Optimizing Passive Keyless Entry System Performance

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Passive Keyless Entry System Overview

Vehicles equipped with Passive Keyless Entry (PKE) systems offer the consumer a method to gain entry into their locked vehicle without having to use a mechanical key or press a button on a handheld key fob. A PKE system has two main components: a) a key fob and b) a base station. The key fob is typically placed in the purse or pocket of the vehicle's authorized user while the base station is mounted in the vehicle and contains a means to generate a low frequency (LF), typically 125kHz, magnetic field around the perimeter of the vehicle and receive radio frequency (RF), typically 315MHz or 433.92MHz. Over time, extensions to this basic system have evolved to include additional features such as keyless engine start, keyless door lock, approach lighting, etc. However, the basic system technology remains unchanged.

The primary technologies enabling PKE are a) LF magnetic field generation and measurement, and b) RF radio transmission and reception. In simple terms, when a PKE system is triggered through an event such as lifting the door handle, an LF magnetic field is generated by the vehicle's base station. A key fob, equipped with means to measure 3-dimensional (X, Y and Z axis) magnetic field strength, captures this information and transmits it over an RF signal back to the vehicle base station. If the key fob is determined to "belong" to the car and is properly located nearby the vehicle, the base station unlocks the driver's door. It should be obvious that proper operation of the system depends on critical parameters such as trigger event to unlock door, response time, repeatable LF field generation, accurate LF field strength measurement, and immunity to LF field disturbances. The focus of this article is to further explore the nature of these parameters, as well as methods to optimize them within the PKE system.

Communication Protocol

PKE system communication spans two frequency domains: LF and RF. Within each domain exists a communication protocol that contains some essential fields. In the LF domain, the base station must send a data pattern robust enough to enable discrimination between valid communication and noise. It should also give order on how authorized key fobs, which could number up to 8 per vehicle, respond with their RF message to avoid collisions. Finally, it needs to provide a period of continuous and constant LF field generation for the fob to obtain accurate measurements of field strength. In the RF domain, the key fob must securely communicate with the vehicle base station with the information needed to determine if it is OK to unlock the vehicle. Typically, the LF domain communicates using Binary or Quad Pulse Length

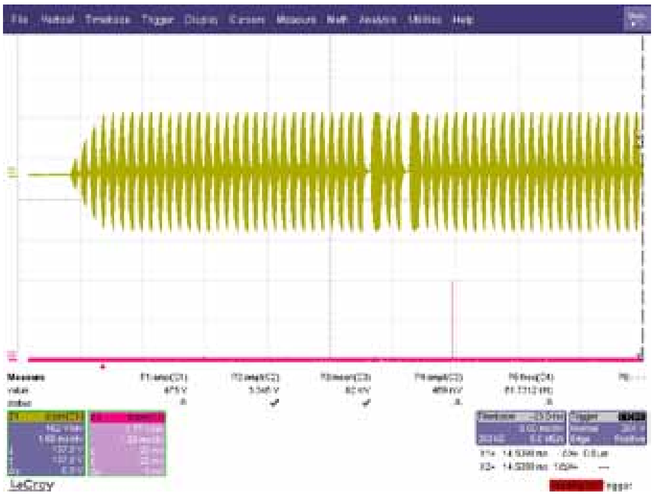

Figure 1. LF Preamble Signal and Device Wake-up

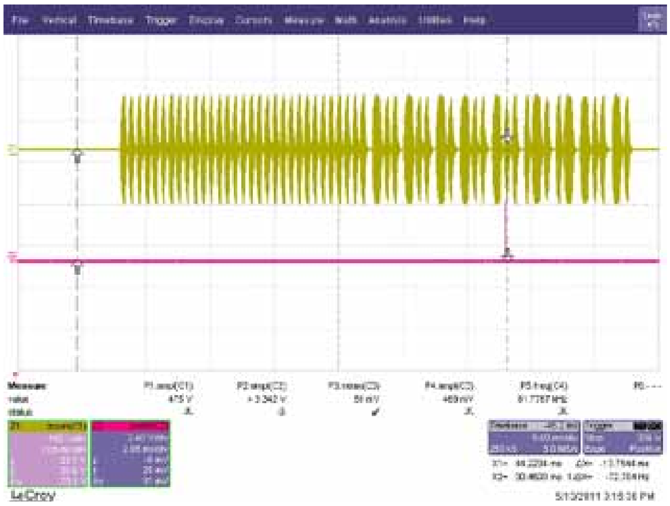

Figure 2. LF Preamble with Payload Data Signal (Receiving 2 Bytes)

Modulation (BPLM or QPLM) at a baud rate of 3.9Kb/S whereas the RF domain communicates using On-Off or Frequency Shift Keyed (OOK or FSK) modulation at data rates from 4Kb/S to 20Kb/S.

LF Wake-up

In order to minimize false wake-up conditions and extend battery life of the key fob, a pre-defined data pattern is needed from the base station to the key fob. This pattern is called a preamble and generally consists of a consecutive string of data bits, e.g., "0" followed by a sync bit of opposite polarity, e.g., "1." The consecutive string of data must be long enough to enable the key fob to initialize and verify existence of valid data bit timing. If the timing check passes, the sync bit is used to align the data reception buffer for the capture of the remaining information. As the number of consecutive bits in the preamble string is increased, the likelihood of waking up on a stray magnetic field is reduced. Several typical LF field modulation patterns are shown in figures 1 and 2.

Anti-collision Methodology

A critical piece of information contained in the LF message sent from the vehicle base station to the key fobs is a rule that provides order to how they reply. Were it not for this information, key fobs paired with the vehicle would likely reply at the same time and corrupt all of the RF responses. A common approach to solving this problem is a time-slotted anti-collision protocol. This consists of assigning specific key fobs to specific time-slots during which they are allowed to reply. For example, assume a vehicle is paired with 4 key fobs with unique identification numbers ranging in value from 1 to 4. The assignment of a unique fob ID number to a specific time slot is pre-defined in the initial LF message. Graphically, this can be seen in figure 3 below.

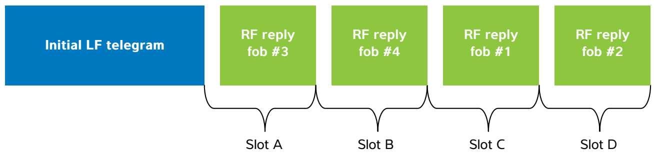

Figure 3. Time Slotted Anti-collision

RSSI Measurement

The remaining critical aspect to the LF message sent from the vehicle base station is the measurement of the field strength for the X, Y, and Z axes. This is typically performed last and done while the LF field is in a continuous wave (CW) mode. Important parameters to consider for this aspect of the PKE system are a) sensitivity, b) accuracy, and c) conversion time.

Sensitivity can take on several meanings depending on its context. Sometimes it refers to the minimum detectable voltage amplitude required to wake-up the LF detection circuitry. At other times, it refers to the minimum voltage amplitude that can be detected and converted into a digital value. In both cases, the typical unit of measure is mV and can be specified as peak-to-peak (V_{P-P}), root-mean-square (V_{RMS}), or peak voltage (V_P). They are related mathematically as follows:

$$V_P = 0.5 \times V_{P-P} = \sqrt{2} \times V_{RMS}$$

Accuracy refers to the amount of error introduced during the analog-to-digital (A/D) conversion process. Primary sources for error are a) A/D reference voltage, b) bits of resolution, and c) variations in the resonant frequency of the receive antenna. When considering a design, it is important to consider how the electronics can compensate for them. Depending on the solution, compensation can add considerable complexity and time to the A/D conversion process.

Conversion time is the amount of time needed to calibrate, convert, and compensate the analog voltage present on each axis of the three-dimensional (3D) receive antenna contained within the key fob. Depending on the architecture of the selected design solution, it is important to consider whether A/D conversions are performed sequentially in series or simultaneously in parallel before finalizing the design. Calibration and compensation techniques vary considerably among IC suppliers and should also be carefully examined to understand their implications to this important aspect of PKE system performance.

Magnetic Field Basics

Fundamental to proper operation of the PKE system is its ability to consistently generate a magnetic field of known and sufficient strength around the perimeter of the vehicle and to accurately measure it. This section will focus on this aspect of PKE and discuss LF magnetic field parameters that influence system performance.

Magnetic Field Generation

A magnetic field, B, is produced as electric current flows through a circular coil of wire (see figure 4).

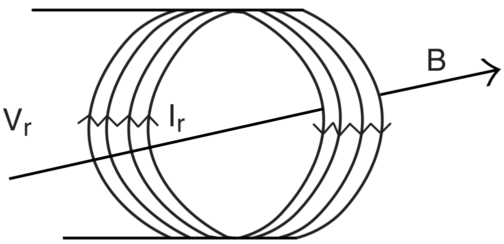

Figure 4. Magnetic Field Formation

The magnetic field is concentrated in the center of the coil and propagates along an axis normal to the plane formed by the cross section of the coil of wire, wrapping from one end of the coil to the other. The amplitude of a magnetic field is quantified in terms of flux. In free space, magnetic field flux follows predictable behavior and is based on current flow and coil geometry. However, flux patterns can be distorted when ferrous objects (e.g., metals that are attracted to magnets) are placed in the field, which is a point worth further consideration when compensation techniques are evaluated.

Figure 5 shows the variation of field strength as a function of distance for two different coils, each having a different radius. It is noteworthy to point out that field strength is proportional to the number of turns in the coil and the amount of current flow. It should also be evident from the logarithmic scale used in the vertical axis of the plot that field strength tends to decay at an exponential rate as the distance, D, from the center of the coil is increased: $1/D^3$. This is a desirable property that limits the practical range of a PKE system to 5 meters. It is also another important factor when considering the complexity of the math associated with some compensation methods.

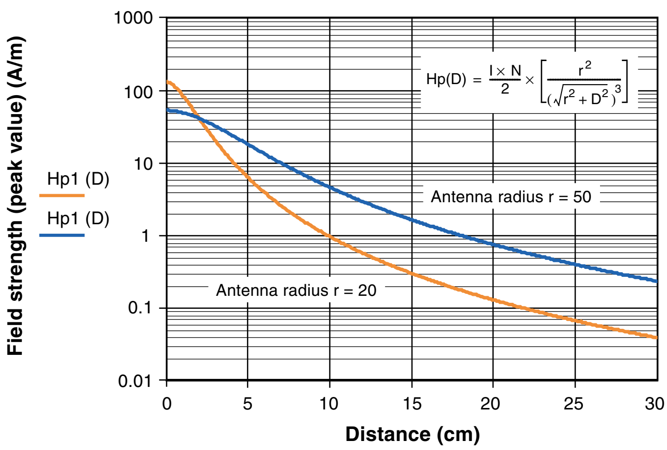

Figure 5. Magnetic Field Strength versus Distance

Resonance

Both vehicle-mounted coils (that generate the LF field) and the portable key-fob-mounted coils (that measure the LF field) must be tuned to resonance at the same frequency for optimal system performance. Resonance occurs when the imaginary term of the coil's complex impedance becomes 0. It is also the frequency at which the capacitive and inductive reactance become equal and cancel each other:

$$Z_{coil} = R + j(X_L - X_C)$$

$$X_C = 1/(2\pi fC) \quad X_L = 2\pi fL$$

The resonant frequency of the resonant circuit is defined by the equation:

$$f_{RESONANCE} = 1/(2\pi\sqrt{LC})$$

Since coils are inherently inductive, the introduction of a capacitive element is necessary to achieve resonance. Resonance can be obtained through either parallel or series connections. In practice, resonance is obtained in the vehicle-mounted coil by adding a series connected capacitor to maximize coil current while parallel capacitance is added to maximize induced voltage in the key-fob-mounted antenna.

Q Factor

A common measure of coil quality is the Q factor. This factor affects both system baud rate and the magnitude of the voltage induced on the measurement coils. The Q factor is defined as the ratio of inductive reactance of an inductor to its DC resistance and can represented with the following equation:

$$Q = \frac{X_L}{R} \text{ where } X_L = 2\pi f_0 L$$

Theoretically, a larger Q results in larger induced voltages on measurement coils and better performance. However, it has a negative affect on data rate. In practice, Q factors of 15 are used and represent a reasonable compromise between these constraining factors. Similar Q factors on both the field generation and measurement coils produce optimal system performance.

Field Strength Measurement

Magnetic field strength is measured by immersing an antenna coil in the field. The induced voltage that is produced in the measurement coil is a function of its coil physical properties (mechanical and electrical discussed previously) and angular alignment to magnetic flux. The component of induced voltage related to angular alignment is maximized when both the field generation coil and the field measurement coil share the same axis. The relationship can be approximated as shown in the equation below:

$V_{induced} = V_{max} \cos(\theta)$, where θ is the angle between the coil axes

In a PKE system, the key fob's orientation is uncontrolled, which requires the use of three measurement coils to assess its position in free space: one for each axis, X, Y, and Z.

Practical Considerations in Position Measurement

The primary objective in a PKE system is to accurately and quickly determine the position of the handheld fob with respect to the vehicle. External factors, such as temperature, magnetic field distortion, resonant circuit component aging effects and initial tolerance, affect the system's ability to accurately measure the fob's position. Other properties inherent to the system—such as sensitivity, A/D conversion profile (logarithmic versus linear), and A/D resolution—also contribute error terms to the measurement process and complexity to the compensation of the measurement. When considering alternative design approaches, it is important to recognize these error sources, understand available compensation techniques, and consider their affects on overall system response time.

An exhaustive study of present-day PKE field strength measurement solutions is beyond the scope of this document. However, to illustrate the concept of LF field strength measurement error compensation techniques, the balance of this study will focus on the Atmel® ATA5790, a completely integrated (excluding the resonant coil circuits) PKE system solution.

Resonant Frequency Trim

Optimal performance is possible only when the field generation and measurement coils are tuned to resonance at the same frequency. This can be done by design with knowledge of the measurement coil's nominal inductance and specifying an appropriately valued resonant capacitor. However, part-to-part tolerance variations in both the coil and capacitor will invariably lead to sub-par performance. To compensate for this, an attractive design feature would be having the capability to fine-tune the resonant frequency back to nominal. The ATA5790 provides this capability by offering integrated variable capacitor arrays, configured in parallel to each of the 3D measurement coil inputs, which can be swept in value from 0-120pF.

In practice, this form of compensation is performed once during the manufacturing process. By incorporating an end-of-line tester capable of controlling the position and alignment of the measurement coil with respect to a constant and well controlled field, part-to-part component variations for each axis and each key fob can be individually quantified and trimmed away. The trim values for each of the variable capacitor arrays are saved in non-volatile memory and used for the life of the product.

Adaptive Compensation of Environment

Another set of factors to consider in the design of a robust PKE system are those that are affected by environmental changes and posses unpredictable qualities that have a negative effect on measurement accuracy. These factors could be temperature, L/C component aging, localized loading/de-tuning of the measurement coils, or any other item that degrades the response of the measurement coil. Performance degradation in this respect is associated with reduced coil-to-coil coupling, which in term results in reduced received signal voltage on the key fob antenna and is synonymous with reading lower RSSI values during fob positioning measurement. In order to compensate for this type of influence, a response from a pre-defined signal while under controlled environmental conditions, $V_{in\ factory}$, must be measured and compared to the response from the same pre-defined signal while being subject to unknown environmental conditions, $V_{in\ service}$. By comparing $V_{in\ factory}$ and $V_{in\ service}$, it is possible to quantify the amount of environmental degradation that has taken place and apply this offset value $V_{compensation}$ to subsequent measurements of the field generated by the vehicle.

For this approach to be effective, several design features must be present: 1) an internal reference signal, 2) a means to apply it to the receiving antenna coil, and 3) a predictable gap in LF field generation in which to perform the measurement. The ATA5790 integrates the first two of these features into a single package. In combination with the specification of an LF communication protocol with provisions for 3), the ATA5790 enables this self-adaptive environmental compensation technique.

An example serves best to illustrate this technique. During the key fob's manufacture it is presented to an in-line line tester where the resonant frequency trim operation is performed and permanently set (see previous section for more detail), all the while being in an environment where the magnetic field surrounding the key fob is well controlled and free from any form of parasitic loading or influence. Next, the ATA5790 initiates a self-test program that connects the measurement coils to an internally generated stimulus signal where the responses of all input coils are measured simultaneously. The measured result from each coil, $V_{X\text{-}internalfactory}$, $V_{Y\text{-}internalfactory}$, and $V_{Z\text{-}internalfactory}$ are stored in non-volatile memory for use throughout the life of the key fob. After the manufacturing process is completed, the key fob is shipped to the customer and put into service.

While in service and during a known gap in the external LF field, the same internally generated stimulus signal used during in-line test is presented to the measurement coils. The response from each coil is measured; $V_{X\text{-}internalservice}$, $V_{Y\text{-}internalfservice}$, and $V_{Y\text{-}internalservice}$ and subtracted from the values obtained during manufacture to determine the amount of compensation required for each axis. Next, measurements of the external LF field generated by the vehicle are made; $V_{X\text{-}externalservicey}$, $V_{Y\text{-}externalservice}$, and $V_{Y\text{-}externalservice}$. By adding the corresponding compensation value to each axis, a more accurate assessment of the key fob's position in space is obtained. In summary, the compensation equations for each axis can be shown as noted below:

$$V_{X\text{-}final} = V_{X\text{-}external\ service} + (V_{X\text{-}internal\ factory} - V_{X\text{-}internal\ service})$$
$$V_{Y\text{-}final} = V_{Y\text{-}external\ service} + (V_{Y\text{-}internal\ factory} - V_{Y\text{-}internal\ service})$$
$$V_{Z\text{-}final} = V_{Z\text{-}external\ service} + (V_{Z\text{-}internal\ factory} - V_{X\text{-}internal\ service})$$

Field Strength Measurement Averaging

Averaging A/D measurement values filter transient conditions and improve repeatability of position information. When this principle is applied to PKE systems, it increases the integrity of the LF field strength measurement process and results in a more accurate assessment of the key fob's position in space. When implementing an algorithm like this, it is important to consider factors affecting response time such as 1) simultaneous versus sequential conversions of X, Y, Z position axes, 2) number of conversions per axis to average, and 3) A/D conversion time.

The ATA5790 gives the designer an advantage over other solutions in both categories 1) and 2) mentioned above. It performs A/D conversion of the X, Y, and Z axes simultaneously through its parallel conversion architecture. Furthermore, updates are possible every 48µs after the initial conversion has taken place: typically in about 1.5mS. With updates available so quickly, implementing an A/D value-averaging algorithm consisting of a running average of 8 consecutive samples is possible with minimal impact.

To illustrate this point, please refer to figure 6, which is a screen shot from an oscilloscope showing the A/D acquisition and averaging of both internal and external field strength measurements (see previous section for details). The red trace shows A/D averaging of 8 consecutive samples, first during a gap in the LF field and then again during a continuous LF field as indicated by the green trace. Note that the initial A/D conversion time takes about 1.5ms while the 7 additional conversions follow roughly every 85μs thereafter. In this illustration software overhead, to calculate and maintain the running average, added time to the best-case update rate of 48μs noted above.

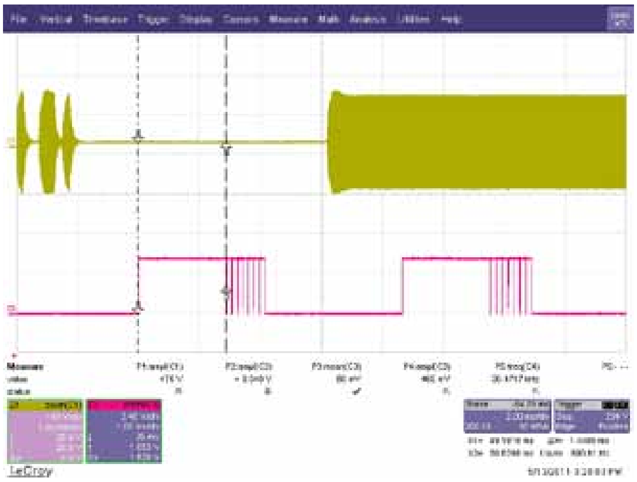

Figure 6. Internal and External A/D Measurements

Architecture of A/D Convertor

Within a PKE system, the architecture of the A/D convertor can have significant implications on positional precision. When considering the profile that models the relationship between coil voltage and distance, it seems intuitive that an A/D convertor with a log transfer function would produce better results. See figure 7.

In reality, there is solid rationale for selecting this approach. Namely, when using the logarithmic A/D conversion transfer function to scale voltage on the receiver coil, signals received at greater distances can be interpreted with a better distance precision per A/D step than would be possible in an A/D convertor with a linear transfer function.

Figure 8 overlays both linear and log A/D responses, each with 8-bit resolution. It is noteworthy to point out that the linear A/D response uses most (240 steps) of its available conversion range of 0 to 255 in the near field (< 50cm), leaving very little (16 steps) for the far field. On the other hand, the log A/D response more uniformly distributes its available conversion range of 0 to 255 across the entire range of distance measurements. Consequently, excellent positional precision is possible over a greater range of distance than is possible with the linear A/D.

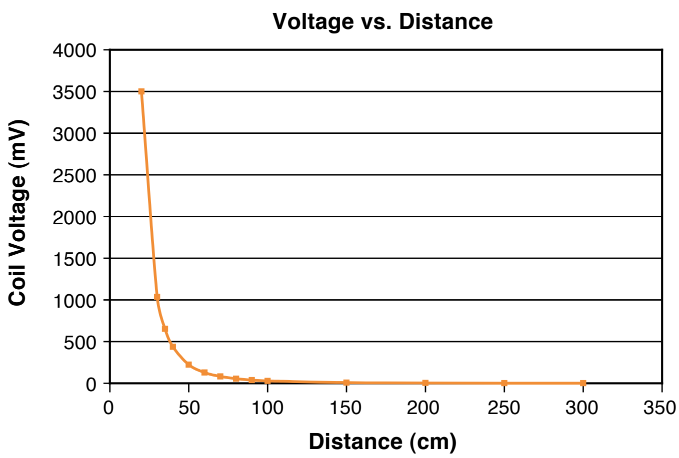

Figure 7. Coil Voltage versus Distance

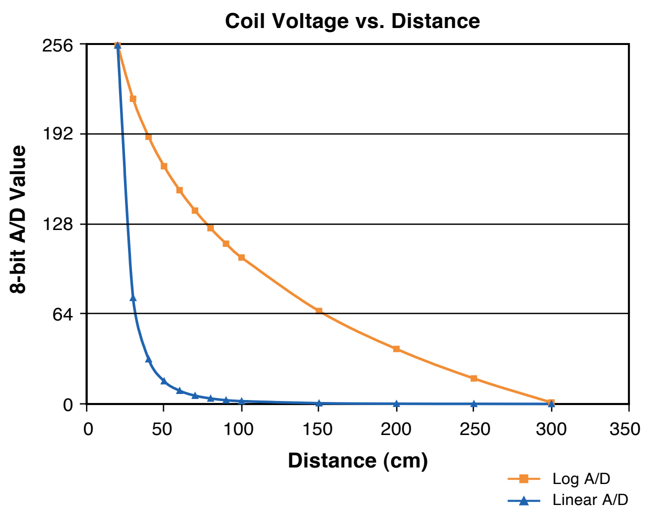

Figure 8. Log and Linear A/D Value versus Distance

For greater detail on the relationship between positional precision and proximity of key fob to the vehicle-mounted antenna, please refer to figure 9.

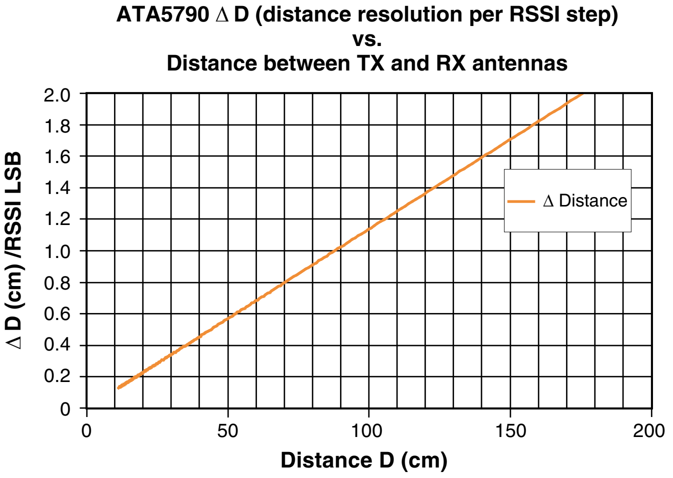

Figure 9. Accuracy of Distance Measurement versus Coil Distance

Summary

The process of obtaining PKE position information that is both accurate and precise is not a trivial effort. This paper explored the many factors that affect response time, accuracy and repeatability, and why they must be considered during the design process. Fortunately, electronic solutions exist today that integrate and enable the implementation of the principles described in this article. One such solution is the Atmel ATA5790, an embedded AVR microcontroller including complete LF functionality for PEG keys. Please visit www.atmel.com for more information.