Application Report
SWRA567B–June 2017–Revised March 2018

Wireless Smoke Alarms With SimpleLink™ Sub-1 GHz Wireless MCU

ABSTRACT

This application report discusses the main challenges related to wireless smoke alarm designs and how they are addressed by the SimpleLink Sub-1 GHz CC1310/CC1312 and multi-band CC1350/CC1352 wireless microcontrollers (MCUs). First, a short introduction is provided of what a smoke alarm is. Section 2 discusses the requirements from wireless technology to support the smoke alarm and other safety and security systems use cases, which validates Sub-1 GHz technology as an excellent fit. Section 3 explains how to build the system based on the CC13xx devices with focus on networking, low power, cloud connectivity and Sub-1 GHz/*Bluetooth*® low energy use-cases. It concludes with a test case describing a potential use case along with its state machine and power consumption analysis (see Section 4).

To get started immediately, visit the following:

- CC1310 product page
- CC1312 product page
- CC1350 product page
- CC1352 product page
- CC1310 LaunchPad™, CC1312 LaunchPad, CC1350 LaunchPad and CC1352 LaunchPad
- Sensor to Cloud
- CC1310 and CC1350 Software Development Kit (SDK)
- CC1312 and CC1352 Software Development Kit (SDK)

NOTE: This document refers to smoke alarms, but most of the wireless and system aspects are relevant for other types of fire alarms

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1 Introduction

Smoke alarms are key components in safety systems. Their main purpose is to detect a fire as soon as it starts by detecting the smoke and initiate the siren for immediate building evacuation. In many cases, fire alarms are part of a system that are also connected to the fire department. Studies done by the National Fire Protection Association (NFPA) indicate fires that happen in houses without smoke alarms or malfunctioning smoke alarms caused twice as many deaths than those in houses with an operating smoke alarm system.

Common fire detection techniques are based on the detection of smoke. There are two common techniques:

- Ionization smoke detectors – this technique uses a radioactive source (typically Americium 241) that emits particles into the air. When the particles collide with air molecules, positive and negative ions are created. The positive ions are attracted to the negatively charged electrode and the negative ions are attracted to the positively charged electrodes. As a result, there is a constant current between the two electrodes. In the presence of smoke, molecules are bigger and a smaller amount of charged ions are generated. Therefore, the electrical current is reduced and can be detected.
- Photoelectric smoke detector – this technique uses a LED that generates a beam of light. A photodiode is located inside the smoke chamber (typically not receiving the light directly). During the presence of smoke, light is reflected from the smoke particles and spreads to other directions. Some of it is received by the photodiode that generates a current that is detected by the detector.

Ionization smoke detectors detect fast flaming fire accurately thanks to the nature of the size of the particles they produce. Photoelectric smoke detectors detect slow smoldering fires better than ionization smoke detectors since it produces larger particles. Since it is very hard to predict the type of fire that might occur, it is advised that both techniques are used either in the same smoke alarm or in separate alarms that are deployed in close proximity.

Connected fire alarms are becoming common and standard around the globe. The connectivity allows the system to react faster. In large buildings, facilities, and residential households, the moment the first fire alarm triggers, the siren immediately begins to ring. It gives a warning and provides sufficient time to evacuate the facility before the fire has reached other places. A connected fire alarm is a requirement by safety regulations in most states and countries. Studies show that when interconnected smoke alarms exist, the tenants were more likely to know about the fire. Wireless connectivity smoke alarms simplify the installation and maintenance and reduce the cost compared to wire connected smoke alarms. Now there is no need to route wires in walls and ceilings or replace damaged wires. However, it introduces other challenges such as power consumption and wireless networking. This application report discusses those challenges in detail and shows how they are resolved using SimpleLink Sub-1 GHz CC13xx wireless MCUs.

2 Wireless Communication Technology

When considering a wireless technology for fire alarm system and other safety sensors, it is important that all of the system requirements are met by the technology selected. Some common system requirements include:

- Range – the system may be installed in houses, offices, facilities, or buildings. Therefore, the technology must support wide area coverage.
- Low power – for battery operated sensors, it is critical that the wireless technology will support the low-power connection. Changing batteries in smoke alarms is a hassle because they are mounted on the ceiling and require a ladder. Unlike hardwired smoke alarms where the battery is used mainly for backup, in wireless smoke alarms there are usually no power lines at all. Therefore, the battery lifetime is a crucial parameter.

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- Security – the wireless technology should provide protection against security attacks. When the safety network is also connected to the internet through the home Wi-Fi network, hackers might use a weakness in the safety system to attack other connected elements in the house such as the door lock.
- Robustness – the connection should be robust against interference, jammers and different RF conditions.
- Scalable – the wireless technology should be scalable so more devices can be added to the network.

Because of its excellent RF performance, its low power and its low cost, Sub-1 GHz wireless technology answers all of the above requirements and is widely used in fire alarms and other safety and security systems. RF signals in Sub-1 GHz frequency bands propagate well in the air, through walls and around corners. Therefore, it is easy to achieve a robust wireless signal coverage of an entire house, a large floor or a building. In addition, the technology enables low power and supports sleepy end nodes: battery operated end devices that are in their lowest power state most of the time and wakeup based on external triggers or timers to transmit and receive messages.

TI's SimpleLink Sub-1 GHz CC13xx wireless MCU provides long range and excellent RF performance that result in a robust connection. They industry lows in terms of power consumption and enable sensors to operate for many years on batteries. They also answer the security and scalability requirements mentioned above when using the 15.4 stack SDK. These qualities make this device the perfect fit for fire alarm systems.

3 Designing the System With Sub-1 GHz SimpleLink Wireless MCU

The low-power wireless MCU (CC1310/CC1312 or CC1350/CC1352) function as the main MCU of the system handling the sensing activities, sirens, LEDs, buttons controls and all of the networking communication activities. The smoke sensor can either be connected directly to the MCU ADC through an amplifier that converts current to voltage or it can be connected to a comparator and trigger the MCU using an interrupt. All SimpleLink Sub-1 GHz devices (CC13xx) have a large number of General-Purpose Input/Output (GPIO), Inter-Integrated Circuit (I2C), Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI) and other interfaces that may be required by the system. By choosing a wireless MCU vs a chipset of MCU and RF transceiver, the system can achieve lower power, integration, size and better cost benefits along with a quicker time to market. The accelerated design cycle is achieved by re-use of wireless protocols and examples that are part of the device SDK.

Figure 1 shows a block diagram of a photoelectric smoke alarm. The CC13xx controls the LED driver that initiates the light beam in the smoke chamber. The transimpedance amplifier (TIA) is connected to the photoelectric diode, which converts the current input to voltage and scales the signal to fit the dynamic range of the ADC. The output voltage is connected to the ADC of the CC13xx devices. The wireless MCU controls LEDs for indications (battery status, for example) buttons (test button for example) and the buzzer/siren circuit.

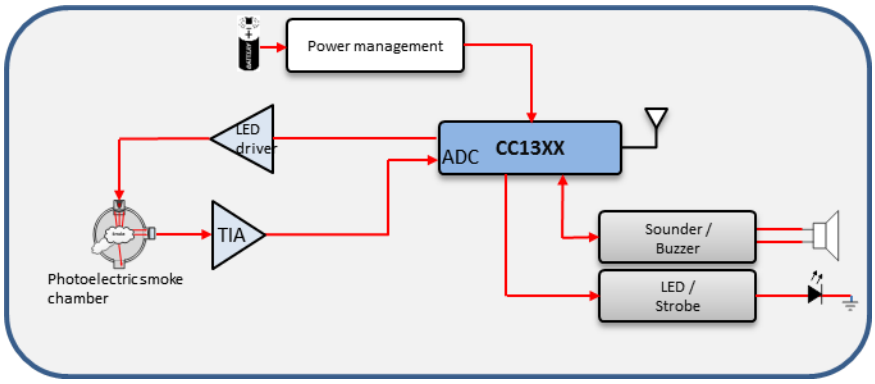

Figure 1. Photoelectric Smoke Alarm System Block Diagram

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3.1 Sub-1 GHz Network

3.1.1 Star Network

For systems that contain a panel, the typical network topology is a star network with sleepy-end nodes as illustrated in Figure 2. In the star network, there is one singular concentrator to which all other nodes are connected. Sleepy-end nodes mean the nodes that are connected to the concentrator are in their low-power state most of the time and wakeup to transmit their message periodically or based on an event that triggers such as when a threshold level that is crossed. The panel functions as the concentrator. Since the panel is powered by hard wires, it can always be on and active in receive mode. In those types of systems, the fire alarm nodes periodically transmit keep alive messages reporting their status and battery level. The panel responses to those keep alive messages with acknowledgment along with any downlink message. Such a message can indicate a fire that is detected by another fire alarm unit in order for all other units to sound their siren; it can be a silence command or indication of a new firmware version ready to be downloaded to the unit. The period in which the fire alarms send their keep alive message is a tradeoff between the response time of each unit to a fire that is detected by another unit and battery lifetime. It is an important parameter of the system and the typical value is 20 seconds.

The CC13xx SDK contains a 15.4 stack that provides a complete solution for the star network based on 802.15.4g standard including a frequency hopping mechanism and added security features. The security features encrypt the packets and mandate credentials for joining the network. It prevents attacks and eavesdropping to the system. The frequency hopping features also help to protect the system against attacks such as denial of service or RF jammers. In addition, it helps the robustness of the network if some of the channels are occupied with other networks. Frequency hopping is also required by FCC regulation in order to utilize higher transmission power. The 15.4 stack supports 50 kbps data rate mode and a long range mode of 5 kbps data rate. The 15.4 standards is based on an advanced CSMA/CA networking algorithm for maximum channel capacity and this algorithm implements a “listen before talk” mechanism to minimize the amount of collisions. Acknowledgments are part of the standard confirm successful transmission.

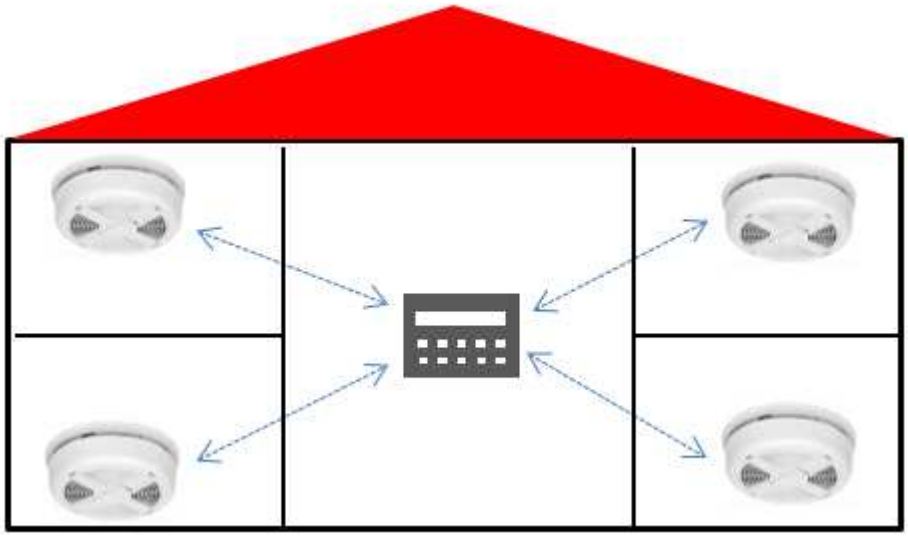

Figure 2. Star Network Smoke Alarm Network

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3.1.2 Other Network Options

For systems that do not have a specific unit that can be powered by hard wires, the traditional star network may not be the best solution. For example, a set of three wireless interconnected fire alarms that can be expanded later to a larger network. A network without a concentrator that is always on requires a different scheme. The basic concept for such a network is that fire alarm units only transmit relevant information such as detection of fire (no "keep alive" messages). Once a unit has a message to transmit it keeps re-transmitting it for a long time. All units wake up periodically and listen for incoming messages. Since every message is transmitted many times, the moment a unit wakes up for the listening period it receives the message. The maximum time it takes a message to reach a fire alarm unit depends on the listening period. On top of this basic concept, the network can have other units that echo the messages in the network for better area coverage in many configurations.

This kind of network or any other proprietary implementation can be easily designed with the CC13xx SDK. The SDK contains an easy way for proprietary RF implementation called Easylink. The Easylink layer exposes a simple set of APIs for controlling the RF. It comes with several simple examples of transmit and receive. This option gives the designer flexibility to build any network protocol. It is the preferred option if someone wants to use their own protocol for the fire alarm network system or they are developing a fire alarm that needs to connect to an existing system that is based on proprietary implementation. Figure 3 illustrates a proprietary fire alarm network.

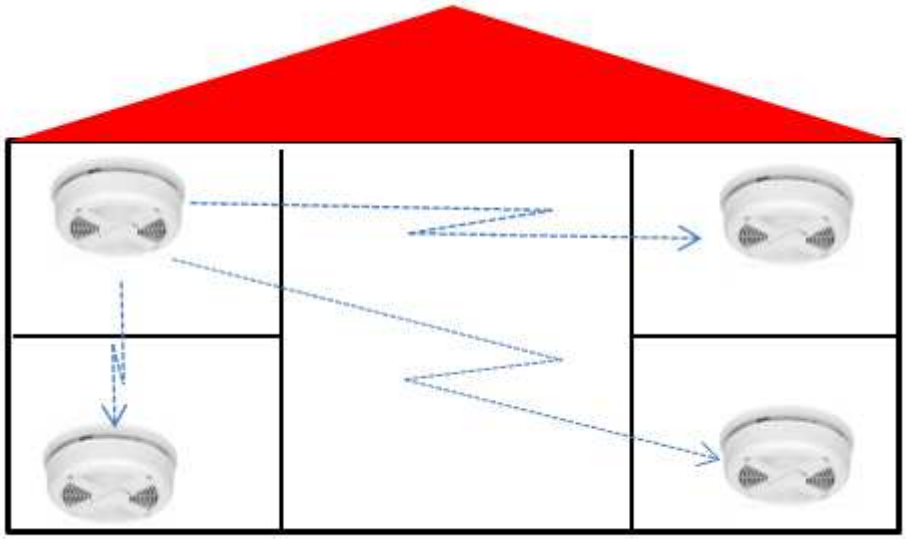

Figure 3. Proprietary Fire Alarm Network

3.2 Low Power for Battery Operated Fire Alarm

In order to achieve 10 years or more of operation out of battery, the system must be very low power. For example, when considering a battery that has 1500 mhA capacity, the average current consumption should be around 17 µA. Under a certain use-case (that is, period between two consecutive measurements, period of sending keep alive messages, and so forth) the energy consumed needs to be evaluated per each of the different activities, modes and phases of the product life cycle.

- Smoke measurement – the energy consumed when running a single smoke detection measurement. Contribution of the smoke measurement can be significant in case of a photoelectric smoke chamber where a LED has to be driven by the system. In that case, it will be active for short periods of time to take a reliable measurement in fixed intervals. In case of the ionization smoke chamber, the current consumption for taking a measurement is smaller.

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- Sending keep alive message – the energy consumed by the wireless MCU for sending a single message. Periodic messages are sent to ensure a proper operation of the system, report battery status, collect logs and data, and poll for incoming messages from a panel such as indication of fire detected by another smoke alarm or software upgrade. The energy consumed by a single event of sending a typical message and receiving an acknowledgment can have a significant implication on the overall lifetime and the period in which those messages are being sent has to be calculated carefully. When considering the energy consumed by the transmission of a message over the wireless medium, it is important to factor the success ratio of such a transmission. If 95% success ratio is assumed (due to collisions, for example) it can be assumed that there will be 5% of re-transmission and the energy budget has to be calculated accordingly.
- Siren – the energy consumed while the siren is on. Under assumption of worst case activity per month or year. The system need to be designed that when low battery indication is set, it can still operate for the time required by code and support emergency events. For example, once the battery level goes down, the battery low indication should be triggered while the battery can still support 7 days of operation while indicating the low battery sound and light and have enough energy for 4 minutes of siren.
- System setup – the energy consumed during initial system setup – depends on type of setup. Might be negligible
- Other activities during the lifetime of the product – The energy consumed by activities such as software update, reporting status, collecting and sending log to manufacture, and so forth.

SimpleLink Sub-1 GHz wireless MCUs provide industry low-power consumption because every component and element described above is optimized. Both the time of the activity and the current consumption during the activity are optimized. The MCU shutdown and standby currents are extremely low (0.185 µA/0.7 µA, respectively). In addition, it has low MIPS/MHz (51 µA/MHz) current consumption, making computation, decision making and housekeeping activities efficient as well. Finally, the RX mode (5.4 mA), and TX mode (13.4 mA @10 dbm) along with optimized and fast transition time between the modes contributes to reduced overall current consumption.

In addition to the power modes and low current consumption of specific activities, the CC13xx devices are equipped with a unique sensor controller engine. This additional small micro controlling unit is extremely low power and is able to operate while the rest of the device is in low-power mode. For on-going activities like controlling the sensors, waiting for interrupt or even simple computation and decision making, this unit can be used. For example, the sensor controller can monitor the ADC and capture an ADC sample every second at average current consumption of 0.95 µA.

Figure 4 illustrates the current profile of a panel connected fire alarm system use case. Smoke measurement is taken in short intervals and controlled by the sensor controller. The keep alive transmission and acknowledge reception is done in longer intervals and controlled by the main MCU.

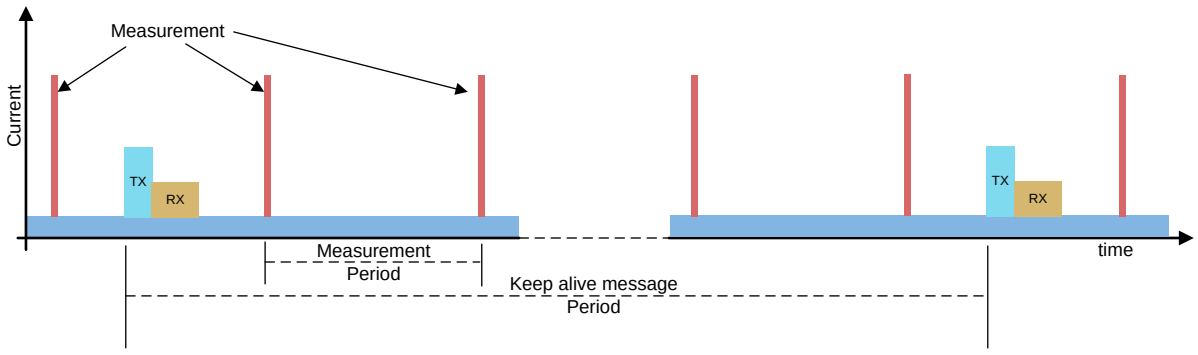

Figure 4. Illustrated Power Profile for Photoelectric Smoke Alarm

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3.3 Cloud Connected Fire Alarm System

Security and safety systems benefit from cloud connectivity. It gives them the ability to dispatch the security company or fire department when necessary. Cloud connectivity also gives the home owner the ability to monitor and control their system remotely. It enables automatic software updates to the panel and to the end nodes for fixing bugs and adding functionality.

Sub-1 GHz technology requires a gateway in order to connect to the internet. The gateway buffers and translates the messages in the Sub-1 GHz network into Ethernet packets and communicates with the internet over Ethernet or Wi-Fi interfaces. TI's Sensor to Cloud reference design provides an end-to-end system for RTOS or Linux connecting Sub-1 GHz end nodes to the cloud over Wi-Fi or Ethernet. This solution provides two-way communication: sensors report to the cloud and the cloud sends commands and controls to the sensors.

3.4 Sub-1 GHz and Bluetooth low energy Dual-Mode Systems

CC1350 and CC1352 devices support both Sub-1 GHz and Bluetooth low energy technologies as part of the SimpleLink MCU platform. The addition of Bluetooth low energy to smoke alarms enables advanced features and use-cases that enhance user experience. Bluetooth low energy technology adds a native user interface to the smoke alarm units. It is currently the easiest wireless technology to connect a device to a phone or tablet. Imagine a simple phone app that can control any function of the smoke alarm with the tip of the finger. Settings like network ID, sensitivity levels or regulatory constraints should no longer need to be programmed in the factory or using jumpers in the back of the unit. The following sections describe some of the more advanced use-cases that can be implemented with the addition of Bluetooth low energy technology to the typical fire alarm in residential or commercial installations.

3.4.1 System Setup

Using the smart phone and mobile application, the system can be configured in an easy way and receive status updates. During the system setup, the phone connects to each fire alarm and transmits network properties and security credentials for the Sub-1 GHz network over Bluetooth low energy. Once the network configuration is complete the fire alarm switches to Sub-1 GHz mode and connects to the Sub-1 GHz network. The phone interface can be used to configure many other aspects of the fire alarm. For example, a user can name fire alarms so the system can notify the location of the fire when it starts. Other parameters of installations such as height can be used in advanced systems to set thresholds. For systems that do not contain a centralized panel with user interface, the addition of Bluetooth low energy can add even more value. It allows interaction with the system that does not have any other user interface except typically a single LED and a single button.

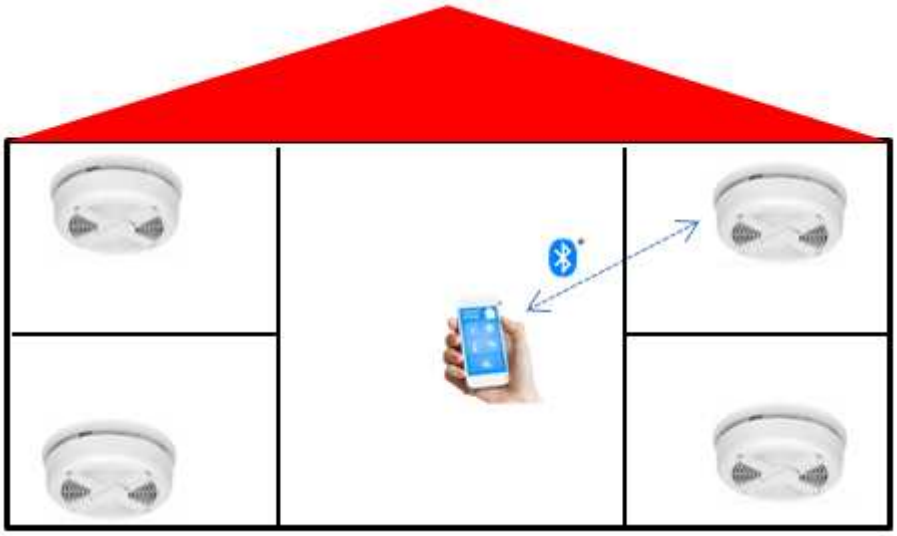

Figure 5. Bluetooth low energy Connection to Smoke Alarm

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3.4.2 Testing, Control and Monitoring

Fire alarms have to be tested periodically. Many alarms are mounted high on the ceiling where it is very hard to reach. With Bluetooth low energy technology, it is easy to enable tests and get test results. In case of false detections, the siren can be disabled using the Bluetooth low energy connection. Battery status and network connection problems can all be monitored using the Bluetooth low energy interface on the smartphone.

3.4.3 Software Updates

With a Bluetooth low energy connection to a mobile application, it is easy to push software updates directly to the smoke alarms, reassuring you that the system is up-to-date and bug free. Just release an update, push it to the mobile app users and they will get a notification to upgrade their system.

3.4.4 Alert Broadcast

Apart from Bluetooth low energy connection mode. This standard provides a connectionless feature called Bluetooth low energy beacons or Bluetooth low energy advertisement. It allows Bluetooth low energy enabled smoke alarms to transmit broadcast messages that are received by a nearby phone without initiation of a connection. When a fire is detected using this feature, the smoke alarm does not only enable the siren but also sends Bluetooth low energy beacons. Those beacons that are captured by the phone can notify hearing impaired people. It can also provide emergency information such as an escape route.

4 Test-Case

This section analyzes the use-cases, state machine and power consumption of a wireless smoke alarm system in star topology.

Consider a smoke alarm system with a photoelectric chamber similar to the one presented in Figure 1. The smoke alarm is connected to a concentrator that can be either a security panel or other smoke alarm in the system that is defined as the concentrator.

There are two tasks that are happening in steady state periodically:

- Taking a smoke measurement
- Sending keep alive messages and receiving an ACK or other message back from the concentrator

The system default timer for taking a measurement is 10 sec. Measurement process is taken by enabling the TIA amplifier and letting it settle. Once it is settled, the LED driver is enabled and the ADC inside the CC13xx starts to capture voltage at the TIA output. The sensor controller compares the ADC readings to pre-defined thresholds. In steady-state mode, the system is transmitting a keep alive message every 20 sec. The purpose of these messages is to let the concentrator know that the sensor is functional and give it the opportunity to send commands back to the end node. One message in particular is notifying the end node that a fire was detected by another sensor. A 20 sec period is the worst case latency for getting a message to any smoke alarm in the system. There are two thresholds that the measurement result can cross: high threshold indicates a fire and low threshold indicates that the smoke level is higher than usual. If low threshold is crossed but not high threshold, the system changes the measurement time interval from 10 sec to 1 sec and the keep alive time interval from 20 sec to 5 sec. High threshold indicates a fire; the system starts the siren, transmits continuous indications to the concentrator and transmits Bluetooth low energy beacons indicating the fire. When the fire alarm receives a message indicating that a fire is detected by another unit, the fire alarm system starts the siren, sends the Bluetooth low energy beacons, runs continuous smoke measurements and reports to concentrator.

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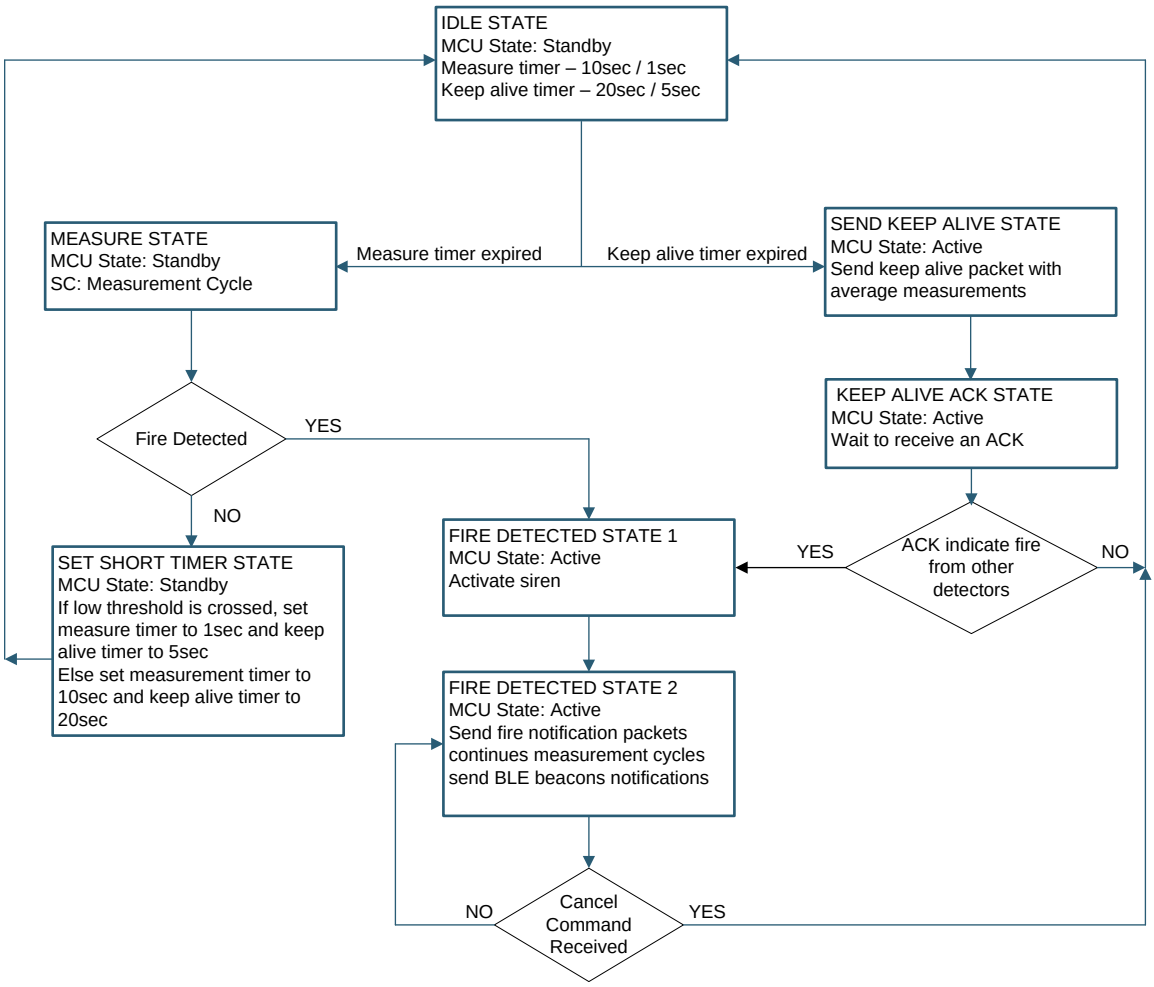

Figure 6. Test-Case State Machine

The following assumptions are taken:

- Low threshold is crossed few times a day due to cooking or steaming. Timers are set for short time interval for accumulated 30 minutes per day.
- Fire event contribution to lifetime power calculation is negligible since it is very rare scenario.
- Max TX retry is 3 – after three unsuccessful consecutive transmissions, the smoke alarm will indicate (by LED) that it lost the network. It will keep trying in the next keep alive interval or if a fire is detected. The probability for the single packet to be unsuccessful is 5%.
- System is based on TI 15.4 stack at 50 kbps with security and frequency hopping.
- Battery – Lithium Ion battery of 1500 mAh and derating factor of 85%.
- Standby power consumption – 0.6 µA
- Smoke measurement power consumption is 200 mA for 100 µsec dictated by the photoelectric LED.
- Sending packets of 20B message (overall message including headers and preamble is 54B). Current is 13.4 mA for 10.5 ms and 10 dBm.
- Receiving packet of ACK and command takes 10.5 ms at 5.5 mA

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According to the power analysis in Table 1, there is over 10 years of battery lifetime.

Table 1. Test Case Power Analysis

Factor	Calculation
Number of measurements per day: 23.5 hours every 10 sec ; 30 min every 1 sec	23.5 * 60 * 6 + 30 * 60 = 10260
Number of keep alive transmissions and ACKs per day 23.5 hours every 20 sec ; 30 min every 5 sec	23.5 * 60 * 3 + 30 * 12 = 4590
Charge consumed during one measurement	200 mA * 0.1 msec = 20 µC
Charge consumed during one transmission cycle	10.5 ms * 13.4 mA + 10.5 ms * 5.5 mA = 198.45 µC
Total charge of measurement per day	10260 * 20 µC = 205.2 mC
Total charge of transmission cycles per day including 5% retransmission	4590 * 198.45 µC * 1.05 = 956 mC
Total charge of standby mode per day	0.6 µA * 24 * 60 * 60 = 51.8 mC
Total Charge per day	205.2 mC + 956 mC + 51.8 mC = 1213 mC/Day
Average current	$\frac{1213\ mC\ /\ Day}{86400\ sec\ /\ Day} = 0.014\ mA = 14\ \mu A$
Battery capacity	1500 mAh = 5400C
Lifetime	$\frac{5400C * 0.85}{1213 mC\ /\ Day} = 3784\ Days = 10.3\ years$

5 Summary

This application report discussed the main challenges related to the wireless smoke alarm system design. The benefits of interconnected smoke alarm systems over unconnected smoke alarm units was explained, specifically, the benefits of wireless interconnected smoke alarm systems over hard wire connected systems. Sub-1 GHz technology is a good choice for the wireless smoke alarm end equipment thanks to its superior RF characteristics. The SimpleLink Sub-1 GHz CC1310 and CC1350 wireless MCU devices enable integrated smoke alarms with robust RF communication, low power for long battery life and advanced networking options. Two types of network options were discussed in detail for two types of wireless smoke alarm systems. Low power aspects and challenges were explored including a test case demonstrated battery lifetime calculation.

6 References

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- *Humidity and Temperature Sensor Node for Sub-1GHz Star Networks Design Guide*
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- *Bringing Wireless Scalability to Intelligent Sensing Applications*
- *Always-on Low-power Gas Sensing with 10+ Year Coin Cell Battery Life Reference Design*
- *Piezo Speaker Strobe Notification Reference Design*

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from A Revision (February 2018) to B Revision	Page
• Update was made in the Abstract.	1

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