How to Choose the Best MEMS Sensor for a Wireless Condition-Based Monitoring System—Part 1

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Part 1 of this article series will discuss some of the design considerations for choosing a suitable MEMS sensor and wireless transceiver suitable for use in harsh RF environments. This article introduces the Voyager platform, a robust, low power, wireless mesh, vibration monitoring platform that enables designers to rapidly deploy a wireless solution to a machine or test setup. Part 2 of this article series will look at the different faults Voyager can detect such as imbalance, misalignment, and bearing defects. Part 3 of this article series on Voyager will focus on the actual power performance in detail, as well as several different operating modes that vary between higher data rates and ultra low power modes.

Introduction

MEMS accelerometer performance has recently advanced to the point where it can now compete with the pervasive piezo vibration sensor. Having key advantages such as lower power consumption, smaller size, higher levels of integration coupled with wide bandwidths, and noise levels below 100 $\mu g/\sqrt{Hz}$ means these MEMS vibration sensors have opened up an entire new condition-based monitoring (CbM) paradigm for maintenance and facility engineers to detect, diagnose, predict, and ultimately avoid faults in their machines. Due to the ultra low power consumption of MEMS accelerometers, wired systems can now be replaced with wireless solutions, single-axis bulky piezo sensors can be replaced with small, lightweight triaxial analog components, and a wider range of machines can now be monitored continuously in a cost-effective way.

Trends in CbM

There are millions of electric motors in continuous operation, consuming about 45% of electricity globally.[1] Most critical motors among these will likely be monitored by a wired CbM system. According to one study, 82% of companies surveyed have experienced unplanned maintenance costing as much as $250,000 per hour. For those companies that have experienced unplanned downtime, outages lasted an average of four hours and cost an average of $2 million, based on an average of two downtime events.[2]

Another study found that 70% of companies are unaware when assets are due for maintenance or upgrade work. This lack of awareness coupled with the costs of downtime are driving companies toward digitalization with around 50% planning to invest in digital twins and artificial intelligence (AI).[3] With the mass movement toward Industry 4.0, organizations are investigating the digitization of the industrial landscape to improve productivity and efficiency.

One key aspect of this movement is the trend toward wireless sensor systems. The CbM industry is due for significant growth over the next few years, with wireless installations accounting for a significant amount of this growth.[4] It is estimated that by 2030 there will be close to 5 billion wireless modules deployed in smart manufacturing worldwide.[5] It is well understood that the most critical assets demand a wired CbM system, but what about all the other assets that are currently deployed? Installing wired solutions will not be feasible for some brownfield sites, giving rise to the demand for wireless CbM solutions.

CbM System Installation and Maintenance

Wired CbM systems offer the best performance, reliability, speed, and security and therefore are deployed on the most critical assets. Due to these advantages, wired systems are still more likely to be deployed in greenfield sites. When installing wired CbM systems, cables may have to be routed across the factory floor, which can be difficult, especially when certain machinery can't be disturbed. 200 ft (60 m) cables are commonly used in industrial wired sensor networks and can cost from $3000 to $20,000 for a single run, including materials and labor.[6] In some cases, wiring harnesses are required, which add extra complexity and can be time consuming to install. If cables are routed through existing infrastructure, it may not be possible to replace or reroute them if they are damaged or in need of an upgrade.

While a wireless system may initially appear more expensive, easier maintenance routines coupled with ease of scalability can lead to significant cost savings over the lifetime of the CbM system. Fewer maintenance routes and less cabling and associated hardware all lead to cost savings. Depending on what level of reporting is required, batteries can last for several years. If an energy harvesting-based wireless system can be deployed, maintenance becomes even easier and less expensive. Once a wireless system is chosen, the next area to focus on is what technology most suits your CbM application?

Wireless Sensor Network Comparisons

Although wireless networks have been deployed for decades, they have only recently seen widespread deployment on the factory floor due to advancements in low power technology as well as immunity to harsh RF interference. This section will discuss the merits of various mesh networks.

Mesh Technologies

There are several common technologies for creating low power, low data rate networks such as Bluetooth® Low Energy, Zigbee, and 6LoWPAN. If you want to develop a dense cluster of wireless sensor nodes that transmit relatively low amounts of data over a short range, as you would expect on a factory floor, then one of these low data mesh or many-to-many network technologies are a good option.

Mesh networks can be used for infrastructure nodes and wirelessly connected to each other, as shown in Figure 1. These nodes can help each other extend a radio signal or even reroute it if a communication link between two specific nodes is disturbed by interference or noise. One of the most important features of mesh technology is the ability to send data from one mote to another via other motes in the network that enable the creation of a large network of interconnected devices covering large areas while consuming very little power. For example, in Figure 1 the distance between Mote 1 and Mote 3 means they cannot communicate directly. However, Mote 1 can transmit data to Mote 3 via Mote 2 without a direct link existing between Mote 1 and Mote 3.

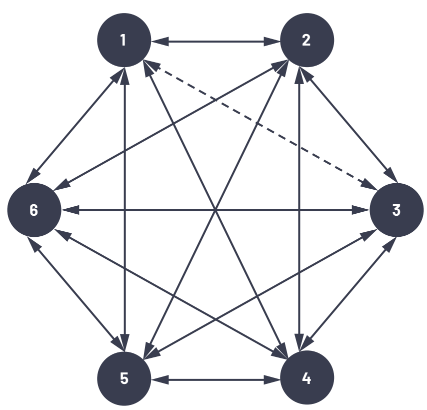

Figure 1. Example of a cluster of motes in a mesh network showing many-to-many communications.

Figure 2 shows an example of a factory floor where Mote 1 is measuring vibration from a motor. This data needs to be transmitted to Mote 6, but the distance is beyond the capabilities of the transceiver. To transmit data directly from Mote 1 to Mote 6 would require a higher transmit power and higher receiver sensitivity. The higher transmit power relates normally to higher peak current consumption and requires a larger battery. With a mesh network, this data can be hopped along each mote from 1 to 6. The power required by each device to transmit over the smaller range is far less than that required to form a direct, longer range wireless link across the factory floor.

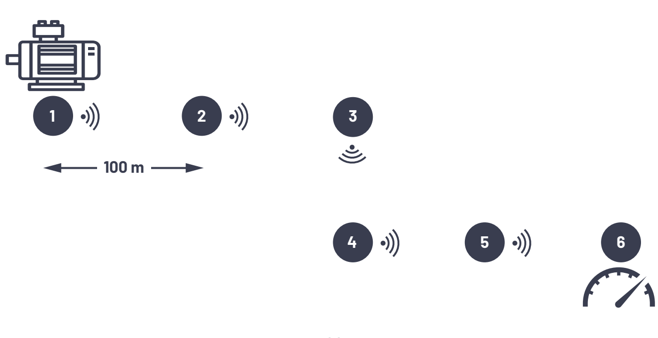

Figure 2. A mesh network implemented on the factory floor showing data hopping.

The key advantages of a mesh network are as follows:

- Self-configuring: With Industry 4.0 becoming a reality, factory managers are seeking better performance as their enterprises become more digitized. One important aspect of this search is the ability to add high density clusters of wireless devices over small geographical locations while maintaining highly reliable performance—in some cases almost as good as a wired system—with little to no manual configuration required as the motes configure themselves.
- Self-healing: Mesh networks are constantly routing data and because of this are constantly exposed to disturbance due to noise, interferences, multipath, fading reflection, etc. from the factory floor. The SmartMesh® IP system (manager and nodes) are always aware of noise levels at each node and share this data to reroute signals away from potentially noisy paths.
- Coverage: The size of the network can be modified with ease by simply adding or removing motes. As shown in Figure 2, the coverage area can be easily extended without suffering extra power consumption of wireless devices.

Table 1 summarizes mesh technologies and their capabilities.

Table 1. Comparison of Mesh Networks

Features	Wi-Fi	BLE	Zigbee	6LoWPAN-Based Mesh
Power	Hours	Months	Months/years	Years
Nodes	32	32,767	64,000	100/50,000
Range (P2P)	100 m	10 m	Up to 300 m	Up to 300 m
Data Rate	11 Mbps to 300 Mbps	1 Mbps	250 kbps	250 kbps
Channel Hopping	✗	✗	✗	✓
Collision Mitigation	✗	✗	✗	✓
Self-Healing	✓	✓	✓	✓
99.999% Reliability	✗	✗	✗	✓

Other Low Power Wireless Technologies

LoRa or LoRaWAN can enable low data rate communications over long ranges, up to 6 miles, while consuming very little power. It is based on various frequency bands and implements peer-to-peer communications. So, for low power, long-distance peer-to-peer communications, these solutions are ideal. NB-IoT or cellular is more expensive and complex to implement, as well as consuming more power than mesh technologies while transmitting smaller amounts of data. However, it does provide high quality cellular service and direct access to the cloud. If your wireless solution requires long distance cellular access with higher data rates compared to Zigbee, then LTE-M may be worth considering.

MEMS Replacing Piezoelectric Vibration Sensor Evolution

Until recently, MEMS sensors were not good enough to compete with IEPE vibration sensors in detecting early vibration fault signatures on critical assets and rotating machinery, as shown in Figure 3. The key limitations of MEMS sensors were noise, bandwidth, and *g* range. Low noise is key to detect low level vibrations, potentially enabling earlier fault detection or even prediction. Bandwidth is key because a lot of asset/motor faults, such as cavitation, bearing issues, and gear meshing often occur earliest at frequencies above 5 kHz and of course time is critical in detecting faults. The *g* range is important as larger assets can produce shocks or impacts up to hundreds of *g*, potentially destroying MEMS sensors designed for less harsh operation.

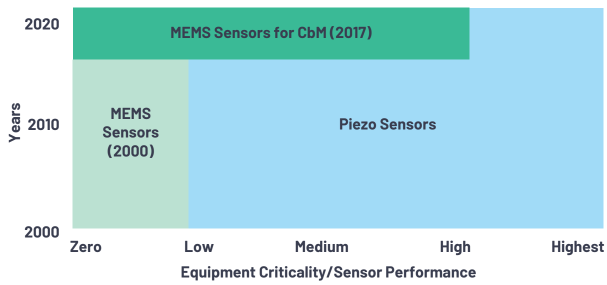

Figure 3. Evolution of MEMS performance for use in CbM applications.

Historically, most MEMS sensors were designed for multiple applications and therefore did not usually have more than one application-specific feature, whereas at least three are required for CbM. Automotive impact detection MEMS sensors are a good example of a single advanced feature application-specific part. They are designed to have a high *g* range but have insufficient bandwidth and/or noise for use in CbM and many other applications. To develop a MEMS sensor suitable for use in CbM applications is very difficult, which is why so few vendors have succeeded to date.

To highlight these advancements in MEMS performance for CbM, a comparison was made between two single-axis, analog output MEMS vibration sensors released in 2010 and 2017, as shown in Table 2. Both MEMS accelerometers were designed for vibration sensing in CbM applications. While the bandwidth of both sensors is quite high, the noise improvements are most significant, to the point that MEMS sensors can now compete with piezo IEPE vibration sensors.

Table 2. Comparison of First and Second Generation MEMS Sensors for CbM

Spec	2010 ADXL001	2017 ADXL100x	Improvements
No. Axes	1	1	–
g Range	±70/±250/±500	±50 to 500	–
Bandwidth (kHz)	10	11	–
Resonance (kHz)	22	21	–
Noise Density	4 mg /√Hz	25 µg/√Hz	160×
Cross-Axis Sensitivity	2%	1%	2×
Temperature Range	–40°C to +125°C	–40°C to +125°C	–
Power Consumption (mA)	2.5	1	2.5×
Standby Current (mA)	–	0.225	–

These noise improvements were also implemented on some high performance industrial triaxial MEMS sensors, as shown in Table 3. While these sensors are not specifically designed for vibration sensing alone, they are extremely high performance MEMS sensors capable of detecting vibrations below 1 m*g* rms at full bandwidth. Coupled with excellent stability and reliability, these sensors have proven very effective in CbM applications on a wide range of machinery, either as the sole vibration sensor or paired with other wide bandwidth MEMS/IEPE sensors. Ultralow noise, narrow bandwidth (<5 kHz) MEMS sensors can play a critical role in detecting vibrations from many assets, usually where the rotational speed is low and sub-hertz or a DC response is advantageous, such as paper/mill processing, food/pharmaceutical, wind power generation, and metal processing industries. Table 3 highlights the improvements in performance of multi-axis MEMS sensors from 2009 to 2017. It should be noted that in achieving wider bandwidths, lower noise and higher *g* ranges, specifications such as standby current will be greater compared to more general-purpose MEMS sensors.

Table 3. Improvement in MEMS Triaxial Sensor Performance

Spec	2009 ADXL345	2017 ADXL356	Improvements
No. Axes	3	3	–
g Range	2/4/6/8/16	±40	2.5×
Bandwidth (kHz)	1.6	2 to 3	1.25× to 2×
Resonance (kHz)	5.5	5.5	–
Noise Density	3 mg/√Hz 3.9 mg/√Hz	80 µg/√Hz	37× to 49×
Cross-Axis Sensitivity	1%	1%	–
Temperature Range	–40°C to +85°C	–40°C to +125°C	25%×
Power Consumption (µA)	140	150	~
Standby Current (µA)	0.1	21	210×

What Level of Vibration Sensors Are Commonly Used in CbM Systems?

Companies that stand to lose high amounts of revenue due to unplanned downtime will continue to rely on wired solutions as they offer the most reliable and accurate performance possible, based on 12-bit to 20-bit resolution sensors. Also, the higher cost of a wired installation is easily justified. For lower criticality assets, the performance requirements are not so stringent, and the capital expenditure limits may well be lower. Vibration sensor resolutions of 10 bits to 16 bits are acceptable and this is the range covered by most MEMS-based wireless CbM systems available today.

There is demand for high performance vibration sensing on lower criticality assets and this trend continues to grow as industrial companies seek to digitize and enhance their efforts to improve performance, production, and efficiency. Historically, cost has been the limiting factor in utilizing piezo vibration sensors on lower criticality assets, but this is now starting to change as more and more designers realize the value and flexibility MEMS sensors can offer in such scenarios. Figure 4 shows the potential vibration sensor resolution from 10 bits to 24 bits. Even though the resolution is clearly lower for MEMS, the performance vs. cost savings are attractive enough to justify monitoring low to medium criticality assets.

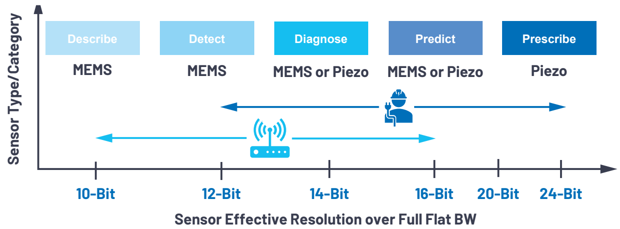

Figure 4. Sensor type and corresponding resolution.

One of the key advantages of MEMS sensors is their low power consumption, typically in the µA range but even the nA range is possible. This makes them ideal for use in wireless CbM applications. While some piezo sensors have low power around 200 µA, they lack integrated features and are expensive compared to MEMS. Some specialized wireless vibration sensors based on piezo sensors do exist and can offer 24-bit resolution at sample rates up to 104 kHz, but battery life is very limited compared to MEMS solutions. Such wireless vibration sensor systems typically have an 8-hour continuous battery life. Another key advantage of MEMS is the fact you can have up to three axes integrated into a small package. A triaxial piezo sensor will be even more expensive, larger, and require more signal conditioning circuitry, which makes them even less suitable for wireless applications.

Future Trend: The Desire for New Revenue Streams

Pumps account for a large percentage of rotating machines currently deployed in factories across the world, and the global market is projected to grow from $38.34B to $46.92B by 2025.[7] Some of these pumps will be critical to ensure a process can continue to run unimpeded, which will require condition-based monitoring to avoid unplanned downtime. What does the future hold for such pumps? According to a recent report by Frost & Sullivan, pumps will adopt analytics capabilities and become intelligent. Growth for pump OEMs will be driven by services based on analytics, AI, or machine learning (ML) to provide diagnostic information on improving pump performance and reliability. It was found that beyond 2025, up to 60% of pump OEMs revenue will likely come from service-related activities that could see the pump industry transition from a product-based to service-based model.[7] This transition is driven primarily by the rapid digitization of manufacturing (IIoT), as well as advances in CbM hardware and algorithms, AI, and ML. It is envisaged that traditional heavy industries like water/wastewater treatment plants, oil refineries, and gas production plants will utilize these intelligent pumps as they seek to digitize their operations. For greenfield sites, it is likely that wired CbM systems will be utilized, but what about existing installations on brownfield sites? To apply this service-based model to deployed pumps and other rotating machinery, wireless CbM systems can offer a fast, seamless, and reliable solution.

EV-CBM-VOYAGER3-1Z Wireless CbM Module

The Voyager platform, shown in Figure 5, is a robust, low power, wireless mesh, vibration monitoring platform that enables designers to rapidly deploy a wireless solution to a machine or test setup. Designers can quickly evaluate ADI MEMS sensor technology for vibration monitoring and at the same time evaluate SmartMesh IP technology for industrial wireless sensing. The overall aim is to accelerate customer asset monitoring and solution development. The mote includes a mechanical enclosure and attachment hardware with a ¼-28 industry-standard stud attachment. The Voyager solution can easily be directly mounted to a motor or test fixture.

Figure 5. Voyager wireless CbM module.

SmartMesh IP

SmartMesh IP wireless sensor networking products are ICs and precertified PCB modules complete with mesh networking software, which enable sensors to communicate in tough Industrial Internet of Things (IIoT) environments. They are built for IP compatibility and based on the 6LoWPAN and 802.15.4e standards. 6LoWPAN is formed from Internet Protocol version 6 (IPv6) and the Low-Power Wireless Personal Area Network (LoWPAN). It is an internet protocol (IP)-based network like Wi-Fi. The SmartMesh IP product line enables low power consumption and >99.999% data reliability even in harsh, dynamically changing RF environments.

Figure 6 shows the highly scalable, self-forming multihop mesh networks of wireless nodes that collect and relay data, combined with a network manager that monitors performance and security and exchanges data with a host application. The mesh forms automatically when the manager and motes are powered. Motes located outside the range of the manager will forward packets through motes within range. Also if the communication link of a node is disturbed due to noise, data/packets can be redirected using another link/path at a different operating frequency so data can be redirected around or away from the source of interference, which is where the self-healing element or the wire-like reliability (99.999%) of SmartMesh IP comes from.

The Voyager kit has been tested for SmartMesh IP mote hopping. This is where a mote, which is out of range of the network manager, can hop through an in-range mote, as shown Figure 6. The multiple hops network ensures that out-of-range motes can stream data to the network manager.

Where Does SmartMesh IP Fit Best?

SmartMesh IP networks are positioned for IIoT applications. In factory settings, sensors are typically deployed in clusters on assets, as shown in Figure 7. Assets that require periodic or even continuous monitoring can be placed at various locations on the factory floor, but in most cases they will not be separated by distances over 100 m. For example, SmartMesh IP has been deployed successfully with thousands of nodes in datacenters in high density clusters.

In the past, low power wireless communication devices have struggled to deal with interference generated from the factory floor. This is not only an area where SmartMesh IP excels, but it was specifically designed for deployment in dense clusters where wired-like reliability is demanded and where synchronous monitoring or control is a requirement.

SmartMesh IP networks communicate using a Time Synchronized Channel Hopping (TSCH) link layer, a technique pioneered by Analog Devices' SmartMesh IP team and a foundational building block of wireless mesh networking standards, such as WirelessHART (IEC 62591) and IEEE 802.15.4e. In a TSCH network, all motes in the network are synchronized to within a few microseconds. Network communication is organized into time slots, which enable low power packet exchange, pair-wise channel hopping, and full path diversity. The use of TSCH allows SmartMesh IP devices to sleep at ultra low power between scheduled communications, typically resulting in a duty cycle of <1%. The network manager utilizes TSCH to ensure motes know precisely when to talk, listen, or sleep. This ensures no packets collide on the network, and that there is ultralow power consumption at every node—routing nodes typically consume <50 μA.

SmartMesh IP networks are among the most secure mesh networks available. All traffic in a SmartMesh IP network is protected by end-to-end encryption, message integrity checking, and device authentication. Additionally, the SmartMesh network manager contains applications that enable the secure joining of the network, key establishment, and key exchange.

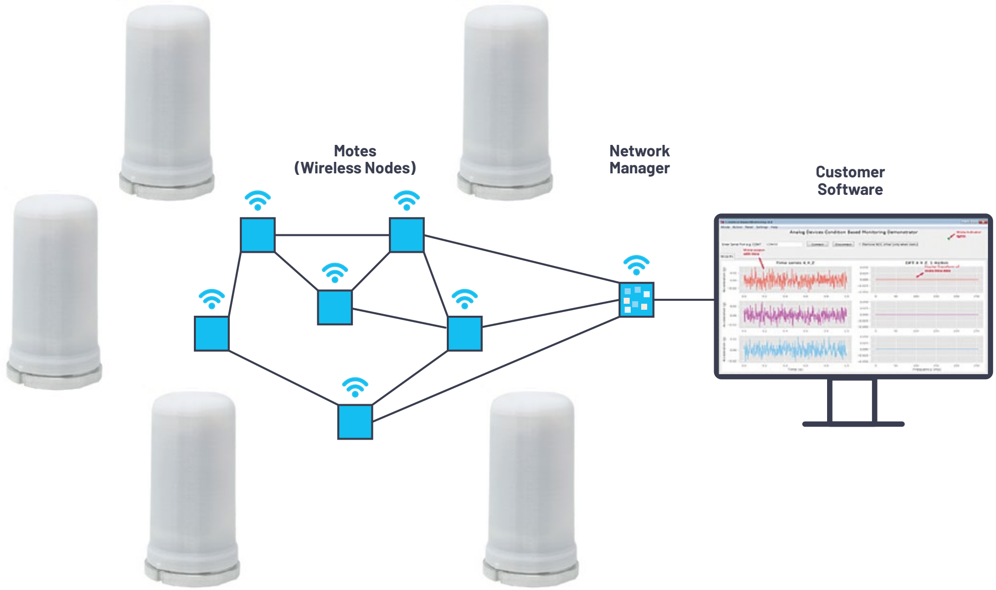

Figure 6. SmartMesh connectivity.

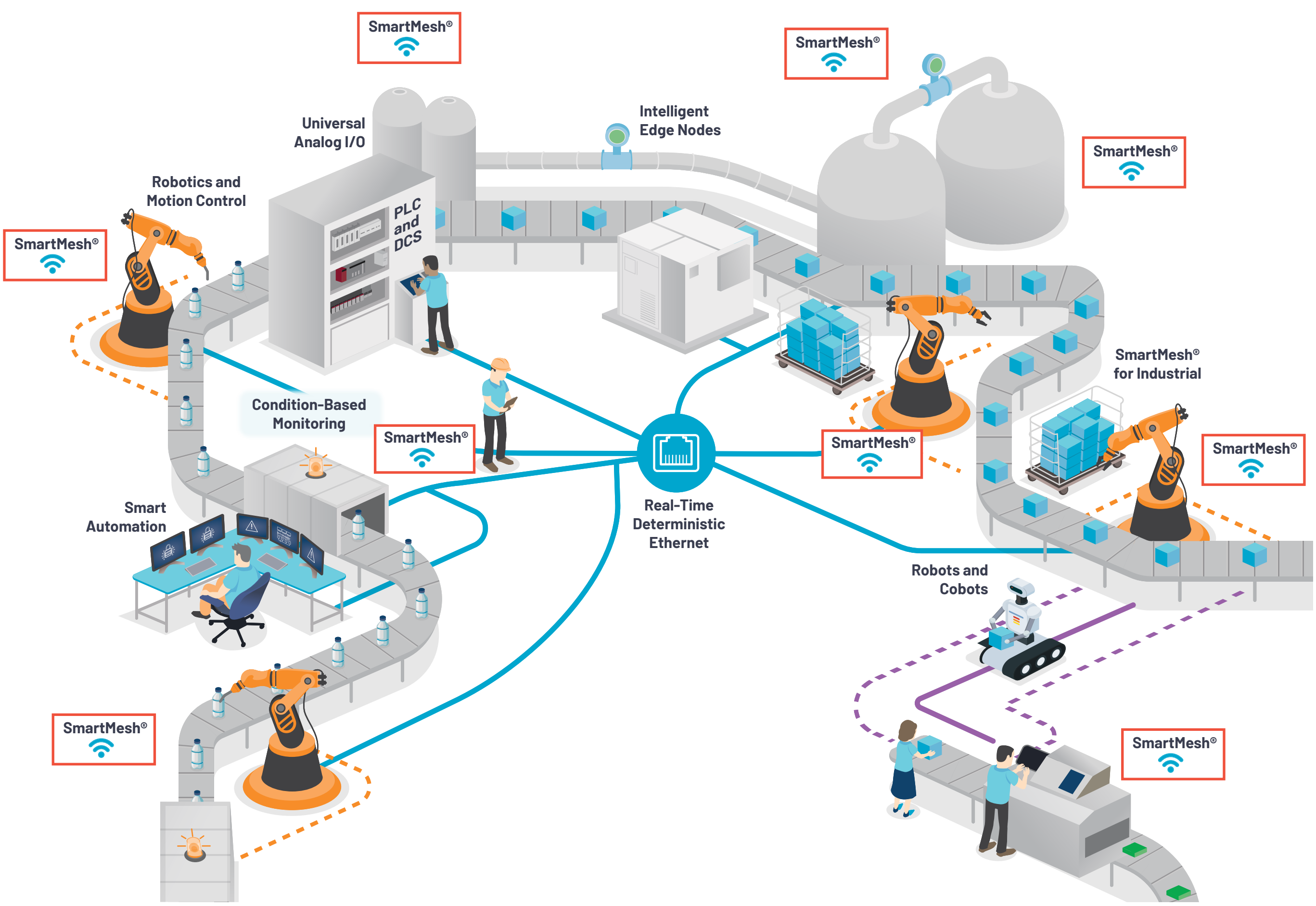

Figure 7. High density of sensors placed in proximity on a factory floor.

Voyager Signal Chain

Figure 8 shows a high level overview of the wireless vibration monitoring platform. It also includes a 3-axis, ADXL356 vibration sensor board and a low power microcontroller, ADuCM4050. A robust low power SmartMesh IP LTC5800 board is included with a chip antenna. The kit includes a SmartMesh IP USB dongle, which serves as a network manager for the wireless network. Embedded firmware and GUI code are available on GitHub.

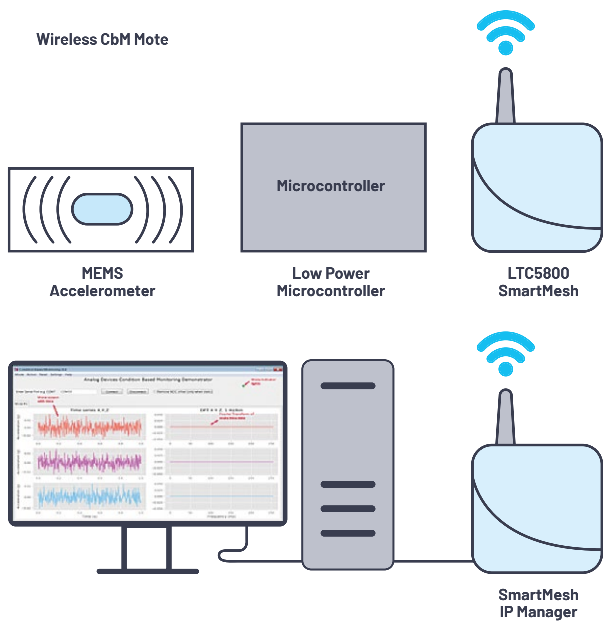

Figure 8. High level overview of Voyager hardware and GUI.

The battery life of the Voyager module was a key design feature and, as a result, high performance, low power devices were selected to sense, condition, process, and transmit vibration data, as shown in Figure 9 and Figure 10.

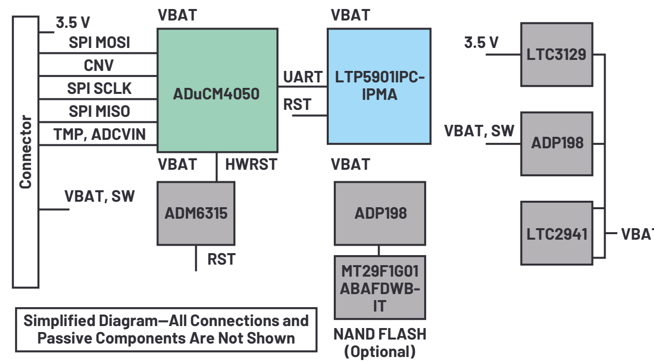

Figure 10. A high level block diagram of the ADuCM4050/SmartMesh.

Voyager Signal Chain Power Consumption

The active and standby power consumption of each signal chain part (taken from the data sheets' worst-case performance) can be seen in Figure 11 and Figure 12, respectively. Please note this does not include the SmartMesh IP transceiver, as its consumption is more nuanced than simply being in active or standby mode. The actual power consumption of the signal chain will be lower. In active mode, the ADuCM4050 consumes the most power as it samples vibration data up to 1.8 MSPS, filters it, then performs a DFT before sending data over UART to the SmartMesh IP transceiver.

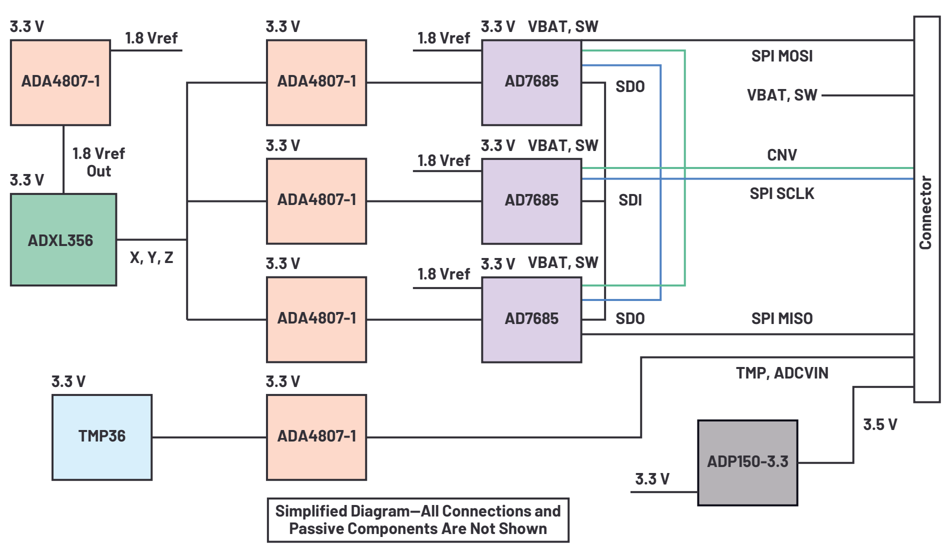

Figure 9. A high level block diagram of the ADXL356 signal chain.

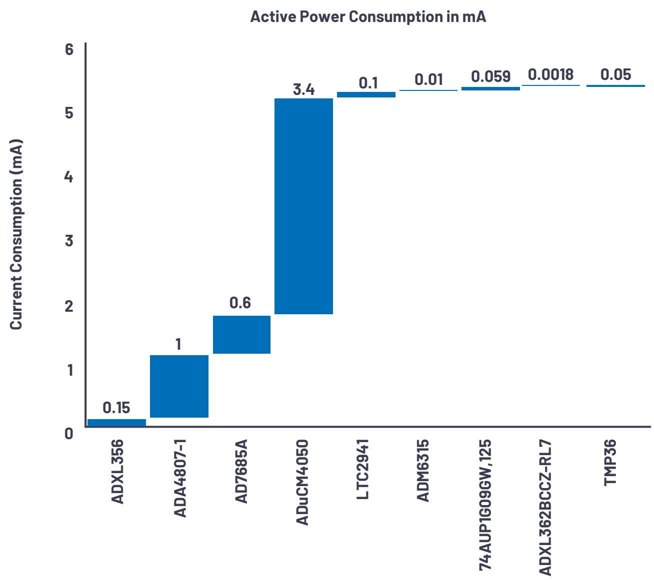

Figure 11. Signal chain power consumption in active mode.

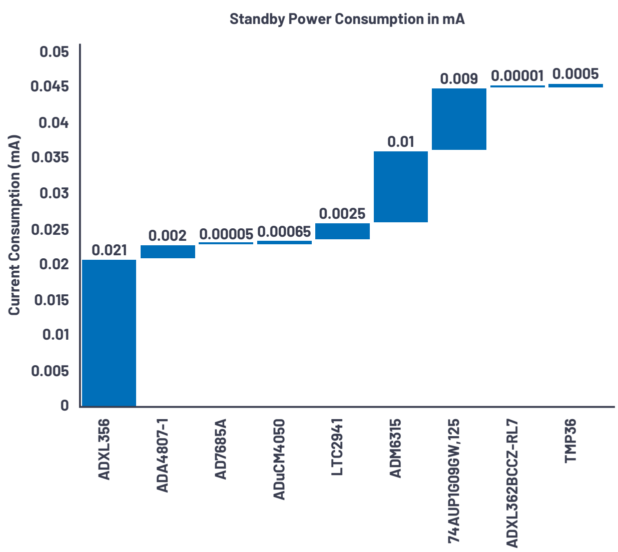

Figure 12. Signal chain power consumption in standby mode.

Figure 11 and Figure 12 show that the active and standby current of the MEMS accelerometer are extremely important when the system is transmitting data and in standby mode. Whether you plan to run a periodic monitoring scheme (once every 6 hours, for example) or a continuous monitoring scheme, these metrics become vital to ensuring your battery-powered sensors run effectively. In active mode, the ADXL356 consumes about 1.4% of the signal chain power consumption. Compared to a typical piezo sensor, the ADXL356 has much lower power consumption. A typical piezo sensor, with 4 mA constant current and a 24 V to 30 V supply, consumes close to 100 W. There are lower power piezo sensors that can reduce power consumption by 90%, but they are still not feasible for long-term use in battery-powered sensor networks.

In standby mode, the ADXL356 consumes 39% of the signal chain current. While this seems high, a comparison and qualification should be made with a wide range of MEMS sensors suitable for vibration sensing in CbM applications, as shown in Table 4, in order to better understand the resulting performance trade-offs in terms of noise vs. current consumption.

Table 4. Comparison of Active and Standby Power Consumption of CbM Capable MEMS Accelerometers vs. Voyager Signal Chain Active and Standby Consumption

	ADXL356	MEMS B	MEMS C1	MEMS C2	MEMS C3	MEMS C4
No. Axes	3	3	3	3	3	3
Active Current	150 µA	1.3 mA	239 µA	239 µA	310 µA	145 µA
Calculated % of Total Active Signal Chain Consumption	1.40%	12.30%	2.30%	2.30%	2.93%	1.40%
Standby Current (µA)	21	16	0.5	0.5	5	0.9
Calculated % of Total Standby Signal Chain Consumption	39%	30%	0.93%	0.93%	9.30%	1.70%
g Range	±40	±2, ±4, ±8, ±16	±16	±64	±20	±8, ±16, ±32
Bandwidth (kHz)	1.5	6.3	4.2 (2.9)	4.2 (2.9)	8.2/8.5/5.6	8 (5.1)
Noise Density (µg/√Hz)	80	75 (110)	130	300	675	630

Figure 13 and Figure 14 show the current consumption and noise for the MEMS sensors in active and standby modes. The active current consumption of the ADXL356 is the lowest along with MEMS C4, which is no longer recommended for new designs. MEMS B has the highest active consumption (11.5 times more than ADXL356), but it should be noted MEMS B has the lowest noise coupled with a wide bandwidth and, as such, is higher performance compared to all of the MEMS C sensors.

While ADXL356 and MEMS B have the highest standby current, the noise performance of these sensors is 1.6 to 9 times better than the alternatives shown in Figure 14. The inverse relationship between current consumption and noise density is clear to see and should be considered when choosing a MEMS vibration sensor for a battery-powered application.

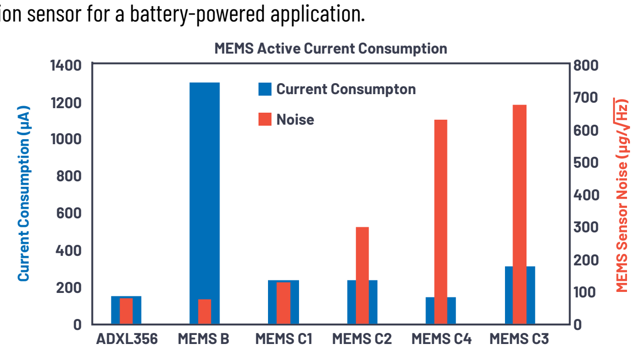

Figure 13. Comparison of MEMS sensor standby current consumption vs. noise density.

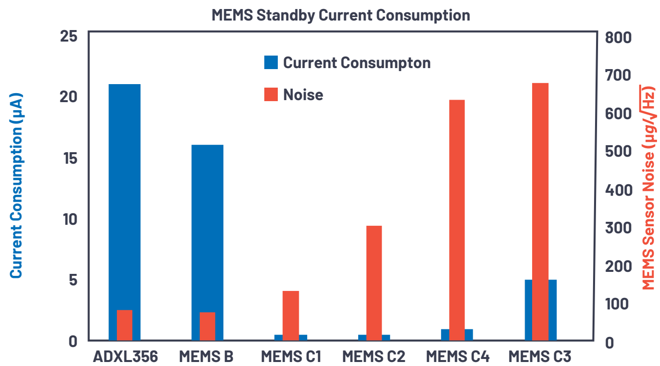

Figure 14. Comparison of MEMS sensor active current consumption vs. noise density.

Another key advantage of the ADXL356 is its ceramic package, offering excellent stability and performance over temperature. This becomes vital when you consider that most MEMS sensors designed into wireless devices will be added to enclosures that are IP6x rated. In some cases, the enclosure will include a potting compound. Ceramic packages can withstand external forces brought about by the potting compound to preserve the data sheet performance of the sensor. With plastic package MEMS devices, potting is not always recommended as deflections of the package can degrade the performance of the sensor.

MEMS Turn-On/Power-Up Times

For MEMS sensors, power-up time refers to the amount of time it takes to go from power-off to standby mode. The turn-on or start-up time refers to the amount of time it takes to go from standby to measurement mode, as shown in Table 5. For the ADXL356, this specification is valid when the output is within 5 m*g* of the final value.

Table 5. MEMS Sensor Power-On Time

Part No.	Power-On/Start-Up Time	Turn-On Time	Comments
ADXL356 (ms)	<10	<10	Typical
MEMS B (ms)	10		Typical
MEMS C1 (ms)	20 to 50	2 to 1300	Min/max
MEMS C2 (ms)	20 to 50	2 to 1300	Min/max
MEMS C3 (ms)	0.1		Analog output: 5 × R × C
MEMS C4 (ms)	20 to 50	2 to 1300	Min/max

These times should be considered when monitoring critical equipment, because if the turn-on time is too long, critical vibration data could be missed as the system enters measurement mode from standby. Power consumption when transitioning between power modes becomes even more vital in a system where the wireless node is power cycled to conserve power. Considering the turn-on time shown in Table 5, by the time MEMS C1, MEMS C2, and MEMS C4 have measured valid data after a worst case of more than 1.3 s, the other sensors will have already made measurements and been in standby mode for a considerable time, saving more power. Figure 15 compares ADXL356, MEMS B, and MEMS C1 in transitioning from standby mode to measurement mode, measuring acceleration data for 1 s, assuming a linear power ramp during this transition, then back to standby mode over a 4.5 s period. Even though MEMS B has a faster power-on/start-up time the active current consumption for a 1 s measurement is significantly higher than the ADXL356. Likewise, MEMS C1 takes up to 1.3 s, worst case, to enter measurement mode, meaning it will have to stay on longer to measure the same data as ADXL356 and MEMS B, effectively consuming more power, as shown in Table 6. If MEMS B and ADXL356 measure data at the worst-case speed of MEMS C1, both parts can stay in standby mode 55% of the time, whereas MEMS C1 only gets to enter this mode for a few ms.

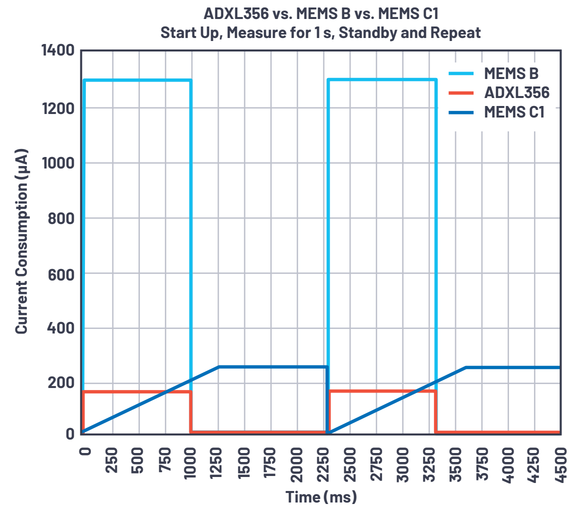

Figure 15. Current consumption for the ADXL356, MEMS B, and MEMS C1 for startup, then a 1 s measurement at the worst-case start-up time for MEMS C1 repeated twice over 4.5 s.

Table 6. Average Current Relative to Figure 15

	MEMS B	ADXL356	MEMS C1
Average Current (µA)	573	77	172

Figure 16 shows 5 s per minute of active data measurement for current consumption, with the device in standby mode for the rest of the time. The average current is shown in Table 7.

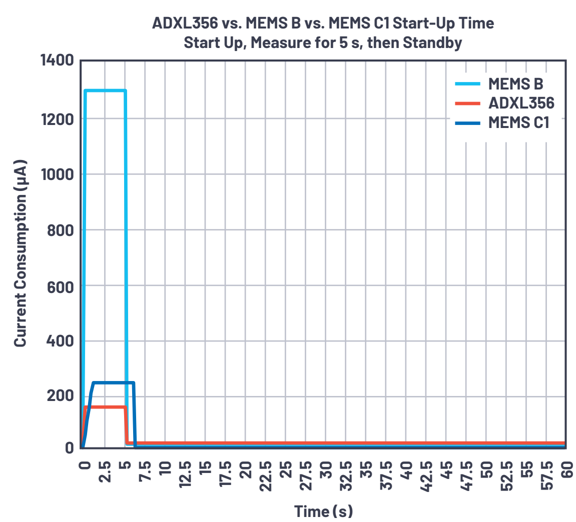

Figure 16. Current consumption for the ADXL356, MEMS B, and MEMS C1 for startup, then a 5 s measurement at the worst-case start-up time for MEMS C1 over 60 s.

Table 7. Average Current Relative to Figure 16

	MEMS B	ADXL356	MEMS C1
Average Current (µA)	128	32	23.4

Even at a less frequent measurement rate (5 s every 60 s), the average current consumption of MEMS C1 and ADXL356 is very close despite the differences in active and standby current consumption. If the measurement rate is less frequent, it would be more viable to power down the MEMS sensor to reduce current consumption, in between measurements, as shown in Figure 17, in which case ADXL356 has the lowest average current consumption.

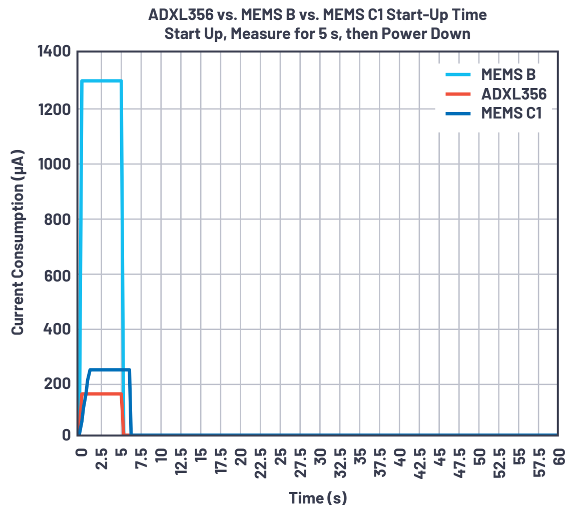

Figure 17. Current consumption for the ADXL356, MEMS B, and MEMS C1 for startup, then a 5 s measurement, then powering down over 60 s.

Table 8. Average Current Relative to Figure 17

	MEMS B	ADXL356	MEMS C1
Average Current (μA)	113	13	23

SmartMesh IP Power Consumption

SmartMesh IP transceivers (such as LTC5800) have several different power consumption profiles. Figure 18 shows data sheet maximum power consumption by mode. However, a typical SmartMesh chip configuration in a network will consume much less current for reasonable operation. A number of factors will determine how much power is consumed, including reporting intervals (1 packet/min vs. 1 packet/second), how many hops are required to transmit data, payload size (1 byte to 90 bytes) and path stability (for example, 80% indoors with dense network).

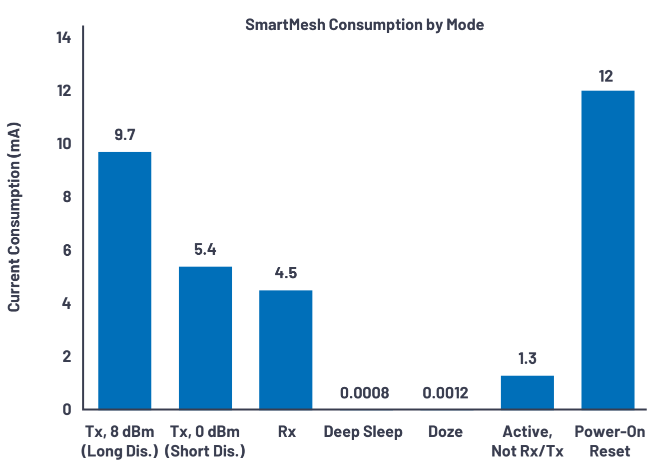

Figure 18. SmartMesh IP current consumption (worst-case data sheet specifications).

Actual battery life depends on many factors, such as how long the motes gather and transmit data vs. the amount of time the motes sleep. The payload size, path stability, interval between transmissions, hop depth, and many other factors all contribute to the amount of power the SmartMesh IP motes will use. An extremely useful and accurate tool, the SmartMesh Power and Performance Estimator, is available to estimate performance and power consumption based on critical factors, and it is shown in Figure 19.

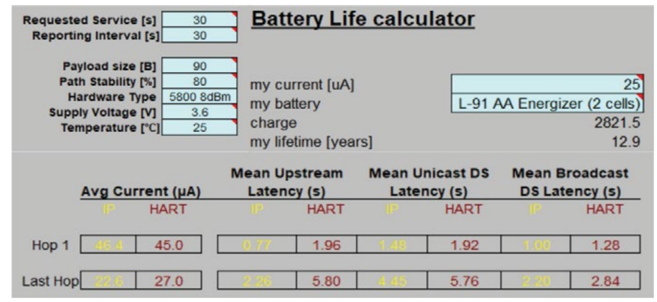

Figure 19. The SmartMesh Power and Performance Estimator tool.

Voyager Module: Transmitting One Complete Dataset

To evaluate power consumption, it would be useful to know how many packets are required to transmit one complete dataset from the wireless mote to the SmartMesh IP Manager. At a reporting interval of 1 s, 60 pkt/min will be sent from the mote to the manager. The x-, y-, and z-axis sampled data each consist of 512 time domain samples of 16 bits (2 bytes). FFT data is also computed and transmitted, as shown in Figure 20.

(512 + 512/2) × 3 = 2304 samples, giving 2304 × 2 bytes = 4608 bytes. 90 bytes are sent in one SmartMesh packet. 4608 bytes/90 bytes = 51.2 packets. 52 SmartMesh packets are required to transmit one complete dataset from the wireless mote to the SmartMesh IP Manager.

To provide a power consumption estimate, we use a 20 mote network as an example, where the motes are arranged in 4 hops, with 5 motes at each hop. Setting the data payload size at 90 bytes and setting the report rate at 1 packet per second, the Hop 1 motes are consuming 587.9 μA for the SmartMesh IC only (static conditions). For worst-case dynamic conditions, it is recommended to increase power consumption by 30%, giving 587.9 μA × 1.3 = 764.3 μA. These results are confirmed with the SmartMesh Power and Performance Estimator Tool.

Figure 21 shows the worst-case battery life estimation (2 × Saft LS14500) for the Voyager module with 4 hops for two scenarios, one where the motes are active once every 60 minutes and the other once per minute for 60 minutes. As expected, the scenario where the motes transmit every minute for 60 minutes have a much smaller battery life. The mote at Hop 1 will have more work to do as this mote will receive all data sent from motes 2, 3, and 4. Hop 1 battery life is 19.1 days (0.052 years), whereas Hop 4's is 20.1 days (0.054 years). When the motes transmit for 1 minute every hour, the Hop 1 battery life is 1.38 years and Hop 4's is 2.12 years.

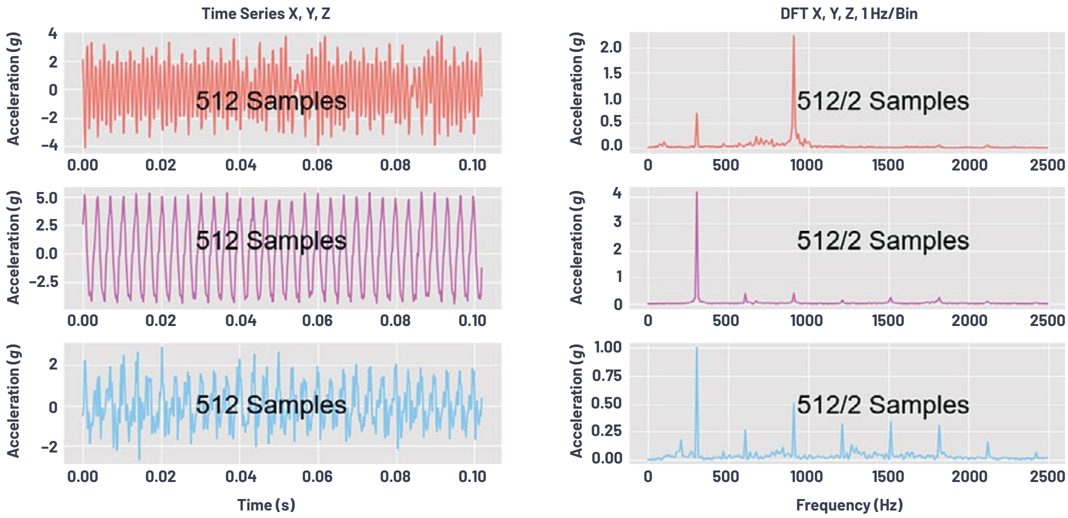

Figure 20. A Voyager GUI showing time domain and frequency domain data.

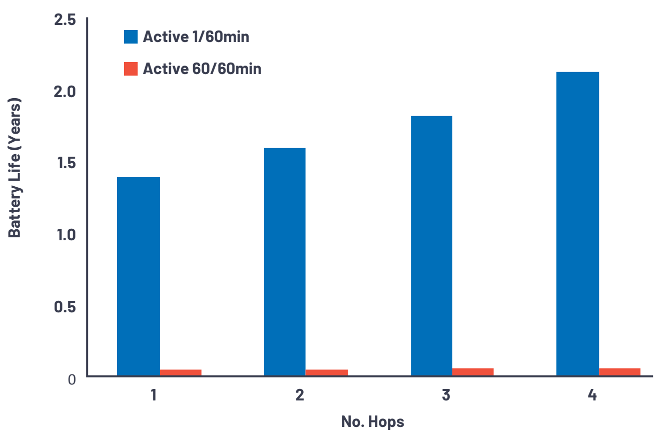

Figure 21. SmartMesh battery life vs. the number of required hops to transmit data.

Conclusion

This article discussed some of the key trends driving the rapid advancements and growth currently seen in the CbM market. Low power, high performance MEMS sensors and high fidelity, low power signal chain components are critical in providing the CbM industry with the wireless capabilities required to quickly deploy on assets and begin to reverse the $50B lost annually to unplanned downtime. An overview of mesh technologies gave a high level view of the key differences between competing wireless technologies and highlighted which ones are most suited to harsh RF environments where synchronized monitoring and control as well as wired-like reliability are required.

Choosing the most suitable MEMS sensor can be difficult and many things will have to be considered such as noise, bandwidth, and *g* range, but lesser referenced data sheet specifications like turn-on time must also be considered along with the data rates required for your wireless system as this can help to decide what operating modes and data rates are most feasible.

Using wireless devices in harsh RF operating environments such as the factory floor requires robust communications paired with low power. This article showed the worst-case data sheet and power estimated values for SmartMesh devices from the SmartMesh Power and Performance Estimator tool to give a high level overview of what is possible. Further investigation is recommended with this tool as sensor networks can be tailored to your specific needs to give a better estimate of potential battery life and performance. In Part 2 of this article series, we will show how the Voyager platform can detect various machine faults early while Part 3 will discuss power consumption and different operating modes of the Voyager module.

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