RF Receiver and Transmitter for Insect Mounted Sensor Platform

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***Abstract*— Low power consumption is a key design requirement for many systems, particularly small sensor platforms. Sub-threshold design allows for very low power operation of digital systems, especially when increased signal delay is not an issue. The objective of the work presented in this paper is to create a low power, small transmitter utilizing a sub-threshold IC, along with off-the-shelf components. This transmitter will be used for a low power sensor platform carried by a cockroach. We have earlier designed and fabricated a low power digital sub-threshold Binary Frequency Shift Keying (BFSK) modulator chip in a TSMC 0.25μm triple well CMOS process. This chip sends out two tones at 115KHz and 345KHz, corresponding to a binary data input. In this paper, we implement the RF transmitter circuit using this BFSK modulator chip with a carrier frequency of 80MHz. This RF transmitter circuit is designed and implemented using off-the-shelf components so that the overall transmitter board (BFSK modulator chip, RF circuit, antenna and batteries) is light, small and has a low power consumption. The signal was transmitted through a small coil antenna for the receiver base station, up to 100 feet away. We also implemented the RF front end and the demodulator circuit for the receiver base station. The receiver base station amplifies and filters the signal, then mixes the signal back down to the baseband. Our demodulator circuit is able to retrieve the original transmitted signal with an SNR of 10dB, at a distance of 100 feet.**

I. Introduction

Wireless sensors are widely used is several applications such as surveillance, environment and habitat monitoring, medical applications, home automation, and traffic control [1], [2]. Typically, these wireless sensors are equipped with sensor devices, a radio transceiver and a battery. A sensor node collects data and then wirelessly communicates it to a base station or to other sensor nodes. A collection of sensor nodes which co-ordinate amongst other to send the gathered information to a base station forms a wireless sensor network (WSN).

Sensor nodes can be mounted on small robots to explore regions where it is impossible for humans to reach. These robots can be either man-made robots or biological insects such as cockroaches, honey-bees, etc. Recent advancements in wireless sensor electronics have made it possible to use small insects as robots [3], [4]. In this work, we propose to use cockroaches as biological robots to carry the electronics of sensor nodes. The cockroaches are small insects and hence cannot carry payloads. Also, in order not to significantly affect the behavior of cockroaches, the form factor of the payload needs to be small. Through experiments, we found that an American cockroach can easily carry 5 grams of load on its back without significantly affecting its motion. The payload can be a printed circuit board (PCB) of dimensions up to 3.5cm $\times$ 1.5cm (length $\times$ breadth). Such a PCB must contain all electronics of the sensor node (i.e. sensing devices, radio electronics, antenna and battery). Also, once the sensor node (on a cockroach) is powered and left in a field to gather information, it difficult to replace the battery of the node. Thus, it is necessary that the electronics of the sensor node consumes *low power* so that the node can gather information for a long duration.

In order to implement a low power, small and light-weight sensor node, we utilize a sub-threshold IC (presented in [3]) in addition to off-the-shelf components for the transmitter of the sensor node. We have earlier designed and fabricated a low power digital sub-threshold Binary Frequency Shift Keying (BFSK) modulator chip in a TSMC 0.25μm triple well CMOS process [3]. This chip sends out two tones at 115KHz and 345KHz, corresponding to a binary data input. In this paper, we implement the RF transmitter circuit based on this BFSK modulator, with a carrier frequency of 80MHz. This RF transmitter circuit is designed and implemented using off-the-shelf components so that the overall transmitter board (BFSK modulator, RF mixer, antenna and batteries) is small, light and consumes low power. The signal was transmitted through a small coil antenna to the receiver base station, up to 100 feet away. We also implemented the RF front end and the demodulator circuit of the receiver base station. The base station amplifies and filters the signal, then mixes the signal back down to the baseband. Our demodulator circuit is able to retrieve the original signal with an SNR of 10dB, at a distance of 100 feet.

The rest of the paper is organized as follows. In Section II we describe the overall transmitter board and the receiver base station design. In Section III, we present system level results we obtained, followed by conclusions in Section IV.

II. Our Approach

A system level diagram of the wireless communication setup proposed in this paper for communication between a sensor node and the receiver base station is shown in Figure 1. As shown in Figure 1, the input to the transmitter (TX) of a sensor node is a serial binary data stream of data rate up to 32Kbps. The BFSK modulator chip [3] (consisting a digital modulator and a digital to analog (DAC) converter) modulates the input data and produces two tones at 115KHz and 345KHz corresponding to a 0 (LOW) and 1 (HIGH) binary data input respectively. The output of the BFSK chip (the output of the DAC, which is a baseband signal) is mixed with a sinusoidal signal at 80MHz (generated using a local oscillator (LO)) and then wirelessly transmitted. At the receiver (RX) base station, the RF signal from the receiving antenna is filtered using a bandpass filter (with a pass band of 58-83MHz) before amplifying it by using a low noise amplifier (LNA). The output of the LNA is again filtered using a bandpass filter (with a pass band of 58-83MHz) and then mixed with sinusoidal signal at 80MHz to obtain the baseband signal from the RF signal at the receiver side. The output of the RX mixer, which is the baseband signal, is then demodulated using a demodulator circuit to replicate the binary data transmitted by the TX. In the following sub-sections, the transmitter and the receiver implementations are discussed in detail. Specifically, Section II-A describes the transmitter implementation proposed in this paper (both BFSK modulator chip and RF front end). The receiver base station implementation is discussed in Section II-B. The different antennas used in this work are presented in Section II-C.

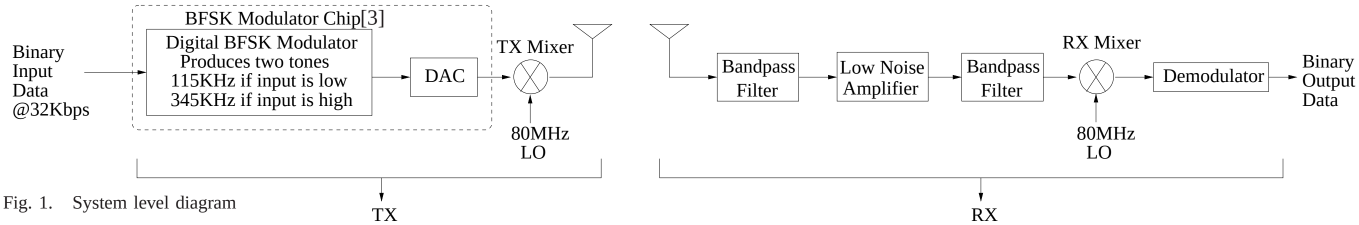

Fig. 1. System level diagram

A. Transmitter

The transmitter shown in Figure 1 has two parts: the sub-threshold BFSK modulator chip with DAC and the RF transmitter section (TX mixer, oscillator). The sub-threshold BFSK chip is briefly described next.

1) Sub-threshold BFSK Modulator Chip

In [3], we presented a low power digital sub-threshold Binary Frequency Shift Keying (BFSK) modulator chip which was designed and fabricated in a TSMC 0.25μm triple well CMOS process. The die photo of the sub-threshold BFSK chip is shown in Figure 2. Sub-threshold circuits are know to exhibit an exponential sensitivity to process, voltage and temperature (PVT) variations. Therefore, to stabilize the performance of the sub-threshold BFSK modulator chip, we used a self-adjusting body bias technique, to phase lock the circuit delay to a reference signal (which is referred to as a *beat clock*) [5]. The digital BFSK modulator circuit was implemented using a network of interconnected, medium-sized Programmable Logic Arrays (PLAs). The output of the digital BFSK modulator circuit is driven to a digital to analog converter (DAC), also implemented on the same die. The BFSK modulator (digital BFSK modulator and DAC) is capable of modulating digital signals with a data rate of up to 32KHz. It sends out two tones at 115KHz and 345KHz, corresponding to a 0 (LOW) and 1 (HIGH) binary data input respectively. Figure 3 is an oscilloscope plot showing the output of the DAC (bottom waveform) for an input signal to the digital BFSK modulator circuit that makes a LOW to HIGH transition (top waveform). Note that the DAC output clearly shows two tones depending on the value of the input. As reported in [3], the sub-threshold BFSK circuit is able to operate using 19.4× lower power than a traditional standard cell based implementation of the same function (which was also fabricated on the same die for comparison).

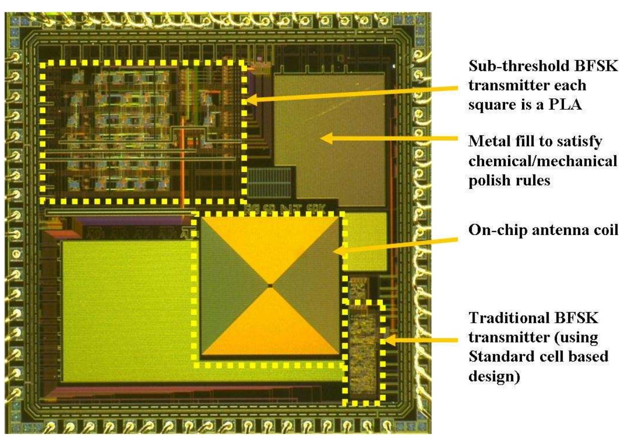

Fig. 2. Die photo of the sub-threshold BFSK chip [3]

The sub-threshold BFSK chip requires a clock signal at 1MHz. This clock signal is generated on the transmitter board using an astable RC OP-AMP circuit. The duty cycle for this clock signal is 90%.

2) RF Transmitter Circuit

As shown in Figure 1, the RF front end of the transmitter mixes the output of the sub-threshold BFSK chip (which is the output of the

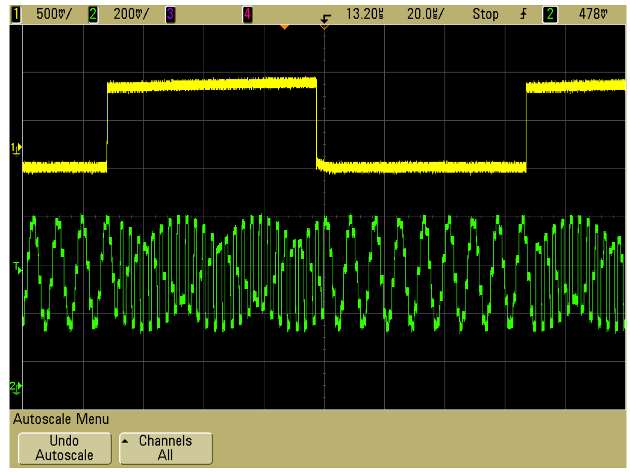

Fig. 3. BFSK Modulation Signal [3]

DAC) with a sinusoidal signal at 80MHz to produce the RF signal. This RF signal is then sent to the transmitting antenna for wireless transmission.

In this work, we use a SA602 mixer chip [6] to mix the BFSK modulated signal from the DAC and an 80MHz sinusoidal signal. The SA602 is a low-power high frequency monolithic double-balanced mixer and is suitable for radio applications [6]. The inputs and output of the SA602 mixer are differential signals. A 80MHz crystal ECX-2236 [7] was used as a local oscillator (LO) for producing the 80MHz sinusoidal input to the SA602 mixer chip. All inputs and outputs were decoupled by 47nF capacitors. The resulting transmitter (the printed circuit board with all the components) that we designed except the transmitting antenna is shown in Figure 4. All components are SMD (surface mounted device) type so as to minimize PCB weight and area. Note the transmitter shown in Figure 4 weighs less than 5 grams and its dimensions are 3.5cm × 1.6cm. We experimented with different antennas for the transmitter, as discussed in Section II-C.

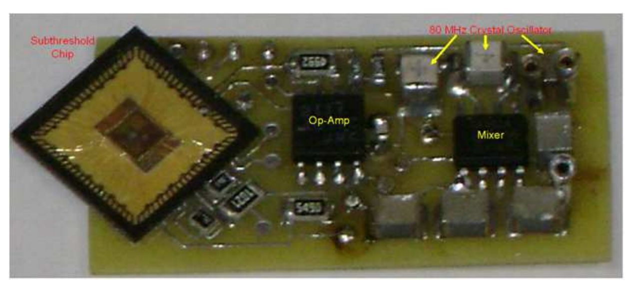

Fig. 4. Transmitter board

B. Receiver

The receiver shown in Figure 1 also has two parts: the RF front end and the demodulator circuit. The RF front end for the receiver is described next.

1) RF Front End for Receiver

At the receiver side, the RF signal received by the receiving antenna is fed to a passive bandpass filter PIF-70+ [8] as shown in Figure 1. PIF-70+ bandpass filter has 58MHz to 83MHz as the passband range with $<$ 1dB loss and stopband frequencies (loss $>$ 10dB) at 16MHz and 280MHz [8]. The output of this bandpass filter is fed to a low noise amplifier (LNA). We used the ZX60-33LN+ LNA [9] for amplifying the filtered RF signal received from the antenna. ZX60-33LN+ is a coaxial type wide bandwidth (50MHz to 3000MHz) LNA with a low noise figure of 1.0dB and a gain of $\sim$ 21.9dB for frequencies less 100MHz. The supply voltage for this LNA is 5V DC. Since the carrier frequency for our transmitted signal is 80MHz, this LNA is suitable for our application. As shown in Figure 1, the output of this LNA (which is the amplified received RF signal) goes into another bandpass filter PIF-70+ to filter out frequencies outside our range of interest, amplified by the LNA.

The output of the second bandpass goes to a mixer for recovering the baseband signal from the RF signal. Similar to the TX board, the SA602 mixer chip is used along with the 80MHz crystal ECX-2236. The output of the SA602 mixer is a baseband signal which is demodulated using a demodulator circuit to recover the transmitted binary data. Figure 5 shows the receiver board that we fabricated containing the bandpass filters, the LNA and the mixer chip.

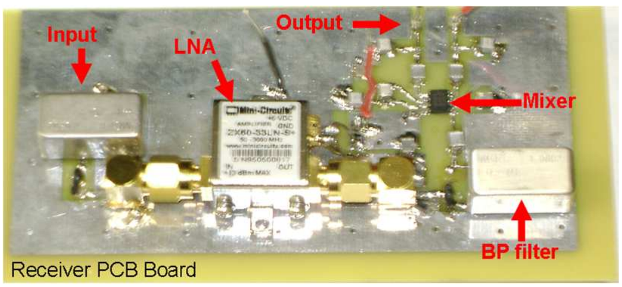

Fig. 5. Receiver board

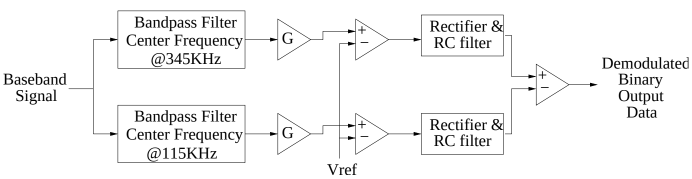

Fig. 6. Demodulator circuit block diagram

2) Demodulator Circuit

A block level diagram of the demodulator circuit we implemented is shown in Figure 6. As shown in Figure 6, the baseband signal output of the RX mixer is passed through two bandpass filters in parallel. One of these bandpass filter has center frequency at 115KHz while the other filter has at 345KHz (as shown in Figure 6). The modified Deliyannis topology [10] was used to implement these bandpass filters. The bandpass filter with center frequency at 115KHz significantly attenuates signal at frequencies greater than 300KHz. Similarly, the bandpass filter at 345KHz significantly attenuates signal at frequencies below 150KHz. Therefore, one bandpass filter passes the 115KHz tone while the other one passes the 345KHz tone. The output of these bandpass filters goes to amplifiers with a gain value of G. Then the output of the amplifiers is compared with a reference voltage ($Vref$) and then the resulting signals are passed on to rectifiers and RC filters. The rectifiers were implemented as a pn diode connected in series with a capacitor (whose other terminal was grounded). The p-terminal of the diode is the input of the rectifier and the n-terminal of the diode (connected to the capacitor) is the output of the rectifier. Low pass RC filters are used to remove high frequency signals present in the output of the rectifiers. The output of both RC filters (rectifier and RC filter blocks shown in Figure 6) are compared with each other using a comparator. This comparator outputs 1 (0) if the voltage signal corresponding to 345KHz tone (top input of the comparator) is higher (lower) than the voltage signal corresponding to 115KHz (bottom input of the comparator). Thus, the output of this final comparator is the demodulated binary output data. Note that off-the-shelf components are used for implementing the demodulator circuit. A picture of our complete receiver setup is shown in Figure 7. This picture shows the receiving antenna, receiver board, supply voltage and oscilloscope (the demodulator circuit can not be seen in the picture).

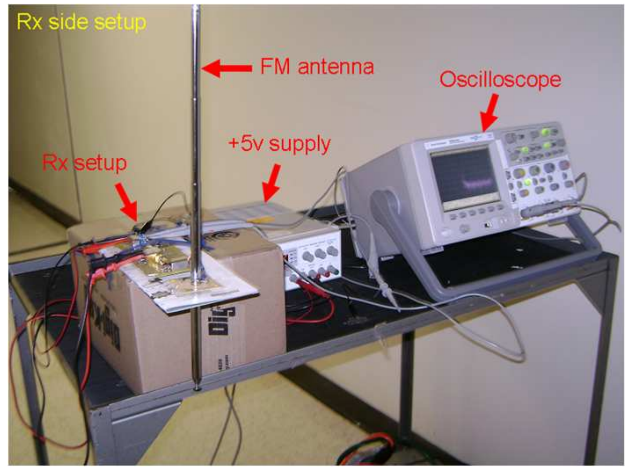

Fig. 7. Receiver Setup

C. Antenna

Low power wireless transmission requires a precisely tuned antenna for both TX and RX. Note that the antenna size limitation comes from the half-wave dipole equation which is $length\_of\_antenna = \lambda/2 = c/2f$. Thus, a lower frequency signal requires a longer antenna to match the wavelength of the signal. Mixing the 115kHz chip output with the 80MHz LO signal reduces the required antenna length from 1.3km (for 115KHz signal) to just 1.87m. Several implementations of TX antennas were tested (for 80MHz signal). Due to the size restrictions on the transmitter side, coiled wire antennas, and board style antennas shown in Figure 8 were primarily considered. Omnidirectional properties must were considered critical for our application.

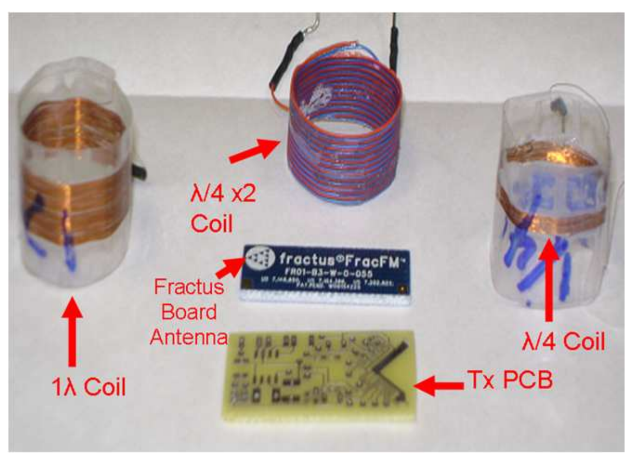

Fig. 8. Different antennas which were used

We referred to a hand book on antenna design [11] to explore different antenna designs that can be used for our application. Based on this book, we designed the following antennas: λ 36AWG wire coil, $\lambda/4$ 36AWG wire coil, $\lambda/4$ 30AWG wire coil, 0.08λ 36AWG wire coil, $\lambda/2$ 30AWG wire coil antenna, $\lambda/2$ dipole antenna made from wire and a board antenna by Fractus. Some of these antennas are shown in Figure 8. The $\lambda/2$ dipole antenna made from 22AWG wire performed best. We used that as a benchmark for testing the other antennas. The second best was 0.08λ 36AWG wire coil antenna. We also tried arrays of small diameter coils wound around coffee stirrers for $\lambda/2$ and $\lambda/4$ 36AWG coil antennas. These antennas also performed reasonably well.

The RX side antenna was not restricted by size. A standard FM band telescopic antenna was used to receive the 80MHz transmission. Specifically, the antenna used at the receiver base station is a 0.5 wavelength dipole made with two extendable FM antennas as shown in Figure 7.

III. Experimental Results

We implemented our system shown in Figure 1 in hardware and verified its functionality and performance. The pictures of TX and RX boards are shown in Figures 4 and 5. The TX board shown in Figure 4 was implemented using components as described in Section II-A.2. The binary input to the transmitter was driven at a data rate of 32Kbps. The RF signal (oscilloscope plot) generated by our transmitter of Figure 4 is shown in Figure 9. We observe from Figure 9 that the RF front end circuit is able to mix the baseband signal (the output of DAC) with the 80MHz sinusoidal signal from the LO. Note that the TX board shown in Figure 4 weighs less than 5 grams and its dimensions are 3.5cm $\times$ 1.6cm (length $\times$ breadth). Hence, our TX is light weight and suitable to be mounted on a cockroach. Note that the dimensions and weight of our transmitter board can be further reduced by using a smaller package for our BFSK transmitter chip and also by using smaller SMD type resistors and capacitors.

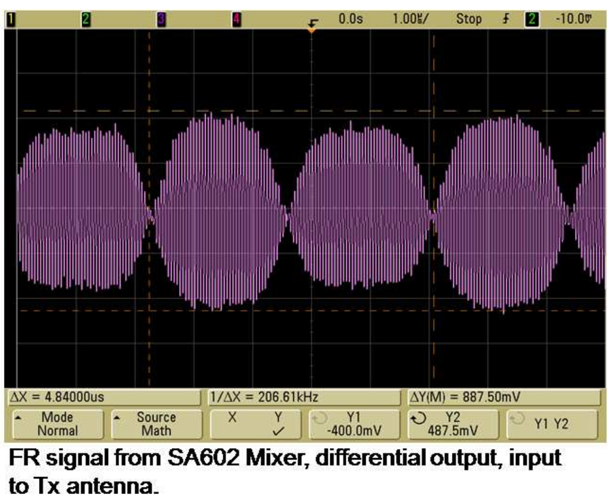

Fig. 9. RF signal transmitted by the transmitter board

The RX board shown in Figure 5 was implemented using off-the-shelf components as described in Section II-B. Figure 10 shows the input (top waveform) and the output of two bandpass filters (center waveform - output of the filter with center frequency at 115KHz and bottom waveform - output of the filter with center frequency at 345KHz) of the demodulator circuit. We observe from this figure that the bandpass filters of the demodulator circuit perform very well and the two tones in the baseband signal are efficiently separated by the filters. The output of these bandpass filters is used to obtain binary output data using comparators, rectifiers and RC filters. We found that our demodulator circuit is able to retrieve the original transmitted binary data from the baseband signal.

From the above discussion we can conclude that our proposed RF front transmitter and the receiver base station (RF front end and the demodulator circuit) perform efficiently. The wireless communication system shown in Figure 1 is able to transfer 32Kbps binary data correctly and efficiently, up to a distance of 100 feet. Our transmitter board is also light weight and occupies small area. Thus it is suitable for mounting it on a cockroach.

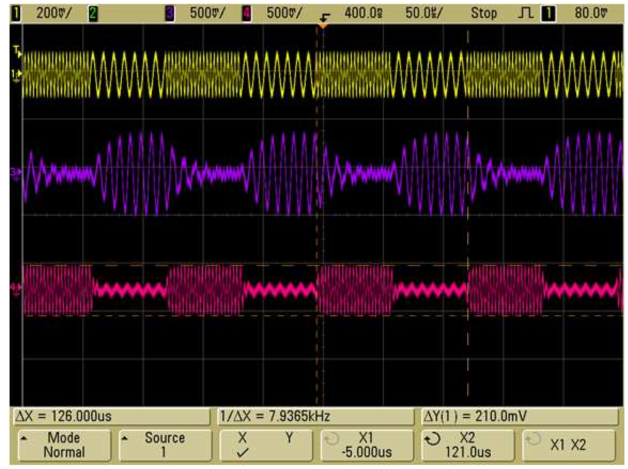

Fig. 10. Output of bandpass filters of demodulator circuit at receiver

IV. Future Work and Conclusions

The extreme low power consumption property of the sub-threshold chip opens up an array of possibilities for extreme low power applications that are fully powered by energy scavenged from ambient light. In this paper, we implemented a low power, small transmitter utilizing a sub-threshold IC in addition to off-the-shelf components. The small footprint of the TX board that we developed may allow for the implementation of robust, fieldable sensors. We also implemented the RF front end and the demodulator circuit of the receiver base station. The base station amplifies and filters the signal, then mixes the signal back down to the baseband. Our demodulator circuit is able to retrieve the original transmitted binary data from the baseband signal, up to 100 feet away.

V. Acknowledgements

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