CHARIoT: A Wireless, Self-Powered Sensing Node

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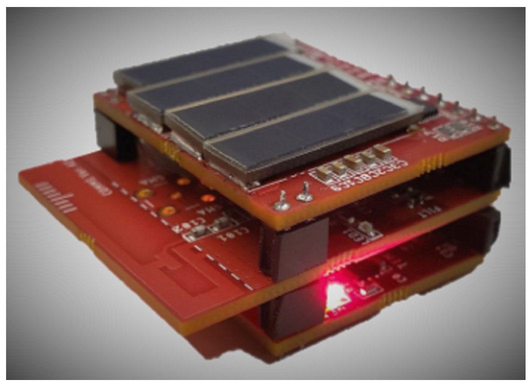


“We are as innovative as we are stupid.”

Project Motivation

- Increasing **demand for IoT devices**, but **no generic platform exists**
- Prior work and new technology:
  - "Smart dust" project at Berkeley in 2001
    - "Autonomous sensing and communication in a cubic millimeter"
    - At the time, Berkeley didn't have the capabilities
  - System-In-Package (SiP) technology
    - Can combine and shrink down entire systems

- Our task was to create **a generalized hardware and software architecture** which could ultimately become a SiP
  - Self-powered
  - Wireless
  - Versatile sensing

Design Priorities

1) **Power:** self-powered
2) **Size:** down-scalable to a SiP
3) **Range:** application flexibility
4) **Cost:** affordable for individual prototypers

Application Priorities

1) **Modularity:** distinct subsystems for power, sensing/processing, and communications
2) **Flexibility:** versatile sensor & communications support

Design Process

- Determined customer needs
- Picked the best components based on these goals
- Prototype #1
  - Bought evaluation modules for key components
  - Wrote unit test code
  - Measured power harvesting/consumption
  - Wired components together to verify system functionality
- Prototype #2
  - Created a PCB design with lots of testing functionality (debug LEDs, test points, extra signals routed out to headers, etc.)
  - Integrated new communications chip (to enable node-node connections)
- Prototype #3 (final)
  - Slimmed the design to a smaller form factor & removed extra stuff
  - Different solar cells
  - Integrated a new sensor (accelerometer)

Components

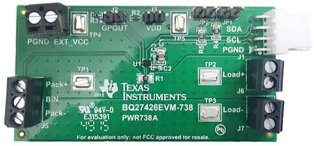
MSP430FR5994

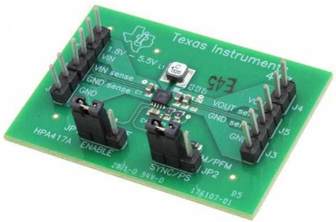
- **Clock**: 32 kHz - 16 MHz
- **Memory**: 256 KB FRAM (non-volatile), 8 KB SRAM
- **Voltage**: 1.8-3.6 V supply voltage
- **Current**: Active mode: 118 µA/MHz **LPM3: 500 nA**
- **Computational Flexibility**:
  - Low energy vector math accelerator (independent of CPU)
  - 32-bit hardware multiplier
- **Peripherals**:
  - 6 timers
  - 12-bit ADC with 20 input channels
  - 4 USCI_A (UART, SPI), 4 USCI_B (I2C, SPI)
  - 68 I/O (80-pin package)
  - AES coprocessor, random number seed

- ✔ Low power
- ✔ Non-volatile memory
- ✔ Flexible
- ✔ Accessible

Solar Power System

- 5 components:
  - BQ25570EVM- Energy Harvesting IC
  - BQ27426EVM- Fuel Gauge IC
  - TPS63031EVM- Buck-Boost Converter
  - RJD2430C1- Li-Ion Battery
  - SLMD121H04L-ND- Solar Cell





Solar Charging Results

Charging Conditions	Charging Rate	Power
Sunny	200-600 mV/hr	34 mW
Cloudy	50 mV/hr	9 mW
Shade	80 mV/hr	15 mW
Cloudy + Shade	10 mV/hr	<2 mW
Indoor	250 mV/hr	15 mW

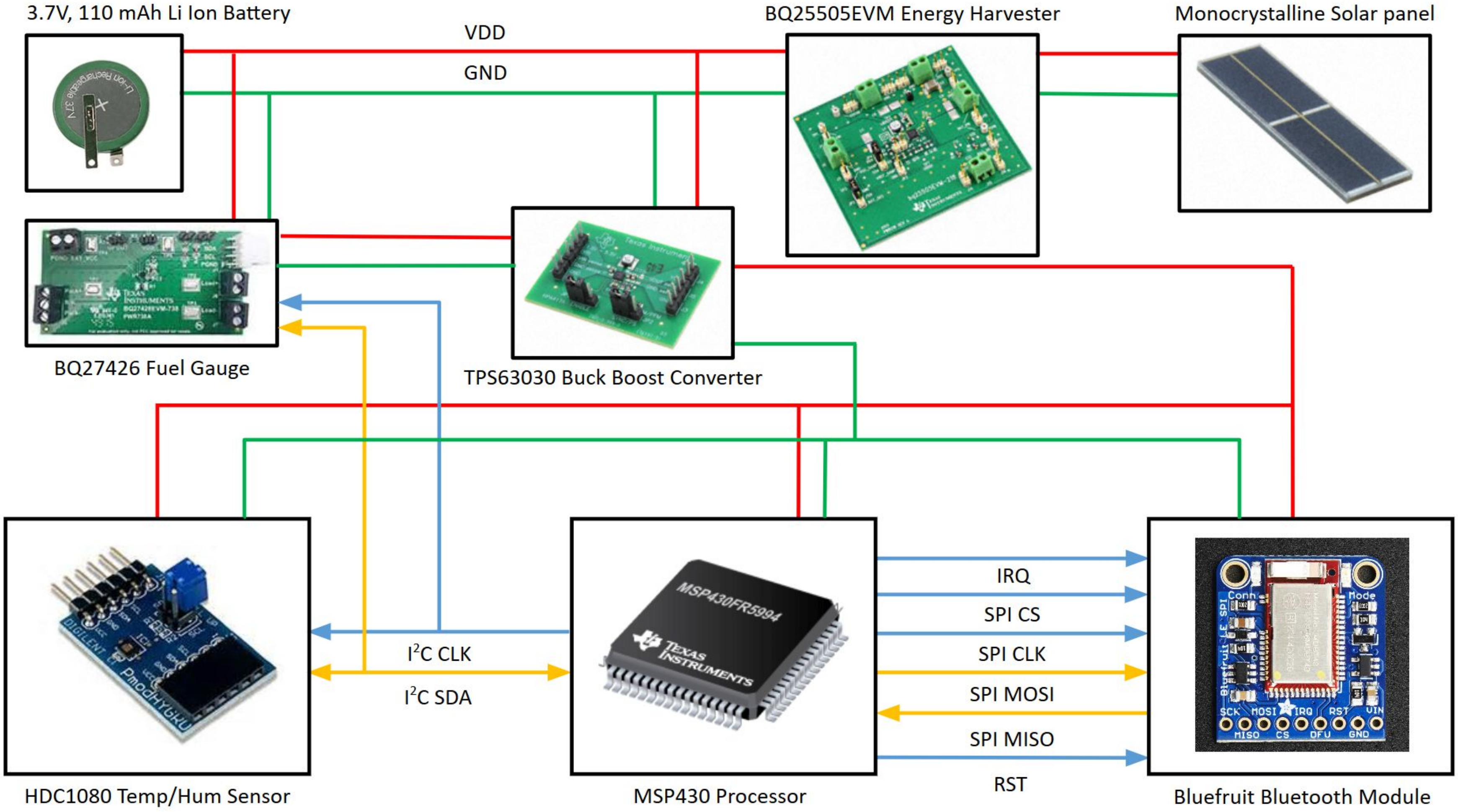
Communications

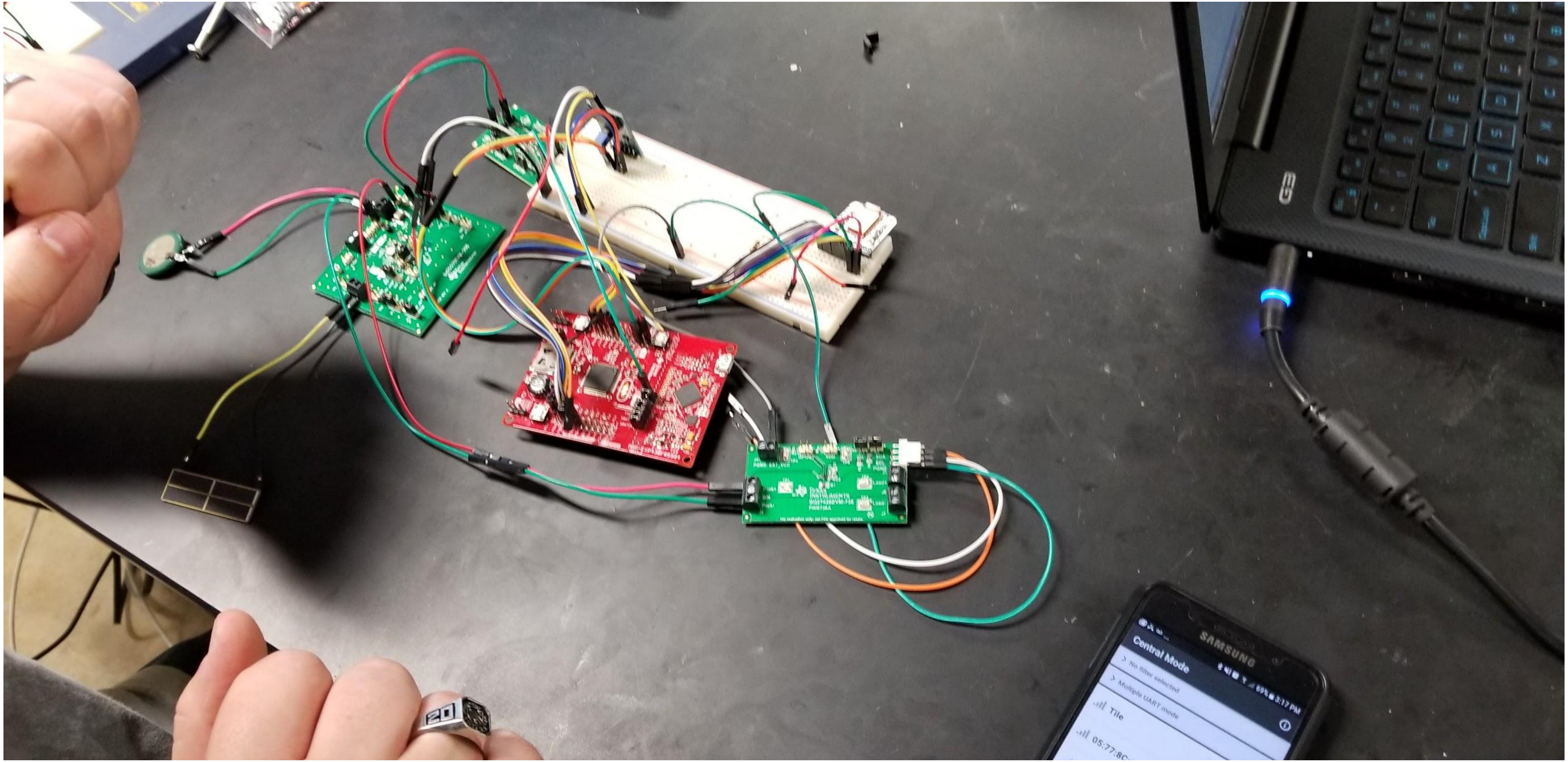
- Bluetooth Low Energy (BLE)
  - Lower Power
  - Lower Range
  - Higher Frequency
  - Smaller size
- LoRa
  - Higher power
  - Higher range
  - Lower frequency
  - Larger size

HDC1080 Temperature & Humidity Sensor

- Benefits:
  - TI Product so we can get bare-die in the future
  - Small form factor (3mm x 3mm)
  - Low power (peak 3.21 µA @ 1 Hz, 2.7-5.5 V supply)
  - **I^2C communication**
  - ±0.2°C accuracy, 14-bit resolution
  - **Easily verifiable data**
- Drawbacks:
  - None

Prototype #1


3.7V, 110 mAh Li Ion Battery
VDD
GND
BQ25505EVM Energy Harvester
Monocrystalline Solar panel
BQ27426 Fuel Gauge
TPS63030 Buck Boost Converter
IRQ
SPI CS
SPI CLK
SPI MOSI
SPI MISO
RST
I2C CLK
I2C SDA
HDC1080 Temp/Hum Sensor
MSP430 Processor
Bluefruit Bluetooth Module


SAMSUNG
Central Mode
No filter selected
Multiple UART mode
Tile

Verification

Voltage Temperature Humidity

0D DC 62 B8 8A C8

1101 1101 1100 1100 0101 0111 000 1000 1010 1100 1000

3548 25272 35528

3548 mV 23.6°C 54.2%RH

$$Temperature\ (°C) = \frac{Temperature\ [15:00]}{2^{16}} * 165°C - 40°C$$

$$Relative\ Humidity\ (\%RH) = \frac{Humidity\ Register\ [15:0]}{2^{16}} * 100\%RH$$

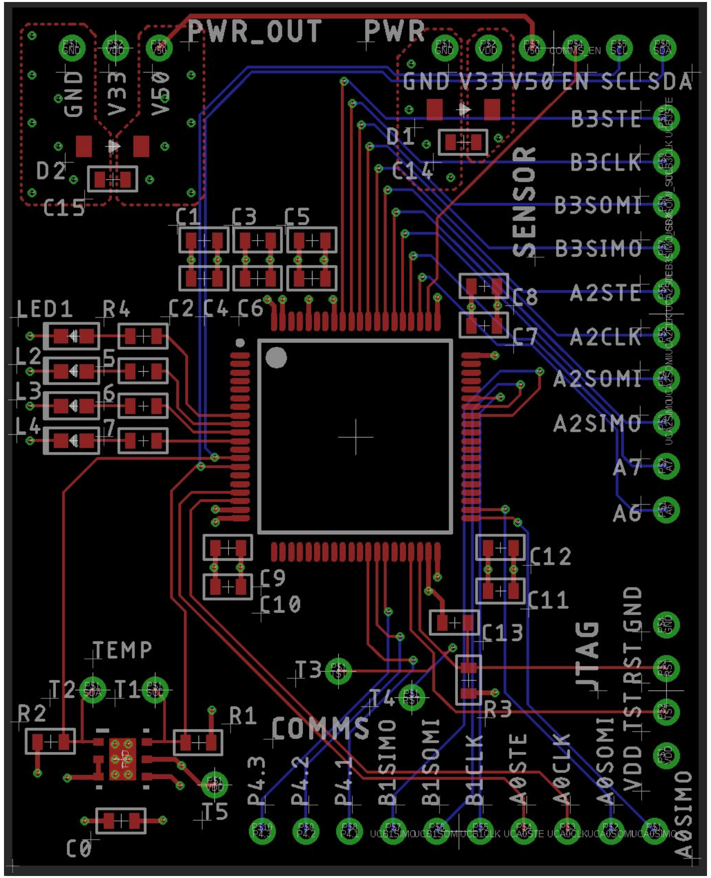
From TI HDC1080 datasheet

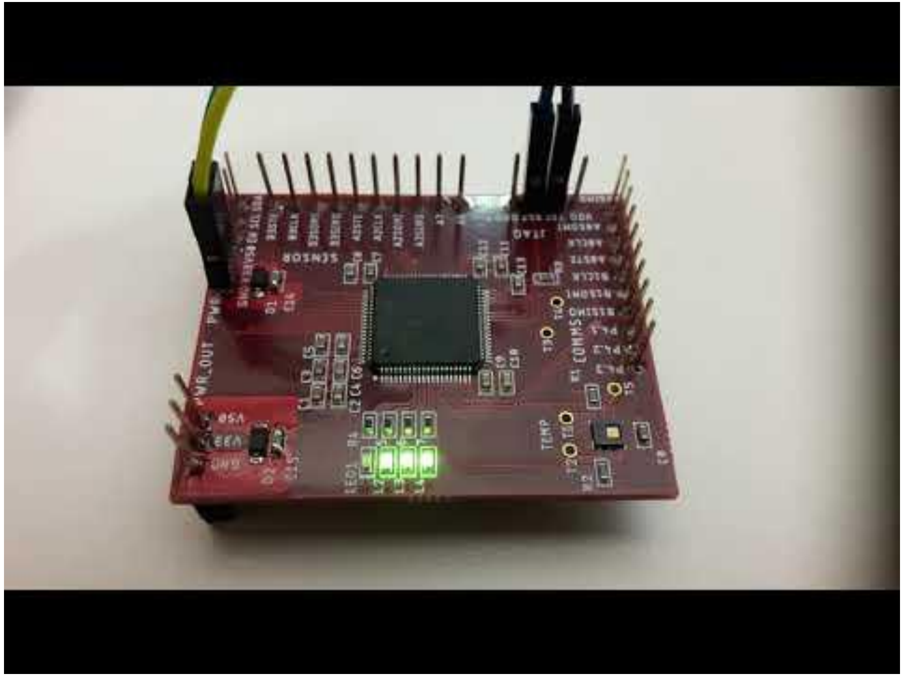
Software

- (Mostly) Independent modules:
  - I^2C Module: Communication for both the sensor and the fuel gauge
  - FRAM Module: Stores data to persistent storage
  - Sensor Module: Gathers data from the sensor
  - Fuel Gauge Module: Polls the fuel gauge to get the current battery state
  - Bluefruit Module: Transmits data through the Bluefruit module
- Application control:
  - A main while() loop passes data between modules and handles scheduling the sense and transmit times

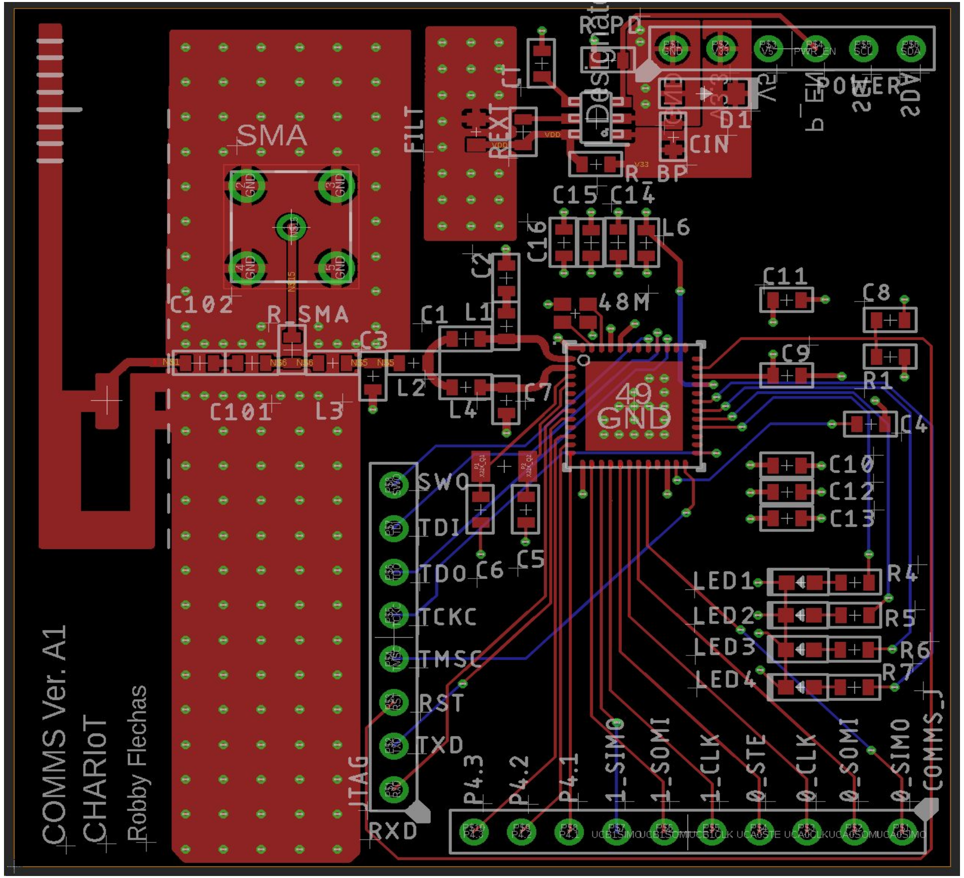
Prototype #2

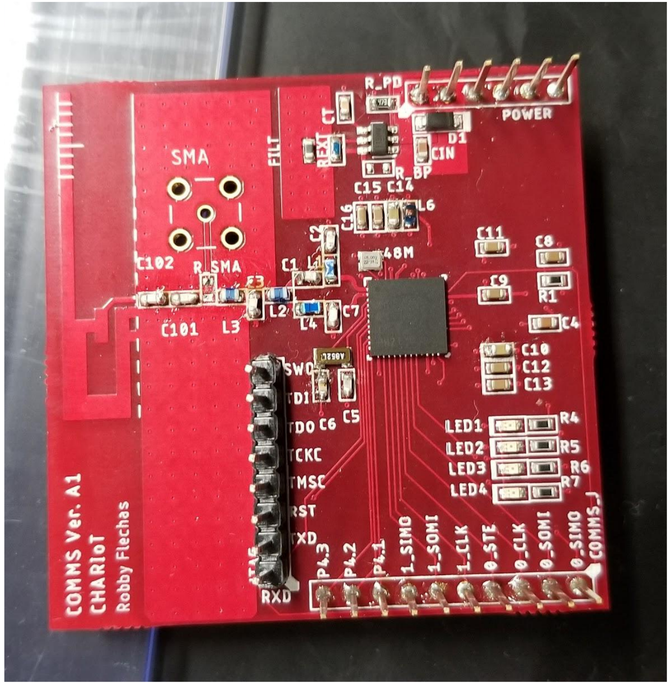
Processor Board Ver. A1



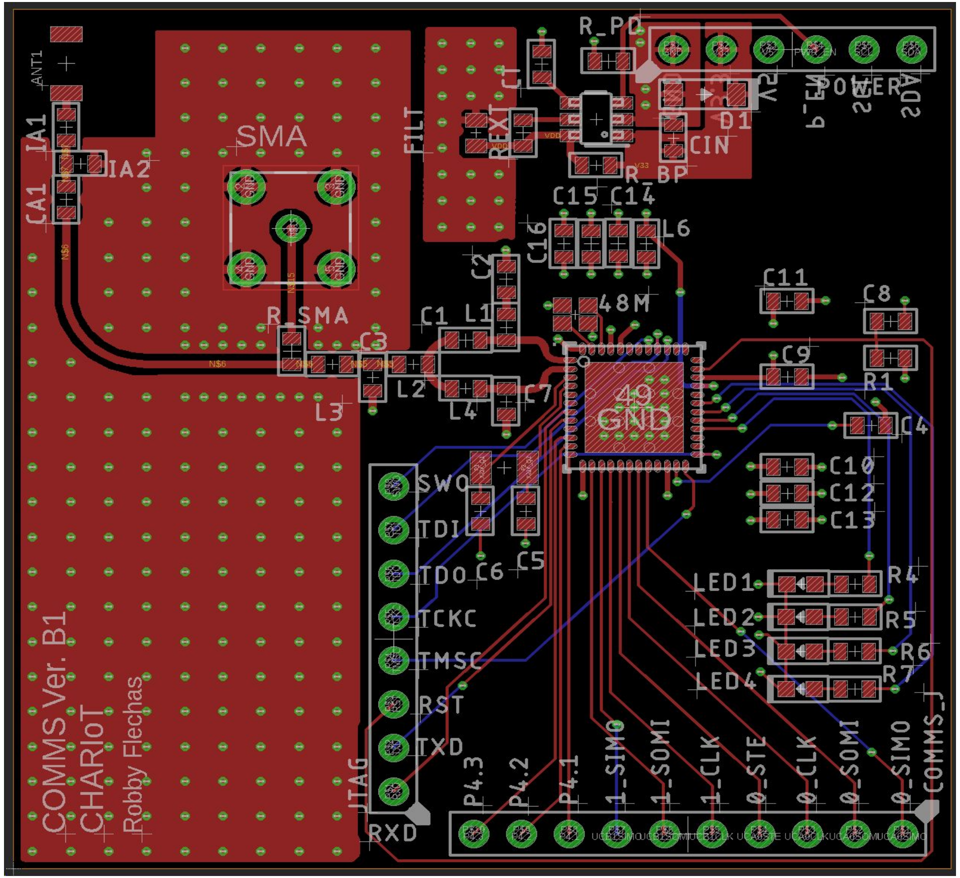


Comms Board Ver. A1 (trace antenna)

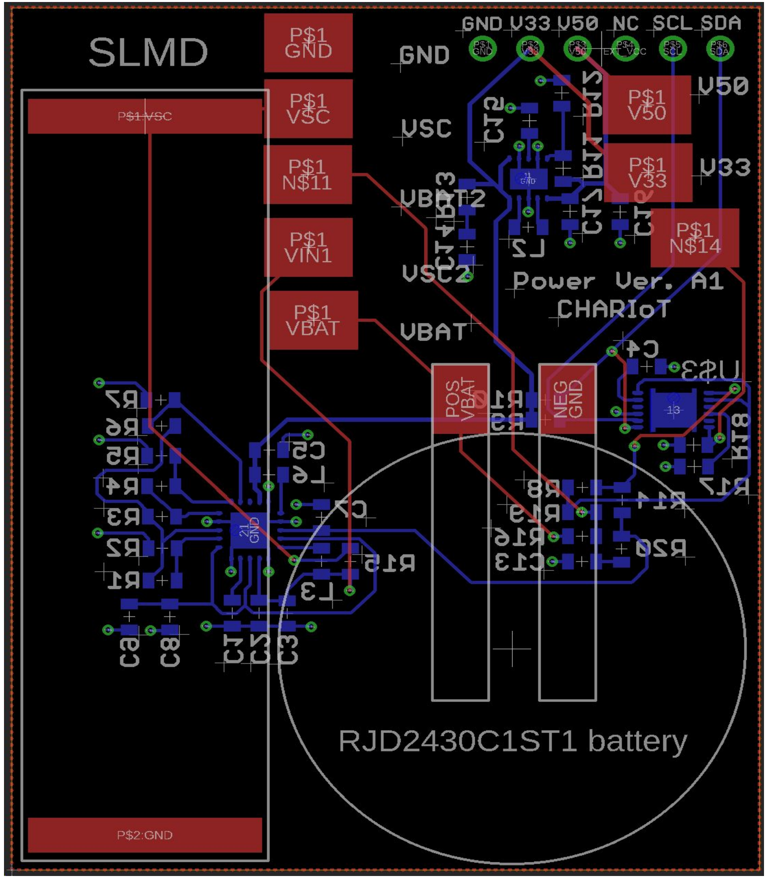




Comms Board Ver. B1 (ceramic antenna)

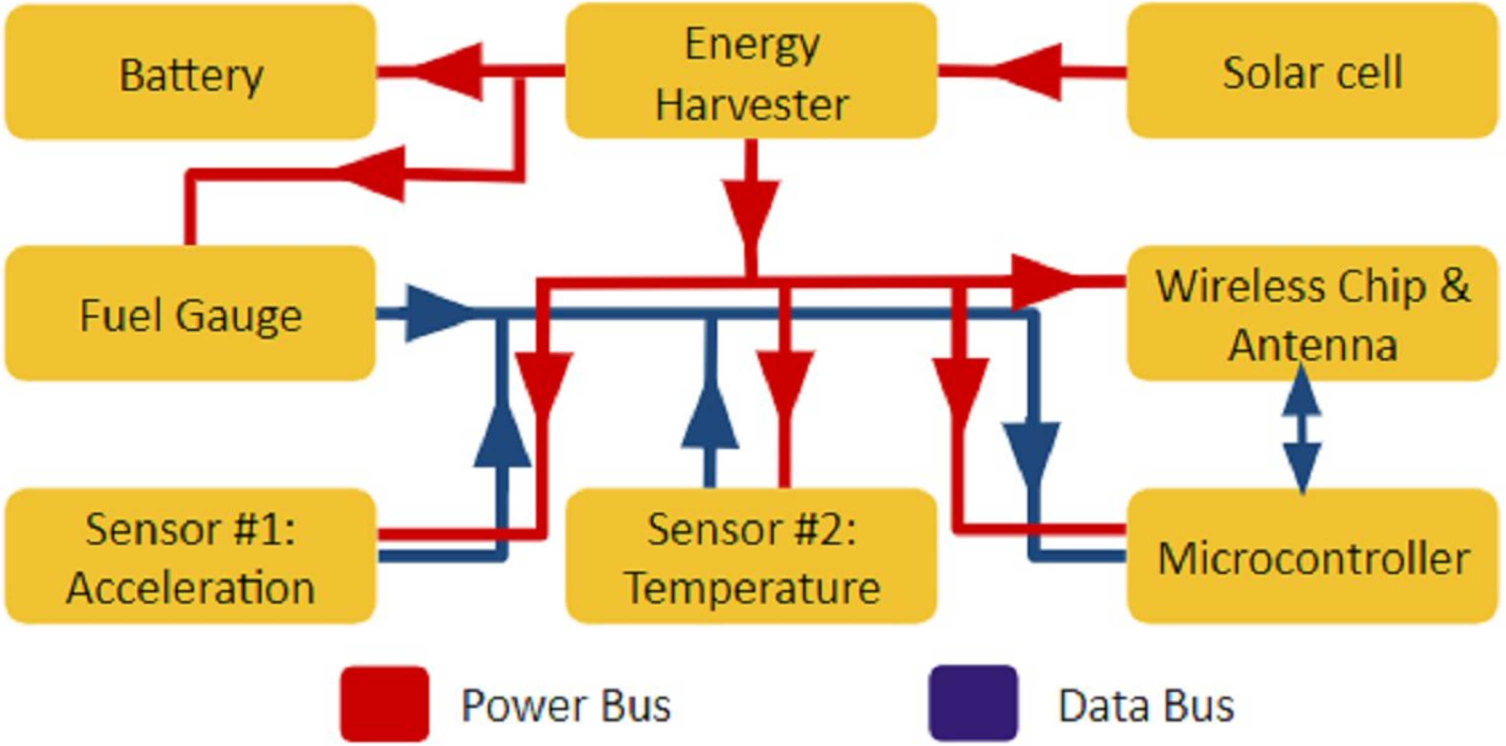


Power Board Ver. A1

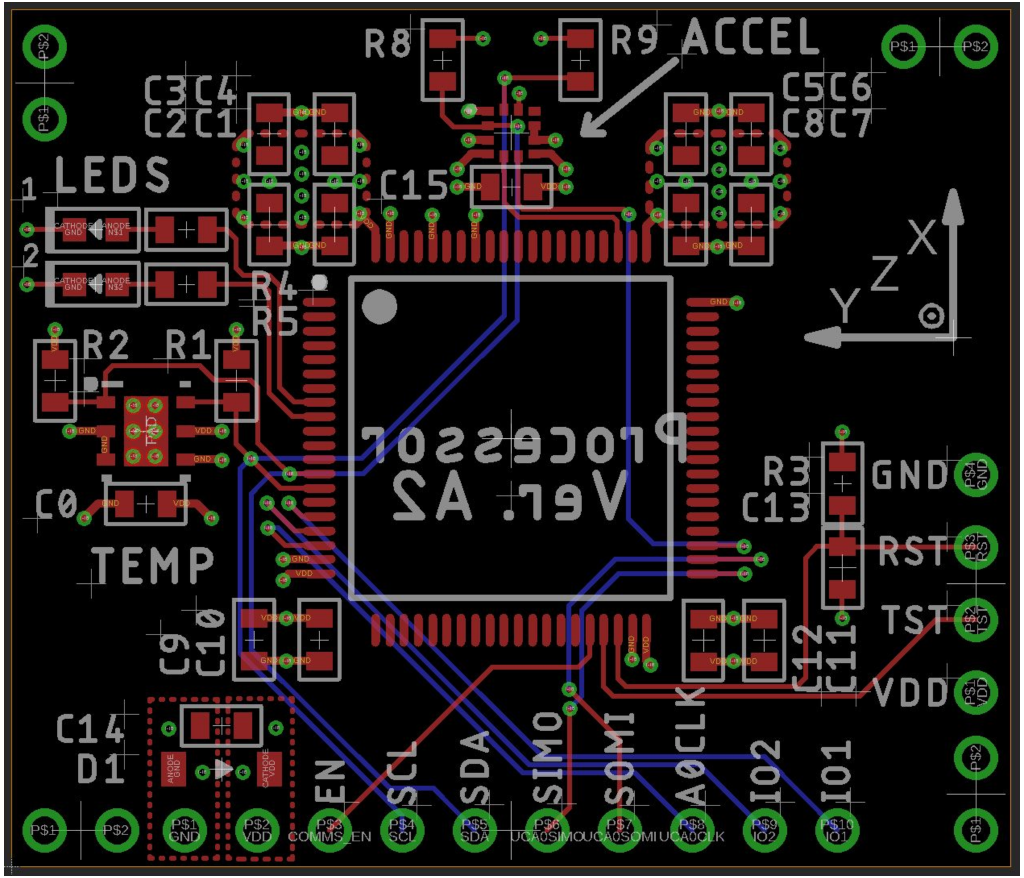


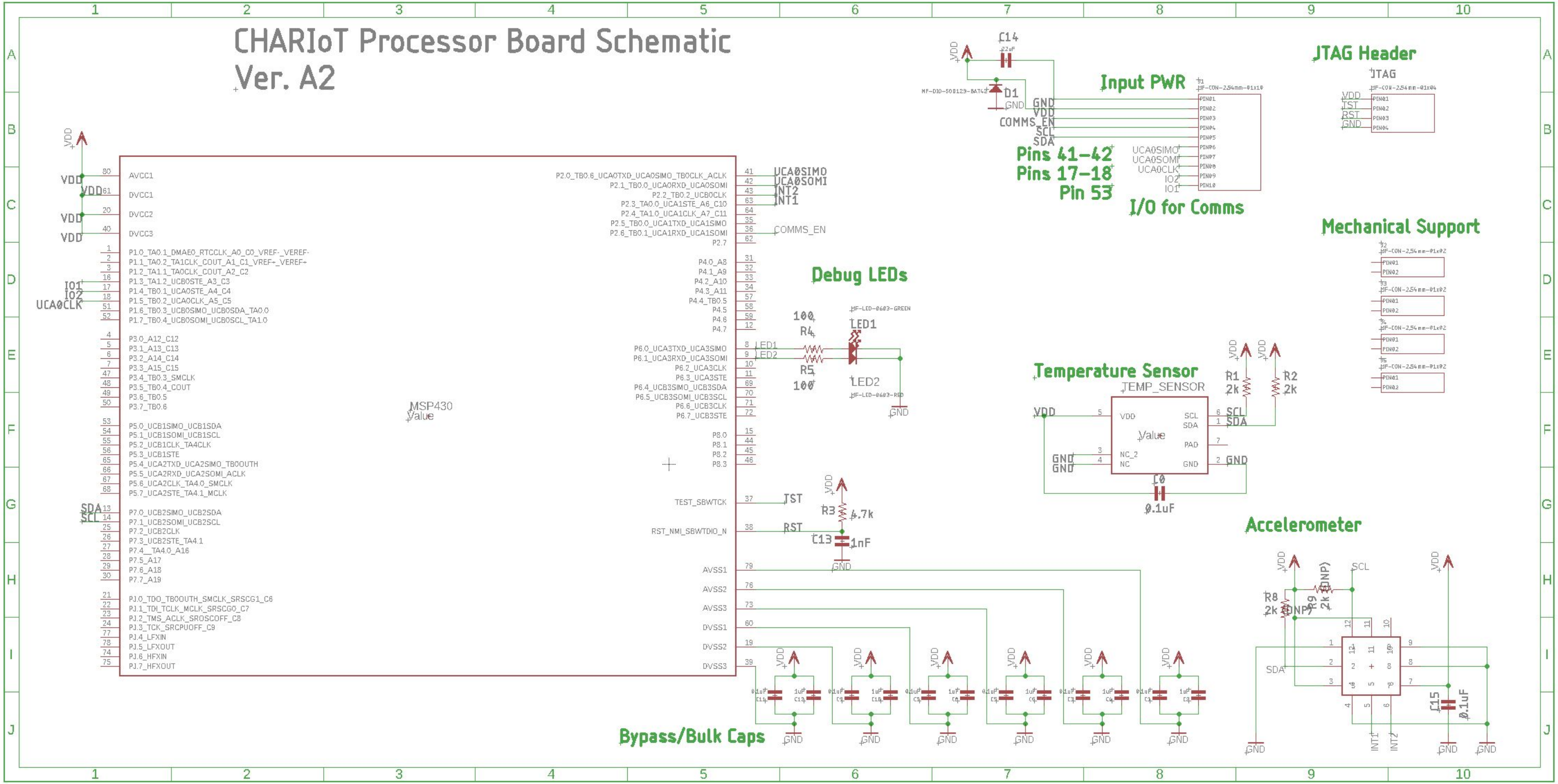
Prototype #3 (final)

System Diagram



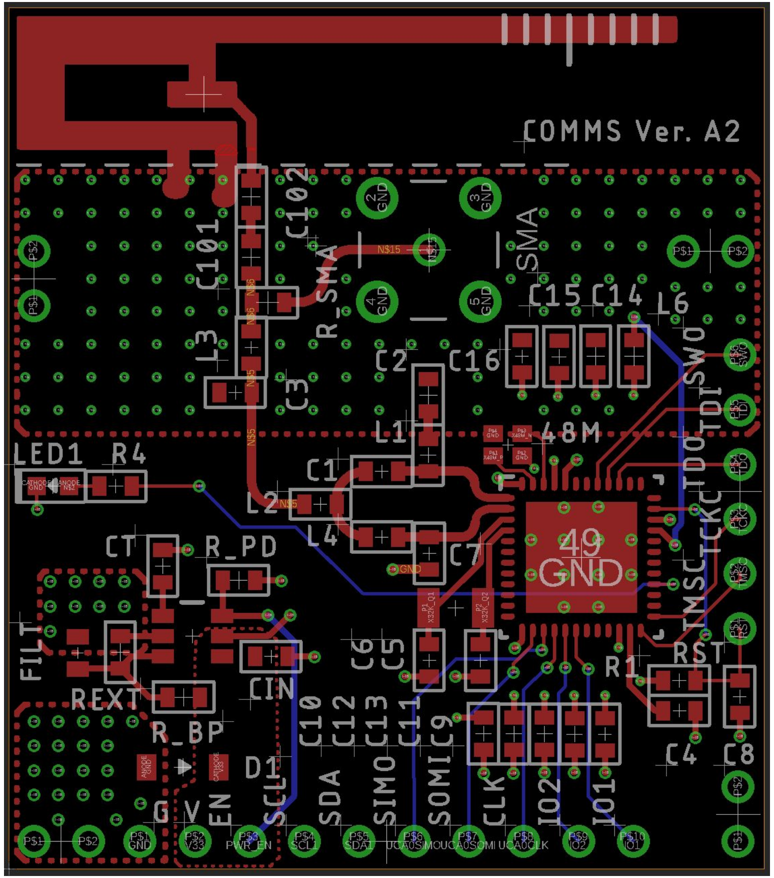
Processor Board Ver. A2

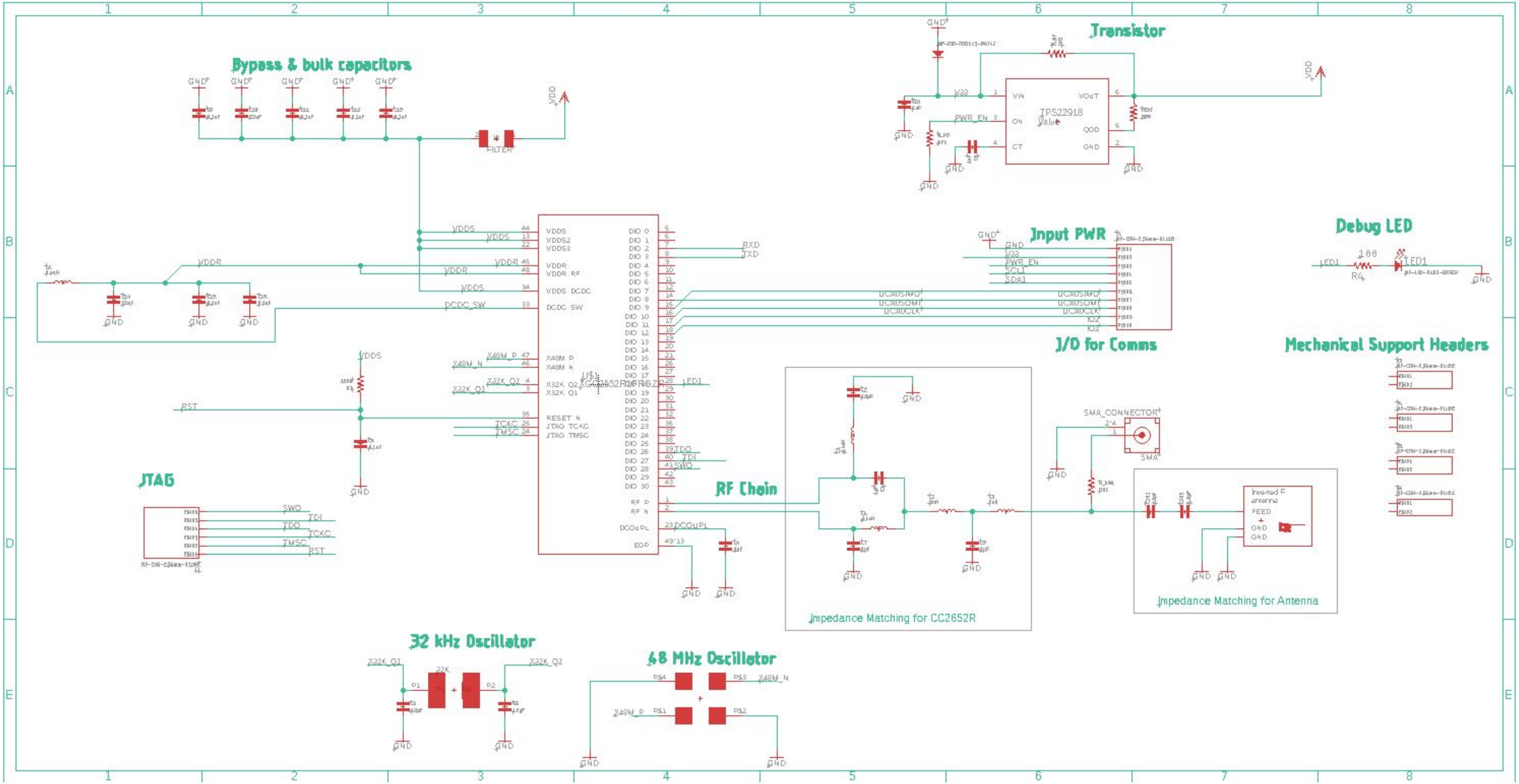




CHARIoT Processor Board Schematic
Ver. A2
Input PWR
GND
VDD
COMMS_EN
SCL
SDA
Pins 41-42
Pins 17-18
Pin 53
UCA0SIMO
UCA0SOMI
UCA0CLK
IO2
IO1
I/O for Comms
C14
D1
JTAG Header
JTAG
VDD
TST
RST
GND
Mechanical Support
Debug LEDs
100
R4
R5
100
LED1
LED2
LED1
LED2
Temperature Sensor
TEMP_SENSOR
VDD
SCL
SDA
PAD
NC_2
NC
GND
Value
C0
0.1uF
R1
2k
R2
2k
MSP430
Value
AVCC1
DVCC1
DVCC2
DVCC3
P1.0_TA0.1_DMAE0_RTCCLK_A0_C0_VREF-_VEREF-
P1.1_TA0.2_TA1CLK_COUT_A1_C1_VREF+_VEREF+
P1.2_TA1.1_TA0CLK_COUT_A2_C2
P1.3_TA1.2_UCB0STE_A3_C3
P1.4_TB0.1_UCA0STE_A4_C4
P1.5_TB0.2_UCA0CLK_A5_C5
P1.6_TB0.3_UCB0SIMO_UCB0SDA_TA0.0
P1.7_TB0.4_UCB0SOMI_UCB0SCL_TA1.0
P2.0_TB0.6_UCA0TXD_UCA0SIMO_TB0CLK_ACLK
P2.1_TB0.0_UCA0RXD_UCA0SOMI
P2.2_TB0.2_UCB0CLK
P2.3_TA0.0_UCA1STE_A6_C10
P2.4_TA1.0_UCA1CLK_A7_C11
P2.5_TB0.0_UCA1TXD_UCA1SIMO
P2.6_TB0.1_UCA1RXD_UCA1SOMI
P2.7
UCA0SIMO
UCA0SOMI
INT2
INT1
COMMS_EN
TEST_SBWTCK
RST_NMI_SBWTDIO_N
TST
RST
R3
4.7k
C13
1nF
AVSS1
AVSS2
AVSS3
DVSS1
DVSS2
DVSS3
Bypass/Bulk Caps
Accelerometer
R8
2k (DNP)
R9
2k (DNP)
SCL
SDA
C15
0.1uF
INT1
INT2
GND
VDD

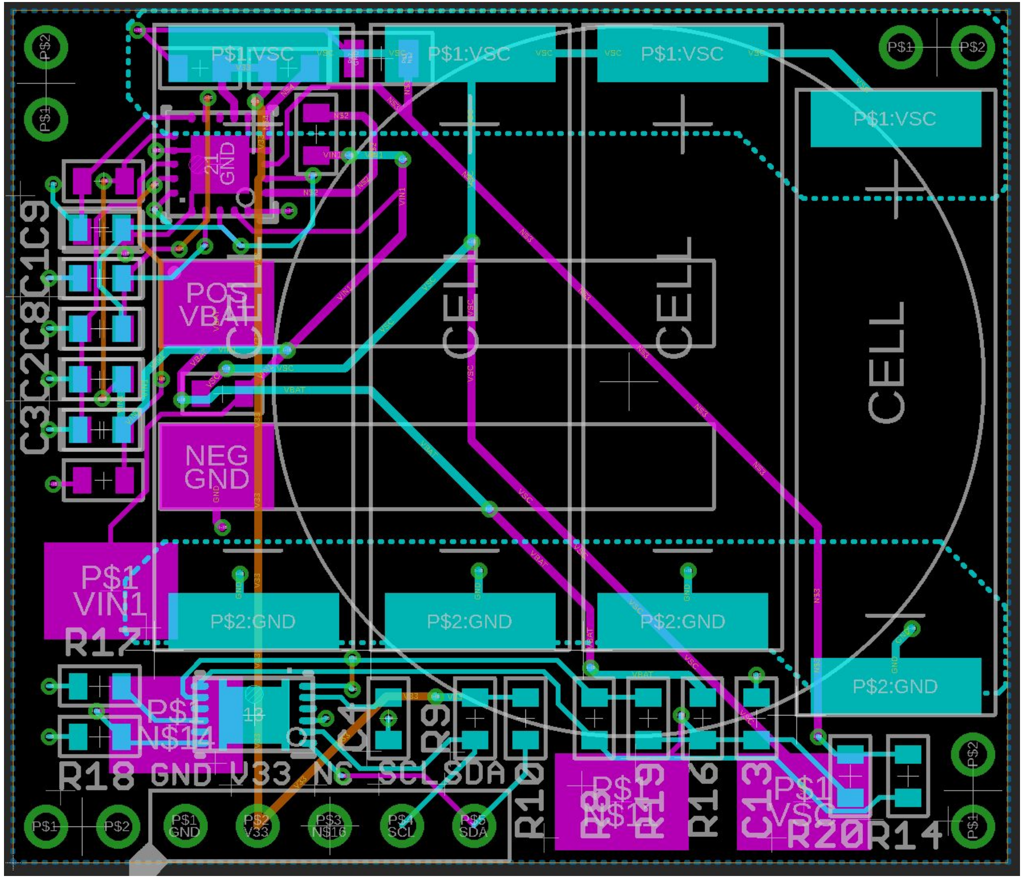
Comms Board Ver. A2 (trace antenna)

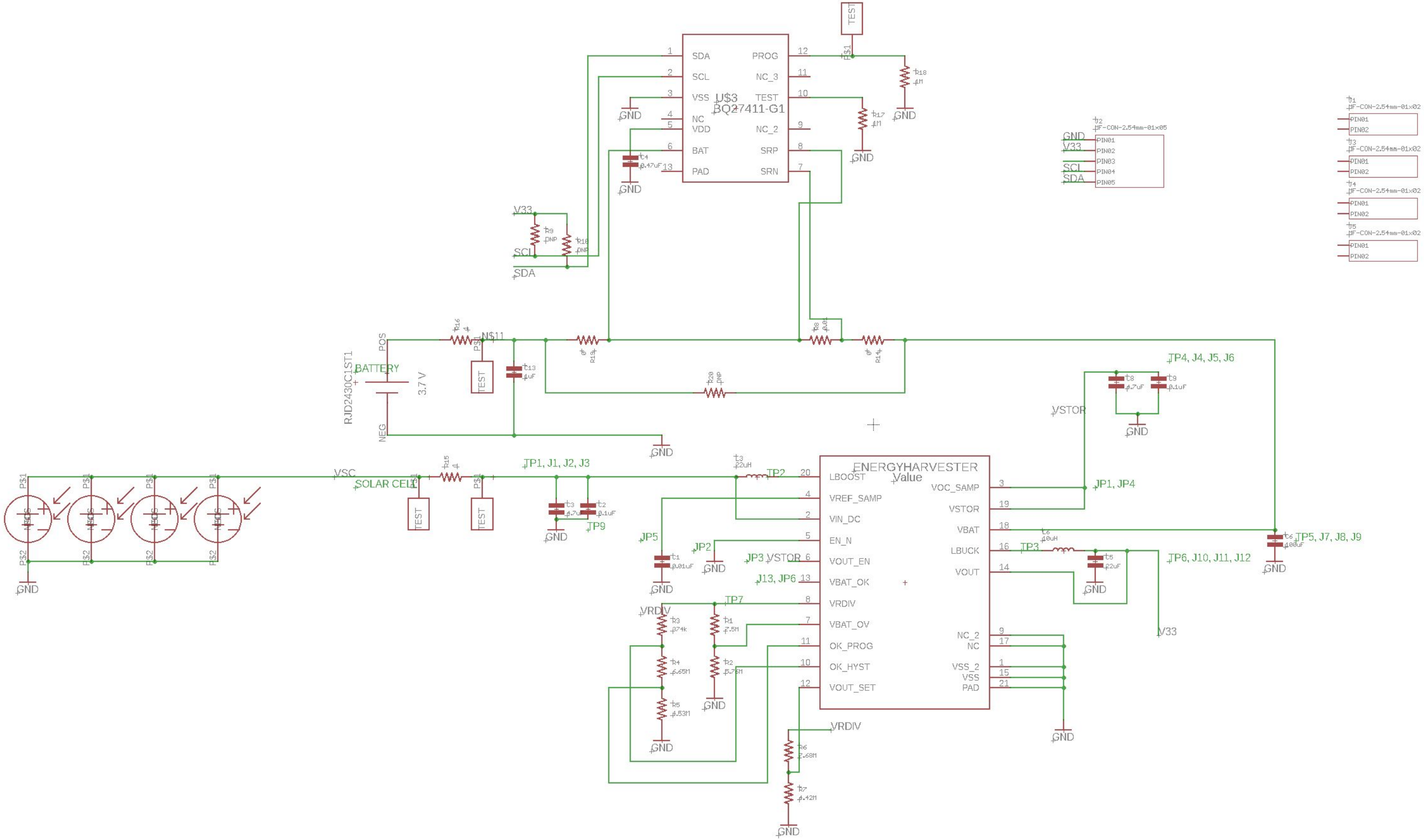




Transistor
TPS22918
VIN
ON
CT
VOUT
QOD
GND
V33
PWR_EN
VDD
Bypass & bulk capacitors
FILTER
Input PWR
GND
V33
PWR_EN
SCL1
SDA1
Debug LED
LED1
R4
100
VDDS
VDDS2
VDDS3
VDDR
VDDR_RF
VDDS_DCDC
DCDC_SW
X48M_P
X48M_N
X32K_Q2
X32K_Q1
RESET_N
JTAG_TCKC
JTAG_TMSC
RF_P
RF_N
DCOUPL
EGP
RXD
TXD
RST
TCKC
TMSC
TDO
TDI
SWO
I/O for Comms
Mechanical Support Headers
SMA_CONNECTOR
SMA
JTAG
RF Chain
Impedance Matching for CC2652R
Inverted F antenna
FEED
Impedance Matching for Antenna
32 kHz Oscillator
48 MHz Oscillator

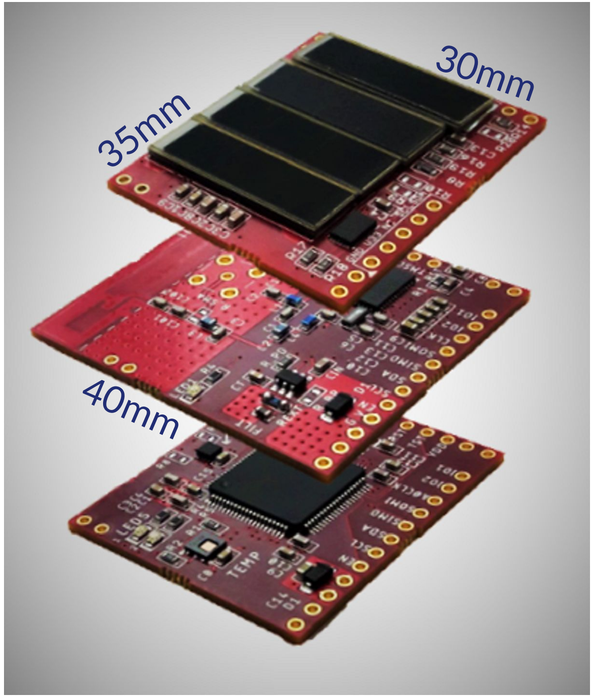
Power Board Ver. A1



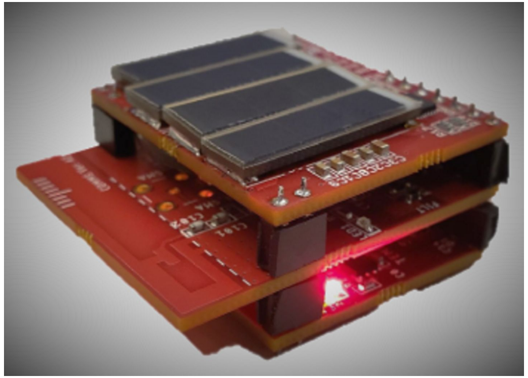


U$3
BQ27411-G1
SDA
SCL
VSS
NC
VDD
BAT
PAD
PROG
NC_3
TEST
NC_2
SRP
SRN
V33
SCL
SDA
GND
TEST
BATTERY
3.7 V
RJD2430C1ST1
POS
NEG
N$11
VSC
SOLAR CELL
TP1, J1, J2, J3
TP2
TP3
TP4, J4, J5, J6
TP5, J7, J8, J9
TP6, J10, J11, J12
TP7
TP9
JP1, JP4
JP2
JP3
JP5
J13, JP6
VSTOR
VRDIV
ENERGYHARVESTER
Value
LBOOST
VREF_SAMP
VIN_DC
EN_N
VOUT_EN
VBAT_OK
VRDIV
VBAT_OV
OK_PROG
OK_HYST
VOUT_SET
VOC_SAMP
VSTOR
VBAT
LBUCK
VOUT
NC_2
NC
VSS_2
VSS
PAD

Final Design



- Small ✓
- Modular ✓
- Self-powered ✓
- Flexible sensing capabilities ✓
- Flexible wireless transmission ✓



Performance & Specifications

Spec 1: Design supports SPI, I^2C, analog sensors that draw less than 5mA combined

- MSP430FR5994 processor contains:
  - Digital hardware modules for **SPI, I^2C, UART** ✅
  - **Multiple analog to digital converters** ✅

- The 5mA combined limit on sensors was just an arbitrary limit to keep sensor power consumption within a reasonable range. Future work could calculate in more detail the limit for a given comms chip.

Spec 2: Battery can power system for 12 hours without charging

- 1 transmit = 8mA current draw, ~5 sec
- Quiescent current= 200uA
- Battery capacity = 100 mAh
- Can **transmit once/hour** for **21.7 days without charging** ✅

$$21.7\ Days = \frac{110maH}{\left(8mA * 5s * \frac{1hr}{3600s} + 0.2mA * 1\ hr\right) * \frac{24\ TX}{Day}}$$

Spec 3: Energy harvester can produce 12mW in direct sunlight.

	Sunny	Shade
Solar Cell Current	~36 mA	~2 mA
Solar Cell Voltage	~1.5 V	~1 V
Charge Current	~10 mA	~0.3 mA
Sense & Transmit	Constantly	Every 4 min.

- In direct sunlight, charge current is **~10 mA**
- Based on resistor settings, lowest voltage threshold for battery is **3 V**

$P = IV$

$P = 10\text{ mA} * 3\text{ V}$

$P = \sim 30\text{ mW} > 12\text{ mW}$ ✓

Spec 4: Can sense and/or transmit 12 times throughout a sunny day

- While in sunlight, charge current is **~ 10 mA**
- To sense and transmit, **8 mA** is pulled over ~5 seconds
- About **0.2 mA** is pulled when the device is not charging (quiescent current)
- Thus, we can transmit **constantly** in direct sunlight without draining battery capacity! ✅

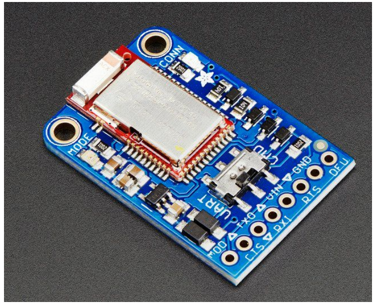
Spec 5: Wireless Range of at least 5m

- ❖ We achieved an outdoor wireless range of **~119 m** ✅
- ❖ We placed a Chariot node on the 90 degree statue in the engineering quad and slowly walked away until we no longer got new data
  - ➢ We were able to make it to the edge of the inner loop

Spec 6: Design can support different wireless transmitters with peak current draw <30mA

- We used the **Adafruit Bluefruit transmitter** for our first prototype ✓
- We used the **TI CC2652R transmitter** for both prototypes 2 and 3 ✓

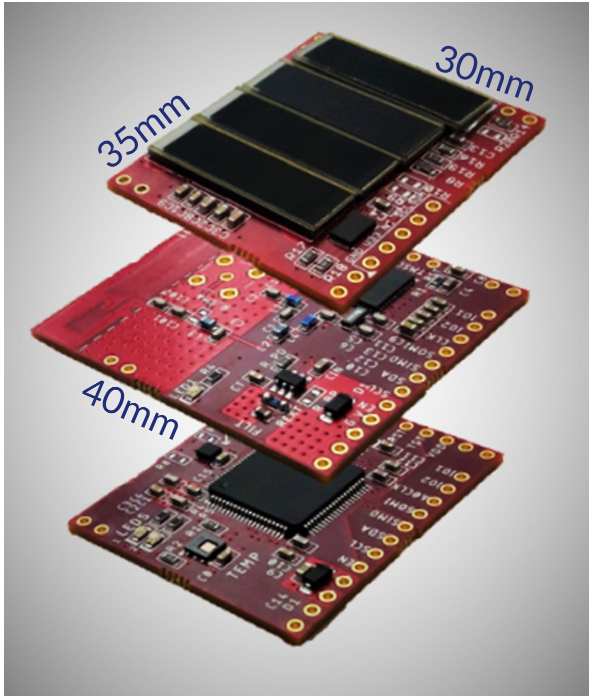
  The TI CC2652R transmitter has a peak current draw of **16mA**



Spec 7: Maximum footprint size: 50mm x 50mm x 20mm (or equivalent volume)

- The PCB design for the showcase prototype had a footprint of **35mm by 40mm**, and the entire assembled prototype stands about **20 mm tall** ✅

- The comms board is the only PCB which actually is **35mm by 40mm**, the sensor and power boards both only have a footprint of **35mm by 30mm**



Spec 8: Less than $500 to produce a single node (not at production scale)

Final Prototype Cost Breakdown per Unit

	Power Board	Communications Board	Processor Board	Final Prototype
Components	$44.58	$14.28	$12.17	$70.98
Base PCB	$7.47	$8.95	$7.45	$23.87
Labor	$48.37	$61.18	$51.25	$160.80
Total	$100.40	$84.42	$70.87	**$255.69**

Estimated Cost Breakdown at 10,000 Unit Scale

	Power Board	Communications Board	Processor Board	Final Prototype
Components	$27.71	$5.92	$6.54	$40.17
Base PCB	$0.86	$1.08	$0.86	$2.80
Labor	$2.24	$2.27	$2.25	$6.76
Total	$30.81	$9.27	$9.66	**$49.74**

Q/A