Design of Energy Efficient Components for Greenhouse/Urban Farming

EE 798 MTP Stage 2 : Presentation

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Agenda

1. Wifi based Actuator for drip irrigation
2. Solar Energy Harvesting

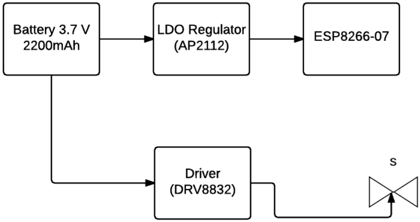
Wifi based Actuator for drip irrigation

- A prototype of the device was previously built, but major improvements needed to be done
- The device required 6 1.5V batteries (3V for ESP8266 and 6V for Solenoid valve)
- Power consumption Analysis and low power optimization options needed to be explored

Work done in Stage 1:

- Circuit redesign to work on a single 3.7V Li-ion/Li-poly battery
- Power consumption estimate for indoor environment
- Initial experiments for power save mode

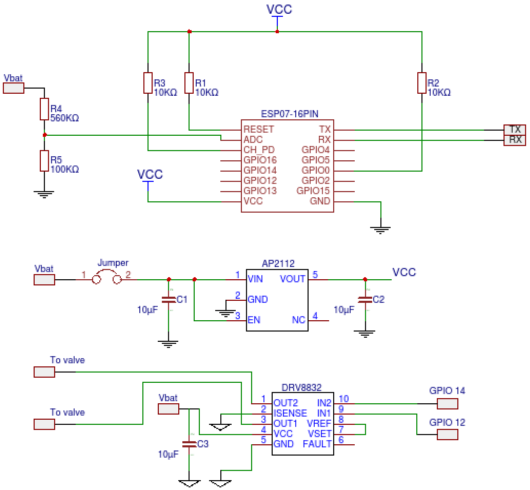
Circuit Redesign



Design 2

- DRV8832 : 1A H-bridge with operating voltage from 2.5V to 6.8V, low power mode under GPIO control
- AP2112 : A 600mA low dropout Regulator to provide stable supply to ESP8266-07.

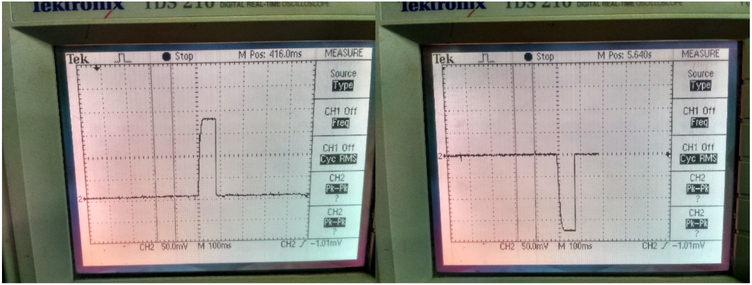
Circuit Schematic



Circuit Schematic

Circuit Redesign - Design 1

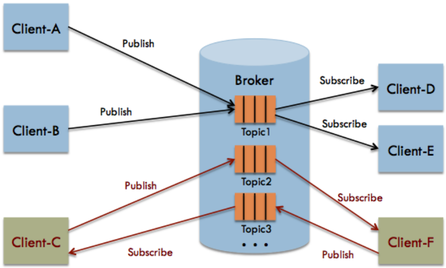
The H-bridge IC can be put to sleep under simple GPIO control. An 80ms square pulse at 3V was found to be sufficient to turn ON and turn OFF the valve



DSO Capture

The voltage across a 0.5Ω series resistor was captured with the battery voltage at 3.6V

MQTT Basic Architecture

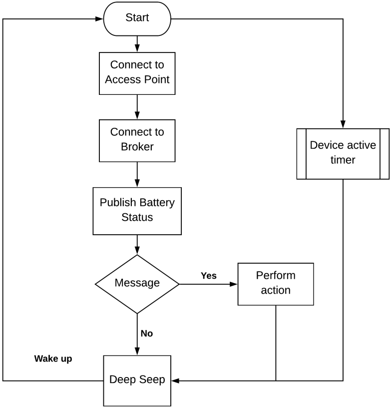


MQTT: Basic Architecture
(Image courtesy: http://micropython-iot-hackathon.readthedocs.io)

- Clients can be simple controller based actuators to even general purpose computers
- Topics are strings, example "/house/temperature", "/farm/device/paramter" etc.

Software and Flowchart

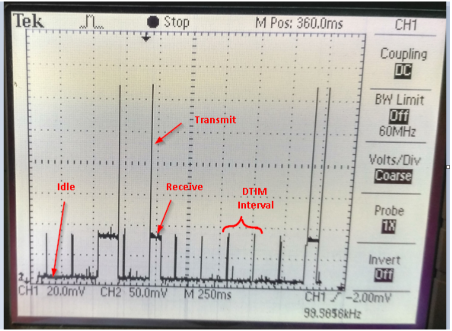
The software is written using NODEMCU firmware which provides a LUA based interpreter.



Flowchart

Device Power Consumption

A peak current of $\approx$ 255mA during transmission was observed whereas $\approx$ 70mA is consumed during reception.
In idle/modem sleep mode, the consumption is $\approx$ 16mA



Current Consumption in Active/ON state

The peak current can go as high as 280mA during transmission - measured using a current sensor (INA219)

Battery Life Calculations

Our Device uses Wifi (IEEE 802.11 standard) and has three distinct phases of operation in active/ON state The average power consumption too can be divided into three phases

- **Phase 1:** Avg. current consumption during network association (connecting to an AP and MQTT broker)
- **Phase 2:** Avg. current consumption when connected to an AP and MQTT broker
- **Phase 3:** Avg. current consumption when user data/messages are exchanged

Phase 3 is not relevant for the device since frequency of user data/messages is bare minimum
Negligible difference between power consumption in Phase 2 and 3

Power Consumption : Outdoor (Phase 1)

A PoE based outdoor access point was setup on KReSIT terrace
Phase 1 Power Consumption depends on time which varies with distance and number of clients

Approximate distance	Number of clients	Average Phase 1 time
15 feet	2	1.987 seconds
15 feet	5	2.412 seconds
30 feet	2	2.785 seconds
30 feet	5	2.942 seconds
45 feet	2	3.857 seconds
45 feet	5	7.883 seconds

Table: Variation in Phase 1 time

Average current consumption in all cases $\approx$ 70mA
Maximum time recorded: 8.78 seconds
The client device failed to connect to AP once during 45 feet, 5 clients condition

Power Consumption : Outdoor (Phase 2)

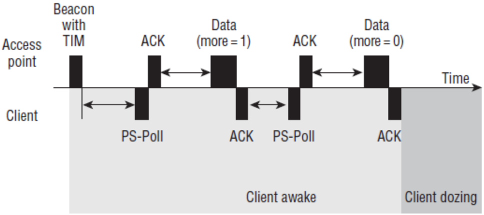
The current consumption varies with distance and the number of clients.
The variation is not as pronounced as the changes in Phase 1 time

Approximate distance	No. of clients	Average Current Consumption
15 feet	2	47.33mA
15 feet	5	48.12mA
30 feet	2	48.60mA
30 feet	5	50.60mA
45 feet	2	50.13mA
45 feet	5	53.20mA

Table: Variation in Phase 2 avg. current consumption

DTIM beacon Intervals

- Wifi uses periodic (100ms) beacons to synchronize traffic within its network
- A client device may choose to turn off reception during this period
- DTIM is beacon which indicates presence of data for the client device

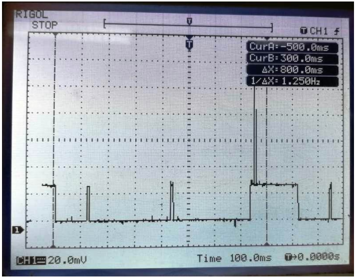


Power Saving Mode Sequence (courtesy: https://mrncciew.com/)

Changing DTIM interval

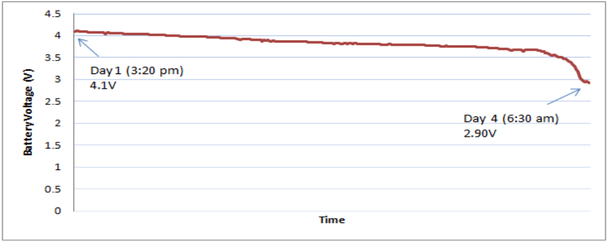
- DTIM interval can be changed from the Access Point
- This should allow more time for the client to be in modem sleep mode
- By default DTIM is set to 1 i.e. 100ms
- Increasing it can reduce power consumption in active state

$$\text{DTIM beacon interval} = \text{DTIM} \times \text{beacon period}$$

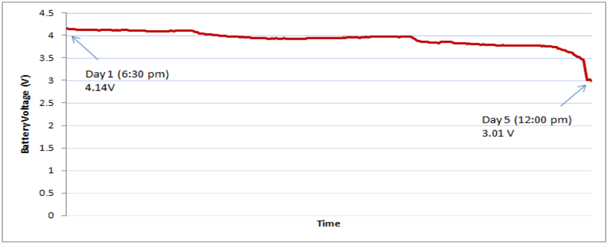


DTIM3 Current Profile

Battery Voltage Logs



Battery capacity - 500 mAh, DTIM1



Battery capacity - 500 mAh, DTIM3

Power Consumption : DTIM3

DTIM3 indeed seems to improve the battery life
The avg.power consumption for DTIM3 also indicates this

Approximate distance	No. of clients	Average Current Consumption
15 feet	2	29.33mA
15 feet	5	30.12mA
30 feet	2	30.40mA
30 feet	5	33.18mA
45 feet	2	32.11mA
45 feet	5	34.03mA

Table: Variation in Phase 2 avg. current consumption

The Phase 1 avg. power consumption remains the same in DTIM3

Battery Life Calculations: DTIM1

Active (T_on) = 60 seconds, Sleep (T_off) = 600 seconds
DTIM1:
Active state avg.current = avg.current in Phase 1 + avg.current in Phase 2

The battery life in hours can be given by:

Power consumed in mAh in one hour = (Active state avg. current $\times$ T_on + Sleep state current $\times$ T_off) $\times$ Number of cycles
Phase 1:
Avg. current consumption during phase 1 = 70mA
Maximum time recorded for phase 1 = 9 seconds
Consumption in mAh for phase 1 = 0.175mAh

Battery Life Calculations: DTIM1

Phase 2:

Avg.current consumption during phase 2 = 53.20mA

Time for phase 2 = 51 seconds

Consumption in mAh for phase 2 = 0.755mAh

Sleep

Sleep current = 1.8mA

Sleep time = 600 seconds

Estimate

Consumption in mAh during sleep = 0.3mAh

Total power consumption in mAh for one cycle = 1.23 mAh

Power consumption in an hour = 6.709mAh

Power consumption in a day = 161.01mAh

Battery life for 500mAh battery should be ≈ 75 hours. But we got only 63 hours!

Actual battery capacity ≈ 400mAh, revised estimate ≈ 59 hours

Battery Life Calculations: DTIM3

Phase 1

Avg. current consumption during phase 1 = 70mA

Maximum time recorded for phase 1 = 9seconds

Consumption in mAh for phase 1 = 0.175mAh

Phase 2

Avg. current consumption during phase 2 = 34.03mA

Time for phase 2 = 51seconds

Consumption in mAh for phase 2 = 0.482mAh

Estimate

Consumption in mAh during sleep = 0.3mAh

Total power consumption in mAh for one cycle = 0.957mAh

Power consumption in an hour = 5.22mAh

Power consumption in a day = 125.28mAh Battery life for 400mAh battery should be $\approx$ 77 hours.

But we got 90 hours due to overestimation during calculation

DTIM4 and DTIM5

Approximate distance	No. of clients	Average Current Consumption
15 feet	2	31.33mA
15 feet	5	32.12mA
30 feet	2	32.00mA
30 feet	5	34.50mA
45 feet	2	33.12mA
45 feet	5	35.20mA

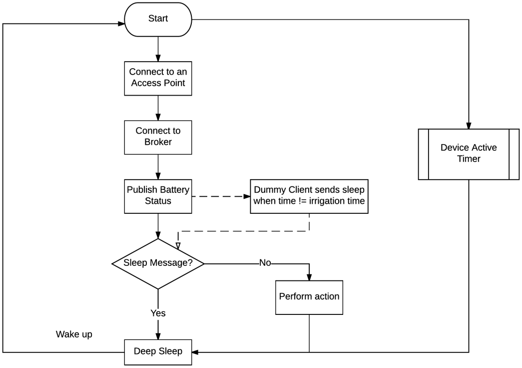
Table: Phase 2 : DTIM4

Approximate distance	No. of clients	Average Current Consumption
15 feet	2	34.33mA
15 feet	5	35.85mA
30 feet	2	35.60mA
30 feet	5	36.24mA
45 feet	2	36.45mA
45 feet	5	38.27mA

Table: Phase 2 : DTIM5

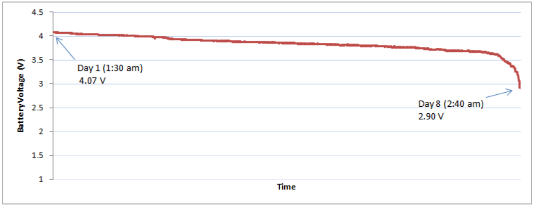
Static IP, Application specific approach

- As a dedicated AP is used, each client could be assigned a static IP
- Avg. phase 1 time reduced to $\approx$ 5 seconds from 8.78 seconds. Power saving of 0.058mAh per cycle

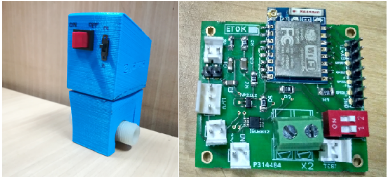


Modified flowchart

Battery log, Prototype 1

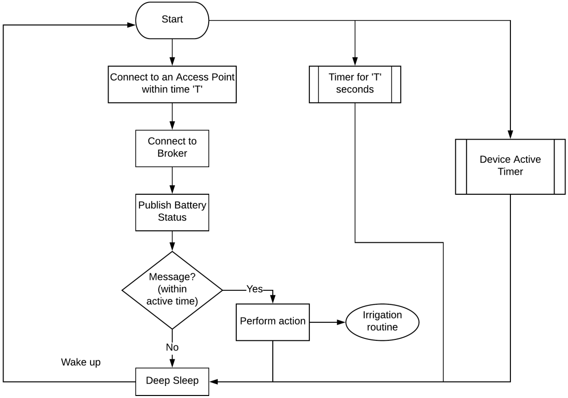


Battery Capacity - 500 mAh, App. specific approach



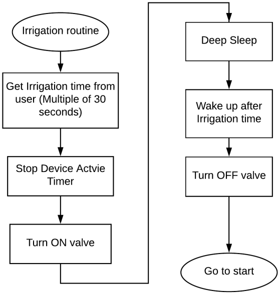
Prototype - 1

Flexible irrigation time, Phase 1 timeout



Modified flowchart

Irrigation routine, Need for harvesting

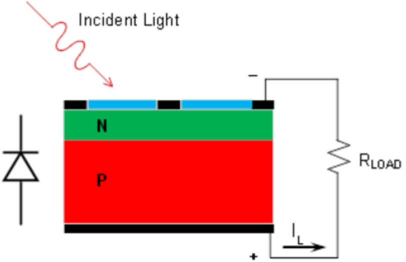


Irrigation routine

- Changing DTIM period helps in power saving
- Even if battery size is increased, ambient energy harvesting necessary to prolong life

Solar Energy Harvesting

- Harvesting Component: Solar cell
- Working Principle :

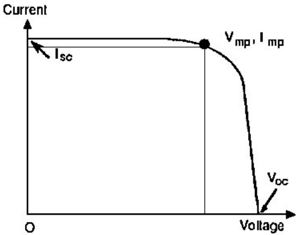


(image courtesy : https://wiki.analog.com/)

Solar cell

,

I-V characteristics

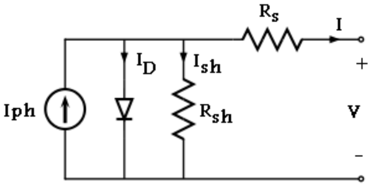


I-V characteristics

- Important Parameters:
  - Voc: Open Circuit Voltage
  - Isc: Short Circuit Current
  - Vmp,Imp: Maximum Power Point

Image : Source (http://thesolarized.blogspot.in)

Electrical Equivalent Model



Diode Current Source Model

- Without Rs ans Rsh

$$I_d = Is(e^{\frac{V}{\eta Vt}} - 1) \quad (1)$$

$$I = Iph - I_D \quad (2)$$

$$I = Iph - Is(e^{\frac{V}{\eta Vt}} - 1) \quad (3)$$

Image Courtesy : Science and Education Publishing

Continued

- With Rs and Rsh

$$I_D = Is(e^{\frac{V+IRs}{\eta Vt}} - 1) \tag{4}$$

$$I = Iph - I_D - \frac{V + IRs}{Rsh} \tag{5}$$

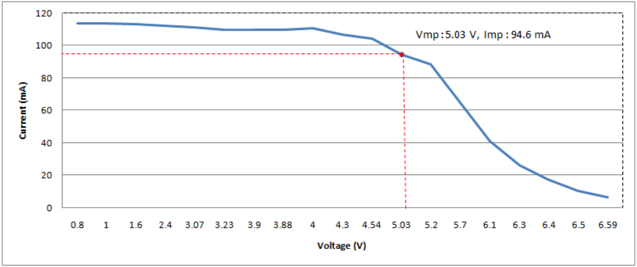
$$I = Iph - Is(e^{\frac{V+IRs}{\eta Vt}} - 1) - \frac{V + IRs}{Rsh} \tag{6}$$

$$P = IphV - IsV(e^{\frac{V+IRs}{\eta Vt}} - 1) \tag{7}$$

- Power output depends on the Voltage (V), temperature and the illuminance level
- The power output will be maximum at a particular set of values (I,V) for a given illuminance

Practical I-V Characteristics

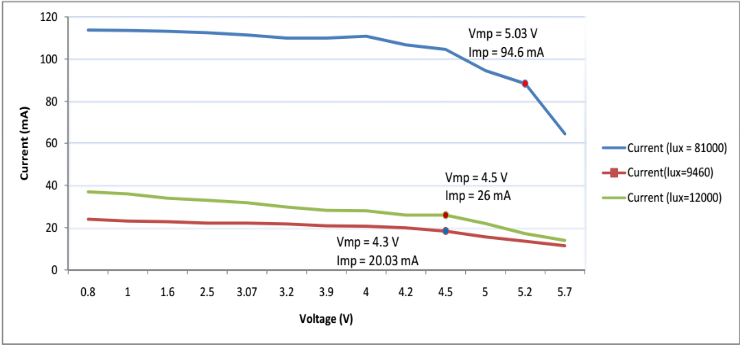
- Rated Voc, Isc: 6V, 200 mA , Size: 15.5 cm x 7 cm
- Measured Voc: 6.7 V, Isc: 124 mA
- Max Power: 475.8 mW , illuminance: 81000 lux



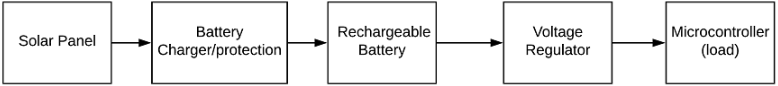
I-V Characteristics

Varying Maximum Power Point

The Maximum power point (Mpp) varies with illuminance level so does Voc and Isc



I-V Characteristics



Setup for Solar harvesting supply

Battery Selection

Parameter	NiMH	Li-ion	Li-po
Typical Voltage	1.2 V	3.7 V	3.7 V
Self Discharge rate/month	10-15 %	1-5 %	1-5 %
Recharge time	High	lower	lower

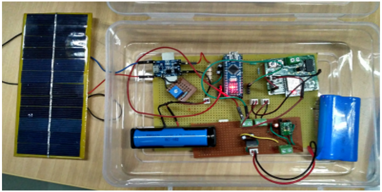
table Courtesy:Battery University.com

Harvesting Strategies : Work done

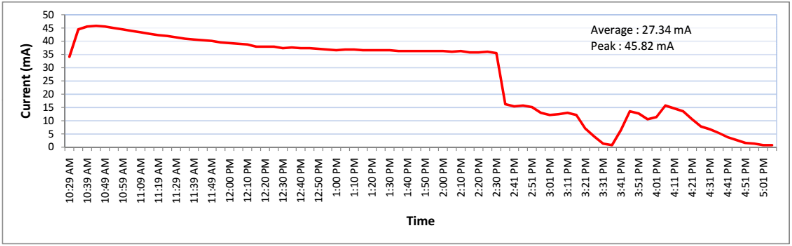
Stage 1

- The Voc of the panel should be higher than 4.2V for Li-ion/Li-poly
- Linear charger based approach showed some promising results with 6V,200mA panel
- A simple DC-DC boost (LM2621) converter followed by a linear charger for a panel with a Voc 3V did not proove useful
- Reducing charge current to avoid collapsing of panel voltage in low illuminance and increasing charge current in high illuminance - Maximum Power Point Control (MPPC)
- A DC-DC boost converter using LTC3105 using MPPC was able to harvest energy from a 3V,150mA panel. But, it needed more testing

Estimate of harvested power

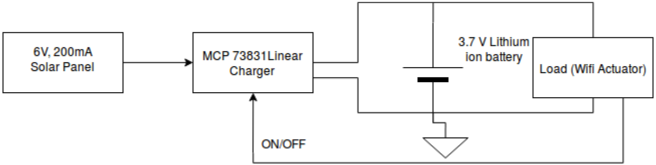


data logger

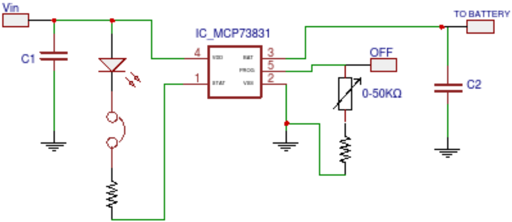


Charge current log

Linear Charger baased Approach: Using MCP73831

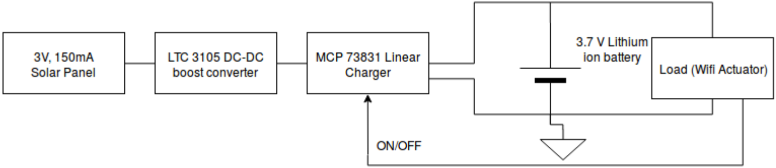


MCP73831 based setup

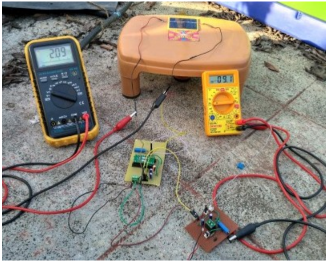


Schematic

Maximum Power Point Control : LTC3105



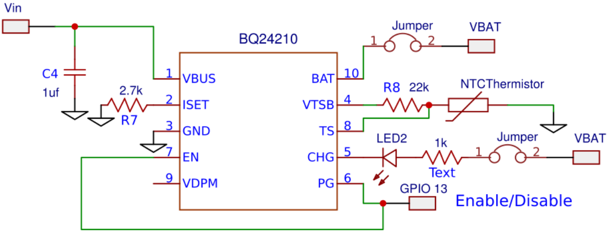
Setup using LTC3105



Setup Outdoors

Charger with MPPC : BQ2410

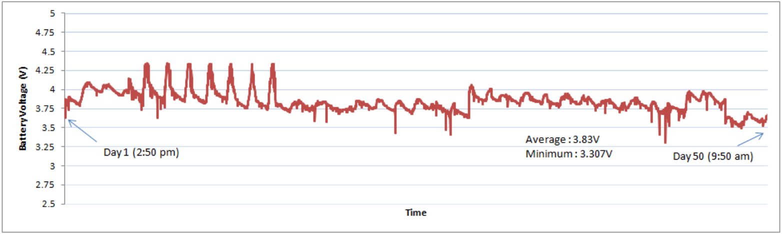
- MPPC or as TI calls it Input voltage dynamic power management
- Has the potential to outperform MCP73831
- Battery temperature monitoring and shortcircuit protection features inbuilt



BQ2410 Schematic

Outdoor test 1 : MCP73831

- Panel-6V,200mA , Battery-500mAh, DTIM1
- Dutycycle-9.09%, Solar charging during sleep

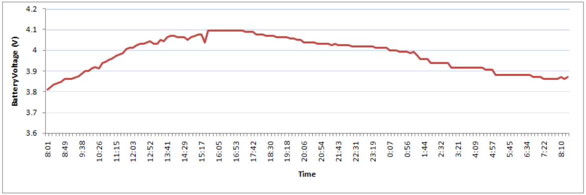


Battery Voltage log

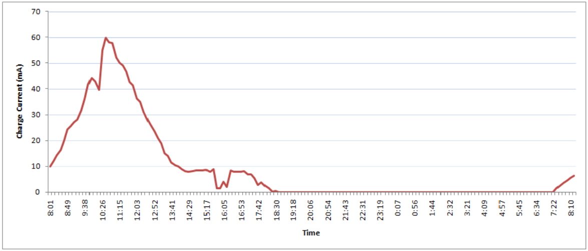
Battery failure on the 50th day due to

- High temperature
- MCP73831 was 4.3V version and not 4.2V
- Access point switched off for two days
- Battery charge recharge cycles

Outdoor test 1



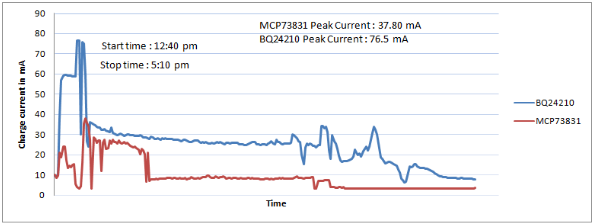
Battery Voltage log - Day 2



Charge Current log - Day 2

MCP73831 vs BQ24210

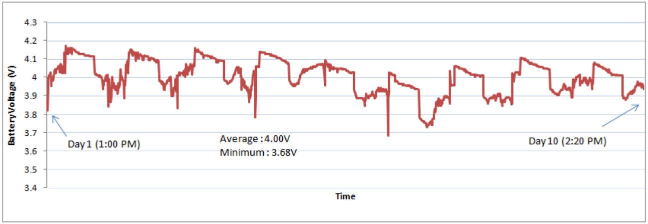
- Panel-6V,100mA, Battery-500mAh, DTIM1
- Battery starting voltage-3.00V, Charge current logging using INA219 and ESP8266



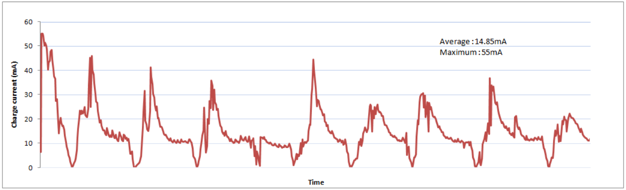
Charge Current : MCP73831 vs BQ2410

Avg. charge current for MCP73831 - 9.30mA
Avg. charge current for BQ24210 - 25.20mA

Outdoor test 2 : BQ24210

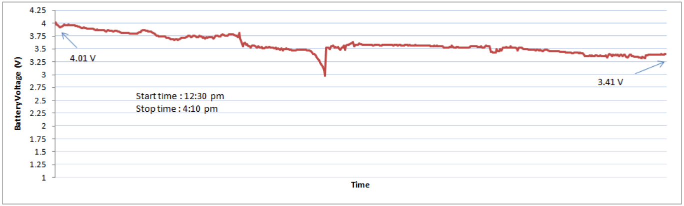


Battery Voltage log : BQ24210

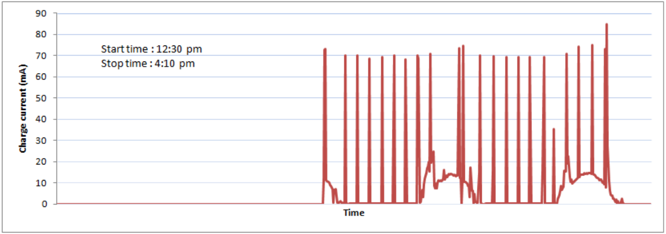


Charge Current log : BQ24210

Outdoor test 3 : LTC3105 + MCP73831

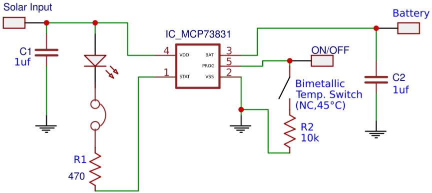


Battery Voltage log : LTC3105

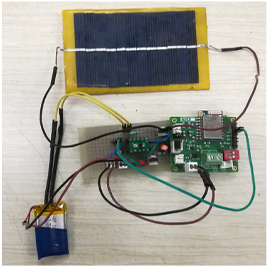


Charge current log : LTC3105

MCP73831 based Harvesting Option

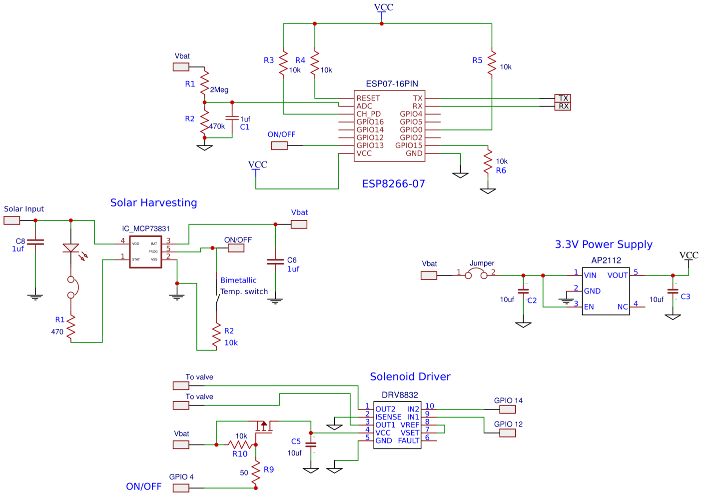


Schematic



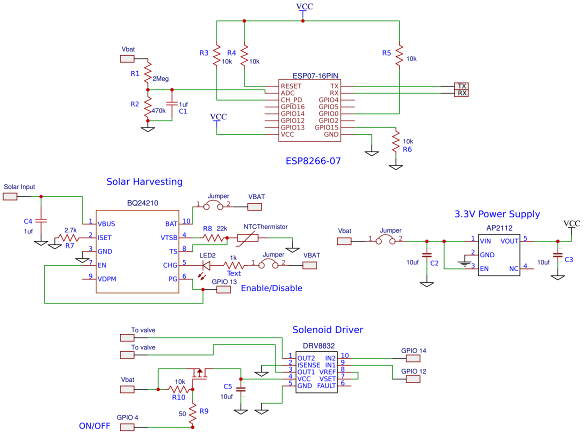
Option 1: Prototype

Circuit Schematic



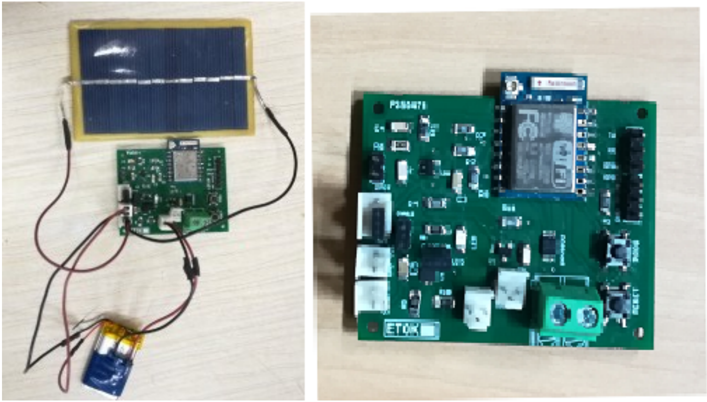
Option 1: Schematic

BQ24210 based Harvesting Option



Option 2: Schematic

Circuit with Solar Harvesting



Option 2: Prototype

Circuit Modification, Improvement in battery life

- The earlier version consumed $\approx$ 1.8mA in sleep. The driver IC came out of low power mode when ESP8266 went to sleep
- A PMOS high side switch was connected to the power of the driver IC
- ESP8266 power led consumed $\approx 360\mu$A in active as well as sleep state. The new version uses an ESP8266 with only a status led and not a power led
- The sleep current for the new circuit with solar haresting is 78μA.
- This results in about 95% reduction in sleep current and 30% reduction in overall power consumption
- If ESP8266 with a power led is used, then sleep current is $\approx 440\mu$A, which gives 19% reduction in overall power consumption

Solar Harvesting Actuator Lifetime estimate : Initial Work

- The energy harvested during the day is sufficient to keep the battery at 3.8V on average
- However, the self-discharge of the battery, the finite charge-discharge cyles and reduction in efficiency of solar panel will eventually reduce harvested energy
- Efficiency of solar panel reduced from 11.4% to 8% over a period of 50 days

Maximum energy that can be harvested is given by:
Average solar energy $\times$ panel area $\times$ η $\times$ $\eta_{chargingcircuit}$
where η is solar panel efficiency and $\eta_{charger}$ is efficiency of charging circuit (BQ24210)
panel area $=$ 40sq.cm ,$\eta = 11\%$ and $\eta_{chargingcircuit} = 65\%$

Future Work

LDO and harvesting IC replacement

- Replace AP2112 LDO with RT9080 (2μA, 600mA, 3.3V). This can reduce sleep current further since AP212 has a quiescent current of 55μA
- BQ24210 is difficult to solder, you can use MCP73831−4.2V version with temperature switch
- New case design with an inclined solar panel. Some sort of heat insulation like styrofoam can be used

Driver IC

- DRV8832 is a low voltage, 1A driver IC but a bit costly and difficult to solder. You can look at BD6211F-E2 (on element14)
- You can actually make an anlog circuit for H-bridge using PMOS on high side and NMOS on low side
- This will bring down the cost drastically

Future Work : Continued

Battery Selection

- I used Li-ion as well as Li-poly batteries of varying capacities
- You can use Li-poly batteries with inbuilt low discharge protection
- A 800mAh battery may be sufficient with solar harvesting. However, a test needs to be done for a duration of six months to ascertain this

This covers all the important aspects to continue development or to deploy them in our test bed.
I would like to be involved in future development remotely after I have left!