Summary: Analysis of Wireless Sensor Networks for Habitat Monitoring

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J. Polastre, R. Szewczyk, A. Mainwaring, D. Culler, and J. Anderson, “Analysis of wireless sensor networks for habitat monitoring,” in Wireless Sensor Networks, 2004, Springer.

Wireless Sensors Networks - Introduction

Wireless Sensor Networks have been used for:

- Fine-grain distributed control
- Inventory and supply-chain management
- Environmental and habitat monitoring

Environmental and Habitat Monitoring- Introduction

Sensor network services useful for:

- Localization
- Tracking
- Data allocation
- Energy-efficient multihop routing

Environmental and Habitat Monitoring- Introduction

Aspects of the system to deploy:

- Communication protocols
- Sampling mechanism
- Power management

Approach: Application driven

Goal : Develop effective sensor network architecture for monitoring applications

Mode of sensing in 2003 - Introduction

- Interested in high fidelity data from the environment
- Typically use sensors on probes
- Traditional data loggers
- Sophisticated weather stations

Mode of sensing in 2003 - Introduction

- Interested in high fidelity data from the environment
- Typically use sensors on probes **- Expensive**
- Traditional data loggers **- Expensive**
- Sophisticated weather stations **- Can monitor different microclimate**
- Problem with direct with human interaction
    - Maine: 15 minute visit → Up to **20% mortality** among eggs/chicks
    - Kent Island: **Hatching success** of Petrel eggs **reduced by 56%**

Enter Wireless Sensor networks

- Significant advance over traditional and invasive methods
- Small nodes deployed prior to sensitive period
- Deployed on small islets previously unsafe for repeated field studies

Key difference with data loggers and traditional probes:

- Real-time data access
- More economical than installing many data loggers
- May greatly increase access to wider arrays of study sites

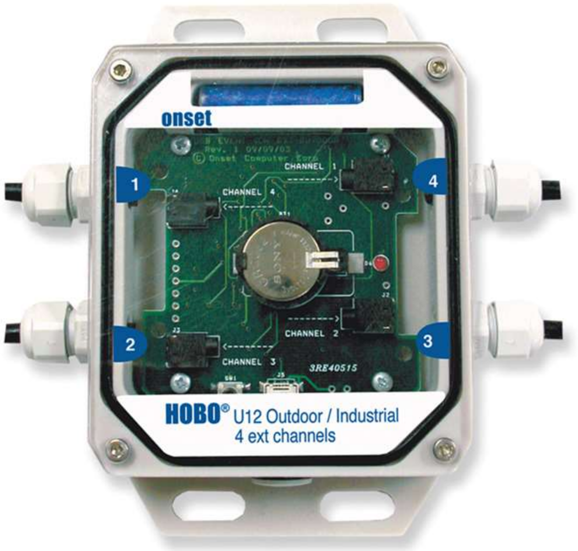


Figure 1: Outdoor data logger (image not from the paper—just an example) [1]

Great Duck Island

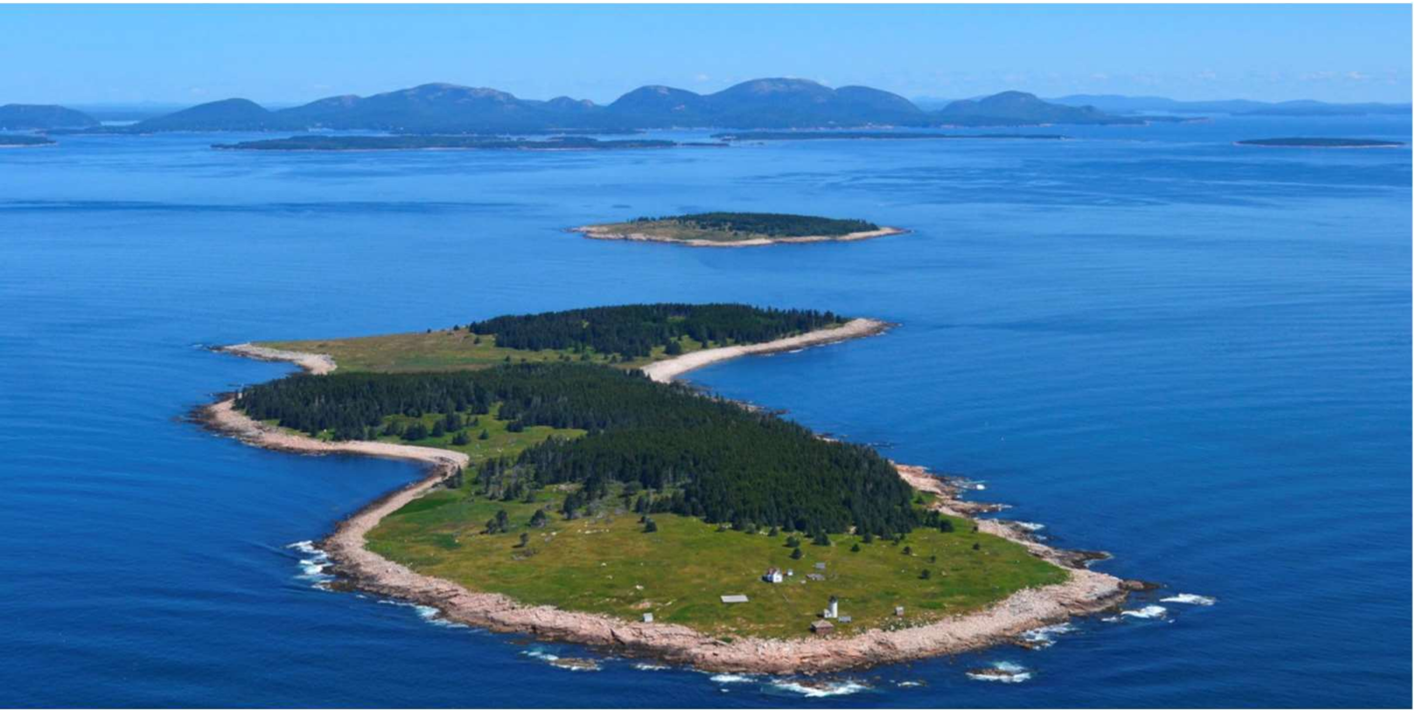


Figure 2: Great Duck Island [2]

- 237 acre island
- 15 km south of Mount Desert Island, Maine
- Approx. 5000 pairs of Leach's Storm Petrel

Great Duck Island - 4 Questions

1) Usage pattern of nesting burrows
    - over 24-72 hr cycle
    - one or both members of breeding pair alternate incubation duties

2) Environmental changes that occur inside and on the surface
    - During seven month breeding season (April to October)

Figure 3: Leach’s Storm Petrel [3]

Great Duck Island - 4 Questions

3) Variation across petrel breeding sites

- Optimal microclimate for breeding, incubation, and hatching

4) Difference between two microenvironments

- Large vs Low number of nesting petrels

Figure 4: Leach’s Storm Petrel [3]

Below the ground: burrows and sensor nodes

- Within 2-6 cm from the surface
- 40 cm to 1 m in length
- Internal diameter approx. 6 cm
- One sensor node per burrow
- Patches may contain 50 burrows

Figure 5: Petrel burrows example (image not from the paper) [5]

Above the ground

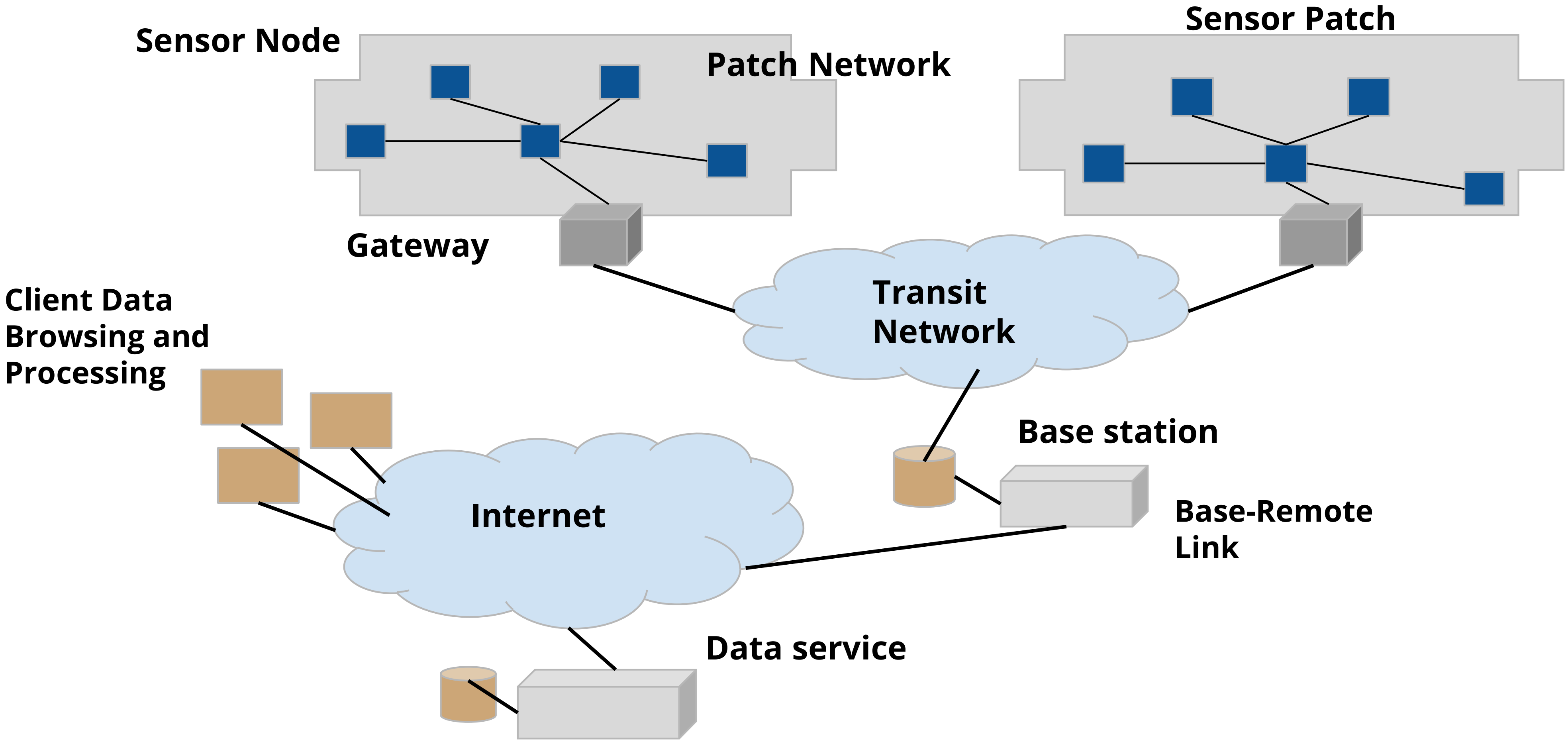
- Environmental conditions vary widely
- Variation in vegetation, density, exposure, location, etc
- Humidity varies depending on vegetation
- Above-ground Vs. Below-ground microclimates

Setup and Network Architecture

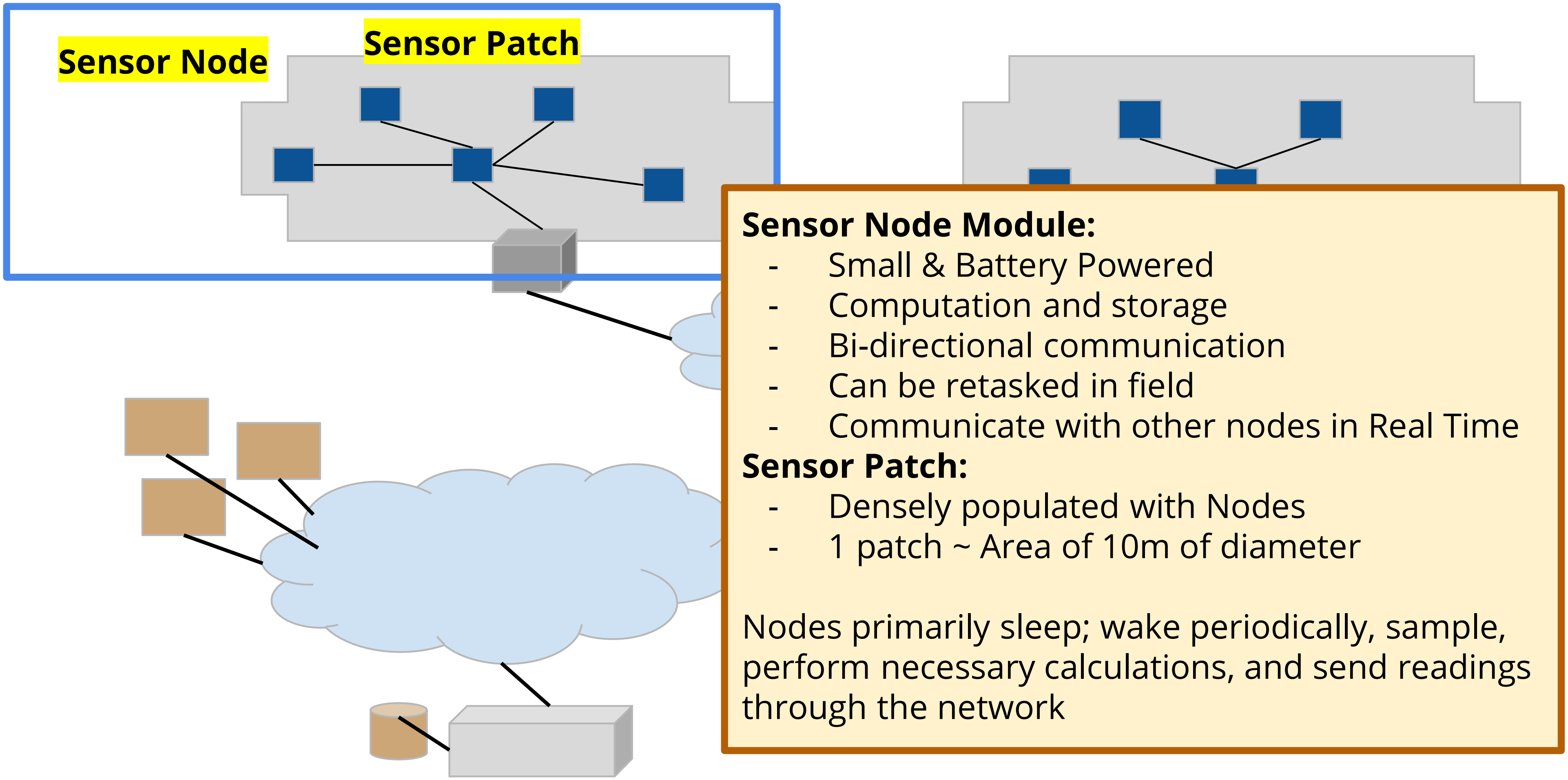
Requirements of the Network Architecture:

- Manage Power consumption over a period of 5 months (Petrel Cycle)
- Operate on the spatial scale of the organism
- Operate at frequencies that match the environment
- Collect data at a rate equal to or greater than the environmental changes that the organism senses i.e. 5-10 times a day.
- Sensors operate reliably and predictably.

Setup and Network Architecture



Setup and Network Architecture



Sensor Node Module:

- Small & Battery Powered
- Computation and storage
- Bi-directional communication
- Can be retasked in field
- Communicate with other nodes in Real Time

Sensor Patch:

- Densely populated with Nodes
- 1 patch ~ Area of 10m of diameter

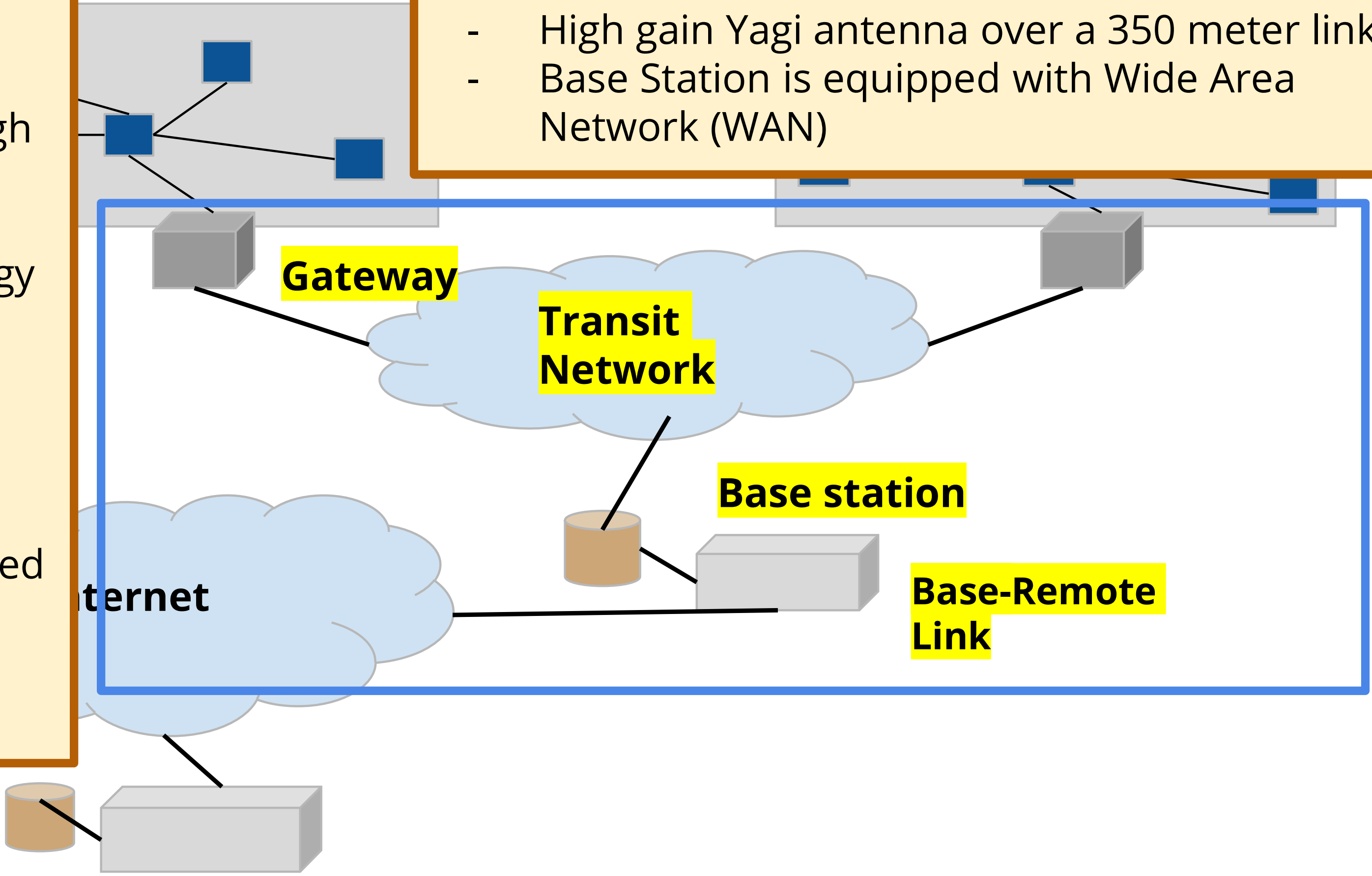
Nodes primarily sleep; wake periodically, sample, perform necessary calculations, and send readings through the network

Setup and Network Architecture

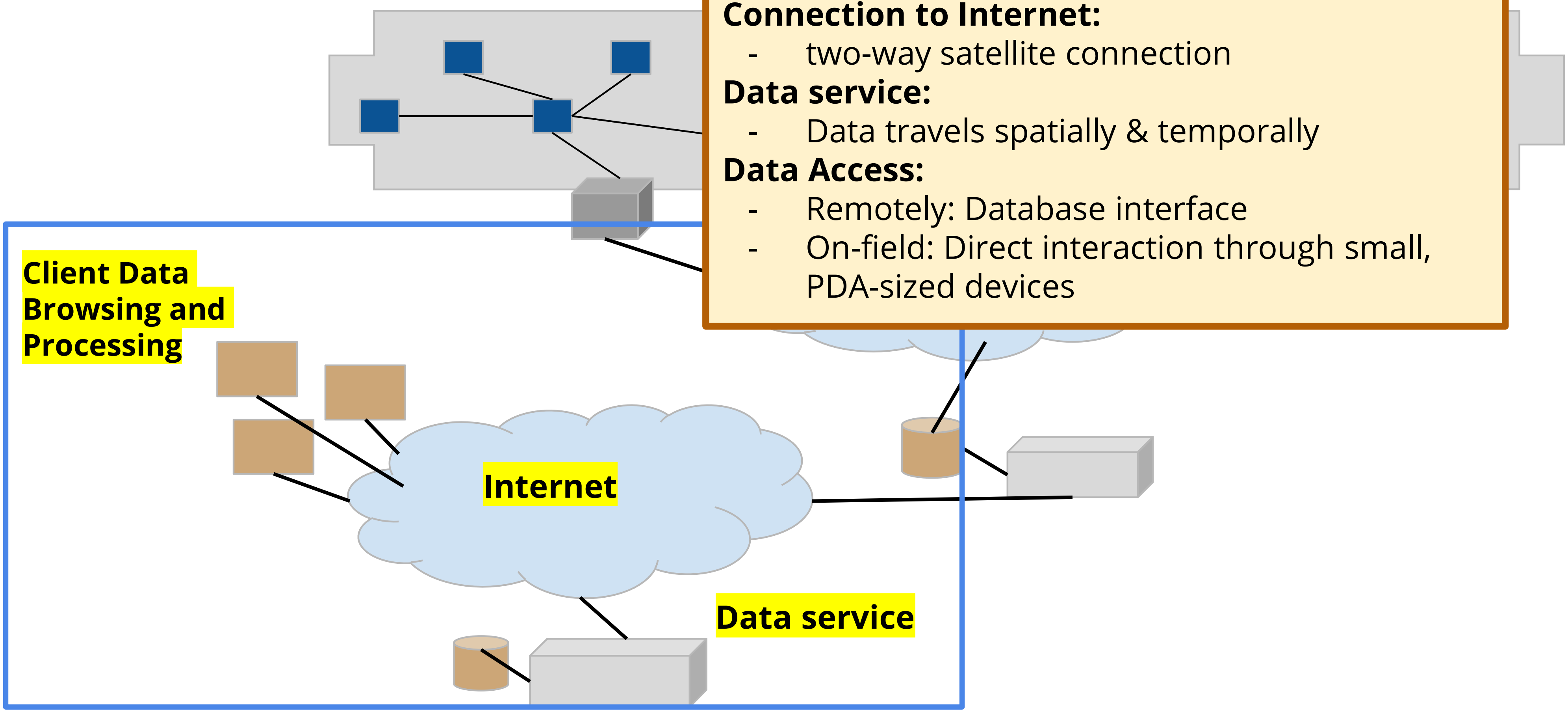
Gateaway:
- A bridge that connects the sensor network to the base station through a transit network
- May include Infrastructure for energy harvesting, batteries, solar panels

Transit Network:
- A single repeater node
- Repeater node ran at a 100% duty cycle powered by a solar cell and rechargeable battery

Remote Link and Communication:
- High gain Yagi antenna over a 350 meter link
- Base Station is equipped with Wide Area Network (WAN)



Setup and Network Architecture



Connection to Internet:
- two-way satellite connection

Data service:
- Data travels spatially & temporally

Data Access:
- Remotely: Database interface
- On-field: Direct interaction through small, PDA-sized devices

Application Implementation

- Application Software
- Sensor Board Design
- Packaging Strategy
- Experimental Goals

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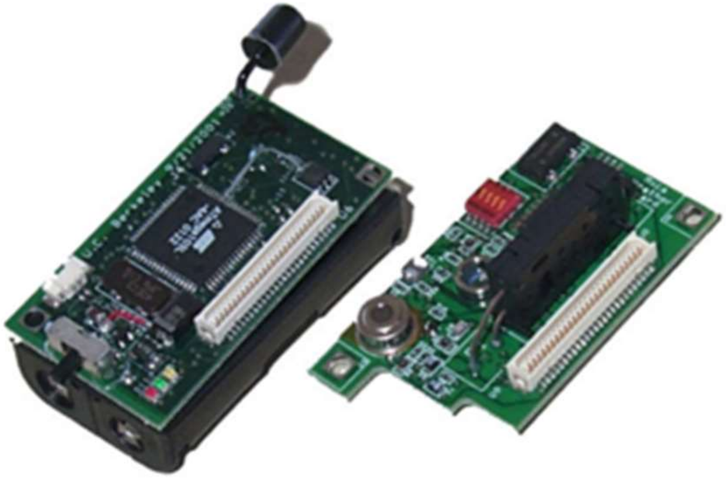

Figure 6: Mica Mote (left) and Mica Weather board (Right) [4]

- Mica mote & Mica Weatherboard sensor
- Low-power peer-to-peer wireless networks
- **Measurement:** 1.25 × 2.25 inches *[4]*
- TinyOs operating System
- **Sampling Rate:** Each node per 70 seconds
- **Data transmitted:** 36-byte data packet which are time stamped with 32-bit sequence numbers.
- **Peer-Peer packets** are shuttled using media access control (MAC) protocol

Application Implementation

- Application Software
- **Sensor Board Design**
- Packaging Strategy
- Experimental Goals

- **Mica Weatherboard sensor**
- **Single Package - light, temperature, humidity, pressure and IR (Thermopile) sensor**
- **Non-intrusive**
- **Fits the size constraint of the petrel-burrow**

Designed Mica Mote

Environmental conditions:
- Photoresistive sensor
- Digital Temperature Sensor
- Capacitive Humidity Sensor
- Digital Pressure Sensor

Occupancy:
- Passive IR detector/ Thermopile

Application Implementation

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Occupancy:

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Miniaturization

12-bit ADC for resolution maximization

Interdependencies among sensors

Failed to consider Fault Isolation

Application Implementation

- Application Software
- Sensor Board Design
- **Packaging Strategy**
- Experimental Goals

Figure 7: Enclosure for above the ground sensors

Requirements:

- Packaging is compatible with environmental conditions:
  - pH < 3, dew, dense fog, flooding
  - Waterproof Packaging

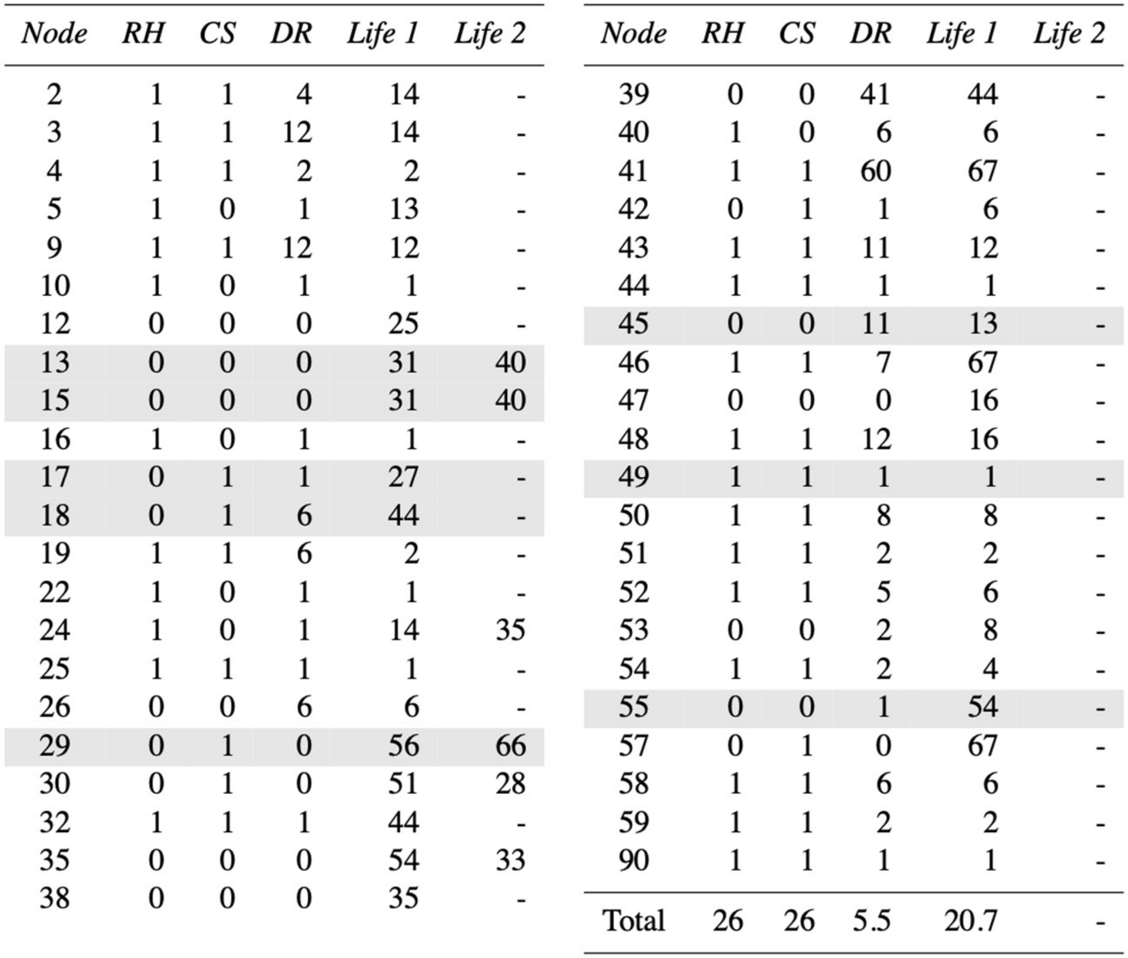
Implementation:

- Sealed the entire mote with Parylene Sealant.
- In-burrow motes - No enclosures
- Above the ground - Placed in ventilated acrylic enclosures

Application Implementation

- Application Software
- Sensor Board Design
- Packaging Strategy
- **Experimental Goals**
  - Verify Deployment Robustness
  - Meet Low-power requirement
  - Sealant efficacy
  - Radio Performance in and out of burrows
  - Node operation and Packet delivery

System Analysis

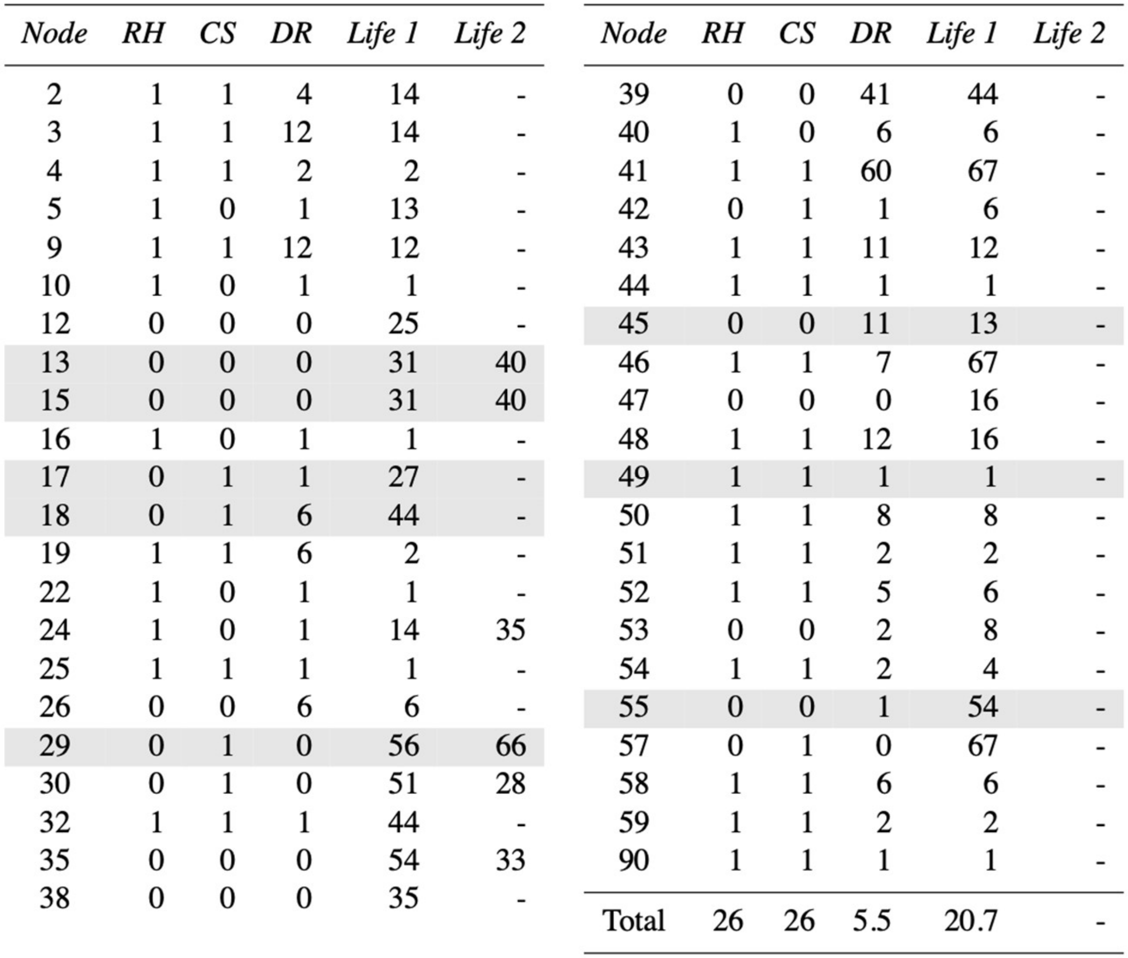


Node	*RH*	*CS*	*DR*	*Life 1*	*Life 2*
2	1	1	4	14	-
3	1	1	12	14	-
4	1	1	2	2	-
5	1	0	1	13	-
9	1	1	12	12	-
10	1	0	1	1	-
12	0	0	0	25	-
13	0	0	0	31	40
15	0	0	0	31	40
16	1	0	1	1	-
17	0	1	1	27	-
18	0	1	6	44	-
19	1	1	6	2	-
22	1	0	1	1	-
24	1	0	1	14	35
25	1	1	1	1	-
26	0	0	6	6	-
29	0	1	0	56	66
30	0	1	0	51	28
32	1	1	1	44	-
35	0	0	0	54	33
38	0	0	0	35	-
39	0	0	41	44	-
40	1	0	6	6	-
41	1	1	60	67	-
42	0	1	1	6	-
43	1	1	11	12	-
44	1	1	1	1	-
45	0	0	11	13	-
46	1	1	7	67	-
47	0	0	0	16	-
48	1	1	12	16	-
49	1	1	1	1	-
50	1	1	8	8	-
51	1	1	2	2	-
52	1	1	5	6	-
53	0	0	2	8	-
54	1	1	2	4	-
55	0	0	1	54	-
57	0	1	0	67	-
58	1	1	6	6	-
59	1	1	2	2	-
90	1	1	1	1	-
Total	26	26	5.5	20.7	-

- Node community on Great Duck Island.

- **Some nodes fell victim to:**
    - Humidity readings of zero
    - Significant clock skew

System Analysis



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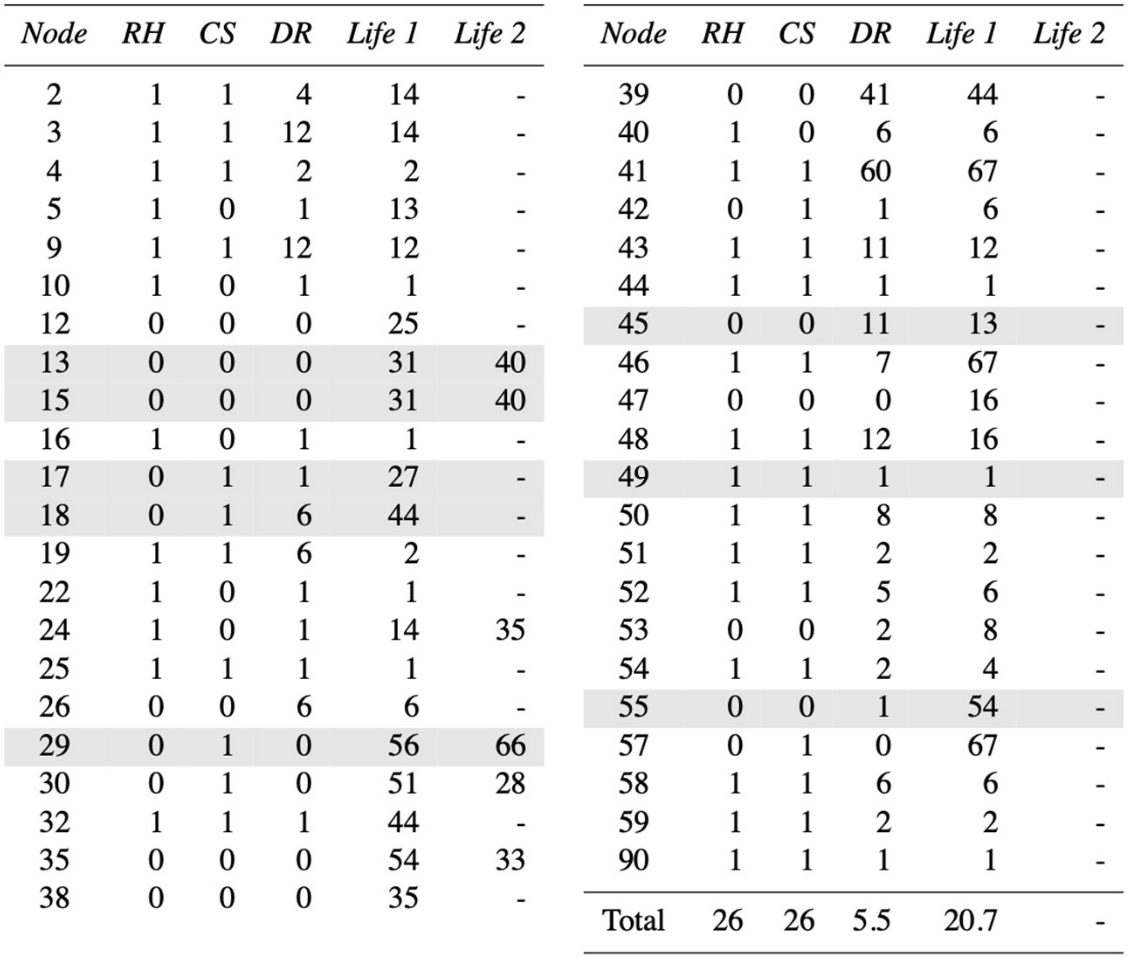
Total	26	26	5.5	20.7	-

Terms:

- **RH** = 1, experienced raw relative humidity readings
- **CS** = 1, experienced excessive clock skew
- **DR**: "Death Row"
  - no. of days after the first sign of abnormality

System Analysis



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Total	26	26	5.5	20.7	-

Terms:

- Life 1: Lifetime for first battery (in days)
- Life 2: Lifetime for second battery (if first died)

Network Analysis

Application: Single hop network

- Want to examine WSN and its performance over time

Two areas considered:

- Packet loss
- Network dynamics

Network Analysis - Packet Loss

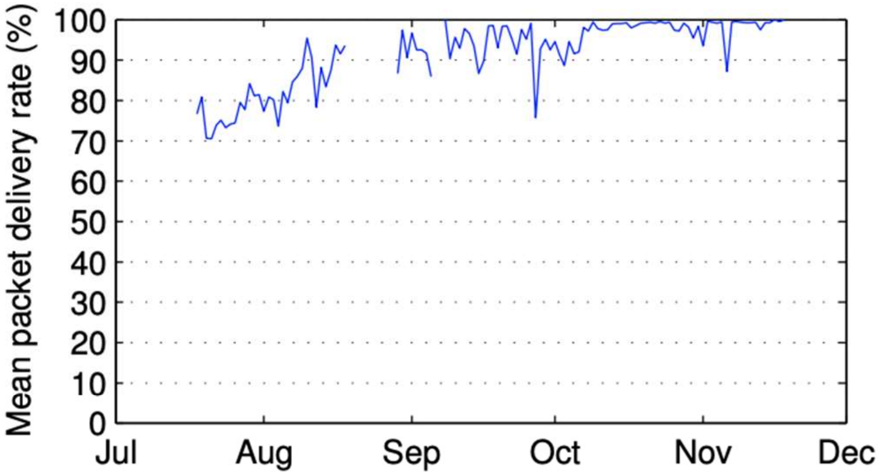
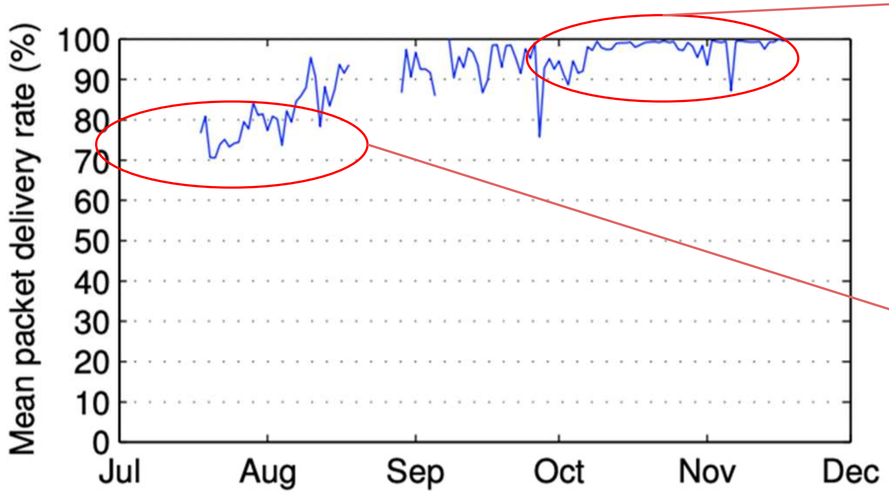


Figure 18.4. Average daily packet delivery in the network throughout the deployment. The gap in the second part of August corresponds to a database crash.

- Primary metric of network performance
- Indicates effective end-to-end application throughput

Network Analysis - Packet Loss

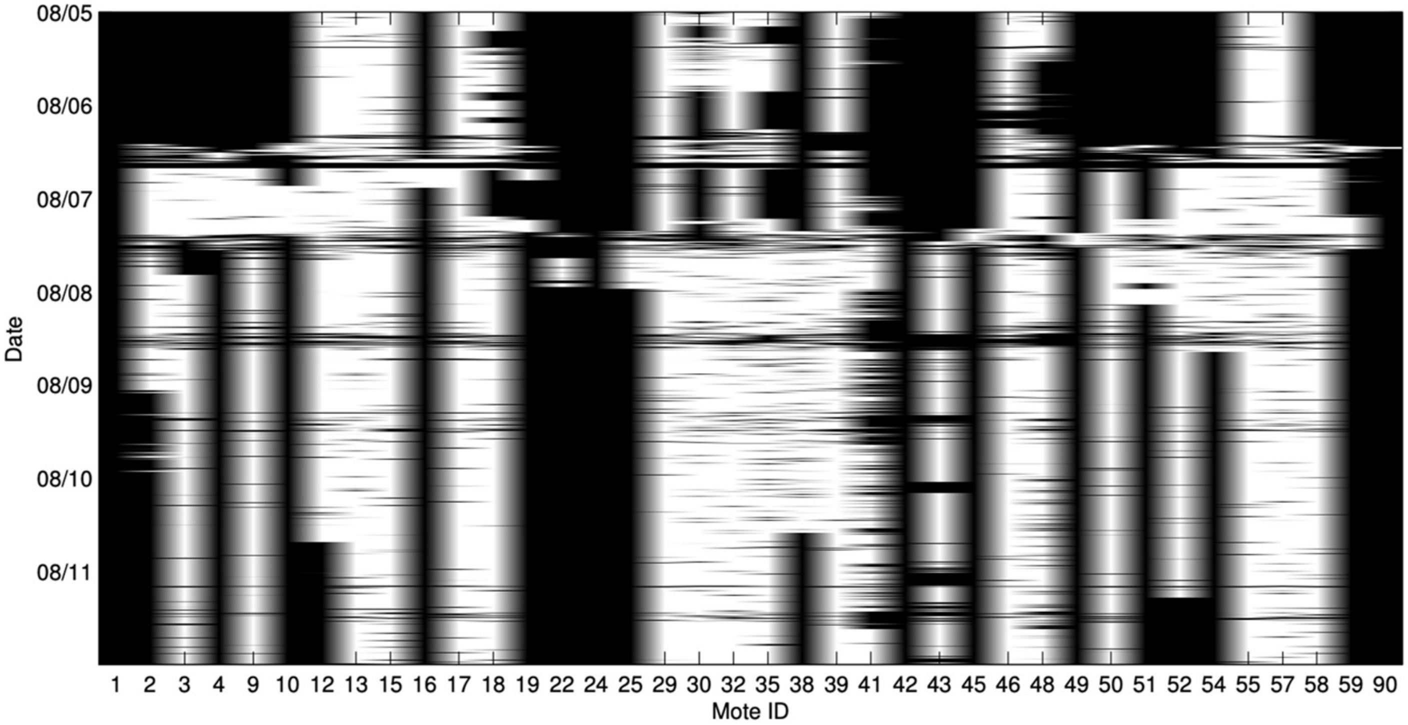


2) Why does the network improve with time?

1) Why was the initial loss rate high?

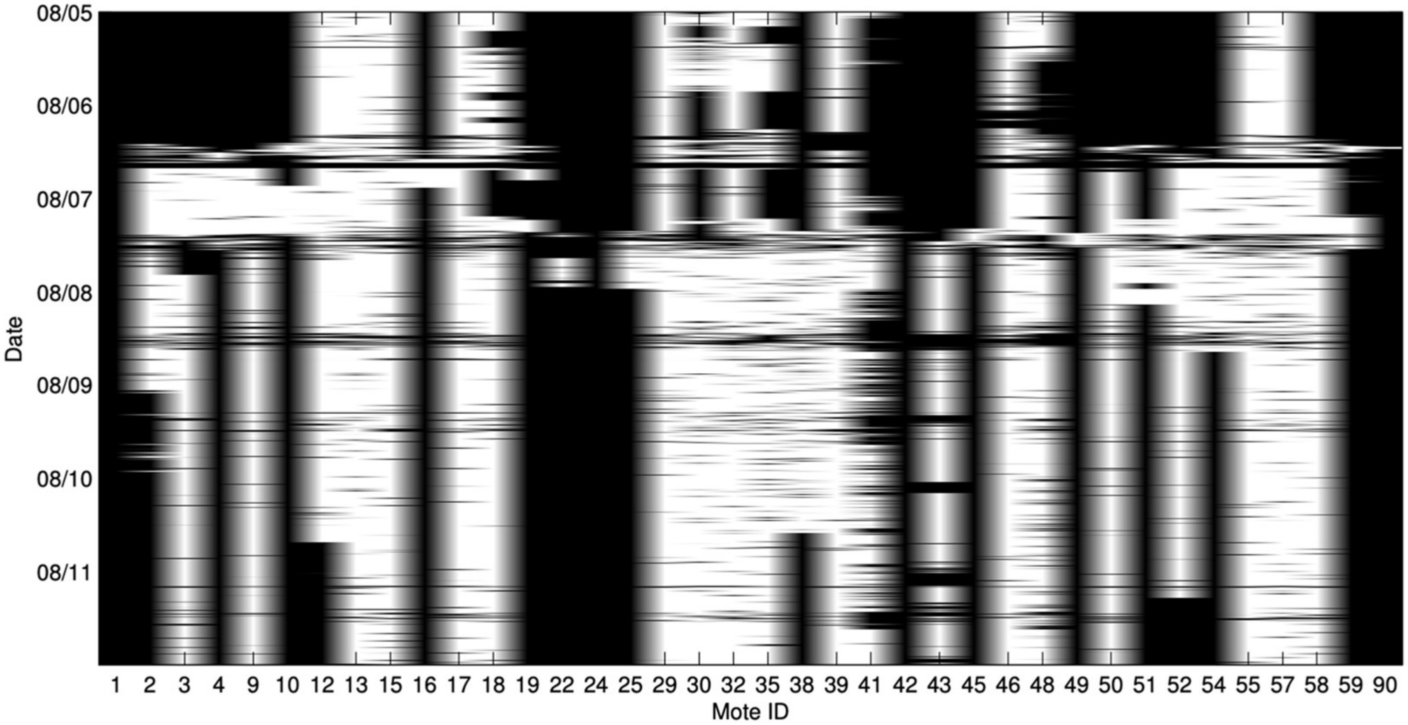
Figure 18.4. Average daily packet delivery in the network throughout the deployment. The gap in the second part of August corresponds to a database crash.

Packet loss patterns during the 1st week of August 2002



- Assign virtual time slots to each data packet
- Corresponds to a particular sequence number from each node
- Data split into time slices.

Packet loss patterns during the 1st week of August 2002



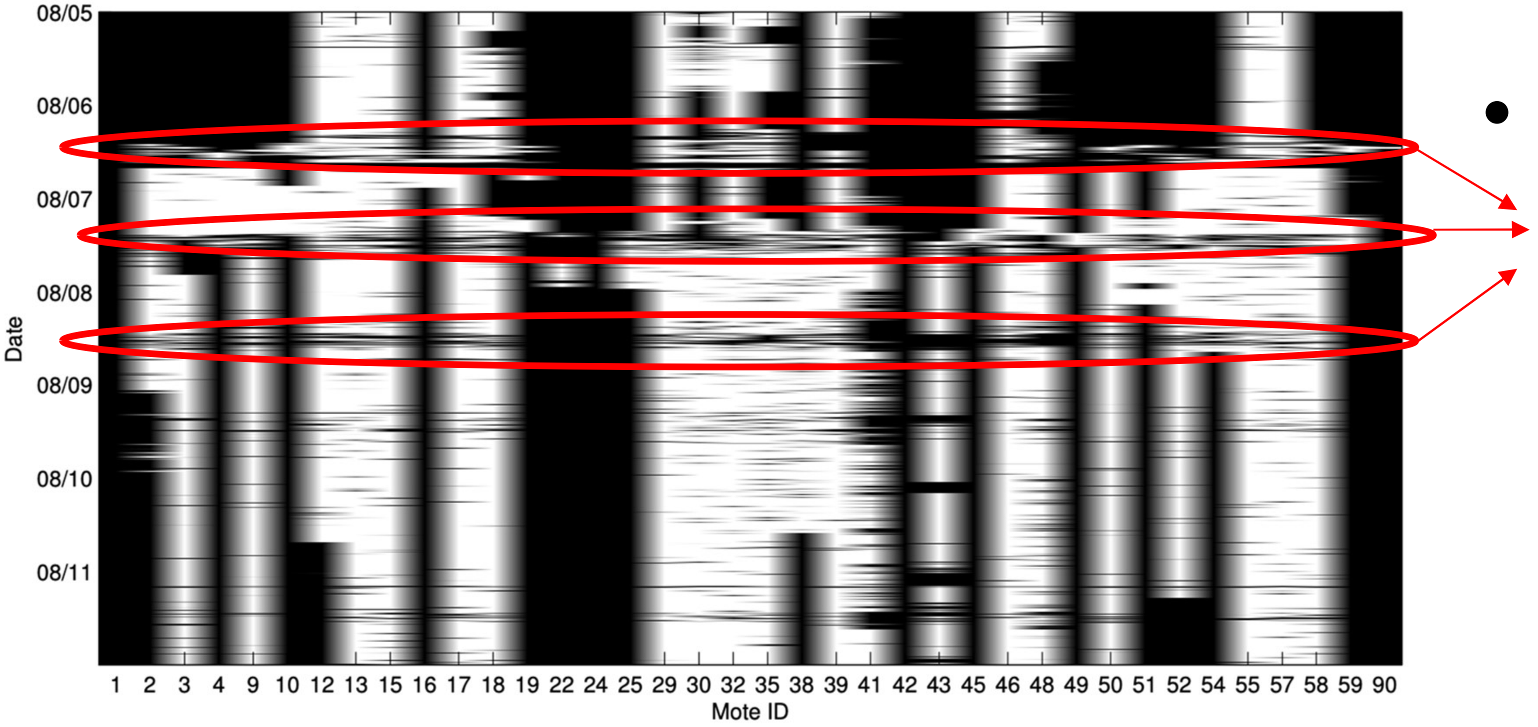
Black line:

- A packet expected to arrive was lost.

White line:

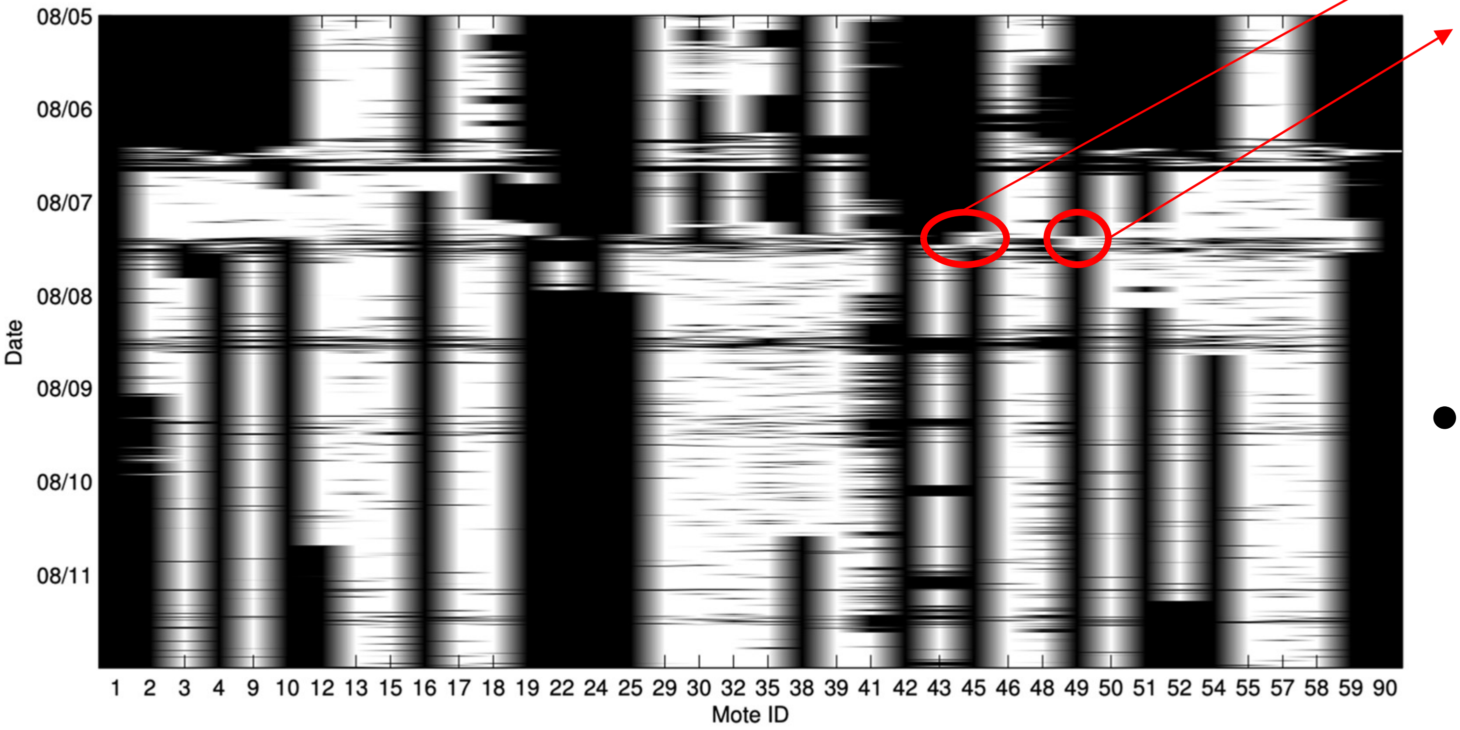
- A packet is successfully received.

Packet loss patterns during the 1st week of August 2002



- Several blacks emerge spanning all nodes (e.g., midday on Aug 6, 7,8)

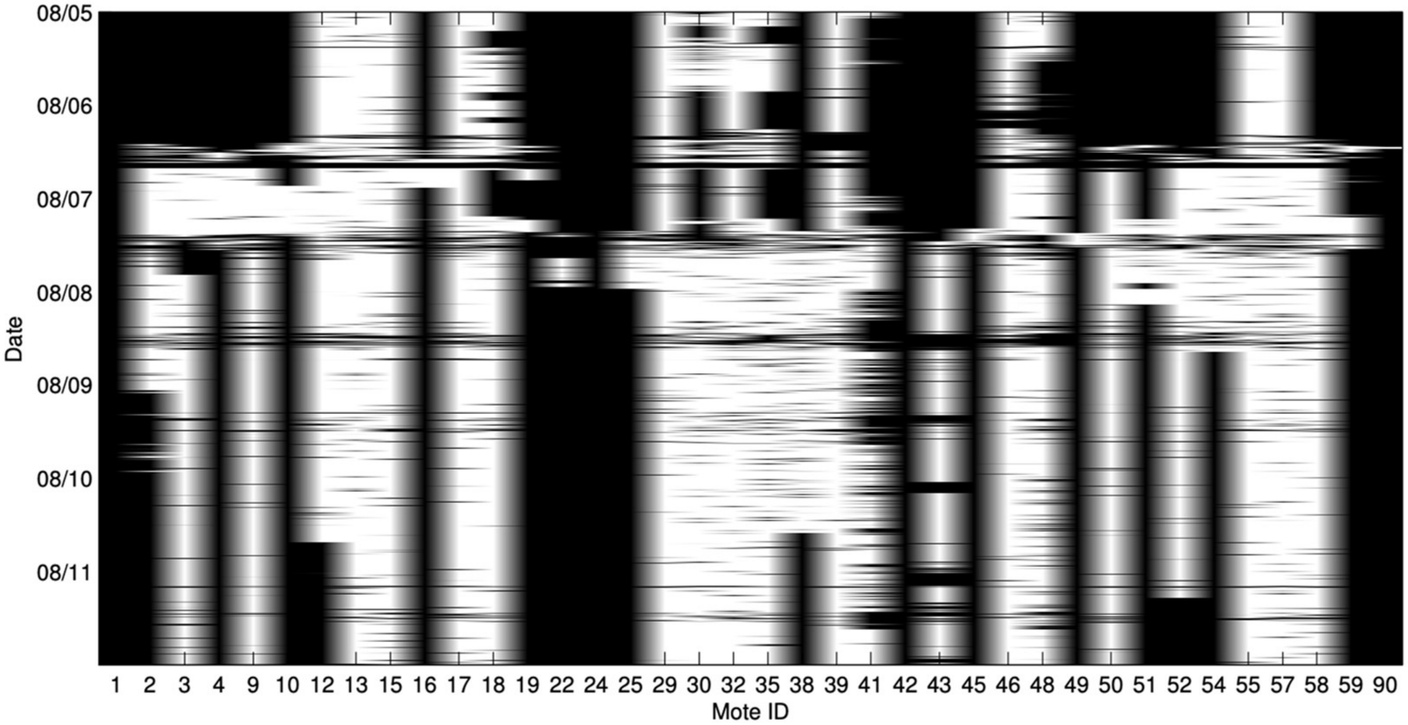
Packet loss patterns during the 1st week of August 2002



- Aug 7: Only time in the sample window when mote 45 and 49 transmit packets successfully

- However, packet loss occurs at other nodes

Sequence numbers from these sensors reveal that



- Sensors transmit data during every sample period since deployment
- Even though those packets were not received.

Empirical distribution Vs. Independent Distribution of Packet Loss

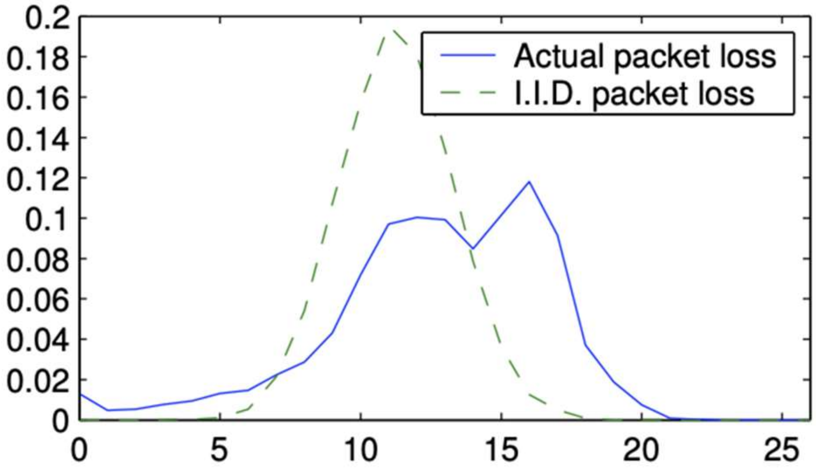


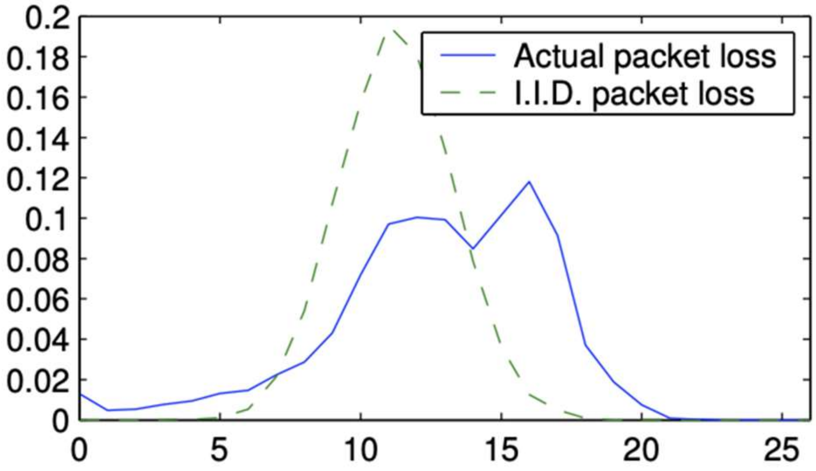
Figure 18.5. Distribution of packet losses in a time slot. Statistically, the losses are not independently distributed.

The two distributions are not the same

Rejected by:

- Parametric technique(chi-squared test yields 10^8)
- Non-parametric techniques (rank test rejects it with 99% confidence)

Empirical distribution Vs. Independent Distribution of Packet Loss



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Packet loss is a combination of:

- Potential losses along two hops in the network
- Packets shared channel that varies with environmental conditions.
- Sensor nodes are likely to have the same battery levels.
- Packet collision at the relay nodes.

Network dynamics

- Very low expected network utilization (5%)
- Collisions won’t play a significant role
- Motes 45 and 49 imply otherwise
- Behavior possible in periodic application
- Nodes can collide repeatedly in the absence of backoff

Network dynamics

- Backoff is provided by CSMA MAC layer
- If MAC works as expected, each node backs off until it finds a clear slot
- Expect channel to be clear at that point
- Clock skew and channel variation might force a slot reallocation

Network dynamics

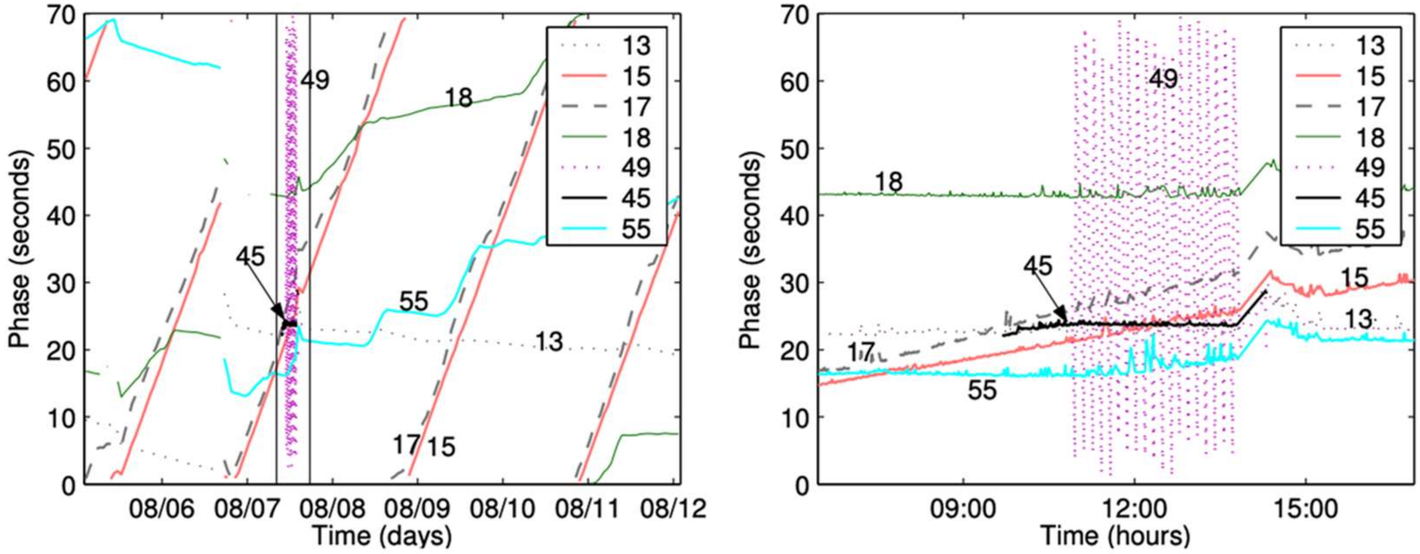
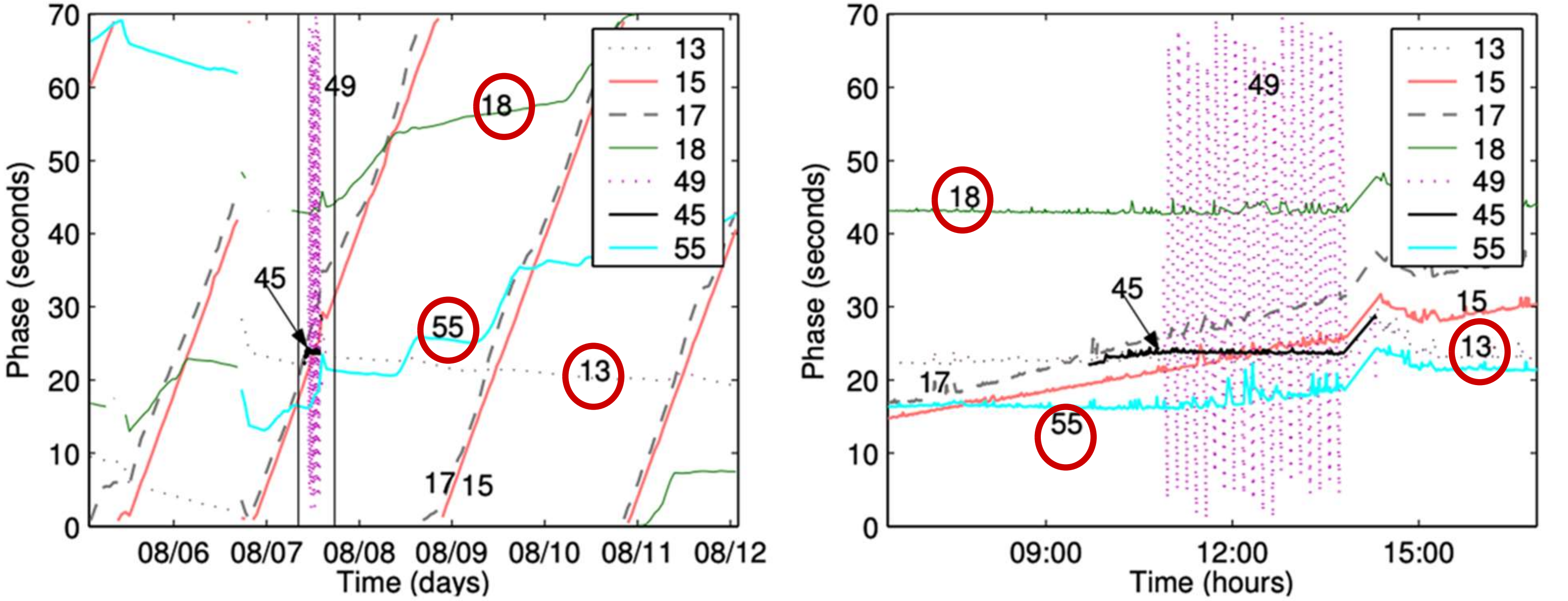


Figure 18.7. Packet phase as a function of time; the right figure shows the detail of the region between the lines in the left figure.

- Look at timestamps of received packet
- Compute phase of each node
- Slope = a drift as a percentage of 70–second cycle

Network dynamics – No clock drifts and MAC delays



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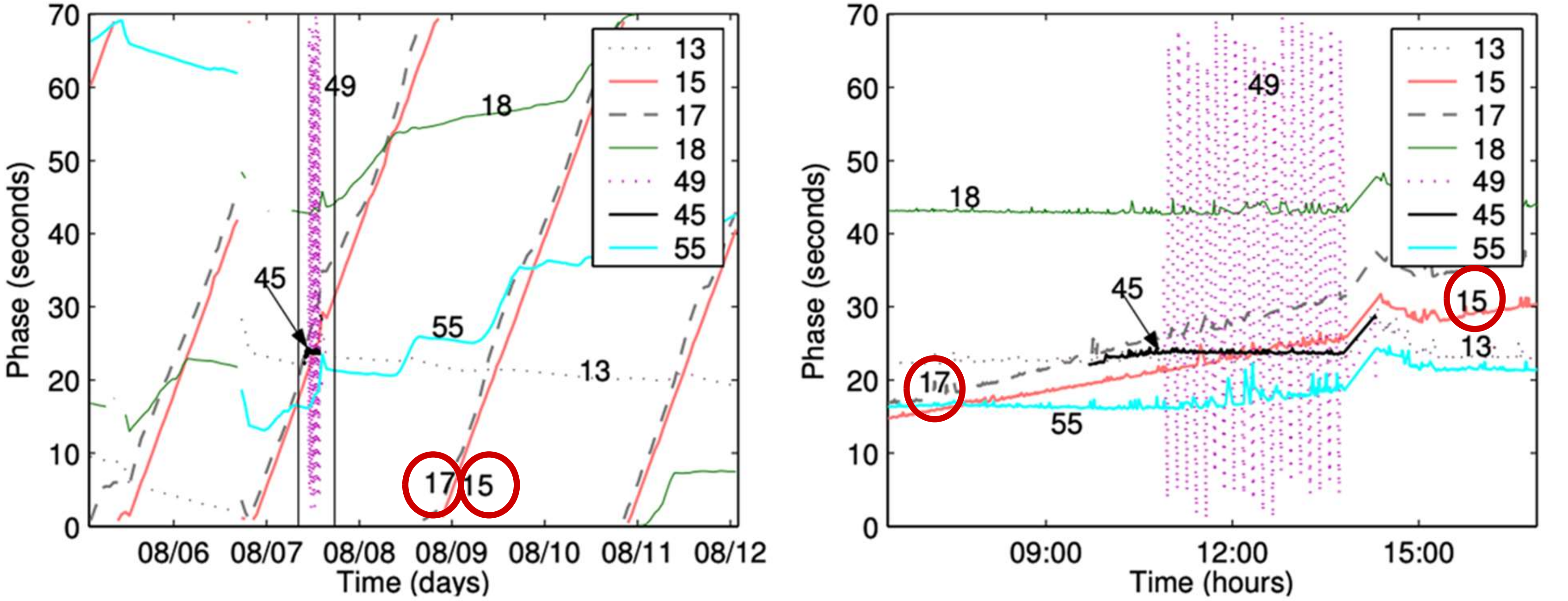
Network dynamics - clock drift and MAC delays present



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Network dynamics - Delay origin

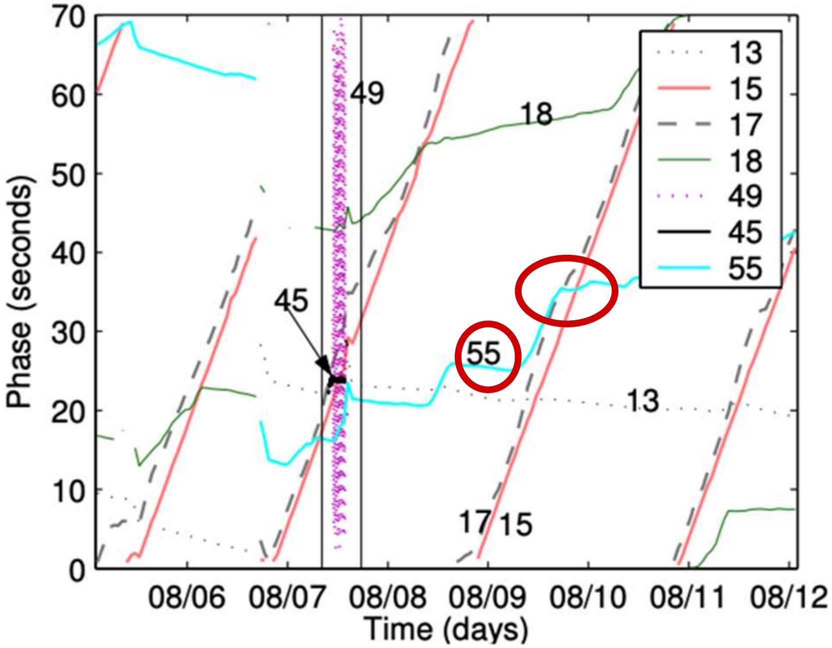
- The delay can come from the MAC layer,
- An average loss 28 ms = a single packet MAC backoff

Paper’s Hypothesis:

- Result of RF automatic gain control circuits
- Nodes in the RF silence of the island
- Adjust gain that it detects radio noise as a packet

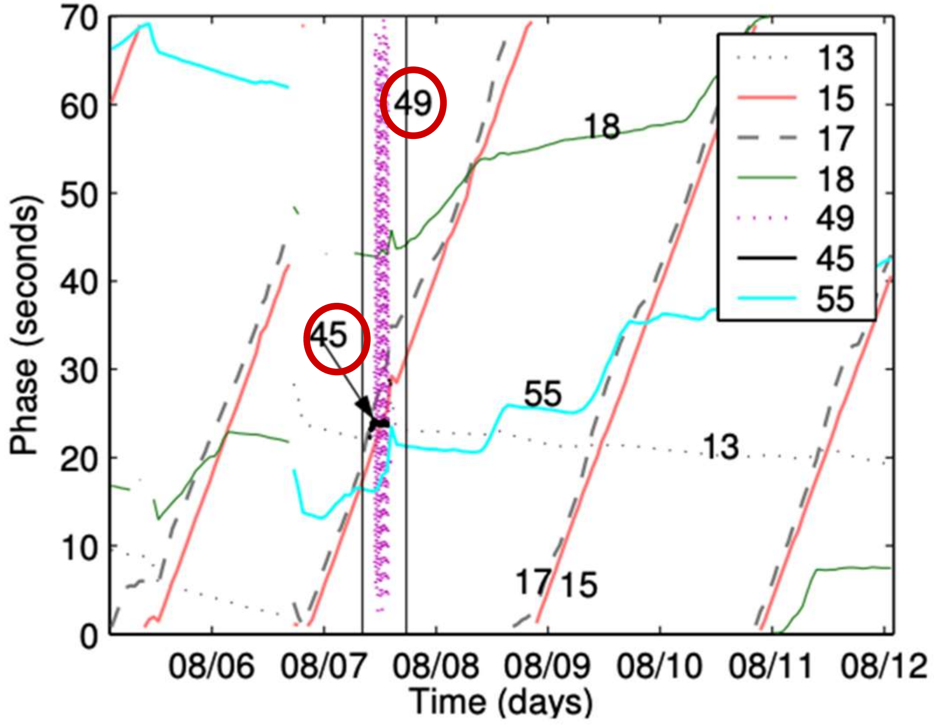
Network dynamics - Correcting the problem

- Incorporate signal strength meter into the MAC
- Combination of digital radio output and analog signal strength
- Additional backoff seems to capture otherwise stable motes



Network dynamics - Delay origin

- Potential for collisions exist
- Nodes back off as expected (e.g. previous example)
- 45 can collide with 13 and 15 (but not other nodes)
- 49 shows no potential for collision, but it shows a very rapid change
- Clock drift or misinterpretation of carrier sense



Node Analysis

- Nodes monitoring allow us to adjust the operation as well as proactively maintain and fix the WSN
  - Sensors on each node provide analog light, humidity, digital temperature, pressure, and passive infrared readings
  - Use a separate 12-bit ADC to maximize resolution and minimize analog noise
- Light readings
  - Essentially a photoresistor, saturated at maximum ADC value, zero at night
  - Periodic patterns of day and night for those outdoor
  - Total Darkness for those in the burrow
- Temperature readings
  - Maxim 6633 digital temperature sensor, but 2°C resolution due to ADC
  - IR radiation from sun heat up the mote and cause higher result.
  - Sensor fails when contact with water

Node Analysis

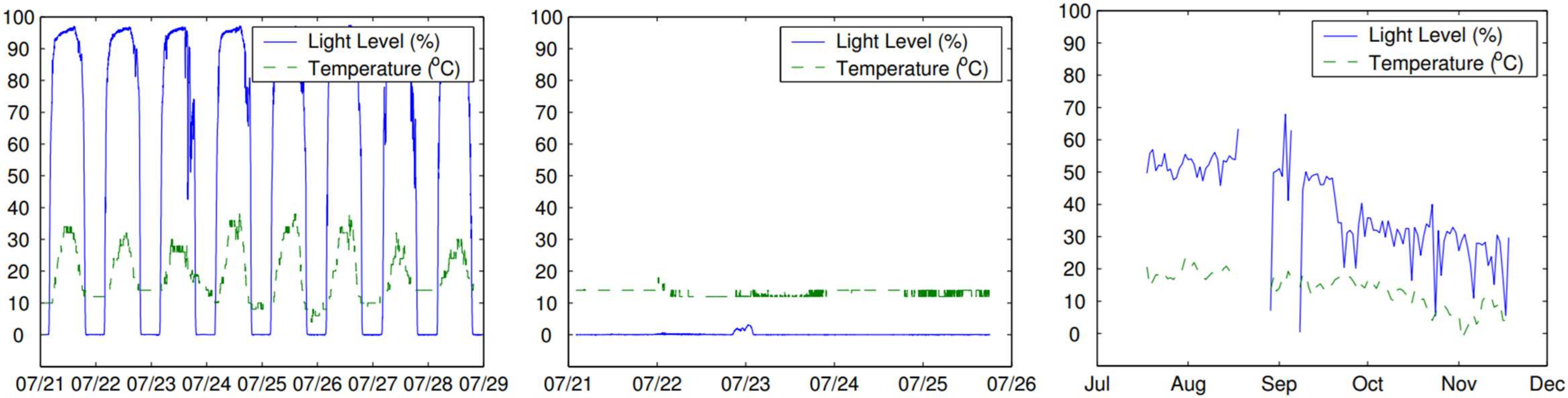


Figure 8: Light and temperature time series from the network

- Humidity readings
  - Up to 15% error from sensor to sensor, 5% variation due to analog noise
  - Wet weather cause very high or small reading
  - High humidity will recover when dry up, but low readings would fail

Node Analysis

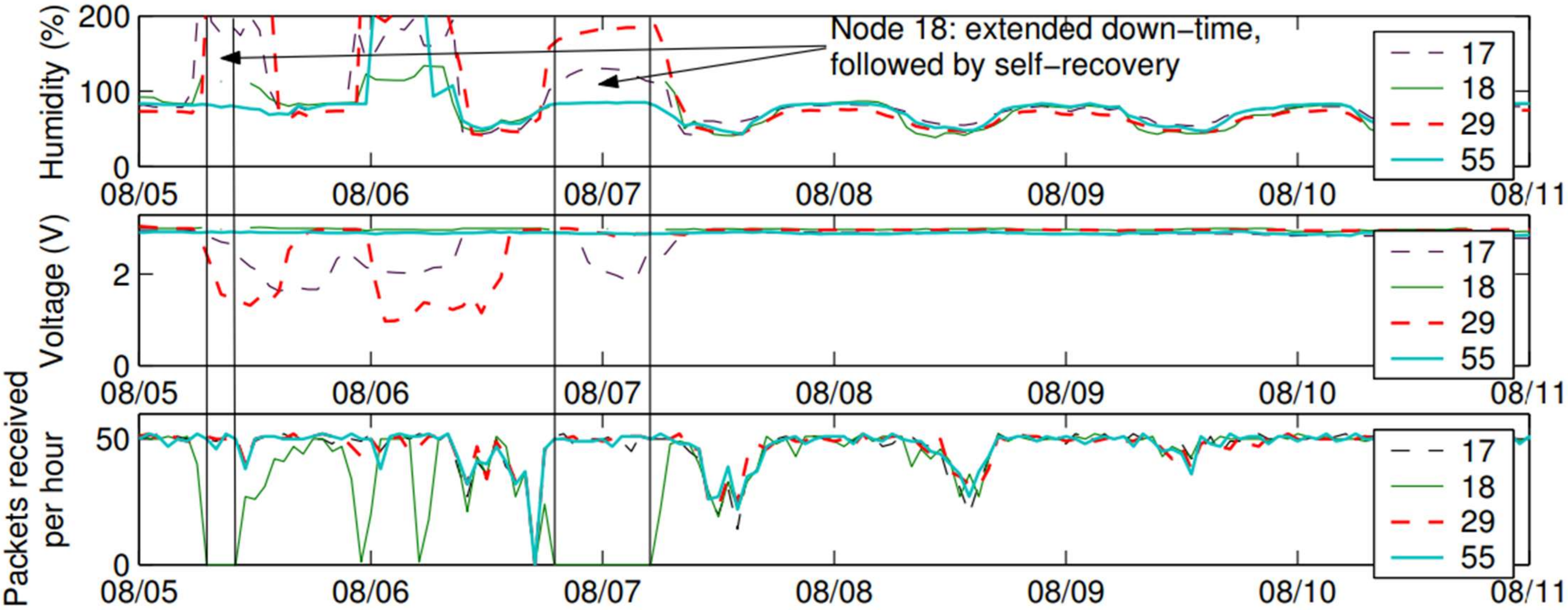


Figure 9: Analysis of Wireless Sensor Networks for Habitat Monitoring

Node Analysis

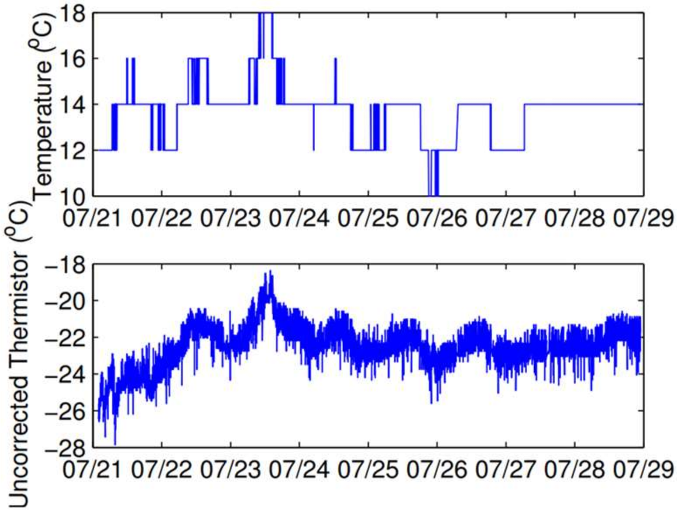


Figure 10: Digital temperature and analog thermistor readings

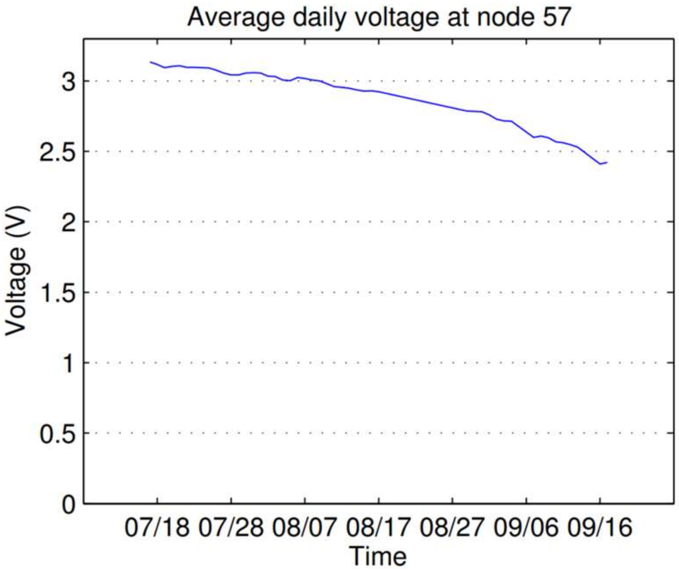


Figure 11: Battery voltage reading shows failure when below 2.3V

- Thermopile readings
    - Lack of periodic daily patterns
- Power management
    - 5 nodes out of 43 have clearly exhausted their original battery supply
    - Batteries failed to supply current when below 2.3V
    - Advocate future platforms eliminate the use of a boost converter
- Node failure indicators
    - Humidity sensor can indicate node health, very low reading indicate node fail

Related Work in 2003

Other published research in similar field:

- Cerpa et. al. - A multi-tiered architecture for habitat monitoring.
  - Focused mainly on wildlife tracking.
  - Lacked long term results or reliability data.
- Wang et. al. - Acoustic method to identify animals using a hybrid iPaq and mote method.
  - Focused more towards identification rather than monitoring.
- ZebraNet - WSN design for tracking and monitoring wildlife.
  - Always-mobile, multi-hop network.
  - Significantly larger and heavier than motes, not suitable for Petrel bird burrowing.

Related Work in 2003

- Center for Embedded Network Sensing (CENS)
  - Deployed a sensing system at James Mountain Reserve in CA.
  - Similar architecture to paper's. Sensor patches with tiered transit network.
- Intel research
  - Deployed network to monitor redwood canopies in Northern CA and monitoring vineyards in Oregon.
- Future work from the authors:
  - Deployed a second generation of multi-hop habitat monitoring network on Great Duck Island.
- All above works are still in their infancy and data is not yet available for analysis.

General takeaways of related work.

- Very few wireless sensor networks systems deployed in the field.
- Little data on long term behavior of WSNs especially for habitat monitoring.

Conclusions

Main contributions

- Highlighted the importance of WSNs for habitat monitoring.
- Presented a network architecture implementation for accomplishing this application.
- Demonstrated their architecture with field-tested evaluation.
    - Application-level data was studied to show behaviors in low level system characteristics like MAC-layer synchronization of nodes.
    - Identified sensor features which predict a 50% node failure within 4 days.

Conclusions (continued)

Results

- Data that was collected failed to depict meaningful insight due to high failure rate.
- However, the test provided important insight into WSN operation in an application environment.

Key takeaways

- The predictive ability based off sensor node failure will lend to proactive maintenance and node self-maintenance.
- Will be important in the development of self-organizing and self-healing WSNs.

Unanswered questions and comments

- Allude to a generalized WSN for habitat monitoring.
    - How does this WSN architecture perform in different habitats? Climate conditions? etc.
- This was one of the first implementations of an outdoor deployed WSN.
    - How has WSN in remote locations developed since?
- Stress the importance of small sized sensor nodes.
    - To prevent interfering with petral activities.
    - Final node size was not provided in paper. Discovered in reference: 1.25 × 2.25in (approx size of a pair of AA batteries).
    - Any comments on if their activities were distrubed?

Unanswered questions and comments

- “Mote” vs “node”: created some ambiguity in terminology.
- Power Management
    - Why not choose sensor ICs with lower supply voltage to further optimize node’s lifetime?
- Initial goal: Developing a sensor network architecture for monitoring applications.
    - Shifts focus to a prediction tool for failure.
    - Initial goal was not entirely met, however the paper provided very valuable results and analysis of outdoor deployed WSNs.

Questions?

Resources

[1] https://prph2o.com/hobo-u12-outdoor-industrial-data-logger/

[2] https://www.coa.edu/islands/great-duck-island/

[3]https://www.coa.edu/live/profiles/1216-leachs-storm-petrel/templates/details/flora-fauna.php

[4] J. L. Hill and D. E. Culler, "Mica: a wireless platform for deeply embedded networks," in IEEE Micro, vol. 22, no. 6, pp. 12-24, Nov.-Dec. 2002, doi: 10.1109/MM.2002.1134340.

[5] https://teara.govt.nz/en/photograph/7223/petrel-burrows