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Impact of the Spatial User Distribution on the Coverage Antenna Pattern of Maximum Ratio Combining in Random Line-Of-Sight

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***Abstract*—In this paper we investigate the impact of the spatial user distribution on the Maximum Ratio Combining (MRC) of the output signals from an ideal 4-port antenna. The antenna consists of four elementary Huygens sources operating in Random Line-Of-Sight (RLOS). The antenna is assumed to be wall-mounted. Two specific scenarios for the user distribution are considered, i.e., the 3D hemisphere and a rectangular prism emulating a corridor or a rectangular room. We present simulation results in terms of the cumulative distribution functions corresponding to the resulting polarisation and pattern diversity of 1-bitstream and the corresponding coverage radiation pattern of the 4-port antenna system. We also show that there is an antenna arrangement that maximizes the diversity gain that will be different for different spatial distributions of users.**

***Index Terms*—antenna, propagation, measurement.**

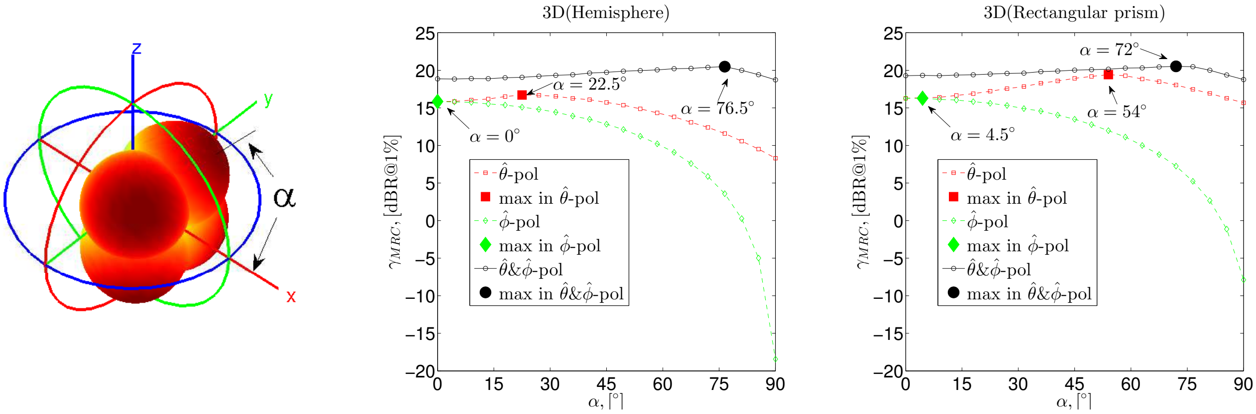
I. Introduction

Testing the Over-The-Air (OTA) performance of wireless devices, e.g., cellular phones, laptops or small base station transceivers, has become indispensably important. Indeed, OTA testing is an essential step towards meeting the increasingly harder performance requirements set upon wireless networks, e.g., the Long Term Evolution (LTE) and beyond [1]. On one hand, the performance of a wireless device (including the antenna) over multipath environments is well-understood and can be successfully tested in a Reverberation Chamber emulating the Rich Isotropic MultiPath (RIMP) propagation channel [2]. The term "rich" means that a large number of waves are impinging the antenna, e.g., in the order of hundreds, and isotropic means that the Angles-of-Arrival (AoA) of the incoming waves are uniformly distributed over the unit sphere. On the other hand, much less is known about the performance of the same device operating over a LOS channel or rather a Random Line-Of-Sight (RLOS) channel [3].

The current trend towards network densification, together with the use of higher frequency bands of the electromagnetic spectrum, leads unavoidably to shorter distances between users and wireless access points [4]. Hence, the Line-Of-Sight (LOS) propagation conditions will soon be the dominating propagation mechanism for many wireless applications. The RLOS channel is the ensemble of probable LOS channels determined by the random orientation of the antenna and/or the LOS wave component impinging at the antenna. Indeed, the orientation of the transmit antenna, the receive antenna or both may vary in an unpredictable way. These orientations can be modelled as random variables. Hence, the resulting RLOS channel realizations determined by the radiation patterns of the antennas will induce a variable performance on the system. Another similar situation may be observed when the orientation of the antennas is deterministic, but restricted by the geometry of the deployment scenario, e.g., vehicles moving along a highway. All the above introduce a randomness of the LOS in terms of the Angle-of-Arrival (AoA), and often also the polarisation of the LOS component, that will have clear impact on the performance of the wireless device.

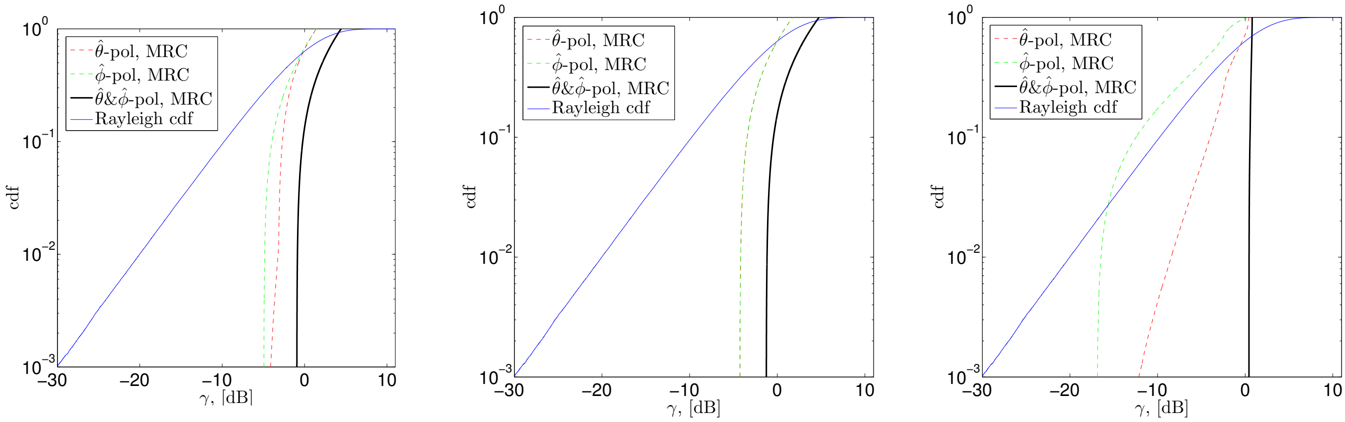
The threshold receiver model can be used to provide an accurate, efficient and cost-effective solution to the OTA performance characterization of an antenna system, both in RIMP and RLOS [5]. The main working idea is that the typical propagation channel is not known and might actually never be known. So testing and designing antenna systems that work well in these two extreme propagation channels, i.e., RIMP and RLOS, will necessarily cover all the possible real-life channels and hence the most typical propagation channel too. To stress the latter point, a real-life hypothesis has been introduced: *if a wireless device is proven to work well in RIMP and RLOS, it will work well in all real-life environments* [11]. Hence, the proposed pragmatic approach relies on making use of two idealized, yet well-defined, channel models to characterize the wireless system and its devices, and studying under which conditions the real-life hypothesis is valid. All this is considerably simplified by using the ideal threshold receiver that is a simple, yet accurate, model of a digital wireless transceiver.

In this paper we present the performance of the Maximum Ratio Combining (MRC) algorithm of a generic 4-port antenna consisting of four elementary Huygens sources in two RLOS propagation scenarios. The two specific scenarios correspond to user distributions uniformly distributed in the 3D hemisphere or uniformly distributed in a rectangular prism. The latter is emulating a corridor or a rectangular room. We assume



(a) (b) (c)

Fig. 1. Far-field radiation patterns of four Huygens source antennas evenly distributed around a cone with aperture 2α, (a). Diversity gain measured in dBR at the 0.01(i.e., 1%) probability level of the cdf as a function of the angle α (see plot (a) in this figure) for the uniform distribution of users in a hemisphere (b), and in a rectangular prism (c).



(a) (b) (c)

Fig. 2. Cumulative distribution functions obtained from a uniform distribution of users in a hemisphere. The plots correspond to the aperture angles providing the maximum MRC diversity gain (in dBR) in the impinging $\hat{\theta}$-polarisation (a), the $\hat{\phi}$-polarisation (b) and in both (c) as indicated in Fig.1b

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the antenna operates at a single frequency. We consider the wall-mounted operation of a small-cell basestation. This paper follows the methodology outlined in [2], [3], [5].

II. Simulation Scenarios

A. Receiver model and performance metrics

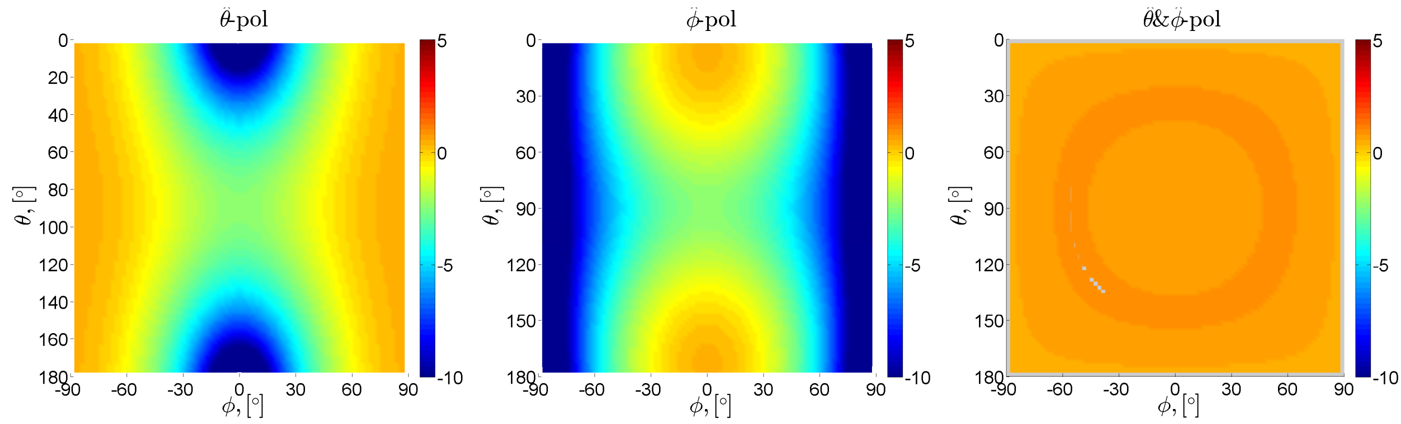
Central to our analysis is postulating that the receiver can be modeled by the ideal threshold receiver [5]. The model is based on the observation that, in digital communication systems, the group error rate (GER) goes very abruptly from only errors to no errors in the Additive White Gaussian Noise (AWGN) channel. It has been shown that by averaging over all the possible fading states, the average throughput is given by, [5]

$$\begin{aligned} \mathsf{TPUT}_{\mathrm{av}}(\gamma_{\mathrm{av}}) &= \mathsf{TPUT}_{\max}\mathsf{PoD}(\gamma_{\mathrm{av}}/\gamma_{\mathrm{th}}) && (1) \\ &= \mathsf{TPUT}_{\max}\left\{1-\mathsf{CDF}(\gamma_{\mathrm{th}}/\gamma_{\mathrm{av}})\right\}\ , && (2) \end{aligned}$$

where PoD(.) is the Probability of Detection (PoD) function, i.e., the complementary cdf (or ccdf) of the outage probability given by the CDF(.) function, γ_{av} is the available average received signal-to-noise ratio (SNR) under the AWGN assumption, γ_{th} is the threshold level of the receiver and may be obtained from conductive (i.e., cable-connected) measurements. Hence, the relative throughput is then given by the PoD as shown in (1). This allows analyzing the performance in terms of throughput in a rather direct way as shown in [3], [6], [9]. The (normalized) SNR at the Maximum Ratio Combining (MRC) receiver can then be obtained as

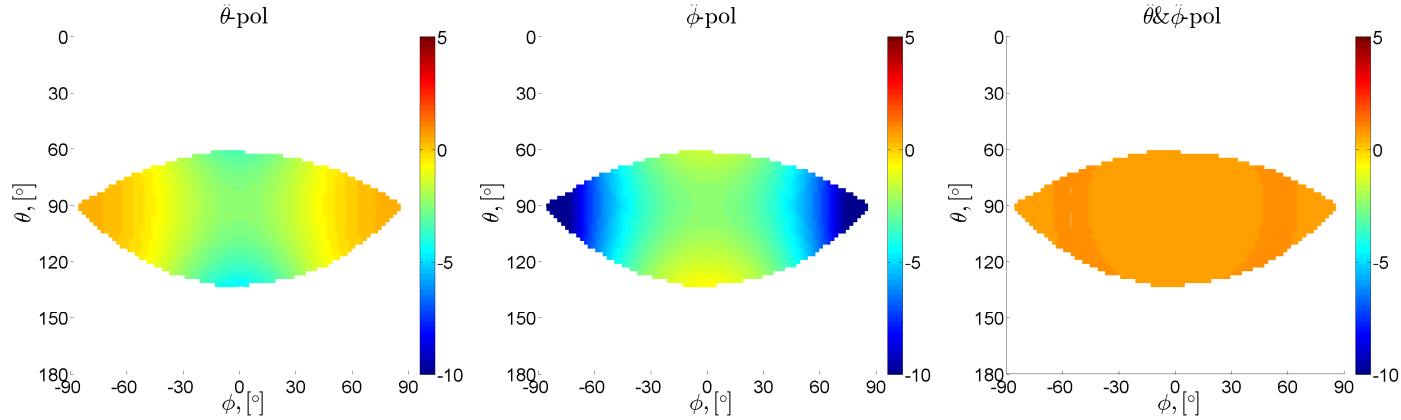
$$\gamma_{MRC} = \sum_{i=1}^{4} \frac{\gamma_i}{4}, \qquad (3)$$

where γ_i is the SNR at the antenna port i. The MRC signal corresponds to a 1-bitstream case and is used to obtain the PoD and cdf outage level. Moreover, since we are dealing with the RLOS channel, the output SNR level is directly proportional



(a) (b) (c)

Fig. 3. 1-bitstream MRC coverage antenna patterns corresponding to the maximum MRC diversity gain in RLOS with users uniformly distributed in a hemisphere for $\alpha = 76.5°$. The results are presented for the impinging $\hat{\theta}$-polarisation (a), the $\hat{\phi}$-polarisation (b) and both polarisations (c).



(a) (b) (c)

Fig. 4. 1-bitstream MRC coverage antenna patterns corresponding to the maximum MRC diversity gain in RLOS with users uniformly distributed in a rectangular prism for $\alpha = 72°$. The results are presented for the impinging $\hat{\theta}$-polarisation (a), the $\hat{\phi}$-polarisation (b) and both polarisations (c).

to the MRC of the far-field components of each elementary Huygens source. Hence, as an additional performance metric we compute 1-bitstream coverage patterns obtained by MRC applied to the $\hat{\theta}$-polarised field components of all ports, to the $\hat{\phi}$-polarised field components of all ports, and to both $\hat{\theta}$&$\hat{\phi}$ polarised field components of all ports. $\hat{\theta}$ and $\hat{\phi}$ denote the unit vectors along the theta and the phi coordinates, respectively, in the spherical coordinate system.

B. Antenna model

We consider an idealized 4-port antenna system comprising four elementary Huygens sources. Each of them are directed at a constant angle from each other along generatrix lines on an imaginary cone as shown in Fig.1(a). The aperture angle 2α is changed to study the impact on the diversity gain and the corresponding 1-bitstream coverage resulting from the MRC algorithm. The angle α takes on values between $0°$ and $90°$. For $\alpha = 0°$, the four Huygens sources are directed towards the positive $\hat{x}$-axis. All the four Huygens sources are, at this position, slant-polarised, i.e., two of the sources have polarisation $+45°$ and the other two have polarisation $-45°$. It is assumed that there is no coupling between the ports and therefore the radiation patterns of each antenna element corresponds to that of an ideal elementary Huygens source. The Huygens sources where simulated with the ViRM-Lab simulation tool [10]. A practical realization of this antenna as a compact ultra-wideband 4-port self-grounded bowtie antenna for $1.5 - 3$ GHz can be found in [7], [8].

C. Propagation channel model

We further assume that the received power is averaged over all the polarisations of the waves impinging at the antenna. Hence, since we are dealing with the RLOS, the obtained cdf for the MRC (SNR) signals is directly proportional to the antenna gain pattern. This pattern is achieved by power combining the $\hat{\theta}$ and $\hat{\phi}$ polarisations, and for lossless, 100% efficient antennas it is directly proportional to the antenna directivity patterns for the polarisation-matched case. Thus, we do not consider the stochastic amplitude variation caused by the orientation of the user and its terminal, but we will consider both the $\hat{\theta}$ (vertical) and the $\hat{\phi}$ (horizontal) polarisations of the impinging waves coming from the user, as well as arbitrary polarisation (referred to as "both" polarisations in the graphs). The latter means that the polarisation angle distribution is uniform. We also assume an uniform distribution for the amplitudes of the impinging waves at the receiver. The specific deployment scenario of interest is an indoor small-cell base station antenna or access point mounted on the wall similar to in [8]. This is modelled by the 4 Huygens sources. Hence, the Angles-of-Arrival (AoA) are obtained for two specific scenarios:

- *Hemisphere*: The users are assumed to be uniformly distributed within the hemisphere of unit radius. The four co-located elementary Huygens sources are situated at the center of the largest circle of the hemisphere.
- *Rectangular prism*: The idea is to simulate a corridor or room of width W, length L and height H. The users are in this case assumed to be also uniformly distributed, but now within a rectangular volume, i.e., $0 \leq y \leq L$, but between heights $h_{\text{low}} \leq z \leq h_{\text{high}}$ and a width $w \leq x \leq W - 2w$, where w is the smallest distance from the vertical walls. The four co-located elementary Huygens sources are situated at the center of one of the two largest vertical sides of the prism.

Specific values for the user distribution in the rectangular prism case were chosen to emulate probable heights of the user equipment in both active or idle modes, i.e., $h_{\text{low}} = 1$ m $h_{\text{high}} = 1.8$ m and $w = 0.5$ m. The dimension of the prism are given by $W = 3$ m, $L = 20$ m and $H = 3$ m, and are assumed to emulate a corridor.

III. Simulation results and analysis

The results presented here focus on how the diversity gain depend on the spatial distribution of users. We simulate 10^6 user positions in each of the hemispherical and rectangular prism volumes.

Fig.1(b) and (c) show the diversity gain at the 0.01 (i.e., 1%) probability level of the cdf of the MRC output, for the uniform distribution of users in a hemisphere, and in a rectangular prism, respectively. The diversity gains are shown as a function of the angle α indicated in Fig.1(a). The plots labeled with $\hat{\theta}$-pol and $\hat{\phi}$-pol are results for two orthogonal polarisations in the spherical coordinates, corresponding to vertical and horizontal polarisations, respectively. Hence, they describe the situation when the impinging waves are of any polarisation. $\hat{\theta}\&\hat{\phi}$-pol denotes the case when impinging waves may have components in either two of the polarisations. The highlighted points on the curves correspond to the maximum value at the respective aperture angles α. Results for both considered user distributions show qualitative similarities, but quantitative differences are observed, especially for the $\hat{\theta}$-polarised component. It is clear, that polarisation will have a major impact on system performance in RLOS. Hence, we will expect a great impact of the user-induced-randomness, e.g., the orientation of the terminal antenna [12]. This is something that future OTA antenna characterization has to take into account in order to fully assess the mobile performance in RLOS as well as other suitable propagation environments.

Fig.2 shows the cumulative distribution functions obtained from a uniform distribution of users in a hemisphere. The plots correspond to aperture angles $\alpha = 22.5°$, $\alpha = 0°$ and $\alpha = 76.5°$ providing the maximum MRC diversity gain in the $\hat{\theta}$-polarisation (a), in the $\hat{\phi}$-polarisation (b) and in both (c), respectively. The cdf of the theoretical Rayleigh is used as reference to compute the MRC gain and therefore the gain is given in dBR, i.e., dB-Rayleigh. An important observation derived from Fig.2(c) is that the cdf corresponding to the case when both polarisations are used in the MRC is constant (the straight vertical line in the figure). Hence, the corresponding PoD will also show the same behaviour as shown by relationships (1) and (2). This means that in this case the throughput is basically a step function as in conductive measurements meaning that performance will be maintained as long as the SNR or power level is above the receiver threshold level. This should be understood here in a statistical sense over all the ensemble of possible positions and orientations of the user's antenna. The cdf plots corresponding to a uniform distribution of users in a rectangular prism are similar in shape to Fig.2 and therefore omitted.

Fig.3 shows 1-bitstream MRC coverage antenna patterns corresponding to the maximum MRC diversity gain in RLOS with users uniformly distributed in a hemisphere for $\alpha = 76.5°$. The results are presented for $\hat{\theta}$-polarisation (a), the $\hat{\phi}$-polarisation (b) and both polarisations (c). Fig.4 shows 1-bitstream MRC coverage antenna patterns corresponding to the maximum MRC diversity gain in RLOS with users uniformly distributed in a rectangular prism for $\alpha = 72°$. The results are presented for $\hat{\theta}$-polarisation (a), the $\hat{\phi}$-polarisation (b) and both polarisations (c). As we can see, the coverage area is directly affected by the user distribution. Even though the maximum value of the coverage is almost the same when the antennas can receive both polarisations, the impact on the cdf of the two considered polarisations is more pronounced. Hence, again, these results corroborate the fact that the user-induced-randomness will have a greater impact on the MRC gain due to orthogonal polarisations.

IV. Conclusion

In this paper we use the threshold receiver model to analyze the impact of the spatial user distribution on the Maximum Ratio Combining (MRC) performance of a wall-mounted idealized 4-port antenna. The antenna consists of four elementary Huygens sources that operate in Random Line-Of-Sight (RLOS). Two specific scenarios for the user distribution are considered, i.e., the 3D hemisphere and a rectangular prism emulating a corridor. As a result of our simulations, we see that there is an antenna arrangement that maximizes the diversity gain and it will be different for different spatial distributions of users. Moreover, polarisation diversity is essential to ensure a satisfactory OTA throughput performance. Hence, it is essential to quantify this behaviour of diversity antenna systems in order to maximize overall system performance. Especially, the incorporation of user-induced-randomness will be essential to provide a full OTA antenna performance characterization for wireless network optimization. Future studies, will include other relevant receive (and transmit) algorithms as well as the incorporation of user-induced-randomness due to the usage of wireless devices.

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