

BER Analysis of mmWave Bidirectional Relay Network

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Millimeter-wave (mmWave) communication is one of the emerging key components for next generation wireless networks. It exploits unlicensed band at 60 GHz in an indoor environment. Since the wave propagation at mmWave frequencies exhibits a quasi-optical behaviour, the inherent line of sight (LoS) channel models provide new research directions. The major challenges in mmWave communication are higher free space path loss (FSPL) due to its smaller wavelength, quasi-optical behaviour of wave propagation and blockage and penetration losses in indoor scenario. The losses can be compensated using multiple antenna (MA) systems and the sparse channel behaviour of mmWave propagation is compensated by optimal and aligned antenna geometry. However, MA system increases hardware constraints as the number of radio frequency (RF) chains increases. In the recent years, space shift keying (SSK) modulation scheme has been identified as a promising MA technique with single RF hardware requirement. In SSK, only one antenna is activated for transmission at any time instant and the index of this active antenna is used to convey information. Reliable communication between the nodes in a network can be established with the aid of relay node in mmWave communication. In this paper, a bidirectional relay network model using mmWave communication in indoor-LoS environment is considered. The concept of physical layer network coding (PLNC) is applied at the decode-and-forward (DF) relay node to enable the network operates in bidirectional half duplex mode. Specifically, the transceiver at the nodes sends the information symbol by employing SSK modulation and detects the symbol based on the maximum likelihood (ML) detection criterion. By considering optimal antenna geometry operating conditions in LoS environment, the end-to-end bit error rate (BER) probability of the proposed PLNC based bidirectional relay network using SSK in mmWave communication is derived in closed form. Analytical frameworks and findings are also substantiated via Monte Carlo simulations.

Keywords: bidirectional relay network, physical layer network coding, bit error probability, indoor LoS, space shift keying, mmWave communications

1. INTRODUCTION

Communication at mmWave band is one of the emerging areas for next generation wireless communication systems wherein the inherent LoS channel model provides new research directions. It provides multi gigabit-per-second data rate and is used to meet the high expectations of future wireless services such as high level of reliability, low level of latency and constant connectivity. It has wide applications in fifth generation (5G) broadband cellular communication, wireless backhaul connections, wireless personal area networks, vehicular area networks, and mobile ad hoc networks [1]. However, the communication at mmWave frequencies suffers from the challenges such as higher FSPL,

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quasi-optical behaviour of wave propagation, high reflection loss and blockage and penetration losses [2].

The small carrier wavelength at mmWave frequencies enables featuring a large number of co-located antennas. However, with hundreds of antennas employed at mmWave frequencies, the number of RF chains required by mmWave MIMO is also huge. This results in unaffordable hardware cost and energy consumption in mmWave MIMO systems. Antenna selection and analog beamforming methods [3-6] have been used as low RF complexity techniques. Antenna subset modulation [3] is an antenna-level modulation technique that eliminates conventional baseband circuitry and takes advantage of the full antenna array with a limited number of RF chains. This technique is motivated by the large number of antennas available in mmWave communication and the requirements for lower complexity mixed-signal hardware. It uses multiple antennas for directional beamforming at mmWave frequencies to overcome the huge path loss, the atmospheric absorption and the high noise levels. In mmWave communications, the rank of the MIMO channel matrix tends to be low, due to the presence of strong LoS components. In [6], antenna array architecture of multiple beamformers is employed, where each beamformer is spaced sufficiently apart from each other to experience independent fading. The advantage of analog beamforming is that it only requires one RF chain, leading to quite low hardware cost and energy consumption. However, since only the phases of signals can be controlled, the performance loss of analog beamforming is obvious. Also, it requires known channel state information at the transmitter.

The low RF complexity directional modulation techniques of [7-9] are designed entirely around the support of directional transmission and reception including features such as directional device discovery, hierarchical beam selection and beam tracking. A Generalized Spatial Modulation (GSM)-based mmWave communications system is proposed in [10] which has lower number of RF chains than the number of transmit antennas. But, it requires minimum of two RF chains in the transmitter. Spatial multiplexing at mmWave carrier frequencies is investigated for short-range indoor applications by quantifying fundamental limits in LoS environments and then performance in the presence of multipath and LoS blockage [11]. Several technical approaches to the next generation wireless local area network (WLAN) are being considered with the possibility of using the 60 GHz mmWave frequency range.

In this paper, the antenna alignment scheme [17] is applied to single RF chain SSK based mmWave system. Moreover, SSK does not require CSI at the transmitter. SSK modulation is an emerging MIMO wireless communication technique, which was first proposed in [12] as a novel space modulation scheme. It was then extended as spatial modulation (SM) to increase the data rate. Now, SM is defined as a modulation scheme in which transmitted symbols are drawn from both the spatial constellation and the signal constellation, whereas SSK modulation uses only the spatial constellation. Although the spectral efficiency is slightly reduced in SSK, it provides exceptional advantages over SM in terms of low detection complexity and simple transceiver structure [13-15]. Line-of-sight space shift keying (LoS-SSK) [17] is a promising technique used in mmWave indoor-LoS communications. Due to small wavelength of operation, it uses LoS transmission and enables packing of a large number of antennas in the nodes. The receiver in SSK utilizes the distinct received signals from different antennas to discriminate the transmitted messages, which results in simple receiver complexity. Hence, the demodu-

lation and detection of the SSK signalling will be easier to implement. SSK can be effectively used in indoor-LoS scenario by exploiting the optimal antenna array geometry operating conditions, namely orthogonal SSK (OSSK) and biorthogonal SSK (BiOSSK). In [17-19], the LoS operating conditions for mmWave communication to maximize the Euclidean distance between two received symbols are obtained. The pure LoS MIMO channel matrix could be made high rank by employing the spherical wave model, by proper design of the antenna arrays [17]. This is useful for systems which can be subject to strong LoS channels such as for example WLAN systems and other short range communication.

At present, communication using bidirectional relay network has received considerable attention due to its high bandwidth efficiency. In bidirectional relay networks, two source nodes exchange their information with the help of a relay node. PLNC protocol is used to exchange the message between two different source nodes with the help of relay node in bidirectional relay networks. It uses two phases of communication strategy, multiple-access phase in time slot I and broadcasting phase in time slot II. In multiple-access phase, two source nodes transmit simultaneously their signals to a relay node over a multiple access channel. In broadcasting phase, the relay node broadcasts the XORed version of the two received signals to the two source nodes over a broadcast channel. The error performance of the PLNC protocol is analyzed in bidirectional relay networks for BPSK modulation over Rayleigh fading channels using ML detection metric at the relay with the max-log approximation [20].

The contributions of this paper are as follows: (i) A PLNC based bidirectional DF relay network in half duplex mode is proposed as a network model for mmWave band in indoor-LoS environment using single RF chain SSK modulation with optimal and aligned antenna array geometry by exploiting the operating modes, OSSK and BiSSK; (ii) A closed form expressions for the BER for the source nodes to relay node, relay node to source nodes and the overall system are derived for the proposed network; (iii) The performance of the proposed PLNC based system is compared with non-PLNC based system.

Notations: Vectors and matrices are written in boldface with matrices in capitals. For a matrix $\mathbf{A}$, $\mathbf{A}^T$ and $\mathbf{A}^H$ indicate the transpose and conjugate transpose, respectively. $\mathbf{I}_n$ stands for the identity matrix of size $n \times n$. $(\cdot)_2$ and $(\cdot)_{10}$ represent binary and decimal equivalents. $|\cdot|$ denotes absolute value and $\|\cdot\|_F$ represents Frobenius norm. The binomial coefficient is denoted by $\binom{\cdot}{\cdot}$.

This paper is organized as follows: Section 2 presents the system model and optimal ML detection scheme of the proposed PLNC based bidirectional relay network using SSK modulation in mmWave-indoor-LoS scenario. Section 3 analyzes the end to end pair-wise error (PEP) probability and BER probability for the proposed model. Simulation results are discussed in Section 4 and Section 5 concludes the paper. Sensor nodes that communicate via wireless technology.

2. SYSTEM MODEL

Consider a bidirectional relay network shown in Fig. 1. In this network, relay node

R between two source nodes S_1 and S_2 , assists in exchange of data between the source nodes using the concept of PLNC. Source nodes S_1 & S_2 and relay node R are equipped with array of N_{S_1} , N_{S_2} and N_R antennas, respectively. For the analytical tractability, $N_R \geq \max(N_{S_1}, N_{S_2})$. The relay node operates at half duplex mode. Let $\mathbf{H}_{S_1R}$ be the $N_R \times N_{S_1}$ matrix and $\mathbf{G}_{S_2R}$ be $N_R \times N_{S_2}$ matrix, representing the channel response between the source node S_1 & relay node R , and source node S_2 & relay node R , respectively. In mmWave indoor-LoS environment, the fading component of LoS can be neglected compared to path loss component. Hence, the channel coefficients in channel matrices are written as $c_{mn} = |c_{mn}| \exp(-jkd_{mn})$, where $k = 2\pi/\lambda$ is the wave number, d_{mn} is the propagation path length between n th transmit antenna and m th receive antenna of two different nodes and $|c_{mn}|$ is the channel gain, calculated from Friis transmission equation. In an indoor-LoS environment, the fading component of LoS can be neglected compared to path loss component. Hence, the small change in channel gain is ignored and channel coefficients are written as $c_{mn} = \exp(-jkd_{mn})$.

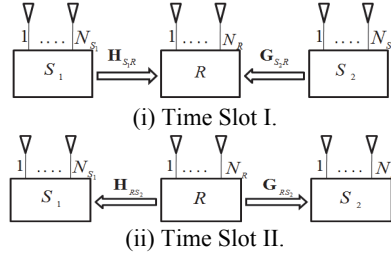


Fig. 1. System model of bidirectional relay network.

In mmWave based LoS environment, $\mathbf{H}_{S_1R}$ and $\mathbf{G}_{S_2R}$ are constrained by the distance between S_p , $p = 1, 2$ and R , their antenna separation and array structure. In SSK modulation, only one antenna is activated at a time and the other antennas are kept silent in order to exploit the multipath characteristics, but with single RF chain. In the proposed system, the concept of PLNC is applied at the relay node to exchange the data between source nodes S_1 and S_2 with the aid of relay node R , located in indoor-LoS environment. The SSK mapping rule adopted by S_1 , S_2 and R of the proposed system is given in Table 1.

2.1 Multiple-Access Phase from Source Nodes to Relay Node in Time Slot I:

In time slot I, both source nodes S_1 and S_2 transmit M ($M = N_{S_1} = N_{S_2}$) data symbols to relay node using SSK modulation. In this modulation, groups of $\log_2 M$ bits are mapped to a spatial symbol $\mathbf{x}$ to activate a particular antenna index to transmit data, while all other antennas remain idle. Let $\mathbf{x}_p$ be $N_{S_p} \times 1$ spatial symbol mapped at the source node S_p , $p = 1, 2$. The $N_R \times 1$ receive signal vector at relay node R is given by

$$\mathbf{y}_R = \mathbf{H}_{S_1R}\mathbf{x}_1 + \mathbf{G}_{S_2R}\mathbf{x}_2 + \mathbf{n}, \quad (1)$$

where $\mathbf{x}_p = \sqrt{E_{S_p}} \begin{bmatrix} 0 & 0 & \cdots & 1 & \cdots & 0 & 0 \end{bmatrix}^T$, $p = 1, 2$ and $\mathbf{n}$ is $N_R \times 1$ noise vector and antenna position

and its elements are circularly symmetric independent and identically distributed white Gaussian random variables with mean zero. Its covariance matrix is $N_0 \mathbf{I}_{N_R}$. Since the data vectors $\mathbf{x}_1$ and $\mathbf{x}_2$ have only one non-zero element as per the signal and energy mapper of SSK in the proposed system, Eq. (1) can be simplified as

$$\mathbf{y}_R = \sqrt{E_{S_1}} \mathbf{h}_i + \sqrt{E_{S_2}} \mathbf{g}_j + \mathbf{n}, \quad i \in \{1, 2, \dots, N_{S_1}\}, \quad j \in \{1, 2, \dots, N_{S_2}\}, \quad (2)$$

where $\mathbf{h}_i$ and $\mathbf{g}_j$ represent i th column of channel matrix $\mathbf{H}_{S_1R}$ and j th column of channel matrix $\mathbf{G}_{S_2R}$, respectively. Since both the channel matrices are known at the relay node R , the probability density function or the likelihood function of the $N_r \times 1$ receive signal vector $\mathbf{y}_R$ is given by

$$f(\mathbf{y}_R | \mathbf{H}_{S_1R}, \mathbf{G}_{S_2R}) = \frac{1}{(\pi N_0)^{N_R}} \exp \left(-\frac{1}{N_0} \|\mathbf{y}_R - \sqrt{E_{S_1}} \mathbf{h}_i - \sqrt{E_{S_2}} \mathbf{g}_j\|_F^2 \right). \quad (3)$$

Since the data transmitted by the source nodes are represented by antenna indices i and j , they are estimated using ML criterion as follows,

$$[\hat{i}, \hat{j}] = \arg \min_{i \in \{1, 2, \dots, N_{S_1}\}, j \in \{1, 2, \dots, N_{S_2}\}} \left(\|\mathbf{y}_R - \sqrt{E_{S_1}} \mathbf{h}_i - \sqrt{E_{S_2}} \mathbf{g}_j\|_F^2 \right). \quad (4)$$

Table 1. SSK mapper rule of the 4×4 system.

Binary data to be transmitted at source nodes	Data symbol and Antenna Index at source nodes		Spatial symbol at source nodes		Binary data to be broadcasted at relay node and its corresponding antenna index		Spatial symbol at Relay node R
$[b_1, b_2]$	$[M_1, M_2]$	$[i, j]$	$\mathbf{x}_1$	$\mathbf{x}_2$	$b_R(\text{PLNC})$	q	$\mathbf{x}_R$
[0 0]	0	1	$[\sqrt{E_{s_1}} \ 0 \ 0 \ 0]^T$	$[\sqrt{E_{s_2}} \ 0 \ 0 \ 0]^T$	[0 0]	1	$[\sqrt{E_R} \ 0 \ 0 \ 0]^T$
[0 1]	1	2	$[0 \ \sqrt{E_{s_1}} \ 0 \ 0]^T$	$[0 \ \sqrt{E_{s_2}} \ 0 \ 0]^T$	[0 1]	2	$[\sqrt{E_R} \ 0 \ 0 \ 0]^T$
[1 0]	2	3	$[0 \ 0 \ \sqrt{E_{s_1}} \ 0]^T$	$[0 \ 0 \ \sqrt{E_{s_2}} \ 0]^T$	[1 0]	3	$[\sqrt{E_R} \ 0 \ 0 \ 0]^T$
[1 1]	3	4	$[0 \ 0 \ 0 \ \sqrt{E_{s_1}}]^T$	$[0 \ 0 \ 0 \ \sqrt{E_{s_2}}]^T$	[1 1]	4	$[\sqrt{E_R} \ 0 \ 0 \ 0]^T$

In SSK mapping, $k = \log_2 N_S$ bits are grouped and mapped into the antenna index. Let $(\hat{i})_{10} = (b_{1_{k-1}} \dots b_{1_1} b_{1_0})_2$ and $(\hat{j})_{10} = (b_{2_{k-1}} \dots b_{2_1} b_{2_0})_2$ be the SSK mapper at source nodes S_1 & S_2 , respectively to select the antenna index. In the DF strategy of relay node, the joint detection $[\hat{i}, \hat{j}]$ is done using ML criterion. The number of elements of the set of all possible pairs of $[\hat{i}, \hat{j}]$ is N_S^2 . With PLNC protocol, the DF relay re-maps it into a new set with the number of elements N_R , using many-to-one mapping. Let $b_{R_n} = b_{1_n} \oplus b_{2_n}$, $n = 0, 1, \dots, k-1$ be the XORed version of the superimposed signal of S_1 & S_2 at the relay node, respectively and q be the antenna index to be selected to broadcast the PLNC encoded

data symbols using the SSK mapper at the relay node and it is defined by $(q)_{10} = (b_{R_{k-1}} \dots b_{R_1} b_{R_0})_2$. For example, based on the estimates of $\hat{i}$ and $\hat{j}$ in 4×4 system (*i.e.* $N_{S_1} = N_{S_2} = N_R = 4$), the data to be transmitted by relay node R using the concept of PLNC in time slot II is decided as follows using the SSK mapper rule given in Table 1.

2.2 Data Broadcasting Phase from Relay Node to Source Nodes in Time Slot II:

In time slot II, relay node broadcasts the PLNC encoded symbol to the source nodes using SSK modulation. Let $\mathbf{x}_R$ be the mapped energy vector to be broadcasted from relay node to source nodes S_1 and S_2 as shown in Table 1. Under the assumption that the channels from relay node R to S_1 and R to S_2 is symmetric ($\mathbf{H}_{S_1R} = \mathbf{H}_{RS_1}$ & $\mathbf{G}_{S_2R} = \mathbf{G}_{RS_2}$), the $N_{S_p} \times 1$ receive signal vectors at source nodes S_p , $p = 1, 2$ are given by

$$\mathbf{y}_{S_1} = \mathbf{H}_{S_1R} \mathbf{x}_R + \mathbf{n}_1, \quad (5)$$

$$\mathbf{y}_{S_2} = \mathbf{G}_{S_2R} \mathbf{x}_R + \mathbf{n}_2, \quad (6)$$

where $\mathbf{x}_R = \sqrt{E_R} \begin{bmatrix} 0 & 0 & \dots & \underset{\substack{\uparrow \\ \text{antenna position}}}{1} & \dots & 0 & 0 \end{bmatrix}^T$ and $\mathbf{n}_p$ is the $N_{S_p} \times 1$ noise vector at source node S_p , $p = 1, 2$ and its elements are circularly symmetric independent and identically distributed white Gaussian random variables with mean zero. Its covariance matrix is $N_0 \mathbf{I}_{N_{S_p}}$.

$$\mathbf{y}_{S_1} = \sqrt{E_R} \mathbf{h}_q + \mathbf{n}_1, \quad (7)$$

$$\mathbf{y}_{S_2} = \sqrt{E_R} \mathbf{g}_q + \mathbf{n}_2, \quad (8)$$

where $\mathbf{h}_q$ and $\mathbf{g}_q$ denote the q th row of $\mathbf{H}_{S_1R}$ and $\mathbf{G}_{S_2R}$, respectively and The transmit antenna index of the relay node is detected using ML criterion in source nodes as given by

$$\hat{q}_{S_1} = \arg \min_{q \in \{1, 2, \dots, N_{S_1}\}} \left(\left\| \mathbf{y}_{S_1} - \sqrt{E_R} \mathbf{h}_q \right\|_F^2 \right), \quad (9)$$

$$\hat{q}_{S_2} = \arg \min_{q \in \{1, 2, \dots, N_{S_2}\}} \left(\left\| \mathbf{y}_{S_2} - \sqrt{E_R} \mathbf{g}_q \right\|_F^2 \right). \quad (10)$$

The transceiver structure of nodes implementing SSK has SSK-mapper (constellation mapping) at transmitter and SSK-demapper (antenna index to bit stream mapping) at receiver. Thus the source nodes exchange their information by estimating the data symbols at S_1 and S_2 are given by

$$\hat{b}_2 = b_1 \oplus \hat{b}_R, \quad (11)$$

$$\hat{b}_1 = b_2 \oplus \hat{b}_R. \quad (12)$$

3. ERROR PERFORMANCE ANALYSIS IN THE PROPOSED SYSTEM

The transmitted data from source nodes undergoes two detections in cascade at the relay node. Let P_e^R , $P_e^{S_1}$, and $P_e^{S_2}$ are the PEP at relay node R , source node S_1 and source node S_2 , respectively. The end to end instantaneous error probability at p th source node S_p is given by

$$P_{EtoE,S_p} = P_e^R(1 - P_e^{S_p}) + (1 - P_e^R) P_e^{S_p}. \quad (13)$$

3.1 Error Probability at Relay Node

Without loss of generality, assuming S_1 and S_2 transmit through i th and j th antennas, respectively, an error event is said to be occurred when $\hat{i} \neq i$ or $\hat{j} \neq j$. Hence, PEP at relay node can be expressed as

$$P_e^R = P((i, j) \rightarrow (\hat{i}, j)|(i, j)) + P((i, j) \rightarrow (i, \hat{j})|(i, j)). \quad (14)$$

Let $P_e^{R_1} = P((i, j) \rightarrow (\hat{i}, j)|(i, j))$ be the PEP between $S_1 \rightarrow R$ link of the network in deciding $(\hat{i}, j)$ when (i, j) was sent. From Eq. (2), it can be written as

$$P_e^{R_1} = P\left(\left\|\mathbf{y}_R - \mathbf{y}_{R,i}\right\|_F^2 < \left\|\mathbf{y}_R - \mathbf{y}_{R,i}\right\|_F^2 \mid \mathbf{y}_{R,i}\right), \quad (15)$$

where $\mathbf{y}_R, i = \sqrt{E_{S_1}} \mathbf{h}_i + \sqrt{E_{S_2}} \mathbf{g}_j$. It is known that

$$\|\mathbf{a} + \mathbf{b}\|^2 = \|\mathbf{a}\|^2 + \|\mathbf{b}\|^2 + 2\Re\{\langle \mathbf{a}, \mathbf{b} \rangle\} \quad (16)$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product. Substituting Eqs. (2) and (16) in Eq. (15) and simplifying further,

$$P_e^{R_1} = P\left(\Re\left\{\left(\sqrt{E_{S_1}}(\mathbf{h}_i - \mathbf{h}_{\hat{i}})\right)^H \mathbf{n}\right\} > \frac{\left\|\sqrt{E_{S_1}}(\mathbf{h}_i - \mathbf{h}_{\hat{i}})\right\|_F^2}{2}\right), \quad (17)$$

where $(\cdot)^H$ denotes the Hermitian operation. Let $Z = \Re\left\{\left(\sqrt{E_{S_1}}(\mathbf{h}_i - \mathbf{h}_{\hat{i}})\right)^H \mathbf{n}\right\}$ is a Gaussian random variable with zero mean and variance, $\sigma_{\Sigma_Z}^2$ given by

$$\sigma_{\Sigma_Z}^2 = \frac{N_0 E_{S_1}}{2} \|\mathbf{h}_i - \mathbf{h}_{\hat{i}}\|_F^2, \quad (18)$$

where $\|\mathbf{h}_i - \mathbf{h}_{\hat{i}}\|_F^2$ is the squared Euclidean distance (ED) between two different SSK symbols. The ML detection performance depends on maximizing the ED between the received symbols. Substituting Eq. (15) for ED in Eq. (17),

$$\|\mathbf{h}_i - \mathbf{h}_{\hat{i}}\|_F^2 = \|\mathbf{h}_i\|_F^2 + \|\mathbf{h}_{\hat{i}}\|_F^2 - 2\Re\{\langle \mathbf{h}_i, \mathbf{h}_{\hat{i}} \rangle\}, \quad (19)$$

where $\langle \mathbf{h}_i, \mathbf{h}_i \rangle$ is the inner product between the sub channels of channel matrix $\mathbf{H}_{S_1 R}$. It is mathematically expressed by

$$\langle \mathbf{h}_i, \mathbf{h}_i \rangle_{i \neq \hat{i}} = \sum_{j=1}^{N_R} \exp \left[-jk \left(d_{ji} - d_{j\hat{i}} \right) \right], i \in \{1, 2, \dots, N_{S_1}\}. \quad (20)$$

It is determined by aligned antenna geometry ULA at the transmitter and receiver in terms of inter-antenna spacing and the distance between transmit and receive array. In mmWave indoor-LoS environment, the high rank MIMO channel is constructed using two operating modes for orthogonal channel construction [17], namely OSSK and BiSSK. In OSSK scheme, one transmit array and one receive array with equal number of antenna elements are used with equal power allocation and ED is maximized when the optimal sub channel condition, $\langle \mathbf{h}_i, \mathbf{h}_i \rangle = 0$ is achieved. Applying this optimal conditions in Eq. (18),

$$\sigma_{\Sigma_Z, OSSK}^2 = \frac{N_{S_1} N_R E_{S_1} N_0}{2}. \quad (21)$$

In BiSSK mode, one receive array and two parallel transmit arrays, spaced by $\lambda/2$ distance, each with the half of the antenna elements in the receive array are used with equal power allocation and maximum ED condition is achieved when $\langle \mathbf{h}_i, \mathbf{h}_i \rangle = -N_R$. Applying this optimal conditions in Eq. (18),

$$\sigma_{\Sigma_Z, BiSSK}^2 = \frac{N_{S_1}^2 N_R E_{S_1} N_0}{2}. \quad (22)$$

Now, Eq. (17) can be written as

$$P_e^{R_1} = P(Z > \frac{E_{S_1}}{2} \|\mathbf{h}_i - \mathbf{h}_{\hat{i}}\|^2). \quad (23)$$

It can be expressed in terms of $Q(\cdot)$ function as

$$P_e^{R_1} = Q \left(\frac{E_{S_1}}{2\sigma_{\Sigma_Z}} \|\mathbf{h}_i - \mathbf{h}_{\hat{i}}\|^2 \right), \quad (24)$$

where $Q(y) = \int_y^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$. Substituting Eqs. (18), (21) and (22) in Eq. (24) for the two operating modes,

$$P_{e, OSSK}^{R_1} = Q \left(\sqrt{\frac{N_{S_1} N_R E_{S_1}}{2N_0}} \right), \quad (25)$$

$$P_{e, BiSSK}^{R_1} = Q \left(N_{S_1} \sqrt{\frac{N_R E_{S_1}}{2N_0}} \right). \quad (26)$$

Let $P_e^{R_2} = P((i, j) \rightarrow (\hat{i}, \hat{j}) | (i, j))$ be the PEP between $S_2 \rightarrow R$ link of the network. From Eq. (2),

$$P_e^{R_2} = P\left(\left\|\mathbf{y}_R - \mathbf{y}_{R,j}\right\|_2^2 < \left\|\mathbf{y}_R - \mathbf{y}_{R,j}\right\|_F^2 \mid \mathbf{y}_R, j\right), \quad (27)$$

where $\mathbf{y}_R, j = \sqrt{E_{S_1}} \mathbf{h}_i + \sqrt{E_{S_2}} \mathbf{g}_j$. Substituting Eq. (2) in Eq. (24),

$$P_e^{R_2} = P\left(\Re\left\{\left(\sqrt{E_{S_2}}(\mathbf{g}_j - \mathbf{g}_{\hat{j}})\right)^H \mathbf{n}\right\} > \frac{\left\|\sqrt{E_{S_2}}(\mathbf{g}_j - \mathbf{g}_{\hat{j}})\right\|_F^2}{2}\right). \quad (28)$$

Similar to the analysis from Eq. (18) to Eq. (24), $P_e^{R_2}$ in the two operating modes can be respectively expressed as

$$P_{e,OSSK}^{R_2} = Q\left(\sqrt{\frac{N_{S_2} N_R E_{S_2}}{2N_0}}\right), \quad (29)$$

$$P_{e,BiSSK}^{R_2} = Q\left(N_{S_2} \sqrt{\frac{N_R E_{S_2}}{2N_0}}\right). \quad (30)$$

Since $P_e^R = P_e^{R_1} + P_e^{R_2}$, assuming the same number of data symbols (M) and $E_{S_1} = E_{S_2} = E_S$ the closed form expressions for PEP at the relay node R is given by

$$P_{e,OSSK}^R = 2Q\left(\sqrt{\frac{N_S N_R E_S}{2N_0}}\right), \quad (31)$$

$$P_{e,BiSSK}^R = 2Q\left(N_S \sqrt{\frac{N_R E_S}{2N_0}}\right). \quad (32)$$

3.2 Error Probability at the Source Nodes

The error performance at the source node $S_p, p = 1, 2$ is measured in terms of PEP, $P_e^{S_p}$. From Table 1, the relay node R broadcasts to source nodes S_1 and S_2 through q th antenna index. An error event is said to be occurred in S_1 and S_2 when $\hat{q} \neq q$. Hence, PEP at source node $S_p, p = 1, 2$ can be expressed by

$$P_e^{S_p} = P(q \rightarrow \hat{q} | q). \quad (33)$$

From Eqs. (7)-(9), PEP at S_1 and S_2 is written respectively as

$$P_e^{S_1} = P(\Re\{(\sqrt{E_R}(\mathbf{h}_q - \mathbf{h}_{\hat{q}}))^H \mathbf{n}\} > \frac{\left\|\sqrt{E_R}(\mathbf{h}_q - \mathbf{h}_{\hat{q}})\right\|_F^2}{2}), \quad (34)$$

$$P_e^{S_2} = P \left(\Re \left\{ \left(\sqrt{E_R} (\mathbf{g}_q - \mathbf{g}_{\hat{q}}) \right)^H \mathbf{n} \right\} > \frac{\left\| \sqrt{E_R} (\mathbf{g}_q - \mathbf{g}_{\hat{q}}) \right\|_F^2}{2} \right). \quad (35)$$

Considering the same aligned antenna array set up in two operating modes for $R \rightarrow S_p$, $p = 1, 2$ link,

$$P_{e,OSSK}^{S_p} = Q \left(\sqrt{\frac{N_R N_{S_p} E_R}{N_0}} \right), \quad (36)$$

$$P_{e,BiSSK}^{S_p} = Q \left(N_R \sqrt{\frac{N_{S_p} E_R}{N_0}} \right). \quad (37)$$

3.3 End to End Error Probability

The End to End error probability, P_{EtoE} of the system is given by, substituting Eq. (28) and Eq. (32) in Eq. (13),

$$P_{EtoE,OSSK} = 2Q \left(\sqrt{\frac{N_S N_R \gamma_{SR}}{2}} \right) + Q \left(\sqrt{\frac{N_S N_R \gamma_{RS}}{2}} \right) - 4Q \left(\sqrt{\frac{N_t N_r \gamma_{SR}}{2}} \right) Q \left(\sqrt{\frac{N_S N_R \gamma_{RS}}{2}} \right), \quad (38)$$

$$P_{EtoE,BSSK} = 2Q \left(N_S \sqrt{\frac{N_S N_R \gamma_{SR}}{2}} \right) + Q \left(N_S \sqrt{\frac{N_S N_R \gamma_{RS}}{2}} \right) - 4Q \left(N_S \sqrt{\frac{N_S N_R \gamma_{SR}}{2}} \right) Q \left(N_S \sqrt{\frac{N_S N_R \gamma_{RS}}{2}} \right). \quad (39)$$

where $\gamma_{SR} = E_S/N_0$ and $\gamma_{RS} = E_S/N_0$ denote the SNR between $S \rightarrow R$ link in the multiple access phase (time slot I) and the SNR between $R \rightarrow S$ link in the broadcasting phase (time slot II).

3.3 End to End Bit Error Probability

Assuming equiprobable transmit symbols, the BER for OSSK mode is given by the symbol-to-constellation mapping as follows

$$P_{b,OSSK} = \frac{\sum_{k=1}^{N_b} k \binom{N_b}{k}}{N_b (M-1)} \left(1 - \left(1 - Q(N_r N_b \gamma_0) \right)^{M-1} \right), \quad (40)$$

where $M = N_S$ is the number of data symbols applied at SSK mapper, $N_b = \log_2 N_S$ is the group of bits mapped to the symbol, $\gamma_0 = E_m/N_0/N_b$ and E_m is the average transmission energy. It is also assumed that all possible detection errors are equally likely and N_S & N_R are power of two. Since two parallel transmit antenna arrays are used in BiSSK mode, $N_S \geq 4$. Hence the bit error probability is given by

$$P_{b,BiSSK} = \frac{\sum_{k=1}^{N_b-1} k \binom{N_b}{k}}{N_b (M-2)} \left(1 - \left(1 - Q(N_r N_b \gamma_0) \right)^{M-2} \right). \quad (41)$$

4. RESULTS AND DISCUSSION

In this section, BER performance of the proposed PLNC based bidirectional relay network using SSK modulation in LoS environment with mmWave carrier frequencies is analyzed using analytical and Monte Carlo simulations. The array setup is specified by OSSK and BiSSK modes for constructing the high rank mmWave-MIMO LoS channel model. The following assumptions are used for the numerical results: since SSK operates effectively at multiple antenna system, the performance analysis is carried out for $N_S \times N_R$ MIMO-LoS system. In OSSK operating mode, $N_S = N_R$, but in BiSSK mode, $N_S = 2N_R$, since there are two parallel arrays at the transmitter, each with N_R antenna elements. It is assumed that the number of antennas at each node is a power of two. The transmit power of all three nodes are set to be equal. The simulation parameters are as given in Table 2. Fig. 2 shows the BER performance of $N_S = N_R = 2$ PLNC based bidirectional relay network in LoS operating conditions using SSK modulation at source nodes and relay node. It is assumed that the $S_1 \rightarrow R$ link and $S_2 \rightarrow R$ links are symmetric to each other.

Table 2. Simulation parameters for BER analysis.

S. No	Parameters	Values
1.	Number of antennas at S_1, S_2 & R	2-32
2.	Distance between antenna arrays at source nodes and antenna array at relay node	3m
3.	Carrier frequency	60GHz
4.	Channel Type	LoS – Deterministic Channel
5.	Optimal Array Setup – operating modes	OSSK and BiSSK

The analytical and simulations results are compared for the OSSK mode. It is observed that error probability for source nodes to relay and relay to source nodes decrease substantially when SNR is increased. The theoretical BER performance of the proposed system agrees well with the simulation results at an SNR greater than 6dB. However there exists a mismatch at an SNR less than 6dB. This mismatch is due to the fact that, the robust modulation and the coding schemes are operational at an SNR 6dB and above due to the inherent propagation characteristics of millimeter wave line of sight indoor environment [16]. At a BER of 10^{-4} the SNR required for source to relay system is 8.8dB, relay to source is 8.47dB and the end to end system is 9dB. Hence BER of the end to end system is dominated by the source to relay BER. It is also observed that the improved error performance is achieved as that of MIMO links, but with single RF chain at the transceiver structure by exploiting OSSK operating conditions. Thus, the transceiver system complexity is considerably reduced.

Fig. 3 shows the comparison of end to end BER of PLNC and non-PLNC based bidirectional relay network using SSK modulation for OSSK and BiSSK operating modes.

Three inferences are obtained from Fig. 3. (i) It is observed that there is 1-dB SNR advantage for the BER performance of BiSSK mode when it is compared to OSSK scheme. This is achieved due to the additional diversity of dual transmit array setup, offered by BiSSK mode; (ii) when the scalability of the antenna array is increased, the BER performance is gradually improved when SNR is increased due to the increase in antenna diversity; (iii) It is shown that there is only the marginal performance gap between PLNC and non-PLNC based systems. However, the performance gap is vanished at high SNR values. Hence, the bidirectional communication with relays requires two time slots in a PLNC system while a non PLNC system requires four time slot with a marginal loss in BER.

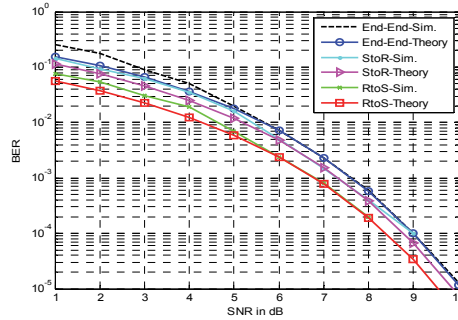


Fig. 2. BER of proposed Bidirectional Relay Network with PLNC in OSSK in $N_{S_1} = N_{S_2} = N_R = 2$ system.

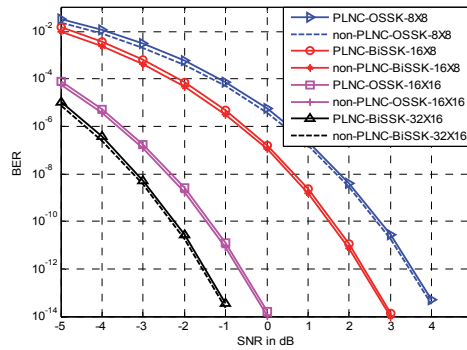


Fig. 3. BER comparison of proposed bidirectional relay network with PLNC and non-PLNC based system.

The end-to-end BER analysis is carried out both for PLNC and non-PLNC based system using two operating modes with various antenna configurations by varying SNR of one hop link while keeping the SNR constant for other hop link. Fig. 4 shows the BER performance with constant SNR at Relay to Source node 2 while, Fig. 5 shows the BER performance with constant SNR at Relay to Source node 1. From the results, it becomes evident that the end-to end BER performance is limited by the minimum of SNR values of Source 1 to relay link or Source 2 to relay link, $\min(\gamma_{S_1R}, \gamma_{S_2R})$. Similar infer-

ences can be obtained from Figs. 6 and 7. wherein performance of OSSK and BiSSK are respectively analyzed.

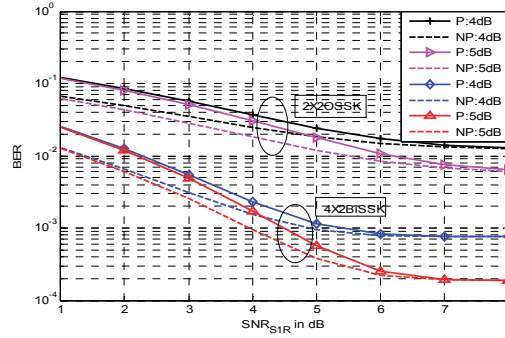


Fig. 4. BER comparison of a proposed network with PLNC and non-PLNC in different array setup when relay to source node 2 link SNR is fixed.

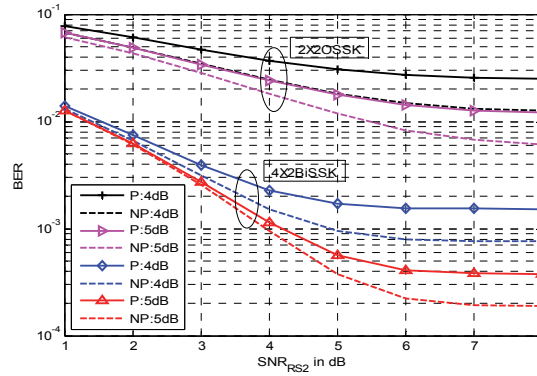


Fig. 5. BER comparison of a proposed network with PLNC and non-PLNC in different array setup when Relay to Source node 1 link SNR is fixed.

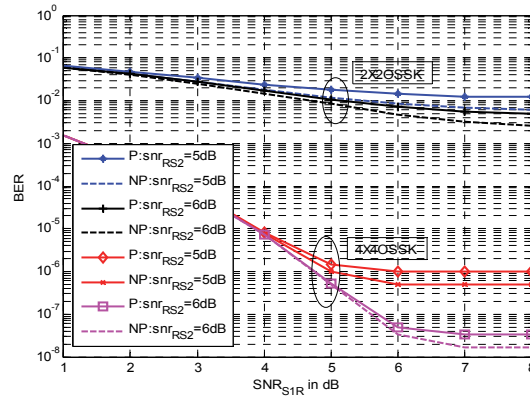


Fig. 6. BER comparison of a proposed network with PLNC and non-PLNC in OSSK array setup when Relay to Source node 1 link SNR is fixed.

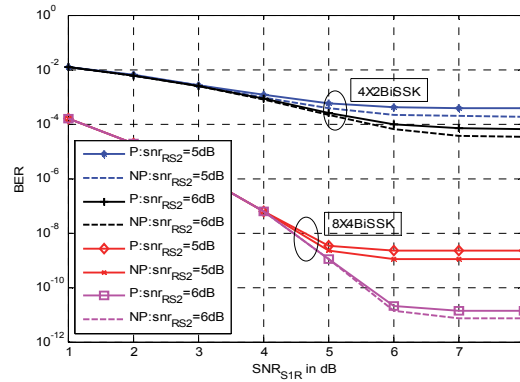


Fig. 7. BER comparison of a proposed network with PLNC and non-PLNC in BiSSK array setup when Relay to Source node 1 link SNR is fixed.

5. CONCLUSION

The proposed PLNC based bidirectional relay network uses low RF complexity space shift keying modulation technique with optimal antenna array geometry to combat the behaviour of wave propagation and FSPL of mmWave frequencies in indoor-LoS channel environment. The proposed system consists of N_{S_1} number of antennas in source node S_1 , N_{S_2} number of antennas in source node S_2 and N_R number of antennas in relay node. The closed form expressions for the bit error probability for the source nodes to relay node in time slot I, relay node to source nodes in time slot II and the overall end-to-end system are derived and compared with the Monte Carlo simulations with optimal antenna alignment geometry. Also, the BER performance analysis is compared for both PLNC based and non-PLNC based system design in half duplex mode. In addition to that, the effect of SNR of one of the links in the end-to-end error performance is analyzed. This is useful for systems which can be subject to strong LoS channels such as WLAN systems, other short range communication and the next generation wireless networks using mmWave communication.

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