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# Testing of Zigbee System, Facing Unintentional and Intentional Electromagnetic Disturbances Present in Railway Environment

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## Abstract

This paper deals with the performance of a sensor network system proposed to monitor and control freight trains, facing electromagnetic disturbances present in the railway environment. A study of existing technologies and systems demonstrated that a solution based on Zigbee technology is appropriate to our problem. A test bench, based on a hybrid coupler that sums the transmitted signal and the interfering one, was developed in order to measure the disturbances which can affect the on-board wireless communication systems. This measurement setup is used to physically simulate a telecommunication submitted to an electromagnetic disturbance but neglecting the contribution of the free propagation. The effect of the disruption of the sliding contact between the catenary and the pantograph on the Zigbee communication is studied. The impact of intentional electromagnetic interferences on communication performance is also analyzed and the relationship between the parameters of a jamming signal and the interruption of the Zigbee transmission is presented in the paper.

## Keywords

Railway Environment, Zigbee Communication,
Electro-Magnetic Compatibility (EMC),
IEEE 802.15.4 Standard, Intentional Electromagnetic Interferences (IEMI)

## 1. Introduction

Nowadays, railway companies aim to offer complete, flexible and appropriate solutions to keep their customers and attract new markets. In the freight transport domain, it is necessary to monitor the cars, to identify sensitive ones (dangerous goods, perishable goods ...), to collect training information such as weight, temperature and location ... useful for logistics management. Therefore, communication between wagons, and between the locomotive and the infrastructure allows a central point to collect information from each car, to ensure traceability. This solution can also be used to improve logistics flows management, including identifying the cars that should not be separated. These cars must be tracked to avoid being isolated and to check the integrity of the train before the roll.

The aim of this project is to propose a communication system between wagons to collect information on the one hand and to transmit them towards a central point like a locomotive (Management of the traction and braking) and the station (Logistics management) on the other hand. This system can also allow to locate isolated cars.

The railway environment is rich of electromagnetic disturbances. Indeed, it is a complex structure composed of several systems such as trains (rolling stock) and infrastructure. The presence of systems operating on high power (train power) and communication systems carrying low power can cause EMC problems.

There are several types of electromagnetic disturbances that can be classified according to their sources. In this work, some examples will be discussed. More details about this subject were described in a previous work presented in [1]. These disturbances are unintentional. However, electromagnetic interferences can be intentionally generated for malicious purposes by jammers available on the market at low cost; these disturbances are called IEMI (Intentional Electromagnetic Interferences).

The reminder of this paper is as follow: section 2 describes some projects for the monitoring of freight trains, then, a proposed system to track and control freight cars is presented. This system is based on Zigbee technology. The characteristics of this technology are detailed in section 3. In order to study the feasibility of this system in railway environment against electromagnetic disturbances, two important types are analyzed. Section 4 describes the transient event generated by the sliding contact between the catenary and the pantograph and summarizes the characteristics of a jammer signal that can be intentionally emitted to interrupt Zigbee communication. Section 5 presents different measurement setups proposed in literature, to evaluate electromagnetic disturbances. After this, the developed test bench is described, and then, in section 6 the performance of Zigbee technology in presence of enumerated electromagnetic disturbances is evaluated.

## 2. Related Work

Most of the research on wireless transmissions in rail is moving towards radio communication between the train and the infrastructure. Whereas, wireless transmission systems aboard the train are not often studied, as described in [2].

Recently, some wireless applications proposed to rail transport have been published. Their purpose is to monitor the wagons or the train itself to ensure preventive maintenance.

In the Swedish rail system, a number of stationary sensors were installed throughout the country [3]. The objective is to monitor the temperature of ball bearing aboard the train. The authors propose two links used in this system. Indeed, aboard the train, the sensors communicate at 2.45 GHz with WSN (Wireless Sensor Network) link, and the external communication is at 868 MHz with RFID (Radio Frequency IDentification) link. The sensors (WSN) were mounted aboard the train with one Gateway (GW). The gateway was placed at a central location aboard the train, to communicate with the two links proposed; the sensors nodes installed aboard the train (WSN nodes) with RFID readers. The measured RSSI (Received Signal Strength Indicator) and LQI (Link Quality Indicator) values during the test were relatively low, which indicates that the communication between the nodes and the GW is difficult in railway environment.

The system proposed in [4], aims to ensure real-time identification and monitoring of freight railcars and their components. The nature of a train arrangement requires installing the sensors in a long linear network. To overcome the limitations in radio transmission range and in low throughput of common WSN solution, the authors propose a heterogeneous multihop network called hybrid technology networking (HTN). This solution employs Wi-Fi together with Zigbee.

The Tr@in-MD (Intelligent Transport for Dangerous Goods) project planned a system that increases the safety of hazardous material transporting and ensures its traceability [5]. This project proposes a system that tracks cars, monitors their status, transmits and analyzes collected information in real time. Tr@in-MD is based on GPS localization and GSM communication. The technologies deployed in this project have certain limitations. Indeed, GPS is an effective technology for localization, but the satellite link requires direct visibility, which is not always available in the presence of tunnels. For the GSM technology, it requires a particular installation that can be expensive.

Identifying the most appropriate technology to ensure wireless communication in railway is the first challenge of this project. Indeed, the constraints of the rail environment such as implementation in a severe and disturbing electromagnetic environment, the low energy consumption of the transmission systems (long service life) and the ease of setting up the installation and configuration, have to be taken into account. The information exchanged is associated with cars such as ID (identifier), weight, material transported, temperature, humidity. Therefore, low cost technology can be used because of the small amount of data.

The particularity of the railway environment guides us to a high frequency solution. Indeed, the disturbances generated by the rolling stock as well as the infrastructure are in the range of few kHz to few MHz, with the possibility of reaching 1 GHz, in the case of a bad contact between the catenary and the pantograph [6].

By comparing the most popular wireless technologies, the study focuses on

Zigbee technology that meets the requirements of the application presented.

The advantages of Zigbee system are multiple, since it is de-signed for the Internet of Things (IoT). The Zigbee devices require low bandwidth and need only a single battery for a long lifetime, which is useful for the localization [7]. This technology provides a network easy to install, reliable, self-configuring and self-healing and supports large number of nodes (65k nodes). In addition, it can coexist with other technologies in the ISM (Industrial, Scientific and Medical) band, because it chooses the quietest channel to operate. Indeed, Zigbee can change the communication channel to use the optimal one. The major disadvantages of Zigbee technology are the low bit rate (250 kbps) and the short-range. Given the intended application, the low throughput of this technology is enough to transmit data associated to the cars, and the maximum distance needed is lower than 22 m. This distance can be reached in the case when the sensors are mounted on top of and the middle of the roof of each wagon.

Thanks to all these properties, Zigbee is a competitive technology for low cost wireless communication systems.

## 3. Zigbee Technology

Zigbee is an LP-WPAN (Low Power Wireless Personal Area Network). It is a wireless network with short-range and low power consumption. The Zigbee standard describes the upper layers, which are based on the IEEE 802.15.4 standard. In fact, Zigbee maintains the PHY and MAC layers of the IEEE 802.15.4. In addition, Zigbee defines the upper layers for networking security and application control (**Figure 1**).

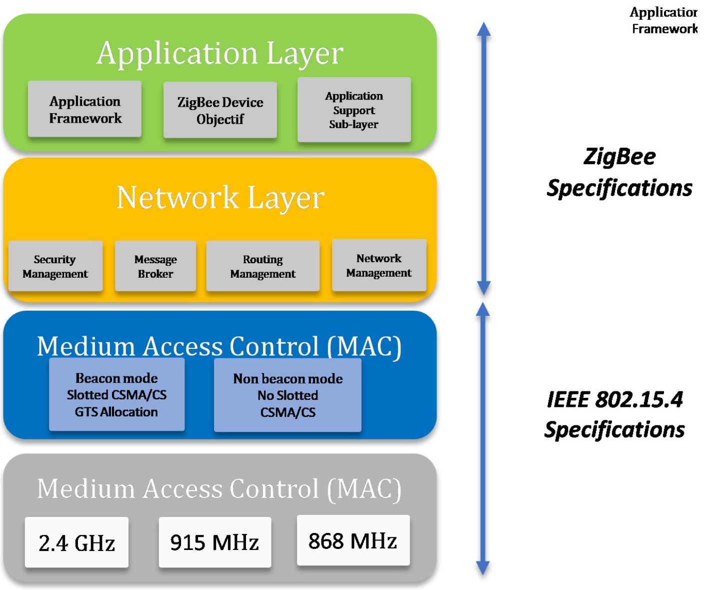

**Figure 1.** Zigbee stack.

A WPAN is composed of several nodes that collect and transmit information to a central point that handles data, or acts as a gateway to another WPAN.

Two types of nodes are defined in IEEE 802.15.4 standard: Reduced Function Devices (RFDs) and Full Function Devices (FFDs). The FFD nodes have all the functions. They can play the role of WPAN coordinator. RFD nodes are terminal nodes that have reduced functions. A RFD can only communicate with an FFD device. They are very often in sleep mode.

## 3.1. Topology

The IEEE 802.15.4 standard defines different possible network topologies: star, point-to-point, and tree topology. Above the two IEEE 802.15.4 layers, the Zigbee network layer allows the creation of mesh networks with automatic routing. These topologies are presented in (**Figure 2**).

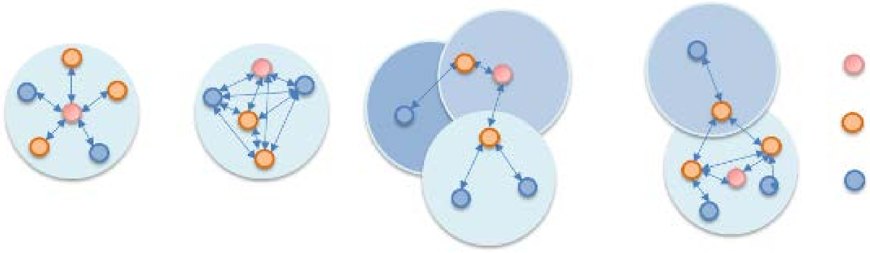

**Figure 2.** Topologies supported by Zigbee technology.

In a star topology, the coordinator node communicates directly with the nodes present in the same radio range. In this case, all the network traffic goes through the coordinator.

The tree topology is a special case of point-to-point topology. Indeed, in a point-to-point topology, each node can communicate with any node of the network. The intermediate nodes (routers) are employed to ensure the packets transmission to destination. On the other hand, in a tree topology, the network is hierarchized with a coordinator and routers managing the devices connected. All communications go through the coordinator.

In a mesh topology, the routers communicate in point-to-point, and therefore, the information may not be fed back to the coordinator to reach the destination.

## 3.2. PHY Layer

The PHY layer of the IEEE 802.15.4 standard supports three frequency bands [8].

(1) The 868 MHz band proposed for Europe.

(2) The 915 MHz band proposed for America.

(3) The 2.4 GHz ISM band, a free band available internationally.

Giving the complexity of the railway environment and the different electromagnetic disturbances present particularly at low frequencies, a communication system in the ISM band around 2.4 GHz is proposed.

As illustrated in **Figure 3**, Zigbee uses 16 channels (11 - 25) spread over ISM band frequencies, each channel is 2 MHz wide. The channels are separated by 5 MHz. The frequency band is spread from 2400 MHz to 2483.5 MHz.

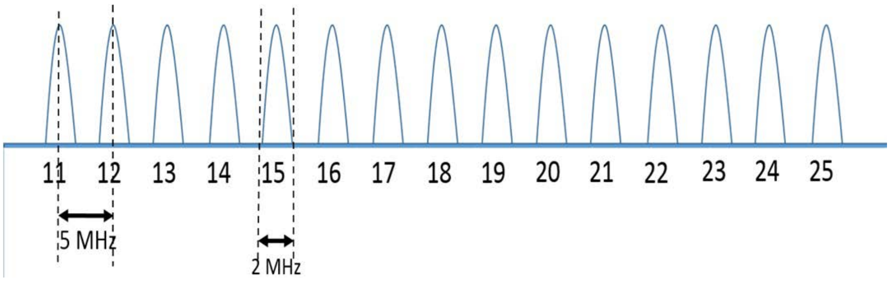

**Figure 3.** Zigbee channels.

The PHY frame is composed of a header (preamble), a block that defines the beginning of the frame (start of packet delimiter), a block that determines the length of the frame (PHY header) and the last (PHY Service Data Unit) containing the data. **Figure 4** shows the physical framework of IEEE 802.15.4.

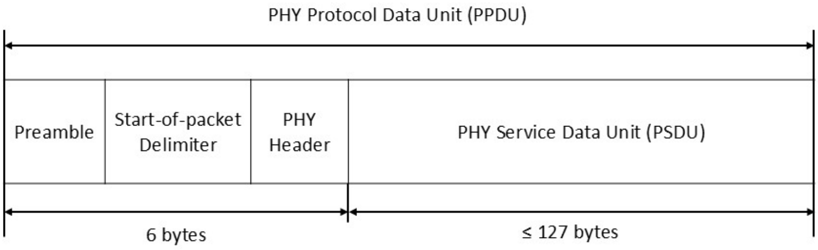

**Figure 4.** PHY frame of IEEE 802.15.4 standard.

### 3.3. MAC Layer

The MAC layer controls channel access and ensures data transmission between Zigbee nodes. It allows the delivery of recognized frames and the association / dissociation of the nodes to the coordinators. Zigbee networks are composed of one or more WPAN coordinators, monitoring the entire network, and managing associations and connections between nodes and coordinators.

The MAC layer defines two access modes to the network:

Coordinated mode:

Where the coordinator transmits periodically beacon frames to confirm their presence and to synchronize the transmission between the different nodes. This mode optimizes energy consumption. Once the information is sent, the node goes into sleep mode.

Uncoordinated mode:

In this case, the nodes use the CSMA/CA protocol to transmit the data. This protocol gives access to the medium once it is estimated free. A time unit called back-off is introduced to delay the transmission and avoid collisions. In this mode, the nodes are constantly active.

IEEE 802.15.4 uses spread spectrum methods to improve the sensitivity level of the receiver, to increase the interferences resistance and to reduce the effect of multipath propagation. The spreading method required by the IEEE 802.15.4 standard for the ISM frequency band is DSSS (Direct Sequence Spread Spectrum)

[8]. The modulation adopted is Offset-QPSK with a bit rate of 250 kbit/s.

In order to study the effect of electromagnetic disturbances on Zigbee system, a test bench was developed, and it will be presented in the following sections.

## 4. Electromagnetic Disturbances in Railway

### 4.1. Transient Event

In order to characterize the transient electromagnetic events generated by the sliding contact between the catenary and the pantograph, Ben Slimen carried out measurements to collect a large number of transient disturbances and to analyze the typical rise times and durations. The results are presented in [9]. During his PhD, Ben Slimen did many measurements dedicated to study the immunity of the GSM-R (GSM for Railway) system. The developed and presented study is focused on a frequency band up to 1 GHz [1].

A statistical analysis of the time and amplitude characteristics of the transient events was carried out in order to describe the data collected by a GSM-R antenna fixed above the locomotive of a moving train. The aim of this statistical study was to model the transient event with an analytical expression [10].

The impulse event can be modeled by a double exponential (1), whose characteristics: rise time, duration and amplitude, are defined to model a main impulse representation of the transient events observed in practice during measurements.

$$V(t) = A\left(e^{\frac{-t}{TD}} - e^{\frac{-t}{RT}}\right) \tag{1}$$

Where: $V(t)$ represents the amplitude of the transient signal, $A$ is the peak amplitude of the signal, $TD$ is the event time duration and $RT$ is the rise time.

**Figure 5** presents the shape of this wave for $TD$ = 5 ns, $RT$ = 0.4 ns and $A$ = 0.45 V, these values correspond to the mean ones issued from the statistical analysis of Ben Slimen [1] and will be used in our study.

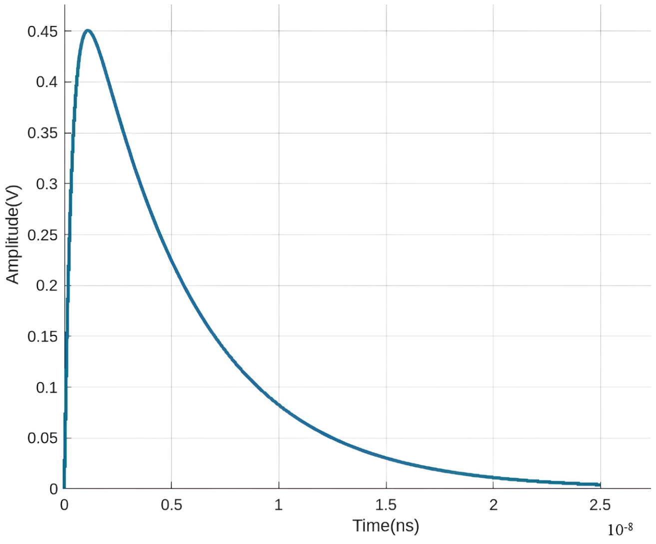

**Figure 5.** Waveform of the signal.

The spectrum of this waveform is shown in Figure 6.

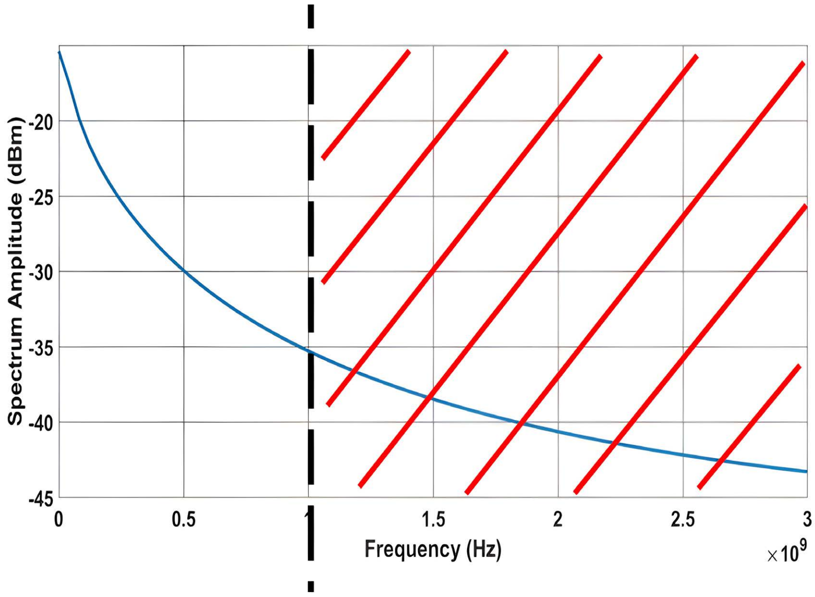

Figure 6. Spectrum of the double exponential waveform.

The transient event model is based on measurements limited to 1 GHz due to the goal of the study (GSM-R communications). As shown in Figure 6, transient event power is focused on low frequencies up to 1 GHz, which is a little lower than our considered frequency band.

In order to study a critical case, it is assumed that the impulse event spectrum maintained constant at the value measured at 1 GHz. Indeed, the simulated spectrum (Figure 6) reached high frequencies (up to 3 GHz) with a gap of 10 dB between 1 GHz and 3 GHz frequency, which could be due to the filtering of the measurements at 1 GHz. Therefore, the maximum value simulated at 1 GHz was kept up to 3 GHz, which is considered closer to reality.

Both spectrums are presented in Figure 7.

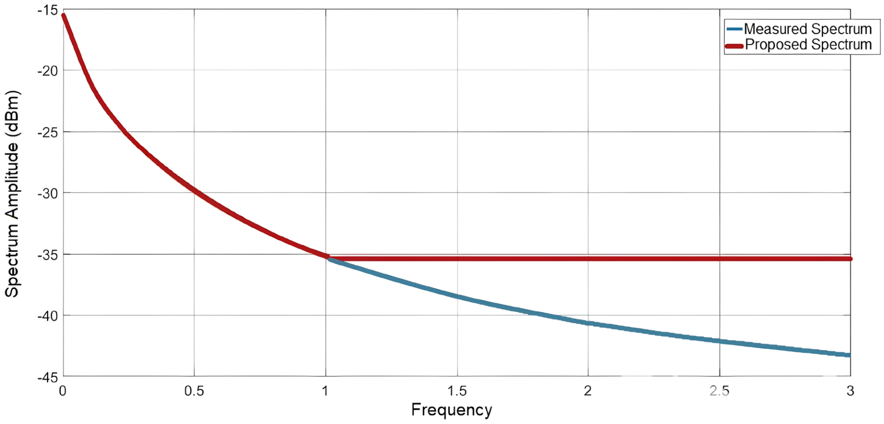

Figure 7. Spectrums: measured and proposed.

From the proposed spectrum, the new form of the transient event can be defined. This impulse may have more potential to disturb the studied radio communication system. This form is shown in Figure 8.

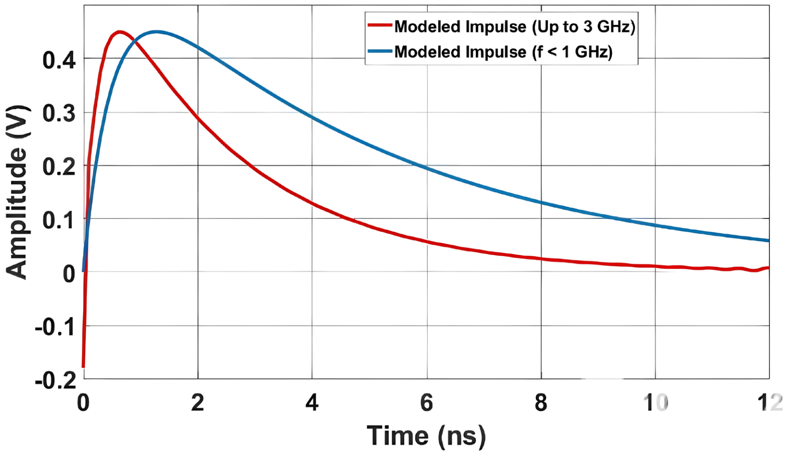

**Figure 8.** Modeled transient impulses.

It is noted that the pulse has almost the same shape as the pulse defined in the work presented in [1], with a faster rise time, which is suitable with a 1 GHz filtering of the initial measurements.

The waveform of the new form of the transient event pulse is shown in Figure 9.

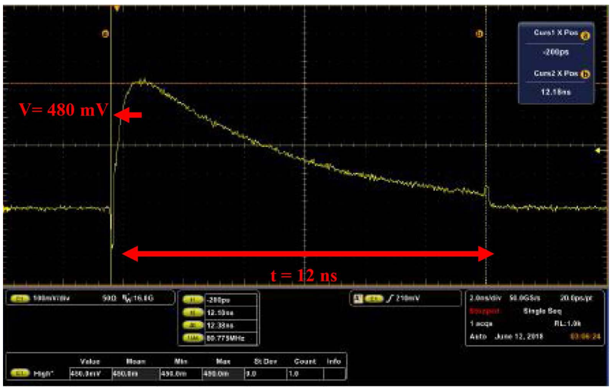

**Figure 9.** The waveform of the modeled impulse (up to 3GHz).

The effect of this transient event on the proposed system is presented in section 6.1.

## 4.2. Intentional Signal Characteristics

In general, the disturbances of industrial origin are unintentional. However, electromagnetic interferences can be intentionally generated; these disturbances IEMI are then used for malicious purposes.

Electromagnetic disturbances can be generated by electromagnetic jammers to interrupt communication, or to access and to modify the information temporarily or permanently. In this work, the effect of an intentional interfering signal, generated in order to interrupt the communication will be studied.

The jamming consists in sending a high-power signal having the role of disturbing or blocking electromagnetic emissions. To achieve its role, the victim signal frequency is known. The interest of using a jamming signal is to study a type of interferences frequently found on the market: jamming-sweep.

The interfering signal (chirp signal) is the result of a sweep in a time duration ST (Sweep Time) and in frequency band from $f1$ to $f2$, as shown in **Figure 10**.

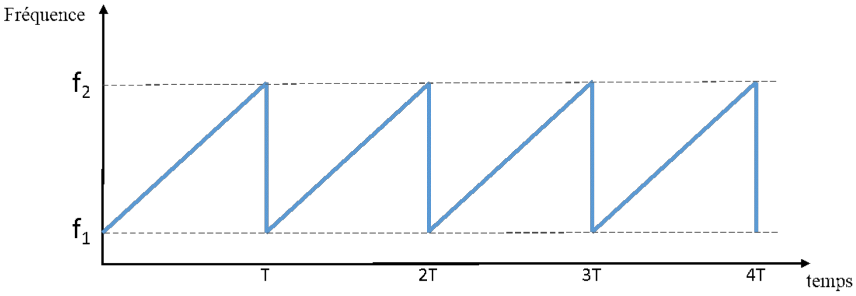

**Figure 10.** A chirp signal.

The jamming signal is defined by the equation (2).

$$J(t) = P_J \cos\left(2\pi f(t) + \varphi\right) \tag{2}$$

$$f(t) = f_0 + kt;\ k = \frac{f_2 - f_1}{ST}$$

$P_J$ is the power of the jamming signal, which emitted from $f_1$ to $f_2$ and ST is the sweep time duration.

The disturbance of this signal on the Zigbee one is presented in section 6.2.

## 5. EMC Proposed Measuring Bench

EMC studies covering different frequencies are realized in many laboratories and companies. These studies are mainly focused on protection of radio communication and restriction on unwanted interferences at particular frequency ranges.

Radiated emission (RE) and radiated Susceptibility (RS) tests are the core items of EMC tests; they are also the main contents to evaluate electromagnetic compatibility in high frequency range. Their common characteristics are: the complex testing system chain, the cost of standardized test, antenna characteristics and electromagnetic field theory applied [11].

In order to study the performance of communication system against electromagnetic disturbances, different test setups are proposed.

In [12], the authors proposed an optimal test bench for measuring radiated emission and testing RF radiated immunity of electronic devices using GPS receiver. This test setup was designed with the help of numerical simulations and experimental setups. The equipment under test (EUT) is placed in the shielded chamber. The chamber is a semi-anechoic one. An equipment in this chamber allows the EUT to rotate around its axe, to measure the radiated emissions.

In [13] a test bench has been built to evaluate the Quality of Service (QoS) of GSM-R facing the electromagnetic emissions from the pantograph electric arc. This test bench is composed of a network simulator connected to GSM-R mobile station. A combiner allows sending two signals: the GSM-R signal and the transient event simulated and generated with an arbitrary waveform generator. The simulator establishes the communication and measures BER (Bit Error Rate) to estimate the GSM-R quality.

In order to study the vulnerability of the IEEE 802.11n communication network facing frequency-sweeping interferences signal, different experiments in a semi-anechoic chamber were carried out in [14]. As a result, the paper shows the impact of the interfering signal that depends on the relationship between the sweep period and the time-window duration.

After studying and analyzing these platforms, a test bench has been developed and proposed to study the immunity of the Zigbee communication against different types of disturbances, which exist at the same frequency range.

The test bench is composed of a hybrid coupler that sums two signals: the useful signal (Zigbee) and the interfering signal (Noise signal). The goal of the proposed test bench is to evaluate the performance of the studied technology without the effect of wireless propagation. Then, the transmitter sensor generally connected to the antenna, is linked via a cable at one input of the coupler. Similarly, the interfering signal generator (received noise simulation) is directly connected to the second input as shown in **Figure 11**.

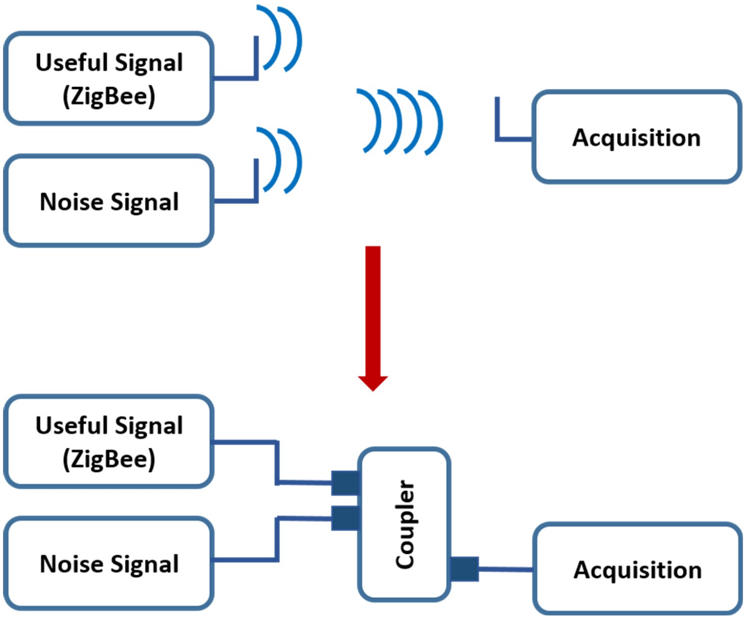

**Figure 11.** Test bench schema.

The coupler, covering the range between 1 to 4 GHz, is a hybrid one (3 dB and 180˚). The latter has four ports. The two outputs produce the sum (Σ) and the difference (Δ) of the two input signals. Since the difference between the signals will not be studied, this port is connected to an adapted load. The maximum input power of the coupler is 20 W, this allows to vary the power of each input and then, the value of the Signal to Interference Ratio (SIR).

The coupler was characterized in the 1 - 4 GHz band.

Its S-matrix has the following form:

$$S = \begin{pmatrix} \alpha & \beta & \gamma & \delta \\ \beta & \alpha & \delta & -\gamma \\ \gamma & \delta & \alpha & \beta \\ \delta & -\gamma & \beta & \alpha \end{pmatrix} \quad (3)$$

$\alpha = -20$ dB; $\beta = -40$ dB; $\gamma = -4.4$ dB; $\delta = -4.2$ dB.

The test bench is composed of different parts as presented in Figure 12:

(1) The useful signal generation: transmitter sensor Xbee-Pro to generate a Zigbee signal.

(2) The noise signal generation: waveform generator or arbitrary waveform generator to produce interfering signal.

(3) The coupler.

(4) The acquisition: Spectrum analyzer, Oscilloscope or receiver sensor Xbee-Pro.

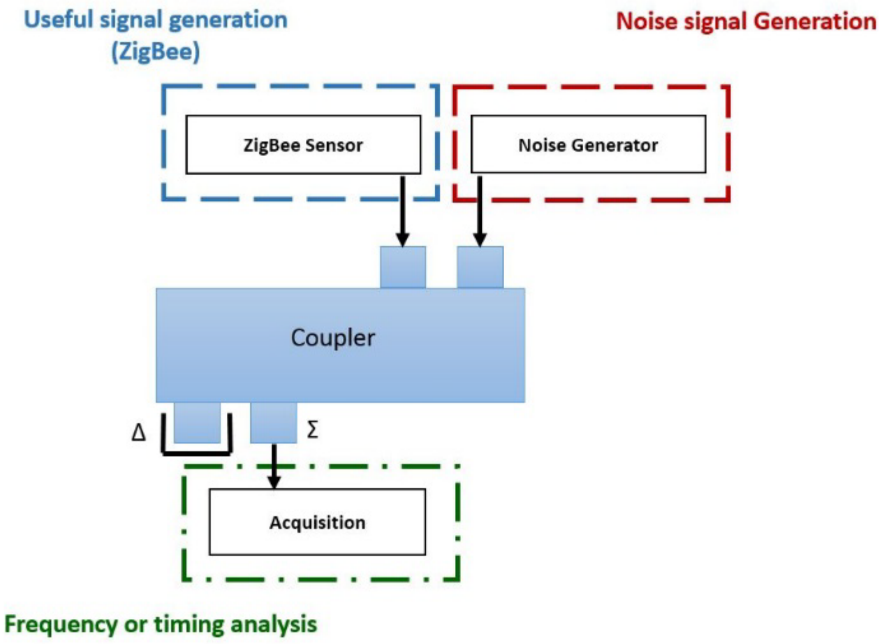

Figure 12. Test bench diagram.

## 6. Testing of Zigbee System Against Electromagnetic Disturbances

### 6.1. Study of the Transient Event Effect on the Zigbee Signal

The immunity of the proposed Zigbee system against transient event is studied. An arbitrary waveform generator (AWG) is used to generate the form of the transient event presented previously in Section 4.1. The Zigbee sensor is configured to transmit at the 2.405 GHz frequency with 0 dBm transmission power. The coupler sums these two signals. The output (Σ) is connected to a signal analyzer (spectrum analyzer or oscilloscope) to measure the received signal. The test bench is presented in Figure 13.

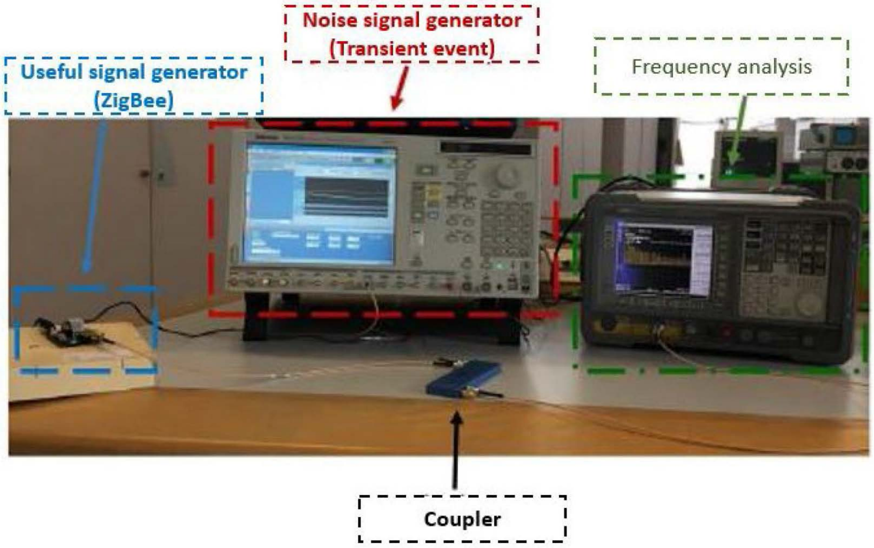

Figure 13. Test bench for disturbances caused by the transient event.

Figure 14 presents the transient event signal visualized on the oscilloscope.

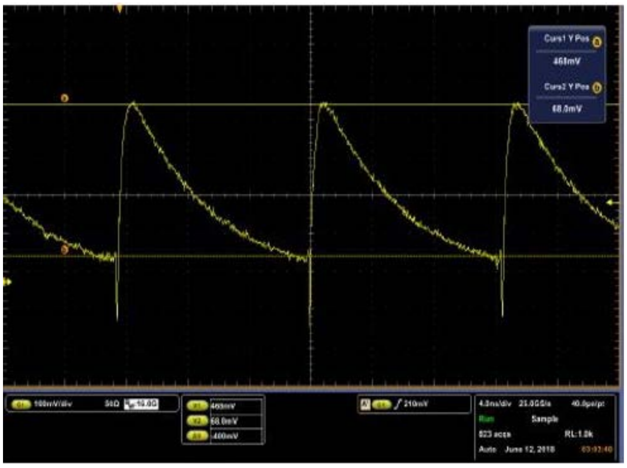

Figure 14. The waveform of the generated transient signal.

The arbitrary generator sampling rate reaches 10 GS/s on a single channel with a repetition rate of 80 MHz, which explains the repetition of the transient pulse on the waveform and the presence of the spectral lines on the spectrum as shown in Figure 15.

In order to determine the power of the interfering signal used in the test bench, the generator was first connected directly to the spectrum analyzer.

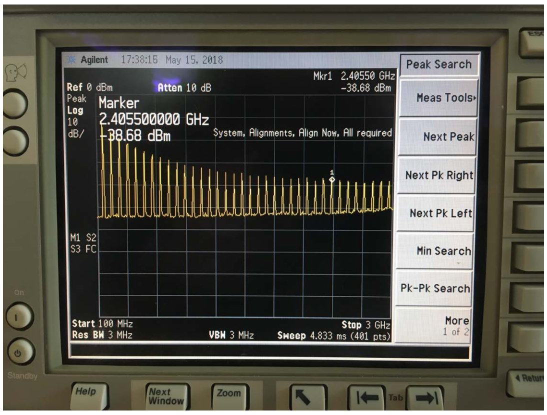

**Figure 15.** Spectrum of the transient event measured by the spectrum analyzer.

The transient event power at 2.405 GHz (Zigbee frequency) is −39 dBm, which is determined as the mean value of several measurements and the transmit power of Zigbee is 0 dBm; the difference between these two powers is almost 39 dB. At this SIR, the interfering signal power is quite low then, the message is received without error and the transmission of Zigbee is not affected.

An amplifier and various attenuators have been used in order to vary the input powers of the coupler, which is useful to modify the SIR value and to study the reliability of Zigbee systems in presence of a transient signal.

The experimental steps are executed as follow:

(1) The transient event power is measured after being amplified by −40 dB. Its value passes from −39.11 dBm to −1.51 dBm. Using the coupler, the power reaches −4.65 dBm. The difference of −4 dB is due to the coupler attenuation.

(2) The Zigbee power is set to 0 dBm. This value passes from 0 dBm to −31 dBm, −22 dBm and −9.9 dBm using various attenuators. With the attenuation due to the coupler (−4 dB), these values reach −36.18 dBm, −26.73 dBm and −14.63 dBm respectively.

(3) The coupler sums the two signals: Zigbee and transient event. Figure 16 shows the link budget calculation when the Zigbee signal is attenuated by 10 dB.

(4) The sum is received with Zigbee receiver and compared with the sent information (Zigbee transmitter).

Table 1 highlights these measurements and the results.

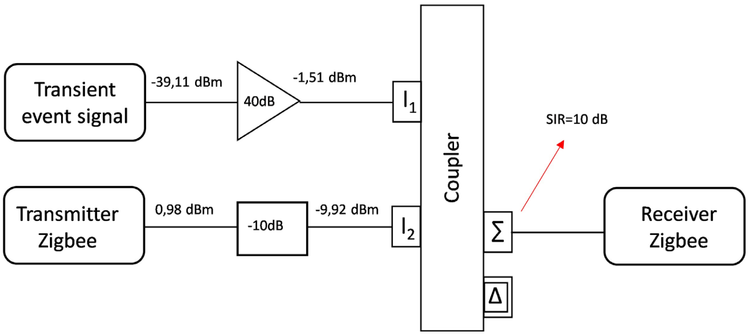

**Figure 16.** Link budget calculation of Zigbee transmission in the presence of a transient event.

**Table 1.** Results of measurement.

| Signal | Transmit power (dBm) | Attenuation (30 dB) | | Attenuation (20 dB) | | Attenuation (10 dB) | | Amplification (40 dB) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Direct link | + Coupler | Direct link | + Coupler | Direct link | + Coupler | Direct link | + Coupler |
| Transient event | -39.11 | - | - | - | - | - | - | −1.51 | -4.65 |
| Zigbee | −0.98 | −31.88 | −36.18 | −22.05 | −26.73 | −9.92 | −14.63 | - | - |
| SIR (dB) | | - | 31.53 | - | 22.08 | - | 9.98 | - | - |
| Information received | | NO | | NO | | YES | | - | - |

As shown in Table 1, when the difference between the transient event power and the ZigBee power is higher than 22 dB, the communication between Zigbee nodes is interrupted. Other scenarios are performed to refine the SIR threshold. Then, when the SIR is higher than 18 dB, the transient event power generated by sliding contact of catenary and pantograph may interrupt the communication between Zigbee devices.

The sensitivity of Zigbee is −102 dBm (for Xbee-Pro model) and the event transit power is around −39 dBm. Then, the SIR threshold of 18 dB can be easily reached.

The difference between Zigbee and transient event powers has to be taken into account to plan the Zigbee nodes. Therefore, the distance between the position of the pantograph and the Zigbee receiver has to be studied. Indeed, according to the measurements made in our project [15] [16], the power received at 8 m from the transmitter Zigbee could reach −55 dBm when the two antennas (Horn antennas) are positioning on the roof of the train. These antennas are directional then, if monopole antennas are used as in general case, the received power will be lower and the communication can be interrupted.

A solution can be to put an additional Zigbee node between the two nodes already installed. This node will act as a relay and will retransmit the information to the same receiver module with higher power.

The proposed test bench can also be used to analyze the Zigbee robustness against intentional attacks as presented in the next section.

### 6.2. Intentional Interferences Effect on the Zigbee System Performance

In this section, the effect of intentional interferences on the performance of a Zigbee system is studied. A jamming-sweep signal is centered on the same frequency of the first Zigbee channel (2.405 GHz) by varying the power and the sweeping time. Then, its effect on a Zigbee signal can be studied using the test bench presented in Figure 12. Zigbee sends 300 bytes (a sentence of 60 bytes length sent continuously 5 times) at 2.405 GHz frequency and 0 dBm power. The interfering signal sweeps from 2.4 GHz to 2.410 GHz with a sweep time ST as presented in **Figure 17**.

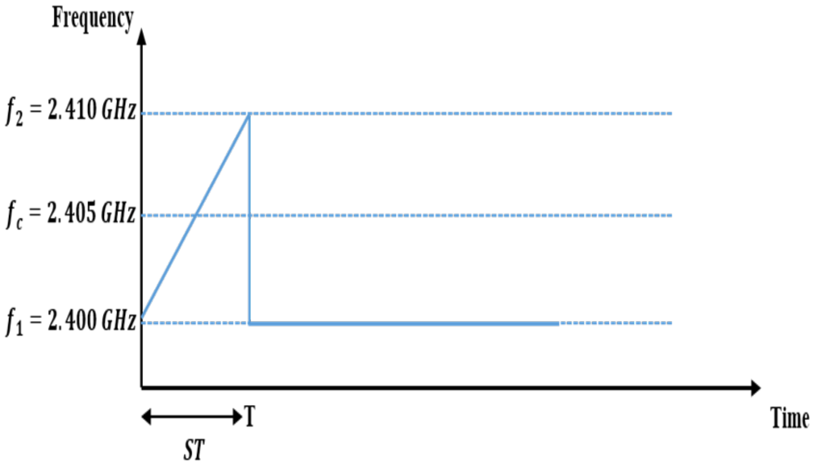

**Figure 17.** Reports of the received data number measured versus SIR (Signal to Interference Ratio) for different ST (Sweep Time) values.

**Figure 18** reports the received data number measured versus SIR (Signal to Interference Ratio) for different ST (Sweep Time) values.

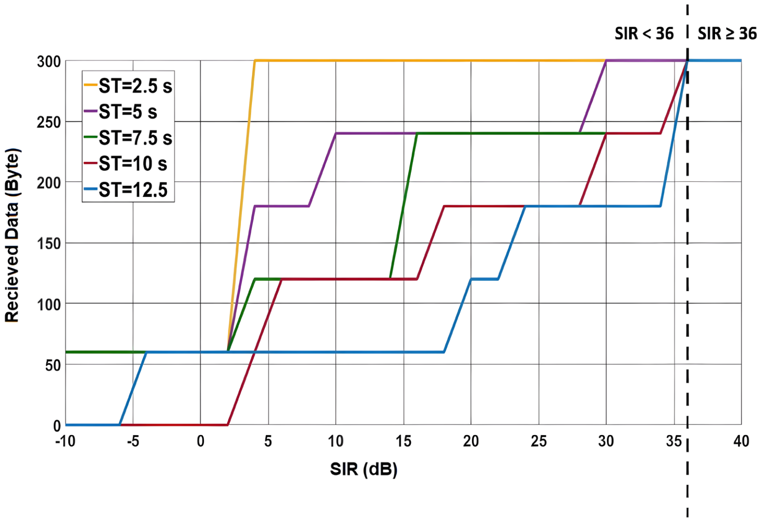

**Figure 18.** Received data in the presence of sweeping interferences in 2.4 GHz - 2.410 GHz band.

It can be noted that for a SIR of 36 dB, the quality of service is guaranteed independently of the value of ST (2.5 s < ST < 12.5 s) because all the bytes are received without error.

However, for a SIR lower than 36 dB, the slower the sweep time (ST is large) is, the greater the interferences.

The step variations that appear in **Figure 18** are due to the number of sentences received. In fact, the number of sentences received (5 times = 300 bytes) depends on the moment when the interfering signal is present. Which justifies that according to the values of the SIR, the length of received data can be 60, 120, 180, 240 or 300 bytes.

We can remark that for a sweep time of 12.5s (2.5 s resp.), the integrity of the information is guaranteed for a SIR > 36 dB (2 dB resp.). Indeed, Zigbee launches the CCA (Channel Clear Assessment) test to identify if the channel is busy; in this case, Zigbee restarts this test after a random time [8]. The slower the sweep time is, the more likely the channel is occupied (busy). Therefore, the transmission is postponed to be retransmitted or abandoned.

The effect of the sweep mode can then be studied. **Figure 19** presents the results of various scenarios where the interfering signal is sent at the same frequency as the Zigbee one (2.405 GHz):

(1) Without sweep time: ST=0 (a sinusoidal signal).

(2) With two different values of sweep time: ST = 2.5s and ST = 12.5 s.

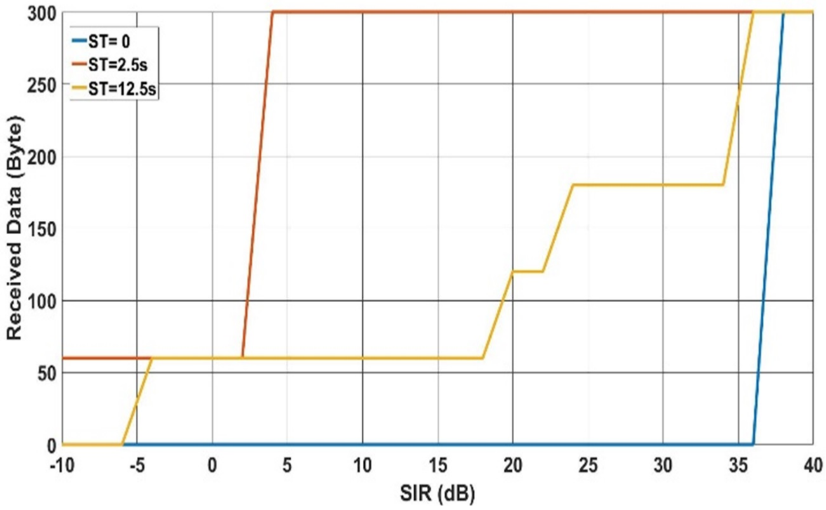

**Figure 19.** Jamming effect with a single sweep.

As shown in **Figure 19**, in the first scenario (ST = 0), the transmission of information is guaranteed for a SIR over 37 dB. However, in the second scenario (with sweep time), the information is transmitted for a SIR greater than 2 dB (for ST = 2.5 s) and 36 dB (for ST = 12.5 s).

For the scenario 1: the interfering signal is a sinusoidal one, then, it is always present in the propagation channel. Thus, during the process, Zigbee system launches the CCA and identifies that the channel is busy. That explains the great value of SIR obtained is this case.

For the scenario 2:

(1) For a small ST (2.5 s), the channel is not occupied for a long time and a small SIR (to guarantee the communication) of 2dB is obtained.

(2) For a great ST (12.5s), the channel is occupied for more time and the SIR is greater (36 dB).

This can be explained: when the sweeping is fast (for example ST = 2.5 s), the information can be transmitted during a next test of the CCA, but a slow sweeping act like a continuous wave (sinusoidal signal) and the information can be abandoned.

The interfering signal can also be generated in a continuous sweep mode, to aim a frequency band instead of a specific frequency. The continuous mode is presented in Figure 20. This continuous mode increases the chance of the interfering signal existence during Zigbee communication.

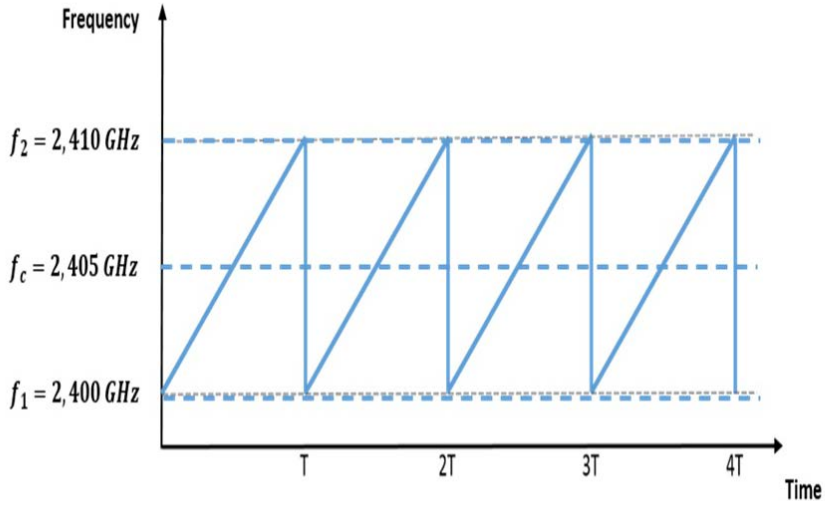

**Figure 20.** Continuous sweep.

In order to study the effect of the sweep mode, two modes are compared: single and continuous sweeps. Figure 21 reports the received data number measured for the two ST values and for two jamming modes: single mode and continuous mode.

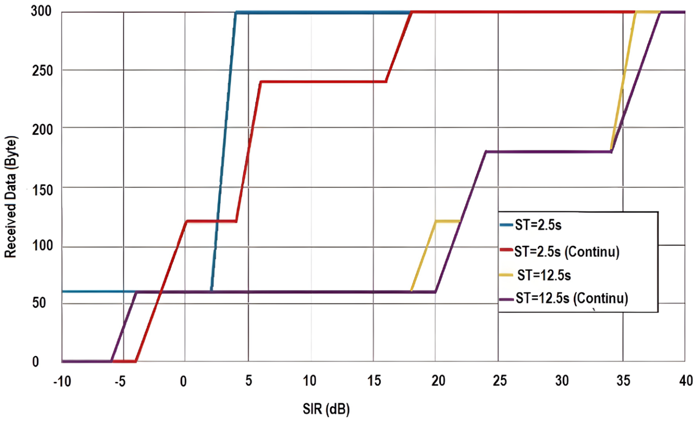

**Figure 21.** Jamming effect with continuous sweep.

For instance, for a SIR higher than 36 dB and whatever the ST value, the system performance is not affected. For a SIR lower than 36 dB, the received data number is affected and the loss depends on the ST value and the jamming mode.

## 7. Conclusions

The purpose of this paper is to find a solution to monitor and track freight trains. This system is based on Zigbee technology as it is an optimal technology offering several advantages for freight trains in term of flexibility, scalability and low installation cost. In order to study the feasibility of such a solution, a test bench is developed. This bench allowed analyzing the performance of the Zigbee against railway disturbances: transient event signal and jamming-sweep signal. It is also possible to do other analyzes with other types of disturbances such as a surrounding Wi-Fi signal that can be present in the same environment.

Similarly, the immunity of any telecommunication system in the bandwidth of the coupler can be studied using this test bench.

The measurements were made in a guided way to study the most unfavorable cases. Other measurements in an anechoic chamber and in free space could be done.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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