A Study of Electromagnetic Robustness of IO-Link Wireless and SmartMesh IP for Applications on an Agricultural Vehicle

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***Abstract*—This paper presents a study on the electromagnetic robustness of IO-link Wireless and SmartMesh IP for their use on an agricultural vehicle. Especially the multipath fading due to the reflective nature of the agricultural vehicle is challenging for such wireless communication protocols. The electromagnetic robustness was tested in a double reverberation chamber as well as on an actual combine harvester. Detailed test setups and procedures are in the paper. Throughout the tests, several key parameters related to the quality of service (QoS) of both protocols were monitored with a specific focus on latency and packet error rate (PER). Test results show that both IO-link Wireless and SmartMesh IP experience a decrease in data throughput and an increase in latency in a (semi-)reverberant environment. In particular, transmission power needs to be carefully regulated for IOLW, while SmartMesh IP is dependent on the mesh formation and the distance between its Manager and Motes. Test results also show that a fully reverberant environment is harsher than the actual harvester. Thus, the initial steps were made to dampen the RC with absorbers to comply with the environment created in a harvester, resulting in a comparable PER of 4.1 %.**

***Index Terms*—Reverberation chamber, Wireless sensors, IO-link Wireless, SmartMesh IP, Agricultural vehicle**

I. INTRODUCTION

While wireless communication has become inherent to our daily life, this is not yet the case for industrial applications where wired communication like Industrial Ethernet is still prevalent. However, as we continue to increasingly equip machinery with sensors, wired communication comes with several drawbacks. First, modifying a wired communication network after installation can be quite strenuous and time-consuming. Second, all necessary cabling is often hard to reach for maintenance or repair. Third, especially in application areas like automotive, avionic or agricultural, cables add significant extra weight to the product-at-hand [1].

In this paper, we focus on the application of wireless communication in the agricultural sector that moves towards the concept of Smart Farming (SF) [2]. SF refers to the extensive use of technologies (e.g. Internet-of-Things, robotics and artificial intelligence) to increase the quantity and quality of agricultural products while optimizing the human labour that is required. SF assumes the use of many sensors that might result in tens of sensors on board an agricultural vehicle (AgV). These sensors might gather data about the AgV itself, its environment, soil conditions, etc. [3]. Also, there is a clear need to lower the ecological footprint of the farming industry, which involves making an AgV more energy-efficient. As a result, the AgV's weight should be minimised. Thus the use of wireless communication and, hence, wireless sensor networks (WSNs) is to be preferred over their wired equivalents.

As the concept of SF moves forward, it evolves to fully autonomous AgVs [4]. To guarantee the safety and trustworthiness of an autonomous AgV, stringent reliability and robustness requirements are being put onto WSNs. The quality-of-service (QoS), with parameters like latency or packet error rate (PER), should be nearly perfect despite all the harsh conditions the AgV is encountering during its operation: various weather conditions, mud, vibrations, etc. Moreover, AgVs will be more electrified. Hence, an increasing use of power electronics will make the electromagnetic (EM) environment on the AgV more challenging and a proper choice of the wireless protocol to be

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No 812.788 (MSCA-ETN SAS).

This publication reflects only the authors' view, exempting the European Union from any liability. Project website: http://etn-sas.eu/.

This work is also supported by a research grant from the Flemish Agency for Innovation and Entrepreneurship (VLAIO) within the HBC.2020.2168 Smart Wireless Agricultural Sensors (SWAS) project.

used needs to be made. Here, robustness does not only imply that the wireless protocol can withstand EM disturbances, but also implies that it can handle multipath fading that occurs because of the metallic nature of the AgV.

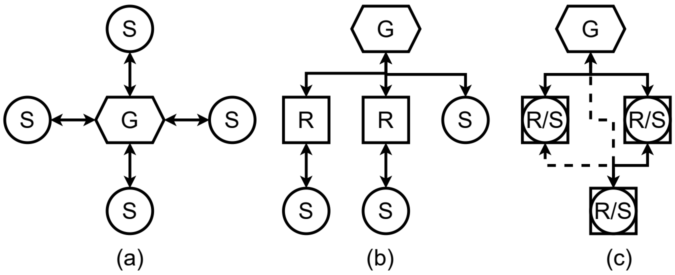
Different WSN protocols are available on the market: ZigBee, ISA100.11a, WIA-PA and others [5]. Although most of these protocols are based on IEEE 802.15.4 standard, their overall organisation, architecture and, hence, their robustness is different. For example, ZigBee does not support channel hopping whereas WirelessHART does. A very relevant parameter of a WSN protocol is its network topology. There are three such WSN topologies (see Fig. 1): a star, a mesh or a hybrid mesh. In a star topology, all sensors, S, are directly connected to the gateway unit, G. In a mesh network, this is not the case and one or multiple hops are needed to get from the sensors, which perform router, R, functions at the same time, to the gateway unit. While this might increase latency compared to the star topology, it allows extending the range of the WSN. A hybrid mesh network combines both and if arranged well, can be a good compromise.

Considering a plethora of WSN protocols, one may need to choose a few of them co-existent with each other and suitable for an AgV for further reliability tests. In this paper, we chose the IO-link Wireless and SmartMesh IP protocols and tested their robustness in a harsh EM environment of a reverberant chamber (RC).

The remainder of this paper is organised as follows. Section II gives a basic introduction to both IO-Link Wireless and SmartMesh IP. Section III details the EM robustness tests that were performed inside an RC, as a worst-case EM environment, on both protocols. Section IV describes the main conclusions of a realistic test of SmartMesh IP on an actual combine harvester. Section V explains the first steps that were taken to mimic the EM environment inside the dampened RC. Finally, Section VI draws concluding remarks.

II. BASIC INTRODUCTION TO IO-LINK WIRELESS AND SMARTMESH IP

This section will give some basic but essential information about the working principle of IO-link Wireless and SmartMesh IP protocols and their key features suitable for the agricultural sector.



(a) (b) (c)

Fig. 1. WSN topologies: (a) Star topology, (b) Hybrid topology, (c) Mesh topology

A. IO-link Wireless

IO-link Wireless [6], abbreviated as IOLW, is a wireless extension to the IO-link protocol [7]. IO-link is standardised in IEC 61131-9 [8] and is compatible with popular fieldbus technologies (PROFIBUS, PROFINET, EtherCAT and others).

IOLW is a star WSN topology in which the gateway and sensors are called the Master and Devices, respectively. IOLW supports both frequency and time division multiple access (FDMA/TDMA). It implements frequency hopping with blacklisting to further strengthen its reliability.

Due to TDMA, the communication phase is split between time slots. IOLW exploits cycles. Each of these cycles utilises FDMA/TDMA with a retransmission option. The cycle by default is set up to 5 ms and consists of three duration equally sub-cycles. IOLW frames contain information that is sent regularly (process data) or occasionally (acyclic data and events in case of the emergent state of a sensor).

IOLW's link quality is based on the residual failure probability (RFP). RFP depends on the maximum number of retransmissions and PER: $RFP = PER^{1+MaxRetry}$. A link quality of 100 % corresponds to the $RFP = 10^{-9}$.

RFP is only one of many tools responsible for the protocol's reliability. Therefore it contains a complete overhead stack in the architecture leading to relatively small payloads. Within one default frame of 5 ms, IOLW supports payloads of 37 and 15 bytes for downlink and uplink, respectively.

B. SmartMesh IP

Unlike IOLW, SmartMesh IP uses a mesh topology. SmartMesh IP is a proprietary solution from Analog Devices [9]. It is based on IEEE 802.15.4 and enables the participants of the network to be access points towards the gateway. The gateway and sensors are called the Manager and Motes, respectively.

SmartMesh IP exploits channel blacklisting and the time-slotted channel hopping (TSCH) technique in which the communication time is split into time slots helping to overcome intersymbol interference by minimising the packet collision. In addition to multiple mesh connections between Motes, the communication is toughened by retransmissions despite the fact that SmartMesh IP packets are UDP packets each of which is 90 bytes long.

To maintain the meshed network, the Manager is responsible for collecting health” reports. These reports are sent from every Mote in the network and contain information about Motes' parameters like power consumption, path stability or the received signal strength indication (RSSI). Using these reports, the Manager improves the network.

SmartMesh IP opens a huge variety of options ([10], [11]) suitable for the agricultural sector. Moreover, the meshed WSN can add more freedom to the sensors' positioning. This is why SmartMesh IP was chosen as a counterpart to IOLW.

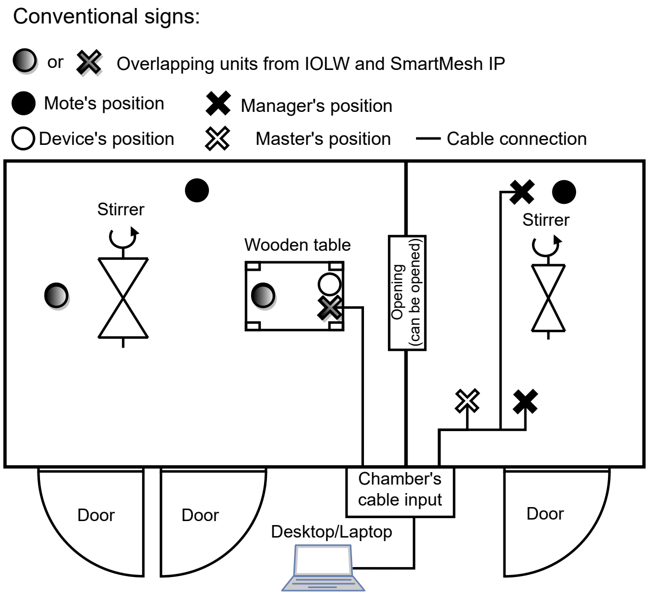


Fig. 2. IOLW and SmartMesh IP test setups inside an RC

III. ROBUSTNESS OF IOLW AND SMARTMESH IP INSIDE AN RC

Since an AgV contains a lot of metallic parts, it represents a semi-reverberant environment. To test the harshest EM environment, the performance of the IOLW and SmartMesh IP protocols was tested inside the double RC available at KU Leuven Bruges Campus. The AgV's rotating parts were recreated with the help of rotating stirrers inside RCs. Fig. 2 shows a schematic overview of the overall test setup for both protocols. The double RC comprises larger and smaller rooms whose dimensions (length, width and height in m) and the lowest usable frequency (LUF) are 6.0×4.2×2.775 with 600 MHz and 2.4×4.2×2.775 with 300 MHz, respectively. The RCs are next to each other and are both stirred. In their common wall, an opening can be made. The double RC allows to more extensively study Line-of-Sight (LoS) and Non-Line-of-Sight (Non-LoS) conditions.

A. Performance of IOLW inside an RC

The IOLW test setup comprised only one Master and one Device. However, during the whole experimental process, both were placed at different locations.

The aim of these tests was to investigate under which conditions or parameters, the wireless communication will remain errorless or almost errorless. Therefore, the following test procedure was used (Fig. 2):

1. One LoS test where both the Manager and Device were placed on the wooden table inside the larger RC.
2. Several Non-LoS tests:
   a) Both the Master and Device were still in the larger RC but while the Master was still on the wooden table, the Device was placed behind the stirrer.
   b) The Master was put in the smaller RC, while the Device was on the wooden table in the larger RC.
   c) The Master was put in the smaller RC, while the Device was put behind the stirrer in the larger RC.

During the tests on IOLW, all the parameters can be conventionally split into two groups: modifiable and monitoring.

The modifiable, meaning that we can control their values, parameters are:

1) Simulation cycle time, i.e. the maximum delay between two subsequent packets in ms;
2) The number of retransmissions (NRTx);
3) The transmission power (TxP) level in dBm;
4) The stirrer's speed (was put to 30 rotations/min and kept for both stirrers in the larger and smaller chambers for all the tests).

The monitoring parameters, used for determining the performance, are:

1) Link quality indicators for the Master and Device in %, the higher, the better;
2) RSSI for the Master and Device in dBm. Again, the higher, the better;
3) Two types of communication errors:
   a) Due to the not received acknowledgement from the Device;
   b) Due to exceeding the NRTx (which is accompanied by an event in IOLW).

Based on errors, two types of PERs can be calculated: the "technical" and "specification" PER that depend on the received acknowledgements and the exceeded NRTx, respectively. For example, if an acknowledgement is not received then the technical error counter will be incremented. Similarly, if the NRTx is exceeded then the specification error counter is increased. To not confuse the reader, we will be solely using the specification PER that will be indicated as PER.

1) Performance of IOLW during LoS tests

For the used devices with their default parameters, the RCs were too reverberant for proper communication. Even during the LoS test, the communication was almost always lost making it impossible to track the monitoring parameters. Therefore the IOLW parameters had to be adapted.

The default TxP of 5 dBm was too high, resulting in high amplitude reflected copies. Therefore the TxP was decreased to 3 dBm resulting in an errorless LoS communication.

When the stirrer rotation was added to the experiment, the IOLW's WSN was hindered, therefore the TxP and NRTx had to be changed and were put to -6 dBm and 6, respectively, to maintain the errorless communication.

The change of simulation cycle time did not affect the communication in any way, thus it was held at the same value (10 ms) during all the tests.

2) Performance of IOLW during Non-LoS tests

Non-LoS tests, even for both the Master and Device located in the larger RC, worsened the communication. However, a combination of the TxP of -6 dBm and NRTx of 6 could lead to almost errorless communication even with the rotating stirrer. Nevertheless, occasional errors were unavoidable.

The opening between the two RCs allowed to put the Master in the smaller RC (see Fig. 2) and still have communication. The Device was put on the wooden table in the larger RC. To maintain stable communication, the TxP and NRTx had to be put to at least -6 dBm and 6, respectively. The stirrer rotation led to occasional errors. However, the stirrer in the smaller room had a higher effect due to its vicinity to the Master. Moreover, the rotation of both stirrers did not lead to any visible change in the monitoring parameters in comparison to the case when only the stirrer in the smaller RC was rotating. Therefore we may assume that IOLW is highly dependable on the Master's stability.

To push the limits of IOLW, the last test was performed when the Master remained in the smaller RC, while the Device was put behind the stirrer in the larger RC. The results correlated a lot with the previous test (when the Device was on the table and the Master was in the smaller RC). The errors were less sporadical and more systematic. In all other senses, the overall trend was similar to the previous test.

B. *Performance of SmartMesh IP inside an RC*

Apart from achieving the best possible communication, the experiments on SmartMesh IP were also targeted to find the minimum possible latency and the corresponding PER with those settings. Thus, customised programs were written for both the Manager and Motes.

The Mote's programming can be split into three stages: program writing in C, C to binary conversion and flashing the binary file onto the Mote to be initialised at every startup.

The Mote's program is made to listen to the WSN and echo any message upon receiving it.

Fig. 3 depicts the main stages of the Manager's program. First, the test's parameters like PUBLISH_RATE (time delay between two subsequent packets), STIRRER_SPEED (stirrer's speed) and other parameters are set up. Then the Manager is initialised and creates a WSN by finding operational Motes. These Motes immediately deliver their connection parameters (e.g. RSSI). After that, the Manager subscribes to all the data notifications from Motes and starts transmitting data to the selected Mote. If a packet is sent from a Mote, the program processes it and saves it in the list. Upon sending all the packets, the program compares the sent list of packets with the list with received packets. This comparison allows the program to calculate the number of correctly received packets, lost packets, disturbed packets, the total time needed to send and receive packets and the PER.

The tests performed at RCs were very similar to those for IOLW (see Fig. 2). During multiple series of tests, a different number of packets (between 100 and 1000) were sent. Results for them were highly correlated, so a decision was made to proceed with 100 packets. The main parameter that was affecting the QoS parameters was the publish rate (PR).

For the tests in the larger RC, both LoS and Non-LoS tests gave a PER equal to zero with PR equal to 4. The elapsed time (ET) between the first sent and the last received packet was approximately 408 s.

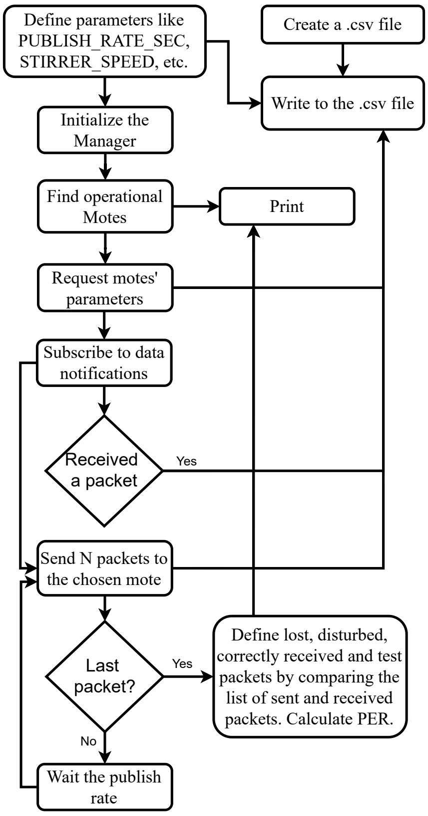


Fig. 3. Manager's echo program flowchart

When the Manager was moved to the smaller RC and the Mote was put on the table in the larger RC, the PER raised to 9 % with the PR of 4 s. That resulted in the ET of 411 s.

When the Mote was moved behind the stirrer in the larger RC with the Manager remaining in the smaller RC, the connection was dropped. Therefore the PR was raised to 6 s. It allowed to have the connection, though the PER became 12 % and the ET increased to 613.4 s.

The stirrer rotation near the Manager influenced the connection, sometimes facilitating it and giving an errorless performance, sometimes worsening it (the maximum achieved PER was 14 %). Positioning of devices further away from each other gave a similar effect as was happening with enabling the stirrer rotation.

C. *Robustness tests inside an RC conclusions*

Let us summarize the results obtained for IOLW and SmartMesh IP in Tables I and II. Test series were classified into four series and corresponded to the test procedure described in III-A.

IOLW and SmartMesh IP have different architecture, thus their latency per packet L_p and per byte L_B in ms is calculated differently. IOLW controls the latency by the cycle time that was equal to 20 ms during all the tests. Hence the Device will be regularly sending data within this time. SmartMesh IP assigns time slots to Motes using a certain pattern. Therefore the latency was measured using timestamps of sent & arrived packets and then averaged.

Tables I and II show that albeit the PER of IOLW is slightly worse during LoS tests, it remains stable and does not exceed more than 0.44 %. This was achieved by varying NRTx and TxP parameters. Alternatively, SmartMesh IP loses more packets during Non-LoS tests and has both higher latency per packet and per byte but the packet's payloads differ. When IOLW was transmitting two bytes of raw data, SmartMesh IP had a higher payload of 90 bytes. IOLW forces to send data from Devices within each cycle time. It means that sensors have to be more active in comparison to SmartMesh IP (compare 20 ms versus $\approx$ 2—7 s) in which Motes go to the sleep mode right after the packet was sent. Since the agricultural sector performs extended monitoring, the transmitting data can reach kilobytes and machines can be working in the field the full day. Therefore it was assumed that SmartMesh IP consumes less energy. Hence the energy consumption question and the payload per packet had higher priority over latency. Thus it was decided to further proceed only with SmartMesh IP and test it on the actual AgV.

IV. Robustness of SmartMesh IP tests on an AgV

An additional test for SmartMesh IP was conducted on a tracked combine harvester CR9.90 [12] at CNHi, Zedelgem, Belgium.

The test setup is presented in Fig. 4. During the test, several Motes at very different positions were considered. One of them was deliberately put behind the metal lid (the sensor marked with dashed edge lines) to test the reverberant/shadowing nature of the AgV. Also, the Manager's position was varied between outside the AgV on some wooden pallets or inside the cockpit. The communication program on SmartMesh IP devices had not been changed since the tests performed in RCs. However, one parameter of the WSN — a hop depth (HD) was included in the scope since the mesh consisted of more than one sensor. HD represents data circulation among the mesh participants. For example, if the HD is 10 then it means that there are no intermediary Motes between the data path from the Manager to the Mote and vice-versa. If the HD is 11, then 10 % of the data will be sent through the intermediary Mote, while the remaining 90 % will flow directly to the Manager.

TABLE I

IOLW test results inside an RC

Test series	PER, %	NRTx	TxP, dBm	L_p,[a] ms/packet	L_B, ms/B
1	[0:0.22]	[2:6]	[-6:5]	20	10 or 1.33[b]
2	[0:0.56]	[3:6]	[-6:-2]		
3	[0:0.094]	6	-6		
4	[0:0.13]				

[a] The packet length (raw data) in the tested single-slot communication between one Master and Device was two bytes;

[b] In the case of double-slot communication, the packet length is increased to 15 bytes.

TABLE II

SmartMesh IP test results inside an RC

Test series	PER, %	NRTx	TxP, dBm	L_p,[a] ms/packet	L_B, ms/B
1	0	3	8	1890.0	21
2	0			2675.0	29.72
3	[4:9]			3203.3	35.59
4	[0:12]			6965.9	77.4

[a] The packet length in the tested communication between one Manager and Mote was 90 bytes.

Fig. 4. SmartMesh IP test setup at CNHi

The aim of the test was to find out the minimum PR for a PER that reaches 0.

The initial test was performed with the Manager on wooden pallets. The PR was set to 4 s, the number of packets to send was 100. Most of the Motes had a direct connection with the Manager, except for one that had an HD of 11. Fig. 4 depicts one troublesome place (marked as TP) on the harvester. The TP Mote had an HD of 10 and was the only one whose PER was higher than zero (namely 5 %). The average ET was 407.5 s.

For the second test, the setup remained the same except for the Manager that was put inside the cockpit. With the same PR equal to 4 and 100 packets, all the Motes showed errorless results. The average ET was 404.8 s. Two Motes had an HD of 20, including the TP Mote. This means that the data was flowing 100 % through an intermediary Mote and only then to the Manager.

After a series of successful tests with the same setup, the PR was decreased to 1 s and the number of packets increased to 1000. This resulted in the ET equal to 1029.5 s.

As was mentioned earlier, to test the behaviour of a Mote in a more reverberant/shadowing environment, the lid was used. One Mote was placed under the lid. It did not lead to errors, supposedly due to a thin opening between the lid and the body of the harvester. Though the opening was small, its total area was sufficient to allow the signal to be transmitted to the Manager error-free. However the TP Mote lost two packets so the PER was 0.2 %, its HD was equal to 10.

The same test setup was repeated but with the Manager outside on wooden pallets. The PR was decreased two times and became 0.5 s. This did not affect any Mote (not even the one under the lid) except for the TP Mote that had an HD of 10 and a PER of 2.4 %. The ET reached 524.74 s. This results in an L_p of 25.24 ms or an L_B of 0.28 ms. The increase of the PER in the last test is predictable because the distance between devices was increased. Nevertheless, the changing HD is not that straightforward since SmartMesh IP is a proprietary protocol with a hidden stack.

Testing SmartMesh IP on the AgV not only revealed its capability to work in such a harsh setup with many reflections but also gathered one of the possible scenarios of the EM environment in the agricultural sector. With this, we proceeded further and decided to maximise the correlation between the lab environment (the RCs) and the actual one (the AgV).

V. RECREATING THE AGRICULTURAL EM ENVIRONMENT IN THE LAB SETTING

Since the EM environment inside RCs is too reverberant compared to an AgV (the difference in L_p is almost 5 times), a typical way of making it less reverberant is to make the RCs' delay times smaller. This can be achieved by using absorbers (see Fig. 5).

The goal of this test was to define the EM environment starting from which the PR parameter inside the RC will coincide with the one achieved during tests on the harvester. Therefore, the PR of 0.5 s with 1000 sent packets were preserved. The positioning was the hardest in terms of wireless communication: the Manager was in the smaller RC, while the Mote was in the bigger RC behind the stirrer.

After a number of tests with different configurations, the optimal positioning had been found (see Fig. 5). This configuration not only preserved the PR parameter but also resulted in the PER of 4.1 % which is within the PER range of the harvester's tests (the maximum PER there was 5 %).

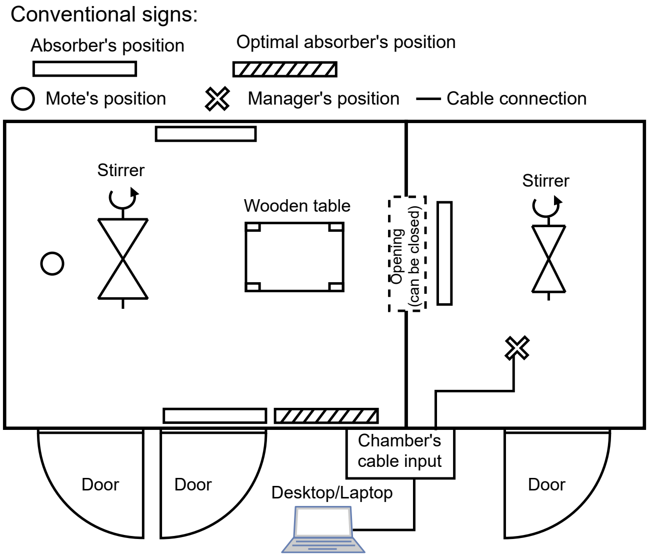


Fig. 5. Simulating the harvester's EM environment in the lab setting

The situation can be further improved by adding more absorbers and positioning them at specific places in the chamber. However, this is out of the scope of this paper and is kept for future work.

VI. CONCLUSION

In this work, the authors studied the problem of robust wireless communication on an AgV considered as a semi-reverberant EM environment. This study helps to select the most optimal protocol for the WSN on an AgV.

The paper considered two WSN protocols: IOLW and SmartMesh IP. Each of them is robust and capable of tackling the tasks needed on the AgV. For this purpose, one may need to tailor different modifiable parameters of the protocol for specific needs. Thus, NRTx and TxP are key parameters of IOLW, whereas for SmartMesh IP, the PR plays an important role in optimizing the QoS.

The tests conducted on the tracked harvester gave valuable insights into a probable EM environment on an AgV. The obtained results will be further extended to achieve a uniform procedure of replicating the EM environment of an AgV in the lab environment.

ACKNOWLEDGEMENT

The authors would like to thank Paul Hartanto and Rob Bergman from Analog Devices for their help in understanding the SmartMesh technology and for providing test samples.

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