Low Complexity Codebook-Based Beam Switching for 60 GHz Anti-Blockage Communication

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Abstract—A low complexity solution to the 60 GHz link-blockage problem is proposed based on the codebook beam switching technique. The directional link is easily blocked by a moving person, which is regarded as one of the severe problems in 60 GHz communication. Codebook based beam switching is a feasible technique to resolve the link-blockage by switching the beams from the blocked path to a backup reflection path. Typically, the selection of the best reflection path is crucial. Based on beam training mechanism, an ordered beam pair list (OBPL) of reflection paths is proposed for more accurate path selection and rapid link switching. Based on the OBPL, a complete and closed-form beam switching process is developed, which can apply for blockages of both LOS path and reflection NLOS paths. The link-blockage detection and LOS link-recovery detection are investigated. Theoretical analysis and numerical results show that for IEEE 802.15.3c indoor channel model, the proposed scheme has a good performance in complexity, applicability and system throughput.

Index Terms—60 GHz communication; link blockage; codebook-based beamforming; beam switching; reflection path

I. Introduction

Due to the ever increasing market demands for Giga-bps data rate indoor wireless applications, such as wireless personal area networks (WPAN), wireless local area networks (WLAN), and uncompressed high definition media interface (HDMI) transmission system, 60Ghz centered millimeter-wave (MMW) communication has received considerable interests recently. Its ultimate advantage is the capability to achieve a multiple Giga-bps system throughput caused by up to 7 GHz bandwidth at 60 GHz carrier frequency for unlicensed use in most regulatory bodies worldwide [1]. With rapid development of low-cost integrated circuits, the commercially viable multiple Giga-bps wireless products are within reach. However, due to the extremely high frequency band, the propagation path loss of 60 GHz is about 21dB greater than that of 5 GHz [2], and the reflection capability of 60GHz radio is rather reduced. In order to compensate the high path loss, the multiple-input multiple-output (MIMO) technique based on antenna arrays has been widely adopted to generate directional radiation. Mainly relying on the LOS path, the directional link can increase system capacity, extend transmission range, and suppress the co-channel interference. But on the other hand, it is easily blocked by the moving person or other objects due to the weak penetrating and reflectivity of 60 GHz radio, especially in the indoor environment with frequent human activities.

The link-blockage by a moving person, termed as human body blockage effect, is regarded as one of the severe problems in 60GHz communication systems. In [3], the effect of human activity on 60 GHz radio link is meticulously analyzed, and the authors summarized several features of this kind of fading: sudden, deep and long-lasting, which helps to determine the link blockage rather than other types of fading. Several anti-blockage schemes have been proposed [4]-[6]. A multi-hop solution is described in [7] to circumvent link-blockage through link relay devices, which increases the system cost due to additional equipments and brings a new problem, i.e. the layout of relay devices. In [8] and [9], the spatial diversity is investigated for redundant links to avoid the simultaneous blockage of all the LOS paths between communication devices. Because the width of human body is about 0.5 meter, this method requires much larger inter-spacing than the half-wave length between various links, which is usually not feasible for the consumer-electronics (CE) with constrained size. The IEEE 802.15.3c activities consider the use of beam switching technique [10]. Usually, there exist one LOS path and several first-order reflection Non-LOS (NLOS) paths in the indoor environment. When the LOS path is blocked, the communication link will be maintained by the switching of beams from the LOS path to a reflection NLOS path based on beamforming.

Beam switching based anti-blockage scheme is more attractive compared to other methods, because it does not require any additional hardware except for the MMW antenna arrays, which are believed to be the necessary equipments in 60 GHz communication system. In [11], the beam switching (BS) mechanisms are classified into two categories: instant decision BS and environment

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learning based BS. In order to select the optimal alternative path with the highest performance merits, e.g. the Signal-to-Noise Ratio (SNR), the Angle-of-Arrival (AOA) of a beam path and the geometrical optics method are adopted in the paper. Obviously, this method is high computational complexity and does not have the generality. In addition, it will spend lots of time on the path selection, which may lead to the communication interruption.

In this paper, we consider a typical HDMI transmission system with large number of antenna elements and propose a reflection path based beam switching scheme that can solve the link-blockage problem with lower complexity and less set-up time. The main contribution of this work is as follows. We propose to use the optimal beam pair of a reflection path to represent the path, and all the best beam pairs of the reflection paths are sorted to form a complete backup list, denoted as the ordered beam pair list (OBPL). Because the paths and channel conditions are stable due to the fixed positions of transmitter and receiver in the HDMI transmission system, we propose to generate the OBPL before the communication process, which leads to a significant reduction of the beam switching time. Based on the OBPL, we develop a complete beam switching process, which applies for blockages of both the LOS and reflection NLOS paths. In addition, we design a LOS recovery detection module to improve the utilization of the LOS path for the larger system throughput. When the LOS path is detected to be blocked, the best reflection path with its optimal beam pair will be selected from the OBPL, and both the transmitter and receiver switch their beams to the beam pair rapidly. To our best knowledge, although the beam switching based anti-blockage schemes have been mentioned by previous works [7], [11], systematic research on the generation, selection and application of the codebook based beam pair of reflection paths is still not presented.

The remainder of this paper is organized as follows. In Section II, the system model is presented. Section III discusses the generation of the OBPL. In Section IV, the complete beam switching process is presented; the link-blockage detection and LOS link-recovery detection module are investigated. The simulation results are given in Section V, and Section VI concludes the paper.

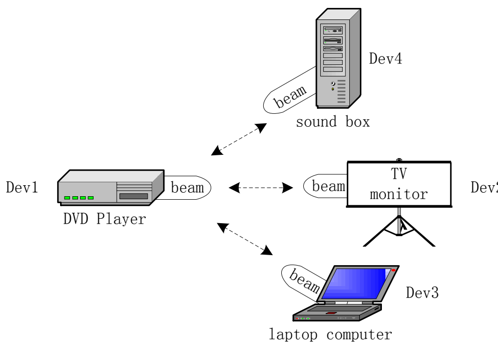


Figure. 1. Typical example architecture of a hdmi transmission system

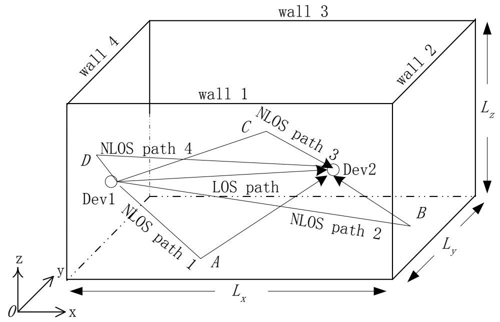


Figure. 2. Three-dimensional indoor environment model based on ray-tracing method

II. System Model

A typical 60GHz HDMI transmission system is shown in Fig. 1. It includes a high - definition video source transmit device, e.g. a DVD Player, and several receiving devices, e.g. TV Display, Laptop, and sound box, etc. We assume that all devices are equipped with MMW antenna arrays for directional communication between Dev1 and other devices.

A. Environment Model

Without loss of generality, we focus on the “downlink”, the communication from the video source device, denoted as Dev1, to the video display device, denoted as Dev2. The proposed scheme is also applicable to the “uplink”. The ray-tracing method is used to find and compute the important paths between the two devices in a predefined indoor environment, whose three-dimensional model with size $L_x \times L_y \times L_z$ is illustrated in Fig. 2.

As shown in the figure, Dev1 with the coordinates (x_1, y_1, z_1) is assumed to have a uniform linear antenna array with N_t elements, and Dev2 (x_2, y_2, z_2) has an array with N_r elements. Due to the specific arrangement of the antenna arrays and placement of the devices, the reflection path from ceiling is not considered as a backup NLOS link [12]. Therefore, only five paths are available for the communication between Dev1 and Dev2: the LOS path, reflection NLOS path 1 via wall 1, reflection NLOS path 2 via wall 2, reflection NLOS path 3 via wall 3, and reflection NLOS path 4 via wall 4. For each path p, we define a two-tuple profile factor $<\alpha_p, \beta_p>$ to describe its characteristics, where α_p and β_p represent its incident angles at the transmit antenna array and receive antenna array, respectively.

B. 60 GHz Wireless Channel Model

The wireless channel model of 60 GHz is given by IEEE 802.15.3c and expressed as [13]

$$r(t) = \sum_{k=1}^{N} \alpha_k s(t - \tau_k) + n(t) \tag{1}$$

where N is the number of received multipath components, α_k and τ_k denote the amplitude and delay of the k-th path, respectively, and $n(t)$ is additive white Gaussian noise with zero mean and two-sided power spectral density $N_0/2$.

If $h(t, \phi)$ is used to represent the channel impulse response with the time parameter t and angle parameter ϕ, equation (1) can be rewritten as

$$r(t) = s(t)h(t,\phi) + n(t) \tag{2}$$

where $s(t)$ is the transmitted signal. According to IEEE.802.15.3c, $h(t, \phi)$ is given by

$$h(t,\phi) = \alpha_{LOS}\delta(t) + \sum_{l=1}^{L}\sum_{k=1}^{K}\alpha_{k,l}\delta(t - T_l - t_{k,l})\delta(\phi - \theta_l - \theta_{k,l}) \tag{3}$$

where α_{LOS} is the complex amplitude of the LOS component, $\alpha_{k,l}$ is the complex amplitude of each ray, T_l is the delay time of the l-th cluster, $t_{k,l}$ is the delay time of the k-th ray in l-th cluster, θ_l is the angle of arrival of the l-th cluster, $\theta_{k,l}$ is the angle of arrival of k-th ray in the l-th cluster. Probability of ray and cluster generation is done by Poisson process and the distribution of the angle is done by Laplacian distribution.

The indoor residential environment with LOS path is modeled as CM1 in IEEE802.15.3c. One thousand times of channel realizations for CM1 are performed, and the results show that the RMS delay spread (RMSDS) is almost equal to zero, as shown in Fig. 3. In any one random realization, 99% of the received energy is contained in the first reach signal, and the energy contained in other multipath signals can be negligible, as shown in Fig. 4. Therefore, CM1 can be approximated as an AWGN channel without multipath, and then equation (a) can be simplified as

$$r(t) = \alpha s(t - \tau) + n(t) \tag{4}$$

where α represents the channel attenuation coefficient, and τ is the signal delay, which are given by

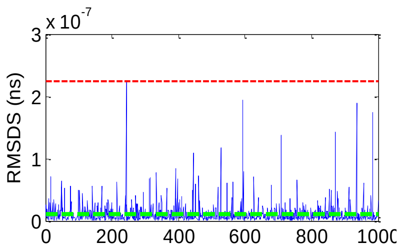


Figure. 3. RMS delay spread of CM1

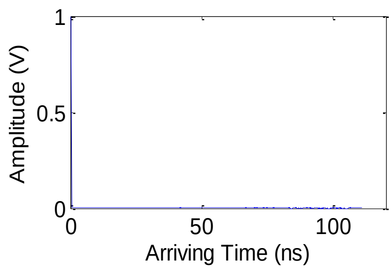


Figure. 4. Amplitude distribution of CM1 in one realization

$$\alpha = 10e^{-PL(d)/20}, \quad \tau = c/d \tag{5}$$

where c is the electromagnetic propagation speed and $PL(d)$ represents the path loss at distance d.

C. Link Budget Model

The link budget model of wireless channel can be expressed as

$$P_r(d)[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - PL(d)[dB] \tag{6}$$

where P_t is the transmit power, P_r is the received power, and G_t and G_r are gains of the transmit and receive antennas, respectively. $PL(d)$ represents the path loss at distance d, which is defined as the energy ratio of the receive signal to the transmit signal. According to IEEE 802.15.3c, the $PL(d)$ of 60GHz radio in the LOS scenario is given as

$$PL_{LOS}(d)[dB] = PL_0 + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[dB], d > d_0 \tag{7}$$

where PL_0 represents the reference pass loss at d=1 meter, n is the power attenuation exponent with an approximate value of 1.53 in LOS scenario, and X represents a zero mean Gaussian distributed random variable with a standard deviation σ.

When the LOS path is blocked, the beams of Dev1 and Dev2 will be switched to the beam pair along a reflection path direction. Therefore, the signal strength will be rather degraded by the reflection loss, denoted as PL_r, and the total path loss in this kind of scenario is given as

$$PL_{NLOS}(d)[dB] = PL_0 + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[dB] + PL_r, d > d_0 \tag{8}$$

where d is the total propagation distance of 60 GHz radio along the reflection path. After the reflection of the concrete wall, the signal strength is degraded, and the signal amplitude is given as $v = (\lambda/4\pi d)\left|\Gamma_0\sqrt{G_t G_r}\right|$, where Γ_0 is the Fresnel reflection coefficient for perpendicular polarization, and given by [14]

$$\Gamma_0 = \frac{\cos\theta - \sqrt{\omega - \sin^2\theta}}{\cos\theta + \sqrt{\omega - \sin^2\theta}} \tag{9}$$

where θ represents the incident angle, and ω is a dielectric constant value of walls. Therefore, the received signal power along the LOS path and reflection NLOS paths are given as

$$P_{r,LOS}(d) = P_t + G_t + G_r - \left(PL_0 + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[dB]\right) \tag{10}$$

and

$$P_{r,NLOS}(d) = P_t + G_t + G_r - \left(PL_0 + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[dB]\right) - PL_r \tag{11}$$

respectively.

D. Human Blockage Model

A person is modeled as a cylinder with radius r_p and height h_p. The z coordinates z_1 of Dev1 and z_2 of Dev2 are assumed to be lower than h_p. Therefore, when a person crosses the communication path, the radio link will be affected by attenuation of received signal strength and duration of shadowing, which is modeled as

$$PL_b = \begin{cases} 0 & ,if \quad unblocked \\ PL_{b0} & ,if \quad blocked \end{cases}, \tag{12}$$

where PL_b represents the signal attenuation caused by human blockage, and PL_{b0} is an attenuation constant value. The movement of a person is considered to follow the Random Way Point (RWP) mobility model with a certain speed and pausing time [11].

III. Ordered Beam Pair List

A. Codebook based Beamforming

We assume that Dev1 has one RF chain module, N_t transmit antennas and phase shifters, so does Dev2 but the number of its antennas and shifters is N_r. The codebook based beamforming model is shown in Fig. 5. At the transmitter of Dev1, signals are up-converted to RF band after baseband processing, then RF signals are weighted by the transmit weight vector, denoted as $\boldsymbol{w} = [w_1, w_2, \ldots, w_{Nt}]^T$, where T represents the matrix transpose operation. The $N_t \times 1$ signal vector $\boldsymbol{s}$ are radiated into free space through MIMO radio channel. At Dev2, the received signals are weighted by receive weight vector, denoted as $\boldsymbol{c} = [c_1, c_2, \ldots, c_{Nr}]^T$, combined and down-converted to baseband. Both transmit and receive weight vectors are pre-defined in codebooks, which are designed to form specific beam patterns for directional link [15]. The combined signal is written as

$$r = \boldsymbol{c}^{\mathrm{H}} H \boldsymbol{w} \boldsymbol{s} + \boldsymbol{c}^{\mathrm{H}} \boldsymbol{n}, \tag{13}$$

where H represents the $N_r \times N_t$ channel matrix, of which each entry is given by (3), $\boldsymbol{n}$ is an $N_r \times 1$ additive white Gaussian noise (AWGN) vector, and $\boldsymbol{c}^{\mathrm{H}}$ means the conjugate transpose matrix of $\boldsymbol{c}$.

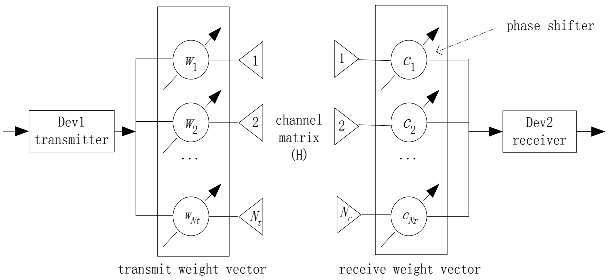


Figure. 5. Code book based beamforming model

We adopt the codebook generation mechanism presented in IEEE 802.15.3c, of which only 90 degree phase resolution shift without amplitude adjustment is used for low power consumption and complexity. For an uniform antenna array, the (n,m)-th weight element of a codebook is defined as

$$W(n,m) = j^{floor\left(\frac{n \times \mathrm{mod}(m+(M/2),M)}{M/4}\right)} \tag{14}$$

for $n = 1,\ldots,N,\ m = 1,\ldots,M$, where j is the imaginary unit, N represents the antenna number, e.g. N_t of Dev1 or N_r of Dev2, M is the beam number, n and m denote the antenna and beam index, respectively, the function $floor(x)$ returns the biggest integer smaller than or equal to x, and $mod(x, y)$ is the modulo function. According to (14), we can generate the transmit codebook of Dev1, denoted as $\boldsymbol{W}$, and the receive codebook of Dev2 is generated with the same method, denoted as $\boldsymbol{C}$.

The array gain of a specific weight vector, i.e. beam pattern, generated by (14) is given as [15]

$$G(\theta) = G_0 \left| A_m(\theta) \right|^2 \tag{15}$$

where $\boldsymbol{G_0}$ is the gain of a single antenna element, and $A_{\mathrm{m}}(\theta)$ represents the array factor, which is generated by the m-th beam pattern of $\boldsymbol{W}$ as

$$A_m(\theta) = \sum_{n=0}^{N-1} W(n,m) e^{j2\pi n (l/\lambda)\cos\theta} \tag{16}$$

where λ is the wave length, l is the inter-spacing of antennas, and θ is the angle difference between the link direction and the normal direction of the antenna array.

Without loss of generality, the total power of the transmit signal $\boldsymbol{s}$ over all antennas is normalized to one. We get inferences as follows

$$E\left[|s|^2 \right] = 1/N_t, \quad w^H w = N_t, \quad c^H c = N_r . \tag{17}$$

Consequently, the output SNR of the beamforming system can be derived from (13) and (17) as

$$\begin{aligned} \gamma_{BF} &= \frac{E\left[\left| c^H H w s \right|^2 \right]}{E\left[\left| c^H n \right|^2 \right]} \\ &= \frac{E\left[\left| c^H H w \right|^2 \right] E\left[|s|^2 \right]}{N_r \sigma^2} = \frac{\left| c^H H w \right|^2}{N_t N_r \sigma^2} \end{aligned} \tag{18}$$

B. Optimal Beam Pair of Paths

When multiple reflection paths are applied to the system for 60 GHz anti-blockage communication, the following important issues need to be considered: (1) how to build a reflection path list to maintain the conditions of all paths effectively, (2) how to select an optimal reflection path from the list as the backup link accurately, and (3) how to switch the communication link from the LOS path to the selected reflection path rapidly. Based on the codebook and beamforming techniques, we propose to use the transmit and receive beam pair to represent a path between two devices, build an ordered beam pair list to maintain the conditions of all paths, and develop a complete beam switching process for rapid link conversion.

1) Low complexity beam training for optimal beam pairs

For any two devices in the HDMI transmission system, the optimal transmit and receive beam pair for a given path is assumed to be determined through beam training mechanism. The beam pair is defined as a two tuple $<w_i, c_j>$, where w_i represents the i-th beam pattern in Dev1's codebook, and c_j represents the j-th beam pattern in Dev2's codebook. The received signal power and Signal-to-Noise Ratio (SNR) of the optimal beam pair will also be obtained in the beam training process, which are important criteria for path selection.

The training sequences (TSs) with different combinations of transmit and receive beams shall be exchanged through a path p to find which beam pair can maximize the system performance, measured by SNR according to (18). Compared to the time spent on signal processing inside devices, it takes a rather long time for training process, which includes TSs transmission, feed back, mapping and acknowledgement stages [10]. However, the shorter setup time is very important for faster system response and better user experience.

Several beam training methods have been proposed, of which there are three typical codebook-based schemes: 1) exhaustive search training based BF (ES-BF), 2) two-level training based BF (2L-BF) [13], and 3) multiple-level training based BF (ML-BF) [2]. The beam number and sector number of transmitter and receiver are assumed to be M_t and M_r, S_t and S_r, respectively. ES-BF needs to attempt all $M_t \times M_r$ transmit and receive beam combinations to select the best beam pair. While 2L-BF requires $S_t \times S_r$ sector level and $B_t \times B_r$ beam level TSs transmissions, where $B_t = M_t / S_t$ and $B_r = M_r / S_r$ represents the beam number of each transmit and receive sector, respectively. Therefore, 2L-BF needs a total of $S_t \times S_r + B_t \times B_r$ attempts. ML-BF adopts multiple levels to further reduce training time with about $4 \times ceiling(log_2 min(M_t, M_r)) + 2 \times (ceiling(log_2 max(M_t, M_r)) - ceiling(log_2 min(M_t, M_r)))$ TSs transmission, where the function $ceiling(x)$ returns the smallest integer bigger than or equal to x.

Considering the relatively fixed positions of transmitter and receiver in the HDMI transmission system, which means the conditions of paths and channel are relatively stable, we propose a new training scheme based on the incident angles of paths, and propose to perform the training before the formal communication. In this way, the beamforming setup time and beam switching time can be significantly reduced compared to the traditional schemes, where the evaluation and selection of the backup paths are conducted only when the link-blockage event occurs.

Denoting the i-th beam pattern of $\boldsymbol{W}$ as $\boldsymbol{w}_i$ ($0 \leqslant i \leqslant M_t - 1$), its maximum gain direction as θ_i, and its half power beam width (HPBW) as $\triangle\theta_i$, the radiation space can be divided into M_t parts by all the beam patterns as shown in Table I.

TABLE I. RADIATION SPACE DIVISION BY BEAM PATTERNS

Beam pattern	Max gain direction	HPBW	Radiation space division
$\boldsymbol{w_0}$	θ_0	$\Delta\theta_0$	$[\,\theta_0 - \Delta\theta_0/2\,,\ \theta_0 + \Delta\theta_0/2\,]$
$\boldsymbol{w_1}$	θ_1	$\Delta\theta_1$	$[\,\theta_1 - \Delta\theta_1/2\,,\ \theta_1 + \Delta\theta_1/2\,]$
…	…	…	…
$\boldsymbol{w_k}$	θ_k	$\Delta\theta_k$	$[\,\theta_k - \Delta\theta_k/2\,,\ \theta_k + \Delta\theta_k/2\,]$
…	…	…	…
w_{M_t}	θ_{M_t}	$\Delta\theta_{M_t}$	$[\,\theta_{M_t} - \Delta\theta_{M_t}/2\,,\ \theta_{M_t} + \Delta\theta_{M_t}/2\,]$

For a given path $p <\alpha_p, \beta_p>$, the optimal transmit beam can be roughly determined according to the incident angle α_p as

$$w_i = \underset{w_k \in W \wedge \alpha_p \in [\theta_k - \Delta\theta_k/2, \theta_k + \Delta\theta_k/2]}{\arg\max} \left(G\left(\alpha_p\right) \right) \quad , \quad k = 0,1,2,...,M_t \tag{19}$$

where $\boldsymbol{w_i}$ is assumed to be the selected optimal beam pattern. Considering the overlap between two adjacent beams and in order to avoid selection error, we put $\boldsymbol{w_i}$ together with its $2x$ ($0 \leqslant x \leqslant M_t/2\text{-}1$) adjacent beams to constitute a new beam set as

$$\begin{aligned} W' &= \left\{ w_{\mathrm{mod}(i-x,M_t)}, w_i, w_{\mathrm{mod}(i+1,M_t)}, \dots, w_{\mathrm{mod}(i+x,M_t)} \right\} \\ M'_t &= 2x+1 \end{aligned} \tag{20}$$

where $\boldsymbol{W'}$ is a much smaller beam set to be trained compared to $\boldsymbol{W}$, and M'_t is the total beam number of $\boldsymbol{W'}$. Because the beam width can be roughly determined by the total beam number M_t of the original codebook $\boldsymbol{W}$. It means that as M_t increases, the beams will become narrower, and the error probability of the optimal beam selection will increase. Accordingly, we can extend $\boldsymbol{W'}$ by changing the value of x to reduce the selection error. Therefore, the value of x can be given according to M_t. Typically, it is sufficient for x to be set the value no more than three when $M_t \leqslant 128$. Because M'_t is much less than M_t, the number of transmit beams to be trained through p is rather reduced compared to the conventional training schemes. At the receiver of Dev2, the receive beam subset C' with the beam number M'_r can be obtained in the same way.

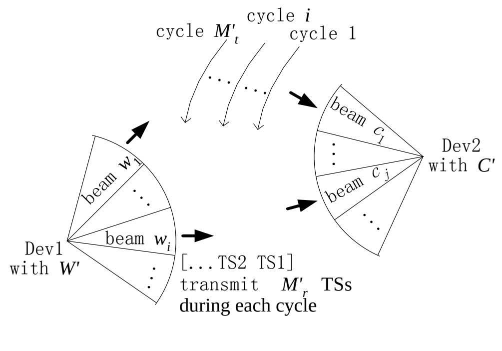


Figure. 6. Beam training process from Dev1 to Dev2

Fig. 6 shows the beam training process from Dev1 to Dev2 through a path p. It includes M'_t cycles, and they shall be sent with each transmit beam included in $\boldsymbol{W'}$ one by one. During each cycle, Dev1 sends M'_r repetitions of TSs with the same beam, and the repetitions will be received by each of M'_r receive beam included in $\boldsymbol{C'}$. During each cycle, Dev2 shall switch its beams one by one, and wait a time period of a TS transmission in each direction for signal reception. After the completion of M'_t cycles, the link from Dev1 to Dev2 through p will have been trained with each beam combination, and Dev2 is qualified with the received information to select the best beam pair of p. With (18) we can formulate the best beam pair selection problem as

$$(\hat{w}, \hat{c}) = \arg\max_{\substack{w \in W' \\ c \in C'}} \left(\frac{\left| c^H H w \right|^2}{N_t N_r \sigma^2} \right) \tag{21}$$

where $\boldsymbol{w}$ and $\boldsymbol{c}$ are beam patterns from $\boldsymbol{W'}$ and $\boldsymbol{C'}$, respectively. If the antenna arrays of Dev1 and Dev2 are symmetric, the best beam pair from Dev2 to Dev1 is same as above. Otherwise a similar training process needs to be conducted for the best beam pair along the opposite direction.

Due to the limited phases adopted in the codebook design, the gain loss of antenna arrays at directions deviate from the maximum gain direction of a beam is inevitable. When the beam pair of a reflection path is used as the backup link, the communication system will also have the gain loss due to the direction difference between the beam pair maximum gain direction and the exact propagation direction of the path. In order to evaluate the effectiveness of the beam pair backup mechanism, the Gain Loss to Maximum gain Ratio (GLMR) is defined as the criterion, and given by

$$\varepsilon_G = \frac{G_{\max} - G_{BP}(\theta_p)}{G_{\max}} \tag{22}$$

where $G_{BP}(\theta_p)$ represents the gain sum of the two beams along the propagation direction of p, and $G_{\max}$ represents the maximum gain sum of the two beams.

2) *Beam switching quality factor*

Due to the fixed positions of transmitter and receiver during a certain period of time, the paths and channel conditions are relatively stable. The beam switching quality factor (BSQF) is proposed to reflect the recent quality of a path. It can be obtained from the past switching experiences of successes and failures. The exponential moving average technique is adopted to provide a low complexity implementation, which is given as

$$q_k(n) = [(1-\beta) q_k(n-1) + \beta S_k(n-1)]\,|_{S_k(n-1) \neq \phi} \tag{23}$$

where $q_k(n)$ represents the n-th beam switching BSQF of the k-th reflection path, β is a smoothing factor to reflect the importance of recent switching results. $S_k(n\text{-}1)$ is the result function of the (n-1)-th beam switching by using the beam pair of the k-th reflection path, which is given as

$$S_k(n-1) = \begin{cases} 0, & \text{if switching failure} \\ 1, & \text{if switching success} \\ \phi, & \text{if path } k \text{ not selected} \end{cases} \tag{24}$$

If $S_k(n\text{-}1)=\phi$, the initial value of q_k can be set to SNR of the k-th path, or a constant value for simplicity.

3) *Generation of Ordered Beam Pair List*

An ordered beam pair list (OBPL) is built to maintain the available paths with their optimal beam pairs and related information. The structure of the OBPL is shown as Table II. For the k-th path (k=0,…4), γ_k represents its SNR at receiver with its optimal beam pair, ε_{GK} is the GLMR value, q_k is the BSQF value, and o_k represents the selection order according to the predefined sorting rules.

TABLE II. STRUCTURE OF ORDERED BEAM PAIR LIST

Available path	Optimal beam pair	SNR	GLMR	BSQF	Order
LOS path	$<w_{i0}, c_{j0}>$	γ_0	ε_{G0}	1	o_0
NLOS path 1	$<w_{i1}, c_{j1}>$	γ_1	ε_{G1}	q_1	o_1
NLOS path 2	$<w_{i2}, c_{j2}>$	γ_2	ε_{G2}	q_2	o_2
NLOS path 3	$<w_{i3}, c_{j3}>$	γ_3	ε_{G3}	q_3	o_3
NLOS path 4	$<w_{i4}, c_{j4}>$	γ_4	ε_{G4}	q_4	o_4

With the OBPL, we develop a sorting rule of paths for rapid beam pair selection. Firstly, a composite weight is defined to reflect the comprehensive characteristics of each path, which is given as

$$\Gamma(k) = a\gamma_k + bq_k + c\varepsilon_{Gk} \tag{25}$$

where Γ is the composite weight of the k-th path, the coefficients a, b, and c are used to adjust the proportions of the three factors, which can result in different sorting rules for various requirements. According to (25), the path selection order can be calculated easily.

IV. BEAM SWITCHING PROCESS

Based on OBPL, a complete beam switching process is developed for 60GHz anti-blockage communication as shown in Fig. 7. Being different from conventional beam switching schemes, it is applicable to both LOS link-blockage and reflection NLOS link-blockage with consistent processing method. The process contains a LOS path recovery detection module, which ensures that the beam can be switched back to the LOS path as soon as possible for larger system throughput. When the 60 GHz communication system is started, a new version of OBPL is generated through the proposed beam training mechanism. The optimal beam pair of the LOS path is firstly selected from the OBPL to establish the communication link because of the order caused by its obviously higher SNR. In order to deal with possible link blockages, several measures are proposed as follows.

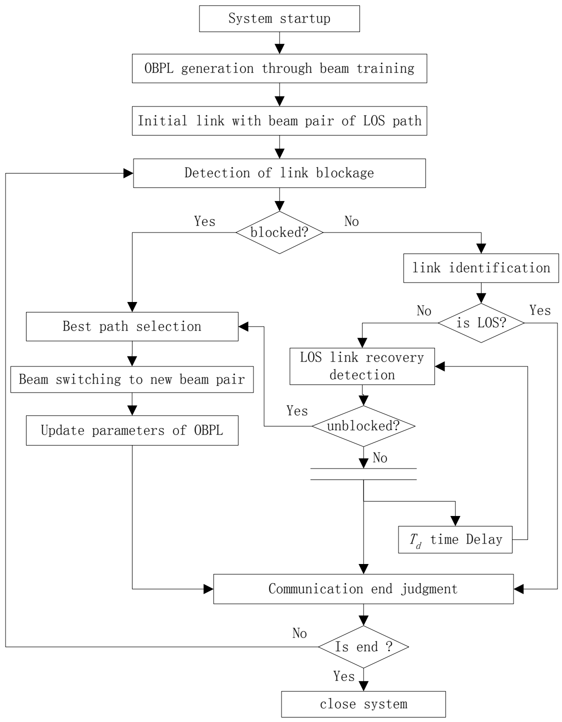


Figure. 7. Link switching process for 60GHz anti-blockage communication

1) Link blockage detection

A link connectivity threshold is defined, denoted as *Th*, and the link blockage detection formula is given as

$$P_r(d) < Th + I_L \tag{26}$$

where I_L represents the implementation loss. During the communication process, the received SNR of the current path will be continuously monitored to judge if the link is blocked according to (26). It has the following advantages: (1) Employing the parameter of SNR only for the link blockage detection, it is more effective and lower complicated compared to the conventional schemes, which usually need to consider the geometric characteristics of paths and the shape of blocking objects; (2) It applies for detections of both LOS path and reflection NLOS paths.

2) Backup beam pair selection and beam switching

When the link-blockage event occurs, the beam switching process will be activated. Firstly, a best backup path with optimal beam pair is directly selected from OBPL according to its order. Secondly, both transmit and receive antenna arrays switch their beams to the beam pair of the selected path, respectively. Finally, all parameters of the OBPL are updated to the current state. Because the OBPL is obtained in advance, and the ordered backup paths along with their optimal beam pairs are ready for selection, the communication link switching time is significantly reduced, which is important for maintaining the link connectivity. As showed in Fig. 7, the proposed process also applies to the link switching from one reflection NLOS path to the LOS path, or to another NLOS path.

3) LOS recovery detection

In order to improve the overall throughput of the system, a LOS recovery detection module is designed to improve the utilization of the LOS path. The link identification mechanism based on OBPL can tell which path is used for the current link. If it is a backup NLOS path, the LOS path will be continuously monitored with its optimal beam pair at intervals of T_d until the removal of the blockage, where the duration T_d can be pre-configured according to the human blockage model. If the blockage of the LOS path is detected to have been removed, a new beam switching will be performed for the link switching from the NLOS path to the LOS path. The process is identical to that presented above.

V. Numerical Results and Discussion

In this part, following the guidelines of IEEE 802.15.3c specifications, we present some simulation results to illustrate performances of the proposed beam switching scheme for 60GHz anti-blockage communication. All the related parameters are listed in Table III.

TABLE III. Related Parameters for Simulation

Parameter	Value	Parameter	Value
CenterA frequency	60.5 GHz	Scenario	Residential (CM1)
Bandwidth	1.728 GHz	Room size	L_x=10m, L_y=5m, L_z=4m
Path loss at 1m	-68.0 dB	Human body size	r_p=0.5m, h_p=1.7m
Implementation loss	1.5 dB	RWP speed uniform distribution	[0, 1] m/s
Minimum sensitivity level	-59.3 dBm	RWP pausing time uniform distribution	[0, 5] s
Propagation loss exponent of CM1	1.53	Codebook design	IEEE 802.15.3c criterion
Transmit power P_t	20 dBm	Blockage loss	20dB

A. Complexity of Proposed Training Scheme

As a measure of system overhead in the optimal beam pair searching for paths, we consider the number of TSs transmission during the training process. For the complexity comparison, we conduct simulations on the total number of TSs transmission for ES-BF, 2L-BF, ML-BF and proposed beamforming scheme. The numbers of total beam resolutions of all schemes are assumed to be the same, and the results are shown in Fig. 8.

As shown in the figure, the proposed beam training scheme significantly reduces the TSs transmission number, which is about 95% shorter than the exhaustive search training scheme, and much shorter than other conventional schemes. We can also verify that with the increase of beam pattern number, the advantages of the proposed scheme are more prominent.

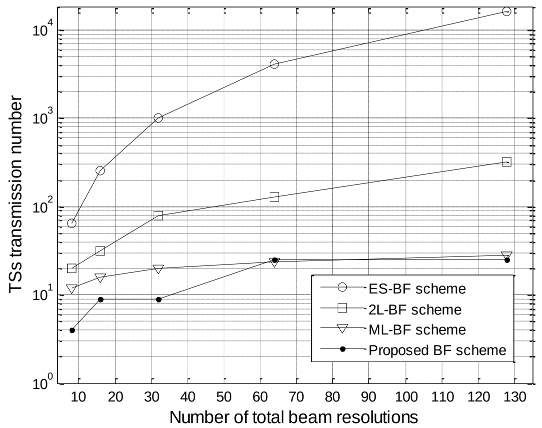


Figure. 8. Comparison of minimum number of required TSs transmission by using different beamforming schemes

B. Gain Loss to Maximum Gain Ratio of Beam Pair

In order to evaluate the effectiveness of the beam pair's representing a reflection NLOS path, the cumulative distribution function (CDF) of γ_G by using different codebooks are simulated, and the results are shown in Fig. 9.

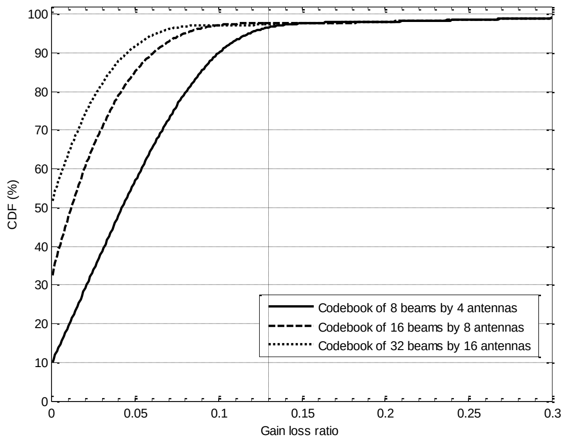


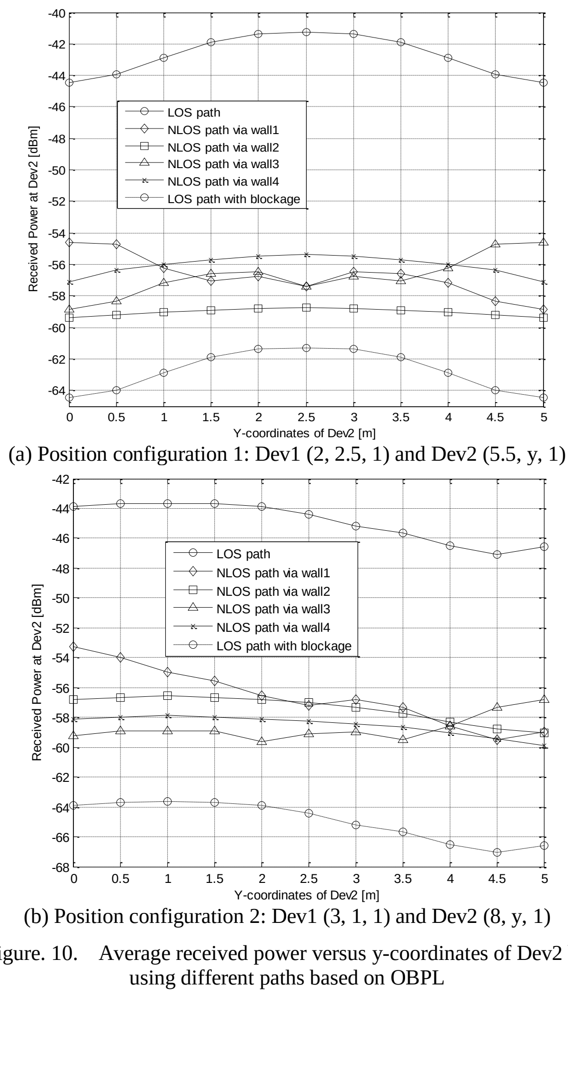
Figure. 9. CDF of gain loss to maximum gain ratio of BPS

It is shown that more than 95% of the GLMR values of the beam pairs with different codebooks are less than 0.13. As the of beam pattern number increases from 8 to 16 and 32, the GLMR value decreases significantly. It can be concluded that the optimal beam pairs corresponding to different reflection paths are effective and robust for backup link. It rather means that the link switching time between different paths can be significantly reduced, because the codebook based beam patterns are easily formed and switched for the phased antenna array.

C. Performance Comparison between Different Reflection NLOS Paths by OBPL

Without loss of generality, we assume that Dev1 and Dev2 are equipped with different numbers of antenna elements and beam patterns, e.g. 16 beams generated by 8 antennas for Dev1 and 8 beams by 4 antennas for Dev2. The best beam pairs for all paths will be selected through beam training mechanism, and their average received power will be calculated according to the radio link budget by (10) and (11), respectively. In this part, we select two random position configurations of Dev1 and Dev2 for generality: (1) Dev1 is fixed at the coordinates (2, 2.5, 1) and Dev2 is put at (5.5, y, 1), and (2) Dev1 is fixed at (3, 1, 1) and Dev2 is put at (8, y, 1). The coordinates y of Dev2 varies from 0 to 5 with step 0.5 meter. In the two configurations, the distances between the two devices are about 3 and 5 meters, respectively, which are typical values for WPAN and HDMI communication systems.

One thousand times of simulations for each position are conducted, respectively. The simulation results based on the average values are shown in Fig. 10 (a) and (b) for the two configurations, respectively. It is shown that all the optimal beam pairs of the corresponding paths have enough received power for communication link, i.e. P_t >59.3 dBm. It means that all the reflection paths with their optimal beam pairs can be used as the backup communication link when the LOS path is blocked. The values of P_t in Fig. 10 (b) are generally lower than that in Fig. 10 (a) due to the longer transmission distances between Dev1 and Dev2.



(a) Position configuration 1: Dev1 (2, 2.5, 1) and Dev2 (5.5, y, 1)

(b) Position configuration 2: Dev1 (3, 1, 1) and Dev2 (8, y, 1)

Figure. 10. Average received power versus y-coordinates of Dev2 by using different paths based on OBPL

In Table IV, we present an example comparison between reflection paths with their optimal beam pairs for y=4.5 meter. It includes path index, optimal beam pair, transmit antenna gain G_t of Dev1, receive antenna gain G_r of Dev2, average value of received power P_r, and selection order according to SNR only, all of which are obtained in beam training process. As shown in the table, when the system switch its link to the optimal beam pair along a reflection path, it can obtain a considerable antenna gain, e.g. about 13.8 dBi of reflection path 3 with the beam pair of w_3 at Dev1 and c_2 at Dev2. In general, the proposed codebook based OBPL mechanism significantly reduces the beam switching time when the link-blockage occurs, for it doesn't need any temporary calculation and selection.

TABLE IV. COMPARISON BETWEEN REFLECTION PATHS WITH THEIR OPTIMAL BEAM PAIRS FOR DEV2 AT COORDINATES (5.5, 4.5, 1)

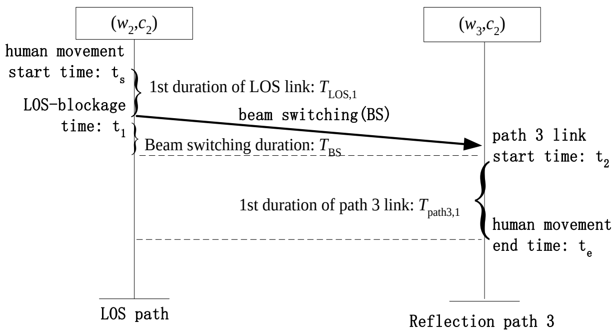
Path	Optimal beam pair	G_t (dBi)	G_r (dBi)	P_r (dBm)	Order
LOS path	(w_2,c_2)	8.0930	5.2086	-43.9614	1
NLOS path 1	(w_5,c_3)	8.2981	5.8484	-58.3137	4
NLOS path 2	(w_1,c_1)	8.9881	6.0104	-59.1842	5
NLOS path 3	(w_3,c_2)	8.3759	5.3799	-54.7001	2
NLOS path 4	(w_1,c_1)	8.7988	5.9656	-56.3677	3

D. Evaluation of The Proposed Beam Switching Process

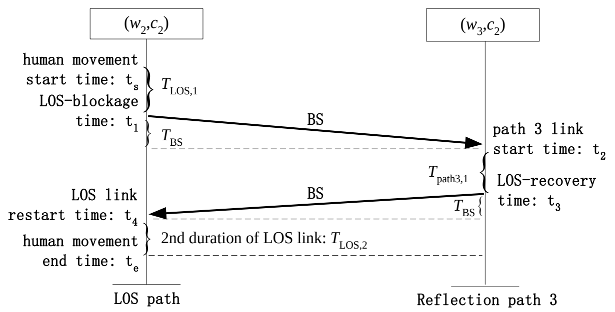
In this part, human blockage is introduced into the communication system to evaluate the performance of the proposed beam switching process. We assume that a person moves according to the RWP mobility model, whose related parameters are listed in Table III. Without loss of generality, Dev1 and Dev2 are assumed to be set at the coordinates (2, 2.5, 1) and (5.5, 4.5, 1), respectively. We rather assume that only SNR is considered as the path selection criteria, i.e. a=1, b=0 and c=0 in (25). Here, two different movement configurations are used for the simulations.

1) Movement configuration 1: A person is assumed to move at a uniform speed of 1m/s from wall 3 to wall 1 along the line x=5. Based on the beam switching process presented in section IV, the simulated communication processes from Dev1 to Dev2 without and with the LOS recovery detection module are shown in Fig. 11 (a) and (b), respectively.

The start time and end time of the human movement are denoted as t_s and t_e, respectively, and only the duration from t_s to t_e is adopted for the process evaluation. For simplicity, we assume that t_s=0 s. At time t_1=0.785s, the communication link is detected to have been blocked by the moving person when he crosses the LOS path. The beam pair (w_3,c_2) of the reflection path 3 is selected quickly according to the OBPL, and the beams of Dev1 and Dev2 are switched from (w_2,c_2) of the LOS path to (w_3,c_2). At time t_2=0.786s, the reflection path 3 begins to be used as communication link. As shown in Fig. 11 (a), because there is no LOS recovery detection module, the reflection path 3 is used until the end of human movement t_e. The duration of path 3 link is $T_{path3,1}$= t_e-t_2 = 4.214s, while the duration of LOS path link is $T_{LOS,1}$ = t_1-t_s = 0.785s. In Fig. 11 (b), the LOS recovery detection is introduced into the process, and the detection interval T_d is set to 0.5s according to the human's movement configuration. At time t_3 =1.286s, the blockage of LOS path is detected to have been removed, and the link are switched back to the beam pair (w_2,c_2). After a short beam switching duration, written as T_{BS} and assumed to be 1ms throughout the paper, at time t_4 =1.287s the LOS path is used as the transmission link again and until t_e. Therefore the total duration of LOS path link is increased to T_{LOS} = $T_{LOS,1}$ + $T_{LOS,2}$ = 4.498s, while the duration of path 3 link is reduced to $T_{NLOS3,1}$ = 0.5s.



(a) Example process without LOS recovery detection



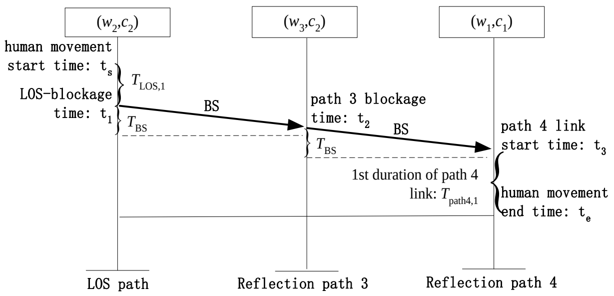
(b) Example process with LOS recovery detection

Figure. 11. Simulated communication processes under movement configuration 1

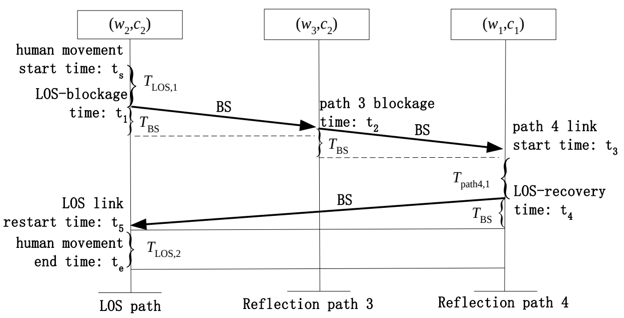
2) Movement configuration 2: A person is assumed to move at a uniform speed of 0.5m/s from wall 3 to wall 1 along the line x=3. Under this configuration, the simulated communication processes from Dev1 to Dev2 without and with the LOS recovery detection module are depicted in Fig. 12 (a) and (b), respectively. The start time of human movement t_s is also assumed to be 0s. At time t_1 =3.856s, the LOS path is detected to be blocked by the moving person, and the beams of Dev1 and Dev2 are switched from the beam pair (w_2,c_2) to (w_3,c_2) according to OBPL. Almost at the same time t_2=3.857s, when the beams just have been switched, the path 3 link is detected to be blocked due to its very adjacent position to the LOS path. Then the link is switched to the suboptimal backup path, i.e. the reflection path 4 with its beam pair (w_2,c_2), according to OBPL, too. In Fig. 12 (a), the reflection path 4 is used as the communication link

from t_3 to the end of human movement t_e, because there is no LOS recovery detection and the path 4 link is not blocked any longer. The duration of path 4 link is $T_{path4,1} = t_e - t_3 = 6.142$s, and the duration of LOS path link is $T_{LOS,1} = t_1 - t_s = 3.856$s. In Fig. 11 (b), because of the introduction of the LOS recovery detection, at time t_4=4.358s, the blockage of the LOS path is detected to be removed, and the beams are switched back to (w_2,c_2). Therefore, the total duration of LOS path link is increased to $T_{LOS} = T_{LOS,1} + T_{LOS,2} = 9.497$s, while the duration of path 4 link is reduced to $T_{path3,1}$ = 0.5s, which is dependent on the interval T_d.

More simulations have been conducted with random positions of Dev1 and Dev2, various human moving configurations, and different sorting rules of paths. All simulation results show that the proposed OBPL based beam switching scheme is feasible for both LOS link-blockage and reflection NLOS link-blockage with the same processing method. The proposed sorting rules of paths are flexible to meet various requirements. In addition, the utilization rate of the LOS path is increased significantly, e.g. it is increased from 15.7% to 89.9% in Fig. 11, and increased from 38.6% to 95.0% in Fig. 12.



(a) Example process without LOS recovery detection



(b) Example process with LOS recovery detection

Figure. 12. Simulated communication processes under movement configuration 2

TABLE V. PARAMETERS OF MODULATION AND CODING

Rec. sensitivity	SF	FEC type	Modulation scheme	Data rate
-70dBm	64	RS(255,239)	π /2 BPSK	25.3 Mbps
-61dBm	4	RS(255,239)	π /2 BPSK	405 Mbps
-59dBm	1	LDPC(672,504)	π /2 BPSK	1300 Mbps
-58dBm	1	LDPC(672,336)	π /2 QPSK	1730 Mbps
-56dBm	1	LDPC(672,504)	π /2 QPSK	2590 Mbps
⩾-54dBm	1	LDPC(672,588)	π /2 QPSK	3020 Mbps

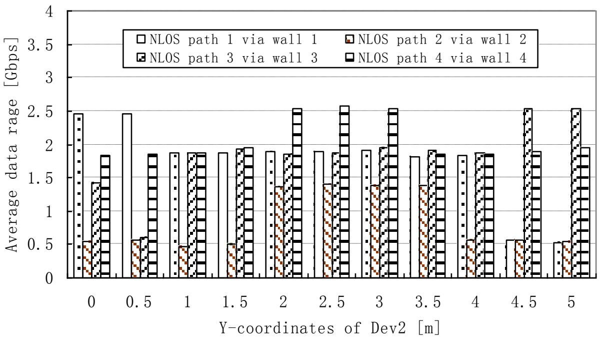


Figure. 13. Average data rate comparison between different reflection paths

Although the increased ratio heavily relies on the specific configuration of human's movement, a greater number of simulations show that the system throughput with LOS recovery detection is improved obviously. Here, the average data rate is adopted to evaluate the system throughput, and the related parameters are show in Table V [11].

The positions of Dev1 and Dev2 are same as that in Fig. 10 (a). The transmission capability comparison between different reflection paths with their average data rates are shown in Fig. 13. It shows that most of the reflection paths with their optimal beam pairs can provide a data rate not less than 1G bps. On the other hand, even the same path has a remarkably various data rate due to the differences in the incident angle and propagation distance caused by different positions of the communication devices. It further means that the sorting and selection of paths through the OBPL are necessary for the better throughput.

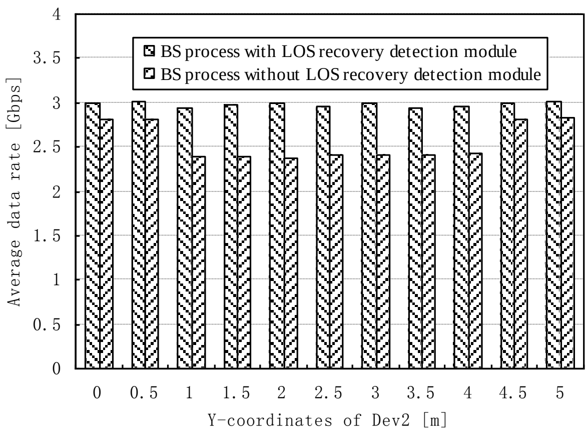


Figure. 14. Average data rate comparison between different beam switching schemes

In the following part, One thousand times of communication simulations with random human blockage are conducted independently. Each iteration contains a 30 seconds of communication process, of which a person is assumed to move according to the RWP mobility model with the uniform speed distribution of [0, 1] m/s and the uniform pausing time distribution of [0, 5] s. Fig. 14 shows the average data rate comparison between the conventional beam switching schemes without the LOS recovery detection and the proposed beam switching scheme with the detection module.

It shows that the average data rates of the proposed beam switching process are generally increased by the value from 6.46% to 25.87% with different positions of devices. In addition, we observe that the average data rate in Fig. 14 is generally higher and more stable than that in Fig. 13 at all positions. This is because the LOS path accounts for a larger proportion of communication duration in Fig. 14, and the selected backup reflection paths from the OBPL have the good performance at each position.

VI. Conclusion

A low complexity reflection path based beam switching scheme has been developed to solve the link-blockage problem in 60 GHz communication systems. The codebook based beamforming is investigated, and an ordered beam pair list corresponding to reflection paths is proposed for the rapid beam switching. Based on the composition of SNR, BSQL and GLMR of paths, a flexible sorting rule is developed for different environments. Based on the OBPL, a complete and closed-form beam switching process is presented, of which the link-blockage detection and the LOS path recovery detection are investigated. Through various simulations, it is shown that the proposed beam switching scheme applies for the blockages of both LOS path and reflection NLOS path with a low complicated and consistent solution.

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