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Simulation-based Investigation on Spatial Channel Hardening of Massive MIMO in Different Indoor Scenarios and with Different Array Topologies

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Abstract

Spatial channel hardening is one of the key properties of a massive MIMO system. In this paper, we investigate the spatial channel hardening based on ray tracing channel simulations with different array antenna topologies deployed in different radio wave propagation conditions. Investigated are 9 different indoor deployment scenarios of massive MIMO. Considered are the empty room, the rich-furniture room and the room-to-room scenarios, where massive multi-antennas are deployed in the co-located, the split and the cell-free array topologies. The simulation results show that the cell-free topology results in the most-spatially-hardened channel in target area, while the co-located antennas the least-spatially-hardened. It is also found that the convergence of channel spatial variations is consistent with the number of paths estimated in multipath scenarios, i.e., the more multipath components are estimated in a propagation scenario, the smaller the number of antennas is required for the channel to reach the spatially hardened state. In our simulations, the rom-to-room scenario leads to the most-spatially-hardened channel, while for the empty room scenario it is the opposite.

1 Introduction

Massive multiple-input and multiple-output (MIMO) is one of the key features of 5G networks. It has the potential to improve the spectrum efficiency and reliability of a wireless network [1]. In a massive MIMO system, a base station (BS) is equipped with an array with a large number of antennas. One of the main advantages is lower variations of the channel gain over the time, the spatial and the frequency domains due to the fact that the small-scale fading is averaged out. The phenomenon of the radio propagation channel becoming more deterministic is called the channel hardening, which is an important feature to establish a robust communication link with high reliability and low latency.

Channel hardening is typically measured as the variance of the channel gain, where the variance tends to decrease with the increase of the number of BS antenna elements [2]. The authors in [3] give a formal definition of channel hardening and an associated criterion for when the channel hardening holds. When the channel is ideally hardened, the channel gain from the BS to a user equipment (UE) is only determined by the large-scale fading, and therefore the channel estimation and decoding at the UE side is simplified.

In [4]-[6], the authors have conducted measurement campaigns to test and estimate the properties of channel hardening as a function of propagation condition and antenna parameters. In [4], the effect of channel hardening was analyzed based on measured data with different aperture size of antennas array. Channel hardening effect was observed to increase by increasing the number of antennas as well as the aperture size. In [5], the authors tested 3 different BS arrays with eight users distributed in an indoor scenario. They observed that even when the users are closely spaced, the performance can be improved by increasing the aperture size of the BS array antenna. In addition, in [6], the authors presented a measurement-based evaluation of channel hardening in a practical indoor scenario with a 128-port cylindrical array and 9 closely spaced users.

Although channel hardening is an important feature for massive MIMO, not all the propagation environments can benefit from channel hardening. Indeed, the authors in [3] showed that channel hardening is observed in independent Rayleigh fading channels, but not in keyhole channels. In [4], the authors observed from measured data that the channel hardening effects appeared for both indoor and outdoor scenarios, and for both strong line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. In indoor environment, the arrays with larger aperture size tend to bring stronger effect of channel hardening. The authors in [7] extended the classical Rayleigh fading channel model to more general physical channel models, where the analysis of the closed-form formulas highlighted the influence of propagation rays and array antenna topologies on channel hardening and offered further insights into the relationship with channel characteristics.

The effect of channel hardening is not only determined by the number of antenna elements and the array aperture size, but also by the array topology. Typical topologies of massive array antennas are the co-located, the split and the distributed (or the cell-free, in other words) systems. First, in the co-located array topology, the antennas are deployed in a concentrated area where the array presents a linear, a planar or a cylindrical geometry. This topology has advantages of low backhaul requirement and easy deployment. Second, in the distributed array topology, the antennas are deployed in a distributed manner and they serve a much smaller number of autonomous users than the co-located topology to overcome the inter-cell interference limitations and benefit from additional macro-diversity. To this end, the authors in [8] proposed a practical architecture for cell-free massive MIMO deployment known as the “radio stripe”. Third, in the split array topology, the multi-antennas are split into several groups and each group is distributed in different location, which can balance the benefits and the requirements between the co-located and the distributed topologies. The authors in [6] measured the impact of the antenna alignment on the channel hardening but the influence of the array topology was not considered in the analysis.

As can be seen from the exposition above, recent works have investigated the channel hardening as a function of the number of antenna elements, the aperture size, the topology of the BS array antennas, the UE distribution and the propagation environment. However, these works are either based on measurement campaigns to test one specific application scenario or based on generic stochastic or theoretical channel models. Alternatively, deterministic simulator-based channel estimations can also be used to compare the hardening effect in different propagation conditions in a structured manner. In such a way, the deterministic multipath propagation conditions can be straightforwardly matched up with the corresponding channel hardening effects allowing for a more controlled comparison. As far as we know, there is a lack of published works comprehensively comparing the channel hardening effect in controlled radio wave propagation scenarios with different array antenna topologies. This paper fills this gap and focuses on the comparable analysis of hardening under different but controlled multipath conditions.

In this paper, we therefore investigate the spatial channel hardening based on 3 types of massive array antenna topologies (co-located, split and distributed) in 3 types of indoor scenarios (empty room, furnished room and room-to-room). Inspired by the channel hardening, the spatial channel hardening concept is proposed to analyze the massive MIMO focusing performance in an area or at the uniformly distributed locations in the target area. This spatial hardening does not only evaluate the channel gain convergence for a single user at one location with the increase of the BS antennas’ number, but also evaluate whether the convergence is steadily spread within an area. We also provide further insight on the convergence of channel by associating it to the number multi-path estimated in different indoor scenarios.

2 Spatial Channel Hardening

Let’s assume a single UE that is active in a region or in several distributed user locations within an indoor environment, and there are totally N distributed UE locations. The spatial channel hardening is defined based on [6] as

$$\frac{\mathrm{var}\left\{\|h_{k,n}\|^2\right\}}{\mathrm{E}\left\{\|h_{k,n}\|^2\right\}^2} \to 0, M \to \infty \qquad (1)$$

for an unlimited increase of the number of the BS antenna elements M, where $k = 1, \dots, K$ is the index for the user, K is the total number of users, $h_{k,n} \in \mathbb{C}^{1\times M}$ is the complex channel transfer vector for user k at location with index n, where $n = 1, 2, \dots, N$. The statistics are computed *across user locations* to get an insight of the spatial stability of the coherently combined signal for a given precoding scheme. More specifically, var $\{\cdot\}$ and E $\{\cdot\}$ denote the variance the mean, respectively, computed across all user locations. It is worthwhile to note that the main difference between 1) the spatial channel hardening defined firstly in [9] as well as here and 2) the channel hardening in [6], is that the spatial channel hardening guarantees that the user performs not only deterministically at one location but also when a user moves in a region of interest. The definitions of channel normalization, channel gain and variance, are all the same as in [9].

3 Channel Simulator

The radio propagation channel is simulated with the Ranplan Professional software [10], which is a 3D ray tracing tool. It has the capability to run system-level simulations and has been tested and validated in the literature [11]. The ray tracing tool can capture the propagation mechanisms in both the LOS and the NLOS scenarios.

The input information for the radio propagation channel computation is the following: 1) the radiation patterns of the antenna elements of the massive MIMO array antenna as well as other properties such as the number of antenna elements, the aperture size, the array antenna topology and antenna locations; 2) the 3D propagation scenarios, where the information includes the 3D geometrical structure of the scenario, the dielectric properties of walls, windows, doors, ceilings, grounds and furniture, the number of users and their locations; 3) the accuracy factors of the ray tracing tool, which include the maximum number of the transmission, the diffraction and the reflection to be calculated before a ray is abandoned.

The output of this propagation engine includes the complex path gain, the path length, and the interactive points between the propagated radio waves and the building structure that will reflect or diffract the rays representing the waves. This information is used to compute the channel transfer function. The indoor scenarios used in this paper are consistent with these defined by 3GPP [12].

4 Numerical Results

The 3D radio wave propagation is assumed to be confined to a typical indoor office defined by 3GPP in [12] with dimension 50×120×3 m^3. The antenna height is set to 2.9 m, and the UE height is 1.0 m. The 3D antenna pattern is adopted in the ray tracing model to calculate signals. 300 UEs are uniformly distributed over the area of interest. The target carrier frequency is 2.6 GHz with 20 MHz bandwidth. The 3 types of array topologies considered in the comparison are: 1) co-located antennas, where all the antennas are integrated into an array with row inter-element distance of 0.1 m and column inter-element distance of 0.05 m, and the center of the co-located array is placed at the location of interest; 2) split antennas, where antennas are split into multiple co-located 2×2 antennas with row inter-element distance of 0.1 m and column inter-element distance of 0.05 m, array antennas are placed uniformly in the area of interest; 3) cell-free antennas, all the antennas are uniformly distributed in the area of interest.

The 3 considered indoor propagation scenarios emulate different multipath propagation conditions: 1) empty room, without any decorations, indoor structure or furniture; 2) furnished room, with plastic furniture to isolate work stations and UEs; 3) room-to-room scenario, where UEs are located in a meeting room and all the antennas are located outside of the meeting room, and the two rooms are isolated using wood wall.

Results depicting the spatial channel hardening as a function of the number of antenna elements of the massive multi-antenna array are shown in Fig. 1-6. It is worthwhile to note that the spatial channel hardening is evaluated using radio propagation channel matrices evaluating the channel variations among all the UEs distributed at target area with the increasing number of antennas.

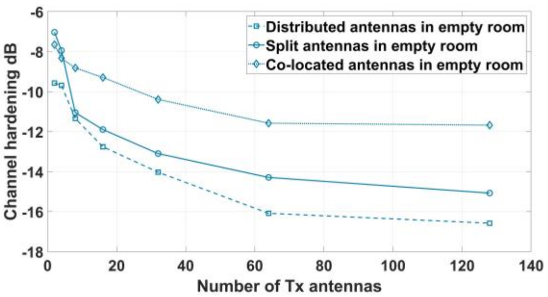

Fig. 1. Various antenna settings in empty room

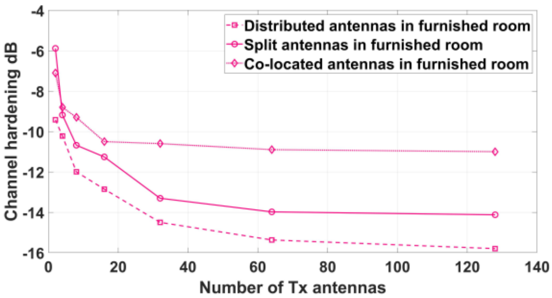

Fig. 2. Various antenna settings in furnished room

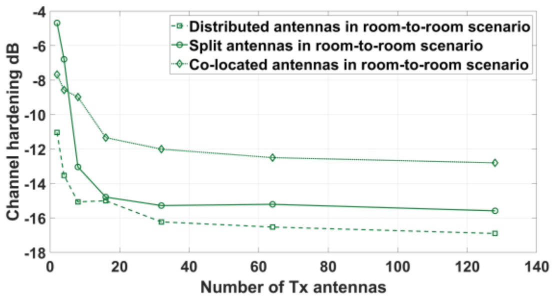

Fig. 3. Various antenna settings in rom-to-room scenario

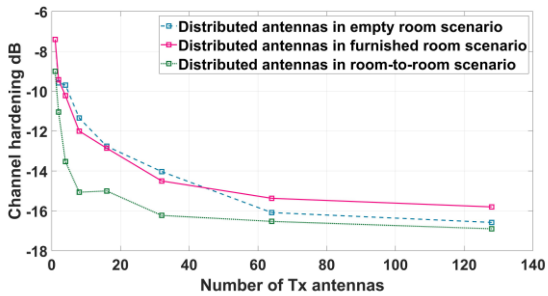

Fig. 4. Distributed antennas in various scenarios

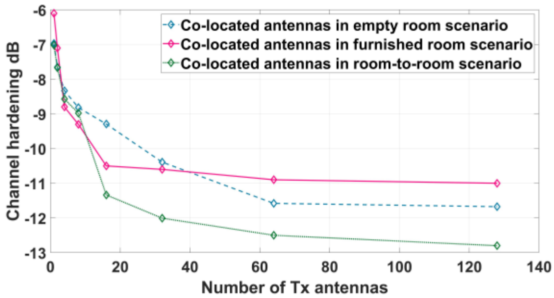

Fig. 5. Co-located antennas in various scenarios

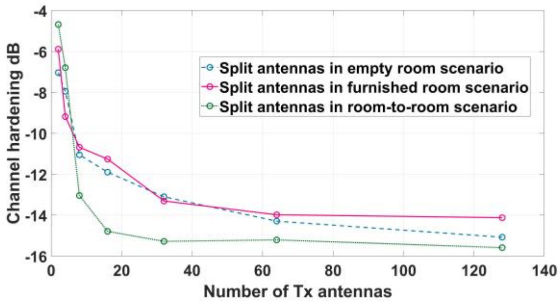

Fig. 6. Split antennas in various scenarios

We also collected the number of paths estimated in different scenarios. Table.1 is the average number of paths that the UE receives, where one path denotes one ray under geometry optics assumption.

	Distributed	Co-located	Split
Empty room	18	16	16
Furnished room	23	24	24
Rom-to-room	29	27	27

Table. 1 Path number estimated for various array antenna topologies in various scenarios

The major findings are listed as follows:

- As shown in Figs. 1-3, the distributed antenna topology is the most spatially hardened among all the 3 array topologies regardless of the propagation scenario, while the co-located antennas are the least spatially hardened. This result is expected because the Tx-Rx channel links within distributed antennas are non-correlated, the channel hardening effect is therefore the most significant. On the other hand, in the co-located topology the Tx-Rx channel links are highly correlated due to the compact structure of the array antennas. The split antenna topology shows an intermediate channel hardening effect because it could be regarded as a combination of the distributed and the co-located antennas topologies.

- The type of propagation channel scenario has also a clear impact on the spatial channel hardening effects as shown in Figs. 4-6. As expected, the channel hardening effect show quite clear convergence pattern with the increasing number of antennas. The spatial channel hardening converges fastest in the rom-to-room scenario with a low threshold number of antenna elements as approximately 20, while the convergence in the furnished room scenario is achieved when the threshold number of antenna elements is almost the double, i.e., around 40. For the empty room scenario, the number of antenna elements required to reach the channel hardening effect is greater than 60.
- The convergence of the spatial channel hardening can be explained by the number of paths for each of the Tx-Rx channel links with different array antenna topologies and propagation scenarios. As shown in Table. 1, the number of relevant propagation paths estimated for each Tx-Rx channel links is the largest in the rom-to-room scenario, followed by the furnished room, and the last is the empty room with the smallest number of paths.

5 Conclusion

This paper presents a simulation-based evaluation of the spatial channel hardening in 3 types of indoor propagation scenarios with 3 types of array antenna topologies. In total 9 combinations of array topology and propagation scenario are compared, and the corresponding average number of received paths in different scenarios are computed and used to explain the spatial channel hardening behavior. The comparison shows that the distributed antenna topology results in the strongest effect of spatial hardening among all the 3 topologies considered, while the co-located antennas topology is the least spatially hardened. The spatial channel hardening convergence is the fastest for the rom-to-room scenario, while the convergence in the empty room is the slowest. The effect of convergence can be explained by the number of paths estimated by the simulator for each Tx-Rx channel links resulting from the combination of the array topologies and propagation scenarios. The results of this paper can be used as a guidance for massive MIMO array antenna deployment. Using a proper massive multi-antenna topology in different scenarios, the number of antennas required is different to reach the convergence of spatially hardened channel.

6 Acknowledgement

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