The Anatomy of an IoT Sensor: Key Elements and Design Considerations

By Ben Garcia, Manager – IoT Sensors

Introduction

Sensors, and their ability to simplify our lives by understanding our world and turning that data into some kind of action, make up the backbone of the Internet of Things (IoT). Modern sensors come in virtually every shape and size, and chances are you have several devices within arm's reach right now that utilize at least one integrated sensor. Fundamentally speaking, a sensor's job is to take input such as light, temperature, or pressure and use that data to respond in an appropriate way. For example, a thermostat turns on the heater when the room temperature drops below a designated threshold. Sensors are far from new; the thermostat has been in use for nearly 140 years, after all. But with the proliferation of connected devices, network-connected sensors have unleashed a technology revolution and elevated their place in our lives from convenient to necessary. They make our homes more comfortable, our cars safer, our coffee timely, and our business more efficient.

Smart sensors are finding way into virtually every corner of business, and the most common types of IoT sensors being developed today include:

Proximity Sensors	Proximity sensors emit beams of infrared light and are used for non-contact detection of objects.
Pressure Sensors	Pressure sensors can recognize changes in liquids or gases. As pressure changes, the sensor can let the system know the status or trigger an alert.
Humidity Sensors	Humidity sensors measure the amount of water vapor in the atmosphere and are common in both residential and industrial HVAC systems.
Temperature Sensors	These sensors measure temperature changes and convert fluctuations into data to direct an action, such as turning on the fan in a piece of machinery that is overheating.
Optical Sensors	Optical sensors convert light into electrical signals and are common in the personal electronic devices we use as well as our smart doorbells and other household IoT products.
Infrared Sensors	Infrared sensors can measure the heat produced by an object and are common in a wide range of industries, from medical devices to military applications.
Gas Sensors	Gas sensors monitor changes in air quality, including the presence of toxic, combustible, or hazardous gasses. The carbon monoxide detectors in our homes utilize gas sensors.
Gyroscope	Gyroscopes measure the angular rate or velocity, often defined as a measurement of speed and rotation around an axis.
Accelerometers	Accelerometers detect the rate of change of velocity over time, including changes to gravity.
Level Sensors	Level sensors are used to detect the level of substances including liquids, powders, and grains.

In this whitepaper, we'll take a step-by-step look at the components of a sensor and discuss the role each plays in the development, including its impact on performance. We'll also explore some of the specific challenges and priorities a designer should consider when starting any sensor design project.

The Anatomy of a Smart Sensor

A battery-powered sensor requires a **printed circuit board** (PCB), which will have an impact on many of the components that make up the sensor including antennas and RF functionality. We won't spend too much time discussing PCBs, but it's important not to underestimate its role in sensor performance.

The **battery** is another key element in sensor design because it has to supply the energy needed, while having enough capacity to let the design remain in service for the requisite number of years. The battery also dictates the size requirements for the device. In a perfect world, increasing performance requirements or longevity could be addressed simply by using a larger battery. But this isn't very practical considering consumers are demanding smaller products by the day. A door or a window sensor, for example, wouldn't be very useful or appealing if it had to be built around a D cell battery; even the bulkiness of AA or AAA batteries is problematic for consumers. One of the trends we're seeing is that while devices are getting smaller, battery life is *actually increasing*.

The next important component in a battery-powered sensor is the wireless **system on a chip** (SoC).
It is critical to optimize an SoC to:

- Receive sensitivity
- Transmit power
- Have the right amount of processor speed
- Have enough flash and ram to implement the protocol

You also need the **sensing elements** that perform the functions the sensor is being designed for in the first place. The next important component is the **software** that runs on the sensor, which has the job of managing all the other components and drives the communication in and out of the sensor.

Finally, the last component will be the **enclosure.** The form factor and size of the enclosure is influenced by the size of the batteries. It will also impact RF performance -- certain plastics and even the dyes used in the coloring of those plastics can have properties that affect RF transmission into and out of the device.

Comparing Common Battery Options for Sensor Development

The table in Figure 1 below compares some of the battery choices developers have when building a connected sensor. As you can see, the CR123A lithium has a voltage of 3.0, making it suitable for a single battery to power a low voltage circuit. This option also has a relatively large capacity, along with a large volume. The second battery listed is a slightly smaller lithium CR2, which has the same 3-volt nominal voltage, with a somewhat lower capacity and smaller size. The third type is a CR2032 lithium coin cell battery, which is the smallest on the list and ideally suited for reducing sensor size.

Battery Type	Nominal Voltage (V)	Capacity (mAhr)	Volume (cm³)	Nominal IR (ohms)	Operating Temperature Range	Max. Pulse Load (mA)
Lithium CR123A	3.0	1500	7.0	Low	-40°C to 60°C	3500
Lithium CR2	3.0	800	5.2	Low	-40°C to 60°C	2500
Lithium CR2032	3.0	235	1.0	5-20	-20°C to 60°C	50
Alkaline AA	1.5	2850	8.1	0.2	-20°C to 54°C	>750
Alkaline AAA	1.5	1200	3.8	0.2	-20°C to 54°C	>750

Figure 1: Comparing common battery choices for smart sensor development

The last two battery types, the alkaline AA and the alkaline AAA, both have sizeable capacity but are large in size compared to the CR2032 coin cell. These batteries only produce 1.5 volts, meaning that two are needed to produce the same three volts that a lithium coin cell can provide. So, unless the design requires a very large capacity, choosing a coin cell has the immediate first order benefit of allowing for the smallest form factor design.

There's another property of lithium coin cell battery to consider: the maximum pulse load or discharge that the battery type can provide. In Figure 1 above, you can see the highlighted CR2032 as well as the other lithium coin cells have a very small max pulse capability. While this number indicates the maximum pulse load that the coin cell can provide, it comes with significant reduction in capacity.

Lithium coin cells can suffer from a large internal resistance; refer to two examples in figure 2. On the left is a circuit powered by only a battery. On the right is a circuit powered by a battery and a power management IC. The high peak current drawing across a lithium coin cell induces or creates a voltage drop that can cause a brown out or even reset the circuit. Additionally, drawing high peak currents from the lithium coin cell can degrade its battery life significantly. Traditionally, these shortcomings have been managed by adding a very large capacitor. The left graph shows the pulse discharge drawn by a high-power RF transmission from a lithium coin cell with a large capacitor in parallel. In this example, the pulse peaks at 38.5 mA. Anything over 15 mA degrades the battery life of a coin cell, which is less than ideal. On the right, you can see the same high-power RF transmission, but here, the same lithium coin cell is being managed by a Silicon Labs EFP01 Energy Friendly Power Management IC (PMIC). Not only is the peak discharge reduced from 38.5 mA to only 11.8 mA, but a much smaller 47 µF storage capacitor can be used.

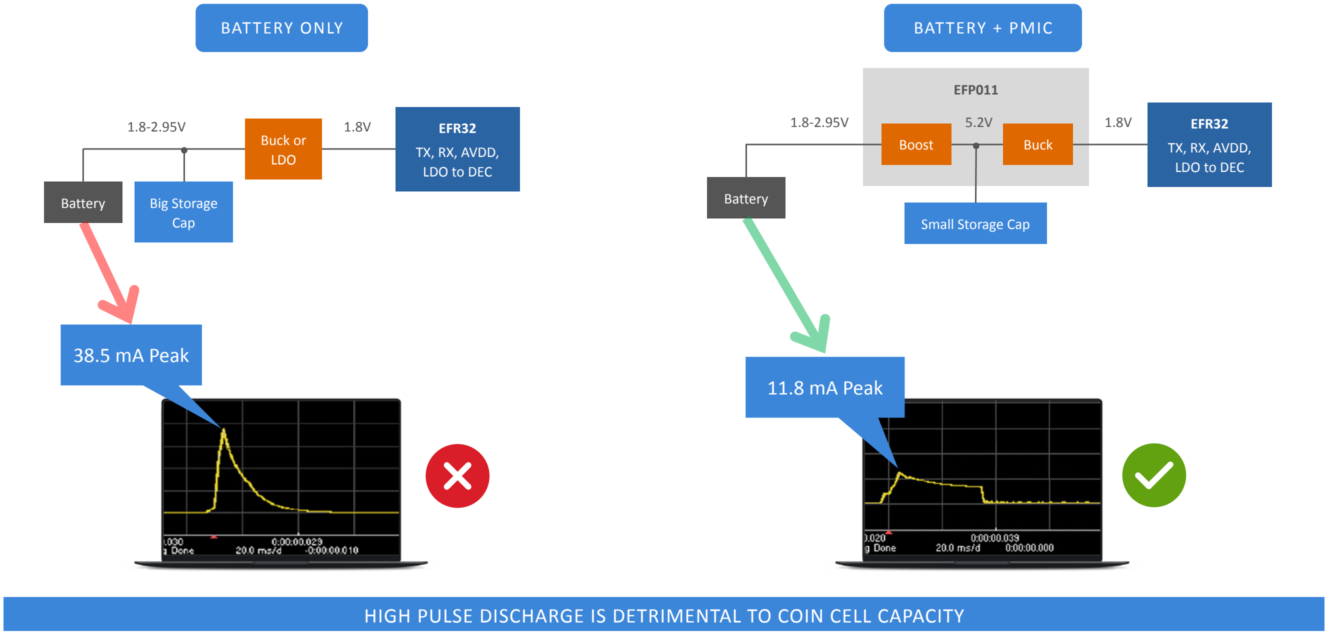

Figure 2: The maximum pulse load or discharge by battery type

Wireless SoCs and Why Silicon Labs is Leading the Way

The next important consideration in building a battery-powered sensor is the wireless SoC. This is the heart of the sensor. The chart below compares Series 1 and Series 2 of [Silicon Labs' EFR32 Wireless Gecko] devices: Series 1 and Series 2 provide low-power, multi-band and multi-protocol options for a broad range of applications. Series 2 makes significant updates to the core platform, including dedicated crypto security cores.

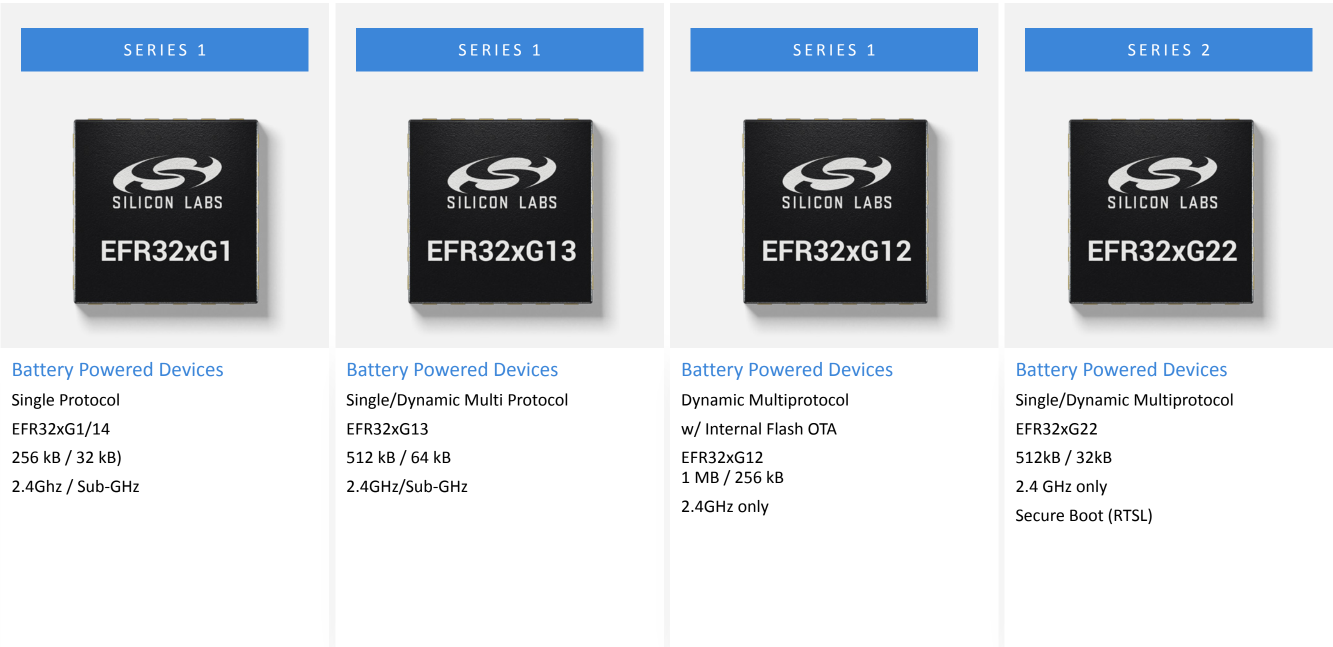

Figure 3: Wireless Gecko has more memory and offers features including over-the-air software updates to support application enhancements and evolving protocol needs

Starting on the left, EFR32xG1 and EFR32xG14 are ideal for single-protocol battery-powered devices targeted at 2.4 GHz or sub-GHz operation. Second on the list is the EFR32xG13 devices, which are well-suited for single and dynamic multiprotocol battery-powered devices that are also targeted at 2.4 GHz or sub-GHz operation. Next, the EFR32xG12 is well suited for dynamic multiprotocol, battery-powered devices targeted at 2.4 gigahertz operation. Finally, the EFR32xG22, these devices are well suited for single and dynamic multi-protocol battery-powered devices targeted at 2.4 gigahertz operation. All Silicon Labs SoCs combine an energy-friendly microcontroller with a highly integrated radio receiver.

The energy modes of operation of the SoCs impact capacity, and ultimately the life of the battery. For a typical wireless contact sensor, the battery life is dominated by the sleep current.

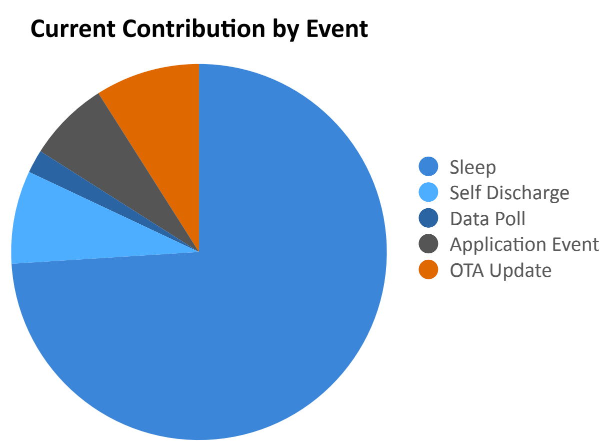

Figure 4: Sleep makes a significant current contribution compared to other events.

You can see in the chart below how big of a contribution sleep comprises. Application events, data polls, and even self-discharges or over-the-air updates during the lifetime of the battery don't compare to the energy consumption of sleeping. In Silicon Labs devices, energy modes are categorized as EM0 for active, EM2 for sleep with RAM retention, EM3 for stop, and EM4 for hibernate. EM4 provides the lowest sleep current but waking up from EM4 requires a lengthy reset time. This makes it difficult to meet the certification requirements of protocol standards like Zigbee and Thread.

EM2 provides a reasonable compromise between the sleep currents and wake-up times. In the lower right-hand side, you can see a table comparing EM2 versus EM4 of an EFR32xG22 device. EM4 in this case consumes a miserly 130 nanoamps of current but requires 8.8 milliseconds to wake up. EM2 consumes 1.9 micrograms of current but allows for a very speedy wake-up time of 13.2 microseconds.

In a wireless system, communication range is determined by the receive sensitivity of the transceiver and its output power. When viewed from a transmitter sending to a receiver, this is commonly referred to as a **link budget**. The communication data rate also affects the sensitivity. In the graph below, you can see that as the data rate decreases, the received bandwidth narrows, which results in greater radio sensitivity. A common technique is to adjust transmit power in a system to match the optimal range needed without consuming more energy that is necessary.

Figure 5: Adjusting the output power of each node can ensure sufficient link budget to provide the desired range.

The Spectrum's Impact on IoT Sensor Operation

Widely used consumer devices mainly coexist in what is called the industrial, scientific, and medical (ISM) frequency band. The ISM spectrum can be divided into two bands: sub-GHz and 2.4 GHz. Sub-GHz has quite a few advantages over 2.4 GHz, including path loss. Path loss is the reduction in power as a signal travels over distance. For example, when a 2.4 GHz signal travels 10 meters through the air, there is a path loss of 60 dB. Compared to a 900 MHz signal, the path loss for the same 10 meters is 51.5 dB. That's an 8.5 dB improvement for the 900 MHz signal.

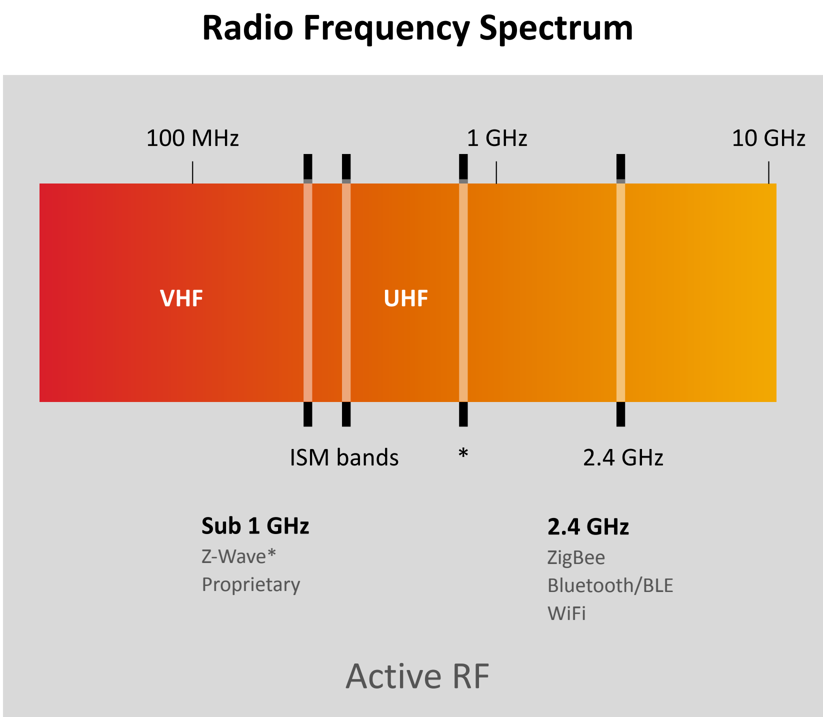

Figure 6: The industrial, scientific, and medical (ISM) spectrum can be divided into two bands: sub-GHz and 2.4 GHz.

2.4 GHz signals can have high data rates, easily greater than 1 MB/s. 2.4 GHz can also have a small antenna, less than a third of the size of a 900 MHz antenna. However, it has limited range. The 2.4 GHz spectrum is also very crowded and subject to lots of interference from things like Wi-Fi and Bluetooth devices. Alternatively, sub-GHz radios offer substantially higher range than 2.4 GHz radios – on the order of kilometers for sub-GHz radios and they enable low power consumption with years of operation on a single battery.

We know that communication range depends on transmit power, receiver sensitivity, and data rate. But range can also be influenced by the choice of antenna, so it's important to understand the characteristics and the trade-offs in order to select the right antenna for your specific design. In a battery-powered sensor application, the size, radiation pattern, ease of design, manufacturability, and the cost should all be considered.

In the illustration below you can see on the left is a dipole antenna. This is a differential structure and it measures typically a half wavelength from end to end. This type of antenna should be kept away from the ground plane and any metal and conductive objects. A dipole antenna can be easily matched to a 50-ohm impedance, but a length of 900 megahertz would be longer than six inches, making it hard to use in a small battery-powered sensor.

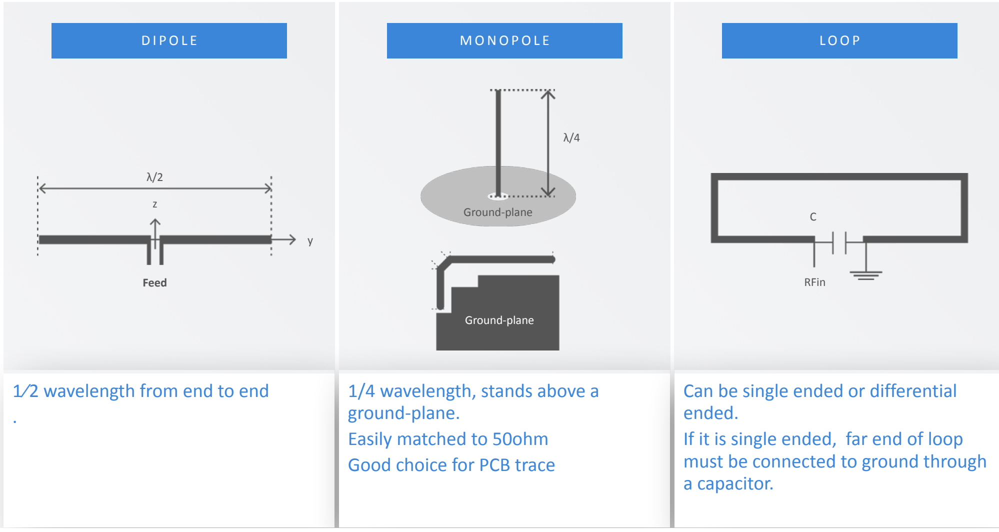

Figure 7: A comparison of dipole, monopole, and loop antennas.

The next type of antenna, shown in the middle, is a quarter-wave monopole. This type of antenna is also easy to match to 50 ohms. A monopole antenna is very easy to design, and its resonant frequency can be adjusted simply by changing the length of the antenna. This type of antenna is a good solution when physical size is acceptable. For instance, at 900 megahertz, a quarter-wave antenna would be about three inches long if there's a ground plane present. The antenna shown on the right is a loop antenna, which comes in two sizes; an electrically small and an electrically large. For devices like battery-powered sensors, only small loop antennas can be considered because large loop antennas have circumferences of nearly one wavelength, which is around 12 inches for something working in the 900 MHz band. A small loop antenna has a very narrow bandwidth, which is advantageous for selectivity, but it makes tuning critical. But once tuned, it's not easily detuned by things like hand effect or nearby objects, making it well suited for handheld devices.

Helical antennas can be built from any conductive material. Small helical antennas operate at right angles to the helix axis, which has to be a consideration when designing one of these into a device because you'll have an antenna protruding from the board. These antennas are also tricky because their impedance depends on numerous parameters including the diameter of the coil, the pitch of the loop, how tightly it's wound, the length of the coil, and the frequency at which it operates.

Any change to these parameters - even nearby objects, including people - can detune a helical antenna. But from a size perspective, a helical antenna can be quite small. In fact, it can be much shorter than a monopole antenna at the same frequency if it's wound tightly enough. The antenna shown on the right is a chip antenna and these are the smallest available, designed for frequencies from 300 MHz, all the way up to 2.5 GHz. Chip antennas have very narrow bandwidth and must be made to the exact frequency. These are probably the most expensive antenna solution and are typically used on surface mounted devices.

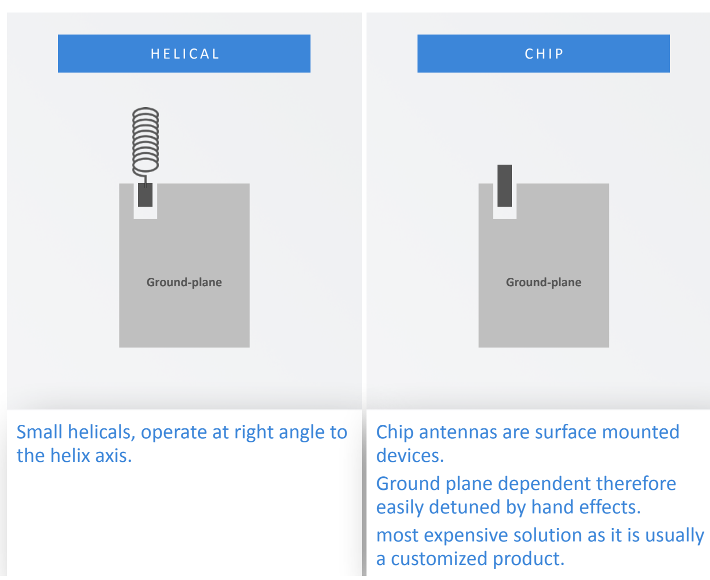

Figure 8: The last two antennas to consider are the helical antenna and the chip antenna, shown below.

Sensor Software and the Brains of the Smart Sensor

The software that runs on a sensor is critical to making a reliable, robust, easy to develop, and secure device. Silicon Labs offers a wide selection of SoCs for battery-powered devices and they all share a common development environment called Simplicity Studio. As you can see in the diagram below, the platform block consists of the multitasking operating system (OS), Vault Security, and RAIL, which stands for radio abstraction layer. RAIL provides an interface layer to the low-level hardware so you can simplify and shorten the development time by abstracting all the complexity of registers, and details needed to set up the underlying hardware in the radio.

Sitting on top of this platform is the protocol stack, which implements all the complexities of the various protocols. For instance, there's a Zigbee stack, a Z-Wave stack, a Thread stack, and a Bluetooth stack. Sitting on top of the protocol is an application layer that exposes various APIs or programming interfaces to the applications above it so they can connect to the protocol stack below. This provides the application layers above access to the features that a protocol stack provides. Lastly, the OS from the program block has interfaces along these upper layers because this OS is responsible for timers, inter-task communication, synchronization, scheduling, interrupts, exceptions, and tasks.

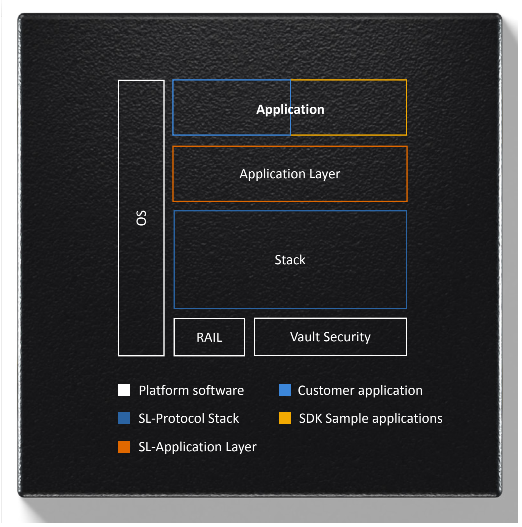

Figure 9: The software that executes on the wireless SoCs has a modular design where higher level functions are layered or built on top of lower layers.

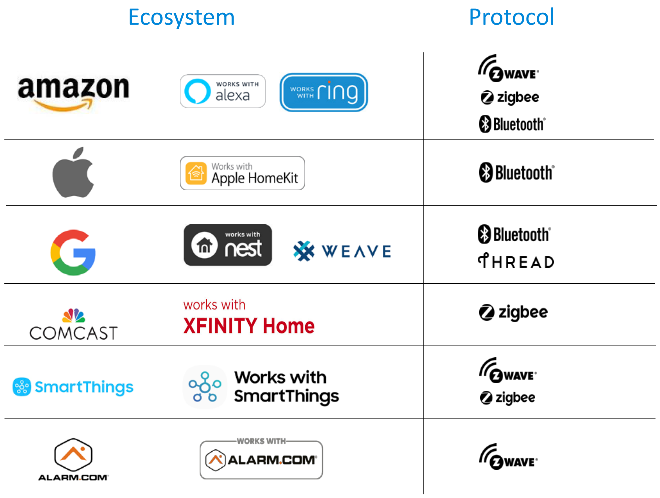

Figure 10: Silicon Labs wireless SoCs support the most popular protocols used by all the major ecosystems. Whether it's Zigbee or Z-wave or Bluetooth or Thread, you can develop a device targeted at major ecosystems.

Silicon Labs EFR32
Wireless Gecko Devices

These low-power SoCs bring together power management, security, and multiprotocol support to help developers meet the demands required for IoT sensor design.

Learn More