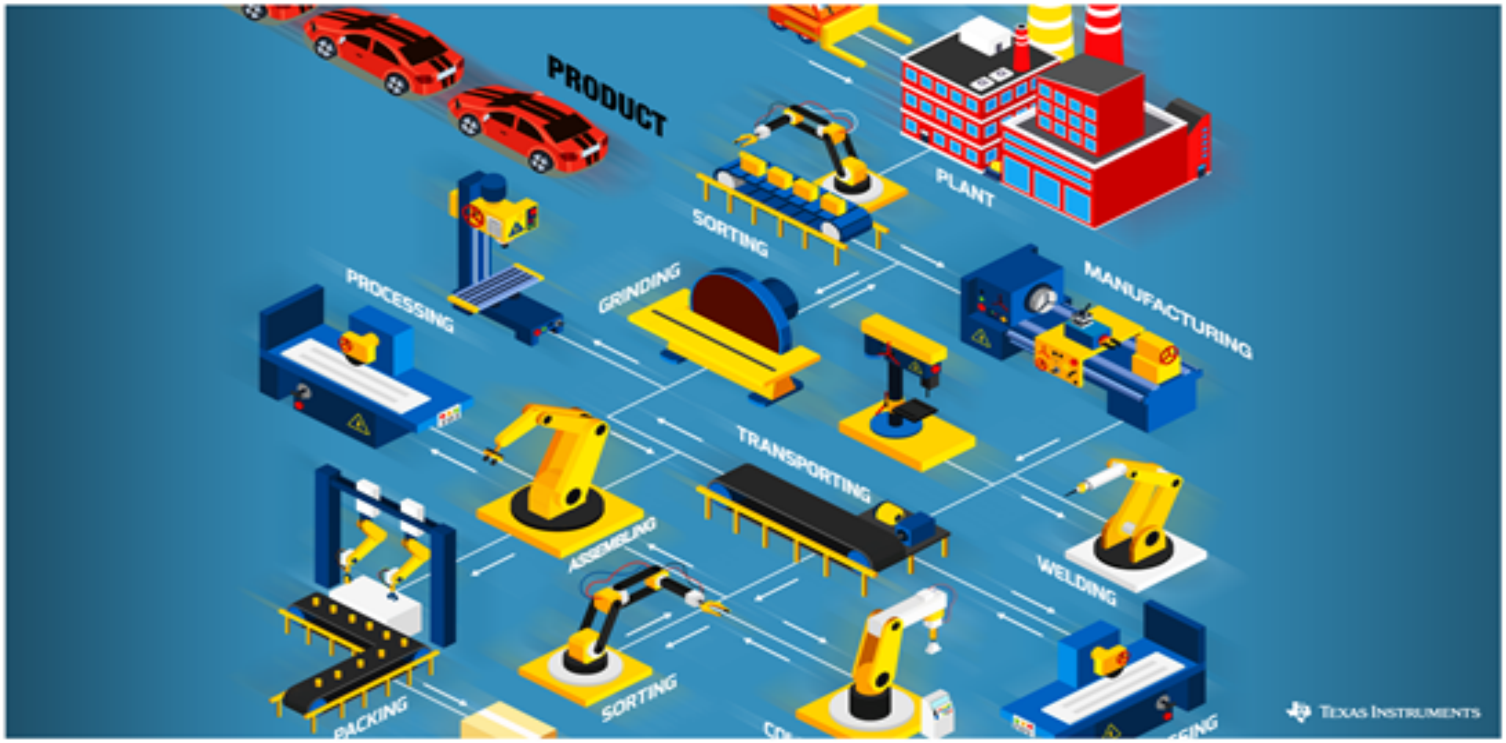


Reaching 10 Years of Battery Life for Intelligent Industrial Internet

Introduction

Challenges

End Node (uW-mW)

MCU

Processors

Wired & Wireless Connectivity

Sensors

Analog Signal Chain

Power Management

HMI

TI-SimpleLink SDK/TI-RTOS/ Micro apps

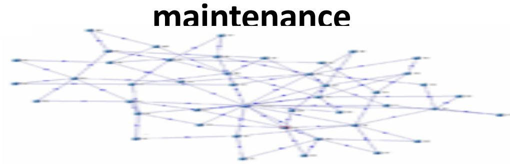
Network

Sensing a complex environment

position/motion material composition proximity gas current/power temperature chemical environment light humidity occupancy biosensing pressure

Security Under Constraints

Auto Configure, Auto Join, 0 maintenance



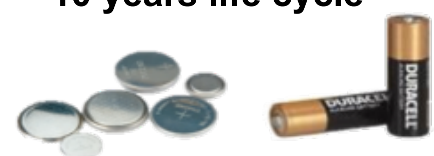
Harsh Wireless Environment

Wi Fi

6LoWPAN

Bluetooth SMART

10 years life cycle



Distributed Intelligence

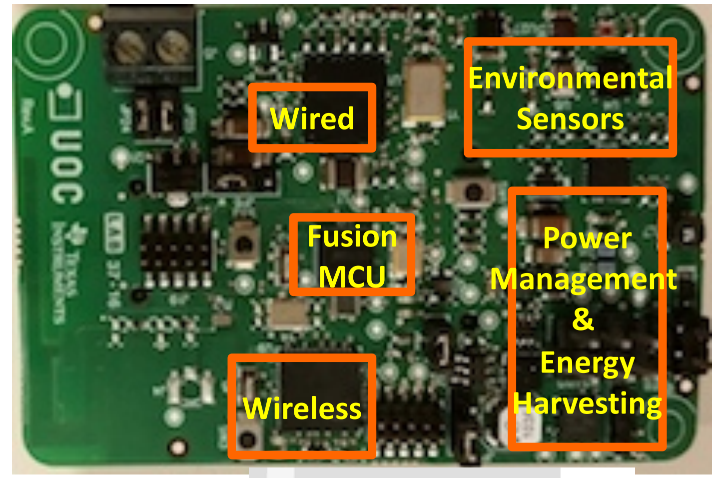
I3Mote Platform

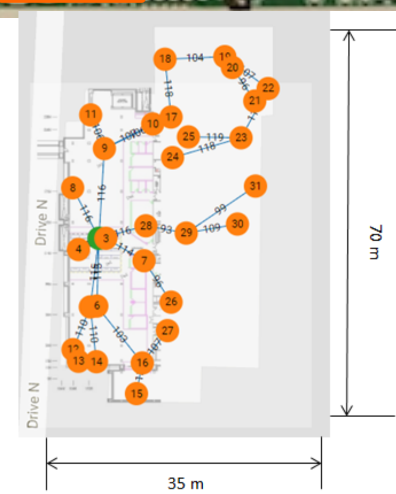
I3: Intelligent Industrial Internet

Mote: small bit of substance, such as a fleck or particle (sensor)

SenseAnywhere:

- Programming Environment
  - Connected MCU: 128KB flash, 20KB SRAM, 48MHz CM3 w/ multi-protocol radio
  - Fusion MCU: 2MB flash, 256KB SRAM, 48MHz CM4 w/ high precision AFE
- MIMO Power Manaegment with complementary Energy Harvesting
- Multi-point, Multi-Modality Sensing: Temp, Humidity, Pressure, Ambient, Accelarometer
- Unique differentiated Ips
- 10 years battery life

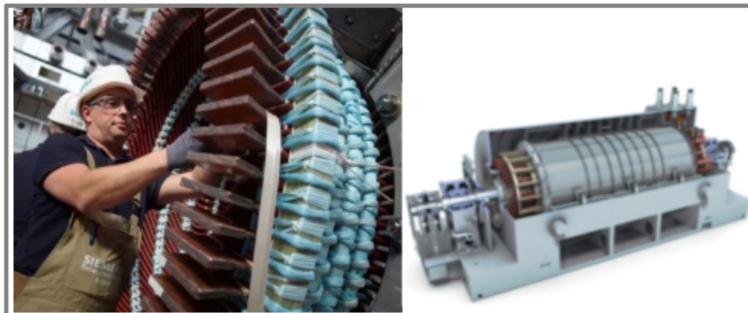




Pilots

Factory Remote Monitoring

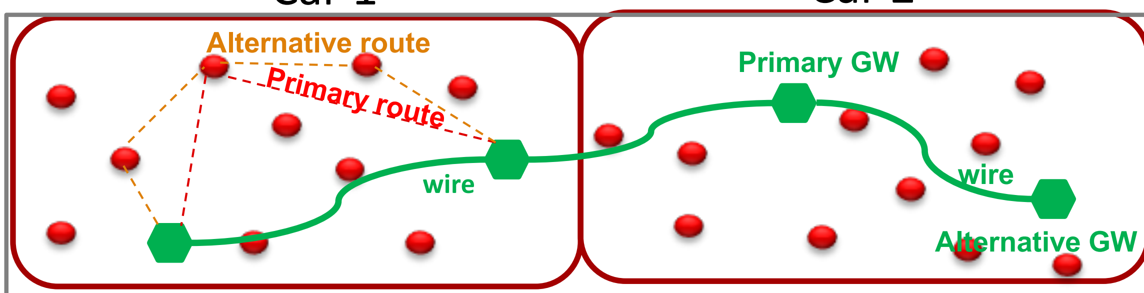
800 pumps/floor, 172x49 m^2 , 10 sensors/pump, 1-10s update, 1TB/y



Motor predictive maintenance

Vrms as indication of vibration, 2kS/s, 100us sync, no wired power supply, no EH due to discharge

Car 1 Car 2



High-Speed Rail In-Car WSN

>50 sensos/car, GW install env., sensor types: temp, humidity, strain, current/voltage, 10-100KBps, RTD=1s, 99.999%

Path to reach 10 years battery life

Path to 10-years Battery Life

Step 1: Lowest Power and Robust Protocol (robust = low power)
- Frequency Diversity: Channel Hopping
- Time Diversity: Time-slotted contention free scheduling
- Power Diversity: Tx Power
- Space Diversity: Freq re-use, mesh

Step 2: Minimize radio wake-up overhead for duty cycled application (including wakeup radio use case)

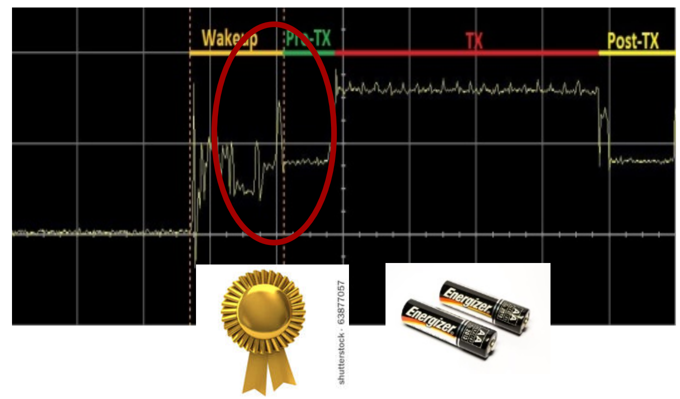
Step 3: Improve power management efficiency

Step 4: Optimize sensor data usage (embedded analytics) and reduce radio duty cycle: 10s → 10m

Step 5: Optimize network topology through smart Gateway

Step 6: Leverage ambient energy harvesting (if applicable)

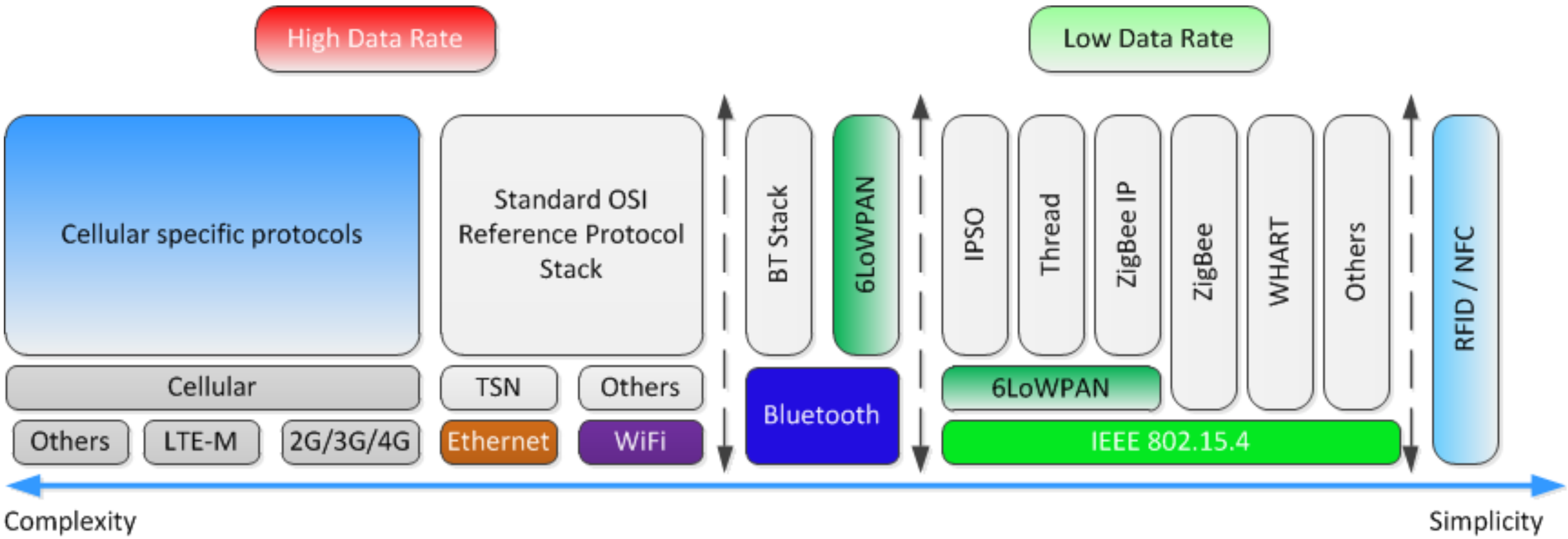
Sub-systems	Active (µA)	Sleep (µA)	Total (µA)
Connectivity	TX: 17.68	2.49	75.96
	RX: 55.25		
	CPU: 0.54		
5 Sensors	9.83	9.41	19.24
MCU Processing	0 (no MIPS)	0.04	0.04
PM	1.63	0	1.63
System Total	84.93	11.94	96.87



Step 1: Lowest Power and Robust Protocol

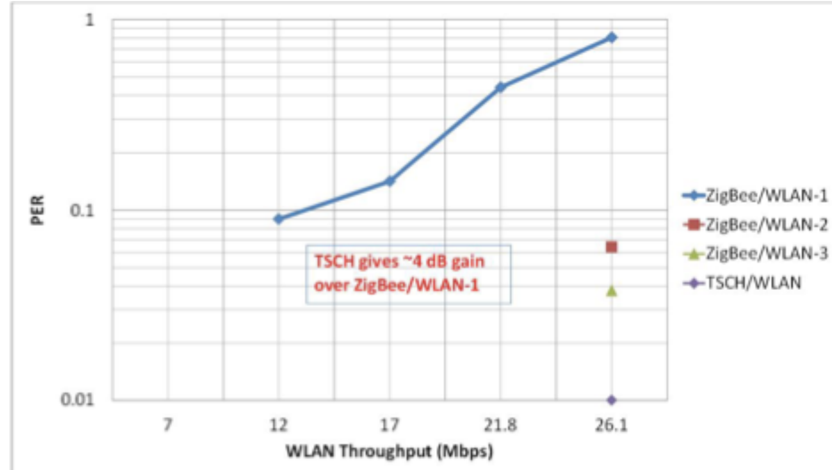
IoT Connectivity Landscape

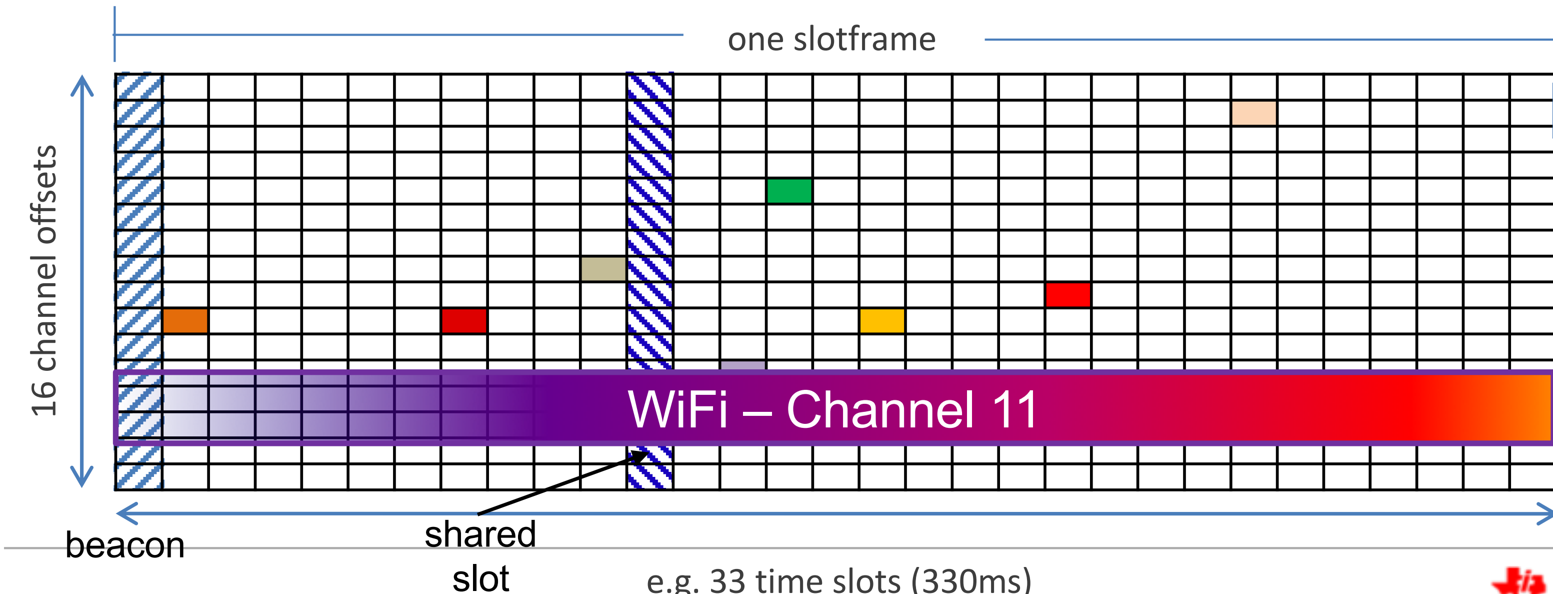
- IoT wireless connectivity – the last mile
- Requirements:
  - Robust, low power, secure, easy to use

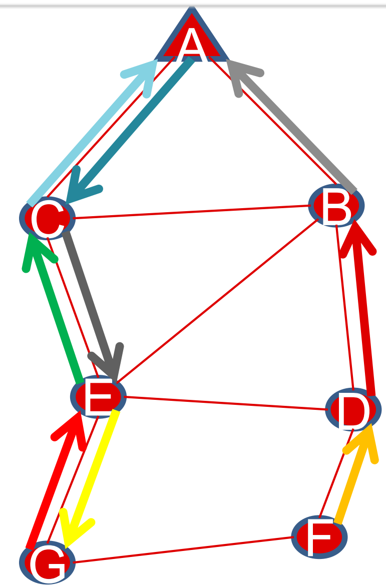


Time Slotted Channel Hopping

- IEEE 802.15.4e TSCH MAC
- Assigned slot: a channel offset and time
- Slotframes repeat continuously
- Each slot has a unique, globally known slot number

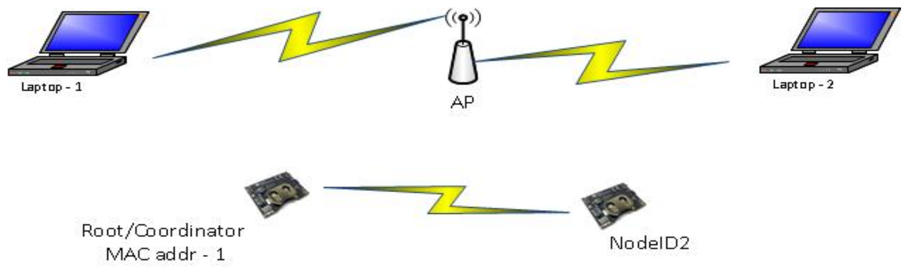


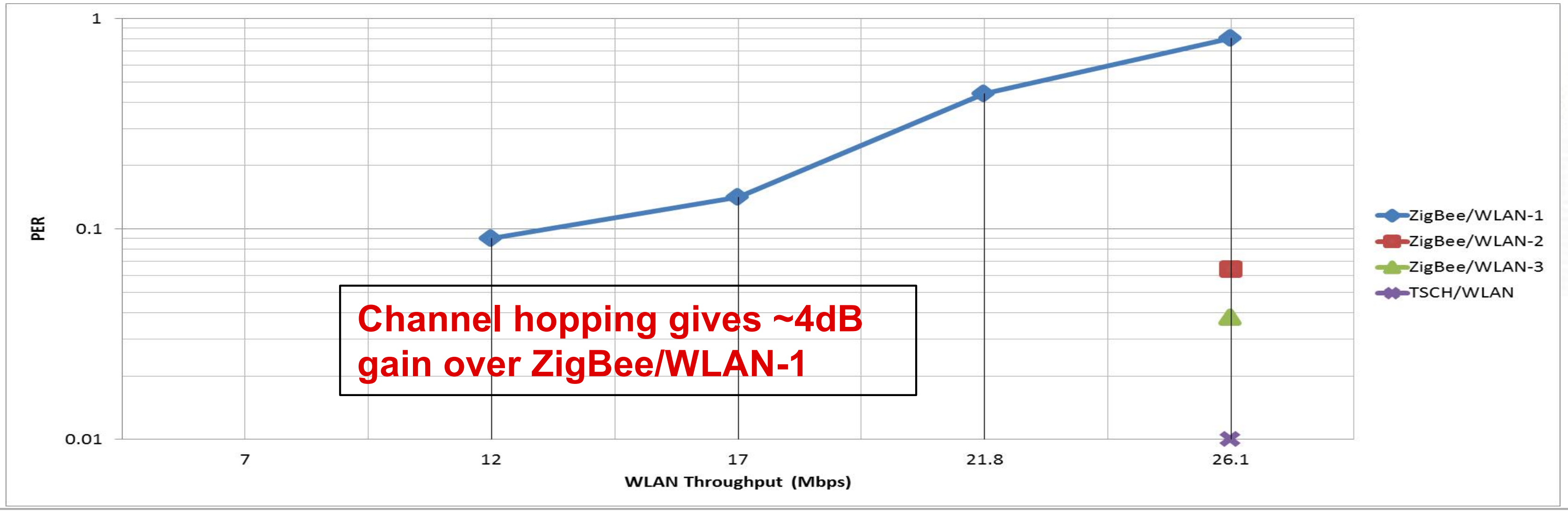




Robustness Test – Quantification in 2.4 GHz

- Interference: Two Wi-Fi nodes in channel 1-4
  - 1470B UDP Traffic generated by jperf
  - Variable rates
- 15.4 traffic: 70B/8sec
  - ZigBee operates in channel 11
  - Uses channel hopping from chan 11 to chan 26

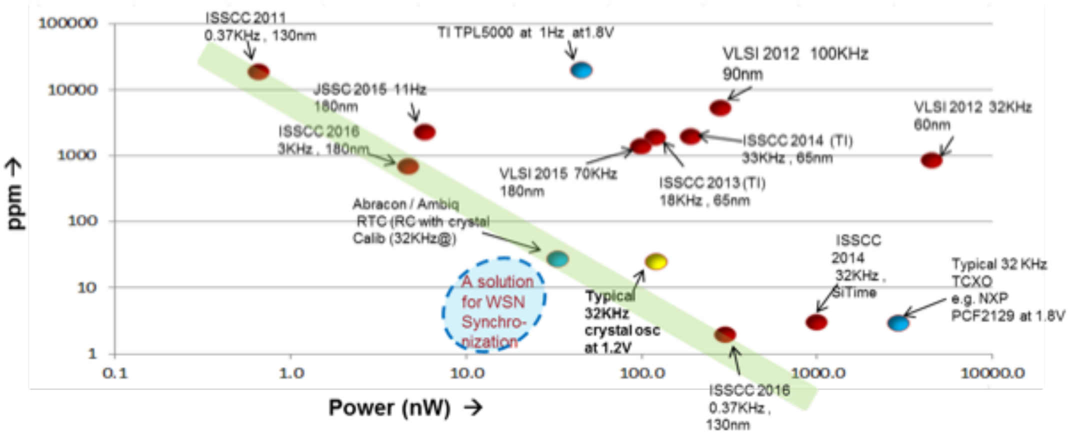


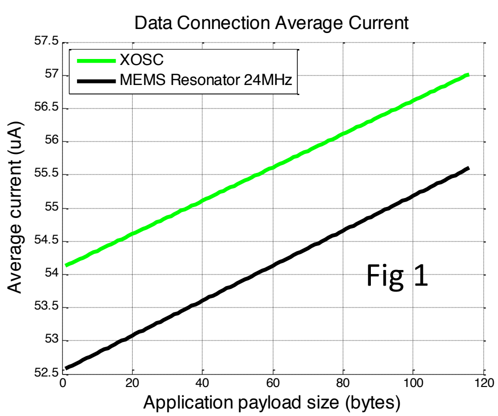


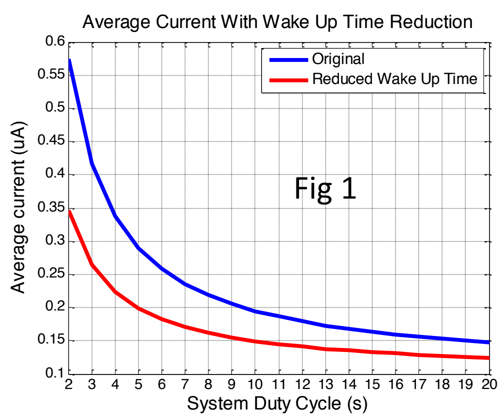
Step 2: Reduce Radio Wake-up Overhead

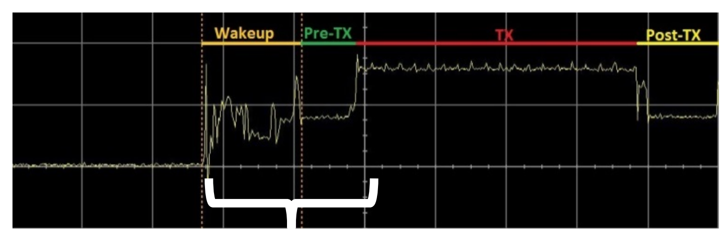
Ultra low power & Fast Wake up – BAW MEMS Clock

- Duty Cycled App
  - wakeup time reduced from 500uS to 5uS
  - Duty cycle 1second (I3Mote with 6TiSCH)
  - Fig 1
- Duty Cycled Sensors saving:
  - HDC1080 humitity+temp sensor on I3Mote
  - wake up time reduced from 2.5ms to 0.1ms
  - Power saving: 15% - 39% (Fig 2)

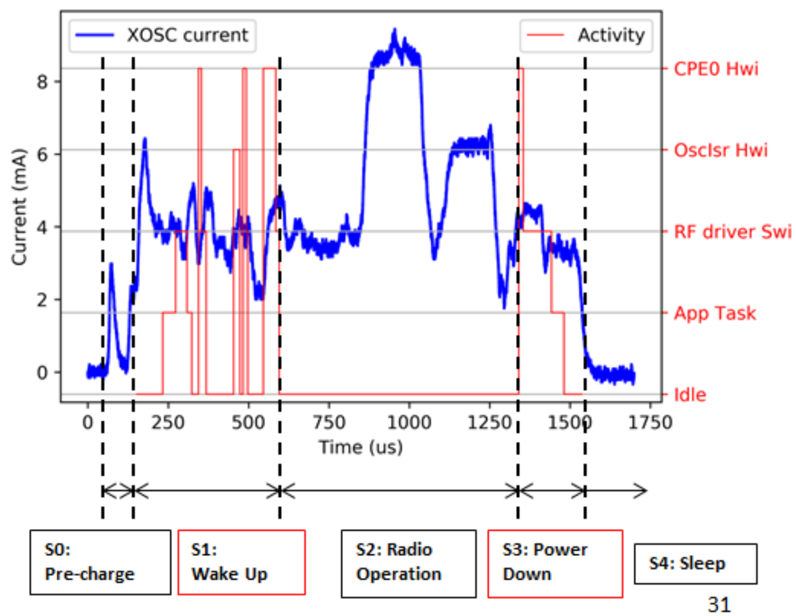




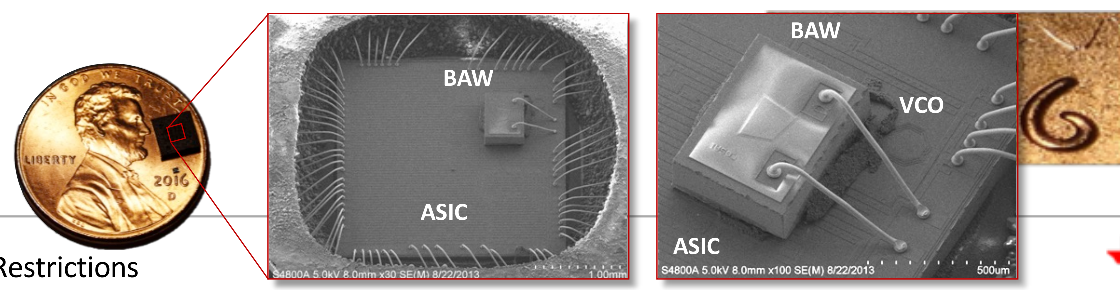




Ultra Low Power and Fast Wake-up - BAW



- For radio TX and RX the system operation consists of Wake-up", "Radio Operation", "Power Down", and "Sleep"
- Wake-up time consumes significant time/current
- It is important to reduce the wake-up time to reduce the power consumption
- How can we optimize → BAW (Bulk Acoustic Wave)
- **BAW Definition**: a crystal-free high-frequency (~2-3GHz), piezoelectric MEMS resonator technology targeting for high performance timing and frequency filtering applications.
- **Timing Applications:** Crystal replacements, oscillators, jitter cleaners, clock integration



Step 3: Improve power management efficiency

Multiple Input, Multiple Output Power Management

Energy Sources

USB
Primary Cell
Energy Harvesting
- Solar
- TEG
- Vibration
- RF
- Electro-magnetic

4-20mA Loop

Power Management

Loads

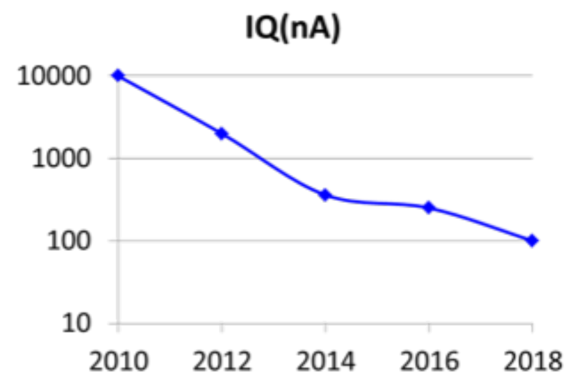
Actuators
Sensors
Analog interfaces
drivers
Processors
RF Communications
Wireline Comms

Cap/Supercap
Rechargeable cell

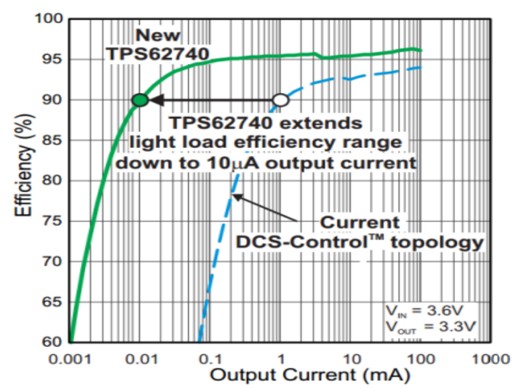
Energy Storage

Improve Power Management Efficiency

About 60% of total power in sleep mode is consumed by analog power management functions



Light load efficiency in lo load current down to mAs



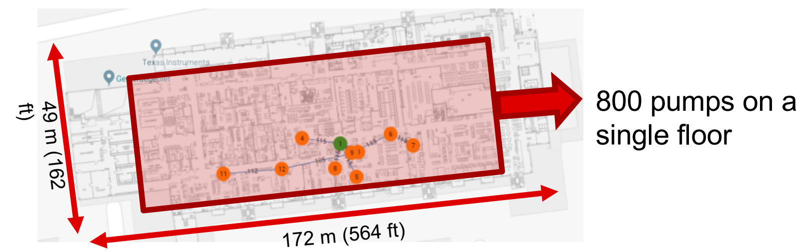
Requirements for New Power Module

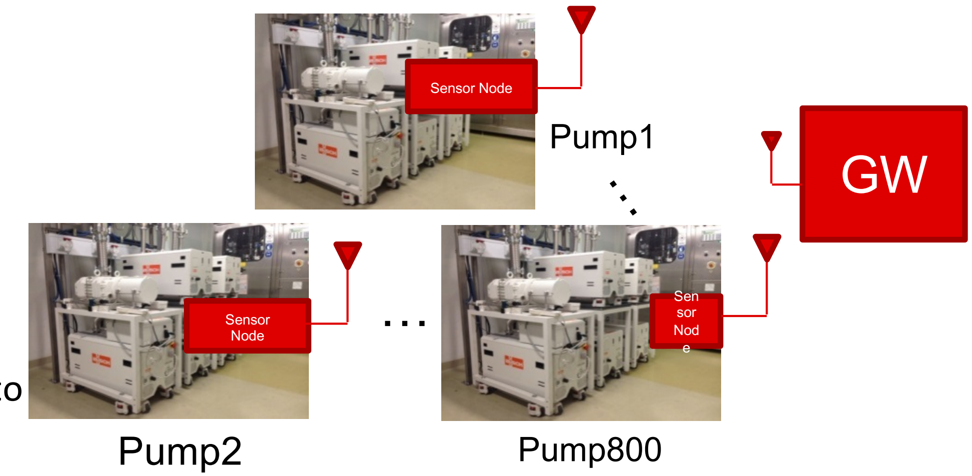
Features	Target	Now
Power efficiency	> 90%	~75 %
Integration	High (single chip)	Low (4 chips)
Ultra low-power metering	Yes	No
Iq (Quiescent Current)	< 100 nA	1.5 uA
Reverse voltage protection	Internal	External diode (reduces the efficiency)
Number of required external inductors	1	3
Automatic power source detection	Yes (with the specific power ordering)	Yes

Step 4: Optimize Sensor Data Usage (Embedded Analytics) and Reduce Radio Duty Cycle

Motivation of Data Analytics: Remote Monitoring

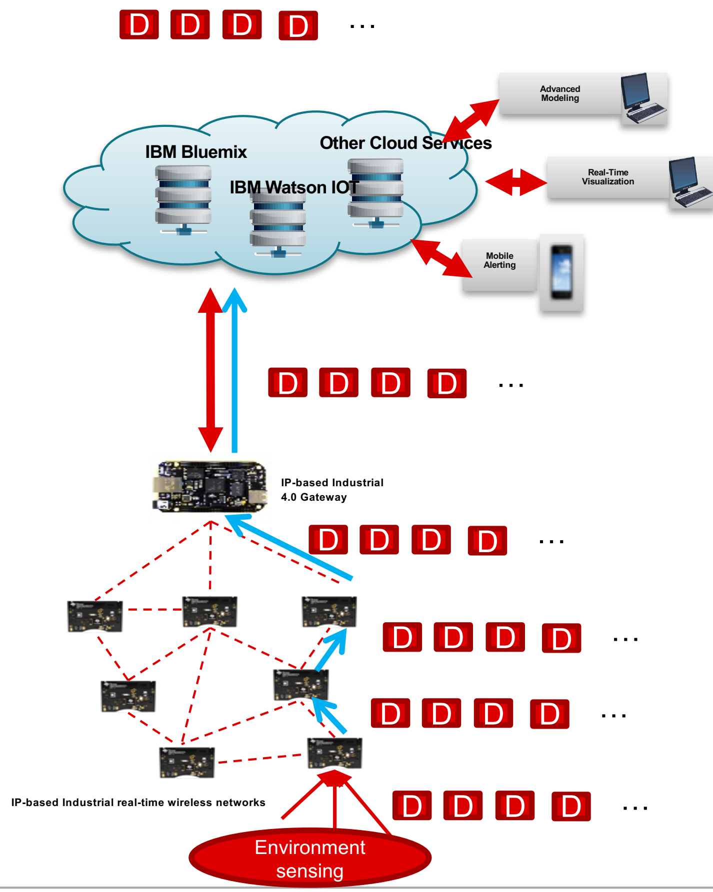
- A factory has 1000 pumps + equipment for monitoring on the factory floor
- More than 10 different kinds of sensor data monitored needs to be read every 1-10s
- In one year, total over-the-air data size is about **~1 TB**, which consumes ~**1.2 MJ** system energy
- ~1% of 1 TB carries “useful” info
  - Energy consumption number can be reduced
  - Supported number of nodes can be increased by upto ~100x
- ***Send necessary information from the se nodes to the central controller***



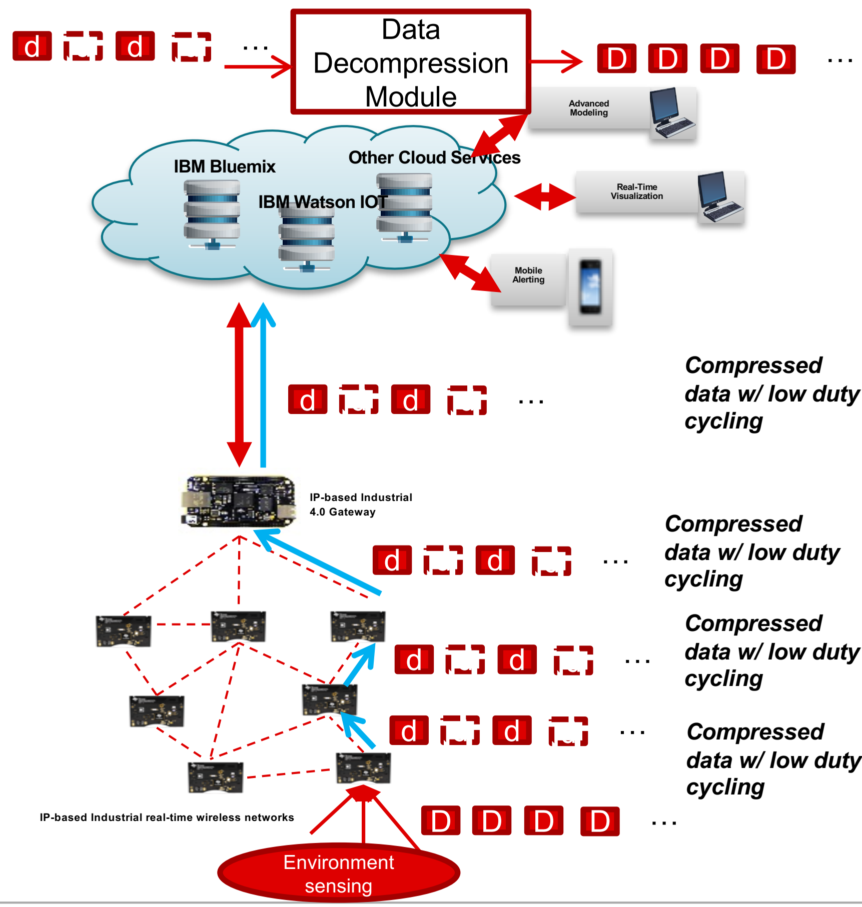


STATUS	DP CURRENT	MB CURRENT	TEMPERATURE	PRESSURE	H2O FLOW	N2 FLOW	PUMP STATUS	WORK TIME	FAULT ID	CHANNEL
	5.4 (A)	4.3 (A)	95.2 (°C)	0 (bar)	1.7 (l/min)	17.7 (l/min)	- N2seal: 0 - OIL: 0	1600 (h)	undefined (hex)	20

Data Duty Cycle Reduction Concept

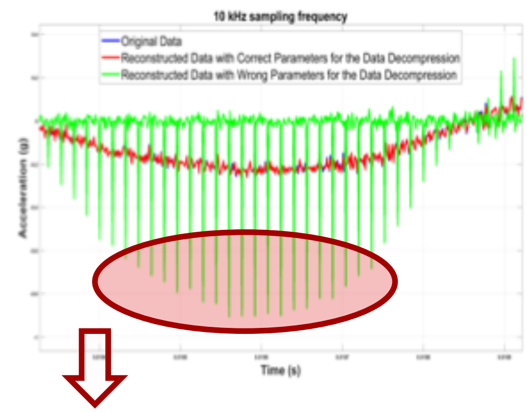


Data Duty Cycle Reduction Concept



Data Compression

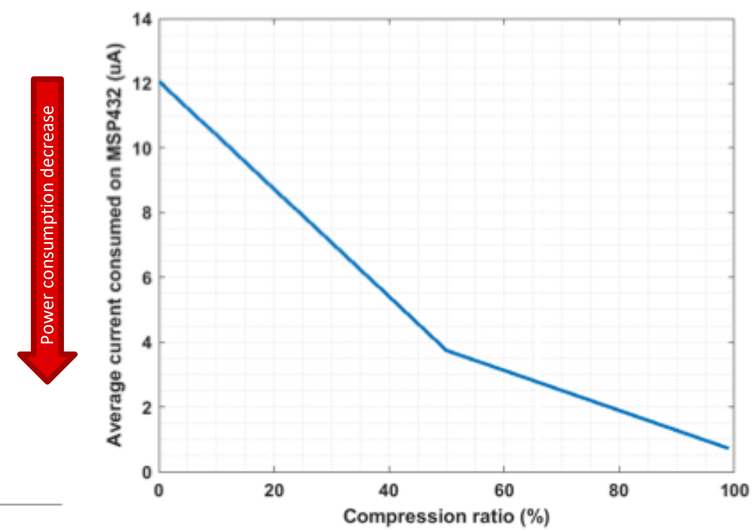
- Slowly varying data example:
  - Temp, humidity, pressure … data duty cycle of read/10s can be reduced to ~20 mins with compression recovery accuracy of 99.5-99.9%
- Data recipient (GW) needs to obtain data variation pattern over time of 1% of the original duty cycle



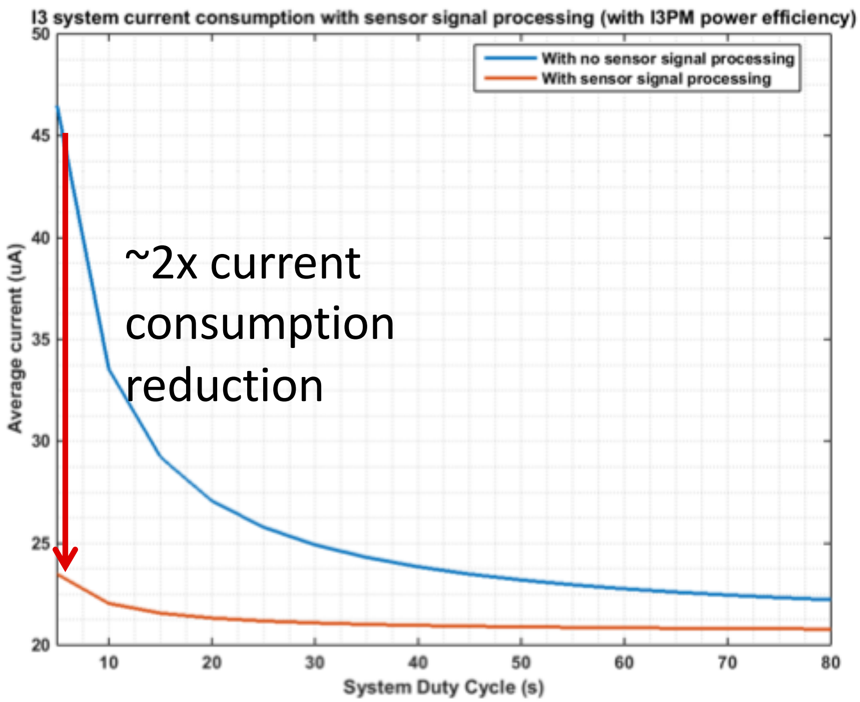
Incorrectly reconstructed data due to unknown decompression parameter at the receiver

Data Compression Performance

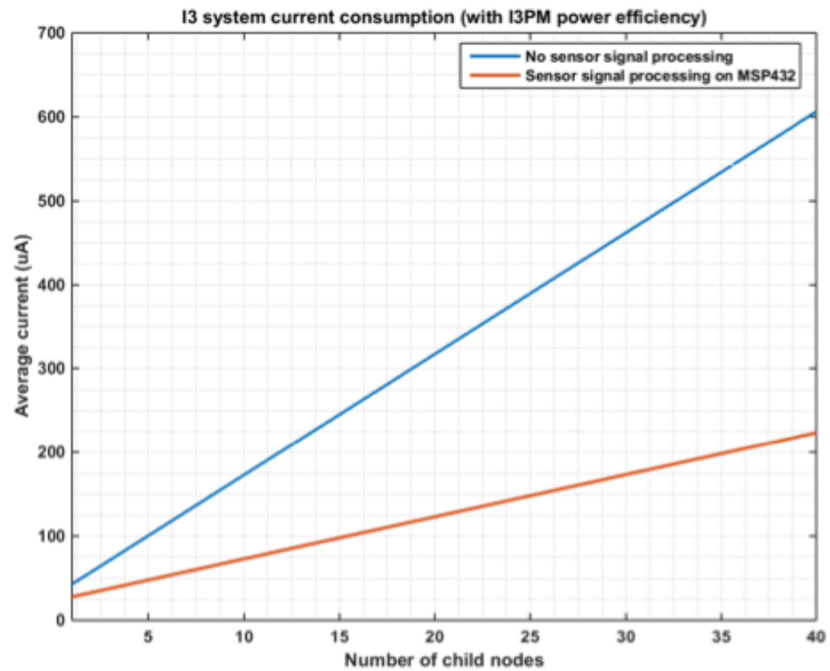
Sensor Data	Compression ratio (%)	Accuracy (%)
Humidity	99.9	99.5
Temperature (Ambient)	99.9	99.9
Vibration (1 Hz signal)	99.9	99.7
Vibration (1 kHz signal)	99	99.8
Pressure	99.9	99.95
Temperature (Oven, low frequency sine wave)	99.67	99.96
Temperature (Oven, high frequency sine wave)	99.3	99.97
Temperature (Oven, square wave)	99.25	99.9



Power saving through “Smart Sensing”



Star topology

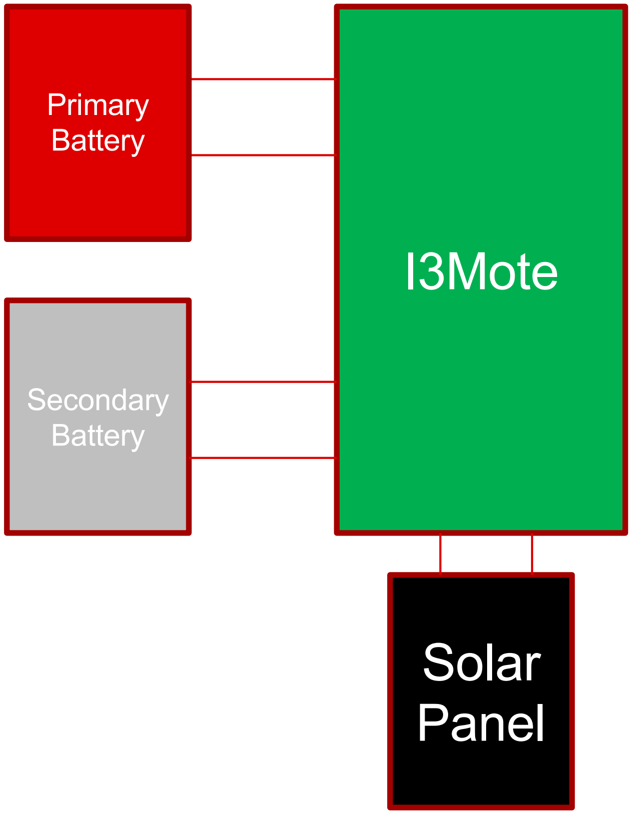


Mesh topology

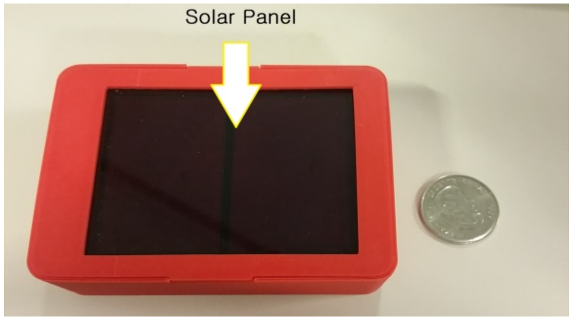
Step 5: Optimize Network Topology through Smart Gateway

Step 6: Energy Harvesting

Application on I3Mote

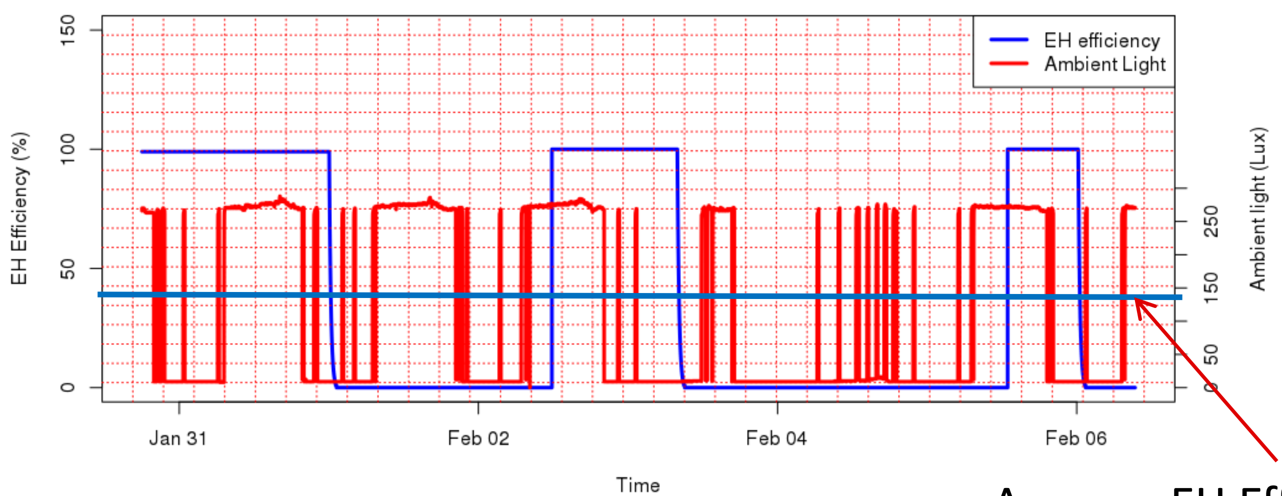


- Rechargeable battery used as the secondary battery
  - Whenever the energy from the secondary battery is available, use the energy from it. Otherwise, use the energy from the primary battery
- Solar panel used to charge the secondary battery



Experiment Results (Under “Normal” Office Light Strength)

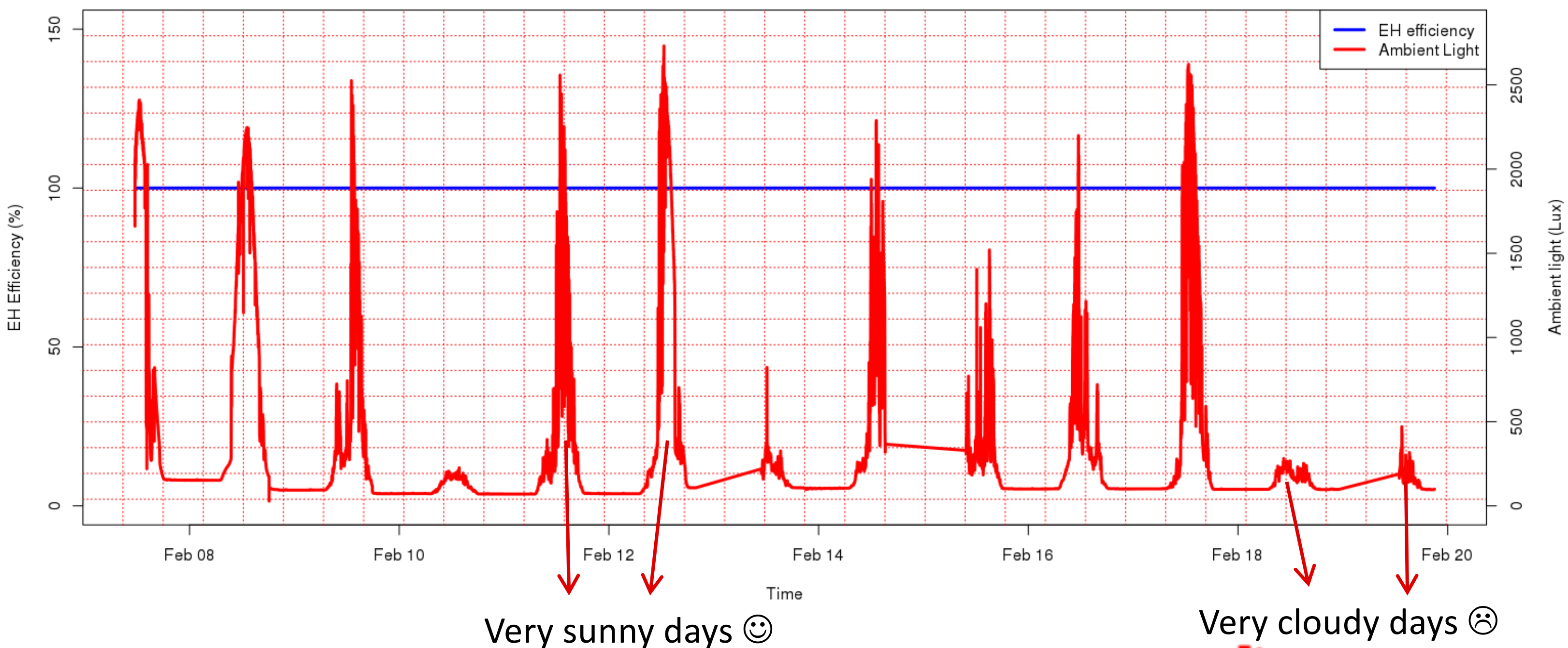
- Office light on during the day (~250 lux) and off during the night
- Average ambient light strength: 120 lux
- Average efficiency: 38.8 %
- Battery life increase: 160%



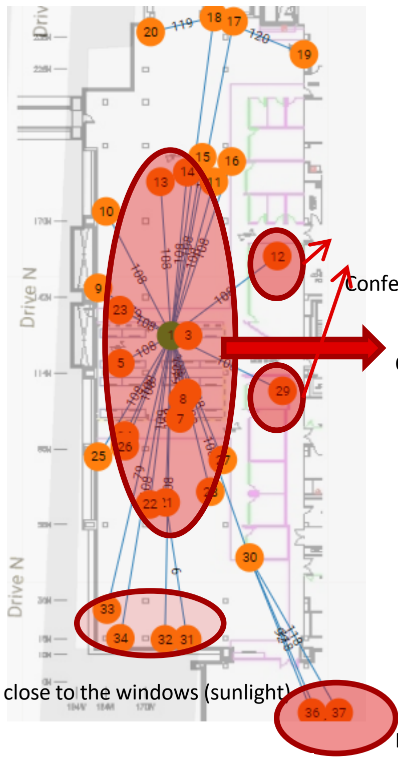
Average EH Efficiency

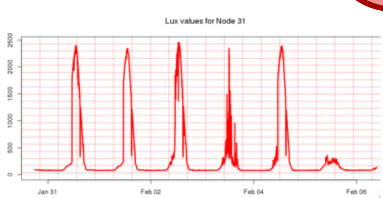
Experiment Results (Location Close to Window)

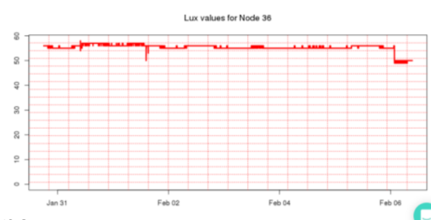
- Node close to window
- Average ambient light strength: 319 lux
- Average efficiency: *100 %* ➔ *No battery required*



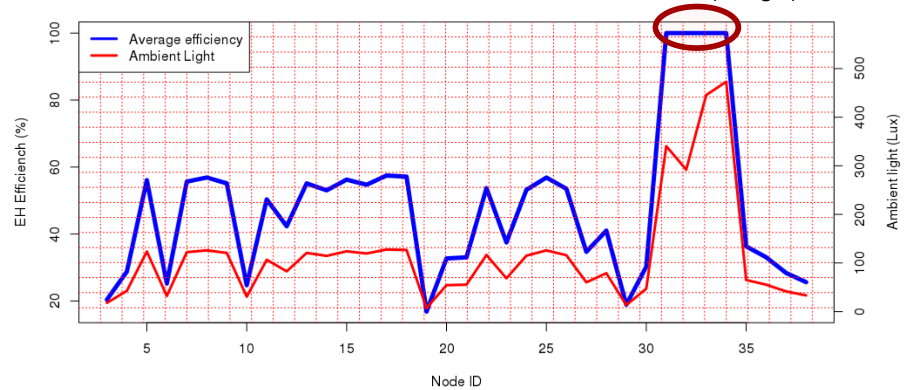
Network Topology

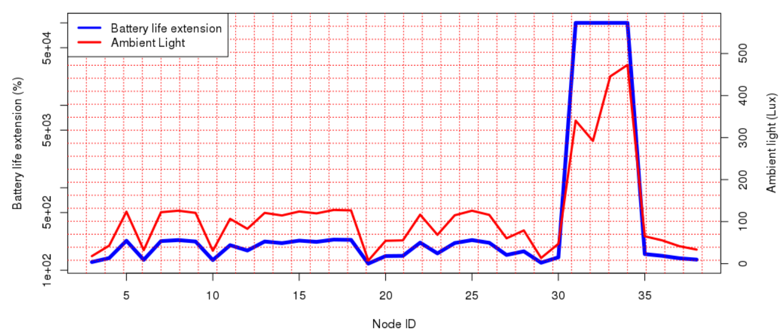






Nodes close to the windows (sunlight)





Texas Instruments

Summary

1. Power performance is one of the key challenges for WSN ”motes”
2. A methodology proposed to reach 10 years battery life

	AA Battery Life (years)
ZigBee (Fully Functionally Device Mode)	4.4 years
TSCH	5.70 years
TSCH + fast wakeup	6.06 years
TSCH+ fask wakeup + improved PM with higher efficiency and low Iq	7.2 years
TSCH + fast wakeup + improved PM + smart sensing with higher efficiency and low Iq	13.12 years

3. It is a system wide optimization which contains
   - Ultra-Low-Power and Robust protocol
   - Fast wake-up clock and low leakage
   - Power management circuits efficiency
   - Smart sensing to reduce duty cycle of radio
   - Energy harvesting as complimentary power supply