Abstract – Modern automobiles frequently come equipped with Remote Keyless Entry (RKE) systems. Stock RKE systems are frequently subject to severe range limitations. This project presents a design for a device which extends the range of existing RKE systems without requiring modification to the automobile. The device functions as a single frequency “Parrot” repeater. The repeater receives and decodes the signal from the user’s key chain transmitter, then verifies the code and transmits it to the automobile. The final design is a low cost, low power, battery operated device suitable for placement in an automobile. A USB interface allows decoding routines for specific automobiles to be loaded on the repeater ensuring the device can function for a wide range of manufacturers systems.

Index Terms - Repeater, Remote Keyless Entry (RKE), Radio Frequency (RF)

I. INTRODUCTION

Remote keyless entry (RKE) systems come as a standard feature on most modern automobiles. These systems allow the owner of an automobile to perform basic functions such as locking and unlocking an automobile. These functions are performed by using a low power transmitter generally attached to the driver’s keychain, called a “fob”.

Standard RKE systems use a low power IC transmitter in the key fob and a low power IC receiver placed somewhere within the automobile. The design is often implemented in the lowest cost and least obtrusive manner possible which limits some systems to ranges as small as 30 ft.

For some uses of RKE systems, such as finding a car lost in a parking lot, a much greater range of operation is desirable. Existing aftermarket RKE systems which offer range extension are expensive and require extensive modification of the automobile. The user is also forced to use the new systems generic key fob instead of the one that matches his or her automobile.

The goal of this project is extend the range of RKE systems to over 100 ft without requiring the user to perform any modifications to his or her automobile. By using a robust antenna design placed in an ideal location along with a highly sensitive receiver the design aims to use existing low cost components to create a system which is capable of significant range extensions.

II. BACKGROUND

The basic operation of an RKE system is rudimentary: When a user presses a button on the key fob, a short sequence of binary data containing a command code and a security code is transmitted to the automobile. The automobile then decodes the transmitted sequence and, if the correct security codes are received, the automobile executes the command.

Figure 1: Basic RKE system operation

RKE systems must be at the same time low cost, low power and operational under a wide range of use.
conditions, from a frigid winter night to a very hot summer day. Because of this encoding and modulation schemes which are simple to implement and easy to decode are selected. Additionally, these devices often have undesirable performance characteristics such as poor frequency and timing stability. To overcome the frequency instability RKE receivers are fairly wideband (specifications call for as much as 600 kHz). Timing instability is overcome be using encoding schemes which allow the detector to resynchronize after every bit is received.

Two encoding schemes are commonly used in RKE systems: Pulse Width Modulation (PWM) and Manchester encoding. Pulse width modulation uses pulses of varying widths to represent binary data. A short pulse at a high level represents one logic value, while a long pulse (usually twice the length of a short pulse) represents the other. Because the data is transmitted as pulses, there is a transition from high to low for every bit in the sequence which allows the detector to synchronize to the received data. In Manchester encoding a high to low or low to high transition occurs in the middle of each bit. A transition from a high level to a low level represents on logic level, whereas a transition from a low level to a high level represents another. Because there is a transition in the middle of every bit the decoder can again be continuously resynchronized.

The most common modulation scheme in RKE systems is Amplitude Shift Keying (ASK), a digital form of AM modulation. ASK modulates a binary signal onto a carrier signal by shifting the amplitude of the carrier according to a binary value. The mathematical representation of ASK is:

$$u(t) = s(t)\cos(2\pi \cdot f \cdot t)$$

Equation 2: ASK Modulation

As equation (2) demonstrates, the binary input signal s(t) merely turns the carrier on and off, so the envelope of the signal corresponds to the binary data being transmitted. Because of this, a simple, low cost envelope detector can be used to retrieve the encoded data.

The binary sequence itself generally contains three parts: A variable security code, a serial number, and a command. The variable part is called a “hopping code”. This is a set of bits defined by a pseudo-random generator. The same random number generator is contained in the automobile, which stores the next several numbers in the random sequence. Each time the user presses a button on the key fob, a new random number is sent to the car. The car will only execute the command contained in the code if the random numbers match – in this way security in ensured for the transmission.

In the United States most devices operate at 315MHz, while in Europe 433.92MHz is often used.

III. DESIGN SPECIFICATIONS

The customer required the final product to be low cost, with a target sale price of $20 to $30. The customer also required that the device to work for most existing vehicles, which meant that the design had to be capable of function for a number of different encoding schemes. A final customer requirement was that the device requires no connection to the vehicle, which meant the device was required to have its own power supply.

Due to physical limitations it was determined that the system would only be designed for one frequency – otherwise antenna and receiver design requirements would be too advanced for a low cost system. Because of the cost of implementing both an ASK and FSK detector, and because nearly all RKE systems use ASK modulation, it was determined that parts using FSK modulation would not be supported.

IV. DESIGN

In order to meet the customer’s specifications for this project several design concepts were introduced. After feasibility analysis it was decided that the best design would be radio frequency repeater. The repeater receives the signal transmitted from the key fob, decodes the signal, including the pseudo random security code, checks the serial number to make sure the transmission came from the correct key fob, stores that signal for a period of time, and then retransmits the signal. The repeater system, as seen in figure (2), can be compared to the original system as seen in figure (1). A basic high level overview is shown in figure (3).
The design was broken into segments, designed individually, and then put together to form a single final design. The design was divided into the antenna design, receiver design, transmitter design, microcontroller design, and USB connection design.

A. ANTENNA DESIGN

The antenna for the project was required to be omni-directional (radiating equally well in all directions in one plane), based on the assumption that the user is not going to be using the device from an elevation significantly above or below the vehicle. The design frequency for this project is assumed to be 315MHz, where the free space wavelength is 0.952m.

Available antenna designs included a loop antenna, quarter wave dipole antenna, and a half wave dipole antenna. In the case of the loop, the input impedance was on the order of a few thousand ohms which made matching the antenna to the input filter impractical. The half-wave dipole and the quarter-wave dipole had very similar characteristics, with the half wave dipole having slightly better directivity. The half-wave dipole was, however, found to be too large for use with the system so the quarter-wave dipole was selected for use.

For theoretical purposes a finite length dipole is analyzed to determine its radiation characteristics. It is assumed that the dipole has a negligible diameter compared to the operating wavelength. Hence the assumed that the dipole has a negligible diameter with respect to the operating wavelength. Hence the electric field and current distribution for this dipole can be described by the equations (3) and (4) for electric field and magnetic field respectively [2].

\[
E_\theta = j\eta \frac{I_0 e^{-jkr}}{2\pi r} \left\{ \cos \frac{kl}{2} \cos \theta - \cos \frac{kl}{2} \right\} \sin \theta
\]

**Equation 3: Electric Field with respect to Phi**

Using the relationship between \(E_\theta\) and \(H_\theta\), \(H_\theta\) can be found and can be written as

\[
H_\theta = \frac{E_\theta}{\eta} = j\frac{I_0 e^{-jkr}}{2\pi r} \left\{ \cos \frac{kl}{2} \cos \theta - \cos \frac{kl}{2} \right\} \sin \theta
\]

**Equation 4: Magnetic Field with respect to Theta**

The quarter wave antenna was simulated using EXPERT MININEC, an engineering tool for the design and analysis of wire antennas. MININEC’s solution is based on the numerical solution of an integral equation representation of electric fields. MININEC assumes that the wire radius is very small with respect to the wavelength and the wire length. The wire must be subdivided into short segments so the radius is also assumed small with respect to segment lengths. MININEC uses the moment method (MM) solution, which is a numerical procedure for solving electric field integral equation.

The quarter-wave antenna had a length \(l = 0.238m\). Simulations were run with various different lengths for the antenna, and the optimum length was found to be 0.226m. Two geometry points were then defined as \((x_1, y_1, z_1) = (0, 0, 0)\) and \((x_2, y_2, z_2) = (0, 0, 0.226)\). The method of moments required that the wire be broken into segments, with a larger number of segments producing more accurate results. The number of segments for this antenna was set to 40; the points at which the different segments of the wire were connected was identified by current nodes. The program was then run to obtain the following results:

![Quarter Wavelength Radiation Pattern](image)

**Figure 4: Quarter Wavelength Radiation Pattern**

<table>
<thead>
<tr>
<th>Freq (MHz)</th>
<th>Resistance (Ω)</th>
<th>Reactance (Ω)</th>
<th>Impedance (Ω)</th>
<th>VSWR dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>315</td>
<td>35.789</td>
<td>-.79302</td>
<td>35.798</td>
<td>1.3978</td>
</tr>
</tbody>
</table>

**Table 1: Quarter Wavelength Characteristics**

The antennas were matched to the receiver and the transmitter using a simple inductor and capacitor matching circuit to ensure maximum power delivery to the receiver.

B. RECEIVER DESIGN

The receiver design for this project followed basic receiver design as found in any communications textbook [4-6]. However, there were several very important design considerations that weighed into the design of the repeater, including the cost of the receiver, the power drawn by the receiver, and the sensitivity of the receiver.

If an expensive receiver was used then the cost of the design would prohibit it from being marketable. The power drawn by the repeater was also very important because the repeater functions off of batteries – the receiver must be frequently turned on to check for transmissions, so a design that didn’t minimize power consumption would run down the batteries too fast. Obviously a highly sensitive receiver is required if the range of the system is to be extended.

The receiver used in this design is microchips rfrXD0420 receiver [9]. This receiver costs $2.79, has a sensitivity of -106 dBm, and an average current consumption of 8.2mA when receiving. This receiver was chosen because it meant the basic design specifications for this project, is easily interfaces with PIC microcontrollers, and because it only required a few inexpensive external components including a
SAW filter, a crystal, a ceramic filter, and a few capacitors and resistors.

C. TRANSMITTER DESIGN

The transmitter design for this project followed basic transmitter designs as found in any communication textbook [4-6]. There were a few important design considerations for the transmitter. These are the cost of the transmitter and the power consumption of the transmitter. The output power of the transmitter is not very important.

If an expensive transmitter was used the cost of the repeater would be too high. The power consumption was an important design factor because the repeater operates on batteries. If the transmitter used a disproportionate amount of power the battery life would not be sufficient. The output power of the transmitter is not that important because the repeater will be placed inside the vehicle and the transmitter only has to provide enough power to get the signal to the existing RKE system, which is also in the vehicle.

The transmitter used in this design is Microchip’s rfPIC12F675 [1]. This transmitter costs $2.25 and draws a max of 14mA when transmitting but only .1A when on standby. This transmitter also has a microcontroller which was disable for the present implementation. The transmitter was selected over other available IC’s because of its extensive documentation and the ease of interfacing it with the PIC microcontroller that was selected.

D. MICROCONTROLLER DESIGN

The receiver routine functions by using one of the microcontroller’s four timers to generate an interrupt at a fixed interval of a small but arbitrary fraction of the transmitted signals bit rate. In order to service the interrupt as simple state machine was constructed which operates at a rate corresponding to the interrupt period.

When power is applied to the device a simple initialization routine is run. Because Microchip microcontrollers rely on extensive multiplexing of pin functions it is necessary to set the I/O pins used by the circuitry to the appropriate directions and values – specifically the transmitter is placed in a low power standby state while the receiver remains active. A reset state is then entered, which is also called after a successful transmission or an invalid reception. The reset state initializes the appropriate variables, sets the interrupt period appropriately, and clears the receive buffer.

The code then enters a detection state. The prototype was constructed for a 2004 Toyota Corolla which uses a Microchip HCS 361 encoder part [3]. The code transmitted by the key fob contains a sync header of total length 10xTE. In order to detect the beginning of a transmission, the first state searches for sync header of the valid length (a range of lengths based on the minimum and maximum expected time for the sync header defines a valid length). In order to do this the receiver input is sampled at the fixed interval of the timer. If a low level is detected a counter containing the number of consecutive lows received is incremented. If a high level is detected, which might indicate the start of a reception, the length of the sync header is tested to ensure it is neither too short nor too long. If the value is valid, it is then divided by 8 to determine the bit time:

$$10T_e / 8 = 1.25T_e$$

**Equation 5: Bit decision boundary**

For the Variable Pulse Width Modulation scheme (VPWM), a short pulse will have a duration of $T_E$, while a long pulse will have a duration of $2T_E$. By setting the decision threshold dynamically for each transmission optimal performance can be gained in a wide variety of conditions – whether the oscillator of the key fob is operating at the upper end or lower end of its spec limits.

![Figure 5: Variable Pulse Width Modulation](image)

<table>
<thead>
<tr>
<th>Length</th>
<th>Level</th>
<th>Detect</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_E$</td>
<td>Low</td>
<td>0</td>
</tr>
<tr>
<td>$2T_E$</td>
<td>Low</td>
<td>1</td>
</tr>
<tr>
<td>$T_E$</td>
<td>High</td>
<td>1</td>
</tr>
<tr>
<td>$2T_E$</td>
<td>High</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2: Decoding rules for VPWM (Variable pulse width modulation)**

After a valid header is detected a receive routine is entered. Decoding VPWM operates as follows: Immediately after the reception of the sync header the routine transitions to a “high” state. While in this state the receiver counts the number of consecutive high samples received. When a low level is sampled the routine then compares the number of samples from the $T_E$ measurement taken from the sync header. If it is larger than $N_{TE}$ (the number of samples corresponding to a period of $1.25T_E$) a 0 is read, if shorter a 1 is read.

It is also noted if the signal is longer or shorter than the worst case lengths, in which case the receiver detects an invalid transmission and resets. At the end of each bit the receiver moves between the high receive state and the low receive state until the total number of expected bits is recorded.
Once all of the bits are recorded the receiver moves into a validation state. The serial number of the car (stored through a learning sequence) is loaded from non-volatile EEPROM into a temporary register. The bytes of the received sequence corresponding to the fixed serial number are then compared to the stored serial number. If there is an exact match the transmit states are entered, if not then the reset state is entered and the data received is discarded.

The transmit states aim to replicate the data exactly as received. Because a bit transition never takes place less than \( T_E \) seconds after the previous one, the interrupt period is set to the “optimal” \( T_E \) (based on the specification sheet, not the received transmission). In addition to changing the interrupt period, the receiver is disabled and the transmitter is enabled.

The first state is responsible for transmitting the 167 bit “Wake Up Preamble” used for waking the cars receiver from an idle state. Once that is completed a long (258x\( T_E \)) pause follows, after which the receiver enters another preamble state, a 19 bit long preamble which precedes the sync header. After the sync header is sent, the transmit routine then alternates between a high and a low state, specifying the number of times to reenter the state based on the received sequence (i.e. the level is held high for \( T_E \) if a 1 is being sent and for 2\( T_E \) if a 0 is being sent, and so on). Once the entire sequence has been sent it repeats itself, excepting the wakeup preamble, for a specified number of repetitions. When the whole process is complete the reset routine is called and the receiver again looks for a valid sync header.

Because all of the decoding and transmitting is implemented in microcontroller code, different receive and transmit routines can be written for each type of automobile. This means so long as the RKE system of an automobile uses ASK modulation at 315MHz (which a majority of automobiles do), the repeater will function. By using the USB interface to load the appropriate routine for a given car, the repeater will be able to function with a wide variety of makes and models.

### E. USB DESIGN

In order for the repeater to be compatible with different types of coding schemes, USB interface was developed. Through USB, the microcontroller could be easily reprogrammed by customers to detect signals with any particular coding scheme.

USB device can be self-powered or bus powered. Self-powered devices rely on the external source, while bus powered devices use power supplied from the bus. All USB devices must follow the standard USB specification, which limits the bus power to 100 mA at 5V [7]. However, requests for additional power (up to a maximum of 500 mA) are allowed. When USB devices are in sleep mode, current is limited to 500 \( \mu \)A, averaged over 1 second. The transition between the two current levels must be completed within 10 ms.

The information of USB devices is provided to the host during the process called Enumeration. This information includes, the power consumption, data rate, data sizes, protocols and other descriptors. This is the first interaction between the devices and the host every time they are attached to the bus.

Each USB device must indicate its bus presence and speed to the host. This is accomplished through a 1.5 k\( \Omega \) resistor which is connected to the bus at the time of the attachment event. Depending on the speed of the device, the resistor either pulls up the D+ or D-line to 3.3V. For a low-speed device, the pull-up resistor is connected to the D-line. For a full speed device, the pull-up resistor is connected to the D+ line.

The main structure of the implemented USB was adapted from the framework provided by Microchip as the design tools for implementing USB communications.

The main() function is a basic infinite while loop. The interrupts are polled through by the USBDriverService(). In this particular project, PortB7 is used to generate an interrupt, which requires the microcontroller to switch into bootloader mode. When an interrupt is received, USBCtrlEPService() is called. This control transfer service is provided by functions in usbctrltrf.c. Control transfers arrive initially as standard request. It is serviced by USBCheckStdRequest() function.

The enumeration process is handled in usb9.c. The USBStdSetCfgHandler() takes care of the most important task in the process which is handling a SET_CONFIGURATION request. This function is modified by users in order to initialize application endpoints.

The application code is also called from the main program loop located in the function named ProcessIO(). When USB transaction is requested, it can call a pre-written function that services the transmit or receive functionality. Figure 1 represents the microchip USB framework files.

A basic program was written to test the functionality of the USB interface. This program simply blinks an LED. This program would be loaded onto the microcontroller memory using the developed USB interface. If the LED blinks as expected, the interface is obviously functional.

### V. LEGAL CONSIDERATIONS

The operation of the repeater within the United States is subject to FCC regulations, Title 47, Chapter 1, Part 15, Section 231 – Periodic Operation including the band of the repeaters operation. It specifies, “The provisions of this section are restricted to periodic operation within the band 40.66-40.70 MHz and above 70 MHz. Except as shown in paragraph (e) of this section, the intentional radiator is restricted to the
transmission of a control signal such as those used with alarm systems, door openers, remote switches, etc.” [47CFR15.231].

The use of a repeater is not specifically granted by the FCC regulations. However, so long as adequate circuitry is included in the design to ensure that the repeater only retransmits a single user's signal, no rules are being broken.

The rules govern maximum transmitted field strength. The transmission, however, will only be going from the repeater to the receiver in a car, a distance that will, in the worst case scenario of a minivan, not exceed a couple of meters. In order to best conserve power the transmitter will operate at an extremely low voltage so the field strength limitations will not be a concern.

It is likely that the device would require FCC approval in order to go to market. This step should be taken in tandem with the rest of the design process in order to ensure that no legal issues are encountered. Should legal issues be encountered, no part of the current design would be usable for the system.

VI. RESULTS

The final design testing for this project has not been completed. However, the basic concept proposed in this paper has been shown to work, that is the use of a repeater to receive, sample, store, and retransmit the signal. The design proposed performs these functions.

The microcontroller code was tested using a Microchip test kit, which included a receiver module and a transmitter module. Using this kit, the code successfully learned the received signal and then stored the signal. The microcontroller then retransmitted the same signal. The prototype was tested on a 2004 Toyota Corolla, which was successfully locked and unlocked using the repeater.

Although the basic concept has been shown to work, it does not yet extend the range. When the system was test with individual modules it extended the range of the key fob signal to 120ft. However, there have been some problems getting the receiver on the final design board to work correctly. This should be worked out by complete design review presentation. If the receiver works as well as expected the range should be at least 120ft.

There has also been a problem getting the USB connection to work correctly. Hopefully the USB connection will also be working correctly by the complete design review.

VIII. CONCLUSION

The objective this project was to extend the range of an existing automotive remote keyless entry without modifying the existing system. The repeater design proposed in this project successfully extended the range. The design also meets all of the design specifications. The cost of mass producing the device is estimated to be $30, the device is independent of the existing system, and using USB connection the device will work for most existing RKE systems.

This project established a basic idea for range extension, the repeater, and proved it can work. However, the design has not been optimized. Before this concept becomes a marketable product it needs further development. This development includes work on power consumption, receiver sensitivity, and making it work for other cars.

The present design consumes too much power. The receiver used is consuming too much power. Possible solutions include changing the receiver or creating an algorithm which allows the receiver to sleep and periodically wake up and check for transmission. The receiver sensitivity can also be increased by either changing the receiver or adding a low noise amplifier in front of the receiver.

The repeater currently only works for a single type of vehicles. However, it has been designed to work for most existing vehicles. In the future work has to be done breaking down the code of other vehicles RKE system so that the microcontroller can be modified. This information will all be transferred to the microcontroller by USB.

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REFERENCES
