Low Power Embedded Design Techniques

University of Colorado
Boulder

Course Project Proposal Update

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EXECUTIVE SUMMARY

1. Team name

Bhishma

No update for this week. We are continuing to work on layout, board fabrication and firmware bring-up.

Current Status and Planned activities for the next week

For next week, we have the following activities lined up:

- Review sessions with TAs and appropriate revision based on feedback.
- Complete the Board Layout.
- Continue Testing of development boards of ethernet processor and power measurement IC.

High-Risk Development Areas & Mitigation Plan:

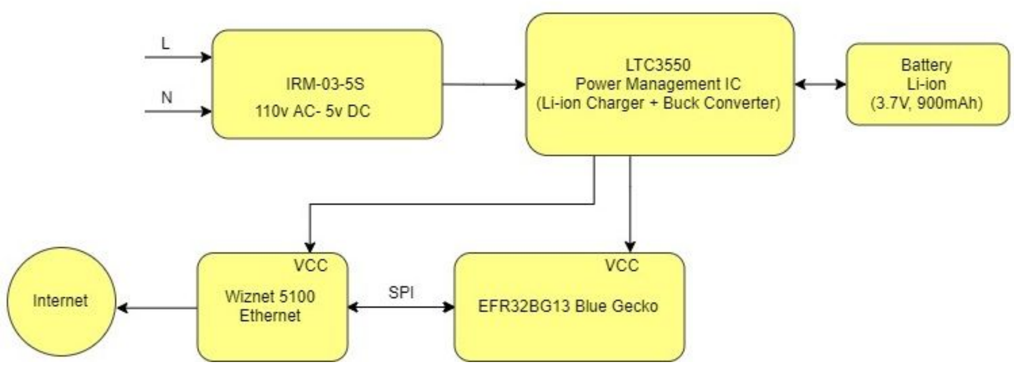
1. Risk: During the preparation of schematic and PCB layouts, we need to make sure the IC dimensions match with the components we are using Altium Designer.
   The mitigation plan is to have each team member cross-verify the other members' schematics.
2. Risk: Careful use of the power measurement IC. We will need to make sure the STPM34 eval board is carefully connected and galvanically isolated. If not, the board may burn out.
   The mitigation plan is to have our connections verified by the TAs before we proceed with the actual testing.

2. Project Overview

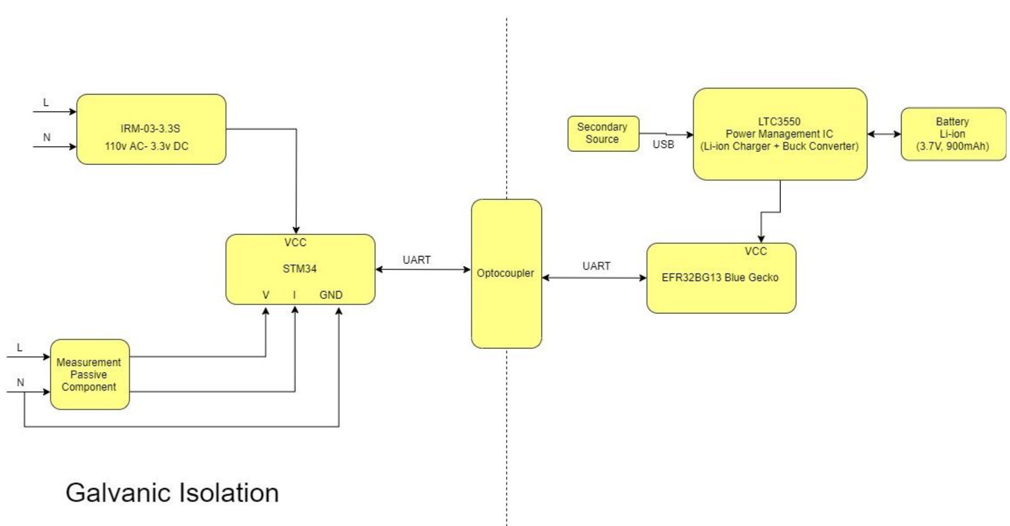
We propose modifications to the original project proposal. Originally, we had planned for three PCBs, with each connected to the internet in a solitary environment. However, this does not support a low-power design methodology. Our initial research had led us to believe that microcontrollers supporting wi-fi could be designed with low-power in mind, but none of these controllers supported an energy profiling tool, and sufficiently low-power energy modes. Modifications have been suggested in the following sections.

The power-monitoring IC will be interfaced with main controller using UART. The low-power nodes will update the master node periodically, and ethernet will be used to upload real-time data periodically and immediately in case of peak load on the AWS cloud. The desktop application will be developed for monitoring and shutting down power if required. An optional feature for OTA firmware updates will be implemented based on available time during the project. The primary power source will be the battery.

Master



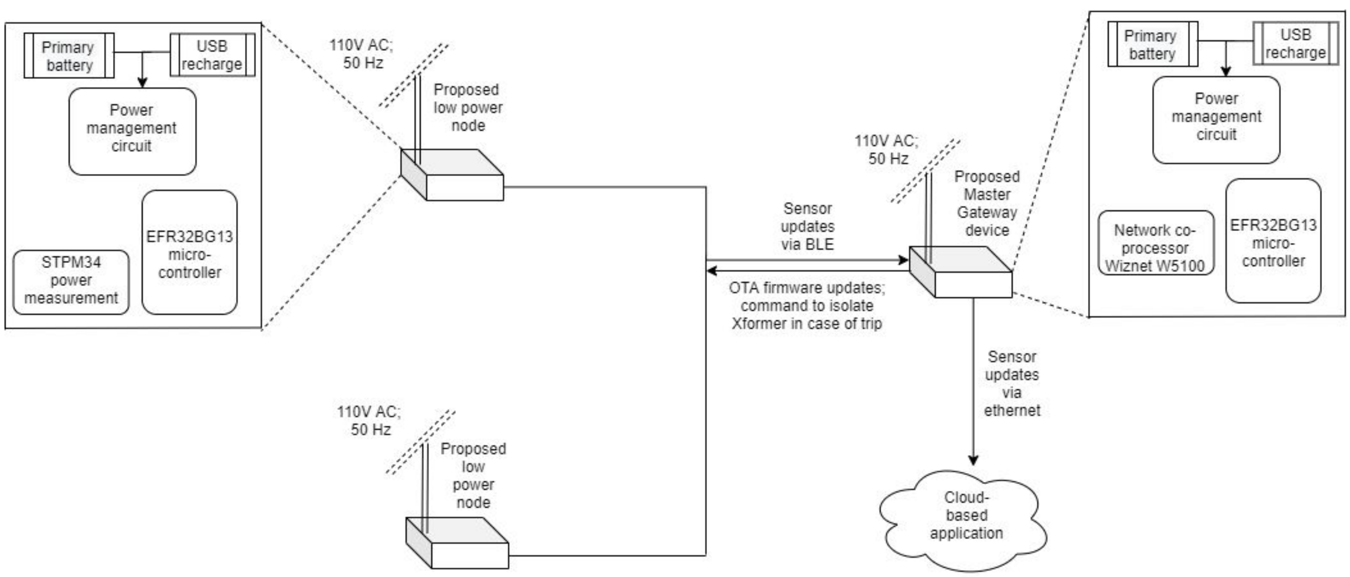
Low Power Slave



3. Need for solution

Load Sharing in the Power grid is an important component. In a 3-phase system, load balance is important to optimize power delivery efficiency. The excess load can not only imbalance but in worst can also trip the grid. So, our product targets this market of power measurement and a real-time update on the cloud-based systems. It also allows manual decision to cut the transformer from the grid in caseload increases.

4. Functional Block Diagram



5. Features

- Energy profiling on the cloud to monitor power usage at the grid-level.
- Internet connectivity via ethernet module, enabling remote logging of data parameters.
- Low power modes enabling minimum average power consumption
- Over the air firmware-update capabilities.
- Python application on the web to monitor and issue control commands
- Ultralife 900 mAh battery with 20 months battery recharge time.
- Utilize AC power for power measurement sections
- Adjustable data-recording interval

6. Specifications

- Dimensions: 80mm x 60mm
- Battery: 1 Li-ion rechargeable battery
- Wireless range: 300m
- DC Voltage Range: 2.7 - 5 V input
- AC Voltage parameter: 110 V AC

7. Major Component Selection

Keeping the above project overview in mind and to integrate low power with our application, we propose the following modifications:

1. Monitoring of single-phase supply instead of three-phase supply. The proposed PCB would fit in a switchboard, connecting to the single-phase, two-line power supply via a power-monitoring IC which senses RMS power.
2. Change of environment from wi-fi radio in all boards, to two boards with BLE capability, communicating with a master Gateway, which will connect to the main application on Cloud via ethernet link on network co-processor.
3. No energy harvesting mechanism. An energy harvesting mechanism does not seem to fit in with our application since the PCB will be stationary and connected to a single-phase supply line. We can consider using a pickup coil, but as a backup, since using a coil would be expensive and take us to a new realm of power management.
4. Using AC-DC converter to power measurement circuit from AC supply, providing galvanic isolation of power measurement circuit from remaining components.
5. Utilizing the rechargeable feature of Li-ion battery to recharge the battery from the USB cable, making use of notification provision to warn the user in case the battery voltage level drops below 3V.

All IC supply comes from the battery. Data lines connected to the power measurement microcontroller will have optocoupler connected in between, which will serve to isolate power.
The functional block diagram has been updated to reflect all the changes.

1. Processor to be used for the low power feature - Silicon Labs Blue Gecko EFR32BG13
2. Processor to be used for Master - Silicon Labs Blue Gecko EFRBG123 + Network Coprocessor
   Processor selected due to familiarity with Simplicity Studio IDE and extensive support for energy profiling and low power modes.
3. Network Coprocessor - Ethernet PHY + MAC + TCP/IP Stack + SPI Interface - Wiznet W5500
   Network Co-processor selected because of low cost, low power SPI interface, and coexistence of ethernet PHY layer with TCP/IP stack. Only microcontrollers were found as an alternative, which would have added complexity.

4. Power measurement IC - STPM34
   Reason for selection: Single phase two-line AC power measurement with external passive components. We had an option of Microchip vs. Maxim. This chip is a lower cost and fulfill our requirements. Shunt resistor and voltage divider resistors for current and power measurement.
5. Buck converter and Battery Charger IC - LTC3550
   Reason for selection: A highly useful IC with a lot of features, allowing us to use only one Si chip for two purposes - charging the battery as well as regulating battery output and maintaining at a particular required level. An extra feature of using this IC is it handles the switching between USB supply and battery discharging due to its internal circuitry, namely a MOSFET.
6. AC-DC power supply converter - IRM-03-3.3 MeanWell's IC is an easy way to provide regulated DC power supply for powering the power measurement IC, also allowing us to maintain a distinct area on the board for isolated and non-isolated components.

Additional component selection includes:

1. Debug Interface
   We will be using a MINI connector as our programming debug interface. This is a proprietary connector from Silicon Labs where programming and debug is done through SWD(Serial Wire Debug). This connector has a reset pin that will drive reset on the Blue Gecko. This interface also provides the feature of Virtual COM port and AEM(Advance Energy Mode). Virtual COM port is useful to add print statements in firmware for debug purposes. AEM is useful to measure the actual current consumption and to verify our assumptions.
2. Test points
   For Supply
   - Buck Output 3.3 V
   - Battery Input
   - USB
   - GND

   For Blue Gecko
   - Rx, Tx, and GND for UART
   - HF XTAL and LF XTAL for clock output
   - CLK, CS, MOSI, MISO, GND for SPI

   For STPM34
   - VCC
   - GDND
   - Clock output
   - Rx and Tx for UART
3. Reset circuit description
   We will be using a Push button directly connected to the RESET pin to reset the Blue Gecko board. Reset is an active low signal on the device, pulled up to AVDD. The device has an internal power-on reset circuit. So only a push-button to drive the reset pin low

will work. The same button will also be tied to the RESET pin of Wiznet 5100. As there is no possible use case where we will have to reset only one of these devices and hence we can use a common reset signal.
We will not be having anything to reset the STPM34 because to reset it we need an expensive push button which prevents a user from the danger of working with direct AC power. Hence, it will be resetted by a power cycle.

4. Clock generation description
   Blue Gecko:
   1. High-frequency crystal 38.4MHz: This crystal is the source for high-frequency RF clock. This clock will be turned off during EM2, EM3, and EM4 low power energy modes.
   2. Low-frequency Crystal 32.768KHz: This crystal is the source for low-frequency clock which will be in operation all energy modes. Effectively, this is the only clock running during low energy mode. This will drive our LEUART(low energy UART) which keeps our communication working during low energy mode.

   Wiznet 5100:
   1. 25MHz crystal oscillator

   STPM34:
   1. 16MHz crystal oscillator
5. List of I/O Ports
   1. Power connection via USB this will be protected by ESD 1 channel bi-directional TVS diode from Ti TPD1E10B06.
   2. Power connection 110V AC input.
   3. Buttons: Push button for Reset.
   4. Ethernet RJ45 connector. This will have data line ESD protection with 4 channel TVS diode from TI TPD4E1U06DBVR .

8. Software Specifications

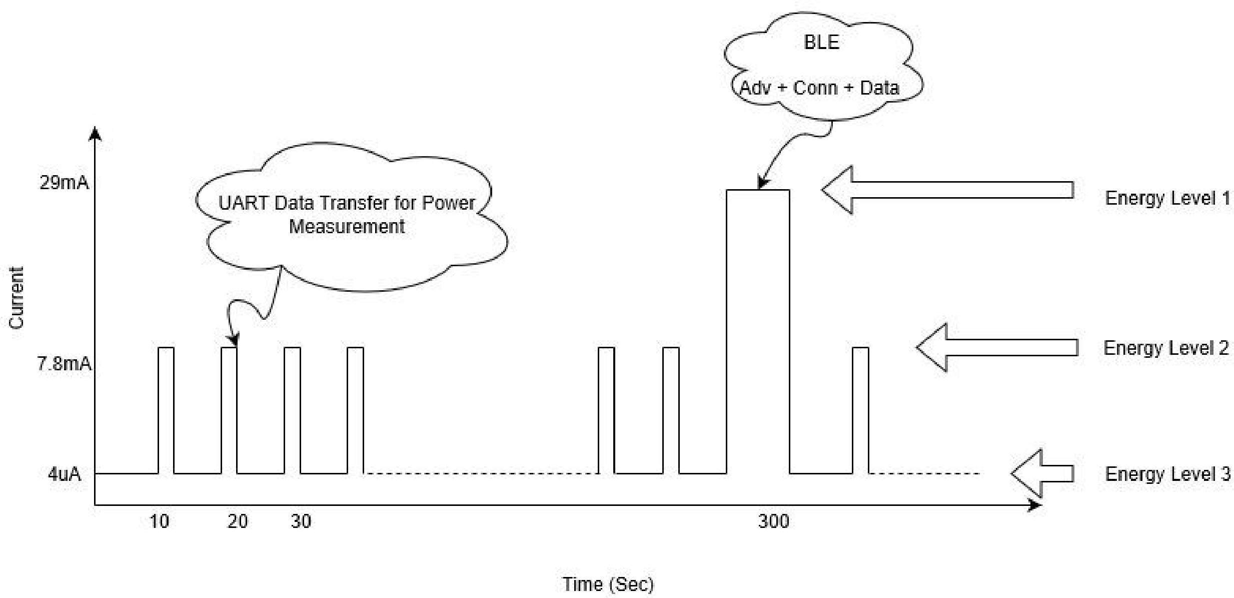
In our application, communication between Low Power Nodes and Master Gateway Node will be achieved by Bluetooth communication. Each slave device will be attached to a wall plug to measure the power, detailed in the circuit below. The power measurement IC will measure the consumed power and the measured value will be stored on the device. The power measurement will be carried out every 10 seconds. The stored data will be sent to the cloud for monitoring and ethernet will be used to send the data over the cloud. AWS cloud services will be used to achieve the same. The frequency to send data over the cloud is 5 minutes. The Gateway is a device having access to both, Bluetooth and Ethernet. It always listens for the connection from the low power nodes which wake up every 10 seconds to read the data from the power measurement circuit and every 5 minutes to send data to the server.

Power being consumed currently from the wall socket.

To present our project we plan on using the Extension Power cord strip. We will open it and add our system in between so that we can monitor the power of all loads connected on that strip.

Progress: We are using the Simplicity Studio IDE and have verified the operationality o the provided parts by running sample Bluetooth test codes. We have also verified our calculations for the maximum current peaks, as mentioned in the update above.
The evaluation boards we are using are the BRD4104A Radio Board, using the EFR32 Blue Gecko processor, mounted atop a Blue Gecko development board. We are also using a Wiznet Ethernet Network Module Board and EVALSTPM34, each interfacing with the Blue Gecko via SPI and UART respectively.

9. Use Case model



Use case diagram

We have decided on three energy modes: Energy level 3(deep sleep), Energy level 2(hibernate) and energy level 1(active), as detailed below:

- Energy level 3(Deep Sleep mode) - The low power device will be in this mode for the majority of the time. The processor has a low current consumption of around 3μA, during which the power measurement IC will be enabled low, at a current consumption value of less than 1μA. We are considering using CRYOTIMER to create a timer interrupt every 10 seconds and take sensor readings, enabling the power measurement IC high.
- Energy level 2(Hibernate Mode) - The low power device will be in this mode every 10 seconds, as it wakes up and takes a reading. The current consumption for the processor in this mode is around 3.3μA. The power measurement IC itself would consume around 4.3 mA for taking a reading, and communication between the two

over UART would cost 3.5mA. We intend to keep the device in this mode for less than 2 ms.

- Energy level 1(Active mode) - The device will be in this mode only while transmitting power-measured data to the master node. This stage will appear once every 5 minutes. Considering a maximum transmission power, the average current in this mode will be around 24mA for a time period of 600ms. The processor itself has a current consumption of around 4.7mA, with an instantaneous spike of over 20mA at the time of connection establishment.

a. Use case peak current - 80 mA
b. Use case recharge time requirement - 20 months.
   The battery has a 10% discharge rate per month.
c. Was a constant current or constant power model will be used if a Super Capacitor?
   For the moment, we are not planning to use a Super Capacitor.

The energy modes and calculations listed above are all for the low-powered slave device. In the case of the master device, there will be some slight changes, as the master board does not feature a power measurement IC. Instead, it has an ethernet network processor, with a maximum current consumption of 183mA. We have factored this consumption in while selecting our bulk capacitance value.
The same limitations of battery recharge time do not apply to the master board, as the battery serves only as a backup in case of power outages. For all other intents and purposes, the master board will be powered from the AC power supply via the AC-DC converter (IRM-03-5).

Verification of Use Case models:

We have begun to play around with the Blue Gecko module, and have managed to validate use case current for the modes involving Bluetooth radio. We want to verify that the average current does not exceed 30mA for 600 ms.

Maximum peak current during bluetooth advertising = 28 mA; Duration of peak = 10ms
Maximum peak current during connection pings = 15 mA; Duration of peak = 2.5 ms
Maximum peak current during transmission = 24 mA; Duration of peak = 5 ms

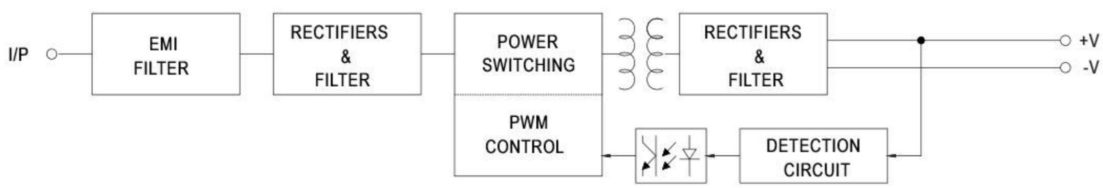
For a single connection event, we observed a wide range of advertisements. On average, we could consider 15 advertisements for connection to establish.
To maintain a connection for 5 minutes, we considered a connection interval of 4 seconds, and slave latency of 32 seconds, implying a connection ping every 32 seconds.
In 5 minutes, that comes to 10 pings, each with the timing of 2.5 ms, equalling 25 ms.
For a period of 5 minutes, transmission occurs once, implying 5 ms and 24 mA.
This comes to an average of:

Average current = Total current / Total time taken
= [(28*10*15) + (15*10*2.5) + (5*24)]/(150 + 25 + 5)
= 26mA,

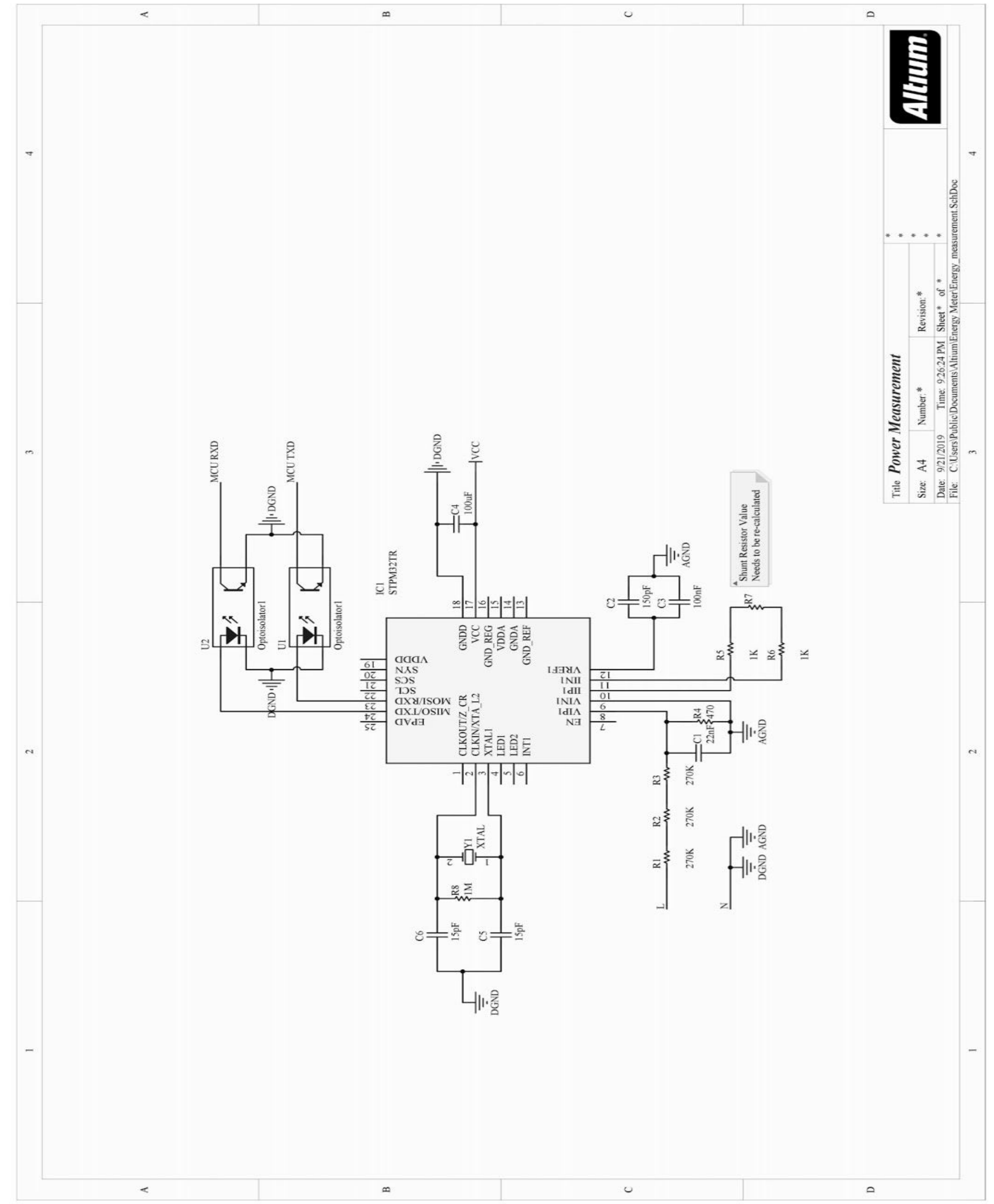
Which is less than our original assumption of 30mA.

10. Power Measurement (Sensor)

Power Measurement is done through ST microelectronics' mixed-signal metering IC. This IC has a UART interface. We will use a 9600 baud rate because at this rate we can use the low power UART peripheral on Blue Gecko. This IC requires voltage and current measurements. Voltage measurement will be implemented using voltage divider of ratio around 1:1800. Current measurement can be done through the Current transformer or shunt resistor. We will be using shunt resistor for current measurement whose value will be such that the ratio of current to voltage is 0.3. IC had two internal Signal Delta ADC which will convert both the voltage measurement from resistor divider for line voltage and from shunt resistor for line current and calculate power along with its reactive components. These values are stored in specific registers which can be accessed via UART by Blue Gecko. UART lines will have optocoupler in between to isolate power between AC & DC. The schematic for this design is attached below.



Isolation for IRM-03-3.3


Power Measurement
Size: A4
Number: *
Revision: *
Date: 9/21/2019
Time: 9:26:24 PM
Sheet * of *
File: C:\Users\Public\Documents\Altium\Energy Meter\Energy_measurement.SchDoc
IC1
STPM32TR
MCU RXD
MCU TXD
Optoisolator1
Shunt Resistor Value
Needs to be re-calculated
DGND
AGND
VCC

11. Battery Selection Engineering

Current in EM1: 4.7mA(±10%) + 20mA(instantaneous) + 24mA(average transmission current)

Current in EM2: 4.3mA [power measurement IC](±10%) + 3.5mA(Communication over UART)(±10%) + 3.3μA(processor's current consumption)

Current in EM3: 3μA + 1μA

Average current over a period of 1 hour =

[{ (24+4.7) * 600ms * (12 times in 1 hour) } +
{ (4.3+3.5+0.0033) * 1.67ms * (360 times in 1 hour) } +
{ (0.004) * 3600 seconds }] / 3600
= (206.640 + 4.691 + 14.4) / 3600
= 0.0627 mAh

We have selected a **rechargeable Li-ion battery** with a capacity of 900mAh and a nominal output voltage of 3.7V. The average DC current as calculated above is 0.0627mA in 1 hour. Based on that value and battery capacity we have device life of 599 days ~ 20 months.
As of now, we are not using energy harvesting for recharging the battery, but a USB rechargeable IC to recharge the battery.

Engineering of Battery Solution:

1. What is the C-rate of the specified battery?
   C-rate of specified battery is (discharge current/battery capacity)
   = (0.0627mA/900mAh)
   = 0.00006967
   = 0.0696 mC

2. Peak discharge rate out of the battery
   Peak discharge rate of battery = 1C = 900mA in 1 hour

3. The lowest nominal voltage out of battery is 3V. Accordingly, we have designed the battery cut-off voltage of the circuit also as 3V.

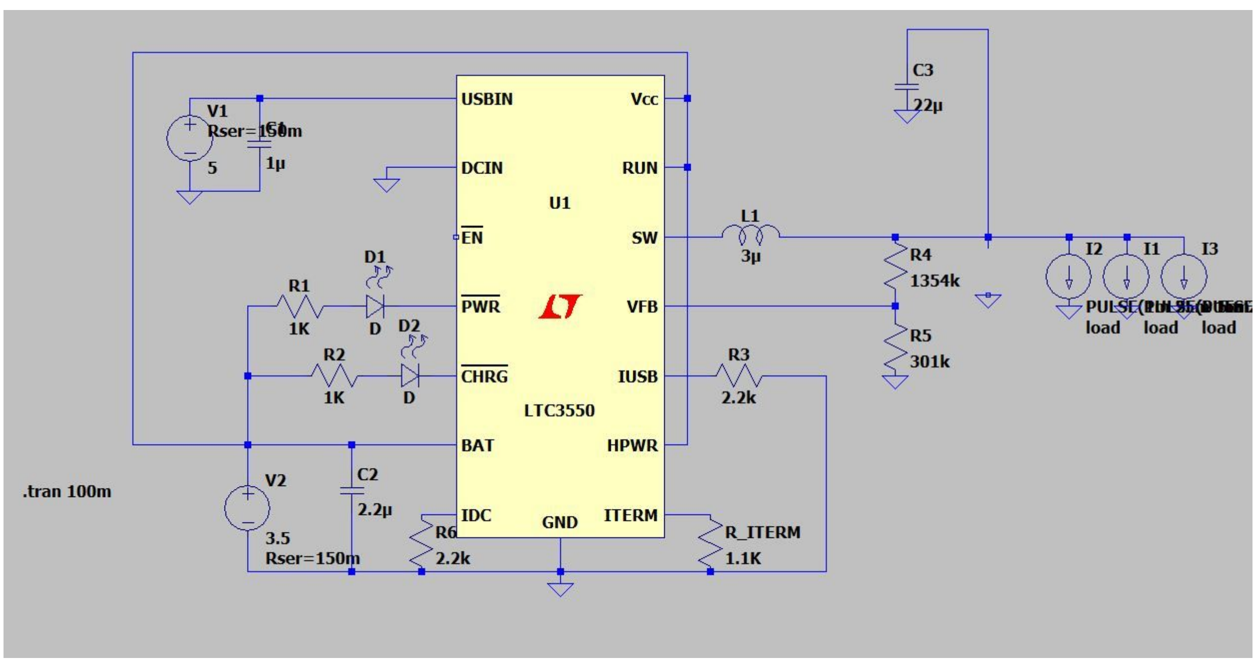
4. This nominal voltage requires a buck solution, as specified in the Power Management section above.

5. The voltage that will be programmed as the cut-off voltage from the battery of the PMU circuit is 3V.

12. Power Management

We have used AC supply to power part of our circuit, namely the power measurement circuit. An AC-DC converter brings supply 110V AC down to either 3.3V or 5V, as per user choice and requirement. This regulated DC voltage is used to supply the power measurement circuit. The UART interface of the power measurement circuit, connected to the Blue Gecko's GPIO, provides isolation by using an optocoupler in between.
We are also using a battery recharging IC, LTC3550, to recharge the battery via USB. We cannot use the AC supply to do so since the whole point of isolation would be lost in that case.

All ICs in our design operates at **3.3V Vcc**. So we have an input voltage range of 3.7V - 3.3V. Output current requirement as mentioned above with safety margin is taken at 0.2A. With this Input and output specification, we generated a power management circuit using the TI Webench tool. From the suggested designs, we choose the one with part number **LTC3550**. This is a buck DC-DC converter. We require a buck converter so that we can maintain 3.3V output, as long as the battery is supplying above 3.3V. Once the battery voltage drops below this level, we expect our recharging circuit to kick in. This helps in extracting maximum capacity from the battery. This device also provides a programmable output voltage using external resistor divider. This gives us the room to maneuver and also fix the part number. Also, this design is relatively simple in terms of components as only a bypass capacitor for input, output and external resistor bridge to program the output voltage is required.



Power management circuit

The diagram above has been referred from the device datasheet and is a generic use-case application model. The actual resistance and inductance values have been calculated and represented in the bulk capacitor update section.

<u>Minimum max voltage of the ICs</u>
Silicon Labs - EFR32BG13 - 3.8V
WIznet 5100 - 3.6V
ST PM34TR - 3.6V

<u>Maximum min voltage of the ICs</u>
Silicon Labs EFR32BG13 - 1.8V
Wiznet 5100 - 3V
ST PM34TR - 2.95V

<u>Planned range of the unregulated voltage</u>
All of these ICs are having a regulated power supply and hence we are not planning to use an unregulated power supply.

<u>The fixed voltage of Digital/Analog portion</u>
Yes; 3.3V Vcc as mentioned above.

<u>Bulk Capacitance Selection and Calculation</u>
We have considered a worst-case simulation of battery voltage dipping to 3.5V, with charging circuit disabled and peak current requirement of 300mA, which is extremely unlikely.
We arrived at the 300mA requirement by considering all the worst-case current consumption of each energy mode, combined, which is very unlikely, as the math actually reflects a worst-case current consumption of less than 250mA.

We have chosen a bulk capacitance value of 22uF, with an input capacitance of 1uF.
Part numbers are
According to the datasheet, the relation between the input voltage and bulk capacitance is given by:

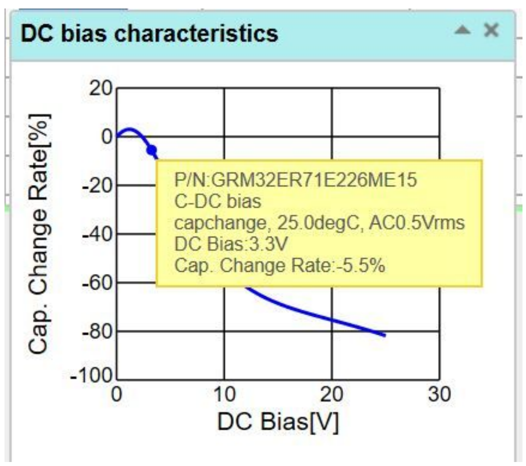
$$C_{IN} \text{ required } I_{RMS} \cong I_{OMAX} \frac{\sqrt{V_{OUT}(V_{CC} - V_{OUT})}}{V_{CC}} \quad (2)$$

According to the datasheet, the relation between the output voltage and bulk capacitance is given by:

$$\Delta V_{OUT} \cong \Delta I_L \left(ESR + \frac{1}{8fC_{OUT}} \right)$$

We have considered a voltage swing of 0.2V. Our required output voltage is 3.3V, and the maximum cutoff voltage for our ICs is given by Wiznet W5100, like 3V. For a safety margin, we have considered 3.1V.
Switching frequency = 1.5MHz
The value of delta load current came as 0.6mA for a pulse current of 300mA.
Factoring all these values in, we get an output capacitance of 20uF and an input capacitance of 1uF. For these parts, ESR = .00456728 ohm.

We have selected a chip monolithic ceramic capacitor, GRM32ER71E226ME15 from Murata.
Its specifications are 22μF ±20%, 25V, Ceramic Capacitor, X7R, 1210 (3225 Metric).

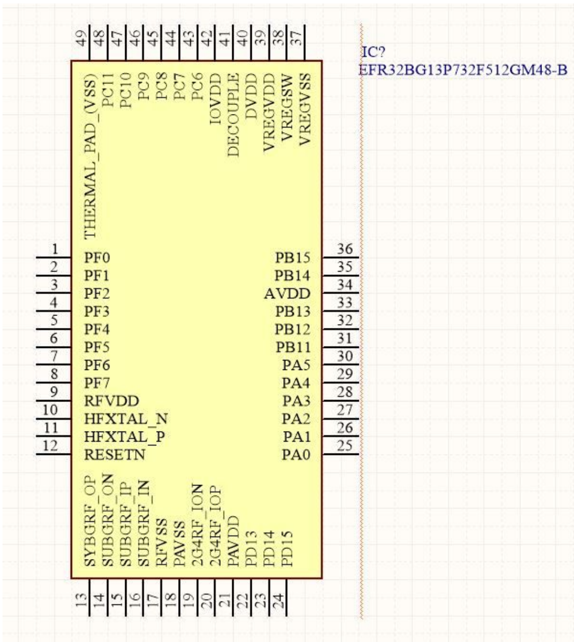


According to the image above, it has a capacitance of 20.79uF at DC bias voltage of 3.3V, which is exactly the capacitance required by our buck circuit to maintain voltage at 3.3V, with a very slight dip of 12mV for worst-case current requirement of 80mA, on the slave device.
On the master device, the maximum current is 300mA being drawn by the ethernet processor. In this case, the circuit allows a dip of 400mV, which still leads to an output voltage of 3.1mV, which is sufficient to drive all our ICs.
We have selected a capacitance with such a large value since we wanted to keep parts common across the master and slave boards.

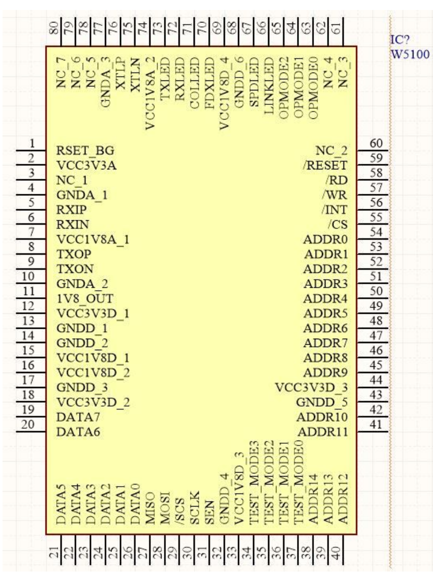
13. Altium Schematic Symbols for Major Components

All our main IC including Processor, Ethernet, Metering IC, and power management IC is available for Altium Designer.

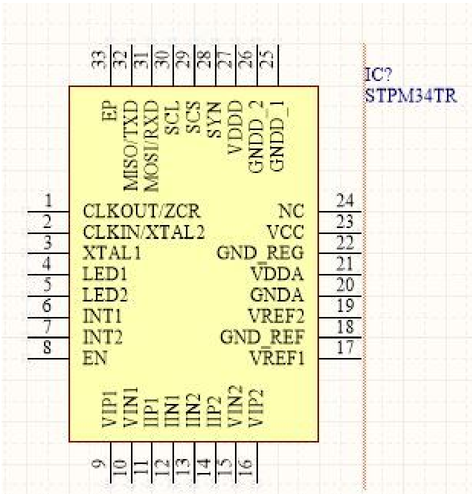
1. EFR32BG13 Blue Gecko



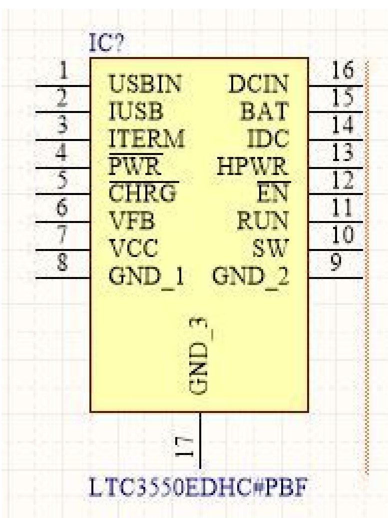
2. Wiznet W5100 Network Coprocessor



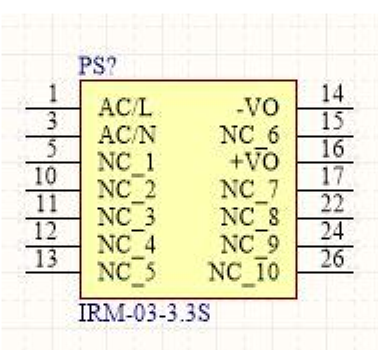
3. STPM34 Power measurement IC



4. LTC3550 buck converter



5. IRM-03-3.3



Timing Information on Communication Bus:

We are utilizing two communication buses, SPI for ethernet coprocessor, W5100, and UART for STPM32(power measurement IC).

In case of W5100, it is the worst-case device as it takes more time for setup and holds over SPI, given below as according to the device datasheet:

Description	Minimum delay	Maximum delay
Input setup time	7 ns	-
Input hold time	28 ns	-
Output setup time	7 ns	14 ns
Output hold time	21 ns	-

The worst-case time for STPM34 depends on the UART bus itself, and the baud rate we decide to use. By default, the power measurement IC has a baud rate of 9600 and is supported by the LEUART mode of EFR32. As per datasheet of metering IC, the max data packet in one transaction is 5 bytes, giving a transmission time of roughly 5 ms.