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Channel Hardening: A Comparison between Concentrated and Distributed Massive MIMO

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***Abstract*—In this letter, a comparative analysis of the hardening effect for concentrated and distributed massive multiple-input multiple-output channels (C-mMIMO and D-mMIMO respectively) is presented. The analysis is carried out in two buildings with similar structural characteristics, considering two frequency bands of interest for 5G deployments, 3.5 and 26 GHz; taking into account both experimental data at 3.5 GHz and simulation results obtained in the 26 GHz band using a rigorous and well-tested Ray-Tracing method (RT). Both, measurements and simulations emulated C-mMIMO and D-mMIMO systems in an indoor cell in the framework of a time division duplex (TDD) - orthogonal frequency division multiplexing (TDD-OFDM) system. To quantify the level of hardening that the specific channels under analysis offer in the frequency domain, the standard deviation of the gain of the channels is used, as well as its evolution as the number of active antennas at the base station (BS) grows. The results obtained for both mMIMO systems show that a sufficiently high level of hardening occurs in indoor environments to contribute to the reliability of communication systems or sensor networks.**

***Index Terms*—5G mobile systems, channel characterization, channel hardening, distributed MIMO, massive MIMO.**

I. INTRODUCTION

It is currently accepted that systems based on the massive MIMO (mMIMO) concept are one of the most important enabling technologies in the development of the applications and services envisioned for 5G and 6G systems [1], [2]. Three specific characteristics of mMIMO systems explain their relevance: great spectral and energy efficiencies, as well as a high reliability. These characteristics are based on both the combination of multipath propagation mechanisms in rich scattering environments and the use of a large number of antennas at base stations (BS), giving rise to three well-known effects: the gain of the array, the favorable propagation and the hardening [3], allowing a linear processing of the signals. Concerning the phenomenon of favorable propagation, it has received much attention among researchers and there are abundant theoretical and experimental studies, [1–4] for instance. The phenomenon of channel hardening, a term initially introduced in [5], has been widely studied and explained from a theoretical point of view; we can refer, among many others, to the works presented in [3] and [5–7]. In these studies, the mMIMO channel is usually modelled as an independent and identical distributed (i.i.d.) Rayleigh uncorrelated or correlated fading channel. In [8], a ray-based channel model is considered which expands channel hardening evaluation beyond the classical Rayleigh fading approach. From an experimental point of view, efforts have also been made to assess its degree of compliance in real propagation environments, including the works [9–13], and more recently in [14].

The effect of hardening on the radio channel is manifested in the three domains: space, time and frequency. In [9], the effect of channel hardening on the reduction of the root mean square delay of the mMIMO channel resulting from encoding/precoding is analyzed. In [10], [11], the effect of channel hardening in the space domain is investigated, based on two measurement campaigns at 5.8 GHz. In [12], the results obtained in an indoor environment in four frequency bands (1.472 GHz, 2.6 GHz, 3.82 GHz and 4.16 GHz), are presented. The results focus on the analysis in the frequency domain and the mean square delay of the equivalent channel. Finally, in [13], [14], a detailed analysis of the hardening phenomenon is presented both in the time domain and in the frequency domain in both indoor and outdoor scenarios in the 3.7 GHz band.

All the aforementioned works refer to traditional concentrated (or collocated) mMIMO base stations (C-mMIMO). On the contrary, there are fewer studies referring to hardening in the case of distributed mMIMO (D-mMIMO). This technology distributes a large number of antennas over an extensive area, conforming a distributed BS. This way, the whole set of BS antennas surrounds each user terminal (UT), rather than having the UTs surrounding the BS, as occurs in the classical cellular concept. This technology combines the idea of distributed MIMO and Cell-Free networks with the massive MIMO concept. In the seminar work [15], it is assumed that both, favorable propagation and hardening occur in Cell-Free distributed systems. However, in [16] where a stochastic BS station deployment is used to model propagation, it is shown that both favorable propagation and hardening only appear in special cases, concluding that the intensity of hardening depends strongly on the propagation environment.

Concerning channel hardening, all the references outlined along with the research works consulted suggest that there is a need for more experimental and site-specific data. The authors have recently carried out a series of comparisons between C-mMIMO and D-mMIMO systems [17], [18], concentrating

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fundamentally on the comparison of both systems regarding the coherence bandwidth values, the obtainable capacity, the spectral efficiency and the user fairness. In [17], the results of a measurement campaign carried out in a medium-size indoor environment in the 3.5 GHz band show that the D-mMIMO system always outperforms the C-mMIMO one in terms of sum capacity, spectral efficiency and user fairness. In [18], a comparison between concentrated and distributed mMIMO channels at 26 GHz in a large indoor environment using Ray-Tracing (RT) shows that the D-mMIMO channel outperforms the C-mMIMO one in terms of channel capacity. Furthermore, considering the spatial distribution of users, in [18] the D-mMIMO system offers a greater capacity to those users located next to each other and concentrated in a specific area of the building. This fact allows us to conclude that favorable propagation is achieved for both mMIMO channels.

In this work, the available data sets already considered in [17], [18] have been used by the authors to carry out a comparison of the hardening effect for C-mMIMO versus D-mMIMO systems in two buildings with similar structural characteristics. In this sense and to the best knowledge of the authors, there is not available in the literature any study focused on channel hardening comparing the effect with both mMIMO systems in two frequency bands of interest for 5G indoor deployments. The results obtained for both mMIMO systems show that a sufficiently high level of hardening occurs in indoor environments to contribute to the reliability of communication systems or sensor networks.

II. Channel Hardening

Let us consider a mMIMO system with M antennas in the BS and Q single-antenna UTs. The MIMO channel matrix obtained by measurements or simulations as described in [17] and [18] respectively, is denoted by $\mathbf{G}_{M\times Q}^{\text{raw}}[k]$. The index k refers to the k^{th} tone or subcarrier in the OFDM framework. Each column of the channel matrix, $\mathbf{g}_q^{\text{raw}}[k]$, of order $M \times 1$, represents the channel vector established between the q^{th} UT and the M antennas of the BS. Following the definition of channel hardening [3], [6], we can state that the channel vector offers hardening if

$$\frac{\mathrm{Var}\left\{\left\|\mathbf{g}_q^{\text{raw}}\right\|^2\right\}}{\mathrm{E}\left\{\left\|\mathbf{g}_q^{\text{raw}}\right\|^2\right\}^2} \to 0 \text{ as } M \to \infty. \tag{1}$$

Since in the cases under study the channel is considered quasi-stationary, in (1), the operations E{.} and Var {.} are performed exclusively in the frequency domain. Equation (1) indicates that, if the channel offers hardening, the signal gains after encoding/precoding suffer fewer and fewer variations on their average level as the number of antennas in the BS increases; i.e. the channel behaves asymptotically as a frequency-flat channel.

The level of hardening is a function of the number of antennas at the BS. Taking into account a maximum number of antennas M at the BS, we define the number of active antennas as M_a, so that M_a will vary between 1 and M.

Starting from the measured or simulated channels, the effective channels are defined and normalized, as follows:

$$\mathbf{g}_q[k, M_a] = \frac{\mathbf{g}_q^{\text{raw}}[k, M_a]}{\sqrt{\frac{1}{M_a}\frac{1}{N_f}\sum_{k=1}^{N_f}\left\|\mathbf{g}_q^{\text{raw}}[k, M_a]\right\|^2}}. \tag{2}$$

In (2), $\mathbf{g}_q^{\text{raw}}[k, M_a]$ denotes the raw vector channel of the q^{th} user, but considering only M_a elements, those active at the BS. Therefore, the vector $\mathbf{g}_q^{\text{raw}}[k, M_a]$ is of order $M_a \times 1$. Considering the definition of active channel according to (2), the average power of each channel $\mathbf{g}_q\,[k, M_a]$ is equal to 1, regardless of the number of active antennas considered.

The gain of an active channel for each q^{th} user is defined as:

$$G_q[k, M_a] = \frac{1}{M_a}\left\|\mathbf{g}_q\,[k, M_a]\right\|^2. \tag{3}$$

Finally, the standard deviation of the channel gain for each user and M_a active antennas is calculated as:

$$\mathrm{std}_q[M_a] = \sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}\left|G_q\,[k, M_a] - 1\right|^2}. \tag{4}$$

To quantify the level of hardening that the specific channels under analysis offer, the standard deviation of the gain of the channels given in (4) will be considered as a valid and useful metric, in a similar way to that proposed in [10–14].

III. Channel Gain Analysis

Channel hardening has been investigated based on the results of the standard deviation of the channel gain obtained for both C-mMIMO and D-mMIMO systems at two indoor modern buildings of the Universidad de Cantabria [17], [18]. Regardless of the fact that to analyze the hardening effect the radio channel is symmetric, the study has considered the UL taking advantage of the data available, and considering up to 8 UTs under both line-of-sight (LOS) and non LOS conditions in both environments. The analysis takes into account experimental channel measurements carried out at 3.5 GHz (3.3-3.7 GHz), 5G n78 band [17], along with simulation results achieved using a rigorous and well-tested RT method at 26 GHz (25.75-26.25 GHz), 5G n258 band [18], [19].

A. Channel Hardening at 3.5 GHz

Let us consider the channel measurements carried out in the environment shown in Fig. 1, which mainly consists of offices and laboratories. Fig 1 includes details of the 8 UTs along with the receiver array (Rx) locations at the BS, which consists of 64 elements for both mMIMO systems [17]. The channel sounder uses a vector network analyzer (VNA) to automatically acquire the $S_{21}(f)$ scattering parameter, which if the VNA has been properly calibrated, represents the complex channel transfer function [17]. In C-mMIMO the Rx consists of a square vertical array with an uniform inter-element distance of 0.58 λ. Concerning the D-mMIMO setup, the virtual array consists of two linear trajectories 23 λ apart from each other with the antennas placed at the ceiling board, and with an inter-element distance of 7 λ.

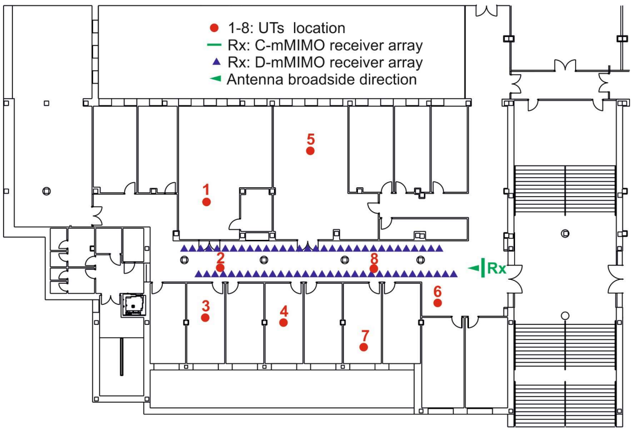

Fig. 1. Top view of the indoor environment (measurements in the 3.3-3.7 GHz frequency band).

Fig. 2 shows the standard deviation of the channel gain as a function of the number of active antennas at the BS, M_a, for UTs 1 to 8 comparing both mMIMO systems. The gain of each active channel considering M_a elements (2)-(3), depends on the order in which the M_a elements are taken from the 64 available. Therefore, the evolution of the curves in Fig. 2 will change depending on the set of antennas that are activated; however, it is very important to notice that the final value, when M_a=64, is necessarily the same. In [14] this subject is discussed, and several possibilities are proposed. Taking into account that the central objective of this work is to evaluate and compare the degree of hardening between the two systems C-mMIMO and D-mMIMO, the proposed option is to activate the antennas at the BS randomly, thus reducing the dependence on the chosen order.

The results shown are compared with the theoretical standard deviation corresponding to an i.i.d. Rayleigh channel. In Fig. 2(a) it can be observed that up to a number of around 10 antennas, all the curves decrease with a slope similar to the i.i.d. Rayleigh channel. From this point onwards, the slope decreases and the standard deviation decreases more slowly than for the reference channel as the number of active antennas grows. Concerning the D-mMIMO case, the results presented in Fig. 2(b) show that, on average, the curves for all the UTs have a slope slightly lower than that of the reference channel, but the stagnation of the C-mMIMO system is not appreciated now. Finally, Table I shows the minimum, maximum and average values reached by the 8 users when all the 64 antennas are activated. The values of the standard deviation reached are very similar for both systems, with the distributed system being slightly more favorable on average.

B. Channel Hardening at 26 GHz

Fig 3 shows the main floor of a large academic building with a spacious hall, a curved corridor, classrooms and administrative areas, including details of both UT and Rx mMIMO locations [18]. The C-mMIMO Rx consists of a square vertical array of $\lambda/2$ dipoles with an uniform inter-element distance of 0.536 λ. Concerning the D-mMIMO setup, the Rx antennas have been almost uniformly spread throughout the building with inter-element distances ranging from 5.5 to 7.5 m (476.6 to 650 λ). For both mMIMO systems, the Rx array consists of 100 elements and the complex channel transfer function results were obtained using a RT based simulator [18], and from those results the effect of the channel hardening will be hereinafter discussed.

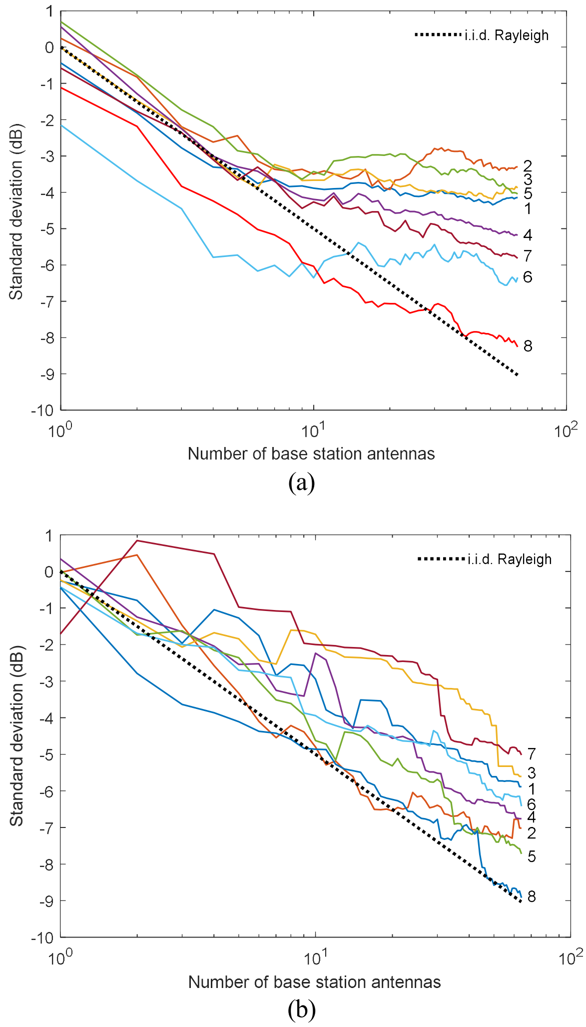

Fig. 2. Standard deviation of the channel gain for the 8 UTs in the 3.5 GHz band. (a) C-mMIMO. (b) D-mMIMO.

TABLE I
STANDARD DEVIATION OF THE CHANNEL GAIN: VALUES

System	std_{min} (dB)	std_{max} (dB)	$\overline{std}$ (dB)
C-mMIMO	-8.25	-3.29	-5.12
D-mMIMO	-8.92	-5.02	-6.67

For this case, the standard deviation of the channel gain as a function of the number of active antennas, is presented in Fig. 4 for both mMIMO systems. For this frequency band, the behavior of the standard deviation against M_a is very similar to that observed in the 3.5 GHz band. Concerning the C-mMIMO system, the stagnation of the standard deviation is observed for some UTs (4, 7 and 8). Moreover and as already observed in the 3.5 GHz band, for the D-mMIMO case the curves of all the UTs have a slope slightly lower than that of the reference channel, but the stagnation suffered by some UTs in the C-mMIMO case is not observed.

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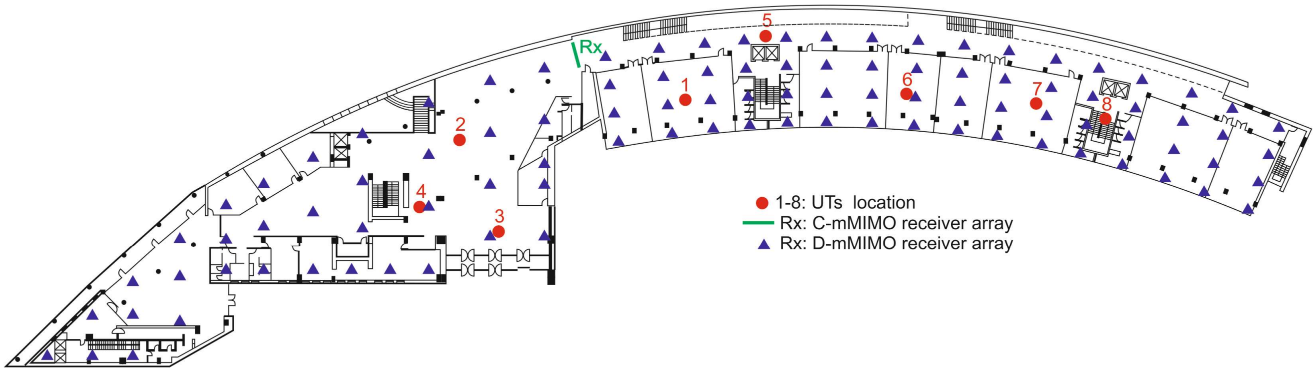

Fig. 3. Top view of the indoor environment (simulations in the 25.75-26.25 GHz frequency band).

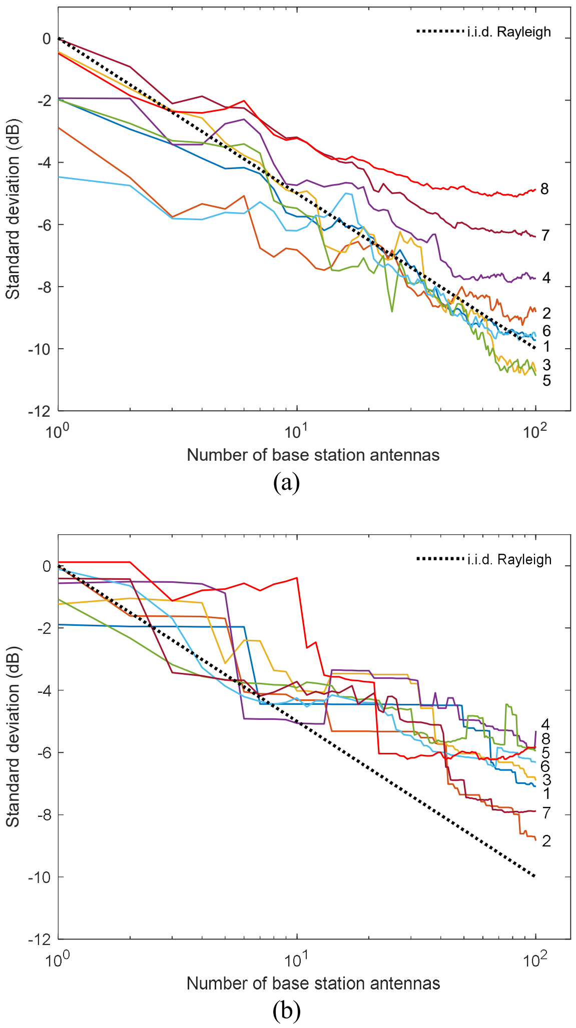

Fig. 4. Standard deviation of the channel gain for the 8 UTs in the 26 GHz band. (a) C-mMIMO. (b) D-mMIMO.

The differences appreciated can be explained by the fact that C-mMIMO exploits spatial microdiversity, while D-mMIMO exploits macrodiversity. In multi-antenna systems, it is well-known that the increase of the diversity gain slows down as the number of antennas increases and, additionally, if the channels are correlated from each other. Results in Fig. 2(a) and Fig. 4(a) are obtained by increasing the number of antenna elements (M_a) from 1 to M, choosing each new active antenna in a random basis. When M_a is considerably much lower than M, the probability that the associated channels are uncorrelated is high. However, the probability that the new channels are correlated increases when M_a increases, as each new antenna will necessarily be close to the ones already active. In D-mMIMO systems, the decorrelation probability between M_a channels is large and stagnation does not occur. However, the differences between the powers received by each antenna of the distributed BS causes the curves to have a less homogeneous decrease, depending on whether the new antennas that come into play have higher or lower path losses.

Finally, Table II shows the minimum, maximum and average values reached by the 8 users when the whole set of 100 antennas are activated (M_a=M=100). It can be seen that the mean value obtained with the 8 UTs for the distributed system is slightly lower than for the concentrated one. However, it can be seen that the spread between the maximum and minimum values of the standard deviation is smaller in the distributed case.

TABLE II
STANDARD DEVIATION OF THE CHANNEL GAIN: VALUES

	System	std_{min} (dB)	std_{max} (dB)	$\overline{std}$ (dB)
M=100	C-mMIMO	-10.88	-4.87	-8.59
	D-mMIMO	-8.84	-5.31	-6.76

V. CONCLUSION

In this work, channel hardening has been investigated comparing concentrated and distributed mMIMO systems in two indoor scenarios and frequency bands, considering both previous experimental and simulation results. The analysis has been carried out over larger bandwidths than those available in the literature from other researchers, this fact enhancing the novelty and usefulness of the current research.

The results achieved show that the effect of channel hardening occurs in the D-mMIMO systems to a similar degree to that of the C-mMIMO ones. Moreover, this also happens for the two considered frequency bands (3.5 and 26 GHz).

Finally, a dependency is observed, not only with the environment, but also between the relative positions between the different UTs and the base stations. Therefore, there is a clear need to carry out more experimental studies or site-specific simulations that might complete the results obtained in this work and in the current literature.

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