Evaluation of the Effect of Base Station Antenna Polarization on the Performance of CoMP Transmission Techniques based on Synchronous Multi-Link Measurements

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Abstract—In this paper, the effect of polarization on the downlink sum-rate capacity of multi-user Cooperative Multi-Point (CoMP) systems using synchronous multi-link measured channels, for two different antenna arrangements, is studied. In the first setup, four antenna patches each of which with dual-polarized antenna elements at the base station (BS) with inter-patch distance varied from half wavelength to 8 m is considered. In the second setup, two BSs located 60 m apart are used, each is provided with dual-polarized antennas spaced half a wavelength apart. Based on the BS antenna element selection, scenarios with different antenna polarizations at the BSs are considered. We assume the existence of four virtual users each equipped with two antennas (V and H-polarized) with half-wavelength inter-element distance. The users are equally spaced with inter-user distance of about 0.5 m and moving in different routes. For each setup, the 8×4 MIMO multi-user channels are used to evaluate the sum-rate capacity of the system, where the minimum mean square error (MMSE) beamforming at both the BS and the mobile station (MS) is used. It is found that the performance improvement gained from using dual-polarized antennas at the BS vanishes if the BS antenna elements are distributed over large distance (i.e., having a large antenna array aperture). However, in the measured environment, for the case of having two BSs each of which is provided with co-located antennas, using dual-polarized antennas provide about 40% improvement in the ergodic sum-rate capacity compared to using single-polarized antennas.

I. INTRODUCTION

EXPLOITATION of the spatial domain in communication systems by using multiple-antenna at the base station (BS) and/or the mobile station (MS) can result in a considerable increase in capacity of cellular systems [1]. A rich scatterer environment combined with spatially separated antennas at the BS and MS yield independent parallel channels between transmitter and receiver; hence, a linear increase in capacity with the number of antennas. Although an increase in the number of antennas increases capacity, this solution is not always practical due to limited size at the MS. As a partial remedy for this dilemma, dual-polarized antennas are found to be useful to improve the MIMO channel condition. Unlike conventional MIMO, CoMP antenna arrangements vary from multiple antennas located at the same BS to multiple cooperated BSs. Therefore, the relative gain that CoMP systems can get from utilizing dual-polarized might be highly dependent on the CoMP antenna arrangement.

It was found in [2] that even when the LOS signal is strong, dual-polarized antennas can create additional degrees of freedom, leading to a cell-capacity increase by a factor of five compared to traditional frequency reuse systems. It was also shown in [3] that the use of spatially separated single-polarized systems will outperform dual-polarized systems due to its array gain. However, this gain has small contribution to capacity at high SNR. In [4] and [5], based on practical measurements, significant improvements due to antenna polarization in indoor environments were reported. Both of the works confirmed that the effect of antenna polarization is prominent under LOS condition as it adds an additional degree of freedom to the channel. In [2] it was experimentally demonstrated that BS cooperation adds yet another additional degree of freedom to the MIMO channel. In [6], based on measurements, the improvement due to BS cooperation was confirmed. Also, in [6], a linearly polarized - tilted by 45° from vertical - BS antennas was used and it was reported that the channel gains for different MS antenna polarizations were similar.

In this work, based on synchronous multi-link measurements, we evaluate the performance gain resulting from using dual-polarized BS antenna elements in CoMP systems over single-polarized ones. We specifically address two points: 1) the effect of the BS inter-element distance on the performance improvement gained from using dual-polarized antenna elements in both LOS and NLOS propagation conditions, where inter-element distance up to 8 m is considered, and 2) the performance gained from using dual-polarized antennas over single-polarized ones when two (or more) BSs are cooperating and each BS is provided with co-located antenna elements. The rest of the paper is organized as follows. Section II describes the measurement setup. In section III data analysis of the CoMP downlink channels is introduced. Numerical results are presented in Section IV and conclusions are drawn in section V.

II. MEASUREMENT SETUP

In this work, results from two different measurement campaigns are used. The measurements took place at the campus the faculty of Engineering, LTH, Lund University, Lund, Sweden, in an area which can be best characterized as suburban micro-cell environment. Both campaigns were carried out using the same measurement equipment, the RUSK-LUND

channel sounder. Also, in both campaigns, a cylindrical array with 128 elements was used at the MS, and an aggregate of 8 transmit elements were used at the BS(s) side. The sounding signal is conveyed to each of the remote BSs locations through the optical backbone network of the campus by means of radio-over-fiber (RoF) transceivers. Please refer to [7] for more details about the equipment used. The difference between the two campaigns was the configuration of the BS antenna elements were: in setup-I the BS elements formed a linear array with variable inter-element spacing at one BS, and in setup-II the BS elements were distributed at two BSs, each BS with 4 co-located elements. More details is given in the sequel.

A. Measurement Equipment

The measurement campaign was carried out with the RUSK LUND channel sounder [8] at a center frequency of 2.6 GHz and a measurement bandwidth of 40 MHz. At the BS side, four dual-polarized patch antennas are used. The arrangement of the BS antennas is different in setup-I and setup-II as will be explained later. The signal broadcasted by the BS is received by a single MS equipped with 64 dual-polarized antenna elements in a stacked uniform cylindrical array configuration; it consists of four rings each of which with 16 dual-polarized antenna elements; see Fig. 1(a). The transmit-receive channels are sounded in a time-multiplexed fashion such that all of the receive antenna elements are visited in succession prior to switching to the next transmit antenna element, where a 6.4 μs sounding signal is used. The data resulting from this operation is referred to as a snapshot, consists 1024 wideband transmit-receive channels (128 MS antenna elements $\times$ 8 BS antenna elements), each of which with 257 frequency bins. A distance wheel is used to trigger the acquisition of the MIMO snapshots every λ, and $\lambda/2$ in setup-I, and setup-II, respectively. The measured snapshots are used to extract the user MIMO channels as detailed in the next section.

B. Setup-I

In setup-I, the BS antennas are placed on the rooftop of a four story building in an equally-spaced linear configuration. The patch antennas are mounted on a tripod to facilitate adjusting the inter-element spacing, which is defined as the distance between two adjacent patch antennas; see Fig. 1(c). The inter-patch spacing, d, is varied to the following 8 values: $\lambda/2$, λ, 0.25 m, 0.50 m, 1 m, 2 m, 4 m, and 8 m. The measurement scenarios include both LOS and NLOS propagation conditions. For each inter-patch spacing value, the MS is moved (at around 0.5 m/s) in three routes: Route 1 is *mainly* LOS, and Routes 2 and 3 are *mainly* NLOS. In the measurement area, there are only few buildings; however, the main interacting objects are leafy trees. Therefore, in both measurement routes, the propagation conditions may alter from LOS to NLOS, or visa versa, due to the sudden appearance or disappearance of heavy branches between the MS and the BS. See Fig. 2.

C. Setup-II

In setup-II, the BS antennas are distributed at two BS sites. At each BS, four co-located antennas are used. Fig. 1(b) illustrates an example of the antenna arrangement at each BS

Fig. 1. Antennas at the MS and at the BS. (a) MS antenna: stacked uniform cylindrical array with 64 dual-polarized antenna elements arranged in four rings. (b) BS antennas: co-located arrangement used in setup-II with inter-patch spacing of $\lambda/2$ (back view). (c) BS antennas: mounted on a tripod to facilitate adjusting the inter-element spacing for setup-I, the photo is with inter-element spacing of 1 m (back view).
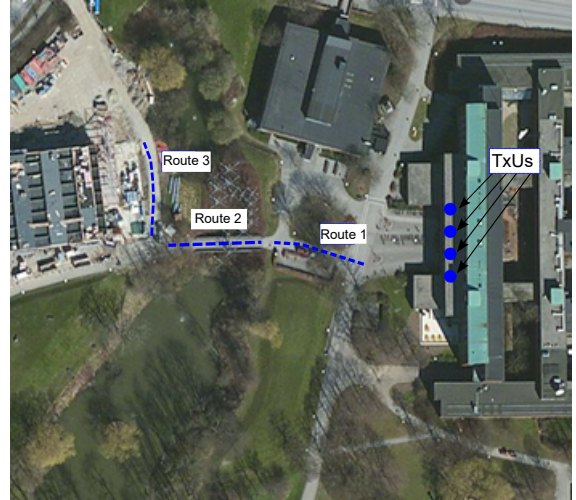

Fig. 2. Aerial photo of the measurement area illustrating setup-I. BS antennas are indicated with the blue circles all placed at one BS. The MS measurement routes are plotted in dashed blue lines: Route 1 is mainly LOS; Route 2 and Route 3 are mainly NLOS.

site, where the distance between adjacent antenna patches is fixed at half wavelength. The map of setup-II is shown in Fig. 3; the movement of the MS covered most of the walking paths as indicated by the red dots.

III. DATA ANALYSIS

A. Extraction and normalization of users' channels

Each measured snapshot has a size of 128 MS elements $\times$ 8 BS elements $\times$ 257 frequency bins. For this work, only a subset of the BS and MS antenna elements were chosen to construct the assumed users' channels as follows.
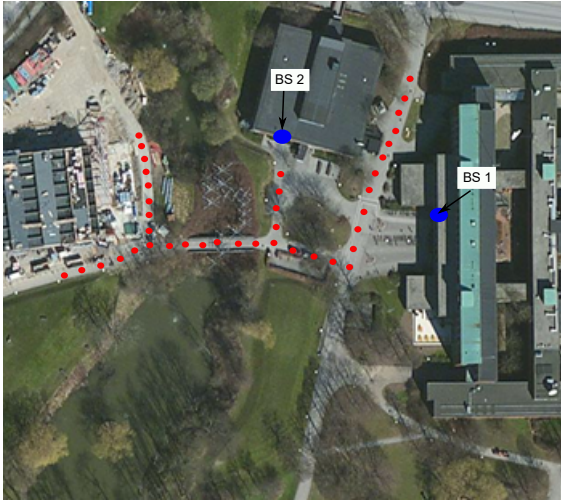
Fig. 3. Aerial photo of the measurement area illustrating setup-II. BS 1 and BS 2 are indicated with the large blue circles. Each BS is equipped with co-located antenna arranged as depicted in Fig. 1(b). The MS measurement route is indicated by the small red circles.

1) Selection of antenna elements at the BSs

For both setups, at the BS(s), only four out of the eight antenna elements are selected in order to allow for the evaluation of different BS antenna configurations. Fig. 4. depicts the different antenna configurations for setup-I. V.Pol, and H.Pol are single-polarized configurations where from each antenna patch one vertically, and one horizontally polarized antenna element is selected, respectively. CoPol1, and CoPol2 are dual-polarized configurations where in CoPol1 one antenna element is selected from each patch; however, adjacent selected antenna elements have different polarizations. In CoPol2, only the antenna elements of the patches at the end of the array are selected, dual-polarized elements from each patch.

In setup-II, we have two BSs, each with two dual-polarized patches, i.e., each BS is with four antenna elements: two are vertically polarized and two are horizontally polarized. However, based on the considered antenna configuration, from each BS, only two antenna elements are selected. The following BS antenna configurations are considered: V.Pol, H.Pol, and CoPol, where the two selected elements at each of the BSs are both vertically, both horizontally, and dual-polarized, respectively.

2) Selection of antenna elements at the MS

We assume the co-existence of four users and each user is equipped with two antennas: one is vertically polarized, and one is horizontally polarized with a vertical inter-element distance of $\lambda/2$ (see the geometry of the cylindrical MS measurement array in section II). Therefore, the MU-MIMO channel has the size of 8 MS elements (4 users each with 2 elements at the MS side) × 4 Tx elements (at the BS side). Each MU-MIMO channel has 257 frequency bins representing the wideband channel. In each frequency bin, the MIMO channel represents a narrowband channel.

To emulate multi-user scenario, we assume that each snapshot represents a virtual user. The analysis is performed such that users are equally-spaced and they are 5λ apart from
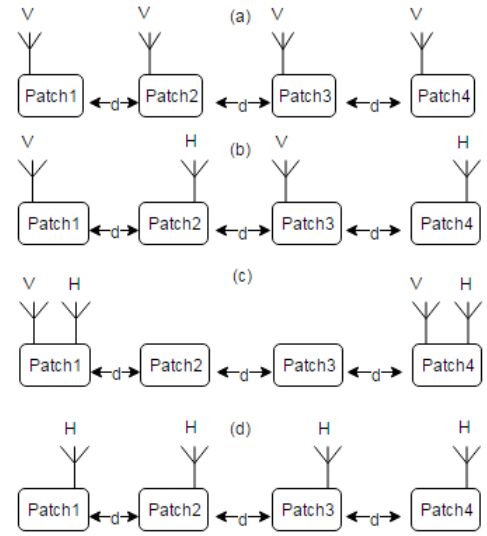

Fig. 4. Antenna configurations for setup-I: a) V.Pol. b) CoPol1. c) CoPol2. d) H.Pol. Equally-spaced antenna patches, where d denotes the distance between the antenna patches.

each other. Also, due to the geometry of the MS cylindrical antenna, a user on a specific position can take one out of 16 azimuth orientations. In the analysis we consider the worst case scenario in terms of the assumption that all users have the same orientation and they all use the same frequency at a time. In setup-I, users' channels are normalized according to:

$$H_{norm}^{(n,s,l)} = H^{(n,s,l)} \left[\frac{1}{L \cdot S \cdot N \cdot M_T \cdot M_R} \sum_{l=1}^{L} \sum_{s=1}^{S} \sum_{n=1}^{N} \left\| H^{(n,s,l)} \right\|_F^2 \right]^{-1/2} \tag{1}$$

where, $M_T = 4$ and $M_R = 2$ are the number of antenna elements at the BS and MS, respectively. In addition, $S = 9$, and $S = 17$ for setup-I, and setup-II, respectively, is the number of snapshots corresponding to spatial averaging over approximately 1 m travel distance. $N = 20$ is the number of frequency bins selected for the analysis. $L = 32$ is the number of possible users extracted from each snapshot having different directions (i.e., patch orientation) that span the azimuth plane.

Normalizing the users' channels using (1) preserves the effects of the small-scale fading, the fluctuation in the channel due to small spatial displacement of users, and the direction of the MS antenna (i.e., patches). It also preserves the different gain to each BS antenna element (a crucial factor that should be preserved for setup-I), which is more pronounced when the inter-element distance at the BS is large. Also, using (1) normalizes away any gain from having a good propagation condition such as LOS; hence, the normalized channel matrices reflect only the effect of both the polarization and the spatial arrangement of the BS antenna elements on the performance, which is the goal of this study. For setup-II, the same normalization of (1) is used; however, it is applied per BS link, i.e., a power control algorithm is assumed to compensate for the distance-dependent loss at each BS.

B. Beamforming design at the BS and MS sides

As mentioned in section I, MMSE beamforming is used at the MS and BS sides [6], [9], [10]. The MS beamformer u_k is calculated as

$$u_k = u_o \left[I + \sum_{i \neq k} H_k w_i w_i^H H_k^H \right]^{-1} H_k w_k, \tag{2}$$

where, $(.)^H$, $(.)^{-1}$, and I are the Hermitian transpose operator, the matrix inverse operators, and the identity matrix of proper size, respectively. u_o is chosen in such a way that the vector has unit norm. H_k, and w_k are the channel and the BS beamformer associated with the kth user, respectively. The BS beamformer w_k is calculated using:

$$W = H^H \left(H H^H + \beta I \right)^{-1}, \tag{3}$$

where, $\beta = M_T/\rho$, and ρ is the SNR, which is fixed at 10 dB.

C. Calculation of sum-rate capacity and condition number

The sum-rate capacity is calculated using:

$$C_{BC} = \sum_{k=1}^{K} \log \left(1 + \rho_k \right), \tag{4}$$

where, ρ_k is the SINR for user k calculated as:

$$\rho_k = \frac{\left| u_k^H H_k w_k \right|^2}{1/\rho + \sum_{i \neq k} \left| u_k^H H_k w_i \right|^2}, \tag{5}$$

where, u_k is beamformer applied by the kth user.

The condition number (singular value spread) of the channel

$$\kappa = \frac{\sigma_{max}}{\sigma_{min}}, \tag{6}$$

is also investigated, where σ_{max} and σ_{min} are the largest and smallest singular value of the MIMO channel matrix respectively.

IV. RESULTS

A. Setup-I: one BS with variable antenna array aperture

It is well known that an increased aperture of the BS antenna array should yield better performance. In this section we study the performance gain that can be achieved by using BS antenna array provided with dual-polarized elements over that achieved using only single-polarized elements. We vary the BS antenna aperture from 0.17 m to 24 m (which corresponds to changing the inter-patch distance, d, from $\lambda/2$ to 8 m; see Fig. 4), where, eight values for the BS antenna aperture are considered: 0.17 m, 0.34 m, 0.75 m, 1.5 m, 3 m, 6 m, 12 m, and 24 m. For each value of the BS antenna aperture, the measurements took place while the MS is moving in three routes: Route 1 is mainly LOS, while Route 2 and Route 3 are mainly NLOS.

Figs. 5(a), (b), and (c) show the sum-rate capacity versus the BS antenna array aperture for the different routes and for the different BS antenna polarization setups. Fig. 5(d) shows the combined result for all three routes. From these figures the following points can be deduced.

The difference in the sum-rate capacity is significant between single-polarized and dual-polarized antenna scenarios
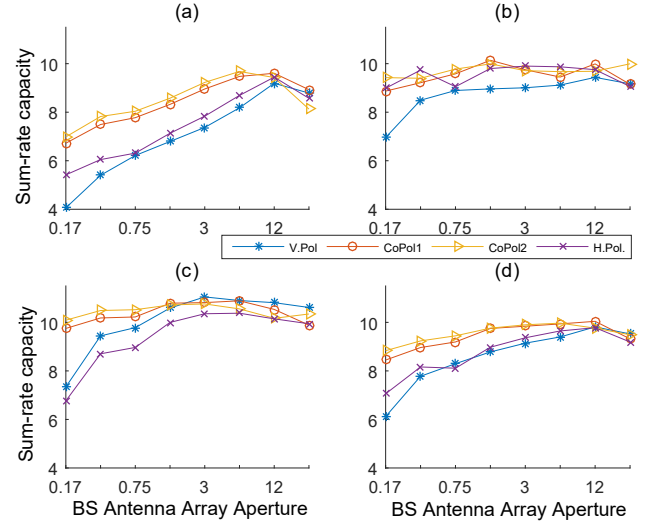

Fig. 5. Sum rate Capacity vs the BS antenna array aperture in meter for: a) Route 1 (LOS), b) Route 2 (NLOS), c) Route 3 (NLOS) and d) All routes combined, of setup-I

when the BS array aperture is small (e.g., less than 1 meter). For all BS antenna configurations, with the increase of the BS antenna array aperture, the sum-rate capacity increases monotonically but eventually saturates when the BS antenna array aperture reaches a "large enough value" where the difference in the sum-rate capacity achieved by the different BS antenna configurations becomes negligible. Table I demonstrates the significant performance improvement achieved by the dual-polarized antenna configurations when the BS antenna array aperture is 0.17 m where improvement as high as 72% is obtained. However, when the BS antenna array aperture is larger than 12 m, having single-polarized antenna elements (V.Pol, H.Pol) or dual-polarized ones (CoPol1, CoPol2) provides no significant impact on the sum-rate capacity.

The above-mentioned behavior can be confirmed by studying the CDF of the condition number of the channel, κ, for the different BS antenna array aperture values, see Fig. 6, where we observe that:

- For BS antenna array aperture of 0.17 m, Fig. 6(a), κ has significantly different values for different antenna configurations.
- For BS antenna array aperture of 1.5 m, Fig. 6(c), κ of the CoPol1 and CoPol2 configurations are similar but has a significant difference from the single-polarized configurations.
- For large BS antenna array aperture value (12 m), Fig. 6(d), κ is almost similar for all antenna configurations.

It is interesting to notice that, using the CoPol2 configuration, where each dual-polarized elements are maximally apart, the performance is slightly better than the CoPol1 configuration.

Table I presents the ergodic sum-rate capacity for BS antenna array aperture of 0.17 m of V.Pol. and CoPol1 configurations. It can be noticed that, in all propagation conditions

(LOS and NLOS), using dual-polarized elements improves the performance; however, the improvement for the LOS conditions is more pronounced.

TABLE I
ERGODIC SUM-RATE CAPACITY FOR DIFFERENT BS ANTENNA CONFIGURATIONS (BS ANTENNA ARRAY APERTURE = 0.17 M)

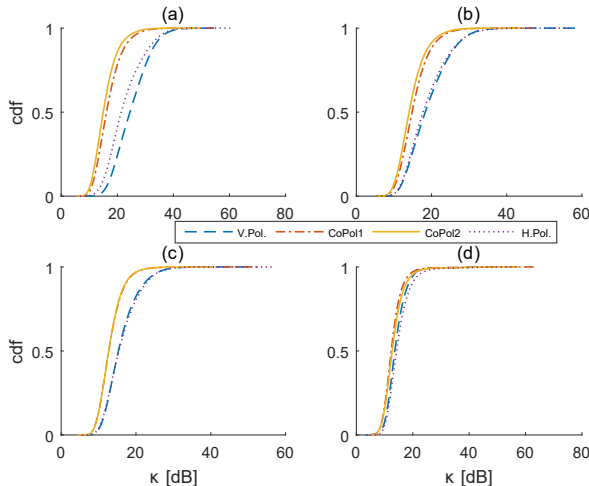| Prop. condition	V.Pol.	CoPol1.	Improvement
Route 1 (LOS)	4.059	6.984	72%
Route 2 (NLOS)	7.341	10.09	37%
Route 3 (NLOS)	6.959	9.425	35%
All Routes	6.119	8.833	44%

Fig. 6. Condition number for different BS antenna array aperture: a) 0.17 m, b) 0.34 m, c) 1.5 m and d) 12 m, for setup-I

B. Setup-II: two BSs, each with two antenna elements

In setup-II, we consider two BSs, 60 m apart, each BS has two antenna elements. At each BS, the inter-element distance is fixed at $\lambda/2$. However, the elements at each BS take one of three configurations: both elements are vertically polarized (V.Pol), both elements are horizontally polarized (H.Pol), and dual-polarized (Co.Pol). Setup-II can be looked at as a special case of Fig. 4(c), where the distance between the co-located antenna pairs is 60 m. The performance comparison of the aforementioned configurations is demonstrated in Fig. 7, where we observe that the dual-polarized antenna configurations give 39% increase in the ergodic sum-rate capacity compared to the single-polarized antenna configurations.

It can be observed that in setup-I, for a BS antenna array aperture of 12 m and beyond, the sum-rate capacity of all considered antenna configurations, converges. While, for setup-II, the sum-rate capacity improvement, when dual-polarized elements are used, persists, even though the distance between the BSs is 60 m. This can be explained as follows. In setup-I, all configurations utilize fully the spatial domain of the BS large antenna array; hence, the improvement gained from the spatial domain dominates the improvement gained from the polarization. While in setup-II, within each BS, the inter-element distance is fixed at $\lambda/2$, so all three configurations have limited gain from the spatial domain (co-located antennas). Therefore, the configuration with dual-polarized antennas
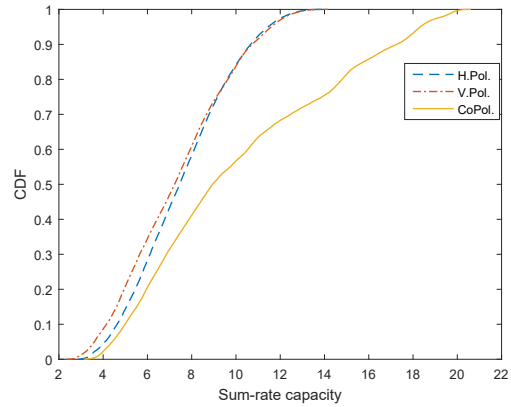

Fig. 7. Distributions of the sum-rate capacity for setup-II using different BS antenna polarizations.

gain extra degree of freedom provided by the polarization; and hence, achieve the highest sum-rate capacity.

V. CONCLUSION

In this paper, synchronous multi-link propagation measurement in outdoor micro-cell environment have been used to evaluate the performance of CoMP systems. We focus on evaluating the improvement in the sum-rate capacity that can be achieved when dual-polarized antenna elements at the BS are used. It is found that: 1) using dual-polarized antenna elements at the BS improves the capacity by about 35% and 72% in NLOS and LOS, respectively, if the aperture of the antenna array is small (less than 1 m). 2) Increasing the BS array aperture gives better capacity to a certain point, then the improvement saturates. 3) If the BS array aperture is "large enough", then the performance improvement gained from using BS dual-polarized antennas is insignificant compared to using single-polarized ones. 4) In the measured environment, for the case of having several BSs each of which is provided with co-located antenna, using dual-polarized antennas provide significant improvement (about 40% improvement in the ergodic sum-rate capacity) compared to using single-polarized antennas.

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