Distributed Sniffer Nodes for Batteryless Sensor Nodes (sdmay24-25)

Website

https://sdmay24-25.sd.ece.iastate.edu/

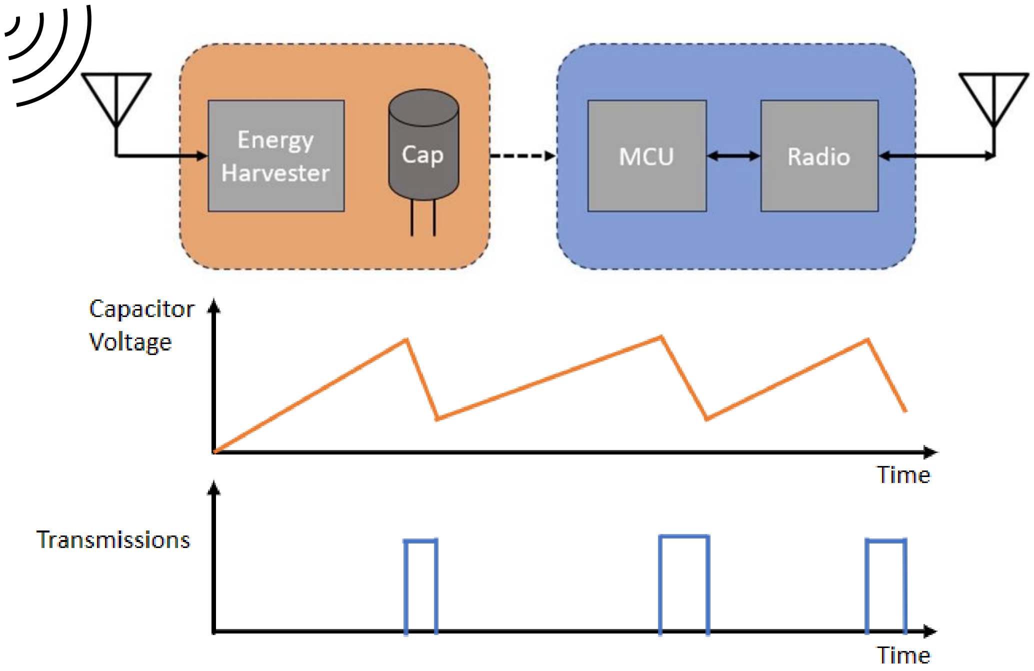
Team Lead/ Software Lead: Thomas Gaul
Hardware Lead: Tori Kittleson
Hardware Member: Matthew Crabb
Software Member: Spencer Sutton
Scribe/Software Member: Ian Hollingworth

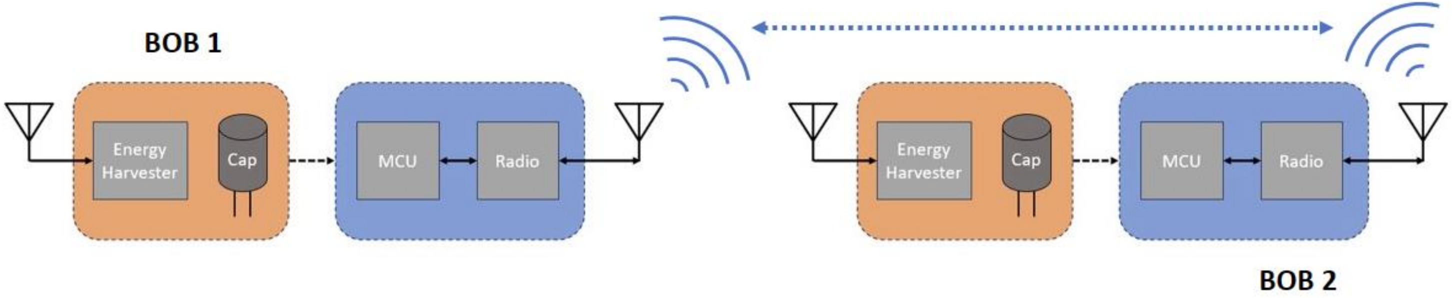
Advisor/Client: Henry Duwe
CPRE/EE 492 Spring 2024

IOWA STATE UNIVERSITY

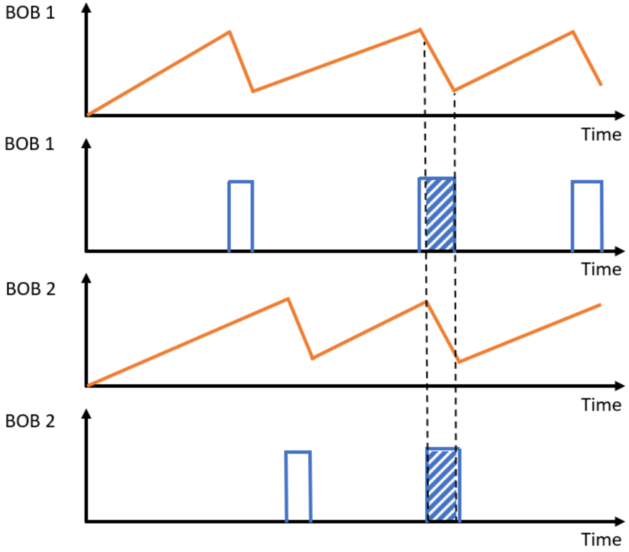
Project Overview

BOB Node - Batteryless sensor designed by client.

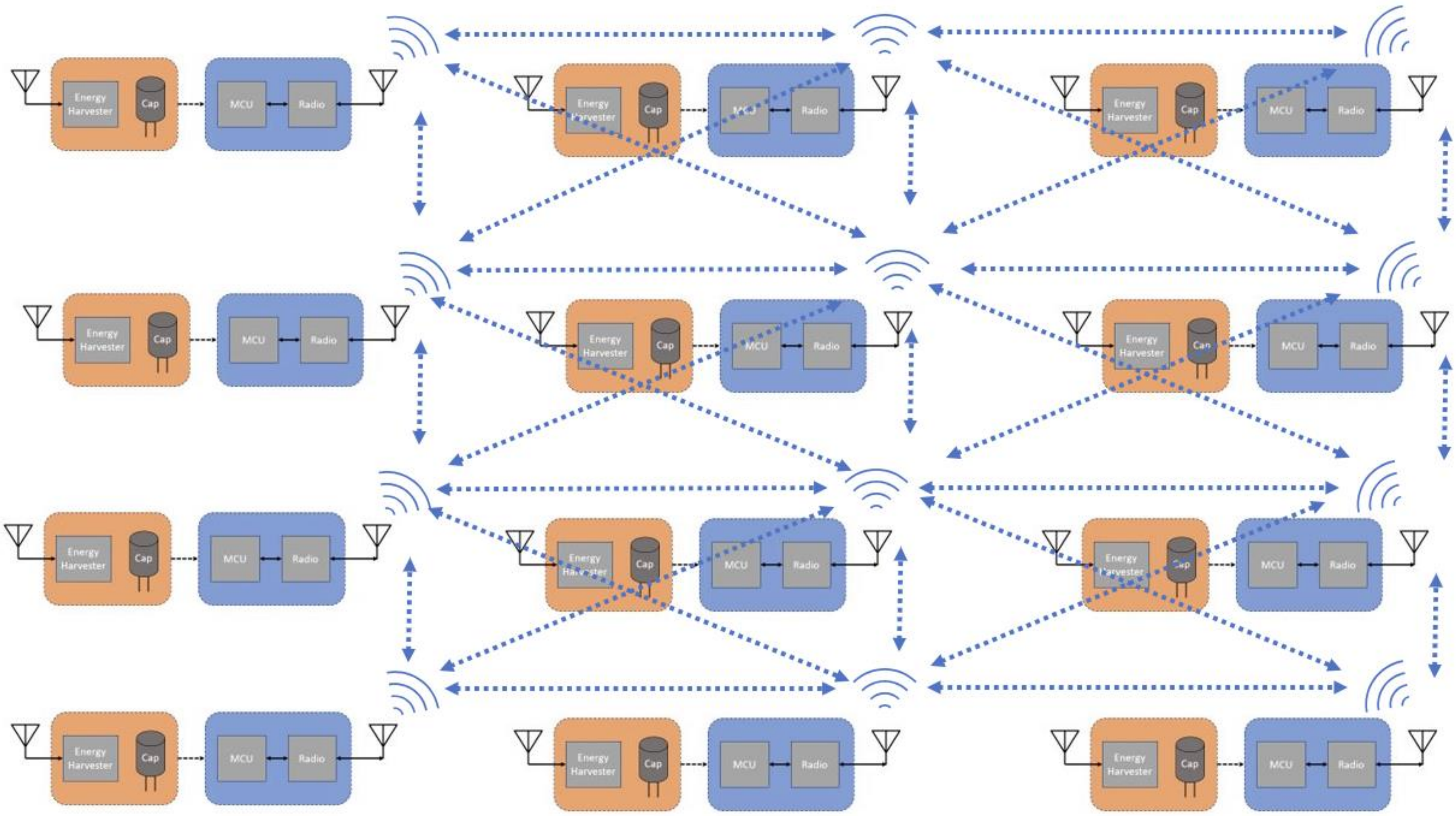




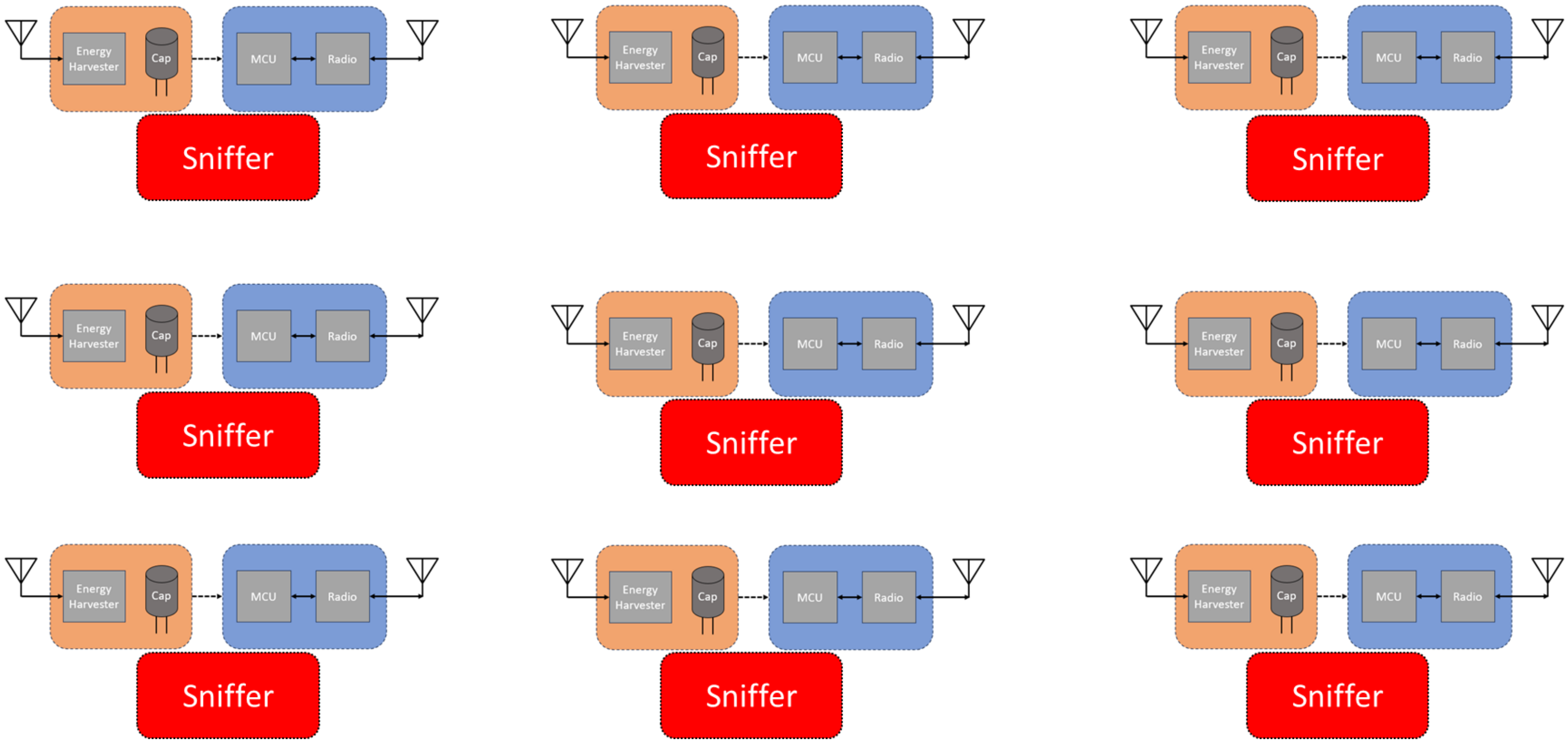
BOB 1
Energy Harvester
Cap
MCU
Radio
Energy Harvester
Cap
MCU
Radio
BOB 2



BOB 1
Time
BOB 1
Time
BOB 2
Time
BOB 2
Time


Energy Harvester
Cap
MCU
Radio

Goal: Create testbed for researchers to use for the batteryless nodes they are developing.



Use Cases

Scenario Node Tests
- Single node experiments
- Multi-node and single lab experiments
- Large scale testing (goal of 100 – 1000)

Users
- Dr. Duwe's research group
- Universities, companies, hobbyists through open-source nature

Potential Impact
- Factory condition monitoring
- Weather monitoring and recording
- Forest fire detection in national parks

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Requirements

Functional

- 9 BOB/Sniffer pairs
- Sink Sniffer Node with continuous power
- Host system to organize and store Sniffer logs
- Sniffer Nodes powered for one week
- Sniffer Nodes inflict minimal effects on BOB Nodes
- BOB Nodes electrically isolated from one another
- Modular stack of BOB and Sniffer custom boards

Non-functional

- Scalable for a potential larger (100+ node) design
- Documentation
- Mechanical durability of system

Deliverables

- Breakout Board Hardware
- MSP Simplified Hardware
- Sniffer Node Hardware
- Sniffer Node Software
- Open-Source Documentation
- Mechanically Sound System

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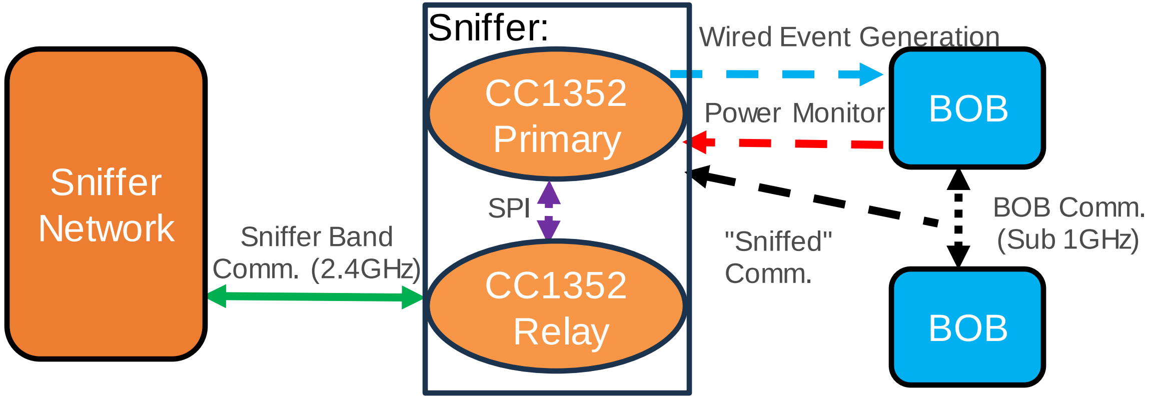
Sniffer Design

Tasks

- Monitor BOB status via GPIO
- Generate events for BOB via GPIO
- Monitor BOB radio communication
- Send test data to be saved



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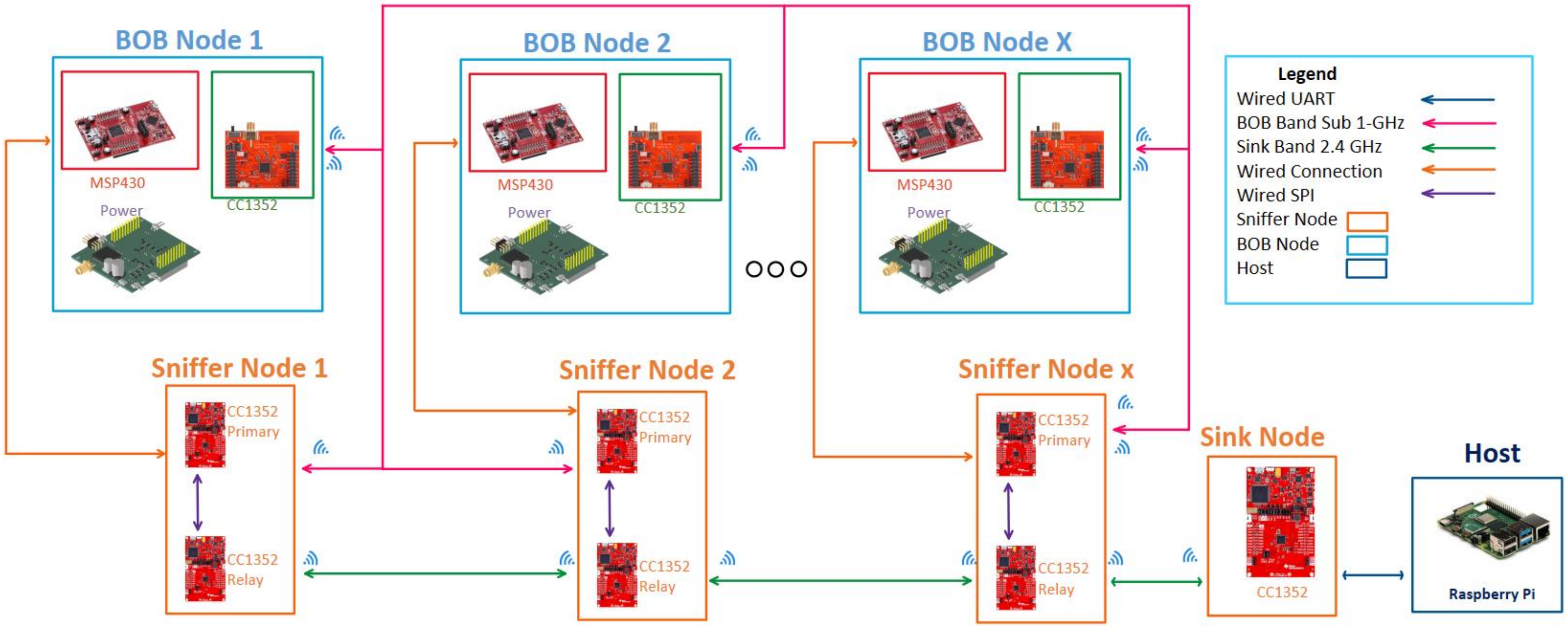
System Design



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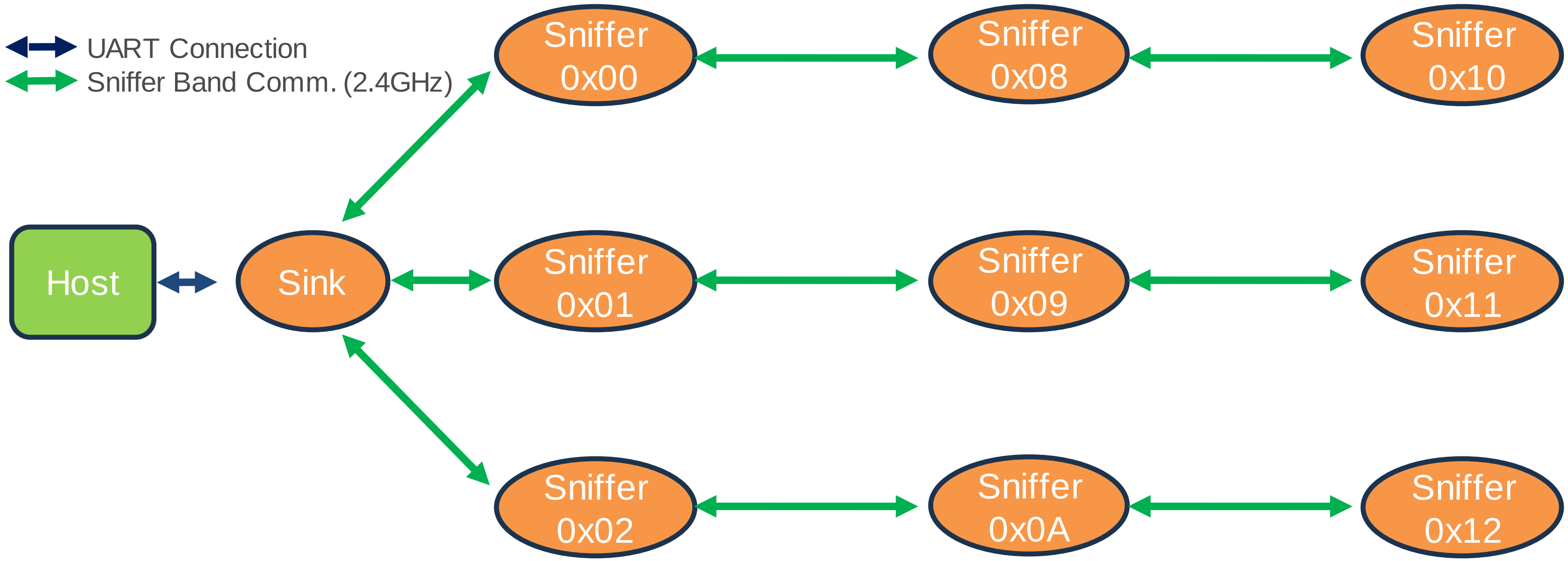
System Design



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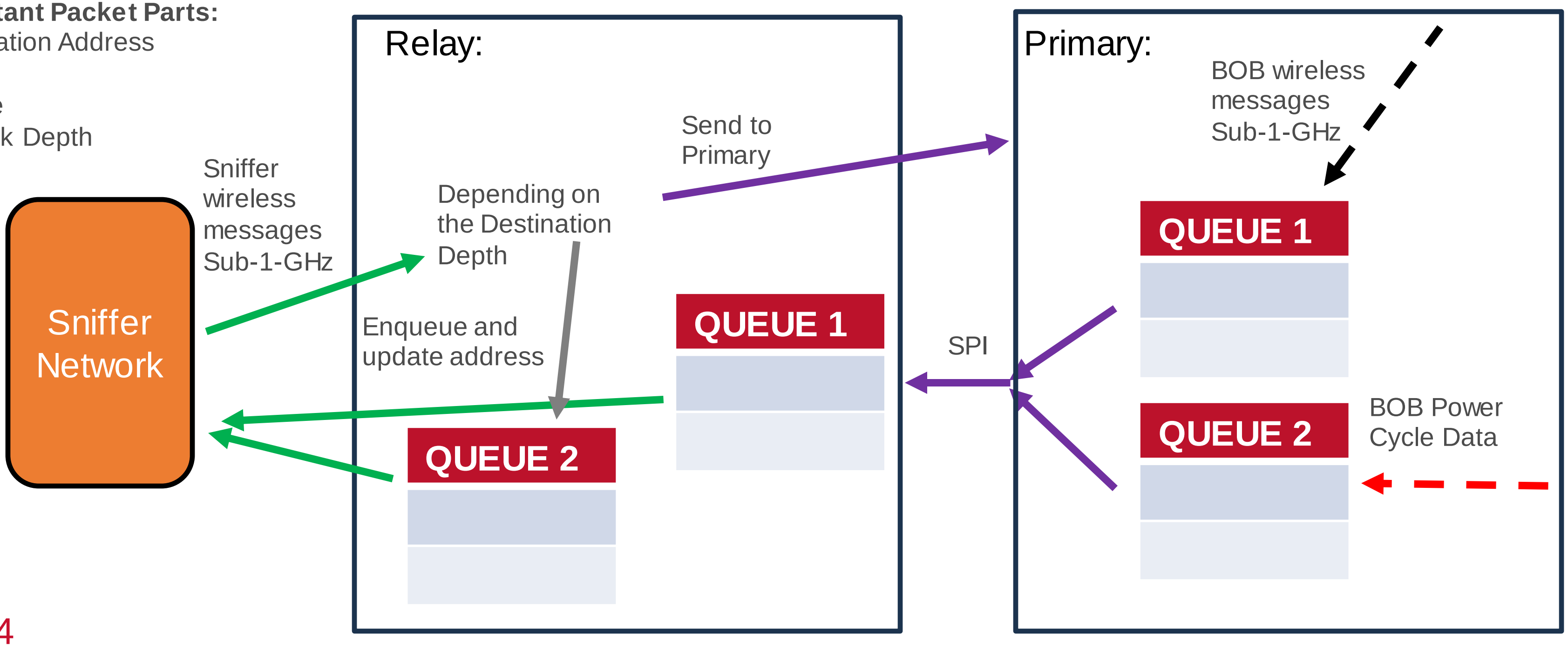
Software Design

Important Packet Parts:
Destination Address
Type
Source
Network Depth
Data



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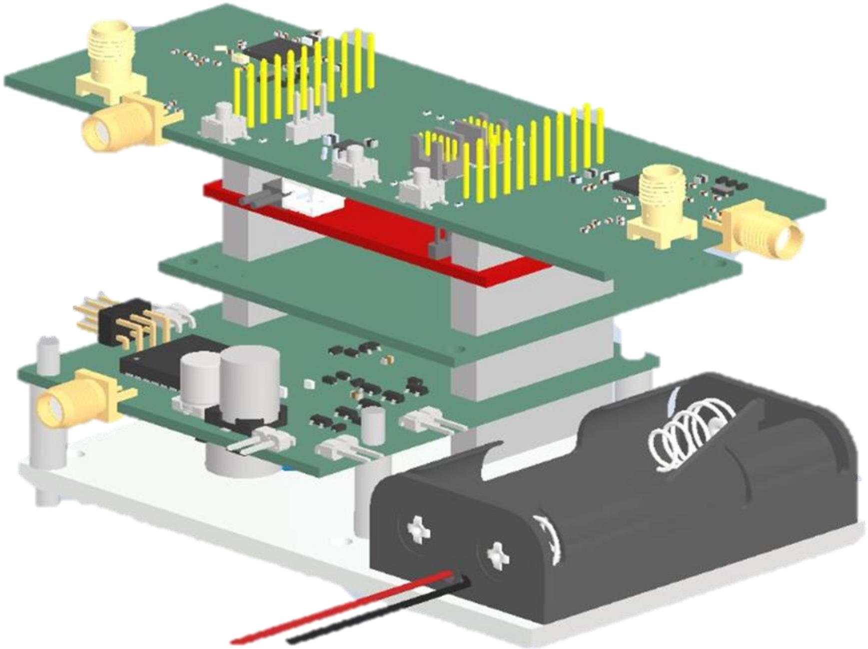
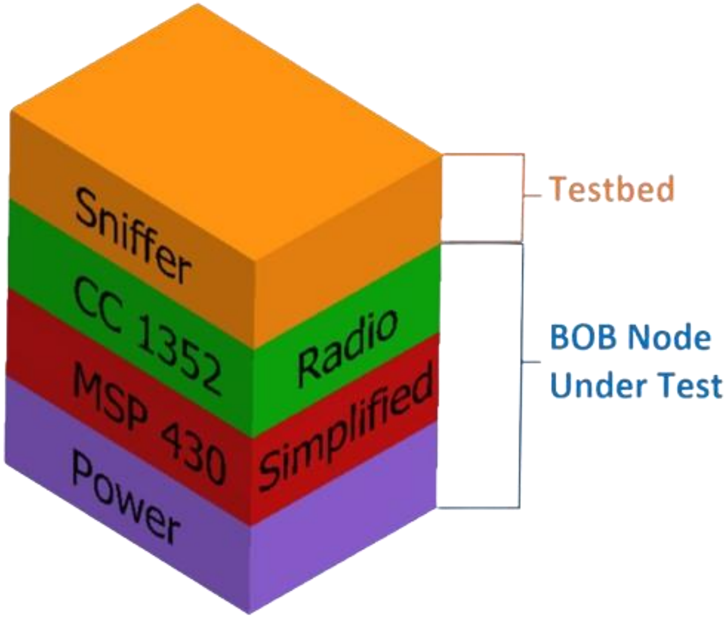
System Physical Design – PCB Stackup and Mounting





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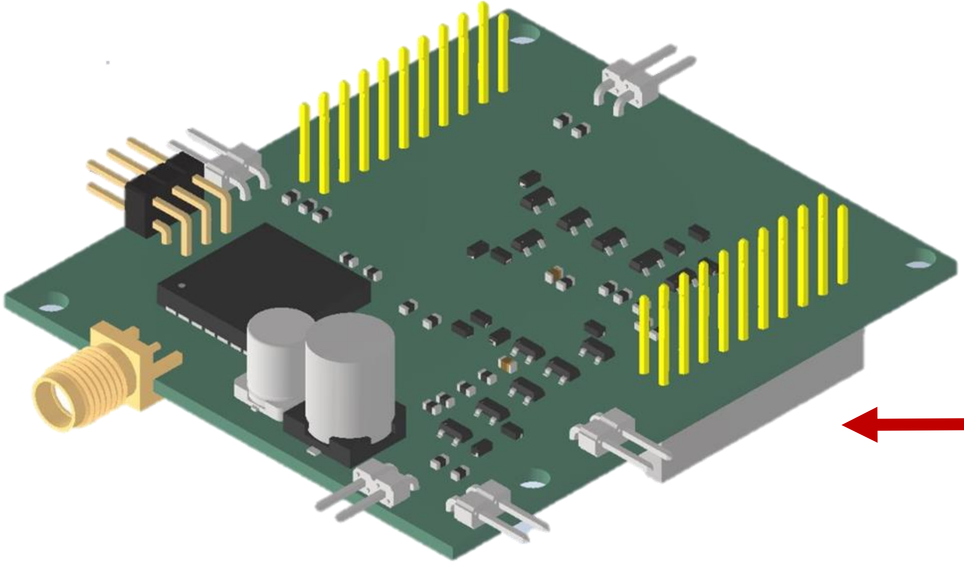
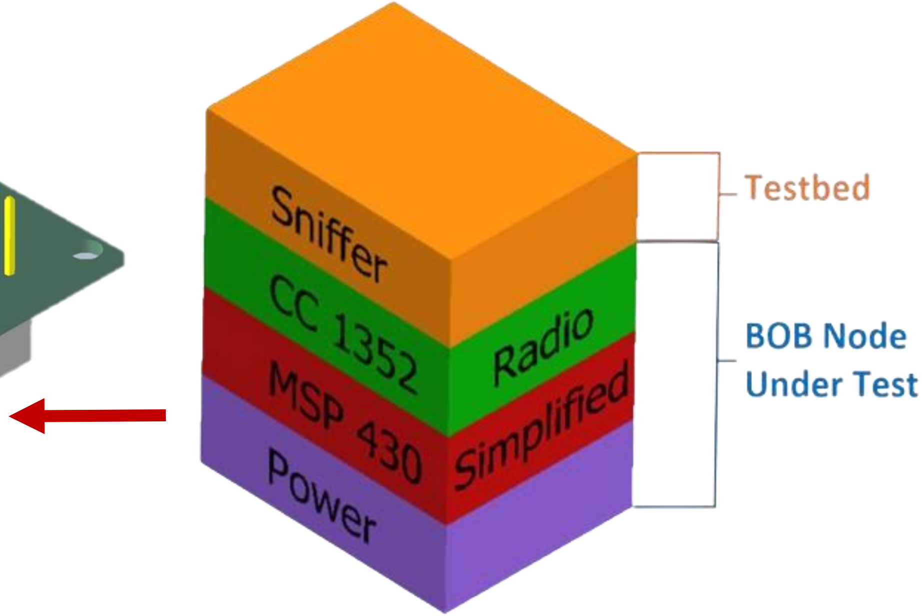
System Physical Design – Power Harvester PCB





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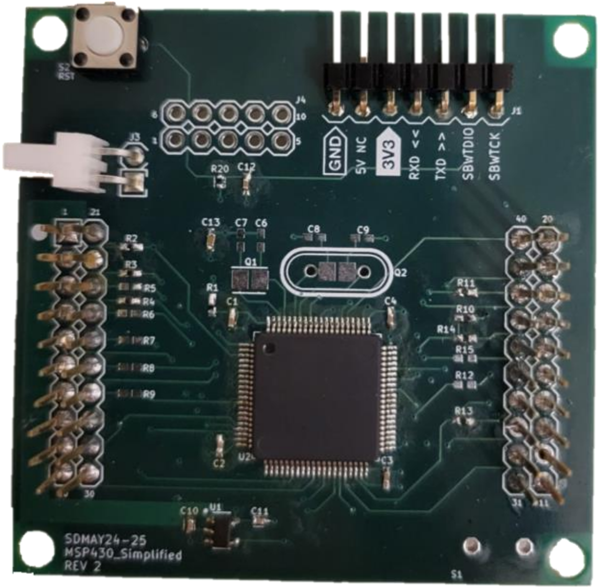
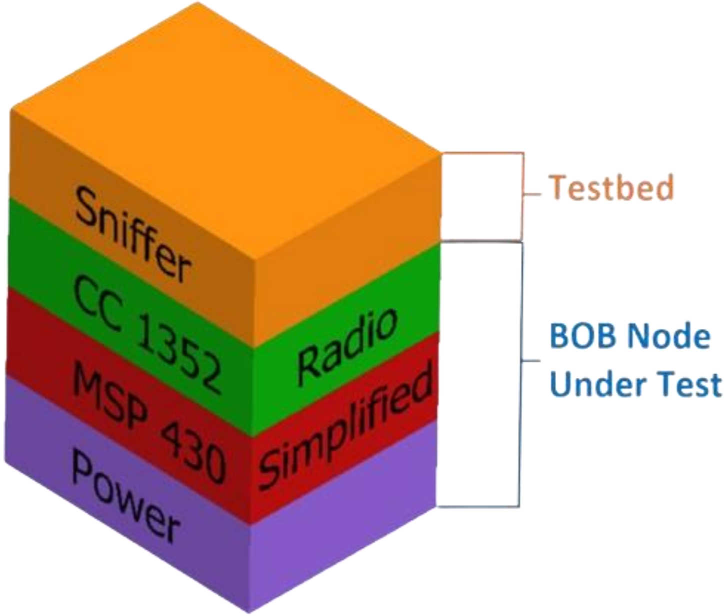
System Physical Design – MSP430 Simplified PCB





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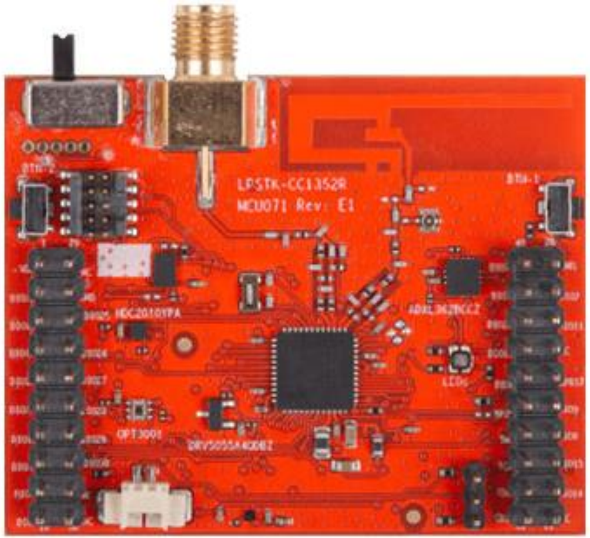
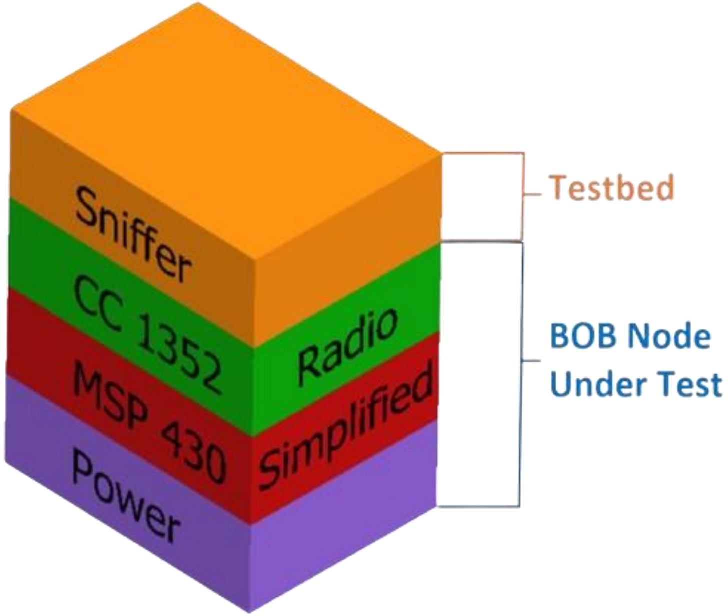
System Physical Design – CC1352 Radio PCB





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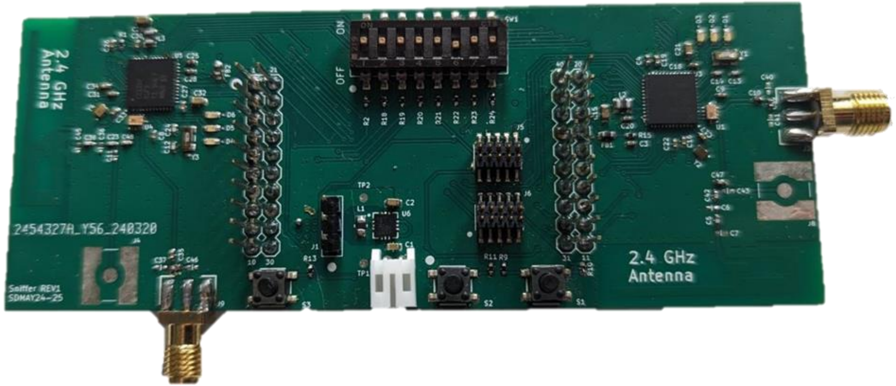
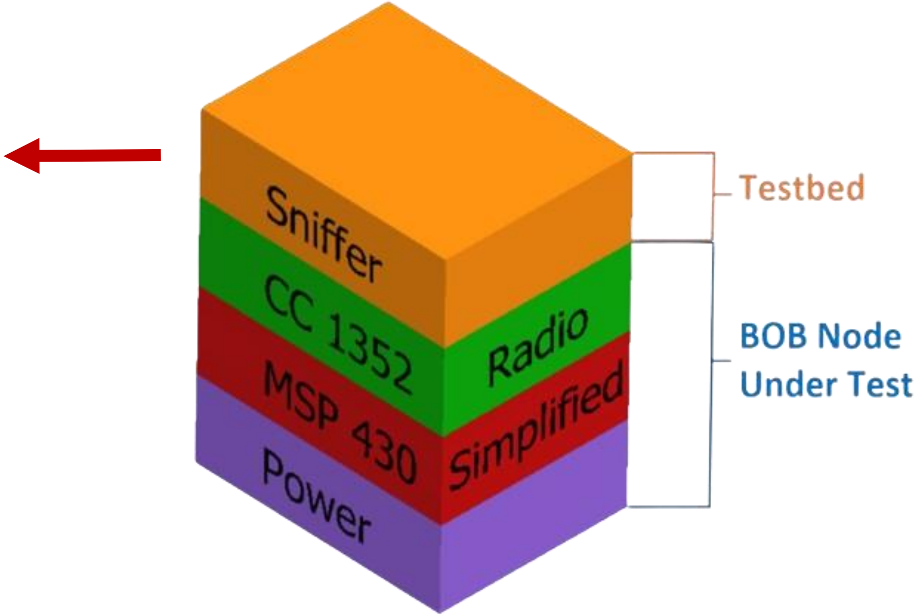
System Physical Design – Sniffer PCB





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Sniffer PCB Design – Battery System

Chose to use rechargeable NiMH AA batteries

Pros:

- Standard size, widely available
- Rechargeable 1,000x
- Simple, low-cost mounting solutions
- Multiple manufacturers
- Off the shelf or custom charging solutions
- Flexibility

Cons:

- Lower capacity than some other options
- Charging, protection, fuel gauge ICs not as widely available

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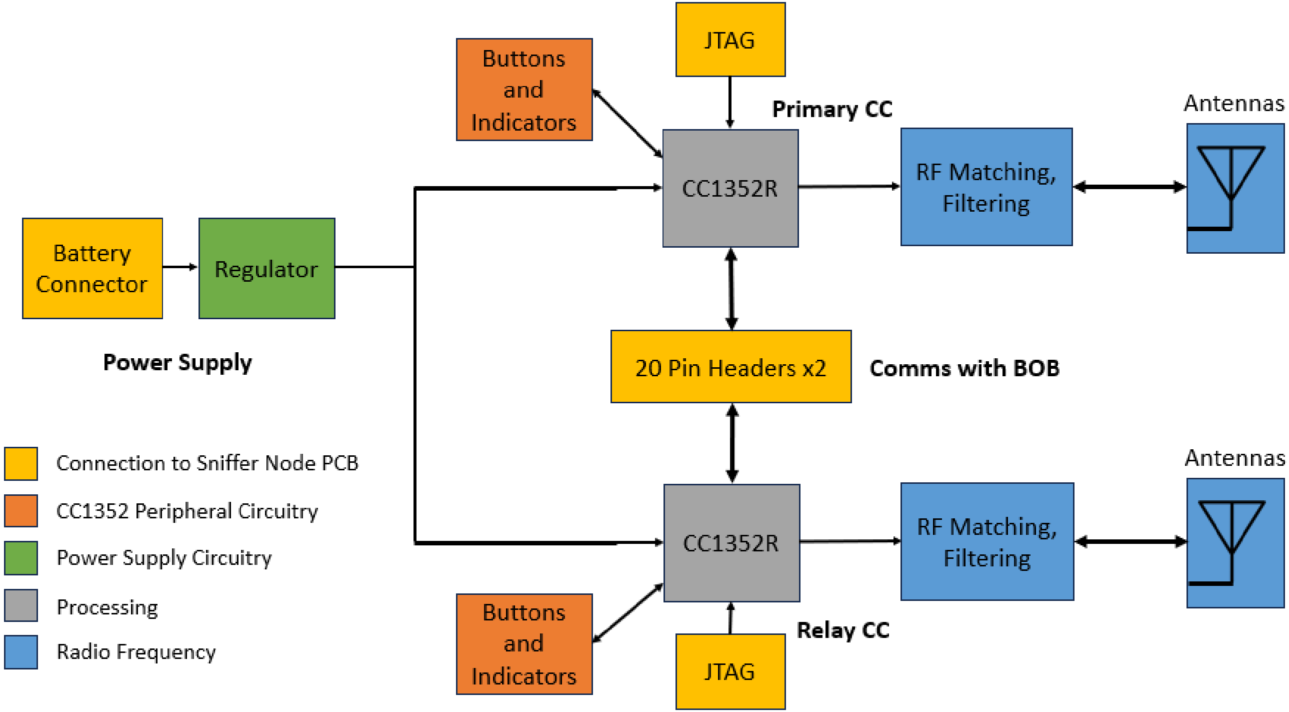
Sniffer PCB Design – Block Diagram



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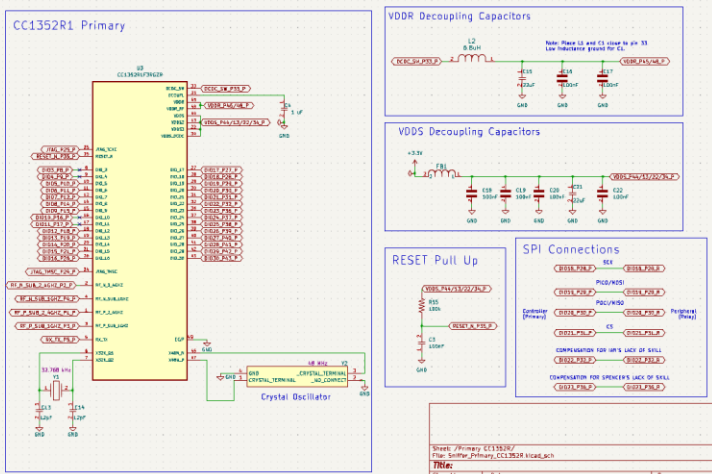
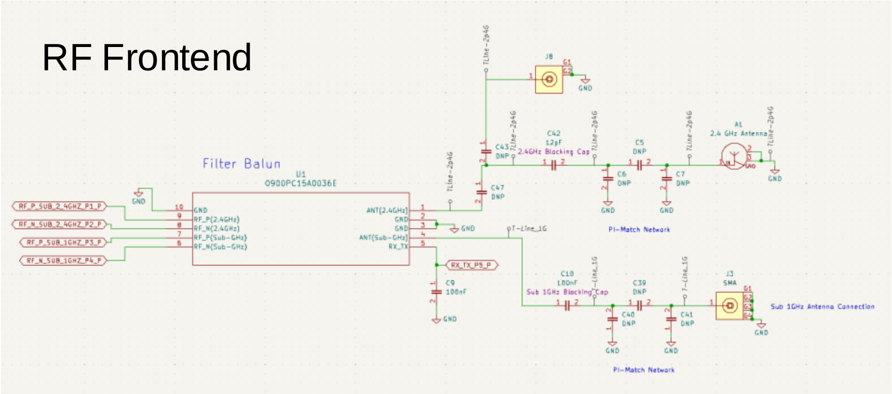
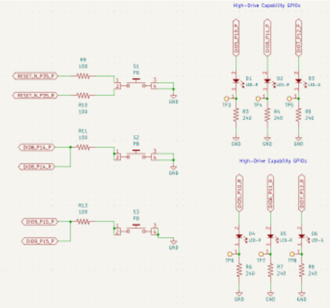
Sniffer PCB Design – KiCad Schematics



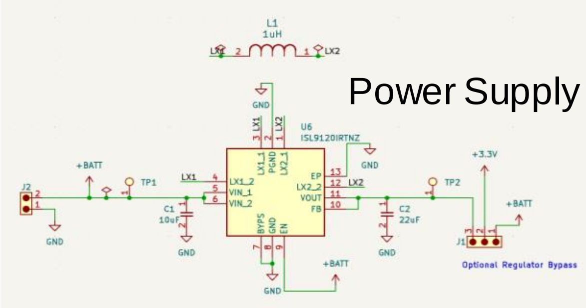
CC1352R and Peripherals



RF Frontend



Buttons + Indicators



Power Supply

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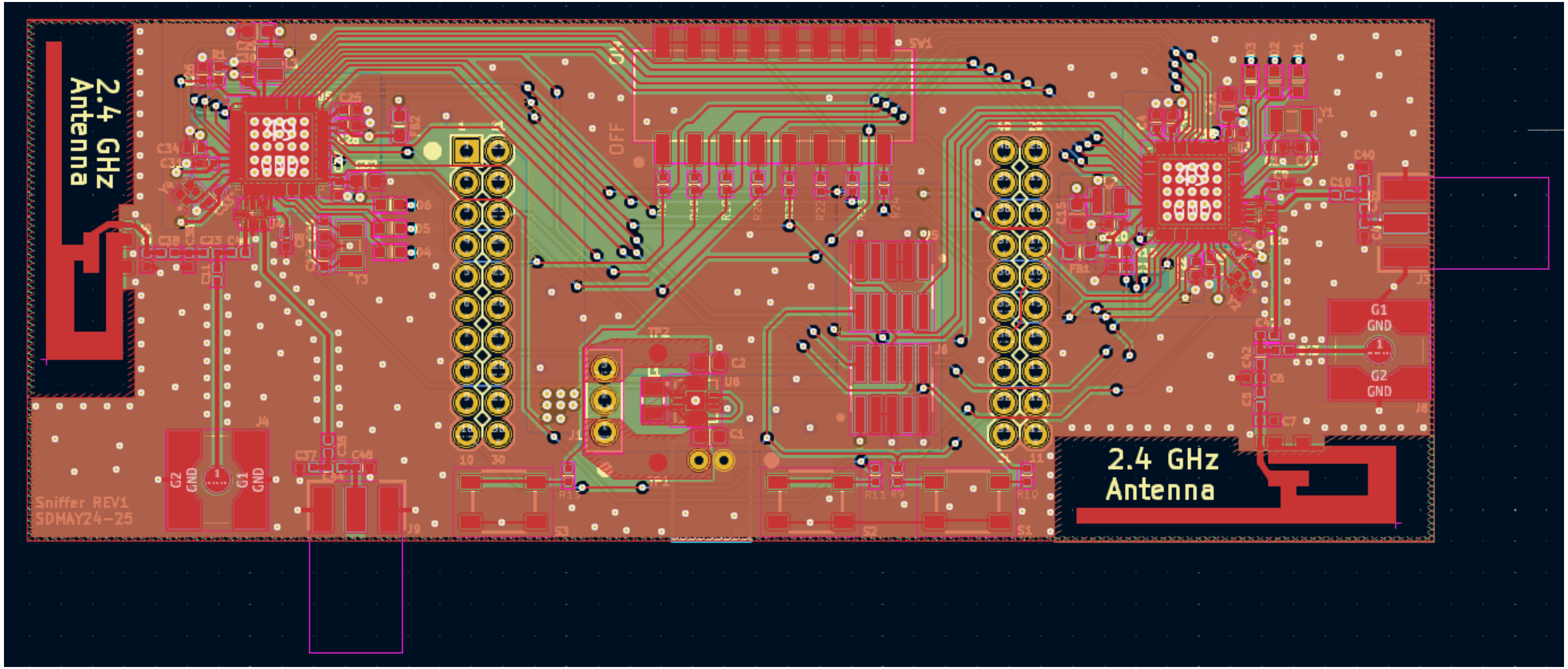
Sniffer PCB Design – KiCad Layout



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Costs

Senior Design Cost Breakdown		
Item	**Cost Per Node**	**Overall Cost**
Breakout Board	-	$37.83
MSP_Simplified	~$31	$234.60
Sniffer Board	~$56	$611.88
Batteries and Chargers	~$12	$112.05
Additional parts	-	$29.29
Mechanical Design	~$4	$34.60
Total	~$103	$1060.25

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Testing

Unit Test

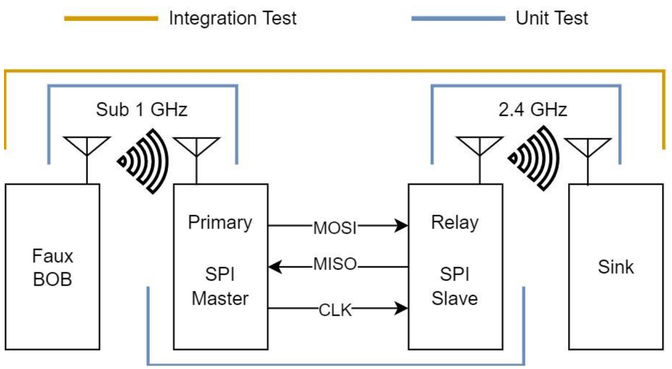
- SPI communication, Sub 1GHz communication, and 2.4 GHz Communication
- Electrical continuity and power checks
- Programming boards

Integration Tests

- SPI with Sub 1Ghz and 2.4 GHz communication
- Software with custom hardware

System wide

- Data transfer between multiple nodes



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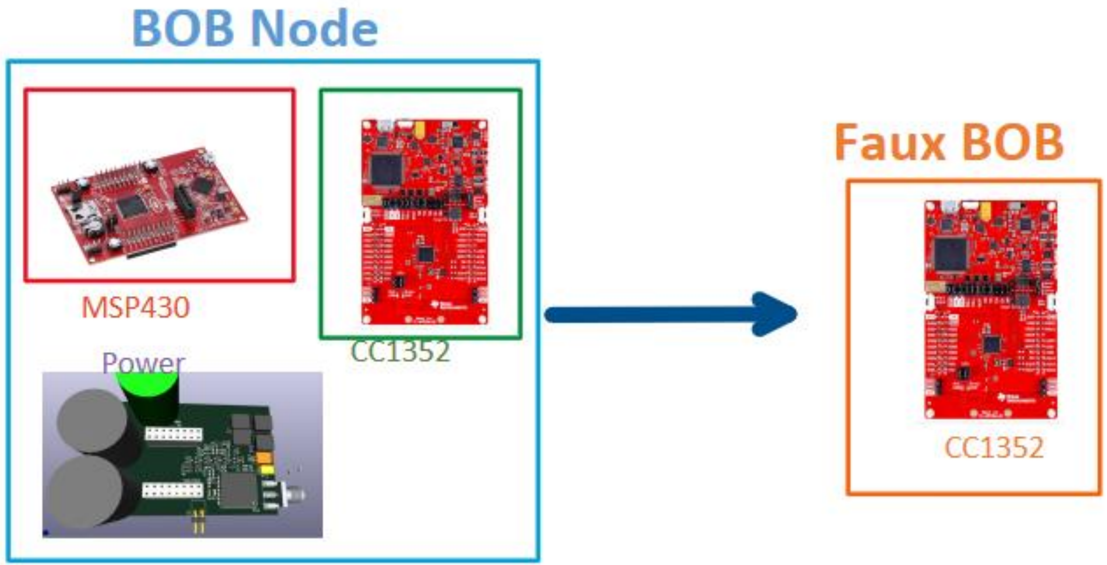
Faux BOB

Goal

- Create a test tool
- Emulate BOB functionality
- Allows us to have a known test



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RF Testing and Tuning

Initial Plan

- Use a spectrum analyzer to tune the internal CC1352R load capacitors
- Ignore Sub-1GHz matching (all components assumed to have 50Ω ref impedance)
- Extract S-parameter information from 2.4GHz PCB antenna using a VNA and match

Problem

- Using equipment requires supervision + approval – could not get access until too late

Solution

- Model antenna on the computer and simulate its operation
- Use simulation tools to find correct matching values

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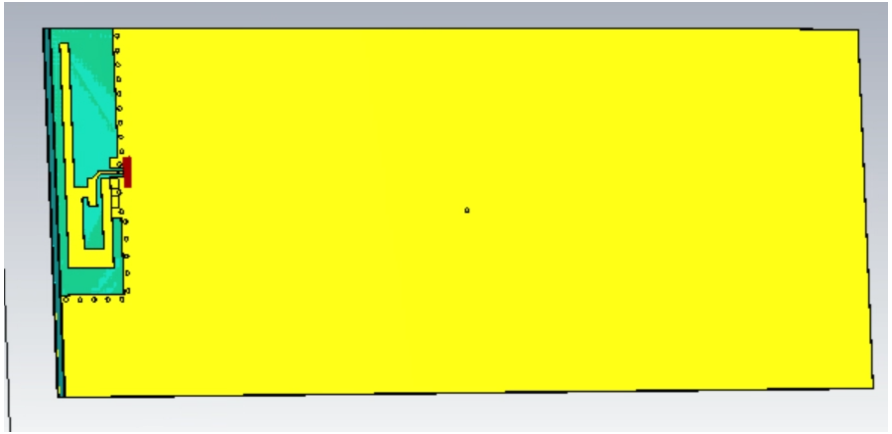
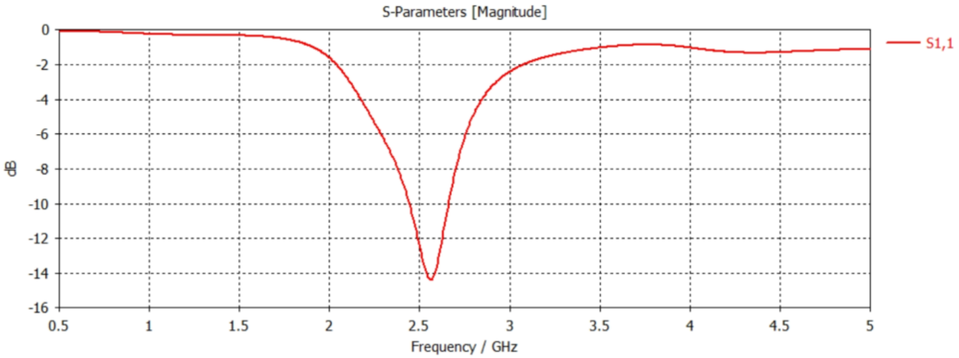
RF Testing and Tuning





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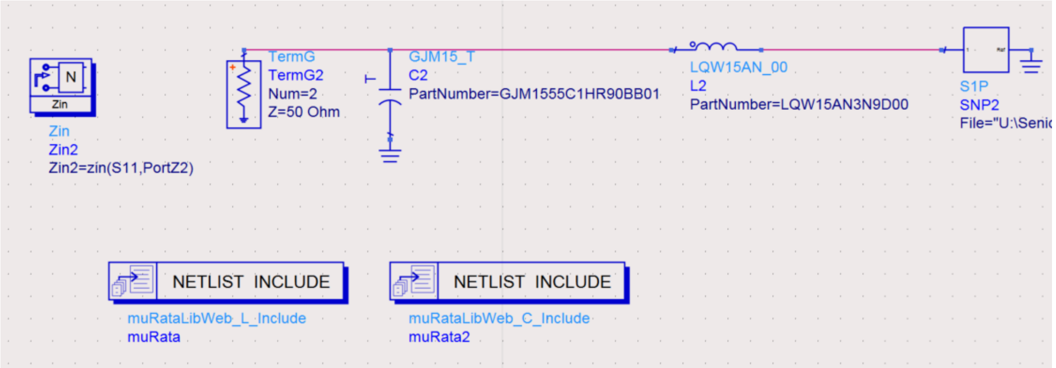
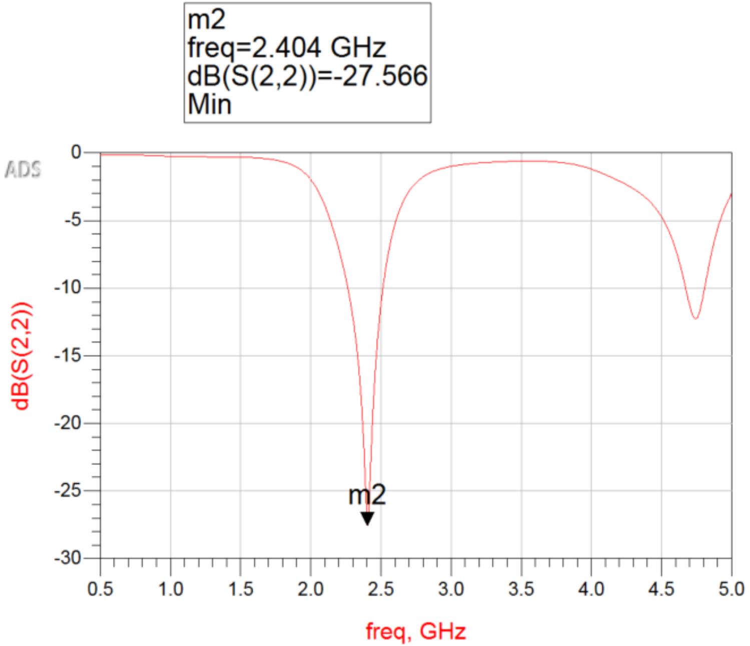
RF Testing and Tuning





freq	S(2,2)	Zin2
2.400 GHz	-27.138 / -80.493	50.000 + j0.001

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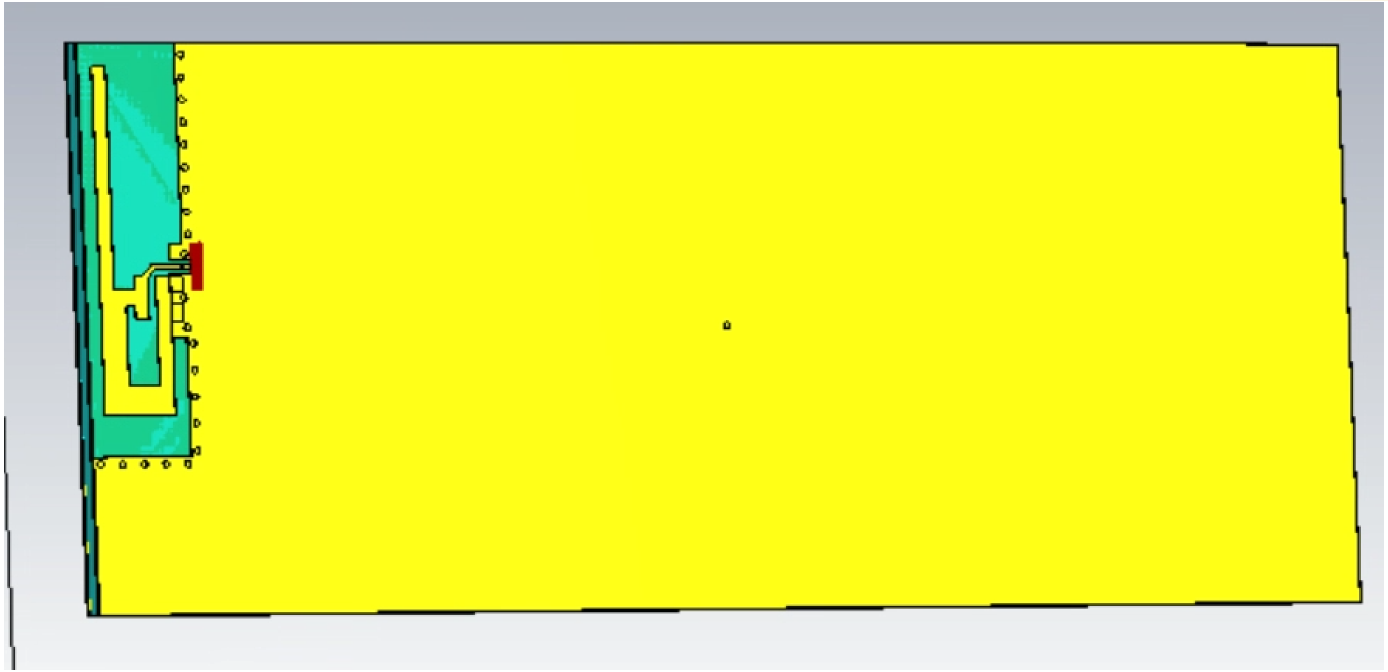
RF Testing and Tuning



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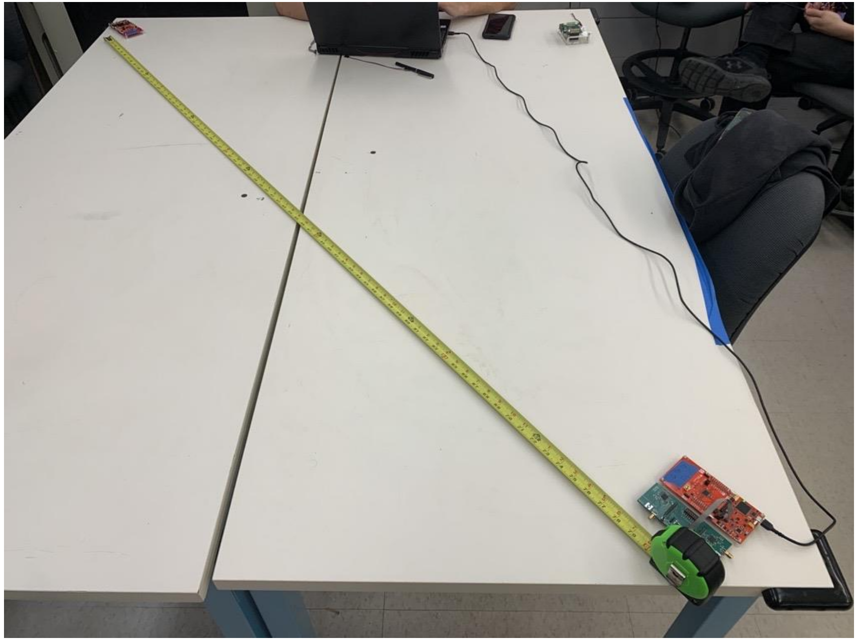
Radio Testing with TI SmartRF Studio



2.4GHz Wireless Testing	
Test Configuration	**RSSI (dBm)**
REF1 → REF2	-52.7
REF1 ← REF2	-53.7
Sniffer (1) → REF2	-53.1
Sniffer (1) ← REF2	-53.1

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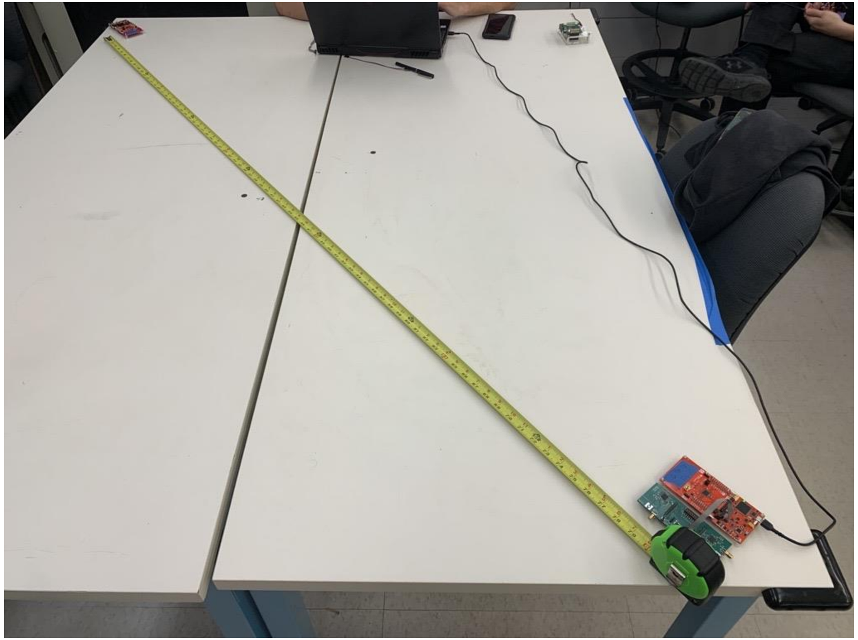
Radio Testing with TI SmartRF Studio



Sub-1GHz Wireless Testing	
Test Configuration	**RSSI (dBm)**
REF1 → REF2	-31.9
REF1 ← REF2	-39.8
Sniffer (1) → REF2	-80.2
Sniffer (1) ← REF2	-80.8
Sniffer (2) → REF2	-39.2
Sniffer (2) ← REF2	-33.4

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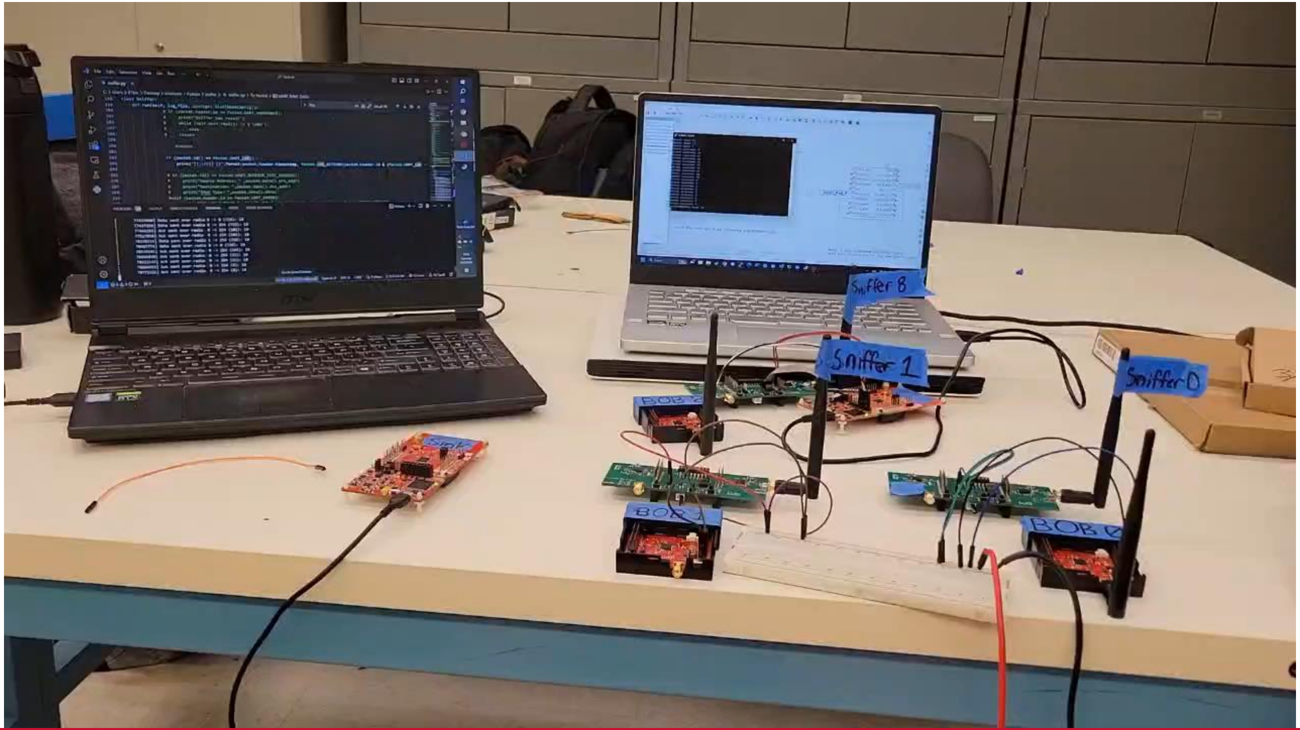
Demo



Challenges & Lessons Learned

Hardware

- RF design
- Multiple PCBs

Software

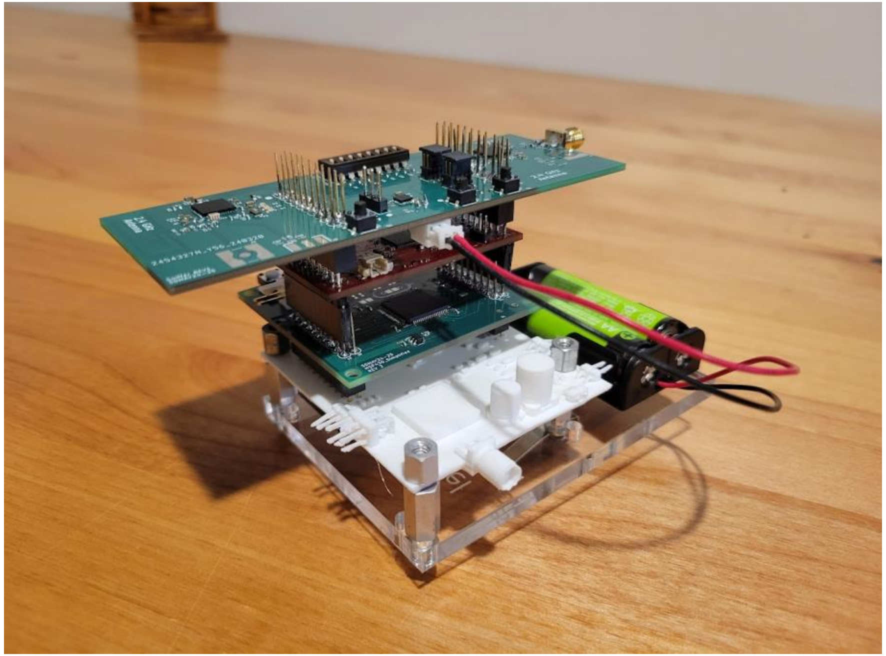
- Real Time Operating System
- Multiple Code bases
- Multi-threading
- Interrupt based programming

Integration Challenges

- CC1352 Revision with Errata
- CC1352 breaking due to clock issues

Future Work

- Integrating more nodes into the communication network.
- More rigorous load testing to ensure no packet loss
- Integrate project with researcher's testbed



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Back-up Slides

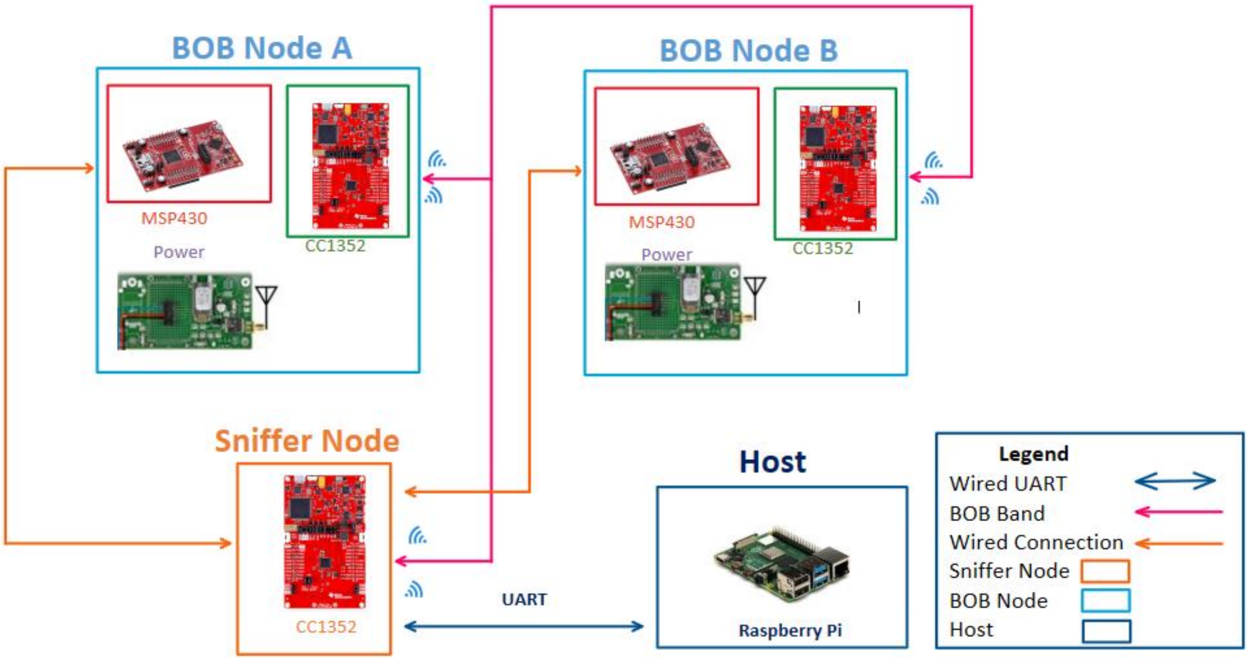
Literature Study

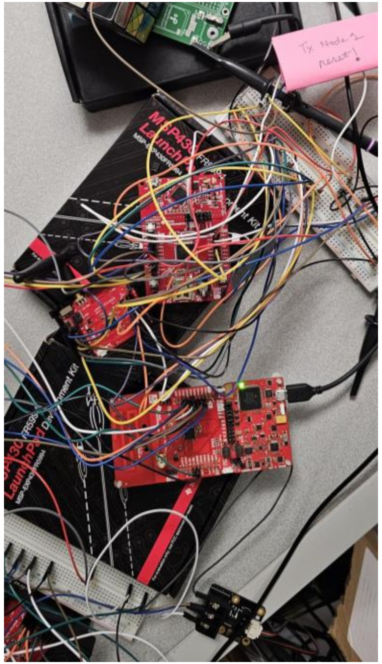
•"Experimental Study of Lifecycle Management Protocols for Batteryless Intermittent Communication"[2]

•"Toward a Shared Sense of Time for a Network of Batteryless, Intermittently-powered Nodes"[3]

•"Reliable Timekeeping for Intermittent Computing"[4]

Current Design





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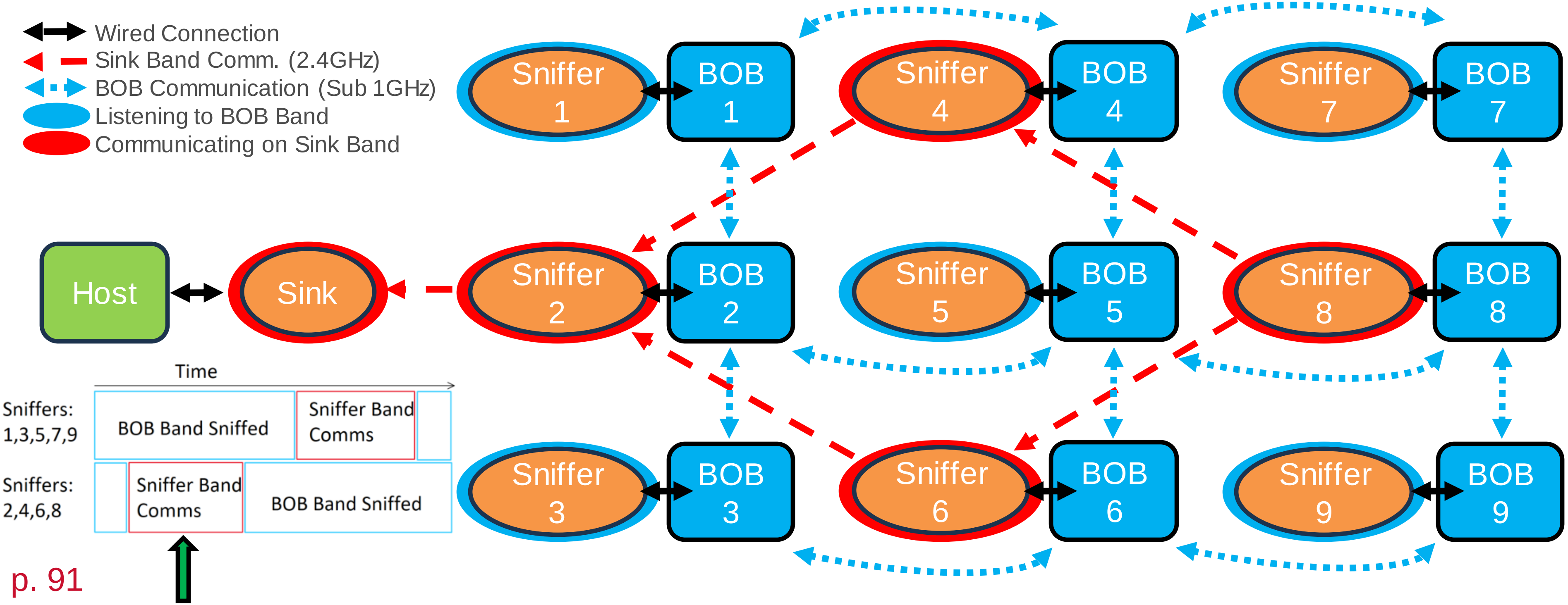
System Design



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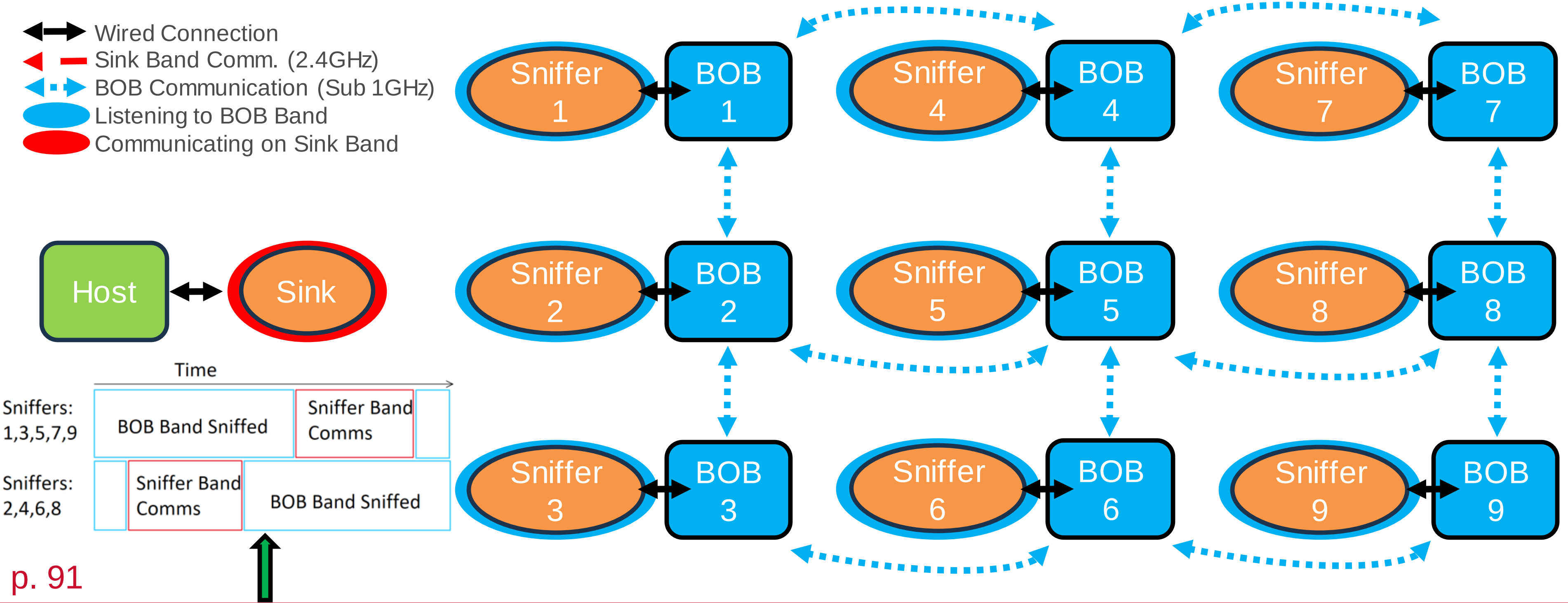
System Design



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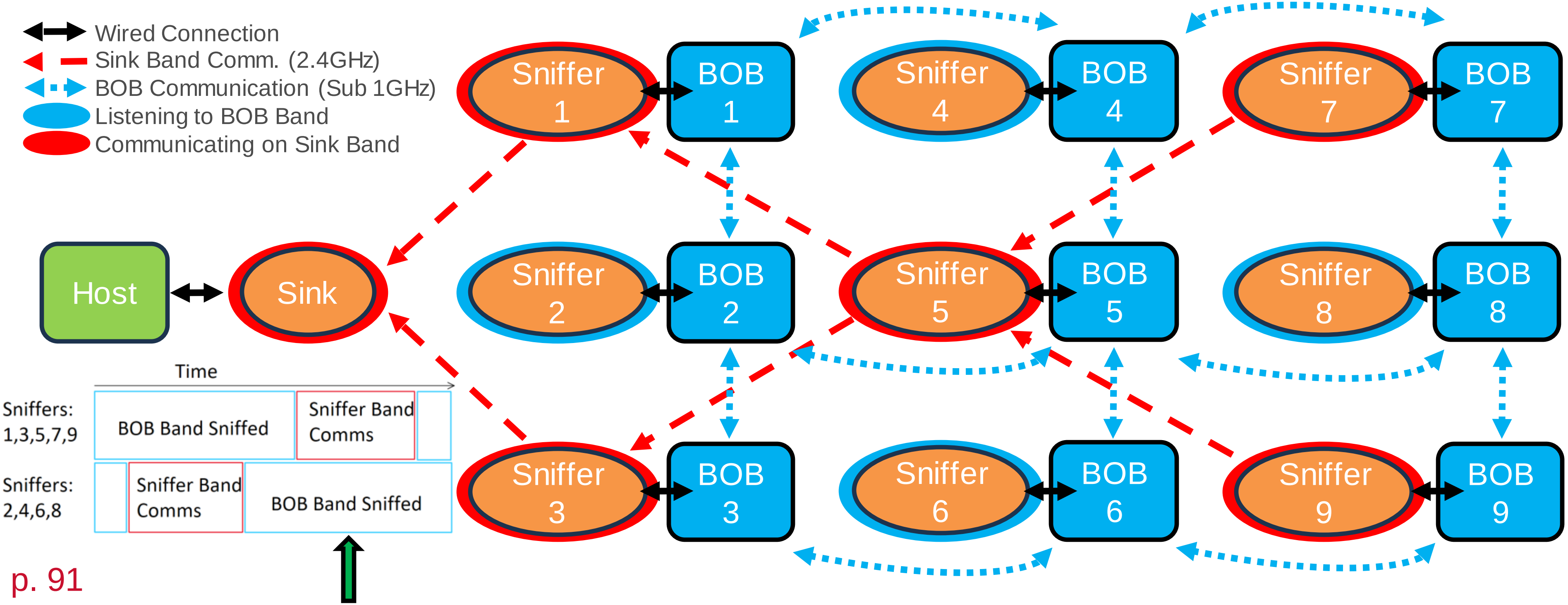
System Design



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Hardware Cost Estimates

Cost for Single Board										
Item #	Designator	Manufacturer	Mfg Part #	Description / Value	Package	Supplier	Link	Qty	Cost	Total Cost
1	U1	GLF Integrated Power	GLF1111	Power Switch/Driver P-Channel 2A	SOT-23-5L	DigiKey	https://www.d	1	0.33	0.33
2	C1, C2	Samsung Electro-Mechanics	CL05A104KA5NNNC	CAP CER 0.1UF 25V X5R 0402	0402	DigiKey	https://www.d	2	0.01	0.02
3	J1	Samtec Inc.	SSW-110-03-G-D	CONN RCPT 20POS 0.1 GOLD PCB	-	DigiKey	https://www.d	2	3.89	7.78
4	J2	Molex	22122024	TH, Right Angle 2 position 0.100" (2.54mm)	-	DigiKey	https://www.d	1	0.77	0.77
5	R1	Stackpole Electronics	RMCF0805ZT0R00	RES 0 OHM JUMPER 1/8W 0805	0805	DigiKey	https://www.d	1	0.018	0.018
6	-	-	-	Board Fabrication	-	JLCPCB	-	1	3.892	3.892
								Total Cost		12.48

Cost Per Breakout Board

Breakout Board PCB Total Cost (5 boards): $20

Cost for single board										
Item #	Designator	Manufacturer	Mfg Part #	Description / Value	Package	Supplier	Link	Qty	Cost	Total Cost
1	U1	GLF Integrated Power	GLF1111	Power Switch/Driver P-Channel 2A	SOT-23-5L	DigiKey	https://www	1	0.33	0.33
2	C1, C2, C3, C4, C10, C11	TDK Corporation	C1005X5R1A104M050B/	CAP CER 0.1UF 10V X5R 0402	0402	DigiKey	C1005X5R1A	6	0.021	0.126
3	J2	Samtec Inc.	SSW-110-03-G-D	CONN RCPT 20POS 0.1 GOLD PCB		DigiKey	SSW-110-03	2	3.89	7.78
4	J3	Molex	22122024	TH, Right Angle 2 position 0.100" (2.54mm)	-	DigiKey	https://www	1	0.64	0.64
5	C6, C7	TDK Corporation	C1005C0G1H220J050BA	CAP CER 22PF 50V C0G 0402	0402	DigiKey	C1005C0G1H	2	0.047	0.094
6	C12	TDK Corporation	C1005X7R1H102K050BA	CAP CER 1000PF 50V X7R 0402	0402	DigiKey	C1005X7R1H	1	0.051	0.051
7	C13	Murata Electronics	GRM155R61A106ME11D	CAP CER 10UF 10V X5R 0402	0402	DigiKey	GRM155R61A	1	0.091	0.091
8	J1	Sullins Connector Solutio	PRPC007SBAN-M71RC	CONN HEADER R/A 7POS 2.54MM	-	DigiKey	PRPC007SBA	1	0.191	0.191
9	Q1	EPSON	FC-135R 32.7680KA-A0	CRYSTAL 32.7680KHZ 12.5PF SMD	-	DigiKey	FC-135R 32	1	0.7	0.7
10	R1, R2, R3, R4, R5, R6, R	YAGEO	RC0402JR-070RL	RES 0 OHM JUMPER 1/16W 0402	0402	DigiKey	RC0402JR-0	17	0.0045	0.0765
11	R18	YAGEO	RC0402FR-0747KL	RES 47K OHM 1% 1/16W 0402	0402	DigiKey	RC0402FR-0	1	0.015	0.015
12	U2	Texas Instruments	MSP430FR5994IPN	IC MCU 16BIT 256KB FRAM 80LQFP	-	Mouser	MSP430FR59	1	11.27	11.27
13	Q2	DNP								
14	-	Würth Elektronik	60900213421	JUMPER W/TEST PNT 1X2PINS 2.54MM	-	DigiKey	6090021342	1	0.31	0.31
15	S1,S2	E-Switch	TL59NF160Q	SWITCH TACTILE SPST-NO 0.05A 12V	-	DigiKey	TL59NF160Q	2	0.284	0.568
16	J2 (trying another comp	Samtec Inc.	SSW-110-23-G-D	CONN RCPT 20POS 0.1 GOLD PCB	-	DigiKey	SSW-110-23	0	5.71	0
17	-	-	-	PCB Fabrication	-	JLCPCB	-	1	4.96	4.96
								Total Cost		27.2025

Cost Per MSP Simplified Single Board Cost

MSP Simplified PCB
Total Cost (10 boards): $31

Approximate Cost Per Board	
Breakout Board	~$17
MSP Simplified	~$31

Hardware Cost Estimates

Item #	Designator	Manufacturer	Mfg Part #	Description / Value	Package	Supplier	Link	Qty	Cost	Total Cost
1	U3,U5	Texas Instruments	CC1352R1F3RGZR	IC RF TXRX+MCU BLE 5.1 48VQFN		Digikey	https://www.d	2	7.2708	14.5416
2	Y1,Y3	EPSON	FC-135 32.7680KA-AG0	CRYSTAL 32.7680KHZ 7PF SMD		Digikey	https://www.d	2	0.505	1.01
3	Y2,Y4	Murata Electronics	XRCMD48M000F1P2AR(	48.0MHZ CRYSTAL UNIT +/-10PPM IN		Digikey	https://www.d	2	0.787	1.574
4	C4,C25	KYOCERA AVX	04026C105KAT2A	CAP CER 1UF 6.3V X7R 0402	0402	Digikey	https://www.d	2	0.32	0.64
5	L2,L3	TDK Corporation	MLZ2012N6R8LT000	FIXED IND 6.8UH 550MA 250MOHM SM		Digikey	https://www.d	2	0.0876	0.1752
6	C15,C21,C29,C32,C2	Murata Electronics	GRM188R60J226MEA0D	CAP CER 22UF 6.3V X5R 0603	0603	Digikey	https://www.d	5	0.0608	0.304
7	C16,C17,C18,C19,C20,C22,C3,C31,C33,C27,C28,C30,C34,C26	KYOCERA AVX	KGM05AR51A104KH	CAP CER 0.1UF 10V X5R 0402	0402	Digikey	https://www.d	14	0.0062	0.0868
8	FB1,FB2	Murata Electronics	BLM18HE152SN1D	FERRITE BEAD 1.5K OHM 0603 1LN	0603	Digikey	https://www.d	2	0.124	0.248
9	R15,R1	Vishay Dale	CRCW0402100KJNED	RES SMD 100K OHM 5% 1/16W 0402	0402	Digikey	https://www.d	2	0.0152	0.0304
10	R9,R10,R11,R13,R2,R18,R19,R20,R21,R22,R23,R24	Vishay Dale	CRCW0402100RJNED	RES SMD 100 OHM 5% 1/16W 0402	0402	Digikey	https://www.d	12	0.0127	0.1524
11	U1, U4,	Johanson Technology In	0900PC15A0036001E	RF Balun 862MHz ~ 928MHz, 2.4GHz ~ 2	0805	Digikey	https://www.d	2	0.5568	1.1136
12	J8, J4	TE Connectivity Linx	CONSMA001-SMD-G-T	SMA Connector Receptacle, Female Soc	-	Digikey	https://www.d	2	3.15	6.3
13	J3, J9	RF Solutions	CON-SMA-EDGE-S	SMA Connector Jack, Female Socket Bo	-	Digikey	https://www.d	2	2.2584	4.5168
14	S1,S2,S3	C&K	PTS 647 SM50 SMTR2 LF	SWITCH TACTILE SPST-NO 0.05A 12V		Digikey	https://www.d	3	0.236	0.708
15	R3,R4,R5,R6,R7,R8	KOA Speer Electronics, I	RK73H1ETTP2400F	RES 240 OHM 1% 1/10W 0402	0402	Digikey	https://www.d	6	0.0134	0.0804
16	D1,D2,D3,D4,D5,D6	Harvatek Corporation	B1931USD-20D000814	LED RED DIFFUSED 0603 SMD	0603	Digikey	https://www.d	6	0.056	0.336
17	J2	JST Sales America Inc.	S2B-PH-K-S	Connector Header Through Hole, Right A	TH	Digikey	https://www.d	1	0.136	0.136
18	L1	TDK Corporation	MLZ2012N6R8LT000	6.8 μH Shielded Multilayer Inductor 550 mA 250mOhm 0805 (2012 Metric)	0805	Digikey	https://www.d	1	0.095	0.095
19	C1	Murata Electronics	GRM188R61A106ME69 D	10 μF ±20% 10V Ceramic Capacitor X5R 0603 (1608 Metric)	0603	Digikey	https://www.d	1	0.098	0.098
20	J1	Sullins Connector Soluti	PRPC003SAAN-RC	CONN HEADER VERT 3POS 2.54MM		Digikey	https://www.d	1	0.076	0.076
21	J7	DIKAVS	n/a	ment conn 2x7pin. Using breakaway pins	n/a	Amazon	B3XBYL3J/ref=	1	11.99	11.99
22	J5,J6	Samtec Inc.	FTSH-105-01-F-DV-P-TR	CONN HEADER SMD 10POS 1.27MM		Digikey	https://www.d	2	2.568	5.136
23	SW1	CTS Electrocomponents	219-8MST	SWITCH SLIDE DIP SPST 0.1A 20V		Digikey	https://www.d	1	0.911	0.911
	RF Test Plan Capacitors below:									
24	n/a, C9, C10, C8, C35	Kemet	CBR04C108B5GAC	0.1 pF ±0.1pF 50V Ceramic Capacitor C	0402	Digikey	https://www.d	4	0.0626	0.2504
30	n/a, C42, C23	Murata Electronics	GJM1555C1H120JB01D	12 pF ±5% 50V Ceramic Capacitor C0G,	0402	Digikey	https://www.d	2	0.06	0.12
31	n/a	Murata Electronics	GJM1555C1H180GB01D	18 pF ±2% 50V Ceramic Capacitor C0G,	0402	Digikey	https://www.d	2	0.12	0.24
								Total Cost		**50.8696**

Cost Per Sniffer Single Board Cost

Sniffer PCB and Stencil Total Cost (15 boards): $81

Approximate Cost Per Board	
Sniffer Board	~$56

Note for Self: add battery cost into this

Hardware Cost Estimates

Total Senior Design Hardware Costs		
Order #	**Order Description**	**Cost**
1	Breakout Board PCB & Part Ord	37.83
2	MSP REV 1 PCB & Part Order	203.8
3	MSP REV 2 PCB & Part Order	30.8
4	Sniffer REV 1 PCB & Part Order	611.88
5	Battery Order	112.05
6	Extra Component Order	29.29
	Total Cost:	**1025.65**

Stack Pinouts

SD)

Table 1

GPIO	MSP430	CC1352 radio	I/O (as seen from the msp)
Data Received	P5.0	DIO22	I
Transmit Request	P5.1	DIO3	O
Transmit Done	P5.2	DIO24	I
SPI Master Ready	P5.3	DIO19	O
SPI Slave Ready	P5.4	DIO7	I
FRAM Written	P5.5	DIO11	O
Power radio	PJ.4		
SPI MOSI	P6.4	DIO9	
SPI MISO	P6.5	DIO8	
SPI CLK	P6.6	DIO10	
SPI SS	P6.7	DIO20	O

Table 2

GPIO	MSP430	CC1352 radio	CC1352 sniffer		Harvester	I/O
Powered ON	P7.7		DIO25	DIO28		O
Event Gen	P7.4		DIO26	DIO29		I
Testbed Reset	P7.5		DIO27	DIO30		I
Easylink Tx		DIO25	DIO24	DIO21		
Event drop	P7.6		DIO9	DIO8		O
Reset	P7.3				Reset	I

Note currently in our setup we have only one sniffer for two msp430 nodes. I/O are defined with respect to msp430 node

Code needs update

Figure 12: Plan to Create Extra NC Pins on the CC1352R Development Board

Stack Pinouts

MSP Board Pinout

Pin #	Func	Pin #	Func	Pin #	Func	Pin #	Func
1	3V3 to CC	21	3V3	40	P5.4	20	GND
2	GPIO	22	GND	39	GPIO	19	P5.1
3	GPIO	23	NC	38	P6.7	18	P5.5
4	GPIO	24	GPIO	37	P3.5	17	GPIO/EN
5	P5.0	25	GPIO	36	GPIO	16	NC
6	P5.2	26	GPIO	35	GPIO	15	P6.4
7	P6.6 (SPI)	27	GPIO	34	RST_MSP	14	P6.5
8	P1.0	28	P7.3	33	P1.1	13	P1.6
9	P7.4	29	P7.5	32	P1.7	12	P2.6
10	P7.6	30	P7.7	31	P2.5	11	GPIO

Figure 14: MSP Simplified Pinout

Stack Pinouts

Harvester Board Pinout							
Pin #	Func	Pin #	Func	Pin #	Func	Pin #	Func
1	NC	21	3V3	40	P5.4	20	GND
2		22	GND	39		19	P5.1
3		23	NC	38	P6.7	18	P5.5
4		24		37	P3.5	17	
5	P5.0	25		36		16	NC
6	P5.2	26		35		15	P6.4
7	P6.6	27		34		14	P6.5
8	P1.0	28	P7.3	33	P1.1	13	P1.6
9	P7.4	29	P7.5	32	P1.7	12	P2.6
10	P7.6	30	P7.7	31	P2.5	11	

Figure 15: Power Harvester Pinout

LIPO Cost Estimate (Slightly Outdated)

Item	Cost per Item	Quantity	Total Cost
LIPO	$5.00	10	$50.00
Battery Mount	$3.00	10	$30.00
Protection/Management ICs	$0.50	10	$5.00
Charger ICs and parts	$1.00	10	$10.00
Charger PCB	$15.00	1	$15.00

Cost per board: $11.00

Updated cost per board (no charging board): $9.5

Time Skew Analysis

CC1352 clock was ran with constant time reporting, compared to real-time clock

Skew ended up > .005%, .01% between any given 2 nodes

Two nodes skewing in opposite directions: take 50 seconds to skew by 5 ms

Prototype Implementations - ????

No Transmit	Min	Max	Mean
Power (mW)	4.6707	7.5945	5.9900
Current (mA)	1.4154	2.3014	1.8152

Transmit every 5ms	Min	Max	Mean
Power (mW)	4.6707	7.5945	5.9900
Current (mA)	1.4154	2.3014	1.8152

$$P_{avg} = 0.5(5.99) + 0.5(26.09) = 16.04mW$$

$$E_{wk} = P_{avg}(7)(24)(60)(60) = 9.701kJ$$

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Prototype Implementations - ????

No Transmit	Min	Max	Mean
Power (mW)	4.6707	7.5945	5.9900
Current (mA)	1.4154	2.3014	1.8152

$$capacity-needed = (0.5(I_{normal}) + 0.5(I_{trans,5ms}))(7)(24)$$

$$capacity-needed = ((0.5)(1.8152) + (0.5)(7.9060))(7)(24) = 816.581\,mAh$$

Transmit every 5ms	Min	Max	Mean
Power (mW)	4.6707	7.5945	5.9900
Current (mA)	1.4154	2.3014	1.8152

$$\boxed{capacity-needed = \left(\frac{P_{avg}}{V_{supplied}}\right)(7)(24) = \frac{2695}{V_{supplied}}\,mAh}$$

+10% buffer

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