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Wireless Sensor Modalities at a Nuclear Plant Site to Collect Vibration Data

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Vivek Agarwal

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ABSTRACT

One of the major contributors to the total operating costs for the domestic nuclear fleet of reactors today is operation and maintenance (O&M) costs. These include labor-intense preventive maintenance programs involving periodic manually-performed inspection, calibration, testing, and maintenance of plant assets and time-based replacement of assets, irrespective of their conditions. This has resulted in a labor-centric business model to achieve high capacity factors. To build an optimal maintenance program, it is time to transition from this labor-centric business model to a technology-centric business model. Fortunately, there are technologies (advanced sensors, data analytics, and risk assessment methodologies) that will support this transition. The technology-centric business model will result in a significant plant life extension and reduction of time-based maintenance activities. This will drive down O&M costs, as labor is a rising cost and technology is a declining cost. This approach will lay the foundation for real-time condition assessments of plant assets, allowing for condition-based maintenance to enhance plant safety, reliability, and economics of operation.

The goal of this project is to address challenges in the area of digital monitoring, i.e., the application of advanced sensor technologies (particularly wireless sensor technologies) and science-based data analytic capabilities to advance online monitoring and predictive maintenance in nuclear plants to improve plant performance (efficiency gain and economic competitiveness). To achieve the project goal, researchers from Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL), in partnership with Exelon Generating Company (Exelon), are performing research and development to demonstrate the application of wireless sensors using a distributed antenna system and advanced data analytics to achieve predictive maintenance.

This report describes the wireless vibration sensors, vibration data and indicators. The wireless vibration sensors presented in this report support three types of wireless communication, namely, Wi-Fi, cellular, and 900 MHz. These wireless vibration sensors are being considered by partner plant sites for installation on plant assets to enable online vibration monitoring to replace periodic measurements. These vibration data, along with other plant process data, will be utilized to develop diagnostic and prognostic models.

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ACRONYMS

BOP	balance-of-plant
CHIP	component health indicator program
DAS	distributed antenna systems
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
ISM	industrial, science, and medical
LTE	long-term evolution
NPP	nuclear power plant
O&M	operations & maintenance
OLM	online monitoring
PM	preventive maintenance
RF	radio frequency
VSN	vibration sensor node

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WIRELESS SENSOR MODALITIES AT A NUCLEAR PLANT SITE TO COLLECT VIBRATION DATA

1. INTRODUCTION

The goal of this project is to address an unsolved challenge in the area of digital monitoring, i.e., the application of advanced sensor technologies (particularly wireless sensor technologies) and science-based data analytic capabilities to advance online monitoring (OLM) and predictive maintenance in nuclear plants and improve plant performance (efficiency gain and economic competitiveness). To achieve the project goals, specific project objectives will be completed during the period of performance of the project.

1) Design a general methodology for the technoeconomic analysis of wireless sensor modalities for use in monitoring equipment condition, especially in balance-of-plant (BOP) systems in a nuclear power plant
2) Apply data-science-based techniques for decision-making to develop and evaluate integrative algorithms for diagnostic and prognostic estimates of equipment condition using structured and unstructured heterogeneous data distributed across space and time (i.e., analytics-at-scale), including new data from wireless sensors in a nuclear plant
3) Develop a visualization algorithm to present the right information to the right person in the right format at the right time
4) Validate the developed approaches and algorithms, using independent data from an operating plant.

One of the objectives includes the identification of a BOP asset or system in collaboration with Exelon Generation Company (Exelon) that could be used as a target asset to install wireless sensors to enhance OLM and to develop a predictive maintenance strategy.

To support the installation of wireless sensors on plant assets, a wireless architecture, based on a distributed antenna system (DAS) to support multiple communication types, is required. Idaho National Laboratory (INL) proposed a wireless network deployment strategy for a nuclear power plant [1] that would enable application with low- to high-power needs, low- to high-frequency ranges, and short- to long-range communications, as shown Figure 1. INL has already performed a technoeconomic analysis of the wireless architecture in Figure 1 [2]. The whole network topology is predominantly operated using a DAS long-term evolution (LTE) system or wireless local area network system, since they can enable:

- High bandwidth and data transmission rates with low latency
- Prioritized data transmission, based on the required quality of experience or quality of service
- Most of the wireless technologies to have either a Wi-Fi or a DAS system as their back-end network (e.g. a Bluetooth Device can connect to Wi-Fi in the back end to upload its data to the internet)
- The system to act as a bridge between end devices/other wireless technologies and the internet, or an outside network
- Easy network maintenance by bringing all the networking technologies under one network architecture.

The transition to predictive maintenance will improve plant economics by reducing costs associated with operating and maintaining the current domestic fleet of nuclear plants (i.e., 96 operating units). Continuing to operate nuclear plants in an electricity market selling wholesale electricity for $22/MWh (PJM spot price, July 2018) becomes unsustainable with the current maintenance paradigm. The average cost to produce electricity in the nuclear industry is approximately $34/MWh, with $22/MWh attributed to operations & maintenance (O&M) costs. On average, annual O&M costs equate to approximately $145M per station.

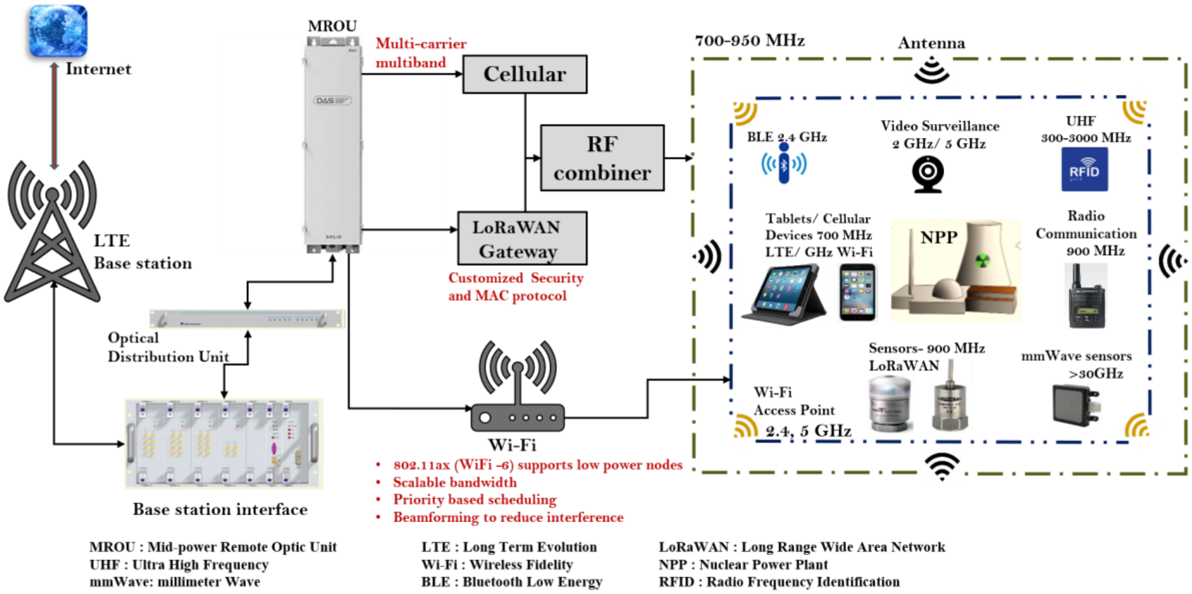

Figure 1. Envisioned multiband wireless technology for nuclear power plant automation [1].

One major contributor to total operating costs in domestic nuclear power plants today is O&M costs, which include labor-intense time-based preventive maintenance (PM) programs. PM programs involve periodic manually-performed inspection, calibration, testing, and maintenance of plant assets and time-based replacement of assets, irrespective of their conditions. This has resulted in a labor-centric business model. It is time to transition from this model to a more optimal predictive maintenance program. To enable this transition, a reliable method is needed to assess equipment condition and risk of failure. Fortunately, there are technologies (advanced sensors, data analytics, and risk assessment methodologies) that can enable this transition. The technology-centric business model will result in significant cost savings by reducing costly PM activities.

This report summarizes the wireless vibration sensor and data indicators used to assess the health of a plant asset. Different wireless vibration sensors are considered based on the availability of network compatibility and ease of deployment. The report is organized as follows:

- Section 2 discusses the vibration data and indicators
- Section 3 discusses different types of wireless vibration sensors capable of transmitting data over Wi-Fi, cellular, 900 MHz, and Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 wireless networks along with proximity probes
- Section 4 presents a summary and discussion of a potential path forward.

2. VIBRATION DATA

Most motors and pumps in an NPP are monitored via periodic vibration monitoring to assess their operating condition based on set of well-defined features. The motors can be categorized into synchronous or asynchronous motors depending on their application and usage. Also, these motors have different types of bearings. Commonly observed bearing types are roller bearing and sleeve bearings. The vibration measurements collected on these motors and pumps at fixed locations are useful in assessing their conditions. The time series data is converted into frequency domain for assessment. The vibration signal collected at bearing locations have specific frequency characteristics, referred to as fault signatures, that are used to assess condition of bearings. By using manufacturer data on machine faults, degradation modes can be determined by comparing the frequency spectrums of the measured data and manufacturer data. There are also techniques that can assess the severity of the bearing faults.

2.1 Rolling Element Bearing Machines

Rolling element machines can be expected to generate high-frequency vibrations if a bearing fault is developing. The analysis parameter should monitor up to 70 orders of rotational speed and can be expected to provide an early warning of a bearing fault. An acceleration band in the 1–20 kHz range should be used for trending purposes and can be utilized to provide early detection of faults.

2.2 Sleeve (Journal) Bearing Machines

Sleeve bearing machines are expected to generate fault frequencies at lower multiples of running speeds than a rolling element bearing machine, therefore it is not generally necessary to monitor to as high a multiple of shaft speed. Sleeve bearing machines can also generate fault frequencies at subsynchronous frequencies, therefore a subsynchronous analysis band is needed. Here subsynchronous frequencies refer to the frequencies present below the running speed of the motor/pump.

2.3 Gearboxes

Gearboxes can generate fault frequencies at very high multiples of shaft rotation, due to gear mesh frequencies. In order to effectively monitor for gear faults, the analysis parameter should monitor up to 120 orders of running speed with high resolution to allow identification of sideband frequencies.

2.4 Plant System Indicator from Vibration Data

Once the raw vibration data is safely stored in the cloud, the data is accessed through an installed sensor cloud server, which provides an interface to visualize the data and evaluate the state of the equipment. One of the steps performed by the plant engineers is to generate plant indicator data from raw vibration data. A single sensor node can trend dozens of different indicators for plant use.

The raw data consists of the asset’s acceleration with time. From this time domain data, an acceleration frequency spectrum is calculated by executing a Fast Fourier Transformation routine. It is also possible to convert the acceleration data into velocity signals in both time and frequency domains. Acceleration generally highlights high-frequency vibrations. Velocity tends to be more effective for evaluating vibration throughout the entire frequency spectrum. Thus, four base-data types are available to be processed into indicators:

- Acceleration time waveform (raw measured signal)
- Acceleration frequency spectrum (calculated)
- Velocity time waveform (calculated)
- Velocity frequency spectrum (calculated).

From these four data types, useful quantitative indicators (mentioned below) can be calculated and trended to characterize machine vibration. Users or plant engineers can then decide which of the available indicators are important to track for their specific applications:

- Peak: Acceleration, Velocity
- Root Mean Square: Acceleration, Velocity
- Spectrum Overall: Acceleration, Velocity

3. WIRELESS VIBRATION SENSOR TECHNOLOGIES

Vibration-monitoring instrumentation contains accelerometers that sense changes in the amplitude and frequency of dynamic forces that can impair rotating equipment. Identifying degradation at its onset by analyzing vibration measurements allows personnel to identify issues such as imbalance, looseness, misalignment, or bearing wear in assets prior to significant degradation and failure. This gives the plant more options and more time to respond, allowing for more effective resolutions.

There are wireless vibration sensors that are utilized by plant sites to measure vibration. These wireless vibration sensors could be uniaxial, biaxial, or triaxial. Also, these wireless vibration sensors can have different wireless connectivity characteristics, such as communicating information over a cellular gateway, enterprise Wi-Fi, or 900 MHz. Among different wireless connectivity modes, the performance of cellular and Wi-Fi are comparable, while 900 MHz has a limited capability to transmit measured vibration spectrum or waveform. A basic architecture to support wireless vibration data transmission from sensor to a dashboard is shown in Figure 2.

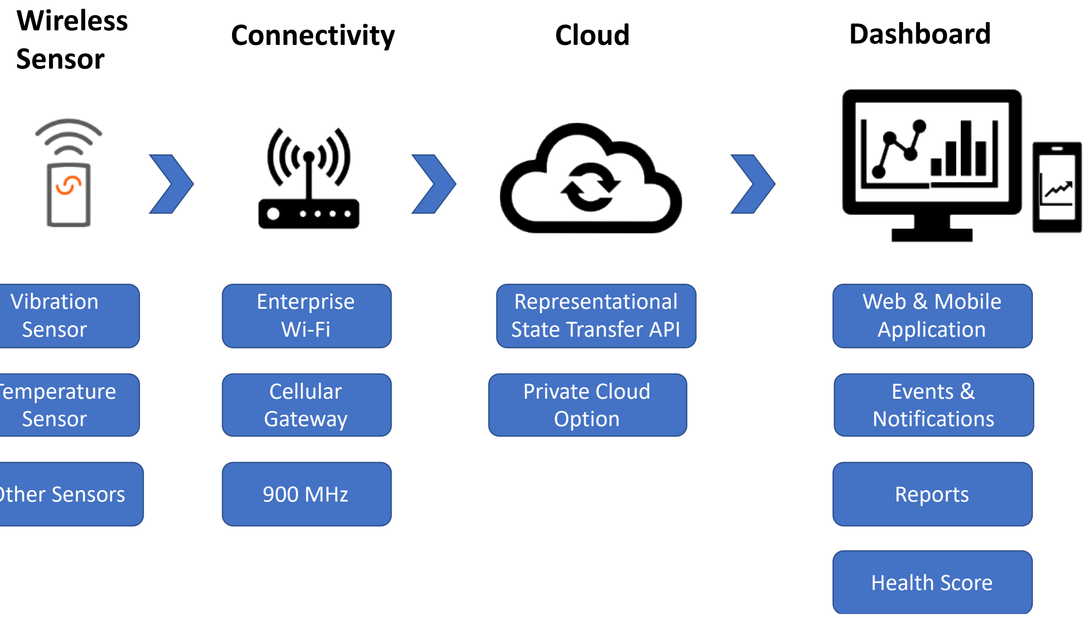

Figure 2. General schematic of wireless data transmission from sensor node to base station for processing, analysis, decision-making, and visualization.

On the dashboard, an update to the component health indicator program (CHIP) database must be performed by the Vibration Technology Program Owner in a timely manner when an adverse trend or equipment degradation is detected from the analysis parameters. The status of each component and overall component health is maintained in the CHIP database. All issues reported in CHIP require the creation of a problem report, as well as a CHIP technology examination, with a notification. The CHIP technology examination and notification shall document the condition and recommended corrective actions.

In this section, different types of wireless vibration sensors compatible with different network communication protocols are discussed along with proximity probes. These are some of the wireless vibration sensors that partner plant sites are considering installing on their plant assets to enable online vibration measurement.

3.1 Wi-Fi-Based Wireless Vibration Sensor

There are many commercially available Wi-Fi-based wireless vibration sensors. These vibration sensors transmit the data over the established enterprise Wi-Fi network from a measurement point to a gateway and from the gateway to the cloud. One of the Wi-Fi based wireless vibration sensors is Petasense [3]. The Petasense wireless vibration sensor, referred to as a vibration mote and shown in Figure 3, contains three accelerometers and a thermocouple. There are two models of vibration motes, and their characteristics are summarized in Table 1. The technical specifications that are common to both the models of the vibration mote are summarized in Table 2. The vibration mote is battery powered and can be epoxy or stud mounted on plant assets.

Figure 3. Petasense triaxial vibration mote [3].

Table 1. Petasense vibration motes specifications [3].

Specifications	**Model 1**	**Model 2**
Accelerometer	Triaxial Micro-electromechanical system	Triaxial Piezoelectric sensor
Frequency response	2 to 1600 Hz (+/- 3 dB)	10 to 5500 Hz (+/- 3 dB)
Measurement range	+/- 0.004 g to +/- 8 g	+/- 0.004 g to +/- 5.17 g
Transverse sensitivity	<10%	<10%
Analog to digital conversion	14 Bit	12 Bit
Resolution	Up to 4000 lines of resolution	Up to 8192 lines of resolution
Sensitivity	0.976 mg/LSB (least significant bit)	50 mV/g
Sampling rates	6 options from 20 Hz to 6666 Hz	Up to 20 kHz

Table 2. Petasense vibration mote features common to both models [3].

Physical	
Dimension	Base diameter: 37.5 m
Weight	125 g
Shock resistance	2 m fall, 16 g continuous vibration
Environmental	
Temperature measurement range	-40°C to 85°C
Operating temperature range	-40°C to 85°C
Power	
Source	CR123A Lithium 1500 mAh 3V battery
Connectivity	
Wireless protocol	802.11 b/g/n Wi-Fi 2.4 GHz Bluetooth low energy 2.4 GHz
Antenna	Integrated antenna with 2.5dBi max gain
Processor	32-bit 144 MHz ARM Cortex processor

3.2 IEEE 802.15.4-Based Wireless Vibration Sensor

One of the wireless vibration sensors based on IEEE 802.15.4 wireless is the Bently Nevada Ranger Pro, as shown in Figure 4 [4]. This sensor measures velocity, acceleration, and temperature. Ranger Pro wireless vibration sensors are efficient for machines with roller-element bearings, which include, but are not limited to, centrifuges, motors, small reciprocating compressors, small hydro and steam turbines, and others. The wireless transmission range of these sensors varies depending on environmental obstacles, gateway antenna type, and the orientation of the sensor relative to the gateway antenna. The technical specifications on the Bently Nevada Ranger Pro are summarized in Table 3.

Figure 4. Bently Nevada Ranger Pro wireless vibration sensor [4].

Table 3. Bently Nevada Ranger Pro wireless vibration sensor technical specification [4].

Accelerometer	
Axis	1 or 3 axis
Sensing element	Piezoelectric ceramic
Amplitude range	+/- 20 g peak
Measurement accuracy	+/- 5% (160 Hz) Z-axis; +/- 10% (160 Hz) X- and Y-axis
Transverse Sensitivity	7% Typical (160 Hz)
Acceleration frequency range	Z-axis: 5 Hz to 10 kHz; X- and Y-axis: 5 Hz to 4 kHz (triaxial sensor only)
Samples per acquisition	1024, 2048, 4096, 8192
Spectral lines	400, 800, 1600, 3200
Temperature Sensor	
Range	-40°C to 120°C
Resolution	0.1°C
Mechanical	
Dimensions	88 mm (height) and 40 mm (diameter)
Weight	230 grams
Environmental	
Temperature range	-40°C to 85°C
Wireless Radio	
Radio	IEEE 802.15.4
Radio frequency	2.45 GHz Industrial, Science, and Medical band (ISM)
Power	
Power source	Replaceable D size 3.6 V Lithium-thionyl chloride

3.3 Cellular Compatible Wireless Vibration Sensor

The KCF Technologies wireless sensor node transmitted X- and Y-direction vibration data, along with temperature data, to the base station over a DART wireless protocol, which then can transmit the data to the cloud either by using the Wi-Fi network or cellular network [5]. The data stored in the cloud is accessed through KCF SMARTDiagnostics® (SD) machine condition monitoring software [6]. SMARTDiagnostics® provides an interface to visualize the data and the state of the equipment. Each sensor node contains two accelerometers and a thermocouple. The sensor node contains a battery and a transmitter to communicate data to the base station. The technical specifications are provided in Table 4. The vibration sensor node (VSN) is software-configurable and scalable. Hundreds of sensor node points can be accommodated, and each sensor node can be configured to transmit data at a user-selected frequency. Unique indicators derived from the data can be implemented to alert users of potential machine health issues. The dimensions of the SD-VSN-3 are given in Figure 5.

Table 4. KCF VSN technical specifications.

Accelerometer	
Range	+/- 19 g typical, +/- 16g nominal
Resolution	0.866 mg
Noise Floor	1.496 mg root mean square (RMS) @ 64 Hz / 12.01 mg RMS @ 8192 Hz
Transverse Sensitivity	10% Typical
Frequency Response	+/- 5% 0-2700 Hz, +/- 3 dB 2700-4000 Hz
Samples per acquisition	4096 (standard) or 1650 (battery saver)
Spectral lines	2048 (standard) or 825 (battery saver)
Anti-aliasing filter	4000 Hz low-pass cut off, 3rd order Sallen-Key
Sampling frequency	64 Hz–8192 Hz configurable
Temperature Sensor	
Range	-4–167°F (-20–75°C)
Resolution	+/- 1°F (+/- 0.5°C)
Mechanical	
Dimensions	2.06 in. Max width × 3.21 in. height (52.3 mm × 81.5 mm)
Weight	6.6 oz (188g)
Environmental	
Min. operating temp	-4°F (-20 °C)
Max operating temp	230°F (110°C) surface @ 72°F (22°C) ambient 212°F (100°C) surface @ 105°F (40°C) ambient 167°F (75°C) surface @ 167°F (75°C) ambient
Wireless Radio	
Radio	KCF DART wireless 2.4 GHz ISM band
Network Communications	Ethernet (IEEE 802.3) Wi-Fi (IEEE 802.11) Cellular
Power	
Power source	3V Lithium Manganese Dioxide

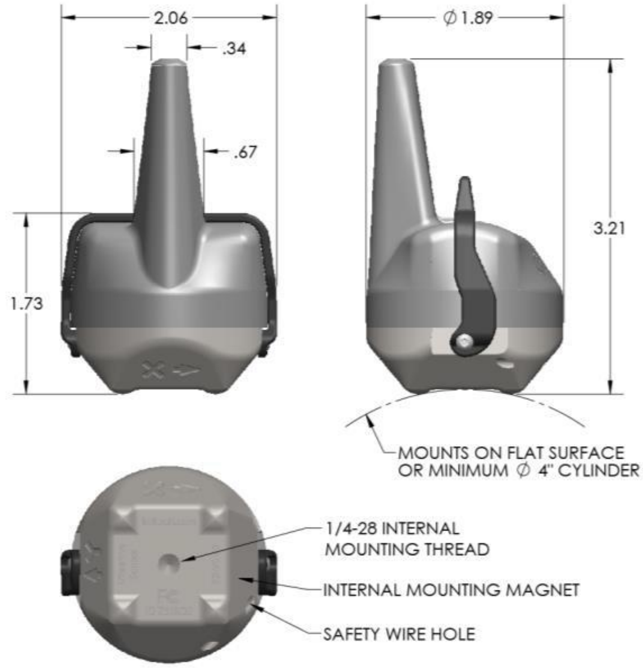

Figure 5. The dimensions of the SD-VSN-3 sensor node [5].

SMARTDiagnostics® uses the 2.4 GHz ISM Radio Frequency (RF) band for sensor node communication. The 2.4 GHz ISM RF band is able to effectively balance energy efficiency and transmission range within industrial facilities. Other bands, such as the 915 MHz ISM band, offer an insufficient data rate to transfer large data sets effectively. The 5.8 GHz band has a range which is too close for practical application in industrial conditions.

SMARTDiagnostics® makes use of five channels, as shown in Figure 6 and mentioned in Table 5. The five channels are overlaid on a Wi-Fi spectral usage chart. Wi-Fi typically operates within channels 1, 6, or 11. If Wi-Fi Channel 6 happens to be used in the plant, SMARTDiagnostics® channels D and E can be enabled. If Wi-Fi channels 1 and 11 are active, SMARTdiagnostics® channels A, B, and C can be used without disruption.

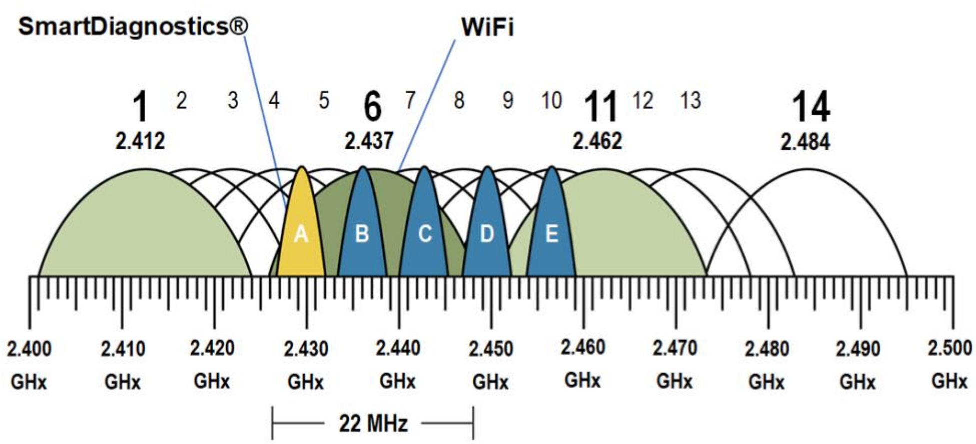

Figure 6. SMARTDiagnostics® uses a modified portion of the 2.4 GHz ISM RF band for the sensor node transmission [6].

Table 5. Center frequencies of the various SMARTDiagnostics® channels [6].

SMARTDiagnostics® Channel	A	B	C	D	E
Center Frequency (MHz)	2429	2436	2443	2450	2457

SMARTDiagnostics® uses one or more of the five available channels, depending on the application. Each channel usually communicates with up to 50 sensor nodes. The wireless coverage area is approximately 200 feet from the base station. Within the 200-foot perimeter, 250 sensors can usually communicate with a single Collection Server in the cloud. Industrial plants can be split into defined areas, with Collection Servers disseminated to support each area.

3.4 Proximity Vibration Probe

Traditionally, plants have relied on proximity probes to measure any vibrational changes in rotating machinery. Proximity probes use the Eddy current principle to measure the distance between the probe tip and the surface to be observed. The proximitor, an electronic device, generates a low power RF signal which is connected to a coil of wire inside the probe tip to the extension cable to measure changes in the field or return signal without physical contact. Figure 7. Bently Nevada proximity sensor system [7].shows a Bently Nevada proximity sensor system [7]. A proximity sensor system is commonly used to measure vibrations in rotating machines with sleeve bearings. Proximity probes are available in many different lengths and diameters.

Figure 7. Bently Nevada proximity sensor system [7].

4. SUMMARY AND PATH FORWARD

This report presents some of the different wireless vibration sensors capable of transmitting data over different communication networks being examined for installation in partner plant assets. We also present an application of vibration data and indicators to assess the health of a plant asset. The report presents some of the commercially available wireless vibration sensors that are under consideration for installation by a partner plant site.

As part of the path forward, plant process data, along with vibration data collected from any of the vibration sensors, will be used to develop diagnostic and prognostic models.

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