CS 4222/5422 WIRELESS NETWORKING

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Topics Covered – Lectures

1. Wireless communications basics
2. SensorTag & Contiki
3. Mobile Devices/IoT & Energy Consumption

Sensor Networks (Early Definition)

- Advancement in Micro-Electro-Mechanical Systems, or **MEMS**, technology makes it possible to build very small sensors
- Nodes that are very small, extremely low computation power, energy constraint, (relatively) low bit-rate can be built
  - *These constraints are fundamental to the design of sensor network protocols*
- Densely deployed, highly redundant
  - *Each sensor node can "hear" many other sensor nodes*
- Deployed in large quantities → - Better coverage - can talk to each other
  - *Nodes are small and cheap* - Redundancy sensing
  - *Several order higher than "ad hoc" network* - Deploy in large quantities
- Design to execute a specific task
  o e.g monitor building

(Cyber physical system)
↳ operate in the cyberspace → operate in virtual env

A more general definition:

- A sensor network is a set of small autonomous systems, called sensor nodes which cooperate to solve at least one common applications. Their task include some kind of perception of physical parameters
  ↳ temp/Hum/ air temp

→ Networks of wireless relays
→ Goal involve on applications

Tasks

o First level calculation
o Smart devices → track pattern

cloud upload

- *Combines sensing, computation and communication*
- Generic set of high-level information processing tasks:
  - *Detection*
  - *Tracking*
  - *Classification*

Milltary applications?

Benefits/Motivation

- Lower cost of wiring → wiring can be expensive / Difficult / Danger
- Retrofit of existing systems → Track where the obj is, quickly
  check container existance
- Harsh Conditions

o Soil quality
o Temp
o regulations

Fruit production etc etc.

Sensor to measure flow rate
⇒ Detect leaks

Early Example/Motivation

- **Smartdust** (2001) a hypothetical system of many tiny micro electromechanical systems (MEMS) such as sensors, robots, or other devices, that can detect, for example, light, temperature, vibration, magnetism or chemicals; are usually networked wirelessly; and are distributed over some area to perform tasks, usually sensing.

Some (Early) Research Prototypes

- **Wildlife conservation through autonomous non-intrusive sensing (2002)**
  - *190 wireless sensors are used to monitor the habitat of nesting petrels (ocean birds) on Great Duck Island, 10 miles off Maine*
- **ZebraNet Wildlife Tracker (2002)**
  - *Wireless sensors are attached to collars of zebras. The devices will monitor the animals' location and activities like eating, moving or resting*
  - *The collars will periodically broadcast a signal to search for other collars in the area. Once two collars establish a connection -- zebra to zebra -- they will trade data*
  - *Every few weeks, biologists could find some of the collared zebras and download detailed data about the entire herd in a few quick transactions*

Some Research Deployments

- Monitoring of Golden Gate Bridge's structure (UC Berkeley, 2007)
  - *64 nodes located on a 4200ft long bridge*
  - *Longest hop is 46*
  - *Provides synchronization with less than 10μs jitter*
- Structural monitoring: buildings, tunnels, mines, etc.
- Environmental Monitoring: air quality, human mobility etc.
- Farming/Agriculture

GPS
↳ Time sync
↳ location

Internet of Things

- The **Internet of Things** (**IoT**) is the interconnection of uniquely identifiable embedded computing devices within the existing Internet infrastructure. (http://en.wikipedia.org/wiki/Internet_of_Things)
  - *Networking – reachable through Internet protocols, so any device can be contacted*
  - *Any THING can be a device and device is "smart" (can compute, sense and communicate)*
  - *Device can perform "many" tasks and can be shared.*

Smart Devices – Examples/Applications

- Personal devices: Smart Watch, TraceTogether token etc
- Home Automation
  - *Smart light Bulb: Controllable through app using ZigBee/BLE/WiFi*
  - *Smart (Power) Meter* → Dont need read meter often
  - *Google Nest: home automation*
    - Thermostats, smoke and carbon monoxide detectors, speakers, displays, security systems (camera, doorbells, locks etc.)
- Industrial Automation
- Many more …….

Smartphone as Sensing Device

- Smartphones are ubiquitous
  - *Sale of smartphones has overtaken personal computers in the year 2011 (Canalys, 2012)*
  - *There are 6.8 billion mobile subscriptions worldwide (ITU, Feb 2013)*
  - *Unique mobile users about 3 billion (Wireless Intelligence, 2012)*
  - *1.4 billion smartphone users by Dec 2013 (Business insider, Feb 2013)*
- Lots of computing power
- Lots of sensors
- Recharge by users

Smartphones (2000 and Beyond)

Project

- Proximity detection
  - RSFI + Sensing

- iPhones (2007)
  - *CPU: 412 MHz ARM 11, 128MB RAM*
  - *Sensors: accelerometer, proximity*
  - *Network: Cellular/WiFi/Bluetooth*
  - *Battery: 1400mAh*
- Samsung S8 (2107)
  - *CPU: Octa-core (4x2.3 GHz & 4x1.7 GHz), 4GB RAM, GPU*
  - *Sensors: Iris scanner, fingerprint, accelerometer, gyro, proximity, compass, barometer, heart rate, SpO2*
  - *Network: GSM/HSPA/LTE, Wi-Fi 802.11 a/b/g/n/ac, Bluetooth/NFC/Infrared*
  - *Battery: 3,000mAh*

Topics Covered – Lectures

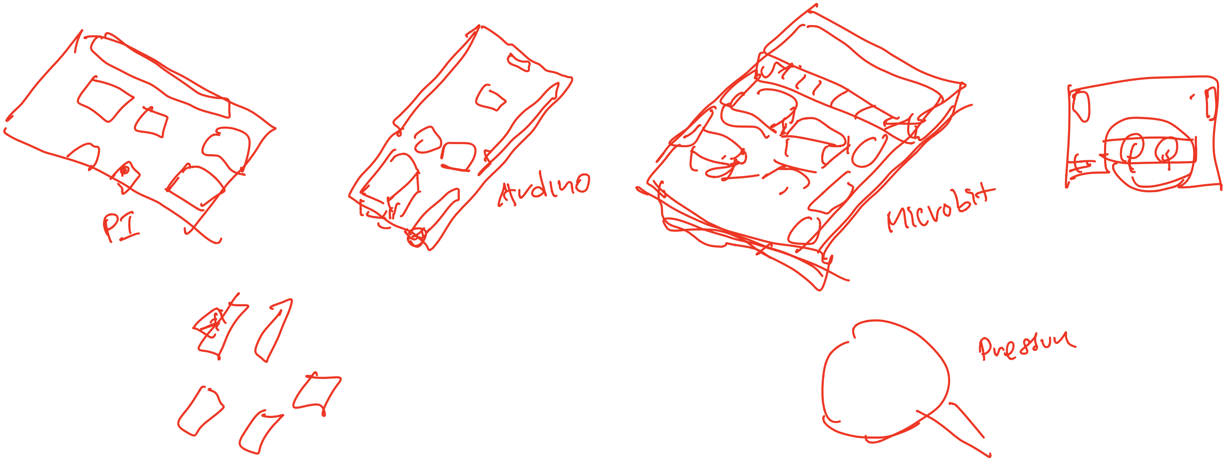
1. Wireless communications basics
2. SensorTag & Contiki
3. Mobile Devices/IoT & **Energy Consumption**

→ Size

→ power

→ sensors dependent on how much the power consume

→ location of use



Sensors

Terms/Units (Quick Revision)

- Voltage: Volts (V): the SI unit of electromotive force
- Current: Ampere or “amp” (A) is the SI unit of electric current
- *Power (W) = volts (V) x amps (A)*
- Energy (Joule) = Power x Time.

- Example:
  - *A device running at 1V draws 1A.*
    - The power consumption is therefore 1W
    - Energy consumed in 1s is 1J

Battery

- Battery lifetime: The **watt-hour** (symbolized Wh) is a unit of energy equivalent to one **watt** (1 W) of power expended for one **hour** (1 h) of time.

  Example:

  - *Dell Latitude E7440 Laptop (3 cell): 34Wh - provides 1W for 34 hours.*
  - *iPad2: 25 watt-hour*

- An **ampere-hour** or **amp-hour** (**Ah**) is a unit of electric charge equal to the charge transferred by a steady current of 1A flowing for one hour,
  - *iPad2 6930mAh, voltage = 25Wh/6.9Ah = 3.6V*
  - *Samsung S4: 2600mAh (3.7V), 9.62Wh*
  - *AA Energizer Alkaline: 2500 mAh (1.5V), 3.75Wh*
  - *Calculator Battery (CR2032): 225 mAh (3V), 0.675Wh*

$$\frac{W}{h} \div \frac{A}{h} = \frac{W}{h} \times \frac{h}{A}$$
$$= \frac{W}{A} = V$$

Energy Consumption

- Mobile nodes are battery powered
  - *Energy constraint is fundamental to the design of low power network protocols*

who consume more power?

- System Components
  1. *Network* (2nd By Avg)
  2. *Screen/Monitor* (By Avg : consume more)
  3. *Computation*
  4. *Sensing* → How often does the sensor collect data

Network Energy Consumption

High data low range

low power

→ High data rate

TABLE IV
CURRENT CONSUMPTION OF CHIPSETS FOR EACH PROTOCOL

Standard	Bluetooth	UWB	ZigBee	Wi-Fi
Chipset	BlueCore2	XS110	CC2430	CX53111
VDD (volt)	1.8	3.3	3.0	3.3
TX (mA)	57	~227.3	24.7	219
RX (mA)	47	~227.3	27	215
Bit rate (Mb/s)	0.72	114	0.25	54

Table taken from Jin-Shyan Lee, Yu-Wei Su, and Chung-Chou Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," IECON, 2007

∴ we can guess that UWB has short range compared to WIFI due to the bit rate

A mobile device with a battery capacity 9.62Wh transmits continuously on:

- WiFi:
  - Considering only network energy consumption
    - power consumption: 3.3V*219mA = 722.7 mW
  - Duration = 9.62/0.7227 = 13.3hrs → Batt life
  - In practice, the duration is much shorter due to energy consumed by other components
- Bluetooth: (1.8V * 57mA = 102.6mW)
  - Duration = 9.62/(1.8*0.057) = 93.76hrs

→ Can use to check (↑bR, ↓R) if like only send nvr receive

Network Power Consumption

→ waiting to sent /
waiting to recieve
⇒ IDLE: consume
energy

- Devices rarely transmit continuously.
- Having different power states allow power consumption to be reduced

Issue:
If go to
sleep, we
lose contact
with others
= latency ↑

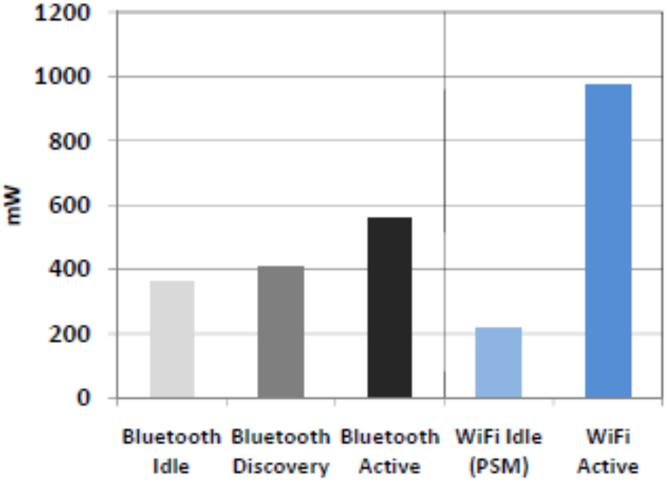


Figure 1: Power consumption of Bluetooth and WiFi radios in different states.

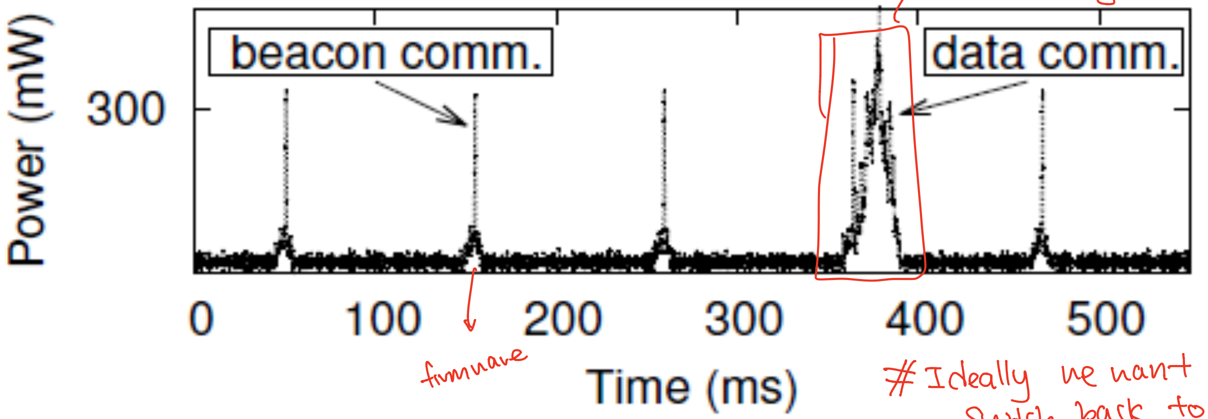
WIFI:
- Powersafe mode (PSM)
  ↳ No recieve or send
- Access point Buffer while sleeping & sent when it is awake

Bluetooth:
- Has complete sleepmode
- IDLE mode can consume more enegy than WIFI in low power mode

Ashish Sharma, Vishnu Navda, Ramachandran Ramjee, Venkat Padmanabhan, and Elizabeth Belding, Cool-Tether: Energy Efficient On-the-fly WiFi Hot-spots using Mobile Phones, in CoNEXT 2009.

Wi-Fi power consumption on a Samsung Galaxy S4

-Ping of 1 byte, wifi wake up to sent.
- Takes long time to sleep



Ideally we want to switch back to sleep ASAP

- WiFi state transition for beacon communication is (relatively) fast
- However, state transition for data communication is (still) slow due to driver/software overhead

"Classic" Bluetooth

Normal IOT device
↪ wake-up, send, sleep

→ init meant for streaming

- Always-on, short range radio
- Initially design as a way to let laptop make calls over a mobile phone
- Data Rate: 1Mbps - 3Mbps
- Three classes
  - *Class 1: 100mW*
  - *Class 2: 2.5mW*
  - *Class 3: 1mW*
- ISM band 2.4GHz (2.402GHz – 2.480GHz)
- TDD, Master-slave polling
- Supports synchronous and asynchronous traffic
- Point-to-point → one master to many slaves

○ Relatively low power consumption
○ Stream audio continuously

https://www.bluetooth.com/learn-about-bluetooth/radio-versions/

Cont’d

“Classic” Bluetooth Timing Considerations

- New slave enumeration = >3s, typically 20s
- Sleeping slave changing to active = 3s typically
- Active slave channel access time = 2ms typically

Bluetooth Low Energy (BLE)

- Data Rate: 125Kbps – 2 Mbps
- Classes
  - *Class 1,1.5: 10-100mW*
  - *Class 2: 2.5mW*
  - *Class 3: 1mW*

→ Data rate reduced
= power consumption ↓

- ISM band 2.4GHz (2.402GHz – 2.480GHz)
- Point-to-point, broadcast, mesh

https://www.bluetooth.com/learn-about-bluetooth/radio-versions/

o Switch high to low power
o support chunks of data
o channel access faster

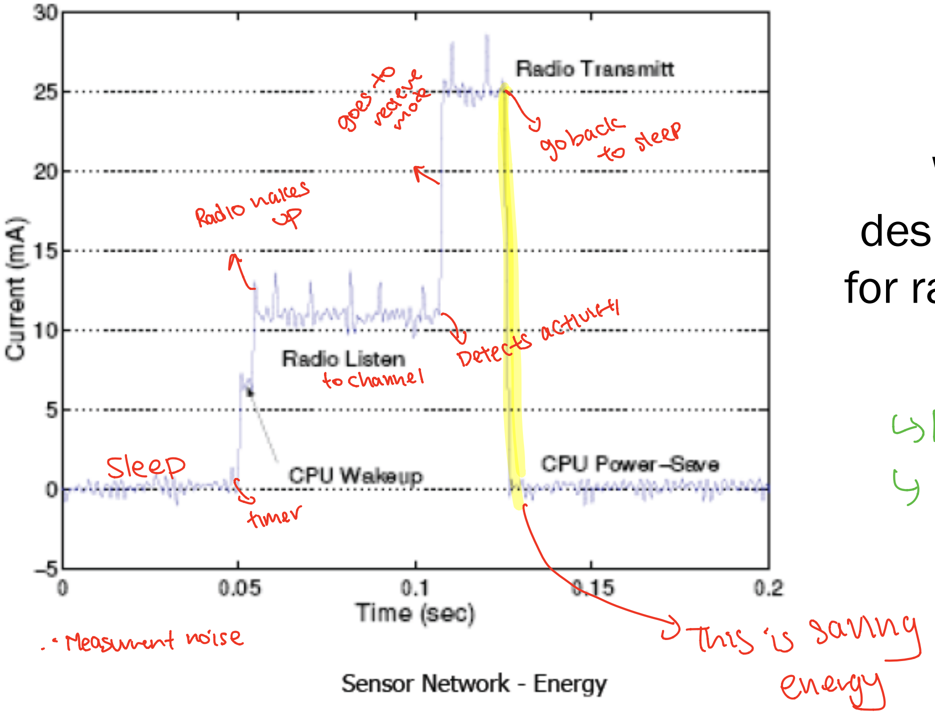
Bluetooth Low Energy (CC2640)

- Tx Current: ~ 6.1mA (0dBm)
- Tx Current: ~ 15mA
- Latency: 3 ms
- Sleep current ~ 1μA
- Designed for sending small chunks of data

latency affected

- *J. Lindh, Measuring Bluetooth Low Energy Power Consumption*; Application Report, Texas Instruments, 2017.

Current Consumption (MICA2)



· Measurment noise

Sensor Network - Energy

do not take too long to switch state

What are the desirable properties for radio to operate in low power?

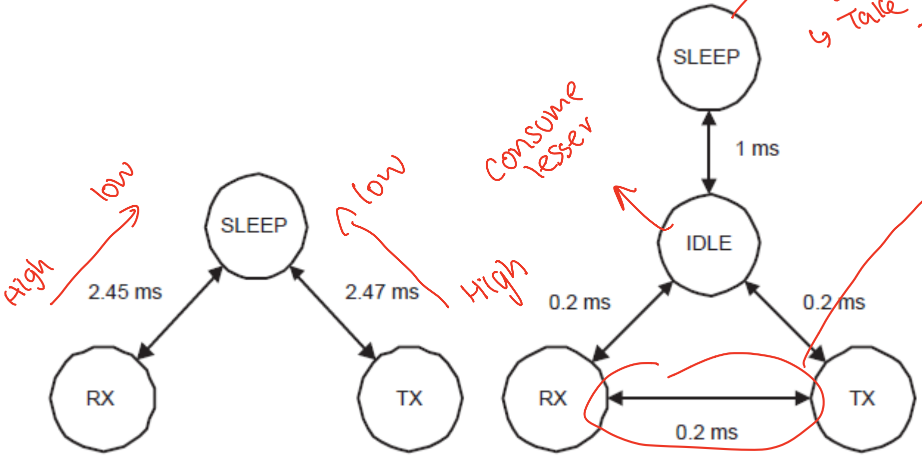
↳ low freq = low power

↳ Not far distance

Example of Different Radio States

- Energy can be saved by putting the network interfaces into low power states when they are not active

Real Sleep
↳ Take abit more time to down



(a) CC1000 Radio Model (b) CC2420 Radio Model

IDlE works as a buffer so that it will not spend to much time to go sleep whilst losing Power

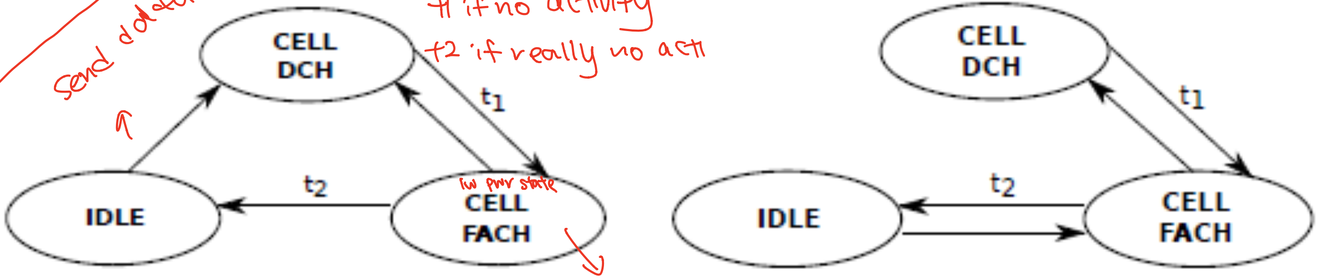
Cellular Network: 3G/4G Radio State

Low ⟺ High ⇒ take time
power   Pwr

t1 & t2
cannot be
too short

t1 if no activity
t2 if really no acti

Low
High
Send data



(a) 3G RRC State Machine: Varient 1

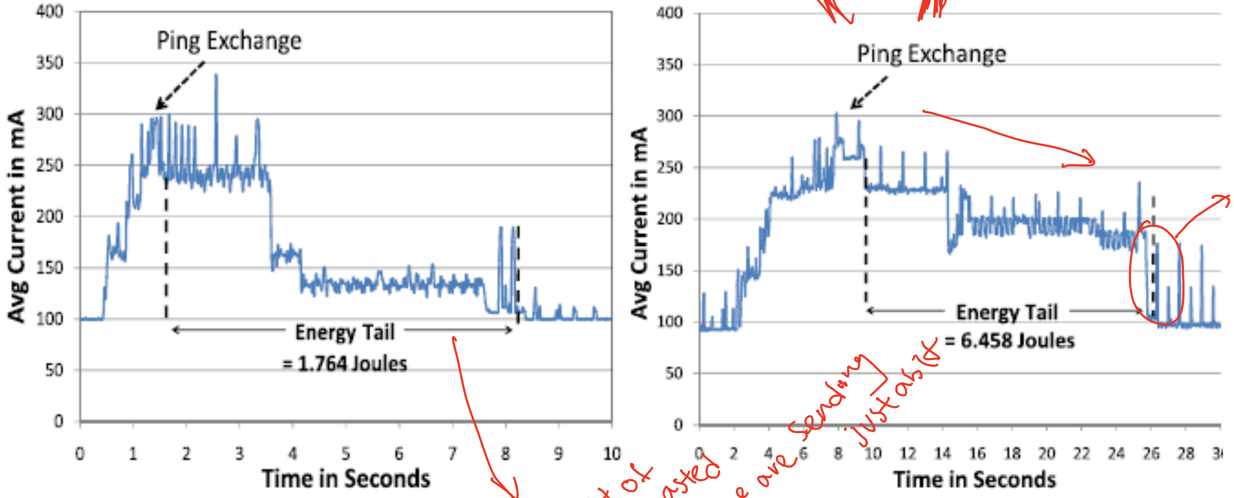
Cell Fach will consume
more power

May
send /
May not

(b)3G RRC State Machine: Varient 2

- State transition in cellular network incurs high overhead
- Radio stays in high power states in anticipation of data transfer

Cellular "Tail" Behavior



(a) GPRS/EDGE (b) 3G

Figure 2: Energy-tail experiment.

Do not go to low power quickly

Decides to save power

The amt of power wasted if we are sending just as if

- This "tail" behavior causes cellular radio to be very inefficient for infrequent transfer of small amount of data

Examples of Duty Cycling (Network Interface)

→ How often wake / sleep

- Compare WiFi (100Mbps) and ZigBee/802.15.4 (250kbps), 1s cycle, assume same voltage
- WiFi, three states;
  - *Transmit: 280mA*
  - *Receive: 180mA*
  - *Idle: 10mA* → To go to sleep mode
- 802.15.4, three states:
  - *Transmit: 30mA*
  - *Receive: 18.mA*
  - *Idle: 0.426mA*

Examples of Duty Cycling (Network Interface)

How much do you save by having longer Idle

- 100% utilization (50% transmit, 50% receive)
  - *WiFi: (180+280)/2 = 230mA*
  - *802.15.4: (18.8+30)/2 = <u>24.4mA</u> (10.6% of WiFi)*
- 10% utilization (5% transmit, 5% receive, 90% idle)
  - *WiFi: 230*0.1 + 10*0.9 = 32mA* → consume
  - *802.15.4: 24.4*0.1 + 0.426*0.9 = <u>2.823mA</u> (8.8% of WiFi)*
- 1% utilization (0.5% transmit, 0.5% receive, 99% idle)
  - *WiFi: 230*0.01 + 10*0.99 = 12.2mA*
  - *802.15.4: 24.4*0.01 + 0.426*0.99 = <u>0.6657mA</u> (5.46% of WiFi)*

Cont'd

Avg current draw =

Trans time * curr trans + curr idle * idle time

$\underbrace{\text{idle time}}_{\text{wakeup} - \text{trans time}}$

- Wakeup 10s, sends 10,000 bytes of data
- WiFi (no overhead) → wake up immediately
  - *Transmit time = 10*8/100000 = <u>0.8ms</u>* (8 → KB)
  - *Average current drawn*
    - (280*0.0008 + 10*9.9992)/10 = <u>10.0216mA</u>

      9.9992 → 10 - 0.0008
- 802.15.4 (no overhead)
  - *Transmit time = 10*8/250 = <u>320ms</u>*
  - *Average current drawn*
    - $(30*0.32 + \underbrace{0.426*9.68}_{\text{IDLE energy}})/10$ = <u>1.372mA</u>

WiFi, three states;

- *Transmit: 280mA*
- *Receive: 180mA*
- *Idle: 10mA* → To ?

802.15.4, three states:

- *Transmit: 30mA*
- *Receive: 18.mA*
- *Idle: 0.426mA*

<Best Radio>

- sleep fast
- High work output
- low power sleep

Energy Characteristics of LCD Display [4]

filter gives the colour

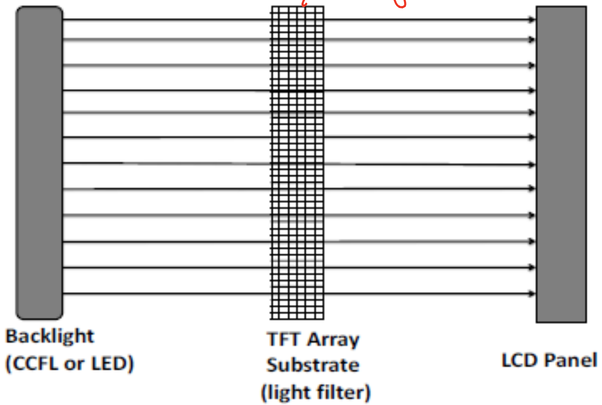


Figure 1: Transmissive LCD Displays

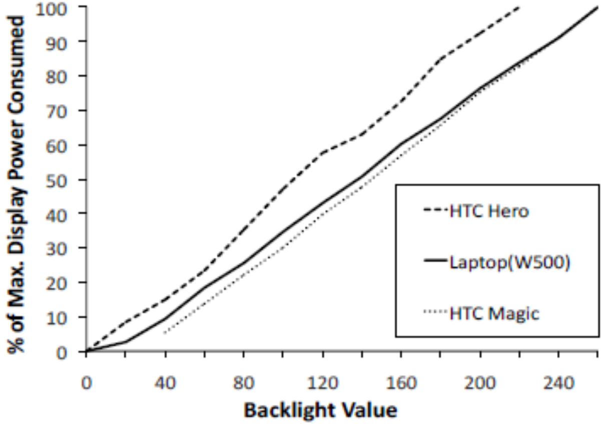


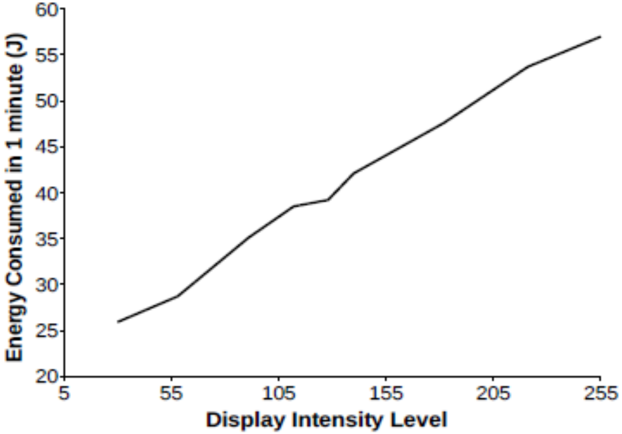
Figure 6: Power vs Backlight level

Most of the power in an LCD display is consumed by the backlight, the light filter requires comparatively less power.

Not every part needs to be high light intensity

B Anand, K Thirugnanam, J Sebastian, PG Kannan, AL Ananda, MC Chan, RK Balan, "Adaptive display power management for mobile games," ACM International Conference on Mobile Systems, Applications, and Services (Mobisys) 2011.

Energy Characteristics of OLED Display [4]



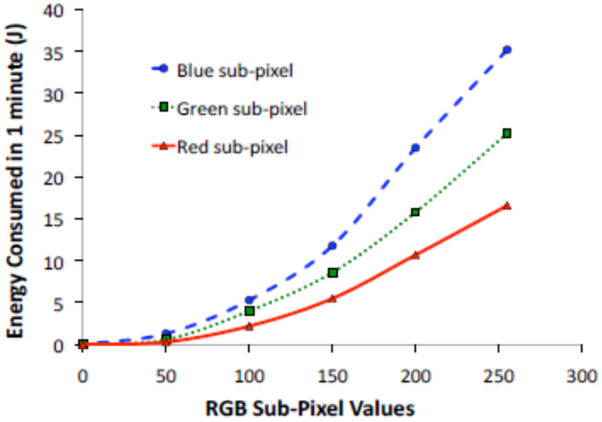


Figure 17: Energy Vs RGB Sub-Pixel Values

- OLED display functions without a backlight
- OLED displays consume less power than a LCD display when the image is dark, but more when the image is bright
- Displaying different color consumed different amount of energy

Power Modes of CC2650 Device

MODE	SOFTWARE CONFIGURABLE POWER MODES				RESET PIN HELD
	ACTIVE	IDLE	STANDBY	SHUTDOWN	
CPU	Active	Off	Off	Off	Off
Flash	On	Available	Off	Off	Off
SRAM	On	On	On	Off	Off
Radio	Available	Available	Off	Off	Off
Supply System	On	On	Duty Cycled	Off	Off
Current	1.45 mA + 31 μA/MHz	550 μA	1 μA	0.15 μA	0.1 μA
Wake-up Time to CPU Active (1)	–	14 μs	151 μs	1015 μs	1015 μs

ARM Cortex-M3: operating frequency up to 48MHz, current in ACTIVE state varies from 1.45mA to 3mA

- Batt → 225 mAH (3v)
- only CPU on → 225 / 3 = 75hrs (No sensing)
  ↳ Days 3

For comparison,

- RaspberryPi 3 (ARM Cortex-A53): 1W - 2W
- [I7-7600U@2.8GHz](#) (laptop): 7.5W (down), 15W (typical), 25W (up)
- [I7-7700@3.6GHz](#) (desktop): 65W (typical)

Sensor Energy Characteristics

○ current (less) ○ usefulness
- less power consume
- can be powered with lower volt

We can guess how far we move
↳ Dont turn on GPS but use Accelerometer to check
∴ But less accuracy

Sensor	Galaxy S3	Galaxy Nexus
Accelerometer	0.23mA	0.139mA
Light	0.2mA	0.75mA
Pressure	0.045mA	0.67mA
Proximity	1.3mA	0.75mA
Magnetic field	6.8mA	4.0mA
Gyroscope	6.1mA	6.1mA
Orientation	7.8mA	10.2mA

Energy savings mechanisms:

- Reduce sampling frequency
- Use low power sensors whenever possible
- Offload to hardware (sensor batching)

e.g Accelerometer
→ How much to sample?
→ What about walking speed

There are many sensors
→ save the data & only aware AP when significant data is collected from sensor

Reference:

- Aaron Carroll and Gernot Heiser. 2013. The systems hacker's guide to the galaxy energy usage in a modern smartphone. In *Proceedings of the 4th Asia-Pacific Workshop on Systems* (APSys '13). ACM, New York, NY, USA, , Article 5 , 7 pages. DOI=http://dx.doi.org/10.1145/2500727.2500734
- A. Caroll, etal, "An Analysis of Power Consumption in a Smartphone," USENIX Annual Technical Conference, 2010.

  - *A detail power analysis of various components in a smartphone*
  - *Question: How much of the system's energy is consumed by which parts of the system and under what circumstances?*

Power Measurement

- Detail power analysis enables more effective energy management
- Fine grained power measurement is challenging
  - Requires information/knowledge of schematics
- Target: Samsung Galaxy S III GTI9300 (S3) smartphone

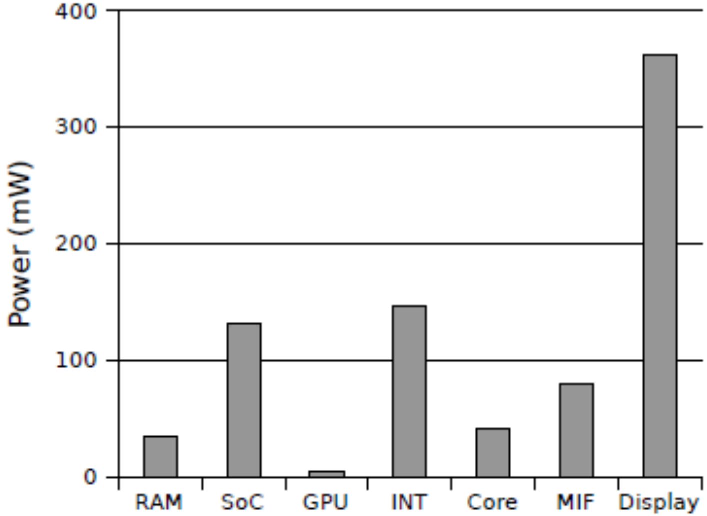
Component	Specification
SoC	Samsung Exynos 4412
CPU	ARM Cortex-A9 quad-core, 1.4 GHz
RAM	1 GiB LP-DDR2
GPU	ARM Mali-400 MP
Display	Super AMOLED, 4.8”, 720 × 1280
Battery	2100 mAh

Table 1: S3 hardware technical specifications.

Software	Version
Android OS	4.0.4
Linux kernel	3.0.15
Baseband	I9300XXLEF
Build	IMM76D

Table 2: S3 software.

Airplane Mode (805mW)



System-on-Chip
- MIF (memory interface),
- INT (internal),
- SoC (remaining miscellany).

Figure 3: Idle power in airplane mode. $P_t = 805\,\mathrm{mW}$.

Gaming (No network traffic)

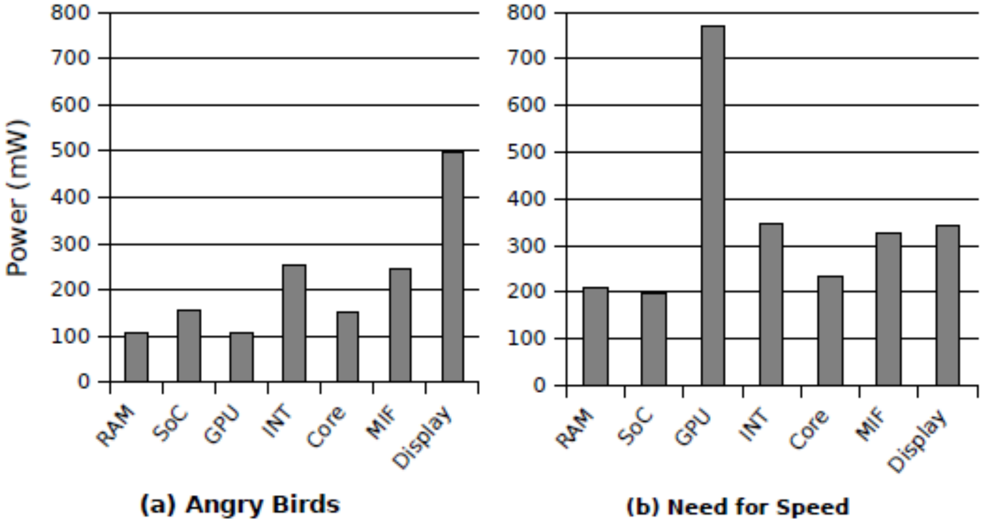


Figure 4: Gaming power consumption for: (a) Angry Birds (2D), $P_t = 1516\,\mathrm{mW}$; and (b) Need for Speed (3D) $P_t = 2425\,\mathrm{mW}$.

Video Playback (No network traffic)

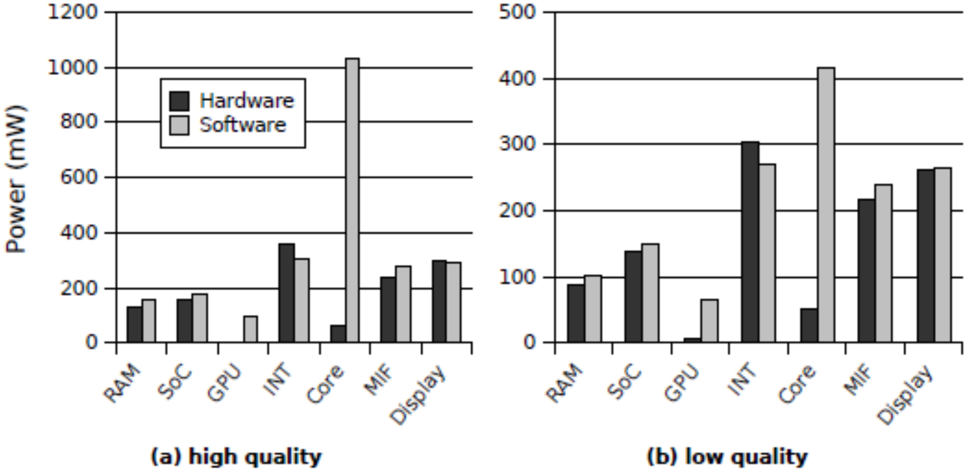


Figure 5: Video playback power consumption at two quality levels with hardware-acceleration and software decoding (a) high quality $P_{t,hw} = 1270\,\text{mW}$, $P_{t,sw} = 2329\,\text{mW}$; and (b) low quality $P_{t,hw} = 1084\,\text{mW}$, $P_{t,sw} = 1571\,\text{mW}$.

Voice Call vs. SMS

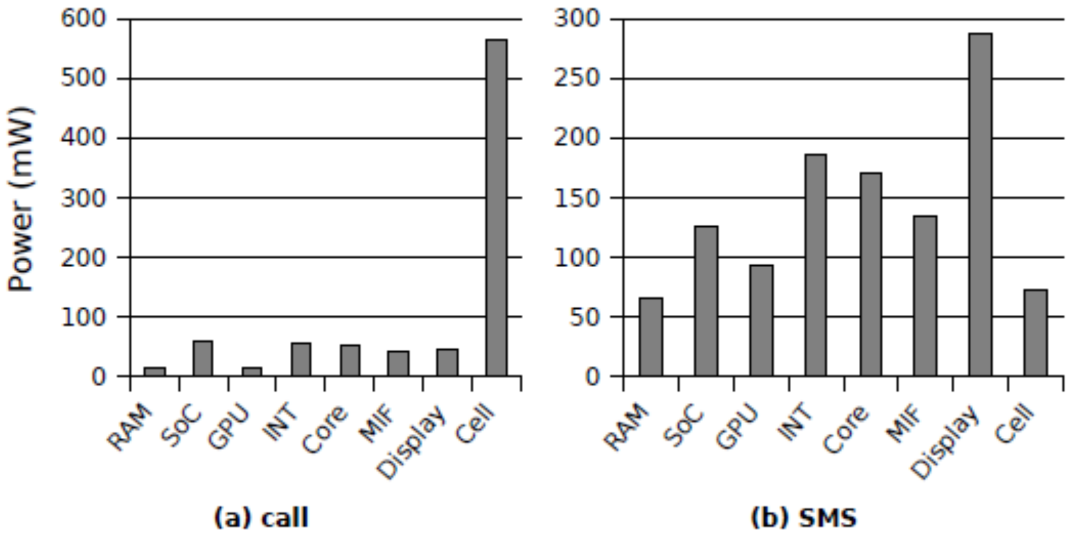


Figure 7: (a) phone call $P_{t,call} = 865\,mW$; and (b) SMS message $P_{t,sms} = 1140\,mW$, over 3G network.

Web Browsing

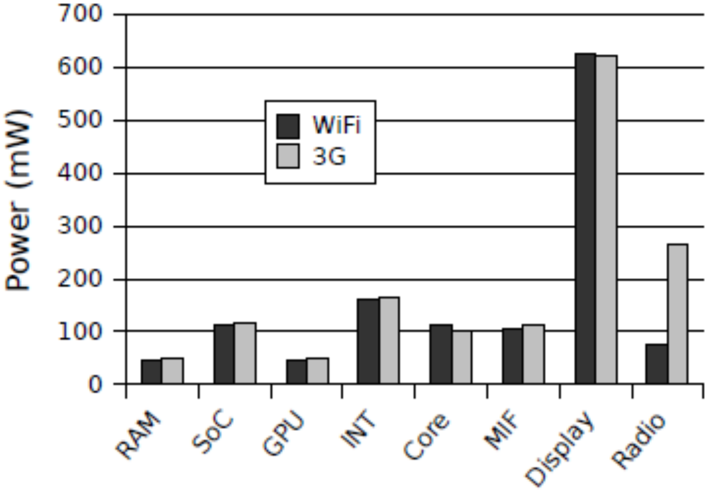


Figure 8: Web browsing over WiFi and 3G network. $P_{t,wifi} = 1275\,\mathrm{mW}$, $P_{t,3g} = 1479\,\mathrm{mW}$.

Sensors

Sensor	Power (mW)
Accelerometer	5 ± 2.3
Gyroscope	30 ± 1.3
Light	3 ± 1.7
Magnetometer	12 ± 0.6
Barometer	1 ± 0.7
Proximity	7 ± 2.2

very large cmp to the rest

Table 4: Sensor power consumption (average $\pm$ std. dev.) above the "dummy" sensor. $P_{\text{dummy}} = 573\,\text{mW}$.

close to AIR

Mode	Power (mW)
Acquisition	386 ± 19.5
Tracking	433 ± 21.5

Table 5: GPS power consumption (average $\pm$ std. dev.) above idle ($P_{\text{idle}} = 573\,\text{mW}$).

similar to screen consumptions

Maximum Power

can be push to limit such that it consume most power

Component	Power (mW)	Workload
Core	2845	AnTuTu Benchmark
RAM	208	Need for Speed (game)
GPU	1415	AnTuTu 3DRating
3G	1137	Speedtest.net (upload)
Display	1124	White screen, bright

Table 6: Maximum power.

which is more likely to be run frequently — Display → Network

Battery

Battery Technology	Watt hours/gram
Lithium-Ions in chemical batteries	0.3
Methanol in fuel cell	3.0
Tritium in nuclear batteries	850.0
Polonium-210 in nuclear batteries	57000.0

Submarine

Thomas Haenselmann, Wireless Sensor Networks: Design Principles for Scattered Systems, Oldenbourg Verlag, 2011.

Energy Harvesting

- Batteries can potentially be recharged by environmental effects
- Some examples
  - ***Solar*** *: solar cell*
  - ***Wind****: micro wind turbine can be used to harvest wind energy readily available in the environment in the form of kinetic*
  - ***Thermal****: capture energy from industrial equipment, structures, and even the human body.*
  - ***Vibration****: vibration from engines can stimulate piezoelectric materials, as can the heel of a shoe.*
  - ***Kinetic:*** *translate movement to change in electromagnetic flux*
  - ***Radio Frequency (RF):*** *convert ambient RF signal into energy (demo video)*

Example: Energy consumption & Lifetime for a sensor motes

- Sample values
  - *Basic Energy consumption : 10mA*
  - *Transmitting (PTX) : 20mA*
  - *Receiving (PRX) : 10mA*
  - *Sleeping : 0.1mA*
- Battery = 2 (1.5V) AA batteries, each provides 2300 mAh
  - *Total battery power = 2 * 1.5 * 2.3 = 6.9Wh*

clk 10MHz ,

Computation

- Clock is 10MHz
  - *1 clock cycle = 0.1μs*
- Assume
  - *average instructions takes 4 clock cycles*
  - *task takes 5000 instructions*
- Time taken = 4 * 5000 * 0.1 = 2ms
- Current drawn ~~10 00~~ mah

  = *Current * Time*

  = *10 * 2 =* ***0.02mAs***

Data Transmission

bits

- Bandwidth available 250kbps

1byte = 8 bits

- Total data transmitted = 50 bytes
- Time taken = (50 * 8)/250000 = 1.6ms
- Current drawn (transmit + CPU) = 30mA
- Current drawn

  = *30 * 1.6*

  = *<u>0.048mAs</u>*

Lifetime and Activity Period

- Duration of active period (compute + transmit) = 3.6ms
- Current drawn per cycle = 0.02 + 0.048 = 0.068mAs

If I operate a sec,
→ How long op
– How long sleep

- Let sensor node operates **continuously**:
  - *Current drawn = 0.068 mAs /0.0036 = 18.89mAs*

    [Batt] [hr in sec]
  - *Lifetime = (2300*3600) mAs / 18.89 = 438,327s or 122hr or ~5days*

    curr

    energy drawn per sec

Lifetime and Activity Period (cont'd)

- Let sensor node operates **<u>once a second</u>**
  - *Idle period = 0.9964s*
  - *Current drawn during idle period = 0.1 * 0.9964 = 0.09964mAs*
  - *Average current drawn (over 1 s) = 0.068 + 0.09964 = 0.1676mAs*

    current drawn per cycle   idle period current
  - *Lifetime = (2300*3600) mAs / 0.1676 = 13,723hr or 572days*

$LT = \dfrac{\text{Batt capacity}}{\text{How much energy drawn per sec}}$

Avg = current in idle + current in cycle

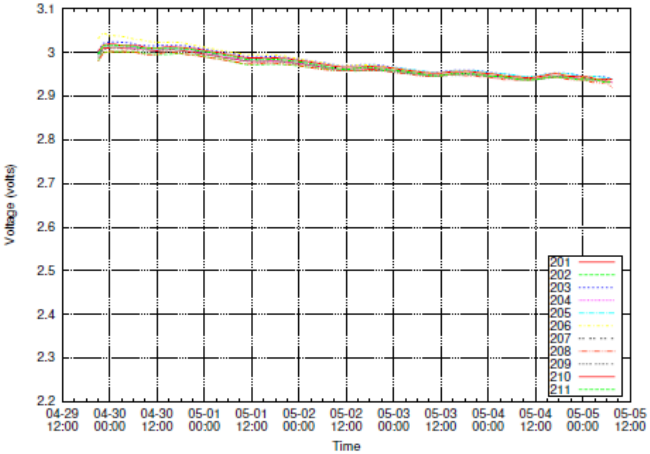
Lifetime and Activity Period (cont'd)

- Let sensor node operates **<u>once 100 second</u>** → 3.6 ms active
  - *Idle period is ~100s, active period is a very small percentage*
  - *Current drawn during idle period = 0.1 * 100 = 10mAs*
  - *Average current drawn (100s cycle) = (0.068 + 10)/100 = 0.10068mAs*
  - *Lifetime = (2300*3600) / 0.10068 = 22,845hr or 952days*
- Max lifetime (no active period) = 2300*3600/0.1 = 23,000hr

Deployment Setup for Measurements (Pasir Panjang MRT, 2009)

- Deployed sensor motes (10 Mica2, 10 MicaZ)
  - Each motes equipped with 2 AA batteries
- A relay node with both Wifi and IEEE 802.15.4 radio
  - Communicates with Mica2 and MicaZ nodes using IEEE 802.15.4
  - Communicates with gateway using Wifi
  - Runs on car battery
- Gateway node had AC power and used GSM to send data to server

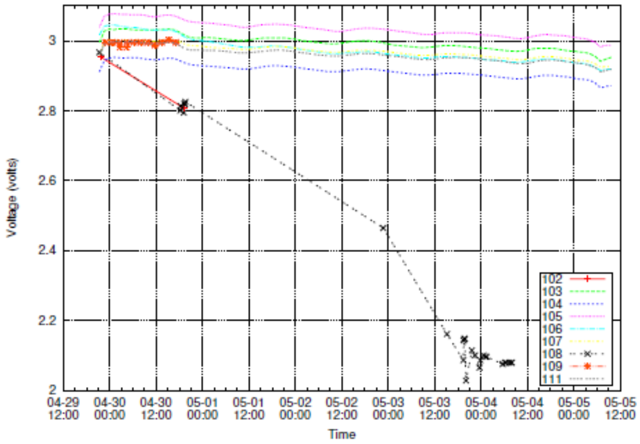
Energy consumption – Mica2



- New Battery Voltage ~ 3V
- Minimum Voltage Required to Operate ~ 2.2V

- Average voltage drop: $88.9mV$, over $5d10h$
  $\Longrightarrow 88.9mV/5.4d = 16.5mV/day$
- Expected life time $= (3015 - 2200)/16.5 = 49.4days$ $(60.6days)$

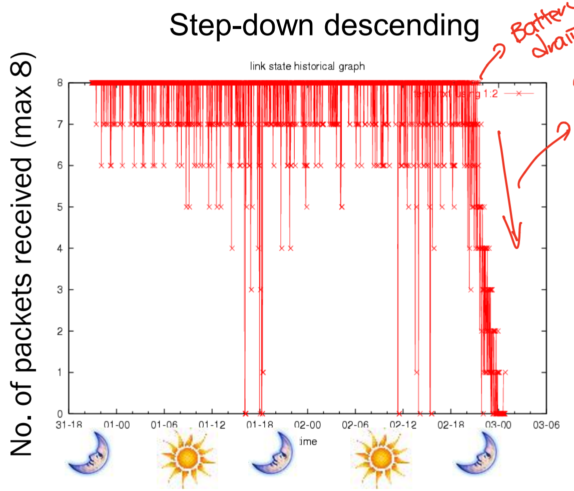
Energy consumption – MicaZ

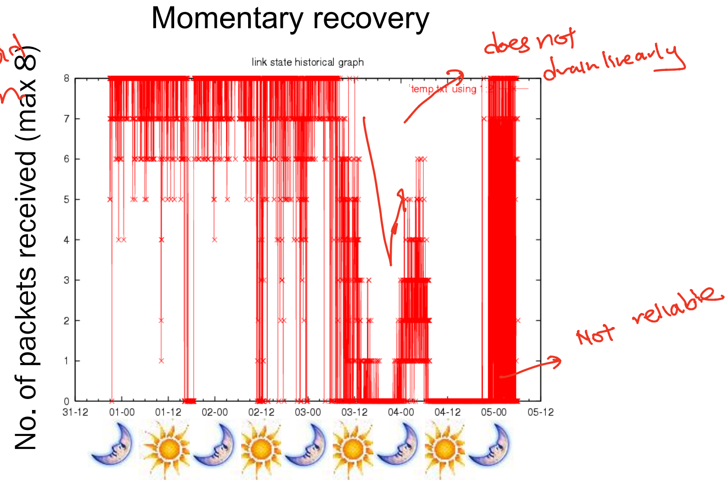


New Battery Voltage
~ 3V
Minimum Voltage
Required to Operate
~ 2.2V

- Average voltage drop: $118.2mV$, over $5d12h$
  $\Longrightarrow 118.2mV/5.5d = 21.5mV/day$
- Expected life time $= (3023 - 2200)/21.5 = 38.3days$
  $(46.5days)$

Effect of (AA) Battery Drained (MICA2)





Effect of battery drained on packet reception rate between two battery-powered devices communicating over a wireless links