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Julien Henaut, Daniela Dragomirescu, Florian Perget, Robert Plana. Validation of the MB-OFDM Modulation for High Data Rate WSN for Satellite Ground Testing. 5th International Conference on Systems (ICONS 2010), Apr 2010, Les Ménuires, France. p.41-46. hal-00475631

HAL Id: hal-00475631

<https://hal.science/hal-00475631>

Submitted on 22 Apr 2010

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Validation of the MB-OFDM Modulation for High Data Rate WSN for Satellite Ground Testing

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Abstract— *Ultra-Wideband (UWB) radio has been proposed for physical layer standard for high Speed wireless personal area network (WPANs). This paper evaluates Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM) as the radio interface for new High Data Rate (HDR) Wireless Sensor Networks (WSN) for satellite ground testing. A commercially available development kit was used to perform measurements on a satellite mock-up which were validated on an Eurostar-3000 satellite structure. Generic software developed tests all the parameter set combinations to help during identification of the relevant parameters. Different sort of antennas, passive repeaters and error correcting codes are mixed to evaluate the best tradeoff. The results show good performances for MB-OFDM in the targeted WSN application. A maximum achievable data rate with less than 8% of frame error rate of 92 Mbits/s is demonstrated.*

Keywords - *WSN for real time measurements, UWB, MB-OFDM, Satellite on ground testing, measurement campaign*

I. INTRODUCTION

To evaluate a system's compliance with its specified requirements, hardware system testing is conducted on the complete and integrated system. This phase is essential in all industry branches, especially in the very regulated and critical aerospace world.

When developing satellites, due to the impossibility of repairing the satellite in space, ground verification has to cover all systems. As a satellite contains many sophisticated microelectronic systems, vibration and mechanical stress are two critical phenomena that need to be analyzed in detail. Both the damages on the satellite and on the calibration of the onboard instruments can be dramatic. This is leading to the necessity for very accurate ground tests using strain gauges or thermal sensors before allowing a launch. The sensor system will be used to perform dynamic and static mechanical tests to determine the structure deformation. A static test uses a known stress applied to the structure. Measurements are taken after the structure has reached an equilibrium state. These tests can last from one hour to a week. Dynamical structural tests can be of very different kind depending on the customers' needs. The most common test is made by a sinusoidal excitation swept at low frequency during a few minutes.

All such systems used by satellite manufacturers today are wired systems. Each sensors put inside the satellite compartments is wired by four lines to a concentrator inside the operator's room. Although good performance is

observed in terms of measurement accuracy, these systems have strong drawbacks. The two most important ones are the weight which changes the mechanical response of the structure and the cost of the systems. An additional drawback concerning its use is that the installation of such a system immobilizes the devices during many weeks due to the placing of every cable and the verification of the correct wiring. The cost and the complexity of such systems doesn't allow a great number of measurement points. This is why research is done on a wireless measurement system based on wireless sensors networks (WSNs).

This paper is divided into five sections. After a brief introduction, section II introduces the reasons for the choice of an UWB modulation in the development of WSNs. The measurement environment and protocol are described in section III and IV, respectively. The results of the different campaigns are shown in section V. Finally conclusions are drawn in the last section.

II. MB-OFDM AS RADIO INTERFACE FOR WSN

A. High Data Rate modulation for WSNs

Many of the specificities of the requirements for the application of WSN in a satellite environment are detailed in [1]. They can be summarized by:

- The wireless systems should allow an increase in the number of points of measurement. Thus, the first specification for satellite systems is to dispose of more than 1000 points of measurement.
- In addition to the large amount of data points, analysis need frequently (every few microseconds) updated data. Thus, the application must provide high data rate (around 100 Mbits/s). This point is the one which distinct the demanded WSN from other WSNs [2].
- Thirdly, one of the aims of such systems is to perform correlation between the different channels (one channel corresponds to one sensor). In such kind of tests, if one measurement point gets lost, the whole data set recorded during the test becomes useless. No loss can be tolerated. The transmission therefore has to exhibit an extremely low error rate.
- Finally, as described in the introduction, a test can last from hours to weeks. As the wireless sensors are spread inside a satellite, they have to be **self-powered**.

In the field of the WSN, there are many emerging and existing standards. The most popular ones are Zigbee, Bluetooth Low Energy or Bluetooth 3.0.

- **Zigbee** targets low power consumption applications with ultra low data rate. The devices operate in the ISM bands with data rates from 20kb/s to 250 kb/s.
- **Bluetooth Low Energy** technology, formerly known as Wibree, was designed to wirelessly connect small device to a mobile terminal. As Zigbee, it provides ultra-low power consumption and data rates of up to 1 Mb/s.
- **Bluetooth 3.0 high Speed** increases theoretically the data rate for WSN from 1 Mb/s to 24 Mb/s.

Most of the WSN projects are oriented for event based monitoring where events happen irregularly and seldom. In such development low data rate protocols are enough and so the work is only focused on reducing the power consumption. In the development of aerospace applications, power consumption is still a key problem but as no HDR-WSN protocols exist, designers have to search solutions in other fields.

B. OFDM as a solution for HDR-WSN

High Data Rate (HDR) modulations have never been considered in the development of WSNs. When targeting HDR with a very good spectral efficiency, Orthogonal Frequency-Division Multiplexing (**OFDM**) techniques are popular schemes. This modulation is well described in [4]. It uses an architecture simultaneously transmitting multiple signals over a single transmission path. Each signal occupies its own unique frequency range, which is realized by modulating the data on a separate carrier.

The system breaks the available bandwidth into narrower orthogonal subcarriers and transmits data as parallel streams. Each sub-carrier is modulated with a conventional modulation scheme (such as phase shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

One of the most important advantages of OFDM over single-carrier schemes is its ability to cope with severe channel conditions, like narrowband interference or frequency-selective fading due to multipath, without complex equalization filters. Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal.

In order to deal with low emitting power to avoid interference with other systems, an UWB implementation of OFDM was proposed as **Multi-Band OFDM** (MB-OFDM). Multiband OFDM was developed by the IEEE 802.15.3a and standardized by ECMA in [5]. The physical layer and radio interface are well described in [6]. This standard is used by the former Wimedia alliance (now Bluetooth Special Interest Group (SIG) and Wireless USB Promoter Group) to promote Wireless Personal Area

Network (WPAN) and short-range multimedia file transfers at data rates of 480Mbit/s and beyond with low power consumption. More precisely, the system offers a data payload communication capability of 53.3, 80, 106, 160, 200, 320, 400 and 480Mbit/s. The physical data rate is always 640Mbits/s. The difference between the payload data rate and this value is due to the introduction of redundancies and different error correcting codes. Figure 1, extracted from [6], gives all the details about these parameters. The lower the payload data rate is, the higher will be the achievable distance of communication for a fixed error rate

The standard ECMA-368 seems to be well adapted for the radio interface of aerospace HDR-WSN, it remains to find the most suitable transmission mode.

| Info. Data Rate | 55 Mb/s | 80 Mb/s | 110 Mb/s | 160 Mb/s | 200 Mb/s | 320 Mb/s | 480 Mb/s |
|----------------------------|-----------|----------|-----------|----------|----------|----------|----------|
| Constellation | QPSK | QPSK | QPSK | QPSK | QPSK | QPSK | QPSK |
| FFT Size | 128 | 128 | 128 | 128 | 128 | 128 | 128 |
| Coding Rate (K=7) | R = 11/32 | R = 1/2 | R = 11/32 | R = 1/2 | R = 5/8 | R = 1/2 | R = 3/4 |
| Frequency-domain Spreading | Yes | Yes | No | No | No | No | No |
| Time-domain Spreading | Yes | Yes | Yes | Yes | Yes | No | No |
| Data Tones | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Prefix Length | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns |
| Guard Interval | 9.5 ns | 9.5 ns | 9.5 ns | 9.5 ns | 9.5 ns | 9.5 ns | 9.5 ns |
| Symbol Length | 312.5 ns | 312.5 ns | 312.5 ns | 312.5 ns | 312.5 ns | 312.5 ns | 312.5 ns |
| Channel Bit Rate | 640 Mbps | 640 Mbps | 640 Mbps | 640 Mbps | 640 Mbps | 640 Mbps | 640 Mbps |
| Multi-path Tolerance | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns | 60.6 ns |

Figure 1. Parameters of the MB-OFDM

III. DESCRIPTION OF THE ENVIRONEMENT

In order to validate the use of MB-OFDM, find the right parameter for payload data rate and how the satellite environment influences the transmission, tests are performed to evaluate the highest data rate achievable in the satellite environment.

The MB-OFDM signal used for the experiment is generated by a commercially available evaluation kit from Wisair [7]. The DV9110M development kit (figure 2) is one of the few commercially available devices capable of providing MB-OFDM compliant modulation with three sub-bands, each of 528 MHz bandwidth from 3.168 GHz to 4.752 GHz. The average output power is UWB compliant with a value of 80 uW (-41.3 dBm/MHz). The hopping sequence is set as f1, f2, f3 f1, f2, f3, where f1 is the center frequency of the lower sub-band (3.423 GHz), and f2, f3 is the center frequencies of the middle (3.960 GHz) and upper sub-bands (4.488 GHz). The kit is based on the Wisair SiGe RF Transceiver and a CMOS based MAC/Baseband chips. It also includes a UWB external antenna patented by Wisair and a motherboard for external 100Mbits/s Ethernet data interface (using a RJ-45 connector) and power supply control. The cards that act like an Ethernet bridge are connected to two laptops and the Ethernet interface is used to exchange the data. When developing their kits, Wisair implemented only a 100

Mb/s Ethernet interface. So, even with the 480 Mb/s parameters it is impossible to have a data rate above 100 Mb/s.



Figure 2. Card used to perform measurements

These cards are used to perform measurements in two kinds of environment: a satellite mockup developed at LAAS-CNRS and an Eurostar-3000 structure. The two environments are presented below.

A. LAAS-CNRS satellite mockup

The goal of the first tests campaign is to obtain some reference measurements based on the satellite mockup. The LAAS-CNRS satellite mockup has been developed using a metallic box. As shown in figure 3 a small hole is used to put the passive repeater described in the next section.

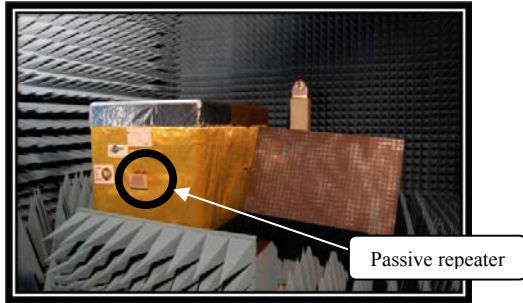


Figure 3. The LAAS-CNRS satellite mockup used to perform the reference campaign

B. Real satellite structure

The measurement campaign has also been performed on a Eurostar 3000 satellite structure. It has the shape of a cube (2x2x2 m) with metallic walls. The inside, where all satellite electronic instruments are placed, is divided in sub-compartments by metallic walls. There are holes in the structure that allows a communication from the inside (where sensors are stuck) to the outside (where the operator stands). The representation of this configuration is given in figure 4.

one can track packet errors or tune specific parameters, such as the payload data rate and Rx/Rx+Tx. This parameter is not an ECMA-368 [5] element. It has been introduced by Wisair in the MAC layer. They introduced a sort of Time Division Multiplexing (TDM) into the OFDM super frame. This super frame is divided in three parts: a beacon used to perform synchronization for all the elements in the network, a part for a kit to send data (Tx) and a part for the kit to receive data (Tx). The ratio Rx/Rx+Tx exhibit the proportion of time in the super frame used to receive data from the master and is given as a percentage.

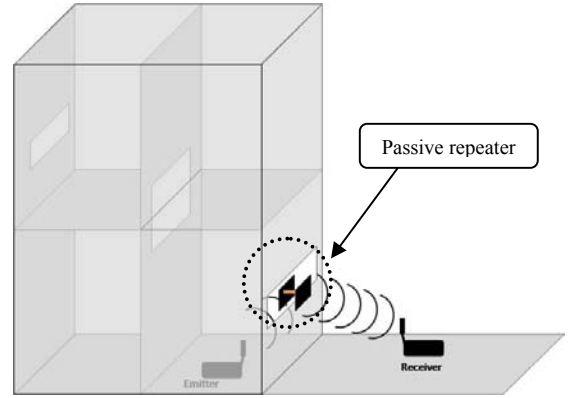


Figure 4. Schematic representation of the Eurostar 3000 structure

The quality of the link can be measured using the WisMan™ application. But, for the purpose of evaluating the effect of the different parameters on link data rate and data loss, specific software was developed in the Java language which allows the entry of a set of parameters and values to be tested using the interface depicted in figure 5. Then, repetitive performance tests can be performed on all the possible parameter values sets.



Figure 5. Parameter set entry software interface

IV. MEASUREMENTS PROCEDURE

The configuration of the Wisair module consists in the programming of some hardware registers on the device. The WisMan™ [7] configuration and control host application gives different levels of control over these registers to configure and monitor the status by accessing UWB devices for reading or modifying their registers. So,

The mode of operation of the software is described in figure 6 thereafter. A control link (here established by wifi) is used by the two computers to exchange control information – parameters values, timestamps, and performance results- while an Ethernet connection is used to send or receive test data through the Wisair cards' interface.

The test data is made of UDP (User Datagram Protocol) packets containing test specific information such as a sequence number and random data. UDP packet size is maximized for Ethernet throughput since Wisair cards fragment and reassemble data depending on WiMedia requirements for packet size and error correction and this does not have an effect on Wisair link performance.

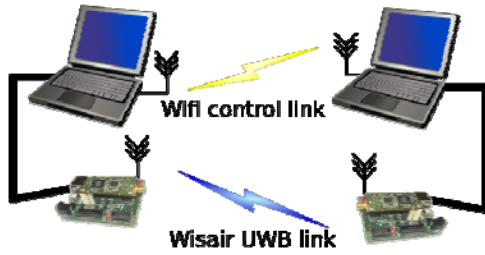


Figure 6. Performance test software mode of operation

Once the sending computer is done transmitting data for a measurement, received packets are counted and timed to calculate data rate and data loss. Relevant result subsets and control data is presented in an interface shown in figure 7 which is also presented during measurement replays. Indeed, each measurement is recorded in a data file in order to allow faster review of the result data after the measurements.

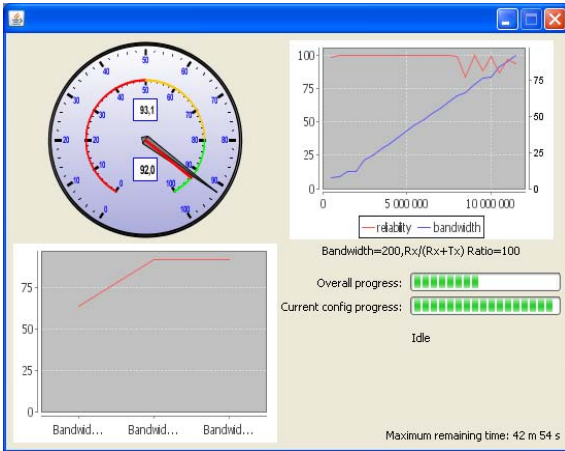


Figure 7. Results and replay interface

V. RESULTS

The purpose of the study is to identify the parameters involved in performance and data loss for this specific application. Three of them seem to be of interest:

- The antenna type: the two Wisair kits are equipped with low directivity Wisair antennas (figure 8a): quasi-omnidirectional, 3 to 5 GHz bandwidth) and high gain Vivaldi antennas (figure 8b): 4-8 dB gain, 3 to 10 GHz bandwidth, fabricated at the “Institut für

Hochfrequenztechnik” of the University of Stuttgart [8].



Figure 8. Antennas used on the wisair kits.
(a) quasi-omnidirectional Wisair antenna (b) high gain Vivaldi antenna

- The passive repeater type: Our previous work [9] shows that the issue of allowing the electromagnetic wave to pass through a hole inside a metallic wall and reach the receiving antenna is a serious problem. A repeater should be used to send the signal between the different sections of the satellite. One repeater is made of two Vivaldi antennas (figure 9a), and another one made of two patch antennas developed at LAAS-CNRS (figure 9 b)[10].

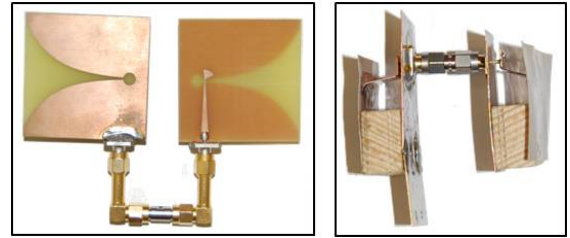


Figure 9. Passive repeaters
(a) Repeater formed by two Vivaldi antennas (b) Repeater formed by two patch antennas developed at LAAS

- The Wisair target link bit rate (TLBR) (as described in II), which optimizes FEC settings to balance between data rate and link robustness. The TLBR is chosen according to figure 1. For this TLBR, decreasing the amount of data on the link (Sustained Data Rate: SDR) results in a decrease in the recorded error rate. In the presented measurements, SDR is decrease down to the point where the PER is less than 8%.

Our work has been split in two similar case studies s. First we conducted thorough testing on a specifically built satellite mockup to determine the exact influence of these parameters. Then we performed validation tests on a Eurostar-3000 satellite structure to confirm our first results. After this second study case, we performed additional tests to try and reach maximum performance. In all the measurements, the link is considered to be good when the Packet Error Rate (the difference between the numbers of packet sent and received) is below 8%. This value of 8% was chosen because it corresponds to an acceptable Bit Error Rate (BER) of around $1e-5$.

A. Measurements on LAAS-CNRS satellite Mockup

We first measured sustained bandwidth with less than 8% data loss using Wisair cards in a direct Line Of Sight (LOS) setup in free space at one meter, reaching 70 Mbps. Then, we tried to reproduce the LOS value with one card inside the mockup and the other outside by varying the passive repeater only. All tests were performed using Wisair antennas and results are presented in figure 10.

Our lab tests showed that we could reach 70 Mbps data rate using Wisair antennas in free space (figure 10a). Excessive data loss is obtained without a passive repeater when trying to transmit the signal in and out of the satellite mockup structure (figure 10d). The achievable data rate obtained with the Vivaldi antennas passive repeater (figure 10b) is the same as the LOS measurements. Finally, the patch repeater appears here to have lower performance (figure 10c) than the Vivaldi ones. The achievable data rate is 15 to 20 Mbits/s lower than the LOS measurements.

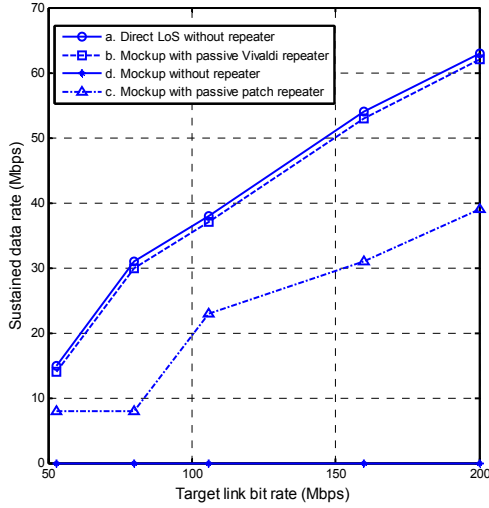


Figure 10. Mockup test set performance results

In these measurements campaign, the best achievable data rate is 70Mbit/s and is obtained for a Vivaldi antenna passive repeater, a 200Mbit/s target data link and a parameter Rx/Rx+Tx ratio of 50%

B. Measurements on Eurostar 3000 real satellite structure

This measurement campaigns' goal was it to compare results gathered on the mockup with results obtained on the real Eurostar-3000 using the same test set. Its results are presented in figure 11. The distance between the emitter and the receiver is around 3 meters.

As expected, using no repeating device, excessive data loss is obtained and performances cannot be measured (figure 11d). Thanks to the repeaters (figure 11b and 11c) performances similar to direct line of sight are obtained. The increase of performance of the patch repeater between the mockup and the Eurostar structure can be explained by the fact that this particular repeater was specially optimized for the thickness of the metallic walls of the

Eurostar-3000 structure. The repeater uses the satellites wall as ground plane. Our mockup has thinner walls and therefore performance is decreased.

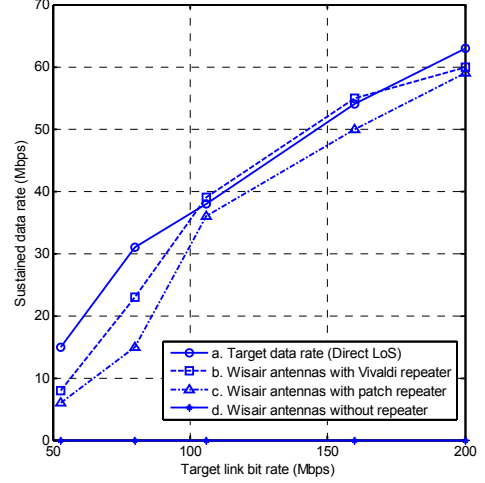


Figure 11. Eurostar-3000 structure test set performance results

This is a first step towards our goal of reaching 100 Mbps at 8% maximum data loss as we obtain 62 Mbps without exceeding the data loss threshold.

Another thing observed here is the strong similarity to lab results, concerning for instance the all but linear impact of target bit rate and the relation between repeater gain and performance.

During measurement, few key issues which need improvement in order to reach a satisfactory level of confidence in the results are identified. The above measurements have shown a high sensibility to external perturbations explained by the short measurement time. It has been chosen to test a great numbers of parameters within a decent overall time. Therefore we opted for a threefold increase in measure time - a few minutes - and less different parameter sets for the following measurements.

Also, we wanted to know if testing even higher target bit rates would yield more performance improvements, or if data loss would then exceed limits.

C. Final tuning stage

During these tests, we tried to reach maximum performance by combining parameter sets which yielded the most reliable and efficient data link while increasing confidence level in results.

In order to get maximum signal strength, we used Vivaldi antennas and Vivaldi repeaters, and tried target bit rates up to 480 Mbps. We also doubled the available bandwidth by settings the Wisair cards' Rx/(Rx+Tx) ratio to allow inside to outside communication only, therefore gaining the previously wasted time allocated for outside to inside communication.

Though trying higher target bit rates did not lead to higher performance, clearly we reached a limit close to that of the Wisair cards' Fast Ethernet interface at 92

Mbps. The highest data rate and lowest data loss are reached when assigning a target bandwidth of 200 Mbps or 320 Mbps to the FEC parameter (figure 12a and 12b). When targeting higher bit rates transmission errors exceed the 8% limit.

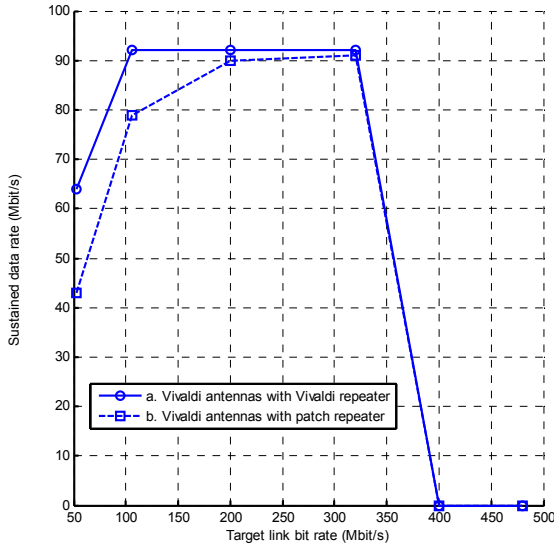


Figure 12. Eurostar-3000 maximum performance test set results

There is one new phenomenon that has been observed during the measurements. When sending signals through a directive antenna into the cavity, the electromagnetic wave radiated by the passive repeater into the satellite will be reflected on the satellite walls and thus arrives at the receiving card from different directions and appears as send by a non-directive antenna. This phenomenon was observed by rotating the emitting antenna of 90° (figure 13 right). The achievable data rate in such a situation is the same as previously (figure 13 left).

This phenomenon has been studied in [11]. The situation of propagation inside the cavity is Non-LOS with metal enclosure (cavity) having large dimensions compared to the wavelength λ of the electromagnetic field. The main assumption of the study presented in [11] is that the electromagnetic environment inside the cavity is comparable to that of a reverberation chamber. This means the environment can be considered as pseudo-homogeneous and pseudo-isotropic. It implies that the orientation of antennas has no impact on the received power level.



Figure 13. The orientation of antennas has no impact on the received power level as the cavity is homogeneous and pseudo-isotropic.

VI. CONCLUSION

In this paper experimental results performed to evaluate the possibility of using the MB-OFDM modulation scheme for real time measurement-WSN are presented. This kind of modulation is new in the field of wireless sensor networks but has decisive advantages for high data rate applications. The principle of the software developed to perform repetitive measurements is validated and constitutes a milestone to evaluate the MB-OFDM modulation scheme in all kinds of environments.

Despite the fact that the Wisair kit consumes a lot of power due to the presence of a versatile motherboard (essential to change the register parameters during measurements), this kit was well suited to validate the performances of MB-OFDM as radio interface for WSN under real conditions. A very good accuracy between the measurements performed on a real Eurostar-3000 structure and the mockup used in lab has been demonstrated. The maximum data rate is obtained by using either the Vivaldi passive repeater or the patch one coupled with directive antennas and the choice of 200Mbit/s as payload data rate. A 92 Mbit/s link which corresponds to the practical limit of the implied Ethernet link is obtained in the satellite.

Despite the harsh propagation environment inside the metallic satellite structure, the choice of MB-OFDM as a good candidate for the radio interface of a new HDR-WSN has been validated.

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