Portable Brainwave Monitor

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Submitted to:
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Abstract

This document includes the information required to develop a portable brainwave activity alarm. The sponsor for this project is Rod Burt with Texas Instruments. This project is important because allows for the monitoring of brainwave signals in unconventional environments. One possible application is to prevent a driver from falling asleep while behind the wheel. The device has the ability to monitor the user’s brainwaves and inform the user of changes in brainwave frequency patterns. The device is implemented with the use of Texas Instruments integrated circuits and micro controllers to create a circuit that amplifies, filters, and processes brainwave signals. The final design employs 4 OPA333 Operational Amplifiers, 1 INA333 Instrumentation Amplifier, and 1 MSP430 Microcontroller.
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Introduction

The purpose of this project was to create a portable and affordable brainwave monitor that could send data wirelessly to a nearby receiver. The project sponsor, Mr. Rod Burt, recommended the use of Texas Instruments components in the device. Mr. Burt envisioned various applications for the device, including the use in automobiles to detect the onset of sleep while driving. Drowsiness behind the wheel leads to over 56,000 automobile accidents and 40,000 injuries or fatalities each and every year (NHTSA).

The device is designed to measure the potential changes of the electric field generated by neurons in the brain. This procedure is known as electroencephalography (EEG) when done in a clinical setting. An electroencephalogram resembles a continuously varying sine wave. These waves are classified by their dominant frequency and represent different states of alertness. These states, shown below (Figure 1), vary in frequency from 1 to 30 Hz. The focus of this device will be to detect waves of a frequency range in this range.

![Figure 1 - Characteristic Brain Waves (Crumbaugh)](image)

The electromagnetic waves generated by the brain are very small in magnitude at the scalp. This requires that a brainwave with a peak-to-peak amplitude of 50 µV be amplified on the order of $10^3$ dB before a useful signal can be seen. The signal must also be filtered of any unwanted frequencies. EEGs commonly use high, low and notch filters to remove noise generated from muscle movement and other physiological factors, as well as the common electricity lines in the United States that supply power at 60 Hz (Knott, Tyner and Mayer).

Clinical EEGs must be administered and interpreted by a trained EEG technician or neurologist. During the procedure, the tech places several electrodes on the patient's head in an established pattern known as the 10-20 system. These electrodes are the human-to-machine interface, and
are often made of silver/silver chloride and covered in an adhesive electrolytic gel. The electrodes are connected to the EEG machine that can detect potential differences between two electrodes. Each pair of electrodes produces one channel that is recorded, and most EEGs record 8-10 channels. During the recording procedure, the patient is asked to do things that will elicit a predictable reaction, such as opening and closing his or her eyes. Once this calibration is complete, the patient is then subjected to various tests, depending on the reason for the EEG. The frequencies of the recording are measured by counting the number of peaks or troughs in a known time period (typically 1 s). This, along with the shape and amplitude of the waveforms, aids in the diagnosis of neurological disorders (Knott, Tyner and Mayer).

Detecting sleep, in theory, can be accomplished in a non-clinical setting using a minimal number of channels. The presence of 14 Hz voltage spikes, known as sleep spindles, is one of the defining neurological characteristics of sleep. Sleep spindles occur between the stages of drowsiness and deep sleep. Brainwaves also shift from Beta frequency dominance down to Alpha dominance as the person becomes drowsy. Detecting these signs at their first appearance may be enough to wake someone behind the wheel of a vehicle in time to save their life (Knott, Tyner and Mayer).

The mathematical algorithm of changing a signal from a time domain to a frequency domain is known as a Fourier Transform. Different types of Fourier Transforms are known as either Discrete Fourier Transforms (DFTs) or Fast Fourier Transforms (FFTs), depending on the methods used to do the calculations. While DFTs and FFTs are not used to process clinical EEGs, it is possible to implement one of these algorithms to aid in the automated detection of sleep.

The main focus of the project was to be able to detect brainwaves, with the actual detection of sleep possibly being out of the project's scope. The project, according to the sponsor, should be able to detect brainwaves in an ultra-portable, low power package. This may then serve as a future platform for further research and development.
System Requirements

An initial meeting with the project sponsor allowed the team to develop several Voice of the Customers (VOCs). The following Top Level Functional Requirements (TLFRs) were discerned, and all the other VOCs were grouped with the constraints. These TLFRs and constraints clearly show the sponsor’s intent for the device to be an ultraportable low power device.

Top Level Functional Requirements

Table 1. Top level Functional Requirements

<table>
<thead>
<tr>
<th>Functional Requirement</th>
<th>Target Value</th>
<th>Customer Importance (0-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Detect brainwave signals</td>
<td>Detect Potentials greater than 10 µV</td>
<td>5</td>
</tr>
<tr>
<td>2. Process brainwave signal</td>
<td>Calculate Frequencies between 1 and 30 Hz</td>
<td>5</td>
</tr>
<tr>
<td>3. Transmit data wirelessly</td>
<td>Communication Range of 1-4 m</td>
<td>5</td>
</tr>
<tr>
<td>4. Determine useful information from the input signal</td>
<td>Detect sleep (Boolean)</td>
<td>3</td>
</tr>
</tbody>
</table>

Constraints

Table 2, below, shows the constraints discerned from the VOCs. Table 3 shows the constraints of the design and the effects they have on the respective components of the device.

Table 2. Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Parameter</th>
<th>Importance to Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portable</td>
<td>Lightweight, wireless</td>
<td>5</td>
</tr>
<tr>
<td>Durable</td>
<td>Able to withstand extended use without breaking</td>
<td>4</td>
</tr>
<tr>
<td>Low Power</td>
<td>Battery life greater than 1000 hours</td>
<td>5</td>
</tr>
<tr>
<td>Reusable</td>
<td>No gel electrodes</td>
<td>5</td>
</tr>
<tr>
<td>Comfortable</td>
<td>Does not interfere with normal user activity</td>
<td>3</td>
</tr>
<tr>
<td>Easy to use</td>
<td>Simple operation</td>
<td>3</td>
</tr>
<tr>
<td>Aesthetic</td>
<td>Looks like something people would want to wear</td>
<td>2</td>
</tr>
<tr>
<td>Low Cost</td>
<td>&lt;$7.00 manufacturing cost</td>
<td>4</td>
</tr>
</tbody>
</table>
A major constraint is the battery life of the design. In this design, a microcontroller will be included in the device and will process the detected signals. This processing will take some power and may drain the battery faster than expected and cause the device to fail prior to reaching its expected life time. This would require a replaceable battery in order to make the device reusable. This problem can be minimized by using ultra low power ICs, microcontroller, and radio.

### Table 3. Constraints and Their Effects

<table>
<thead>
<tr>
<th></th>
<th>Packaging</th>
<th>Microcontroller</th>
<th>Battery</th>
<th>Transmitter</th>
<th>Electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portable</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durable</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Power</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Various Environments</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Reusable</td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>No Gels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Comfortable</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aesthetic</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Low Cost</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
Design Concepts

Three designs were developed that could have met the functional requirements of the project. Out of the three designs, only the final design satisfied the functional requirements and fit within the constraints of the project.

Considered Designs

The first rejected concept was very similar to the design that has been implemented, with a few key differences. The amplification and head device subsystems would have been identical, but the signal processing would have occurred differently. The design considered transmitting each sample from the ADC without any onboard processing. The signal processing aspect would then be accomplished by a computer receiving the data. Although this would have resulted in more processing power for a better FFT, the constant use of the end device radio would have required too much power and could have violated the low power constraint.

The second rejected concept was developed around the phenomena of event related potentials (ERPs). ERPs are brainwave spikes that occur a few milliseconds after they are provoked, either by light or sound. These potentials could have been monitored for a change from the average response time. Aside from the stimulus becoming irritating or even dangerous, the brain could potentially react to any other outside lights or noise.

Final Design

The design was developed by analyzing the functional requirements and determining which subsystem was affected by each requirement. The TLFRs are to detect the brainwave, process the signal, wirelessly transmit the frequency data and do something useful with it.

The first functional requirement is to detect the brainwave. This is accomplished using electrodes mounted to a head device as inputs to a differential operational amplifier. The electrodes used are Ag-AgCl EL120 electrodes from Biopac Systems, Inc. These electrodes are reusable with twelve 2 mm contact posts for hair penetration (Figure 2). The head device was designed using SolidWorks and rapid prototyped using Accura 25 plastic. The amplifier used is the Texas Instruments INA333 instrumentation amplifier. This was chosen because of its low power and low noise properties. Further amplification and filtering is accomplished using Texas instruments OPA333 operational amplifier. This too was chosen for its low power and low noise properties. The actual detection of the signal is accomplished using an analog to digital converter (ADC). The ADC chosen for this design is an integrated with microcontroller.

Figure 2. EL120 Electrodes.
The next functional requirement is to process the signal. Signal processing is done on a Texas Instruments MSP430 mixed signal processor. The processor used is the MSP430F2274 included with the EZ430 RF2500 Wireless Development Tool. This development kit includes a USB interface and two target boards that both contain a microcontroller and radio.

The third functional requirement is to transmit data wirelessly. This is done using the Texas Instruments CC2500 radio on the EZ430 RF2500 target boards. Data transmission is handled using the SimpliciTI End Device to Access Point wireless protocol.

The last functional requirement is to accomplish something useful with the data. This is accomplished using a combination of the MSP430 and a graphical user interface written in Visual Basic.

Each subsystem will be described in more detail following the design matrix below.
In the design matrix in Figure 3, there are four instances of coupling. The use of gel-less electrodes (FR 1.1) affects the choice of amplifier (DP 1.4.1) because the amplifier must be able to detect a low voltage signal. The functional requirement of reducing noise (FR1.3) affects the amplifier choice (DPS 1.4 and 1.4.1). This requirement also affects the decision to locally amplify the signal on the device (DP 1.4.1.1) because the farther away the signal is amplified, the more noise can be introduced.
**Mechanical Design Hardware**

Head Gear Support

This component is made up of two parts. First is the main support arch which rests on the top of the head. This helps reduce pressure points and distribute the load of the entire headgear over a larger area. The arch is made of Accura 25, which is a flexible plastic used by 360 Engineering to rapid prototype designs. Appendix A shows all of the head gear prototypes in order of production.

The second part of the support structure is the earpiece. These were purchased separately and integrated into the head support. There is one for each ear and were chosen for their soft flexible properties. They are very comfortable and can flex to accommodate any ear shape. Having these properties allows for a more comfortable and universal fit. A picture of the earpiece purchased is shown below.

![Figure 4. Earpiece](image)

Circuit and Battery Compartment

These compartments are the same design since both will be required to house the basic PCB and all attached components. The PCB with the microprocessor and amplifiers is placed on one side of the head. The battery is mounted on a PCB on the other side so that the user interface and processing component are separate. This compartment seals the circuit board from the environment and protects it from outside contaminants.

Electrode Array

The electrode array is composed of a single adjustable head band that has the electrodes attached. The array has an adjuster that allows the user to increase or decrease the length of the band. This provides support for the entire system and will allow the user to apply enough force to the electrodes to maintain good contact and to keep a clear signal. The head band will also pivot at a center point to allow for a better fit and to increase attainable comfort.

**Electrical Design Hardware**

The block diagram in Figure 5 below gives a visual representation of the circuit design. The circuit begins with two electrodes hooked up to the head to detect the brainwave signal. Once the signal is detected it passes through the DC gain (INA333). The skin acts as a battery providing a resistance that adds a DC offset to the signal and will put a limitation on the front end gain of the
circuit. The next stage is AC coupling to remove the DC component and output a straight AC signal which will be amplified with an AC gain (OPA333) so a functional signal can be filtered. The Anti-Aliasing Filter (Fourth order Butterworth filter) removes any distortion and the clean signal is sent to the micro controller for processing. The micro controller is responsible for the Analog to Digital Conversion, the FFT and is also responsible for storing the data about the brainwave frequencies being detected. Once sleep is detected, a signal is sent to the Radio Transmitter Antenna which sends that signal wirelessly to a receiver. The second micro controller is used as a pass through which is USB interfaced with a computer.

Figure 5 - Block Diagram for Circuit Design

The schematic for the initial gain circuit for the 2-electrode concept was designed with the assumption that contact between the electrode and skin creates a battery-like potential. Ideally, this potential should be the same for both electrodes, and in this case, the contact potential does not affect the quiescent point of the amplifier. As seen in Figure 6, when the contact-related potential is matched, the gain resistor can be minimized to yield a rail-to-rail output. However, the contact-related potential may not be matched in a real case, and the amplifier’s quiescent point may be shifted.
Figure 6 - Contact Related Potential Matched. Gain resistor 3.5k Ohms. Rail to rail output.

Figure 7 demonstrates that if the same gain resistor is not modified from the ideal case, a good portion of the signal will be lost. To allow for some contact-related potential difference, the gain resistor must be increased as shown in Figure 8.

Figure 7 - Contact Related Potential 50mV. Gain resistor 3k Ohms. Clipped output.
Figure 8 - Contact Related Potential 50mV. Gain resistor 7.14k Ohms. Adequate output.

First Gain Stage
The INA333 Instrumentation Amplifier was chosen as the first amplification stage. The INA333 is specifically designed to remove noise using high common-mode rejection (100dB at G≥10). This is the best configuration for our project due to the low signal amplitude and high noise components that make up a brainwave. The value of the gain for this INA stage is 10 V/V. The gain equation used to calculate the value is shown in Equation 1. This was chosen so that the circuit would not amplify the DC offset associated with the skin to electrode contact. Figure 9 - INA333 Instrumentation Amplifier, First Stage shows the schematic of the first stage amplification stage.

\[ G = 1 + \frac{(100k\Omega)}{Rg} \]

Equation 1 - First Stage Gain
Figure 9 - INA333 Instrumentation Amplifier, First Stage

AC Coupling
A capacitor is included between the INA stage output and the input of the Butterworth filter which allows for AC coupling and also has a pole at DC and creates a first order highpass filter. The AC coupling rejects the DC signal and passes the AC along to the next stage. The capacitor was adjusted so that its time constant was decreased which in turn decreased the response time of the circuit. The time constant is the rate at which the capacitor reaches steady state.

Fourth Order Butterworth Filter
A Fourth Order Butterworth filter was designed using the OPA333 Operational Amplifier. The OPA333 was chosen because it is optimized for low-voltage and single-supply operation. The Butterworth filter circuit was chosen for the design because it is maximally flat in the passband and has a sharp roll off into the stopband. It also has a narrow transition band which helps with the rejection of unwanted frequencies that are close to the cutoff frequency. In this case the unwanted frequency is 60 Hz and the cutoff frequency is 30 Hz. The steepness of the slope of the transition band is directly impacted by the order of the Butterworth polynomial; the higher the order, the steeper the slope of the transition band. The slope of this fourth order filter was steep enough that it cancelled the 60 Hz frequency but still passed the very low brainwave frequencies that were important to the success of the project. Knowing the cutoff frequency and picking a value for the resistor, we used the equations below to determine the value of the other components in the circuit. This design is a low pass filter that passes frequencies under the cutoff frequency (30 Hz).

\[
H(s)_{overall} = \frac{w_c^2}{s^2 + 0.765w_c s + w_c^2} * \frac{w_c^2}{s^2 + 1.848w_c s + w_c^2}
\]

Equation 2 - Overall Transfer Function
\[ H(s)_1 = \frac{w_c^2}{s^2 + 0.765w_c s + w_c^2} \]

Equation 3 - First Stage Transfer Function

\[ w_c = 2\pi f_c \]

Equation 4 - Cutoff Frequency

\[ C_1 = \frac{2}{0.765 \cdot w_c R_1} \]

Equation 5 - Capacitor 1 Value

\[ C_2 = \frac{1}{w_c^2 C_1 R_1^2} \]

Equation 6 - Capacitor 2 Value

\[ H(s)_2 = \frac{w_c^2}{s^2 + 1.848w_c s + w_c^2} \]

Equation 7 - Second Stage Transfer Function

\[ C_3 = \frac{2}{1.848 \cdot w_c R_2} \]

Equation 8 - Capacitor 3 Value

\[ C_4 = \frac{1}{w_c^2 C_3 R_2^2} \]

Equation 9 - Capacitor 4 Value

Final Gain Stage
The final amplification stage was made with the OPA333 as well. The gain of this stage was originally 1000 V/V. However, testing proved that this gain was not sufficient to amplify the low amplitude signal provided from the brain. The gain was increased to 2500 V/V to amplify the
microvolt signal acquired from the brain (≈200 µV amplitude). Equation 10 was used to calculate the gain for the final stage.

\[ A_v = \frac{R_f}{R_{in}} \]

Equation 10 - Final Stage Gain

![Figure 10 - Final Amplification Stage](image)

Constant Voltage Source Buffer
A voltage buffer was used to supply a constant voltage of 1.5 Volts to bias the inputs of all the stages with the exception of the second stage of the Butterworth filter. A voltage divider was used to decrease the 3 Volt supply. The equation for the voltage divider is shown in Equation 11. This was done by using two resistors of the same value which cut the 3 Volts in half for a final output supply voltage of 1.5 Volts. Figure 11 shows the buffer circuit.

\[ V_{out} = V_{in} \cdot \frac{R_{d1}}{R_{d2}} \]

Equation 11 - Voltage Buffer Output Expression

![Figure 11 - Voltage Buffer Supplying 1.5 Volt Bias](image)
Design Software

The Texas Instruments MSP430 was programmed using the IAR Embedded Workbench using the C language. The 200 series MSP430 included with the ez430-RF2500 development kit has several important features that were utilized in this project. The main clock is driven by a 16 MHz digitally controlled oscillator for quick response time. The MSP430x2274 also has an integrated 12 kHz oscillator (VLO) for low frequency, low power applications. A timer module is driven from the VLO and sets the sampling frequency at 60 Hz. This timer is able to wake the MSP430 from its low power mode to continue with code execution. During normal operation, the MSP430 spends approximately 95% of the time in low-power mode, with the CPU and main clocks shut off to conserve power. This design allows the device to have a battery life of 1053 hours of continuous use from a single 2032 medical device battery.

Samples are taken with a 10-bit successive approximation analog to digital converter. The ADC uses a data transfer controller to store samples into the FFT input array without help from the CPU. The FFT input array is 64 data points wide in order to work within the memory limits of the microcontroller and provides a frequency resolution of .9375 Hz, which has been found acceptable for this project. After the input array is filled, an FFT is computed and the input array is cleared. The output array is then searched for the highest value. The frequency at that value is considered the dominant input frequency.

The software uses the integrated CC2500 radio along with Texas Instruments’ SimpliciTI wireless protocol to transmit the data from an end device to an access point. The access point then passes the data through a USB interface to a graphical user interface where the data can be displayed.

The software also includes additional features to aide end user. The GUI displays both the end device-access point connection strength and a warning when the electrodes are improperly connected. There is also an option to log data into a file so that it can be viewed in a graphical format later.

The GUI is shown in Figure 12. Figure 13 shows a block diagram of how the system works. Appendix F – Device Software contains the software that controls the MSP430.
Figure 12 - Graphical User Interface
Figure 13 - Block diagram of signal processing
**Subsystem Verification and Validation**

Each subsystem was tested independently before final assembly.

**Mechanical Test Plan and Results**

The skin impedance was measured with different electrode types to determine which type of material is the best to use for this application. The results are shown below in Table 4 - Skin Impedance.

Table 4 - Skin Impedance

<table>
<thead>
<tr>
<th>Description</th>
<th>Forearm (kΩ)</th>
<th>Forehead (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Med</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>TD-142G</td>
<td>286</td>
<td>42/42.5</td>
</tr>
<tr>
<td>Steel Chip (dry)</td>
<td>317/233</td>
<td>150</td>
</tr>
<tr>
<td>Steel Chip (wet)</td>
<td>180</td>
<td>25</td>
</tr>
<tr>
<td>Dry Skin</td>
<td></td>
<td>233</td>
</tr>
</tbody>
</table>

**Electrical Test Plan and Results**

Using TINA T.I. software, the entire circuit was simulated to test the cutoff frequency and the voltage gain. MATLAB was also used to verify that the cutoff frequency requirements were met by plotting the transfer function of the circuit. The plots below depict the TINA and MATLAB results.
Figure 14 - Transfer Function from MATLAB Test

MATLAB code used to plot above figure:

R=16000;
C=.33e-6;
k=.016733;
K=101;
num=[(K)/(R^2*C^2)]
den=[1 ((3-k*K)/(R*C)) 1/((R*C)^2)]
sysa=tf(num,den)
ltyview(sysa)
Figure 15 - Circuit Tested in MATLAB

Figure 16 - Bode Plots of Figure 14

Using a function generator, the input was varied between high and low frequencies to determine if the circuit was only passing the required low frequencies. Using a battery-powered oscilloscope, the output of the circuit was measured. The input was from gel electrodes attached to the forehead for the first trial to determine what signal is attainable with the circuit.
amplification. The second trial involved electrodes with no gel. The output was measured again to demonstrate that a readable signal was achieved, showing that the circuit design was adequate.

The electrical circuit was validated using an oscilloscope by graphically showing different physiological potentials. Two electrodes were placed on a test subject’s body and the amplified potential was displayed on the oscilloscope. The following figures have been recreated from the oscilloscope measurement data.

![Heartbeat graph](image)

Figure 17. Oscilloscope reading with electrodes held in the left and right hands. Note that the spike is clipping to the 3V Rail.
Software Test Plan and Results

The software can be broken down into three primary functions: Capturing and converting an analog input via the onboard ADC, transforming the input stream via a fast Fourier transform algorithm, and sending a wireless signal when the transformed signal shows certain characteristics.

The first function uses the MSP430’s onboard 10-bit ADC to capture an analog signal that varies from 0-3V and transform it to a digital number in the range of 0-1023. We were able to demonstrate this functionality by writing a test program that reads the voltage on an input pin and uses the ez430-RF2500’s onboard LEDs and Pulse Width Modification functionality to change the brightness of the LED in proportion to the input voltage. The demonstration program was able to successfully light the LED to full brightness (PWM duty cycle = 100%) when the input is 3 volts, shut the LED off (PWM duty cycle = 0%) when the input 0 volts, and vary the brightness between the two rails.

The next function uses an FFT algorithm to convert an array of data into its corresponding spectrum of frequencies. This was tested by using MATLAB to generate various complex sine wave functions of known frequencies. The functions were then converted into arrays of data that simulated various sampling rates and periods. The arrays were then processed by the FFT functions of both the MSP430 and MATLAB. The output spectra of the MSP430 were compared to the spectra generated by MATLAB, which was considered the standard (or correct)
spectra, and found to be within an acceptable margin of error.

Figure 19. MATLAB simulation of an active brainwave and its FFT.
The last function required that the MSP430 send a wireless signal when a certain criterion was met. This was tested by using the ez430 RF2500’s integrated push-button switch to generate an interrupt. The switch was considered a simulation of the alarm criterion being met. When the button was depressed, the software generated an interrupt and sent a signal to the receiving device. The receiving device was able to illuminate its LEDs to show that the signal was successfully received.

Once the three components were integrated, the system needed to be validated. This was done using a function generator to input a frequency between 1 and 30 Hz to the ADC on the End Device. The End Device then computed the FFT and transmitted the data to the Access Point which was able to display it on a computer monitor.
**System Testing and Results**

The graph below shows the current draw of the circuit over time. Each small spike is an ADC sample being placed into the FFT input array. This has been calibrated to occur at 60 Hz in order to cancel out 60 Hz noise. After 64 data points are collected, an FFT is executed. The plateau area is where the CPU has been turned on to compute the FFT, and the large spike is the radio turning on to transmit the FFT result.

![Current Use vs. Time](image)

Figure 21. Current Use vs. Time.

The system was tested by placing the headset on an awake user and logging the frequency bin data for a few minutes. This was repeated on the same user while he was falling asleep.

Figure 22 and Figure 23 below show these two results, respectively.

In Figure 22 it appears that all of the frequency bins are pretty much equal throughout the whole time. Figure 23, however, shows an increase in lower frequency activity as the user falls asleep. This could possibly be sleep spindle related, but more testing would need to be conducted in order to determine if this is accurate.
Figure 22. A normal, awake adult. Note that for the most part, each range shares relatively the same percentage of frequencies.

Figure 23. Drowsiness and Sleep in a normal adult. Note the low frequency spikes that occur at various times.
**Budget**

Table 5 - Budget shows the budget for the project as of April 27, 2009. Table 6 - Estimated Production Model Budget shows what the planned production cost of the design is. Appendix G – Gantt Chart contains the Gantt chart for the project.

Table 5 - Budget

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Table 6 - Estimated Production Model Budget

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| Grand Total     |          | $6.44      |
Conclusion

Overall, the project was a success. The final design fulfills the three of the four functional requirements along with some features that added ease of use. The programming includes a contact meter, a wireless signal strength meter, a data logger and battery condition meter. The mechanical support includes an adjustable head strap, and separate compartments for the circuitry; one for the processing circuit and one for the battery circuit. The electrical components include the fourth order Butterworth filter which helped the programming with the processing by filtering out 60 Hz from the acquired signal. The final design is capable of detecting and recording brainwave activity, but the physiological usefulness of the recorded data is questionable. More in depth testing of this functionality would need to be accomplished before a sleep detecting feature could be implemented. However, the prototype of this project is fully capable of performing those tests.
Recommendations

Mechanical

Head Gear Support
Dimensioning the head piece had a few constraints. Trying to measure a variable arc length from ear to ear for different people and turning this variable measurement to a constant measurement yielded some difficulty and inaccurate measurements. The first prototype was too small and did not fit 5 out of the 6 team members, and on one of the members it was a rigid fit. By implementing an adjustable strap it would allow for variable arc length change for different users and a more comfort fit. Next aspect to consider would be the circuit size, having a length of 65 mm most of the circuit compartment occupies the side of the head which does not allow for increase comfort and flexibility. Having a two layer circuit versus one layer circuit would decrease the size of the circuit significantly and allow for a small overall head gear size, and makes the head piece lighter and flexible.

Electrode Head Strap Interface
This was one of the more difficult tasks of the mechanical side. Given the adjustable head strap we were using it did not allow for a cut out of an electrode insert to mount the electrodes to the head strap and fix their position relative to the head strap. So instead of the electrode fitted inside of the strap it was mounted on the surface. Another aspect to consider is the force on the electrodes to assure good contact and to mainteinance a good signal. With the head strap available they allowed for enough force but it came with added discomfort. It was tradeoff between contact and comfort.

Circuit Casing and Batter Casing
Circuit size had a length of 65 mm which yielded a larger circuit compartment which occupies a significant area on the side of the head which does not allow for increased comfort and flexibility. Having a two layer circuit versus one layer circuit would decrease the size of the circuit significantly and allow for a smaller circuit casing and overall head gear size and would make the head piece lighter and flexible.

Electrical

Variable Gain
The ability to adjust the gain on the final amplifier stage would help accommodate users’ with different skin impedances. This feature could be controlled automatically by the microcontroller.

Software

Memory
With the current program and microcontroller, the on-board memory is a limiting factor in the resolution of the FFT. Increased memory would allow for more onboard signal processing, including windowing and zero padding. A possible solution would be to use an external RAM chip or an MSP430 from the 500 family. This would have the added benefit of increased ADC resolution as well.
DSP
An external DSP chip, like one from the Texas Instruments TMS320C674 Family would help with signal processing. Aside from dramatically increasing the FFT capabilities, this would be essential for implementing a multiple channel device.

Multiple Channel Capability
Adding the functionality of detecting brainwaves from multiple channels would aid in the development of sleep detection algorithms, and could even allow the device to be used at a clinical level, with other modifications.

Testing Methods

Sleep Study
Conducting a full sleep study on multiple users would help us determine the exact brain patterns that need to be detected and help with signal processing and filtration. This would allow the implantation of precise algorithms that would detect if someone was drowsy or asleep.

Variable Environmental Conditions
EEG’s typically are done in a controlled environment. Having an un-controlled environment was one of the constraints of the project. The environment the team was exposed to had 60 Hz noise artifact and varying conditions such as user movement and environmental noise. Further signal processing would be required to eliminate artifacts generated in an unpredictable environment.
Acknowledgements

Team 3517 would like to thank Texas Instruments, Rod Burt, Fred Highton, Dr. Barton, Dr. Ryan, Joe Hartley, and all of the Senior Capstone coordinators.

References


Appendix A – Headpiece Models

Figure 24 - Prototype 1

Figure 25 - Prototype 1 Side View

Figure 26 - Prototype 2

Figure 27 - Prototype 2 Side View

Figure 28 – Final Prototype

Figure 29 - Prototype 3
Appendix B – Circuit Schematic
Appendix C - PCB Layouts

Figure 30 - First Board

Figure 31 - Final Board
Appendix D - Circuit Board Progression

Figure 32 - INA Stage Alone

Figure 33 - Full Circuit Using Surf-Boards

Figure 34 - Final Circuit
Appendix E - Test Results

Figure 35 - Manuel's Heartbeat on Battery Powered Oscilloscope

Figure 36 - Henry's Heartbeat on Battery Powered Oscilloscope

Figure 37 - Manuel's Heartbeat on Digital Oscilloscope

Figure 38 - Jason's Brain Activity on Digital Oscilloscope, Eyes Open, Eyes Closed

Figure 39 - FFT of Rod's Brain Activity
Appendix F – Device Software

This program determines the frequency input into pin A0. The Green LED flashes when an FFT has been computed (every 64 samples), and the Red LED flashes every second. The sampling frequency is 60 Hz. To operate, put fft2f.c, team3517.c, and main.c in the same folder. To compile properly go to Project -> Options -> C/C++ compiler -> Optimizations and check "none"

Compiled with IAR Embedded Workbench 430 version 5.0

/*******************************************/
#include "msp430x22x4.h"
#include <math.h>
#include "fft2f.c"
#include "team3517.c"
#include <stdlib.h>
#include <intrinsics.h>
#include "stdio.h"
#include "bsp.h"
#include "mrfi.h"
#include "nwk_types.h"
#include "nwk_api.h"
#include "bsp_leds.h"
#include "bsp_buttons.h"
#include "vlo_rand.h"

/* macros */
#define M_PI 3.14159265358979323846
#define NSAMPLES 7

void linkTo(void);
void MCU_Init(void);
float avgsamp(unsigned int samp[NSAMPLES]);
void compmsg(uint8_t *msg, float *data);

__no_init volatile int tempOffset @ 0x10F4; // Temperature offset set at production
__no_init volatile char Flash_Addr[4] @ 0x10F0; // Flash address set randomly

void createRandomAddress();

//Global Variables
static int maxloc = 0; // location of maximum fft value
static float out[32]; // fft output array - magnitude only
static float in[128]; // input array to fft
int count = 0; // counts number of array bits collected
unsigned short int fill = 0; // checks if in[64] has been filled
short int fftgo = 1; // 1 means compute fft, 0 means wait for more samples
unsigned int samples[NSAMPLES]; // array for ADC samples
uint8_t sFFTdone = 0;
```c
void main (void)
{
  addr_t lAddr;
  WDTCTL = WDTPW + WDTHOLD; // Stop WDT

  // delay loop to ensure proper startup before SimpliciTI increases DCO
  // This is typically tailored to the power supply used, and in this case
  // is overkill for safety due to wide distribution.
  volatile int i;
  for(i = 0; i < 0xFFFF; i++){}
}
if( CALBC1_8MHZ == 0xFF ) // Do not run if cal values are erased
{
  volatile int i;
  P1DIR |= 0x03;
  BSP_TURN_ON_LED1();
  BSP_TURN_OFF_LED2();
  while(1)
  {
    for(i = 0; i < 0x5FFF; i++){}
    BSP_TOGGLE_LED2();
    BSP_TOGGLE_LED1();
  }
}

// SimpliciTI will change port pin settings as well
P1DIR = 0xFF;
P1OUT = 0x00;
P2DIR = 0x00;
P2OUT = 0x00;
P3DIR = 0xC0;
P3OUT = 0x00;
P4DIR = 0xFF;
P4OUT = 0x00;

BSP_Init();

if( Flash_Addr[0] == 0xFF &&
    Flash_Addr[1] == 0xFF &&
    Flash_Addr[2] == 0xFF &&
    Flash_Addr[3] == 0xFF )
{
  createRandomAddress(); // set Random device address at initial startup
}
lAddr.addr[0]=Flash_Addr[0];
lAddr.addr[1]=Flash_Addr[1];
lAddr.addr[2]=Flash_Addr[2];
lAddr.addr[3]=Flash_Addr[3];
SMPL_IOCTL(IOCTL_OBJ_ADDR, IOCTL_ACT_SET, &lAddr);

BCSCTL1 = CALBC1_8MHZ; // Set DCO after random function
DCOCTL = CALDCO_8MHZ;
BCSCTL3 |= LFXT1S_2; // LFXT1 = VLO
```
TACCTL0 = CCIE; // TACCR0 interrupt enabled
TACCR0 = 12000; // ~ 1 sec
TACTL = TASSEL_1 + MC_1; // ACLK, upmode

// keep trying to join until successful. toggle LEDs to indicate that
// joining has not occurred. LED3 is red but labeled LED 4 on the EXP
// board silkscreen. LED1 is green.
while (SMPL_NO_JOIN == SMPL_Init((uint8_t (*)(linkID_t))0))
{
    BSP_TOGGLE_LED1();
    BSP_TOGGLE_LED2();
}
// unconditional link to AP which is listening due to successful join.
linkTo();

void createRandomAddress()
{
    unsigned int rand, rand2;
    do
    {
        rand = TI_getRandomIntegerFromVLO(); // first byte can not be 0x00 or 0xFF
    }
    while((rand & 0xFF00)==0xFF00 || (rand & 0xFF00)==0x0000);
    rand2 = TI_getRandomIntegerFromVLO();

    BCSCTL1 = CALBC1_1MHZ; // Set DCO to 1MHz
    DCOCTL = CALDCO_1MHZ;
    FCTL2 = FWKEY + FSSEL0 + FN1; // MCLK/3 for Flash Timing Generator
    FCTL3 = FWKEY + LOCKA; // Clear LOCK & LOCKA bits
    FCTL1 = FWKEY + WRT; // Set WRT bit for write operation

    Flash_Addr[0]=(rand>>8) & 0xFF;
    Flash_Addr[1]=rand & 0xFF;
    Flash_Addr[2]=(rand2>>8) & 0xFF;
    Flash_Addr[3]=rand2 & 0xFF;

    FCTL1 = FWKEY; // Clear WRT bit
    FCTL3 = FWKEY + LOCKA + LOCK; // Set LOCK & LOCKA bit
}

void linkTo()
{
    linkID_t linkID1;
    uint8_t msg[10];

    // keep trying to link...
    while (SMPL_SUCCESS != SMPL_Link(&linkID1))
    {
        __bis_SR_register(LPM3_bits + GIE); // LPM3 with interrupts enabled
        BSP_TOGGLE_LED1();
        BSP.Toggle_LED2();
    }
// Turn off all LEDs
if (BSP_LED1_IS_ON())
{
    BSP_TOGGLE_LED1();
}
if (BSP_LED2_IS_ON())
{
    BSP_TOGGLE_LED2();
}

P2DIR = 0x00;
ADC10CTL0 = ADC10SHT_0 + ADC10ON + ADC10IE + MSC;
ADC10CTL1 = INCH_0 + CONSEQ_2;
ADC10DTC1 = NSAMPLES; // takes NSAMPLES before triggering interrupt
// ADC10AE0 |= 0x00; //sets ADC10 channel to 3 (pin3)

BCSCTL1 = CALBC1_8MHZ;
DCOCTL = CALDCO_8MHZ;
BCSCTL3 |= LFXT1S_2;

TACCTL0 = CCIE; // TACCR0 interrupt enabled
TACCR0 = 179; // 1/60 seconds
TACTL = TASSEL_1 + MC_1; // SMCLK, upmode
P1OUT = 0x00;

SMPL_Ioct1(IOCTL_OBJ_RADIO, IOCTL_ACT_RADIO_SLEEP, 0);

while (1)
{
    __bis_SR_register(LPM3_bits+GIE); // LPM3 with interrupts enabled

    // turn on fftgo every 32 samples
    if(count == 64 && fftgo == 0)
    {
        fftgo = 1;
    }
    count ++;

    if(count > 64)
    {
        count = 0;
    }

    ADC10SA = (unsigned short) samples; // store NSAMPLES to samples array
    ADC10CTL0 = ADC10SHT_0 + ADC10ON + ADC10IE + MSC;
    __bis_SR_register(CPUOFF + GIE); // LPM0 with interrupts enabled
    ADC10CTL0 &= ~ENC;
    ADC10CTL0 &= ~(ADC10ON);
    // turn off A/D to save power
    // Fill up input data array
    if (fill < 64) {
        in[fill*2] = (avgsamp(samples) - 512);
        in[fill*2 +1] = 0;
        fill++;
    }
// When in is full
if (fill > 63) {
    shiftin((avgsamp(samples) - 512), in);
}

// When fftgo is on
if (fill > 63 && fftgo == 1) {
    fftgo = 0; // don't compute fft next time
    sFFTdone = 1;
    if (inrange(in)) {
        fftreal(in, out); // compute fft
        maxloc = findmaxloc(out); // determine maximum location
        // flashgreen(1);
        sFFTdone = 2;
    }
}

if (sFFTdone != 0) {
    msg[0] = 0xFE;
    if (sFFTdone == 2) {
        flashred(1);
        compmsg(msg, out);
        sFFTdone = 0;
    }
}

SMPL_IOCTL(IOCTL_OBJ_RADIO, IOCTL_ACT_RADIO_AWAKE, 0);
if (SMPL_SUCCESS == SMPL_Send(linkID1, msg, sizeof(msg)))
{
    flashgreen(1);
}
else {
    flashred(20);
}

SMPL_IOCTL(IOCTL_OBJ_RADIO, IOCTL_ACT_RADIO_SLEEP, 0);
sFFTdone = 0;

#pragma vector=ADC10_VECTOR
__interrupt void ADC10_ISR(void)
{
    __bic_SR_register_on_exit(CPUOFF); // Clear CPUOFF bit from 0(SR)
}

#if 1
/*-----------------*/
*/
#pragma vector=TIMER0.Vector
__interrupt void Timer_A (void)
{
    __bic_SR_register_on_exit(LPM3_bits); // Clear LPM3 bit from 0(SR)
}
float avgsamp(unsigned int samp[NSAMPLES]){  
  int n = 0;  
  float avg = 0;  
  for (n; n<NSAMPLES; n++){  
    avg = samp[n] + avg;  
  }  
  return(avg/NSAMPLES);  
}

void compmsg(uint8_t *msg, float *data){  
  float sum = 0;  
  int i = 5;  

  for(i; i < 23; i++){  
    sum = sum + data[i];  
  }  

  msg[0] = (uint8_t) (100*(data[5] + data[6])/sum);  
  msg[1] = (uint8_t) (100*(data[7] + data[8])/sum);  
  msg[2] = (uint8_t) (100*(data[9] + data[10])/sum);  
  msg[3] = (uint8_t) (100*(data[11] + data[12])/sum);  
  msg[4] = (uint8_t) (100*(data[13] + data[14])/sum);  
  msg[5] = (uint8_t) (100*(data[15] + data[16])/sum);  
  msg[6] = (uint8_t) (100*(data[17] + data[18])/sum);  
  msg[7] = (uint8_t) (100*(data[19] + data[20])/sum);  
  msg[8] = (uint8_t) (100*(data[21] + data[22])/sum);  
  msg[9] = (uint8_t) maxloc;  
}
Appendix G – Gantt Chart

- Preliminary Head Gear Design (ME)
- Head Gear Material Research (ME)
- Competitor Research (ME)
- First Stage Amp with AC Coupling (EE)
- FFT Algorithm (CE)
- First PCB (EE)
- Second Order Butterworth Filter, Anti-Aliasing (EE)
- Electrode Research (ME)
- Fourth Order Butterworth Filter (EE)
- Electrode/Head-Strap Interface (ME)
- Circuit Compartment Design (ME)
- Electrode Testing, Impedance (ME)
- Breadboard Test Circuit (EE)
- Test PCB and Breadboard System (EE)
- A/D Test (CE)
- Head Gear Support Design (ME)
- Integrate FFT Algorithm (CE)
- SimpliciTI (CE)
- Computer Interface (CE)
- Head Gear System Integration (ME)
- Head Gear Rapid Prototype (ME)
- Second PCB (EE)
Appendix H – TI Product Implementation

In the final design, there are five integrated circuits, and one microprocessor. The first amplification stage uses the INA333 instrumentation amplifier. This amplifier is designed with low noise and high common mode rejection which is ideal for the high noise brain wave signal that is being amplified in this design. The INA333 is the most important component in the design; without it, the signal would contain too much noise and be tough to filter and process. The remaining four ICs are OPA333 operational amplifiers. The OPA333 was the best operational amplifier for the design because it has single-supply operation, and it operates with a supply voltage of 1.8V to 5.5V which was in the range of our 3V, 2032 medical battery. The OPA333 worked well in the fourth order Butterworth filter due to its zero-drift design. This created a steady output for the MSP430 microcontroller to process. The MSP430 is responsible for the signal processing side of the project. It was important for the project to use a mixed-signal processor that had onboard ADC capabilities and enough processing power to compute Fourier Transforms. The specific device used in the design is the MSP430F2274 found on the eZ430-RF2500 Wireless Development Tool. This packaging was convenient for the design due to its small size and ample processing power. Also, the tool had a built in wireless transmitter and receiver which is exactly what was needed for the project as one of the functional requirements. All 3 TI components worked extremely well in this project. The team had no significant issues with the interfaces of each component, and is satisfied with the final result.