3 Sensor Tag Design

The RF sensor tag can be realized on a single printed circuit board. The specifications for construction and operation follow.

3.1 RF Sensor Tag

The RF sensor tag comprises of a microcontroller to sample and transmit analog sensor inputs, a high-frequency FET switch for load modulation of data, and a reflecting patch antenna that accepts a CW signal from the transmitter (4) and reflects this signal with modulated data back to the receiver (5). These operations are summarized by the block diagram in Figure 15.

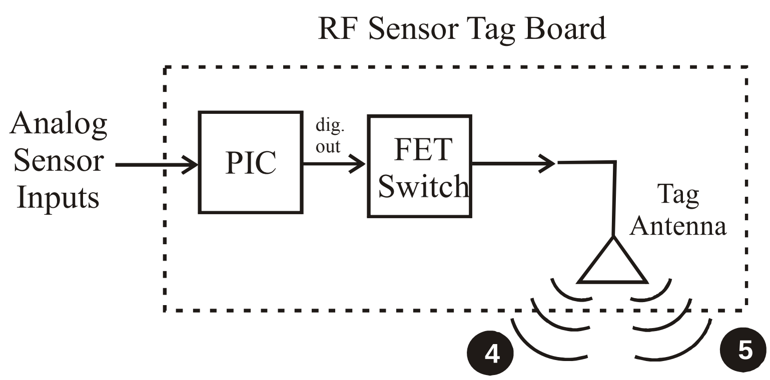

Figure 15: Block Diagram for RF Sensor Tag.

Figures 16 and 17 show photographs of the final realized RF tag board design, complete with 5.8 GHz patch antenna. Figures 18 and 19 illustrate the circuit and board diagrams that constitute the RF backscatter tag. Table 4 provides a list of components used in populating this circuit board.

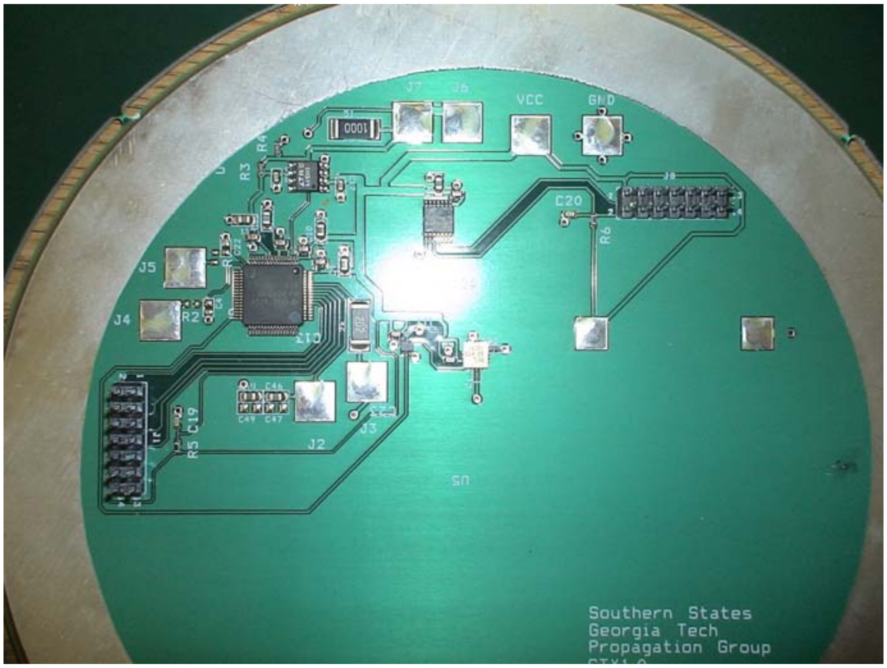

Figure 16: Photograph of an RF Tag circuit board (baseband side).

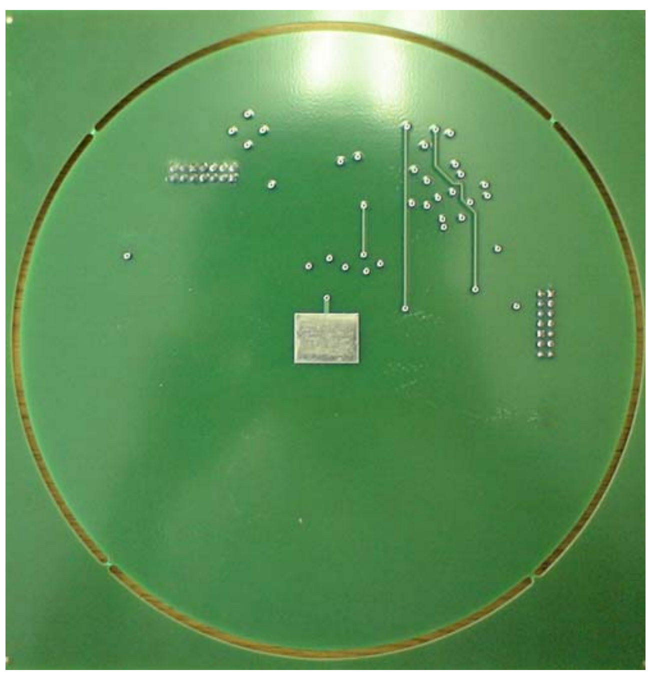

Figure 17: Photograph of an RF Tag circuit board (antenna side).

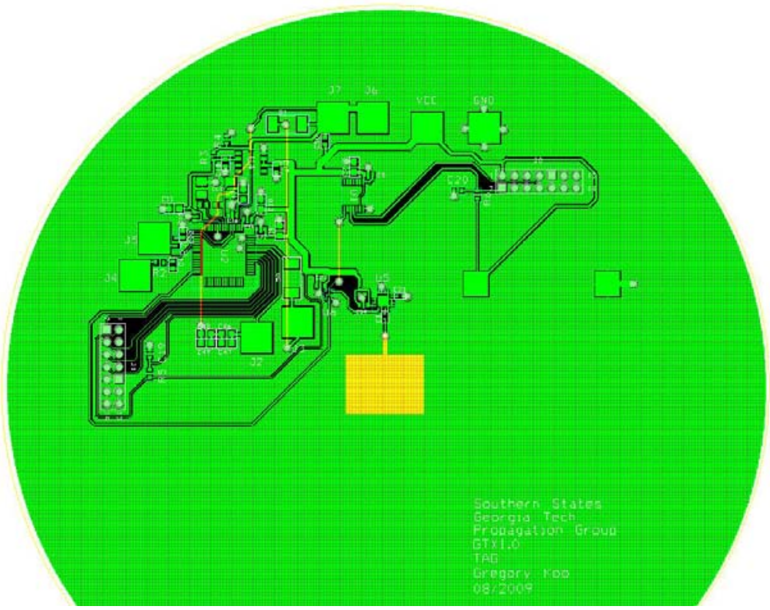

Figure 18: RF tag circuit board layout.

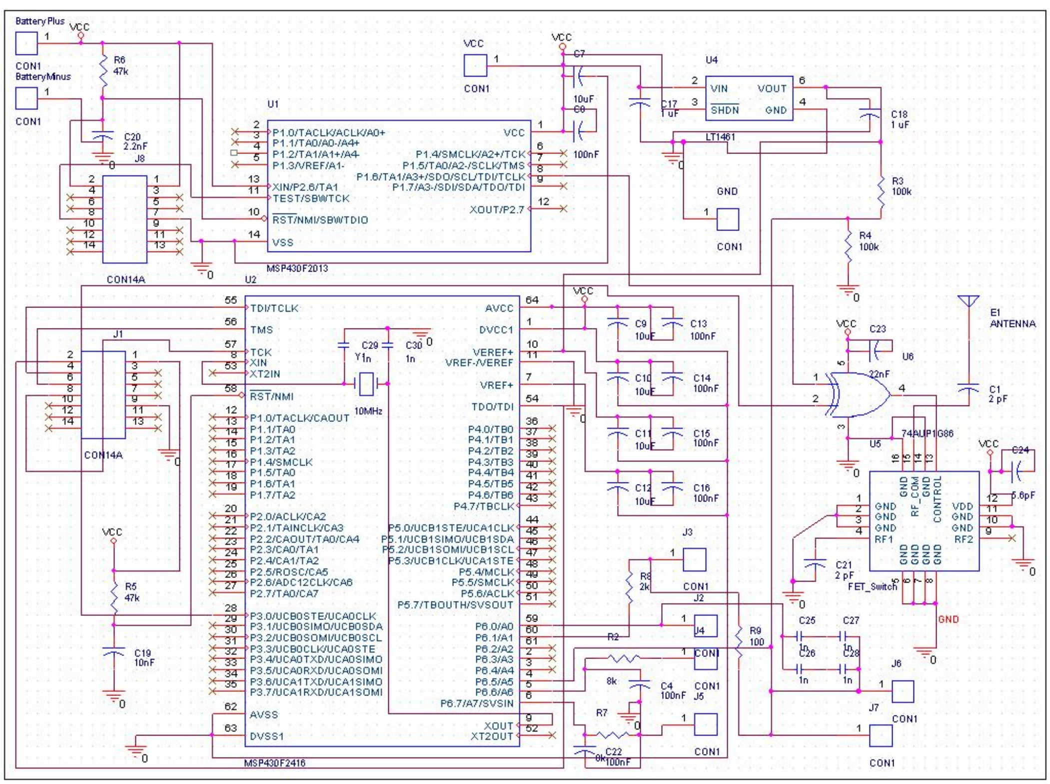

Figure 19: Schematic for the RF tag circuit board.

Table 4: Bill of Materials for RF sensor tag board

Quantity	Part Reference	Value	Part Number	Cost
Parts Purchased from Digikey at http://www.digikey.com				
7	46,48,C7,C9 C10,C11,C12	10µF	490-3905-1-ND	\$0.53
2	C17,C18	1uF	445-1818-1-ND	\$0.58
2	C1,C21	2pF	478-4410-1-ND	\$1.98
5	C8,C13,C14, C15, C16	100nF	709-1101-1-ND	\$0.74
1	C23	22nF	709-1087-1-ND	\$0.66
1	C24	5.6pF	709-1000-1-ND	\$0.49
1	C20	2.2nF	478-3705-1-ND	\$0.30
1	C19	10nF	399-1092-1-ND	\$0.03
2	R3,R4	100kΩ	311-100KDCT-ND	\$0.17
2	R5,R6	47kΩ	P47.0KHCT-ND	\$0.07
1	51	100Ω	541-100AFCT-ND	\$0.40
1	50	2kΩ	PT2.0KXCT-ND	\$0.40
1	U4	3V Regulator	LT1461DHS8-3#PBF-ND	\$3.00
1	U6	XOR Gate	568-2571-1-ND	\$0.36
1	U1	MSP430F2013	MSP430F2013TPW-ND	\$1.96
1	U2	MSP430F249	296-23084-1-ND	\$9.50
2	J1,J8	14pin Conn	WM26914-ND	\$1.60
Parts Purchased from Minicircuits at http://www.minicircuits.com/				
1	U5	FET Switch	CSWA2-63DR+	\$14.95

3.2 Data Packet

The data packet is constructed as shown in Figure 20. After the analog values for the coarse CT, fine CT, and 1.5V reference input are sampled, an offset error is calculated and removed from the coarse and fine ct values. Since the microcontroller ADC provides 12 bit quantization, the output of ADC follows the given formula,

$$N_{ADC} = 4095 \ x \ \frac{Vin - V_{R-}}{V_{R+} - V_{R-}}$$

Onboard the tag, the ADC is provided a 3V reference by an LT1461 voltage regulator instead of the ADC's internal reference to reduce noise. The coarse and fine CT circuits are provided a 1.5V DC bias to maintain positive voltages. A theoretical mean value of 2047 is the output of the ADC when both the coarse CT and fine CT are not being driven. During operation, the coarse and fine ct swing about this 1.5V bias, and it becomes crucial to maintain an accurate dc offset since values used at the receiver depend on microvolt accuracy. Thus, before stored in a packet, the 1.5V ADC reference is sampled and compared against its theoretical value of 2047 and an offset error is determined. The error is then removed from the CT data.

Next, a three-bit cyclic redundancy check (CRC) is created for both the coarse and fine CT. Once the checksum process is completed, the CT data, checksum, and sync bits are merged together to form a complete packet. The packet is then transmitted out least significant bit first. Note that the coarse and fine CT sub segments are also least significant bit first.

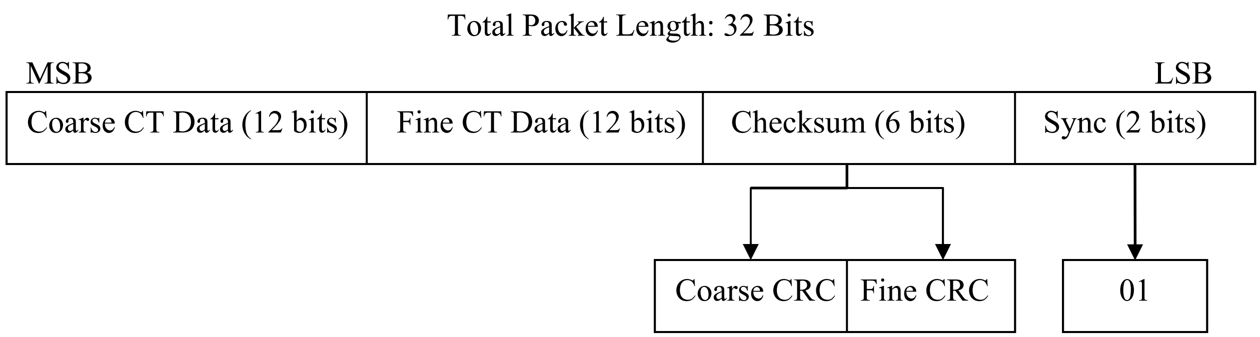

Figure 20: GTX1.0 data packet format.

3.3 Spread Spectrum Multiple Access

Multi-User Interference

In spread spectrum system design, the limiting factor is multi-user interference. For each additional user that operates within range of a receiver, the carrier to interference ratio (CIR) is given by,

$$CIR = \frac{M \times P_{desired\ user}}{P_n + (Q-1) * P_{users}}.$$

If the system is not noise limited and perfect power control is assumed, the previous equation can be approximated as

$$CIR = \frac{M}{(Q-1)}.$$

Here Q represents the total number of active users (tags), in view of a receiver in a perfect power environment. For a typical setup, the number of tags in an environment cannot be reduced in order to increase the CIR, since a minimum number of tags may be required for operation. The only variable that can be controlled becomes M, the processing gain.

Processing gain M is essentially a quality factor that determines how efficiently a given spread spectrum system will work. The higher the processing gain, the higher the bit error rate, which results in a more solid informational link. To increase processing gain, the relative rates between a chipping sequence, and the data sequence that it modulates must be changed. Processing gain is given as

$$M = \frac{Chip\ Rate}{Data\ Rate},$$

where the chip and data rate can be determined in terms of bits per seconds. For the Southern States implementation, the ratio of the chip rate to the bit rate is 63. This means that for every data bit, there are 63 chips. To increase the chip rate, repeated chip sequences may be sent out per bit, or a longer chipping sequence may be used.

Spreading Sequence Selection

However, there are subtle differences between the various spread spectrum sequences available. For example, consider two different chipping sequences, such as a 63 bit long Gold sequence and a Kasami sequence. If both sequences were implemented in a spread spectrum system, the processing gains would be equal if the chip rates were identical. This leads to the incorrect assumption that using one sequence versus another does not matter. For a system with few active users, this assumption can be approximated as true, but for a large number of users, a noticeable difference between CIR will result when different types of sequences are used.

The explanation for this result can be found within the cross correlation properties that a set of sequences exhibits. Spread spectrum sequences such as the Gold and Kasami exhibit a property that for any pair of spreading sequences generated by each method, a hard cross-correlation bound results. When multiple users are present in a system, the cross correlation between the desired user and interfering users adds to the interference. For each additional user, interference increases by an amount proportional to the cross correlation.

As example, Figures 21 and 22 show the autocorrelation between two Gold sequences and two Kasami sequences, respectively.

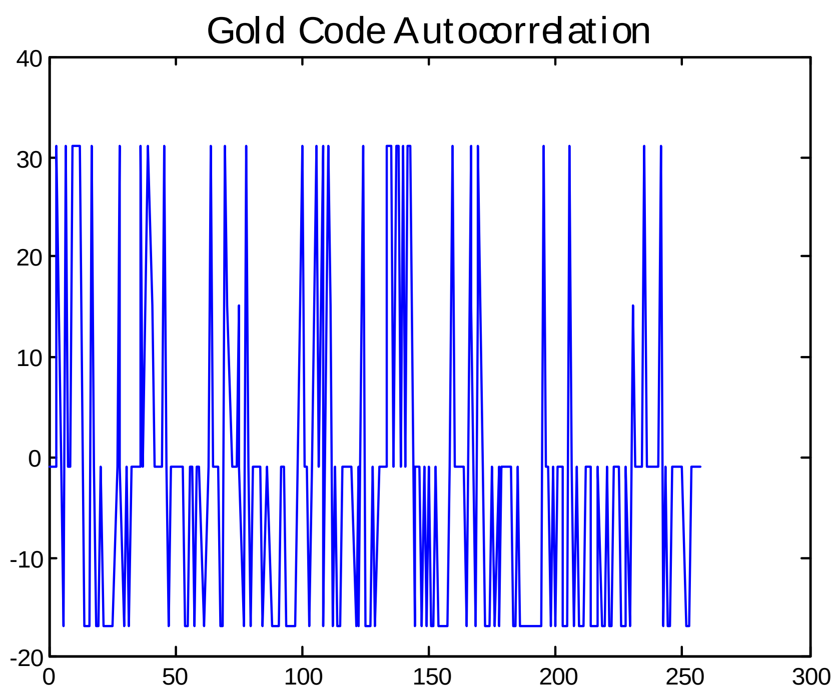

Figure 21: Example autocorrelation for a 255-chip Gold code spread-spectrum sequence.

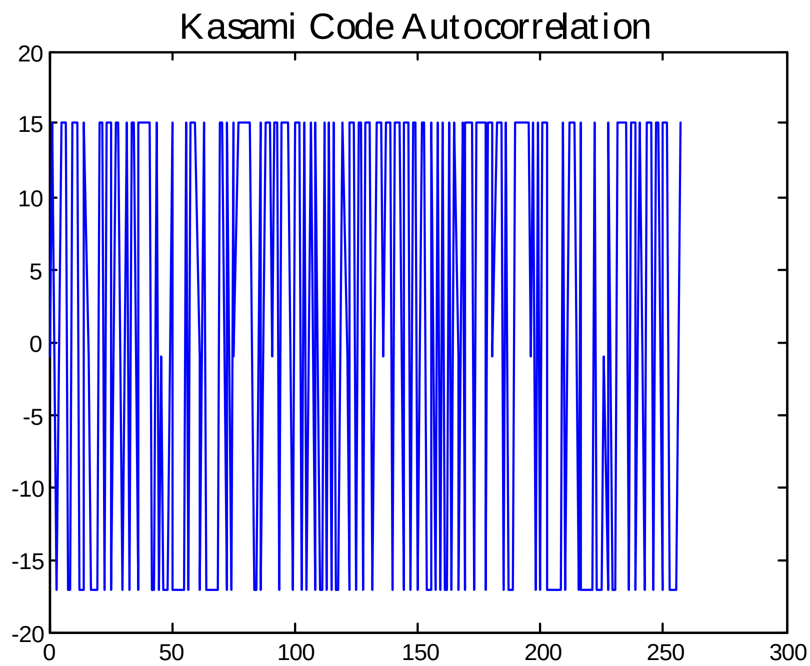

Figure 22: Example autocorrelation for a 255-chip Kasami code spread-spectrum sequence.

The Gold sequences have an upper cross correlation bound of 31, and the Kasami, 15. This means that for each additional user, the multi-user interference increases linearly by 31 and 15. For a three user system, the following theoretical CIR results

$$CIR = \frac{M}{(Q-1)}$$

$$CIR_{GOLD,KASAMI} = \frac{255}{(3-1)} = 127.5 = 21dB$$

However, the processing gain *M* used above is incorrect for non-ideal sequences because perfect cross correlation is assumed. For some sequences, such as the orthogonal spreading sequences, this assumption will hold, but for the Gold and Kasami sequences, the processing gain must be altered to include non-ideal cross correlation. Instead, let M be defined as

$$M_{ACTUAL} = \frac{Max\ Autocorrelation\ Value}{Max\ Cross\ Correlation\ Value}.$$

Implementing this improved processing gain equation, the CIRs of the respective codes now become,

$$CIR_{ACTUAL} = \frac{M_{ACTUAL}}{Q-1}$$

$$CIR_{GOLD} = \frac{255/31}{(3-1)} = 4.11 = 6.14dB$$

$$CIR_{KASAMI} = \frac{255/15}{(3-1)} = 8.5 = 9.29\,dB$$

As a result of the lower cross correlation bound, the Kasami sequences provide approximately a 3 dB improvement in CIR. By taking the cross correlation bounds into account, an optimal spreading method was selected in order to increase CIR, increase BER, and decrease the required chip rate.

After a thorough review of the many direct sequence spread spectrum sequences available, the Kasami sequences were selected since they exhibit the lowest cross correlation bound for non-orthogonal spreading sequences. Note that orthogonal codes were not reviewed since clock synchronization between tags would not be possible in a passive backscatter sensor.