# Selecting the Optimal Battery for your Embedded Application

Battery technology is largely attributed to the invention of the voltaic pile by an Italian physicist named Alessandro Volta. More than two hundred years ago, Volta observed that the energy stored in the chemical bonds of a solution (at the time, he had not confirmed it was the chemical bonds) could be converted into electrical energy and used for other purposes. Over the following two centuries, countless innovations occurred to improve the original design. A few examples included improving the efficiency of the manufacturing process, increasing the stored energy density, and developing reversible chemical reactions, which opened the path to rechargeable batteries. From an applications perspective, it became clear that there is tremendous potential in storing electrical energy for use by a secondary system. Anyone who has ever started a car, relied on a hearing aid or pacemaker, or used a mobile telephone can recognize the value of this concept and has been the beneficiary of the battery.

Embedded designers who are busy developing next-generation portable or low-power applications must, at some point, select the most appropriate battery for their system. But how is this actually done? The last time I skimmed through a Digi-Key catalog, the battery section contained more than five thousand unique battery products with a seemingly endless variety of sizes, voltages, chemistry and functions. Given the vast array of battery options, it's reasonable to ask, "How can I find the optimal battery for my application?"

Although many types of batteries are available for a wide range of applications, let's focus on primary batteries (i.e. non-rechargeable) that are offered at lower cost and more commonly used in mainstream embedded applications. Table 1 summarizes a number of battery types commonly used in consumer and industrial applications.

**Table 1. Summary of Common Battery Types**

| Battery Type | Anode (-) | Cathode (+) | Nominal Voltage | Approximate Energy Density (MJ/kg) | Special Characteristics |
|---|---|---|---|---|---|
| Alkaline | Zn | $MnO_2$ | 1.5 | 0.50 | Long shelf life, supports high to medium drain applications |
| Zinc-Carbon | Zn | $MnO_2$ | 1.5 | 0.13 | Economical in terms of cost per hour for low current consumption |
| Lithium (BR) | Li | $CF_x$ | 3 | 1.30 | Wide temperature operation. High internal impedance (low pulse current). |
| Lithium (CR) | Li | $MnO_2$ | 3 | 1.00 | Good pulse capability, stable voltage during discharge. |
| Lithium Thionyl Chloride | Li | $SOCl_2$ | 3.6 | 1.04 | Very low self discharge rate. Can support 20 year battery life. |
| Zinc-Air | Zn | $O_2$ | 1.4 | 1.69 | High energy density. Relatively short battery life (e.g. weeks to months). |

### Alkaline

Alkaline batteries are typically fabricated using manganese dioxide and zinc powder with a caustic alkali (potassium hydroxide) as an electrolyte. This battery technology is one of the most common and is used in many standard applications, such as smoke detectors, personal medical equipment, portable audio devices and high-energy flashlights. They are easy to obtain by both OEMs and consumers. The nominal voltage of an alkaline cell is 1.5 V with a discharge voltage of 0.9 V.

### Zinc-Carbon

Similar in composition to alkaline, zinc-carbon batteries actually predate alkaline technology. These lower-performance batteries address cost-sensitive applications, such as toys, alarm clocks and radios, which do not require high performance. These are readily available to OEMs. The nominal voltage of this type of cell is 1.5 V with a discharge voltage of 0.9 V.

### Lithium (BR)

Lithium batteries come in a variety of form factors but are most commonly known as “coin cell” batteries. They are typically fabricated using a carbon mono-fluoride gel and a lithium alloy. This particular composition has good high-temperature characteristics. These are best known for their low self-discharge characteristics and, as such, are used in applications requiring very long service intervals with relatively low power requirements. Examples of these applications include water and gas meters, heat cost allocators, electronic toll collection systems and tire pressure monitoring systems. These are readily available to OEMs. The nominal voltage of this type of cell is 3.0 V with a discharge voltage of 2.2 V.

**Lithium (CR)**

Like the BR, the CR type still uses a lithium alloy for the anode, but the cathode is replaced with a manganese dioxide material. This material has the advantage of reducing the internal impedance of the battery, and, thus, the CR cell is generally better suited for supplying higher pulse currents than its BR counterpart at the expense of a slightly higher self-discharge rate and lower performance at high temperatures. Applications include remote keyless entry, RFID and watches. They are easy to obtain by both OEMs and consumers. The nominal voltage of this type of cell is 3.0 V with a discharge voltage of 2.2 V.

**Lithium Thionyl Chloride**

These batteries are a relatively new invention and have extremely low self-discharge rates enabling a battery life of approximately 20 years. Additionally, they benefit from a very flat discharge profile over time so that the terminal voltage stays relatively constant over their entire service life. These batteries are typically fabricated using a solution of lithium tetrachloroaluminate in thionyl chloride as the liquid cathode with a zinc alloy as the anode. This is a more costly battery technology than other lithium chemistries and is used in applications demanding extremely long battery life, such as water and gas meters and industrial and military electronic applications. These are not common in consumer applications and are available to OEMs through a select set of suppliers. The nominal voltage of this type of cell is 3.6 V with a discharge voltage of 2.2 V.

**Zinc-Air**

Zinc-air batteries are unique in that they provide a very high energy density as compared to the batteries discussed thus far. They are powered by oxidizing zinc with oxygen from the air facilitated by a hydroxide-based solution. Consumers are most familiar with this type of battery for hearing aids and camera batteries; however, much larger batteries are used in marine and railroad navigation applications. These batteries have a shelf life of multiple years, but once they are placed into service, the battery life of a consumer application is on the order of hundreds of hours. They are easy to obtain by both OEMs and consumers. The nominal voltage of this type of cell is 1.4 V with a discharge voltage of 0.9 V.

Engineers assess a number of parameters when evaluating the suitability of a battery type for a particular application. The following is a list of some of the most common factors used in this battery/application analysis.

**Nominal Voltage**

This refers to the voltage of the battery cell as measured across the positive and negative terminals of the battery. Often, multiple batteries are partitioned in series or parallel to provide a more desirable cell voltage or current supply for the application.

**Energy Capacity**
This refers to the stored energetic content of the battery. The SI unit for energy is *Joules*, but this is specified in the form of *mA-hr* by most battery manufacturers. Since the total energy in a battery is a function of both the amount of current that can be sourced and the terminal voltage, using units of Joules is a more consistent way to compare batteries with different chemistries. You can easily convert a battery capacity from *mA-hr* to *Joules* with the following formula:

$$\mathcal{E}(Joules) = capacity(mA - hr) \times terminal\ voltage(V)\ \times 3.6$$

**Energy Density**
Different battery chemistries rely on different electrochemical reactions to provide electrical energy. Some of these reactions are more potent than others, which can lead to smaller batteries with the same energy content as their larger counterparts. This size-to-energy ratio is referred to as energy density. As a general rule, the higher the energy density, the more costly the battery technology is. Designers constantly struggle to find the optimum balance of cost and energy density.

**Self-Discharge Rate**
A battery will not last forever. Even if it sits on a shelf unused, electro-chemical reactions are still taking place, slowly diminishing the energy content of the battery. This naturally occurring process is often referred to as the self-discharge rate. Alkaline batteries are generally expected to have a service life of seven to ten years. Lithium BR and CR style batteries have a service life of ten to 15 years. Lithium thionyl chloride cells can last over 20 years. Self-discharge rates and other deteriorative mechanisms affecting battery life can be highly dependent on temperature and duty cycle characteristics. Fluctuating duty cycle requirements can often have an adverse effect on the ultimate discharge characteristic of a battery.

**Dynamic Considerations**
A number of dynamic physical parameters affect the performance of a battery. Variations in temperature, output impedance, duty cycle and energy delivery affect battery loading conditions and, ultimately, shape the battery selection process. It is important to note that some of these effects are of the first order and must be given appropriate consideration.

Many systems have high dynamic bandwidth with respect to power demand. For example, it is not uncommon for wireless sensing systems, such as advanced metering infrastructure (AMR) class gas or water meters, to have **dormant** power consumption on the order of micro-Watts and an active **peak** consumption of Watts.

In other words, if a dynamic system power demand bandwidth is five to six orders of magnitude (e.g., microwatts during “sleep-mode low-duty-cycle” and watts during “active and high-duty-cycle radio transmit mode”), this creates additional power delivery requirements that must be accommodated by the battery itself or in conjunction with some other energy storage device. A capacitor is often placed in parallel with the battery to provide peak energy demand. In these cases, additional design considerations, such as capacitor cost, size, charging scheme and capacitor leakage management must also be considered.

**Other Considerations**

Engineers must consider a number of other factors when selecting a battery for their applications. Battery discharge profiles can vary greatly depending on the battery chemistry and the power demand profile (both peak load and duty cycle). Environmental considerations (especially temperature) can affect battery performance. System-level considerations, such as battery replacement intervals and system voltage requirements, also influence the battery selection process. In addition, there can be a number of environmental considerations, such as recycling, toxic materials, heavy metals, safety and shipping regulations.

Like most engineering problems, the designer must weigh a set of potentially conflicting requirements to develop the optimal solution to meet the system specifications.

To illustrate this point, consider an exaggerated example. Law enforcement personnel sometimes use high-voltage, non-lethal weapons commonly referred to as electronic control devices or “stun guns” to incapacitate combative subjects who pose a risk to the officer, innocent citizens or themselves. These devices work by delivering thousands of volts to the assailant’s body, temporarily disrupting the nervous system and rendering the individual immobile. The system uses a transformer, among other techniques, to step up the battery voltage to a level thousands of times higher than its original terminal voltage.

Instead of using a transformer, the device designer could instead choose to achieve the design objective by arranging 30,000 AAA alkaline batteries in series. This design would also be able to deliver a 45,000 volt shock to the assailant along with the obvious practical limitations of using a stun gun that was 1.33 kilometers in length and weighed 360 kilograms (not to mention the thumb switch rated at 50 kV!).

This example is intended to be ridiculous in its scope, but it does highlight the fact that, by using modern electronics, we can overcome some of the natural limitations of a battery’s electrical chemistry and use it in different ways.

For example, zinc-air batteries have long been used in hearing aids because of their high energy densities (1.69 MJ/kg) and ability to deliver high peak currents. The batteries typically have a service life of less than three months since this is the time it takes for the electrolytic reaction ($2Zn + O_2 \rightarrow 2ZnO$) to reach its conclusion. However, for the application, this is a perfectly acceptable service life, and the batteries themselves are distributed in “calendar packs” so that the user has a new replacement battery for each month.

Another aspect of this battery chemistry is that the terminal voltage of a single cell is typically 1.4 V. Specialized low-voltage circuits have been designed for hearing aids to address this limitation, but the battery voltage does not translate easily into mainstream embedded electronics. Additional provisions would be needed to take a nominal 1.4 V cell and make it useful for standard CMOS embedded electronics.

Fortunately, more and more devices are integrating advanced power management units to address exactly these types of challenges. Imagine a chip with an integrated dc-dc “boost” converter. This could easily take the lower 1.4 V input voltage of a zinc air battery (or, more likely, the 1.5 V input of a common alkaline battery) and boost it to whatever value is most appropriate for the system.

Even more importantly, if the boost converter is dynamically programmable, it can change the output voltage based upon the needs of the system so that the energy transferred from the battery to the system is always operating in the most efficient way possible. This would enable the system engineer to optimize the power supply efficiency for the specific use case during run time.

For example, imagine a bidirectional wireless sensor node for a home security application. This could be a glass break sensor that has a bi-directional communication link (i.e., it is a transmitter and a receiver). This sensor monitors the condition of a window and periodically reports the status of the window and the battery back to the main control panel. Communication between the sensor and the control panel consists of a transmit/receive/acknowledge protocol that reduces the number of redundant messages the sensor sends to the panel. The majority of the time, the sensor is in low-power mode to maximize battery life. For simplicity, let’s define the different states the glass break sensor can occupy:

**Table 2. Glass Break Sensor Operating States**

| | Frequency | Description |
|---|---|---|
| **Measurement** | Event-driven | Piezo shock sensor interfaced to system I/O. Upon breakage event, the system wakes up. |
| **Transmit** | Once per minute | Transmits sensor and battery status back to the control panel. |
| **Receive** | Once per minute | Receives acknowledgement from panel. |
| **Sleep** | All other times | Maintains low-power sleep mode, real-time clock and I/O function for sensor. |

The system consists of the following components: a microcontroller (MCU) with an integrated dc-dc converter, a sub-GHz radio transceiver, a piezo shock sensor and a single alkaline battery, as shown in the following simplified block diagram.

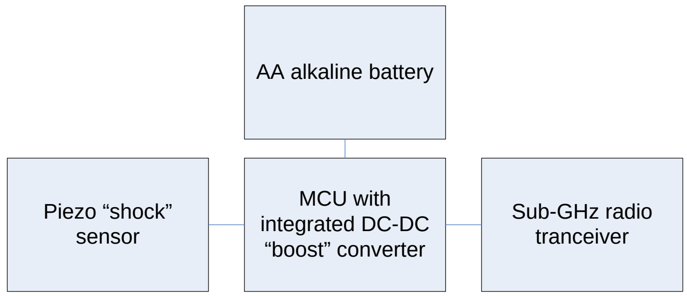


**Figure 1. Glass Break Detection System Diagram**

Let’s make the following assumptions about the system:

1. The piezo sensor is self-powered and generates a 3 V “pulse” if the glass is fractured. This signal is sufficient to trigger the interrupt on the change feature integrated in the MCU I/O.
2. The MCU core is regulated to 1.8 V by an internal regulator. The RAM, power management unit and real-time clock can operate as low as 0.9 V, so it can operate on a single AAA alkaline battery.
3. The power amplifier (PA) in the transmit block of the sub-GHz transceiver provides higher output power and higher efficiency when its voltage rail approaches the maximum rated power rail.
4. The low noise amplifier (LNA), receive chain, PLL and synthesizer in a radio is regulated by an internal 1.8 V regulator. The minimum operating voltage is 1.8 V.

If we look carefully at the system assumptions, it is clear that the ability to dynamically adjust the battery voltage can optimize power efficiency and performance. For example, we can obtain maximum TX power efficiency when the transceiver is supplied with 3.0 V. Since the alkaline battery only has a 1.5 V nominal terminal voltage, this can be achieved with the integrated dc-dc boost converter with approximately 90 percent efficiency. However, the RX chain is internally regulated to 1.8 V. If we supplied the same 3.0 V during the RX transaction, our efficiency would be reduced to 60 percent by the internal low-dropout (LDO) regulator. It would be a much better choice to dynamically adjust the output of the dc-dc converter from 3.0 to 1.8 V and increase the efficiency during the RX transaction of the sensor.

Let's compare the system using a lithium coin cell battery with a fixed-voltage rail versus a single alkaline battery using the dynamic switching technique described above. Assume that the switching loss is zero percent using the coin cell since the switch mode supply is not used and the terminal voltage is 3.0 V. In addition, the coin cell may need to be sized for the peak current demand, dictating the use of a large, expensive coin cell. For the alkaline battery, we will assume a switching loss of 10 percent.

The following tables detail the energy required for each element of the application transaction of the wireless sensor. The sleep duration is one second minus the sum of all of the other transactions. The processing, receive, and transmit functions occur once per minute.

**Table 3. Glass Break Sensor Energy Requirements Using Lithium Battery**

| CR2450 Lithium Battery, 3.0V, 620 mA-Hr rated capacity, $0.62 (est) | | | | | | |
|---|---|---|---|---|---|---|
| **Mode** | **Frequency** | **Duration** | **Current (I)** | **Voltage (V)** | **Switching Loss** | **Energy (J)** |
| **Sleep** | 60 | 954.9E-3 | 600.0E-9 | 3.0 | 0% | 103.1E-6 |
| **Processing** | 1 | 100.0E-6 | 4.0E-3 | 3.0 | 0% | 1.2E-6 |
| **Transmit** | 1 | 15.0E-3 | 27.0E-3 | 3.0 | 0% | 1.2E-3 |
| **Receive** | 1 | 30.0E-3 | 18.0E-3 | 3.0 | 0% | 1.6E-3 |
| | | | | | | **2.94E-3** |

With this usage profile, the CR2450 battery would last approximately 4.33 years.

**Table 4. Glass Break Sensor Energy Requirements Using Alkaline Battery**

| AAA Alkaline Battery, 1.5V, 1125 mA-Hr rated capacity, $0.25 (est) | | | | | | |
|---|---|---|---|---|---|---|
| **Mode** | **Frequency** | **Duration** | **Current (I)** | **Voltage (V)** | **Switching Loss** | **Energy (J)** |
| **Sleep** | 60 | 954.9E-3 | 600.0E-9 | 1.5 | 0% | 51.6E-6 |
| **Processing** | 1 | 100.0E-6 | 4.0E-3 | 1.8 | 10% | 800.0E-9 |
| **Transmit** | 1 | 15.0E-3 | 27.0E-3 | 3.0 | 10% | 1.4E-3 |
| **Receive** | 1 | 30.0E-3 | 18.0E-3 | 1.8 | 10% | 1.1E-3 |
| | | | | | | **2.48E-3** |

With the same usage profile, the AAA alkaline battery would last approximately 4.65 years. This represents 16 percent higher efficiency resulting in a 7 percent increase in service life with a 60 percent decrease in battery cost. This demonstrates the gains that can be achieved by using more modern dynamic techniques of energy conversion. It is also important to note that this is highly dependent on the duty cycle of the functions that benefit most from the high-efficiency power supply. As the receive mode duration or duty cycle increases, so do the benefits of using the alkaline battery approach with the switched mode supply. Additionally, the output of the dc-dc converter can actually be higher than that of the lithium battery (e.g., 3.3 V) and provide even greater output power and enhanced range.

Given the growing sophistication of battery technologies and chip-level power management techniques, we have come a long way since the voltaic pile of Alessandro Volta. Two hundred years of technological evolution and innovation in the fields of chemistry, electrical engineering and manufacturing have resulted in batteries thousands of times more sophisticated in design and function. Today's system designers have many more options to choose from when selecting the appropriate battery to support their next embedded application.