Impact of Polarization on Distributed Optical Beamforming

Srishti Sharma and Swades De

***Abstract*—In this letter, we propose the concept of distributed optical beamforming and its feasibility requirements. We quantify the importance of polarization beamforming among the beams for maximized beamforming. As a first step towards distributed polarization beamforming (DPolB), in this work we consider coplanar sources and receiver for beamforming and demonstrate the critical requirement of polarization alignment for maximized beamforming gain. We determine theoretically and verify via simulations the optimal polarization angle at the sources such that the electromagnetic waves interfere constructively at the receiver. Subsequently, we propose a novel method for automated polarization beamforming of multiple optical beams independent of source locations. Performance of the proposed DPolB is analytically captured in terms of average beamforming gain and verified using simulations. We also verify that the reduction in gain caused by slight deviation from coplanarity is not significant.**

***Index Terms*—Distributed beamforming, polarization beamforming, wireless power transfer, wireless information transfer.**

I. Introduction

Distributed beamforming is a cooperative communication technique in which power from N independent sources can be constructively combined at an intended location to scale receive power up to N^2 times. This technique has been adopted in radio frequency (RF) domain to increase the wireless information and power transfer efficiencies [1], [2]. We study it in optical wireless domain for relatively long range applications, and propose distributed optical beamforming (DOB). The term 'distributed' implies that the sources operate independently. Similar to RF beamforming, a critical challenge for DOB is carrier synchronization, which includes the alignment of frequency, phase, and polarization of the received beams.

A few prior works studied enhancement of optical wireless power transfer (WPT) efficiency [3]–[5]. Generally, lasers are used as sources for optical WPT over large distances; but employing high powered lasers can breach the human safety limit. For example, ANSI Z136.1 regulation for human safety at 1550 nm is ≤ 100 mW/cm^2 [6]. Deployment of multiple low power sources to achieve this goal is of high interest.

Carrier phase synchronization for distributed transmit beamforming was proposed in the RF domain [1] using master-slave architecture. Distributed WPT was studied in [7] considering frequency and phase synchronization. Optical beamforming for WPT was proposed in [8] that used beam steering and focusing; beamforming efficiency was low, 1.3%, possibly because phase and polarization alignments were not considered for the white light source. Biased beamforming for multi-LED system was proposed in [9] to maximize the data rate. Most prior works on beamforming considered frequency and phase synchronization [7], [10], where they either considered polarization synchronization is already achieved or overlooked it. However, as we demonstrate in this paper, N-fold beamforming gain cannot be achieved without polarization alignment.

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DOB task can be divided into two parts: (1) distributed polarization beamforming (DPolB) where the beam polarization states are adjusted to maximize the total received intensity, when all the sources are frequency and phase aligned; (2) distributed phase beamforming (DPB) where the phases of the beams are aligned to increase the received intensity, when the frequency and polarization states are aligned. DPB can be realized using the phase synchronization method in [11]. The study in this paper focuses on achieving DPolB.

Our key contributions are as follows: $1)$ The idea of DOB is proposed and it is mathematically proven that beamforming is incomplete if polarization vector of the beams are not uniquely aligned at the receiver. $2)$ It is shown that, alignment of sources at any random polarization angle is insufficient for DOB. $3)$ It is also demonstrated that, when the sources and the receiver are coplanar, vertically polarized beams offer perfectly co-polarized input at the receiver independent of the source locations. $4)$ It is proven that, sources being horizontally polarized is equivalent to the scenario where all sources are linearly polarized with random polarization angles. $5)$ The system performance is quantified in terms of average beamforming gain, and it is shown that for large N, up to 2.467 gain is achievable on top of DPB. $6)$ To achieve the aforementioned gains, a self-contained transmitter-end vertical polarization alignment setup is proposed for independent optical sources.

To the best of our knowledge, the importance of unique polarization alignment for DOB as well as a setup to achieve it have not been reported before in the literature.

Notations: $\|x\| = \sqrt{x^H x}$ denotes $\mathcal{L}_2$ norm of a complex number x, where H is the Hermition operator. I^+ denotes a set of positive integers. U denotes uniform random distribution.

II. DOB System Model

We consider a generalized system model for DOB (DPB+ DPolB) in Fig. 1, and develop a mathematical description for the source field. Each transmitter consists of a laser and a beamforming assembly. The receiver consists of a photodetector for information or energy reception. RF antennas at the transmitter and receiver are proposed for beam steering which can be realized using any localization algorithm. The optical beam is considered to experience distance dependent attenuation with path loss factor α. Turbulence induced polarization

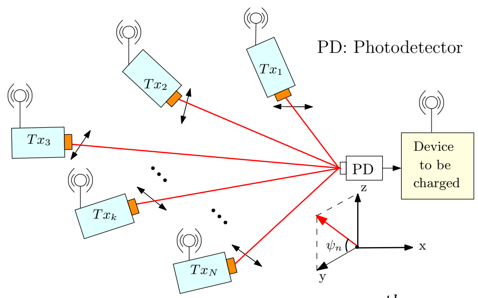


Fig. 1: Generalized DOB system model. Tx_k: k^{th} transmitter unit.

variation in signal propagation is considered negligible [12], [13]. We assume perfect pointing of the source to the receiver.

A. Optical Source

Consider N independent monochromatic laser sources with identical frequency. A generalized form of the linearly polarized electric field of source n in source plane is given by [14]

$$\mathbf{E}_n(\mathbf{r},t) = A_n e^{\left[\frac{-\alpha d_n}{2} + j(\mathbf{k}_n\cdot\mathbf{r}_n - \omega t + \Phi_n)\right]}\mathbf{p}_n \tag{1}$$

where A_n is the amplitude, ω is the angular frequency, d_n is the distance between each source-receiver pair, $\mathbf{r}_n = x_n\hat{a}_x + y_n\hat{a}_y + z_n\hat{a}_z$ is the position vector and $\mathbf{k}_n = k(\sin\theta_n\cos\phi_n\hat{a}_x + \sin\theta_n\sin\phi_n\hat{a}_y + \cos\theta_n\hat{a}_z)$ is the wave vector for the n^{th} source. Further, θ_n denotes the elevation angle, ϕ_n denotes the azimuth angle, and $k = \frac{2\pi}{\lambda}$ is the wave number with λ representing the wavelength of the field. Φ_n is the total initial phase offset of the field at position $\mathbf{r}_n$.

Motivated by ground to ground communication and power beaming applications using optical sources [15], in this work we analyze a 2D system model with coplanar sources and receiver. For a beam lying in x-y plane, polarization vector $\mathbf{p}_n = \sin\phi_n\cos\psi_n\hat{a}_x - \cos\phi_n\cos\psi_n\hat{a}_y - \sin\psi_n\hat{a}_z$, where ψ_n is the polarization angle or orientation of electric field with respect to y-axis. It is notable that, (1) characterizes a beam defined on a single phase only, which effectively models a pencil beam and is valid at every point in space. Therefore, the scope of inferences derived in this work can be extended to any other wavefront geometry without loss of generality.

B. Total Received Intensity

N individual electric fields, as expressed by (1), interfere at a receiver placed at the origin. Using the principle of mathematical induction, the received intensity is obtained as

$$\begin{aligned} I_R = \left\|\sum_{n=1}^{N}\mathbf{E}_n\right\|^2 &= \sum_{m=1}^{N} A_m e^{-\alpha d_m}\sum_{n=1}^{N} A_n w_n \\ &\times\left(\cos(\mathbf{k}_m\cdot\mathbf{r}_m - \mathbf{k}_n\cdot\mathbf{r}_n + \Phi_n - \Phi_m)\right)\mathbf{p}_m\cdot\mathbf{p}_n \end{aligned} \tag{2}$$

where $w_n = e^{-\alpha\frac{\epsilon_n}{2}}$ and $\epsilon_n = d_n - d_m$. Our aim is to demonstrate the effect of polarization synchronization, assuming DPB. (2) indicate that w_n affects the magnitude of the total intensity, not the orientation of polarization vectors. Therefore, for mathematical convenience we consider $w_n = 1$ which gives $d_m = d_n = d$. Hence, at the receiver location all the signals are co-phased but may not be co-polarized. *Polarization beamforming is a generalized concept that aims to maximize the received intensity. Therefore, the validity of* (2) *is independent of the type of adopted photodetector. Though for brevity, the analysis is presented with WPT as an application, the idea is also applicable for wireless information transfer.*

III. Analysis of the Impact of Source Polarization

In this section, we analyze the impact of two extreme source polarization angles on receiver intensity at $\mathbf{r} = (0,0,0)$ and determine the optimal polarization angles for DPolB.

A. Effect of Horizontal Polarization

In horizontally polarized electromagnetic (EM) wave, the polarization vector lies in the source-receiver plane.

Claim 1. *For coplanar sources and receiver, if all the sources are horizontally polarized, the average received intensity is dependent on the source distribution.*

Proof. Consider a scenario where all sources are horizontally polarized, i.e., $\psi_n = 0\ \forall\ n \in \{1,\ldots,N\}$. From (2), the total received intensity, $I_R = \sum_{m=1}^{N}\sum_{n=1}^{N} e^{-\alpha d}A_m A_n\cos(\phi_m - \phi_n)$. Since all sources are independently positioned at random locations, ϕ_m and ϕ_n can be considered to be independent and identically distributed (i.i.d.) random variables. Then, the average received intensity can be expressed as

$$\begin{aligned} \mathbb{E}[I_R] = \sum_{m=1}^{N}\sum_{n=1}^{N} e^{-\alpha d}A_m A_n\{&\mathbb{E}[\cos\phi_m]\mathbb{E}[\cos\phi_n] \\ &+ \mathbb{E}[\sin\phi_m]\mathbb{E}[\sin\phi_n]\}. \end{aligned} \tag{3}$$

It is notable from (3) that the average received intensity is a function of the distribution of ϕ_i, $i \in \{1,\cdots,N\}$. □

To impart general fairness to the positioning of the sources, the azimuthal angles are considered uniformly distributed, s.t. $\phi_m \sim U(0,\varphi)$, $\forall m \in \{1,\cdots,N\}$. Therefore, $\mathbb{E}[\cos\phi_u] = (\sin\phi)/\phi$ and $\mathbb{E}[\sin\phi_u] = (1-\cos\phi)/\phi$, s.t. $u := m, n$. Substituting these in (3) and taking $A_m = A$, $\forall m \in \{1,\cdots,N\}$, the average received intensity is given by

$$\mathbb{E}[I_R] = 2e^{-\alpha d}(1-\cos\varphi)\left((NA)/\varphi\right)^2 \tag{4}$$

which shows that the received intensity increases with φ. However, this is true only up to $\varphi = \pi$, i.e., when the sources are distributed on a semicircle, because major components of the field arrive in parallel, adding constructively at the receiver. When this distribution space goes above π, received intensity decreases as the major components of sources combine in anti-parallel, leading to destructive interference. The importance of vertical polarization is demonstrated by contrasting to the scenario with horizontal source polarization. For a large number of sources, the average intensity at center is

$$\mathbb{E}[I_R] = \begin{cases} e^{-\alpha d}\left(\frac{2NA}{\pi}\right)^2, & \text{sources lying on semicircle} \\ 0, & \text{sources lying on circle.} \end{cases} \tag{5}$$

where d is the radius of semicircle or circle. (5) indicates that, when the sources are randomly distributed on a semicircle, the average received intensity varies quadratically with N, which is still $< 50\%$ of maximum achievable beamformed intensity.

Further, the arrangement of sources on a circle leading to 0 intensity at the center is due to the mismatch of polarization angles from the different sources at that location. With an optimum polarization angle at the sources, the mismatch can be eliminated. It is notable that, unlike the spatial phase variation on the PD surface, polarization of the received optical beam is only a factor of source-receiver orientation.

B. Effect of Vertical Polarization

In vertically polarized EM wave, polarization vector is perpendicular to the source-receiver plane.

Claim 2. *For coplanar sources and receiver, if all the sources are vertically polarized, then the received intensity is independent of source positions and is maximum.*

Proof. Consider that, out of N beams k beams received from the distinct sources are not polarization synchronized at the intended receiver. Thus, using (2) total intensity at receiver is

$$I_R^{as} = \sum_{m=1}^{k}\sum_{n=1}^{k} I_{m,n}\cos\gamma_{m,n} + \sum_{m=k+1}^{N}\sum_{n=k+1}^{N} I_{m,n} \tag{6}$$

where $\mathbf{p}_m \cdot \mathbf{p}_n = 1$ if beams are synchronized at receiver, else $\mathbf{p}_m \cdot \mathbf{p}_n = \cos\gamma_{m,n}$. $I_{m,n} = e^{-\alpha d} A_m A_n$ and $\gamma_{m,n}$ is the angle between m^{th} and n^{th} beams at the receiver, given by

$$\begin{aligned}\gamma_{m,n} =& \cos^{-1}(\cos\psi_m\cos\psi_n\cos(\phi_m-\phi_n) \\ &+ \sin\psi_m\sin\psi_n).\end{aligned} \tag{7}$$

Using (2) and (6) we obtain the reduction in received intensity $\Delta I = I_R - I_R^{as}$ due to asynchronization of k sources as

$$\Delta I = \sum_{m=1}^{k}\sum_{n=1}^{k} I_{m,n} - \sum_{m=1}^{k}\sum_{n=1}^{k} I_{m,n}\cos\gamma_{m,n}. \tag{8}$$

From (7), we observe that $\gamma_{m,n}$ is the function of source coordinates and polarization angles. For ΔI to be zero, $1-\cos\gamma_{m,n} = 0 \Rightarrow \gamma_{m,n} = 2\pi i$, $i \in I^+$. Since two sources can never be placed at same location, i.e., $\phi_m \neq \phi_n \;\forall\, \phi_m, \phi_n$, this condition will only be satisfied when $\psi_m = \psi_n = \frac{\pi}{2}$, otherwise it becomes a function of source coordinates. □

Remark 1. *The assumption of $\phi_m = \phi_n$ does not alter the solution $\psi_m = \psi_n = \frac{\pi}{2}$. In such a special case, owing to coaligned source beams, the polarization angles being aligned to any arbitrary value results in beamforming at the receiver.*

IV. Polarization Beamforming (DPolB) Gain

In this section, we evaluate the performance of the proposed DPolB. For this, we propose a figure of merit, namely, polarization beamforming gain. *DPolB gain is defined as a ratio of average received intensity with polarization beamforming and that without polarization beamforming.*

Without the loss of generality, we assume that all sources involved in beamforming have equal intensity, i.e., $A_m = A \;\forall\; m \in \{1, \cdots, N\}$. From (2), the total received intensity after beamforming at location $\mathbf{r} = (0, 0, 0)$ can be written as

$$\begin{aligned}I_R = e^{-\alpha d} A^2 \sum_{m=1}^{N}\sum_{n=1}^{N} &[\cos(\phi_n-\phi_m)\cos\psi_n\cos\psi_m \\ &+ \sin\psi_n\sin\psi_m].\end{aligned} \tag{9}$$

In the absence of DPolB, with $\psi_m \sim U(0,\pi)$, $\forall\, m \in \{1, \cdots, N\}$, the average received intensity is given by

$$\begin{aligned}I_{RW} = \mathbb{E}[I_R] =& e^{-\alpha d} A^2 \Big\{ \sum_{\substack{m=1\\ m\neq n}}^{N}\sum_{n=1}^{N} [\cos(\phi_n-\phi_m) \\ &\times \mathbb{E}[\cos\psi_n]\mathbb{E}[\cos\psi_m] + \mathbb{E}[\sin\psi_n]\mathbb{E}[\sin\psi_m]] + N \Big\} \\ =& e^{-\alpha d} A^2 \big(N + N(N-1)\,(2/\pi)^2\big).\end{aligned} \tag{10}$$

Consider that there is a deviation δ_n in vertical polarization of n^{th} source. Then the total intensity at the receiver is

$$\begin{aligned}I_R = e^{-\alpha d} A^2 \sum_{m=1}^{N}\sum_{n=1}^{N} &[\cos(\phi_n-\phi_m)\sin\delta_n\sin\delta_m \\ &+ \cos\delta_n\cos\delta_m].\end{aligned} \tag{11}$$

(11) indicates that the total received intensity is a function of source coordinates. Hence, even if $\delta_n = \delta_m$ (i.e., all the sources are aligned perfectly but not vertically polarized), then also there will be power reduction. Using the fact that ϕ_n and δ_n are i.i.d. random variables, (11) can be written as

$$\begin{aligned}I_R =& e^{-\alpha d} A^2 [N + N(N-1)\{\cos(\phi_a-\phi_b)\sin\delta_a \\ &\times \sin\delta_b + \cos\delta_a\cos\delta_b\}]\end{aligned} \tag{12}$$

where $a, b \in \{1, \cdots, N\}$ s.t. $a \neq b$ [1]. By taking the expectation of (12), the average intensity $\mathbb{E}[I_R]$ is found as

$$I_{RB} = \mathbb{E}[I_R] = e^{-\alpha d} A^2 [N + N(N-1)\mathbb{E}[\cos^2\delta_n]] \tag{13}$$

where $\mathbb{E}[\sin\delta_n] = 0$, as δ_n is symmetric about zero.

Remark 2. *When $\delta_n = 0 \;\forall\; n$, i.e., vertically polarized sources, the average received intensity is proportional to N^2, which is the maximum possible value with DPolB. Thus, vertical polarization forms the best case scenario.*

Remark 3. *For $\delta_n = \frac{\pi}{2} \forall n$, i.e., horizontally polarized sources, the received intensity is proportional to N. Thus, horizontal polarization offers the poorest beamforming gain.*

DPolB gain G_p is obtained as the ratio of (13) and (10):

$$G_p = \frac{1 + (N-1)\mathbb{E}[\cos^2\delta_n]}{1 + (N-1)\,(2/\pi)^2}. \tag{14}$$

(14) indicates that G_p depends on the accuracy of vertical polarization alignment and the number of the sources involved.

V. Proposed Polarization Alignment Method

We now present a transmitter-end polarization angle correction method to maximize the beamforming gain in DPolB, as presented in Section IV. The overall objective is to make sources vertically polarized without significantly sacrificing on the signal intensity. Fig. 2 shows the block diagram of the proposed polarization offset correction module at n^{th} optical transmitter. The proposed methodology operates automatically when the laser is switched on for power beaming.

To orient any random polarization angle ψ_n to vertical (along a_z), optical source (Laser_n) output is incident on

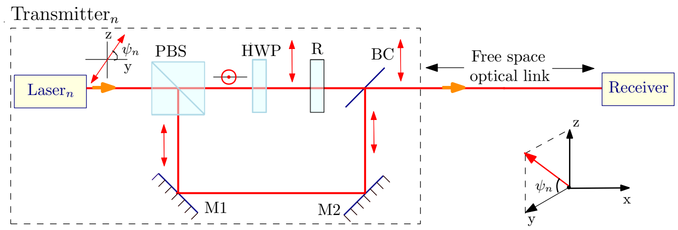
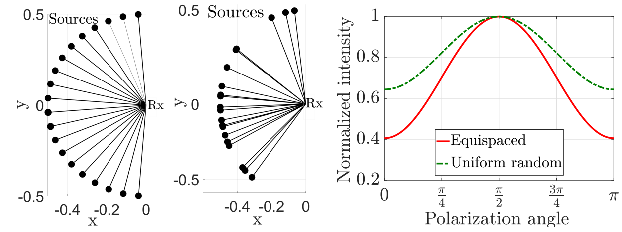


Fig. 2: Proposed transmitter-end polarization alignment module. HWP: half wave plate, BC: beam combiner, PBS: polarization beam splitter, R: retarder, M: mirror, ψ_n: polarization angle of source n.



(a) (b) (c)

Fig. 3: (a) Equispaced and (b) uniform random source distribution on the periphery of semicircle around the receiver. (c) Variation of normalized intensity at the receiver location with polarization angle.

a polarization beam splitter (PBS) which divides the laser beam into two orthogonal components. The reflected beam is s-polarized, i.e., along $\hat{a}_z$ and the transmitted beam is p-polarized, i.e., along $\hat{a}_y$. Thus, the reflected beam is polarized in the desired direction and the transmitted beam polarization is orthogonal to the desired direction. The p-polarized beam is then incident on a half wave plate which rotates the plane of polarization of the beam by 90°to along $\hat{a}_z$. Also, since the two outputs of the PBS are in orthogonal directions, mirror M1 is used to bring the reflected beam parallel to the transmitted beam. It is further reflected by mirror M2 so that the two beams can be combined at the BC. The retarder is used to compensate for the extra path length dependent phase difference acquired by the reflected beam. Ignoring the stray losses, the combined intensity is equal to the incident intensity. The output of BC is the vertically polarized, which is optimum for beamforming at the receiver. *Note that, this work does not concern with the photodetection properties of the receiver; the focus is on the concept of polarization beamforming and a transmitter-end polarization correction methodology.*

It may be noted that, in polarization controller based correction setup proposed in [16], polarization angles of the beams are modified as per the feed-forward and feedback signals from the control circuit and the setup operates in real time. *By the virtue of PBS, our proposed setup is a feedback independent, self-contained assembly and requires no electrical or mechanical control of the components.*

VI. Results and Discussion

The impacts of source polarization are studied via MATLAB simulation of DOB system presented in Section II, with $N = 20$ sources placed on the periphery of a semicircle of radius 50 cm in x-y plane and receiver at the origin. Two arrangements of sources are considered: equispaced (Fig. 3a) and uniform random (Fig. 3b). Operating wavelength is 1550 nm. Attenuation constant α is 0.2 dB/km (for clear sky) [17].

A. Performance with Co-polarized Sources

Fig. 3c demonstrates the effect of co-polarized sources. From the figure we observe that, for both equispaced and uniform random source distribution, when source polarization angles are all $\frac{l\pi}{2}$, where $l \in I^+$, the received intensity is maximum. As the polarization angle changes to $\frac{l\pi}{2} \pm \rho$, where $\rho \in [0, \frac{\pi}{2}]$, the received intensity decreases sinusoidally. We observe that, for the case presented, the equispaced source location distribution is not superior to uniform random distribution in terms of power transfer for co-polarized sources.

Remark 4. *Unlike co-phasing in DPB, co-polarization of all sources to any chosen common polarization angle is not a sufficient condition for constructive interference in DPolB.*

B. The Case of Horizontal Polarization

Fig. 4a shows the peculiar case of all sources being horizontally polarized. We observe that when sources are randomly distributed on a semicircle and circle, the total received intensity is respectively less than 50% and 10% of the expected maximum beamformed intensity. This is because, for every source located at ϕ_n, there exists a source approximately at the location $\phi_n + \pi$ whose polarization vectors are nearly anti-parallel, resulting in effective intensity close to zero. These simulation results conform with theoretical result in (5).

C. Effect of Source Polarization and Location Distribution

Fig. 4b compares the received intensity variation with N for different source polarization angles with equispaced and uniform random source distribution of Figs. 3a and 3b.

1) $\psi_n = \frac{\pi}{2}$: The received intensity is observed to increase as N^2 only when sources are co-polarized with $\psi_n = \frac{\pi}{2}$ for both equispaced and uniform random source distributions. This conforms with Claim 2 in Section III.

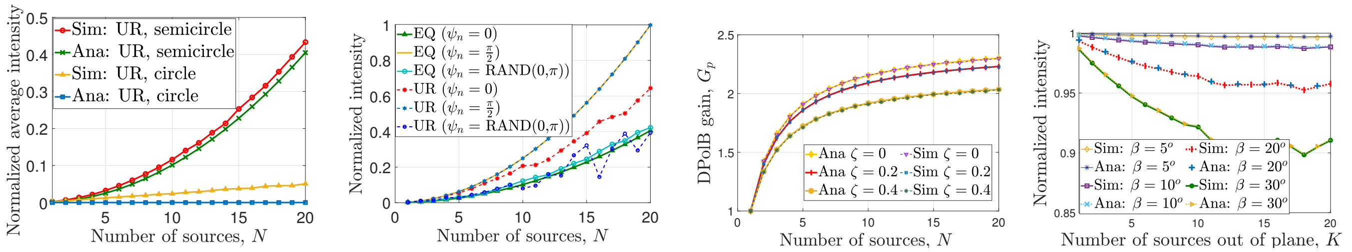
2) $\psi_n = 0$: Performance is degraded when all the sources are horizontally polarized. Performance with the uniform random distribution in Fig. 3b is better than equispaced distribution because sources in the former are nearly clustered together, thereby causing relatively constructive interference.

3) $\psi_n = \text{RAND}[0, \pi)$: For equispaced source distribution with random polarization, average performance is similar to the case with $\psi_n = 0 \ \forall n \in \{1, \cdots, N\}$. For uniform random source distribution the received intensity variation is not smooth, because addition of each source may increase or decrease the received intensity based on its location and polarization orientation. However, a long-run average performance is noted to be similar to the horizontal source polarization.

D. DPolB Gain

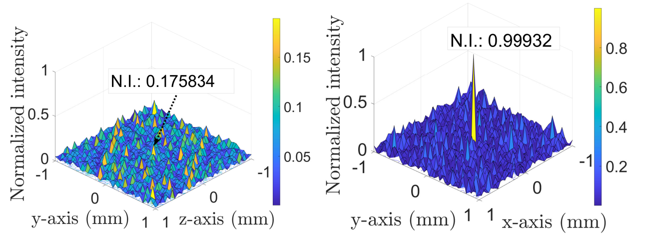
Consider polarization alignment error $\delta_n \sim U(-\zeta\frac{pi}{2}, \zeta\frac{pi}{2})$, where $\zeta \in (0, 1)$. Then, by (14), G_p is expressed as

$$G_p = \frac{1 + 0.5(N-1)(1 + \text{sinc}(\zeta))}{1 + (N-1)\,(2/\pi)^2}. \quad (15)$$



(a) (b) (c) (d)

Fig. 4: (a) Normalized average received intensity with horizontally polarized sources; (b) Normalized received intensity for EQ and UR (Fig. 3b) source distribution; (c) Average DPolB gain; (d) Normalized intensity with K among $N = 20$ uniform random distributed sources out of the intended plane by angle β. EQ: equispaced; UR: uniform random; HP: horizontally polarized; VP: vertically polarized.



(a) (b)

Fig. 5: Normalized intensity (N.I.) in y-z plane for uniform random source distribution: (a) without DPolB, (b) with DPolB.

In Fig. 4c, G_p versus number of sources N shows that, even for $N = 2$, $G_p > 1$. For large N, $G_P \approx \frac{\pi^2}{8}(1 + \text{sinc}(\zeta))$, and for perfect beamforming (for $\delta_n = 0$), $G_p = 2.467$. Fig. 4c also captures the effect of polarization alignment error. For example, with $N = 15$ and polarization alignment error $\approx 36°$, DPolB gain reduces by $\approx 13\%$. These results further demonstrate the significance of polarization beamforming.

Fig. 5a shows the received intensity for uniform random source location and polarization distributions, on a 2×2 mm^2 receiver aperture located at the center. Fig. 5b shows that the proposed polarization correction setup in Fig. 2 enables constructive interference at the desired location. Further, the simulation results in Fig. 4d capture the impact of deviation from coplanarity for uniform random source distribution of Fig. 3b. For example, with 20 distributed transmitters, 5°misalignment results in $\approx 1\%$ intensity reduction; the penalty is $\approx 5\%$ at 20°misalignment. Therefore, under realistic non-coplanarity in the setup, the reduction in gain is limited to ≈ 0.05, as demonstrated through the numerical results and Fig. 4d.

Remark 5. *Average gain reduction as a result of K 'out of plane' sources at a deviation angle of β, s.t. $\phi_{m \in \{1,\cdots,N\}} \sim U(0, \varphi)$ is given by* $R_a = 1 - \frac{1}{N^2}\left[(K \cos\beta + N - K)^2 + \left[2(K-1)\left((1-\cos\varphi)/\varphi^2\right) + 1\right] K \sin^2\beta\right]$.

VII. Conclusion

This study has demonstrated that polarization states of the interfering beams significantly impact the received intensity. The effect of source polarization on DOB has been analytically captured and verified via simulations, and it has been concluded that vertical polarization offers the best performance. A transmitter-end polarization alignment method has been proposed which is sufficiently robust for any source-receiver distribution in a plane with unique normal. The DPolB gain is noted to be ≥ 1.5 for $N > 2$. It has also been demonstrated that the loss of coplanarity of sources does not significantly affect the gain. These results highlight the importance of additional polarization alignment on the DOB gain.

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