Analyzing the Propagation Features of the Texas eZ430-RF2500 Device

Eurico Moura B. Sobral, Rafael Dueire Lins and Zanoni Dueire Lins

Abstract**—** The Texas eZ430-RF2500 is a new device developed for wireless networking applications. This paper analyzes the propagation features of this device for the several operating modes.

Keywords **— propagation, Texas, eZ430-RF2500.**

I. Introduction

Technological development has been responsible for the appearance of smaller and smaller devices with reasonable processing power, low power consumption, and also allowing wireless communication. In this scenario we find the device eZ430-RF2500, from Texas Instruments, a platform for the development of micro controlled systems, supporting serial communication and Radio Frequency (RF). These devices are extensively used in Wireless Sensors Networks (WSN). The main purpose of a WSN is to collect data and, if necessary, to act upon the information collected, controlling a particular event. Applications of these networks have emerged in several areas, such as environmental monitoring, disaster forecasting, transportation, medicine, entertainment, military projects, etc.

This paper analyzes the propagation features of the Texas eZ430-RF2500 [1] device for the several operating modes. In addition, its performance is evaluated system to get operating conditions.

II. The Texas eZ430-RF2500

The Texas device eZ430-RF2500 (Figure 1) is a platform that may be used for prototyping micro controlled systems with radio transmitter and receiver. This chip is part of a family of similar devices which in the last few years were improved to be compatible with other devices and interfaces, besides becoming easier for use. The eZ430-RF2500 has two main boards, one responsible for USB I/O, called the *emulation board* and another, *target board*, where lies the micro controller MSP430F2274 [2][3] and the chip RF CC2500 [4]. These two boards communicate via the serial interface USCI (*Universal Serial Communication Interface*) which works as a UART (*Universal Asynchronous Receiver Transmitter*). On the other hand, the communication between the MSP430F2274 and the CC2500 is done through the SPI (*Serial Peripheral Interface*).

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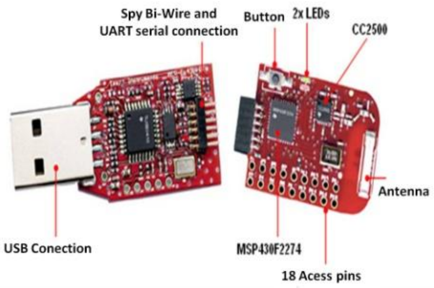

Figure 1 – eZ430-RF2500 (real size)

The USB interface (*Universal Serial Bus*) also allows applications for which a PC receives and sends information to the device, being also possible to have access to the peripheral devices to the microcontroller on the target board. All communication between the eZ430-RF2500 and a PC is done through the USB interface.

The USB is also used for programming and debugging the device directly, which may be embedded into other devices afterwards, and thereafter all communication is done via radio to another compatible device. This paper analyzes the radio communication features of the eZ430-RF2500, focusing of propagation issues.

III. Modeling the eZ430-RF2500 Propagation

Whenever one refers to electromagnetic propagation two aspects are taken into account: the macro and micro behavior. The first case looks at large distance increments, while the latter one analyses increments to that distance. The modeling of electromagnetic propagation is still a challenge. Propagation models are also divided taking into account the propagation environment as *indoors* and *outdoors*. The eZ430-RF2500 works in the 2.4GHz ISM (*Industrial, Scientific and Medical*) band. This section briefly looks at some propagation models used at this band and see how they "predict" the behavior of equalization and modulation of the device under analysis.

A. Signal Propagation

Several are the effects that arise with signal propagation such as diffraction and reflection, as seen in references [5][6]. During the propagation of an electromagnetic wave such phenomena act in group interfering in the direct wave propagation. Thus, it is of Paramount complexity the modeling of wave propagation in "real" scenarios. In general, signal modeling takes into account the power of the signal along a path. In the case of open space propagation, Friis equation (Equation 1) [6] may be used to estimate the power level of the received signal at the receptor given a certain distance of the transmitter. Such equation has parameters: P_T – the power transmitted, G_T – the gain of the transmitting antenna, G_R – the gain of the receiving antenna, d – the distance between transmitter and receiver, and λ – the signal wavelength.

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi)^2 d^2}. \quad (1)$$

This equation does not take into account the phenomenon of electromagnetic reflection, when it propagates close to the ground, however. Thus, even more complete models that take into account phenomena such as reflection, diffraction, spreading, etc. have some deterministic and empirical character.

B. Outdoor Signal Propagation Models

The Model of Young

The model proposed by Young is based on data collected in outdoor environments at New York City in 1952 over a frequency range from 150 MHz to 3.7 GHz [6][7]. The use of this model for signal propagation in wireless networks is unusual, but it seems to be applicable because its band range includes the 2.4 GHz band. The formula of the model of Young is:

$$PL(d) = \frac{d^4}{G_t G_r (h_t h_r)^2 \beta} \quad (2)$$

where *d* is the distance between transmitter and receiver, *G* stands for the antenna gains, and *h* their height (indices *t* and *r* indicate a transmitter or receiver). The parameter β is called the *clutter factor* [7] and is experimentally obtained. Supposing that the antennas of the transmitter and receiver are similar and have gain $G_t = G_r = 1$ and that both are placed at the same height $h_t = h_r = 1$, then formula (2) can be simplified into:

$$PL(d) = \frac{d^4}{\beta'} \quad (3)$$

or, expressing in dB units

$$PL(d)[dB] = 40\log(d) - 10\log(\beta'). \quad (4)$$

The Log-distance Model

This is probably the most referenced model in the technical literature for signal propagation modeling in wireless networks [6-8]. It assumes an exponential relationship between incremental path loss and distance [8],

$$PL(d) \propto \left(\frac{d}{d_0}\right)^n \quad (5)$$

where *d* is the distance between transmitter and receiver, d_0 is a reference distance (typically assumed to be 1 m) and *n* is the attenuation factor [8]. From this relationship the path loss function, in dB units, is defined by:

$$PL(d)[dB] = PL(d_0)[dB] + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right). \quad (6)$$

Formula (5) indicates that the path loss at a given distance *d* is the sum of the path loss observed at a reference distance d_0 and the additional loss imposed by (4). The attenuation factor *n* is found experimentally.

The 2-Ray Model

This model takes into account both the direct transmitted and the floor reflected signals interfering at the receptor, as shown in Figure 2. The intensity of those signal may be related by the Fresnel reflection coefficient (Γ) [6][8]. Γ depends on factors such as the incidence angle (θ_i), the electrical permissivity of the medium (ε_r), and signal polarization as shown in equations (7) and (8).

$$\Gamma_{Hor} = \frac{sen(\theta_i) - \sqrt{\varepsilon_r - \cos^2(\theta_i)}}{sen(\theta_i) + \sqrt{\varepsilon_r - \cos^2(\theta_i)}} \quad (7)$$

$$\Gamma_{Ver} = \frac{\varepsilon_r \cdot sen(\theta_i) - \sqrt{\varepsilon_r - \cos^2(\theta_i)}}{\varepsilon_r \cdot sen(\theta_i) + \sqrt{\varepsilon_r - \cos^2(\theta_i)}} \quad (8)$$

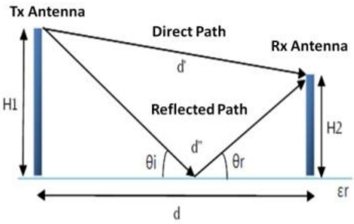

Figure 2 – 2-Ray Propagation Model

The distances for the direct transmission and the reflected signal are shown in Equations (9) and (10), respectively.

$$d' = \sqrt{d^2 + (H_1 - H_2)^2} \quad (9)$$

$$d'' = \sqrt{d^2 + (H_1 + H_2)^2} \quad (10)$$

$$D_{dif} = d'' - d'$$

The phase difference between the transmitted and reflected signals may be calculated by the path difference between signals [6], as indicated in Equation 11.

$$\theta_{dif} = \frac{D_{dif} 2\pi}{\lambda} \quad (11)$$

The power of the received signal is given by the sum of the powers of the direct and reflected signals. Considering the horizontal polarization one has:

$$P_{total} = P_{dir} + \cos\left(D_{dif} \cdot \frac{2\pi}{\lambda}\right) \cdot \frac{\Gamma_{Hor}}{|\Gamma_{Hor}|} \cdot P_{ref} \quad (12)$$

where,

$$P_{dir} = P_T \frac{G_T G_R \lambda^2}{(4\pi \cdot d')^2}, \quad (13)$$

$$P_{ref} = P_T \frac{G_T G_R \lambda^2}{(4\pi \cdot d'')^2 \cdot |\Gamma_{Hor}|}. \quad (14)$$

The value of the power of the signal converted into dBm is calculated by Equation 15:

$$P_{dBm} = 10\log\left(\frac{P_{total}}{1mW}\right) \quad (15)$$

C. Indoor Propagation Models

The modeling of signal propagation in indoor environments may be presented either for specific or general scenarios. The specific one takes into account all details of the environment such as furniture, materials, building structures, etc. On the other hand, the general one makes approximations about the propagation "behavior". The former are more complex, thus they are seldom used. Here, the general models studied for analyzing the Texas eZ430-RF2500 are presented.

The ITU Model

The model of ITU (International Telecommunication Union) was developed for indoor WLAN operating from 900 MHz to 100 GHz [9]. The proposed attenuation formula is:

$$PL(d)[dB] = 20 \cdot \log(f) + N \cdot \log(d) + \mathrm{Lf}(m) - 28 \quad (16)$$

where, *f* indicates the operational frequency in MHz, N is the distance power loss coefficient, Lf is the floor penetration loss factor and *m* is the number of floors between AP and terminals. Some specific formulas for Lf are defined in [9] as a function of the frequency and different kinds of environments. Table 1 presents some values for the loss coefficient *N* with relation with the kind of the propagation environment and signal frequency.

Table 1. Loss coefficient *N* for some environments

Frequency	Residential	Office	Commercial
900 MHz	-	33	20
1.2 to 1.3 GHz	-	32	22
1.8 to 2.0 GHz	28	30	22
4 GHz	-	28	22
5.2 GHz	-	31	-

Table 2 shows the expressions for calculating the floor loss factor as a function of the frequency of the signal and propagation environment.

Table 2. Values of Floor Loss Factor Lf(m)

Frequency	Residential	Office	Commercial
900 MHz	-	9 (m=1) 19 (m=2) 24 (m=3)	-
1.8 to 2.0 GHz	4m	15 + 4(m-1)	6 + 3(m-1)
5.2 GHz	-	16 (m=1)	-

The Log-distance Model with floor and partition attenuation factor

This model is based on the log-distance model adapted to indoor propagation considering the effects of floors, soft partitions and walls between AP and wireless terminals [10]. Using this model the attenuation at a point at a distance *d* from the source can be computed using the formula:

$$PL(d)_{dB} = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + FAF_{dB} + p \cdot SPAF_{dB} + q \cdot WAF_{dB} \quad (17)$$

where *FAF* (Floor Attenuation Factor), *SPAF* (Soft Partition Attenuation Factor), and *WAF* (Wall Attenuation Factor) represent the loss increment caused by each kind of obstacle. Parameters *p* and *q* indicate the number of soft partitions and walls between the transmitter and receiver. Reference [10] suggests a value of *n*=2 for free space propagation in this model (additional path loss is attributed to physical obstructions).

The Model by Souza and Lins

This model, described in reference [10], takes into account the air humidity as empirical evidence shows that it influences the signal propagation. Described in Equation 18, it applies both to indoor and outdoor environments.

$$PL(d,UR)_{dB} = \beta_0 + \beta_1 \log(d) + \beta_2 d + \beta_3 \log(UR) \quad (18)$$

where **βi** are the attenuation coefficients, **d** is the distance and **UR** stands for the relative air humidity. The coefficients **βi** are positive, 0 < UR < 1, d ≥ 1 meter (reference distance). The unavailability of equipments for measuring the air humidity did not allow to test the efficiency of this model in the case of the Texas eZ430-RF2500 device.

IV. Outdoor Test Set-up

In order to make "real-world" applications with the Texas eZ430-RF2500 device one needs to know how its radio works in terms of propagation. Such data is not available in the manufacturer data sheet and was the first limitation the authors of this paper faced in using the device which at first was thought to incorporate a liquid level measuring device and a presence sensor. Thus, tests were set up to find the radius of reachability and power of the cell covered by the radio of the device both indoors and outdoors.

A. *Methodology*

The Texas eZ430-RF2500 device was programmed to send/receive packets 1-byte long and to send via the USB gate to a computer the values of the power received/transmitted (register RSSI). The device was also configured to work using FSK modulation at a 250 KBaud rate. Besides that, tests were also performed with the PN9 (*data whitening*) activated, which corresponds to the application of a pseudo-random sequence to the transmitted data. Such sequence tends to improve the performance of the receiver. A software module was developed to collect all data and its interface is shown in Figure 3.

The outdoor tests were performed at the parking lot of the Center of Technology and Geosciences of UFPE, during late evening to avoid the circulation of people and vehicles. The transmitter and receiver were in direct visibility and for each distance measured ten power samples were measured. The final value for a given distance was taken as the average of the samples obtained, as the maximum variance obtained was of 3%.

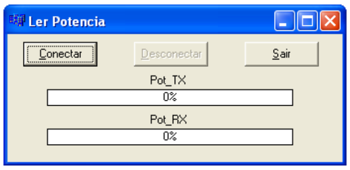

Figure 3 – Interface for the data acquisition software

B. *Results obtained*

Table 3 presents the results obtained for the power measured at the transmitter and receiver. As already mentioned, the device was programmed to send one byte to the receiver that would acknowledge it. The transmission power was set to 0 dBm. In Table 3 one may observe that at distance zero the average power is -17 dBm. The losses are probably due to antenna coupling and also to the fact that they are omnidirectional.

Another important detail happens for a distance between transmitter and receiver of 24 and 28 m. At such distance there was a sudden interruption in signal reception. This was due to oscillating interferences that made it fall below the receiver sensibility making one believe that one had reached the signal propagation boundary. At a larger distance, the signal reappears, however. Those oscillations are predictable in the 2-Rays model.

Table 3 – Data for the indoor test environment

	FSK_250K	FSK_250K	FSK_250K_PN9	FSK_250K_PN9
Distance	TX_PW[dBm]	RX_PW[dBm]	TX_PW[dBm]	RX_PW[dBm]
0	-16	-18	-17	-18
2	-66	-66	-66	-65
4	-73	-75	-71	-70
6	-77	-77	-80	-80
8	-80	-81	-73	-73
10	-74	-75	-72	-72
12	-82	-82	-81	-80
14	-80	-81	-77	-76
16	-79	-80	-75	-75
18	-78	-79	-78	-77
20	-79	-80	-78	-77
22	-83	-84	-83	-83
24	-82	-84	No Signal	No Signal
26	No Signal	No Signal	-84	-83
28	-84	-84	-85	-84
30	-85	-86	-82	-81
33	-81	-81	-83	-82
38	-84	-85	-84	-84
43	-85	-85	-82	-81
48	-86	-86	-83	-83
53	-86	-87	-84	-84
58	-84	-85	-86	-86
63	-83	-85	-87	-86
68	-86	-87		
78	-87	-88		
88	-87	-88		
98	-87	-89		

C. *Analysis of the Results*

As one may observe in Figure 4, the model of Young presented a large margin of error with RMSE = 16.5 dB and RMSE_PN = 15.7 dB. The RMSE – *Root Mean Square Error* was calculated using Equation 19, and provides a measure of how close the model predicted and experimental data obtained are. The smaller the RSME, the more representative the model is.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}} \qquad (19)$$

In the model of Young the oscillations provoked by the interfering signals are not represented. In the case of the model one assumed the gain of the antenna as one for simplification and that β=0.03, to allow the best possible fitting between the model and the experimental data. One may also observe an improvement in the level of the received signal using the PN9 resource in some points (between 40 and 60 meters). In the plotting of Figure 5 one may also observe that the Log-distance model performs better than the Young one as the values obtained are: RMSE = 9.4 dB and RMSE_PN9 = 8.8 dB. The Log-distance model has shown to be a good option to model the propagation behavior of the Texas eZ430-RF2500 device outdoors. The attenuation parameter used for the model was n=2.5, while the theoretical value used is 2. The calculation for factor $PL(d_0)_{dB}$ may be done using Friis equation to free space. The value found to a frequency of 2.5 GHz, considering the gain of the antenna as one was 40.39 dB.

The last model tested for outdoor environments was the 2-Ray model, which as may be seen in Figure 6, has shown to be less representative, although reference [12] points that under more favorable conditions it performs better than the results shown here. The values obtained were RMSE = 14.2 dB and RMSE_PN9 = 12.9 dB, exhibiting a performance slightly better than Young.

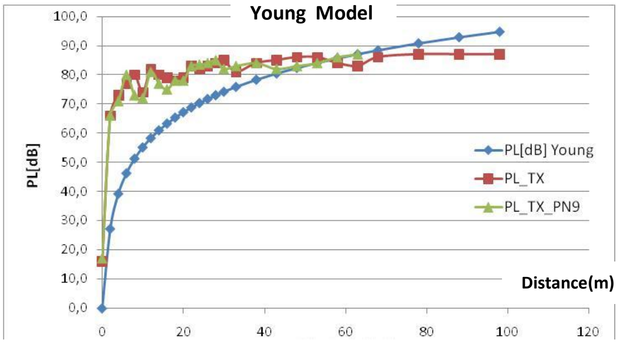

Figure 4 – Young and experimental results.

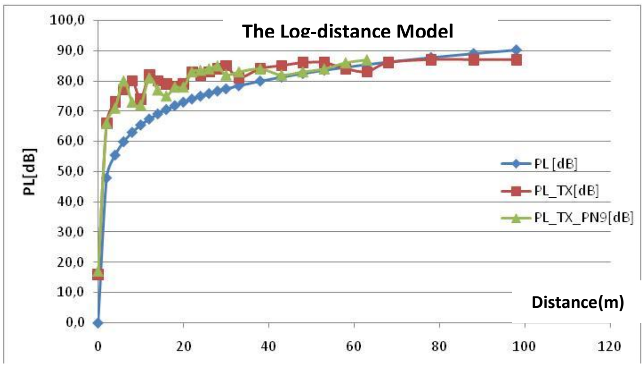

Figure 5 – Log-distance model vs experimental data.

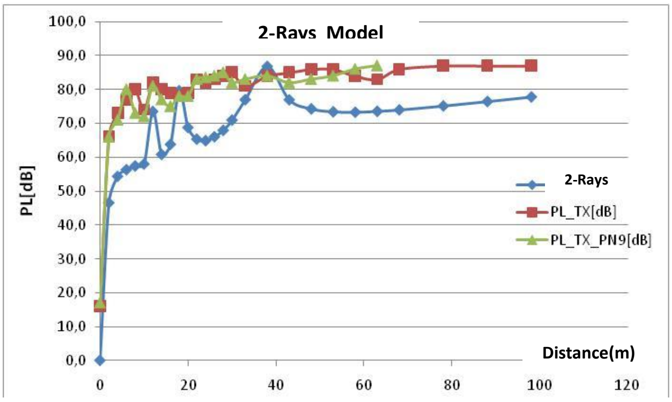

Figure 6 – 2-Rays model vs experimental data.

Issues such as antenna polarization and gain, difference in height between transmitter and receiver, ground reflectance, etc have influence in the model. The values adopted are presented in Table 4.

Table 4 – Parameters used for the 2-Ray Model

Parameter	Value
P_t	0 dBm
G_t	1
G_r	1
H_t	1.5 m
H_r	1.5 m
ε_r	10

Besides the correct choice of parameters, there are other environmental aspects that also influence the results as, for instance, other electromagnetic sources in the same frequency range such as 802.11 networks, cell phones, etc. The propagation tests ought to take all that into account, although it is not always possible as in the case of the experiments performed here. Although the models used did not fit well the behavior of the device they provide a preliminary estimation of the propagation behavior of the device freeing one of preliminary testing its reachability in open air environments. The 2-Ray model foresees oscillations in the power of the signal, which may be used to explain the rise of a shade region close to the transmitter.

The use of the application of a pseudo-random sequence to the output of the transmitter, the PN9 resource, has shown to be of little efficiency in improving reception yielding a shortening of the radius of the propagation region in relation to the direct transmission. An option would be use this resource only in outdoor environments when one wants to work at short distances.

V. Indoor Test set-up

The indoor propagation tests try to find the reachability of the device using two different modulations: FSK (Frequency Shift Keying) and MSK (Minimum Shift Keying).

A. Methodology

Similarly to the tests outdoor, the data acquisition software (Figure 3) was used to collect and study the power of the received signal. The two modulations used 250 kBaud with and without data whitening (PN9). The experiments were set-up at a flat which has its layout sketched in Figure 7.

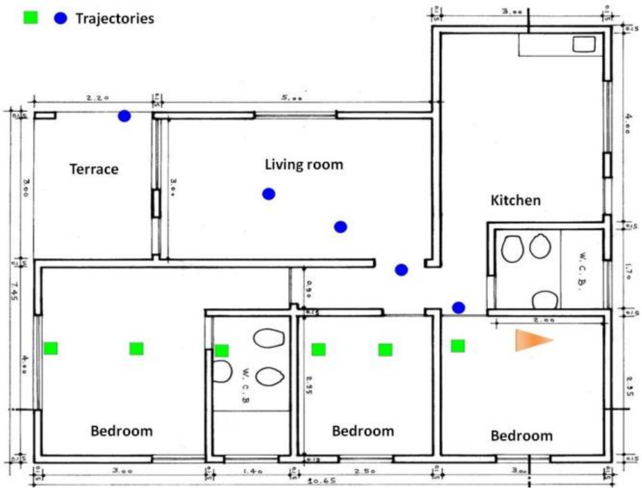

Figure 7 – Sketch of the indoor test scenario

Two batches of tests were performed using two different paths. Trajectory 1, is free of obstacles and goes from the bedroom towards the living. Trajectory 2 goes through the walls of a bedroom and a bathroom. The propagation models used are the ITU and Log-distance (considering the obstacles). The metric used to compare the results of the measures with the model predicted ones was the RMSE, again.

B. Results and Analysis

The parameter recommended for the ITU model is N=28 and the floor loss was considered negligible, once the essays were performed on the same floor. The frequency considered was 2,433 MHz. For the Log-distance model with WAF one has as parameter n=2, the path loss from source to the distance of reference is $PL(d_0)_{dB}$=40.39, the same used in the outdoor environment. The wall attenuation was considered 6dB following the data presented in reference [11]. The values of the parameters used are presented in Table 5 and Table 6. They were adjusted to minimize the RSME.

Table 5 – Parameters used in test path 1

Modulation	FSK	FSK_PN9	MSK	MSK_PN9
ITU (N)	58	65	66	64
Log. Dist with WAF (n)	4.9	5.5	5.6	5.5

Table 6 – Parameters used in test path 2

Modulation	FSK	FSK_PN9	MSK	MSK_PN9
ITU (N)	68	68	66	68
Log. Dist with WAF (n)	5.5	5.2	4.9	5.1

Table 7 and Table 8 present the values of RMSE comparing the ITU model and measured data obtained for the two modulations with and without data whitening (PN9). From Table 7 one may observe a RMSE over 10 dB and in the case of modulation FSK_PN9 the power of the signal was below the sensitivity of the receiver causing loss of the link without reaching the 9 m distance between the transmitter and the receiver. In all cases, MSK modulation presented the best performance, being able to receive signals with -93 dB of intensity. Data whitening (PN9) has not shown any improvement for the received signal.

Table 7 – RMSE for ITU model for different modulations following path 1

	PL(d)[dB]				
Model / Distance	ITU	FSK	FSK_PN9	MSK	MSK_PN9
1.5 m	49.9	69	78	68	71
3.0 m	67.4	82	82	83	82
4.5 m	77.6	83	86	89	87
6.0 m	84.9	84	86	91	91
7.5 m	90.5	84	86	89	90
9.0 m	95.1	87	-	93	92
	RMSE	**10.9**	**14.08**	**10.2**	**10.7**

In the case of Trajectory 2, the one with obstacles, it is possible to observe in Table 8 that the maximum distance reached was 7.5 m and that FSK modulation reached only 6.0 m radius. Other devices that operate in this frequency range, such as Wi-Fi routers 802.11g, easily surpass such a distance in the same scenario. This is due to the protocol used, kind of modulation used, antenna, level of the power transmitted, etc.

Table 8 – RMSE for ITU model for different modulations following path 2

	PL(d)[dB]				
Model / Distance	ITU	FSK	FSK_PN9	MSK	MSK_PN9
1.5 m	51.7	70	74	67	74
3.0 m	72.2	80	85	79	85
4.5 m	84.1	86	87	88	87
6.0 m	92.6	83	84	83	84
7.5 m	99.2	-	93	93	93
9.0 m	104.6	-	-	-	-
	RMSE	**11.1**	**12.5**	**9.14**	**12.52**

The Log-distance model with WAF has performed better than ITU for Trajectory 1(Table 9) as the average RSME obtained was below 10 dB. In the case of Trajectory 2 (Table 10) the same behavior was not observed as the average RSME was below 11 dB. This may be due to the attenuation factor of the walls (WAF) which was considered to be 6 dB may not be adequate as the bathroom wall is covered with ceramic tiles, are thicker than the other walls, besides having water pipes that absorb microwaves.

Table 9 – RMSE for Log-distance model for different modulations following Trajectory 1

Model / Distance	PL(d)[dB] Log. distance with distance WAF	FSK	FSK_PN9	MSK	MSK_PN9
1.5 m	55.0	69	78	68	71
3.0 m	69.8	82	82	83	82
4.5 m	78.4	83	86	89	87
6.0 m	84.5	84	86	91	91
7.5 m	89.3	84	86	89	90
9.0 m	93.1	87	-	93	92
	RMSE	**8.5**	**11.5**	**7.8**	**8.2**

Table 10 – RMSE for Log-distance model for different modulations following Trajectory 2

Model / Distance	PL(d)[dB] Log. distance with distance WAF	FSK	FSK_PN9	MSK	MSK_PN9
1.5 m	55.0	70	74	67	74
3.0 m	69.8	80	85	79	85
4.5 m	78.4	86	87	88	87
6.0 m	84.5	83	84	83	84
7.5 m	89.3	-	93	93	93
9.0 m	93.1	-	-	-	-
	RMSE	**12.4**	**14.3**	**11.2**	**14.3**

VI. Conclusions and Lines for Further Work

The Log-distance model has shown to be a good option to model the propagation behavior of the Texas eZ430-RF2500 device outdoors. The 2-Rays and Young models did not adequately represent the outdoor propagation behavior of the device.

The use of the application of a pseudo-random sequence to the output of the transmitter did not improve reception level and yielding a shortening of the radius of the propagation region in relation to the direct transmission. This resource may only be recommended in outdoor environments when one wants to work at short distances.

The results obtained in the case of indoor environments show that MSK modulation provides better propagation results reaching a radius of 9 m without link loss. Similarly to the outdoor case, the use of data whitening did not improve the level of the received signal. Thus its use only consumes more processing power that implies in greater power consumption by the device.

In indoor environments, the ITU and Log-distance models were not representative of the propagation of the Texas eZ430-RF2500 device.

The development of a more adequate propagation model for the Texas eZ430-RF2500 device is left as a line for future research.

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