Censored Multipath Component Cross-Polarization Ratio Modeling

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***Abstract*—In wireless channel measurements, the relatively weak cross-polarized multipath components (MPCs) are typically severely affected by the measurement noise level. As shown in this letter, the typical cross-polarization ratio (XPR) model parameter estimation, which ignores the existence of censored samples, may lead to significant errors. We demonstrate how to achieve accurate parameter estimates with a maximum likelihood estimator that properly takes into account both the measured XPRs and the censored samples. Also, a new XPR model is presented in which the average XPR is modeled as a function of the MPC excess loss. The new model is shown to be insensitive to the channel measurement noise level. A practical example with measured data in an indoor environment at 60 GHz demonstrates the utility of the approach.**

***Index Terms*—cross-polarization ratio (XPR), maximum likelihood estimation, channel characterization and modeling, censored data, radio propagation, millimeter-wave propagation measurements.**

I. Introduction

Polarization offers a degree of freedom for wireless systems that can be exploited for diversity, polarization multiplexing, improvement of localization accuracy, etc. Design and performance evaluation of systems using polarization require as a prerequisite knowledge of typical channel cross-polarization ratios (XPRs), i.e., the ratio of the power carried in the main polarization versus that in the cross-polarization. XPR might be defined as the average over all multipath components (MPCs) in the channel, or per MPC [1], [2].

In channel measurements, the channel sounder noise level always limits which MPCs can be measured. The measurements are typically planned so that the measurement dynamic range is sufficient for capturing all significantly strong MPCs at the main polarization. The weaker cross-polarization component is naturally more severely limited by the noise level and therefore many MPCs may have only the main polarization component above the noise level [3], [4]. These measurement samples are called censored samples.

If the XPR model is parametrized based on the measured XPRs, i.e., based on MPCs with *both* the main and the cross-polarization above the noise level, all the censored samples are ignored and, in fact, the parametrization is not based on all the measured MPCs. We will demonstrate how to take into account all the measured MPCs, including the censored samples, in MPC XPR parametrization by using a Tobit maximum likelihood estimation [5]. The same maximum likelihood estimation can be used also for other channel parameters affected by the noise level, such as path loss [6]. In [4], the noise level censoring is taken into account in modeling the mean power decay and correlation between the different polarization components with respect to the mean power decay of each component. However, the XPR is not modeled directly.

Typically the XPR is modeled as a simple log-normal distribution with a constant average and standard distribution. This simple model does not reflect the known physical reasons for depolarization, which occurs when MPCs are reflected, scattered, or diffracted. Therefore, XPR becomes related to the excess loss, i.e., the difference between the free-space path loss (FSPL) and the main polarization level. In [7], the MPC XPR dependency on delay and angular properties is investigated at 3.6 GHz but the dependency on MPC strength is not tested. To the best of the authors' knowledge, the XPR dependency on the MPC excess loss has not been investigated before even though their physical relationship is intuitively evident.

In this letter, we present for the first time, (i) an XPR model parameter estimation that takes into account all the measured MPCs[1], and (ii) a new XPR model that characterizes the XPR as a function of the MPC excess loss. Measurement results at 63 GHz in an indoor cafeteria room from [8] are used as an example. Note, however, that neither the parameter estimation nor the model are specific to any frequency or environment as long as the censoring of the cross-polarization components happens due to a limited dynamic range of the measurements.

The measurements are introduced in Sec. II. The XPR models and the estimation method are in Sec. III-A and III-B, respectively. In Sec. IV-A, it is shown that taking the censored samples into account can have a significant effect on the model parameter estimates. In Sec. IV-B, the new model is shown to be accurate and insensitive to the particular measurement noise level of the used sounder setup. Finally, conclusions are presented in Section V.

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[1]In [4], all the measured MPCs are taken into account, nevertheless XPR is not explicitly modeled.

II. MPC XPR Measurements at 63 GHz

The channel measurements used for the XPR analysis are conducted in a cafeteria with a size of $14 \times 13.5 \times 2.8$ m^3 [8]. A solid wall is separating the main cafeteria from a smaller space, which allows measurements of non-line-of-sight (NLOS) links in addition to line-of-sight (LOS) links. The channel sounder has a radio frequency of 61–65 GHz and is based on a vector network analyzer (VNA), a signal generator, and up- and down-converters. At the transmitter (TX) side, a 20 dBi standard gain horn antenna is rotated in 3° steps to measure the channel power angular delay profile (PADP). At the receiver (RX) side, an omnidirectional antenna is used. Both the TX and RX antenna heights are about 2 m. A Hamming window function is used in the calculation of the channel impulse response in order to suppress the delay domain side-lobes. The antenna gains and the window function loss are compensated for in the PADP amplitudes, so that the direct path amplitude in LOS link corresponds to the value of FSPL. Three TX locations in LOS and three in NLOS conditions are measured with azimuth scanning with vertical-to-vertical (VV) and with horizontal-to-vertical (HV) polarizations of the antennas. To measure the cross-polarization channel, i.e. HV, the TX horn antenna is rotated by 90°. Furthermore, one TX location is measured with horizontal-to-horizontal (HH) and vertical-to-horizontal (VH) polarizations. In this measurement, the RX antenna is rotated by 90° and the TX antenna is scanning in the elevation domain. In this letter, XPR is the ratio of main and cross-polarization and no distinction is made between the ratio of VV-to-HV and HH-to-VH.[2] Additionally, XPR is modeled as an MPC property that does not depend on the link-level LOS/NLOS condition.

MPC detection is based on searching for the local maxima in the PADP. A noise threshold level 15 dB above the average measured noise is used to avoid detecting noise peaks as MPCs and to ensure good signal-to-noise ratio for the detected paths. In this work, the direct paths in LOS links are not considered as an MPCs since the ratio of measured main to cross-polarization of the direct path (about 30 dB) is a property of the antennas and of the possible antenna orientation difference in the measurement, and therefore, it is not a channel property. Since the antenna cross-polarization discrimination (XPD) is quite high, it is assumed to have negligible effect on the measured MPC XPR.

First, MPC delays and main polarization amplitudes are detected in the delay domain from the main polarization:[3]

$$P(\tau) = \max_{\varphi} \mathrm{PADP}_{\mathrm{main}}(\tau, \varphi), \tag{1}$$

where $\mathrm{PADP}_{\mathrm{main}}$ is the main polarization PADP. The MPC main polarization amplitude M_i of the i^{th} MPC is detected as a local maximum, i.e., amplitude above local sliding window average:

$$M_i(\tau_i) > \frac{1}{w} \int_{\tau_i - w/2}^{\tau_i + w/2} P(\tau) d\tau, \tag{2}$$

where $w = 1$ ns is the length of a sliding window. Additionally, the peak amplitude $M(\tau_i)$ is required to be greater than the previous, i.e., $P(\tau_i - \Delta)$, and the following value, i.e., $P(\tau_i + \Delta)$, where $\Delta = 0.25$ ns is the delay resolution. The i^{th} MPC has main polarization amplitude M_i, delay τ_i, and the angle φ_i is defined based on the maximum of the $\mathrm{PADP}_{\mathrm{main}}$ at delay τ_i.

The main and cross-polarization peaks, i.e., local maxima, are considered to belong to the same MPC only if the peak values are found relatively close in both delay and angular domains. The i^{th} MPC cross-polarization amplitude C_i is defined in our case by the largest $\mathrm{PADP}_{\mathrm{cross}}$ within ±0.5 ns and ±6° of the MPC delay and angle detected from the $\mathrm{PADP}_{\mathrm{main}}$. $\mathrm{PADP}_{\mathrm{cross}}$ is the cross-polarization PADP. These tolerances and the length of a sliding window are verified by careful examinations of the measured PADP and the detected MPC. One example measurement result is presented in Fig. 1.

A total of 929 MPCs are detected from the seven measurements. The XPR values can be calculated for 149 MPCs that have also the cross-polarization above the noise threshold. The remaining 780 MPCs are censored samples for which the XPR is *known* to be greater than the difference between the main polarization and the noise threshold.

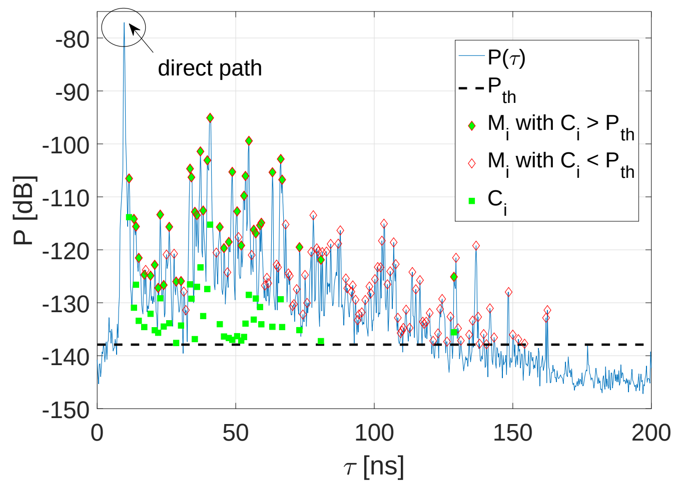

Fig. 1. Example of a main polarization $P(\tau)$ as defined in (1), noise threshold level $P_{\mathrm{th}} = -137.9$ dB, main polarization with cross-polarization above and below the noise threshold, and measured cross-polarization levels. In this example, the main polarization is VV and the cross-polarization is HV. A total of 129 MPCs are detected and 40 of them have detectable cross-polarization above the noise threshold.

III. XPR Models

A. The Models

In this letter, we consider two XPR models. Typically XPR is modeled by a log-normal distribution $\mathrm{XPR}|_{\mathrm{dB}} \sim \mathcal{N}(\mu, \sigma^2)$, where the mean and standard deviation, μ and σ, are constants, e.g., [1], [2]. However, the simple model with constant μ does not reflect the physical effect of depolarization. As the

[2]The method and models in this letter can be easily extended to full polarimetric model if such measurement data is available, e.g., [4].

[3]In principle, a more accurate two-dimensional peak search could be used in both delay and angular domains. The one-dimensional search is justified by the large measurement bandwidth, i.e., good delay domain resolution as well as a visual examination of the recorded PADP and detected peaks.

MPC is reflected, scattered, or diffracted, some of its power is depolarized from the main to the cross-polarization. A new model is introduced in this letter in which the mean value of the log-normal distribution is a linear function of the MPC excess loss in dB. The MPC excess loss is defined as the difference between the main polarization amplitude and FSPL corresponding to the MPC delay. The μ can be written as

$$\mu(E) = \alpha \cdot E + \beta, \quad E \geq -\beta/\alpha, \tag{3}$$

$$\mu(E) = 0, \qquad E < -\beta/\alpha, \tag{4}$$

where $E = M - \mathrm{FSPL}(\tau)$ is the excess loss of the MPC. The average XPR is assumed to be always positive or zero[4]. This assumption guarantees that with very large excess loss the MPC polarization is random.

It should be noted that the XPR can be defined also as the ratio of total powers in the main and the cross-polarization, as, e.g., in [7], and the XPR statistics are estimated over different measurement locations rather than for different MPCs. Also with this *different* XPR *definition* similar censoring does occur, and similar maximum likelihood estimation can be used, if for some locations the cross-polarization measurement is only noise, as happens, e.g., in [3].

B. Maximum Likelihood Estimation of the Model Parameters

The normal method to parameterize an XPR model is to characterize the measured XPRs. The problem is that it includes *only* those MPCs that have both main and cross-polarization components above the noise threshold, i.e., *only measured XPRs*. In order to characterize *all measured MPCs*, including the censored samples, a Tobit maximum maximum likelihood estimation is used [5]. In [6], a log-likelihood function is given for censored path loss data. Similarly, a log-likelihood function can be written for censored XPR data as

$$\begin{aligned} L(\mu,\sigma) = &\sum_{i=1}^{N} I_i \left[-\ln(\sigma) + \ln \phi\left(\frac{M_i - C_i - \mu}{\sigma}\right)\right] \\ &+ \sum_{i=1}^{N} (1 - I_i) J_i \ln\left[1 - \Phi\left(\frac{M_i - P_{\mathrm{th}} - \mu}{\sigma}\right)\right] \\ &+ \sum_{i=1}^{N} (1 - I_i)(1 - J_i) \ln\left[\Phi\left(\frac{P_{\mathrm{th}} - C_i - \mu}{\sigma}\right)\right], \end{aligned} \tag{5}$$

where (μ, σ) are the XPR distribution parameters in dB; M_i, C_i, and P_{th} are the main polarization, cross-polarization, and noise threshold level in dB, respectively. $\phi(\cdot)$ is the probability density function (PDF) and $\Phi(\cdot)$ is the cumulative distribution function (CDF) of the standard normal distribution. I_i is a function that is set to 1 for MPCs with both the main and the cross-polarization above noise and is set to 0 if the main or the cross-polarization component is censored. J_i indicates which polarization component is censored, with 1 for the cross-polarization (XPR> $M_i - P_{\mathrm{th}} > 0$ dB) and 0 for the main polarization (XPR< $P_{\mathrm{th}} - C_i < 0$ dB). In this letter,

[4]This behavior is, in fact, not seen in the used measurement results because even with the largest measured excess loss levels the average XPR does not go to zero.

TABLE I
XPR STATISTICS FOR THE MEASURED XPRS AND FOR ALL THE MEASURED MPCS INCLUDING THE CENSORED SAMPLES.

Data	μ	σ
Only measured XPRs	16.3	7.9
All measured MPCs	21.8	7.6

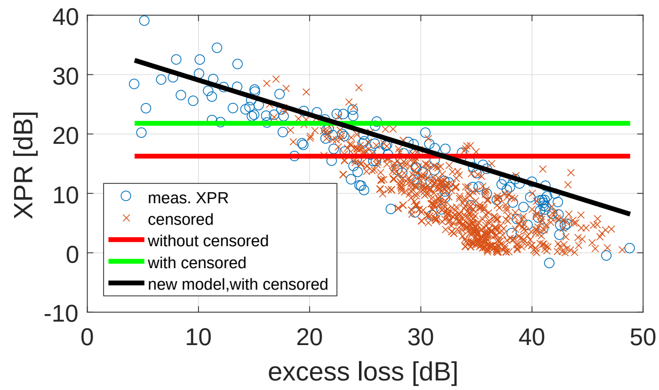

Fig. 2. Measured XPR values (o), censored samples (x marks the smallest XPR, i.e., the difference from main polarization to noise level), lines mark the mean XPR values of the models. The red and green lines are the XPR model with constant μ without and with the censored samples, respectively. The black line is the new model with the censored samples.

all observations have either both measured main *and* cross-polarization values, i.e., $I_i = 1$, *or*, the main polarization is measured but the cross-polarization is censored, i.e., $I_i = 0$ and $J_i = 1$. The parameter estimates are found by

$$[\hat{\mu}, \hat{\sigma}] = \underset{\mu,\sigma}{\mathrm{argmin}}\{-L(\mu,\sigma)\}, \tag{6}$$

or as

$$[\hat{\alpha}, \hat{\beta}, \hat{\sigma}] = \arg\min_{\alpha,\beta,\sigma}\{-L(\mu(E),\sigma)\}. \tag{7}$$

IV. RESULTS AND DISCUSSIONS

A. Influence of the Censored MPCs

The estimates for the XPR model parameters with constant μ and σ are shown in Table I. The parameters for measured XPRs, i.e., the 149 MPCs with both main and cross-polarization components above the noise threshold, are $\mu = 16.3$ dB and $\sigma = 7.9$ dB. When also the censored data samples are taken into account with (5)-(6), the parameter estimates for all measured MPCs above the noise threshold are $\mu = 21.8$ dB and $\sigma = 7.6$ dB. Ignoring the censored samples underestimates the average XPR by about 5 dB.

To explain this difference, let us examine the XPRs and censored samples from all the seven measured links. The measured XPR values vary between -1.8 dB and 39 dB with the dB-scale mean of $\mu = 16.3$ dB. For the censored samples it is known that the XPR is larger than $M_i - P_{\mathrm{th}}$. The estimated $\mu = 21.8$ dB for all the MPCs is about 5 dB larger mostly because there is a total of 71 censored samples for which the XPR is known to be greater than the average of the measured 149 XPR, i.e., $M_i - P_{\mathrm{th}} > 16.3$ dB. Especially these censored samples increase the average. On the other hand, censored samples far smaller than μ (very small argument in $\Phi(\cdot)$ in (5)) have only a small effect on the estimation.

TABLE II
THE NUMBER OF MEASURED XPRS AND CENSORED SAMPLES WITH DIFFERENT THRESHOLD VALUES.

Threshold	XPRs	Censored samples
P_{th}	149	561
P_{th} +5 dB	65	457
P_{th} +10 dB	21	340

TABLE III
XPR STATISTICS WITH CONSTANT μ AND $\mu(E)$ WITH DIFFERENT THRESHOLD VALUES.

	Threshold	μ	α	β	σ
Constant μ	P_{th}	21.8	-	-	7.6
Constant μ	P_{th} +5 dB	24.1	-	-	8.6
Constant μ	P_{th} +10 dB	27.0	-	-	8.5
$\mu(E) = \alpha \cdot E + \beta$	P_{th}	-	−0.58	34.8	3.9
$\mu(E) = \alpha \cdot E + \beta$	P_{th} +5 dB	-	−0.59	34.5	4.0
$\mu(E) = \alpha \cdot E + \beta$	P_{th} +10 dB	-	−0.56	32.9	3.8

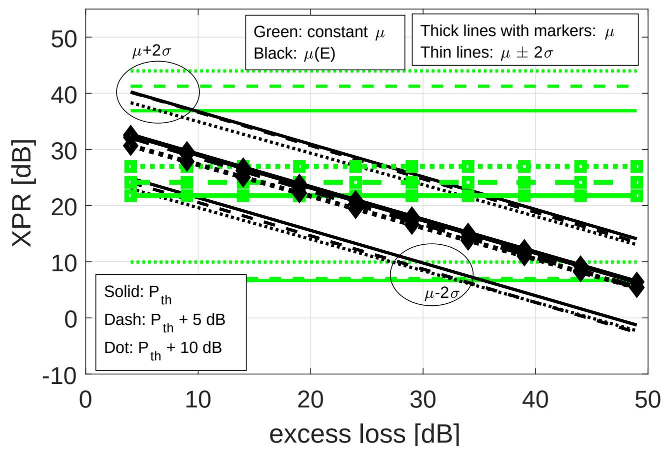

Fig. 3. Comparison of constant μ (green) and $\mu(E)$ (black) with noise threshold levels P_{th}, P_{th} +5 dB, and P_{th} +10 dB. The μ- and $\mu \pm 2\sigma$-lines are shown with different types of lines. The $\mu(E)$-model is shown to be robust against differences in measurement noise level.

B. Influence of the Noise Level

The XPR model parameters in Table I are true, in fact, only for the specific noise threshold in these channel measurements. With a different channel sounder, or even with the same sounder with different VNA settings, the noise level is different. This makes it difficult to compare XPR statistics from different sources.

To study the effect of the noise level, we compare three different noise levels. The number of measured XPRs and the censored samples is presented in Table II with noise thresholds P_{th}, P_{th} +5 dB, and P_{th} +10 dB. In practice, a higher threshold level affects the MPCs in two ways, (i) weak paths, many of which have low XPR, are buried under the threshold, and (ii) some strong MPCs become censored samples. The results are presented in Table III and Fig. 3. All these parameter estimates include also the censored samples. With the constant μ-model, the parameters change as a function of the threshold level.

As shown in Table III and Fig. 3, the new model with the average XPR as a function of the MPC main polarization excess loss is not sensitive to differences in the noise threshold level. The new model also has clearly smaller σ showing that it fits the measured data much better (see also Fig. 2). The XPR decreases about 0.6 dB for every dB of excess loss. The resulting XPR values are greater than 20 dB for MPCs with under 10 dB excess loss and smaller than 10 dB for over 30 dB excess loss. Also results in, e.g., in [3], [4], [9] report high XPR values for 60 GHz, relative to [1], [2].

V. CONCLUSION

In this letter, we examined two separate but related issues related to MPC XPR modeling. Firstly, it is shown that it is important to include all measured MPCs with maximum likelihood estimation method, including those samples for which the cross-polarization is unavailable due to measurement noise level.

Secondly, a new physically sound XPR model is presented that models the depolarization effect by making the average XPR a function of the MPC excess loss. Unlike the conventional XPR model, which can give quite different model parameters depending on the noise level in the measurement, our novel XPR model yields very similar results for different noise levels. Furthermore, our measurement results indicate that the physical depolarization effect increases significantly with increasing excess loss; an effect that is included in the new XPR model.

The maximum likelihood estimation method, and the new model, are demonstrated with, and parameters are given for, channel measurements at the 60 GHz range in an indoor cafeteria. Proper 60 GHz MPC XPR parametrization will require more measurements, both indoor and outdoor, and the parametrization, with the method and models presented in this letter.

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