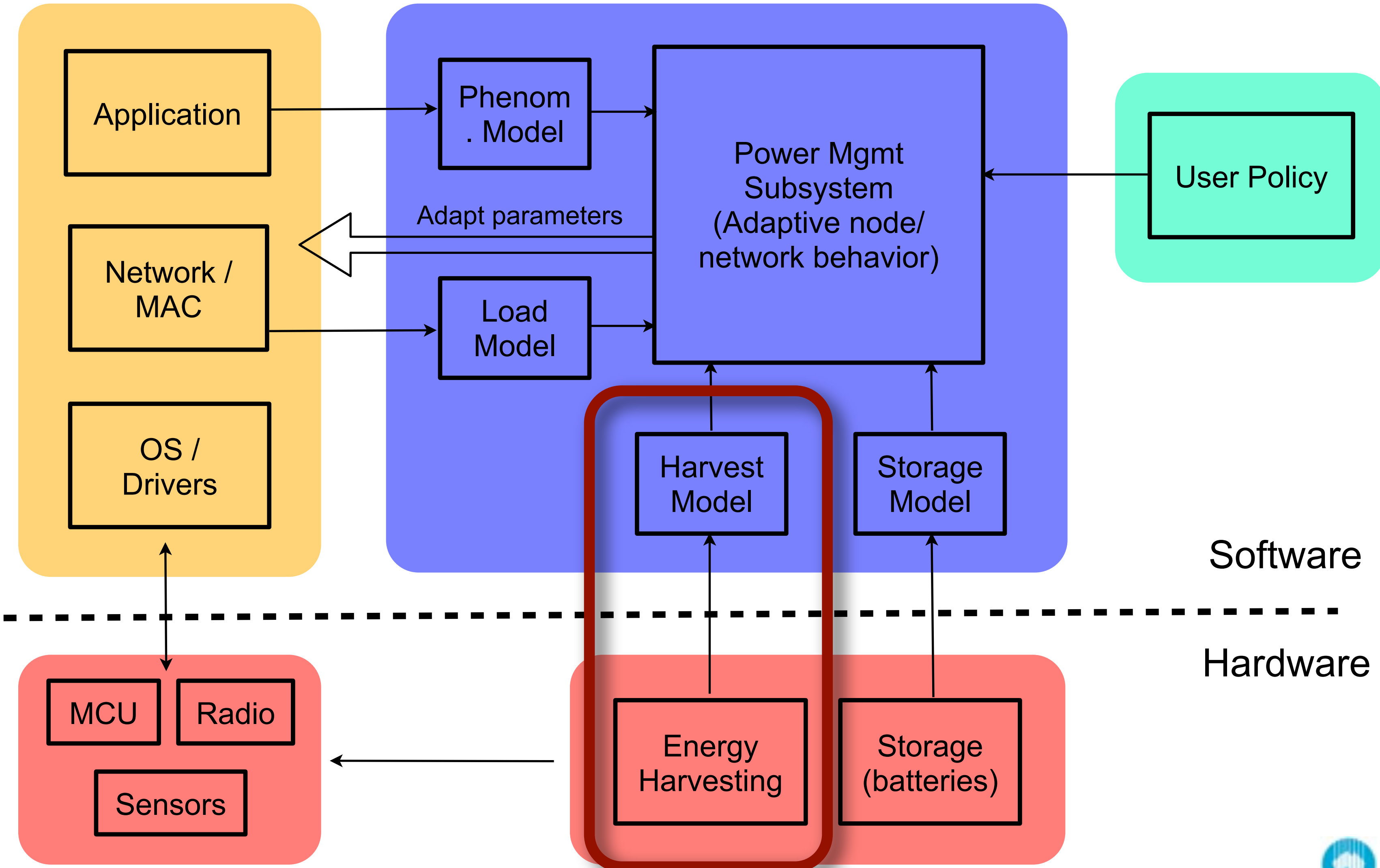
System Architecture



User Policy

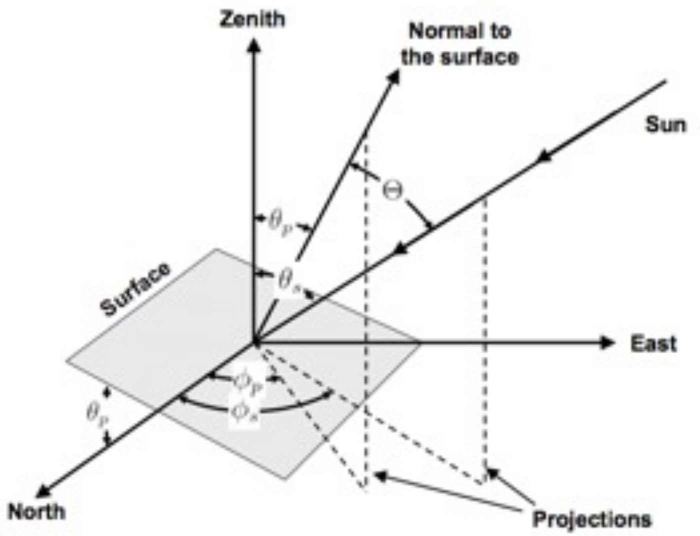
- User sets policies for network at start of deployment which can be **updated** as deployment progresses:
  - Deployment lifetime (e.g. 2 years)
  - Flexible sensor suite per node:
    - e.g. temperature, humidity, leaf-wetness, wind, sap-flow
  - Max and min sample rates for each sensor

System Architecture

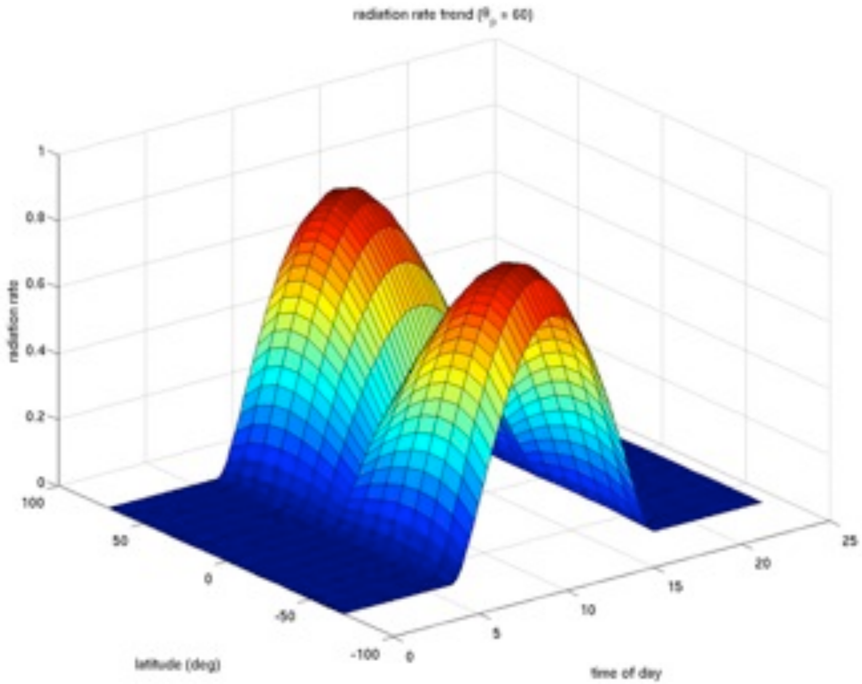


Energy Prediction - Atmospheric Model

- Can gain a certain amount of *a priori* information simply due to the day of the year:



Jeong et.al, 2008



$$\cos\Theta = \cos\theta_p \cdot \cos\theta_s + \sin\theta_p \cdot \sin\theta_s \cdot \cos(\phi_p - \phi_s)$$

$$\cos\theta_s = \sin\delta \cdot \sin L + \cos\delta \cdot \cos L \cdot \cos h$$

$$\sin\phi_s = -\cos\delta \cdot \sin h / \sin\theta_s$$

Energy prediction

- Previous work in using time-series predictions
- Weather station data from nearby stations can also be used to gain valuable prediction information:
  - Can typically get forecasts up to 4 days ahead

```
conditions = {'Clear' : '1',
              'Scattered Clouds': '2',
              'Partly Cloudy' : '3',
              'Haze' : '4',
              'Mostly Cloudy' : '5',
              'Patches of Fog' : '6',
              'Overcast' : '7',
              'Fog' : '8',
              'Light Drizzle' : '9',
              'Light Rain' : '10',
              'Rain': '10',
              'Heavy Rain' : '10'
             }
```

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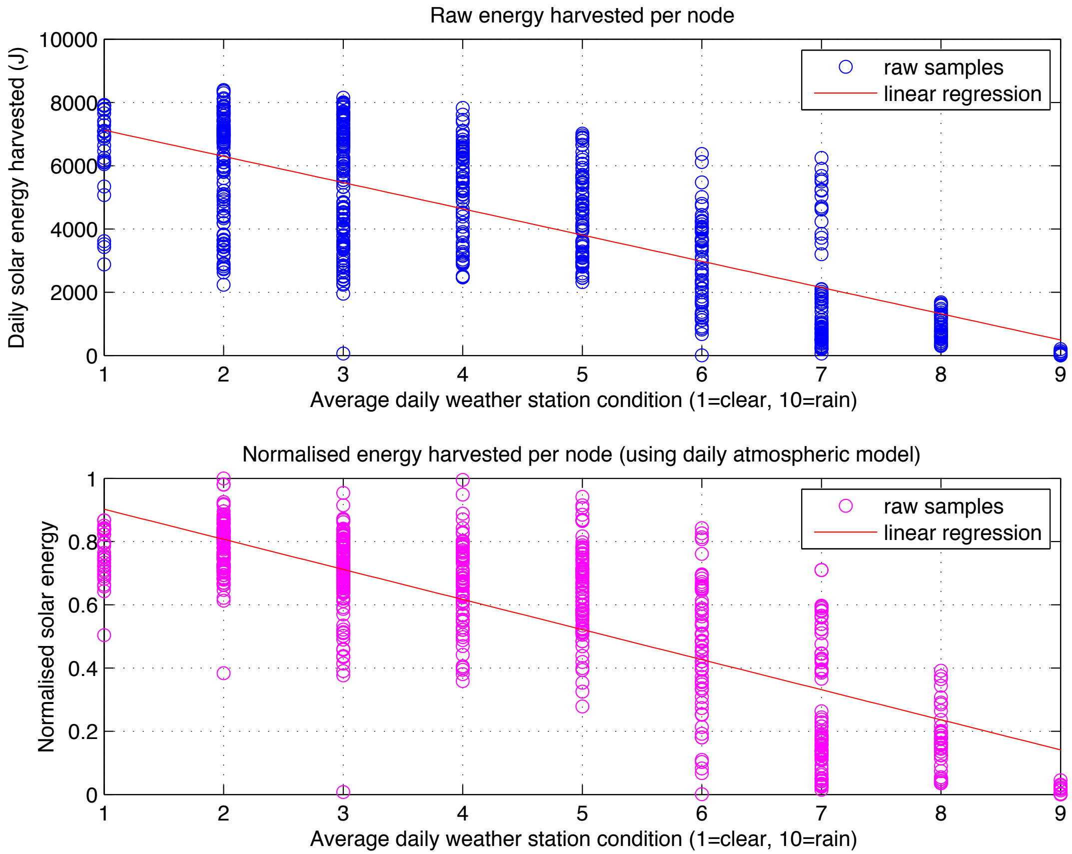
Energy Prediction - Mapping to PV data

- Using the learned mapping between weather station prediction categories we can predict energy that will be harvested:

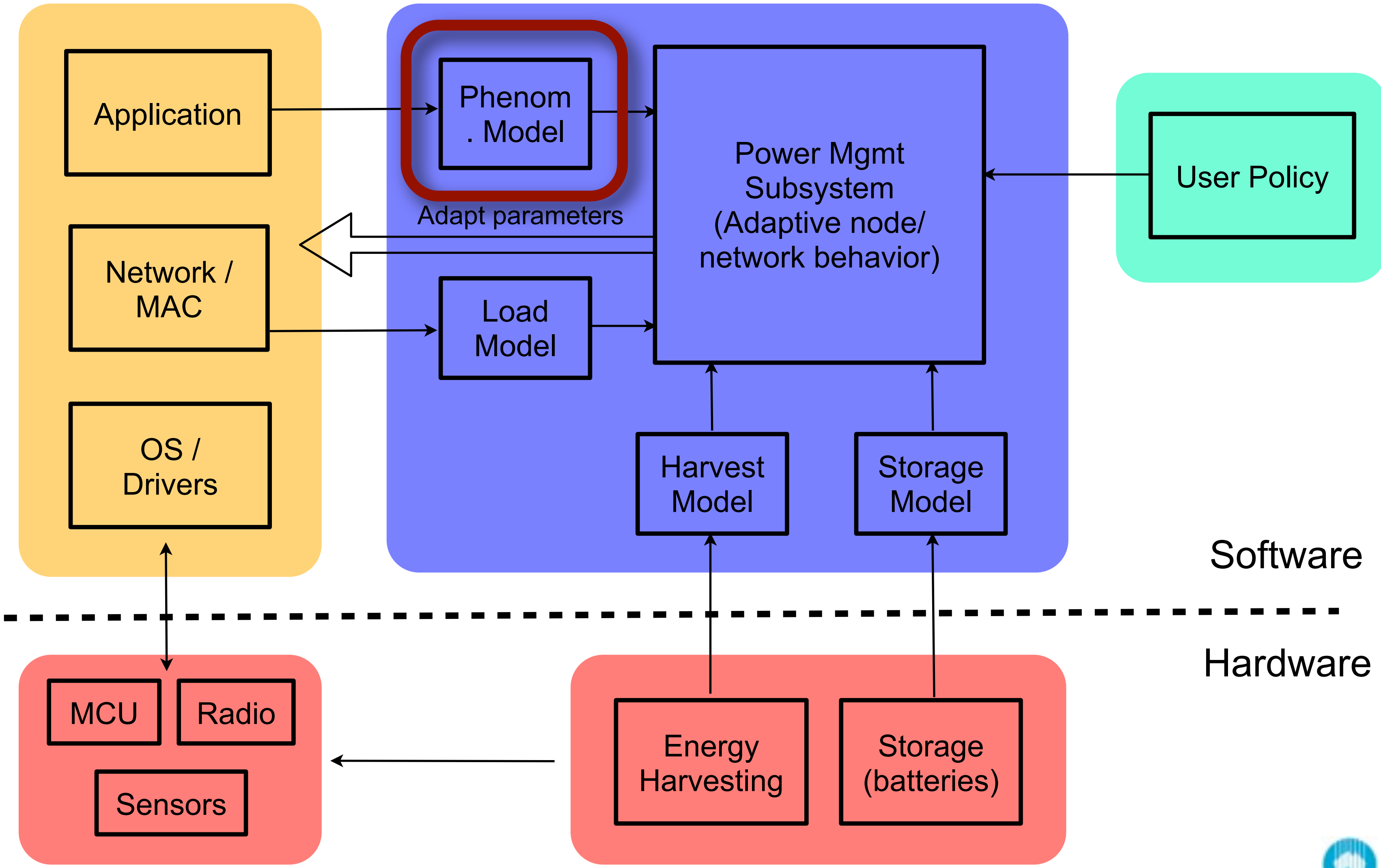


User confidence value

$$\gamma \in (0, 1]$$

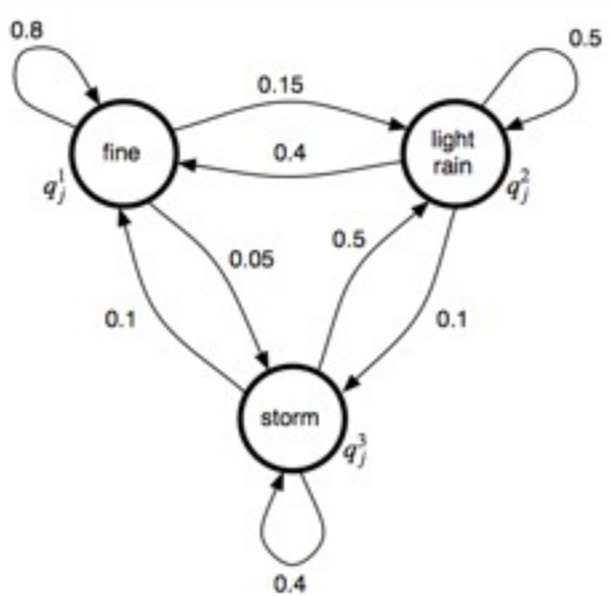
$$\int_{\hat{E}_h}^{1} p(E_h | C_{ik}) dE = \gamma$$

System Architecture



Phenomena Dependent Sampling

- We can redistribute available energy to the phenomena that need it most at the times that need it most
  - e.g. during a storm some phenomena are very dependent
- Use a state-machine for each phenomena type and use the concept of **information surprise**:



$$H(X) = -\sum_{i=1}^{n} p(x_i) \log_2 p(x_i)$$

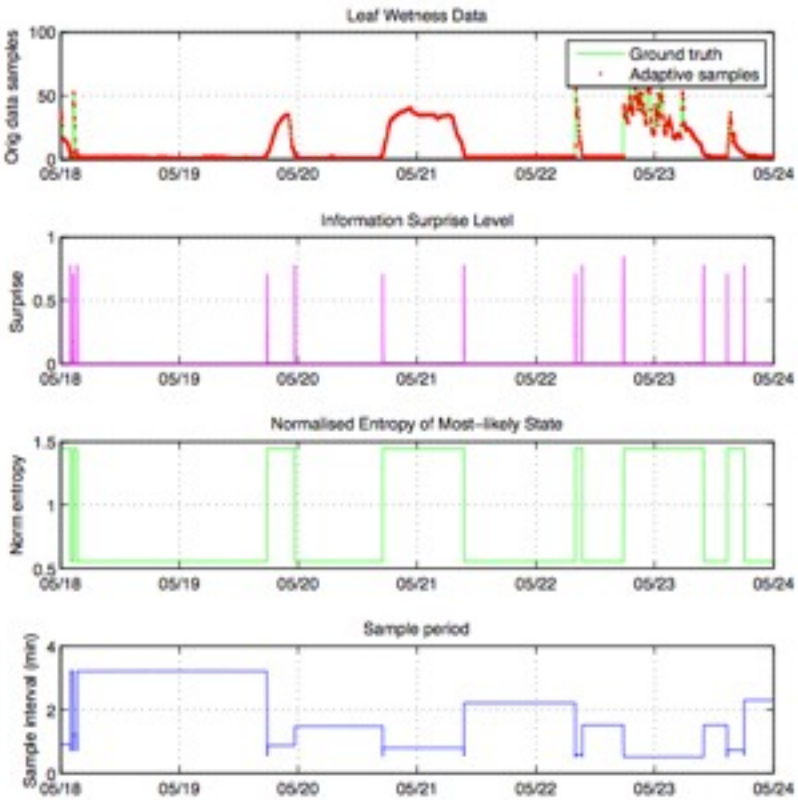
Entropy

$$\Theta_{q_j} = \sum_{k \in q_j} P(q_j^k|X) \log \frac{P(q_j^k)}{P(q_j^k|X)}$$

Information Surprise

Phenomena Dependent Sampling

- Use surprise as a trigger for re-evaluating which state a phenomena is in
- Calculate sample rate as a function of the relative entropy of that state

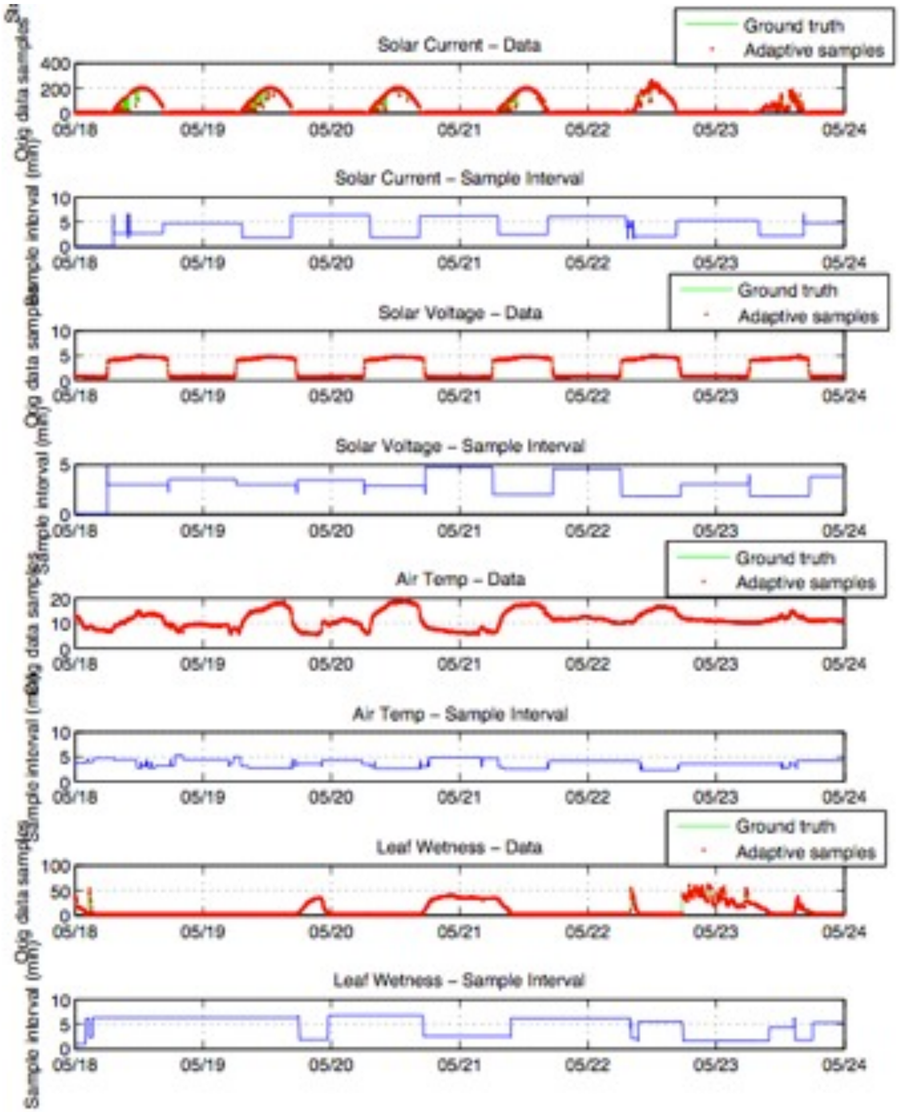


$$\hat{H}(q_j) = \frac{H(q_j^l)}{\sum_k H(q_j^k)}$$

Relative entropy of state

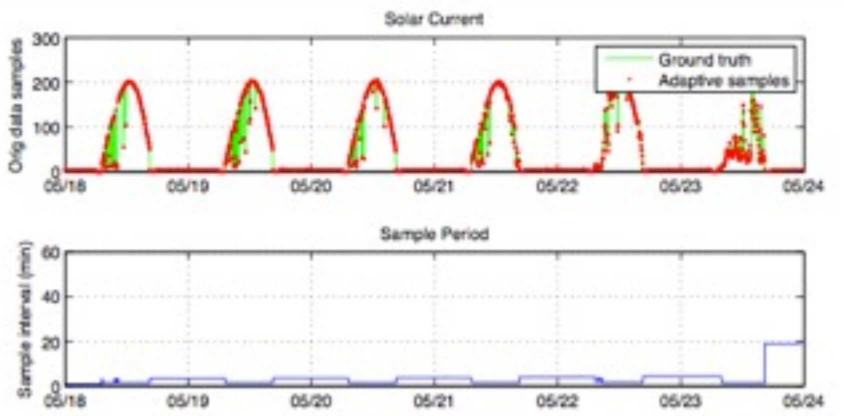
Phenomena Dependent Sampling

- Multiple sensor example:
  - Solar voltage/current
  - Air temperature
  - Leaf wetness
- Essentially for the amt of energy allocated to a node for sampling - we bias the energy towards phenomena which are in an interesting state

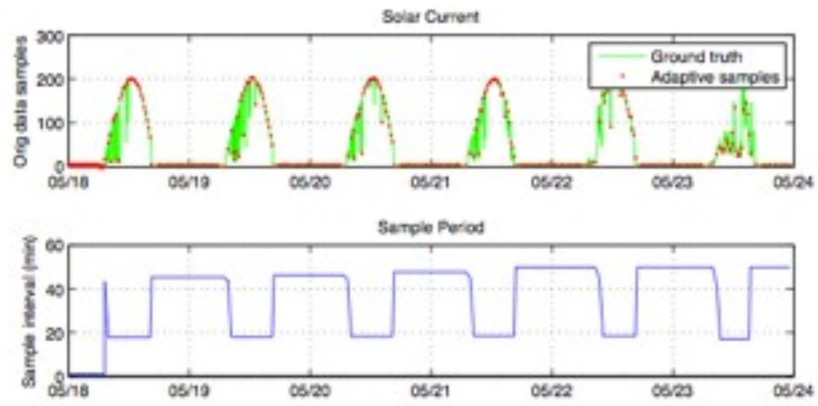


Phenomena Dependent Sampling

- Example of the impact of user policy:



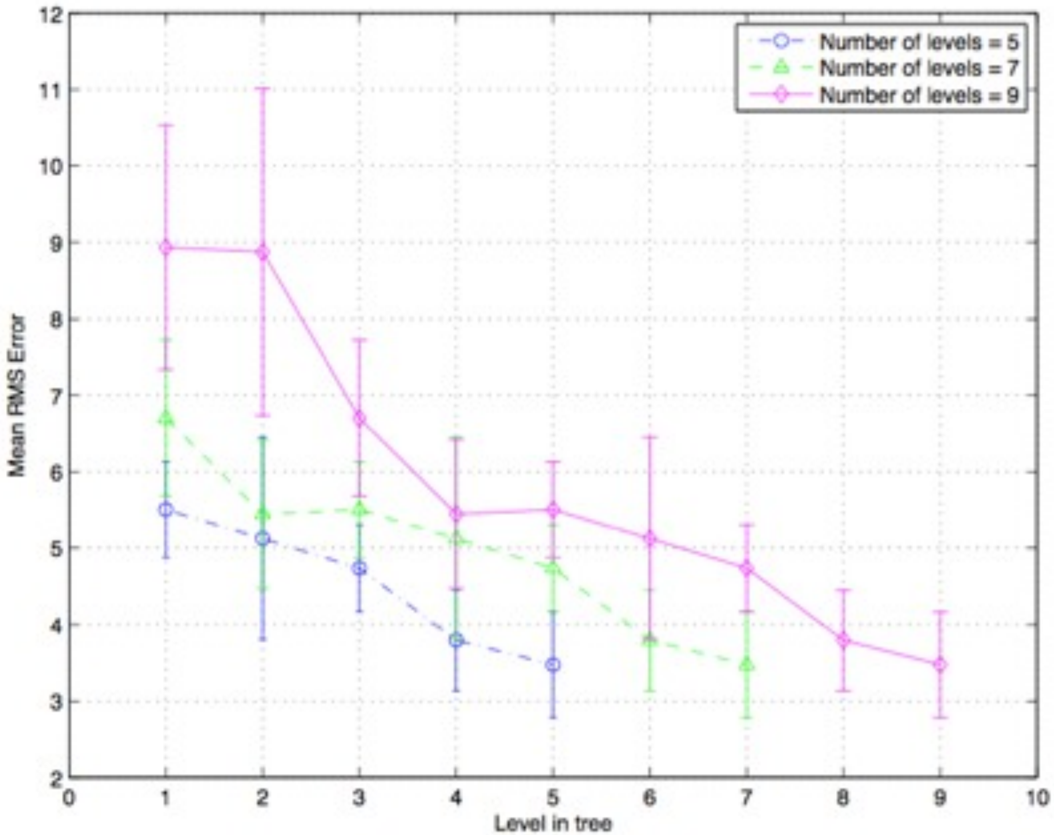
High amt of energy available



Small amt of energy available

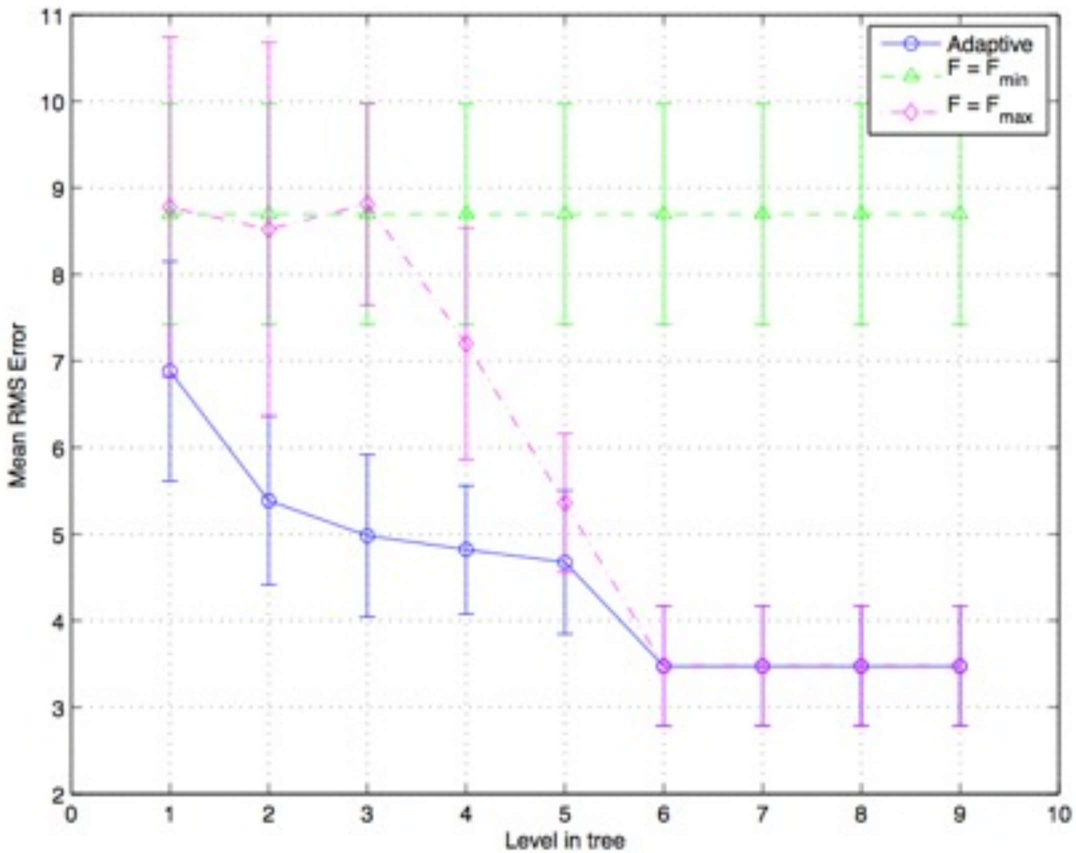
Evaluation

- Impact of increased forwarding cost for nodes (less energy for sampling)

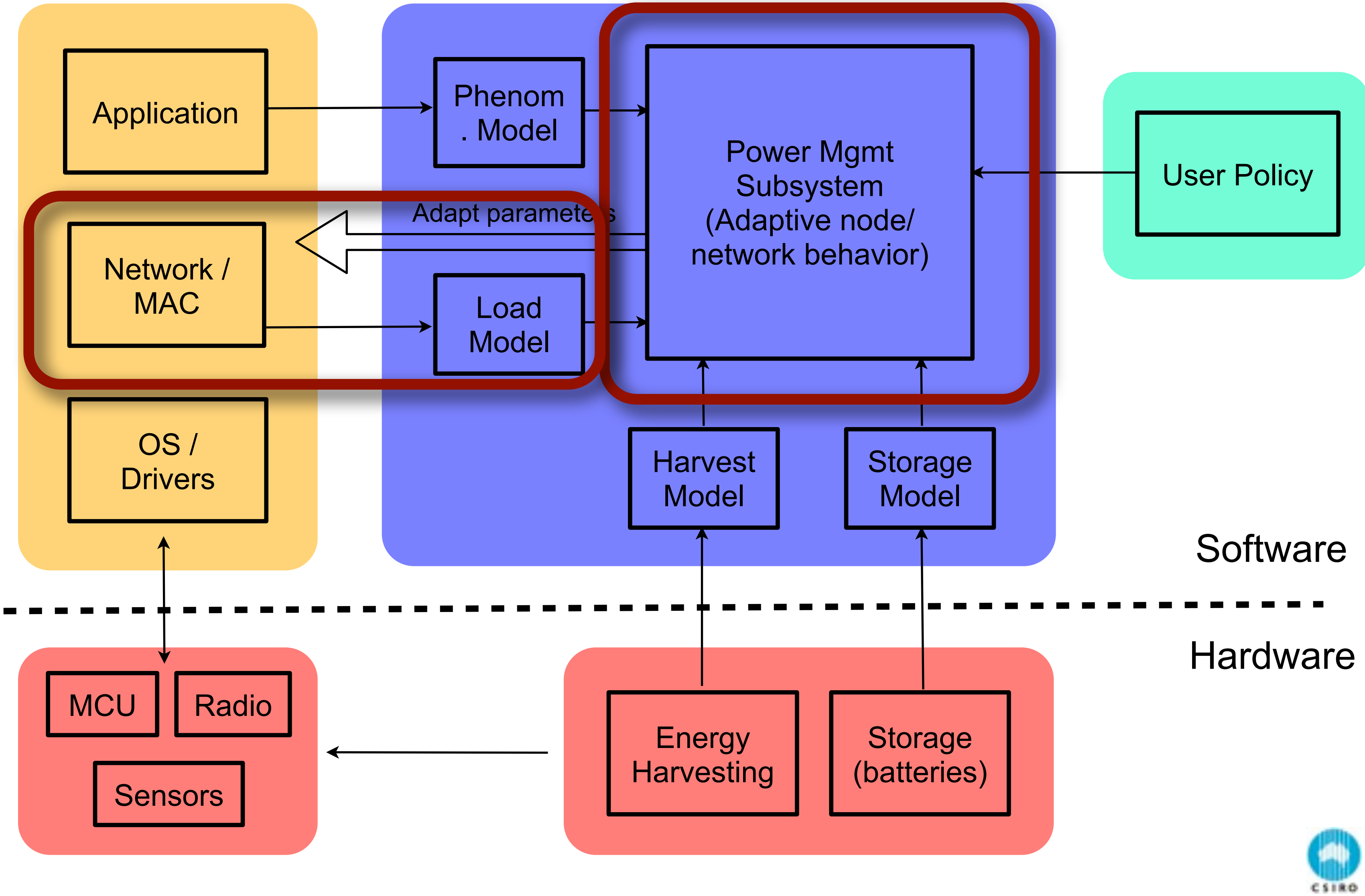


Evaluation

- Comparison of adaptive with min-max sampling rates



System Architecture



Adaptive Processing - Related Work

- A number of papers on adaptive processing
- Most just have the concept of a node duty cycle
  - Don’t really map through to the impact of this on the utility of the network

Energy Management	Adaptive duty-cycling		10
	Adaptive duty-cycling with solar energy harvesting		9, 6, 11, 19, ours
Solar energy and Prediction	System Implementations		9, 14, 3, 16, 13, 2, 18
	System Modelings		12, 18, 8
	Duty-cycling & prediction	node level	6, 19, 11, ours
		network level	4, 20
Adaptive sampling	Spatial		1, 22, 17
	Temporal	Event-trigerred	1, ours
		Filter-based	7, 15

What is a useful utility function?

- **Maximum amount of information** about phenomena being measured over the lifetime of network
- Network responsiveness
  - Feedback on state of the network / phenomena + ability to change the state of the network.
- Separate high-fidelity and low fidelity data:
  - High-fidelity data -> high latency
  - Low-fidelity data -> low latency

Sample rate **Report rate**

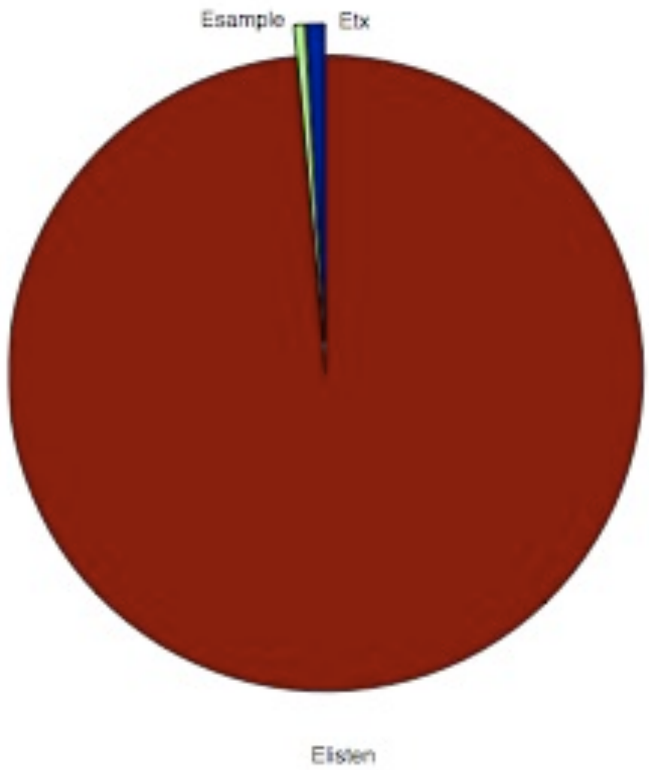
$$\max_{F_s,F_r} \quad \alpha F_s(k) + \beta F_r(k)$$

$$\alpha = F_s^{max} \text{ and } \beta = F_r^{max}$$

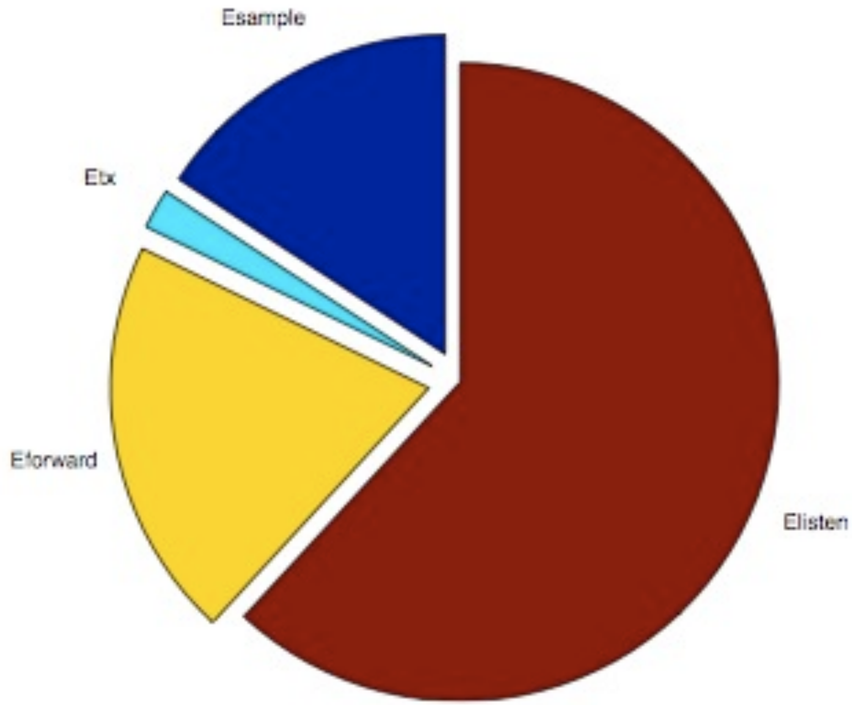
User parameters

Energy consumers in WSN

- In typical WSN applications, almost all energy is consumed by radio listening (LPL MAC):



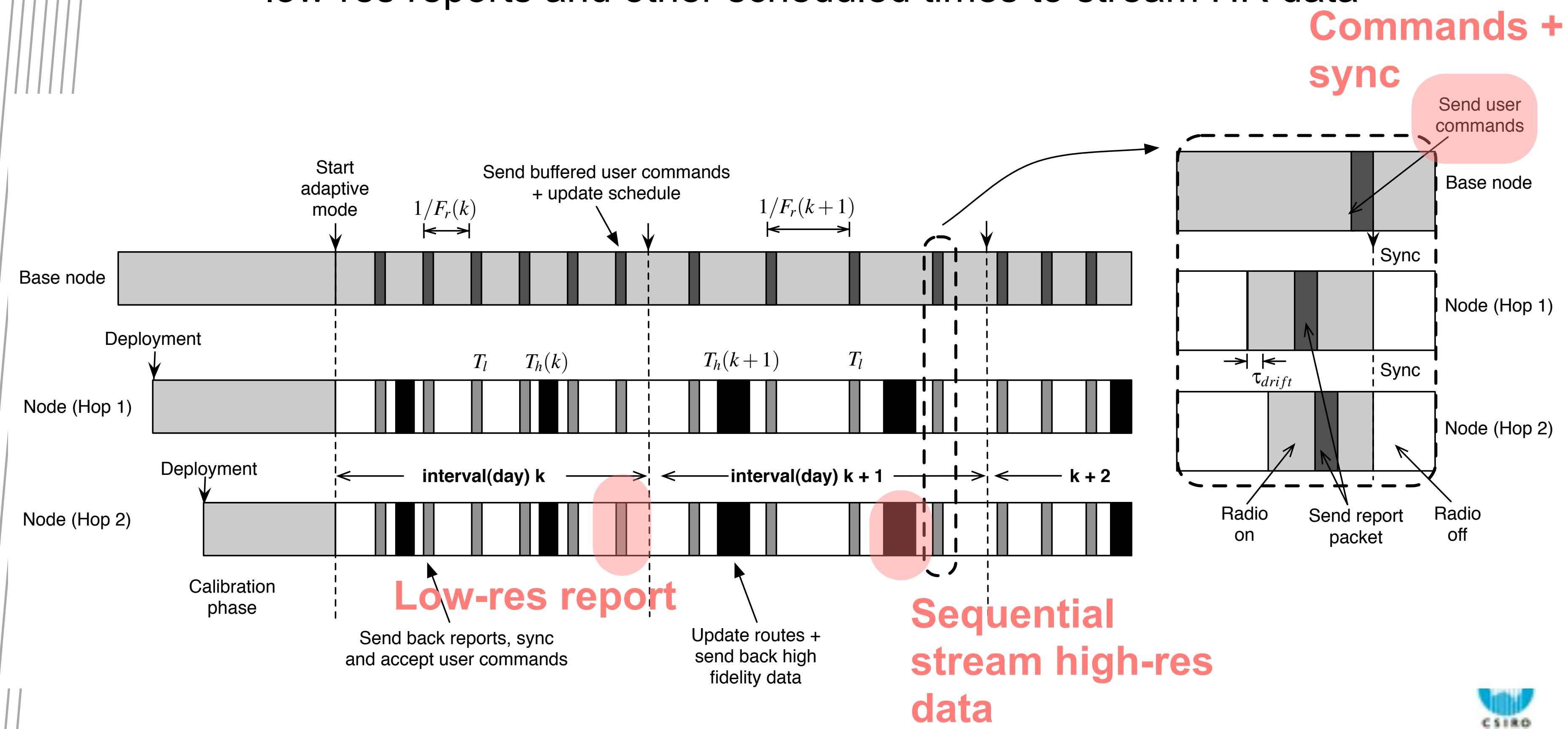
1 sensor / 5 min / no forward



7 sensor / 10 sec / 5 level forward

Network procrastination!

- Separate out the reporting of high-fidelity data from reporting of node and phenomena state
  - Currently investigating the feasibility of a protocol where where network radios are off, turning on at scheduled times to send back low-res reports and other scheduled times to stream HR data



Energy Neural Operation - Single hop scenario

- Goal of our system is to maintain, long-term energy neutral operation, whilst not using all available energy resources:

Consumed energy

$$N_k \left(E_{sleep}(k) + E_{samp}(k) + E_{lr}(k) + E_{hr}(k)\right) \leq \sum_{j=k}^{k+N_k-1} \left(\hat{E}_h(j) - E_l(j)\right)$$

Net harvested energy

System Optimization - Single hop scenario

- We then maximize the **sample frequency** and **summary report** frequency within the energy and user-policy constraints
- Formulate as a LP optimization problem:

$$\max_{F_s, F_r} \quad \alpha F_s(k) + \beta F_r(k)$$

Parameters to maximize

$$\text{subject to:} \quad \left(T_{int} N_s E_s + \left(\tfrac{\tau}{Nb}\right) P_{on} T_{int}\right) F_s(k)$$

Sample rate

$$+ \left(P_{lpl} T_{lr} T_{int}\right) F_r(k)$$

Summary report rate

$$\leq \frac{1}{N_k} \sum_{j=k}^{k+N_k-1} \left(\hat{E}_h(j) - E_l(j)\right) - E_{sleep}$$

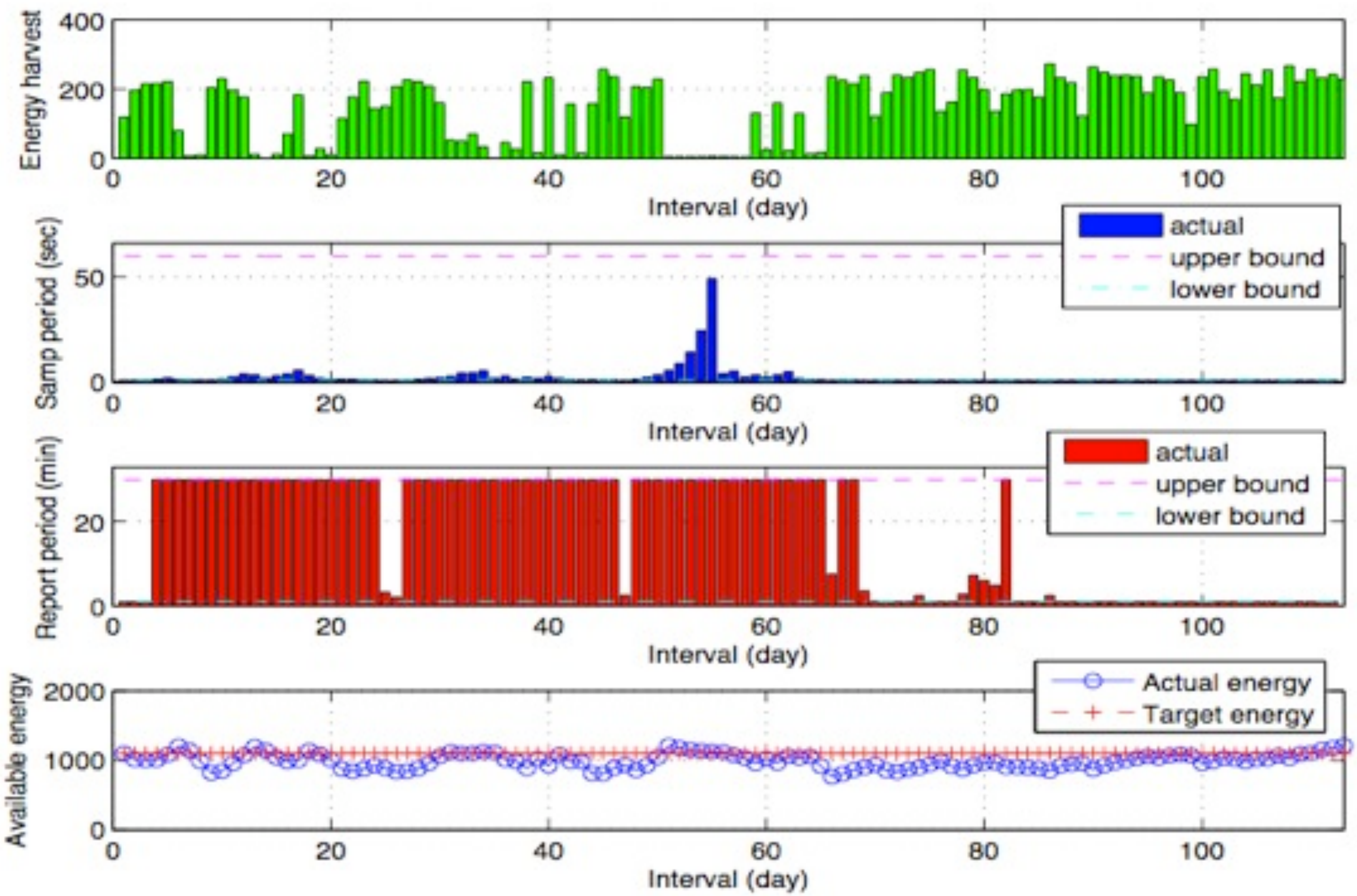
Net incoming energy

$$F_s^{min} \leq F_s \leq F_s^{max}$$
$$F_r^{min} \leq F_r \leq F_r^{max}$$

where $\alpha = F_s^{max}$ and $\beta = F_r^{max}$.

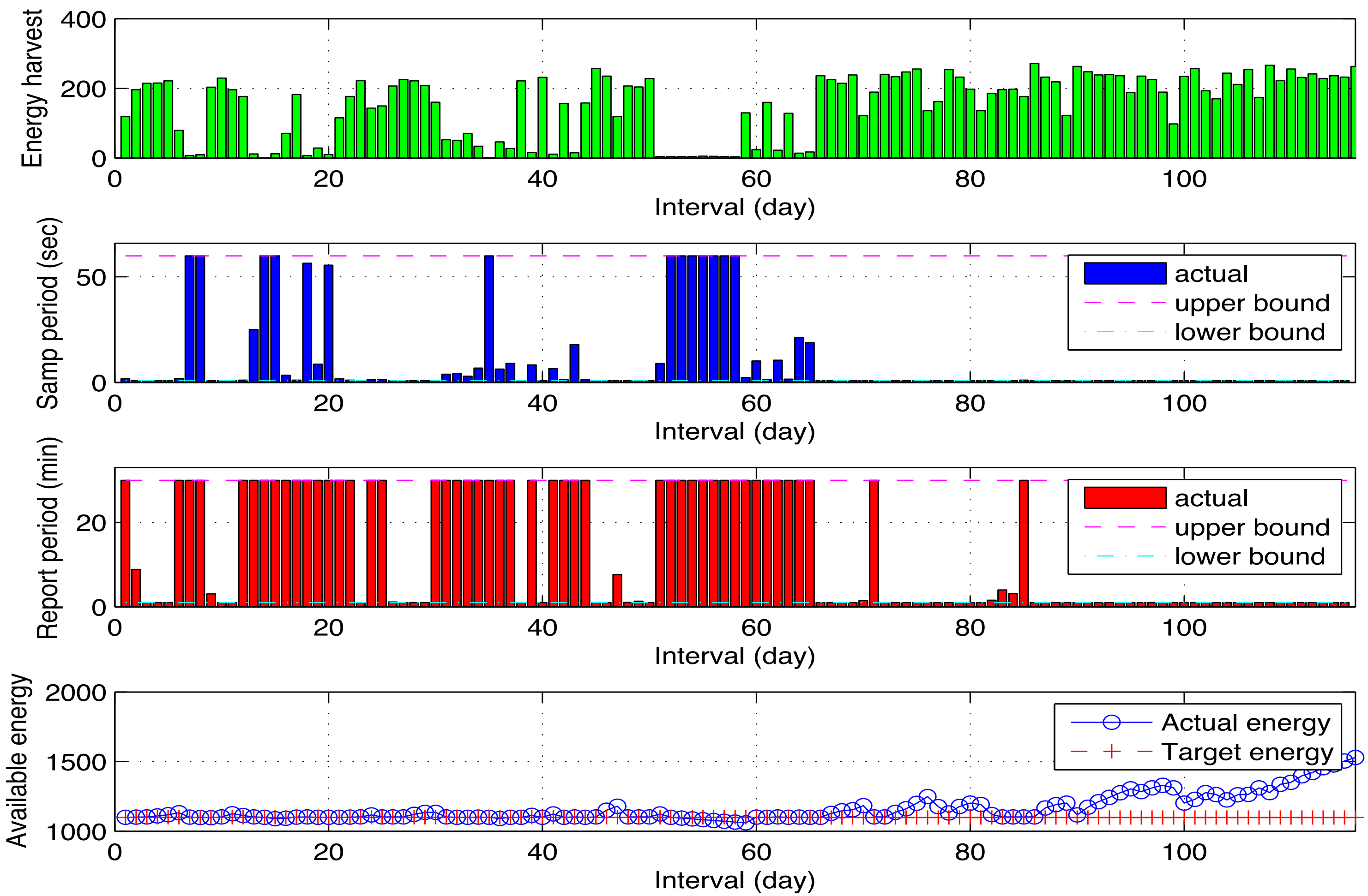
Adaptive Behavior

- Example of behavior of optimized system
  - 3 day ahead prediction



Adaptive Behavior

- Example of behavior of optimized system
  - today's prediction only

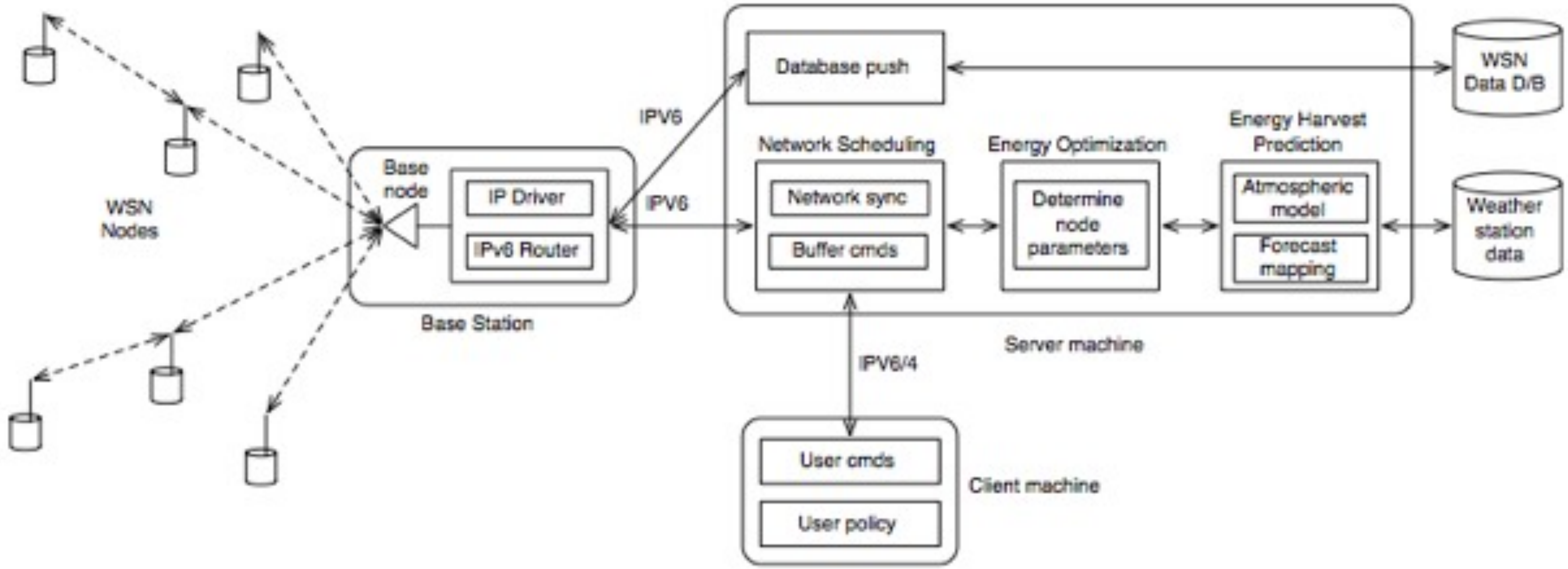


Current status

- Extending protocol to multi-hop networks
  - Need to incorporate times to update routing paths
  - Take into account forwarding cost in nodes
  - Nodes along the same path will need to synchronize their times for radios on for reports (added jitter interval) and sequential streaming - constrains freedom in these parameters
  - Look at adding energy awareness parameter to routing
    - e.g. nodes harvesting very little energy are biased to becoming leaf nodes (avoid forwarding cost)
- Incorporate existing protocols (e.g. CTP, Koala) to manage streaming back of high-fidelity data or manage all aspects
- Implementing with Berkeley IP stack for commands and data routing
- Extended indoor testbed and then outdoor deployment experiments

System Implementation

- Based around use of Berkeley low-power IPV6 stack for TinyOS 2.2 (BLIP)



Overview

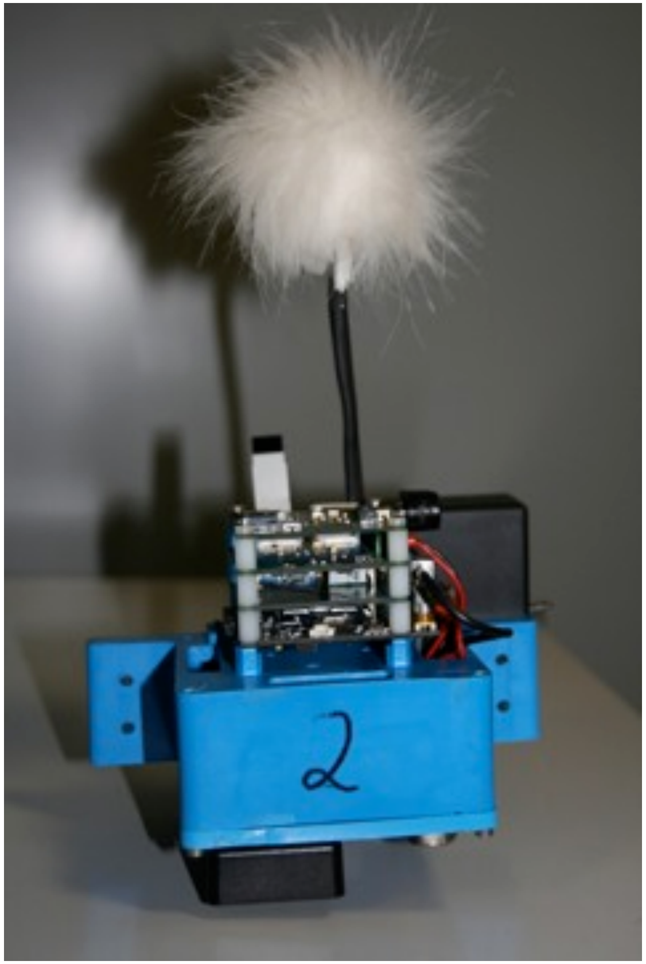
- Background of CSIRO's work in WSN
- Current application drivers
- Adaptive energy management
- **Audio/video processing in WSN**

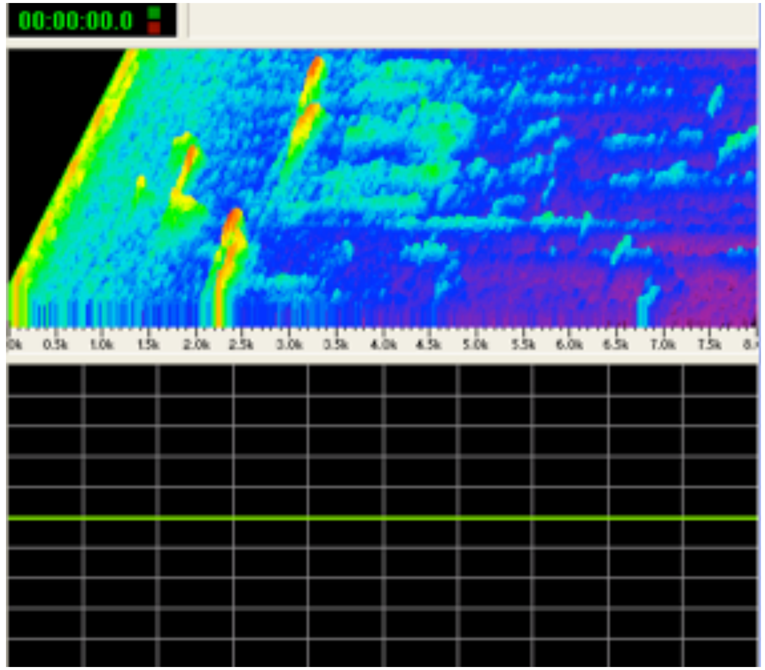
Multimedia nodes

- Increasing interest in the use of audio-visual nodes in deployments
- Adaptive energy mgmt strategies particularly important here given the high power consumption of various states of devices (e.g. DSP on)

Audio/Video nodes

- Audio nodes: current capability in recording and logging locally





Example of audio recorded and stored by Fleck audio node. (movie)

Acoustic Node Deployment 1

- Audio logged to SD flash card
  - Portions of audio corresponding to manual point count surveys marked
  - Temperature, humidity, node status, etc also logged to SD flash
- Data routed in real-time to 4WD gateway, then to database in Brisbane via NextG
  - Everything except the raw audio (temp, humidity, node status, average audio power)

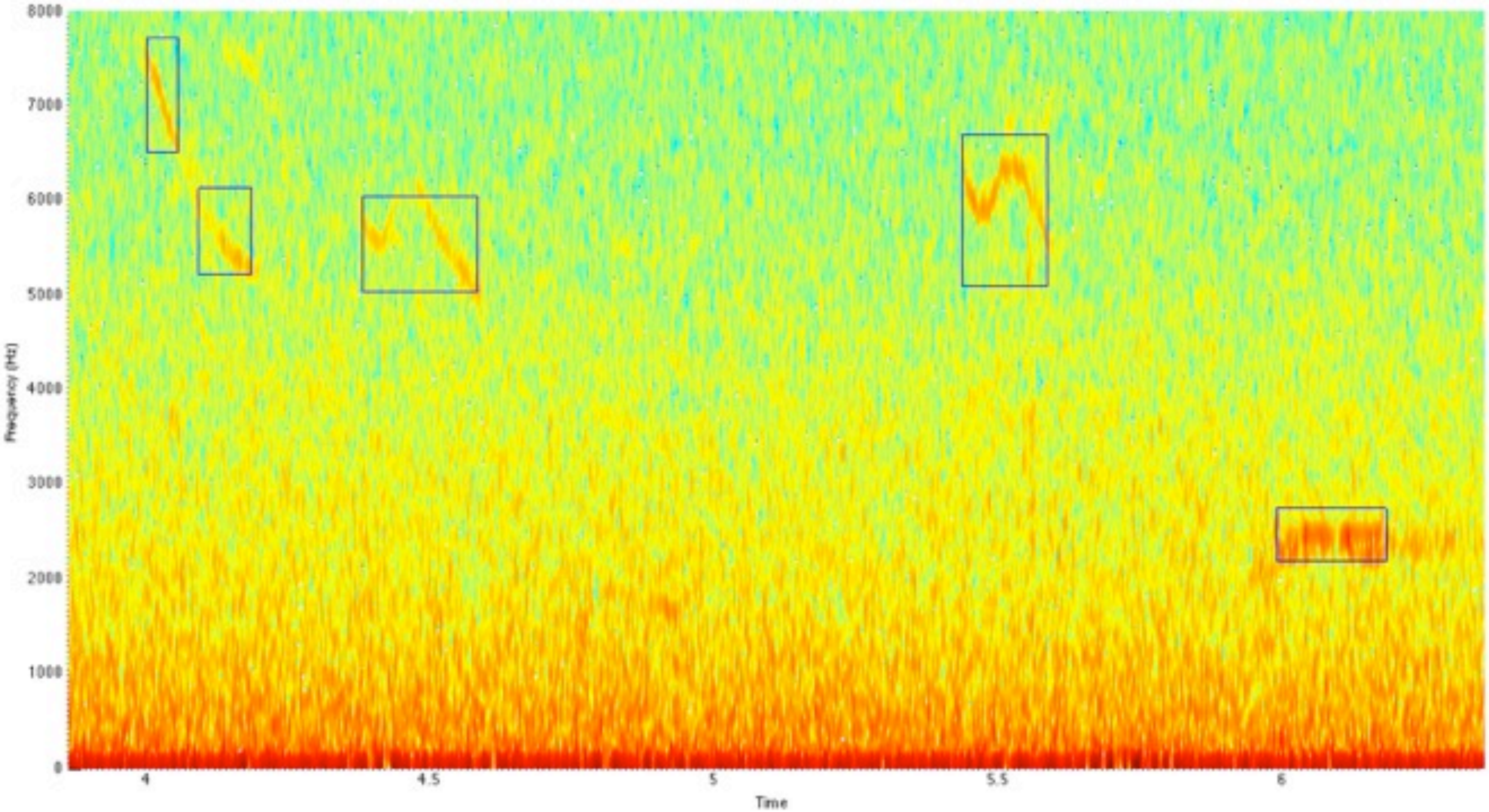
- Outcomes
  - Approx. 300hrs audio collected over 2 week period
  - Manual point count survey data for around 10hrs of this
    - ground truth labelling

Acoustic Node Deployment 2

- Upper Somerset Catchment (Maleny/Woodford)
- Deployed January 2009
- SEQWater study monitoring frog populations as an indicator of water quality in creeks that feed into Somerset Dam
  - Initial 1-week manual survey period by SEQWater
  - Deployment of individual nodes at 6 locations for 3 months
    - No networking (except for in-situ configuration during deployment)
    - Logging of audio + temp/humidity according to schedule (2-3 hours/night)

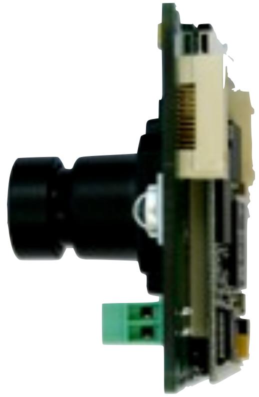
Audio Processing (cont.)

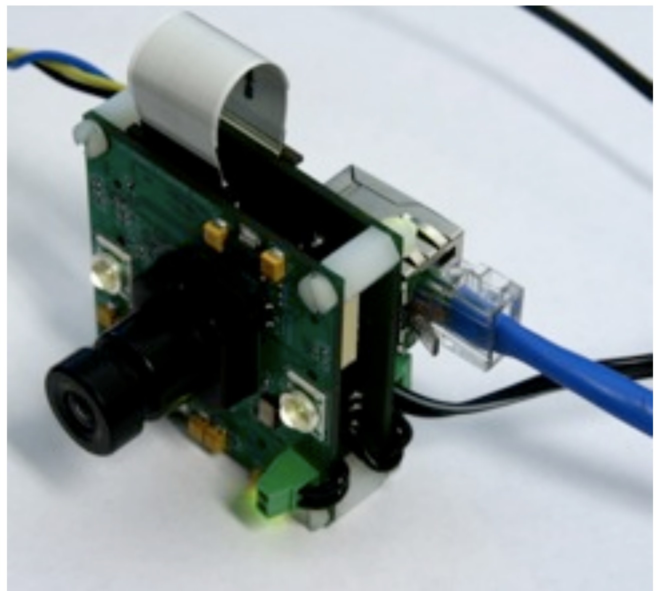
- Time-frequency segmentation of audio for events of



AD Blackfin DSP / Camera Board

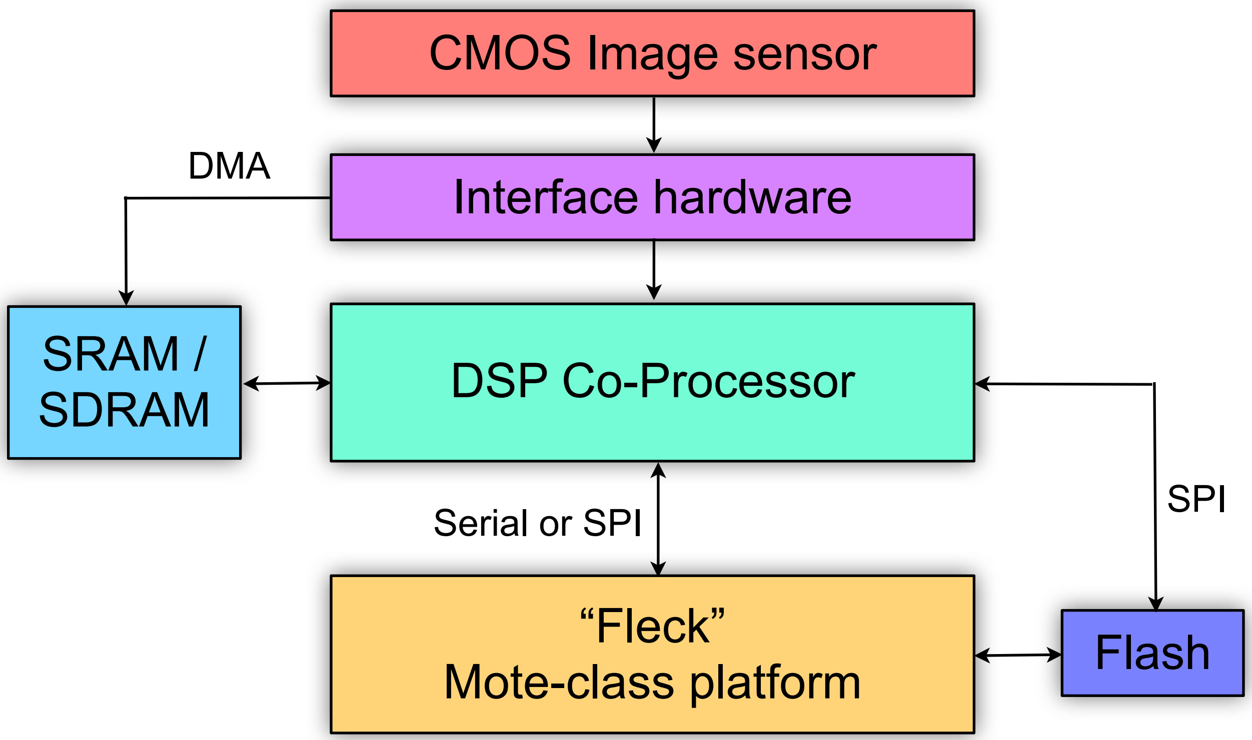
- Blackfin DSP (ADSP-BF537)
  - AD 32 bit, 600 MHz processor
  - 132KB SRAM + 32MB external SD RAM
  - 4MB flash
  - 16bit external memory bus
  - No MMU
  - Runs uClinux or AD Visual DSP++
- Programming
  - JTAG or ethernet interface for programming
- Fleck interface
  - Serial
  - (Currently implementing SPI interface - with Fleck as SPI master)





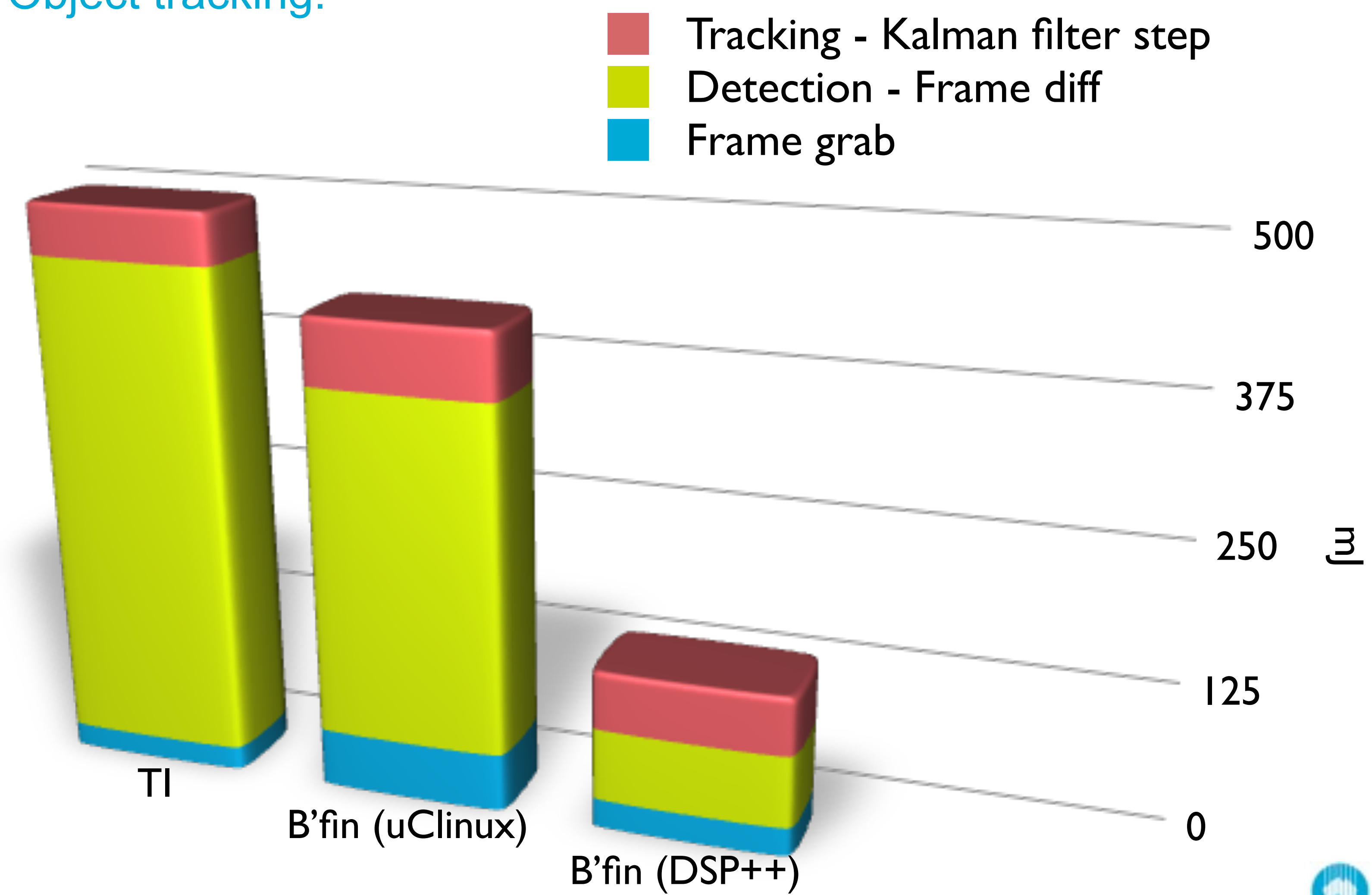
Camera hardware architecture

- Given the limited resources in “mote-class” platforms we introduce an additional co-processor for dealing with raw image information



Platform Comparisons - Energy

- Object tracking:

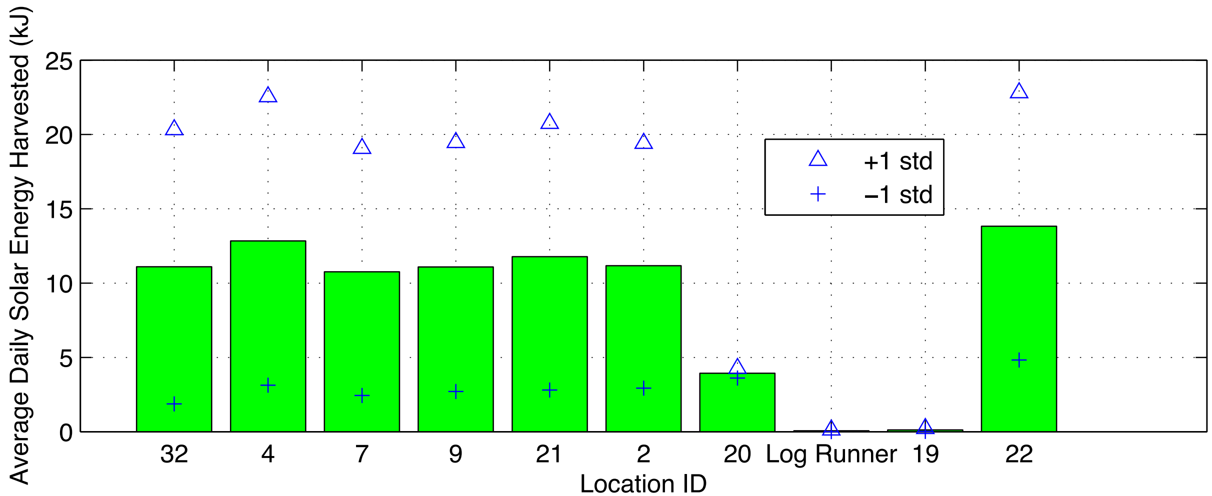


* Frame diff not done at every step

Energy - putting it into perspective

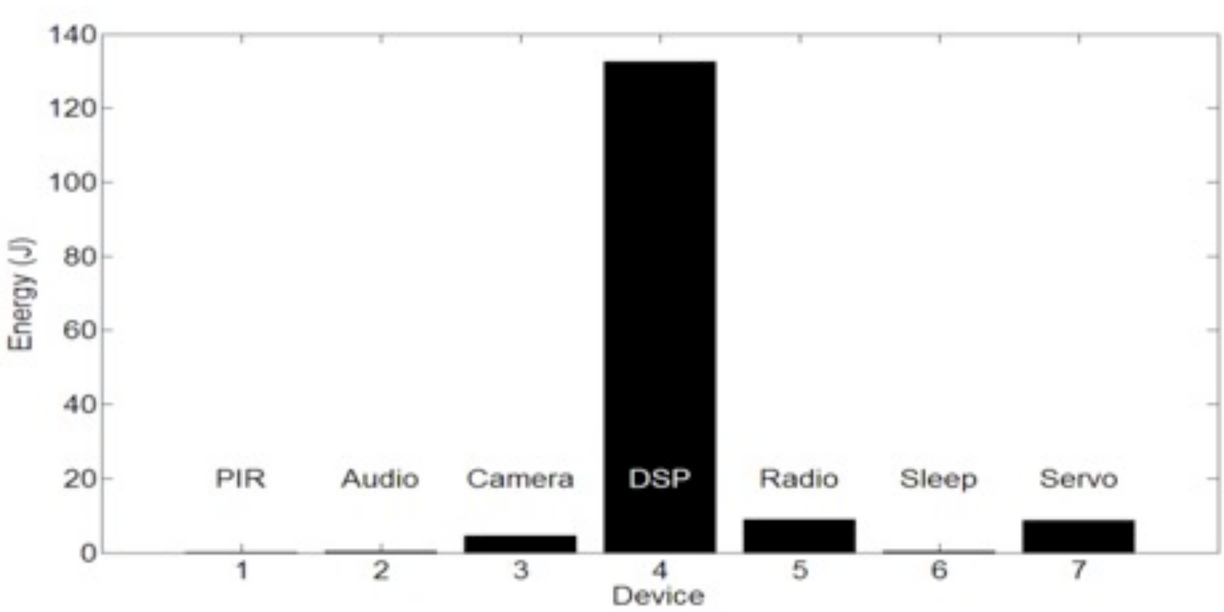
- Battery storage
  - Battery capacity: 2700mAh @ 3.3V (~32kJ)
  - Image-grab, Compression (ignore power-up/down time)
    - TI: ~100 000 images, B'fin - DSP++: ~260,000 images
  - Tracking (continuous @ 10 frames / second)
    - Blackfin (DSP++): ~260,000 frames or ~7 hours

- Solar power
  - 6V, 300mA poly-crystalline panel



Camera node capabilities

- Capabilities under development:
  - Smart energy management
  - Calibration
  - Event detection
  - Multi-camera Object Tracking
  - Compression



Future Research Directions

- Continuing work in meeting goals of maximizing the utility of environmental sensor networks within energy and user-policy constraints
- Energy management for AV nodes
  - Extend work with adaptive energy management to audio-video nodes
  - Smart triggering strategies
- Effective cooperation of nodes with different capabilities
  - Audio, video, microclimate, etc
  - How do we program these types of networks to achieve a single task?

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Thank you

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