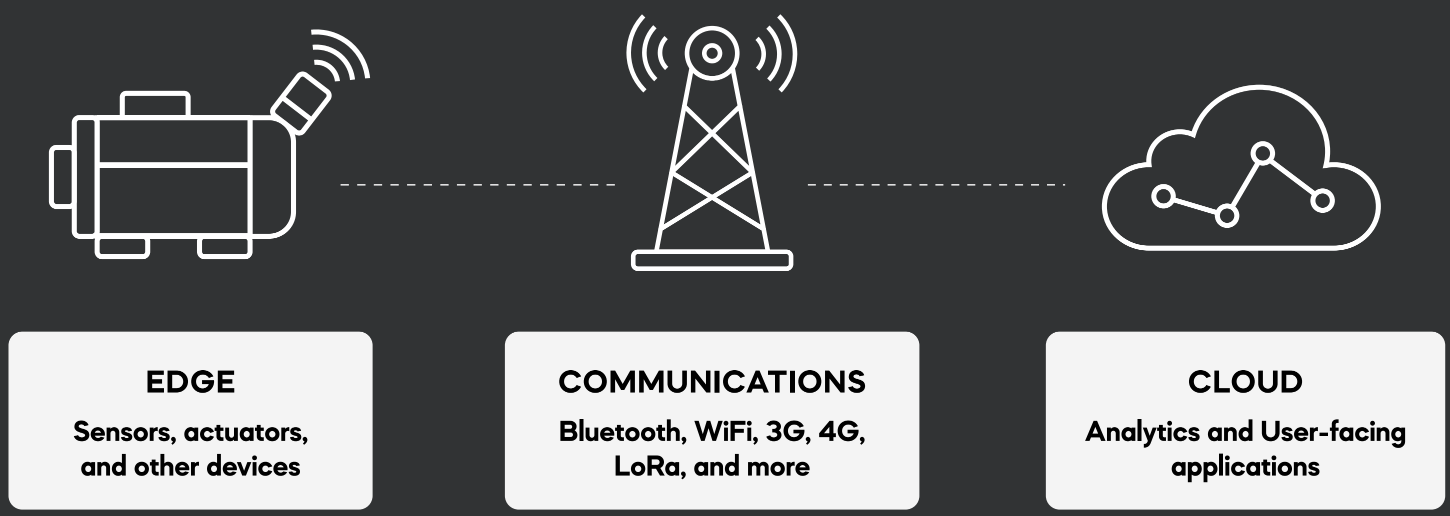
XIDAS IOT

Practical Power Solutions For Wireless IoT

Introduction to IoT

The Internet of Things is one of this generation's most promising technological advances with forecast potentials suggesting the market will grow to around $1.6 trillion by 2025. The concept of IoT is to connect billions of "things" (beyond computers and smartphones) to the internet, all of which are collecting and sharing data to ultimately offer insights and actions to the user. By turning the physical world into a giant, all-encompassing information system, the Internet of Things (sensors and actuators embedded in physical objects) can improve work processes, unlock supply and demand, create new business models, and reduce costs and risks. Simply, the Internet of Things empowers the world and infrastructure around us to be "smart". You already see it with "smart homes": the ability for your air conditioning to understand your preferences, your bathroom to detect/notify you of leaks, and for your lights and music to turn on when you say. "Smart" factories will have the ability to understand their machinery and assets, predict wear and breakdowns, improve up-time, and increase their efficiencies regarding both production and energy consumption. "Smart" farms will be able to optimize crop production with water usage, pesticide detection and more.



A large piece of the IoT architecture is the interface between the physical and digital world, the "edge". The "edge" consists of sensors and actuators that interact with the surrounding environment. Sensors take measurements and collect data, perform some analytics and machine learning, then transmit to the cloud where further global analytics and machine learning can present actionable insight. For IoT to be successful, edge devices need to provide the following:

1 WIRELESS

The vast majority of IoT sensors are required to be wireless. This is mainly due to their lack of access to a power line as well as an ethernet cable. Imagine wanting to monitor the water and humidity of the soil on your farm. What if you want to measure the strain of a bridge over time? It can even be quite expensive to hire an electrician and wire power to sensors monitoring the health of industrial machines in a factory, often costing a few thousand dollars per sensor.

2 SMART

Today's IoT edge-devices are not conventional sensors that simply convert physical variables into electrical signals. They should be able to capture and analyze signatures as well as monitor for alarms and environment. They should have the ability to pre-process data, reducing the load on gateways and cloud resources. Smart sensors are also capable of self-calibration, self-identification, and self-validation.

3 SMALL

In the theme of placing these sensors in as many places as possible, the smaller the better. IoT sensors should ultimately disappear unobtrusively and blend into any environment. Many of the potential things these edge devices monitor have small footprints themselves or will be mounted on or integrated into small areas (i.e. sensors in faucets, small pipes, small motors, etc.), so size becomes a determining design requirement.

4 COST EFFECTIVE

To create a large information infrastructure where billions to trillions of data points are being collected, billions of sensors are required. It is important that IoT sensors can be economically deployed in large numbers. This includes both upfront costs as well as long-term maintenance and support.

For each of these key elements, the biggest limitation is power...

IoT's Power Problem

Leading sensor manufacturers have all started introducing wireless versions of their sensors. Additionally, new IoT companies are emerging that leverage advances in MEMS transducers and couple them with edge intelligence and big data analytics to provide application specific solutions. All these wireless devices must balance what the edge device does with how much power capacity the battery can provide.

1. Wireless edge devices consume power in a range from low current drains when monitoring to large pulses of power when transmitting. There are multiple telemetry options to wirelessly transmit the data to the cloud, such as Bluetooth, or LoRa which have considerably lower power consumptions, but with the drawback of requiring multiple custom vendor specific gateways that need power, particularly for larger systems. WiFi provides considerably more flexibility, but with 5x more power requirements when transmitting.

2. The Intelligence on the edge-device is another element that needs to be balanced during design. The more computing power, the higher the consumption of energy from the battery. There are significant new developments in the field of low-power microcontrollers, and smart MEMs transducers that are helping with balancing the power consumption curve, but still requires users to read the small print from manufacturers in how they plan to use the edge-device. For example, since wireless sensor life is a critical cost driver, manufacturers will state life cycles of 3 to 5 years in brochures, but even today this typically mean an edge-device sampling data periodically and only transmitting that data to the users application once or twice a day.

3. The Size limits the amount of power capacity available to edge device. Smaller battery footprint means lower power capacity available to the sensor.

4. The Cost of the battery can often be the most expensive component in the sensor.
Selecting the correct battery technology to enable wide temperature ranges for industrial applications, being able to handle high current pulses for wireless transmissions, low yearly discharge rates all contribute to the cost of the battery and hence IOT edge device.

In general, current wireless sensors typically state a 2-5-year lifetime in "ideal conditions", but in reality battery replacements occur within 1-2 years.

Battery Solutions for IoT Sensors

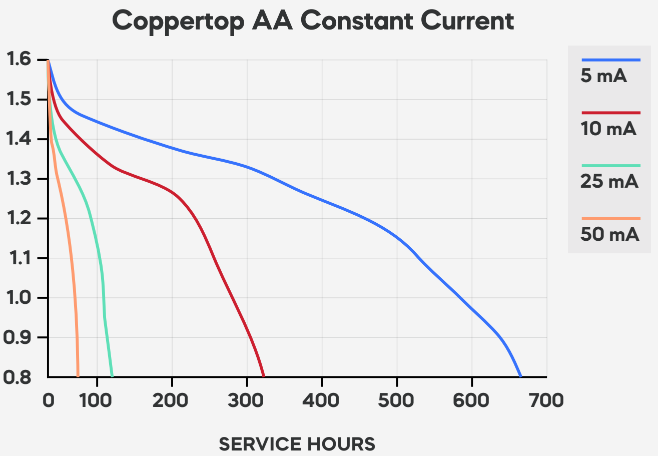
Extending battery life – the continuous goal for wireless IoT solutions, involves the following:

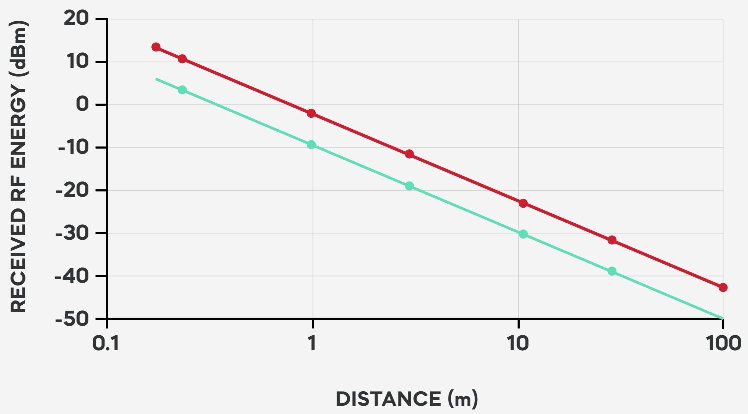
- Minimizing wireless transmission times through edge intelligence
- Leveraging the latest ultra-low power microcontrollers
- Leveraging energy harvesting solutions where possible
- Selecting battery technologies that maximize lifetime

When selecting battery technologies for IoT, particularly industrial edge devices, the following are typical driving requirements:

- 3.6V and 1.7V
- -20°C to +85°C
- Low microamp discharges to a few hundred milliamps over a second or two
- Slow yearly discharge rates

The first misconception when selecting batteries is to simply view the mAH specification of the battery to determine lifespan. The most cost-effective and prevalent batteries are alkaline, and when used in electronics do not last too long, because their voltage outputs degrade very quickly. For example, you can see at an average of 5mA, although the battery has a 700 mAH service hour, the voltage drops off much quicker. Most alkaline batteries also only operate from -20oC to +54oC. Lithium based batteries are a better option, as the voltage discharge curve is considerably better. Lithium batteries also come in very cost-effective Lithium-polymer versions that have temperature ranges to +50oC, to slightly more costly Li-SOCL2 versions with wide temperature ranges, high energy density's and, low self-discharge rates per year.





Issues with Battery Solutions

Replacement and Maintenance – The cost and maintenance headache associated with battery replacement is quite problematic and can be inhibitive to implementing an IoT system from the very beginning. Let us consider an industrial plant as an example that contains thousands of industrial assets such as motors, blowers, and pumps. The predictive maintenance application proposes implementing wireless IoT sensors on each of these industrial assets to monitor their condition and predict wear/breakdown before it happens. With current lifetimes, batteries will have to be replaced every 1-2 years by factories. Each battery replacement can cost $250 to $500... thousands of these every few years is a costly endeavor. Over a 10-year life, even at $250 every two years, that $1000 per IoT sensor, on top of the onetime cost of a few hundred dollars.

Estimated cost of one battery replacement every 1-2 years

● = Time
● = Cost

● (Time)	Identify & locate	30 (minutes)
● (Time)	Paperwork & logistics	30 (minutes)
● (Time)	Pull repair stock items	15 (minutes)
● (Time)	Traveling to & locating devices	30 (minutes)
● (Time)	Power module change	5 (minutes)
● (Time)	Return & verify operation	40 (minutes)
● (Time)	Disposal of old batteries	15 (minutes)
● (Time)	Total time in minutes	165 (minutes)
● (Cost)	Hourly labor rate	$85
● (Cost)	**Labor cost**	**$233.75**
● (Cost)	Consumables / other costs	$15.00
● (Cost)	Inventory cost of spares	$45.00
	Total	**$293**
	Cost over 10 years (two-year battery life cycle)	**$1,465**

The maintenance effort also becomes more complex as scale increases, since not every sensor dies at the same time. Constant replacement can be a serious headache:

1. The energy demands of finished devices vary from one type to another, causing different battery replacement intervals.
2. Lifespan varies from those devices in high usage areas versus lower (i.e. occupancy sensors in one area see more traffic and transmit more will consume power faster)
3. Environmental conditions impact on battery performance and lifespan, i.e. cold or warm temperatures.

Environmental Toxicity – Apart from the costs associated with replacing batteries there is another even more major worldwide concern. According to the Environmental Protection Agency (EPA), each year Americans alone throw away more than three billion batteries. That is about 180,000 tons of batteries. More than 86,000 tons of these are single use alkaline batteries. Imagine, placed end to end these dead alkaline batteries alone would circle the world at least six times. Unlike compostable trash, batteries are a hazardous waste. Sealed inside are harmful materials which you do not come into contact with during normal use. When that battery enters a landfill, however, the casing can be crushed or can easily degrade. This causes toxins to leach into the environment - the air you breath and the water you drink. The billions of IoT wireless sensors projected are only going to exacerbate the situation.

The Need for Small Energy Harvesting Power Solutions

Extensive research and development is going into energy harvesting solutions that are practical for wireless sensors. Like cleantech for larger power requirements, the need for small portable and practical energy harvesting solutions is one of the only ways the IoT industry is going to help with the battery landfill problem.

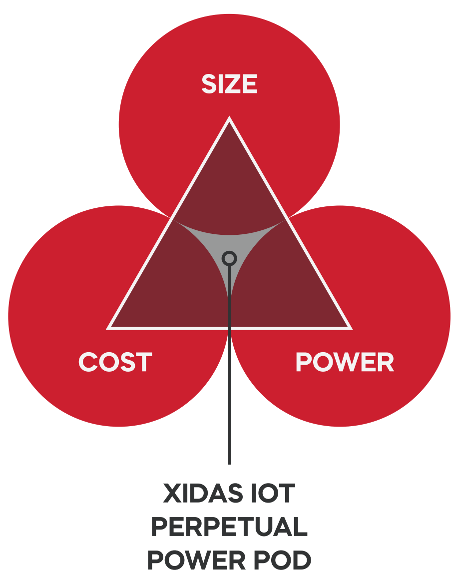
Energy harvesting is the continuous collection of ambient energy to power wireless devices. If the amount of power harvested is higher than the amount the edge device consumes, then energy harvesting devices can provide a continuous source of power. Increasing the edge device lifetime to 10+ years dramatically reduces the cost and concern of battery maintenance. End-users can now “fit-and-forget”.

Balancing the Size, Power, and Cost Needs of Energy Harvesting Solutions for IoT

New low power microcontrollers combined with local smart intelligence, allows for reduced telemetry transmission times with IoT sensors. This drives down the power consumption of IoT edge devices, down to 1-2mW of average power for most applications.

Energy harvesting solutions need to satisfy this power need, while balancing size and cost. For example, a vibration-based energy harvesting device that can harvest the power required, but cost close to a $1000 and is 10x the size of the sensor itself... it's not practical. Neither are smaller energy harvesting devices that can only harvest microwatts. The trifecta of small size, adequate power output, and low cost is the goal.

With multiple venture capital companies and research organizations investing in portable energy harvesting, we are now starting to see practical solutions, and users need to consider energy harvesting in conjunction with batteries to both reduce the environmental issues



Integrating Energy Harvesting into your IOT Solutions

If an electronic or IoT edge device has a DC input, an integrated solar or vibration energy harvesting power pod or battery can be easily used. These small devices will include the transducer, the energy harvesting and battery charging circuitry, small rechargeable batteries or supercaps for energy storage when the harvesting source (light/vibrations etc.) is not available and some level of protection and regulation circuitry for the DC output. If the energy harvesting solution needs to be integrated into the edge device, then designers need to design and integrate each of the following parts of the power system:

Transducer

These are products that harvest the energy from vibrations, light, heat, or RF. Some examples being piezoelectric, electromagnetic, or solar cell components.

Energy harvesting and power management ICs

Each transducer will have its own set of output characteristics and matching energy harvesting ICs to help boost transducer signals while maximizing energy conversion efficiencies is key. Important to note that whatever the transducer specifies as output power, there will be power loss due to the energy harvesting and power management circuitry.

Secondary Batteries or Supercaps

Energy sources from light, heat, vibrations etc. are rarely available continuously. Rechargeable small batteries need to be included to help store harvested energy for these downtimes. These batteries should be selected to accommodate the high pulses required during wireless transmission as well as being able to be trickle charged across the temperature ranges of the application. For example, industrial applications require -20°C to +85°C

Current Energy Harvesting Solutions

The three most common energy harvesting solutions for IoT sensors are vibration, light and directed energy (RF or Infrared). There are benefits and constraints of each, with a lot of research and development in optimizing efficiencies continuing worldwide.

Vibration Energy Harvesters

Machines vibrate. From helicopters and trains to air conditioning units and compressors, there are plenty of sources to harvest energy from. There are two major types of transducer technologies that can capture energy from vibrations in the environment: Piezoelectric and Electromagnetic. Piezoelectric generators convert mechanical energy into electrical energy due to the inherent polarization characteristics of certain crystals. Electromagnetic transducers consist of a magnet that generates a current in a coil when its magnetic field moves.

Electromagnetic transducers produce larger amounts of power at lower vibrating frequencies and acceleration. Piezoelectric generators are better suited for higher frequencies and large impulse movements. In both cases, the power density of each dramatically decreases with their volume.

Most vibrating surfaces (motors, pumps, trucks, trains, bridges, and more) surrounding popular IoT applications oscillate at quite low frequencies and accelerations. Industrial machine condition monitoring is one IoT application that provides extremely high potential and value to steel, oil & gas, paper & pulp, energy, pharmaceutical, and other factory plants. Majority of the industrial assets in these factories (motors, blowers, pumps, gearboxes, etc.) vibrate at sub-60 Hz frequencies and sub 1 G accelerations. At these small vibrations and frequencies electromagnetic energy harvesting solutions provide the best option to extract significant amounts of energy (1-2 mW of power) for the sensor.

Until recently these transducers were large and awfully expensive ($500 to $800). However, with funding from the National Science Foundation (NSF) and university research, small transducers are now commercially available for less than $30 that can be integrated into edge-devices. Small fully integrated vibration batteries, like solar batteries are also available for the first time to power electronics and IOT devices with direct DC inputs.

Electromagnetic transducer | **Vibration perpetual power pod** | **Conventional D-size battery**

Solar Energy Harvesters

The use of ambient light to power a wireless sensor is an extremely common approach. Most of the conventional solar panel options currently available fit in one of three types: 1st generation monocrystalline, polycrystalline (also known as multi-crystalline), and 2nd generation thin film, including amorphous. Just as in vibration energy harvesting technologies, there is significant research and investment going into 3rd generation of solar cells that include Cadmium Telluride and Concentrated PV with efficiencies closer to 40% as opposed to 10-15% for 1st and 2nd generation cells. Not many are in mass production yet, but worth keeping an eye on.

Traditional solar cells also have the same size, power, and cost triangle dilemma discussed earlier. The table below provides a good overview of what is available today (size and power) based on the light level available. Just like batteries, solar cells also have a yearly discharge rate (typically between 1 to 3% per year), but if treated and packaged well (i.e. encapsulated and UV treated), can last for 20 years. Although large, they are ideal for outdoor applications where there is availability of sunlight (albeit with the same additional components included as described for vibration energy harvesters). Indoor versions of these cells can also be designed and provided, with size dependent on location (see table below).

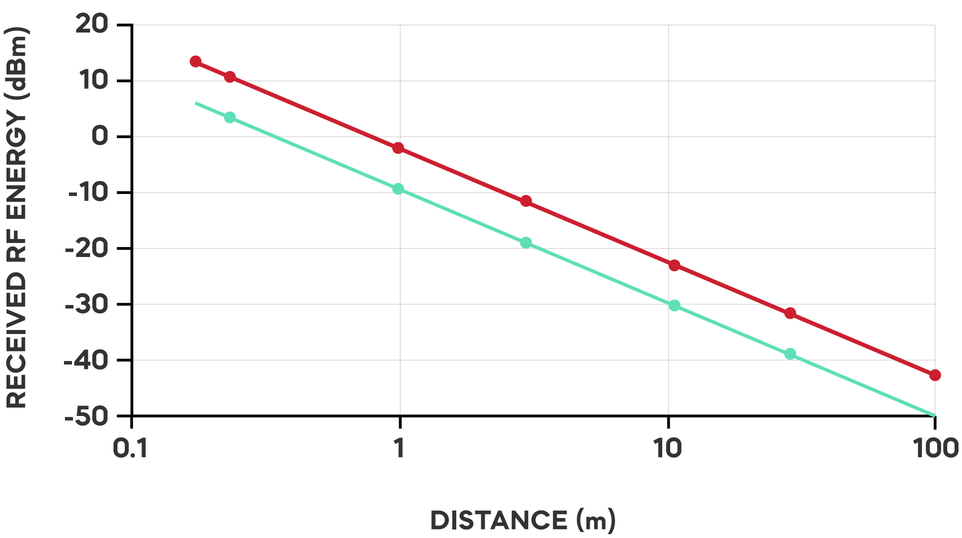
LUX	ENVIRONMENT	POWER PRODUCED	
		uW/cm^2	uW/in^2
200	Warehouse, Dining Area, Auditorium, Lobbies, Stairwells, Corridors	6	39
500	Conference Room, Office Desk, Retail Store, Workstation, Library, Living Room	17	110
1,000	Near Windows, Directly Underneath, Light Fixtures, Detailed Workstation	35	226
10,000	Outdoor Overcast, Shaded Areas	400	2,581
25,000	Light Overcast, Indirect Sunlight	1,000	6,452
100,000	Direct Sunlight	4,200	27,097

Thin film solar cells will be seeing a tremendous growth over the next decade, currently being used for portable outdoor battery packs for things like cell phone chargers to secondary batteries for campers. Because of the size, and lack of power for indoor applications, solar is not as prevalent for IoT sensors yet – but watch this space.

Directed Energy Harvesters

Two of the most popular forms of directed energy harvesting is the use of RF signals or the use of Infrared.

RF signals propagate a radio frequency such as 900 MHz or 2.4 GHz over the air to the sensor. With an embedded receiver/harvester within the sensor, the sensor can convert the signals into electrical power. The first limitation with this approach is the propagation loss of the signal over the air. The distance the sensor can be from the transmitting source is constrained. Based on Friis equation, for 900 MHz and 2.4 GHz for a 30 dBm transmitter, assuming 0 dB transmit and receive antenna gain, receiving devices can receive on the order of several tens of milliwatts if they are in close proximity to the source (several centimeters). For the table top range of 1 meter, the available power drops to less than 1 mW and the receive power dissipates further to the microwatt level at 10 meter distance. Additionally, the efficiency of the receiving harvester plays a large factor into how much power is available to the sensor. Modern designs can achieve more than 50 percent efficiency in the harvester. Thus, RF directed energy is not always practical for IoT sensors that require 1 mW of power and are far away from power sources.



IR techniques beam out infrared light as oppose to RF signals. The key advantage here is that much larger amounts of power can be delivered at further distances. Hundreds of milliwatts of power can be provided to sensors as far as 10 meters away. The large limitation associated with Infrared methods is line of sight. Unlike RF signals, the receiver must be able to “see” the transmitter. Since the form of energy is light, any object that obstructs the view will block the energy from arriving at the sensor. Thus, there are implementation and installation limitations for various applications.

	WiCharge (IR)	PowerCast (RF)
Power	100 mW	1 mW
Range	10 meters	2 meters
Other	Requires Line of Sight	Does Not Need Line of Sight

So How Long Will Your Wireless Sensors Last?

When selecting wireless IoT edge devices there will always be a battery life specification. Since manufacturers are all competing with each other, this specification becomes a key marketing differentiator. However, when reading the small print, life-time is always based on a "best case condition". A typical example is the 2 year battery life expectancy of most IoT sensors - based on a few sensor measurements throughout the day and transmitting 2-4x every 24 hours. However, what happens if you need to obtain a lot more sensor measurements, obtain different sensor measurements, or transmit more often?! Or what happens when you have multiple alarms and the edge device needs to send data to the cloud more often until issues are resolved?

Manufacturers do not provide calculators or details on how long the sensor will last. This is left to the user, and its not as simple as just looking at the mAH of the battery. Here is some guidance in calculating the life of your wireless sensors under your use-case:

> Determine from the IoT edge device supplier, what the current draws are for transmitting, receiving, sampling and any edge processing. This will allow you to determine your pulse draws during various operation modes.
>
> Create your power profiles from the data provided. An example of something considerably basic is below (sampling a simple sensor like temp once every 2 minutes and transmitting to the cloud via WiFi 4x a day). Sampling for air quality, video or other conditions would be considerably more, but this serves as a good base example:

CONDITION	CURRENT (mA)	DURATION (sec)	FREQUENCY (times per day)	AVERAGE CURRENT (uA)
Background	0.01	86400	1	10.000
Pulse 1	0.15	1	726	1.261
Pulse 2A	150	4.5	4	31.250
Pulse 2B	250	0.5	4	5.787
Total				**48.30**

The next step would be to obtain the battery details. This would not just be the specified battery capacity (i.e. 1.55 Ah), but also the average battery efficiency in your application. When calculating actual lifetime expectancy of a battery, several factors must be considered, such as discharge rate, pulse amplitude, pulse duration, cutoff voltage, environmental conditions, and self-discharge rate. A -5% efficiency reduction rate is a good rule of thumb for a high-pwerforming LiSoc2 across the whole temperature range.

TEMP (°C)	CAPACITY (mAh)	RATIO (%)	CAPACITY IN RATIO (mAh)	EFFICIENCY (%)	AVAILABLE CAPACITY (mAh)
-20	1400	5	70.0	95.5	66.8
0	1500	15	225.0	95.5	214.8
20	1550	50	775.0	95.5	739.9
40	1475	15	221.3	95.5	211.2
60	1400	10	140.0	95.5	133.7
85	900	5	45.0	95.5	43.0
Total		**100**	**1476.3**	**1476.3**	**1409.4**

Determine leakage current of any supercaps (required to accommodate transmission pulses like WiFi). A typical number is 15 uA and this would then be added to the 48.3 uA average current (63.3 uA). This results in an average of 23,538 hours (1.409 Ah/0.0000633 A), equating to 2.68 years. This is one of the simplest IoT applications. Sampling longer, using multiple sensors, adding more edge intelligence and communicating with the cloud more than 4 times a day will degrade the battery life considerably.

Conclusion

Whether you are designing wireless sensors or engineering an IoT system for your company, "power" becomes a major driving factor in the decision process. The correct batteries or application-specific energy harvesting solutions contribute considerably to reducing the overall cost and benefits of the application. Future IoT product developments should focus around reducing the constraints and limitations surrounding the current power solutions. IoT solution providers focus on proving users with upfront costs and SAAS based costs for the applications software, but leave figuring out maintenance costs, including batteries to the user. It would be nice to provide on-line tools and energy harvesting and battery options where this significant IoT application cost can also be determined before a customer commits.

XIDAS

In 2017, Xidas was selected as one of five companies to testify in front of Congress on the benefits of the internet of things to US industry, and was identified as a leading US pioneer in IoT by the National Science Foundation (NSF), being funded to develop optimized energy harvesting batteries for IoT sensors. The company has been producing integrated smart micro-sensors for medical applications, including a zero-power implantable pressure sensor the size of an eyelash. This technical note is intended to serve as an overview for both users and developers of next generation IoT solutions, helping provide some guidance on battery options.