A wireless sensor platform for industrial non-hermetic metallic enclosures

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A Wireless Sensor Platform for Industrial Non-hermetic Metallic Enclosures

M. Adel Ibrahim[1], Galal Hassan[2], Hossam S. Hassanein[2] and Khlaed Obaia[3]
[1]Electrical & Computer Engineering, Queen's University, Kingston, Canada
[2]School of Computing, Queen's University, Kingston, Canada
[3]Oil & Gas, Edmonton, Canada

Monitoring the reliability of equipment in industrial environments requires the installation of wireless sensors inside such equipment. A common challenge associated with having a wireless sensor inside a metallic enclosure is hindered wireless signal propagation and reception. We design a wireless sensor platform for such industrial applications and test its resilience to the shielding effect of metallic enclosures. A generic model of an industrial metallic enclosure is created with only 1 *mm* gap in its structure. We show that our sensing platform can successfully establish a low-data-rate wireless link. Signal measurements are made to quantify the received signal strength.

wireless sensor network (WSN); hardware; sensor platform; wireless sensor; industrial environment; industrial internet of things; harsh environment

I. Introduction

Industrial processes are becoming smarter and more efficient. Wireless sensor networks (WSNs) have enabled low cost monitoring, control, and optimization of modern industrial processes. The deployment of WSNs is usually correlated with reducing maintenance costs, unscheduled downtime, risk of accidents, and industrial waste. This results in more optimised industrial processes and significant added economic value.

One essential component of any WSN is the sensor platform (SP). It is the piece of hardware designed to host all the hardware components needed for the operation of the network. The SP is usually designed to satisfy specific application requirements such as cost, size, lifetime, latency, and data rate.

Industrial equipment is generally made of metals (e.g., steel) due to their strength, ductility and durability. These properties allow industrial equipment to tolerate high levels of mechanical stress. While metals have numerous desirable mechanical properties, their high electrical conductivity causes reflection and attenuation to electromagnetic waves. This makes it hard to install wireless sensors inside metallic industrial equipment. Machinery and equipment with metallic enclosures and structures are very common in industrial settings, e.g., pumps, turbines, metallic pipes, valves, combustion chambers, engines, pipes, chemical reactors, motors and robotic arms. Their control systems must have some sort of feedback in order to optimise and stabilize their operation. As the future heads for smarter and more automated equipment and machines, the need for transmitting data wirelessly in and out of its metallic enclosures becomes more pressing.

We design a wireless sensor platform for industrial applications and test its resilience to the shielding effect of metallic enclosures. Section 2 presents background and related work. Our SP is introduced in Section 3. Sections 4, 5 and 6 respectively detail the enclosure model, RF unit specifics and the test scenarios and signal measurements. Finally, Section 7 concludes the paper.

II. Background and Previous Work

WSNs are composed of a number of hardware sensor nodes (motes) that are linked wirelessly through a radio frequency (RF) link. Each sensor node hosts a radio transceiver, a microcontroller, a power supply and some sensors. A protocol stack manages communications on all the layers starting from the physical layer and up to the application layer. Different applications depict different requirements for the hardware design of the SP. This work is about a SP developed specifically operate from within a metallic enclosure.

In the literature, SPs are custom developed for each industrial application. For example, to monitor the impeller wear for a centrifugal pump [1], to count the grains in a seed drill [2], monitor water pipelines [3], aid search and rescue robots in hazardous situations [4], or monitor axial tension of bolts in civil steel structures [5]. Numerous other examples can be added to the list; however, none has tackled the challenge of transmitting a radio signal from within a metallic enclosure. In this work, the problem is approached on the hardware system level.

A. Classification of industrial enclosures

As shown in Fig. 1, industrial enclosures can be divided into two types (based on their material): metallic and non-metallic. Metallic enclosures are those made completely or partially from metals. Metallic enclosures impose a much bigger challenge on the hardware designer because of their high electrical conductivity. Further on, enclosures can be sub-classified (based on the type of concealment) into two types: hermetic and non-hermetic.

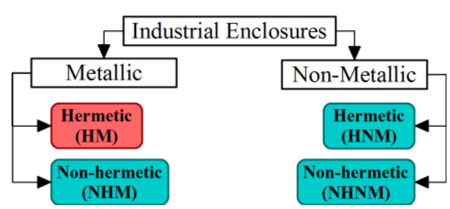

Fig. 1. Classification of industrial enclosures according to their material and type of concealment. The green types are the ones addressed by this work while the red is not.

Non-metallic enclosures are those made completely from non-metals. This type of enclosures (whether hermetic or non-hermetic) do not impose any challenges to RF signals. Thus, they are not the focus of this work because arbitrary RF signals are able to propagate through these enclosures with no or minimal attenuation.

Hermetic metallic (HM) enclosures are perfectly concealed and can be described as airtight. In other words, the metallic structure provides no or negligible clearances between its metallic components. Examples of HM enclosures are: pumps, turbines, gas cylinders, and combustion engines. This type of enclosures is beyond the scope of this work because, wireless communications from within these enclosures cannot be achieved by a propagating electromagnetic wave however, it requires different techniques [6] which are classified into either electromagnetic techniques (inductive coupling, capacitive coupling, and magnetic resonance coupling) or acoustic techniques.

Non-hermetic metallic (NHM) enclosures are those with a low level of concealment. They are often designed to provide mechanical shielding from abusive environments. NHM enclosures have relatively large clearances between the metallic components of their structure. They can still be described as airtight if the containment structure is not fully metallic. Examples of NHM enclosures are shipping enclosures, refrigerators, and industrial ovens.

NHM enclosures are very common in countless industrial applications. This enclosure type can represent any industrial setting where the SP is surrounded mostly by metals but not from all direction. Thus, the assumption is that it is possible for the RF signal to propagate and reach it destination. In this work we investigate the propagation of RF signals transmitted by a SP from within an NHM enclosure.

B. *Previous work on sensor platforms*

Low frequencies (sub-1 GHz) holds the best potential in escaping industrial NHM enclosures because free-space path loss is directly proportional to the signal's frequency [7]. Most SPs presented in the literature has RF transceivers that operate at relatively high frequencies assuming an open-air environment around the platform. Moreover, they usually have a large form factor which makes them inadequate for confined cavities. Arkas [8] is an example of this type of platforms because, it was designed for environmental monitoring and it uses the ZigBee protocol which operates at 2.4 GHz. Consequently, Arkas lacks the ability to cope with constraints introduced by NHM enclosures (e.g. small form factor and suitable RF transceiver). The SP in [9] is another example of a platform that does not satisfy the desired constraints. It has a high frequency RF interface (i.e. Wi-Fi/Bluetooth).

The RoSe platform developed by the authors in [10] is a good example of a robust ultra-low power platform. It worked at a sub GHz band which is more suitable for NHM enclosures. Their work represents a well thought out design process and a rigorously tested product, unfortunately, the RoSe was designed for food monitoring applications which assumes an open-air environment around the antenna. The transceiver used (SX1211) had a maximum output power of 12.5 dBm which could be insufficient and it does not support spread spectrum.

The authors in [11] have demonstrated an integrated system on chip (SoC) solution that can minimize power consumption. Their WiseNet node architecture has achieved an impressive figure of power consumption as little as 1 mW in receive mode with a -95 dBm sensitivity at 24 Kbps. The authors while aiming to introduce a generic SP, the transmitter supported only some of the ISM band frequencies (433 and 868 MHz) and had an output power limited to 10 dBm.

In [12], an RFID platform has been developed which utilizes an energy harvesting technique to power its own components when interrogated by a reader. The platform utilized a printed dipole antenna to harvest RF energy. The range of interrogation has been assessed up to 1.5 m. While this range is suitable for passive RFID applications it is not suitable for industrial WSNs.

A low power SP was developed in [13] for environmental monitoring. A ZigBee radio working at 2.5 GHz was used, however, the range wasn't sufficient and a second version was developed using 868 MHz radio. The system had two voltage regulators which caused an efficiency drop in terms of power consumption. The sensors utilized were digitally interfaced to the controller using Maxim's proprietary 1-Wire protocol. The system was implemented and partially deployed with a reported range of 3 km and a life expectancy of more than 3 years using a bulky 10 Ah battery. Again, open air environment were assumed for this platform.

The sprouts platform [14] is the closest work to the scope of this work. Intended to be installed in a NHM enclosure. However, the system was intended for scenarios with high clearance and/or short required communication range. While maintaining a small form factor, the frequency of its RF transceiver (2.4 GHz) is also too high to allow the EM wave to escape the metallic enclosure with enough power.

When it comes to different application domains, several design constraints can change. Consequently, a different SP will emerge from the design cycle. This is obvious in [25] where the requirements for multimedia applications have dictated the use of a power hungry processor chip and a high bitrate transceiver (Bluetooth). Needless to say, industrial WSNs with a low data rate requirement will not benefit from the platform presented in [25]. Indeed, a generic platform designed for NHM enclosures is not present in the current literature.

III. The Sensor Platform

It is common in industrial environments to find the SP installed within a metallic structure of some sort in order to shield it from mechanical abuse. In typical scenarios the metallic structure exists already, and the SP has to be designed to fit inside the machine's cavities without disturbing its operation. Thus, the hardware designer of the platform must satisfy the following four requirements:

1. The SP should not interfere with the operation of the machine. For example: installation should not involve any mechanical modification (e.g. drilling) that can compromise the structural integrity of the machine.

2. The SP should tolerate harsh operating conditions (e.g., vibrations, mechanical shocks, extreme temperature or pressure and reactive substances).
3. The RF link must be resilient to the shielding effect of the surrounding metallic structure (i.e., the RF signal should have enough power to overcome reflections, attenuations, or parasitic interference).
4. The life time of the SP should satisfy its application-specific design goals (e.g. cost, efficacy and recycling constraints).

In this work we design a hardware platform that satisfied all four requirements. The first requirement is application dependent because industrial equipment have different operation conditions. This imposes a different set of requirements on the hardware of an SP for each piece of equipment. Thus, we consider one representative application as a case study. The application of choice in this work is the problem of monitoring the teeth of mining shovels. This problem has been introduced by the authors in [14] where a potential solution was proposed by using a 2.4 GHz wireless sensor but was not implemented. In this work we develop a different platform working at the sub-1 GHz band and produced a functional prototype.

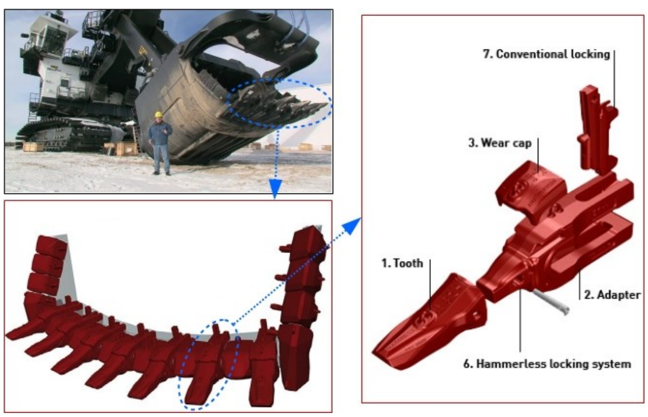

Fig. 2 An electric rope shovel (upper left), a set of adapters/teeth (lower left), and an adapter/tooth assembly (right) [16].

In our design we are constrained by the size of the cavity inside the shovel teeth adapter (item #2 in Fig. 2, right) which is 228×76×25 *mm*. The platform shown in Fig. 3 is designed to host all the required components including the battery within the given cavity. It includes magnetic anchors to hold itself to the cavity wall. This enables its installation by untrained technicians without any drilling, welding or any mechanical alterations to the equipment. In this manner, the first requirement is satisfied.

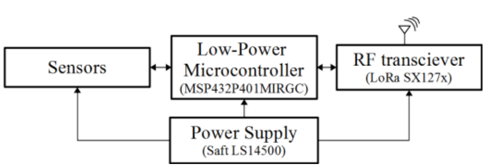

Fig. 3. Block diagram of the hardware sensor platform.

In order to satisfy the second requirement we list all harsh operating conditions. In the given mining application the harsh conditions were extreme temperatures, and elevated mechanical stresses (vibrations and shocks).

Mining operations usually take place in remote areas with extreme weather conditions. For example, in Alberta, Canada, one of the largest oil sand mining operations are carried out in Fort McMurray where the temperatures can swing from an extreme minimum of −45℃ on a cold winter night to an extreme maximum of 36℃ on a hot summer day [17]. Fig. 4. Shows the cumulative density function (CDF) of extreme (maximum and minimum) daily temperatures on record between 1955 and 2016.

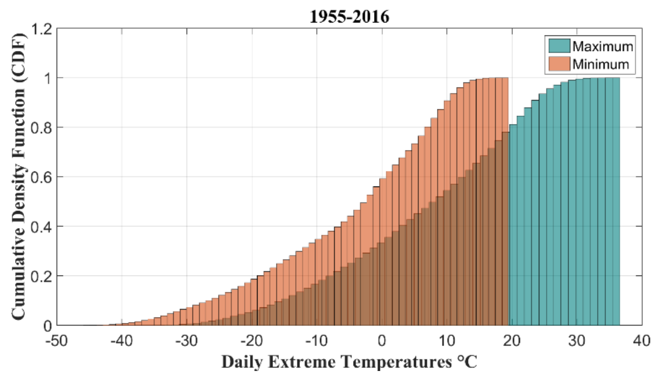

Fig. 4 CDF of daily extreme temperature records in Fort McMurray between 1955 and 2016 [17].

As for the maximum operating temperature, most components available on the market will sustain an operating temperature of 85℃ or more. However, to ensure the sensor's resilience to low temperatures, only components with operating temperatures down to −40℃ or less has been used in the circuit design. The probability of temperatures less than −40℃ is 0.005387. Further on, a transparent epoxy pouring was used to encapsulate the printed circuit board (PCB). The thermal conductivity of the used epoxy is $0.237\ W/(m \cdot K)$ [18]. With such low thermal conductivity, the operating temperature of the platform extends even below −40℃.

Some electric rope shovels have a nominal capacity of up to 122 metric tonnes [19]. A sensor within its bucket's teeth is expected to experience significant levels of vibrations and mechanical shocks during operation. Our platform is protected from such stresses by the epoxy pour whose compressive strength is 85 N/mm^2 [18]. This allows for compressive loads (mechanical vibration and shocks) to be transferred safely through the package without rupturing the PCB.

The third hardware requirement is about allowing the electromagnetic wave to escape the enclosure with enough power to reach its destination reliably. There are two design methodologies to satisfy this requirement. The first one works by treating the metallic enclosure and its gaps as a resonant cavity [20]. This means several aspects of the design has to be optimised to a specific enclosure given its exact dimensions. A custom antenna design, its position and orientation inside the enclosure, and the frequency of operation f_o. If the SP were to be installed in different enclosure, its performance will completely differ. While this method allows the wave to escape the enclosure more efficiently (using less transmitting power P_t), it only works for one specific type of enclosures and a significant portion of the design process will have to be repeated for any other enclosure.

The second method is more generic and applicable to almost all enclosures, however it is more energy demanding. It starts by calculating the cutoff frequency f_c (lowest resonant frequency) of the enclosure and its gap and choosing a higher operating frequency f_o for the platform. Then it is a matter of getting a transceiver with sufficient transmitting power that can balance the link budget at the required range R given the receiver's sensitivity S_{min}. It gets tricky because this will increase energy consumption and reduce the lifetime. Thus, the number of data packet transmitted N_p and the size of data payloads should be optimized to balance the energy budget. This method is also more cost effective since it is more generic. The sensor platform presented in this work has an aggregate components cost of no more than a 120 Canadian dollars (estimated on Feb. 2nd, 2017).

The fourth hardware requirement is about the life time of the SP. In this context we identify one bottleneck which is the energy budget. The other factor that could affect the lifetime is hardware failures due to harsh operating conditions but, this is already addressed in the second requirement. The energy budget of our platform is discussed in section V.

IV. NHM ENCLOSURE MODEL

We designed a NHM enclosure model as shown in Fig. 5 and Fig. 6. The base and the cover were each machined from a single piece of steel. It has two identical gaps ($228.6 \times 1\ mm$) on opposite sides. The depth of each gap is $76.2\ mm$. A total of 8 Screw holes were threaded on the edges to secure the cover tightly to the base. The total weight of the model is 23 Kg. The dimensions of this model are chosen to mimic the cavity in the shovel's adapter in our case study. The gaps in the model are similar to those between the adapters and the shovel's bucket when the adapter is installed. The signal is received by an antenna mounted on top of the operator's cabin which is about $25\ m$ away from the moving bucket.

From a signal propagation stand point, representing various industrial enclosures with one physical model is infeasible. However, a model representing an extreme RF shielding case could be used to set a lower bound for the performance of the SP. With a gap of only $1\ mm$, this model has a significant shielding effect compared to typical industrial NHM enclosures which usually have wider gaps and openings. Thus, the SP that proves to work for this particular enclosure is likely to work for other less concealed enclosures.

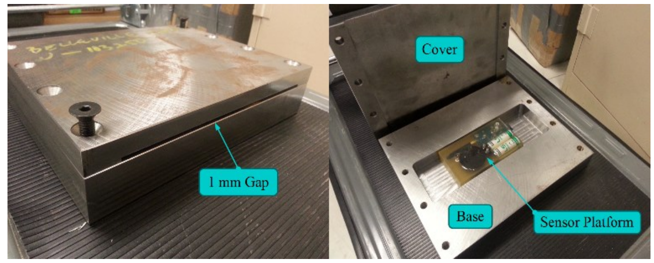

Fig. 5 The NHM enclosure model and the sensor platform inside its cavity.

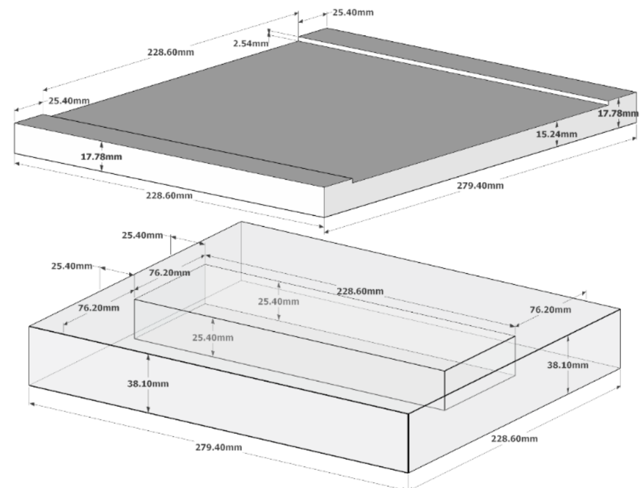

Fig. 6 CAD drawing of the enclosure model.

V. COMMUNICATION LINK

The modem chip selected for our platform was the Semtech SX127x. It incorporates a LoRa™ spread spectrum module that achieves 8dB better sensitivity than using FSK modulation at an equivalent data rate. For compatibility with existing systems the selected chip provides the standard radio modulation and demodulation techniques (GFSK, FSK, OOK, and GMSK) [21]. LoRa™ uses a spread spectrum technique namely, Chirp Spread Spectrum (CSS). It also uses forward error coding in combination with whitening and interleaving in order to achieve this improved sensitivity. LoRa™ operates in the 433MHz, 868MHz, and 915MHz bands making it suitable for ISM bands in both Europe and North America. LoRa™ is designed for Low Power Wide Area (LPWA) networks, however, in this work we implement our own network stack to create the WSN. The chip also provides ease of access to multiple modulation settings thus increasing flexibility of implementation; allowing the user to balance receiver sensitivity, power consumption and bitrate. This is crucial for optimizing the lifetime of our SP while ensuring a resilient communication link.

The energy budget is composed of two variables that needs to be balanced. One variable is the total energy supply E_s while the other is the total energy consumption E_c. For a given lifetime, the budget balancing condition can be represented as:

$$E_s \geq E_c \qquad (1)$$

We start by estimating E_c first and then E_s to satisfy the condition in (1). For the given case study, the lifetime goal is one year. In our platform E_c is the sum of the energy consumed by each of functional blocks in Fig. 3. Therefore

$$E_c = E_{TRx} + E_{\mu c} + E_{sensors} \quad (2)$$

Where E_{TRx}, $E_{\mu c}$ and $E_{sensors}$ are the energy consumed by the transceiver, the microcontroller and the sensors respectively. Considering a duty cycle of one packet every minute. The total number of transmitted packets is 525600. Every packet consumes $125\,mA$ at $3\,V$ for a time on air of $387\,ms$. Therefore,

$$E_{TRx} = 125 \times 10^{-3} \times 3 \times 525600 \times \frac{387 \times 10^{-3}}{60 * 60} = 21.19\,Wh \quad (3)$$

The microcontroller will be in an active state for 2 seconds every one minute. These 2 seconds accounts for reading the sensors and assembling a data packet to be transmitted. It consumes$1.28\,mA$ in the active state and $630\,nA$ in the chosen low power mode. Therefore,

$$E_{\mu c} = (1.28 \times 10^{-3} \times 2 \times 525600 + 630 \times 10^{-6} \times 58 \times 60 \times 24 \times 365) \times \frac{3}{60 \times 60} = 17.126\,Wh \quad (4)$$

The circuit is designed so that the sensors are powered off most of the time, except during the 2 seconds active period of the microcontroller. This makes the sensors consume a negligible amount of energy overall $(E_{sensors} \approx 0)$. Therefore $E_c = 38.316\,Wh$.

In our application, energy harvesting was not an option. The platform relies solely on energy storage (battery). The capacity of our chosen battery cell (Saft LS14500) is $2.6\,Ah$ at $20°C$. However, the capacity at -40℃ is rated at $1.4\,Ah$ only. Since it is not possible to know the future operating temperature over a one year period, it is a safe estimate to use the mean value of the two ratings ($2\,Ah$). The same applies to the rated voltage. It is $3.6\,V$ at $20°C$ and as low as $2.4\,V$ at $-40°C$. Similarly we consider their mean value which is $3V$. Therefore, the average energy capacity of one cell is $6\,Wh$. In order to satisfy the condition in (1), the platform is supplied with 7 battery cells which allows for $E_s = 42\,Wh$.

To save energy further during the shovel down times, the platform has a vibration sensor onboard which allows the system to switch to a low power mode whenever the shovel is not moving. If the shovel starts moving, the vibration sensor will immediately interrupt the sleeping microcontroller and puts it in the active mode again.

VI. Measurements and Results

An experiment to test the communication link and quantify the received signal strength (RSS) is conducted. Data packets are sent from the platform inside the enclosure and received at the other end (without errors) and then used to quantify the RSS. The settings used in the experiment are listed in Table I.

A. *Experimental setup*

The LoRa™ transmitter is programmed to transmit with maximum power ($20\,dBm$). However, due to coupling losses and implementation imperfections, the actual measured power at the input of the antenna was $18.5\,dBm$. A custom designed patch antenna of a $3dB$ maximum gain was used.

In a wide open outdoor area, the platform was activated and placed inside the cavity of the enclosure. The lid was closed tightly using four corner screws. The enclosure was placed on a turntable with a degree scale. The receiver Yagi antenna ($18\,dB$ maximum gain) was placed horizontally $30\,m$ away from the enclosure. RSS readings were collected with 10º steps of angular rotation.

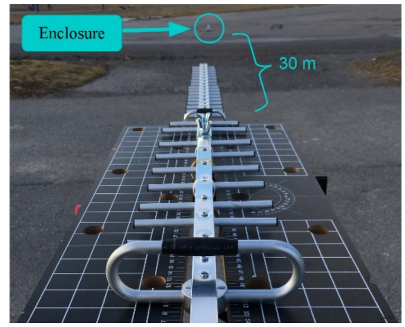

Fig. 7 The experimental setup showing the Yagi antenna at the receiver side and the enclosure 30 m away.

Fig. 8 The orientation of the enclosure with respect to the angle of rotation in the horizontal and the vertical position.

Table I. Programmed LoRa™ settings

Parameter	Value	Units
Spreading Factor	12	
Bandwidth	500	KHz
Coding Rate	4/5	
Center Frequency	915	MHz
Preample	20	$Symbols$
Data Payload	20	$Bytes$
Transmit Power	20	dBm

B. *Measurements*

The RSS readings from all angles around the enclosure are shown in Fig. 9. Two sets of measurements are provided: one for when the enclosure is placed horizontally and the other when it was placed vertically as shown in Fig. 8. At each angle, 20 readings were collected and their average is used in the plot. Confidence intervals are two times the standard deviation of all readings recorded at that angle. In other words it includes 68% of the population of readings assuming a normal distribution.

As shown in Fig. 9, orienting the enclosure vertically gives higher RSS readings over all the angles. The reason behind this observation comes back to the complex relationship between the antenna inside the enclosure and the structure of the enclosure because it exists in the reactive field of the antenna. The pattern of the RSS readings started to repeat itself at 180°. This is expected since the enclosure and the antenna inside it are symmetrical around the rotation axis. While the RSS readings are at a very low level, it is still within the link budget corresponding to the used settings ($151\ dB$).

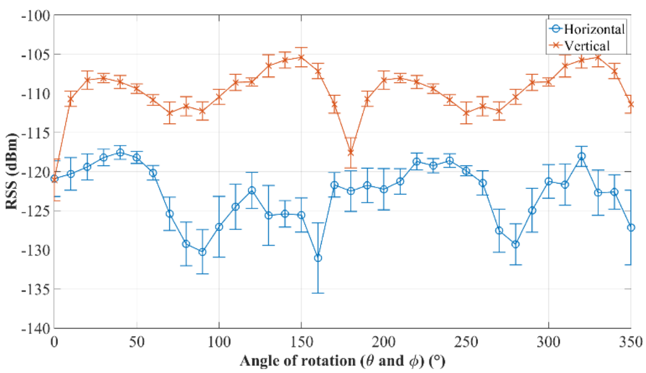

Fig. 9 Received signal strength at 30 m range for all agles around the enclosure when placed horizontally and vertically.

VII. Conclusion

In this work we designed and implemented a low cost wireless sensor platform for metallic enclosures. The platform was installed inside an industrial NHM enclosure made of steel with a $1\ mm$ gap. We demonstrate the viability of having a wireless communication link with a range of $30\ m$. The received signal strength was measured from all angles around the enclosure. The aggregate bit rate is $1.172\ kbps$ which can accommodate low resolution sensory data such as temperature, pressure, flow rate, and binary state variables. An example application of monitoring mining shovel's teeth is presented. The platform have an energy budget enough for at least one year of continuous operation.

Acknowledgment

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