ULTRASONIC OFDM PULSE FOR BEACON IDENTIFICATION AND DISTANCE MEASUREMENT IN REVERBERANT ENVIRONMENTS

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Abstract: In this work we propose a frame architecture for asynchronous data transmission using ultrasonic OFDM pulses in reverberant environments. The frame has two different OFDM pulses modulated with BPSK. The first pulse plays an important role, it is used for time synchronization and to demodulated the unknown data in the second pulse by a differential demodulation scheme. The proposed frame architecture proved to be robust to the multipath in different scenarios. Results have demonstrated that it is possible to keep the bit error rate low in the presence of strong signal echos where other techniques fails, moreover, the simulations show that it would increase the reliability of ultrasonic indoor location systems.

1 INTRODUCTION

Location is an active area of research in the signal processing community with a large potential from the point of view of applications (Sayed et al., 2005; Liu et al., 2007). The GPS is the most popular system for outdoor location achieving an accuracy between 20 to 30 m (Sayed et al., 2005).

Recently, there has also been a great interest in using the existing mobile phone antenna infrastructure to perform outdoor location without the need of any additional hardware besides the mobile phones. However, such systems present in urban areas an accuracy about 100 m (Lakmali and Dias, 2008; Gustafsson and Gunnarsson, 2005). This accuracy is not enough for indoor applications, where the system must provide the exact position of the object. To perform indoor location, there are 2 main types of solutions: Ultrasonic (US) and Radio Frequency (RF) based systems. RF based systems are extremely inexpensive but require the profiling of the entire location scenario to get a RF fingerprint resulting in an accuracy from 1 to 5 meters approximately (Stuntebeck et al., 2008; Bahl and Padmanabhan, 2000). On the other hand, the ultrasound technology is the best suited to achieve the necessary accuracy level in three dimensions, that can be less than 1 cm in some cases (Gonzalez and Bleakley, 2009; Prieto et al., 2007).

1.1 LocUS Location System

LocUS is an ultrasonic based location system in development, with the main goal of perform indoor location using only ultrasonic signals. These ultrasonic signals will be used to get distance information, from time-of-flight (TOF) measurements, and also to implement data communication. Unfortunately, almost all of the known ultrasonic location systems use an auxiliary RF channel for measuring the propagation delay from the source to receiver (except the M. Hazas and A. Hopper's system (Hazas and Hopper, 2006) that presents an accuracy less than 25 cm in 95% of the cases). Although this auxiliary RF channel allows very simple clock synchronization and delay measurement solutions, it also gives away two important advantages that US-based systems bear in reference to RF-based ones: the immunity to RF interference, and the ability to safely operate in the presence of critical electronic instrumentation such as medical or life-support systems. Therefore, one way to avoid the use of an auxiliary RF signal to measure the TOF is to synchronize the clocks of the nodes (Skeie et al., 2001). To achieve this, the nodes should be able to send to each other the clock information using the ultrasonic channel. Due to the reflection of the ultrasonic signals on the walls the acoustic communication channel presents a strong multipath effect causing inter-symbolic interference, for that reason, OFDM (Orthogonal Frequency Division Multiplex-

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ing) could be a viable solution for location and communication. This technique has already been used in ultrasonic underwater communications (Mason et al., 2007; Nakashima et al., 2006). OFDM is a very flexible modulation technique, robust to multipath and that simplifies the channel equalization. It is also very sensitive to synchronization, which may be an advantage when the application requires the measurement of the TOF (Levanon and Mozeson, 2004).

In this paper it will be presented an asynchronous data transmission with OFDM pulses (section 2). In section 3 is presented some concerns in the pulse choice like the shape, size, etc. Some simulated results and a comparison with other techniques will be presented in section 4. At the end it will be presented brief conclusion.

2 ASYNCHRONOUS DATA TRANSMISSION WITH OFDM

An architecture for asynchronous data transmission using OFDM pulses is proposed. There will be used two pulses, one for time synchronization (e.g. time-of-flight measurement) and another for some data information transmission (e.g. source identification). The group of the synchronization pulse and the data information pulse is called frame.

2.1 Frame prototype

Figure 1 presents the proposed prototype for the frame, as mention before, there are two different main pulses in the frame: The *OFDM Sync.* and the *OFDM Data*. The first pulse is known by the receiver besides to allow synchronization it will be used to demodulate the second pulse, the *OFDM Data*, by a differential demodulation scheme (Haykin, 2001). This method was chosen manly because the OFDM pulse is robust to environments with multipath however it does not produce a very high resolution in time synchronization, how will be seen further. Therefore, the differential demodulation needs to be robust to this small jitter.

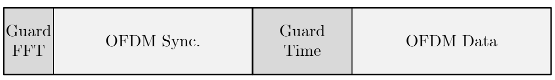


Figure 1: Asynchronous data transmission with OFDM, frame prototype.

The *Guard FFT*, presented in Figure 1 is a protection in the demodulation process due to the time synchronization jitter. The *Guard Time* has the same function of *Guard FFT* plus the reduction of the inter-symbolic interference (Schulze and Luders, 2005).

The frame building for the asynchronous data transmission with OFDM pulses will be presented using an example with 17 bit modulated BPSK (Binary Phase Shift Keying) per pulse. The BPSK is a good modulation for differential demodulation due to the phase difference (Haykin, 2001), 17 bits were chosen because this data may be enough to identification and some data communication. But the extrapolation for other data sizes and modulations would not be a problem.

2.2 OFDM Pulse

In the OFDM the information is divided in N blocks and each value of this block is sent using a different carrier, in order to avoid the ISI (inter-symbolic-interference) the OFDM uses carriers that are orthogonal to each other, reducing this way the total signal bandwidth (Schulze and Luders, 2005).

Moreover, the FFT (Fast Fourier Transform) and IFFT (Inverse Fast Fourier Transform) can be used to improve the efficiency of the system and the implementation simplicity. Figure 2 presents the block diagram of a possible OFDM communication system using the FFT.

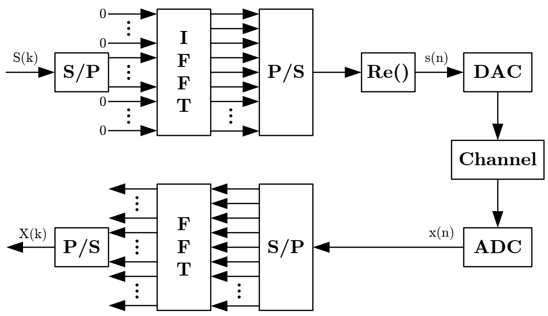


Figure 2: Block diagram of a OFDM communication system.

The system input, $S(k)$, can be symbols from some classic modulation like PSK (Phase Shift Keying) or QAM (Quadrature amplitude modulation) (Schulze and Luders, 2005). Moreover, the system only modulates the carriers of the pass-band transmission system, as shown in Figure 2.

In order to better understand the OFDM pulse a simple example was chosen, an OFDM pulse with only three bits, 0 1 0, of information that can be modulated with BPSK resulting in the symbols 1 -1 1. Therefore, for this three symbols, carriers 5, 6 and 7 of an IFFT with size 1000 were chosen. Figure 3 presents the three individual chosen carriers modulated BPSK. Resulting in the OFDM pulse of Figure 4.

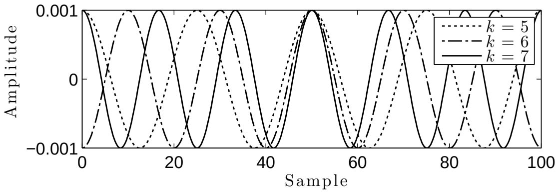


Figure 3: OFDM example:3 carriers coded BPSK.

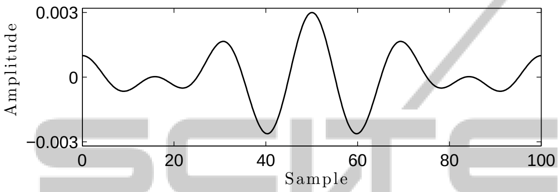
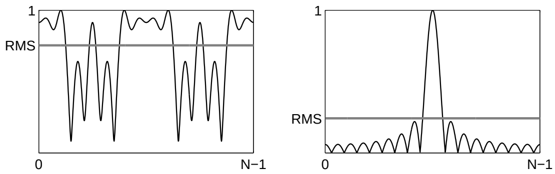


Figure 4: OFDM example: The OFDM pulse.

The different combination of carrier codes creates different pulse shapes and pulse amplitudes. The systems are normally limited in amplitude and not in energy due to the DAC(Digital-to-Analog Converter) and amplifiers limitations. Therefore, it will be important to maximize the pulse energy for the same amplitude or, in other words, we need to minimize PMEPR (Peak-to-Mean Envelope Power Ratio) (Schulze and Luders, 2005). In Figure 5 we compare two different OFDM pulse envelopes where all the 17 carriers where BPSK modulated. The first case (Figure 5(a)) shows an OFDM pulse envelope with the lowest PMEPR and the second case (Figure 5(b)) shows an OFDM pulse envelope with the greatest PMEPR. As can be seen the two examples are very different and give an idea of how different the pulses envelope can be.



(a) Best PMEPR value. (b) Worst PMEPR value.

Figure 5: Greatest and lowest PMEPR for an OFDM pulse with 17 carriers (RMS - root mean square).

3 OFDM PULSE CHOICE

In order to maximize the OFDM pulse detection the system must use a matched filter (Levanon and Mozeson, 2004). Moreover, it is possible to demonstrate that the probability of pulse detection is proportional to the pulse energy, (each mens that the most important thing for pulse detection will be energy of it and not the envelope of it) (Levanon and Mozeson, 2004).

Due to the maximum signal amplitude limitation impose by the hardware (DACs, ADCs, amplifiers, etc.) the OFDM pulse must have the PMEPR as low as possible in order to maximize the probability of detection.

However, to have good TOF measurement with less error as possible the OFDM pulse must have an autocorrelation function similar to an impulse (Levanon and Mozeson, 2004). Therefore, the mainlobe heigh (at the origin) and the relationship between the this lobe and the sidelobes must be as big as possible. However, the mainlobe heigh have a direct relation with the energy of the OFDM pulse, but the peak-to-peak amplitude are limited by the source.

Due to the receiver and/or source movement Doppler effect will occur (Haykin, 2001), therefore, the correlation between the received pulse and the matched filter's pulse will change with the doppler shift. As a result of this we must look not only to the autocorrelation function but also to the output of the match filter for different frequencies shifts. To the output of match filter in function of time delay and doppler shift will be called ambiguity function (Levanon and Mozeson, 2004). Consequently, the ideal ambiguity function is a function that has a single infinite spike at the origin and is zero elsewhere (Levanon and Mozeson, 2004).

To explain how to chose an OFDM pulse, a pulse with 17 carriers modulated BPSK was chosen. Although, the extrapolation for other pulse sizes would not be a problem, it only take more time to find the best pulse. These OFDM pulses must have an ambiguity function similar to the ideal ambiguity function. Therefore, the mainlobe heigh (at the origin) and the relationship between the this lobe and the sidelobes must be as big as possible (similar to the autocorrelation function). However, the mainlobe heigh have a direct relation with the energy of the OFDM pulse, but the peak-to-peak amplitude are limited by the source.

Therefore, we must minimize the PMEPR and maximize the MSR (Mainlobe-to-Sidelobe Ratio). With these 17 carriers modulated BPSK we only have 131072 possibilities, to test all off them will not be a big problem. Moreover, we only need to test half of them because one pulse and its complement will produce the same ambiguity function. And we do not need to test all of the half set because a pulse and it carriers inverse produce the same pulse envelope and ambiguity function (i.e. considering one pulse with 3 carriers coded BPSK the pulse [1 1 -1] has the ambiguity function of pulse [-1 1 1]).

The values for MSR and PMEPR are shown in Figure 6 and 7 respectively. Note that, the MSR tests were only performed for zero Doppler shift.

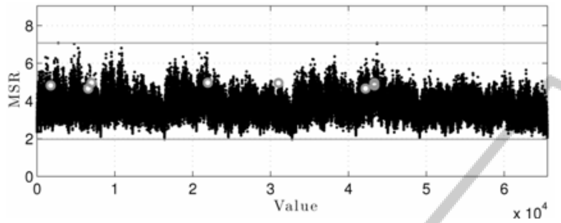


Figure 6: Mainlobe-to-Sidelobe Ratio for OFDM with 17 carriers coded BPSK.

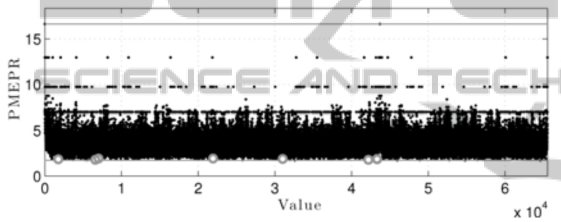


Figure 7: Peak-to-Mean Envelope Power Ratio for OFDM with 17 carriers coded BPSK.

The PMEPR values are between 1.73 and 16.82 and the MSR are between 1.97 and 7.08. In order to chose the best OFDM pulse with a big MSR and a low PMEPR we sort the MSR and PMEPR values by the ratio of MSR and PMEPR from the shortest to biggest (Figure 8) and is represented the last eight values in Figures 6 and 7 by a grey circle.

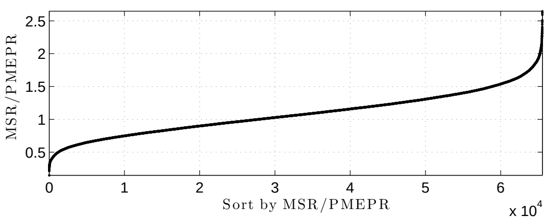


Figure 8: Sort of the MSR and PMEPR ratio.

It is logic that the best value is the last one. It has a bigger MSR (4.95) and a smaller PMEPR (1.91). In that case, the BPSK codes are [00111100100101010], [11000011011010101], [10101011011000011] or [01010100100111100]. How can be seen the codes are complemented in phase and frequency.

For compare this pulse with others we chose three more pulses and we normalize all pulses to have the same maximum amplitude. We chose: the pulse with the biggest PMEPR [01101010111111100], the pulse with the biggest MSR [00000101010101010] and the pulse with the lowest MSR and PMEPR ratio [00000000000000000]. The ambiguity function of these examples are shown in Figures 9, 10, 11 and 12. Where N is the size of the pulse and d the distance between two OFDM adjacent carriers. For a better comparative we normalize all the ambiguity function to the maximum value of the ambiguity function with the biggest PMEPR.

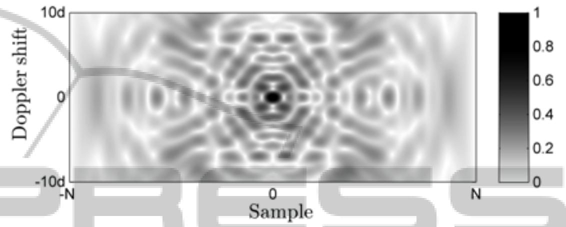


Figure 9: Ambiguity function of the pulse with the lowest PMEPR.

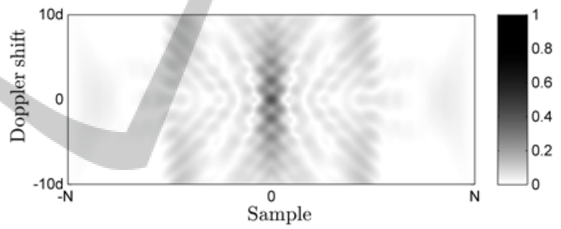


Figure 10: Ambiguity function of the pulse with the biggest MSR.

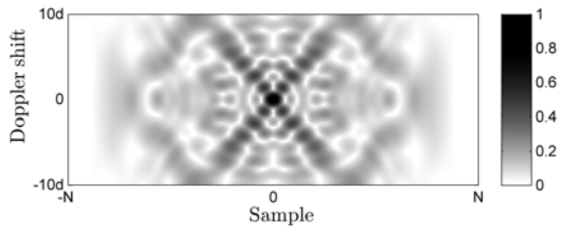


Figure 11: Ambiguity function of the pulse with the biggest MSR-PMEPR ratio.

3.1 Pulse Size

To choose the best pulse size is necessary to know the limitations of the system that will be used to transmit the information, the limitations come mainly from the channel conditions (air) and the waves propagation (ultra-sounds).

For detection point of view a pulse must be as big as possible (for the same amplitude the energy increase with the length of the signal) (Levanon and

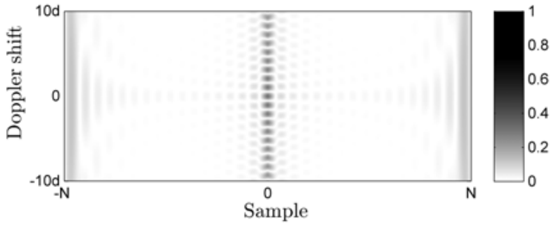


Figure 12: Ambiguity function of the pulse with the lowest MSR-PMEPR ratio.

Mozeson, 2004). On the other hand the length of the signal is inversely proportional to the distance of two adjacent carriers and consecutively to the Bandwidth of the resultant signal. So in the first analysis a huge pulse will be the best, however it will introduce a problem, the carriers will be very near and a little relative speed between the source and the receiver produce a catastrophic change in the carriers. Therefore an up and a lower bound to the pulse size is presented:

$$\frac{N_p}{B} \leq T_{Pulse} \leq \frac{c+v}{2vf_c} \tag{1}$$

where T_{Pulse} is the time length of the pulse, B is the maximum bandwidth for resultant pulse, c is the wave propagation speed, v is the maximum allowed relativity speed between the source and the receiver and f_c is the central frequency of the resultant desired pulse. Note that, in this equation only a maximum Doppler shift of a half of the distance between the adjacent carriers will be allowed, moreover, the resultant pulse has a very narrow band so the Doppler is approximately equal for all the carriers.

The *Guard Time* must be greater or equal than *Guard FFT* and greater than the minimum time to avoid the inter-symbolic interference. Normally the minimum time to avoid the inter-symbolic interference is bigger than the *Guard FFT*. Mathematically the lower bound to *Guard Time* is:

$$T_G \geq \max\{T_{G_{FFT}}, T_{ISI_{min}}\} \tag{2}$$

where the minimum to avoid the inter-symbolic interference can be approximated, for the omni-directional transducers, by the solution of the equation:

$$20\log(acT_{ISI_{min}}) + \alpha c T_{ISI_{min}} = \log(r) + \alpha r \tag{3}$$

Where a is the maximum ratio between the reflection wave amplitude which does not interfere in the direct wave and the direct wave amplitude. The coefficient α is the attenuation of wave due to the absorption of ultra-sound by the air and it is given in dB/m. Finally, r is the maximum distance between the source and the receiver.

3.2 Asynchronous Receiver

The block diagram of a possible asynchronous receiver is shown in Figure 13. The Synchronization part consist in a simple algorithm: after the system detect the pulse, it chooses the maximum of the output of the detector on the next N samples (the length of the pulse plus the *Guard FFT* time if it exists); After that the system demodulates the data using the synchronization pulse by a differential comparison.

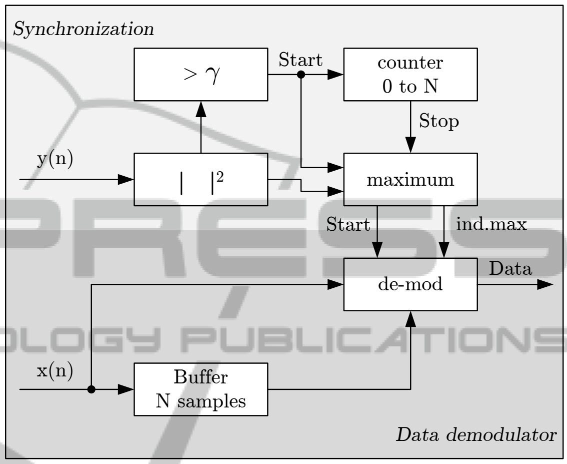


Figure 13: The block diagram of the asynchronous OFDM receiver.

4 RESULTS

To test the proposed asynchronous data transmission with OFDM pulses a practical example was chosen, the source and the receiver are almost motionless, therefore, a 0.02 m/s of maximum relativity speed was chosen. The system works at 40 KHz of central frequency with 2 KHz of bandwidth and sampling rate of 200 KHz. Nevertheless the system must have at least 10 different channels for communication and 17 bits to transmit. So each channel has a maximum bandwidth of 200 Hz. Therefore, from the equation 1, we can compute the size of the pulses:

$$85 \text{ ms} \leq T_{Pulse} \leq 107 \text{ ms} \tag{4}$$

A $T_{Pulse} = 100$ ms can be chosen, as a result of this the distance between two adjacent carriers is 10 Hz ($d = 10$ Hz) and each pulse has 10000 samples.

Too choose $T_{G_{FFT}}$ the pulse ambiguity function must be used. It can be seen that the main lobe had about 6 ms of width. Therefore 3 ms is the distance in time from the maximum of main lobe to the minimum of it. So we use 5 ms for $T_{G_{FFT}}$ to allow a poor accuracy in the received instant.

Finally to compute the *Guard Time*, the maximum distance between the source and receiver must be used. It is 5 m ($r = 5$), therefore the attenuation of wave during propagation due to the absorption of ultrasounds by the air is 1 dB/m ($\alpha = 1$) and a reflected wave with amplitude of one fifth ($a = 0.2$) of the direct wave does not produce a relevant inter-symbolic interference. With these values the $T_{ISI_{min}}$ is 15 ms so 15 ms can be used for the *Guard Time*.

One possible frame for the given example is shown in Figure 14;

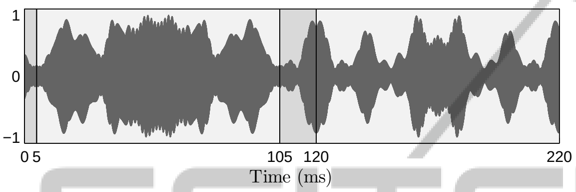


Figure 14: Asynchronous data transmission with OFDM, example of a frame.

To validate the proposed frame we will compare it with other used method. This method uses a very common pulse for synchronization, a chirp (Levanon and Mozeson, 2004), and an usually differential modulation (DBPSK) to data transmission which allows some synchronization jitter (Haykin, 2001). As a result of using DBPSK for transmit the same data we will need one more extra bit. This extra bit is going to be used as a reference for differential demodulation. The chirp ambiguity function is presented in Figure 15 and the block diagram of the frame in Figure 16.

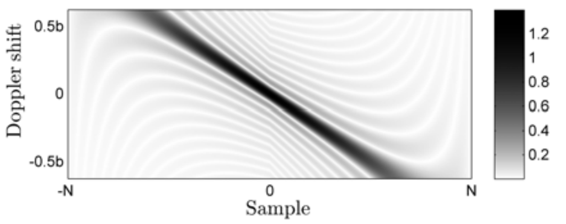


Figure 15: Ambiguity function of a chirp pulse.

Figure 16: Asynchronous data transmission with chirp and DBPSK, frame prototype.

The first primordial characteristic to be set is the size of the frame, therefore both frames must have the same length (220 ms). The chirp has almost the double of energy compared to the chosen OFDM pulse, so it will produce the double of main peak in the match filter output. Consequently, in this comparative, we are going to use a chirp with a half size of the OFDM pulse (50 ms), as a result we maintain similar capability of detection for both cases. We do this because we want give more time (170 ms) to the data in order to reduce the total bandwidth. But even with this data length, it is impossible to get the same bandwidth that we can obtain using the OFDM pulses. Moreover, we want to transmit 18 bits (17 bits plus one bit for differential demodulation) in 170 ms so we need about 212 Hz of bandwidth instead of the 170 Hz in the case of the OFDM pulse. One possible frame of this example is shown in Figure 17;

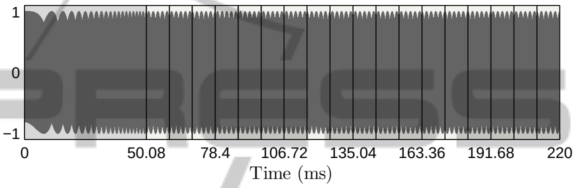


Figure 17: Asynchronous data transmission with chirp and DBPSK, example of a frame.

The main goal of the proposed frame is the robustness to multipath that exist in the rooms when we use ultrasonic waves to communicate (reverberant environment). All tests will be performed to demonstrate how robust the proposed frame is and how better or worst it is comparatively to other common technique.

To test our system we use two different approaches. In the first one we use a synthetic impulse response to simulate the multipath, in the second one we use an ultrasonic room acoustics simulator.

4.1 Test with a Synthetic Impulse Response

To simulate the robustness to multipath we implement a synthetic impulse response. The system begins to receive the direct pulse at instant 0 and receives three more attenuated echoes. This impulse response is shown in Figure 18 where $\mathcal{N}(\mu, \sigma)$ represent a Gaussian independent variable with μ mean and σ^2 variance.

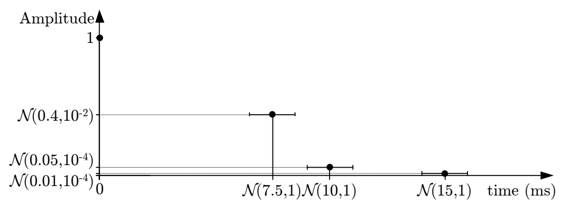


Figure 18: The synthetic impulse response for test the system.

The data to send was chosen randomly for OFDM and Chirp plus DBPSK, in DBPSK the first bit was set to one in all simulations. Moreover, it was added white noise to resultant signal and the threshold was set to have a probability of false alarm of the 10^{-9}. The Bit error rate (BER) was computed for each signal (OFDM or Chirp plus DBPSK) and 1 million simulations per signal amplitude to noise standard deviation were performed. The result of this test is shown in Figure 19. How you can be seen the OFDM had an excellent behavior comparatively to the Chirp plus DBPSK, which has a BER floor greater than 10^{-2}.

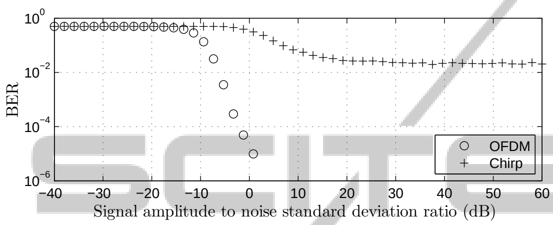


Figure 19: The Bit error rate in a multipath channel for a theoretical impulse response.

4.2 Tests in a Room Simulator

To test and compare the two methods we use a simulator implemented by the authors and presented in (Albuquerque et al., 2010), it is an acoustic simulator that assumes specular reflections and aimed to simulate ultrasonic communications. Moreover, it takes in to account the attenuation due the air propagation losses (as a function of the signal frequency, room temperature, air pressure and humidity), wall reflections and source and receiver beams. The proposed simulator was used to model a real room and it closely matched the experimental observations.

In this simulator two test are performed in the follow room conditions:

- The room has 5x5x3m of dimension;
- The reflection coefficient of the wall is 0.7;
- The reflection coefficient of the floor is 0.5;
- The reflection coefficient of the ceil is 0.9;
- No noise was added to the incoming signal;
- For each position were sent 170 bits (10 frames);
- For the source was used an approximated beam function from the Murata transmitter MA40B4T;
- For the receiver was used an approximated beam function from the Murata receiver MA40B4R;
- The source and the receiver were placed at 1m from the floor;
- The room temperature was set to $22°C$;
- The atmospheric pressure inside the room was set 1 atm;
- The relativity humidity inside the room was set to 33%.

The first test was conducted in the room of Figure 20, the source was located at $1cm$ of the "top" wall and $10cm$ of the "left" wall. The main propagation direction of the source was to "down" and parallel to "left" wall. The receiver started "walk" at 2 m from the "top" and "left" wall and stopped at about 27.5 cm from the source. Therefore, the simulator get the probability of bit error with a "step" resolution of 2.75 mm resulting in 900 probabilities (Figure 21). How can seen the two frames have a good behavior (the OFDM has a small advantage) in this test.

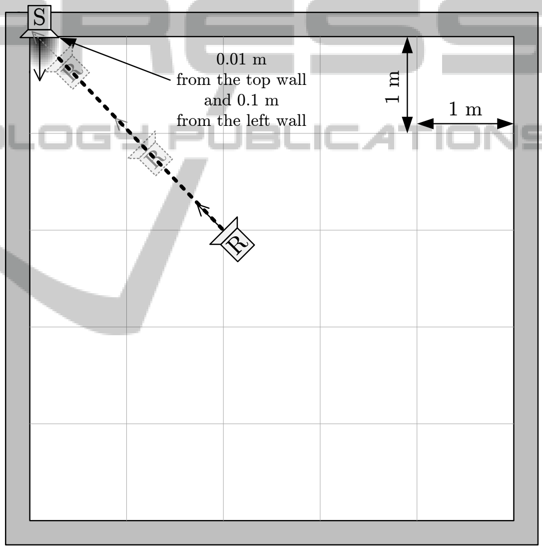


Figure 20: First simulator test room.

The second test was conducted in the room of Figure 22, this room is similar to the room of the first test, but this one has a wall with a 1 m of width and 20 cm of deep. The source was placed at the centre of the "top" and at 1 cm from it. The main propagation direction of the source was set to "down" and parallel to "left" wall. The receiver started "walk" at 1 m from the "left" and "bottom" wall and stopped at 1 m from the "right" and "bottom" walls. The simulator get the probability of bit error with a "step" resolution of 3 mm resulting in 1000 probabilities (Figure 23). How can seen there will be in these type of cases that the proposed prototype will present a better result in comparative to other usual techniques. With an appropriated code correction it will be possible to reduce the probability of bit error to almost zero where with other techniques it is impossible.

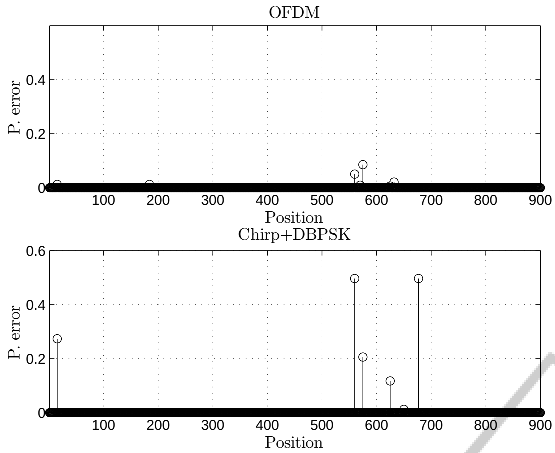


Figure 21: The probability of error in the first simulator test.

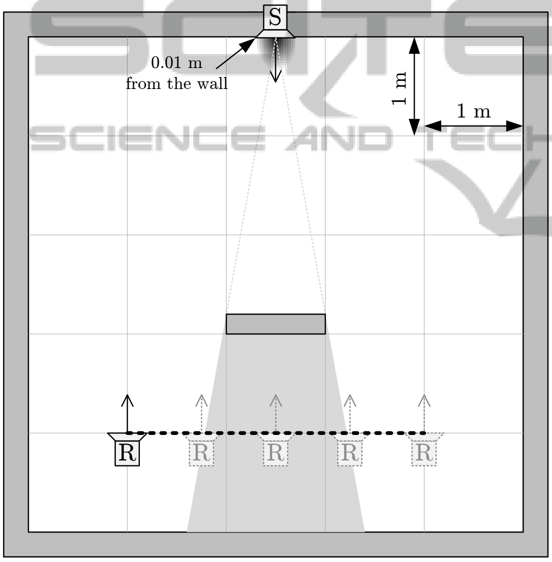


Figure 22: Second simulator test room.

5 CONCLUSIONS

In this paper is proposed an asynchronous data transmission with OFDM pulses which is robust to the multipath effect. To achieve these goals OFDM with BPSK modulated carriers was used. It was presented the OFDM pulse restrictions and it was given some advices of how to build the proposed asynchronous data transmission and how to choose the size and the shape of the OFDM pulse. Therefore, some simulations to compute the bit error rate of the proposed system were performed. The performance of the proposed technique, in the presence of multipath, is undoubtedly better than the use of the chirp with DBPSK. Moreover, some considerations can be made

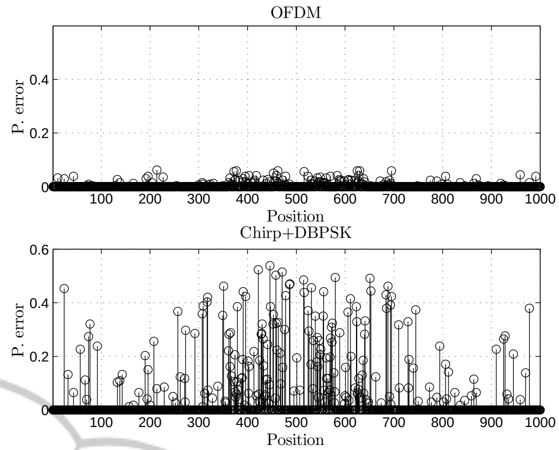


Figure 23: The probability of error in the second simulator test.

about the Doppler effect. The OFDM pulse may be robust than the chirp pulse. Because the ambiguity function is more similar to the ideal ambiguity function which mays allow to recovery the instant and the speed of the source with a better precision.

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