High-Bandwidth IOP Sensing Backscatter Transceiver

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Abstract

This document describes the design and build of a mobile phone attachment that communicates with an ASIC embedded smart contact lens. The portable device enables patients and clinicians to conveniently and instantaneously measure intraocular pressure (IOP). The device replaces bulky and expensive benchtop RF synthesizer and signal analyzer machines required for communication to the smart contact lens into a portable and convenient device. The transceiver transmits VHF ISM band radio and can capture reflected backscatter On-Off-Keying modulated message signals at bandwidths from DC to 130MHz.
Chapter 1: Introduction

The wireless backscatter transceiver designed in this document is a mobile phone attachment that communicates to the active contact lens. By replacing large and expensive benchtop RF synthesizer and signal analyzer instruments, the portable device enables patients and clinicians to conveniently and instantaneously measure intraocular pressure (IOP). The transceiver operates in the VHF ISM band and can capture reflected backscatter On-Off-Keying modulated message signals at bandwidths from DC to 130MHz.

1.1 Glaucoma and Intraocular Pressure

Glaucoma describes an eye disorder that leads to progressive damage to the optic nerve and ultimately blindness. People with the glaucoma illness may lose nerve tissue, resulting in vision loss [19]. Primary open-angle glaucoma reigns as the most common form of glaucoma caused by the inability to release excess fluid buildup in the cornea, generating intraocular pressure that damages the optic nerve (Fig. 1-1). Because glaucoma exhibits no pain, diagnosis is difficult and often realized after considerable damage to the optic nerve occurs.

Fig 1-1. Glaucoma informational diagram [7]
1.2 Weaknesses of Goldmann Applanation Tonometry

The gold standard for glaucoma detection is the Goldmann Applanation Tonometry (GAT) exam (Fig. 1-2). In the GAT procedure, deflection is measured when an applanation force applied to the cornea. The measured deflection or force corresponds to an eye pressure. *The problem lies in the inability to measure eye pressure continuously to uncover trends in IOP.* Studies show that IOP varies throughout the day similarly to sleeping schedules in a circadian rhythm [3]. The GAT procedure often misses proper diagnosis because the IOP measurements are static.

![Fig 1-2. IOP Measurement via Goldmann Applanation Tonometry [20]-[23]](image)

1.3 The Cal Poly Active Contact Lens Group

The Active Contact Lens Group at Cal Poly aims to improve upon existing IOP measurement solutions with an intraocular pressure sensing contact lens which *continuously* detects eye pressure by measuring the resistance to changes in corneal radius. This advantage allows the contact lens to paint a better picture of how physicians can better treat patients with proper medication, procedures, diagnosis, and therapy.

In the past, several Cal Poly Active Contact Lens Projects consisted of: integrated circuit development [15], RF front-end development on the lens [24], and encapsulation in a polymeric material [24]. In the latest work, Sung Tran’s master thesis titled, “Development of a Sensor Readout Integrated Circuit Towards a Contact Lens for Wireless Intraocular Pressure Monitoring” [15] describes the current electronic architecture in integrated circuit form.

This project aims to unlock the development of ASIC and antenna development by creating hardware tools that can verify and characterize the IOP sensing systems in development.
1.4 Acquiring IOP Measurements Electronically

The architected IOP sensing Smart Contact Lens consists of an integrated sensor, dual-band antenna, capacitive strain gauge, and wireless transceiver. Fig. 1-3 describes a simplified architecture of the contact lens AM modulator topology. The capacitive strain gauge generates capacitance proportional to intraocular pressure, which modifies a time constant $\tau$ that controls the modulation frequency of the Current Starved Voltage Controlled Oscillator (CSVCO). In other words, the sensor changes the frequency of a pulse generator. The simulated CSVCO operating frequency simulated in [15] operates at frequencies of 10-70MHz given strain gauge capacitance of 10-20pF [15]. The CSVCO output feeds into the gate of a MOS switch.

By varying $R_{DS}$ of the MOSFET transistor in Fig 1-3, the antenna reflectance $\Gamma_A$ (Eq. 1-1) of the contact lens changes. The $R_{DS}$ is modulated through $V_{GS}$ which is the square wave output of the CSVCO. Modulating RF power in square waves yields binary ASK or On-Off-Keying – a form of amplitude modulation. Modulating reflected RF power by varying an antenna’s reflectance describes the fundamental principle of backscatter communication.

$$
\Gamma_A = \frac{Z_{R_{DS}} - Z_A}{Z_{R_{DS}} - Z_A}
$$

Eq. 1-1

The load modulation topology provides us with a method to couple the physiological parameter of intraocular pressure to the operating frequency of the CSVCO.

![Fig 1-3. Contact Lens Modulation Scheme and Communication Topology](image-url)
1.5 The IOP Sensing Transceiver

The IOP Sensing Transceiver is a transceiver that transmits RF power, receives the modulated backscatter signal and determines the envelope’s frequency at accuracies under 1%. The final system consists of two subsystems: RF Front End and Precision Frequency Counter. The inputs are the modulated backscatter signal and 5VDC power from an Android OTG capable smartphone. The outputs of the system are 2.4GHz CW RF power and serial out.

The 2.4GHz RF Front End handles operating frequencies in the VHF range and are responsible for generating and receiving RF backscatter signals.

The Precision Frequency Counter operates on lower frequencies up to 130MHz. The subsystem receives the message signal from the RF Front-End and measures the frequency. The frequency is sent by serial to either USART or SPI serial interface to be displayed and stored on the Android smartphone.
The Precision Frequency Counter and 2.4GHz RF Front-End blocks were built on separate PCB’s and the RF envelope signal was bridged together using an SMA cable. The IOP sensing transceiver system is displayed in Fig. 1-5 with labels noting the two subsystems. Two antennas for transmitting and receiving are visible and connected to the RF Front-End with coax cables. The two PCB’s are designed such that they could be stacked and separated using nylon standoff’s.

The following list summarizes the design and test of the hardware subsystems on the transceiver:

Chapter 2 – 2.4GHz RF Front-End
Chapter 3 – Design of a 300MHz 33dB IFA and Hysteretic Level Detector
Chapter 4 – Precision Digital Frequency Counter
Chapter 5 – Final System Performance and Test Method

Fig. 1-5: Backscatter Transceiver System
Chapter 2: 2.4GHz RF Front End

2.1 Introduction
This chapter covers the design, test, and build of a 2.4GHz backscatter RF front-end. High-frequency RF amplification techniques are described for both Transmitter (TX) and Receiver (RX) regarding biasing, gain, power, and noise mitigation. The techniques for demodulating high-bandwidth On-Off-Keying and Amplitude Modulation signals up to 130MHz are described. Lastly, the PCB design covers characteristic impedance, electromagnetic compatibility (EMC) and systems integration.

2.2 TX Block Diagram
The TX chain is a simple 2.4GHz constant width (CW) baseband generator. Three main components describe the functional activities for this entire subsystem. First, a 2.4GHz local oscillator is generated by the Crystek VCO. Second, the bandpass filter removes any intermodulation products present in the output spectrum. Third, the LNA provides low distortion amplification as a final output stage to a 25mm patch antenna.

![TX Chain Functional Block Diagram](image1)

Fig. 2-1: TX Chain Functional Block Diagram

2.3 TX Hardware Schematic
The components chosen for the TX chain were optimized for time to market and accuracy. The components chosen on this subsystem are internally matched to 50Ω and do not require external matching circuits. The VCO frequency can be modulated from 2400MHz to 2500MHz via R1 10kohm trimmer.

![TX Chain Hardware Schematic](image2)

Fig. 2-2: TX Chain Hardware Schematic
2.5 TX Voltage Controlled Oscillator (VCO)

The Crystek CVCO33BE-2400-2500 VCO was optimized for size, simplicity, and power efficiency. The chip operates at 3V, requires only 19mA, and is conveniently sized for handheld applications at 7.62x7.62mm. The frequency tune port accepts voltages from 0-3V, enabling the use of a simple trimmer potentiometer on 3V supply to adjust the oscillation frequency full swing. The output power of the transceiver is rated at 2dBm.

2.6 TX Low Noise Amplifier (LNA)

Analog Device’s HMC374 broadband 0.3-3GHz Amplifier is compact and low noise. The HMC374 LNA is simple to implement removing the need for external matching circuits which also saves space. The low noise figure of 1.5dB allows for a high signal-to-noise ratio that increases the receiver’s sensitivity to the backscatter signal.

The output power must be lower than the P1dB point for the lowest amount of distortion. The P1dB point is the power level where an amplifier begins to clip, resulting in a drop of expected power of 1dB. The HMC374 boosts power of the VCO from 3dBm to 12dBm. Low distortion is expected because the power level is 5dBm lower than the P1dB point at 17dBm per supply voltage of 3V.

RF choke L1 acts as high-impedance to RF. DC is passes through while limiting leakage of RF power retrograde into the 3V supply. A wire wound ferrite core inductor was chosen for the high inductance per volume at size 0603 versus air core and ferrite bead type inductors. Murata’s LQW series offered the best inductance vs. SRF performance. 58nH is the highest inductance in the LQW lineup while staying under the SRF of 2400MHz.

\[
\text{Calculated } X_L = j\omega L = 2\pi f L = 2\pi \times 2400 \text{MHz} \times 58\text{nH} = 874.6\Omega
\]

Expected \(X_L = 6000\Omega\) from official Murata SimSurfing tool pictured in Fig. 2-4.

The power of the TX chain was tested in Fig. 2-3 measuring in at 9.81dBm, which translates to about 9.5mW. The slight power drop can be attributed to the aggregate losses of the RF interfaces, BPF, and decoupling caps.
2.7 RX Block Diagram

The receiver described in this section is a 2.4GHz receiver that is compatible with the amplitude modulation (AM) family of signals up to 130MHz. AM modulated backscatter is received by the Taoglas WPC25B 25mm patch antenna and is amplified by 21.6 dB via ADL5545 gain block amplifier. The TDK bandpass chip filters any unwanted signal products and an optional attenuator can be fitted to attenuate the signal up to 9dB to prevent peaking from the ADL5511 envelope detector. The Analog Devices ADL5511 directly downconverts the message signal from 2.4GHz down to DC.

![2.4GHz Backscatter Receiver](image)

Fig. 2.5: RX Chain Functional Block Diagram

2.8 RX Hardware Schematic

![RX Chain Hardware Schematic](image)

Fig. 2-6: RX Chain Hardware Schematic
2.9 RX Gain Block Amplifier (GBA)

The RX GBA provides a high-level of gain that increases operating range and allows safer TX output power levels. The RX gain block amplifier uses the same inductor used in the TX block because similar operating frequency, current, and performance. The forward gain of the amplifier characterized by parameter S21 averages about 21.6dB at 2400MHz. The official datasheet for ADL5545 is inconsistent regarding forward gain measured. The information used was found in the scattering parameter file(.s2p) and viewed using Avago AppCad.

2.10 RX Envelope Detector

The Analog Devices ADL5511 envelope tracking RF power detector is the workhorse of the transceiver system. The small 3mm QFN chip functions as a demodulator on the TX chain that directly converts the input RF envelope into the intermediate frequency (IF) or message signal. As depicted in Fig. 2-7, V_{ENV} dynamically tracks input RF power and outputs the envelope of the signal received. The maximum bandwidth of the IC is rated at 130MHz, allowing for high-speed signal acquisition. In other words, V_{ENV} signal will follow the amplitude of the RF input power. Power received can be measured because input RF power is normalized to an output voltage (Fig. 2-8). The ability to normalize the voltage to a real power level can be used to verify an expected input power from the contact lens. The output of the envelope detector is interfaced with the IF signal conditioning system on the frequency counter PCB. The R4 75Ω resistor is used to match the high impedance input of the ADL5511 to 50Ω.

2.11 RX Chip Attenuator

To prevent damage or clipping from the ADL5511 envelope detector IC, a chip attenuator was placed in the signal chain. The chip can be purchased in several levels of attenuation and a zero-dB component is installed by default. The attenuator used a π-pad variant which can precisely attenuate signals while maintaining 50 ohms input and output impedance.
2.12 Antennas
The antennas chosen for this project are the Taoglas WPC25B ISM patch antenna fitted with an MMCX Female Connector. The operating frequency of the antenna is 2400-2500MHz and the impedance is pre-matched to 50Ω. The measurements in Fig. 2-9 validates successful sensitivity of RF power from 2400-2500MHz with values far below the -3dB cutoff.

2.13 Decoupling Capacitors
The decoupling capacitors chosen for this design are Murata GJM1555C1H130GB01D 13pF 0402 capacitors with C0G/NP0 rating. The GJM series is a high-Q, low-loss RF capacitor. The 13pF capacitor exhibits series resonant frequency (SRF) at 2.4GHz, ensuring the lowest possible attenuation at the operating frequency. The series resonant frequency is where the parasitic inductive and dominant capacitive impedances equalize, resulting in a minimum impedance. The result is a capacitor that is practically a short to 2.4GHz RF and infinite impedance to DC.

2.14 Bandpass Filters (BPF)
The TDK DEA252450BT-2027A1 on component F1 is a BPF with a center frequency of 2450MHz and a bandwidth of 100MHz. This filter allows for the whole range of the VCO to fit inside of the filter bandwidth. The component is somewhat large for a filter at 2.5x2.0mm, however features low insertion losses (1dB) at the passband and precise attenuation at the stop bands. The insertion loss of the filter is shown in Fig. 2-11.
2.15 Power

The power distribution system is optimized for low noise, accuracy, and ease of assembly. Analog Devices ADP122/123 series LDO regulators in the TSOP package fit the selection criteria well. The strong PSRR of 60dB at 100kHz, small TSOP packaging, and 300mA of output current make for an ideal LDO for this application. Two supply rails powering the RF Front-End PCB are rated at 3VDC, and 4.75VDC.

Calculating safe output power is based on the formula in Eqn. 2-1 and was found to be 447mW at worst case scenario of an ambient temperature of 120 Fahrenheit.

\[
\text{Estimated Max Pwr} = \frac{\text{Max Device Temp} - \text{Max Ambient Temp}}{\theta_{JA}} \quad \text{Eqn. 2-1 [18]}
\]

\[
\text{Estimated Max Pwr} = \frac{125^\circ C - 48.9^\circ C}{170^\circ C/W} = 447mW
\]

Completing a tolerance analysis on the power (P) and current (I) at worst case reveal a well-managed power distribution network on the TX hardware. The power and current are under 3/4ths of the rated values.

The maximum power on the RX TSOP package is very close to the estimated maximum value. The tolerance can be dismissed because the LFCSP package variant with an integral thermal paddle doubles the thermal performance.

The ripple reduction of the LDO is evident in the high attenuation of the input voltage ripple as shown in Table 2-1. 47dB of attenuation was measured in the TX and 42dB of attenuation was observed on the RX system.

The output voltage of the ADP122 is fixed at 3VDC and the ADP123 is an adjustable output voltage governed by Eqn. 2-2. The lack of resistor sizes resulted in a voltage of 4.63V.

### Table 2-1. Measured RF Front-End Ripple

<table>
<thead>
<tr>
<th></th>
<th>RX</th>
<th>TX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage</td>
<td>4.68V</td>
<td>3.078V</td>
</tr>
<tr>
<td>Input Voltage Ripple</td>
<td>310mV</td>
<td>310mV</td>
</tr>
<tr>
<td>Output Voltage Ripple</td>
<td>2.51mV</td>
<td>1.41mV</td>
</tr>
</tbody>
</table>

### Table 2-2. RX Power Tolerance Analysis (TSOP)

<table>
<thead>
<tr>
<th></th>
<th>I (mA)</th>
<th>P(mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADI ADL5545 GBA</td>
<td>70</td>
<td>333</td>
</tr>
<tr>
<td>ADI ADL5545 Envelope Detector</td>
<td>22</td>
<td>102</td>
</tr>
<tr>
<td>Total Current/Power Draw:</td>
<td>92</td>
<td>435</td>
</tr>
<tr>
<td>% of Rated Current/Power</td>
<td>30.6%</td>
<td>97.3%</td>
</tr>
</tbody>
</table>

### Table 2-3. TX Power Tolerance Analysis (TSOP)

<table>
<thead>
<tr>
<th></th>
<th>I (mA)</th>
<th>P(mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADI HMC374 LNA</td>
<td>90</td>
<td>270</td>
</tr>
<tr>
<td>Crystek CVCO33BE-2400-2500</td>
<td>19</td>
<td>57</td>
</tr>
<tr>
<td>Total Current/Power Draw:</td>
<td>109</td>
<td>327</td>
</tr>
<tr>
<td>% of Rated Current/Power</td>
<td>36.3%</td>
<td>73.2%</td>
</tr>
</tbody>
</table>
2.16 Layout and PCB Design: EMC

The RF Front End PCB is a four-layer FR-4 stack with SMA-F connectors as RF interfaces. The layout of the RF PCB is designed such that the two subsystems RX and TX have minimal cross interference. The RX and TX blocks are separated with distance and are fenced by grounded vias spaced 100mil apart. Proper grounding is also ensured by using solid continuous ground planes with sufficient via stitching.

Fig. 2-12: Altium 3D Render of RF Front End PCB Displaying Signal Paths
2.17 Layout and PCB Design: Transmission Line Design

When designing microwave hardware, all components need to comply to the same characteristic impedance to prevent reflections and loss. The RF Front-end utilizes the microstrip transmission line model which is one of the cheapest and simplest transmission lines to implement. The goal is to design a transmission line with a characteristic impedance ($Z_0$) of 50 ohms.

An online calculator was used to calculate characteristic impedance based on the Wheeler’s formulas below [16]. The diagram in Fig. 6-9 describes the parameters of trace width ($W$), trace thickness ($T$), dielectric thickness ($H$), and dielectric constant ($\epsilon_r$) which are used to calculate characteristic impedance. After applying the parameters to the calculator, a transmission line with 14mil trace width was projected to be the ideal solution.

Characteristic Impedance

$$Z_0 = \frac{\eta_0}{2\pi} \sqrt{\frac{2}{1 + \frac{t}{\pi}}} \cdot \ln \left( 1 + 4 \cdot \left( \frac{\eta_0}{w_{eff}} \right) \right) \cdot (X_1 + X_2) \quad \text{Eqn. 6-3}$$

Effective Trace Width

$$W_{eff} = W + \left( \frac{t}{\pi} \right) \cdot \ln \left( \frac{4\epsilon_r \eta_0}{\eta_0} \left( \frac{w_{eff}}{w_{eff} + \frac{w_{eff}}{2\pi}} \right) \right) \cdot \frac{E_r + 1}{2 \cdot E_r} \quad \text{Eqn. 6-4}$$

Impedance 1

$$X_1 = 4 \left( \frac{14E_r + 8}{11E_r} \right) \left( \frac{\eta_0}{w_{eff}} \right) \quad \text{Eqn. 6-5}$$

Impedance 2

$$X_2 = \sqrt{16 \cdot \left( \frac{\eta_0}{w_{eff}} \right)^2 \cdot \left( \frac{14E_r + 8}{11E_r} \right)^2 + \left( \frac{E_r + 1}{2 \cdot E_r} \right)^2 \cdot \pi^2} \quad \text{Eqn. 6-6}$$
To implement the microstrip TL, signal traces are placed above a ground plane with no copper adjacent as depicted in Fig. 6-10. Any ground or signal traces should also be cleared or pulled back from the RF signal trace as to make sure the microstrip model is as accurate as possible. Applying the design to the RF Front-End PCB resulted in Fig. 6-11 where the RF signal path follows a 14mil microstrip TL.

Fig. 2-14: Cross Section of Microstrip Model [32]

Fig. 2-15: Applied Microstrip Model to RF 4-Layer RF PCB
Chapter 3: Design of a 300MHz 33dB IFA and Hysteretic Level Detector

3.1 Introduction:
To increase the transceiver’s range and sensitivity, a powerful 33dB intermediate frequency amplifier (IFA) was designed to amplify the backscatter envelope to a robust signal for sampling. The amplifier gain programming, simulations and final hardware tests are covered in this chapter. To digitize the amplified backscatter envelope, a hysteretic level detector was built to accomplish this goal. The design, simulation, and hardware implementation of the level detector is also covered in this chapter.

3.2 Block Diagram
The IF signal conditioning block consists of two cascaded single-supply non-inverting amplifiers and a Schmitt trigger comparator. The signal conditioning block amplifies the RF envelope detected from the RF Front-End PCB and multiplies the signal ~50x for greater noise immunity. The Murata NFL18ST LPF chip attenuates any fast transients before being input into a level detection circuit. The amplified signal’s zero-crossing is detected which toggles the comparator output. The comparator output is a clock input to the frequency detector circuit.

3.3 Design of a 33dB Single-Supply 300MHz IFA
The strategy designing the IF amplifier was to create a rail-to-rail amplifier with large gain. The LT6253-7 was chosen for strong 2GHz gain bandwidth product, rail-to-rail capability, and relatively low supply current of 3.5mA. The single supply amplifier is a dual-feedback topology with the input signal on the non-inverting terminal for high input impedance. Half supply acts as the virtual ground and gain is set by the non-inverting op-amp equation (Eqn. 3-1). Two cascaded op-amps at Av=7 yield a gain of 49.7 or 33dB.

\[
\frac{V_{OUT}}{V_{IN}} = \left(1 + \frac{R2}{R1}\right) \quad \text{Eqn. 3-1}
\]

\[
\frac{V_{OUT}}{V_{IN}} = \left(1 + \frac{1210}{200}\right) = 7.05
\]
3.4 IFA Software Simulation

The signal and biasing of the op amp are centered half-supply at 2.25V to take advantage of the full range of the amplifier. The operation of the IFA was verified through simulation on LTSpice using the stock LT6253-7 models. Simulations in Fig. 3-3 validated stable operation of the amplifier from 1-100MHz.

Fig. 3-2: IF Amplifier LTSpice Schematic Diagram

Fig. 3-3: IF Amplifier LTSpice Gain Simulation
3.5 IFA Hardware Implementation

The IFA was implemented similarly on hardware except for decoupling caps at the bias and supply. A dual op-amp MSOP-10 package allowed for two LTC6253-7 amplifiers on a single chip.

![300MHz Single-Supply Amplifier Av=36](image)

**Fig. 3-4: IF Amplifier Hardware Schematic Diagram**

**Measured Data:**

The IFA provided strong voltage gain for the IF signal, however gain is somewhat inconsistent. The LTC6253-7 requires a gain of 7 or higher to be stable; the board was assembled with a gain of 6 by mistake. The stability issues of the op-amp at lower frequencies on the assembled board are caused by insufficient gain. Though the execution of the circuit is somewhat sloppy, the circuit behaves well enough to fulfill the functional requirements of the system as pictured by Fig. 3-5.

![Op-Amp A Output, Av=9 and Op-Amp B Output Av=9.82](image)

**Fig. 3-5: IF Amplifier, 50mVpp Sine Input at 50MHz**
The -3dB cutoff point is the point where amplifier performance begins to degrade noticeably. The IFA measured a cutoff frequency at 77MHz. The Schmitt trigger comparator can function with a small 50mV of voltage swing, allowing the amplifier to be used far beyond the cutoff. Fig. 3-6 displays the amplifier operating at the -3dB point while maintaining a strong 1.37V of swing from an initial voltage swing of 2.02V.

![Graph showing amplifier performance](image)

Fig. 3-6: IF Amplifier -3dB Point at Measured at 77MHz

### 3.6 Design of a High-Speed Schmitt Trigger Comparator with 20mV of Hysteresis

The bandwidth of the transceiver demanded a toggle frequency of at least 100MHz. The design used in this project utilizes a high-speed Analog Devices LT1711 4.5ns comparator with a toggle frequency of 200MHz. To reduce transition uncertainty, hysteresis is added by R1 and R2.

![LTSpice schematic](image)

Fig. 3-7: Schmitt Trigger Comparator LTSpice Schematic
Configuring Transition Levels with 20mV Hysteresis:

Low-to-High Transition:

The voltage required to transition into the high-state ($V_{TH}$) should be higher than the middle point of 2.25V. The effective circuit of the resistor feedback network is pictured in Fig. 3-8. The 4.5V point is taken from the inverted Q! output. Because the comparator is on the low state, Q! is set high to 4.5V.

$$\frac{(4.5V - V_{TH})}{10k} = \frac{V_{TH}}{1k}$$

KCL at + terminal

$$V_{TH} = 2.455$$

Voltage required to transition high

Fig. 3-8: $V_{TH}$ Effective Circuit

High-to-Low Transition:

The voltage required to transition into the low-state ($V_{TL}$) should be lower than the middle point of 2.25V. The effective circuit of the resistor feedback network is pictured in Fig. 3-9. The 2.25V point is taken from the split rail and the bottom of the circuit is at zero/ground. Because the comparator is on the high state, Q! is set low to ground (0V).

$$V_{TL} = 2.25V \left(\frac{10k}{10k+1k}\right)$$

Voltage Divider

$$V_{TL} = 2.045$$

Voltage required to transition low

Fig. 3-9. $V_{TL}$ Effective Circuit
### 3.7 Hysteretic Comparator Software Simulation

The designed Schmitt trigger comparator performed as expected under an LTSpice software simulation with the LT1711 stock models. Hysteresis changes the input reference such that transitions are much better defined. The reduction in transition uncertainty can be observed in Fig. 3-10 where the hysteresis enables a clean edge regardless of a noisy input signal.

![Fig. 3-10: Schmitt Trigger Comparator LTSpice Simulation](image)

### 3.8 Hysteretic Comparator Hardware Implementation

The hardware implementation transfers over the design from simulation to hardware. A Murata NFL18ST 3rd order LCL low pass filter (LPF) is installed to increase the comparator stability even further. The LPF has a default cutoff of 100MHz and higher cutoff variants are available. The comparator is a mixed signal device which has both analog and digital components. Because the LT1711 is a high-speed comparator with a fast 4.5ns rise time, large current spikes cause ground bounce that permeate the entire power distribution network. High-frequency decoupling techniques like paralleling three capacitor sizes with different capacitances reduce ground bounce dramatically. Additionally, a 330Ω Murata BLM18 ferrite bead ensures isolation between the IFA and comparator supplies.
A schematic error prevented the feedback loop from working properly because the loop was supposed to be connected to the compliment output. The calculations for the transition points are valid and within 5% of the expected value but unfortunately reversed.

Table 3-1: Measured Schmitt Trigger Comparator Performance

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Theoretical</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOL</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>VOH</td>
<td>4.28</td>
<td>4.3</td>
<td>0.46%</td>
</tr>
<tr>
<td>VTH</td>
<td>2.02</td>
<td>2.045</td>
<td>1.2%</td>
</tr>
<tr>
<td>VTL</td>
<td>2.38</td>
<td>2.455</td>
<td>3.1%</td>
</tr>
</tbody>
</table>
Figure 3-12 shows a capture of the input signal and reference signal. The red waveform signifies what the correct hysteresis signal would yield if connected to the complimentary output. The blue line represents the half-supply 2.25V feedback signal that the hysteresis loop is centered around.

The comparator introduces more uncertainty to the system as the reference follows the input signal where opportunities for unwanted transitions are increased. The dirty edges can be observed in Fig. 3-13 on both high and low transitions.

Fortunately, the IFA design was strong enough to overcome the design mistakes for a stable and effective frequency counter. The 3rd order LPF and 33dB amplification provided a clean and strong signal that reduced the effects of the design mistakes.

![Fig. 3-12: Measured Input and Feedback](image)

3.9 2.25VDC Reference

The split rail 2.25VDC reference is created using a simple voltage divider. The output is filtered with a parallel 1uF capacitor and a series 600Ω ferrite bead. The circuit was improvised on the frequency counter PCB after the realization of an unstable amplifier with a capacitive load. 100Ω resistors are used for greater accuracy and voltage regulation.

Voltage Measured: 2.225V

Percent difference from Theoretical: 1.11%

![Fig. 3-14: 2.25VDC Reference Generator](image)
3.10 Power
The LDO chosen for the signal conditioning circuit is the ST LDLN025M45R 4.5V high-PSRR LDO. Solving the rated power is based on the formula in Eqn 3-2 and was found to be 505mW at worst case scenario of an ambient temperature of 120 Fahrenheit.

\[
Estimated \ Max \ Pwr = \frac{Max \ Device \ Temp - Max \ Ambient \ Temp}{\theta_{JA}} \quad Eqn. \ 3-2 \ [18]
\]

\[
Estimated \ Max \ Pwr = \frac{150^\circ C - 48.9^\circ C}{200^\circ C/W} = 505mW
\]

Completing a tolerance analysis on the power (P) and current (I) reveal safe tolerances on the signal conditioning hardware system. Power was calculated to be 50.9% of the estimated maximum power. Current was estimated to be 22.8% of the estimated maximum current.

The ripple reduction of the LDO is not as evident in this system. It is possible the high-speed components of this system are much more demanding and have faster current transients than the LDO can manage. The system manages to work effectively with the ripple present.

<table>
<thead>
<tr>
<th>Table 3-2. TX Power Tolerance Analysis (SOT)</th>
<th>Table 3-3. Measured RF Front-End Ripple</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Table 3-2" /></td>
<td><img src="image2" alt="Table 3-3" /></td>
</tr>
<tr>
<td><img src="image1" alt="Table 3-2" /></td>
<td><img src="image2" alt="Table 3-3" /></td>
</tr>
</tbody>
</table>
Chapter 4: Precision Digital Frequency Counter

4.1 Introduction

After the signal is acquired, amplified and digitized by the subsystems in the prior sections, the frequency counter is a subsystem that can detect the modulation frequency of signals up to 200MHz. The measurement circuits described in this chapter include a frequency divider, microcontroller and external system clock. The firmware and programming of the ATmega328p are described in context of the interfaces available on the board and frequency counting algorithm.

4.2 Block Diagram

There are three main components to the frequency counting circuit: An external frequency divider, microcontroller and a crystal oscillator. The comparator outputs to the clock input of a 12-bit counter acting as a frequency divider to slow the frequency within the acceptable clock input range for the Atmel ATmega328p microcontroller. The external crystal oscillator acts as the system clock for the microcontroller that drives all timing activities.

![Frequency Counter Block Diagram]

Fig. 4-1: Frequency Counter Block Diagram
4.3 Toshiba 74VHC4040FT 12-bit Counter

The Toshiba 74VHC4040FT is a 12-bit counter with an asynchronous reset that can accept signals as fast as 210MHz at 4.5V. The counter can be used as a numerical counter, or it can be used as a frequency divider. The counter is used to slow the input clock to a more easily measurable signal by the MCU. If the signal input is an 8MHz square wave, the third bit output Q3 will output a square wave of 1MHz. The output frequency of a given chip used in frequency division mode is provided by Eqn 4-1.

\[ F_{\text{out}} = \frac{F_{\text{in}}}{2^n} \quad \text{Eqn. 4-1} \]

where \( n \) is the chosen bit output from Q1 to Q12. The output can be chosen by moving a 0Ω resistor to either R3 (Q2), R4 (Q3), and R5 (Q4).

Fig. 4-2: Frequency Divider/Counter IC taken from Q3 output.
### 4.4 ATmega328p MCU

The microcontroller used to measure the frequency of the modulated backscatter is the ATmega328p in 5x5mm MLF package. While the microcontroller is not as powerful and efficient as newer ARM-based MCU systems, third-party support and ease of use allowed a timely completion of the project’s main requirements. ATmega328p contains three independent timer/counter modules, SPI, USART, and TWI interfacing in box.

The frequency counter PCB contains a header that allows the ATmega328p to be programmed in-circuit by off-the-shelf OEM Atmel programmers and third-party programmers such as the Sparkfun USBtiny Pocket Programmer. Additional GPIO available on the frequency counter PCB include a serial header and 5 port-B pins including the i2c bus.

The ATmega328p can be only programmed with third-party programmers after the proper fuses are set, otherwise the programmer cannot communicate to the MCU. The fuses configured for this embedded application are listed in Table 8-1 and programmed with the Atmel AVR ISP mkII.

Interfacing Atmel Studio 8 with third-party programmers such as the Sparkfun USBTiny Pocket Programmer involves creating an external tools profile as shown in Fig. 4-4. The USBTiny utilizes AVRdude, an open-source in-system programmer for the Atmel ATmega microcontroller segment. The command attribute is set to the location of the AVRdude program. The argument for the tool profile is the following command:

```
-c usbtiny -p m328p -v -U flash:w:$(TargetDir)$(TargetName).hex:i
```

<table>
<thead>
<tr>
<th>Fuse Type</th>
<th>Value (Hex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Fuse</td>
<td>0x62</td>
</tr>
<tr>
<td>High Fuse</td>
<td>0xD9</td>
</tr>
<tr>
<td>Extended Fuse</td>
<td>0xFF</td>
</tr>
</tbody>
</table>

Table 4-1: ATmega328p Fuse Settings
4.5 16MHz Crystal

Clock stability and tolerance are critical for any frequency measurement system. The system clock frequency was chosen at 16MHz for widespread adoption for third-party code and near-peak performance of the ATmega328p MCU capped at 20MHz. Initially prototyped on an Arduino Uno R3, a change was made to increase frequency stability and tolerance by converting the clock generator from resonator to a crystal based system. By switching to a Kyocera CX2016DB series crystal oscillator, the frequency stability and tolerance are 200 and 500 times more accurate in stability and tolerance than the Murata CSTCE series resonators installed in the Arduino Uno R3.

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>Frequency Stability</th>
<th>Frequency Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyocera CX2016DB16000H0FLJC1 (ACL Backscatter Transceiver)</td>
<td>16MHz</td>
<td>15ppm</td>
<td>10ppm</td>
</tr>
<tr>
<td>Murata CSTCE16M0V53-R0 (Arduino Uno R3)</td>
<td>16MHz</td>
<td>3000ppm</td>
<td>5000ppm</td>
</tr>
<tr>
<td>Performance Comparison</td>
<td>-</td>
<td>200x more stable</td>
<td>500x more accurate</td>
</tr>
</tbody>
</table>
### 4.6 Firmware Behavioral Description

The firmware behavior is described by Fig. 8-5 describing the MCU activities on a flowchart diagram.

![Flowchart Diagram](image)

**Fig. 4-5: MCU Frequency Detection Activities**

<table>
<thead>
<tr>
<th>Module</th>
<th>ATmega328p Control Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>- Clock Input from IF Signal Conditioning Circuit</td>
</tr>
<tr>
<td>Output</td>
<td>- String of information and frequency detected in ASCII</td>
</tr>
<tr>
<td>Functionality</td>
<td>The process initializes all necessary processes for frequency detection and information sharing.</td>
</tr>
</tbody>
</table>
4.7 Frequency Counting Algorithm

The frequency counting algorithm utilizes three timers on the ATmega328p to accomplish accurate and responsive frequency measurements.

Timer0: Starts the measurement of every measurement cycle

Timer1: Counts message signal edges using a large 16-bit register

Timer2: Measures a precise amount of time to count clock edges from the message signal (500uS)

The timing diagram in Fig. 4-6 describe the counting activities of each timer and how the values are used to generate a frequency value. The message signal counts per time holds the frequency information that can be correlated to an IOP.

![Frequency Counting Algorithm Timing Diagram](image-url)

Fig. 4-6: Frequency Detection Algorithm Timing Diagram
An example of a timing scenario on Fig. 4-6 is the measurement of a 100MHz signal sampled from the Q4 (R5) output.

1. 74HC4040FT 12-bit counter will divide the signal to a lower frequency compatible for the MCU

\[ F_{out} = \frac{F_{in}}{2^n} \quad \text{Eqn. 4-2} \]

\[ F_{out} = \frac{100MHz}{2^4} = 6.25MHz \]

2. A 6.25MHz clock is sampled by the T1 input stopped after 500µs yields a precise amount of counts.

\[ \text{Counts} = F_{out} \times T_{meas} \quad \text{Eqn. 4-3} \]

\[ \text{Counts Measured} = 6.25MHz \times 500\mu s = 3125 \text{ Counts} \]

3. Because the measurement time is known, the measured counts can be converted into a frequency.

\[ \text{Frequency Measured} = \frac{\text{Counts Measured}}{\text{Time Measured}} \quad \text{Eqn. 4-4} \]

\[ \text{Frequency Measured} = \frac{3125 \text{ Counts}}{500\mu s} = 100MHz \]
4.8 Power

The LDO chosen for the frequency counting circuit is the ST LDLN025M45R 4.5V high-PSRR LDO. Solving the rated power is based on the formula in Eqn. 4-5 and was found to be 505mW at worst case scenario of an ambient temperature of 120 Fahrenheit.

\[
Estimated \ Max \ Pwr = \frac{Max \ Device \ Temp - Max \ Ambient \ Temp}{\theta_{JA}} \quad \text{Eqn. 4-5 [18]}
\]

\[
Estimated \ Max \ Pwr = \frac{150C - 48.9C}{200C/W} = 505mW
\]

Completing a tolerance analysis on the power (P) and current (I) were completed and found to be under half of the rated constraints.

The ripple reduction of the LDO is not as effective in this system. It is possible the high-speed components of this system are much more demanding. Majority digital electronic components in the system are likely to explain the higher ripple.

| ATmega328p | 2 | 9 |
| 74HC4040FT | 20 | 90 |
| Green LED | 20 | 90 |
| Misc. Loads | 10 | 45 |
| Total Current/Power Draw: | 52 | 234 |
| % of Rated Current/Power | 20.8% | 46.3% |

Table 4-4. Measured RF Front-End Ripple

| Output Voltage | 4.4843 |
| Input Voltage Ripple | 310mV |
| Output Voltage Ripple | 277mV |

Table 4-5. TX Power Tolerance Analysis (SOT)
Chapter 5: Final System Performance and Test Method

5.1 Introduction

In this chapter, the contact lens simulator and final system test method and results are described. To verify the functionality of the IOP sensing transceiver, a contact lens simulator was fabricated to generate the modulated backscatter signals. Lastly, the test method and performance of the final system tests are covered.

5.2 Active Contact Lens Simulator

Using the Infineon BFR series RF NPN transistor, a backscatter modulator was fabricated to modulate the reflectance of a WPC25B Taoglas 25mm patch antenna. A schematic of the contact lens simulator is pictured in Figure 5-1. The MOD port is connected to a BNC-F connector and the SMA-F port connects to the BX antenna.

The ACL simulator allows for simple measurements to be done using off-the-shelf arbitrary waveform generators. The NPN transistor is biased using a 1K resistor at 1Vpp, 500mV offset.

The modulated signal as pictured in Fig. 4-2 proves the functionality of an effective amplitude modulator where the 50MHz sidebands of the signal can be easily seen.

Fig. 5-1: Active Contact Lens Simulator

Fig. 5-2: 50MHz Backscatter Signal Measured, 3 in. from a 2.4GHz 10dBm RF generator
5.3 Final Hardware System Performance

The complete hardware system was evaluated on the following criteria:

1. Measured Frequency Accuracy

The IOP sensing transceiver is being used to measure eye pressure, a physiological parameter where inaccuracies can have great consequences. The final hardware system performed admirably with frequencies within 1% error on all frequencies within 1-60MHz. Due to the limitations of the Rigol DG1062Z Arbitrary Waveform Generator, modulated backscatter could only be generated up to 60MHz.

![Percent Error vs Frequency](image)

Fig. 5-3: Measured Frequency Error vs. Modulation Frequency at D = 6 in.

2. Distance-to-Lock at Full Speed

If the antennas are not pointed directly at each other or at a distance too far, the signal amplitude becomes too small to measure robustly or “lock” on to the signal. A greater distance-to-lock allows for less human error allowing for practical eye pressure measurement at a glance. As pictured in Fig. 5-4, the test system measured a respectable distance to lock of 12.7 inches at 60MHz.

![Distance to Lock](image)

Fig. 5-4: Distance to Lock Testing at 60MHz Modulation Frequency
3. Power Received vs. Frequency

Measured from the envelope detector output, the power received resembles the relationship pictured in Fig. 5-5. The minimum amplitude stayed above 20mV$_{pp}$ needed for accurate and stable frequency detection throughout the whole range.

![Backscatter Power Received vs. Modulation Frequency](image)

**Fig. 5-5**: Backscatter Power Received vs. Modulation Freq. at D = 6 in.

4. Power Consumption

Because the transceiver will be ultimately attached to an Android smartphone with a finite power source, the transceiver needs to draw less than 500mA according to the Android USB OTG standard [25]. The continuous power draw from the system measures: 280mA or 1.397W at 5VDC. The continuous power draw is half the maximum power output available from the USB.
Chapter 6: Conclusion and Future Topics

6.1 Conclusion

While the execution of the device was not perfect, the project was a great success overall. This device achieved the following significant milestones:

1. Generates 10dBm of clean TX power in a compact footprint
2. Achieves response time of 1ms with a 1kHz sampling rate
3. Receives modulated backscatter signals up to 60MHz (Faster than any off-the-shelf AM transceiver)
4. Captures frequencies within 1% accuracy
5. Delivers 1400mW of low-noise power safely under high temperatures of 120F
6. Locks onto signals within 1-60MHz at distances up to 12.7 inches

The IOP Sensing transceiver is the first-of-its-kind to achieve backscatter modulated signals up to 130MHz and will enable many low power, high-bandwidth devices within and outside of medical device. The form factor of the device can easily be shrunk down to a fraction of the size using modern IC and PCB fabrication techniques allowing for a highly mobile transceiver system.
6.2 Future topics
Transceiver Improvements

The following list describes validated hardware revisions that should be done before proceeding to build the device on a product level.

1. Rebuild board repairing IFA Instability at lower frequencies or redesign using dedicated IFA chip
2. Redesign comparator for a proper hysteretic reference
3. Design a proper rail-splitter reference with low output impedance and high-PSRR
4. Utilize shutdown pins on components to lower continuous power draw
5. Reduce ground bounce on Precision Frequency Counter PCB for lower output voltage ripple on power rails
6. Convert Precision Frequency Counter PCB to 4-Layer Stack up for reduced footprint and signal integrity
7. Utilize smaller package variants of components to reduce footprint
8. Integrate a faster MCU to increase sampling rate and reduce power consumption
9. A greater theoretical understanding of the power received and reflected by the contact lens/contact lens simulator

Active Contact Lens Development

The contact lens transceiver is a stepping stone that will allow the development of next generation low power ophthalmological medical devices. With an electronic contact lens transceiver built, testing ASIC designs and antennas are much more accessible.

Finding Uses for BX Technology in Rich Media Applications

The world is changing every day and the requirements for digital radios need to be increasingly lower power and higher bandwidth. The transceiver designed in this project has bandwidth approaching ultra-wideband capability and incredibly high transmission efficiency. In perspective, the rated envelope bandwidth of the ADL5511 envelope detector at 130MHz can potentially yield data rates capable of streaming eight 1080P videos simultaneously.
Chapter 7: References

[1] Analog Devices, ADP122, “5.5 V Input, 300 mA, Low Quiescent Current, CMOS Linear Regulator,” ADP122 Datasheet


[12] GC Electronics, MSDS#268, “Solder 60/40 Rosin Core”, Solder 60/40 Rosin Core Safety Data Sheet.


[18] Maxim Integrated, Appl. Note 3930


[27] Murata, LQW18AN58NG80, “High Frequency Inductor with Low DC resistance and High Current Capability,” LQW18AN58NG80 datasheet.


Appendix A — ABET Analysis of Senior Project Design

Project Title: High-Bandwidth IOP Sensing Backscatter Transceiver

Mark Manuel: MM

Tina Smilkstein: TS

• 1. Summary of Functional Requirements
The full-duplex transceiver transmits VHF ISM band radio and can capture reflected backscatter On-Off-Keying modulated message signals from an ASIC embedded contact lens at bandwidths up to 100MHz. The measured backscatter frequency matches to corresponding intraocular pressures and displayed for the user.

• 2. Primary Constraints
Difficulties anticipated manifest itself in high speed design and self-interference from the duplex operating antennas. The small form factor of the device inhibits the antennas from being far apart, therefore creative self-interference techniques are required [7].

• 3. Economic
Financial Capital:

Projected funding overhead in the tools to design, manufacture, and validate a working system costs about $100 – $200 thousand dollars. Required electronic test equipment such as a vector network analyzer and signal analyzer can cost up to $50,000 per machine.

Projected labor costs for a single device costs around $53,328 dollars as quantified in the cost analysis.

Human Capital:

A medium sized company manufacturing 100,000 devices a year requires about 250 employees serving roles as engineers, assemblers, accountants and marketers.

Manufactured or Real Capital – Made by people and their tools.

The tools required to manufacture and design this device consist of an electronics design lab and several large-scale semiconductor, PCB manufacturing, and raw material mining operations downstream.

Natural Capital – The Earth’s resources and bio-capacity.

Manufacturing the VHF transceiver mirrors devices such as mobile phones. According to a TruCost environmental study, a single smartphone consumes 12,000 liters of fresh water and 18 square meters of land from the result of mines and polluted groundwater [4]. 100,000 devices reduce the Earth’s usable groundwater supply by 1.2 million liters and usable land by 180,000 square meters.

• When and where do costs and benefits accrue throughout the project’s lifecycle?

The costs of the system have accrued decades before the start of the project as the institutions of electronics manufacturing established long before the start of the project. The upfront costs however begin as soon as the device begins the design phase and end at the lifecycle of the device at the disposal stage. The benefits accrue once the device approval begins use for the general population.

• What inputs does the project require? How much does the project cost? Who pays?
The project inputs labor, several integrated circuits and printed circuit boards. The estimated project costs total $53,328 as quantified in the cost analysis. The project designer supplies labor and development materials and Cal Poly supplies electronic test equipment and facilities.

The original estimated cost of development component parts total to $1659 dollars.

• How much does the project earn? Who profits?

The project’s profits in intellectual property generated. The project designer profits from any intellectual property gained from development activities.

• Timing

When do products emerge? How long do products exist? What maintenance or operation costs exist?

Products emerge from concept generation, simulated hardware and physical hardware. Ideas generated from this project last infinitely, and products last until electronic components fail at about 5-10 years or greater. The estimated development time requires 9-months.

• 4. If manufactured on a commercial basis:
  • Estimated number of devices sold per year

The prevalence of Glaucoma affects 2.7 million people in the U.S. If 1% of glaucoma patients purchased this tool, a minimum of 27,000 transceivers will be manufactured.

• Estimated manufacturing cost for each device

As stated before, the VHF transceiver project closely resembles the manufacturing process of a smartphone. A report by the IEEE spectrum found the price of an Apple iPhone to cost about $250 [21].

• Estimated purchase price for each device

The estimated purchase price of the device totals $500.

• Estimated profit per year

Estimated profit per year for 27,000 devices selling at $500 with a profit margin of 50% yields $6.75 million dollars per annum.

• Estimated cost for user to operate device, per unit time (specify time interval)

The estimated cost for the user to operate the device per month is estimated at about $5 dollars, as the device only requires power from a battery.

• 5. Environmental
The environmental impact study for the transceiver quantizes (1) CO2 footprint, (2) land consumption, and water consumption.

**CO2 Footprint:**

A quantitative energy analysis using CES EduPack in Appendix B quantizes CO2 footprint per device manufactured. A corresponding energy impact is weighted for each itemized part composing the transceiver system. Table A-1 is the resultant effect of the CO2 footprint on a single device per supply chain stage. Correspondingly, manufacturing 100,000 devices releases 11.5 Million pounds of CO2 in the atmosphere.

**Land & Water Consumption:**

Manufacturing the VHF transceiver mirrors devices such as mobile phones. According to a TruCost environmental study, a single cell phone consumes 12,000 liters of fresh water and 18 square meters of land per device manufactured [11]. Toxic water from mines mixes with fresh groundwater and mines occupy a significant amount of space. The Earth’s usable groundwater supply reduces by 1.2 million liters and 180,000 square meters per 100,000 transceivers manufactured.

**Table A-1. CO2 footprint per device manufactured calculated in Appendix B**

- Which natural resources and ecosystem services does the project improve or harm?

The project does little or no benefit to the Earth’s natural resources and ecosystem services.

- How does the project impact other species?

Toxic contaminants contaminating groundwater affect all species that consume water from lakes and rivers in mining areas. Radio waves emitted from RF transceivers can also impact certain insects such as bees[5]. The 11 Millions pounds of CO2 affects many ecosystems across the globe through global warming effects.
• 6. Manufacturability

Manufacturing challenges exist because of high-speed circuit design and sensitive RF electronics requiring high precision PCB materials and tolerances. Because the device measures a physiological property, a qualification process by a regulatory body such as the FDA may generate challenges in a mass-produced manufacturing environment.

• 7. Sustainability

• Describe any issues or challenges associated with maintaining the completed device, or system.

The system may encounter challenges mechanically as the system may wear as a portable device. Batteries wear with use and may require replacement on cycles of 1-5 years.

• Describe how the project impacts the sustainable use of resources.

The project consumes several materials such as water, land, and rare earth minerals and metals. A relatively small number of waste generates from this small production niche device created with recyclable materials [11].

• Describe any upgrades that would improve the design of the project.

Potential upgrades include processing to a smartphone requiring less components and greater accessibility through voice commands. Per Table A-1 and Appendix B, most of the energy required to manufacture the device is in material embodied energy. Environmental impacts are less severe if recycled materials are used.

• Describe any issues or challenges associated with upgrading the design.

Upgrading the design requires a complete PCB and mechanical redesign because of the high speed and RF electronics. A high level of tuning integrates the circuits implemented in the device.

• 8. Ethical

The development of the device commits to the IEEE code of ethics [26] to accept responsibility in making decisions consistent with the safety, health and welfare of the public and to disclose factors that might endanger the public or the environment.

Today’s increasingly connected world depends on the ISM band spectrum heavily. The transceiver operates on ISM band, and transmits RF power over the air shrinking usable bandwidth. The device can generate significant RF pollution on the shared spectral resource. The transceiver also generates a large amount of waste as quantified in section 5.

A utilitarian argument justifies the potential medical and economic benefits over transceiver over consumption of the ISM band and Earth’s natural resources. The contact lens system tries to reach the greatest amount of good for the least amount of sacrifice. The prevented Glaucoma induced blindness for millions worldwide is worthwhile. The transceiver’s few and far in between measurement behavior and small anticipated production generates low relative environmental impact and spectral bandwidth costs.

• 9. Health and Safety

The device may emit harmful RF power when used, and chemical toxins during assembly.
Though the device constrains a safe RF power level, the exposure to high frequency RF at any power follows health risks. Health benefits from proper diagnostics of the Glaucoma illness far outweigh incidental low-power RF exposure.

Electronics assembly can expose an operator to several hazardous chemicals such as lead, vaporized solder flux and several other solvents[12].

**10. Social and Political**

- Describe social and political issues associated with design, manufacture, and use.

The device may look embarrassing to the user as an antenna embedded contact lens generates concern. The design may cause social issues as the device highlights a person’s glaucoma condition to the public.

- Who does the project impact? Who are the direct and indirect stakeholders? How does the project benefit or harm various stakeholders?

The project directly impacts Glaucoma patients, insurance providers, U.S. Medicare and Medicaid, and physicians through better control of the illness.

Indirectly, the economic benefits from controlled Glaucoma affects all U.S. taxpayers through increased GDP and reduced medical costs. The IOP data generated has learning potential for Glaucoma researchers and researchers of other related conditions.

- To what extent do stakeholders benefit equally? Pay equally? Does the project create any inequities?

The private and federal insurance providers benefit the greatest in gross revenue because of reduced medical visits and procedures. In other words, the return on investment yields high for this device considering the cost of treatment of late stage Glaucoma. The patients benefit the greatest in relative worth through improved health and vision. [15]

- Consider various stakeholders’ locations, communities, access to resources, economic power, knowledge, skills, and political power.

Because of the high price of the device at $500 or more, many low-cost health insurance providers may not approve of the device. The device may generate class equity tensions because of accessibility – have vs. have nots.

**11. Development**

**Book:**


**Why:** “High-speed digital design: a handbook of black magic” encompasses high frequency circuits and techniques for electronic systems operating greater than 10MHz. The contact lens system warrants high speed digital design techniques at frequencies up to 2.4GHz.

**Authority:** The book established authority through reference of 35 peer-reviewed articles in several scientific, mathematical and engineering journals.

**IEEE Articles:**

Why: Byeon lays out system level architecture for On-Off-Keying transceiver architectures implemented on the contact lens system. The article realizes real circuits that provide modulation and demodulation.

Authority: The peer reviewed article exhibits a high level of authority from review and publication in an IEEE journal.


Why: Sim’s article describes several methods to eliminate self-interference in full-duplex radio applications. The full-duplex radio in the contact lens application benefits greatly from self-interference cancellation techniques proposing higher signal to noise ratio and measurement sensitivity.

Authority: The article exhibits a high level of authority because extensive evidence of peer review and publication in an IEEE journal.


Why: Gong’s article encompasses amplitude shift keying (ASK) demodulator designs and their potential in On-Off-Keying demodulators. On-Off-Keying lies under a subset of ASK, therefore the circuits described may prove useful.

Authority: The article exhibits a high level of authority through extensive evidence of peer review and publication in an IEEE journal.


Why: Jain’s article describes a successful topology implemented in a full-duplex radio application. The radio described in the article may prove useful.

Authority: The article exhibits a high level of authority because extensive evidence of peer review and publication in an IEEE journal. The article logically explains the circuit functionality free of errors.

Datasheets:


Why: The LTC6253-7 performs well in high frequency signal processing applications due to its high gain bandwidth(GBW) and rail-to-rail operation. The contact lens system requires low power and high speed signals processing hardware up to 70MHz.

Authority: The datasheet exhibits a high level of authority through logic and comprehensive coverage of performance characteristics. The performance graphs and tables prove consistent with normal op-amp behavior and free of errors.


Why: The WPC.25B.35 patch antenna operates from 2.4GHz to 2.5GHz ISM band radio. The contact lens system optimizes ISM band 2.4 GHz radio use.

Authority: The datasheet exhibits a high level of authority through logic and comprehensive coverage of
performance characteristics. The performance graphs and tables prove consistent with normal antenna behavior and free of errors.

**Patent:**


**Why:** Khandani’s patent describes self interference cancellation techniques for radios operating in full-duplex mode. The contact lens requires full-duplex operation and signal to noise ratio would benefit from self-interference techniques.

**Authority:** The datasheet exhibits a high level of authority through logic and relatable citations. The self-interference technique proves statements with known and verifiable physical phenomena. The citations cited in the patent also exhibit high values in authority.

**Application Notes**


**Why:** Semtech application note AN1200.04 encompasses high speed RF design guidelines for PCB layout and circuit optimization. The tutorial advises proper technique for well known RF design principles and warns of potential problems that may arise.

**Authority:** The application note AN1200.04 proves its authority through logic, and experience as a high speed, high reliability RFIC manufacturer. The tutorial uses real world examples and comprehensive design instruction to prove validity.

**Thesis (M.S.)**


**Why:** The hardware defined in the thesis communicates to the transceiver. Sung Tran’s thesis defines the parameters for a large majority of the backscatter transceiver specifications.

**Authority:** Tran’s thesis exhibits a high level of authority by successful defense at the reputable Cal Poly State University in San Luis Obispo. The article logically explains the design and simulation of each circuit.
# Appendix B: CES EduPack 2017 – Eco Audit Report

## Eco Audit Report

### Energy Analysis

<table>
<thead>
<tr>
<th>Life Phase</th>
<th>Energy (kcal/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent annual environmental burden (averaged over 4 year product life):</td>
<td>4.49e+04</td>
</tr>
</tbody>
</table>

### Detailed breakdown of individual life phases

#### Material:

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Recycled content* (%)</th>
<th>Part mass (lb)</th>
<th>Qty.</th>
<th>Total mass (lb)</th>
<th>Energy (kcal)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed Circuit Board</td>
<td>Printed circuit board assembly</td>
<td>Virgin (0%)</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>7e+02</td>
<td>0.6</td>
</tr>
<tr>
<td>High Performance IC's</td>
<td>Integrated circuit, large</td>
<td>Virgin (0%)</td>
<td>0.01</td>
<td>1</td>
<td>0.01</td>
<td>8.7e+03</td>
<td>7.1</td>
</tr>
<tr>
<td>Supporting IC's</td>
<td>Integrated circuit, small</td>
<td>Virgin (0%)</td>
<td>0.01</td>
<td>1</td>
<td>0.01</td>
<td>1.9e+03</td>
<td>1.6</td>
</tr>
<tr>
<td>Component</td>
<td>Process</td>
<td>Amount processed</td>
<td>Energy (kcal)</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----------------------------------------------</td>
<td>------------------</td>
<td>---------------</td>
<td>------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS Enclosure</td>
<td>Acrylonitrile butadiene styrene (ABS)</td>
<td>1 lb</td>
<td>2.2e+03</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>2.2e+03</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Typical: Includes 'recycle fraction in current supply'

### Manufacture:

<table>
<thead>
<tr>
<th>Component</th>
<th>Process</th>
<th>Amount processed</th>
<th>Energy (kcal)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS Enclosure</td>
<td>Polymer molding</td>
<td>1 lb</td>
<td>2.2e+03</td>
<td>100.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>2.2e+03</td>
<td>100</td>
</tr>
</tbody>
</table>

### Transport:

Breakdown by transport stage

<table>
<thead>
<tr>
<th>Stage name</th>
<th>Transport type</th>
<th>Distance (miles)</th>
<th>Energy (kcal)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shenzen, China to US</td>
<td>Air freight - long haul</td>
<td>7e+03</td>
<td>1.9e+04</td>
<td>100.0</td>
</tr>
</tbody>
</table>
## Breakdown by components

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (lb)</th>
<th>Energy (kcal)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed Circuit Board</td>
<td>0.05</td>
<td>5.1e+02</td>
<td>2.6</td>
</tr>
<tr>
<td>High Performance IC's</td>
<td>0.01</td>
<td>1e+02</td>
<td>0.5</td>
</tr>
<tr>
<td>Supporting IC's</td>
<td>0.01</td>
<td>1e+02</td>
<td>0.5</td>
</tr>
<tr>
<td>Resistors</td>
<td>0.01</td>
<td>1e+02</td>
<td>0.5</td>
</tr>
<tr>
<td>Capacitors</td>
<td>0.01</td>
<td>1e+02</td>
<td>0.5</td>
</tr>
<tr>
<td>Solder</td>
<td>0.01</td>
<td>1e+02</td>
<td>0.5</td>
</tr>
<tr>
<td>LCD Indicator Panel</td>
<td>0.01</td>
<td>1e+02</td>
<td>0.5</td>
</tr>
<tr>
<td>ABS Enclosure</td>
<td>1</td>
<td>1e+04</td>
<td>52.1</td>
</tr>
<tr>
<td>USB Cable</td>
<td>0.5</td>
<td>5.1e+03</td>
<td>26.0</td>
</tr>
<tr>
<td>USB Port</td>
<td>0.01</td>
<td>1e+02</td>
<td>0.5</td>
</tr>
<tr>
<td>Android Smartphone</td>
<td>0.3</td>
<td>3e+03</td>
<td>15.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.9</strong></td>
<td><strong>1.9e+04</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

## Use:

**Summary**

**Static mode**

<table>
<thead>
<tr>
<th>Energy input and output type</th>
<th>Electric to thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country of use</td>
<td>World</td>
</tr>
</tbody>
</table>
### Power rating (W)

| Power rating (W) | 10 |

| Usage (hours per day) | 24 |
| Usage (days per year) | 20 |
| Product life (years) | 4 |

#### Relative contribution of static and mobile modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy (kcal)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>3.6e+04</td>
<td>100.0</td>
</tr>
<tr>
<td>Mobile</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3.6e+04</td>
<td>100</td>
</tr>
</tbody>
</table>

#### Disposal:

<table>
<thead>
<tr>
<th>Component</th>
<th>End of life option</th>
<th>Energy (kcal)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed Circuit Board</td>
<td>Re-manufacture</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>High Performance IC's</td>
<td>Landfill</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>Supporting IC's</td>
<td>Landfill</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>Resistors</td>
<td>Landfill</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>Capacitors</td>
<td>Landfill</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>Solder</td>
<td>Landfill</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>LCD Indicator Panel</td>
<td>Landfill</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>ABS Enclosure</td>
<td>Recycle</td>
<td>76</td>
<td>79.2</td>
</tr>
</tbody>
</table>
### EoL potential:

<table>
<thead>
<tr>
<th>Component</th>
<th>End of life option</th>
<th>Energy (kcal)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed Circuit Board</td>
<td>Re-manufacture</td>
<td>-6.9e+02</td>
<td>11.5</td>
</tr>
<tr>
<td>High Performance IC's</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Supporting IC's</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Resistors</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Capacitors</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Solder</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>LCD Indicator Panel</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>ABS Enclosure</td>
<td>Recycle</td>
<td>-5.3e+03</td>
<td>88.5</td>
</tr>
<tr>
<td>USB Cable</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>USB Port</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Android Smartphone</td>
<td>Landfill</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>-6e+03</td>
<td>100</td>
</tr>
</tbody>
</table>

### Notes:
The Tables and figures left unlabeled to preserve the originality of the ECO Audit.
Appendix C: ATmega328p Firmware

/*--------------------------------------------------------------------------*/
* File Name : main.c
* 
* Project : Active RFID Wireless Contact Lens Transceiver
* Organization : California Polytechnic State University
* Hardware : Atmel ATmega328P
* Description : This firmware interfaces the ATMega328 to the
* Sparkfun IOIO V.2 breakout board and detects
* the frequency of an external clock signal.
* Frequency detected is transmitted over SPI to
* the IOIO subsystem.
* 
* Hardware : 1. ATMEL ATmega328P Microcontroller
* 2. Sparkfun IOIO V.2 Breakout Board
* 
* Created : 4/20/2018
* Engineers : Mark Manuel
* *--------------------------------------------------------------------------*/

#define F_CPU 16000000UL
#include <avr/io.h>
#include <util/delay.h>
#include <avr/interrupt.h>
#include <stdlib.h> // Standard C library
#include <string.h>
#include <math.h>
#include "UART.h" //function prototype
void initTimer0(void);
void initTimer1(void);
void initTimer2(void);

volatile int fs_timer_status = 0; // Sampling Frequency Status
volatile int FC_L = 0; // Lower Frequency Counter Value
volatile int FC_H = 0; // Higher Frequency Counter Value
volatile int FC = 0; // 16 Bit Frequency Counter Value
volatile int samp_dur_status = 0; // Sampling Duration Status

int main(void)
{
    double frequency = 0;
    static char freq_print[16];
    initTimer0();
    initTimer1();
    initTimer2();
    uart_init(38400, F_CPU); //Initialize UART bus at 38.4kbaud

    DDC |= 1<<PC1; // Pin B5 output
    DDC |= 1<<PC0; // Pin B0 output
    sei(); // Enable global interrupts

    while(1)
    {
        /*************************************************************************/
        TCCR0B = 0x0; // Stop Sampling Rate Timer
        TCCR1B = 0x0; // Stop Frequency Counter
    }
TCCR2B = 0x0;  // Stop Sampling Duration Timer
/*----------------------------------------*/
/*----------------------------------------*/
TIFR0 = 0x2;  // Reset Sampling Rate Timer
TIFR1 = 0x2;  // Reset Frequency Counter
TIFR2 = 0x2;  // Reset Sampling Duration Timer
/*----------------------------------------*/
_delay_us(10);
/*----------------------------------------*/
TCCR0B = 0x03;  // Start Sampling Rate Timer: SysCLK/64
PORTC |= 1<<PC1; // Turn on C1: total sampling begins
TCCR1B = 0x07;  // Start Freq. cnt: External CLK on T0 pin, RET
TCCR2B = 0x04;  // Start Sampling Duration Timer: SysCLK/64
PORTC |= 1<<PC0;  // Turn on C0: sampling period begins

while(!fs_timer_status) // Wait until 1000uS passes
{
  while(!samp_dur_status) // Wait until 500uS passes
  {
  }
  TCCR1B = 0x00;  // Stop frequency counter
  TCCR2B = 0x00;  // Stop measurement frame timer
}
TCCR0B = 0;  // Stop sampling rate timer
PORTC &=~(1<<PC1);  // Turn off C1 after sample is taken
samp_dur_status = 0;  // Unset sampling duration status
fs_timer_status = 0;  // Unset sampling period status

frequency = (double)FC * 8 / 499;  // Counts * Prescaler / time(uS)
dtostrf(frequency, 7, 6, freq_print);  // Converts freq into ASCII str.

_delay_ms(1);
serial_print_freq(freq_print, FC_L, FC_H);  // Print Data to Terminal
/*----------------------------------------*/
return 0;
}  // end main

void initTimer0(void)
{
  TCCR0A = 0x02;  // timer overflow mode
  TCCR0B = 0x03;  // timer clk = system clk / 64
  OCR0A = 249;  // Overflow every 1000 Hz
  TIFR0 = 0x02;  // clear previous timer overflow
  TIMSK0 = 0x02;  // timer overflow interrupt enabled
}

void initTimer1(void)
{
  TCCR1A = 0x00;  // timer overflow mode
  TCCR1B = 0x07;  // Start Freq. cnt: External CLK on T0 pin, RET
  OCR1A = 0;  // Overflow every 1000 Hz
  TIFR1 = 0x02;  // clear previous timer overflow
  TIMSK1 = 0x00;  // timer overflow interrupt enabled
}

void initTimer2(void)
{
  TCCR2A = 0x02;  // timer overflow mode
}
TCCR2B = 0x08; // timer clk = system clk / 64
OCR2A = 124; // Stop recording after 500us
TIFR2 = 0x02; // clear previous timer overflow
TIMSK2 = 0x02; // timer overflow interrupt enabled

ISR(TIMER0_COMPA_vect)
{
    fs_timer_status = 1; // Kick out of total sample
}
ISR(TIMER2_COMPA_vect)
{
    samp_dur_status = 1; // Kick out of sampling period
    FC_H = TCNT1L;
    FC_L = TCNT1H;
    FC = TCNT1; // Store counts into global var
    TCNT1 = 0x00;
    PORTB &= ~(1 << PB0); // Turn off B0 when sampling duration closes
}

/* File Name : UART.C
 *
* Project   : Active RFID Wireless Contact Lens Transceiver
* Organization : California Polytechnic State University
* Hardware   : Atmel ATmega328P
* Description : This firmware contains the UART library for the USART serial bus
* *
* Hardware   : 1. ATMEL ATmega328P Microcontroller
* *
* Created    : 4/20/2018
* Engineers  : Mark Manuel
*-------------------------------------------------------------*/
#include "UART.h"

void usart_init(uint32_t baudin, uint32_t clk_speedin)
{
    uint32_t ubrr = (clk_speedin/16UL)/baudin-1;
    UBRRL = (unsigned char)(ubrr>>8);
    UBRRH = (unsigned char)ubrr;
    /* Enable receiver and transmitter */
    UCSRB = (1<<RXEN0)|(1<<TXEN0);
    /* Set frame format: 8data, 1stop bit */
    UCSRC = (1<<USBS0)|(1<<UCSZ00);
    UCSR0A &= ~(1<<U2X0);
}

/*the send function will put 8bits on the trans line. */
void usart_send( uint8_t data )
{
    /* Wait for empty transmit buffer */
    while ( !( UCSR0A & (1<<UDRE0)) );
/* Put data into buffer, sends the data */
UDR0 = data;
}

/* the receive data function. Note that this a blocking call 
Therefore you may not get control back after this is called 
until a much later time. It may be helpful to use the 
istheredata() function to check before calling this function 
@return 8bit data packet from sender */
uint8_t usart_recv(void)
{
    /* Wait for data to be received */
    while (!(UCSR0A & (1<<RXC0)))
    ;
    /* Get and return received data from buffer */
    return UDR0;
}

/* function check to see if there is data to be received 
@return true is there is data ready to be read */
uint8_t usart_istheredata(void)
{
    return (UCSR0A & (1<<RXC0));
}

void serial_print(char serial_phrase[])
{
    int char_cnt = strlen(serial_phrase);
    int i;
    for(i=0; i<char_cnt+1; i++)
    {
        usart_send(serial_phrase[i]);
    }
}

void serial_print_num(uint8_t data)
{
    uint8_t temp0 = 0;
    int temp1 = 0;
    int j=0, k=0;
    // Begin with: 76543210
    temp0 = data & ~(0xF0); //00003210
    temp1 = data; //76540000
    temp1 = temp1 >> 4; //00007654
    temp0 = (temp0 + 48); // Convert to ASCII
    temp1 = (temp1 + 48); // Convert to ASCII
    char i[6] = "ABCDEF"; // Decimal to Hex Conversion on lower nibble
    for(j=0; j<7; j++)
    {
        if(temp0 == 58 + j){
            temp0 = i[j];
        }
    }
    for(k=0; k<7; k++)
    {
        if(temp1 == 58 + k){
            temp1 = i[k];
        }
    }
    usart_send(temp1); // Send upper character to serial terminal
    usart_send(temp0); // Send lower character to serial terminal
void serial_print_nl(char serial_phrase[]) {
    int char_cnt = strlen(serial_phrase); // Count number of letters in string
    int i;
    for(i=0; i<char_cnt+1; i++) {
        usart_send(serial_phrase[i]);
    }
    usart_send(\n); // New line
    usart_send(\r); // Carriage Return
}

void serial_print_freq(char freq_str[], uint8_t FC_L, uint8_t FC_H) {
    serial_print("Freq. Measured: ");
    serial_print(freq_str);
    serial_print("MHz");
    serial_print("TCNT1: ");
    serial_print_num(FC_L);
    serial_print_num(FC_H); // Send Lower bit of freq cnt
    usart_send(\n); // New line
    usart_send(\r); // Carriage Return
    _delay_ms(50);
    usart_send(12);
}

/******************************************************************************/
* File Name : UART.H
*
* Project : Active RFID Wireless Contact Lens Transceiver
* Organization : California Polytechnic State University
* Hardware : Atmel ATmega328P
* Description : UART.C firmware header file
* 
* Hardware : 1. ATMEL ATmega328P Microcontroller
* 
* Created : 4/20/2018
* Engineers : Mark Manuel
******************************************************************************/

#define F_CPU 16000000UL
#include <avr/io.h>
#include <util/delay.h>
#include <avr/interrupt.h>
#include <util/twi.h>
#include <stdlib.h> // Standard C library
#include <string.h>
#include <math.h>
#define BAUD_PRESCALE 103

void usart_init(uint32_t baudin, uint32_t clk_speedin);
void usart_send( uint8_t data );
uint8_t  usart_recv(void);
uint8_t usart_istheredata(void);
void serial_print(char serial_phrase[]);
void serial_print_num(uint8_t data);
void serial_print_nl(char serial_phrase[]);
void serial_print_freq(char freq_print[], uint8_t FC_L, uint8_t FC_H);