Designing Self-Sustainable Photovoltaic Sensor Network

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Qualifying Exam

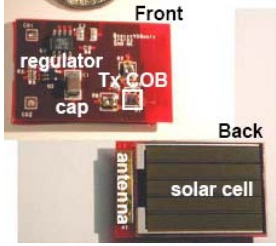
April 25th, 2006

Target Environment

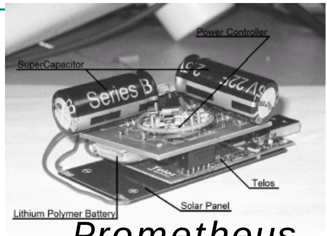
- Outdoor application
  - Wired power and battery has limitations.
  - Solar energy is available, but budget varies.
- Large-scale, multi-hop networks
  - Multi-hop is needed to cover large WSN.
  - Power saving for multi-hop is not easy.
    - RADIO ON for synchronizing nodes.
    - RADIO OFF for power saving.
  - Power saving for single-hop is trivial.

Related Work on Solar Powered Sensor Network

- Trio [DHJ+06]
  - Real deployment of large sensor nodes.
  - Multi-hop routing.
  - Operate only for several hours with full radio cycle.
- Other Previous Works
  - RF transmit beacon [ROC+03], Prometheus [JPC05] Heliomote [RKH+05], ZebraNet [ZSLM04]



RF TX beacon



Prometheus


Heliomote

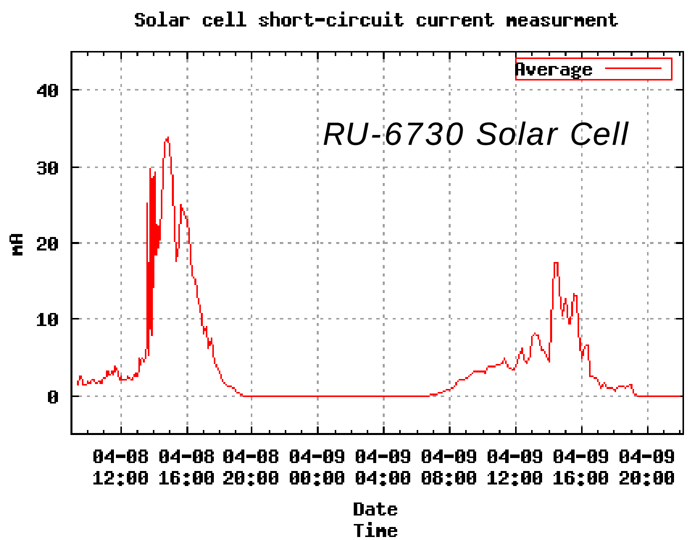

ZebraNet

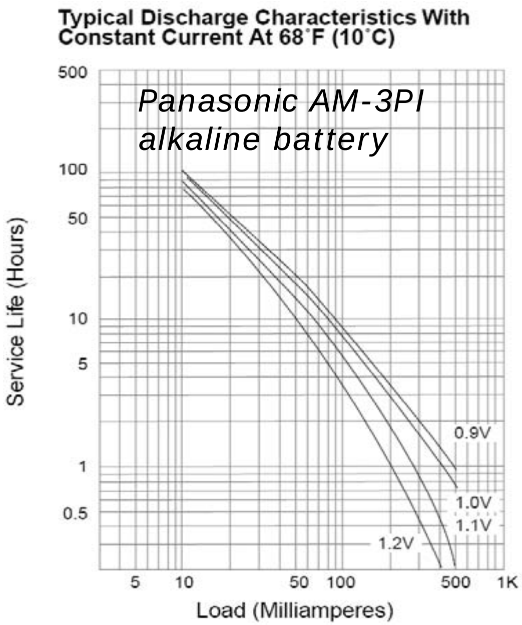

Trio

	Trio [DHJ+06]	RF TX beacon [ROC+03]	Prometheus [JPC05]	Heliomote [RKH+05]	ZebraNet [ZSLM04]
Multi-hop	Yes	No	No	No	No
Sustainable Operation	No	No (No battery)	Yes	Yes	Yes
Duty-cycling	On-off duty-cycle	On-off duty-cycle	On-off duty-cycle	On-off duty-cycle	GPS assisted time-sync
Deployment	~ 500	Lab bench	Lab bench	Lab bench	~ 10

Goals

- Power saving for multi-hop networks under solar energy source.
  - Solar Energy: time-varying, low-rate
  - Battery: constant rate, possibly at high rate





Approaches

1. Modeling energy budget and consumption.
   a. Energy budget: Analysis of varying solar radiation.
   b. Energy consumption: Estimation based on on-off duty-cycle and power consumption measurement of Trio.

2. Experiments with single-hop & on-off duty-cycle.

3. Proposal of ideas that can achieve low duty-cycling in multi-hop under varying solar energy.

Organization

- Introduction
- Modeling of energy budget, consumption
  - (a) Solar energy budget
  - (b) Energy consumption and duty-cycling
  - (c) Charging and energy storage
- Power saving in multi-hop networks under solar energy
- Experiment and Discussion
- Future work

Organization

- Introduction
- **Modeling of energy budget, consumption**
  - (a) Solar energy budget
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Modeling of Energy Budget – Solar Energy Radiation

- Need to model solar energy as variable that can change over time.
- Solar irradiance is assumed as 100mW/cm^2 ($= 1\text{kW/m}^2$), but varies on time and location.
- We can model solar radiation as PSH.

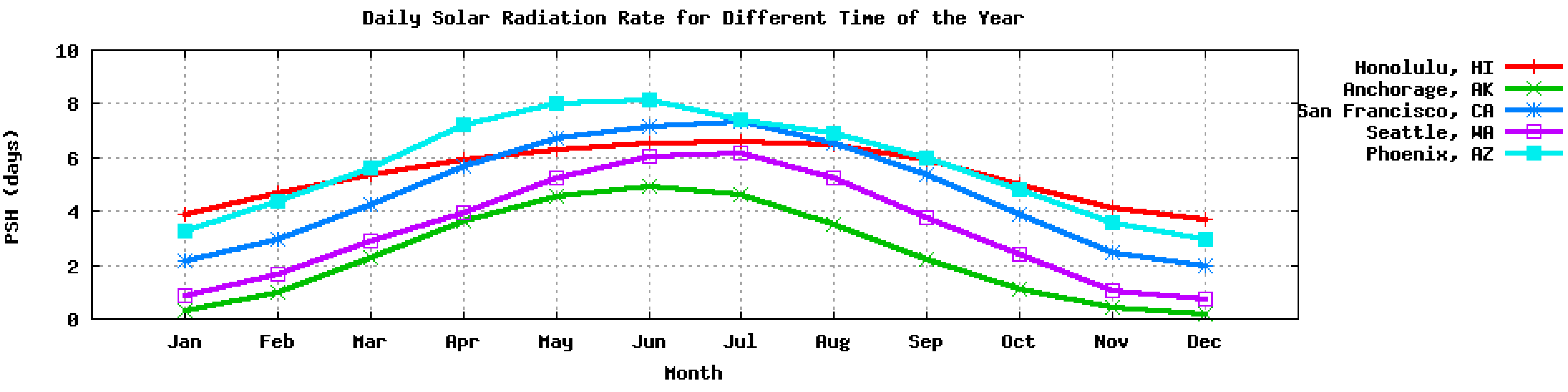
$$\text{PSH (Peak Solar Hours)} = \frac{\text{Solar Radiation}}{\text{Duration} \cdot 1\,\text{kW/m}^2}$$

- For solar cell outputting P_{solar} at 100mW/cm^2, available energy E_{avail} can be calculated as:

$$E_{avail} = \text{PSH} \cdot P_{solar}$$

Modeling of Energy Budget – Solar Energy Radiation (cont.)

- Modeling solar radiation at a specific location:
  - Requires meteorological data.
  - We used data from *Meteonorm* software.
- Example: PSH for San Francisco, CA
  - Max: 7.35 hours in Jul
  - Min: 1.97 hours in Dec
  - Avg: 4.71 hours

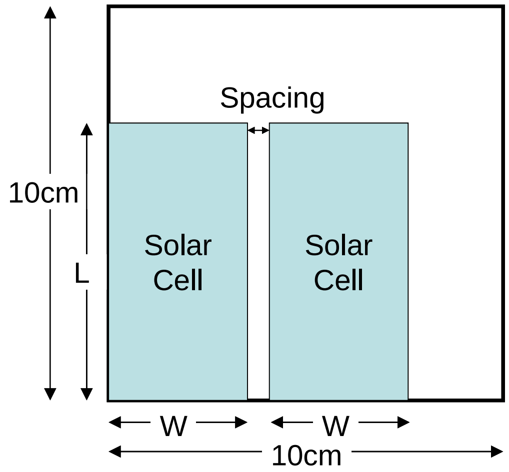


Modeling of Energy Budget – Solar Cell Energy Conversion

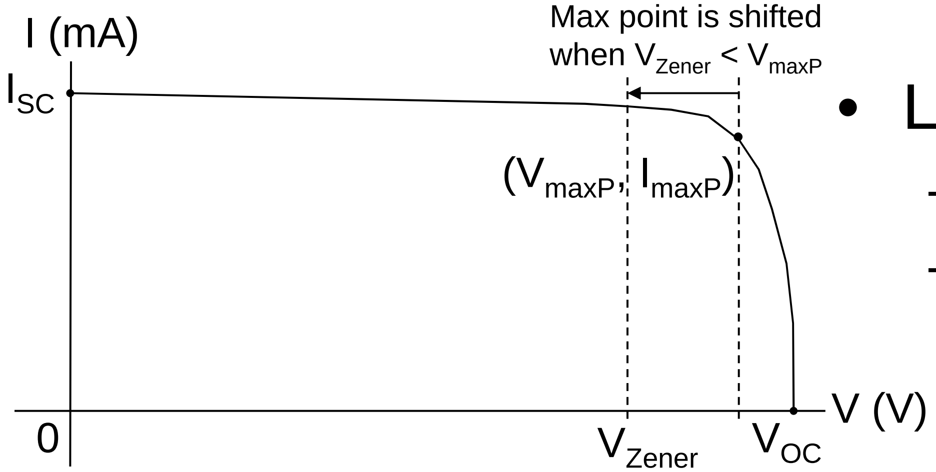
- Power converted by solar cell is given by:
  - P_{solar} = Area * Efficiency * Irradiance
- Estimate P_{solar} for solar cell used for Trio.
- Also consider P_{solar} for previous works.

Model No.	**Material**	**Reference**
BR-378234C [Sun]	Thin film polycrystalline	RF transmit beacon
BR-748264C [Sun]	Thin film polycrystalline	Prometheus
RU-6730 [RU6]	Polycrystalline	Trio
S-MPT4.8-75 [Sola]	Thin film polycrystalline	Heliomote
SPE-50-6 [Solb]	Single crystalline	

Modeling of Energy Budget – Solar Cell Energy Conversion (cont.)



- Space Constraint:
  - Dimension L and W are given.
  - Maximize solar cell output power by connecting multiple solar cells in parallel within the area.
  - 10cm by 10cm

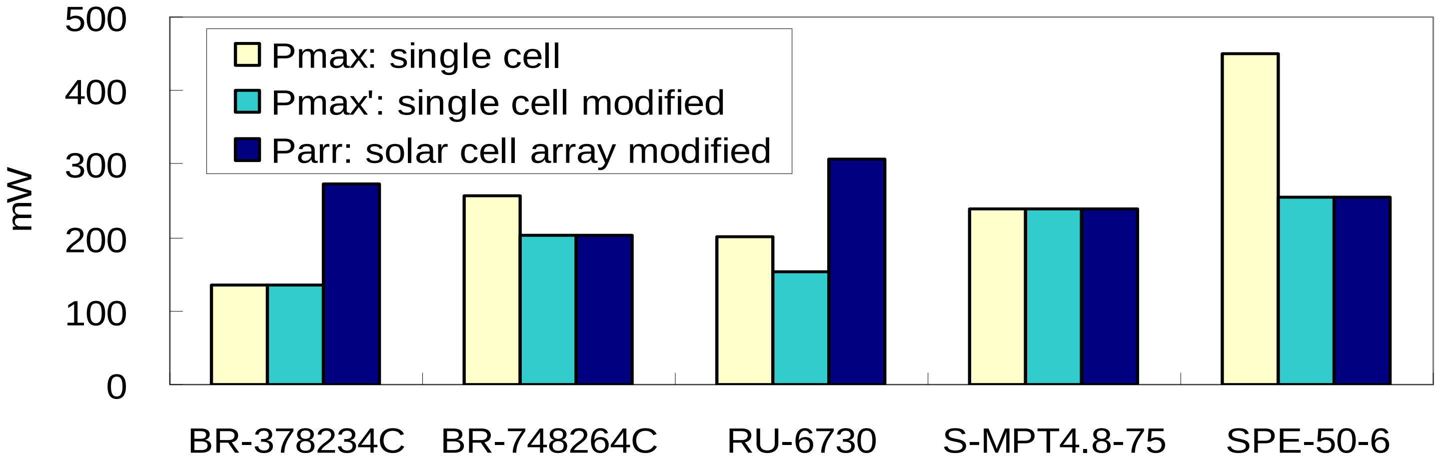


- Load Constraint:
  - I-V char. is given: V_p, I_p, P_{max}
  - Output voltage ≤ 5.1V due to Zener diode.

Modeling of Energy Budget – Solar Cell Energy Conversion (cont.)

- Solar cell module output based on published rates with output load and space constraints:

Model No.	Ref	L	W	N_L	N_W	V_p	I_p	P_{max}	V_p'	P_{max}'	P_{arr}
Unit		mm	mm			V	mA	mW	V	mW	mW
BR-378234C [Sun]	RF beacon	37	82	2	1	3.4	40	136	3.4	136	272
BR-748264C [Sun]	Prometheus	74	82	1	1	6.4	40	256	5.1	204	204
RU-6730 [RU6]	Trio	67	37	1	2	6.7	30	201	5.1	153	306
S-MPT4.8-75 [Sola]	Heliomote	94	76	1	1	4.8	50	240	4.8	240	240
SPE-50-6 [Solb]		95	57	1	1	9.0	50	450	5.1	255	255



Modeling of Energy Consumption – Trio Node

- Trio node power consumption measurement:
  - Radio consumes most power.
  - Reducing radio duty-cycle will reduce power consumption.

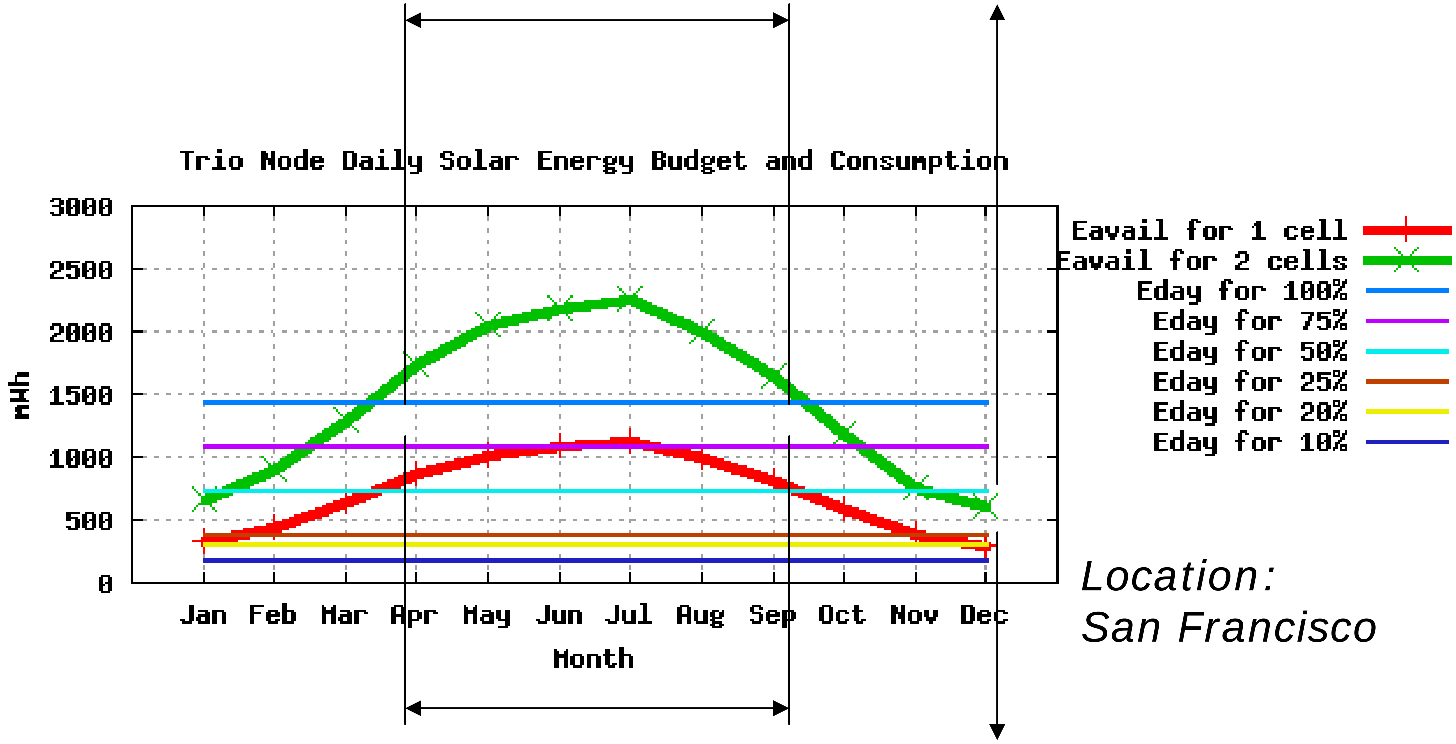
Subsystem	V (V)	I (mA)	P (mW)
Telos + Trio (sleep state)	2.84	0.588	1.670
CPU + Radio On (active state)	2.86	21.100	60.346
Buzzer	2.82	20.000	56.400
PIR	2.82	0.600	1.692
Magnetometer	2.83	5.800	16.414
Microphone	2.83	1.000	2.830

- Power consumption for duty-cycle rate R:
  - $P_{cons} = R*P_{active} + (1-R)*P_{sleep}$
- Daily energy consumption: $E_{day} = P_{cons} * 24$ hours

Duty cycling rate	P_{cons} (mW)	E_{day} (mWh)
100%	60.3	1448.3
75%	45.7	1096.2
50%	31.0	744.2
25%	16.3	392.1
20%	13.4	321.7
10%	7.5	180.9

Modeling of Energy Consumption – Trio Node (cont.)

- 2 solar-cell case: 100% for Apr. to Sep. 25% for all the year

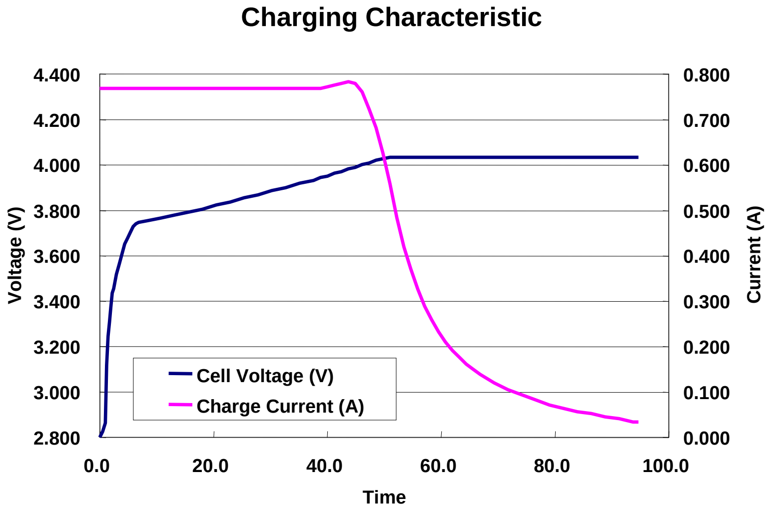


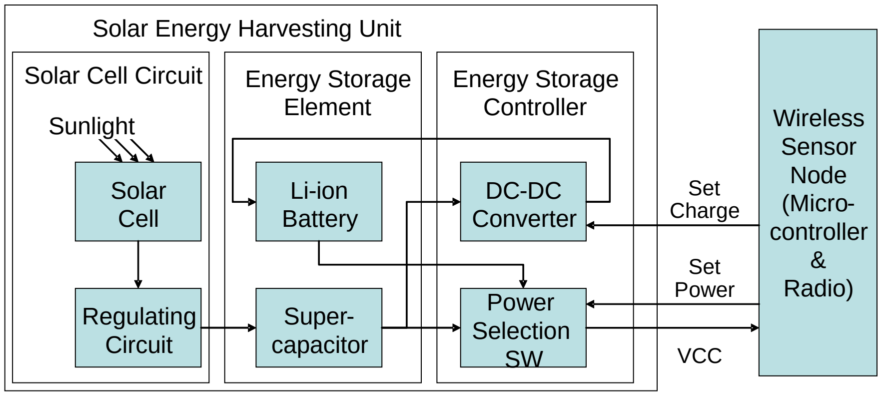
Location: San Francisco

- 1 solar-cell case: 50% for Apr. to Sep. 10% for all the year

Charging to Energy Storage Element

- Supercap for primary, lithium-ion for secondary.
  - Reduces battery charging frequency.
- Software-controlled battery charging.
  - Unlike other batteries, Li+ battery should be charged only when there is sufficient charge in the supercap.
  - Pros: Simple hardware:
    micro-controller, DC-DC converter, analog switch.
  - Cons: Requires correct software for charging control.





Consideration of other types of storage element

- Battery is needed during overcast days.
  - Supercap-only method doesn't have sufficient capacity.
- Comparison of charging efficiency is not available yet.

	(1) Trio [DHJ+06]	(2) Heliomote [RKH+05]	(3) Everlast [SSC05]
Storage	One Li+ battery with one 22F cap	Two AA NiMH batteries	One 100F capacitor
Capacity	E_{bat} = 2625mWh	E_{bat} = 4320mWh	E_{cap} = 86.8mWh
B_{day}	14.5 days at 10% 6.7 days at 25%	23.9 days at 10% 11.0 days at 25%	0.48 days at 10% 0.22 days at 25%
Charging control	Software, pulse charging	Hardware, trickle charging	Hardware, trickle charging
overcast days?	YES	YES	NO

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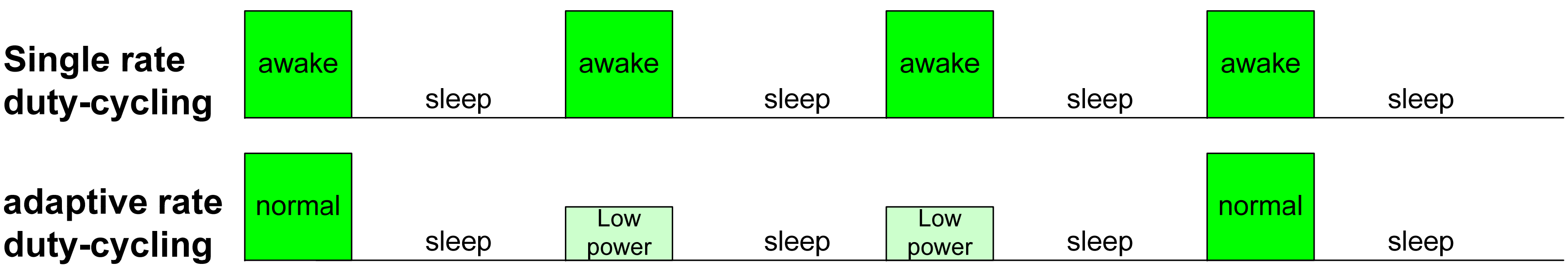
Related Work on Duty-Cycling

- Protocols with no synchronization: Prometheus, Heliomote
  - Periodic turns on/off, no synchronization.
- Low power MAC protocols:
  - Dual channel (data + control): PAMAS [SR98]
  - Synchronous: S-MAC [YHE02], T-MAC [vDL03]
  - Asynchronous: B-MAC [PHC04], Seesaw [BSE06]
- Network level protocols: system-wide energy scheduling.
  - FPS [HDB04], VigilNet [HKL+05], LEACH [HCB00]

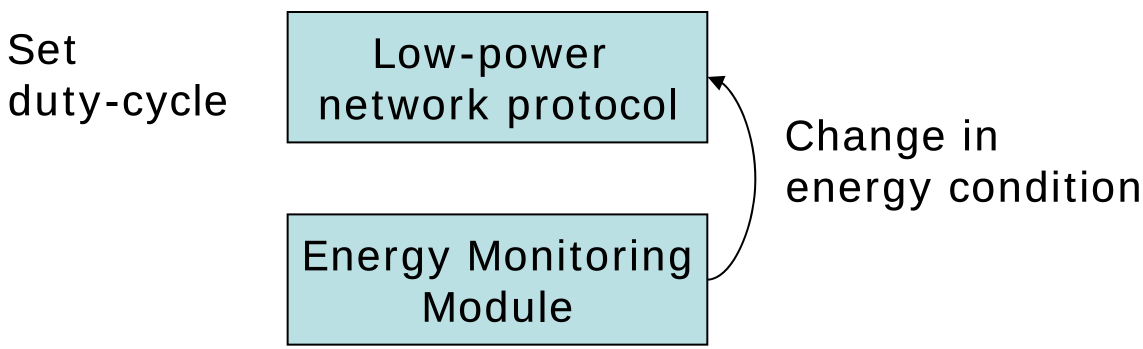
Limitation of previous low duty-cycle protocols

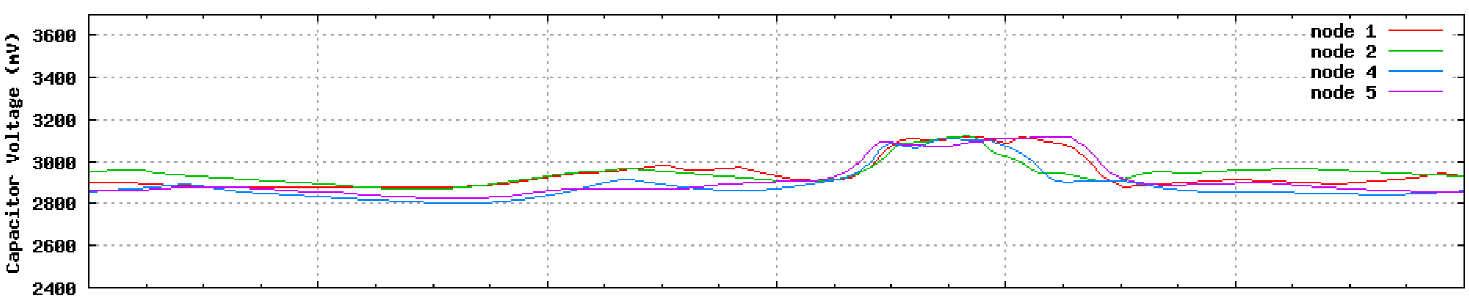
- Previous protocols use single duty-cycle rate.
  - Works well for battery.
  - Could drain energy source for time varying source.
- We need a low duty-cycle protocol that can adjust rate based on solar energy.



Interfacing low-power network protocol with energy harvesting

- Energy monitor notifies change in solar radiation.
  - Use CapVol due to high correlation among nodes.
- Low-power network protocol adjusts the duty-cycle when notified.

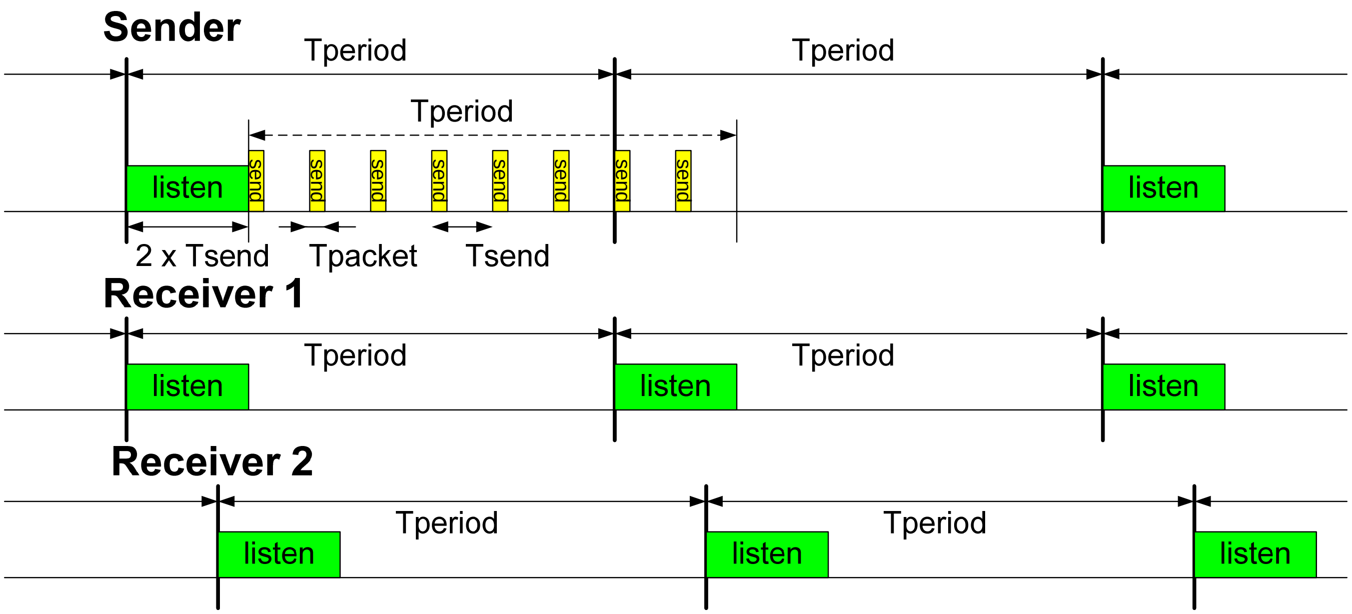




CapVol measurement in 04/06/2006

Implementing Duty-Cycling for Trio

- Needs to address system dependent issues.
  - Use of low level timer is dependent on Atmel μ-controller.
  - Use of long preamble works for CC1000, not for CC2420.
  - Instead of long preamble, a sender can send multiple packets with same interval [Seesaw: BSE06].



Seesaw Protocol

Duty-Cycling Estimation for Seesaw Implementation

- Seesaw implementation could achieve 1.5% duty-cycle at $\lambda = 0.2$.

T_{period}	15ms	50ms	100ms	200ms	500ms	1000ms
Data rate (pkts/sec)	66.7	20	10	5	2	1
Duty-cycle rate ($\lambda = 0.2$)	100%	30%	15%	7.5%	3%	1.5%
Duty-cycle rate ($\lambda = 0.1$)	N/A	60%	30%	15%	6%	3%

- Facts and assumptions
  - TinyOS packet length: 39 bytes, CC2420 data rate: 250 kbps
  - T_{period} <= 1000 ms due to latency requirement
  - T_{packet} >= 39 bytes/250 kbps = 1.248 ms, let T_{packet}=1.5ms
- Estimating performance metric
  - Duty-cycle rate = $T_{listen}/T_{period} = 2T_{send}/T_{period} = 2T_{send}/(\lambda T_{period})$
  - Date rate = 1 packet / T_{period}

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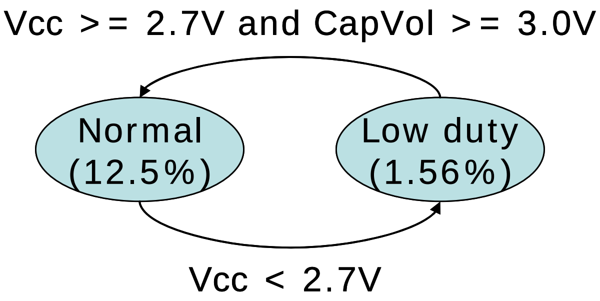
Experiment

- Measurements:
  - April 6th, 2006 – April 9th, 2006
- Metrics to measure:
  - Vcc, BatVol, CapVol
  - Power source, Charging and Duty-cycle.
- Duty cycling:
  - Naïve duty-cycling, no use of low-power MAC
  - Two mode: normal (12.5%) & low duty-cycle (1.56%)
- Communication:
  - Single hop btw. each Trio and the base.
  - Sending rate: once every 4 sec with radio on.

4 Trio nodes on the patio of a private building in El Cerrito, CA facing the west

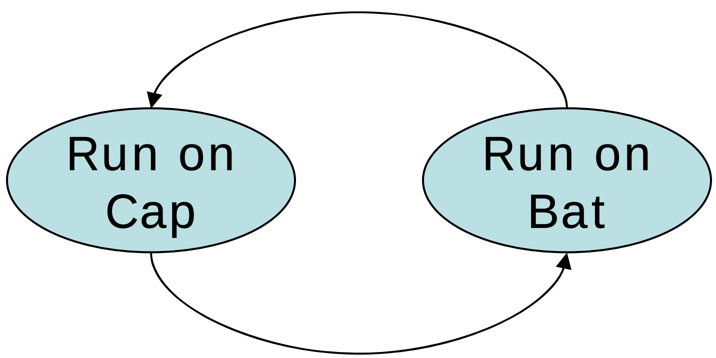


Experiment Setting
– Power source check logic

- Power source logic

(1) Low Vcc, Low Bat:
(1) Vcc < 2.7V and BatVol >= 2.8V

(2) High Vcc, High Cap:
Vcc >= 2.7V and CapVol >= 3.0V

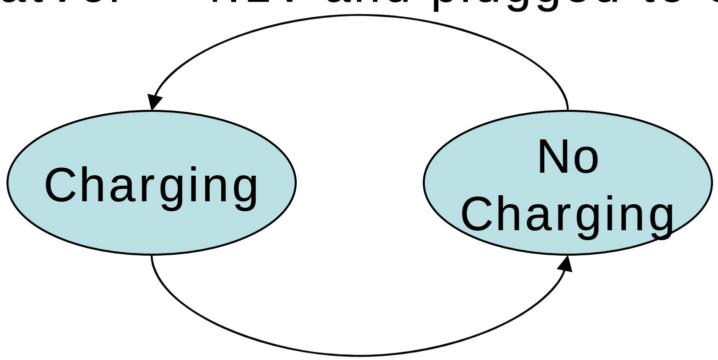


(3) Low Vcc, High Bat:
Vcc < 2.7V and BatVol >= 2.8V

- Charging logic

(1) High Radiation:
BatVol < 4.1V and CapVol >= 3.3V

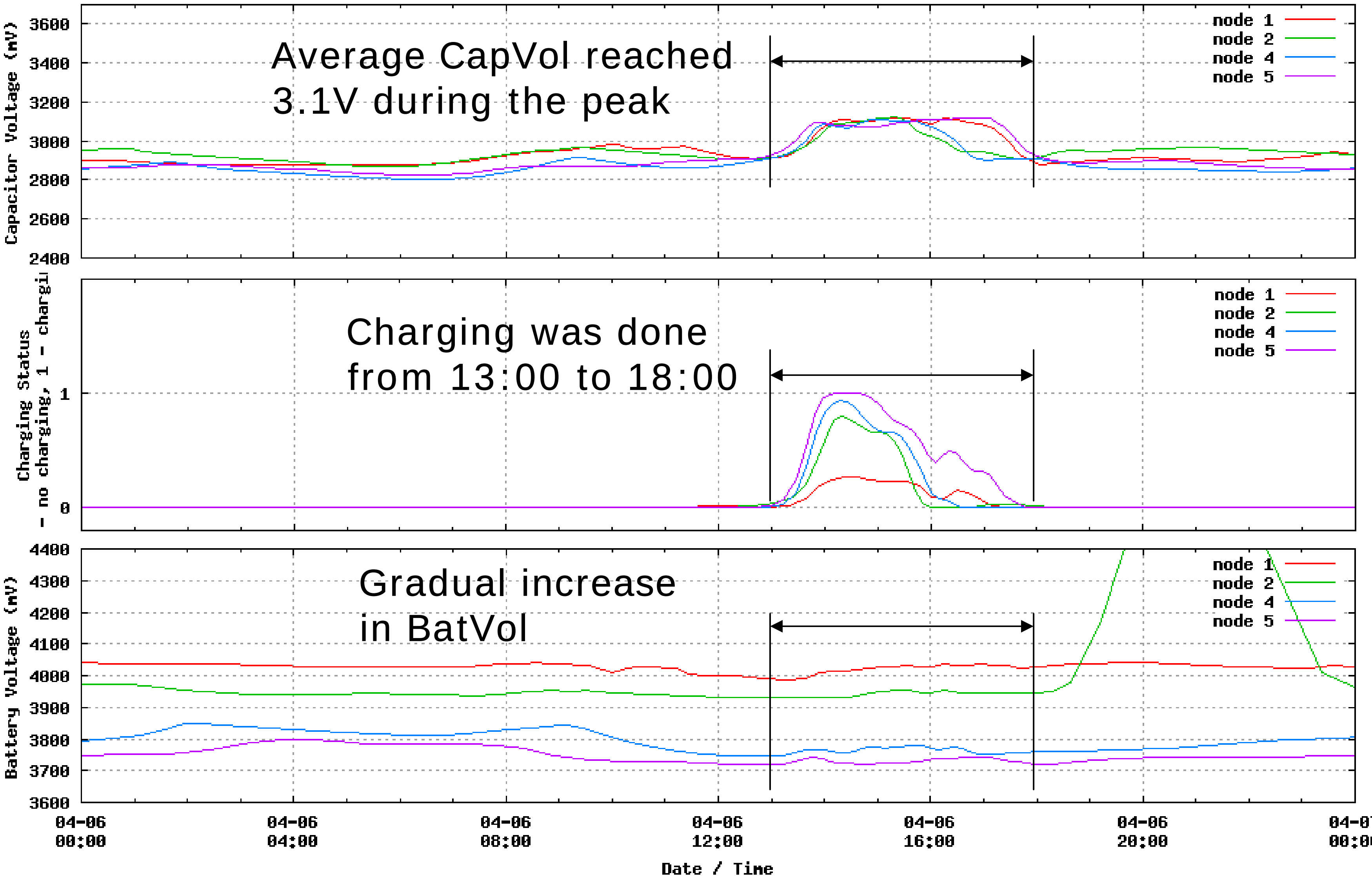
(2) USB Charging:
BatVol < 4.1V and plugged to USB



(3) Low Radiation:
BatVol < 4.1V CapVol >= 3.0V

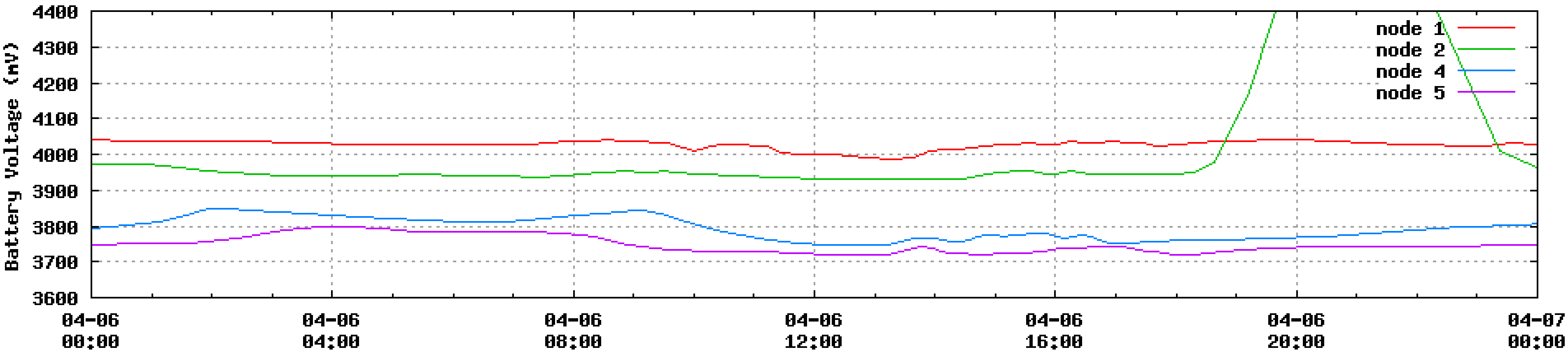
(3) Overcharging:
BatVol >= 4.1V

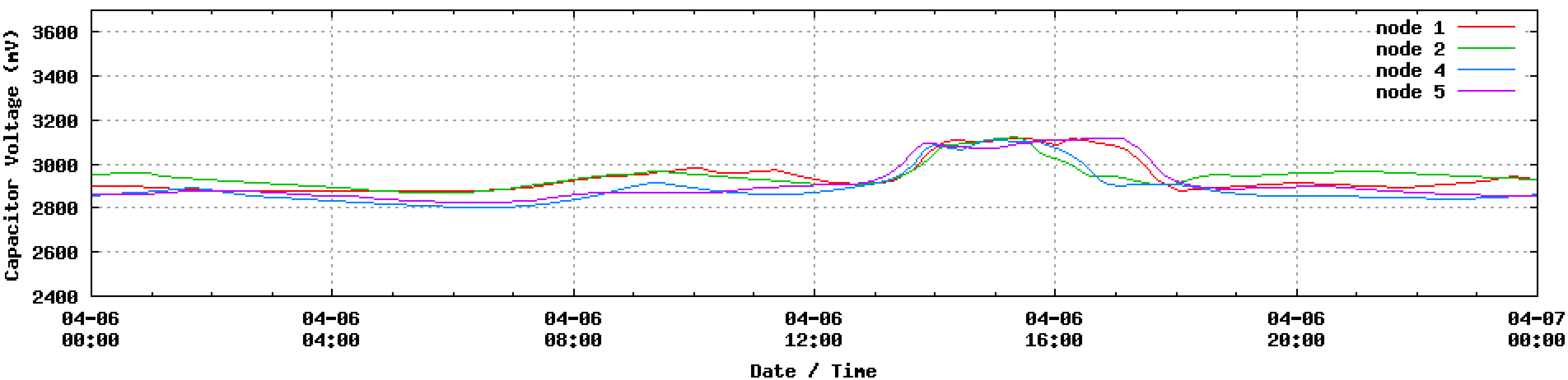
Experiment: One day trend
– Verifying the charging logic



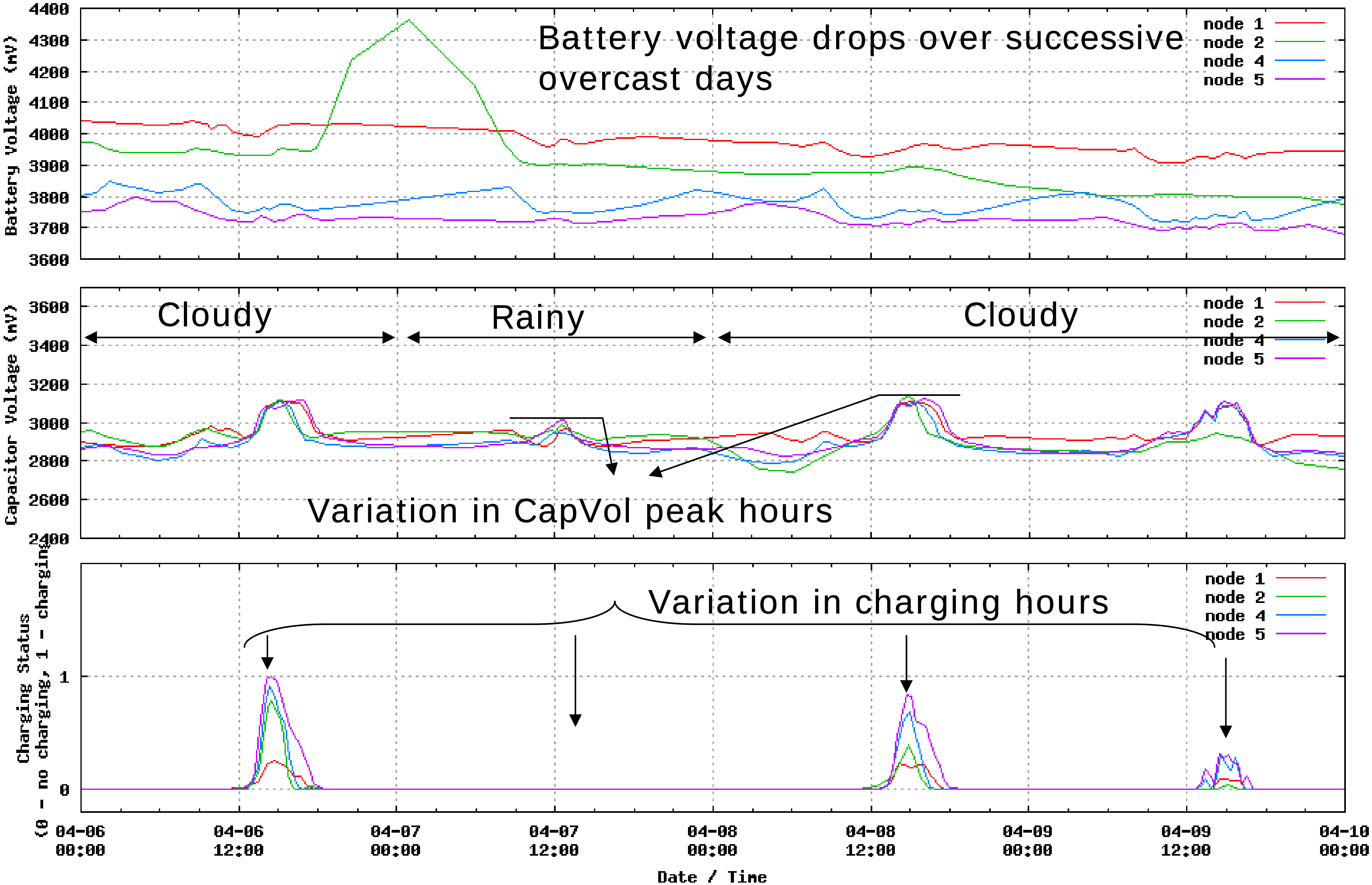
Experiment: One day trend – Balancing Energy Consumption

- Trio nodes maintain about the same level for BatVol and CapVol while operating continuously.





Experiment: Four day trend – BatVol, CapVol variation with weather



Summary of Experiment Results

- Charging logic is correctly working.
- Naïve duty-cycling with single-hop traffic works sustainably over sunny or cloudy days.
- Battery level decreases over successive overcast days.

Research Timeline

- May 2006 to December 2006:
  - Implementation and evaluation of low duty-cycle MAC and network protocol for Trio.
  - Comparative analysis of energy storage design.
- January 2007 to August 2007:
  - Dissertation work.

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Possible Questions

Possible Questions

- Why do we use solar energy?
  - Solar energy has the highest energy density among energy harvesting methods.
  - Commercially available.

Power Source	P/cm^3 ($\mu W/cm^3$)	E/cm^3 (J/cm^3)	$P/cm^3/yr$ ($\mu W/cm^3/Yr$)	Secondary Storage Needed	Voltage Regulation	Comm. Available
Primary Battery	-	2880	90	No	No	Yes
Secondary Battery	-	1080	34	-	No	Yes
Micro-Fuel Cell	-	3500	110	Maybe	Maybe	No
Heat engine	-	3346	106	Yes	Yes	No
Radioactive(^{63}Ni)	0.52	1640	0.52	Yes	Yes	No
Solar (outside)	15000 *	-	-	Usually	Maybe	Yes
Solar (inside)	10 *	-	-	Usually	Maybe	Yes
Temperature	40 * †	-	-	Usually	Maybe	Soon
Human Power	330	-	-	Yes	Yes	No
Air flow	*380 ††*	-	-	Yes	Yes	No
Vibrations	200	-	-	Yes	Yes	No

[RSF+04]

Possible Questions

- How about just using batteries?
  - Non-rechargeable lithium batteries have high energy density.
  - Even the high density battery have limited lifetime

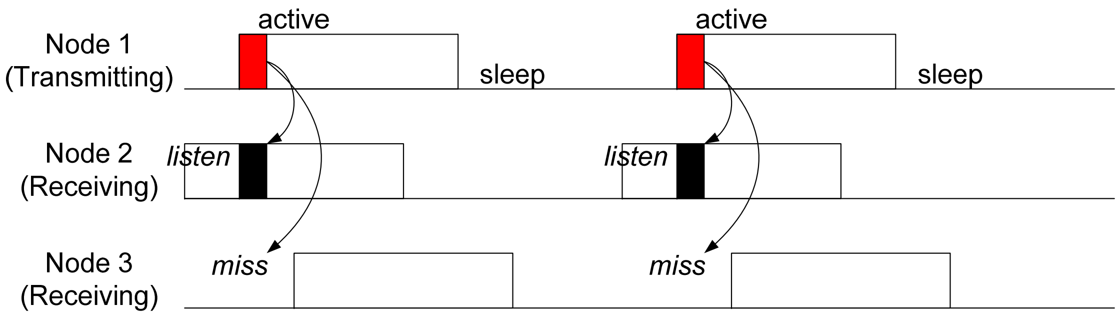
Type	Manu-facturer	Rated Voltage	Capacity	Price	Energy Capacity	Bdays			
						100%	50%	25%	10%
D	Tadiran	3.6V	16.5Ah	$14.24	59.4	41.0	79.8	151.5	328.4
C	Tadiran	3.6V	7.2Ah	$11.04	25.92	17.9	34.8	66.1	143.3
AA	Tadiran	3.6V	2.4Ah	$6.90	8.64	6.0	11.6	22.0	47.8

From Digikey.com

Possible Questions

- For power saving, duty-cycling is needed.
- Single-hop case:
  - Sender duty-cycles, but receiver is always on.
  - Synchronized when sender is awake.
- Multi-hop case:
  - Both sender and receiver duty-cycle radio.
  - Synchronized when both sender and receiver are awake.

Naïve duty-cycling



Possible Questions

- Definitions and Units
  - Spectral irradiance ($W/m^2 \cdot \mu m$):
    Power received by a unit surface area in a wave length differential $d\lambda$.
  - Irradiance (W/m^2):
    Integral of the spectral irradiance extended to all wavelengths of interest.
  - Radiation (kWh/m^2):
    Time integral of the irradiance over a given period of time.

Possible Questions

- I-V characteristic varies depending on the solar irradiance.

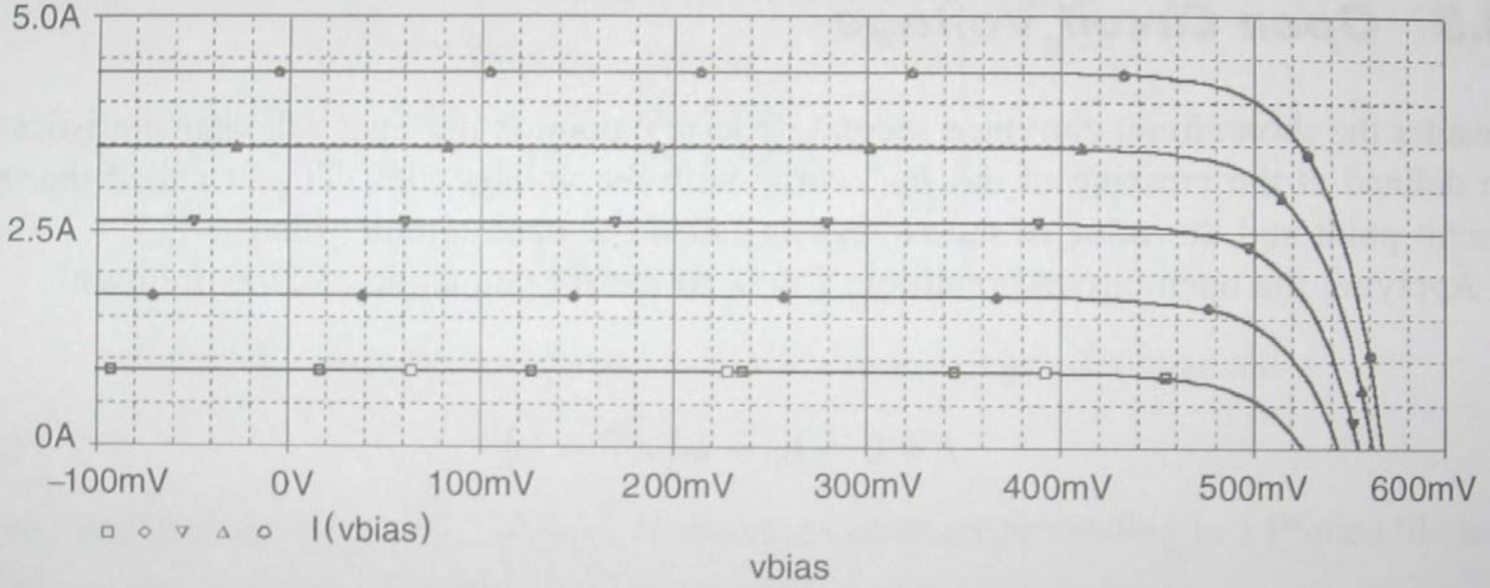
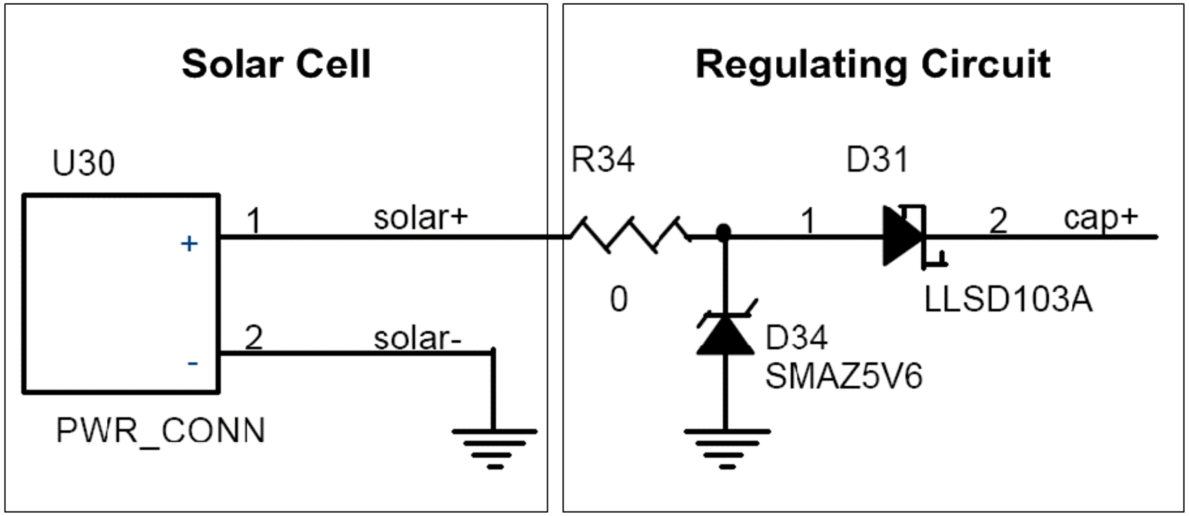


Figure 3.4 $I(V)$ plots of a solar cell under several irradiance values: 200, 400, 600, 800 and 1000 W/m^2

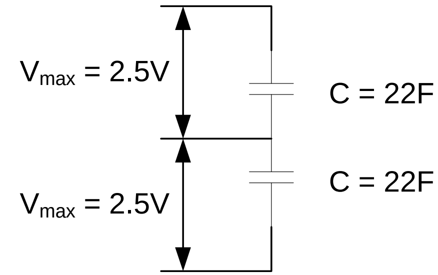
From "Modelling Photovoltaic Systems Using PSpice" by Luis Castaner, Santiago Silvestre

Possible Questions

- Load Limitation with Zener diode:
  - The reverse voltage across the Zener diode is regulated below V_{Zener} as long as the current is limited to a certain level.



Possible Questions



- Capacity of supercap:
  - $E_{cap} = ½\ CV_{max}^2 + ½\ CV_{max}^2 = CV_{max}^2$
    $= 22F * (2.5V)^2 = 137.5\ J$
    $= 38.2\ mWh$
- Capacitor of battery:
  - $E_{bat} = C * V = 750mAh * 3.5V = 2625\ mWh$
- Supercap alone is not sufficient for overcast days:
  - E_{day} for 10% = 181 mWh
- Bday: # days a node can operate with no sunlight.
  - $B_{day} = E_{bat} / E_{day}$

Duty cycling Rate	**100%**	**75%**	**50%**	**25%**	**20%**	**10%**
E_{day} (mWh)	1448.3	1096.2	744.2	392.1	321.7	180.9
B_{day}	1.81	2.4	3.53	6.7	8.15	14.5

Possible Questions

- Heliomote Battery Capacity:
  - $E_{bat} = 2 * C * V$
    $= 2 * 1800mAh * 1.2V = 4320\ mWh$
- Everlast Capacitor Capacity:
  - $E_{cap} = ½\ CV_{max}^2$
    $= ½ * 100F * (2.5V)^2 = 312.5\ J$
    $= 86.8\ mWh$
- Bday: # days a node can operate with no sunlight.
  - $B_{day} = E_{bat} / E_{day}$ or E_{cap} / E_{day}

Duty cycling Rate	**100%**	**75%**	**50%**	**25%**	**20%**	**10%**
E_{day} (mWh)	1448.3	1096.2	744.2	392.1	321.7	180.9
B_{day} (Heliomote)	3.0	3.9	5.8	11.0	13.4	23.9
B_{day} (Everlast)	0.1	0.1	0.1	0.2	0.3	0.5

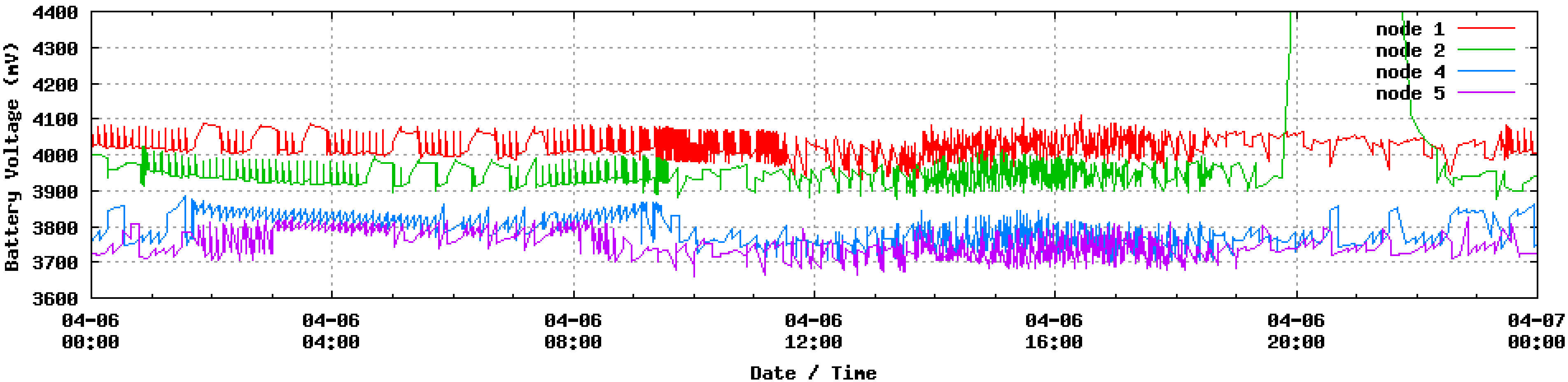
Possible Questions

- Possible receiver duty cycle with Seesaw:
  - TinyOS packet length on CC2420: 39 bytes
    - 8 bytes header, 2 bytes footer, 29 bytes data
  - CC2420 data rate: 250 kbps
  - Assume $T_{packet} = 1.5$ ms
    - 39 bytes / 250 kbps = 1.248 ms
  - Assume $T_{period} = 200$ms.
  - For channel utilization λ:
    - $T_{send} = T_{packet} / \lambda$
    - $T_{listen} = 2T_{send}$
    - Duty-cycle = $2T_{send}/T_{period} = 2T_{packet} / (\lambda\ T_{period}) = 0.015 / \lambda$
    - For $\lambda = 0.1$, duty-cycle = 0.15
      $\lambda = 0.2$, duty-cycle = 0.075
      $\lambda = 0.5$, duty-cycle = 0.03

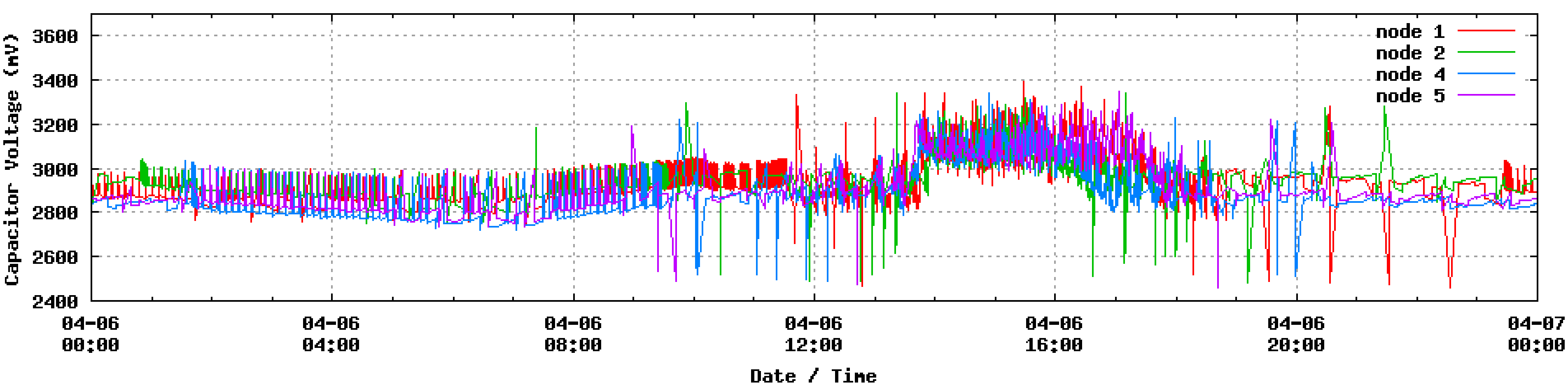
Back-up Slides

Experiment Results (April 6th, 2006) – One day measurement

- Battery Voltage

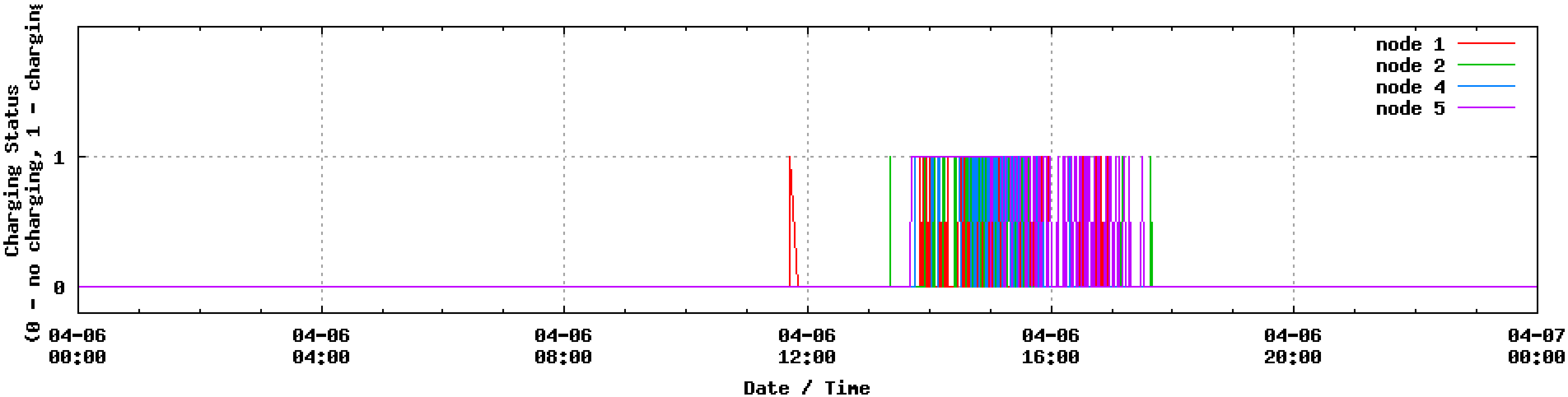


- Capacitor Voltage

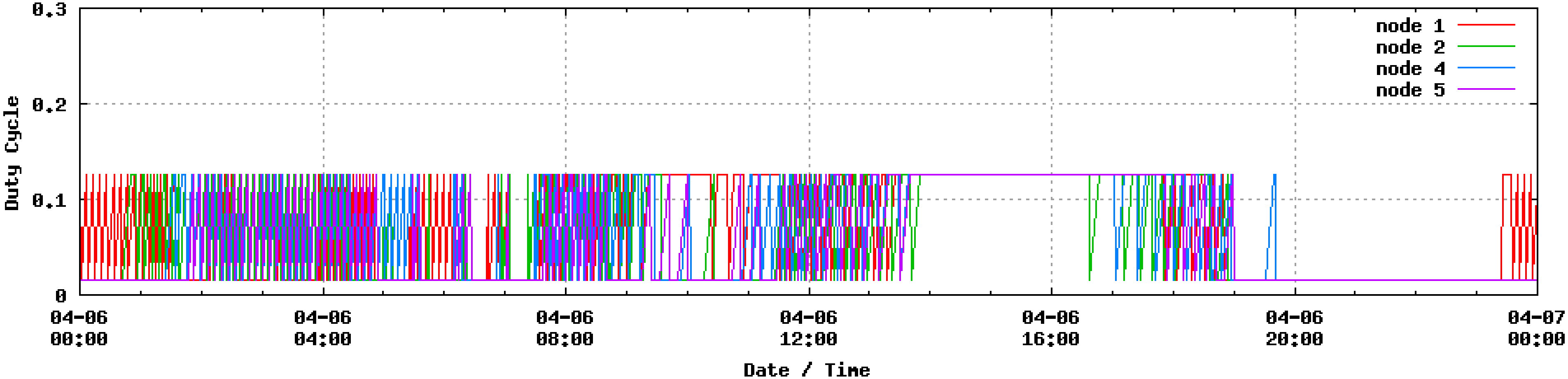


Experiment Results (April 6th, 2006) – One day measurement

- Charging Status

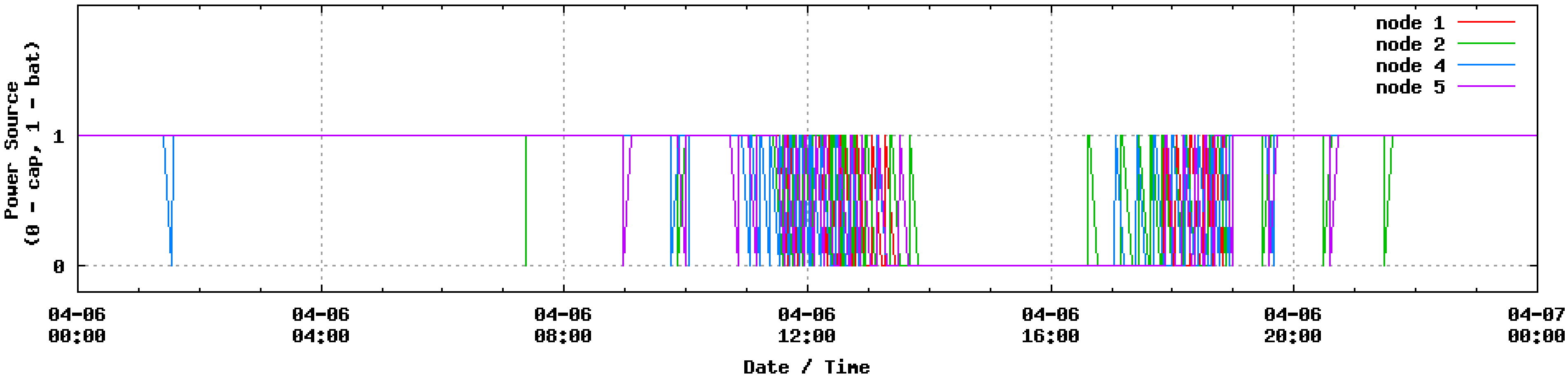


- Duty Cycle

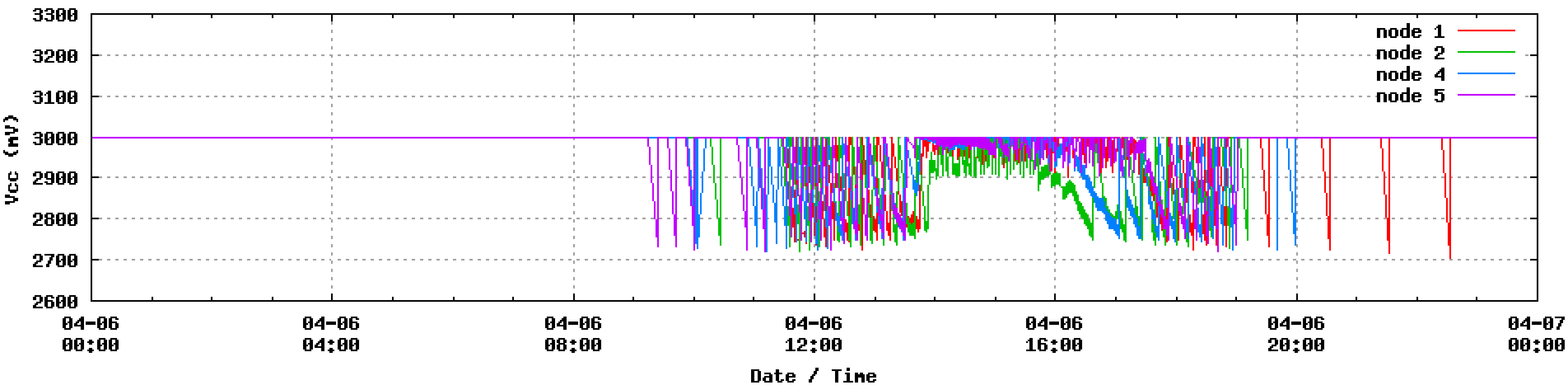


Experiment Results (April 6th, 2006) – One day measurement

- Power Source Status

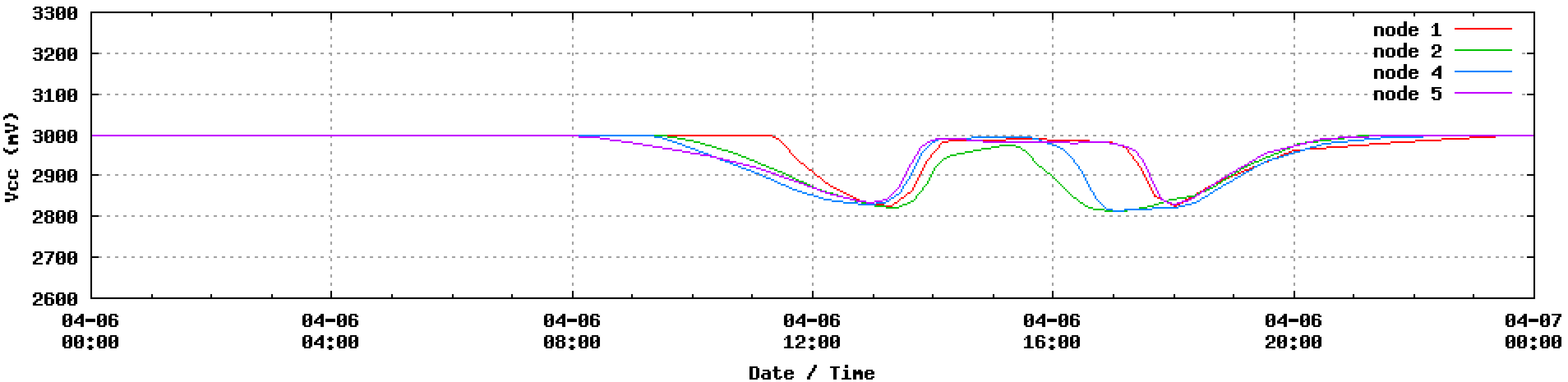


- Vcc

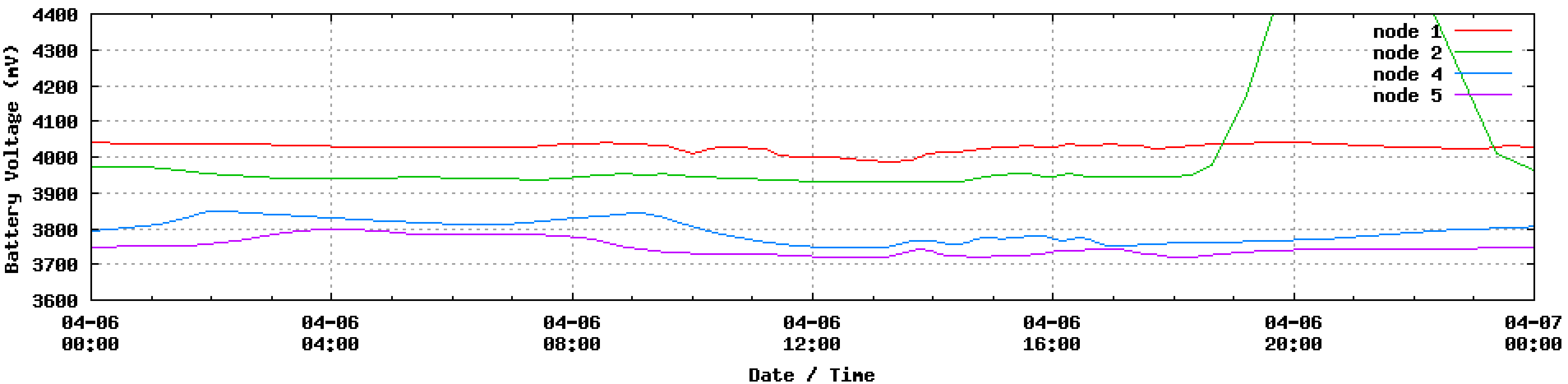


Experiment Results (April 6th, 2006) – One day measurement

- Vcc

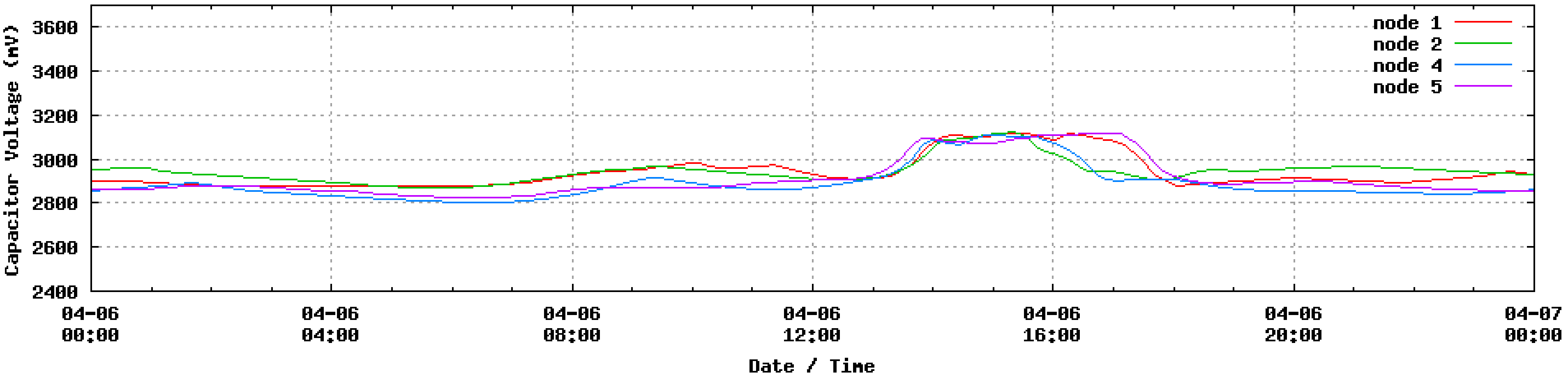


- Battery Voltage

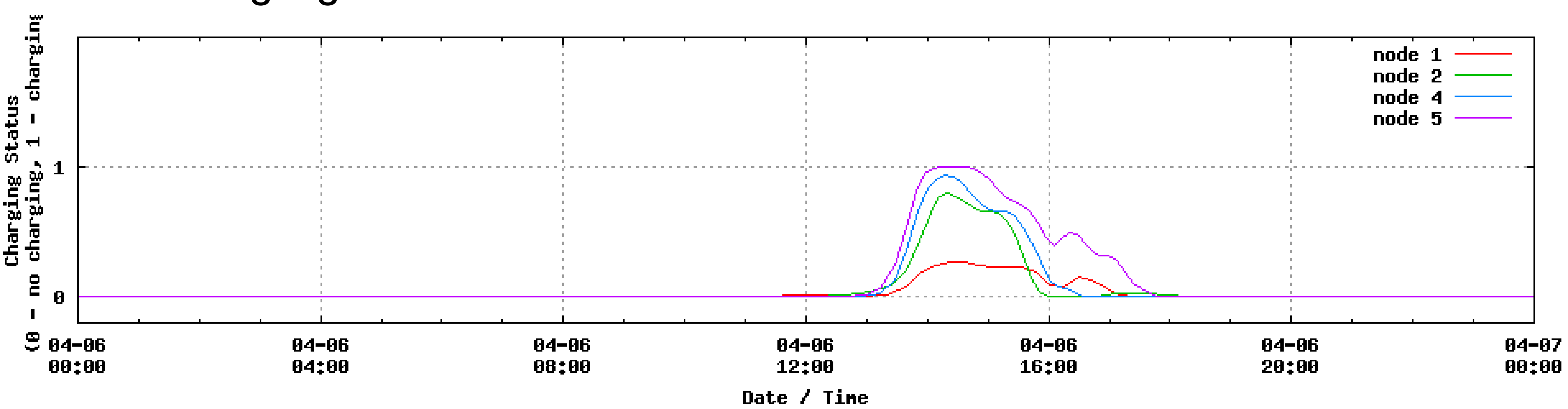


Experiment Results (April 6th, 2006) – One day measurement

- Capacitor Voltage

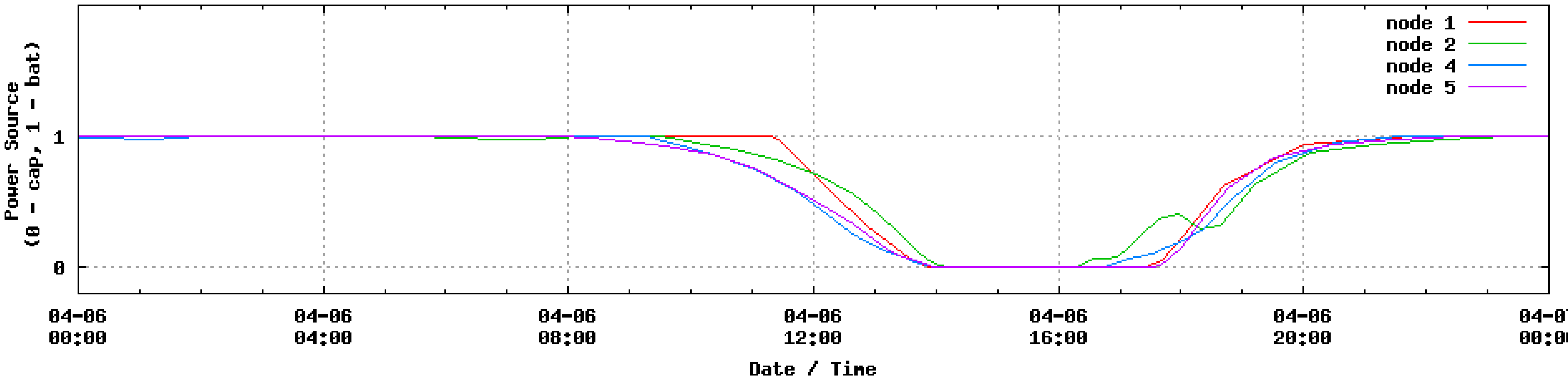


- Charging Status

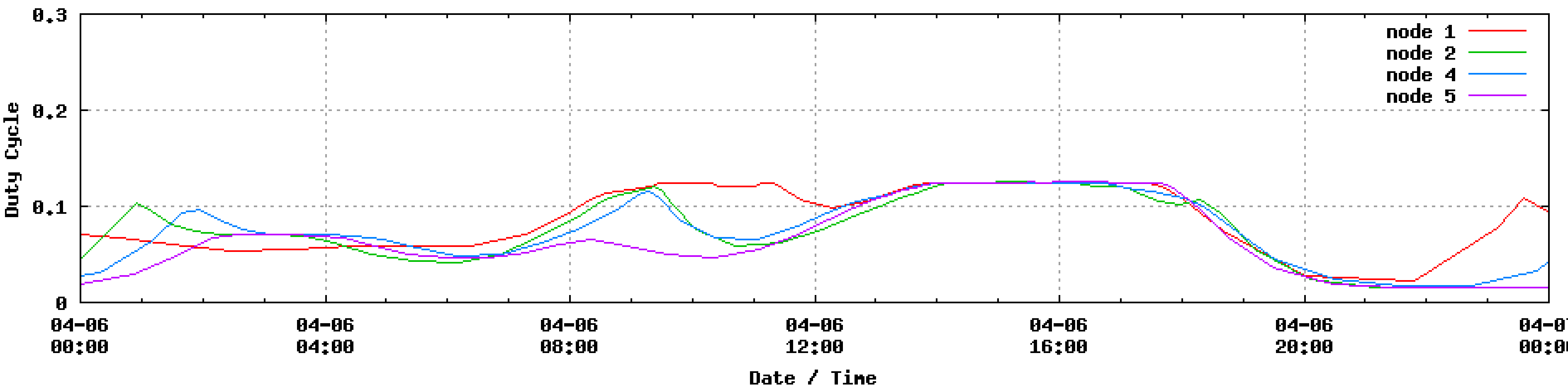


Experiment Results (April 6th, 2006) – One day measurement

- Power Source

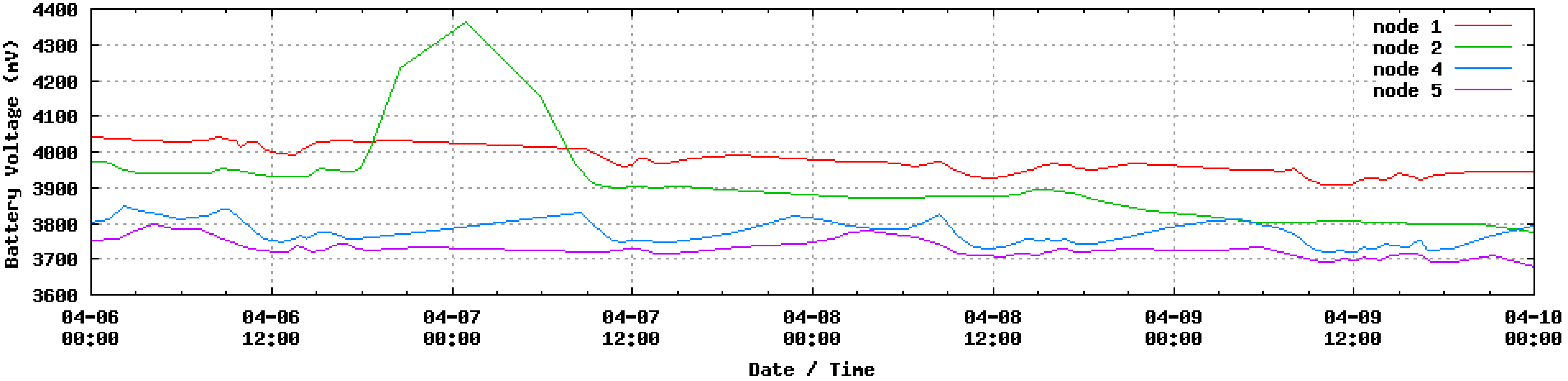


- Duty Cycle

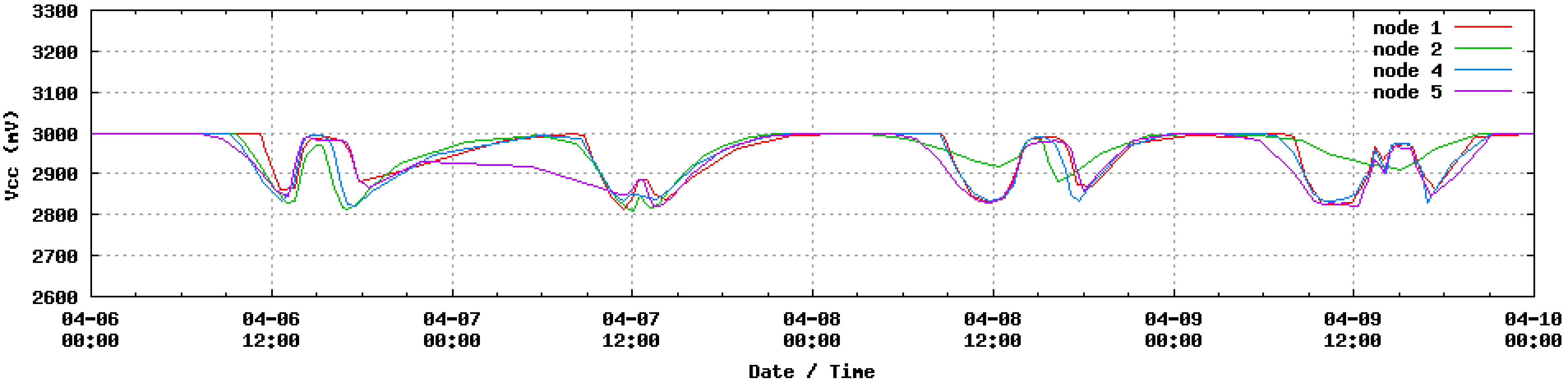


Experiment Results (April 6th-9th, 2006) – Four day measurement

- Battery Voltage

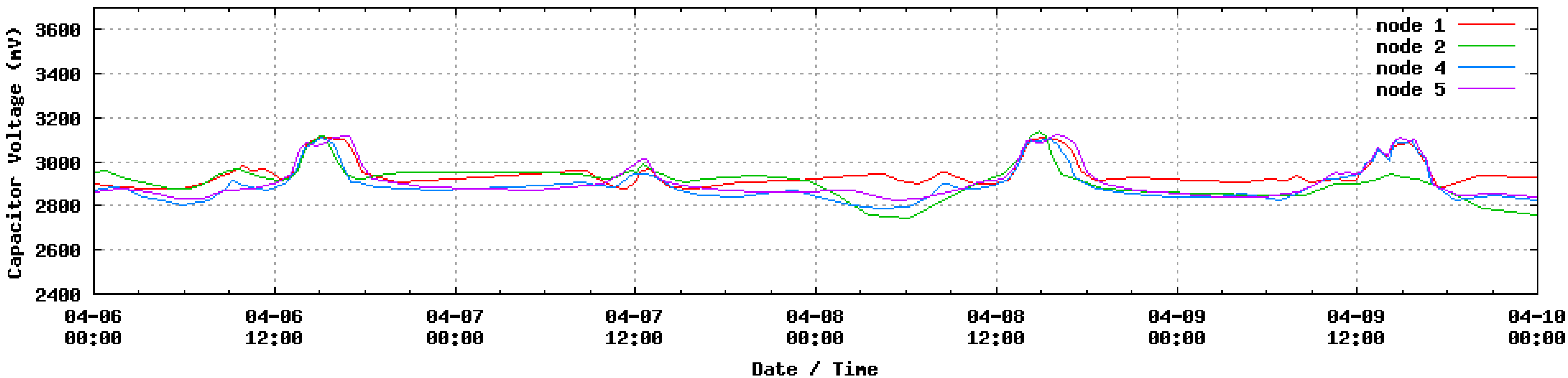


- Vcc

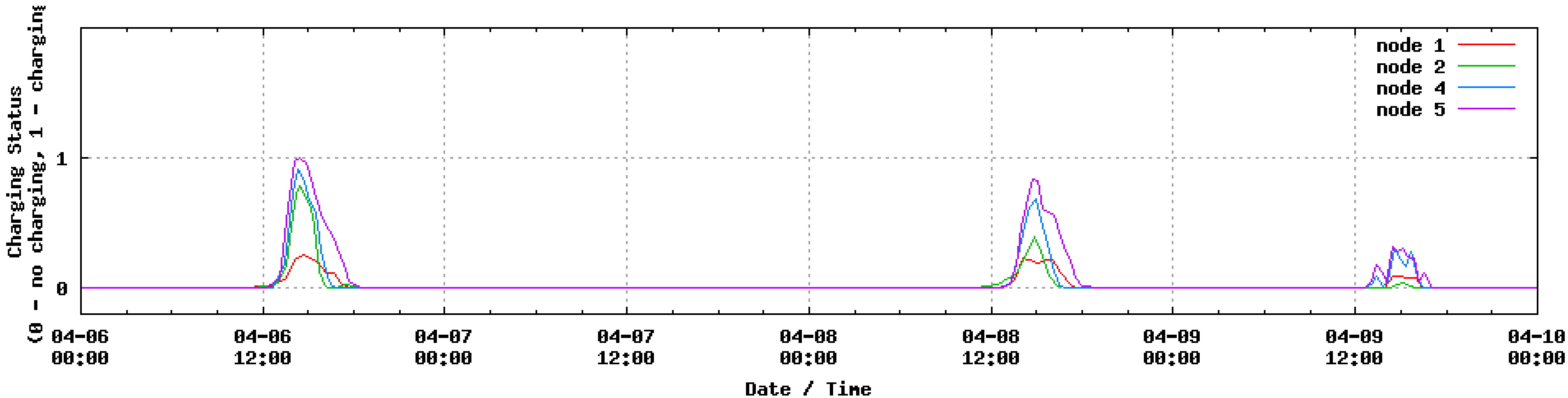


Experiment Results (April 6th-9th, 2006) – Four day measurement

- Capacitor Voltage

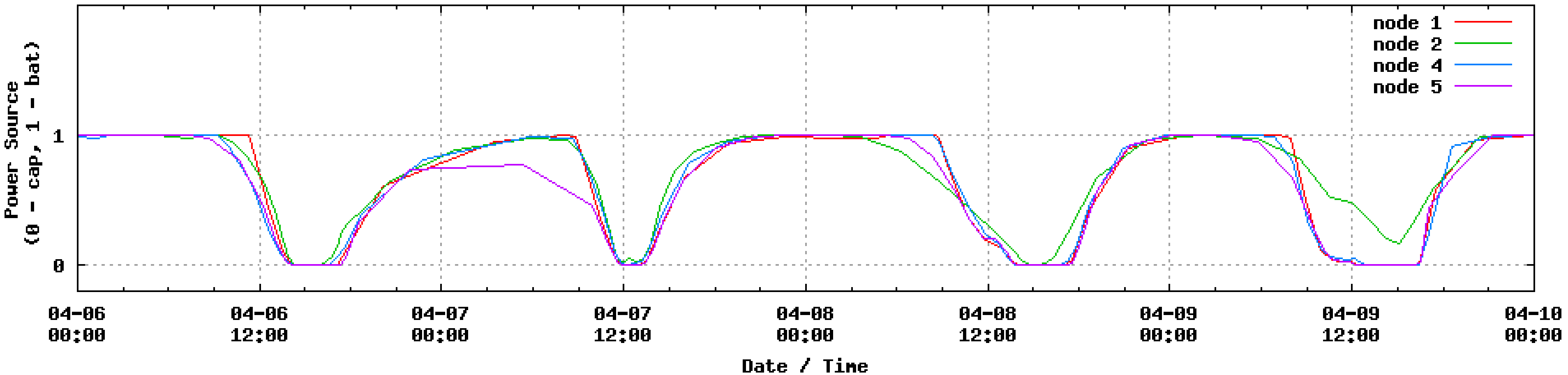


- Charging Status

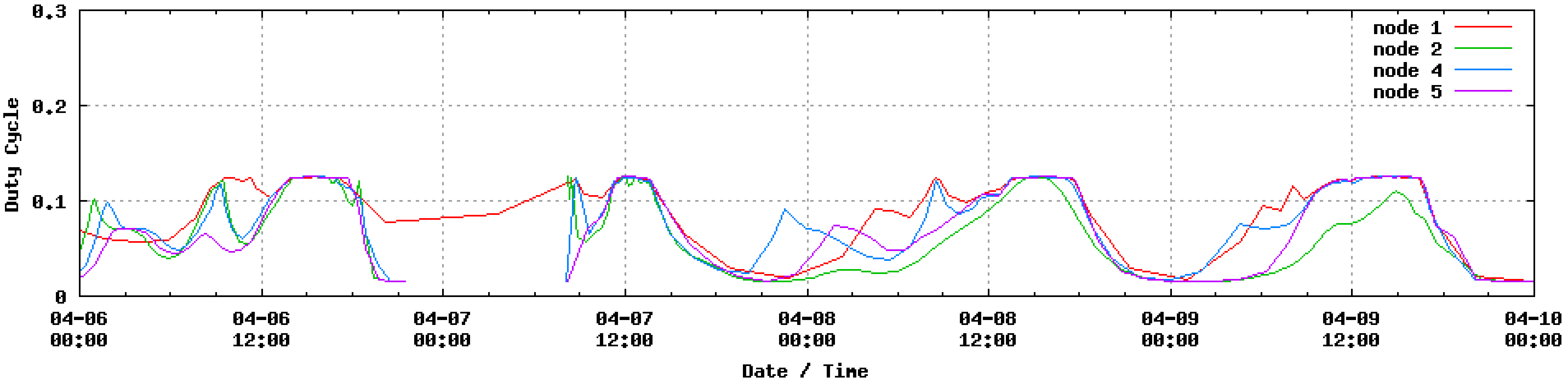


Experiment Results (April 6th-9th, 2006) – Four day measurement

- Power Source



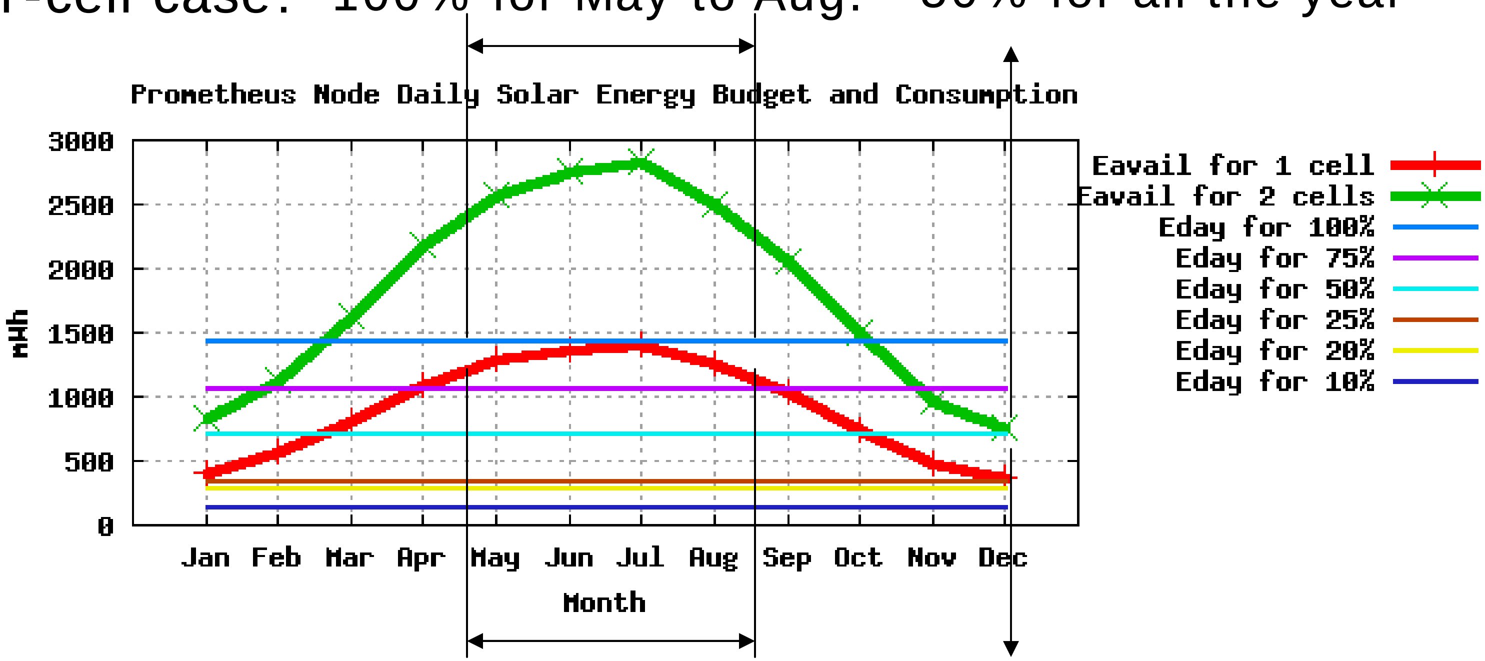
- Duty Cycle



Modeling of Energy Consumption – Prometheus Node

- Parameters:
  - Energy Budget: P_{max}= 384mW at (V_p,I_p) = (4.8V,40mA)
  - Energy Consumption: P_{active} = 60mW, P_{sleep} = 0.015mW

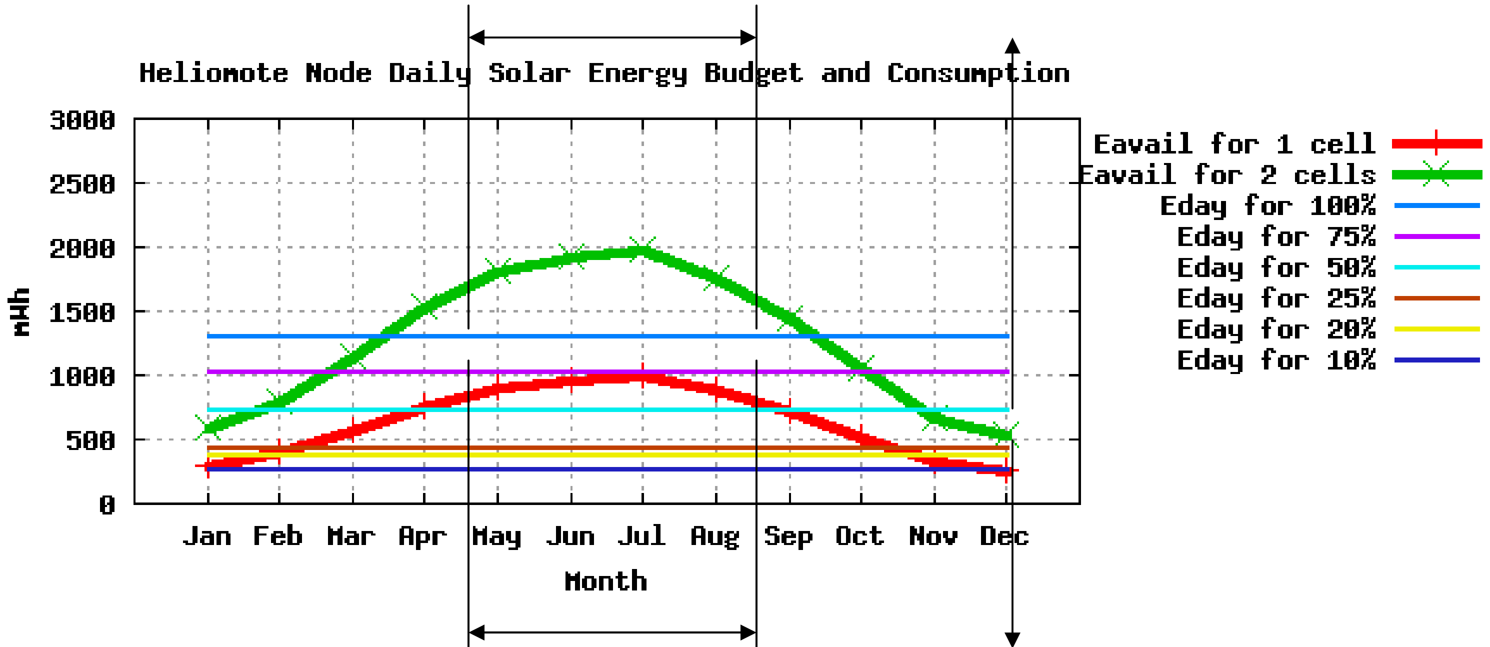
- 2 solar-cell case: 100% for May to Aug. 50% for all the year



- 1 solar-cell case: 75% for May to Aug. 20% for all the year

Modeling of Energy Consumption – Heliomote Node

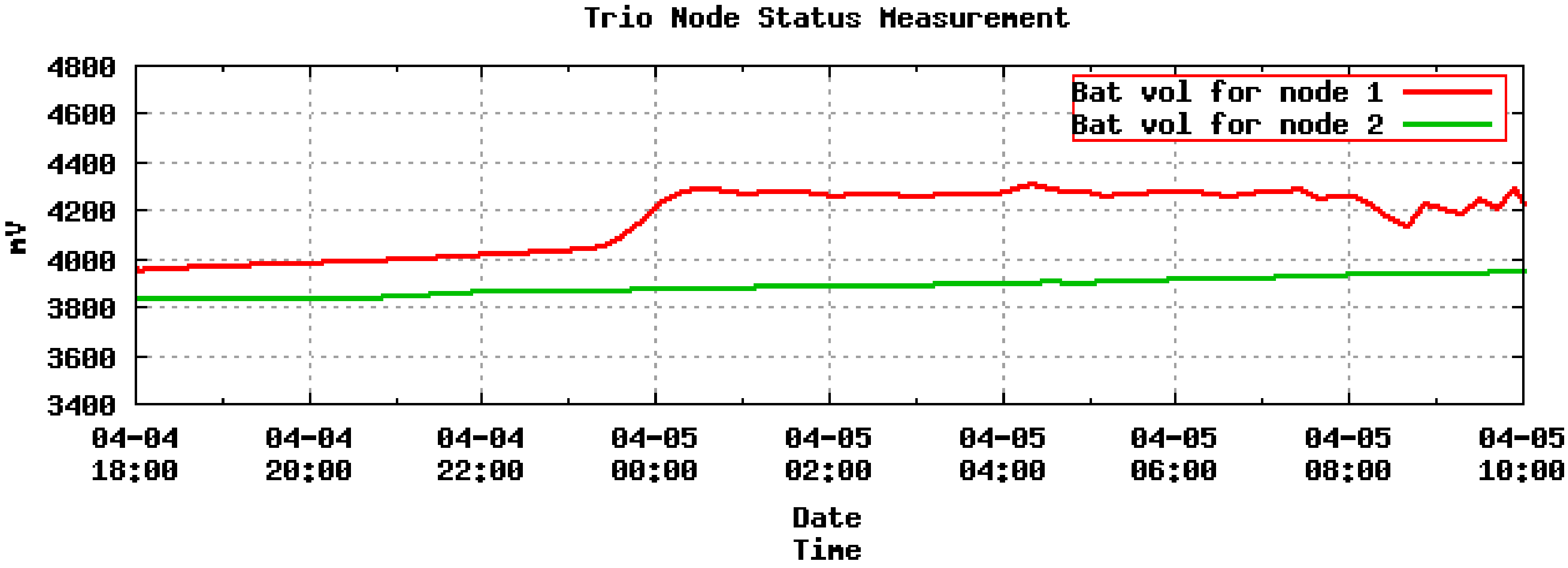
- Parameters:
  - Energy Budget: P_{max} = 270mW at (V_p, I_p) = (3V,90mA)
  - Energy Consumption: P_{active} = 54.88mW, P_{sleep} = 6.72mW
- 2 solar-cell case: 100% for May to Aug. 20% for all the year



- 1 solar-cell case: 50% for May to Aug. 10% for all the year

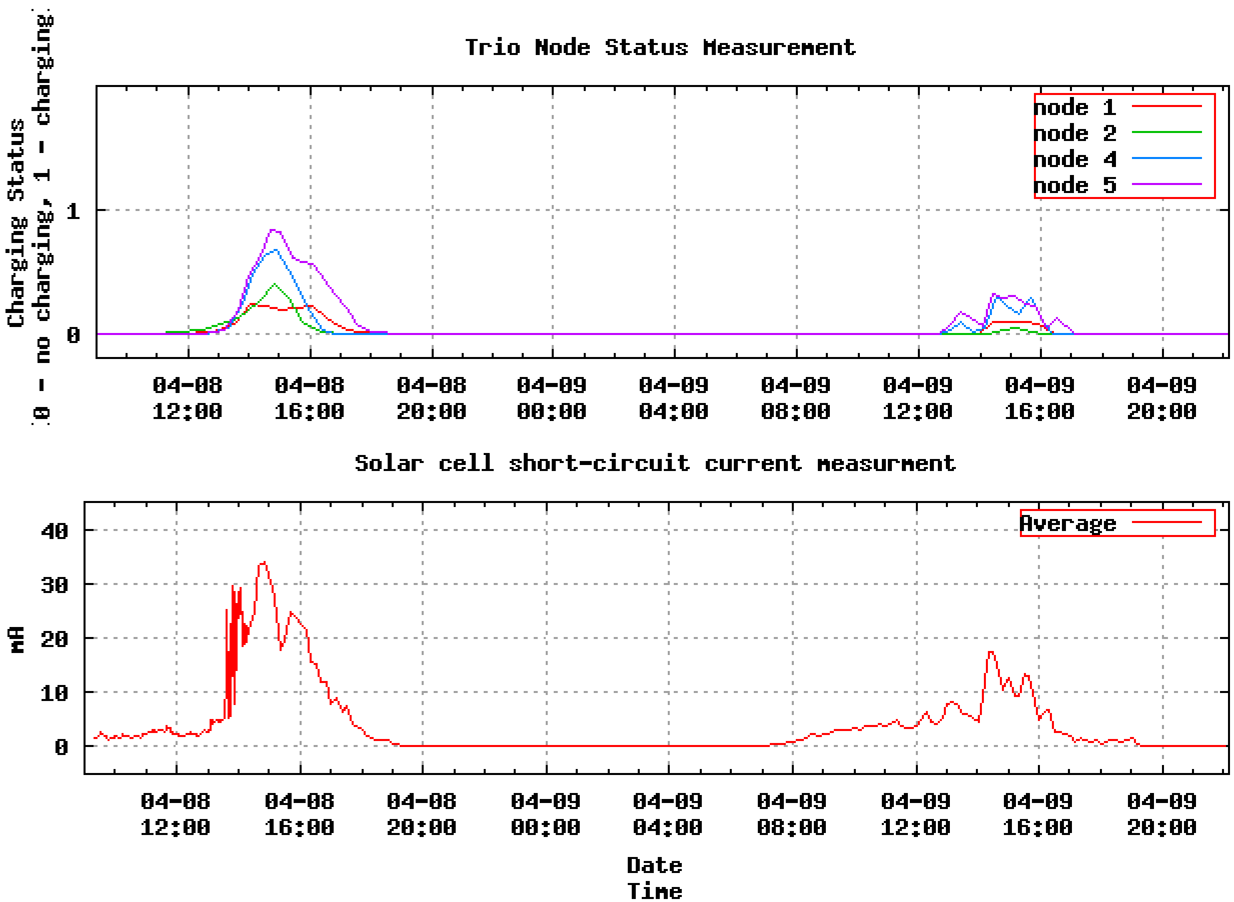
Experiment Results – Charging through USB port

- Trend of BatVol of two Trios with USB plugged.
- BatVol monotonically increases up to 4.1V and saturates around 4.2V.



Experiment: Four day measurement – Variation in Solar Radiation

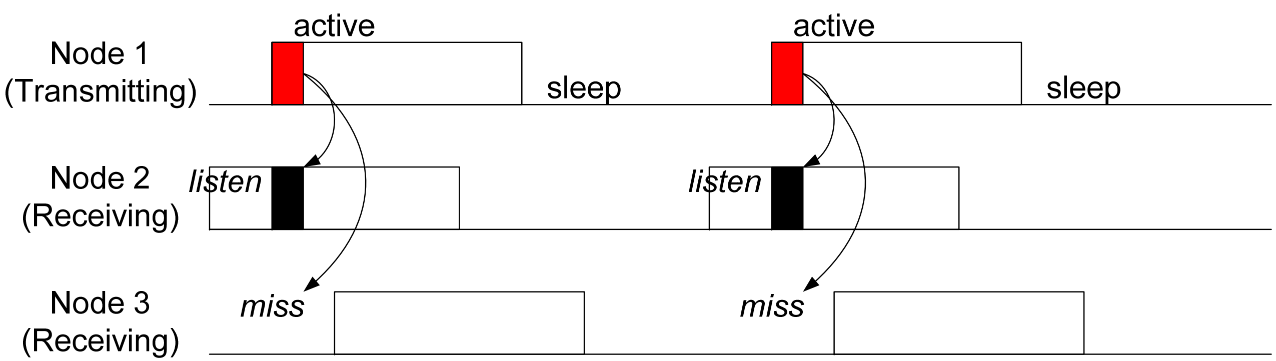
- High correlation between charging frequency and solar cell short circuit measurement.



Previous Work on Duty-Cycling – Naïve duty-cycling

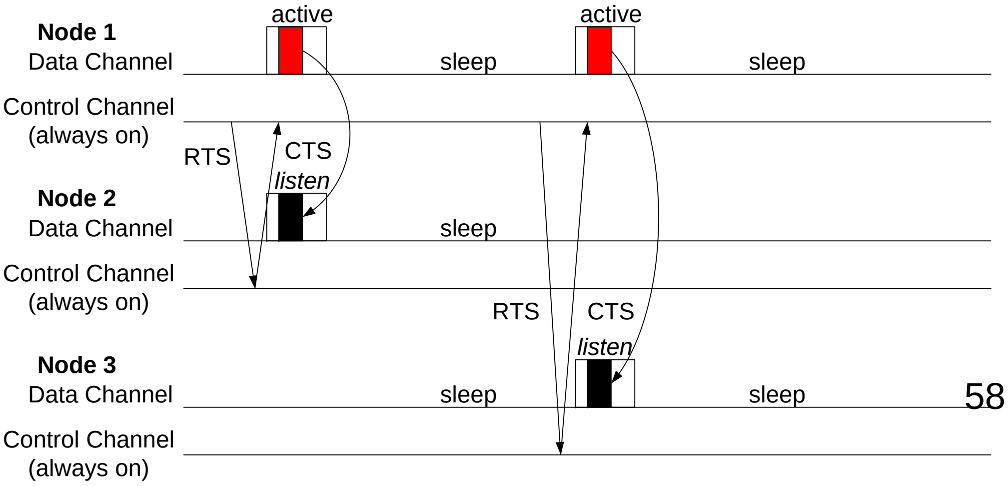
- Used for Prometheus and Heliomote.
- Power Saving:
  - Periodically turns on for T_{on} and turns off for T_{off}.
- No synchronization among nodes.
- Pros: Easy to implement, Platform independent.
- Cons: Doesn't work for multi-hop network.

Naïve duty-cycling



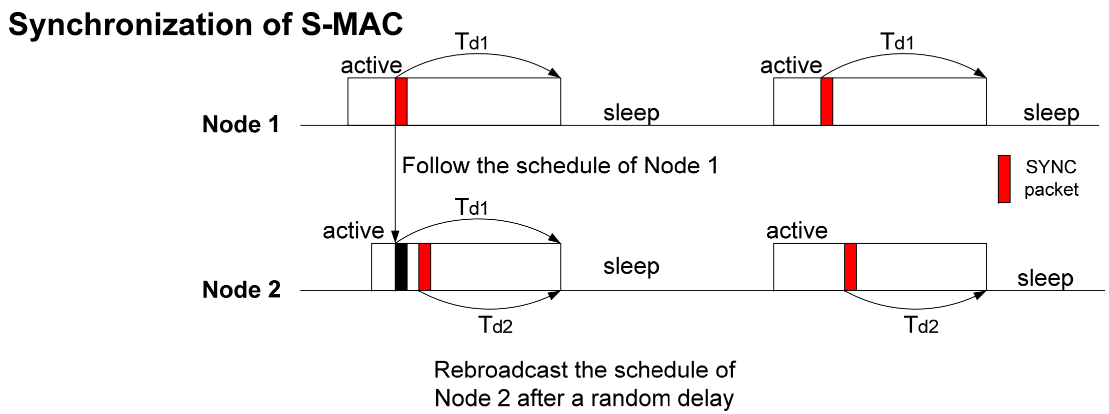
Previous Work on Duty-Cycling – Dual-channel MAC: PAMAS [SR98]

- Synchronization of PAMAS:
  - Each node sends and receives RTS/CTS messages over control channel, which is always turned on.
- Power Saving of PAMAS:
  - Data channel is turned on when activity is expected.
- Pros: Easy to implement.
- Cons: Requires dual-channel, control channel still consumes power



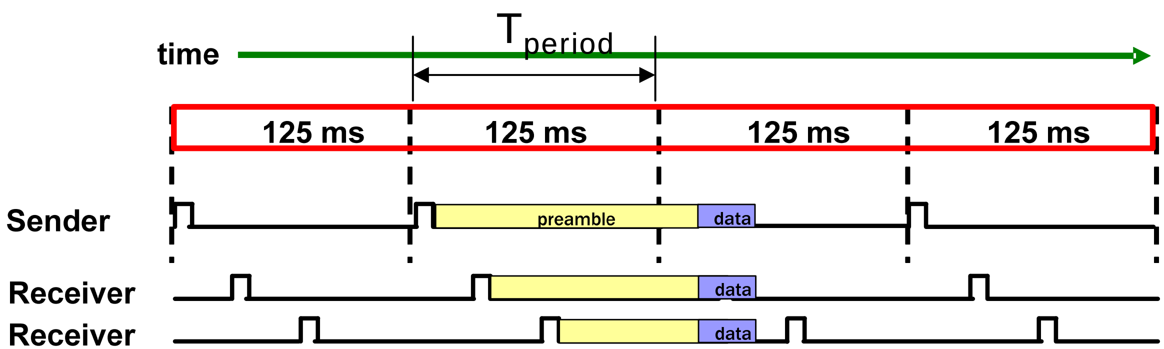
Previous Work on Duty-Cycling – Virtual Clustering (S-MAC, T-MAC)

- Power Saving of S-MAC:
  - Each node is turned on only for its time slot.
- Synchronization of S-MAC:
  - Each node sets up its own schedule by
  - (1) Sending its SYNC packet when it hasn't found neighbor.
  - (2) Following schedule of a neighbor whose schedule is earlier.
  - Channel contention is addressed by RTS/CTS.
- Pros: Algorithm can be applied to any platform.
- Cons: Overhead of RTS/CTS, Atmel specific implementation.



Previous Work on Duty-Cycling – Low-power listening (B-MAC)

- Power Saving for B-MAC:
  - Each node sleeps after listen with no channel activity.
- Synchronization for B-MAC:
  - Preamble from sender node is long enough to span T_{period}.
- Pros: No separate synchronization step is needed.
- Cons: Long preamble is not supported on Trio node.



Source: XMesh Routing Layer, Martin Turon et al. TinyOS Tech Exchange 2005.

Previous Work on Duty-Cycling – Network-level protocols

- Pros: System-wide energy scheduling.
- Cons: Tied to a specific network protocol.
- FPS [HDB04]:
  - Assumes treelike sense-gateway routing.
  - Power Saving: Wakes up only for its time window.
  - Synchronization: Slot is reserved with advertisement and reservation request among parent and child nodes.
- VigilNet [HKL+05] and LEACH [HCB00]:
  - Form a cluster among nodes.
  - Synchronization: Cluster heads take care of synchronization among nodes.
  - Power Saving: Non-cluster heads are turned off for power saving when they are not sending or receiving.

Experiment Setting – Power source check logic

- If (Vcc < 2.7V and BatVol >= 2.8V)
  Run on battery.

- Else if (Vcc < 2.7V and BatVol < 2.7V)
  Run on capacitor.

- Else if (Vcc >= 2.7V and CapVol >= 3.0V)
  Run on capacitor.

Experiment Setting – Charging Logic

- If running on battery
  CapVol = CapVol - 0.35V.

  Adjustment Step

- If (*BatVol < 4.1V and*
  CapVol < 3.0V)
  Stop charging.

  Charging Stop Condition

- Else if (*BatVol < 4.1V and*
  CapVol >= 3.3V)
  Start charging.

  Charging Start Condition

- Else if (BatVol < 4.1V and
  node is plugged to USB)
  Start charging.

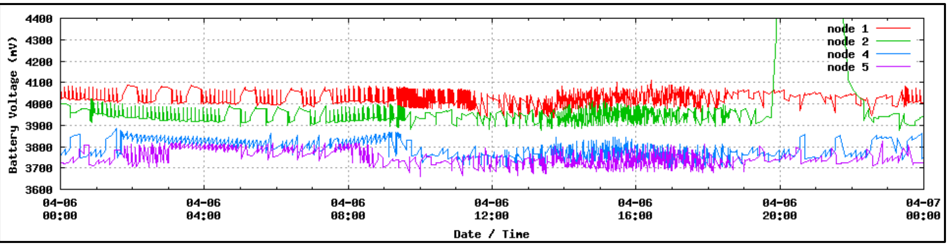
  USB Charging Condition

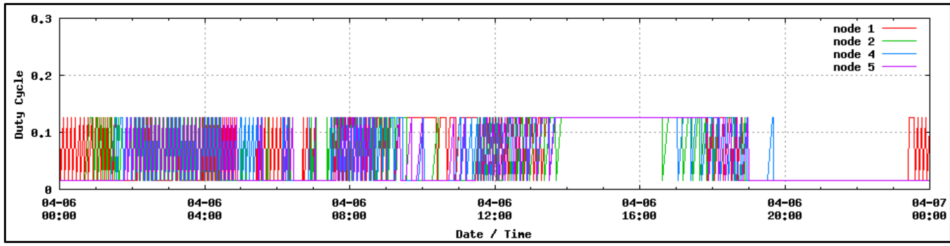
- Else if (BatVol >= 4.1V)
  Stop charging.

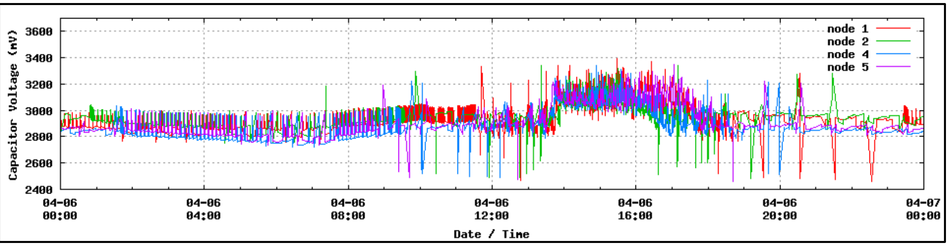
  Overcharging Detection Condition

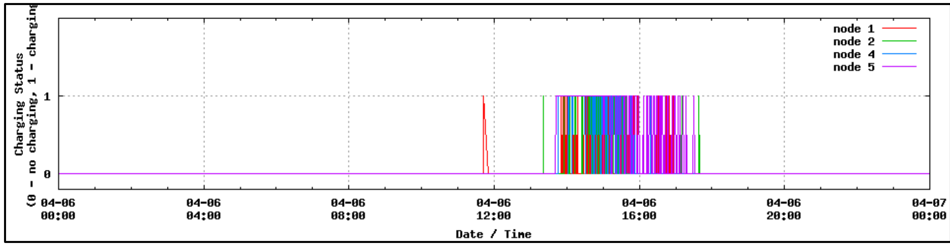
Experiment Results
– One day measurement

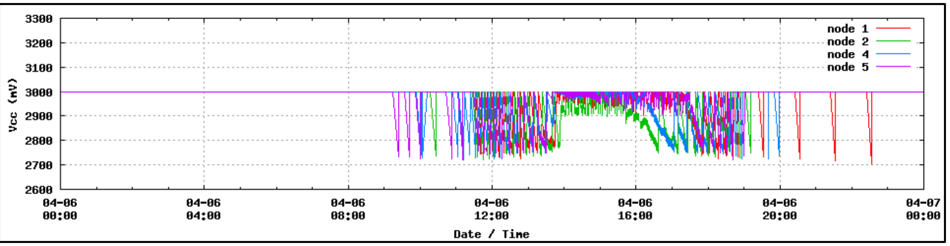
- One day measurement on April 6th, 2006.
- Use trend data for easier analysis.

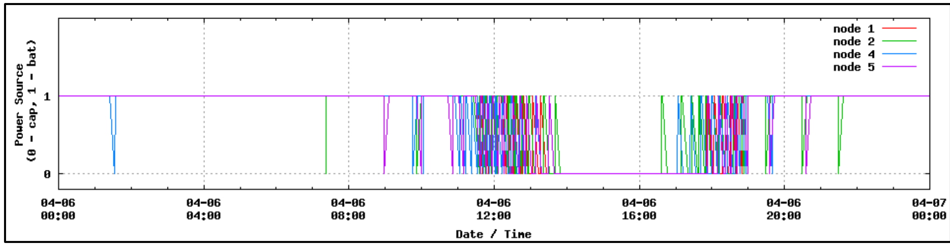




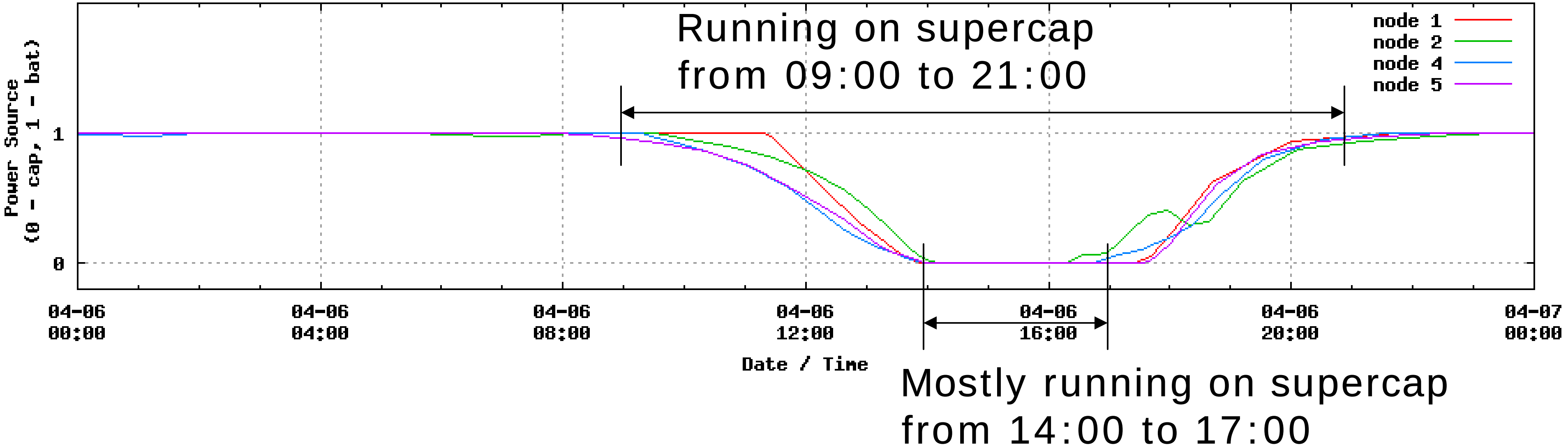


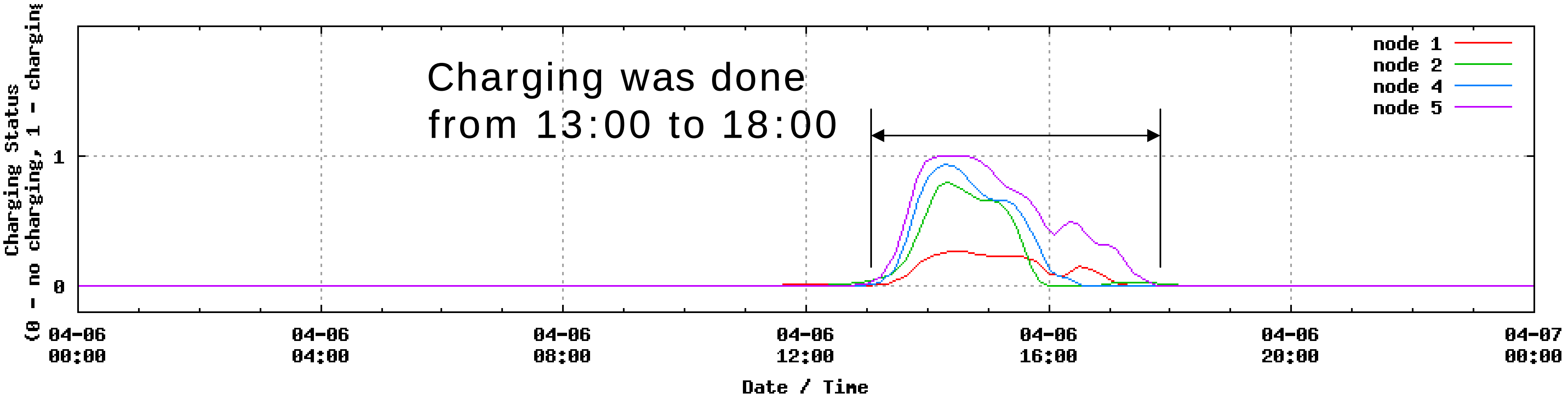






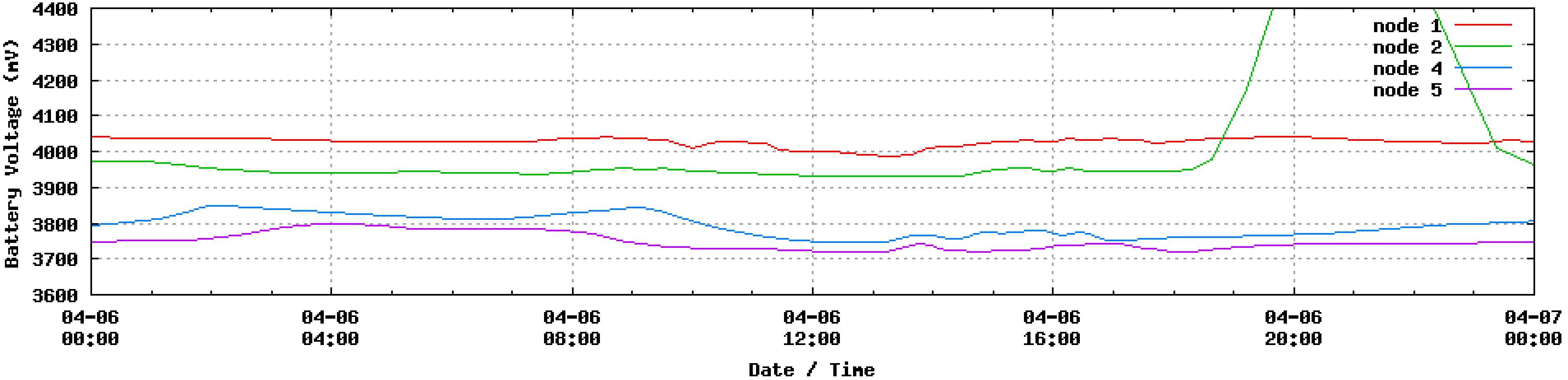
Experiment: One day measurement – Solar Radiation Hours





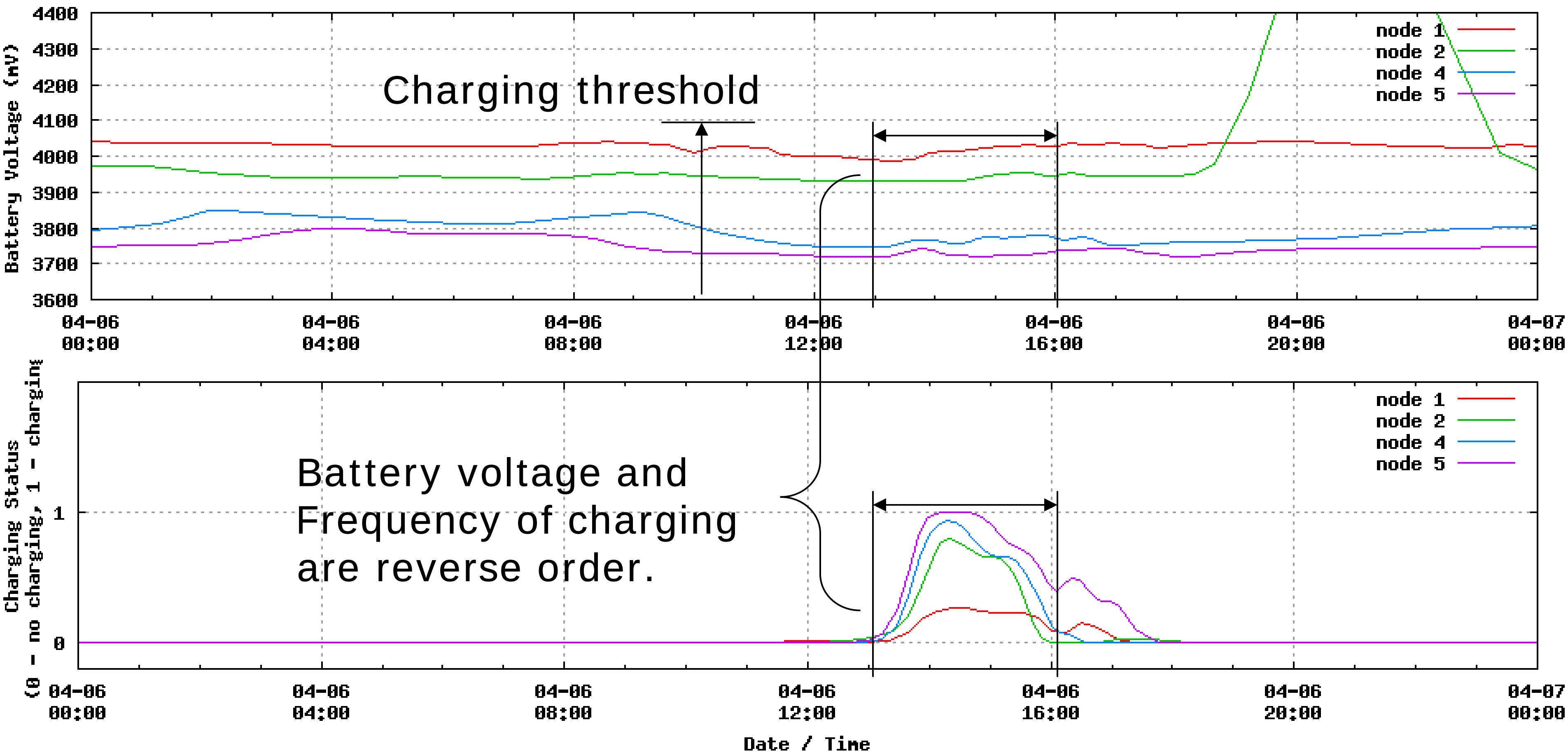
Experiment: One day measurement – Battery Voltage Trend

- Initial battery voltage is different among nodes.
  - Due to pre-charging.
  - Either from solar cell charging or USB charging.



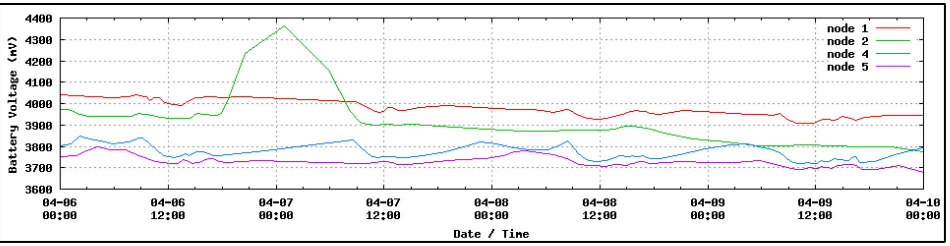
Experiment: One day measurement – Charging and Battery Voltage

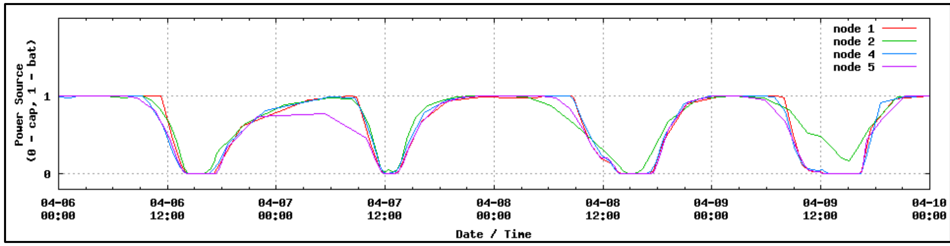
- Node with lower BatVol charges more frequently.
  - Due to overcharging detection condition.

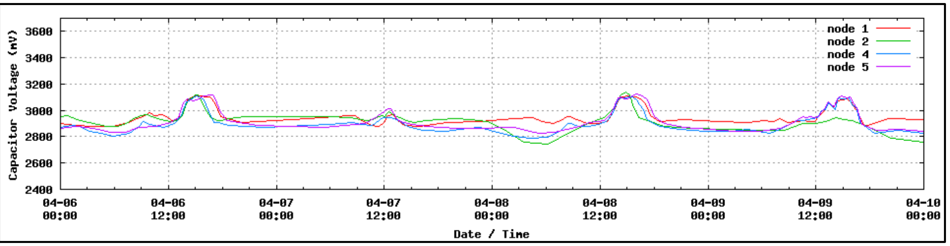


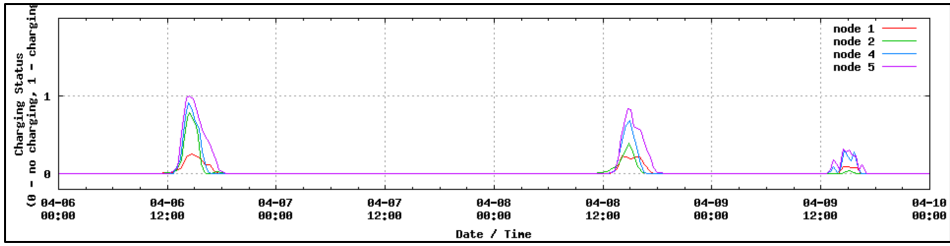
Experiment Results
– Four day measurement

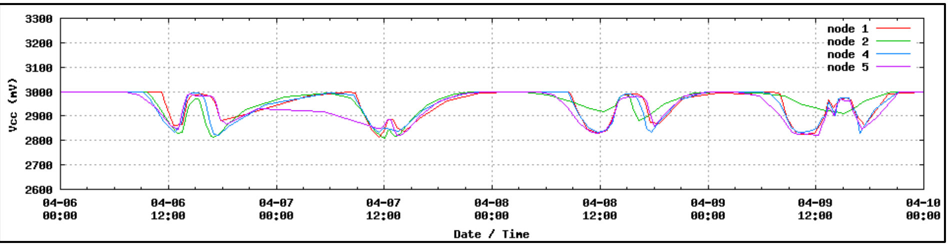
- From 2006/4/6 through 2006/4/9.

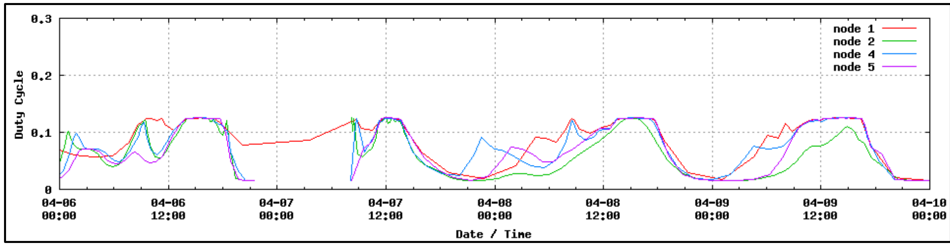






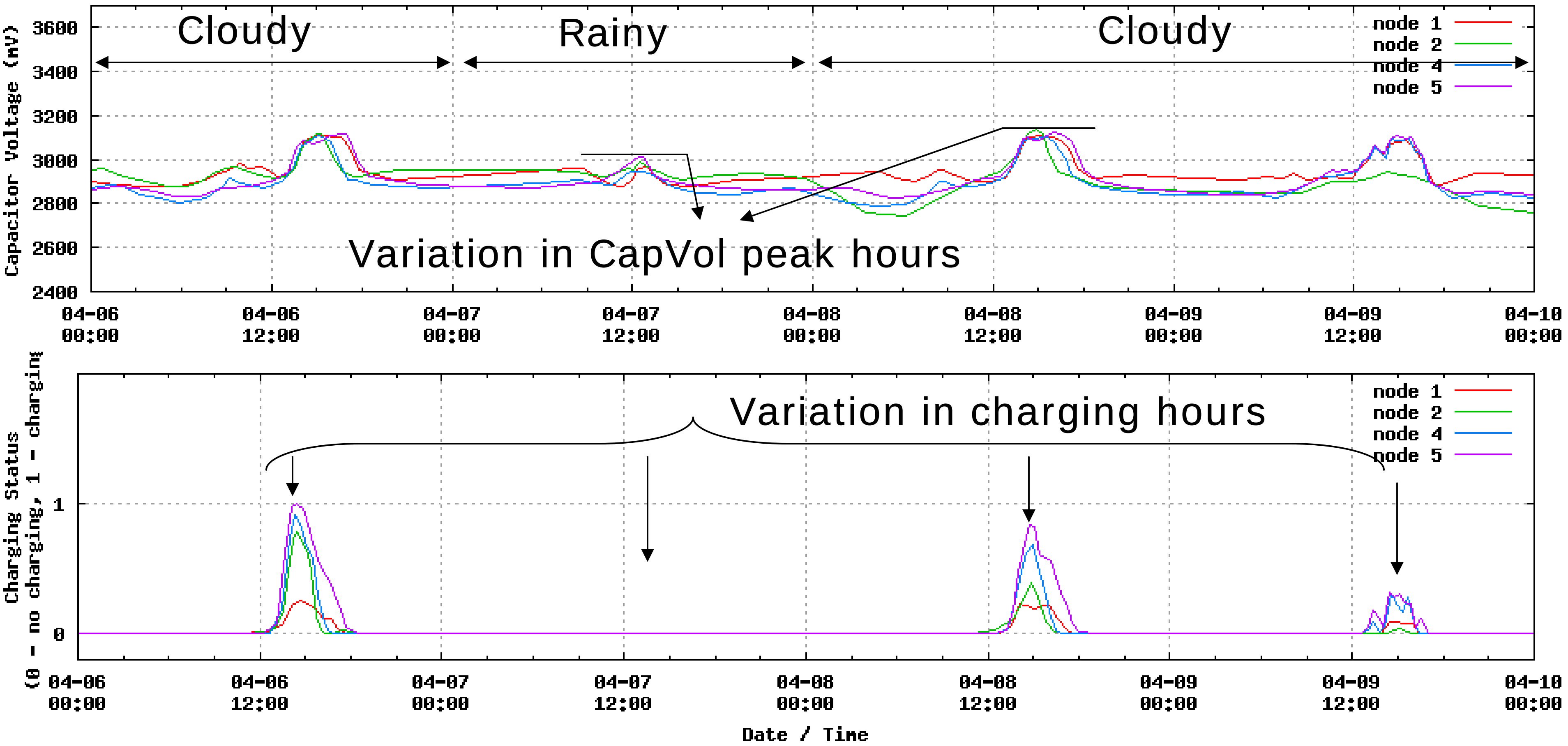






Experiment: Four day measurement – Verifying the charging logic

- CapVol and charging hours are highly dependent on solar radiation and weather.



Experiment

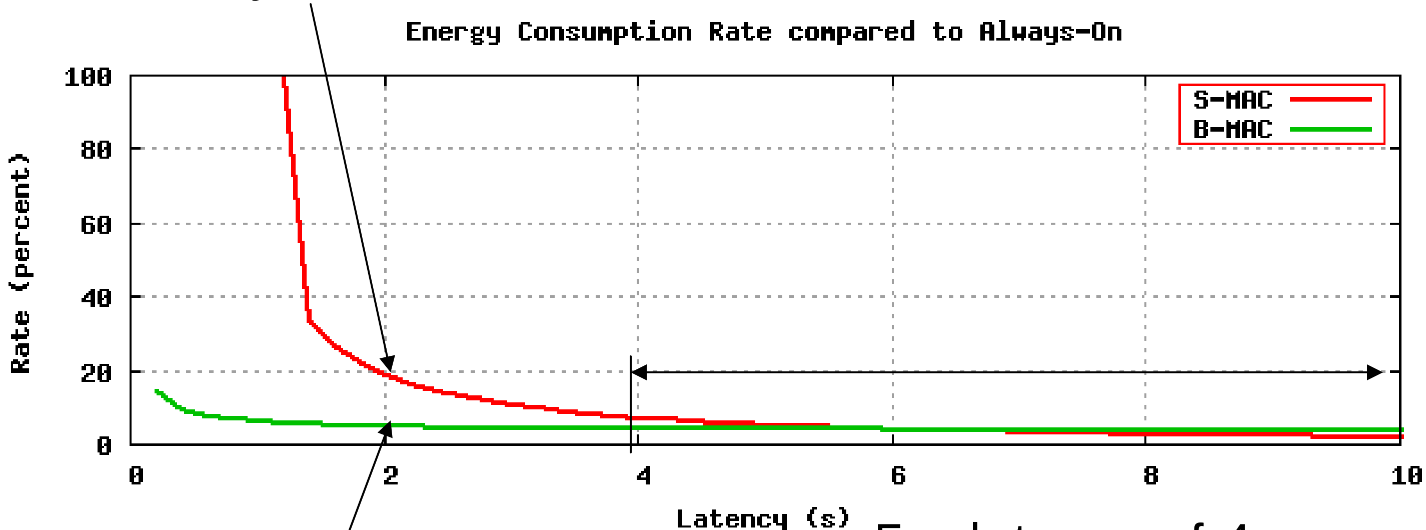
4 Trio nodes on the patio of a private building in El Cerrito, CA facing the west

- Metrics to be measured:
  - Vcc, BatVol, CapVol
  - Power source, Charging and Duty-cycle.
- Two-mode duty-cycling:
  - Normal duty-cycle (Vcc >= 2.7V):
    - Duty-cycle rate 12.5% (= 8192ms / 65536ms)
  - Low duty-cycle (Vcc < 2.7V):
    - Duty-cycle rate 1.56% (= 8192ms / 524282ms)
- Communication:
  - Single hop btw. each Trio and the base.
  - Sending rate: once every 4 sec with radio on.

Estimating energy saving with choice of protocol – S-MAC, B-MAC vs. Always-On

- Used simulation data from B-MAC paper [PHC04].
- Simulation with 10 hop multi-hop network.

S-MAC for latency of 2 sec:
20% of always-on

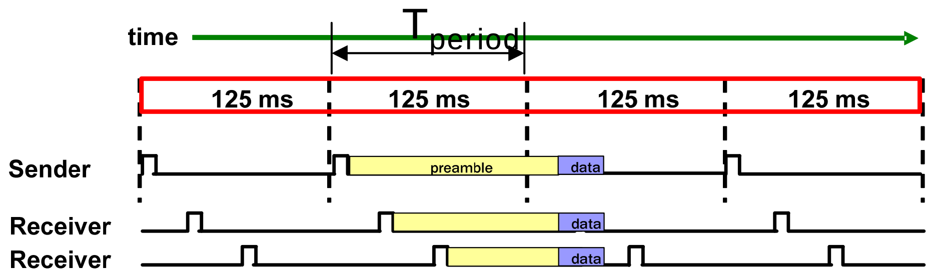


B-MAC for latency of 2 sec:
Around 6% of always-on

For latency of 4 sec or longer:
Both S-MAC, B-MAC less than 10% of always-on

Implementing duty-cycling for Trio – Comparing B-MAC and Seesaw

- B-MAC [PHC04]:



Source: XMesh Routing Layer, Martin Turon et al. TinyOS Tech Exchange 2005.

- Seesaw [BSE06]: