

# Distributed Polarization Beamforming for Optical Wireless Power Transfer

Srishti Sharma and Swades De

Department of Electrical Engineering and Bharti School of Telecommunication  
Indian Institute of Technology Delhi, New Delhi, India

**Abstract**—Wireless power transfer (WPT) via electromagnetic waves provides a promising solution to perpetual energy delivery to devices which are hard to charge or replace. To this end, we leverage distributed beamforming with optical sources. This work proposes a framework for distributed optical beamforming that addresses a key challenge of polarization synchronization across multiple independent optical transmitters for non-coplanar source-receiver arrangement. We show that unique polarization orientation is not sufficient in non-coplanar arrangement. Thus, we propose a polarization synchronization module which aligns the source beams from arbitrary direction in one plane to achieve maximum beamforming gains. We also propose and compare different polarization detection configurations and mathematically capture the fraction of source beam power required for polarization detection. We experimentally validate the efficacy of the optimal polarization in achieving beamforming gains. Distributed optical beamforming-assisted power maximization can be used to enhance end-to-end wireless power transfer efficiencies.

**Index Terms**—Distributed beamforming, polarization, wireless power transfer, polarization synchronization

## I. INTRODUCTION

Distributed beamforming technology enables constructive interference of  $K$  independent spatially separated transmitters at the receiver node to obtain  $K$ -fold beamforming gains. This technology can be utilized for wireless power transfer (WPT) specifically in optical domain as it allows short as well as long-range WPT, power transfer in kW levels, and is immune to electromagnetic interference. Generally, lasers are used as sources as they provide high powered, coherent, monochromatic and directional beams, and act as an efficient source for optical power transfer over large distances. However, laser power cannot be increased beyond 1kW without compromising with beam quality. Also, high intensity beams can exceed safe exposure limit [1]. Thus, it is still challenging to transfer watt-level of power over large distances.

### A. Literature Review and Motivation

WPT using optical sources has been proposed in a few prior works [2]–[4], and numerous efforts have been made to increase the power transmission efficiency [5], [6]. The work in [7] reviews the recent progress made so far in the area of high intensity laser power beaming. Light field optimization for optical WPT has been studied in [8]. The work in [9] proposes a dual-closed loop controller which optimizes the duty cycle of the laser input current to improve transmission efficiencies. Although various demonstrations for

laser power beaming have been reported, it is still considered in the development stage due to low end-to-end power conversion efficiencies [6]. One of the promising solution for large power requirements is to transfer power using multiple sources employing distributed optical beamforming. However, the major challenge for distributed beamforming is phase and polarization synchronization of received beams.

The first work involving carrier synchronization for distributed transmit beamforming was proposed at radio frequencies [10], where the authors used master-slave architecture for carrier phase synchronization. The authors in [11] studied distributed WPT system without and with frequency and phase synchronization, and observed that optimal distributed beamforming is better in terms of coverage probability. The authors in [12] proposed biased beamforming concept at visible light frequencies jointly optimizing the beamforming and biasing for data rate maximization. The work in [13] proposed WPT using optical beamforming wherein they considered steering and focusing of optical beam with transmission efficiency of 1.3%. Most previous works on beamforming have focused on frequency and phase synchronization [10], [14], [15], generally assuming that polarization synchronization is already in place or neglecting it altogether. Recently, polarization beamforming works have been proposed at radio frequencies [16], [17]. Additionally, the work in [18] studies the impact of transmitter and receiver polarization on received power. Furthermore, the work in [19] utilized polarization aspect in distributed optical beamforming and proposed optimal polarization for coplanar transmitter-receiver arrangement. Nevertheless, transmitter could lie arbitrarily in the Euclidean space, a generalized polarization synchronization methodology is required.

For energy transfer, one can use either transmitter-end or receiver-end beamforming, in which the capability to control phase and polarization of beams are respectively with transmitter or receiver. The transmitter-end scheme generally requires optical channel state information (CSI) feedback at the transmitter, whereas receiver-end can operate without CSI feedback but requires processing capability at receiver [20], [21]. In this work, we propose receiver centric polarization synchronization module for alignment of sources arbitrarily placed in the Euclidean space. *To the best of our knowledge, this is the first work that focuses on polarization synchronization of distributed sources for non-coplanar arrangement.*

## B. Contributions

The main contributions of this work are as follows:

- 1) We study the impact of source polarization on distributed beamforming when the sources and the receiver lie arbitrarily in the Euclidean space.
- 2) We show that unique polarization vector orientation at the receiver is insufficient to attain maximum beamforming performance for sources in arbitrary arrangement.
- 3) We propose a receiver-end polarization synchronization module which allows us to achieve  $K$ -fold beamforming gains in generalized transmitter-receiver scenario.
- 4) We experimentally validate the optimum polarization of the proposed beamforming module, thereby demonstrating the efficacy of our proposed approach.
- 5) We also propose and compare three different configurations for realizing a polarization detection unit based on efficiency, accuracy, and cost.

**Remark 1:** *Arbitrary placement or non-coplanar arrangement of sources and receiver in Euclidean plane refers to a scenario where sources are positioned at arbitrary azimuth and elevation angles.*

## II. SYSTEM MODEL

We consider a scenario where  $K$  sources are randomly deployed in the Euclidean space to wirelessly transfer power to a target node equipped with a photodetector (PD). In the scope of this work, the output of laser is considered as a pencil beam, i.e. it is characterized by a unique phase and polarization angle and suffers negligible divergence. We assume that sources emit monochromatic, linearly polarized light. Polarization properties of such a beam remain unchanged on propagation [22]. Since, turbulence-induced polarization angle changes are negligible, we assume that the channel does not cause polarization changes [23]. Additionally, we consider that all the transmitters lie in the field of view of the receiver.

A general form of linearly polarized electric field received from the  $k^{\text{th}}$  transmitter located at position  $(d_k, \theta_k, \varphi_k)$  with respect to the receiver is given by

$$E_k(t) = E_{ok} e^{-\gamma d_k} \cos(\beta_k \cdot \mathbf{r}_k - \omega t + \Phi_k) \mathbf{p}_k \quad (1)$$

where  $E_{ok}$  is the amplitude,  $\gamma$  is the attenuation,  $\Phi_k$  is the total phase shift introduced due to propagation distance and channel, and  $\mathbf{p}_k$  is the received polarization vector, which is different than the transmit vector in the reference  $x$ - $y$ - $z$  plane by the virtue of relative transmitter and receiver position,  $\omega$  is the angular frequency,  $\mathbf{r}_k = x_k \hat{a}_x + y_k \hat{a}_y + z_k \hat{a}_z$  is the position vector,  $\beta_k = \beta(\sin \theta_k \cos \varphi_k \hat{a}_x + \sin \theta_k \sin \varphi_k \hat{a}_y + \cos \theta_k \hat{a}_z)$  is the wave vector for  $k^{\text{th}}$  source, which represents the direction of wave propagation.  $\theta_k$  denotes the elevation angle,  $\varphi_k$  denotes the azimuthal angle, and  $\beta = \frac{2\pi}{\lambda}$  denotes wave number,  $\lambda$  is the wavelength of optical wave. For a beam in  $x$ - $y$  plane, polarization vector is  $\mathbf{p}_k = [p_{xk}, p_{yk}, p_{zk}]^T$  where

$$\begin{aligned} p_{xk} &= -\sin \theta_k \sin \varphi_k \cos \psi_k - \cos \theta_k \sin \psi_k \\ p_{yk} &= \cos \varphi_k \cos \psi_k \\ p_{zk} &= \cos \theta_k \sin \varphi_k \cos \psi_k + \sin \theta_k \sin \psi_k. \end{aligned} \quad (2)$$

$\psi_k$  denotes the polarization orientation angle. The total received intensity from the  $K$  sources is obtained using the principle of mathematical induction as [19]

$$I_R = \sum_{l=1}^K \sum_{k=1}^K \mathbf{E}_l^H \mathbf{E}_k = \sum_{l=1}^K \sum_{k=1}^K e^{-\frac{\gamma(d_l+d_k)}{2}} E_{ol} E_{ok} \times \cos((\beta_l - \beta_k) \cdot \mathbf{r} + \Delta\Phi_{lk}) \mathbf{p}_l \cdot \mathbf{p}_k \quad (3)$$

where  $\Delta\Phi_{lk} = \Phi_l - \Phi_k$ . In this work, we focus on polarization synchronization and consider that the phases of the sources are synchronized using adaptive optics techniques [24].

## III. DISTRIBUTED POLARIZATION BEAMFORMING

In this section, we propose polarization synchronization method and different configurations for polarization detector.

### A. Polarization Dependent Analysis for Beamforming

In this subsection, we first analyze the impact of two extreme polarization orientations i.e., horizontal and vertical on the received polarization. We compute received polarization for  $\psi_k = 0$  and  $\psi_k = \frac{\pi}{2}$  which are respectively given by

$$\begin{aligned} \mathbf{p}_k^h &= [-\sin \theta_k \sin \varphi_k, \cos \varphi_k, \cos \theta_k \sin \varphi_k] \\ \mathbf{p}_k^v &= [\sin \theta_k, 0, \cos \theta_k]. \end{aligned} \quad (4)$$

We observe that  $\mathbf{p}_k^h$  is the function of both elevation and azimuth coordinates of the sources. However,  $\mathbf{p}_k^v$  is a function of only elevation angles and is independent of the azimuth angles. Thus, if elevation angles of all sources is made negligible with respect to receiver, i.e.,  $\theta_k = \frac{\pi}{2}$ , sources can be aligned perfectly at the receiver if all of them take vertical polarization orientation. This is achieved through the polarization beamforming module proposed next.

### B. Proposed Polarization Beamforming Module

We propose a receiver-centric distributed polarization beamforming module, which consists of two beam steering units and one polarization synchronization unit as shown in Fig. 1. The beam steering unit consists of multiple spatial light modulators (SLM) arranged sequentially forming a surface. Each SLM receives single beam from a distinct transmitter. Each of the received beams are steered in 3 dimension by the beamsteering unit 1 such that they all lie in the same plane and point in the same direction. After beamsteering, as the beams point along  $x$ -axis, their corresponding polarization vector is defined in  $y$ - $z$  plane as  $[0, \sin \varphi_k \cos \psi_k, -\sin \psi_k]^T$ . After passing through beam steering unit 1, all the beams pass through their respective polarization synchronization unit which consists of polarization detector, offset estimator and polarization controller (PC). The polarization detection element measures the polarization of the received beam which is fed to the offset estimator which computes the offset from the vertical. Based on the computed offset, PC aligns the polarization of the received beams to vertical. The output of the polarization synchronization unit after rotation in  $y$ - $z$  plane is given by

$$\mathbf{p}_k^s = \begin{bmatrix} \cos \psi_k^p & -\sin \psi_k^p \\ \sin \psi_k^p & \cos \psi_k^p \end{bmatrix} \begin{bmatrix} \sin \varphi_k \cos \psi_k \\ -\sin \psi_k \end{bmatrix} \quad (5)$$

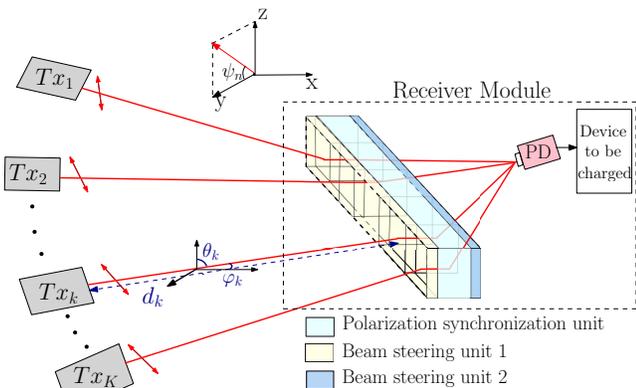


Fig. 1. Proposed receiver end polarization beamforming module

where  $\psi_k^p$  is computed by the offset estimator. It is then followed by the beam steering unit 2 which points all the beams to the receiver direction. For steering purposes, we assume that the location of transmitters and PD are known to the polarization beamforming module. Steering can be achieved through the methods proposed in [25], [26]. It is notable that multiple SLM surfaces can be replaced by a single surface if distinct transmitter beams can be managed to fall on spatially separated pixelated area such that each beam can be individually processed for the purpose of steering.

**Remark 2:** The proposed polarization beamforming module reorients the beams from arbitrary directions into a single planar configuration and aligns polarization of individual beam to vertical.

### C. Polarization Detector Configurations

Fig. 2 show three configurations for polarization detection where  $\kappa$  fraction of total incident light (captured by  $I_o$ ) is used for polarization angle determination. Objective of the proposed setups is identical but differ in efficiency, accuracy and cost.

1) *Setup I:* The laser output falls on a beam splitter (BS), BS1 which reflects  $\kappa$  fraction of light and transmits the rest. The reflected light is incident on BS2, which divides it into two halves of equal intensity. One portion is incident on a horizontal polarizer (HP), which passes the horizontal component of the beam, followed by the detection at the PD1. Similarly, another portion of the beam passes through the vertical polarizer (VP) followed by PD2. Polarization angle of the laser output beam is determined using the relation

$$\psi_k = \tan^{-1}(I_v/I_h) \quad (6)$$

where  $I_v$  and  $I_h$  are the intensities detected by PD1 and PD2.

2) *Setup II:* The setup in Fig. 2(b) is similar to the one proposed in Fig. 2(a), but with one polarizer less. Polarization angle of the output beam is given by

$$\psi_k = \sin^{-1}(2I_s/I_o) \quad (7)$$

where  $I_s$  denotes intensity of the vertical component of beam detected by PD1. In Fig. 2(b), VP can also be replaced by HP, in which case

$$\psi_k = \cos^{-1}(I_p/I_o). \quad (8)$$

$I_p$  is the horizontal component intensity detected by PD1.

3) *Setup III:* The critical challenge for the configurations in Fig. 2(a) and 2(b) is the alignment of HP and VP. If polarizers are not perfectly orthogonal, then it may cause error in the determination of polarization angle. To address this issue we propose the configuration in Fig. 2(c) which reduces the number of required optical components thereby making the setup cost-effective. It uses a polarization beam splitter (PBS) to obtain horizontal and vertical components of the beam. PBS is advantageous as it provides perfectly orthogonal components. Thus, PBS rules out any chance of error in determination of the polarization angle. Additionally, the proposed configuration reduces the fraction of optical beam required for polarization angle determination due to reduction in the number of components, thereby minimizing reflection and absorption losses. Polarization angle, here again is determined using (6).

Table I compares the three configurations proposed for polarization correction. Description of the symbols used in Table I are given in Table II. Proposed configurations can act as an alternative to expensive in-line polarimeter. Setup III provides the best accuracy among the three, but it is the most expensive due to the use of PBS. However, the cost is still less than that of a single polarimeter.

### D. Evaluation of Optimum $\kappa$ -Ratio

$\kappa$ -ratio can be chosen based on the precision and sensitivity of optical components. A large value of  $\kappa$  will degrade the efficiency of the proposed polarization beamforming module. To determine the polarization of the incident light correctly using the polarization correction blocks proposed in Fig. 2, the reflected light  $I_o$  must satisfy the conditions given in Table I. Therefore, the optimum value of  $\kappa$  is given by  $\frac{I_o}{I_i}$ , where  $I_i$  is the light incident by the laser source.

**Remark 3:** Optimum value of  $\kappa$  depends on the individual source power and the sensitivity requirement of optical components employed in the polarization detector configurations.

## IV. RESULTS AND DISCUSSION

In this section, we evaluate the performance of proposed module for distributed polarization beamforming and experimentally validate the optimal polarization imparted by the polarization synchronization unit. MATLAB based simulations are carried out for performance analysis.  $K = 20$  laser sources are considered emitting monochromatic light of 1550 nm. Atmospheric attenuation  $\gamma = 0.2$  dB/Km.

### A. Experimental Verification of Optimum Polarization

In this subsection, we validate the optimum polarization utilized in this work to verify the effectiveness of the proposed polarization beamforming module. Fig. 3(a) shows the experimental setup to analyze the impact of polarization when transmitters and receiver lie in one plane. He-Ne laser is used as an optical source. The laser preprocessing module is used to collimate, control the intensity, and spatially filter the beam. The objective of this module is to generate a point beam.

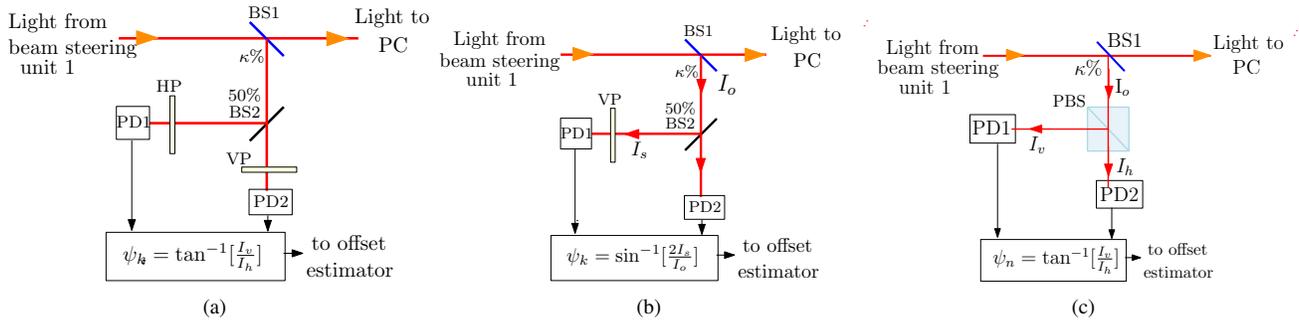


Fig. 2. Polarization detector configurations. (a) Setup 1: Using two polarizers, (b) Setup 2: Using one polarizer, (c) Setup 3: Using PBS.

TABLE I: Comparison of the proposed polarization correction setups.

	Setup I	Setup II	Setup III
<b>Components required to <math>\psi_k</math></b>	50:50 BS, 2 polarizers, 2 photodetectors	50:50 BS, 1 polarizer, 2 photodetectors	PBS, 2 photodetectors
<b>Orthogonality of components</b>	No surety that the two components generated are perfectly orthogonal	No surety that the beam incident on PD1 is perfectly vertical.	PBS ensures that the two components generated are perfectly orthogonal.
<b>BS ratio</b>	BS does not divide the light in a perfectly 50:50 ratio due to AR coating on the second surface		N.A.
<b>Power required to operate</b>	Maximum	Less compared to block I	Least amongst the three
<b>Accuracy</b>	Poor	Poor	Best
<b>Angle of incidence</b>	Perfect 45° incidence at BS required		Perfect 0° incidence at PBS required
<b>Conditions that <math>I_o</math> must satisfy for the setups to operate correctly</b>	$ \frac{I_o}{2} \cos \theta  > \frac{I_{th}}{T_p}$ and $ \frac{I_o}{2} \sin \theta  > \frac{I_{th}}{1-R_{BS}T_p}$	$ \frac{I_o}{2} \cos \theta  > \frac{I_{th}}{T_p}$ and $ \frac{I_o}{2}  > \frac{I_{th}}{1-R_{BS}}$	$ I_o \sin \theta  > \frac{I_{th}}{1-R_{PBS}}$ and $ I_o \cos \theta  > \frac{I_{th}}{1-R_{PBS}}$
<b>Absorption Losses</b>	Maximum (due to large no. of components)	Less compared to block I	Least amongst the three.

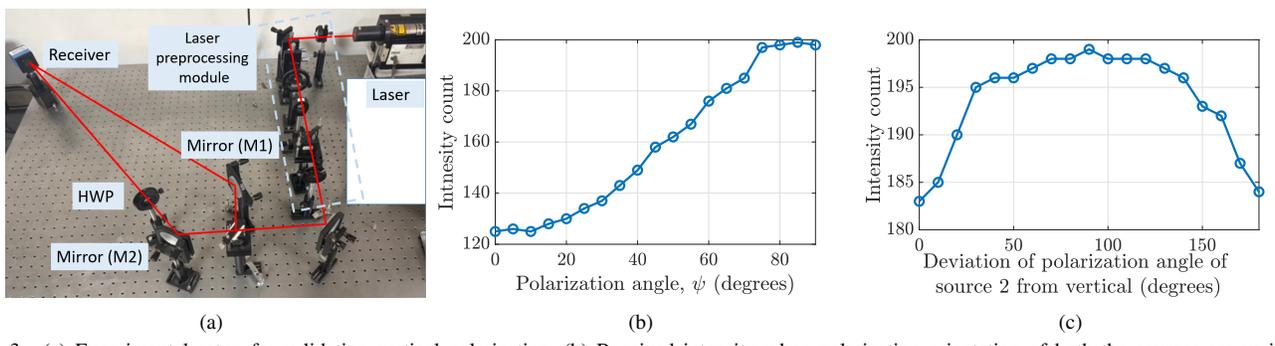


Fig. 3. (a) Experimental setup for validating vertical polarization, (b) Received intensity when polarization orientation of both the sources are varied, (c) Received intensity when polarization one one beam is changed.

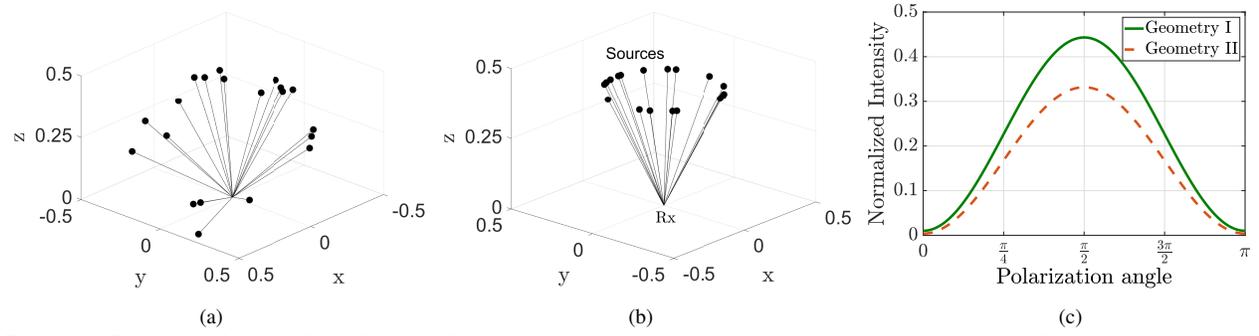


Fig. 4. (a) Transmitter Geometry I (b) Geometry II, (c) Normalized intensity with respect to polarization angle for different transmitter geometries.

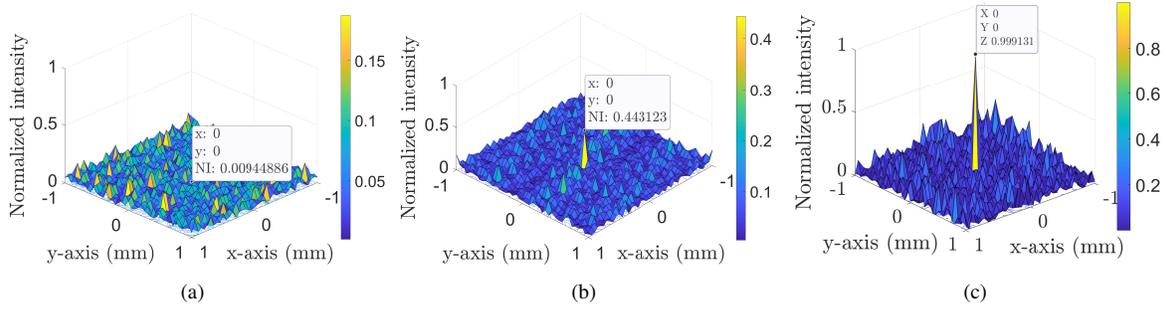


Fig. 5. Normalized received intensity (a) without polarization synchronization (b) with vertical source arrangement, (c) with proposed synchronization module.

TABLE II: List of symbols used in the Table 1.

$I_{th}$	Photodetector threshold intensity
$R_{PBS}$	Reflectance of PBS
$R_{BS}$	Reflectance of BS
$T_p$	Transmittance of polarizer.

A BS is used to generate the two source beams. Therefore, the beam reflected by mirrors M1 and M2 are assumed to be independent source beams whose polarization is required to be synchronized. Due to limited availability of optical components, a setup with only two sources is considered.

The analysis in [19] showed that vertical polarization transfers the maximum possible intensity in coplanar scenario. We experimentally verify this claim to ensure the effectiveness of our proposed beamforming module. Fig. 3(b) shows the total received intensity when polarization orientation of both sources are altered and kept identical. When polarization orientation of both sources are close to  $90^\circ$ , the received intensity is maximum. Fig. 3(c) shows the received intensity when the polarization of one source is varied using HWP and the polarization of the other beam is maintained vertical. The results indicate vertical polarization alignment of beams lying in one plane is sufficient for beamforming purpose.

**Remark 4:** Two source beams are generated from a single source to compensate for the frequency and phase difference between the two beams. Notably, the objective of this work is to demonstrate polarization beamforming assuming that the phases of the combining beams are already synchronized.

### B. Impact of Polarization Angle on Beamforming in Non-Coplanar Scenario

Fig. 4(a) and 4(b) show two different source geometries considered for the analysis. Fig. 4(c) shows normalized received intensity versus polarization angle when all the sources are co-polarized to vertical for Geometry I and Geometry II. Simulation results show that even if the polarization angles of all the sources are aligned, the received power is less than the expected beamformed intensity. It is even less than the total transmitted power even if we neglect the channel losses. Thus, no linear polarization exists for arbitrary source arrangements which is independent of source positions.

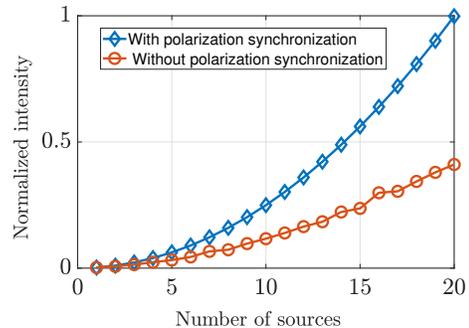


Fig. 6. Performance with proposed polarization synchronization module.

### C. Performance of Polarization Beamforming Module

Fig. 5(a) shows the received intensity for randomly polarized sources over an area of  $2 \times 2 \text{ mm}^2$  with a receiver aperture located at the center. Fig. 5(b) shows the received intensity for vertically polarized sources where we observed improved performance but not maximum. Fig. 5(c) includes polarization beamforming module giving maximum performance.

Fig. 6 shows the received normalized intensity with and without polarization beamforming with respect to number of sources. We observe that the intensity obtained if polarization angles of the interfering beams are not synchronized is less than 50% of the expected beamformed intensity for a large number of sources. Thus, polarization synchronization is necessary for  $K$ -fold beamforming gains.

### D. Impact of $\kappa$ -Ratio on Beamforming

Minimum optical intensity ( $I_o$ ) required to vertically align polarization angle will depend on the choice of optical components and their sensitivity. As the setup III is most efficient we compute  $I_o$  for it. Minimum  $I_o$  required will depend on the specifications of PBS and two PDs. For instance, consider Thorlabs polarizing beam splitter (PBS10-1550). It is a 10 mm laser line cube with AR coating reflectance  $< 0.25\%$ . Assuming the worst case scenario, we take  $R_{PBS} = 2.5 \times 10^{-3}$ . Consider Thorlabs PD (APD310) to detect free space optical input. PD sensitivity is quantified in terms of noise equivalent power (NEP). For APD310,  $\text{NEP (at 1550 nm)} = 13.3 \text{ pW}/\sqrt{\text{Hz}}$ . Thus, minimum detectable intensity is given by

$$I_{th} = \text{NEP} \times \sqrt{\text{BW}} = 0.419 \mu\text{W} \quad (9)$$

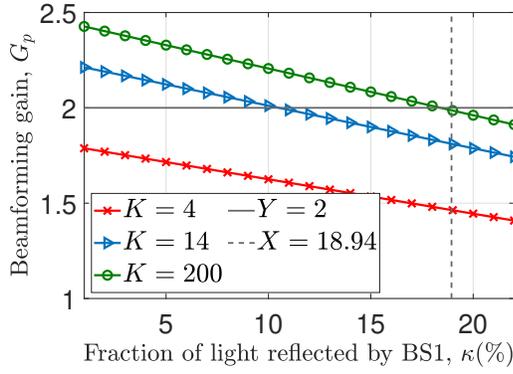


Fig. 7. Variation of average beamforming gain with  $\kappa$ .

where measurement bandwidth (BW) is in the range 5 MHz–1000 MHz. Using the conditions in Table I, the lower limit of reflected light is  $I_o > 0.6 \mu\text{W}$ . For the sources with output powers on the orders of mW, say  $I_i = 1\text{mW}$ ,  $\kappa = 0.06\%$ , which is very low. If source power is on the orders of Watts or kW, then negligible energy is extracted to determine the source polarization. In similar way, the minimum optical intensity required for setup I and setup II can also be obtained.

We also analyze impact of  $\kappa$ -ratio on the polarization beamforming gain,  $G_p$ . It is defined as the ratio of received average intensity with and without polarization beamforming [19]. Since, the standard non-polarizing beam splitters are available in fixed ratio (8:92, 10:90, 30:70, etc.), we determine  $\kappa$  such that the beamforming gains are not affected severely. With polarization beamforming as  $K \rightarrow \infty$ ,  $G_p > 2$  can be achieved if  $0 < \kappa < 18.94$ . Fig. 7 shows the variation in beamforming gain with increase in  $\kappa$ , for different  $K$ . We observe that for the standard Thorlabs plate BS (BSN06),  $\kappa = 10\%$ ,  $G_p \geq 1.5$  and  $G_p \geq 2$  can be obtained if  $K > 5$  and  $K > 20$ , respectively.

## V. CONCLUSION

Through this work, we have demonstrated that a unique polarization orientation of the sources is not sufficient for polarization beamforming when the sources lie arbitrarily in the Euclidean space. We analyzed horizontal and vertical transmit source polarization and concluded that for vertical polarization, received polarization is dependent only on elevation angles of the transmitters. Thus, we proposed receiver-centric polarization beamforming module which first aligns the beams from arbitrary directions in one plane and then perform polarization synchronization. We proposed different polarization detection configurations and compared their efficiencies. We also computed the fraction of power required for polarization detection and analyzed its impact on beamforming gain. We experimentally verified that the vertical polarization arrangement of the synchronization module for all the incoming beams is sufficient for maximum beamforming gains.

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