Power Considerations for Wireless Sensing

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Trends in global communication

Data may be the most valuable commodity of the 21st century. The flow of information about our health, environment, and goods in production and shipment empowers us to make better decisions and live healthier, safer and more sustainable lives. The trend towards automation and machine-to-machine (M2M, aka IoT) communication is accelerating and shaping the evolution of global internet and wireless communication networks. According to Cisco, M2M connections are growing by 19% CAGR in the period of 2018-2023, the fastest growth rate of all connection types, exceeding the growth rate of total connections (10%) and smartphones (7%). By 2023 M2M connections are expected to account for half of total global internet connections.[1]

New generations of artificially intelligent cloud computing (e.g. IBM Watson) promise to take increasing volumes of data and digest it into actionable intelligence for decision makers. With communication and data processing evolving rapidly, it is worth taking a closer look at the edge nodes – the sensors that do the dirty work of interfacing with the analog world, collecting and communicating the information that powers the digital economy.

Power requirements for wireless sensing

This white paper will show that the battery power requirements for wireless sensors are highly variable, with drastic changes in power occurring on the order of milliseconds. At first approach, this can make power analysis of wireless sensors somewhat daunting. By building up a simple model describing the common functions of wireless sensors, we can hopefully make the power analysis more intuitive.

Certainly, a significant share of M2M devices are hardwired for data and/or power supply. Examples of hardwired devices include smart thermostats, security cameras and some hospital equipment. However, there are many use cases where wired connections are not feasible. Wireless sensors proliferate in applications where relatively small amounts of data (< 10 Mbps) need to be collected about many targets, over wide areas, and in locations that are constrained by size and access. Examples of such applications include asset tracking, reconfigurable factories, wearable health devices, and remote monitoring of the environment or precision agriculture. For these applications power is typically supplied by batteries (sometimes augmented by energy harvesting) and data transmission occurs via communication protocols designed to send data packets over various distances referred to as Personal, Local or Wide Area Networks (PAN, LAN, WAN, respectively).

The power requirements for sensors vary widely depending on the use case. Important variables to consider are the sensing mechanism, computational requirements, frequency of data transmission and distance over which the data is transmitted. Figure 1 shows a highly simplified block diagram of a wireless sensor. It is helpful to make some generalizations to understand power requirements across a diverse array of sensing applications.

Sensing mechanisms range from simple temperature measurements to more complex

[1] Cisco Annual Internet Report (2018–2023) White Paper. (2020, March 10). Cisco. https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

applications like pulse oximetry (requires LEDs to probe the color of the blood) or voice recognition (requires microphones and intensive computation). Many sensing elements are solid-state or fabricated via MEMS processes. They are durable, commoditized and power efficient. In general, the power required to take various measurements has decreased steadily such that simple measurements like temperature require only tens of microwatts.

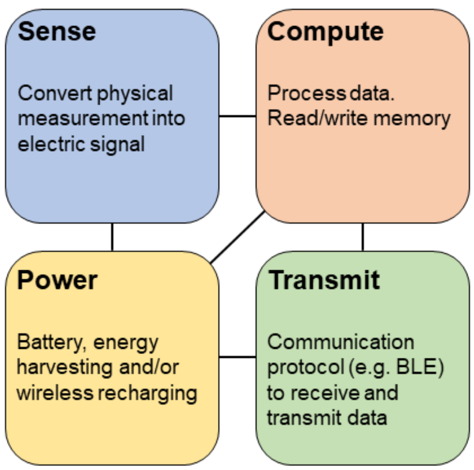

Figure 1 – A general block diagram of a wireless sensor

The power needed to compute depends on the complexity of sensor data and how much reading and writing of data occurs. For example, the latest Arm Cortex-M4 40 nm processors consume 12 microwatts per MHz of clock speed so compute power falls in the range of tens of microwatts to several milliwatts.

The data generation rate of a typical wireless sensor is at least one order of magnitude lower than the transmission rate (100 Mb/s) offered by standard consumer-oriented wireless connectivity protocols (e.g. Wi-Fi, 4G LTE). Therefore these protocols are overkill for most wireless sensing applications and will wipe out the power budget of a small sensor. Instead, low-power transmission protocols (Table 1) interface with the global internet via gateways such as smart phones with BLE capability or commercial cell towers with LTE-M. The frequency of transmission events depends on the application. A transmission event consists of several to tens of milliseconds at transmit power.

Table 1 – Summary of power requirements for several wireless data protocols

Protocol	Applications	Range (km)	Transmission rate (max)	Transmit power (max)
BLE	PAN, LAN	0.01 – 0.4	2 Mb/s	50 mW
Zigbee	LAN, mesh networks	0.01 – 3	250 kb/s	400 mW
LoRa	WAN	10 – 20	50 kb/s	400 mW
LTE-M	WAN	10 – 20	1 Mb/s	600 mW

For many sensors, transmit is the largest peak power draw but could be relatively infrequent, whereas sense and compute may occur more frequently or constantly at lower power levels. While measuring average power draw is a rational first step in analyzing a sensor's power needs, average power will often fail to predict real-world performance for a battery-powered sensor. The combination of various power draws with varying frequencies results in additive, harmonic power profiles that strain the electrochemistry of batteries. Figure 2 charts the power requirements for a variety of sensing and transmission mechanisms. The power needed varies over four orders of magnitude. Considering that many sensors are multifunctional, sending and receiving data at various intervals, there is enormous potential for complexity.

All of components identified in Figure 2 have minimum supply voltages (MSV), typically in the range of 1.5 to 2.0 V. Below this voltage the chips will lose functionality, e.g. the BLE chip will lose connection, the microprocessor will lose data or the sensing element will fail to measure properly. MSV critically impacts sensor performance and choice of battery. As we will see in later sections, when a battery delivers high power its voltage drops. This can happen within milliseconds when reacting to changing power draw from sensor components. If the battery voltage approaches MSV, even for milliseconds, the sensor will malfunction and lose data.

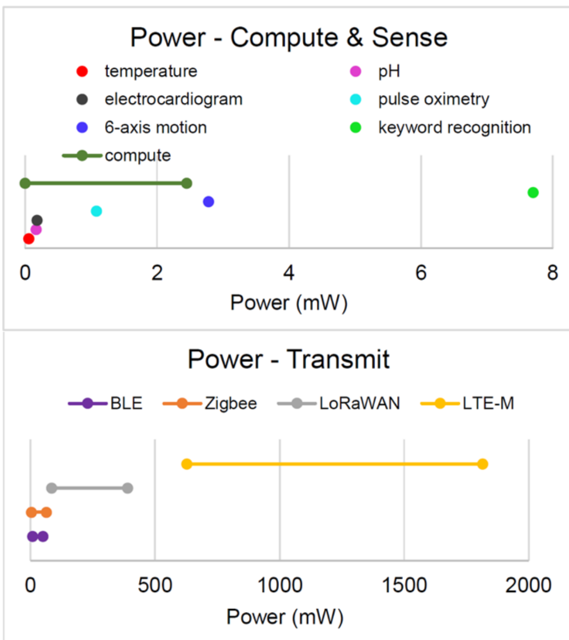

Figure 2 – Power requirements for sense, compute and transmit functions in a wireless sensor. The chips and modules used to generate this chart are listed in the Appendix.

Power analysis: practical examples

The variability of wireless sensing power demands is further illustrated in Figure 3 by two BLE sensors. The blue curve shows the current consumption of a 6-axis IMU motion sensor. There is a constant 3 mA current associated with the IMU and data processing, and a high frequency transient current between 3 and 8 mA corresponding to BLE transmission at 20 Hz. The red curve represents temperature sensing with BLE transmission at 2 Hz.

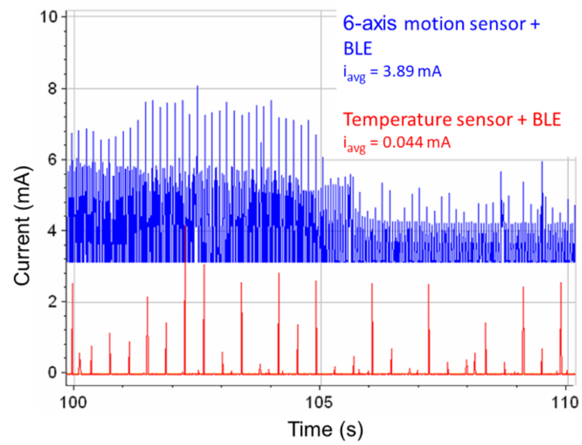

Figure 3 – Current consumption over 10 seconds for a 6-axis IMU sensor based on Bosch BMI160 and Nordic nRF52832 reporting position data at 20 Hz (in blue) and nRF52832 module reporting temperature data at 2 Hz (red).

When evaluating the power requirements of a new device, engineers will often start with an average current measurement (like the one presented in the legend of Figure 3) and then choose a battery with capacity to satisfy the average runtime required. While this analysis is a useful starting point it fails to account for the internal resistance (more precisely, the impedance) of the battery and how that interacts with the MSV of the device components. As a result, batteries that are rated with sufficient energy (or capacity) will fail to deliver the expected runtime reliably because they cannot deliver enough power.[2]

[2] Energy vs Power. (2020). Diffen. https://www.diffen.com/difference/Energy_vs_Power

High power batteries for wireless sensing

As an approximation, for each electron flowing through a circuit in a battery powered device, there is an ion (e.g. lithium) moving between the electrodes of the battery. Just like electrons traveling in wires, lithium-ions traveling through a battery encounter resistance. The resistance the ions face is more dynamic than electronic resistance (it is inversely related to the frequency of the applied electric signal) and its technical name is impedance. We know from high school physics the voltage (V) on a resistor (R) at a current (I). Likewise we can identify the voltage drop (V_d) on a battery with impedance (Z).

$$V = I * R \quad (1)$$
$$V_d = I * Z \quad (2)$$

When you draw current from a battery, the voltage drop detracts from the intrinsic chemical potential of the reactions occurring at the electrodes. The chemical potential of a lithium-ion battery is around 3.7 V, while alkaline batteries (e.g. AA type) operate at 1.2 V. So a lithium-ion battery that has 100 ohm impedance and is supplying 20 mA is actually only delivering an electric potential of 1.7 V. The missing potential (2.0 V) is waste heat generated within the battery.

As mentioned above, impedance is dynamic and it tends only to increase the more aggressively you discharge a battery. Inside the battery the lithium-ions pile up and have a hard time finding their way from the anode to the cathode. This effect is called polarization and is most noticeable when the initial voltage drop exceeds ~ 50 mV. Figure 4 illustrates the polarization process in a hypothetical battery. When the discharge current increases at t_o there is an immediate voltage drop, and the voltage continues to fall as the battery becomes polarized.

Polarization is reversible if the battery can rest, which may be the case in sensors with low background current and long periods between transmissions. But in applications with high sense and compute power requirements and/or high data transmission rates, polarization will progress resulting in the battery reaching MSV earlier than one would expect based on capacity calculations alone. Imagine the difference between an electric vehicle cruising at 45 mph in light traffic and an electric race car going for a record lap, and you have a great metaphor for a battery-powered sensor as you ramp up the data transmission rate.

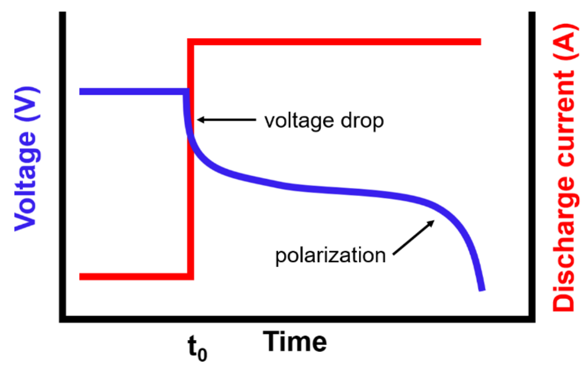

Figure 4 – Representation of voltage drop and polarization in response to an increase in battery discharge current. The discharge current rises sharply at t_0.

As the battery voltage drops below the MSV of one or more sensor components, the sensor will encounter errors or potentially a lost connection. In the case of BLE transmission, establishing a connection between sensor and receiver is among the most power-demanding modes of operation. This can result in a "death-loop" for the battery where the BLE module continually hits MSV, restarts and again draws high current from an already polarized battery. If a device engineer finds themselves with glitches due high impedance in their battery, their choices are to: 1. Find a different battery with lower impedance 2. Try to attenuate the voltage drop by adding additional components (e.g. a capacitor) or 3.

Decrease the power budget (i.e. reduce functionality) of the sensor.

Millibatt for small wireless sensors

For a battery to meet high power demand from other sensing components, it must facilitate the rapid movement of ions between the electrodes. We can make simple analogies to compare this requirement with our everyday experience. Six-lane highways move more cars than country roads. Large pipes move more water than narrow ones. The key geometric principle is surface area – increasing surface area between two battery electrodes increases the number of ions that can move between the electrodes. For a fixed volume, increasing surface area necessitates decreased thickness of the electrodes, meaning the ions also have a shorter distance to travel. Moving more ions over a shorter distance is the synergistic recipe for high-power batteries.

A battery with higher internal surface area will have lower impedance, decreased voltage drop according to Equation 2 and less polarization. Therefore, a battery with higher internal surface area can operate more power intensive sensing operations without reaching the MSV.

Small batteries (those approximately < 100 mAh) currently do not have sufficient power to reliably power the range of applications identified in Figure 2. So Millibatt developed an improved manufacturing process for small batteries that blends micromachining and photolithography with traditional electrode processing to yield 10x higher internal surface area in the same battery volume. The Nimbus line of rechargeable lithium-ion coin cells delivers the benefits of advanced high-power batteries in a familiar package. Figure 5 below shows impedance curves of Millibatt's Nimbus 9 (9.5 mm diameter, 2.7 mm thick) compared with the Panasonic ML920 (9.5 mm diameter, 2.1 mm thick). Nimbus delivers drastically lower impedance across a wide range of operational frequencies (0.1 – 10,000 Hz).

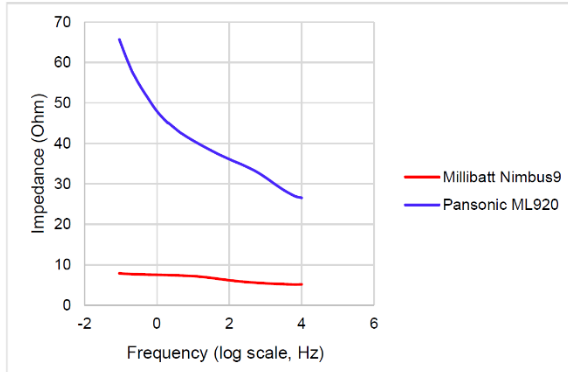

Figure 5 – A comparison of impedance measurements for Nimbus 9 and ML920 coin cells.

Hopefully at this point the reader can appreciate the importance of high-power batteries in wireless sensing and has a grasp of how to conduct a power analysis when designing a new sensor. For size constrained applications, Millibatt's Nimbus provides a robust power solution for small wireless sensors in diverse use cases. Please let us know what you are working on by reaching out through our website. We are here to help analyze and solve the power problems in your wireless sensor.

Appendix: Chips and modules included in Figure 2
NXP PCT2202, Texas Instruments LMP91200, Maxim MAX30003 and MAX30102, XMOS XK-VF3000-L33-AVS, Bosch BMI 160, ARM M4 40LP, Raytac MDBT42Q, DIGI XBee-PRO S2C and XBee 3 LTE-M/NB-IoT, Semtech SX1261