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(54) Title: REDUCING FALSE WAKE-UP IN A LOW FREQUENCY TRANSPONDER

(57) Abstract: A bidirectional remote wake-up keyless entry (RKE) transponder comprises an analog front-end (AFE) having a programmable wake-up filter that predetermines the waveform timing of the desired input signal, minimum modulation depth requirement of input signal, and independently controllable channel gain reduction of each of its three channels, X, Y, and Z. The wake-up filter parameters are the length of high and low durations of wake-up pulses that may be programmed in a configuration register. The wake-up filter allows the AFE to output demodulated data if the input signal meets its wake-up filter requirement, but does not output the demodulated data otherwise. The AFE output pin is typically connected to an external device for control, such as a microcontroller (MCU). The external device typically stays in low current sleep (or standby) mode when the AFE has no output and switches to high current wake-up (or active) mode when the AFE has output. Therefore, in order to keep the external control device in the low current sleep mode when there is no desired input signal, it is necessary to keep no output at the AFE output pin. This can be achieved by controlling the wake-up filter parameters, minimum modulation depth requirement of input signal, and channel gains of the AFE device. These features can reduce false-wake-up of the bidirectional RKE transponder due to undesired input signals such as noise signals.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.
REducing False Wake-Up in a Low Frequency Transponder

Field of the Invention

The present invention relates generally to inductively coupled magnetic field transmission and detection systems, such as remote keyless entry (RKE) and passive keyless entry (PKE) systems, and more particularly to an apparatus and method for reducing false wake-up in such systems.

Background of the Invention Technology

In recent years, the use of remote keyless entry (RKE) systems for automotive and security applications have increased significantly. The conventional remote keyless entry (RKE) system consists of a RKE transmitter and a base station. The RKE transmitter has activation buttons. When an activation button is pressed, the RKE transmitter transmits a corresponding radio frequency data to the base station. The base station receives the data and performs appropriate actions such as unlock/lock car doors or trunks if the received data is valid. In the conventional RKE systems, the data is transmitted from the RKE transmitter to the base station, but not from the base station to the transmitter. This is often called unidirectional communication.

Much more sophisticated RKE systems can be made by using a bidirectional communication method. The bidirectional remote keyless entry system consists of a transponder and a base station. The transponder and base station can communicate by themselves without human interface buttons. The base station sends a command to the transponder and the transponder can respond to the base station accordingly if the command is valid. By utilizing the bidirectional communication method, one can unlock/lock his/her car doors or trunks remotely without pressing any buttons. Therefore, a fully hands-free access to the room or car is now possible.

The bidirectional communication RKE system consists of base station and transponder. The base station can send and receive low frequency command/data, and
also can receive VHF/UHF/Microwave signals. The transponder can detect the low
frequency (LF) data and transmit data to the base station via low frequency or
VHF/UHF/Microwave. In applications, the bidirectional transponder may have the
activation buttons as optional, but can be used without any activation button, for example,
to unlock/lock car doors, trunks, etc.

For a reliable hands-free operation of the transponder that can operate without
human interface, the transponder must be intelligent enough on decision making for
detecting input signals correctly and managing its operating power properly for longer
battery life. The idea in this application describes the dynamic configuration of the
transponder, that can reconfigure the transponder’s feature sets any time during
applications, to communicate with the base station intelligently by itself in the hand-free
operation environment.

Referring to Figure 1, depicted is a prior art passive remote keyless entry (RKE)
system. These wireless RKE systems typically are comprised of a base station 102,
which is normally placed in the vehicle in automobile applications, or in the home or
office in security entrance applications, and one or more RKE transponders 104, e.g., key-
fobs, that communicate with the base station 102. The base station 102 may comprise a
radio frequency receiver 106, antenna 110 and, optionally, a low frequency
transmitter/reader 108 and associated antenna 112. The transponder 104 may comprise a
radio frequency transmitter 122, an encoder 124 coupled to the transmitter 122,
antenna 118 and, optionally, a low frequency transponder 126 and associated
antenna 120. The transmitter 122 may communicate with the receiver 106 by using very
high frequency (VHF) or ultra high frequency (UHF) radio signals 114 at distances up to
about 100 meters so as to locate a vehicle (not shown) containing the base station 102,
locking and locking doors of the vehicle, setting an alarm in the vehicle, etc. The encoder
124 may be used to encrypt the desired action for only the intended vehicle. Optionally,
the low frequency transponder 126 may be used for hands-free locking and unlocking
doors of a vehicle or building at close range, e.g., 1.5 meters or less over a magnetic field 116 that couples between the coils 112 and 120.

The RKE transponder 104 is typically housed in a small, easily carried key-fob (not shown) and the like. A very small internal battery is used to power the electronic circuits of the RKE transponder when in use. The duty cycle of the RKE transponder must, by necessity, be very low otherwise the small internal battery would be quickly drained. Therefore to conserve battery life, the RKE transponder 104 spends most of the time in a "sleep mode," only being awakened when a sufficiently strong magnetic field interrogation signal is detected. The RKE transponder will awaken when in a strong enough magnetic field at the expected operating frequency, and will respond only after being thus awakened and receiving a correct security code from the base station interrogator, or if a manually initiated "unlock" signal is requested by the user (e.g., unlock push button on key-fob).

This type of RKE system is prone to false wake-up, short battery life, unreliable operating range that is too dependant upon orientation of the key fob (not shown). Thus, it is necessary that the number of false "wake-ups" of the RKE transponder circuits be keep to a minimum. This is accomplished by using low frequency time varying magnetic fields to limit the interrogation range of the base station to the RKE transponder. The flux density of the magnetic field is known as "field intensity" and is what the magnetic sensor senses. The field intensity decreases as the cube of the distance from the source, i.e., 1/d^3. Therefore, the effective interrogation range of the magnetic field drops off quickly. Thus, walking through a shopping mall parking lot will not cause a RKE transponder to be constantly awakened. The RKE transponder will thereby be awakened only when within close proximity to the correct vehicle. The proximity distance necessary to wake up the RKE transponder is called the "read range." The VHF or UHF response transmission from the RKE transponder to the base station interrogator is effective at a much greater distance and at a lower transmission power level.
When magnetic flux lines cut a coil of wire, an electric current is generated, i.e., see Maxwell’s Equations for current flow in an electric conductor being cut by a magnetic field flux. Therefore the detected magnetic flux density will be proportional to the amount of current flowing in the pick-up coil.

In a closely coupled or near field noisy environment, however, a noise source, e.g., magnetic or electromagnetic, could cause the analog front-end and associated external control device to "wake-up" or remain "awake" and thus cause increased power consumption and thereby reduce battery life. An effective way of conserving battery power is to turn off, e.g., disconnect or put into a "sleep mode" the electronic circuits of the RKE device and any associated circuitry not required in detecting the presence of an electromagnetic RF signal (interrogation challenge) from the keyless entry system reader. Only when the interrogation signal is detected, are the electronic circuits of the RKE device reconnected to the battery power source (wake-up). A problem exists, however, when the transponder receiver is exposed to noise sources such as electromagnetic radiation (EMR) emanating from, for example, televisions and computer monitors having substantially the same frequency as the interrogation signal, the RKE device will wake-up unnecessarily. If the RKE transponder receiver is exposed to a continuous noise source, the battery may be depleted within a few days.

Therefore, there is a need for preventing or substantially reducing false "wake-up" of the RKE transponder.

**SUMMARY OF THE INVENTION**

The present invention overcomes the above-identified problems as well as other shortcomings and deficiencies of existing technologies by providing an apparatus, system and method for reducing false "wake-up" of a remote keyless entry (RKE) transponder, thereby decreasing wasted power consumption and increasing battery operating time.

In an exemplary embodiment, according to the present invention, a RKE transponder comprises an analog front-end (AFE) having a plurality of radio frequency
channels, e.g., channels X, Y and Z (more or fewer channels are contemplated and within the scope of the invention) whose amplification (gain) may be independently controllable and programmed for each of the channels. An external control device, e.g., digital processor, microcontroller, microprocessor, digital signal processor, application specific integrated circuit (ASIC), programmable logic array (PLA) and the like, may control the sensitivity of each of the plurality of channels having excess noise that may cause false wake-up of the RKE transponder.

The programmable controllable gain for each of the plurality of channels may be used to desensitize an individual channel during noisy channel conditions, otherwise the channel noise source may cause the AFE and external control device to remain awake, causing increased power consumption and thus reducing battery operating time. For example, an undesirable noise source may cause a false wake-up of a RKE transponder when the RKE transponder, e.g., key fob, is placed proximate to a computer or other noise source that may generate signal pulses at frequencies to which the RKE transponder is tuned.

The external control device may dynamically configure the gain for each of plurality of channels through, for example a serial communications interface, e.g., \( I^2C \), CAN, SPI (Serial Peripheral Interface) and the like. Each of the plurality of channels may have an associated sensitivity adjustment control register in which the desired gain of the associated channel is programmed by the external control device through the serial interface. Thus, the digital controller may dynamically program each channel's gain as is appropriate in a noisy environment so as to reduce the time in which the external control device and other power drawing circuits are enabled (awake). The gain of each channel may be independently reduced by, for example, -30 dB.

Dynamic gain configuration for each of the plurality of channels of the AFE may also be used to improve communications with the base station by rejecting a noisy signal condition on a particular channel. For example, when a noise source is interfering with a channel, it could possibly swamp the channel and prevent normal communications from
occurring on the other channels because the RKE transponder automatic gain control (AGC), generally, tracks the strongest channel signal. The external control device can recognize this condition using a noise alarm function, more fully described herein, to reduce the sensitivity of the noise corrupted channel so as to allow desired communications on the other channel(s).

The external control device may also be used to dynamically change the channel sensitivity of the AFE so as to limit the RKE transponder range, e.g., when determining whether the RKE key fob is outside or inside of an automobile.

Control of each channel's sensitivity may be used to improve the balance of the plurality of channels in a RKE transponder so as to compensate for signal strength variations between the individual channel coils and parasitic effects that may be under user control.

A feature of the embodiments of the invention is software control differentiation between a strong signal and a weak signal such that the RKE system only communicates when a desired signal to noise ratio is present. In a noisy environment where a constant level noise source is present, it may be difficult to achieve good reception for communications purposes. The noise source may cause wake-up of power consuming functions but not be able to properly communicate. By insuring that only a strong enough signal, e.g., enough to activate the AGC, can wake-up the RKE system, unnecessary power consumption will be reduce.

Communications from a base station consists of a string of amplitude modulated signal pulses that are demodulated by the RKE device to produce a binary (off and on) data stream to be decoded by the external control device. If the amplitude modulation depth (difference between the strength of the signal carrier when "on" to the strength of the noise when the signal carrier is "off") is too weak (low), the demodulation circuit may not be able to distinguish a signal level high ("on") from a signal level low ("off"). A higher modulation depth results in a higher detection sensitivity. However, there is an advantage to having an adjustable detection sensitivity, depending upon an application.
and the signal conditions. Detection sensitivity may be controlled by setting the minimum modulation depth requirement for an incoming signal. Thus, decoding of an incoming signal may be based upon the strength of the signal to noise ratio.

According to a specific exemplary embodiment, a particular minimum modulation depth requirement may be selected, e.g., 12 percent, 25 percent, 50 percent, 75 percent, etc. The incoming signal then must have a modulation depth (signal + noise) / noise greater than the selected modulation depth greater than the selected modulation depth before the incoming signal is detected (circuits in wake-up power consuming mode). The minimum modulation depth requirement may be programmed (stored) in a configuration register, and may be reprogrammed at any time via an SPI command from the external control device.

A technical advantage of the present invention is substantially eliminating false wake-up from unwanted noise that unnecessarily uses power and thus reduces battery life. Another technical advantage is maintaining communications on the other channel(s) when a channel is unusable because of unwanted noise. Still another technical advantage is using a noise alarm function to reduce power consumption and maintain communications. Another technical advantage is differentiating between a strong signal and a weak signal so that only a strong signal will wake-up the power consuming circuits. Yet another technical advantage is configuring minimum modulation depth requirements before enabling decoding of an incoming signal. Another technical advantage is dynamically programming gain for each channel, signal strength necessary for activation, and/or configuration of minimum modulation depth requirements with an external control device and storing these programmed parameters in configuration registers. Other technical advantages should be apparent to one of ordinary skill in the art in view of what has been disclosed herein.
**BRIEF DESCRIPTION OF THE DRAWINGS**

A more complete understanding of the present disclosure and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying drawings wherein:

Figure 1 is a schematic block diagram of a prior art remote keyless entry system;
Figure 2 is a schematic block diagram of an exemplary embodiment of a remote keyless entry system, according to the present invention;
Figure 3 is a schematic block diagram of the analog front-end (AFE) shown in Figure 2;
Figure 4 is a schematic block diagram of a exemplary channel of the three channels, detector, wake-up filter and demodulator shown in Figure 3;
Figure 5 is a schematic timing diagram of an exemplary wake-up sequence;
Figure 6 is a schematic waveform diagram of the wake-up timing sequence shown in Figure 5;
Figure 7 is a table showing exemplary wake-up filter timing parameter selections;
Figure 8 is an exemplary flow diagram of determining whether a received signal meets the wake-up filter requirements;
Figure 9 is an exemplary state diagram for operation of the wake-up filter.
Figure 10 is a schematic signal level diagram of minimum modulation depth requirement examples, according to the present invention;
Figure 11 is a table showing options for minimum modulation depth requirements and examples thereof;
Figure 12 is an exemplary SPI timing diagram;
Figure 13 is an exemplary table showing the bit organization of the of configuration registers; and
Figure 14 is an exemplary table of SPI commands to the AFE transponder circuits and configuration registers thereof.
The present invention may be susceptible to various modifications and alternative forms. Specific embodiments of the present invention are shown by way of example in the drawings and are described herein in detail. It should be understood, however, that the description set forth herein of specific embodiments is not intended to limit the present invention to the particular forms disclosed. Rather, all modifications, alternatives, and equivalents falling within the spirit and scope of the invention as defined by the appended claims are intended to be covered.

**Detailed Description of Specific Embodiments**

Referring now to the drawings, the details of exemplary embodiments of the present invention are schematically illustrated. Like elements in the drawing will be represented by like numbers, and similar elements will be represented by like numbers with a different lower case letter suffix.

Referring to Figure 2, depicted is a schematic block diagram of an exemplary embodiment of a remote keyless entry (RKE) system, according to the present invention. The RKE system, generally represented by the numeral 200, comprises a base station 202, which is normally placed in the vehicle in automobile applications, or in the home or office in security entrance applications, and one or more RKE transponders 204, e.g., keyfobs, that communicate with the base station 202. The base station 202 may comprise a radio frequency receiver 206, antenna 210, and a low frequency transmitter/reader 208 and associated antenna 212. The transponder 204 may comprise a radio frequency transmitter 222, antenna 218, a low frequency analog front-end (AFE) 228, low frequency antennas 220a, 220b and 220c, and an external control device 224 coupled to the transmitter 222 and AFE 228.

The transmitter 222 may communicate with the receiver 206 by using very high frequency (VHF) or ultra high frequency (UHF) radio signals 214 at distances up to about 100 meters so as to locate a vehicle (not shown) containing the base station 202, unlocking and locking doors of the vehicle, setting an alarm in the vehicle, etc. The
external control device 224 may encrypt the transmitting data to the base station. The low frequency AFE 228 may be used for hands-free locking and unlocking doors of a vehicle or building at close range, e.g., 1.5 meters or less over a magnetic field 216 that couples between coil 212, and coils 220a, 220b and/or 220c.

The RKE transponder 204 is typically housed in a small, easily carried key-fob (not shown) and the like. A very small internal battery may be used to power the electronic circuits of the RKE transponder 204 when in use (wake-up condition). The turn-on time (active time) of the RKE transponder 204 must, by necessity, be very short otherwise the small internal battery would be quickly drained. Therefore to conserve battery life, the RKE transponder 204 spends most of the time in a "sleep mode," only being awakened when a sufficiently strong magnetic field interrogation signal having a correct wake-up filter pattern is detected or an action button is pressed. The RKE transponder 204 will awaken when in the strong enough magnetic field 216 (above a sensitivity level), and with a correct wake-up filter pattern that matches the programmed values in the configuration register. Then the RKE transponder 204 will respond only after being thus awakened and receiving a correct command code from the base station interrogator, or if a manually initiated "unlock" signal is requested by the user (e.g., unlock push button on key-fob).

The base station 202 acts as an interrogator sending a command signal within a magnetic field 216, which can be identified by a RKE transponder 204. The RKE transponder 204 acts as a responder in two different ways: (1) the RKE transponder 204 sends its code to the base station 202 by UHF transmitter 222, or (2) the LF talk-back by clamping and unclamping of the LC antenna voltage. The base station 202 generates a time varying magnetic field at a certain frequency, e.g., 125 kHz. When the RKE transponder 204 is within a sufficiently strong enough magnetic field 216 generated by the base station 202, the RKE transponder 204 will respond if it recognizes its code, and if the base station 202 receives a correct response (data) from the RKE transponder 204, the door will unlock or perform predefined actions, e.g., turn on lights, control actuators,
etc. Thus, the RKE transponder 204 is adapted to sense in a magnetic field 216, a time varying amplitude magnetically coupled signal at a certain frequency. The magnetically coupled signal carries coded information (amplitude modulation of the magnetic field), which if the coded information matches what the RKE transponder 204 is expecting, will cause the RKE transponder 204 to communicate back to the base station via the low frequency (LF) magnetic field 216, or via UHF radio link.

The flux density of the magnetic field is known as "magnetic field intensity" and is what the magnetic sensor (e.g., LC resonant antenna) senses. The field intensity decreases as the cube of the distance from the source, i.e., $1/d^3$. Therefore, the effective interrogation range of the magnetic field drops off quickly. Thus, walking through a shopping mall parking lot will not cause a RKE transponder to be constantly awakened. The RKE transponder will thereby be awakened only when within close proximity to the correct vehicle. The proximity distance necessary to wake up the RKE transponder is called the "read range." The VHF or UHF response transmission from the RKE transponder to the base station interrogator is effective at a much greater distance and at a lower transmission power level.

The read range is critical to acceptable operation of a RKE system and is normally the limiting factor in the distance at which the RKE transponder will awaken and decode the time varying magnetic field interrogation signal. It is desirable to have as long of a read range as possible. A longer read range may be obtained by developing the highest voltage possible on any one or more of the antenna (220a, 220b and/or 220c). Maximum coil voltage is obtained when the base station coil 212 and any RKE transponder coil 220 are placed face to face, i.e., maximum magnetic coupling between them. Since the position of the RKE transponder 204 can be random, the chance of having a transponder coil 220 face to face with the base station coil 212 is not very good if the transponder 204 has only one coil 220 (only one best magnetic coil orientation). Therefore, exemplary specific embodiments of the present invention use three antennas (e.g., 220a, 220b and 220c) with the RKE transponder 204. These three antennas 220a, 220b and 220c may be
placed in orthogonal directions (e.g., X, Y and Z) during fabrication of the RKE transponder 204. Thus, there is a much better chance that at least one of the three antennas 220a, 220b and 220c will be in substantially a “face-to-face” orientation with the base station coil 212 at any given time. As a result the signal detection range of the RKE transponder 204 is maximized thereby maximizing the read (operating) range of the RKE system 200.

In addition to a minimum distance required for the read range of the RKE key-fob 204, all possible orientations of the RKE key-fob 204 must be functional within this read range since the RKE key-fob 204 may be in any three-dimensional (X, Y, Z) position in relation to the magnetic sending coil 212 of the interrogator base station 208. To facilitate this three-dimensional functionality, X, Y and Z coils 220a, 220b and 220c, respectively, are coupled to the AFE 228, which comprises three channels of electronic amplifiers and associated circuits. Each of the three channels is amplified and coupled to a detector (Figure 3) which detects the signals received from the X, Y and Z antennas 220a, 220b and 220c, respectively.

Referring to Figure 3, depicted is a schematic block diagram of the analog front-end (AFE) 228 shown in Figure 2. The AFE 228 contains three analog-input channels and comprises amplifiers for these three channels, e.g., X, Y, Z. Each of these channels comprise radio frequency amplitude limiting, antenna tuning, sensitivity control, automatic gain controlled amplifier, and a detector. Each channel has internal tuning capacitance, sensitivity control, an input signal strength limiter, and automatic gain controlled amplifiers. The output of each channel is OR’d and fed into a demodulator. The demodulator output is fed into a wake-up filter, and available at the LF DATA pin if the data matches the programmed wake-up filter pattern. The demodulator contains a signal rectifier, low-pass filter and peak detector.

The detectors are coupled to a summer for combining the outputs of the three detectors. A wake-up filter, configuration registers and a command decoder/controller are also included in the AFE 228. X, Y and Z antennas 220a, 220b and 220c are coupled
to the LCX, LCY and LCZ inputs, respectively, and one end of each of these antennas may be coupled to a common pin, LCCOM/Vpp pin.

The AFE 228 in combination with the X, Y and Z antennas 220a, 220b and 220c may be used for three-dimensional signal detection. Typical operating frequencies may be from about 100 kHz to 400 kHz. The AFE 228 may operate on other frequencies and is contemplated herein. Bi-directional non-contact operation for all three channels are contemplated herein. The strongest signal may be tracked and/or the signals received on the X, Y and Z antennas 220a, 220b and 220c may be combined, OR'd. A serial interface may be provided for communications with the external control device 224. Internal trimming capacitance may be used to independently tune each of the X, Y and Z antennas 220a, 220b and 220c. The wake-up filter may be configurable. Each channel has its own amplifier for sensitive signal detection. Each channel may have selectable sensitivity control. Each channel may be independently disabled or enabled. Each detector may have configurable minimum modulation depth requirement control for input signal.

Device options may be set through configuration registers and a column parity bit register, e.g., seven 9-bit registers. These registers may be programmed via SPI (Serial Protocol Interface) commands from the external control device 224 (Figure 2).

The following are signal and pin-out descriptions for the specific exemplary embodiment depicted in Figure 3. One having ordinary skill in the art of electronics and having the benefit of this disclosure could implement other combinations of signals and pin-outs that would be within the spirit and scope of the present invention.

VDDT: AFE positive power supply connection.

VSST: AFE ground connection.

LCX: External LC interface pin in the X direction. This pin allows bi-directional communication over a LC resonant circuit.
LCY: External LC interface pin in the Y direction. This pin allows bi-directional communication over a LC resonant circuit.

LCZ: External LC interface pin in the Z direction. This pin allows bi-directional communication over a LC resonant circuit.

LCCOM: Common pin for LCX, LCY and LCZ antenna connection. Also used for test-mode supply input (Vpp).

LFDATA/CCLK/RSSI/SDIO: This is a multi-output pin that may be selected by the configuration register. LFDATA provides the combined digital output from the three demodulators. The SDI is the SPI digital input, when $\overline{CS}$ is pulled low. The SDO is the SPI digital output when performing a SPI read function of register data. RSSI is the receiver signal strength indicator output.

SCLK/ALERT: SCLK is the digital clock input for SPI communication. If this pin is not being used for SPI ($\overline{CS}$ pin is high) the $\overline{ALERT}$ open collector output indicates if a parity error occurred or if an ALARM timer time-out occurred.

$\overline{CS}$: Channel Select pin for SPI communications. The pin input is the SPI chip select-pulled low by the external control device to begin SPI communication, and raised to high to terminate the SPI communication.

Referring to Figure 4, depicted is a schematic block diagram of a exemplary channel of the three channels, detector, wake-up filter and demodulator shown in Figure 3. The following are functional descriptions for the specific exemplary embodiment
depicted in Figure 4. One having ordinary skill in the art of electronics and having the benefit of this disclosure could implement other combinations of signals and pin-outs that would be within the spirit and scope of the present invention.

RF LIMITER: Limits LC pin input voltage by de-Q'ing the attached LC resonant circuit. The absolute voltage limit is defined by the silicon process’s maximum allowed input voltage. The limiter begins de-Q'ing the external LC antenna when the input voltage exceeds $V_{DEQ}$, progressively de-Q’ing harder to ensure the antenna input voltage does not exceed the pin’s maximum input voltage, and also to limit the voltage range acceptable to the internal AGC circuit.

MODULATION FET: Used to “short” the LC pin to LCCOM, for LF talk-back purposes. The modulation FET is activated when the AFE receives the “Clamp On” SPI command, and is deactivated when the AFE receives the “Clamp Off” SPI command.

ANTENNA TUNING: Each input channel has 63 pF (1 pF resolution) of tunable capacitance connected from the LC pin to LCCOM. The tunable capacitance may be used to fine-tune the resonant frequency of the external LC antenna.

VARIABLE ATTENUATOR: Attenuates the input signal voltage as controlled by the AGC amplifier. The purpose of the attenuation is to regulate the maximum signal voltage going into the demodulator.

PROGRAMMABLE ATTENUATOR: The programmable attenuator is controlled by the channel’s configuration
register sensitivity setting. The attenuator may be used to desensitize the channel from optimum desired signal wake-up.

AGC (Automatic Gain Control): AGC controls the variable attenuator to limit the maximum signal voltage into the demodulator. The signal levels from all 3 channels may be combined such that the AGC attenuates all 3 channels uniformly in respect to the channel with the strongest signal.

FGA (Fixed Gain Amplifiers): FGA1 and FGA2 may provide a two-stage gain of about 40 dB.

DETECTOR: The detector senses the incoming signal to wake-up the AFE. The output of the detector switches digitally at the signal carrier frequency. The carrier detector is shut off following wake-up if the demodulator output is selected.

DEMODULATOR: The demodulator consists of a full-wave rectifier, low pass filter, and peak detector that demodulates incoming amplitude modulation signals.

WAKE-UP FILTER: The wake-up filter enables the LFDATA output once the incoming signal meets the wake-up sequence requirements.

DATA SLICER: The data slicer compares the input with the reference voltage. The reference voltage comes from the modulation depth setting and peak voltage.

Referring now to both Figure 3 and Figure 4, the AFE 228 may have an internal 32 kHz oscillator. The oscillator may be used in several timers: inactivity timer, alarm timer, pulse width timer - wake-up filter high and low, and period timer - wake-up filter.
The 32 kHz oscillator preferably is low power, and may comprise an adjustable resistor-capacitor (RC) oscillator circuit. Other types of low power oscillators may be used and are contemplated herein.

The inactivity timer may be used to automatically return the AFE 228 to standby mode by issuing a soft reset if there is no input signal before the inactivity timer expires. This is called "inactivity time out" or TINACT. The inactivity timer may be used is to minimize AFE 238 current draw by automatically returning the AFE 228 to the lower current standby mode if a spurious signal wakes the AFE 228, doing so without waking the higher power draw external control device 224. The inactivity time may be reset when: receiving a low frequency (LF) signal, CS pin is low (any SPI command), or a timer-related soft reset. The inactivity time may start when there is no LF signal detected. The inactivity time may cause a AFE 228 soft reset when a previously received LF signal is absent for TINACT. The soft reset may return the AFE 228 to standby mode where the AGC, demodulator, RC oscillator and such are powered-down. This may return the AFE 228 to the lower standby current mode.

The alarm timer may be used to notify the external control device 224 that the AFE 228 is receiving a LF signal that does not pass the wake-up filter requirement - keeping the AFE 228 in a higher than standby current draw state. The purpose of the alarm timer is to minimize the AFE 228 current draw by allowing the external control device 224 to determine whether the AFE 228 is in the continuous presence of a noise source, and take appropriate actions to "ignore" the noise source, perhaps lowering the channel's sensitivity, disabling the channel, etc. If the noise source is ignored, the AFE 228 may return to a lower standby current draw state. The alarm timer may be reset when: CS pin is low (any SPI command), alarm timer-related soft reset, wake-up filter disabled, LFDATA pin enabled (signal passed wake-up filter). The alarm timer may start when receiving a LF signal. The alarm time may cause a low output on the ALERT pin when it receives an incorrect wake-up command, continuously or periodically, for about 32 ms. This is called "Alarm Time-out" or TALARM. If the LF signal is periodic and
contains an absence of signal for greater than TINACT, the inactivity timer time out will result in a soft reset - no ALERT indication may be issued.

Referring to Figures 5 and 6, Figure 5 depicts a schematic timing diagram of an exemplary wake-up sequence and Figure 6 depicts a schematic waveform diagram of the exemplary wake-up timing sequence shown in Figure 5. The pulse width (pulse time period) timer may be used to verify the received wake-up sequence meets both the minimum Wake-up High Time (TWAKH) and minimum Wake-up Low Time (TWAKL) requirements. The period timer may be used to verify the received wake-up sequence meets the maximum TWAKT requirement.

The configurable smart wake-up filter may be used to prevent the AFE 228 from waking up the external control device 224 due to unwanted input signals such as noise or incorrect base station commands. The LFDATA output is enabled and wakes the external control device 224 once a specific sequence of pulses on the LC input/detector circuit has been determined. The circuit compares a “header” (or called wake-up filter pattern) of the demodulated signal with a pre-configured pattern, and enables the demodulator output at the LFDATA pin when a match occurs. For example, The wake-up requirement consists of a minimum high duration of 100% LF signal (input envelope), followed by a minimum low duration of substantially zero percent of the LF signal. The selection of high and low duration times further implies a maximum time period. The requirement of wake-up high and low duration times may be determined by data stored in one of the configuration registers that may be programmed through the SPI interface. Figure 7 is a table showing exemplary wake-up filter timing parameter selections that may be programmed into a configuration register so that each RKE transponder will wake-up. The wake-up filter may be enabled or disabled. If the wake-up filter is disabled, the AFE 228 outputs whatever it has demodulated. Preferably, the wake-up filter is enabled so that the external device or microcontroller unit 224 will not wake-up by an undesired input signal.
While timing the wake-up sequence, the demodulator output is compared to the predefined wake-up parameters. Where:

 TWAKH is measured from the rising edge of the demodulator output to the first falling edge. The pulse width preferably falls within $TWAKH \leq t \leq TWAKT$.

 TWAKL is measured from the falling edge of the demodulator output to the first rising edge. The pulse width preferably falls within $TWAKL \leq t \leq TWAKT$.

 TWAKT is measured from rising edge to rising edge, i.e., the sum of TWAKH and TWAKL. The pulse width of TWAKH and TWAKL preferably is $t \leq TWAKT$.

The configurable smart wake-up filter may reset, thereby requiring a completely new successive wake-up high and low period to enable LFDATA output, under the following conditions:

 The received wake-up high is not greater than the configured minimum TWAKH value.

 The received wake-up low is not greater than the configured minimum TWAKL value.

 The received wake-up sequence exceeds the maximum TWAKT value:

 $TWAKH + TWAKL > TWAKT$; or $TWAKH > TWAKT$; or $TWAKL > TWAKT$

 Soft Reset SPI command is received.

If the filter resets due to a long high ($TWAKH > TWAKT$), the high pulse timer may not begin timing again until after a low to high transition on the demodulator output.
Referring to Figure 8, depicted is an exemplary flow diagram of determining whether a received signal meets the wake-up filter requirements. In step 802, the wake-up filter is in an inactive state. Step 804 checks for a LF input signal and when a LF input signal is present, step 810 sets the AGC active status bit if the AGC is on. The step 812 sets the input channel receiving status bit for channel X, Y and/or Z. Step 806 checks if the LF input signal is absent for longer than 16 milliseconds. If so, step 808 will do a soft reset and return to step 804 to continue checking for the presence of a LF input signal.

In step 806, if the LF input signal is not absent for longer than 16 milliseconds then step 814 determines whether to enable the wake-up filter. If the wake-up filter is enabled in step 814, then step 816 determines whether the incoming LF signal meets the wake-up filter requirement. If so, step 818 makes the detected output available on the LFDATA pin and the external control device 224 is awakened by the LFDATA output. Step 820 determines whether the data from the LFDATA pin is correct and if so, in step 822 a response is send back via either the LF talk back or by a UHF radio frequency link.

In step 816, if the incoming LF signal does not meet the wake-up filter requirement then step 824 determines whether the received incorrect wake-up command (or signal) continue for longer than 32 milliseconds. If not, then step 816 repeats determining whether the incoming LF signal meets the wake-up filter requirement. In step 824, if the received incorrect wake-up command continues for longer than 32 milliseconds then step 826 sets an alert output and step 816 continues to determine whether the incoming LF signal meets the wake-up filter requirement. Referring to Figure 9, depicted is an exemplary state diagram for operation of the wake-up filter.

Referring back to Figure 3, the AFE 228 may provide independent sensitivity control for each of the three channels. The sensitivity control may be adjusted at any time of operation by programming the AFE 228 configuration registers. Sensitivity control may set in a one of the configuration registers for each channel, and may provide a sensitivity reduction, for example, from about 0 dB to about -30 dB. Each channel may
have its own sensitivity control from about 0 dB to about -30 dB by programming one of the configuration registers.

Each channel can be individually enabled or disabled by programming the configuration registers in the analog front-end device (AFE) 228. If the channel is enabled, all circuits in the channel become active. If the channel is disabled, all circuits in the disabled channel are inactive. Therefore, there is no output from the disabled channel. The disabled channel draws less battery current than the enabled channel does. Therefore, if one channel is enabled while other two channels are disabled, the device consumes less operating power than when more than one channel is enabled. There are conditions that the device may perform better or save unnecessary operating current by disabling a particular channel during operation rather than enabled. All three channels may be enabled in the default mode when the device is powered-up initially or from a power-on reset condition. The external device or microcontroller unit 224 may program the AFE 228 configuration registers to disable or enable individual channels if necessary any time during operation.

The AFE 228 may provide independent enable/disable configuration of any of the three channels. The input enable/disable control may be adjusted at any time for each channel, e.g., through firmware control of an external device. Current draw may be minimized by powering down as much circuitry as possible, e.g., disabling an inactive input channel. When an input channel is disabled, amplifiers, detector, full-wave rectifier, data slicer, comparator, and modulation FET of this channel may be disabled. Minimally, the RF input limiter should remain active to protect the silicon from excessive input voltages from the antenna.

Each antenna 220 may be independently tuned in steps of 1 pF, from about 0 pF to 63 pF. The tuning capacitance may be added to the external parallel LC antenna circuit.

The automatic gain controlled (AGC) amplifier may automatically amplify input signal voltage levels to an acceptable level for the demodulator. The AGC may be fast attack and slow release, thereby the AGC tracks the carrier signal level and not the
amplitude modulated data bits on the carrier signal. The AGC amplifier preferably tracks
the strongest of the three input signals at the antennas. The AGC power is turned off to
minimize current draw when the SPI Soft Reset command is received or after an
inactivity timer time out. Once powered on, the AGC amplifier requires a minimum
stabilization time (TSTAB) upon receiving input signal to stabilize.

Referring to Figure 10, depicted is a schematic signal level diagram of modulation
depth examples, according to the present invention. Configurable minimum modulation
depth requirement for input signal defines what minimum percentage an incoming signal
level must decrease from its amplitude peak to be detected as a data low.

The AGC amplifier will attempt to regulate a channel’s peak signal voltage into
the data slicer to a desired VAGCREG - reducing the input path’s gain as the signal level
attempts to increase above VAGCREG, and allowing full amplification on signal levels
below VAGCREG.

The data slicer detects signal levels above VTHRESH, where VTHRESH < VAGCREG.
VTHRESH effectively varies with the configured minimum modulation depth requirement
configuration. If the minimum modulation depth requirement is configured to 50%,
VTHRESH = 1/2 VAGCREG, signal levels from 50% to 100% below the peak (VAGCREG)
will be considered as data low.

Only when the signal level is of sufficient amplitude that the resulting amplified
signal level into the data slicer meets or exceeds VAGCREG, will the AFE 228 be able to
guarantee the signal meets the minimum modulation depth requirement. The minimum
modulation depth requirements are not met when signal levels into the data slicer exceed
VTHRESH, but are less than VAGCREG.

If the SSTR bit is set in the configuration register 5 as shown in Figure 13, the
demodulated output is inhibited unless the input level is greater than the AGC threshold
level, which may be approximately about 15 millivolts peak-to-peak. This will produce
detection of only signals have higher signal to noise ratios, resulting in less false wake-up,
but at a loss in sensitivity determined by the minimum modulation depth requirement setting. The trade-off is between sensitivity and signal to noise ratio.

The present invention is capable of low current modes. The AFE 228 is in a low current sleep mode when, for example, the digital SPI interface sends a Sleep command to place the AFE 228 into an ultra low current mode. All but the minimum circuitry required to retain register memory and SPI capability will be powered down to minimize the AFE 228 current draw. Any command other than the Sleep command or Power-On Reset will wake the AFE 228. The AFE 228 is in low current standby mode when substantially no LF signal is present on the antenna inputs but the device is powered and ready to receive. The AFE 228 is in low-current operating mode when a LF signal is present on an LF antenna input and internal circuitry is switching with the received data.

The AFE 228 may utilize volatile registers to store configuration bytes. Preferably, the configuration registers require some form of error detection to ensure the current configuration is uncorrupted by electrical incident. The configuration registers default to known values after a Power-On-Reset. The configuration bytes may then be loaded as appropriate from the external control device 224 via the SPI digital interface. The configuration registers may retain their values typically down to 1.5V, less than the reset value of the external control device 224 and the Power-On-Reset threshold of the AFE 228. Preferably, the external control device 224 will reset on electrical incidents that could corrupt the configuration memory of the AFE 228. However, by implementing row and column parity that checks for corruption by an electrical incident of the AFE 228 configuration registers, will alert the external control device 224 so that corrective action may be taken. Each configuration byte may be protected by a row parity bit, calculated over the eight configuration bits.

The configuration memory map may also include a column parity byte, with each bit being calculated over the respective column of configuration bits. Parity may be odd (or even). The parity bit set/cleared makes an odd number of set bits, such that when a Power-On-Reset occurs and the configuration memory is clear, a parity error will be
generated, indicating to the external control device 224 that the configuration has been altered and needs to be re-loaded. The AFE 228 may continuously check the row and column parity on the configuration memory map. If a parity error occurs, the AFE 228 may lower the SCLK/ALERT pin (interrupting the external control device 224) indicating the configuration memory has been corrupted/unloaded and needs to be reprogrammed. Parity errors do not interrupt the AFE 228 operation, but rather indicate that the contents in the configuration registers may be corrupted or parity bit is programmed incorrectly.

Antenna input protection may be used to prevent excessive voltage into the antenna inputs (LCX, LCY and LCZ of Figure 3). RF limiter circuits at each LC input pin begin resistively de-Q'ing the attached external LC antenna when the input voltage exceeds the threshold voltage, \( V_{DE.Q} \). The limiter de-Q'es harder, proportional to an increasing input voltage, to ensure the pin does not exceed the maximum allowed silicon input voltage, \( V_{ILC} \), and also to limit an input signal to a range acceptable to the internal AGC amplifier.

LF talk back may be achieved by de-Q'ing the antennas 220 with a modulation field effect transistor (MOD FET) so as to modulate data onto the antenna voltage, induced from the base station/transponder reader (not shown). The modulation data may be from the external control device 224 via the digital SPI interface as “Clamp On,” “Clamp Off” commands. The modulation circuit may comprise low resistive NMOS transistors that connect the three LC inputs to LCCOM. Preferably the MOD FET should turn on slowly (perhaps 100 ns ramp) to protect against potential high switching currents. When the modulation transistor turns on, its low turn-on resistance (\( R_m \)) damps the induced LC antenna voltage. The antenna voltage is minimized when the MOD FET turns-on and is maximized when the MOD FET turns-off. The MOD FET’s low turn-on resistance (\( R_m \)) results in a high modulation depth.

Power-On-Reset (not shown) may remain in a reset state until a sufficient supply voltage is available. The power-on-reset releases when the supply voltage is sufficient for
correct operation, nominally VPOR. The configuration registers may all be cleared on a Power-On-Reset. As the configuration registers are protected by row and column parity, the ALERT pin will be pulled down - indicating to the external control device 224 that the configuration register memory is cleared and requires loading.

The LFDATA digital output may be configured to either pass the demodulator output, the carrier clock input, or receiver signal strength indicator (RSSI) output. The demodulator output will normally be used as it consists of the modulated data bits, recovered from the amplitude modulated (AM) carrier envelope. The carrier clock output is available on the LFDATA pin if the carrier clock output is selected by the configuration setting. The carrier clock signal may be output at its raw speed or slowed down by a factor of four using the carrier clock divide-by configuration. Depending on the number of inputs simultaneously receiving signal and the phase difference between the signals, the resulting carrier clock output may not be a clean square wave representation of the carrier signal. If selected, the carrier clock output is enabled once the preamble counter is passed. When the LFDATA digital output is configured to output the signal at the demodulator input, this carrier clock representation may be output actual speed (divided by 1) or slowed down (divide by 4). If the Received Signal Strength Indicator (RSSI) is selected, the device outputs a current signal that is proportional to the input signal amplitude.

Referring to Figure 12, depicted is an exemplary SPI timing diagram. The SPI interface may utilize three signals: active low Chip Select (CS), clock (SCK) and serial data (SDIO). The SPI may be used may be used by the external control device 224 for writing to and reading from the configuration registers and controlling the circuits of the AFE 228.

Referring to Figure 13, depicted is an exemplary table showing the bit organization of the configuration registers. As depicted each configuration register has nine bits, however, it is contemplated and within the scope of the invention that the configuration registers may have more or less than nine bits. Bit 0 of each register may
be row parity for that register. All registers except register 7 may be readable and re-writable. Register 6 may be the column parity bit register, wherein each bit of the register 6 may be the parity bit of the combination of bits, arranged per column, of the corresponding registers. Register 7 may be a status register of circuit activities of the AFE 228, and may be read only. For example, the status register 7 may indicate which channel caused an output to wake-up the AFE 228, indication of AGC circuit activity, indication of whether the "Alert Output Low" is due to a parity error or noise alarm timer, etc.

Figure 14 is an exemplary table of SPI commands to the AFE transponder circuits and configuration registers thereof.

The present invention has been described in terms of specific exemplary embodiments. In accordance with the present invention, the parameters for a system may be varied, typically with a design engineer specifying and selecting them for the desired application. Further, it is contemplated that other embodiments, which may be devised readily by persons of ordinary skill in the art based on the teachings set forth herein, may be within the scope of the invention, which is defined by the appended claims. The present invention may be modified and practiced in different but equivalent manners that will be apparent to those skilled in the art and having the benefit of the teachings set forth herein.
CLAIMS

1. A method for reducing false wake-up of a multi-channel remote keyless entry (RKE) transponder, said method comprising the steps of:
   receiving a signal with a multi-channel analog front-end (AFE) of a remote keyless entry (RKE) transponder; and
   determining whether the received signal meets a predefined criteria, wherein if the received signal does not meet the predefined criteria then change the gain of any of channel receiving the signal so that the signal will not wake-up other power consuming portions of the RKE transponder.

2. The method according to claim 1, wherein the predefined criteria is met when the received signal is substantially on for a predefined on period and substantially off for an alarm time-out period.

3. The method according to claim 2, further comprising the step of starting a noise alarm timer upon receiving the signal, wherein the noise alarm timer determines the alarm timeout period.

4. The method according to claim 1, wherein the predefined criteria is determined with a smart wake-up filter.

5. The method according to claim 1, wherein the predefined criteria is determined with a digital discrimination filter.

6. The method according to claim 1, further comprising the step of waking-up an external control device for accepting signal data when the received signal meets the predefined criteria.

7. The method according to claim 1, wherein the gain of the channel is dynamically adjusted.
8. The method according to claim 2, wherein the alarm timeout period is determined from an AFE internal oscillator frequency.

9. The method according to claim 2, further comprising the step of disabling each channel of the AFE which receives a signal that does not meet the predefined criteria.

10. The method according to claim 2, further comprising the step of disabling each channel of the AFE which receives a signal that does not meet the predefined criteria within the alarm timeout period.

11. The method according to claim 1, wherein the received signal is at a frequency from about 100 kHz to about 400 kHz.

12. The method according to claim 1, wherein the received signal is at a frequency of about 125 kHz.

13. The method according to claim 1, wherein the multi-channel AFE comprises three channels.

14. A method for reducing false wake-up of a remote keyless entry (RKE) transponder, said method comprising the steps of:

   receiving an amplitude modulated (AM) signal with an analog front-end (AFE) of a remote keyless entry (RKE) transponder; and

   determining whether the received AM signal meets a minimum modulation depth requirement, wherein

   if the received AM signal meets the minimum modulation depth requirement then the received AM signal is detected, and

   if the received AM signal does not meet the minimum modulation depth requirement then the received AM signal is not detected.
15. The method according to claim 14, wherein the minimum modulation depth requirement is greater than or equal to 12 percent modulation depth.

16. The method according to claim 14, wherein the minimum modulation depth requirement is greater than or equal to 25 percent modulation depth.

17. The method according to claim 14, wherein the minimum modulation depth requirement is greater than or equal to 50 percent modulation depth.

18. The method according to claim 14, wherein the minimum modulation depth requirement is greater than or equal to 75 percent modulation depth.

19. The method according to claim 14, further comprising the step of storing the minimum modulation depth requirement into a minimum modulation depth requirement configuration register.

20. The method according to claim 19, further comprising the step of programming the minimum modulation depth requirement in the minimum modulation depth requirement configuration register with an external control device.

21. The method according to claim 20, wherein the step of programming the minimum modulation depth requirement in the minimum modulation depth requirement configuration register is done through a SPI (Serial Peripheral Interface).

22. The method according to claim 14, further comprising the step of dynamically programming the minimum modulation depth requirement into a minimum modulation depth configuration register.

23. The method according to claim 22, wherein the step of dynamically programming the minimum modulation depth requirement into a minimum modulation depth configuration register is done with an external control device.
24. The method according to claim 14, further comprising the step of waking-up certain power consuming portions of the RKE transponder when the AM signal is being decoded.

25. A multi-channel remote keyless entry (RKE) transponder having reduced false wake-up, comprising:
   a multi-channel analog front-end (AFE), wherein each channel of the multi-channel AFE has programmably controllable gain; and
   a signal correlation circuit for determining whether a signal received by each channel of the AFE meets a predefined criteria, wherein if the signal on any channel does not meet the predefined criteria then that channel's gain is reduced or disabled so that the signal that does not meet the predefined criteria will not wake-up other power consuming portions of the RKE transponder.

26. The RKE transponder according to claim 25, wherein a gain value for the programmably controllable gain of each channel of the plurality of channels is stored in a programmable configuration register.

27. The RKE transponder according to claim 25, wherein each channel of the plurality of channels is independently enabled or disabled depending upon respective configuration bits in a programmable configuration register.

28. The RKE transponder according to claim 25, wherein each channel of the multi-channel AFE comprises an amplifier and a signal detector.

29. The RKE transponder according to claim 25, wherein the signal correlation circuit is a smart wake-up filter for determining whether the received signal meets the predefined criteria.
30. The RKE transponder according to claim 25, wherein the signal correlation circuit is a digital discrimination filter for determining whether the received signal meets the predefined criteria.

31. The RKE transponder according to claim 25, further comprising a external control device.

32. The RKE transponder according to claim 31, wherein the gain of each channel of the multi-channel AFE is dynamically adjusted by the external control device.

33. The RKE transponder according to claim 31, wherein the external control device is selected from the group consisting of a digital processor, microcontroller, microprocessor, digital signal processor, application specific integrated circuit (ASIC) and programmable logic array (PLA).

34. The RKE transponder according to claim 25, wherein the multi-channel AFE comprises three signal input channels.

35. The RKE transponder according to claim 25, wherein the multi-channel AFE receives signals at about 125 kHz.

36. The RKE transponder according to claim 25, wherein the multi-channel AFE is adapted to receive signals from about 100 kHz to about 400 kHz.

37. The RKE transponder according to claim 25, wherein the gain of each channel is adjusted so that the received signal from each channel is substantially balanced with each of the other channels.

38. The RKE transponder according to claim 25, wherein the gain of each channel of the multi-channel AFE is stored in a gain configuration register.

39. The RKE transponder according to claim 38, wherein the gain of each channel is programmed into the gain configuration register by an external control device.
40. A remote keyless entry (RKE) transponder having reduced false wake-up, comprising:
   an analog front-end (AFE); and
   an amplitude modulation (AM) depth detector circuit for determining
   whether an AM signal received by the AFE meets a minimum modulation depth
   requirement, wherein if the received AM signal meets the minimum modulation
   depth requirement then the received AM signal is detected, and if the received
   AM signal does not meet the minimum modulation depth requirement then the
   received AM signal is not detected.

41. The RKE transponder according to claim 40, wherein the minimum
    modulation depth requirement is greater than or equal to 12 percent modulation depth.

42. The RKE transponder according to claim 40, wherein the minimum
    modulation depth requirement is greater than or equal to 25 percent modulation depth.

43. The RKE transponder according to claim 40, wherein the minimum
    modulation depth requirement is greater than or equal to 50 percent modulation depth.

44. The RKE transponder according to claim 40, wherein the minimum
    modulation depth requirement is greater than or equal to 75 percent modulation depth.

45. The RKE transponder according to claim 40, further comprising a
    modulation depth configuration register for storing the minimum modulation depth
    requirement.

46. The RKE transponder according to claim 45, further comprising an
    external control device, wherein the external control device programs the minimum
    modulation depth requirement into the modulation depth configuration register.
47. The RKE transponder according to claim 40, wherein certain power consuming portions of the RKE transponder wake-up only when the AM signal is being decoded.

48. The RKE transponder according to claim 40, wherein the AFE further comprises a plurality of input channels and the AM depth circuit determines whether an AM signal received by each of the plurality of input channels meets a minimum modulation depth requirement, wherein if the received AM signal meets the minimum modulation depth requirement then the received AM signal is detected, and if the received AM signal does not meet the minimum modulation depth requirement then the received AM signal is not detected.

49. The RKE transponder according to claim 48, wherein a gain value for the programmably controllable gain of each channel of the plurality of channels is stored in a programmable configuration register.

50. The RKE transponder according to claim 48, wherein each channel of the plurality of channels is independently enabled or disabled depending upon respective configuration bits in a programmable configuration register.

51. The RKE transponder according to claim 48, wherein the plurality of input channels are three channels.

52. The RKE transponder according to claim 48, wherein the minimum modulation depth requirement applies equally for the plurality of input channels.

53. The RKE transponder according to claim 52, wherein the minimum modulation depth requirement for the plurality of input channels is stored in a minimum modulation depth requirement configuration register.
54. The RKE transponder according to claim 53, wherein the minimum modulation depth requirement configuration register is dynamically programmable with the minimum modulation depth requirement.
Figure 1 (Prior Art)
Figure 2
Figure 3
Figure 4
Figure 5

Required Output Enable Sequence (Programmable)

\[ t \geq TWAKH \quad t \geq TWAKL \quad t \leq TWAKT \]

Where \( t \) = total time period = \( TWAKH + TWAKL + \Delta t \)

Figure 6

Legend:
- TAGC = AGC stabilization time
- TE = Time element of pulse
- TPAGC = AGC stabilization gap
- TWAKH = Minimum output enable filter high time
- TWAKL = Minimum output enable filter low time
- TWAKT = Maximum output enable filter period
- TPAGC = High time after TAGC
- TSAB = TAGC - TPAGC
<table>
<thead>
<tr>
<th>WAKH</th>
<th>WAKL</th>
<th>TWAKH (ms)</th>
<th>TWAKL (ms)</th>
<th>TWAKT (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>00</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
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<td>01</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<td>4</td>
<td>10</td>
</tr>
<tr>
<td>00</td>
<td>XX</td>
<td>Filter Disabled</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7**
Figure 9
Figure 10

Modulation Depth = \frac{A - B}{A} \times 100%
### Figure 11

<table>
<thead>
<tr>
<th>Configuration 5</th>
<th>Min Modulation Depth Requirement</th>
<th>Signal level A</th>
<th>Signal level B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit 6 Bit 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 0</td>
<td>75%</td>
<td>10 mVpp</td>
<td>2.5 mVpp</td>
</tr>
<tr>
<td>0 1</td>
<td>50%</td>
<td>10 mVpp</td>
<td>5 mVpp</td>
</tr>
<tr>
<td>1 0</td>
<td>25%</td>
<td>10 mVpp</td>
<td>7.5 mVpp</td>
</tr>
<tr>
<td>1 1</td>
<td>12%</td>
<td>10 mVpp</td>
<td>8.8 mVpp</td>
</tr>
</tbody>
</table>

\[
\text{Mod } \% = \frac{A - B}{A} \times 100\%
\]
**Figure 12**

**Figure 13**
<table>
<thead>
<tr>
<th>Command</th>
<th>Address</th>
<th>Data</th>
<th>Row Parity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>XXXX</td>
<td>XXXX XXXX</td>
<td>X</td>
<td>Clamp on – enable modulation circuit</td>
</tr>
<tr>
<td>001</td>
<td>XXXX</td>
<td>XXXX XXXX</td>
<td>X</td>
<td>Clamp off – disable modulation circuit</td>
</tr>
<tr>
<td>010</td>
<td>XXXX</td>
<td>XXXX XXXX</td>
<td>X</td>
<td>Enter Sleep mode (any other command wakes the device)</td>
</tr>
<tr>
<td>011</td>
<td>XXXX</td>
<td>XXXX XXXX</td>
<td>X</td>
<td>AGC Preserve On – to temporarily preserve the current AGC level</td>
</tr>
<tr>
<td>100</td>
<td>XXXX</td>
<td>XXXX XXXX</td>
<td>X</td>
<td>AGC Preserve Off – AGC again tracks strongest input signal</td>
</tr>
<tr>
<td>101</td>
<td>XXXX</td>
<td>XXXX XXXX</td>
<td>X</td>
<td>Soft Reset – resets various circuit blocks</td>
</tr>
</tbody>
</table>

Read Command – Data will be read from the specified register address.

<table>
<thead>
<tr>
<th>Command</th>
<th>Address</th>
<th>Data</th>
<th>Row Parity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>Config Byte 0</td>
<td>P</td>
<td></td>
<td>General – options that may change during normal operations</td>
</tr>
<tr>
<td>0001</td>
<td>Config Byte 1</td>
<td>P</td>
<td></td>
<td>LCX antenna tuning and LFDATA output format</td>
</tr>
<tr>
<td>0010</td>
<td>Config Byte 2</td>
<td>P</td>
<td></td>
<td>LCY antenna tuning</td>
</tr>
<tr>
<td>0011</td>
<td>Config Byte 3</td>
<td>P</td>
<td></td>
<td>LCZ antenna tuning</td>
</tr>
<tr>
<td>0100</td>
<td>Config Byte 4</td>
<td>P</td>
<td></td>
<td>LCX and LCY sensitivity reduction</td>
</tr>
<tr>
<td>0101</td>
<td>Config Byte 5</td>
<td>P</td>
<td></td>
<td>LCZ sensitivity reduction and modulation depth</td>
</tr>
<tr>
<td>0110</td>
<td>Column Parity</td>
<td>P</td>
<td></td>
<td>Column parity byte for Config Byte 0 -&gt; Config Byte 5</td>
</tr>
<tr>
<td>0111</td>
<td>Device Status</td>
<td>X</td>
<td></td>
<td>Device status – parity error; which input is active, etc.</td>
</tr>
</tbody>
</table>

Write command – Data will be written to the specified register address.

<table>
<thead>
<tr>
<th>Command</th>
<th>Address</th>
<th>Data</th>
<th>Row Parity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>Config Byte 0</td>
<td>P</td>
<td></td>
<td>General – options that may change during normal operation</td>
</tr>
<tr>
<td>0001</td>
<td>Config Byte 1</td>
<td>P</td>
<td></td>
<td>LCX antenna tuning and LFDATA output format</td>
</tr>
<tr>
<td>0010</td>
<td>Config Byte 2</td>
<td>P</td>
<td></td>
<td>LCY antenna tuning</td>
</tr>
<tr>
<td>0011</td>
<td>Config Byte 3</td>
<td>P</td>
<td></td>
<td>LCZ antenna tuning</td>
</tr>
<tr>
<td>0100</td>
<td>Config Byte 4</td>
<td>P</td>
<td></td>
<td>LCX and LCY sensitivity reduction</td>
</tr>
<tr>
<td>0101</td>
<td>Config Byte 5</td>
<td>P</td>
<td></td>
<td>LCZ sensitivity reduction and modulation depth</td>
</tr>
<tr>
<td>0110</td>
<td>Column Parity</td>
<td>P</td>
<td></td>
<td>Column parity byte for Config Byte 0 -&gt; Config Byte 5</td>
</tr>
<tr>
<td>0111</td>
<td>Not Used</td>
<td>X</td>
<td></td>
<td>Register is readable, but not writable</td>
</tr>
</tbody>
</table>

Note: “P” denotes the row parity bit (odd parity) for the respective data byte.

Figure 14