Distributed Synchronization of Electronic Fireflies

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Abstract

The electronic firefly is designed to emulate the biological organisms for the purpose of developing innovative solutions to challenging technological problems. The biological organisms can be emulated with circuits and simulated with a computer for their functionalities. The overall focus of this design project is to construct an experiment that emulates a biological system and to then identify potential industrial uses.

Contents

1 Introduction

Coupled oscillation exist in many living and non-living systems in the world. In the natural world there are an unlimited number of examples of synchronization. Have you ever been outside at night to hear the crickets chirping and notice that they do this in unison or watched the rhythmic patterns of an animal walking? Even inanimate objects can exhibit this characteristic. In 1665 the Dutch physicist Christiaan Huygens, the inventor of the pendulum clock, noticed an unusual phenomena. He noticed that pendulum clocks in close proximity will synchronize the swinging action of the pendulum where once they were out of phase in finite time. Another display of this coupled oscillation can be seen in different species of firefly that will flash in unison[1, 2].

In [1] we came across an experiment that provides a mathematical system based on an electrical circuit known as a relaxation oscillator. This circuit represents the concept of how the real fireflies synchronize by sensing other firefly flashes in the proximity and eventually flashing in unison.

At an individual level each firefly flashes at its own rhythm but when put in proximity of another they become coupled resulting in synchronization. Each firefly is made up of four phototransistors that will sense light around the 940nm wavelength. When a firefly receives a flash from another firefly, an increase in charge on a capacitor will occur until the voltage across reaches a threshold. This will cause the capacitor to discharge through a switch and the firefly will flash at a earlier time than without any environmental influences.

The goal of this experiment is to investigate the features of self-organization for electronic fireflies. First we will look at the interactions of two fireflies to determine the factors that link them together. We will search for requirements on frequency and phase difference to determine what roles they play on synchronization. Further we will look at the interaction of the nine fireflies in different topologies and determine the interactions between the systems. Lastly we consider the affects of a disturbance in the system, where the disturbance will be a firefly that has much different phase and frequency than the other eight in the system, and the affect it has on the system under similar topologies as before.

2 About The Fireflies

Fireflies are beetles in the family Lampyridae and occur as more than 2000 species worldwide. According to Darwin each sect of firefly evolved differently therefore they exhibit their own characteristics. The firefly that we wish to mimic is the Pteroptyx Cribellata, which can be found in India to the Philippines and New Guinea. This specific firefly is unique because mass groups of these fireflies gather together and flash in unison.

A good description of this act is described by Smith (1935) as follows: "Imagine a tree thirty-five to forty feet high thickly covered with small ovate leaves, apparently with a firefly on every leaf and all the fireflies flashing in perfect unison at the rate of a about three times in two seconds, the tree being complete darkness between the flashes. Imagine a dozen such trees standing close together along the river's edge with synchronously flashing fireflies on every leaf. Imagine a tenth of a mile of river front with an unbroken line [mangrove] trees with fireflies on every leaf flashing in synchronism, the insects on the trees at the ends of the line acting in perfect unison with those in between. Then, if one's imagination is sufficiently vivid, he may form some conception of this amazing spectacle."

Case and Buck found that each flash is triggered by nerve impulses in the brain that travel down the ventral nerve cord to the firefly's lantern. To synchronize these fireflies must have a sensing mechanism to know when neighbors are flashing. Imagine a group of fireflies; in one firefly it is close to the normal time of blinking but a neighbor flashes and this stimuli causes the insect to flash sooner than otherwise would have occurred. This is precisely what our firefly circuits are achieving.

3 List of Components & Descriptions

In this section, the listed components are recommended for building the firefly. Each components are described according to their specifications.

3.1 Part Description

(1)**LM555**

The 555 timer is a digital logic circuit that is used to produce a periodic square wave signal. The resistors and capacitors in the 555 timer have a direct effect on the duty cycle and the frequency which will be discussed a little later. Figure 1 shows the internal circuit and pin numbers of a 555 timer.

Pin 1 (Ground) This is the pin that connects to the ground of the device. When it is operated from the positive power supply, pin one is normally connected to circuit common.

Pin 2 (Trigger) Pin 2 is the input of the 555 timer which causes the output to go high and begin the timing cycle. Triggering occurs when the voltage going into the trigger is $\frac{2}{3}$ above the voltage supply to $\frac{1}{3}$ below the voltage supply. Trigger input current is about 0.5 microamps. The action is level sensitive and the trigger voltage may move very slowly. To avoid retriggering, the trigger voltage must return to a voltage above $\frac{1}{3}$ of the power supply before the end of the timing cycle.

Pin 3 (Output) This is the output pin of the 555 timer. When the timing cycle begins at high level this output is 1.7 volts less than the supply voltage; and then it returns to a low level near 0 at the end of the cycle. The maximum current from the output at both low and high levels is approximately 200 mA.

Pin 4 (Reset) Pin 4 is the pin which resets the timer and returns the output to a low state. When this pin is not in use, it is normally connected to the positive supply.

Pin 5 (Control) When the external voltage is used in this pin, it will allow changing the triggering and threshold voltage of the timer. When the timer is operating in the astable or oscillating mode, this input could be used to alter or to modulate the frequency output. If this pin is not in use it would be better to connect a capacitor to avoid possible false or erratic triggering from noise effects.

Pin 6 (Threshold) The threshold has the similar function as the trigger pin to the timer. Pin 6 is used to reset the latch and cause the output to go low. The reset would occur when the voltage going into this pin is from a voltage below $\frac{1}{3}$ of the input power supply to a voltage above $\frac{2}{3}$ of the input power supply.

Pin 7 (Discharge) This pin is an open collector output which is in phase with the main output on pin 3 and has similar current sinking capability. Pin 7 is usually connected to a resistor in series with a capacitor in the astable connection.

Pin 8 (V +) This is the positive supply voltage of the 555 timer. The operating range is from +4.5 volts (minimum) to +16 volts (maximum).

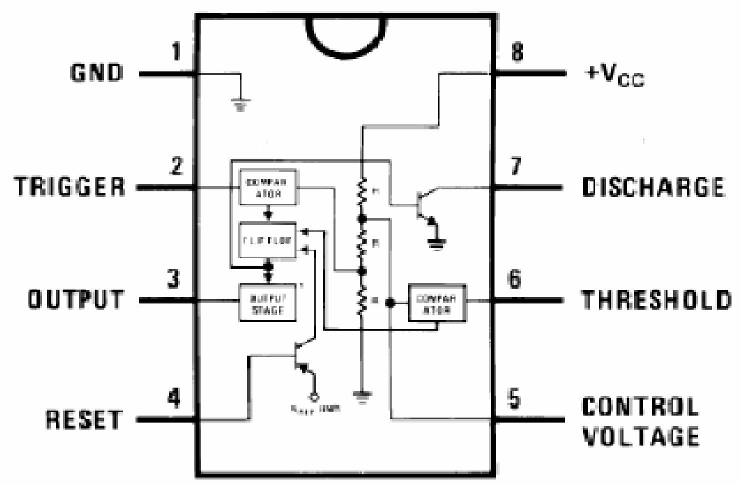

Figure 1: 555 timer.

(2)**LED IR EMITTING ALGAAS 940NM**

This LED has an operating temperature of -40 to 100 degree Celsius. The current ratings for this LED are 100mA for the forward current and 10uA for the reverse current. The forward voltage rating is 1.6V. The emission angle of light is 40 degree in the infra-red wavelength of 940nm.

(3)**Green LED**

This is a green LED and the model type is T 1-3/4. Its lens is round, style of 5 mm. Its lead style is radial, Millicandela rating of 120, voltage rating of 4V.

(4)**IC Phototransistor**

This phototransistor senses wavelengths of light around 880nm and has a half angular response curve of 20 degree. The operating temperature is from -40 to 100 degree Celsius and emitter collector voltage of 5V.

(5)**Pot 50KΩ Resistors**

This resistor is a ceramic resistor. It has the resistance of 50kΩ, 0.3 W of power, single turns, top adjustment, and with the tolerance of ±25%.

(6)**Capacitors**

10μf Capacitor: This capacitor is a tantalum capacitor. It has the capacitance of 10μF, voltage-rated of 10V, maximum temperature of 125 degree Celsius, and with the tolerance of ±10%.

20nF Capacitor: This capacitor is a ceramic capacitor. It has the capacitance of 20nF, voltage-rated of 50V, general purpose of featuring and with the tolerance of ±5%.

100μF Capacitor: This capacitor is an electrolytic capacitor. It has the capacitance of 100μF, voltage-rated 10V, maximum temperature of 85 degree Celsius, featuring of aluminum, and with the tolerance of ±20%.

(7)**DIP Switch**

This is an 8 pin switch package that has a voltage rating of 24 volts and a current rating of 25mA (see APPENDIX **??**). DIP switches are always toggle switches, which means they have two possible positions (on or off).

(8)**Power Source**

For power we are using a common 9V alkaline battery. The operating temperature of the battery is -20 to +54 degree Celsius. It also features 570 mAh rated capacity, 4.8V rated cut-off voltage and 620Ω rated load.

(9)**Chip socket**

This socket is a DIP socket. It has gold contact finishing, solder contact termination, 8 pins with length of 0.095" each, and the width of this socket is 0.3".

4 Design Analysis and Simulation:

The internal and external (astable connection) of 555 timer, the design of the electronic firefly circuit[1] and the simulation of various component values of the designed firefly will be briefly discussed in this section.

4.1 Circuit Analysis

Before analyzing the design of electronic firefly, it is very import to have a basic understanding of the 555 timer and astable mode, since the astable 555 timer is the heart of the whole design.

4.1.1 Astable 555 Timer

The 555 timer is composed by two comparators, three resistors, one SR flip-flop, two transistors and two inverters. In this project, we are using the astable 555 timer (oscillator) to generate the flash of light in our electronic fireflies. Connect pin 2 (trigger) and 6 (threshold) to form a self-trigger timer. When we supply 5 volts Vcc to R_1 (see Figure 2), C starts charging. When the Vc' is less than $\frac{1}{3}Vcc$, the output of the comparator, connected to pin 2, is in **High** state and the comparator, connected to pin 6, is in **Low** state, the output $\bar{Q}$ of the flip-flop is set to **Low**. This **Low** state is converted to **High** state by the inverter; therefore, the output of the 555 timer is **High**. When Vc' is between $\frac{1}{3}Vcc$ and $\frac{2}{3}Vcc$, the two comparators are in **Low** state which makes the output of the flip-flop remain in the same output as previous state (see Figure 2). The power source keeps charging the capacitor until Vc' reaches $\frac{2}{3}Vcc$, in this case, the input R of the flip-flop is set to **High** and the S is set to **Low**, so the output $\bar{Q}$ of the flip-flop is **High** and the output of the timer is **Low** (see Table 1). R_1, R_2, and C set the on-time, off-time and duty cycle which is the percentage of on-time in a period. (see Equations (1), (2), (3), (4)) of the astable 555 timer.

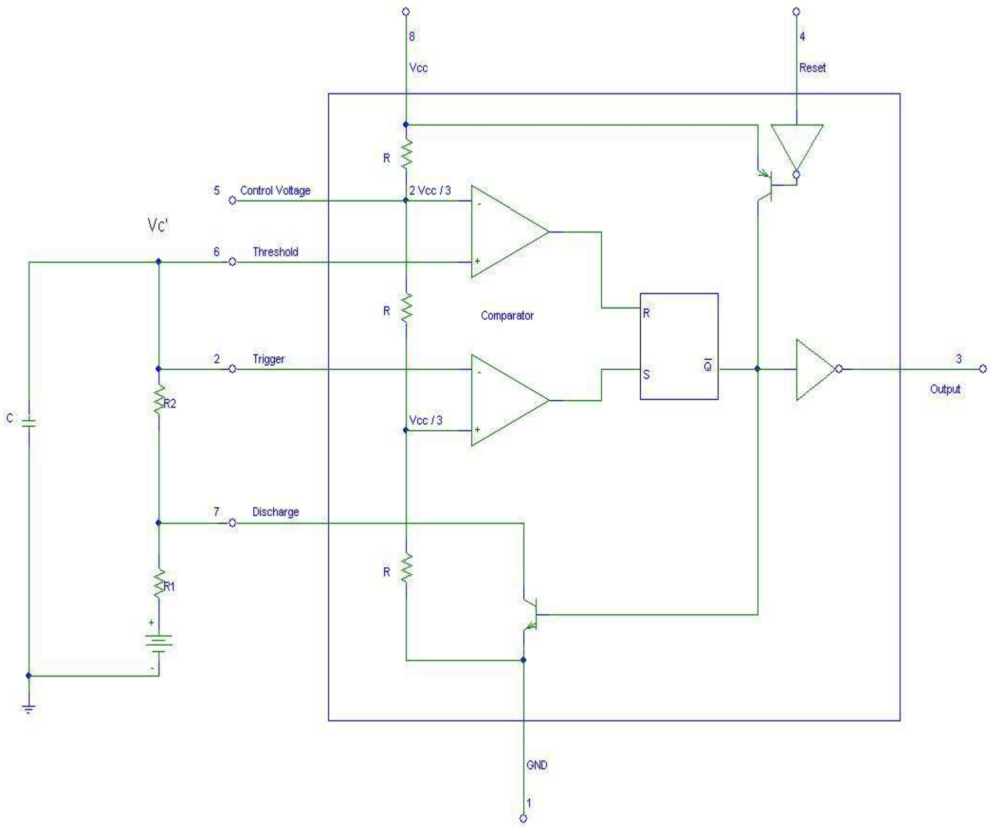

Figure 2: 555 timer internal circuit.

$$D(dutycycle) = \frac{R_1 + R_2}{R_1 + 2R_2} \tag{1}$$

From the Figure 3, the tH(on_time) is derived by the following equations:

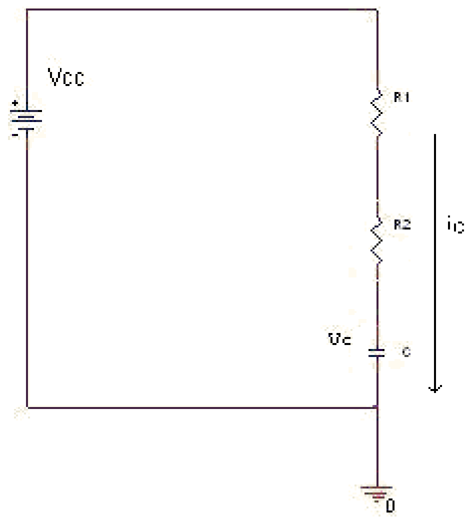

Figure 3: Equivalent circuit for on-time.

The current of the equivalent circuit:

$$i_c = C\frac{d_{v_c}}{d_t} = \frac{V_{cc} - V(0_-)}{R_1 + R2}$$

The initial voltage of V_c is:

$$V_c(0_+) = \frac{V_{cc}}{3}$$

$$V_c = V_{cc}[1 - \frac{2}{3}e^{-(\frac{tH}{(R_1+R_2)C})}]$$

$$V_c = \frac{2}{3}V_{cc} = V_{cc}[1 - \frac{2}{3}e^{-(\frac{tH}{(R_1+R_2)C})}]$$

So,

$$tH(on - time) = (R_1 + R_2)Cln2 \quad (2)$$

From Figure 4, the tL(off_time) is derived from the following equation.

$$C\frac{d_{v_c}}{d_t} + \frac{1}{R_2 + R_d}V_c = 0$$

$$\begin{aligned} V_c(t) &= \frac{1}{3}V_{cc} \\ &= \frac{2}{3}V_{cc}e^{-\frac{tL}{(R_2+R_d)C}} \end{aligned}$$

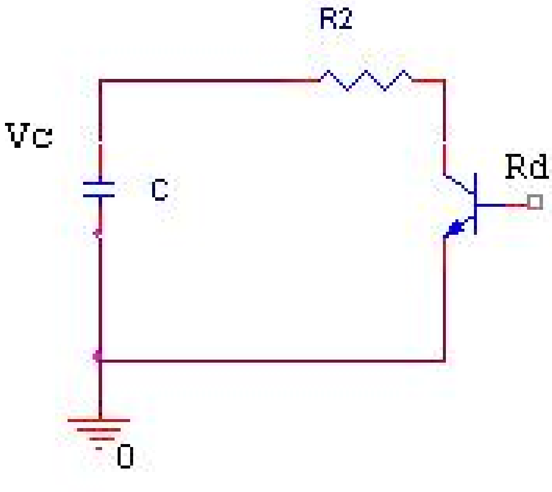

Figure 4: Equivalent circuit for Off-time.

Table 1: SR Flip-Flop Truth Table

S	R	Q	$\bar{Q}$
1	0	1	0
0	0	1	0
0	1	0	1
0	0	1	0

R_d is negligible

$$tL(off - time) = R_2 C ln 2 \tag{3}$$

$$T(period) = tH + tL = (R_1 + 2R_2) C ln 2 \tag{4}$$

4.1.2 Circuit Design

The designed circuit of the electronic firefly is shown in Figure 6[1]. When Q_1, Q_2, Q_3, or Q_4 receive lights from the adjacent fireflies, the charging and discharging times will be increased depending on the intensity of lights. For example, when Q_1 or other phototransistor receives lights, the battery (9 volts DC) will charge C_3 directly. So, it changes the blinking frequency. When Q_1 or other transistor do not receive lights, the capacitor C_3 is charged by battery through R_1 and R_2. The frequency is set by the value of R_1, R_2 and C_3 (see Equation 4).

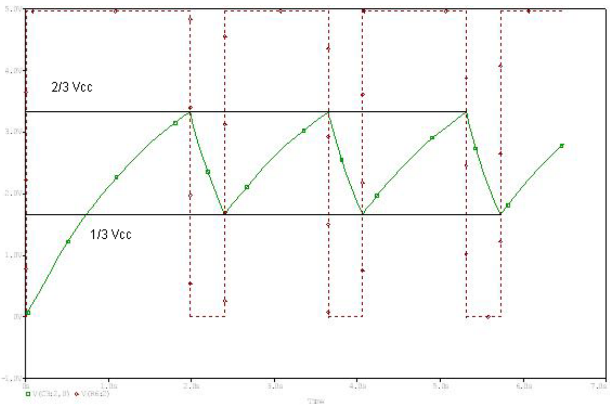

Figure 5: The voltage Output of Vc and 555 timer.

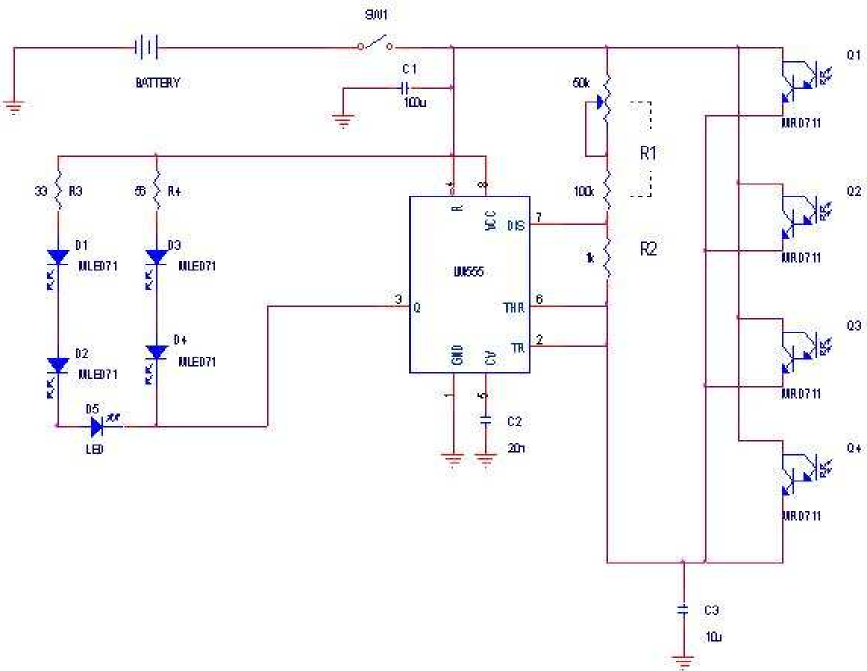

Figure 6: Electronic firefly circuit.

4.2 Simulation Results

We use several simulations, including the simulation without any input, with arbitrary inputs, with changing resistances and capacitance. The output of 555 timer is effected by these three components R_1, R_2 and C_3 (see Figure **??**).

4.2.1 Without any Input From Phototransistors

Figure 7 is the simulated output wave produced by taking the voltage difference from positive side of D_5 to the negative side of D_5.

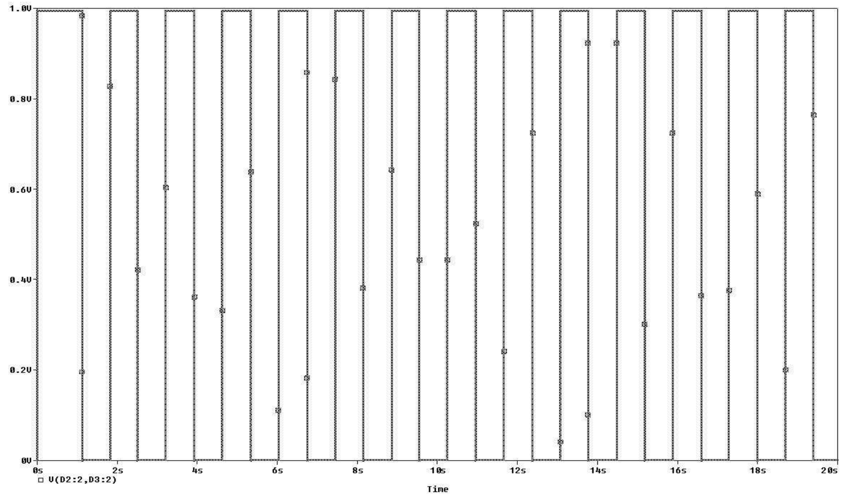

Figure 7: Output of the LED without any input.

4.2.2 With Arbitrary Inputs From Phototransistors

In this simulation, we assume that four phototransistors are receiving lights from different IR LEDs with different frequencies. In Figure 8, the voltage output of green LED (D_5 in Firure 8) shows the non-periodic wave form.

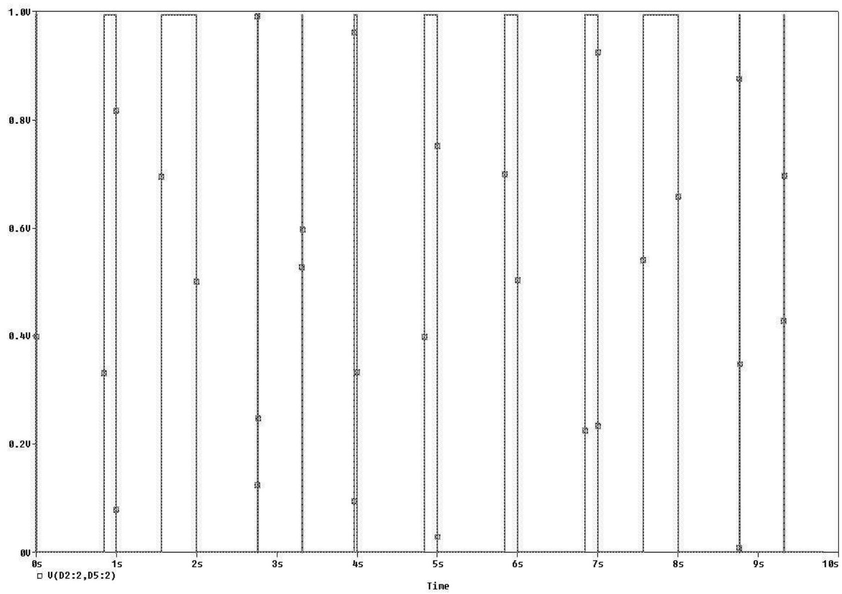

Figure 8: Arbitrary Inputs.

4.2.3 One Phototransistor Keeps Receiving Lights For 10 Seconds

When one of the phototransistor is receiving light for an extended period of time, say 10 seconds, the output voltage of green LED (D_5 in Firure 8) is around 4.3 volts. This voltage output is between $\frac{1}{3}$ and $\frac{2}{3}$ of the 9 volts supply voltage, so the flip-flop will hold the same output with the previous state. In this case, at 0 second, the output voltage of green LED (D_5) is 9 volts which is larger than $\frac{2}{3}$ of the supply voltage. So, the output of the 555 timer is in "lo" state and the LED is in "o" state (see Figure 9).

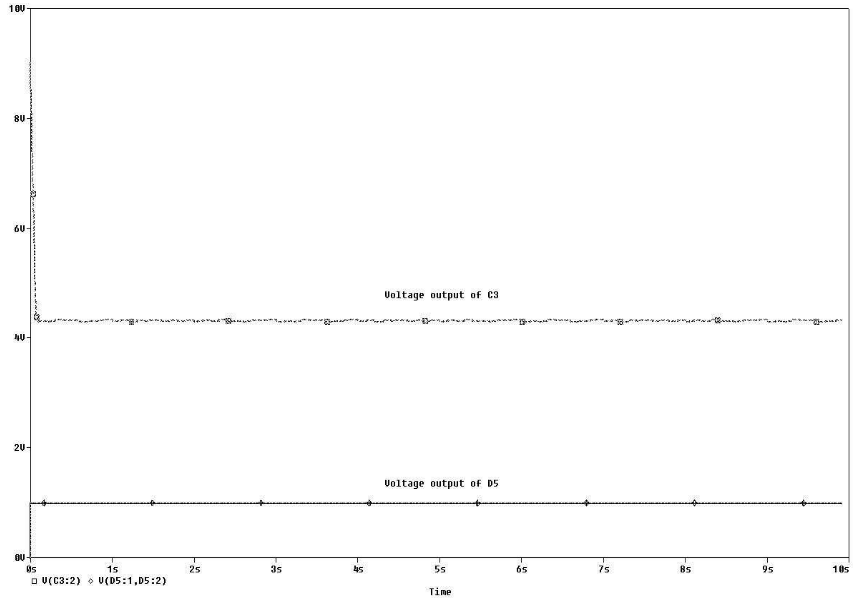

Figure 9: Voltage uutputs of C_3 and D_5.

4.2.4 Change the Resistances of R_1 & R_2 Without any Input From Phototransistors

(1)R_1=120KΩ, R_2=1KΩ
The on time is about 0.007 second, and the off time is about 0.8 second (see Figure 10 and Equations 2 and 3).

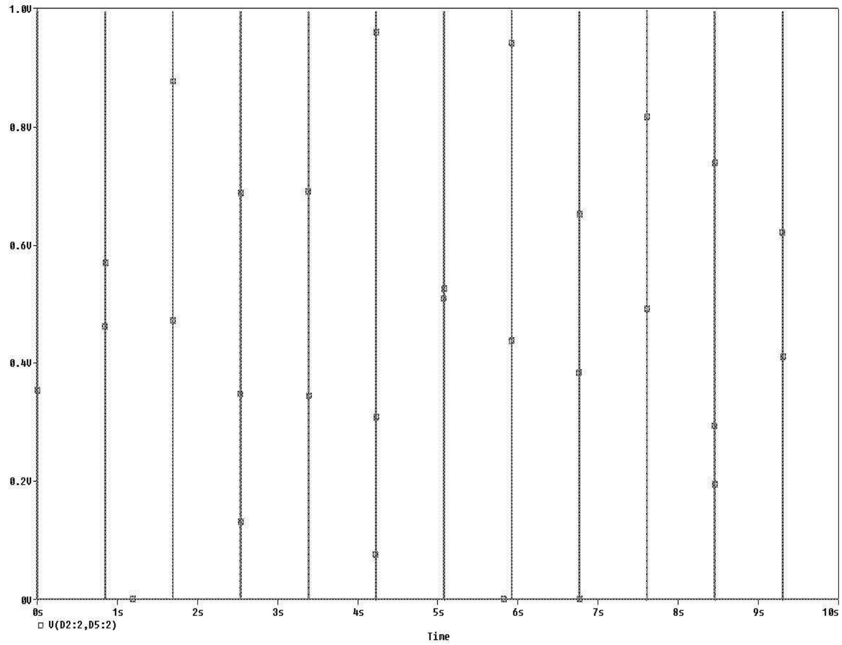

Figure 10: The on/off time of the original circuit

(2)R_1=120KΩ, R_2=100KΩ

R_1 remains unchanged, we change R_2 to 100KΩ. When we change the resistance of R_2, the on time and off time are also changed (see Figure 11 and Equations 2 and 3).

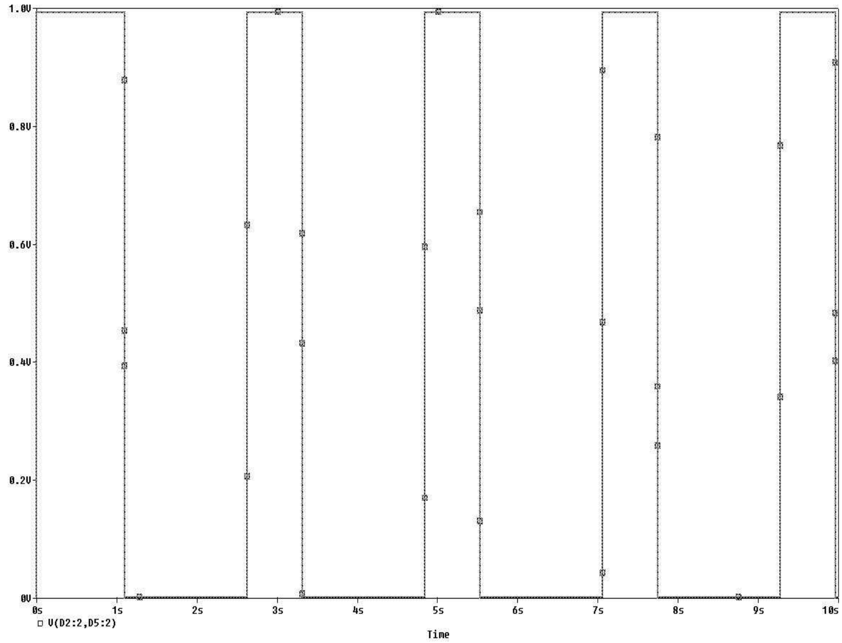

Figure 11: Change R_2 affects both on-time and off-time

(3)R_1=1KΩ, R_2=100KΩ
In this simulation, the resistance of R_2 remains unchanged, but we decrease the resistance of R_1 to 1KΩ. Comparing Figures 11 and 12, the on time is decreased but the off time stays the same value.

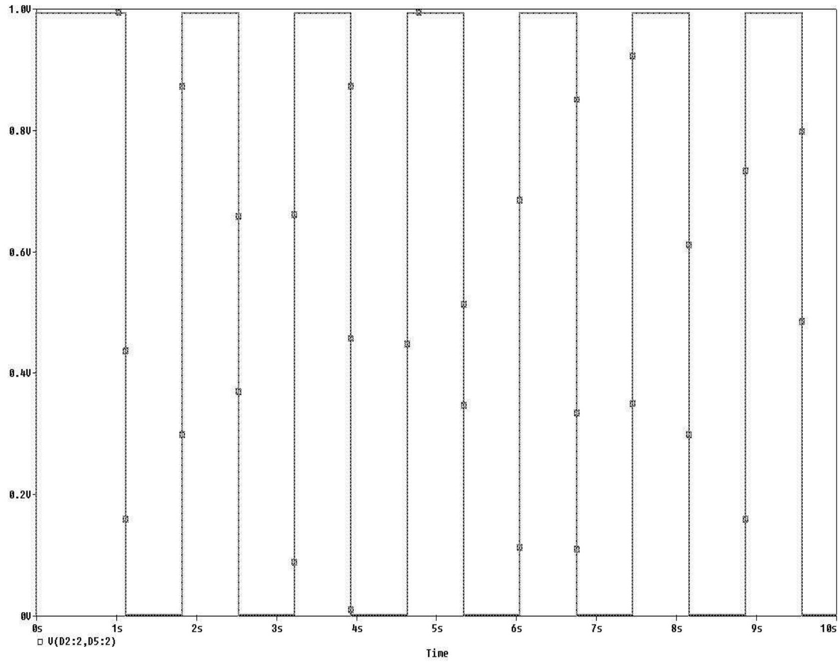

Figure 12: Decreased on-time.

4.2.5 Change The Capacitance of C_3 Without Any Input From Phototransistors

(1)Change C_3 to a larger capacitance 100μF
From Equation 4, when the capacitance of C_3 is increased, the period is also increased (see Figure 13). Since we do not give any input to the phototransistors, the output wave form should be periodic.

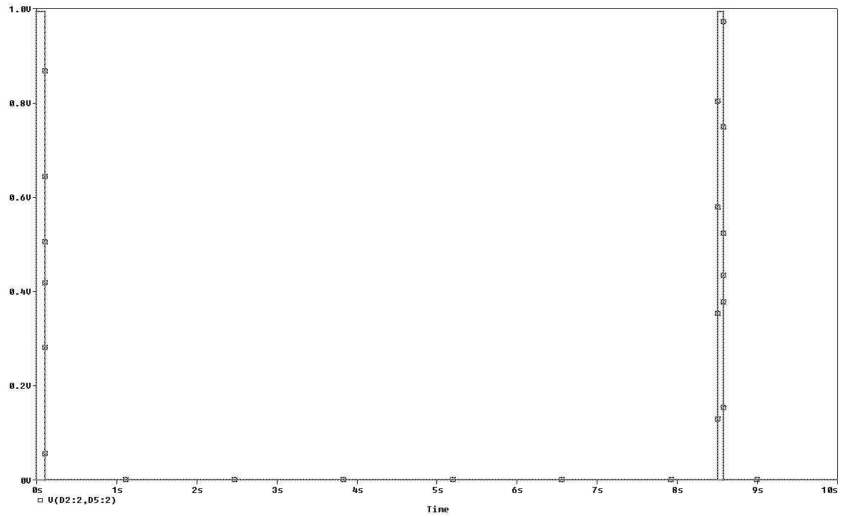

Figure 13: Longer period with a larger C_3.

(2)Change C_3 to a smaller capacitance 1μF

This time we change C_3 to a smaller value, the period is decreased as shown in Figure 14.

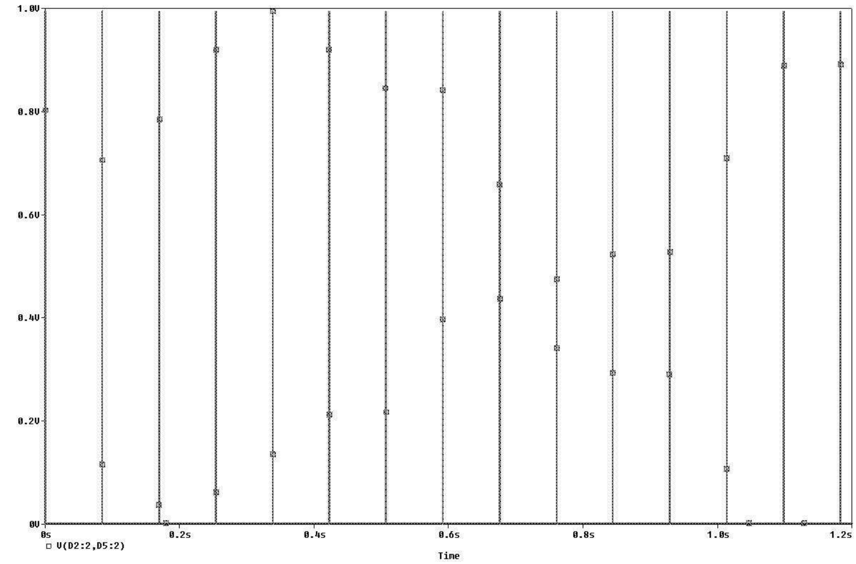

Figure 14: Shorter period with a smaller C_3.

5 Long Range Receiver

In this project, we consider about the time consuming of redesign the circuit and the spacing of our circuit board, We decide not to use the long range receiver.

The behavior of long range receiver is exactly opposite to the short range receiver. When the long range receiver is receiving lights, the collector and emitter is disconnected. So, in the simulation, in order to represent the long range receiver we have to add an inverter in the short range receiver (see Figure 15, 16 and 17). Since the behavior of long range and short range receiver are total opposite, we can add two long range **emitter**, which is working in the opposite way with the short range emitter (see Figure 15), instead of inverting the output of the long range receiver.

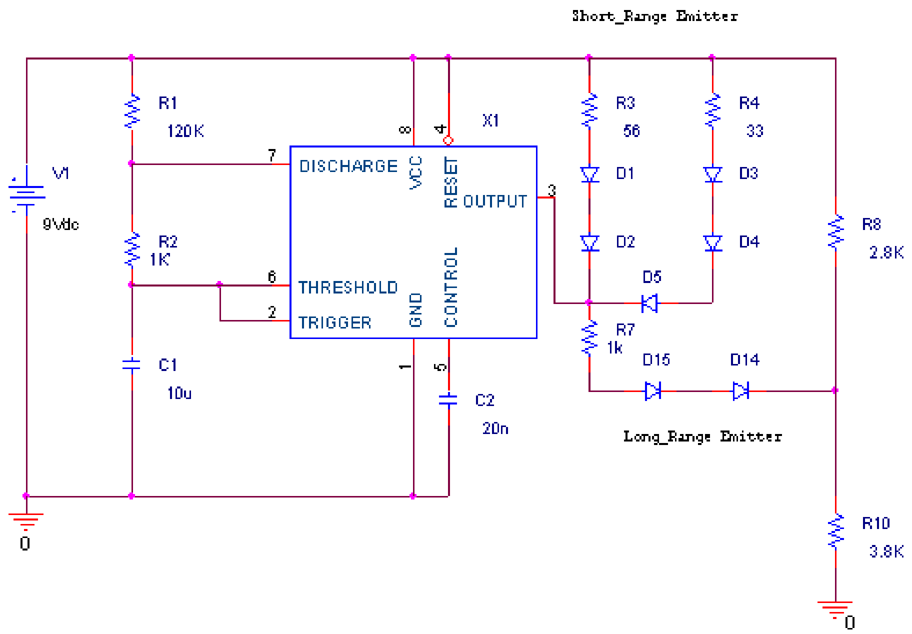

Figure 15: Design of long range receiver and short range receiver.

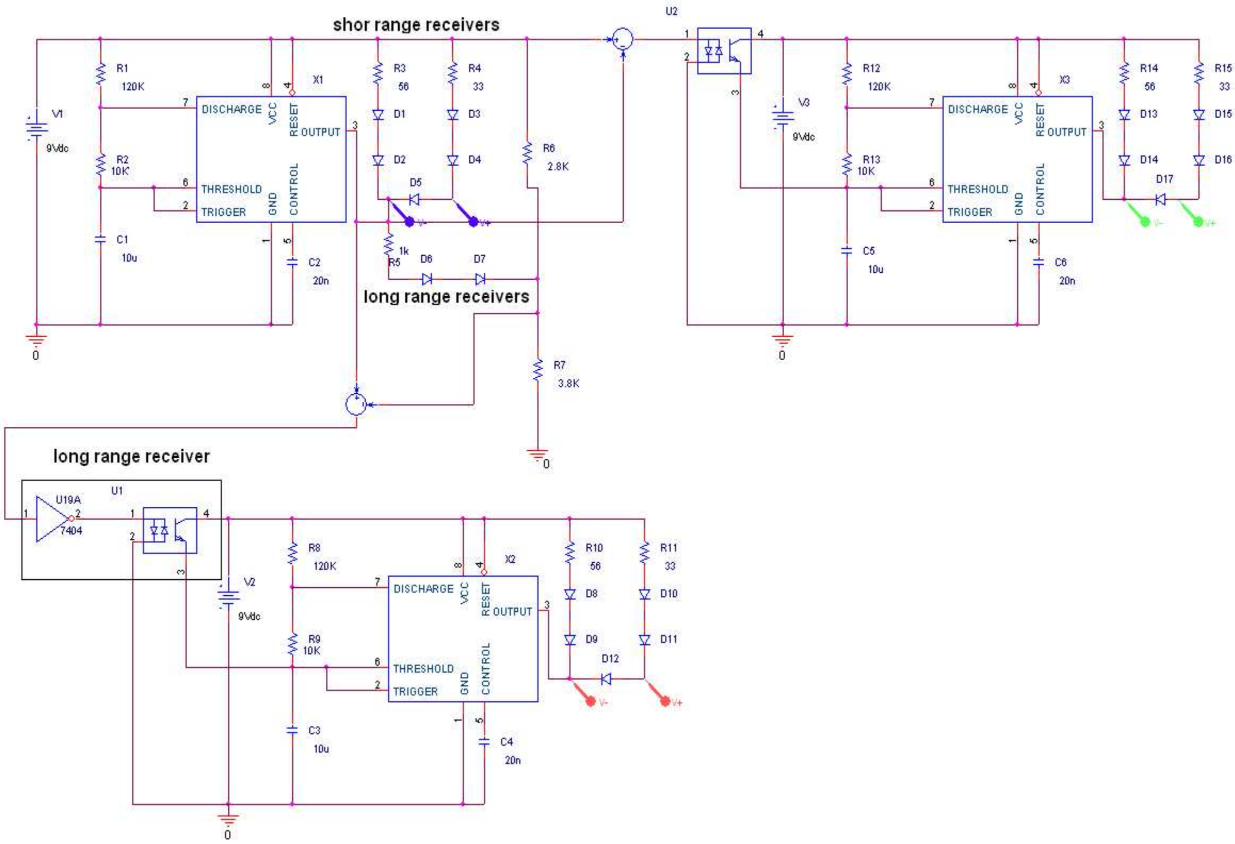

Figure 16: Simulation of the design.

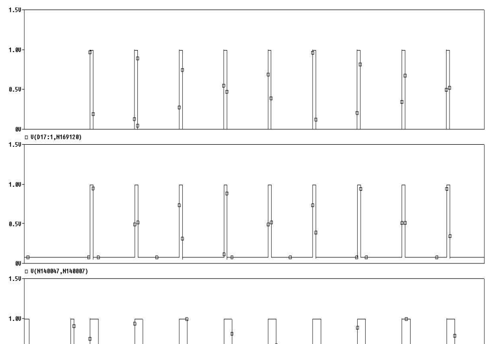

Figure 17: Output waveform of long and short range receiver combination.

6 Timeline

(1) First week, the group has received the fireflies design project and the back ground information on the fireflies. Each group member has to do the research on how the electronic fireflies synchronize with each other; and understand the electronic circuit design in the fireflies.
(2) Second week, after knowing the back ground information and the circuit design in the fireflies. We have a discussion of how we are going to start this project and design the actual layout of the fireflies on the breadboard.
(3) Third week, we start to order parts that requires in this design. By doing so we have to carefully read the specification of each part, and choose the right one that would meet the requirement for this design. Meanwhile, we also did the computer simulation on the firefly to double make sure that the circuit design would work.
(4) Fourth week, the group has started building and design the fireflies project on breadboard. By the end of forth week we have finished two fireflies on breadboards and test for synchronization; and everything turns out as we expected.
(5) Fifth week, we finish building 4 fireflies on the 2X3 circuit boards and text for the synchronization. At the same time, we also did the computer simulation on three fireflies; and also start the website design.
(6) Sixth week, we begin troubleshooting for the long range sensors to replace the short range sensors; and more of the website design.
(7) Seventh week, the long range sensor testing has failed due to the characteristic of long range sensor and the circuit for short range sensor will not fit for long range sensor. However, finish building all nine fireflies, and continue on more website design.
(8) Eight week, we test all nine fireflies' synchronization and more website design.
(9) Ninth week, we demonstrate nine fireflies' synchronization and finish the website design.

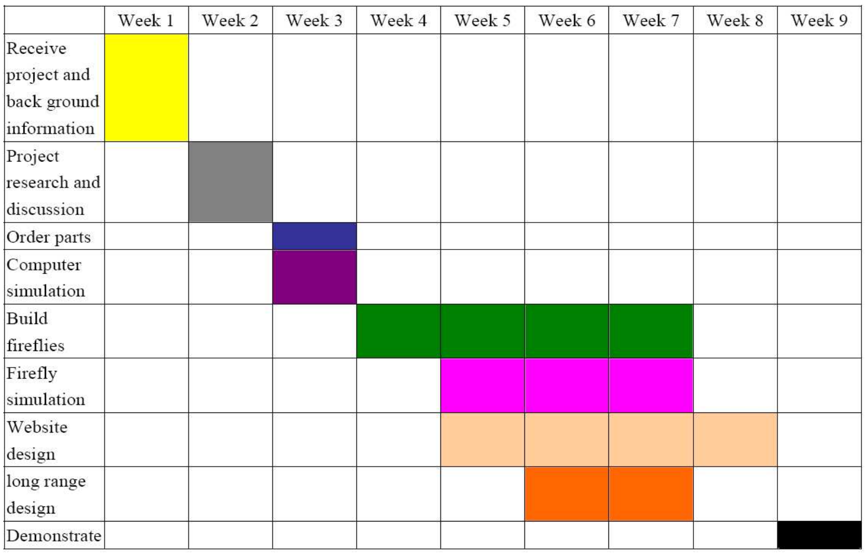

Figure 18: Time Table.

7 Webpage

The webpage has been designed to not only give everyone involved in the firefly project quick and easy access to all the current information, but also to allow dissemination amongst any interested public. The webpage has contact information for the team members as well as the advisors, making it easy for anyone desiring more information to contact the necessary parties.

The first purpose of the webpage is to catch the attention of anyone of possible interest in the firefly project. The range of possibly interested targets includes Electrical Engineering students and professors, those interested in fireflies, those interested in Bioluminescence Research, those interested in synchronizing, and those with a passion for gadgets. For this reason the webpage must appeal to a diverse group, and be able to catch and hold the attention of varied people. For this reason the webpage has been designed with a variety of pictures to catch the eye of the casual reader that fits any aforementioned groups. Obviously the webpage will not be able to satisfy the curiosity of each individual, so links to related websites are supplied.

The most important viewer of the website is naturally the individual interested in performing this experiment. It is therefore desired to give a complete set of directions for the experiment. The most important source for this information is the project report, and the report is therefore included on the webpage. The webpage also goes further than a paper document is able to do by supplying not only the parts list, but also links to the data sheets for the vital parts of the experiment.

Besides displaying pictures of the electronic fireflies and directions of how to build them, the website also delivers footage of them in action. This is done twofold. The first example of the electronic fireflies in action is video footage of testing done in the lab. Also shown on the webpage are the computer simulations run to show what is going on in each electronic firefly to allow it to synchronize with its neighbors. This allows an example of not only that they work, but how and why.

8 Discussion

It was hard at first to believe that the biological organisms can be emulated with circuits and simulated with computer. The firefly is a specie that will blink according to a natural frequency upon the night falls and communicate with their neighbors. With this idea in mind, we are building electronic fireflies which will emulate the fireflies' behavior. If the distributed synchronization in project is successful developed, then in the future it would be an immense improvement for distributed computing, the internet, distributed networked groups of autonomous vehicles, and other applications.

References

[1] Moss F Garver W. Elecronic fireflies. *Scientific American*, 269:128–130, 1993.

[2] Avila Ramirez Guisset J.L. The phase information associated to synchronized electronic fireflies. *University of Bruxelles*, 2000.