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Published in:
2012 6th European Conference on Antennas and Propagation (EUCAP)

DOI:
10.1109/EuCAP.2012.6206252

2012

Document Version:
Peer reviewed version (aka post-print)

R. Tian, B. K. Lau, and J. Medbo, “Impact of Rician fading and cross-polarization ratio on the orthogonality of dual-polarized wireless channels,” in *Proc. 6th Europ. Conf. Antennas Propagat. (EuCAP’2012)*, Prague, Czech Republic, Mar. 26-30, 2012.

Impact of Rician Fading on the Orthogonality of Dual-Polarized Macrocellular Channels

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***Abstract*—The paper examines the impact of Rician fading on the orthogonality of dual-polarized MIMO channels in a measured urban macrocellular scenario. The measurements confirm the previous finding that the Rician K-factors of the cross-polarized channels are strongly correlated to those of the co-polarized channels. However, the Rician K-factors do not in general give direct indications on the orthogonality of dual-polarized channels. Our results show that, in the presence of strong Rician fading, the co- and cross-polarization ratios largely determine the channel orthogonality. In particular, good channel orthogonality is achieved when the co- and cross-polarization ratios are close to 1 and very small, respectively. Nevertheless, more than 70% of the measured route achieves better channel orthogonality than the average performance of the reference IID Rayleigh channel, indicating that efficient multi-stream MIMO communication can be achieved in the measured scenario.**

I. INTRODUCTION

The use of two linear polarization states of plane waves that are orthogonal to each other, for example vertical (V) and horizontal (H) polarizations, has been known to introduce two degrees of freedom in a wireless communication channel [1]. Utilizing polarization diversity, low signal correlation can be obtained, which has the benefit that the two antenna elements may be placed closer to one another as is desired in some applications such as in mobile terminals [2]. The polarized propagation channel has been measured and/or modeled in [3]–[10]. In most of these studies, the focus is to model the capability of the channel in coupling between co- and cross-polarized radio waves. In particular, the studies in [4], [5], [9] investigate the impact of Rician fading on dual-polarized channels. According to these studies, the Rician K-factor of the cross-polarized channel K_{CX} is modeled as proportional to that of the corresponding co-polarized channel K_{CO}, *i.e.*,

$$K_{\mathrm{CX}} = \alpha K_{\mathrm{CO}}, \tag{1}$$

where α is determined by the cross-polarization coupling of the channel, and the Rician K-factors K_{CO} and K_{CX} are employed to characterize the dominant propagation component(s) of the co- and cross-polarized channels, respectively. The linear dependence in (1) seems to suggest that it is sufficient to model a single K-factor of the dual-polarized channels. However, as will be explained in this paper, the simple model can lead to misleading conclusions. In particular, the Rician K-factors do not in general give direct indications on the orthogonality of the dual-polarized channels.

This work was financially supported by Vetenskapsrådet (Grant no. 2010-468) and VINNOVA (Grant no. 2009-02969).

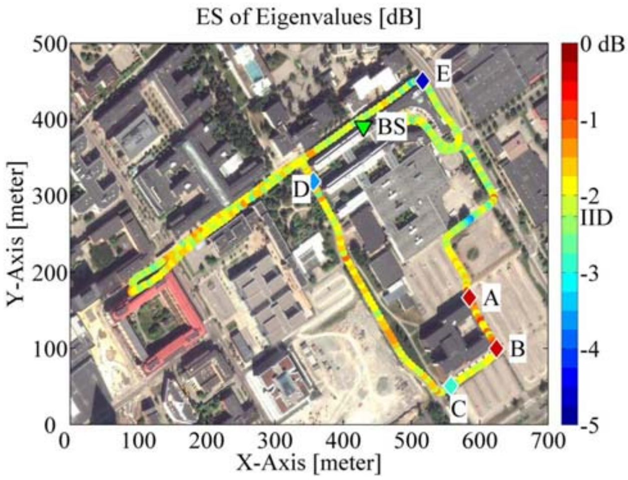

Fig. 1. The ES of channel eigenvalues along the measurement route.

In a multipath propagation channel, Rician fading occurs due to the presence of one or several dominant propagation components. This is the case either in the line-of-sight (LOS) scenario or in the propagation scenario with a dominant cluster of scatterers (that is not necessarily LOS). For single-polarized MIMO channels, Rician fading reduces the richness of the multipath propagation, which can in turn degrades the orthogonality of the channels, especially when the transmitter-to-receiver distance is much greater than the array size. From the perspective of multi-stream MIMO transmissions (*i.e.*, spatial multiplexing), this condition creates a dominant subchannel with significantly higher channel gain than other subchannels. However, the same conclusion does not apply when dual-polarized radio waves are utilized. For example, when cross-polarized antennas are employed at both the transmit (TX) and receive (RX) sides of a 2×2 MIMO system, the channel becomes fully orthogonal in the pure LOS scenario. In this case, the eigenvalues of the channel become equal and the channel is optimized for spatial multiplexing.

The purpose of this work is to examine the impact of Rician fading on the orthogonality of dual-polarized MIMO channels. The investigation is based on measured propagation channels in an urban macrocellular environment as shown in

Fig. 1. The rest of the paper is organized as follows. Section II briefly describes the setup of the measurement campaign. In Section III, the characteristics of the measured dual-polarized propagation channels are discussed. Section IV presents the orthogonality of these channels . In Section V, the mutual dependence among various channel parameters such as the Rician K-factor and the co- and cross-polarization ratios as well as their impact on channel orthogonality are investigated. Finally, Section VI concludes the paper.

II. Measurement Setup

The measurement campaign was carried out in an urban macrocellular scenario at Kista, Stockholm, Sweden. The measurement route is plotted on a map as shown in Fig. 1, where at least two samples of the channel are measured per wavelength along the entire route.

The elevated base station (BS) is equipped with a V-polarized electric dipole antenna and a H-polarized magnetic dipole antenna, which are mounted on the rooftop of a $25\,\mathrm{m}$-tall building. The mobile station (MS) is a measurement van equipped with two electric and two magnetic dipole antennas, which are mounted on the roof of the measurement van and arranged as a square array with side lengths of $0.3\,\mathrm{m}$. The channel transfer functions between all BS and MS antennas were measured coherently at $2.65\,\mathrm{GHz}$ using a channel sounder that was customized from an LTE testbed [11]. More details of the measurement setup can also be found in [12].

III. Polarization Characteristics

In this study, the focus is on dual-polarized 2×2 MIMO channels. The four MS antennas are thus considered as two independent realizations of the V/H cross-polarized antennas. The 2×2 channel matrix $\mathbf{H}$ is then formed as

$$\mathbf{H} = \begin{bmatrix} h_{\mathrm{VV}} & h_{\mathrm{VH}} \\ h_{\mathrm{HV}} & h_{\mathrm{HH}} \end{bmatrix}, \tag{2}$$

where h_{VH} denotes the channel transfer function between H-polarized TX antenna and V-polarized RX antenna. Similar notations are applicable to all other antenna pairs. Two common parameters for characterizing dual-polarized channels are cross-polarization ratio (XPR) and co-polarization ratio (CPR), which quantify the cross- and co-polarization coupling capability between TX and RX antennas. In this study, they are defined as

$$\chi_{\mathrm{CX,V}} = \frac{\mathrm{E}\{|h_{\mathrm{HV}}|^2\}}{\mathrm{E}\{|h_{\mathrm{VV}}|^2\}}, \chi_{\mathrm{CX,H}} = \frac{\mathrm{E}\{|h_{\mathrm{VH}}|^2\}}{\mathrm{E}\{|h_{\mathrm{HH}}|^2\}}, \tag{3}$$

where $\chi_{\mathrm{CX,V}}$ is defined as the power ratio between the cross-polarized coupling from the V-polarized TX antenna to the H-polarized RX antenna (h_{HV}) and the co-polarized coupling of the V-polarized TX and RX antennas (h_{VV}). Similarly, $\chi_{\mathrm{CX,H}}$ denotes the XPR for H-polarized channels. The CPR, which describes the power ratio between the co-polarized V-channels (h_{VV}) and H-channels (h_{HH}), is also defined in a similar manner, *i.e.*,

$$\chi_{\mathrm{CO}} = \frac{\mathrm{E}\{|h_{\mathrm{VV}}|^2\}}{\mathrm{E}\{|h_{\mathrm{HH}}|^2\}}. \tag{4}$$

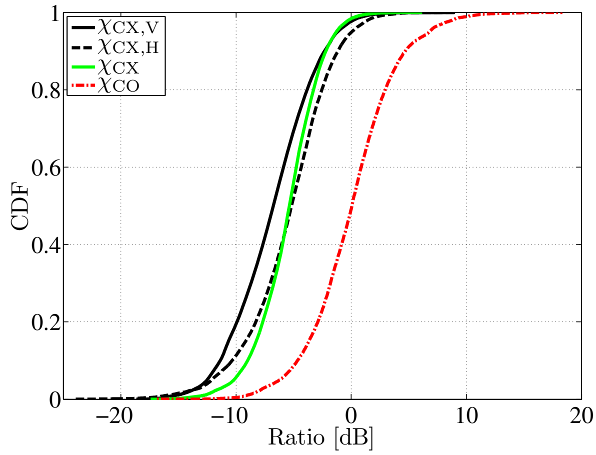

Fig. 2. The CDF of cross- and co-polarization ratios.

The XPR and CPR of the dual-polarized channels are evaluated from the measurements, and the cumulative distribution function (CDF) of their samples along the measurement route is shown in Fig. 2. At median probability (50%), the CPR is obtained as $0\,\mathrm{dB}$, which indicates the quasi-equivalent ability of the channels to support co-polarization coupling of the V- and H-polarized waves. On the other hand, the XPR is found to be smaller than $-5\,\mathrm{dB}$ at median probability, which is consistent to other polarization studies on urban macrocellular environments. For the rest of the paper, χ_{CX} is denoted as the representative XPR of the channel, and it is simply the mean value of $\chi_{\mathrm{CX,V}}$ and $\chi_{\mathrm{CX,H}}$ (see Fig. 2).

IV. Channel Orthogonality

In this study, we employ the ellipticity statistic (ES) of the channel eigenvalues [13] to characterize the orthogonality of the dual-polarized MIMO channels. The ES performance quantifies the relative spread among the channel eigenvalues, and a higher eigenvalue spread of the MIMO channel can be interpreted as SNR degradation, as shown in [14]. For instance, ES $= 1$ or $0\,\mathrm{dB}$ denotes equal eigenvalues in the case of fully orthogonal MIMO channel, whereas ES $= 0$ denotes non-orthogonal channel, with at least one zero eigenvalue in the channel.

A. Average Performance

The ES performance of the measured channel eigenvalues is plotted along the measurement route in Fig. 1. The results are smoothed over a 10-wavelength window, in order to obtain local averaging. To improve readability, a 30-fold down sampling is also performed. Throughout the measurement route, with only a few exceptions, the dual-polarized channels achieve a similar or better ES performance than that of the IID Rayleigh channel, whose average ES performance is also indicated on the color bar in Fig. 1. The CDF of the ES values obtained from the data samples is given in Fig. 3. As can be observed from the steeper slope of the CDF curve, it is clear that the measured dual-polarized channels achieve

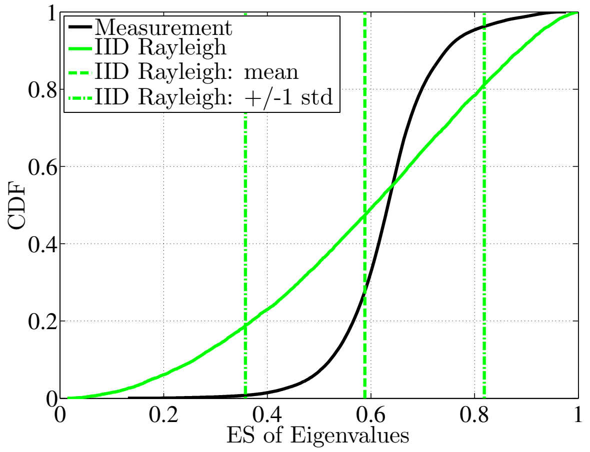

Fig. 3. The CDF of the ES of channel eigenvalues.

better orthogonality than the IID Rayleigh channel. As a result, 70% of the measured channels achieve better performance than the average performance of the IID Rayleigh channel. This observation shows that the dual-polarized channel generally exhibits good and robust channel orthogonality, indicating that efficient multi-stream MIMO communication can be achieved in the measured scenario.

B. *Performance at Representative Positions*

In order to relate Rician fading to the orthogonality of the measured channels, the ES performance of five representative positions A-E as indicated in Fig. 1 is studied in greater details. All these positions are characterized by strong Rician fading (*i.e.*, relatively large K-factors). The analysis is carried out by estimating the XPR, CPR, and the respective Rician K-factor for the co- and cross-polarized channels of the dual-polarized channels at these positions. The XPR and CPR parameters are obtained according to the discussion in Section III. The Rician K-factors are obtained using maximum likelihood estimation based on the channel envelopes. These parameters (smoothed over a ten wavelength window) are summarized in Table I for the chosen positions.

1) Good Channel Orthogonality: Both positions A and B feature a high degree of channel orthogonality, with $\mathrm{ES} \approx 0\,\mathrm{dB}$. With small values of XPR as well as the CPR (*i.e.*, χ_{CO}) being close to 1 (or $0\,\mathrm{dB}$), good orthogonality of the dual-polarized channel is preserved. These positions have been identified as LOS scenarios.

TABLE I
ANALYSIS OF FIVE REPRESENTATIVE POSITIONS.

Position	A	B	C	D	E
ES [dB]	-0.4	-0.3	-2.8	-3.7	-4.6
χ_{CX} [dB]	-10.4	-11.7	-7.2	-1.0	-0.2
χ_{CO} [dB]	1.0	0.5	-8.3	9.9	12.6
K_{CO} [dB]	11.8	13.8	8.5	12.2	14.2
K_{CX} [dB]	6.2	10.9	4.5	9.9	12.1

2) Poor Channel Orthogonality: On the other hand, the obstructed-LOS positions D and E feature poor channel orthogonality. At these positions, the XPR is as high as 1 and the CPR is far from 1 due to depolarization effects from the buildings nearby. Moreover, K_{CX} is found to be nearly as strong as K_{CO}, which indicates that the multipath propagation is limited by dominant scattering objects. These conditions constrain the multipath richness and further degrade channel orthogonality. As a result, the channel orthogonality is worse than that of the IID Rayleigh channel.

3) Moderate Channel Orthogonality: Positions between B and C as shown in Fig. 1 are non-LOS scenarios due to the presence of the nearby building. Position C features the worst case among these positions, whose ES performance is only slightly worse than that of the IID Rayleigh channel. Therefore, the dual-polarized channels in non-LOS scenarios but with strong Rician fading can still achieve similar channel orthogonality as that of the IID Rayleigh channel. This phenomenon is mainly attributed to sufficiently rich multipath propagation even in cases of relatively large K-factors.

C. *Summary*

According to the discussion above, in the presence of strong Rician fading, the orthogonality of the dual-polarized channel is found to be largely determined by the propagation characteristics, such as XPR and CPR. Good channel orthogonality is achieved in the LOS scenario, in which case the XPR is of small value and the CPR is close to 1 (or $0\,\mathrm{dB}$). Under this scenario, the orthogonality of the dual-polarized channel outperforms that of the reference IID Rayleigh channel. However, this is not the case if instead XPR is close to 1 whereas the CPR departs significantly from 1. Under this condition, the channel orthogonality is no longer preserved due to more significant multipath propagation.

Moreover, it is conceivable that depolarization of dominant paths by scattering objects can effect a unitary transformation of the dual-polarized channel that simply rotates the linear polarization states. If such a situation of strong Rician fading occurs, the XPR can be close to 1 (or $0\,\mathrm{dB}$) (*i.e.*, in the case of $\pm 45°$-polarization states received by V- and H-polarized antennas) but still results in good channel orthogonality. However, such a situation has not been detected in the measurement data. In the next section, the mutual dependence among the propagation characteristics and their impact on channel orthogonality is analyzed in more detail.

V. ANALYSIS

The above study addresses the impact of different channel parameters on the orthogonality of the measured dual-polarized MIMO channels. Nevertheless, the analysis is performed based on several chosen positions. In this section, the study is extended to consider all measured samples collected along the route. The calculated results for all parameters of interest are then smoothed and downsampled for the plots, as is performed for the ES performance in Section IV-A.

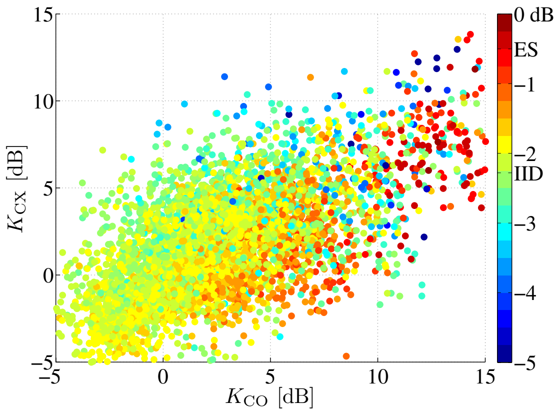

Fig. 4. Dependence between K_{CO} and K_{CX} and their impacts to the ES performance.

A. K_{CO}, K_{CX} and ES

As shown in Fig. 4, the measurements confirm the previous finding that the Rician fading of the cross-polarized channel is strongly correlated to that of the co-polarized channel, such that a linear dependence between K_{CO} and K_{CX} as indicated by (1) represents a good model for the data. However, it is noteworthy that this observation can be partly due to the finite cross-polarization discrimination of the dual-polarized antenna elements used in the measurements.

In LOS scenarios, strong Rician fading helps to improve the orthogonality of the dual-polarized channels. However, this is not the case for non-LOS scenarios where strong Rician fading is mainly attributed to dominant scattering objects that cause strong cross-polarization coupling (*i.e.*, polarization leakage) and hence limit the independence (and orthogonality) between the dual-polarized channels. The different effects of these two phenomena can be observed in the mixture of good and poor ES performance when the K-factors become stronger in Fig. 4. Nevertheless, when the Rician fading is less significant, the ES performance of the dual-polarized channel is comparable to that of the reference IID Rayleigh channels. This corresponds to the case of rich-scattering multipath propagation.

B. CPR, XPR and ES

The dependence of the ES performance on the CPR and XPR can be observed from Fig. 5. As can be seen in Fig. 5(a), the plot is approximately symmetrical about $|\chi_{\mathrm{CO}}[\mathrm{dB}]| = 0\,\mathrm{dB}$. The CPR of $0\,\mathrm{dB}$ indicates equally strong gain of the respective V- and H-polarized channels, which contributes to good channel orthogonality. The channel orthogonality is optimized when the CPR is close to 1 (or $0\,\mathrm{dB}$) and the XPR is small, since the ES can be seen to approach its highest value of $0\,\mathrm{dB}$. This situation corresponds to the case of strong Rician fading in the LOS scenario, where the orthogonality of the dual-polarized channel is largely preserved.

On the other hand, the channel orthogonality degrades as the CPR departs from 1 (or the absolute value $|\chi_{\mathrm{CO}}[\mathrm{dB}]|$ increases from $0\,\mathrm{dB}$) and as the value of χ_{CX} increases. This is better

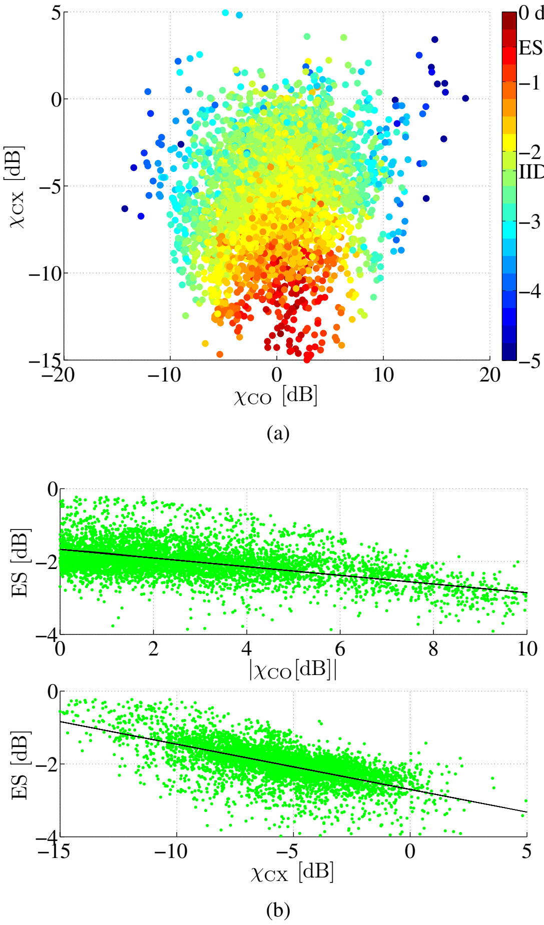

Fig. 5. Dependence between CPR and XPR and their impacts to the ES performance.

illustrated with the linear fitting shown in Fig. 5(b). The impact of the CPR can be understood as the large values of $|\chi_{\mathrm{CO}}[\mathrm{dB}]|$ indicate significant gain imbalance between the dual-polarized channels. Therefore, better channel orthogonality is obtained with $|\chi_{\mathrm{CO}}[\mathrm{dB}]|$ being close to $0\,\mathrm{dB}$. When it comes to the impact of XPR, it is noted that the scattering with strong cross-polarization coupling generally enriches the multipath propagation, which should improve channel orthogonality. However, in the case of dual-polarized channels, better channel orthogonality is obtained with small values of χ_{CX}.

C. CPR, K_{CO} and ES

The mutual dependence between CPR and K_{CO} as well as their impact on the ES performance of the dual-polarized channels are illustrated in Fig. 6. In the case of less significant Rician fading, the CPR is about $0\,\mathrm{dB}$. In this case, the XPR is high (*i.e.*, approaching $0\,\mathrm{dB}$) as can be seen from Fig. 5(a). This corresponds to the rich-scattering multipath propagation, which leads to similar channel orthogonality as that of the reference IID Rayleigh channel.

However, in the presence of strong Rician fading, the impact of CPR on channel orthogonality can be classified into two

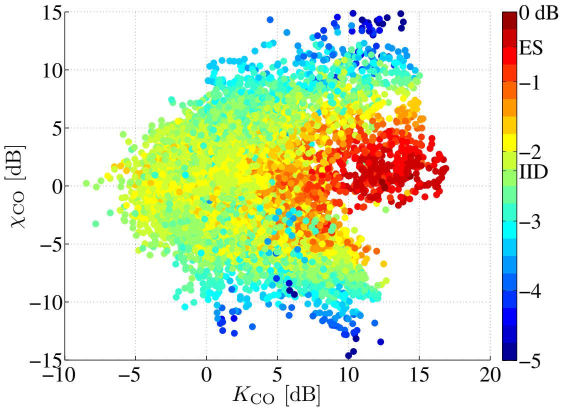

Fig. 6. Dependence between CPR and K_{CO} and their impacts to the ES performance.

groups: On the one hand, with stronger Rician fading, the magnitude of CPR $|\chi_{CO}[\mathrm{dB}]|$ increases as well. In this case, larger values of $|\chi_{CO}[\mathrm{dB}]|$ indicate higher degrees of gain imbalance between the dual-polarized channels. The XPR is also high, as can be observed in Fig. 5(a). Thus, channel orthogonality is not attained. Under this situation, the channel orthogonality can be worse than the IID Rayleigh channel. On the other hand, the channel orthogonality is significantly improved for those strong Rician fading positions where the CPR is about $0\,\mathrm{dB}$. In this case, the Rician fading helps to enhance channel orthogonality. As discussed above, this corresponds to the LOS scenario in general. Moreover, as discussed previously, the channel orthogonality in this situation is further improved by the small XPRs.

VI. Conclusions

This work examines the impact of Rician fading on the orthogonality of dual-polarized MIMO channels in a measured urban macrocellular scenario. The measurements confirm the previous finding that the Rician K-factors of the co- and cross-polarized channels can be adequately modeled as linearly proportional to each other. However, strong Rician fading can either enhance or degrade channel orthogonality, with respect to the IID Rayleigh channel. In particular, given similar K-factors, LOS scenarios are found to be favorable to channel orthogonality, whereas obstructed or non-LOS scenarios can be detrimental to orthogonality. In addition, optimal orthogonality is invariably associated with the CPR approaching $0\,\mathrm{dB}$ and the XPR departing from $0\,\mathrm{dB}$, as they imply equal channel gain as well as the absence of depolarization (*i.e.*, independence between channels).

Acknowledgment

The authors would like to acknowledge Ms. Mona Hashemi and Mr. Henrik Asplund of Ericsson Research, Kista, Sweden, for providing information on the measurement setup.

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