Corrosion Batteries:

Repurposing today's infrastructure to power tomorrow's Smart City

CNS Research Review

Dhananjay Jagtap, ECE Graduate Student

Prof. Pat Pannuto, CSE

Cities need to be “Smart”

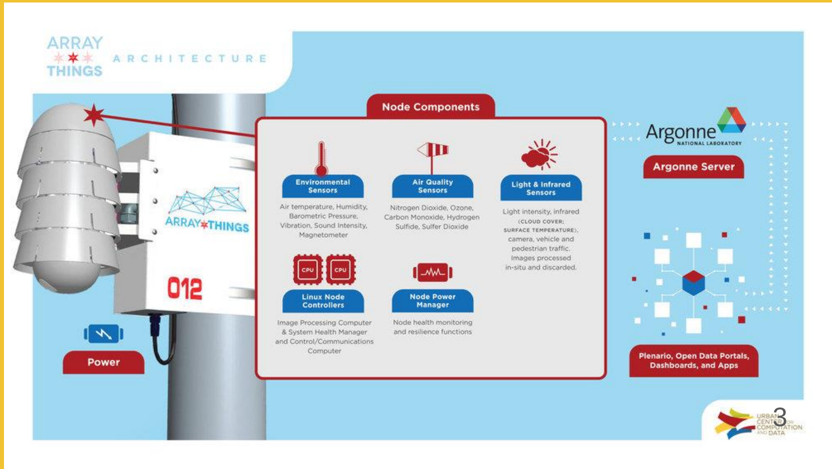
Cities are getting bigger, more complex, and need ground level data to make prudent planning decisions and guide every day operations effectively.

Deployability is the Challenge

- IoT devices are essential to realize a smart city.
  - Deployment is hard because:
  - (1) **Hard to power,** (2) **Hard to communicate**
    - Communication problem potentially solved by LP-WANs
    - This talk is about the power problem

- Solving ***deployability*** is fundamental to scaling IoT

Infrastructure-reliant platform is expensive to deploy and limited in scope



How to solve the Power Problem?

- **Plug it in (supply power from mains)**
  - Costly, doesn't scale
  - Needs new infrastructure

- **Ship it with energy reserves (batteries)**
  - Maintenance, environmental impact, lifetime, ultimately doesn't scale

- **Scavenge energy from the environment (solar, thermal, RF energy)**
  - Interesting! But normally unreliable
  - **Insight: What if there are already reliable battery-like things in the world, we just need to tap into them**

“Monitoring” class of Smart City application

- **Smart city applications have given rise to a new class of applications which are large in scale and intermittently operating.**

- One interesting smart city application: infrastructure health monitoring, **specifically corrosion**
  - E.g. Pipes, underground tanks, bridges, etc

- **Corrosion costs annually about 276 billion USD equivalent to 3.1% of US GDP within the US and 1.8 trillion USD globally.**

- Knowing the health of structures is crucial for preemptive maintenance and to prevent accidents.

What should an infrastructure monitoring system look like?

- Easy to install

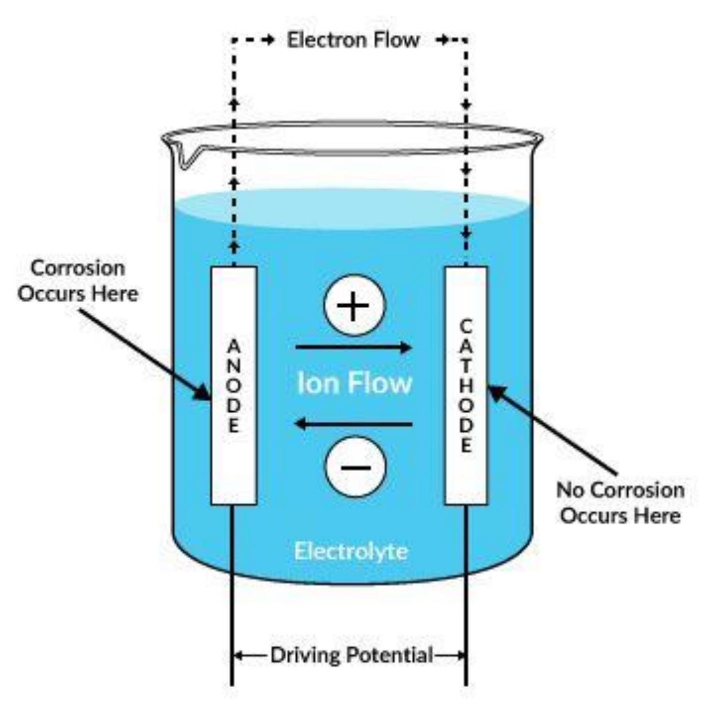
- No need for new or specialised infrastructure

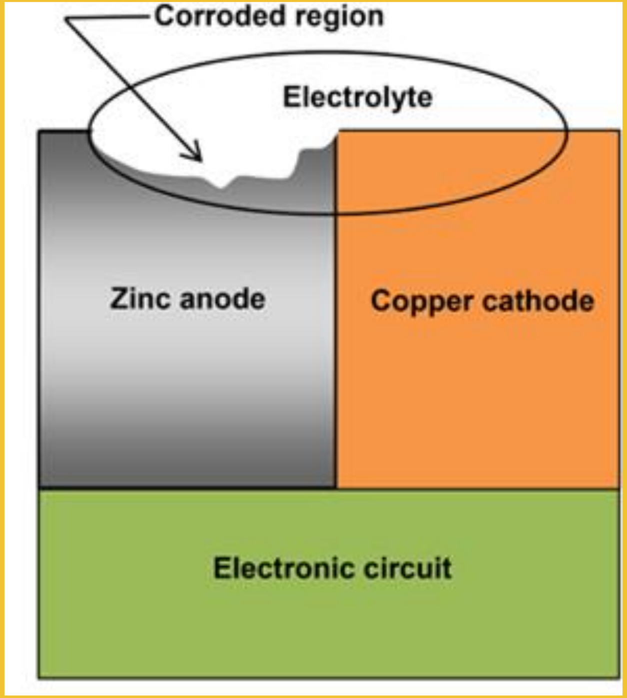
- “Plug it and forget it” systems which fade into the background

Outline

- ➔ Introduction to Smart Cities
- ➔ **Corrosion Basics**
- ➔ Goals and Contributions
- ➔ Does Corrosion really work as a battery?
- ➔ Designing a trickle charge Energy Harvesting System
- ➔ Does it *really* work?
- ➔ The road ahead

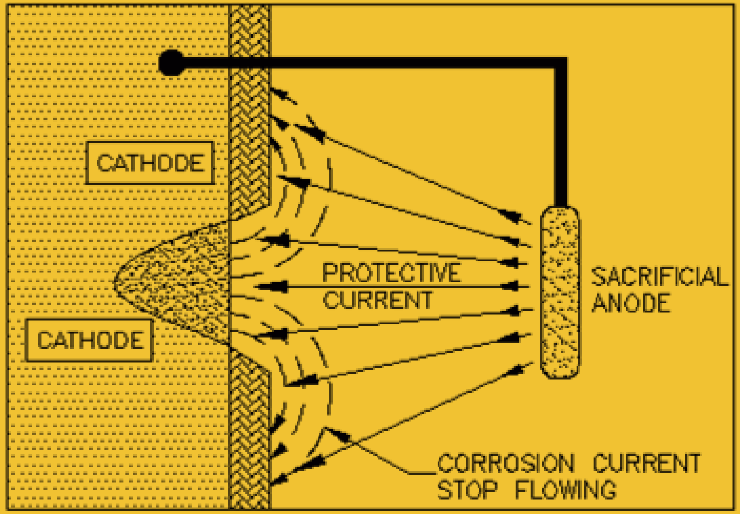
Galvanic corrosion forms an electrolytic cell - a battery!



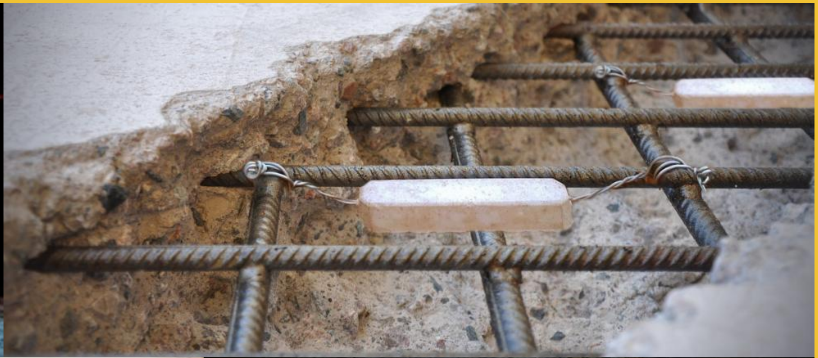


Galvanic Corrosion as a protection mechanism

<u>Point</u>: The cell potential indicates if protection is working. If it is, it can power a sensor.



Galvanic batteries are everywhere



Corrosion solves the Power Problem

- Corrosion is a spontaneous process which sets up local ***“batteries”***
  - low instantaneous, but continuously available, power

- Corrosion batteries are **predictably available** making them ***reliable***
  - do not have to be connected to a **separate mains**
  - are **virtually inexhaustible** until the anode is consumed

Outline

- ➔ Introduction to Smart Cities
- ➔ Corrosion Basics
- ➔ **Goals and Contributions**
- ➔ Does Corrosion really work as a battery?
- ➔ Designing a trickle charge Energy Harvesting System
- ➔ Does it *really* work?
- ➔ The road ahead

Goals

- To develop embedded corrosion monitoring systems powered from the corrosion protection itself.
  - Proactively detect premature failure of corrosion control
  - System which is self-contained, imposes no additional maintenance burden

Outline

- ➔ Introduction to Smart Cities
- ➔ Corrosion Basics
- ➔ Goals and Contributions
- ➔ **Does Corrosion really work as a battery?**
- ➔ Designing a trickle charge Energy Harvesting System
- ➔ Does it *really* work?
- ➔ The road ahead

Characterizing Corrosion batteries

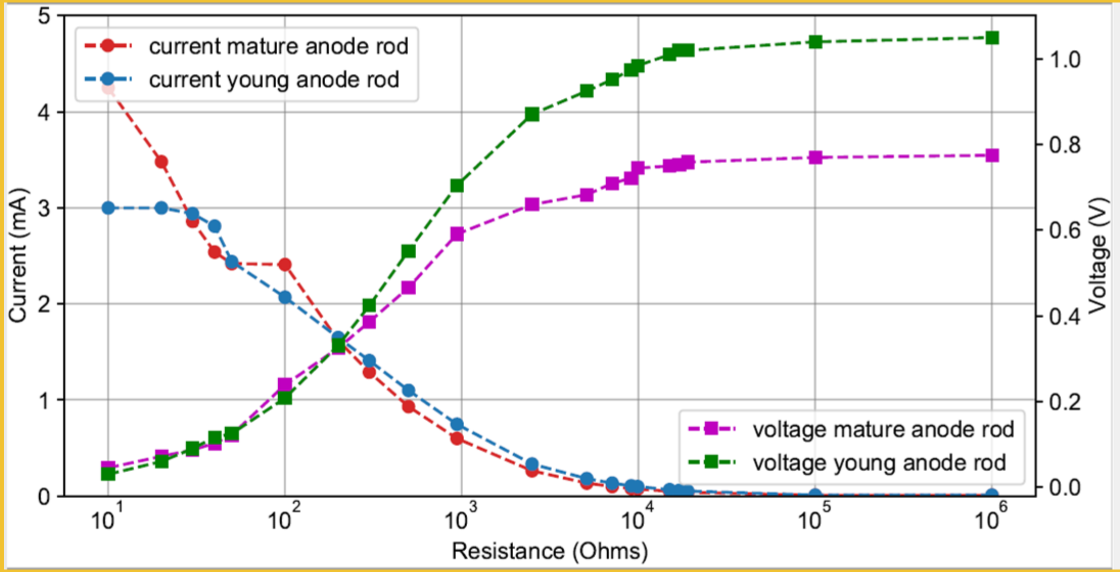
- We build a corrosion battery using a stainless bucket filled with water and a magnesium rod.

- We characterise the battery based on
  - Nominal performance
  - Temperature
  - Surface area in contact with electrolyte
  - Salinity
  - pH

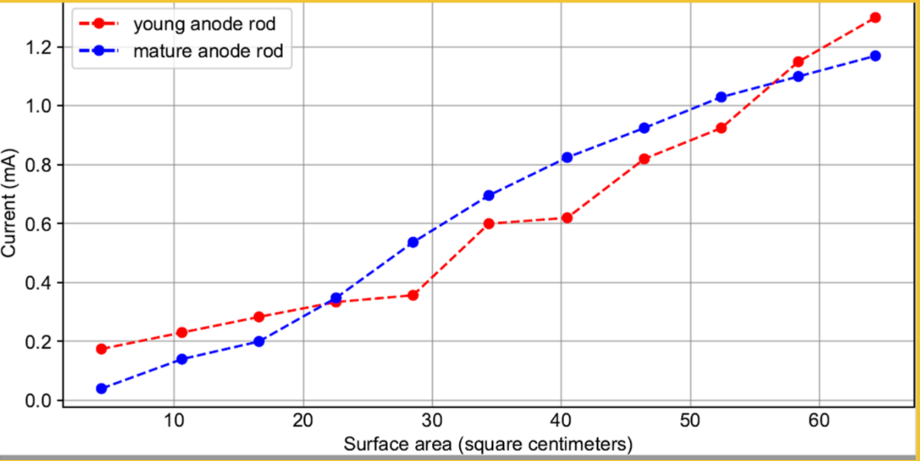
Characterizing Nominal Performance of Corrosion Batteries

- Our corrosion battery yielded an voltage of 1.2V as expected.
- Peak power: 0.64mW
- Peak power point occurs at half open circuit voltage

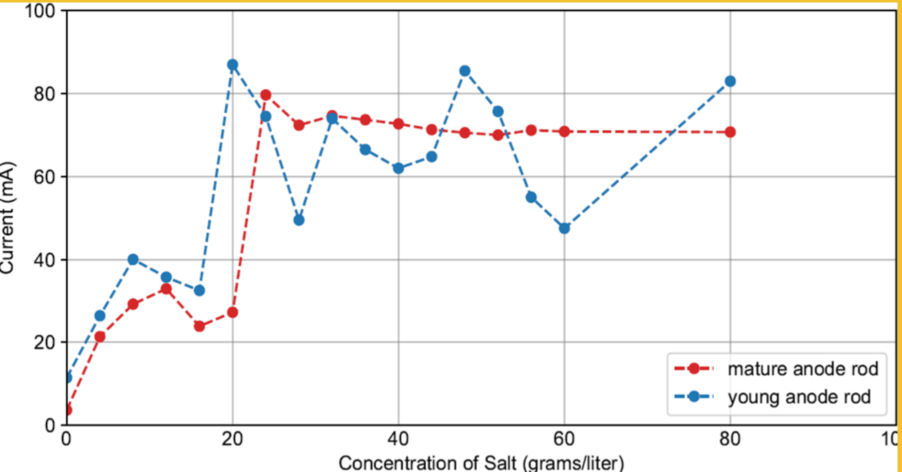
Sufficient energy for an energy harvesting application



Testing the limits of Corrosion battery

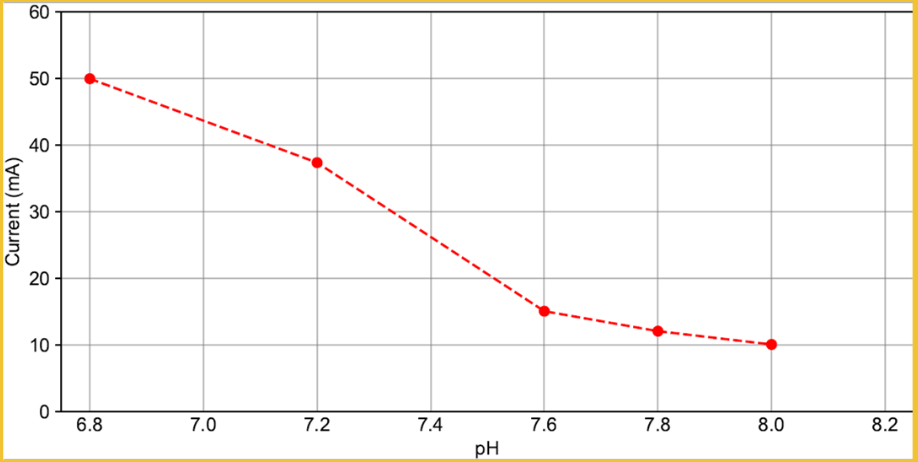


Corrosion current is directly proportional to the surface area in contact with the electrolyte

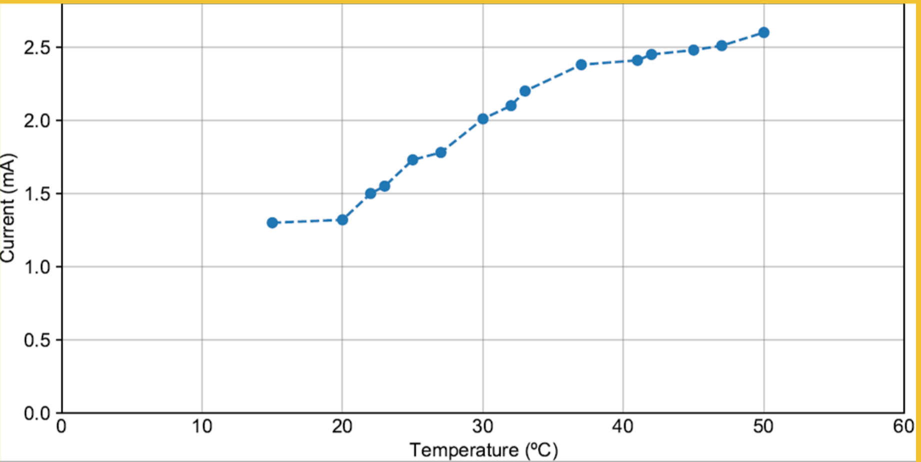


Corrosion current increases as the salinity of the electrolyte increases and then saturates

Testing the limits of Corrosion battery



Corrosion current decreases with the increase in pH of the electrolyte



Corrosion current is directly proportional to the temperature of the electrolyte

Outline

- ➔ Introduction to Smart Cities
- ➔ Corrosion Basics
- ➔ Goals and Contributions
- ➔ Does Corrosion really work as a battery?
- ➔ **Designing a trickle charge Energy Harvesting System**
- ➔ Does it *really* work?
- ➔ The road ahead

Sensor design Considerations [What must the system do?]

Goal: Infrastructure monitoring that is infrequent but periodic collection of data and communicating it (**sense and send**)

1) Periodic wake-ups to trigger sense and send events

2) A mechanism for sensing the health of cathodic protection

3) Means of communicating the data

Design Challenges [Why is it Hard?(no energy)]

≠

- Conventional Batteries have a higher instantaneous power than corrosion batteries. This means that corrosion batteries without a energy buffer has a limitation on the type of events it can execute.

- But corrosion batteries have a higher energy density than conventional batteries. Which means if designed properly can outlast a battery when executing intermittent events.

Periodic Wake-ups

RTC Model	Resolution (ms)	Current Draw (nA)	Min V	Energy per 24h (mJ)
NXP PCF85263A	10	320	3.3	91.2
Maxim DS139X	10	500	1.8	77.8
ST M41T62	10	310	1.3	34.8
Abracon AB18X5	10	51	1.8	14.3
Ambiq AM08x5	8	14	1.5	1.8
RC: 432 MΩ, 100 μF	~30 min	N/A	N/A	0.3 (at 2.4 V)

- Cathodic protection system governs wake-ups
    - No need for a continuous monitoring system
    - Inspection every 30 days for 30 years
- Regular checks needed
    - Need sense and send event at least once or twice a day
- No solution is completely satisfactory, RTC comes close
    - Implies need to develop satisfactory solutions for these specific class of applications needing once a day versus once a second granularity.

Sensing Considerations

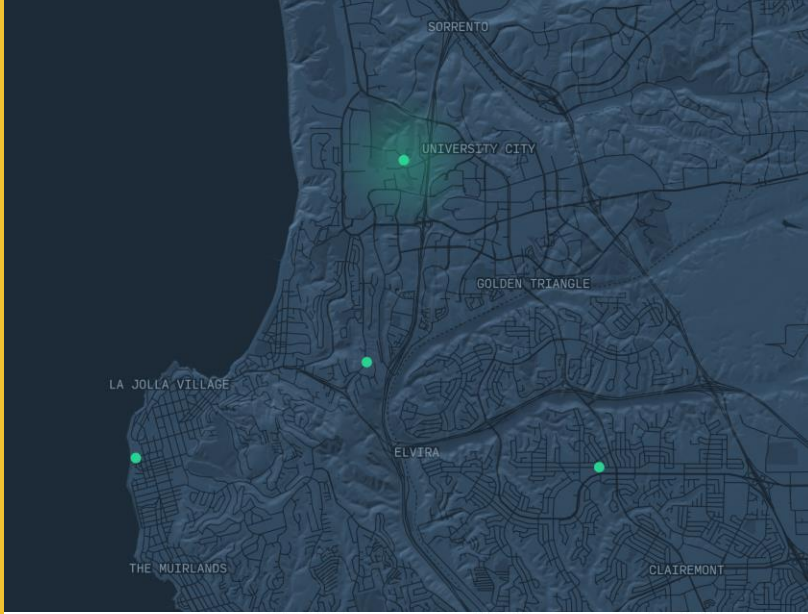
- We need to monitor the voltage to understand the cathodic protection capability
- To measure the voltage we can use the ADC on board the MCU by sampling the voltage
- Precautions must be taken as the sensor is powered by the cell whose voltage is being measured
- But in our case using a differential ADC works

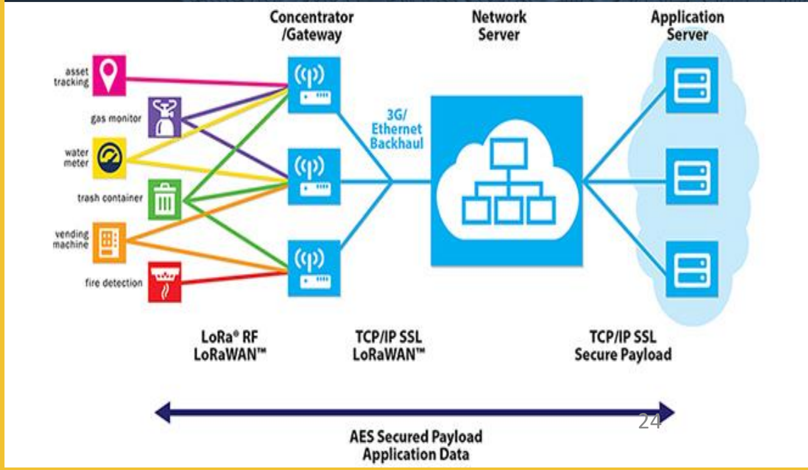
Communication Considerations

- Recent LPWAN technologies offer wide area coverage of urban and peri-urban spaces without needing local gateways for each sensors.

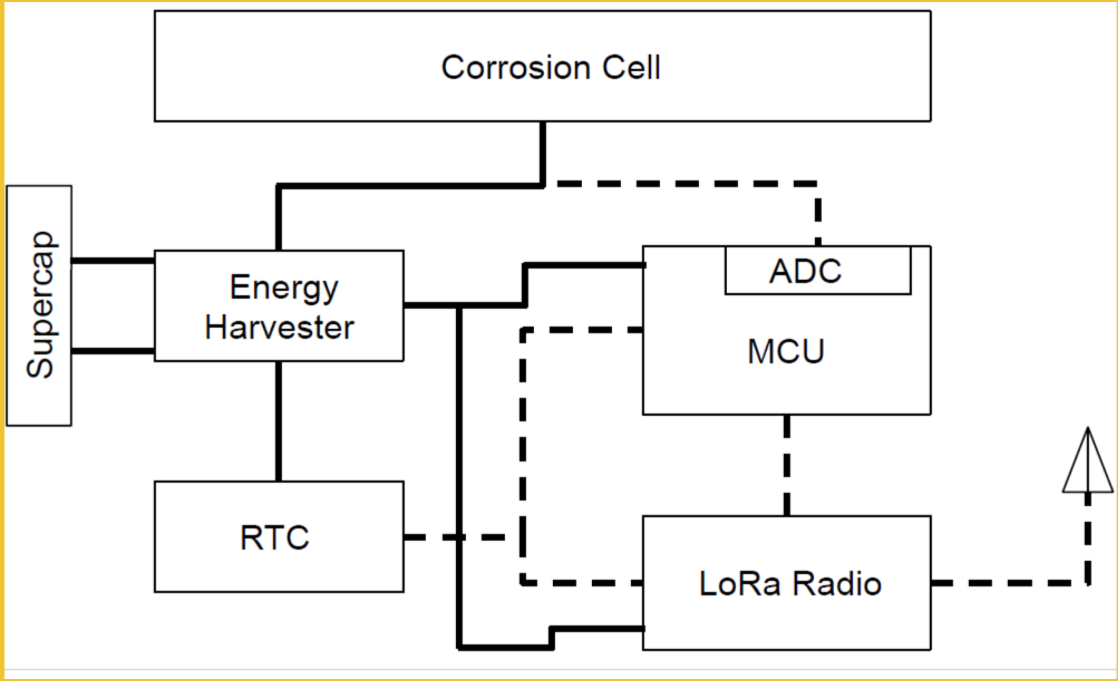
- In our application we wish to transmit small packets of data which the voltage value of the battery periodically.

- We used the Murata LPWAN module and were able to recover the data using commercially available LoRaWAN infrastructure.





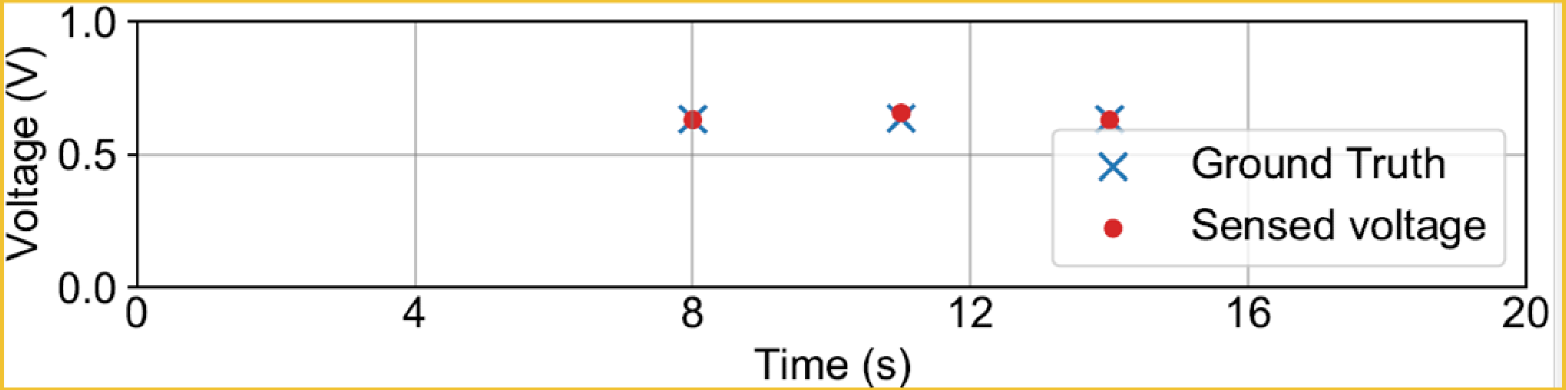
Overall Block Schematic



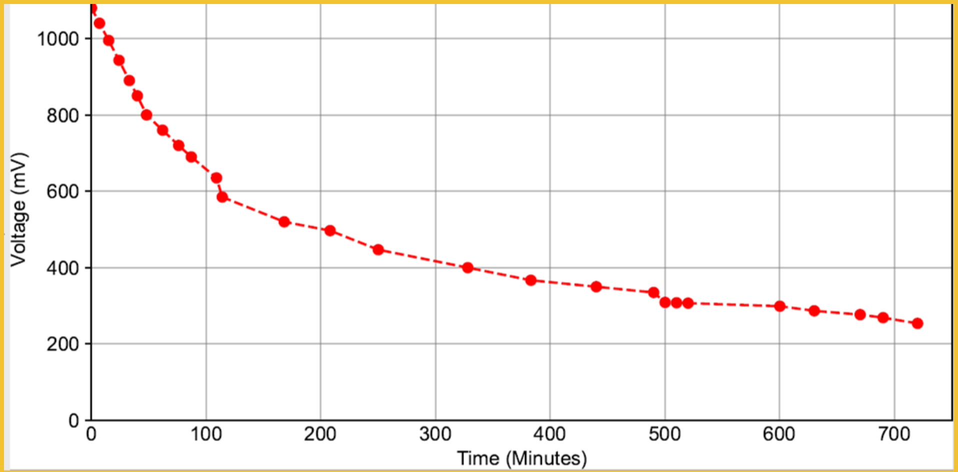
Outline

- ➔ Introduction to Smart Cities
- ➔ Corrosion Basics
- ➔ Goals and Contributions
- ➔ Does Corrosion really work as a battery?
- ➔ Designing a trickle charge Energy Harvesting System
- ➔ **Does it *really* work?**
- ➔ The road ahead

A real-world corrosion cell successfully powers our sensor and enables wirelessly transmitted corrosion control health data

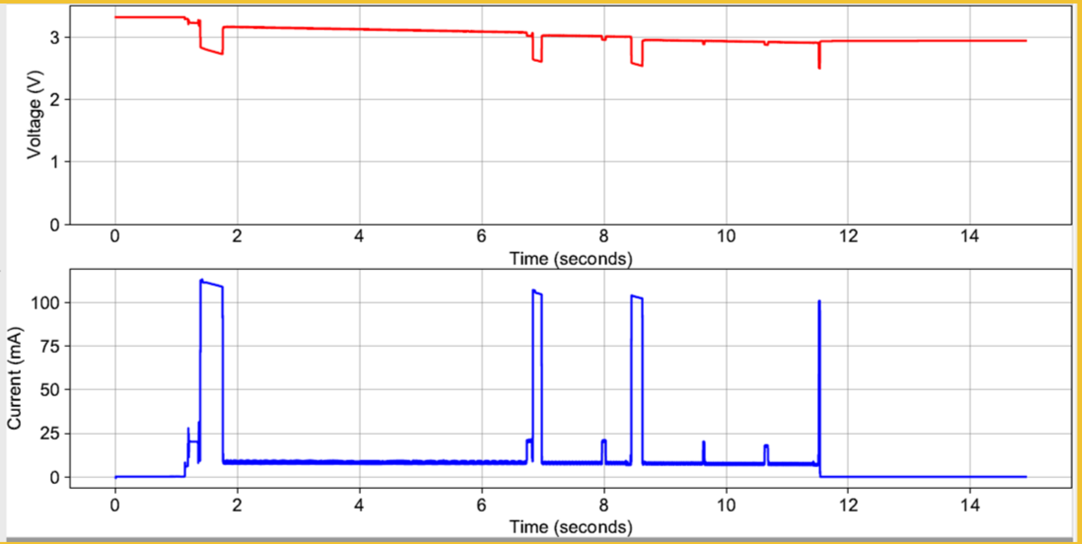


Our sensor successfully detects premature failure



- We observe that over a period of 12 hours the EMF drops as the anode gets corroded.
- Using our ADP 5091 IC our monitoring system will stop working once the EMF drops below 380 mV.
- This will indicate the need for maintenance before the cathodic protection system fails completely.
- This ensures preemptive maintenance.

The energy buffer enables intermittent, high-capacity operation



- Each send event needs a peak current of 128mA. As this cannot be sourced by corrosion battery.
- We need to trickle charge the capacitor to be able to source the current when executing a sense and send event.
- In our case we use a 0.5F capacitor which allows us to send 4 packets every event approximately every 3 hours.

Takeaways

- Built self-contained, infrastructure monitoring without needing construction of new infrastructure
- Whose lifetime *by construction* will last the life of the infrastructure
    - *"Better than batteries"*

- Wide-area deployment requires thinking differently about system endpoints
    - Once-a-day operation is plenty, allows for many, minimalist devices
    - Reliable, simple endpoints key to deployability and scale

It is to be noted that we built this entire system at home during the COVID-19 pandemic is a testament to the fact that it is a simple, rugged and robust system that will work in real life deployments.

Outline

- ➔ Introduction to Smart Cities
- ➔ Corrosion Basics
- ➔ Goals and Contributions
- ➔ Does Corrosion really work as a battery?
- ➔ Designing a trickle charge Energy Harvesting System
- ➔ Does it *really* work? Did we build it?
- ➔ **The road ahead**

Future Directions: Reliable energy harvesting enable predictably intermittent computing

Exploring the domain of reliable energy sources for powering IoT devices.

The tradeoff is low instantaneous power but long lifetime

For eg. Trees all over the world have a constant internal temperature of about 21.4C all over the world regardless of the species.

Energy can be reliably harvested based on thermal difference between ambient and internal temperature.

Our Contributions

- We introduce the concept of the ambient corrosion battery , a widely available energy source in the built environment

- We characterize the performance of one specific and common ambient corrosion battery, the home hot water heater

- We show how the stability of ambient corrosion battery changes the design of energy harvesting frontends and systems compared to less predictable sources like RF and solar

- We implement and evaluate an end-to-end system which demonstrates the viability and efficacy of a self-powered cathodic protection monitoring system