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MIMO Performance Evaluation of Isotropic, Directional and Highly-Directional Antenna Systems for mm-Wave Communications

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Abstract—In this paper, we investigate how directional and highly-directional antenna systems using fixed beams can be beneficial in terms of aggregated channel and antenna gains, channel correlation and the massive multiple-input multiple-output (MIMO) capacity in both line-of-sight (LOS) and non-LOS (NLOS) scenarios for single user MIMO (SU-MIMO). It is shown that narrower beams have stronger aggregated channel and antenna gain. However, narrow beamwidth triggers a higher channel correlation as fewer scatterers are seen. A possible solution to reduce the correlation among the beams is to properly decorrelate the beams in advance. To this end, we partition the area of interest and devote one specific partition to each beam to minimize the possible overlaps among the beams. Simulation results show that fixed beam SU-MIMO systems using such highly-directional beams can provide higher MIMO capacity in comparison to isotropic and directional antenna systems.

Index Terms—5G mobile communication, aperture antennas, directional antennas, millimeter wave communication.

I. Introduction

Connectivity for a wide range of applications is one of the key drivers for the next generation of mobile communications. This imposes the need for even lower latency, higher reliability, and higher data rates as well as better energy efficiency in comparison to the current 4G systems [1]. Here, millimeter wave (mm-Wave) communications hold promise to combat the scarcity of bandwidth and consequently, provide a wider bandwidth and higher data rates [2]. Nevertheless, providing coverage becomes more challenging. While merely increasing the transmit power cannot be a solution, the use of multiple-input multiple-output (MIMO) systems can be the key.

One of the advantages of MIMO systems is that it enables higher capacity that comes from exploiting the uncorrelated channels [3]. Furthermore, by moving from MIMO to massive MIMO systems further improvements can be achieved in terms of spectral efficiency, energy efficiency, robustness, and reliability [4]. To make such systems feasible, hybrid feeding architectures have recently attracted a great deal of research interest to cope with the downside of the increased complexity. For instance, the most recent work [5] has studied the impact of reducing the number of radio frequency (RF) chains by using analog and digital transceiver structures. The study has shown that hybrid relay systems can achieve 95% of the spectral efficiency of a fully digital relay system even by removing half of the RF chains.

Another line of research to reduce the hardware complexity relates to lens antennas [6] and phased array fed (PAF) reflectors [7], [8], which can provide antenna gains of 40 dBi and higher. Particularly, the ability of generating highly-directional multiple beams makes such systems interesting in 5G [9], [10]. However, decreasing the beamwidth restricts the angular spread of the received signals, which affects the eigenvalues of the channel covariance matrix, and consequently, the observed propagation channel [5]. In other words, due to a smaller beamwidth fewer scatterers can be observed. Therefore, the beams that are sharing the same scatterers will be more correlated, which deteriorate the potential of MIMO systems. This loss of MIMO performance leads to the question if highly-directional antennas can be beneficial to a multi-beam MIMO system.

Motivated by the above discussion, we compare the performance assessments of isotropic, directional, and highly-directional antenna setups in this paper. This is done in terms of observed channel gain, correlation, and capacity in an urban micro-cellular (UMi) scenario for single-user MIMO (SU-MIMO). Section II describes the system model, simulation setup, and beam realization. In Section III, the simulation results are presented and discussed. The conclusion is drawn in Section IV.

II. System Model

We generate the channel coefficients based on a quasi deterministic radio channel generator (QuaDRiGa) presented in [11]. This simulation platform is calibrated against 3GPP channel models and its capabilities have been also evaluated by measurements in [12].

A. Simulation Setup

For the simulation a SU-MIMO scenario in UMi line-of-sight (LOS) and non-LOS (NLOS) environments is considered. To evaluate the performance of the beams we distinguish between near (1 m to 75 m) and far (75 m to 150 m) regions as stated in Table I. The scenarios are also illustrated in Fig. 1(a). The user equipment (UE) is randomly dropped with a
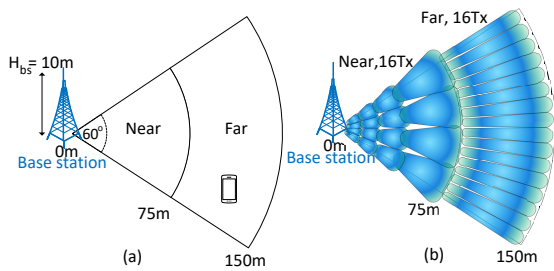
Fig. 1. Top view illustrations of (a) both near and far scenarios and (b) beam footprints of applied highly-directional beams with beam diversity in both near and far scenarios.

Fig. 2. Example of the scatterer distribution by QuaDRiGa for 3GPP 38.901 NLOS using QuaDRiGa's multi-bounce model.

uniform distribution within a sector with 150 m radius and angle between $\pm 30°$. The height of each UE is fixed at $H_{ue} = 1.5$ m, while the base station (BS) is located at the origin at a height of $H_{bs} = 10$ m. The UE has $N_r = 4$ isotropic antenna elements mounted planar with an element spacing of $\lambda/2$ along x and y axis. The channel characteristics to obtain the MIMO channel coefficient matrix $\mathbf{G}$, are in accordance with 3GPP 38.901 model [13], e.g., applied pathloss and shadow fading are stated in Table 7.4.1-1 in [13]. An example of the scatterer distribution of the NLOS case in QuaDRiGa is shown in Fig. 2. The orthogonal frequency-division multiplexing (OFDM) technique with 100 subcarriers is utilized by the BS that communicates with the UE through a channel bandwidth of 20 MHz at a center frequency of 28 GHz. The baseband frequency domain channel can be expressed as [14]

$$\mathbf{H}_n = \sum_{l=1}^{L} \mathbf{G}_l \cdot \exp(-2\pi j f_n \tau_l), \tag{1}$$

where $\mathbf{G}_l$ is the channel coefficient matrix of the lth path, f_n is the nth sample frequency in Hz and τ_l denotes the delay in seconds of the lth path.

TABLE I
APPLIED SIMULATION PARAMETERS

Parameter	Value
Center frequency [GHz]	28
Channel bandwidth B [MHz]	20
Number of carriers N	100
BS height H_{bs} [m]	10
UE height H_{ue} [m]	1.5
Number of users	1
BS antenna	see Section II-B
Propagation model	3GPP 38.901 UMi NLOS and LOS [13]
Number of drops	1000
Number of digital inputs (N_t)	16
Number of user antennas (N_r)	4
Distances	1 m-75 m (near) 75 m-150 m (far)

B. Antenna Configurations

In this paper, we consider four different radiation patterns on the BS side. The theoretical isotropic radiation pattern (0 dBi) is used as a reference to show one extreme, where signals are radiated and r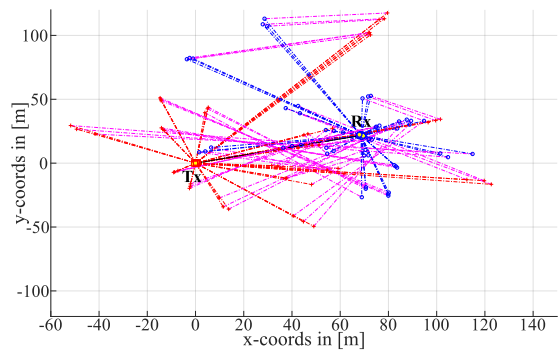eceived with equal intensity in all directions. The directional antenna has a 3dB beamwidth of $90°$ in azimuth and elevation with a corresponding gain of 7.5 dBi, which corresponds to that of a typical patch antenna. The highly-directional beams can be divided into two cases: Highly-directional beams generated to cover the area of interest (HD) and highly-directional beams with beam diversity to partition the area of interest (HD partitioned).

In the former case, each beam covers the whole area of interest with its beamwidth. This results in 12 dBi antenna gain and an elevation tilt of $22°$ for the near region and 20.1 dBi antenna gain and an elevation tilt of $3°$ for the far region. However, in the latter case, all beams together partition the area of interest with an overlap at the 3 dB beamwidth. Therefore, narrower beams can be used, which result in higher antenna gains. As illustrated in Fig. 1(b), we choose four separated elevation tilts for the near region where each beam has an antenna gain of 19.7 dBi. For far regions, the considered distance is covered by a single beam, hence, they are tilted by the same angle in elevation and shifted in azimuth where each achieves an antenna gain of 33.5 dBi.

For the simulation, we fix the number of available digital inputs to $N_t = 16$, which we relate to the maximum number of separated beams. Hence, we run the simulation separately for each of the four cases under the same conditions, where we have 16 beams deployed at the BS. The distance between the beams for isotropic, directional and HD cases is $\lambda/2$ in a planar array constellation. For the HD partitioned case it is assumed that they are generated by a reflector systems where each beam has its center of origin at the reflector.

III. PERFORMANCE ANALYSIS

In this section, we obtain the channel matrices of both near and far scenarios for NLOS and LOS environments. Based on these, the observed channel matrix $\mathbf{H}$ in terms of observed channel and antenna gain, channel correlation and capacity are evaluated.

A. Observed Channel Gain

In general, the channel gain depends on the paths that influence the transmitted signals. This means, by changing the beam direction, different channel gain can be obtained. Thus,
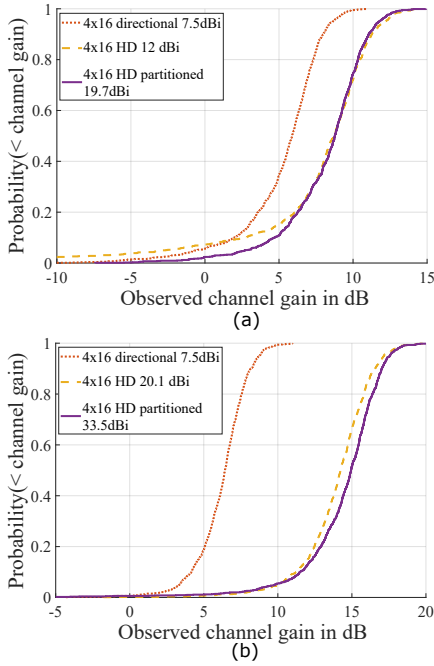
Fig. 3. NLOS: Channel gain in dB with respect to the channel gain observed with isotropic antenna elements for directional, HD, and HD partitioned cases for (a) near region and (b) far region.

Fig. 4. NLOS: Eigenvalue distribution for isotropic, directional, HD and HD partitioned cases for (a) near region and (b) far region.

the beam characteristics, such as beamwidth and pointing direction, have a significant impact on the observed channel matrix. Consequently, for the isotropic beams the pure channel elements are obtained while for the directional, HD, and HD partitioned cases the channel elements show the influence of the channel and the beam characteristics. For evaluation of the observed channel gain the squared Frobenius norm can be calculated, which is related to the eigenvalues in the following way [15]

$$\left\| \mathbf{H} \right\|_{\mathrm{F}}^{2} = \sum_{i=1}^{N_{\mathrm{t}}} \sum_{j=1}^{N_{\mathrm{r}}} |h_{i,j}|^{2} = \sum_{k=1}^{K} \lambda_{k}, \qquad (2)$$

where $h_{i,j}$ are the elements of the channel matrix, λ_k is the kth eigenvalue of the covariance matrix $\mathbf{HH}^{\mathrm{H}}$, where $(\cdot)^{\mathrm{H}}$ is the conjugate transpose, and K denotes the rank of the matrix which is $K \leq \min\{\mathrm{N_t}, \mathrm{N_r}\}$. Therefore, $\left\| \mathbf{H} \right\|_{\mathrm{F}}^{2}$ sums the power transmission factors λ_k and represents the maximum power gain that can be extracted from the propagation channel. In Fig. 3 the cumulative distribution functions (CDF's) of the observed channel gains of 1000 realizations are plotted. The channel gain of the isotropic antenna case is used as a reference for the other three cases. Fig. 3(a) shows the near scenario, where the observed channel gain increases due to the focused beams. However, the gap between the HD and HD partitioned cases is relatively small compared to the antenna gain per beam. This is due to the narrower beams that are used in the HD partitioned case. The narrow beams cause some channel elements, $h_{i,j}$, to not contribute while if the area is not partitioned more observed channel elements can actually contribute due to the broader shape. Furthermore,
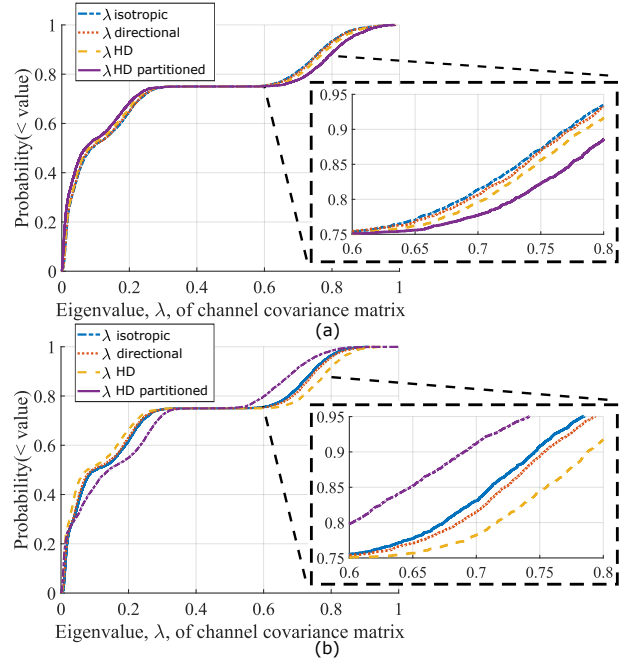
we can see that directional as well as both HD and HD partitioned cases perform in few cases worse than isotropic due to coverage difficulties for narrow beams near the BS. However, this coverage problem is not seen in Fig. 3(b) that shows the results for far regions. Indeed, if the UE is further away narrower beams can be used, and consequently, the higher antenna gain can be achieved which all result in an observed channel with bigger Frobenius norm.

B. Channel Correlation

In this subsection, we evaluate the influence of spatial filtering on the correlation properties of the propagation channel. To this end, the influences of path-loss, shadow fading, and antenna gain should be removed by normalizing the channel matrix in the following manner [15]

$$\mathbf{H}_{\mathrm{norm}} = \frac{\mathbf{H}}{\left\| \mathbf{H} \right\|_{\mathrm{F}}^{2}}. \qquad (3)$$

To analyze the channel, we are looking at the eigenvalue distribution of the channel covariance matrix, $\mathbf{H}_{\mathrm{norm}}\mathbf{H}_{\mathrm{norm}}^{\mathrm{H}}$. As previously mentioned, each eigenvalue represents the power transmission factor of the possible channels, and the number of eigenvalues is determined by the rank of the channel covariance matrix. In Fig. 4 the CDF's of the eigenvalue distribution are plotted for the near and far scenarios. According to the results in [5], the distribution of eigenvalue depends on the angular spread which is linked to the opening angle of the radiation beam. Indeed, smaller angles observe fewer scatterers. This results in a higher correlation, and leads to fewer strong eigenvalues as well as some weaker ones. On the other hand, a wider angular spread sees a higher

number of scatterers. Hence, it leads to a lower correlation and more moderate eigenvalues. It is notable that the case of a small angular spread can be linked to the case of using narrow beams, while a high angular spread can be linked to isotropic beams. Both near and far simulations confirm such a behavior for the isotropic, directional and HD cases. The isotropic antennas observe all scatterers that leads to a low correlation, while if the beamwidth is narrowed the number of strong eigenvalues and weak eigenvalues increases.

On the other hand, for far regions, the HD partitioned case does not show the same tendency as the other cases. Actually, it outnumbers the isotropic case and shows a lower correlation. This is due to the beam diversity that is achieved by partitioning the area of interest in smaller pieces and observing different areas instead of the unit area. Hence, the observed channels by each beam show less correlation since each beam observes different scatterer clusters. The reason why the advantage is not seen in the near region in Fig. 4 is due to the chosen number of beams. We have observed that an optimum constellation depending on the distance can be found by varying the number of beams and their beam shapes. However, this is not within the scope of this work.

C. Capacity

In the next step, we study the system performance in terms of MIMO capacity under different configuration setups. The capacity formula with the channel state information available at the receiver is found by using [15] as:

$$C = \sum_{k=1}^{K} \log_2\left(1 + \frac{\text{SNR}}{N_\text{t}}\tilde{\lambda}_k\right), \tag{4}$$

where $\tilde{\lambda}_k$ is the eigenvalue normalized by the Frobenius norm of the isotropic system, denoted by $\left\|\mathbf{H}_\text{iso}\right\|_\text{F}^2$ and SNR is defined as:

$$\text{SNR} = \frac{\text{P}_\text{t}}{\sigma_\text{n}^2}\left\|\mathbf{H}_\text{iso}\right\|_\text{F}^2. \tag{5}$$

To have a fair comparison among the different radiation patterns, we fix $\frac{\text{SNR}}{N_\text{t}} = 10$. By doing this, the effective SNR for each of the four cases is the same, hence, the distance dependency is excluded. The CDF's of the capacity for the near and far scenarios are shown in Fig. 5. For the near scenario, shown in Fig. 5(a), the HD case performs the best. This is achieved due to the slightly lower correlation compared to the HD partitioned case, while there is only a minor difference in the observed channel gain. This changes for the far distance scenario shown in Fig. 5(b) due to the much lower correlation of the HD partitioned case. In general, it can be seen that the narrow beams are beneficial. However, it can cause some coverage problems that is seen in Fig. 5(a) where the 10th percentile shows a degradation of the narrow beam performance.

D. Influence of a Low Scatterer Environment

So far, we evaluated the performance assessment of our system under NLOS assumption, however, in the real world
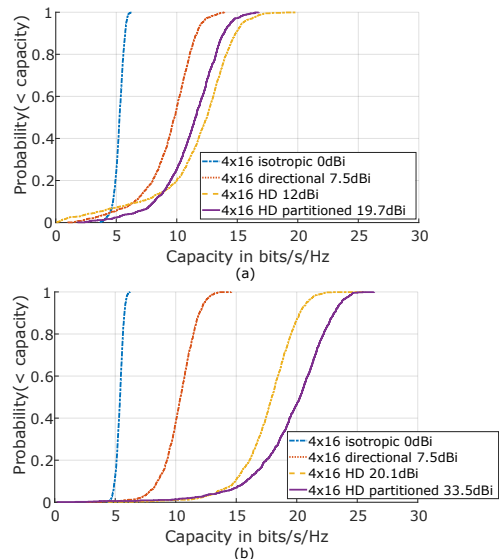

Fig. 5. NLOS: Capacity for isotropic, directional, HD and HD partitioned cases for (a) near region and (b) far region.

users experience a mixture of NLOS and LOS scenarios. In LOS scenario, the number of scatterers is significantly reduced, which leads to a higher channel correlation. As a result, a lower MIMO gain can be expected. Fig. 6 represents the channel gain in LOS scenario. As the squared Frobenius norm is the sum of the square of the absolute values, the number of scatterers influences how many observed channel elements contribute to the overall gain. Hence, there is a lower chance that a highly-directional beam contributes in low scatterer environments. Therefore, we see in Fig. 6(b) that although each beam in the HD partitioned case has a much higher antenna gain, the observed channel gain drops for some cases below the performance of the HD case. In Fig. 7, the distributions of channel eigenvalues are plotted. As we discussed earlier in Section III-B, the eigenvalues are distributed in a wider range because of a low amount of scatterers observed by each beam, hence, we observe more weak and strong eigenvalues. These attributes can be easily seen for all discussed scenarios, which means that for none of the antenna systems a remarkable MIMO gain can be obtained. However, it is noteworthy that the isotropic system always shows a slightly lower correlation since it can see most of the sparsely distributed scatterers.

IV. CONCLUSION

In this paper, we investigated the performance of isotropic, directional and highly-directional fixed beams for MIMO communications. It was shown that highly-directional antenna beams can achieve higher channel gains for both NLOS and LOS scenarios compared to the other counterparts. On the other hand, highly-directional beamforming suffers a high correlation in case of NLOS. Fortunately, this correlation can be compensated by beam diversity at the transmitter side where we can obtain even a lower correlation than isotropic antenna
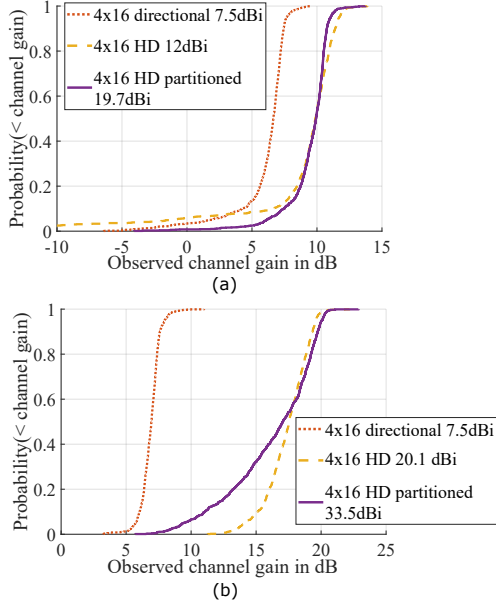
Fig. 6. LOS: Channel gain in dB with respect to the channel gain observed with isotropic antenna elements for directional, HD, and HD partitioned cases for (a) near region and (b) far region.
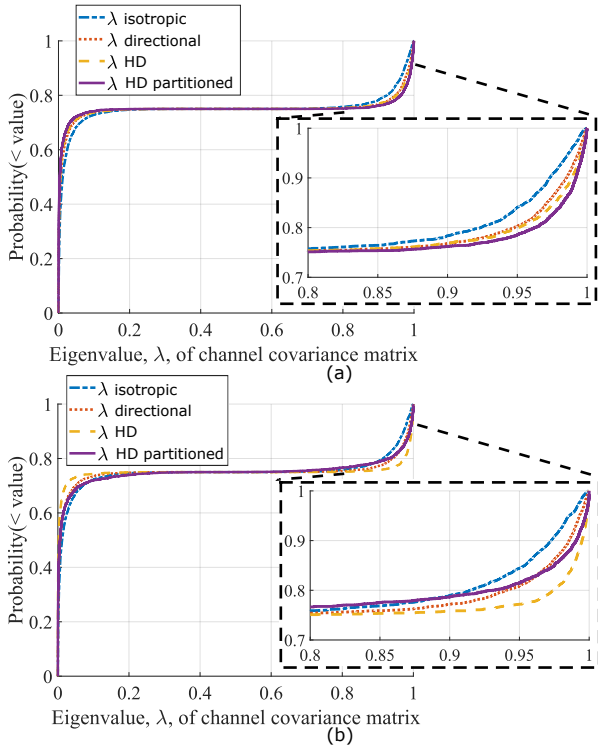
systems. Furthermore, highly-directional MIMO systems provide a higher SU-MIMO capacity in comparison to directional or isotropic antenna systems. This helps to make future 5G base stations more energy efficient. In the case of LOS, the achievable MIMO gain is negligible for all systems, though highly-directional systems still show a great performance in terms of channel gain.

All in all, it was shown that highly-directional antenna systems can outperform directional and isotropic antenna MIMO systems in terms of channel gain, channel correlation, and MIMO capacity. This means that highly-directional antenna systems like PAF reflector systems can enhance the MIMO capacity by using their ability to generate simultaneous highly-directional beams with their sub-arrays. In future, we will show how and how much MU-MIMO systems benefit from this type of beamforming.

REFERENCES

[1] Ericsson AB, "5G radio access," Stockholm, Sweden, Tech. Rep. 284 23-3204 Rev C, Apr. 2016.
[2] T. S. Rappaport et al., "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, May 2013.
[3] A. M. Tulino, A. Lozano, and S. Verdu, "Impact of antenna correlation on the capacity of multiantenna channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 7, pp. 2491–2509, Jul. 2005.
[4] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.
[5] M. Fozooni, H. Q. Ngo, M. Matthaiou, S. Jin, and G. C. Alexandropoulos, "Hybrid processing design for multipair massive MIMO relaying with channel spatial correlation," *IEEE Trans. Commun.*, pp. 1–1, 2018.
[6] J. Brady, N. Behdad, and A. M. Sayeed, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3814–3827, Jul. 2013.
[7] A. B. Smolders et al., "Building 5G millimeter-wave wireless infrastructure: Wide-scan focal plane arrays with broadband optical beamforming," *IEEE Antennas Propag. Mag.*, accepted 2018.
[8] A. Dubok et al., "Double-reflector configuration for optimal exposure of wideband focal-plane arrays with optical beamforming," *IEEE Trans. Antennas Propag.*, vol. 65, no. 8, pp. 4316–4321, Aug. 2017.
[9] A. Elsakka et al., "On the use of focal-plane arrays in mm-Wave 5G base stations," in *Conf. EuCAP*, Apr. 2018, pp. 1–4.
[10] T. A. H. Bressner, U. Johannsen, and A. B. Smolders, "Single shot DoA estimation for large-array base station systems in multi-user environments," in *Proc. IEEE LAPC*, Nov. 2017.
[11] S. Jaeckel, L. Raschkowski, K. Börner, and L. Thiele, "QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3242–3256, Jun. 2014.
[12] X. Zhao et al., "Channel measurements, modeling, simulation and validation at 32 GHz in outdoor microcells for 5G radio systems," *IEEE Access*, vol. 5, pp. 1062–1072, Jan. 2017.
[13] 3rd Generation Partnership Project, "Study on channel model for frequencies from 0.5 to 100 GHz," Tech. Rep. 38.901 V14.1, Jul. 2017.
[14] S. Jaeckel, "Quasi-deterministic channel modeling and experimental validation in cooperative and massive MIMO deployment topologies," Ph.D. dissertation, Dept. Elect. Eng. and Info. Tech., TU Ilmenau, Aug. 2017.
[15] G. Tsoulos, *MIMO System Technology for Wireless Communications*, ser. Electrical Engineering & Applied Signal Processing Series. CRC Press, 2006.

Fig. 7. LOS: Normalized eigenvalue distribution for isotropic, directional, HD and HD partitioned cases for (a) near region and (b) far region.