Dependability Enhancements for Transmission over MISO TWDP Fading Channels

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***Abstract*—In this paper, we propose an outage optimal beamformer design for transmission over multiple-input single-output two-wave with diffuse power fading channels. We identify the structure of the outage optimal beamformer and are thereby able to reduce the generally complicated beamformer optimization to a simple line search. To further enhance the reliability of the transmission, we employ distributed antenna arrays and investigate the performance of outage-optimal antenna array selection. We finally evaluate the transmission latency of the considered system under latency-optimal rate adaptation.**

***Index Terms*—TWDP fading, outage optimization, transmission latency, beamforming**

I. Introduction

With the introduction of full dimension multiple-input mulitple-output (FD-MIMO) in mobile communications [1], the importance of directional channel models for the performance investigation of wireless transmissions increased significantly. Many elaborate so-called geometry based stochastic channel models have been developed, which allow for accurate simulation of mobile networks [2]–[4]. These models are, however, not suitable for analytic investigations and optimizations of the transmission system, due to their inherent complexity.

Fortunately, in many situations, the most important channel characteristics, at least from a link-level perspective, can be captured by much simpler channel models, which provide analytic tractability to a certain level. Rician fading, for example, has been used for decades to model situations in which the transmission is dominated by a single strong specular component, whereas, more recently, two-wave with diffuse power (TWDP) fading [5] has been shown to be relevant for communication in the millimeter wave (mmWave) band [6], [7]. Generalizing TWDP fading to an arbitrary number of specular components complicates the analysis significantly [8], [9].

The performance of transmissions under TWDP fading has been evaluated in many situations: in [10], BPSK transmission combined with maximum ratio combining is investigated; in [11], the outage probability of cooperative relay networks is derived; in [12], the capacity of single-input single-output (SISO) TWDP channels is calculated; and in [13], robust beam-alignment for TWDP fading millimeter wave channels is proposed.

In this paper, our focus is on beamforming over multiple-input single-output (MISO) TWDP fading channels in distributed antenna systems (DASs). We derive the structure of the outage optimal beamformer for single-user transmission and utilize this structure to determine the optimal beamformer by means of a simple line search. Compared to our prior attempt of a gradient-based optimization [14], this line search is significantly less complex and provably optimal. We investigate the outage and latency performance of the proposed beamformer and combine it with antenna array selection in DASs to further enhance the dependability, in terms of reliability and timeliness, of the wireless transmission.

Notation: The Kronecker-delta symbol is δ_{i-j}; that is, $\delta_{i-j} = 1$ if $i = j$ and $\delta_{i-j} = 0$ otherwise. The vector-valued circularly-symmetric complex Gaussian distribution with mean $\boldsymbol{\mu}$ and covariance $\mathbf{C}$ is $\mathcal{CN}(\boldsymbol{\mu}, \mathbf{C})$. The uniform distribution over the interval $[a, b]$ is $\mathcal{U}(a, b)$. The phase of a complex number z is $\arg(z)$.

II. System Model

We consider single-user transmission over a MISO DAS consisting of R antenna arrays that are each equipped with N transmit antennas. Our focus is on downlink transmissions, though the uplink direction is equivalent. We denote the MISO channel between antenna array r and the user as $\mathbf{h}_r \in \mathbb{C}^{N\times 1}$. The input-output relationship of the user thus is

$$y = \sum_{r=1}^{R} \delta_{r-s} \mathbf{h}_r^{\mathsf{H}} \mathbf{f}_r x + n, \quad \|\mathbf{f}_r\| = 1, \tag{1}$$

where n denotes complex Gaussian noise of variance σ_n^2 and $\mathbf{f}_r$ is the beamformer employed at distributed antenna array r. The transmitter utilizes antenna array selection to activate only a single antenna array s; we discuss the employed selection strategy further below.

A. Effective TWDP Channel Model

To characterize the wireless channel between antenna array r and the user, we employ a directional channel model. Assuming that the transmission is dominated by two strong specular components $\mathbf{h}_{r,1}$ and $\mathbf{h}_{r,2}$ that are not resolvable in time within the given transmission bandwidth, the directional MISO channel can be decomposed as

$$\mathbf{h}_r = \sum_{i=1}^{2} \mathbf{h}_{r,i} + \mathbf{d}_r = \sum_{i=1}^{2} \alpha_{r,i} e^{-j\psi_{r,i}} \bar{\mathbf{h}}_{r,i} + \mathbf{d}_r, \tag{2}$$

where $\alpha_{r,i} \in \mathbb{R}_+$ is the pathloss of the i-th specular component and $\psi_{r,i}$ is its phase-shift. Unit-norm vector $\bar{\mathbf{h}}_{r,i} = \mathbf{a}(\Theta_{r,i})$ represents the normalized antenna array response w.r.t. a plane wave with angle of departure (AoD) $\Theta_{r,i} = (\phi_{r,i}, \theta_{r,i})$ in azimuth $\phi_{r,i}$ and elevation $\theta_{r,i}$. Vector $\mathbf{d}_r \sim \mathcal{CN}\left(\mathbf{0}_N, 2\sigma_d^2\mathbf{I}_N\right)$ is a Rayleigh-fading component denoted as diffuse scattering component. W.l.o.g., we can assume $\alpha_{r,1} \geq \alpha_{r,2}$.

We assume that the beamformers $\mathbf{f}_r$ at the distributed antenna arrays are adapted relatively slowly over time. For example, these could be analog beamformers in mmWave transmission, which cannot be adapted from one transmission time instant to the next. Specifically, during transmission with fixed beamformers $\mathbf{f}_r$, we assume that the phase-shifts are uniformly distributed random variables $\psi_{r,i} \sim \mathcal{U}(0, 2\pi)$, whereas the macroscopic pathloss values $\alpha_{r,i}$ and the AoDs $\Theta_{r,i}$ are constant. This assumption is reasonable, e.g., in mobile scenarios, where it can be hard to keep track of the phase-shifts, since they vary significantly when the user just moves by a fraction of the wavelength, whereas the macroscopic channel properties $\alpha_{r,i}$, $\Theta_{r,i}$ vary slowly over space and time and are thus relatively easy to track.

With this assumption, the effective SISO channel $h_{e,r} = \mathbf{h}_r^{\mathsf{H}}\mathbf{f}_r$ can be written as

$$h_{e,r} = \sum_{i=1}^{2} h_{r,i} + d_r = \sum_{i=1}^{2} V_{r,i} e^{j\xi_{r,i}} + d_r, \quad (3)$$
$$h_{r,i} = \mathbf{h}_{r,i}^{\mathsf{H}}\mathbf{f}_r, \quad d_r = \mathbf{d}_r^{\mathsf{H}}\mathbf{f}_r,$$
$$V_{r,i} = \alpha_{r,i}\left|\bar{\mathbf{h}}_{r,i}^{\mathsf{H}}\mathbf{f}_r\right|, \ \xi_{r,i} = \psi_{r,i} + \arg\left(\bar{\mathbf{h}}_{r,i}^{\mathsf{H}}\mathbf{f}_r\right),$$

with $d_r \sim \mathcal{CN}(0, 2\sigma_d^2)$ and $\xi_{r,i} \sim \mathcal{U}(0, 2\pi)$ since $\psi_{r,i}$ is uniformly distributed. This corresponds to a TWDP fading channel, characterized by its average gain $\Omega_r = V_{r,1}^2 + V_{r,2}^2 + 2\sigma_d^2$, its K-factor $K_r = (V_{r,1}^2 + V_{r,2}^2)/(2\sigma_d^2)$ and its Δ-parameter $\Delta_r = 2V_{r,1}V_{r,2}/(V_{r,1}^2 + V_{r,2}^2)$.

III. Beamformer Optimization

According to (3), the beamformer $\mathbf{f}_r$ crucially impacts the fading parameters of the effective channel. Consider an arbitrary beamformer $\mathbf{f}_r$; we decompose it as follows

$$\mathbf{f}_r = \left(\mathbf{I}_N - \bar{\mathbf{h}}_{r,2}\bar{\mathbf{h}}_{r,2}^{\mathsf{H}}\right)\mathbf{f}_r + \bar{\mathbf{h}}_{r,2}\bar{\mathbf{h}}_{r,2}^{\mathsf{H}}\mathbf{f}_r = \mathbf{f}_{r,2}^{\perp} + \mathbf{f}_{r,2}^{\parallel}. \quad (4)$$

Obviously, $\mathbf{f}_{r,2}^{\perp}$ does neither impact the amplitude $V_{r,2}$ nor the phase $\xi_{r,2}$ of the second specular component as it is orthogonal to it. However, it still impacts the amplitude of the first specular component $V_{r,1}$. Thus, $\mathbf{f}_{r,2}^{\perp}$ should be aligned with the projection of first specular component onto the null-space of $\bar{\mathbf{h}}_{r,2}$: $\mathbf{f}_{r,2}^{\perp} \propto \left(\mathbf{I}_N - \bar{\mathbf{h}}_{r,2}\bar{\mathbf{h}}_{r,2}^{\mathsf{H}}\right)\bar{\mathbf{h}}_{r,1}$. By this, we maximize the gain Ω_r and the K-factor K_r of the TWDP channel, and we minimize the depth of fading holes caused by destructive interference of $h_{r,1}$ and $h_{r,2}$. Hence, w.l.o.g., any unit-norm beamformer that maximizes the received signal to noise ratio (SNR) or that minimizes the outage probability of the considered system can be written as

$$\mathbf{f}_r = c\,\mathbf{f}^{\perp} + \sqrt{1-c^2}\,e^{j\varphi}\,\mathbf{f}^{\parallel}, \quad c \in [0,1], \quad (5)$$
$$\mathbf{f}^{\perp} = \frac{\left(\mathbf{I}_N - \bar{\mathbf{h}}_{r,2}\bar{\mathbf{h}}_{r,2}^{\mathsf{H}}\right)\bar{\mathbf{h}}_{r,1}}{\left\|\left(\mathbf{I}_N - \bar{\mathbf{h}}_{r,2}\bar{\mathbf{h}}_{r,2}^{\mathsf{H}}\right)\bar{\mathbf{h}}_{r,1}\right\|}, \quad \mathbf{f}^{\parallel} = \bar{\mathbf{h}}_{r,2}. \quad (6)$$

Here, $c^2 = \left\|\mathbf{f}_{r,2}^{\perp}\right\|^2$, $1-c^2 = \left\|\mathbf{f}_{r,2}^{\parallel}\right\|^2$ and $\varphi = \arg\left(\bar{\mathbf{h}}_{r,2}^{\mathsf{H}}\mathbf{f}_r\right)$.

With this decomposition and $p^2 = |\bar{\mathbf{h}}_{r,2}^{\mathsf{H}}\bar{\mathbf{h}}_{r,1}|^2$, the two specular components of the effective channel $h_{e,r}$ are

$$h_{r,1} = \alpha_{r,1}e^{j\psi_{r,1}}\left(c\sqrt{1-p^2} + \sqrt{1-c^2}e^{j\varphi}\bar{\mathbf{h}}_{r,1}^{\mathsf{H}}\bar{\mathbf{h}}_{r,2}\right),$$
$$h_{r,2} = \alpha_{r,2}e^{j\psi_{r,2}}\sqrt{1-c^2}e^{j\varphi}. \quad (7)$$

Since $\psi_{r,2} \sim \mathcal{U}(0, 2\pi)$, we can choose φ to maximize $V_{r,1}$ by setting $\varphi = -\arg\left(\bar{\mathbf{h}}_{r,1}^{\mathsf{H}}\bar{\mathbf{h}}_{r,2}\right)$, without impacting the distribution of $h_{r,2}$, leading to

$$h_{r,1} = \alpha_{r,1}e^{j\psi_{r,1}}\left(c\sqrt{1-p^2} + \sqrt{1-c^2}\,p\right). \quad (8)$$

With this results, we have reduced the beamformer optimization to a single-parameter search over $c \in [0, 1]$.

A. Maximum Mean SNR Beamforming

The mean SNR for transmission over the effective SISO channel $h_{e,r}$ is $\bar{\beta}_r = \Omega_r/\sigma_n^2$. Hence, the beamformer that maximizes the mean SNR can be found by maximizing $V_{r,1}^2 + V_{r,2}^2$ w.r.t. the beamforming line search parameter

$$\max_{c\in[0,1]} \alpha_{r,1}^2\left(c\sqrt{1-p^2} + \sqrt{1-c^2}\,p\right)^2 + \alpha_{r,2}^2(1-c^2). \quad (9)$$

For $c \in [0, 1]$, this function goes from $\alpha_{r,1}^2 p^2 + \alpha_{r,2}^2$ to $\alpha_{r,1}^2(1-p^2)$, with a unique maximum either at a border or strictly within the interval. This optimum can easily be found by a line search algorithm, such as, bisection.

B. SNR Outage Optimal Beamforming

If we assume that the transmission rate cannot be adapted to fast SNR variations caused by the random phase shifts $\psi_{r,1}, \psi_{r,2}$ of the two specular components, the system has to tolerate outages whenever the instantaneous SNR $\beta_r = |h_{e,r}|^2/\sigma_n^2$ falls below the minimum requirement β_{thresh} of the selected transmission rate. The SNR outage probability thus is

$$P_{\text{out},r}^{\text{snr}}(f) = \mathbb{P}\left(\beta_r < \beta_{\text{thresh}}\right) = \mathbb{P}\left(|h_{e,r}| < \sqrt{\bar{\gamma}_r f}\right), \quad (10)$$
$$\beta_{\text{thresh}} = \frac{\bar{\gamma}_r f}{\sigma_n^2}, \quad \bar{\gamma}_r = \alpha_{r,1}^2 + \alpha_{r,2}^2 + 2\sigma_d^2,$$

where we introduced the fading margin f to specify the threshold SNR β_{thresh} in terms of the channel gain $\bar{\gamma}_r$. We utilize f further below for transmission rate adaptation.

The outage probability of the effective TWDP fading channel $h_{e,r}$ can be stated in integral form [15] as

$$P_{\text{out},r}^{\text{snr}}(f) = 1 - \frac{1}{2\pi}\int_0^{2\pi} \dots$$
$$Q_1\left(\sqrt{2K_r\left(1 + \Delta_r\cos\left(\alpha\right)\right)}, \frac{\sqrt{\bar{\gamma}_r f}}{\sigma_d}\right)d\alpha, \quad (11)$$

where $Q_1(\cdot,\cdot)$ is the Marcum Q-function. $P_{\text{out},r}^{\text{snr}}(f)$ depends on the beamformer $\mathbf{f}_r$ via Ω_r, K_r and Δ_r. A closed-form minimization of the outage probability w.r.t. the beamforming parameter $c \in [0, 1]$ is not feasible; hence, we have to resort to a line search. However, our simulations have shown that the achieved outage probability is not very sensitive to small variations of c and therefore a coarse quantization of the interval $[0,1]$ is sufficient for the line search.

Mathematically, it is hard to proof that $P^{\text{snr}}_{\text{out},r}(f)$ only has a single unique minimum in the interval $c \in [0,1]$; yet, phenomenologically it is relatively easy to understand: At $c = 1$, $\mathbf{f}_r$ is perpendicular to $\mathbf{h}_{r,2}$ and thus we have a Rice fading situation. At this point, fading is minimal, only caused by the diffuse component, however, the average received signal power may also be small, depending on how strong $\mathbf{h}_{r,1}$ overlaps with $\mathbf{h}_{r,2}$. By reducing c, the average received signal power may be increased, yet, also the amount of fading will grow, since the signal will be received over both specular components, leading to multi-path interference and TWDP fading. Therefore, at first the outage probability may decrease with reducing c; however, at some point in the interval $[0,1]$ it will start to increase again, since the overlap of $\mathbf{f}_r$ with the strong specular component $\mathbf{h}_{r,1}$ reduces and the amount of fading grows. Where exactly in the interval $[0,1]$ this happens depends on the overlap between $\mathbf{h}_{r,1}$ and $\mathbf{h}_{r,2}$ and also on the pathloss values $\alpha_{r,1}$, $\alpha_{r,2}$.

C. Antenna Array Selection

We assume that the transmitter is able to perform fast antenna array selection, such that, for a given random realization of the multipath phase shifts $\psi_{r,1}, \psi_{r,2}$, the transmitter can select the antenna array that achieves the largest instantaneous SNR

$$s = \underset{r\in\{1,\dots,R\}}{\arg\max}\ \beta_r = \underset{r\in\{1,\dots,R\}}{\arg\max}\ \frac{|h_{e,r}|^2}{\sigma_n^2}. \tag{12}$$

With this selection strategy, the SNR outage probability of the system is obtained as the product of the individual outage probabilities of the antenna arrays

$$P^{\text{snr}}_{\text{out}}(f) = \prod_{r=1}^{R} P^{\text{snr}}_{\text{out},r}(f). \tag{13}$$

This fast selection strategy based on the instantaneous SNR may not be feasible in practice; yet, it enables to harvest the full diversity gain provided by the DAS. Alternatively, one could also consider a slow selection strategy by selecting the antenna array that achieves the lowest outage probability. For such a slow approach the outage probability is

$$P^{\text{snr}}_{\text{out}}(f) = \min_{r\in\{1,\dots,R\}} P^{\text{snr}}_{\text{out},r}(f), \tag{14}$$

which is significantly worse than the fast approach.

IV. Latency-Optimal Fading Margin

In this section, we investigate how to select the fading margin f to achieve minimal transmission latency.

Since the system operates at non-zero SNR outage probability $P^{\text{snr}}_{\text{out}}(f)$, we cannot impose a hard constraint on the transmission latency ℓ. Instead, we minimize a bound ℓ_t on the transmission latency that is violated with low outage probability $P^{\text{lat}}_{\text{out,max}}$

$$\min_f\ \ell_t, \quad \text{s.t.} \quad \mathbb{P}\left(\ell > \ell_t | f\right) \leq P^{\text{lat}}_{\text{out,max}}. \tag{15}$$

To achieve this goal, we have to calculate the outage probability $P^{\text{lat}}_{\text{out}}(f, \ell_t) = \mathbb{P}\left(\ell > \ell_t | f\right)$ of the latency.

A. Outage Probability of Latency

To determine the transmission latency, we have to specify the correlation properties of our channel model. We adopt a block-fading channel model, in which the channel stays constant during a coherence block of T_c seconds and B_c Hertz, and where channel realizations of different coherence blocks are statistically independent. Our latency results will be given in terms of transmission time instances (TTIs), i.e., number of coherence blocks required to transmit a given amount of data. Notice that these TTIs could be allotted in time but also in frequency, depending on the available bandwidth of the system.

With a fixed fading margin f, the transmission system is designed to operate at transmission rate

$$R(f) = \log_2\left(1 + \frac{\bar{\gamma}_r f}{\sigma_n^2}\right). \tag{16}$$

Hence, the amount of data transmitted per TTI is $N(f) = B_c T_c R(f)$. Given a packet size N_p, the system therefore requires $P(f) = \lceil N_p / N(f) \rceil$ successful transmissions to fully transmit the packet. We assume that an unsuccessful transmission during a TTI triggers a resubmission in the next TTI until success. The probability that a successful packet transmission requires exactly $P(f) + j$ TTIs is

$$\mathbb{P}\left(\ell = P(f) + j | f\right) = \binom{P(f)+j-1}{P(f)-1} \dots \\ P^{\text{snr}}_{\text{out}}(f)^j \left(1 - P^{\text{snr}}_{\text{out}}(f)\right)^{P(f)}. \tag{17}$$

In words, during the first $P(f)+j-1$ TTIs, $P(f)-1$ arbitrarily positioned transmissions are successful and j transmissions fail, and the transmission in TTI $P(f)+j$ is successful. From this we can calculate the probability that the latency is less than or equal to $P(f)+j$ as

$$\mathbb{P}\left(\ell \leq P(f) + j | f\right) = \sum_{i=0}^{j} \mathbb{P}\left(\ell = P(f) + i | f\right), \tag{18}$$

and finally the outage probability of the latency as

$$P^{\text{lat}}_{\text{out}}(f, \ell_t) = \begin{cases} 1 - \mathbb{P}\left(\ell \leq \ell_t | f\right), \ell_t \geq P(f) \\ 1,\ \text{otherwise} \end{cases}. \tag{19}$$

With this results, we can now solve the optimization in (15). However, this is not feasible in closed-form. It rather requires calculating the SNR outage probability (13) for a host of fading margins (e.g., corresponding to the modulation and coding schemes (MCSs) supported by the transmission system), and from it the outage probability of the latency (19).

V. Simulation Results

In our simulations, we assume that the DAS employs uniform linear arrays (ULAs), each consisting of N isotropically radiating antenna elements. We assume equal pathloss values for all arrays and paths $\alpha_{r,1} = \alpha_{r,2} = \alpha, \forall r$ and normalize the macroscopic channel gain as $\bar{\gamma}_r = \alpha_{r,1}^2 + \alpha_{r,2}^2 + 2\sigma_d^2 = 1$. We furthermore consider a ratio of specular to diffuse power of $(\alpha_{r,1}^2 + \alpha_{r,2}^2)/(2\sigma_d^2) = 20$ and set the noise variance to $\sigma_n^2 = 10^{-2}$. We consider randomly distributed AoDs

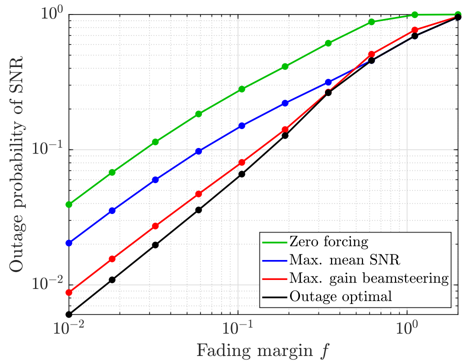

Fig. 1. Average outage probability of the SNR as a function of the fading margin f for different beamforming methods and $N = 8$.

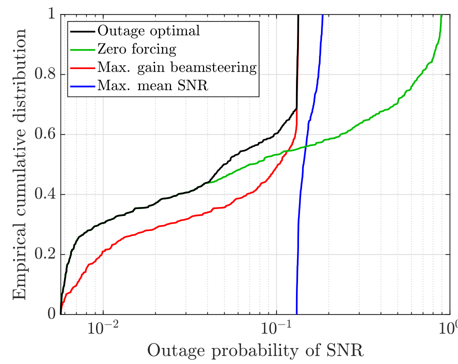

Fig. 2. Empirical distribution of the SNR outage probability for random realizations of the angles $\theta_{r,1}$, $\theta_{r,2}$ with $N = 8$ and $f \approx 0.1$.

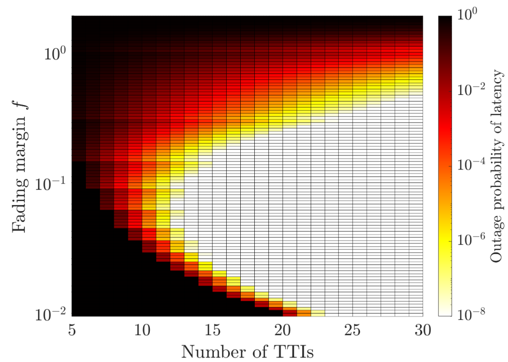

Fig. 3. Outage probability of the transmission latency $P_{\text{out}}^{\text{lat}}(f, \ell_t)$ as a function of the SNR fading margin f and the number of TTIs ℓ_t with $N = 8$ and a single realization of $\theta_{r,1} \approx -15°$ and $\theta_{r,2} \approx 40°$.

$\theta_{r,1}, \theta_{r,2} \sim \mathcal{U}(-90°, 90°)$ and average our results over 500 random AoD realizations. For each of these, we simulate 10^5 random realizations of the phases $\Psi_{r,1}, \Psi_{r,2}$ to accurately determine the SNR outage probability.

A. *Outage Probability of SNR*

We first consider a single antenna array $R = 1$ with $N = 8$ antenna elements and investigate the SNR outage probability of different beamforming strategies as a function of the fading margin f. In addition to the max. mean SNR beamformer and the outage optimal beamformer of Sec. III, we also investigate a zero forcing (ZF) beamforming strategy that nulls the signal over the second specular component by setting $c = 1$ in (5), which leads to Rician fading of the effective SISO channel. Furthermore, we consider a max. gain beamsteering approach that aligns the beamformer with the first specular component by setting $\mathbf{f}_r = \bar{\mathbf{h}}_{r,1}$; notice, this corresponds to $c = \sqrt{1 - \left|\bar{\mathbf{h}}_{r,2}^{\mathsf{H}} \bar{\mathbf{h}}_{r,1}\right|^2}$ and $\varphi = \arg\left(\bar{\mathbf{h}}_{r,2}^{\mathsf{H}} \bar{\mathbf{h}}_{r,1}\right)$ in (5) and is thus also a feasible solution of the line search.

The corresponding outage probabilities of these beamforming methods are shown in Fig. 1. The solid lines represent theoretically calculated outage values according to (11), whereas the marked points are simulated values. We observe that the outage optimal beamforming strategy achieves the lowest outage probability. However, its gain over max. gain beamsteering is not significant. The worst performance is achieved by the ZF approach. Notice though that these results are averaged over random realizations of the AoDs. For a given fixed realization of the AoDs, the ZF approach can still outperform the others.

This is shown in Fig. 2, where we plot the empirical cumulative distribution of the outage probability for randomly drawn AoDs at a fixed fading margin of $f \approx 0.1$. Here we observe that in more than 50 % of the cases ZF is actually better than max. gain beamsteering; however, in the other cases its performance is so poor that the average outage probability is heavily biased towards the larger values. We also observe that our outage optimal design basically switches between ZF and max. gain beamsteering, with a relatively small transition region where it outperforms both. Maximizing the mean SNR appears to provide very little variation in the achieved outage probability; however, its outage performance is overall worse than max. gain beamsteering.

B. *Latency Investigations*

In this section, we investigate the latency performance according to the framework of Sec. IV. We consider a packet size of $N_p = 3 B_c T_c \log_2\left(1 + \bar{\gamma}_r / \sigma_n^2\right)$; that is, with a fading margin of $f = 1$, the system would need at least three error-free TTIs to transmit the packet.

In Fig. 3, we plot the outage probability of the latency $P_{\text{out}}^{\text{lat}}(f, \ell_t)$ according to (19) for a given fixed random realization of the AoDs $\Theta_{r,1} \approx -15°$ and $\Theta_{r,2} \approx 40°$ employing our outage optimal beamformer. If we prescribe an outage upper bound of say $P_{\text{out,max}}^{\text{lat}} = 10^{-6}$, we observe that the lowest latency of $\ell_t = 12$ TTIs is achieved with a fading margin of $f \approx 0.1$. With a smaller fading margin, the SNR outage probability $P_{\text{out}}^{\text{snr}}(f)$ would be smaller; however, the latency would be increased because the transmission rate $R(f)$ would be too small. Conversely, with larger f, the transmission rate would be higher, but $P_{\text{out}}^{\text{snr}}(f)$ would be too large.

We next investigate the average latency performance, averaged over random realizations of the AoDs $\Theta_{r,1}, \Theta_{r,2}$, of the beamforming methods as a function of the number of transmit antennas N. For each random realization, we determine the minimal latency ℓ_t by optimizing over the fading margin according to (15). The corresponding results are shown in Fig. 4. We observe that the average latency of ZF, max. gain beamsteering and outage optimal beamforming reduces with growing number of antennas. The average latency of the ZF approach is significantly higher than max. gain beamsteering;

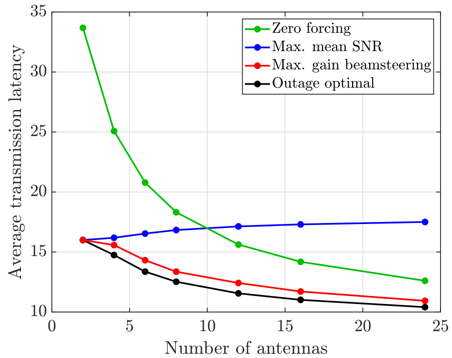

Fig. 4. Average transmission latency in TTIs versus number of antennas N for different beamforming strategies, considering an outage probability of $P^{\text{lat}}_{\text{out,max}} = 10^{-6}$ and a single antenna array $R = 1$.

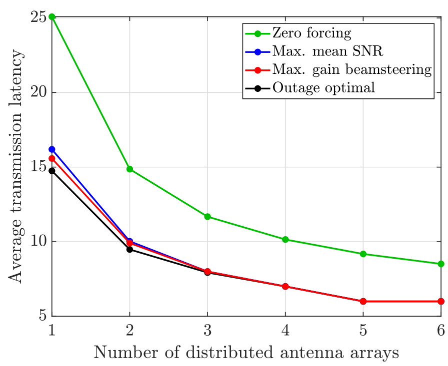

Fig. 5. Average transmission latency in TTIs versus number of distributed antenna arrays R for different beamforming strategies, considering an outage probability of $P^{\text{lat}}_{\text{out,max}} = 10^{-6}$ and $N = 4$.

however, similar to our observation above, for a significant proportion of the random realizations of the AoDs $\Theta_{r,1}, \Theta_{r,2}$, ZF actually achieves lower latency than max. gain beamsteering. We also observe in Fig. 4 that the latency of the max. mean SNR approach even increases with growing N. This effect is partly due to the employed normalization of our directional channel model: we consider normalized directional channel vectors, i.e., $\|\mathbf{h}_{r,i}\| = 1$, irrespective of the number of antennas. With increasing N, the angular resolution of the antenna array increases and it is therefore more and more difficult to find a beamforming direction that extracts a significant amount of power out of both specular components.

Finally, we investigate the average transmission latency as a function of the number of antenna arrays R, considering $N = 4$ antennas per array. The corresponding results are shown in Fig. 5. We observe that the macroscopic diversity provided by the DAS can give a significant reduction in the average transmission latency. Furthermore, the difference between max. gain beamsteering and our outage optimal beamformer diminishes, suggesting that max. gain beamsteering is a viable practically relevant beamforming approach.

VI. Conclusion

TWDP fading can lead to severe outage conditions in wireless communications. In this paper, we have proposed an outage optimal beamformer design for transmission over MISO TWDP channels and demonstrated its performance advantage over more common heuristic beamforming approaches. We have investigated not only the outage probability but also the latency performance of the proposed beamformer, and exhibited significant latency reductions with growing number of antennas and increasing number of distributed antenna arrays.

In our paper, we have focused on the comparatively simple situation of a single-user transmission. Even though this is relevant, e.g., for transmissions in the millimeter wave band, future work should address the even more challenging situation of multi-user multiple-input mulitple-output (MIMO) transmission and multi-cell interference under TWDP fading.

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