Massachusetts Institute of Technology – MIT

Real Time Wireless Electrocardiogram (ECG) Monitoring System

Introductory Analog Electronics Laboratory

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Abstract

This project integrates wireless technology with an electrocardiogram (ECG) monitoring system. An ECG signal will be acquired, modulated and transmitted wirelessly to a remote receiver. The receiver will demodulate and process the ECG signal so as to provide sound feedback of the heartbeats and a low heart rate alarm. The strategy to undertake this project is to develop separate modules, each one responsible for a feature. They will be tested independently first, and only after they are tested and proved to be working separately, they will be integrated in a single product in an attempt to ensure efficacy and reliability.

Introduction

The real time ECG monitoring system is a system designed to capture the electrocardiogram of a user, modulate and transmit it to a receiver and demodulator, which will then analyze the heart beats and sound a beep for each pulse, providing an audible feedback. An alarm will sound in case the heart rate is below a certain threshold.

There are several uses for this system, ranging from just knowing your heart rate while exercising, to keeping track when a doctor should be contacted if the user's heart rate gets too low. Since the system is wireless, the patient can move, and the heart rate can be accompanied from afar.

The system is primarily composed of seven modules, each of which will be independently implemented and tested.

Two 9V batteries will be used to power the transmitter in order to make the system portable and safe, since it is isolated from the power line. The receiver will be powered from the +-9V from an existing power supply, however batteries can also be used.

Main Boards

The system is composed of two main boards, one used for modulation and transmission, and one used for receiving, demodulation, analysis of the signal and warning sounds.

Transmission Board

The transmission board is responsible for modulating the ECG signal on a 455kHz carrier wave. It is essentially composed of the Modulator module.

Modules:

Modulator

The modulator is the circuitry responsible for modulating the captured ECG signal, using amplitude modulation (AM) with a carrier frequency of 455kHz. It utilizes an Op. Amp., and a Variable Controlled Resistor (VCR) to modulate the signal over a carrier frequency.

The modulator receives a single input, the ECG signal, and outputs a radio frequency through its antenna.

Receiving Board

The receiving board is responsible for receiving the signal through an antenna, demodulating it, and analyzing the ECG to detect the heart beats and produce a sound for each beat, and detecting if the heart rate is below a certain threshold and sounding an alarm if so.

Modules:

Demodulator

The demodulator module will receive the electromagnetic waves emitted from the transmitter, it will then filter the carrier wave, leaving only the original ECG signal.

The input of this module is the radio frequency transmitted from the modulator, and the output is, ideally, the same signal that the ECG capture device produced.

Heartbeat detector

The heart beat detector will ignore the entire portion of the ECG signal that is below a certain threshold, identifying only the peaks that correspond to one beat of the heart, known as R-peaks of the ECG wave. The output of this module is a pulse for each heartbeat, which will be fed into the low heart rate detector. In case the heartbeat frequency is too low, this module is going to output a signal that will be used to sound an alarm. An LED also blinks for each heartbeat.

Sound amplifier

The sound amplifier module amplifies the pulse received from the detector module and outputs that signal to a speaker, so the user can listen to a sound for each heartbeat.

Low heart rate detector

The low heart rate detector determines if the heart rate is below an adjustable threshold. In case the heart rate is lower than this threshold, a signal is sent to the emergency signal reset module.

Emergency signal reset

The emergency signal reset is a module that receives the signal from the low heart rate detector and if the signal is low, the module sounds an alarm that is maintained on for a predefined period of time or until the user turns the alarm off by means of a button. The alarm will also sound if the ECG monitor has been taken off.

ECG capture module

The ECG capture module is the one designed in Lab. 5, and has already been assembled. The leads are connected to the body using electrodes, and the outputs are connected directly to the heartbeat detector.

Modules in further detail:

Modulator Module

The modulator module is composed of a Wien Bridge Oscillator for sine wave generation, and a variable gain Op. Amp. using a JFET as a Voltage Controller Resistor (VCR).

The sine wave generation uses a Wien Bridge Oscillator, which provide good frequency stability and low distortion, while being a simple to implement circuit.

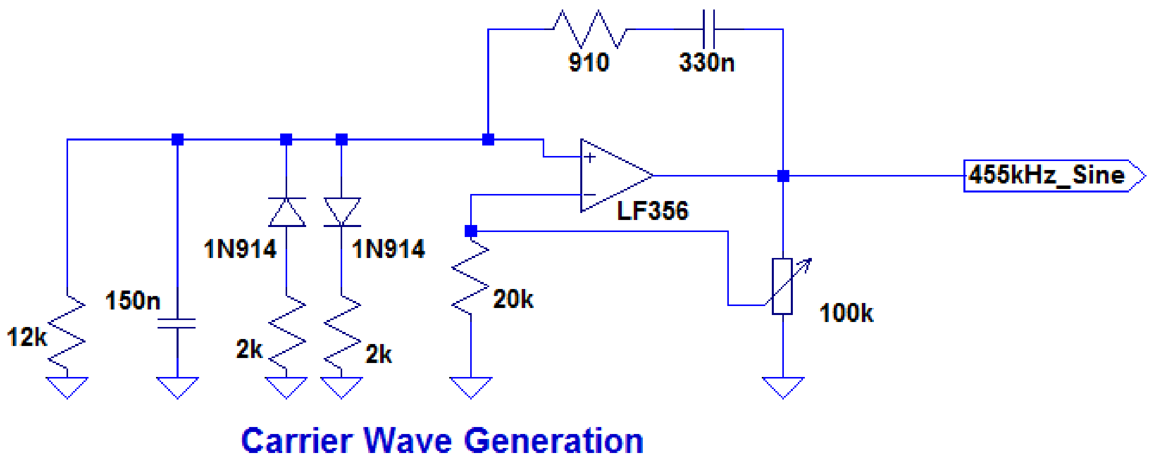

Figure 1. Wien Bridge Oscillator. 100kΩ potentiometer is used to carefully adjust the carrier frequency.

The resistor and capacitor values can be chosen by setting the RC time constants to achieve the desired frequency, in this case, 455kHz.

$$f = \frac{1}{2\pi RC}$$

After initial values have been obtained and tested, adjustments were made, and the final values were reached.

The carrier wave will be modulated using an LF353 Operational

Amplifier, on a non-inverting configuration, and a Variable Controlled Resistor (VCR). The carrier wave is fed through a voltage divider, in order to reduce the amplification, and avoid distortion. The VCR is implemented using a 2N5459 JFET, biased at about -2.0V. A voltage divider is used to provide this bias voltage by using a -5.1V reference, implemented with a 1N751A 5.1V Zener diode, which is needed to maintain the reference voltage despite changes in the supply voltage.

By varying the JFET's gate voltage, we can vary the resistance between the inverting output and ground, thus changing the voltage gain of the Op. Amp to a maximum of approximately 20.

$$A_v = 1 + \frac{10^4}{R_{JFET}}$$

The ECG signal, around 300mV, is fed to the JFET's gate, through a coupling capacitor. The effect thus achieved is the amplitude modulation of the carrier wave, which is output to the 110µH antenna.

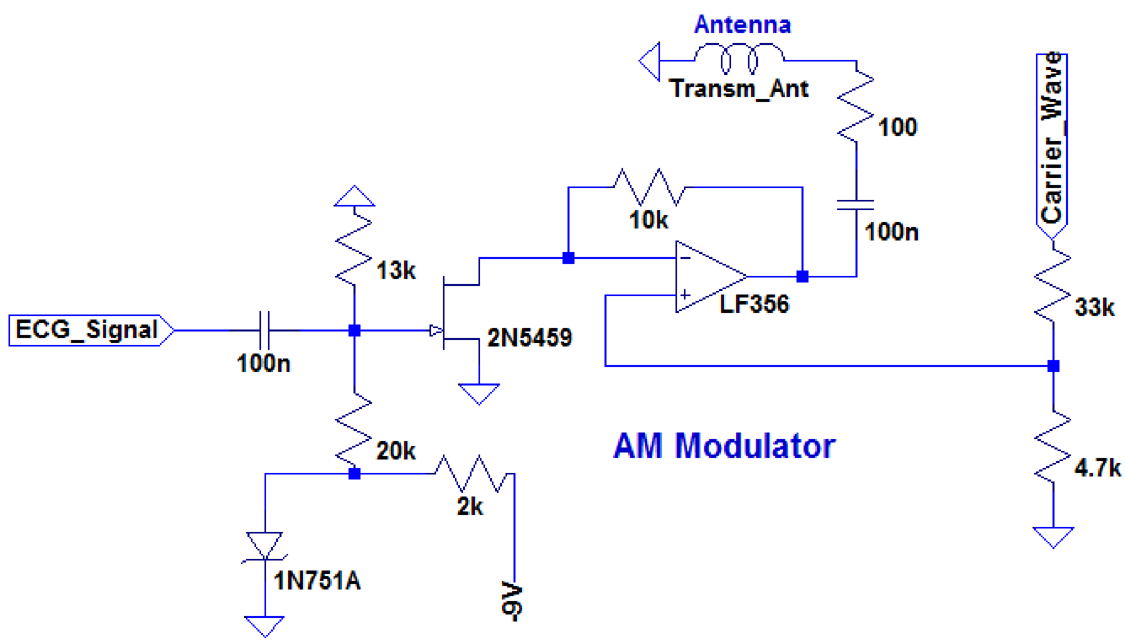

Figure 2. AM Modulator. VCR controls gain of Op. Amp.

Demodulator

The demodulator module is composed of a receiving antenna, properly adjusted to resonate at the carrier waver frequency. The modulated signal is then amplified in the order of 10 by two LF356 in series, so as to reduce distortion. The signal is then demodulated using an envelope detector, ensuring that the correct value for the RC time constant of the detector has been properly attained.

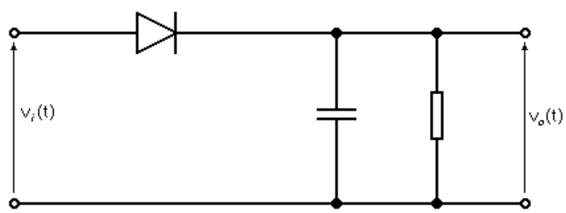

Figure 3. Envelope Detector. Used to demodulate the AM signal. The time constant of the RC filter must be calculated in order for the system to work properly.

Amplification is essential in order for the signal to be properly demodulated, since the forward voltage drop through the diode must be overcome.

The demodulated signal is buffered to reduce distortion of the original signal. It is then sent through a coupling capacitor, to reduce the DC offset, to the heartbeat detector.

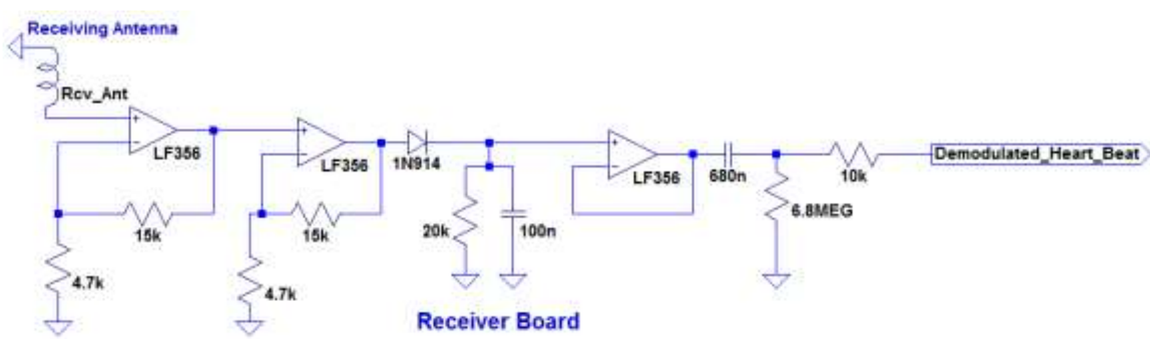

Figure 4. Demodulator. Gain stage provided by 2 Op. Amps. In series, followed by envelope detector, buffer and coupling capacitor.

Heartbeat Detector

It is possible to compare the voltage level of the ECG signal to a certain threshold and output a signal only when that voltage is higher than the threshold. This can be done by using a voltage comparator.

The R-peak is the most prominent peak of the ECG signal, and by detecting it, one can identify one beat of the heart. Because of the huge difference between the amplitude of the R-peak and the rest of the wave, one can safely select a threshold for comparison in which only the R-peaks are going to surpass (see figure 5).

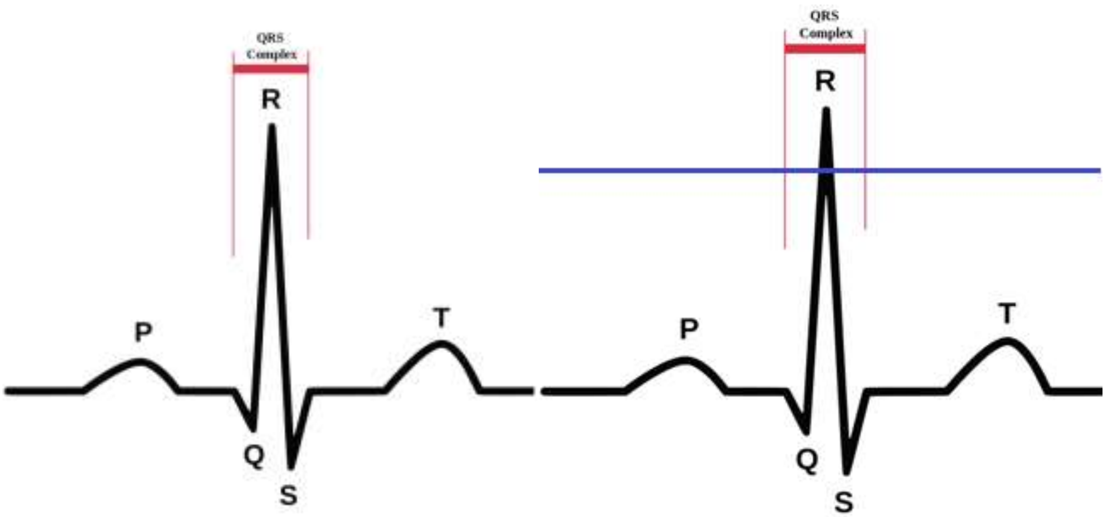

Figure 5 – ECG Signal, with detail to the R-peak and an arbitrary threshold (in blue)

The output of the comparator is going to be a pulse for each beat of the heart (See Figure 6); this signal will be used as the input for the low heart rate detector, one of the key modules of this project, which will be discussed in details later.

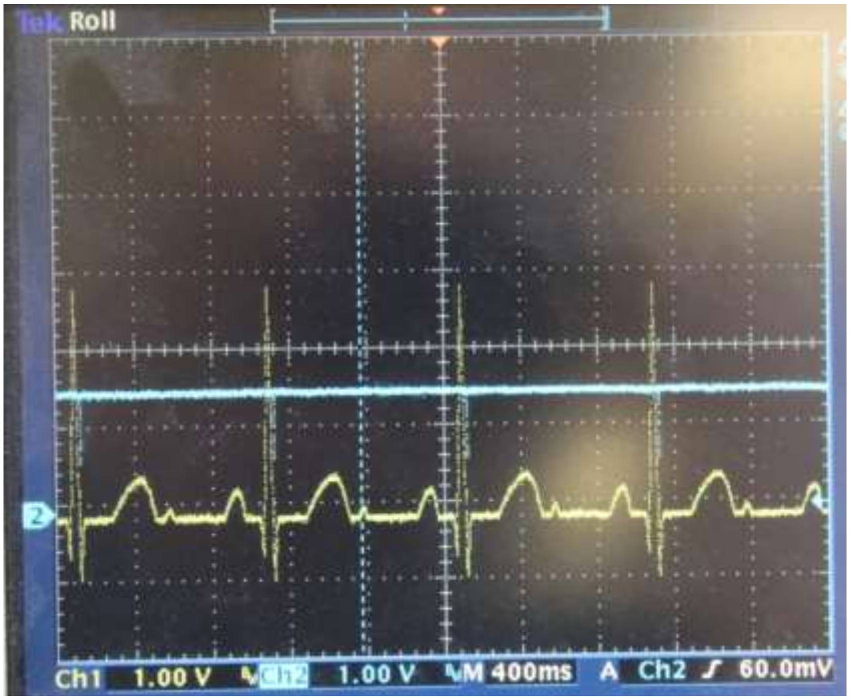

Figure 6. Pulses can be noted (blue signal) for each R-peak of the ECG (yellow signal)

This functionality works very well for an ideal system, where the ECG signal is going to be constant in amplitude, however, when working with wireless transmission, the amplitude of the received signal varies a lot with the distance and the positioning of the antennas. For this reason, comparing the ECG signal with a constant voltage threshold is not a good approach anymore, because sometimes the signal intensity will fall too much at the point where no heart beat is detected, or the signal can be too strong and the detector will detect the whole wave as a pulse.

In order to solve the issue with the voltage variation, a solution to make the comparison threshold variable was implemented. This solution consists of an active peak detector, which in a simple explanation, will charge a capacitor very quickly, but will discharge it slowly. This will keep track of the maximum amplitude of the signal at any time.

To make the system more reliable, the voltage on the capacitor was not used directly, but only around 85% of its value is actually used as the threshold voltage.

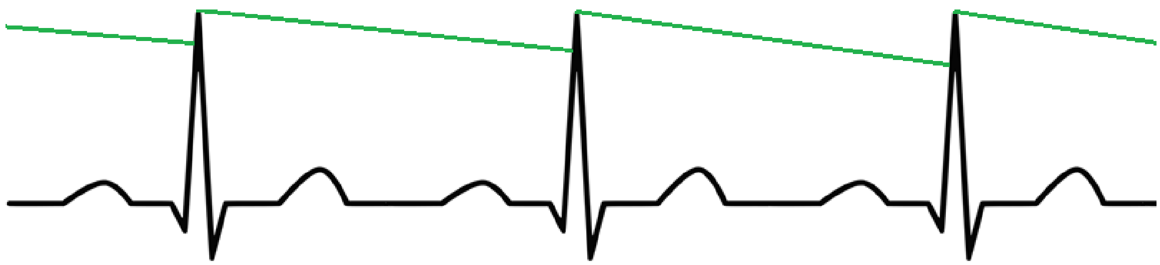

Figure 7 – ECG Signal, with detail to the output of the active peak detector (in green)

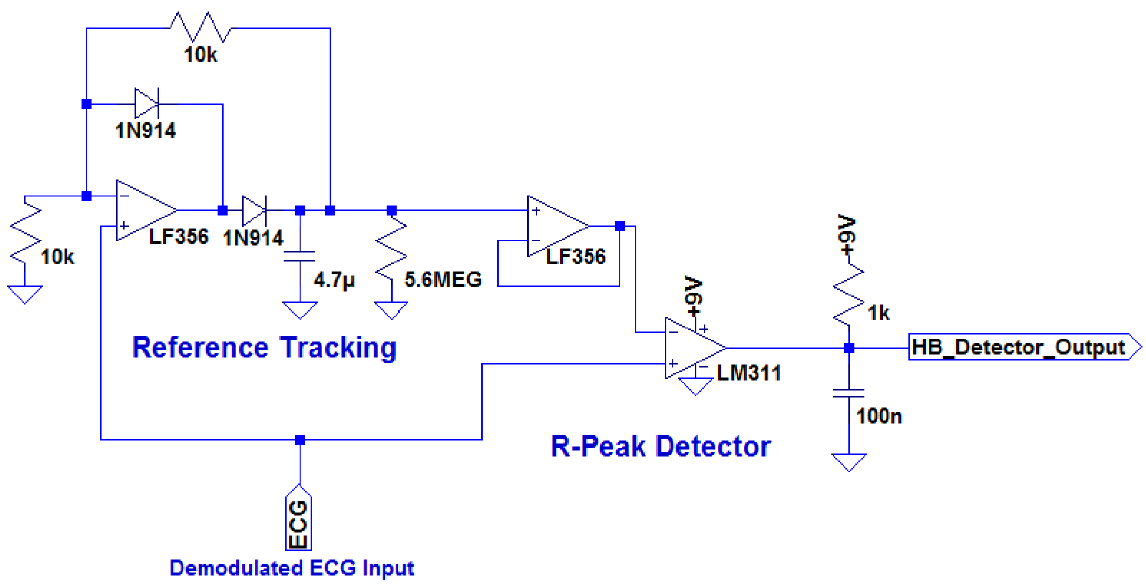

Figure 8. Heartbeat detector. Variable threshold can be seen on top left.

The system is expected to output a "beep" for each beat of the heart, and this module will be responsible for outputting the signal for further amplification and reproduction. One important thing to notice is that when a beat of the heart is detected, the output of this module is a pulse that lasts for only a few milliseconds, which is not enough to be audible, or at least not enough to cause a good listening experience.

For this reason, a timer was used in order to delay this pulse for about ten times of its original duration. Generating an output that lasts for approximately 400 milliseconds for each heartbeat. This new output is now appropriate to be used to deliver a "beep" for each heartbeat.

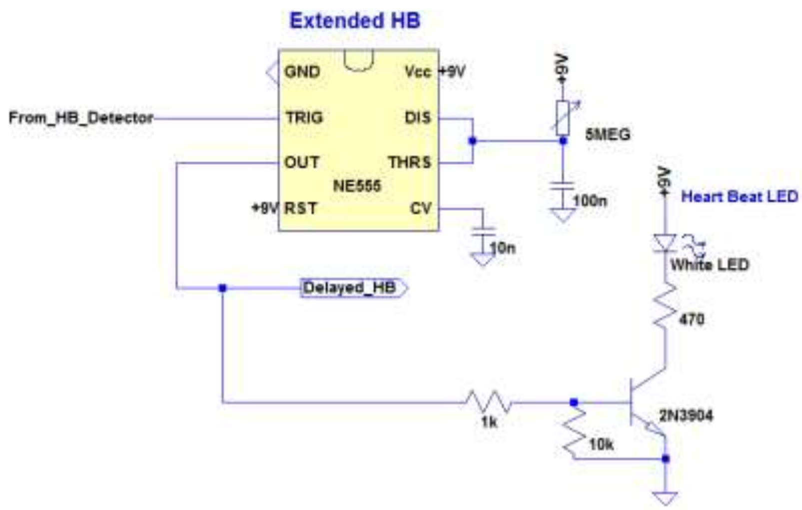

Figure 9. Heartbeat signal holder.

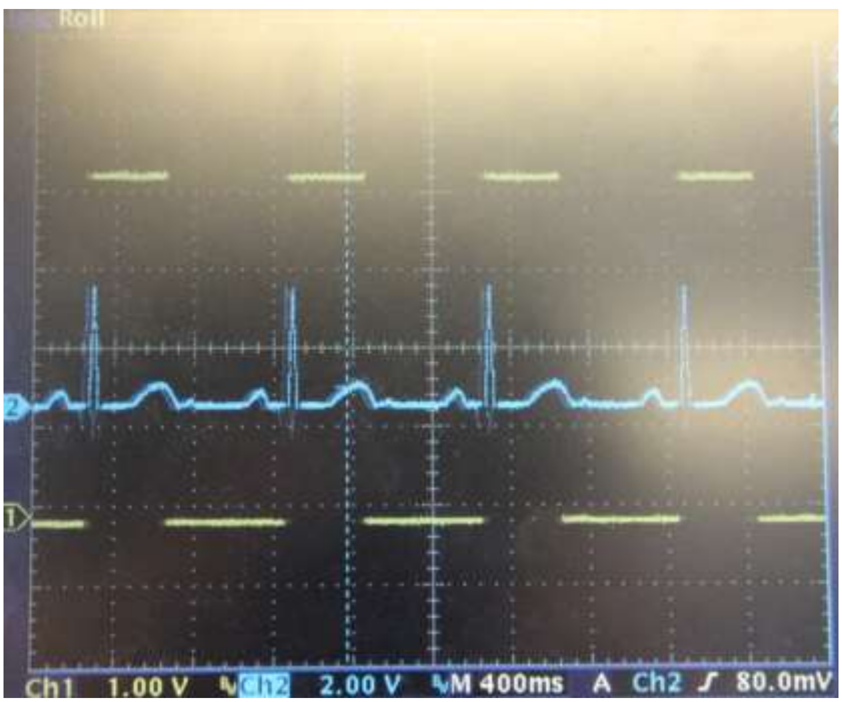

Figure 10. Heartbeat signal. After each R-peak of the ECG (blue signal) a 400ms high signal is output (yellow signal).

The low heart rate detector determines if the heart rate is below an adjustable threshold. In case the heart rate is lower than this threshold, a signal is sent to the emergency signal reset module.

Low Heartbeat Detection Module

The low heartbeat detection module will output a pulse just in case the heart rate falls behind a predefined threshold. This can be done using a timer operating as a missing pulse detector.

Observing the figure below, we can see at the left, a timer operating in its monostable mode. Besides the normal circuitry, a transistor is added to the configuration in a way that each time a pulse is applied to the input (note that the logic is inverted and this pulse is a zero volts pulse), the capacitor is going to be discharged by the path that the transistor will create when zero volts is applied to its base.

Those intermittent discharges do not allow the capacitor to charge above the threshold of the timer, which causes it not to change its output. What means that with an equal or higher frequency of pulses at the input of the timer will cause the circuit to keep the output in the same level (in this case 5V). However, in case the frequency is too low, the capacitor will charge above the timer's threshold, what will cause the timer to change its output to zero volts (see figure 7). Signaling, in this case, that the heart rate is too low and the alarm must be fired.

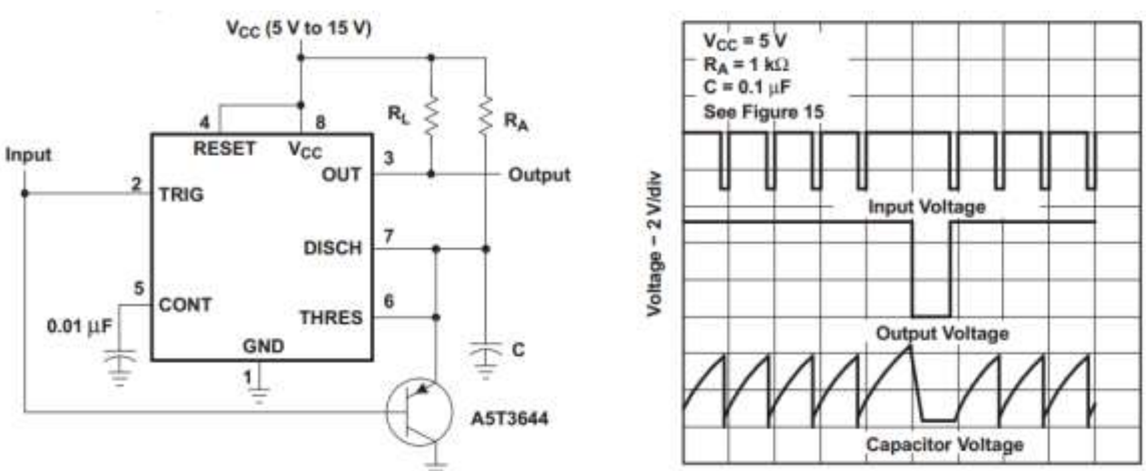

Figure 11 – Timer operating as a missing pulse detector. Source: Texas Instruments Timer 555 Datasheet

Alarm reset and automatic alarm restart

In case the alarm was fired, a constant tone is sent to the sound amplifier and a red LED is turned on, so that the user can know that something is wrong. But sometimes, the user is already aware of the situation and wants to turn the alarm off even though the heart rate is still below normal. For this reason, a reset button was implemented; by pressing this button, the user can signal the system to turn off the alarm.

In case the heart rate goes back to normal, it is expected that the system is going to sense this and go back to its normal operation, being ready to detect another fault. This is exactly what the system does and the details are going to be explained in the next paragraphs.

The first part of the alarm system is a timer operating in its bistable mode; which means that when the signal of low heart rate is received from the low heart rate detector, this timer will raise its output and keep it high signaling that the alarm is on. This state will only change when a zero volts signal is applied to the reset terminal of the timer.

The second and third part of this circuitry are two more timers, which together are going to turn off the alarm in case the heart rate is normal for at least five seconds, or the user pressed the reset button. They will also guarantee that the alarm will not be triggered again if the user pressed the reset button and the heart rate is still too low. The circuitry for these three timers can be seen in the figure below.

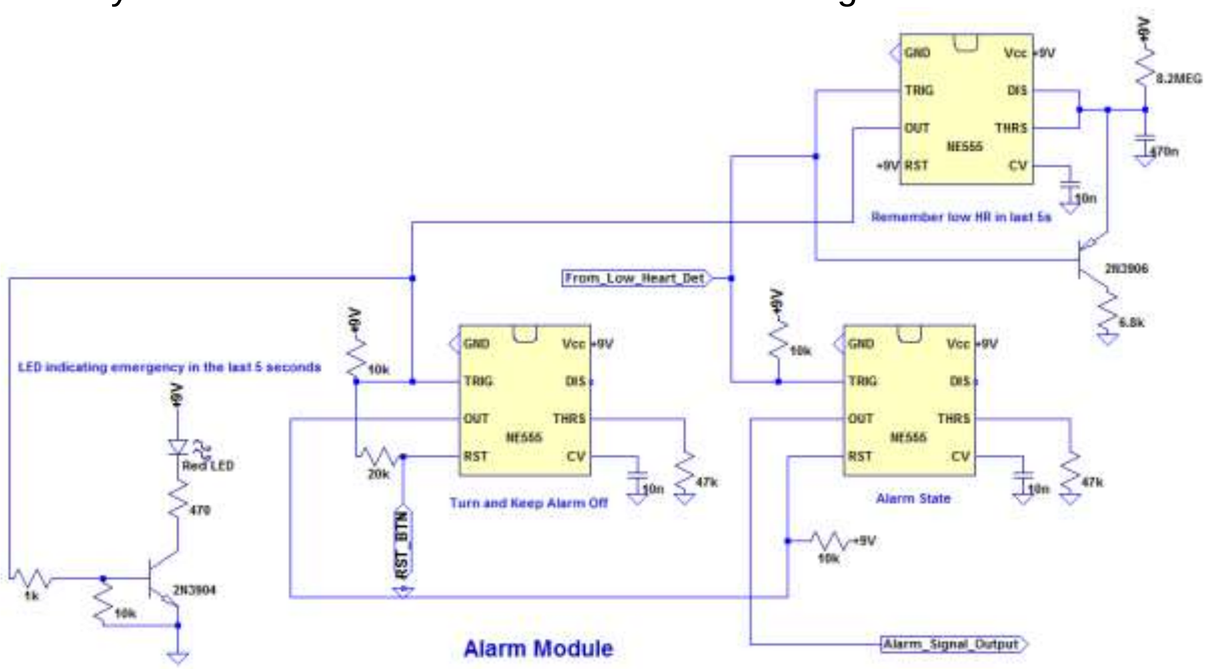

Figure 12. Alarm Module.

Sound Amplifier

The sound amplifier module is composed of a Common Collector amplifier, and a signal selector that selects an input signal, either the heartbeat beats, or the alarm. A square wave generator at roughly 1kHz produces the sound that will be output by a speaker. A square wave provides a distinctive sound that draws attention from the user in case the alarm has sound.

The input selection is done using a 2N3906 PNP BJT operating as a switch. When the alarm is activated, using a 9V signal, the transistor doesn't conduct, and so the heartbeat beeps are not introduced on top of the alarm sound, creating a bad user experience. When the alarm is not activated, the heartbeat beeps as expected.

The amplifier is driven by a 2N3904 BJT used as a switch, with a potentiometer to control the Common Collector base current, and so, the volume of the speaker.

The last stage of the amplifier is done using a 2N2222 BJT on Common Collector configuration.

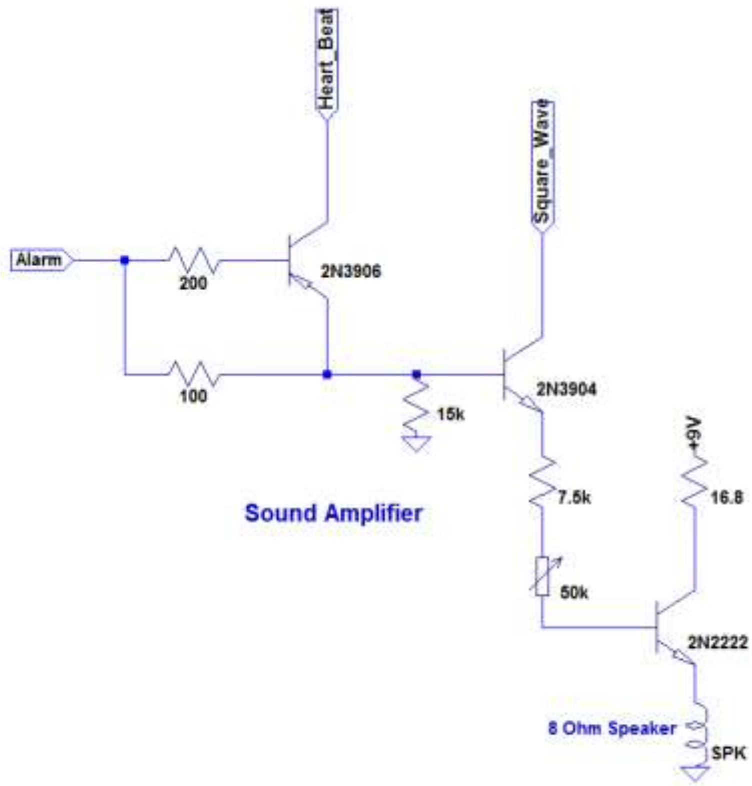

Figure 13.Sound Amplifier. Composed of input selector and amplifier.

The 1kHz 50% duty cycle tone to be output by the speaker is produced by a square wave generator implemented using a NE555 on the astable configuration. The resistor and capacitor values can be chosen to achieve a frequency close to 1kHz using standard values.

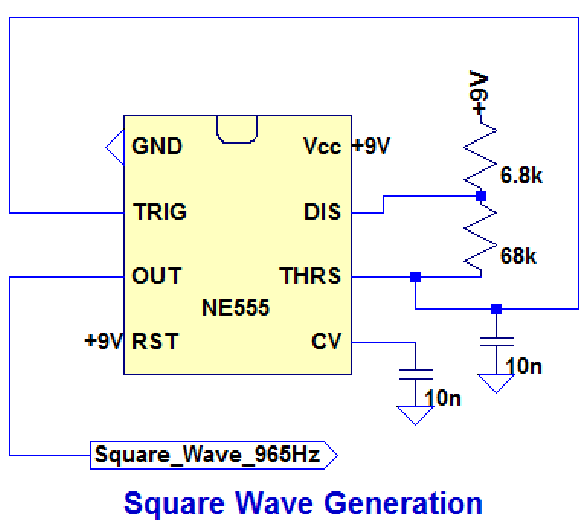

Figure 14.Square wave generator. Operating at 1kHz, the square wave generator produces the tone that will drive the speaker.

Conclusion

The Real Time Wireless ECG Monitoring System enables the user to listen to the heartbeats, and monitor the heart rate remotely.

In order for the system to properly work on varying distances, which results in variable receiving intensities, a variable threshold comparator had to be implemented. This allows the user to move the transmitting or receiving antennas without compromising the analysis of the ECG.

The carrier wave must be a sine wave, which involves the use of a dedicated sine wave generation that must have good performance and low distortion. The Wien Bridge Oscillator sine wave generator used provides low circuit complexity and low distortion.

Most circuitry has resistors and capacitors, however, due to the low frequencies involved (<1Hz) the capacitors and resistor must be chosen carefully.

The experimented values can vary a lot from the calculated values. Most of the circuitry designed required some tuning in order to reach the expected behavior.