AN1275

KEELOQ® with Advanced Encryption Standard (AES) Receiver/Decoder

Author: Enrique Aleman
Microchip Technology Inc.

OVERVIEW

This application note describes a KEELOQ® with AES code hopping decoder implemented on a Microchip Mid-range Enhanced Flash MCU (PIC16F886). The purpose of this implementation is to demonstrate how KEELOQ code hopping technology can be implemented with the AES encryption algorithm for even greater security. This allows for a higher level of security solutions for keyless entry systems and access control systems. The software has been designed as a group of independent modules written in C.

The Advanced Encryption Standard (AES) is a means of encrypting and decrypting data adopted by the National Institute of Standards and Technology (NIST) on October 2, 2000. The algorithm used in AES is called the Rijndael algorithm after its two designers, Joan Daemen and Vincent Rijmen of Belgium. AES is a symmetric block cipher that utilizes a secret key to encrypt the data. This implementation of AES is based on a 16-byte block of data and a 16-byte key. It was also designed to balance speed, code size, and readability.

KEELOQ code hopping creates a unique transmission on every use by using a cycle counter. The cycle counter is then used to validate the transmission.

The combined AES/KEELOQ algorithm uses a programmable 128-bit encryption key unique to each device to generate 128-bit hopping code. The key-length and code-hopping combination increases the security for remote control and access systems.

KEY FEATURES

The set of modules presented in this application note implement the following features:

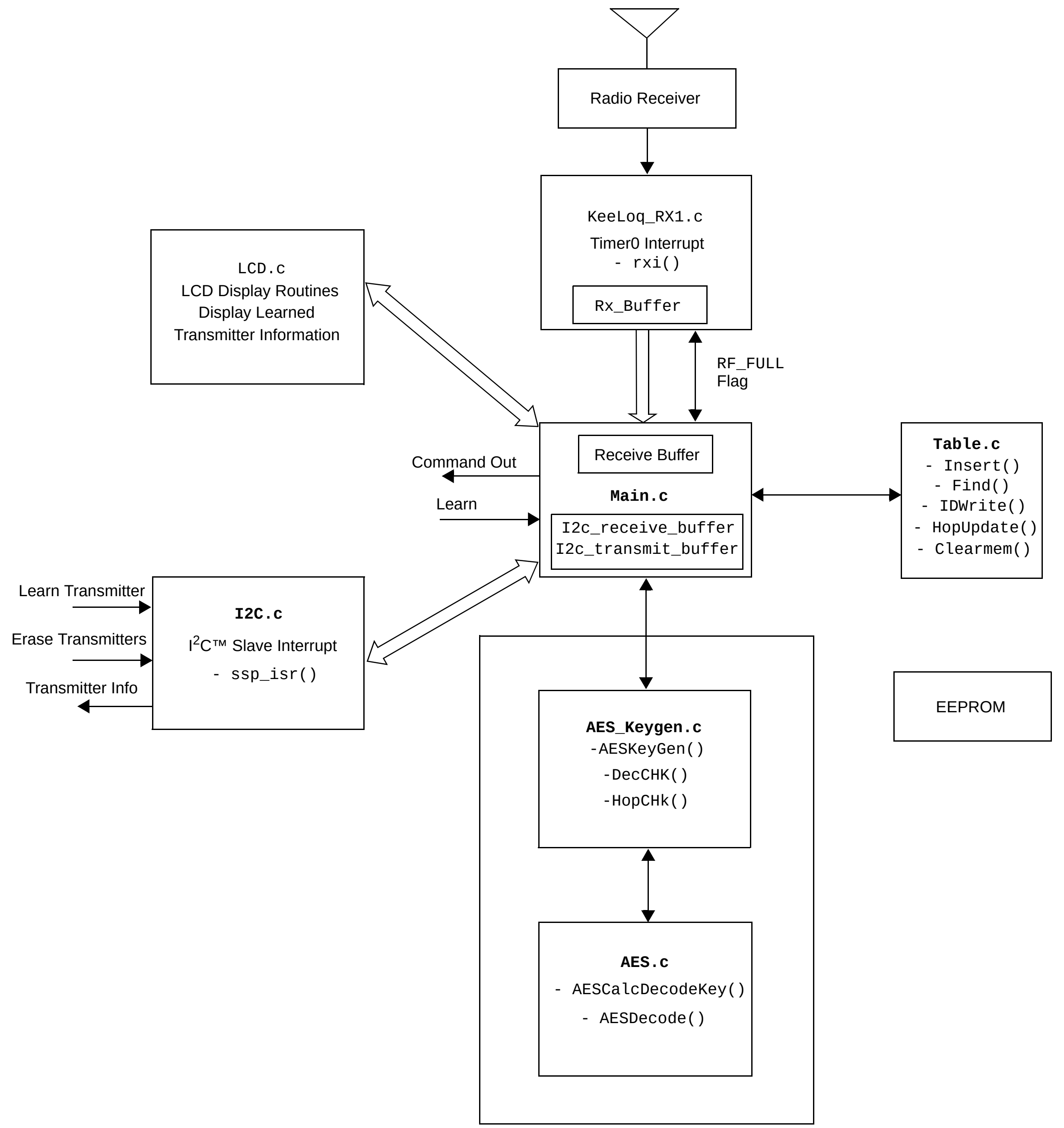
- Source compatible with HI-TECH C® compilers
- Pinout compatible with the KEELOQ 3 Development Kit
- Normal Learn mode
- Learns up to 8 transmitters, using the internal EEPROM memory of the PIC® microcontroller
- Interrupt driven Radio Receive (PWM) routine
- Compatible with KEELOQ/AES hopping code encoding with PWM transmission format selected, operating at TE = 200 µs.
- Automatic synchronization during receive, using the 8 MHz internal oscillator
- I^{2}C™ slave routines are included so that the decoder can be designed into a larger control system.
- LCD routines are included to display decrypted data and messages.

MODULES OVERVIEW

The code presented in this application note is composed of the following basic modules:

`AES.c`	This file contains the functions and tables of the C version of the AES code.
`Aes_keygen.c`	This file arranges the received encrypted data into the AES block to calculate the key and decrypt.
`Aes_keygen.h`	This file contains the function definitions for AES encryption.
`Delay.c`	HI-TECH C® delay routines.
`delay.h`	This file contains the function definitions for `delay.c`.
`I2c.c`	This file contains the state machine for I^2C™ slave communications.
`I2c.h`	This file contains the function definitions for I^2C.c.
`Keeloq_RX1.c`	This file contains the incoming transmission receiver routine. It has been modified from the original KEELOQ® receive routine to accommodate the 168-bit incoming AES transmission.
`Keeloq_HW.h`	This file contains the hardware definitions for the KEELOQ 3 Development kit.
`KeeLoq_RX.h`	This file is the variable and function definitions for `KeeLoq_RX1.c`.
`lcd.c`	Standard HI-TECH LCD routines.
`Lcd.h`	Header file `lcd.c`.
`Main.c`	This file integrates the modules and contains the program main loop.
`Table.c`	This file has the EEPROM read and write routines. Saves the learned transmitter information.
`Table.h`	Header file for `table.c`.

FIGURE 1: MODULES OVERVIEW



RECEIVER MODULE

The receiver module has been developed around a fast and independent Interrupt Service Routine (ISR). The whole receiving routine is implemented as a simple state machine that operates on a fixed time base. In this implementation, the ISR is polling the incoming transmission line every 60 µs. The operation of this routine is completely transparent to the main program.

After a complete code word of 168 bits has been properly received and stored in a 22-byte buffer, a status flag (`RF_FULL`) is set and the receiver becomes idle. The main program then is responsible for using this data in the buffer and clearing the flag to enable the receiving of a new code word.

In order to account for variations in incoming transmission timing, the receiver routine constantly attempts to resynchronize with the first rising edge of every bit in the incoming code word. This allows the decoder to operate from the internal RC oscillator. In doing so, the last rising edge/bit of every code word is lost (resulting in an effective receive buffer capacity of 168-bit).

The only resource/peripheral used by this routine is Timer0 and the associated Overflow Interrupt. This is available on every mid-range PIC® MCU. Timer0 is reloaded on overflow, creating a time base of about 60 µs.

This time base corresponds to a transmission timing element (Te) of 200 µs. For other timing elements, the time base will need to be adjusted; for example, for Te=400 µs, the time base should be modified to 120 µs.

This is only but an example of how the receiving routine can be implemented. The designer may want to make use of other peripherals to write a different version of the receiver code.

These include:

- Using the INT pin and selectable edge interrupt source
- Using the Timer1 and CCP module in capture mode
- Using comparator inputs interrupt

All of these techniques pose different constraints on the pinout, or the PIC MCU, that can be used.

FIGURE 2: CODE WORD TRANSMISSION FORMAT

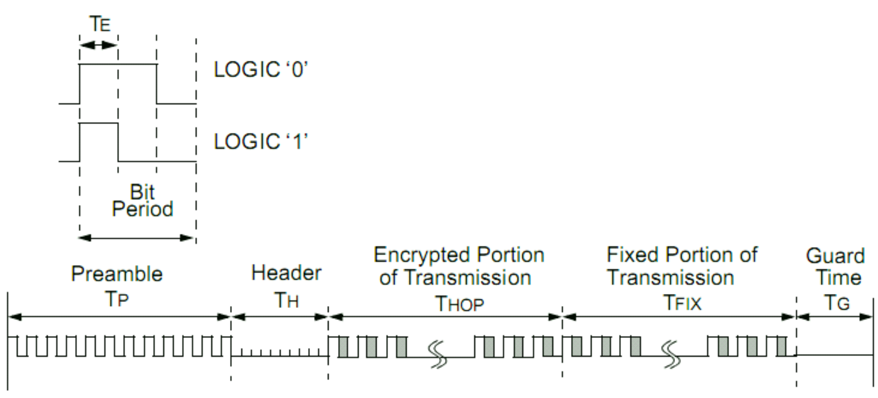


TABLE 1: KEELOQ®/AES PACKET FORMAT

Plaintext: 40 bits				Encrypted: 128 bits				
CRC (7 bits)	VLOW (1 bit)	Function Code (4 bits)	Serial Number (32 bits)	CRC (16 bits)	Function Code (16 bits)	Serial Number (32 bits)	User (32 bits)	Counter (32 bits)
Plain text transmitted LSb first. Encrypted portion transmitted MSB first.								

KEY GENERATION

Key generation is performed by the `AESKeyGen()` function in `aes_keygen.c`.

To generate the encryption key, the manufacturing key and the 32-bit serial number (received in plaintext) are used as inputs to the decoder. The 32-bit serial number is padded as follows to complete a 128-bit block:

```
0xA5A5A5A55A5A5A5A + (32bit-Serial) + 0x00000000
```

Two functions are called:

`AESCalcDecodeKey(key1)`: this function places the key in the proper sequence for the decode function.

`AESDecode(block,key1)`: this function performs the actual decode.

AES DECRYPTION MODULE

Once the encryption key is generated, it is placed into *key1* to be used for decoding the encrypted data, so again, the two functions (`AESCalcDecodeKey(key1)` and `AESDecode(block,key1)`) are called.

The decrypted data is now in the *block* buffer.

AES Functions

`AESDecrypt`	Uses the key variable to decrypt the block data. The block variable is modified with the deciphered data. The key variable contains the original encrypt key for that block of data.
`AESCalcDecryptKey`	Takes the encrypt key loaded into the key variable and modifies it to the decryption key.

TABLE MODULE

One of the major tasks of a decoder is to properly maintain a database that contains all the unique ID's (serial numbers) of the learned transmitters. In most cases, the database can be as simple as a single table, which associates those serial numbers to the synchronization counters. This module implements a simple "linear list" of records.

Each transmitter learned is assigned a record of 16 bytes (shown in Table 2), where all the relevant information is stored and regularly updated.

The 32-bit synchronization counter value is stored in memory twice because it is the most valuable piece of information in this record. It is continuously updated at every button press on the remote. When reading the two stored synchronous values, the decoder should verify that the two copies match. If not, it can adopt any safe resync or disable technique required depending on the desired system security level. The current implementation limits the maximum number of transmitters that can be learned to eight. The user can modify the program to suit more transmitters learned. This number can be changed to accommodate different PIC microcontroller models and memory sizes by modifying the value of the constant `MAX_USER`.

The simple "linear list" method employed can be scaled up to some tens of users. But due to its simplicity, the time required to recognize a learned transmitter grows linearly with the length of the table. It is possible to reach table sizes of thousands of transmitters by replacing this module with another module that implements a more sophisticated data structure like a "Hash Table" or other indexing algorithms.

Again, due to the simplicity of the current solution, it is not possible to selectively delete a transmitter from memory. The only delete function available is a Bulk Erase (complete erase of all the memory contents) that happens when the user presses the Learn button for up to 10 seconds. (The LED will switch off. At the release of the button, it will flash once to acknowledge the delete command).

TABLE 2: TABLE MODULE

Offset	Data	Description
+0	FCode	Function Code(s) learned
+2	IDHi	Serial Number (Bits 31 ..24)
+3	IDMi1	Serial Number (Bits 23…16)
+4	IDMi0	Serial Number (Bits 15…8)
+5	IDLo	Serial Number (Bits 7..0)
+6	CNTHi	Counter (Bits 31 ..24)
+7	CNTMi1	Counter (Bits 23…16)
+8	CNTMi0	Counter (Bits 15…8)
+9	CNTlO	Counter (Bits 7..0)
+10	CNTHi	Counter Copy (Bits 31 ..24)
+11	CNTMi1	Counter Copy (Bits 23…16)
+12	CNTMi0	Counter Copy (Bits 15…8)
+13	CNTlO	Counter Copy (Bits 7..0)

I^{2}C™ MODULE

An interrupt driven I^{2}C slave state machine is included in this implementation. The I^{2}C state machine accepts the Learn and Erase commands as described in AN1248, "*PIC® MCU-Based KEELOQ® Receiver System Interfaced Via I^{2}C™*".

LCD MODULE

Also included in this implementation are routines for interfacing with a small LCD module. This permits the data to be displayed for testing or application purposes.

THE MAIN PROGRAM

The main program is reduced to a few pages of code. Most of the time, the main loop goes idle waiting for the receiver to complete reception a full code word.

Double buffering of the receiver is done in RAM, in order to immediately re-enable the reception of new codes and increase responsiveness and perceived range.

LOADING THE PROJECT

This project has been developed for the KEELOQ 3 Development Kit base station. The *.hex* file provided can be programmed into the base station using a PICkit™ 2 device programmer.

To load the Project into MPLAB® IDE:

1. Launch MPLAB IDE, and open the project's workspace KEELOQ 3 AES `Decoder.mcw`.
2. Verify that the HI-TECH C language tool suite is selected (*Project>Select Language Toolsuite*).
3. In the workspace view, all the source files mentioned above should be listed.

Because of statutory export license restrictions on encryption software, the source code listings for the AES algorithms are not provided here. These applications may be ordered from Microchip Technology Inc. through its sales offices, or through the corporate web site: www.microchip.com\KeeLoq.

CONCLUSION

A KEELOQ with AES encryption algorithm provides maximum security by combining KEELOQ Code Hopping technology with the 128-bit encryption key algorithm. The decoding portion works similar to a standard KEELOQ decoder: the algorithm calculates the encryption key used to encrypt the transmission; with this key, the function codes and the cycle counter are calculated. The cycle counter is then compared to the currently stored counter value and validated.

The implementation presented in this application note is modular and can be easily modified by the user.

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ADDITIONAL INFORMATION

Microchip's Secure Data Products are covered by some or all of the following:

Code hopping encoder patents issued in European countries and U.S.A.

Secure learning patents issued in European countries, U.S.A. and R.S.A.

REVISION HISTORY

Revision B (June 2011)

- Added new section **Additional Information**
- Minor formatting and text changes were incorporated throughout the document

Note the following details of the code protection feature on Microchip devices:

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