Measurement Based Indoor Radio Channel Modeling and Development of a Fading Optimized Circular Polarized Patch Antenna for Smart Home Systems within the SRD Band at 868 MHz

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Abstract. Radio based smart home systems become more widespread over the next years. The reason for that is that the demands of home builders and homeowners are tending to green homes with high energy efficiency. Additionally smart homes deliver interoperability of home electronics and control panels in ways that enhance security, convenience, comfort and overall quality of life.

A drawback of radio based systems is the difficult predictability of signal quality, especially in indoor propagation scenarios due to the high variance in signal strength introduced by fading. So a priori knowledge of the expected path loss is crucial for an efficient dimensioning of the necessary radio network. This paper presents the results of an extensive measurement campaign to deduce realistic radio channel models for short range devices (SRD) applications at 868 MHz. Additionally, a concept to reduce fading effects is presented. This concept is based on the idea to mitigate fading caused by depolarization losses by using a circular polarized antenna in interaction with a linear polarized antenna. A proof of concept of this method was embedded in the previous mentioned measurement campaign.

1 Introduction

Indoor radio channels suffer usually from slow fading. That means that the characteristics of the channel vary only slowly in time compared with the duration of a data symbol. This can become a very dramatic effect in the communication between two (or more) radio devices. Especially if these devices are non-mobile devices, like in a smart home system, which keep a fix distance between each other and the receiver is located in a deep fade, since it will remain in this deep fade for a long (or unlimited) time interval [10]. A deep fade can significantly decrease the SNR of a communication link, which results in a reduced data rate or in a complete drop out of the radio link.

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Another effect which can also cause deep fades is fast fading. Fast fading occurs in indoor scenarios due to moving obstacles such as moving people. [4] In a fast fading channel, the transmitter may take advantage of the variations in the channel conditions using time diversity (which is often used by smart home systems). However, this paper does not cover the influences of moving people and objects on the radio channel, for further information on this topic, see e.g. [4].

The main reason for fading in indoor environments is multipath propagation. Transmitted radio waves are reflected and scattered on walls, ceilings, floors and other obstacles and can combine at the receiver in a destructive manner, due to different phase shifts of the arriving signal paths [5]. Another effect is depolarization. The scattered and reflected waves that contribute to multipath fading can also transfer energy from the transmitted polarization plane into the orthogonal polarization plane (called cross-polarization coupling) [1]. Such coupling occurs as a result of oblique reflections from the walls as well as due to scattering from indoor clutter, such as furniture [7]. This effect can cause significant degradation in signal quality if the transmitting and receiving antennas are using the same polarization. This effect contributes also to fading (polarization fading).

Since the delay spread of indoor channels is in the range of nanoseconds [3] and the bandwidth of the most indoor devices is relatively small (the SRD bandwidth @ 868 MHz is below 600 kHz), the channel can be assumed to show flat fading, so the coherence bandwidth is much larger than the signal bandwidth and the channel does not show a frequency-selective behavior.

These fading effects can lead to a significant reduced signal quality between sender and receiver and represent a significant problem for radio communication in indoor transmission scenarios.

One way to mitigate fading introduced by cross-polarization coupling is to use a circular polarized (CP) antenna in interaction with a linear polarized antenna. The benefit of using a circular polarized antenna at one end of the communication link is the irrelevance of the orientation angle of the polarized wave, so the CP antenna can receive radio waves at an arbitrary polarization plane and the effect of cross-polarization coupling can be annihilated. The only drawback of this method is the additional 3 dB polarization loss introduced by using a circular polarized antenna in combination with a linear polarized antenna. One example of the reduction of fading using a circular polarized antenna in comparison to a vertical linear polarized antenna can be seen in Fig. 1. So this method is based on the idea that all values are decreased by 3 dB but the mean value of the received power level is much higher than without this method. This is due to the fact that the influence of the fading spikes is drastically reduced.

Another positive effect of using a CP antenna is that the orientation of the linear polarized antenna does not influence the communication link anymore. This is particularly advantageous since the orientation of the antennas can seldom be guaranteed for the most indoor application scenarios. This approach is especially practical if a master-slave relationship between a central radio module and one or more radio subunits is given (like in centralized smart home systems). The central radio module can use the CP antenna while the minor radio devices still use low-cost and space-saving linear polarized antennas.

To verify this theoretical concept a measurement campaign in six buildings was performed (see Section 2).

So the two main objectives of this paper are:

1. Basic design and implementation of a circular polarized patch antenna which should be used in an actual smart home system and which can be used for indoor radio channel modeling. This antenna is subject to further improvements regarding size and cost reduction. The antenna itself is a well known design (truncated-corner square patch), however the advantage of using a circular polarized antenna at one end of the link and a linear polarized antenna at the other end of the link in comparison to the conventional usage of linear polarized antennas at both ends should be proven on the basis of a comprehensive measurement campaign.
2. Development of a path loss prediction model which covers a versatile number of scenarios and can be used for a simple estimation of the expected path loss in an actual smart home installation. There does not exist many of these prediction models for this specific frequency domain which are based on an extensive measurement campaign.

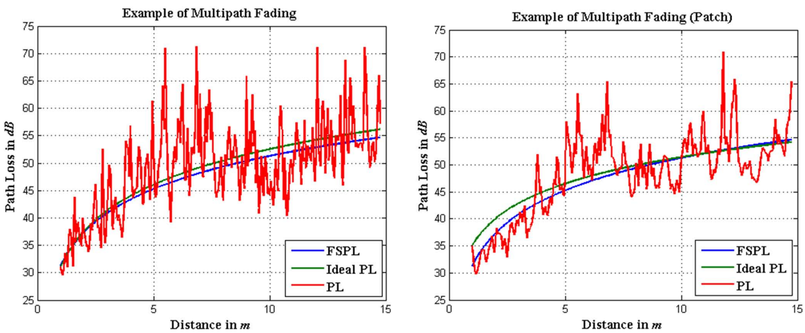

Fig. 1 a) A channel encounters strong fading using two vertical linear polarized antennas. The red graph (PL) represents the actual fading the channel encounters, the blue graph (FSPL) represents the theoretical free space path loss and the green graph (Ideal PL) represents the actual path loss the channel encounters without fading effects. b) Mitigation of Fading using a CP antenna in interaction with a vertically linear polarized antenna.

2 Measurement Setup and Procedure

2.1 Measurement Setup

The measurement setup is depicted in Fig. 2. The transmitting part of the setup is shown on the left side of the figure. The transmitting antenna is a cross polarized log-periodic antenna which is used to generate a horizontal and vertical polarized electromagnetic wave (denoted with XSLP9142 [8]). The circular polarized patch antenna can be used as an alternative transmitting antenna.

The two input ports of the cross polarized antenna are fed by two carrier wave (CW) generators at 873.8 MHz and 874 MHz at an output power of $P_{CW_{dBm}} = 14$ dBm. These slightly different frequencies were chosen to distinguish between the two polarizations states in the spectrum which were received by a CP patch antenna (or a dipole antenna as reference) and measured by a spectrum analyzer which stored it on a PC for further data processing.

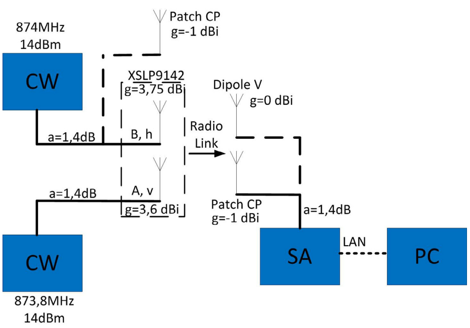

Fig. 2 Measurement and test setup for the indoor radio channel modeling and the circular polarized patch antenna

The height of the phase center of the transmitting and receiving antenna was $h = 1.16$ m. The transmitting antenna was located at a fixed position while the receiving antenna was moved along the measuring track during a single measurement run. A truncated-corner patch antenna design was used for the circular polarized antenna (see Section 2.2). The spatial resolution of a single measurement path was $d = 0.05$ m (distance between two measurement points) which results in a spatial sampling rate (SSR) of

$$\lambda = \frac{c_0}{f} = \frac{c_0}{874MHz} = 0.343m$$
$$SSR = \frac{\lambda}{d} = \frac{0.343m}{0.05m} = 6.86 \tag{1}$$

samples per wavelength which results in a sufficient detectability of fading spikes (where λ is the wavelength, c_0 is the speed of light and f is the operating frequency).

The path loss PL can be fairly simple measured by using the relationship:

$$PL = P_{Tx_{dBm}} - P_{Rx_{dBm}} \tag{2}$$

where $P_{Tx_{dBm}}$ is the transmitted and $P_{Rx_{dBm}}$ is the received power. Taking into account antenna gains and cable losses it follows:

$$\begin{aligned} PL &= (P_{CW_{dBm}} - a_{Tx} + g_{Tx}) - (P_{SA_{dBm}} + a_{Rx} - g_{Rx}) \\ PL &= P_{CW_{dBm}} - a_{Tx} - a_{Rx} + g_{Tx} + g_{Rx} - P_{SA_{dBm}} \end{aligned} \tag{3}$$

where $P_{SA_{dBm}}$ is the power at the spectrum analyzer and a is the cable loss and g is the respective antenna gain at Rx and Tx.

2.2 Circular Polarized Patch Antenna

To perform the measurements it was necessary to develop an antenna with the desired electrical parameters, with focus on an axial ratio < 3 dB (to achieve a good circularity of the antenna), accurate impedance ($Z = 50\Omega$) and resonance frequency ($f = 873.9$ MHz) matching.[1]

A truncated-corner square patch was chosen as basic design. The advantage of this kind of antenna is its simple geometry which is fast to simulate and easy to layout. Another advantage is that a circular polarized wave can fairly easy be created just by using a single-feed and without a 90° phase shifter. The impedance of the antenna can be matched by shifting the feed along one axis of the antenna.

Circular polarization can be achieved by combining two orthogonal modes with slightly different resonance frequencies. A single-feed patch with two opposite 45° truncated corners produces two orthogonal modes which resonate at different frequencies separated by almost 90° phase difference. The angle between the electric field vectors of both modes is given by the geometry of the antenna and is assumed to be 90° for rectangular patch antenna [2].

The antenna was designed using the simulation software "Sonnet Software". The simulation itself was performed in an iterative manner where the geometric parameters like patch size, corner truncation and feed point position were altered and simulated one after another until a satisfying solution was found. The resulting geometry of the antenna is depicted in Fig. 3a). The bottom side of the FR-4 material is completely metalized (copper). The resulting antenna is left-hand circular polarized (LHCP). However, since the other antenna in the communication link is always linear polarized, the handedness of the circular polarized field does not matter.

[1] The prototype antenna was designed for a resonance frequency at $f = 873.9$ MHz and not for the actual SRD frequency at $f = 868.3$ MHz.

Fig. 3b) shows the current density of the antenna at resonance frequency. The radial pattern shows the two orthogonal modes of the circular polarized wave with the highest current density in the center and the lowest at the corners.

Fig. 4 represents the $|S_{11}|$ parameter of the antenna. The two resonance frequencies represent the two orthogonal modes of the antenna. The antenna has a $|S_{11}|$ of 20.7 dB, a beamwidth of $\theta_{-3dB} \approx 60^\circ$, an antenna gain of $g = -1$ dBi and a bandwidth of roughly $B = 13.2$ MHz. However, the bandwidth of the antenna is of inferior importance since the actual band of the SRD application is very narrow (600 kHz).

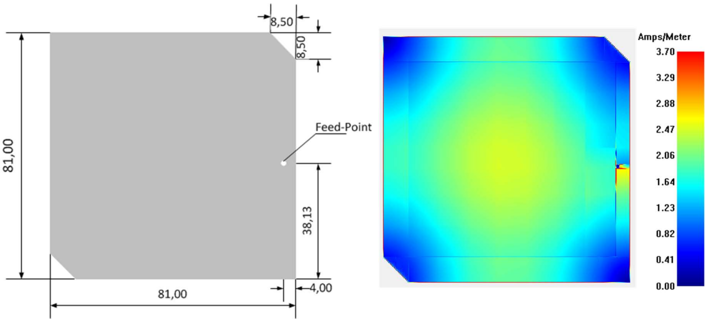

Fig. 3 a) Geometry of the circular polarized patch antenna (values in mm). b) Current density at resonance frequency.

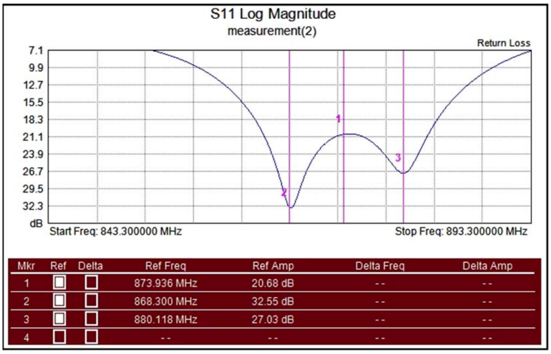

Fig. 4 $|S_{11}|$ of the realized CP antenna

2.3 Measurement Procedure

The measurements where performed in six buildings on the campus of the Hochschule Darmstadt. All of these buildings differ in parameters like material, geometry, usage etc. So a huge variety of different fading scenarios was achieved (see Table 1).

Table 1 List of buildings which were used during the measurement campaign

Building (name)	Type	Building materials	Designated usage
B11	One-story lightweight construction building	Wood	Lectures and seminars
B14	Two-storied shipping container architecture	Metal and wood	Lectures and seminars
C10	High-rise building (15 floors)	Reinforced concrete	Offices, lectures, seminars and labs
D11	Industrial building	Bricks and metal	Workshops, lectures and labs
D1617	Office building (5 floors)	Bricks and drywalls	Offices, seminars and labs

A section of a floor plan of one of the buildings can be seen in Fig. 5. The plan shows the entrance and the hallway of building B11. Basically two types of measurements were performed, LOS measurements within rooms and floors (denoted with yellow arrows) and NLOS measurements with walls, doors and furniture between transmitter and receiver (denoted with red arrows). The starting point and the direction of the single measurement runs were chosen randomly to guarantee an equal distribution of all possible propagation scenarios within the building.

3 Path Loss Prediction Model

The log-distance path loss model was used for the path loss prediction model. It is based on the assumption that the (mean) path loss PL is a function of distance d to the γ-th power

$$PL \sim d^{\gamma} \tag{4}$$

Where γ is the path loss exponent which indicates how fast path loss increases with distance. A logarithmic distance is used in the actual model, so the exponent γ becomes a factor and the formula reads:

$$PL = PL_0 + 10 \cdot \gamma \cdot \log_{10} \frac{d}{d_0} + X_g \tag{5}$$

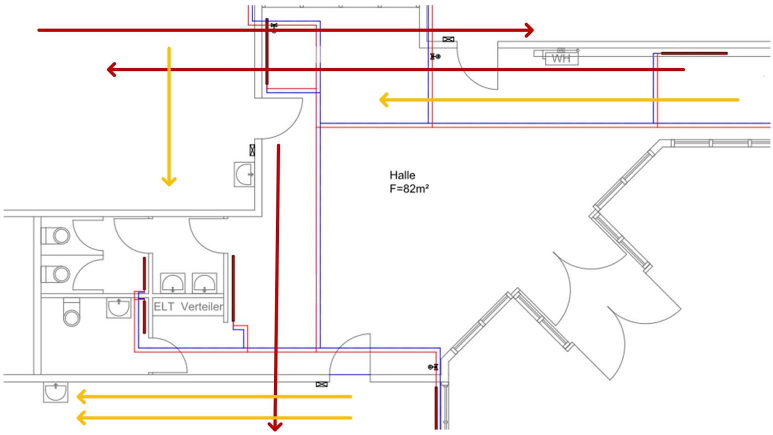

Fig. 5 Section of a floor plan of one of the buildings (B11) used for the measurement campaign

where PL_0 is the path loss at a certain distance d_0 and X_g is a normal distributed random variable which represents fading with zero mean and a standard deviation σ in dB. PL_0 and d_0 represent the path loss from the transmitter to the distance d_0 where the measurement starts [9]. d_0 can be freely chosen and was determined to be one meter for all measurements ($d_0 = 1$ m). The value of γ is dependent on the propagation scenario of the measurement, it is two ($\gamma = 2$) for free space path loss (FSPL), greater than two ($\gamma > 2$) when the path loss increases faster than in free space and smaller than two ($\gamma < 2$) when it increases slower than in free space.

For a homogenous environment γ can be assumed to remain constant for different distances between transmitter and receiver. However, if the propagation properties are changing (e.g. a wall separates transmitter and receiver) the path loss exponent γ is also changing. For this reason it is appropriate to divide the measuring track into several separate segments. γ can then be calculated separately for each of the segments. To compensate the additional path loss introduced by obstacles which influence the path loss exponent it is necessary to introduce new attenuation factors in Equation 5 [9]:

$$PL = PL_0 + 10 \cdot \gamma \cdot \log_{10} \frac{d}{d_0} + X_g + m \cdot FAF_{dB} + n \cdot WAF_{dB} \tag{6}$$

where FAF_{dB} represents a "Floor Attenuation Factor" and WAF_{dB} means "Wall Attenuation Factor". m and n are representing the number of floors respectively walls which are penetrated by the radio wave [9].

4 Results

The results of over 13,000 measuring points and 270,000 single measurements where recorded and processed to obtain a general fading model of the investigated buildings and an adequate data set to study the effects of the optimized circular polarized antenna in combination with a linear polarized antenna on fading.

Table 2 shows the cumulated results of the measurement campaign separated for every building. The first three columns are representing the path loss exponents for a vertically (V), horizontally (H) and circular polarized (CP) transmitted wave. The last six columns representing the standard deviation of fading for a LOS and NLOS connection between transmitter and receiver. All results are mean values of the results of the two available receiving antennas: a vertical polarized dipole and the circular polarized patch antenna.

Table 2 Path loss exponent γ and standard deviation σ in dB of fading for every building

Results Tx antenna Propagation	γ V	γ H	γ CP	σ V LOS	σ H LOS	σ CP LOS	σ V NLOS	σ H NLOS	σ CP NLOS
B11	1.59	1.95	1.8	3.18	4.54	2.51	5.28	4.91	11.60
B14	1.94	1.70	1.71	4.59	4.11	4.58	5.45	5.19	7.25
C10	1.69	1.56	1.65	4.84	5.00	4.86	7.93	6.94	5.63
D11	1.99	2.07	2.03	3.86	4.28	3.3	5.50	5.50	4.15
D1617	1.95	2.3	2.17	4.3	5.02	3.67	5.33	5.12	6.01
Average Value	1.83	2.00	1.90	4.21	4.68	3.83	5.62	5.39	5.98

Some observations in Table 2 are remarkable:

- The path loss exponent is smallest if a vertically polarized wave is transmitted. One possible explanation for that is that the walls in a building can be treated as dielectric materials. Horizontal polarized waves can penetrate the walls if the angle of incidence fits to the permittivity of the wall material (Brewster angle phenomenon). Vertical waves do not suffer a similar effect and will be therefore reflected (according to [7]).
- The average path loss exponent is below two ($\gamma < 2$). This means that the path loss inside of the measured building increases slower than in free space. The reason for that is that the rooms and hallways of the buildings serve as a kind of wave guides due to reflections at floors and ceilings (see also the previously mentioned subitem).
- For a NLOS scenario the standard deviation is smallest if a horizontal wave is transmitted. A possible explanation for this phenomenon is the following: horizontal waves suffer less from reflections on walls (see the first subitem), so multipath fading becomes less important.

The results of Table 2 are independent from the used receiver antenna. Table 3 shows the standard deviation in dependency of the used receiver antenna (vertically polarized dipole or circular polarized patch antenna). Two points are remarkable:

- The standard deviation is the smallest for the transmitter/receiver antenna combination linear to circular (or vice versa). This outcome confirms the theoretical considerations introduced in Section 1.
- The combination circular/circular shows also good results, especially for LOS conditions. The explanation for this is that the energy of single-bounced reflected paths of the circular polarized transmitted wave disappears at the receiver since an odd number of reflections cause a reverse of the handedness of the circular polarized wave [6].

Table 3 Standard deviation σ in dB of fading in dependency of the used receiver antenna. Rx antenna: V = vertical polarized dipole, CP = circular polarized patch antenna.

Rx antenna	V	V	CP	CP	CP	V	V	CP	CP	CP
Tx antenna	V	H	V	H	CP	V	H	V	H	CP
Propagation	LOS	LOS	LOS	LOS	LOS	NLOS	NLOS	NLOS	NLOS	NLOS
σ /dB	4.90	5.40	3.52	3.96	3.83	6.00	5.67	5.52	5.12	5.98

A graphical representation of fading can be seen in Figure 6. It shows a percentile measure of the encountered fading. Most measurement values of the patch antenna are below the according measurement values of the dipole. For example the 90th percentile (see Figure 7) shows that 90% of the measurement values of the patch (LOS) are below a value of 5-6 dB, while 90% of the measurement values of the dipole are below a fading value of 7.5-8.5dB. The same situation shows for a NLOS connection, the fading of 90% of the measurement values of the patch are below 8-9dB, while 90% of the values of the dipole are below 9-9.5dB.

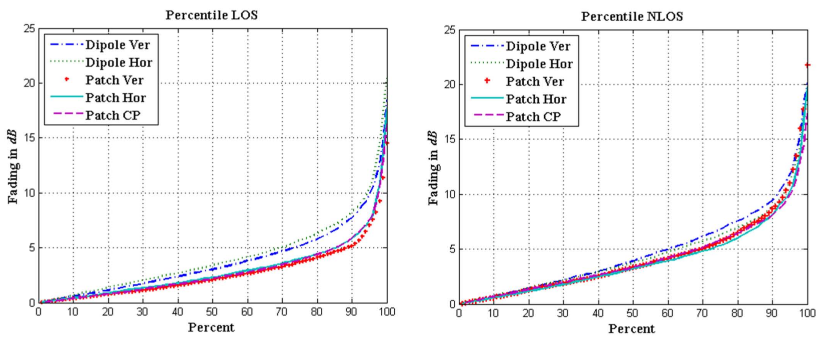

Fig. 6 Percentile measure of fading

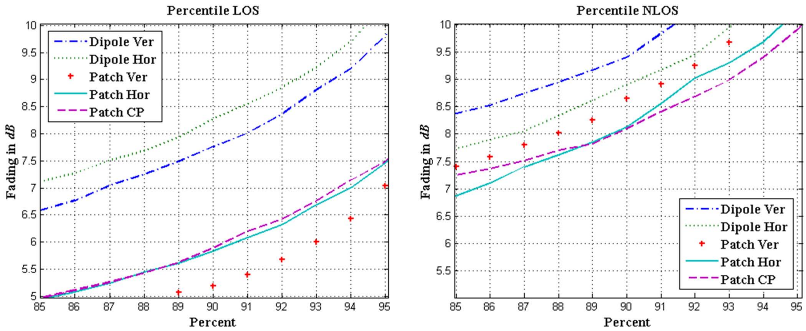

Fig. 7 Percentile measure of fading, segment of the 90th percentile

Two other papers which describe similar topics like this paper are e.g. [6] and [9]. [6] discusses different anti-multipath fading schemes using circular polarization under LOS conditions at 10 GHz. The results show that the mean amplitude fade level is reduced by $7-11$ dB by using CP transmission/reception. The results by using CP to linear transmission/reception are slightly less good.

[9] introduces a 914 MHz path loss prediction model with a similar approach like in this paper. Different propagation scenarios were considered (e.g. grocery store, retail store and two office buildings). The path loss exponent and standard deviation was determined within a value range of $\gamma = 1.81-5.04$ and $\sigma = 4.3-16.3$ dB, these relatively high values occur due to fact that the knowledge of the number of floors and walls between sender and receiver were not taken into account (see also Section 3). In relatively open environments (retail/grocery store) the path loss exponent is much smaller $\gamma = 1.81-2.18$ which is similar to the values which were encountered in this paper. The standard deviation of the most scenarios $\sigma = 4.3-8.7$ dB is also similar to the values presented in this paper.

5 Conclusion

The results of an extensive measurement campaign were presented. This measurement campaign was performed to create a measurement based fading model and to evaluate the possibility to fight fading using a circular polarized and a linear polarized antenna in an one-to-one transmission link within an indoor scenario.

The path loss exponent was measured within a range of values $\gamma = 1.83-2$ and the standard deviation with mean value of $\sigma = 4.24$ dB for LOS conditions and $\sigma = 5.67$ dB for NLOS conditions.

The method to combat fading using an optimized circular polarized truncated corner patch antenna has shown significant results. The results have shown that it is possible to mitigate fading by a notable amount, up to 3.5 dB for LOS and 1.5 dB for NLOS conditions (based on the 90th percentile), by replacing a linear polarized antenna (which is normally used in indoor SRD communication systems) by a circular polarized antenna. This is of practical importance since this is a very cost-efficient, space-saving and easy-to-realize method.

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References

1. Cox, D., Murray, R., et al.: Cross-polarization coupling measured for 800 MHz radio transmission in and around houses and large buildings. Antennas and Propagation. IEEE Transactions on Antennas and Propagation 34(1) (1986), doi:10.1109/TAP.1986.1143714
2. Golio, M.: The RF and Microwave Handbook, pp. 6–127. CRC Press (2001)
3. Hashemi, H., Tholl, D.: Analysis of the RMS delay spread of indoor radio propagation channels. In: IEEE International Conference on Discovering a New World of Communications (1992), doi:10.1109/ICC.1992.268160
4. Horvat, G., Rimac-Drlje, S., et al.: Fade Depth Prediction Using Human Presence for Real Life WSN Deployment. Radioengineering 22(3), 758 (2013)
5. Molisch, A.: Wireless Communications, 2nd edn., 27 p. John Wiley & Sons Ltd. (2011)
6. Kajiwara, A.: Line-of-Sight Indoor Radio Communication Using Circular Polarized Waves. IEEE Transactions on Vehicular Technology 44(3) (1995)
7. Kyritsi, P., Cox, C.: Propagation characteristics of horizontally and vertically polarized electric fields in an indoor environment: simple model and results. In: IEEE VTS 54th Vehicular Technology Conference (2001)
8. Schwarzbeck Mess - Elektronik, XSLP 9142 Kreuzpolarisierte Breitband UHF-SHF Log.-Per. Messantenne Dual Polarized UHF-SHF Broadband Log.-Per. Test-Antenna 800 MHz... 3 (5) GHz (2013), http://www.schwarzbeck.com/Datenblatt/manx9142.pdf
9. Seidel, S., Rappaport, T.: 914 MHz path loss prediction for indoor wireless communication in multifloored buildings. IEEE Transaction on Antennas and Propagation 40(2) (1992)
10. Vireerackody, K.: Characteristics of a simulated fast fading indoor radio channel. In: Vehicular Technology Conference (1993), doi:10.1109/VETEC.1993.507051
11. Wong, K.: Compact and Broadband Microstrip Antennas, 162 p. Wiley Press (2002)