A 60GHz Wireless Cooperative Communication System Based on Switching Beamforming

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Abstract

The challenge of penetrating obstacles along with impact from weak multipath effects makes 60GHz signal very difficult to be transmitted in non-line of sight (NLOS) channel. So 60GHz system is vulnerable to obstructions and thus likely results in link interruption. While the application of cooperative technology to solve link blockage problem in 60GHz system should consider the characteristic of directional transmission for 60GHz signal. Therefore in this paper a system is proposed to solve the link blockage problem in 60GHz NLOS communication environment based on the concept of cooperation and also the beamforming technology, which is the basis of directional transmission for 60GHz communication system. The process of anti-blockage solution with cooperative communication is presented in detail, and the fast switching and recovery schemes are well designed. The theoretical values of symbol error rate (SER) using decode and forward (DF) cooperation and amplify and forward (AF) cooperation are presented respectively when the common channel interference exists. Simulation results demonstrate that the performance based on DF cooperation is better than the performance based on AF cooperation when directional transmission is used.

1. Introduction

$\mathbf{W}$ith the increasing production of full-HD even Ultra-HD film and television programs, the demand of wireless communication with high transmission rate and low latency experience has become especially urgent. Due to the limitations of spectrum resource, transmitting power and technical standard, Wi-Fi, UWB and other short-range wireless communication technologies can not achieve Gbps transmission rate[1][2].With apparent advantages of several GHz license-free spectrums, 10W maximum transmit power, low-cost CMOS devices implement and so forth[3][4][5], 60GHz wireless communication technology has become the first choice for Gbps level short-range wireless communications. Meanwhile it also can be seen a general tendency of applying higher frequency bands in the brewing fifth generation of mobile communication technology and the 60GHz band has performed a great potential in becoming an alternative frequency band[6][7]. This motivation has prompted the effort of several standardization groups such as the IEEE 802.15 Task Group 3c (TG3c) [8], ECMA387 [9], IEEE802.11ad [10]. Recently IEEE 802.15.3c group has been formed to develop a 60GHz mmWave Wireless Personal Area Network (WPAN) standard including physical layer and MAC layer.

60GHz signal belongs to millimeter wave band, the wavelength of 60GHz signal is much shorter than mobile communication signal and WiFi signal. 60GHz wireless communication occupies up to 7GHz of unlicensed spectrum, which is sufficient for future high rate communication system. The path loss attenuation in millimeter wave band is much larger than low frequency. Friis free space propagation [11] formula explains the reason of high path loss for 60GHz frequency signal.

$$P_R = P_T G_T G_R \frac{\lambda^2}{16\pi^2 R^2} \tag{1}$$

The average transmitting power and receiving power are denoted as P_T and P_R, G_T and G_R are the antenna gains of the transmitter and receiver respectively, λ is the wavelength of signal. R is the distance between the transmitter and receiver. With higher carrier frequency, the lower λ will be and that results in lower receiving signal power. The path loss of 60GHz signal is higher at least 28dB than 2.4GHz signal and 21dB than 5GHz signal from formula (1) On the other hand, 60GHz signal suffers great atmospheric absorption by a range of 15 to 30 dB/km based on the atmospheric conditions [3]. Therefore 60GHz communication system is not suitable for long distance wireless communication, but is very suitable for short distance indoor wireless communication.

The attenuation of signal crossing blockage showed an increased trend with the increase trend of signal frequency. So the blockage attenuation of 60GHz signal is much larger than low frequency band signal, for example the material block attenuation will be up to 30dB compared with 5GHz band signal[12]. At the same time, the scattering phenomenon for mmwave signal is weak. Therefore, 60GHz systems rely on line-of-sight (LOS) transmission to achieve high data rate. The obstacles and moving people can easily block the LOS transmission in indoor environment, thus greatly reduce the transmission data rate.

Since 60GHz signal suffers large path loss in the process of transmission, some methods should be carried out to avoid the waste of energy. For 60GHz communication, only 5mm wavelength makes it feasible to integrate a large number of antenna elements on the whole

package for both the 60GHz transmitter and receiver [13]. Antenna array beamforming is preferred for 60GHz wireless communication because of the large antenna gain, small size and fast electronic steerability[14]. At the same time it is especially meaningful in solving the notable non-line of sight (NLOS) blockage problem using reflection path. So antenna array beamforming provides directional transmission gain and fast beam switching mechanism, which can overcome the high path loss problem and blockage problem.

In order to solve link blockage problem, switching beamforming or adaptive beamforming[15] is adopted to seek proper reflection path when the direct communication path is blocked. In such case, the antenna array will re-adjust its parameters to point to the best reflecion path instead of keeping the direct path between the transmistter and receiver. Although the switching beamforming technology based on reflection path can overcome communication interrupt problem to a certain extent when the LOS link is blocked, it still bring a certain degree of energy loss. If the room is larger, the reflector is less, the system throughput will obviously degrade if reflection path is used only. So an alternative relaying path should also be considered to keep the network connectivity[16] , thus to provide the required data rate for multimedia applications. Recently, some literatures have proposed using relay to overcome the 60GHz link blocking problem. Literature [17] proposed multi-hop relay scheme to solve the problem of millimeter wave link blockage. At the same time, the location of relay is also analyzed in this paper. Literature [18] analyzed the 60GHz relay system, and designed MAC layer scheme under multi-hop transmission. Letter[19] analyzed the communication success probability when two devices is randomly selected in mmwave wireless personal area networks.

However the existing researches on relay or cooperation are normally based on omni-directional antenna, while 60GHz systems usually adopt directional transmission. The research on directional transmission relay system is relatively rare, so the application of relay or cooperative technology in 60GHz system should consider the characteristics of directional transmission for 60GHz signal. A combination of beamforming technology and cooperative technology are proposed for 60GHz NLOS communication in this paper. The directional transmission gain from the beamforming technology can offset the serious path loss, at the same time cooperative technology is adopted for 60GHz WPAN system to overcome the link blockage problem.

The organization of this paper is as follows: a 60GHz directional transmission cooperative communication model is established in Section 2. In section 3 the selection scheme of optimal cooperative node is proposed. Section 4 presents the resolution process for the link blockage. Section 5 gives the symbol error probability of 60GHz directional cooperative communication system. Section 6 presents the simulation results of 60GHz directional cooperative communication under NLOS channel. Section 7 concludes this paper.

2. 60GHz Cooperative Communication Model

IEEE 802.15.3c standard builds the network by using the piconet as its basic unit, which is a collection of all devices(DEVs) connected together[8]. To support Ad hoc, all DEVs are equal with the same priority and can communicate with each other. DEVs are divided into piconet controller (PNC) and common devices, where PNC is responsible for managing the whole network, including timing management, resource allocation, task scheduling etc. In order to ensure the self-organization and robustness of the network, PNC is dynamically selected from network nodes and supports seamless switching between DEVs when the former PNC suddenly leaving or failing to work. According to IEEE 802.15.3c, the channel access and data

transmission is based on the superframe structure [8], which is composed of three parts: beacon period (Beacon), competitive access period (CAP) and channel time allocation period (CTAP).

Generally, WPAN system supports intercommunication between any two DEVs. For common WPAN system, omnidirectional antennas are equipped by all DEVs. And it is assumed that no matter where the receiving and sending DEVs are located, the transmission beteen them can always be constructed. While actually 60GHz system generally adopts directional communication. If every DEV always point to fixed direction in all communication process, it is apparently unable to realize intercommunication for 60GHz-WPAN. Naturally array antenna beamforming technology becomes the preferred technology for 60GHz-WPAN. In order to reduce the complexity of network organization, switching beamforming based on beam codebook is adopted.
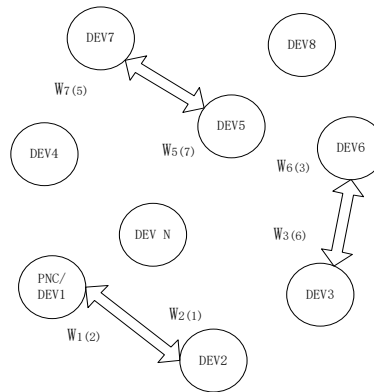
Fig. 1. Schematic diagram of 60GHz-WPAN link transmission in one superfram

As shown in **Fig. 1**, there are N DEVs in the WPAN, each of them equips an antenna array to achieve directivity control. DEV1 is selected as PNC then beam training is conducted based on 802.15.3c beam codebook under unobstructed environment [8]. After beam training, the interconnecting optimal beam pairs of DEVs are found and the antenna weight vectors corresponds these optimal beam pairs are recorded, as shown in **Table 1**. Then the antenna array can choose their interconnecting optimal beam pairs to communicate with each other.

Table 1. Antenna weight vectors record form of interconnecting DEVs beam pairs

DEV number \ DEV number	DEV1	DEV2	DEV...	DEV N
DEV1	O	$<W_{1(2)},W_{(2)1}>$	...	$<W_{1(N)},W_{N(1)}>$
DEV2	$<W_{2(1)},W_{1(2)}>$	O	...	$<W_{2(N)},W_{N(2)}>$
DEV...	...	...	O	...
DEV N	$<W_{N(1)},W_{1(N)}>$	$<W_{N(2)},W_{2(N)}>$	...	O

$W_{1(2)}$ and $W_{2(1)}$ indicate the weighted vector value respectively when DEV1 and DEV2 intercommunicate using their optimal beam pairs. The subscript 1(2) indicates the optimal weighted vector for DEV1 pointing to DEV2. The process of beam training is carried out in the initial stage of 60GHz-WPAN establishing. So when every DEV communicates with other DEV under unobstructed environment, there is no need for beam training. The antenna weight vectors can be invoked from **Table 1** to realize the directional communication between every two DEVs. This mechanism brings great convenience and saves the beam training time in the process of switching DEVs.

In **Fig. 1**, 3 pairs of links have transmission request in this superframe, which is link DEV1-DEV2, DEV3-DEV6, DEV5-DEV7 respectively. At the beginning of communication, weight vectors are invoked directly from the weight vector table, that is $<W_{1(2)}, W_{2(1)}>$, $<W_{3(6)}, W_{6(3)}>$, $<W_{5(7)}, W_{7(5)}>$, carrying out directional communication between DEVs until the blockage happened.

Then a 60GHz multi-user cooperative communication model is established based on switching beamforming, as shown in **Fig. 2**. The symbol error probability (SER) derivation and simulation of 60GHz multi-user cooperative communication system are given based on this.
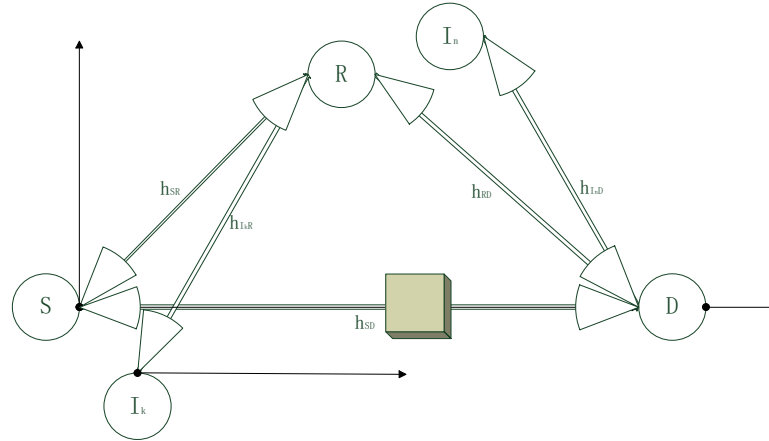

Fig. 2. 60GHz cooperative communication system model based on switching beamforming under STDMA mode

It is assumed that all DEVs are in the same horizontal plane. Node S is 60GHz signal transmission DEV, node D is 60GHz signal destination DEV which pairing with node S. Node R is a 60GHz DEV used to cooperative effect between node S and node D. For the selection process of cooperative node, we should choose the spare node in this time slot, which will not affect the node transmission task of itself. Make node S as ordinate origin, make S-D straight line as the X axis, rectangular coordinate system is established. The distance between S and D is marked as d_{SD}. D point coordinates can be expressed as $(d_{SD}, 0)$. When the communication link between node S and node D are not blocked, that is to say the path between node S and node D is LOS path, the array antenna main response axis(MRA) of node S and the MRA of node D are pointing to each other.

Assuming the link between node S and node D is blocked by one barrier. In order to keep the link between node S and node D transmitting normally, we should select a DEV as a cooperative node for cooperative communication. For example, take R as the cooperative node, the transmission link will changed at this time as S-R-D. Weight vectors of transmission node S, cooperative node R and destination node D are also directly selected from the weight vector shown in **Table 1**.

Through establishing a weighted vector form of interconnection beam pairs for WPAN DEVs, we set up a DEV interconnection mechanism based on the beam codebook for 60GHz -WPAN and realize fast free switch for every communication DEV when link blockage happening. On one hand, it is satisfied for the directional transmission of links, on the other hand, it is also convenient for switching the communication DEVs.

3. Selection Scheme of Optimal Cooperative Node

A key problem which is how to select the optimum cooperative node is investigated in this section. In 60GHz-WPAN, the nodes without sending or receiving task in one slot time usually contain multiple nodes. The system should select the most appropriate cooperative node from multiple nodes. The optimum signal to noise ratio (SNR) judgment is adopted as metrics to select the best cooperative node. That is to select the best cooperative node R_i from nodes $R_1, R_2, \ldots R_M$ which maximize $SNR_{S\text{-}Ri\text{-}D}(i=1,2\ldots M)$. Due to the cooperative system performance is influenced by two-hop links, assuming the SNR of first hop link is $SNR_{S\text{-}R}$, the SNR of second hop link is $SNR_{R\text{-}D}$. The overall performance is generally affected by the smaller SNR of one hop link from the two-hop links[20].

$$SNR_{S-R-D} = \min(SNR_{S-R}, SNR_{R-D}) \tag{2}$$

In order to measure the $SNR_{S\text{-}Ri\text{-}D}(i=1,2\ldots M)$ of every cooperative link, the antenna weight vectors record form of interconnecting DEVs beam pairs in **Table 1** is improved. After beam training, when the antenna weight vectors corresponding optimal beam pairs are recorded, the SNR of each link at the receivers are measured. Then a SNR form of interconnected devices is defined and established as **Table 2**.

Table 2. WPAN SNR form of interconnected devices

DEV number \ DEV number	DEV1	DEV2	DEV...	DEV N
DEV 1	O	SNR_{12}	...	SNR_{1N}
DEV 2	SNR_{21}	O	...	SNR_{2N}
DEV...	...	...	O	...
DEV N	SNR_{N1}	SNR_{N2}	...	O

Where SNR_{12} is the receiver SNR between DEV1 and DEV2 when DEV1 and DEV2 using their optimal beams. So at the beginning of the WPAN establishment, the link SNR for each set of DEVs is obtained. Now, assuming that DEV4, DEV8, DEVN three nodes are idle, which can participate in cooperation. The selection process of optimal cooperative node is described as follows.

1) Judge the blockage state.

The transmitting node DEV1 and receiving node DEV2 using their interconnecting optimal beam pairs to communicate with each other. At the initial time of each frame signal, the received SNR compares with threshold SNR of blockage, judge the blockage state, if SNR_{12} is less than the preset threshold of blockage[21], the direct path between DEV1 and DEV2 is predicated blockage, cooperation mechanism is opened.

2) Choose the biggest SNR link from the three cooperative links as the optimum cooperative link.

The overall SNR of two-hop links DEV1-DEV4-DEV2 is indicated as $SNR_{1\text{-}4\text{-}2}=\min\{SNR_{14}, SNR_{42}\}$ if selects DEV4 as the cooperative node. In the same way, selecting DEV8 or DEVN as cooperative node respectively, $SNR_{1\text{-}8\text{-}2}=\min\{SNR_{18}, SNR_{82}\}$, $SNR_{1\text{-}N\text{-}2}=\min\{SNR_{1N}, SNR_{N2}\}$ respectively. The system only need to read SNR_{14}, SNR_{42}, SNR_{18}, SNR_{82}, SNR_{1N}, SNR_{N2} from **Table 2** and brings into $SNR_{1\text{-}4\text{-}2}$, $SNR_{1\text{-}8\text{-}2}$, $SNR_{1\text{-}N\text{-}2}$, then get three overall SNRs. Assuming that $SNR_{1\text{-}4\text{-}2}$ is bigger than $SNR_{1\text{-}N\text{-}2}$, and $SNR_{1\text{-}N\text{-}2}$ is bigger than $SNR_{1\text{-}8\text{-}2}$, then link DEV1-DEV4-DEV2 is selected as the optimum cooperative link.

3) Second test for optimum cooperative link.

The calculative cooperative link SNR from **Table 2** may be changed due to the link through cooperative node also may be blocked. In order to solve this problem, the selected optimum cooperative link needs to be tested again. After selecting optimum cooperative link, a detection signal will be sent by DEV1 to test the SNR of optimum cooperative link. If the SNR is greater than the predefined threshold, we can predicate this cooperative link is not blocked and select this cooperative link as the backup path when the direct path is blocked. If the optimum cooperative link SNR is less than the predefined threshold, this cooperative link is predicated also blocked. In this case, the second largest SNR link DEV1-DEVN-DEV2 is selected as the cooperative link. System tests whether the SNR of this cooperative link is bigger than predefined threshold. If this link SNR is bigger than predefined threshold, select this cooperative link as the backup path when the direct path is blocked. Else repeats the above steps, until finds the link whose link SNR is greater than the threshold SNR and selects this cooperative link as the backup path when the direct path is blocked.

Using the WPAN SNR form of interconnected devices to determine the optimal cooperative node avoids the complex process to find the optimal cooperative node beam pairs when the direct path is blocked. This cooperative method effectively shortens the time of switching the beam and improves the communication efficiency when the link is blocked.

4. The Resolution Process for Link Blockage

Cooperative communication is introduced based on switching beamforming, converting the original single-hop transmission to two-hop transmission. **Fig. 3** presents the integrated flow diagram for 60GHz cooperative communication based on switching beamforming. The specific transmission process can be divided into the following two stages.

The first stage (slot time), take **Fig. 1** as example, when the direct link DEV1-DEV2 is detected blockage, DEV4 is selected as the optimal cooperative node. The weighted vector of DEV1 is transformed from $W_{1(2)}$ to $W_{1(4)}$ according to **Table 1**, the beam of DEV1 is transformed from pointing to DEV2 to pointing to DEV4 (Due to adopt predefined beam codebook, the MRA direction of DEV1 maybe not pointing to cooperative node, but can ensure the cooperative node within the range of beam main lobe). At the same time, the weighted vector of DEV4 is transformed to $W_{4(1)}$, the beam of DEV4 is quickly pointing to DEV1. Thus the first-hop transmission link DEV1-DEV4 is established.

The second stage (slot time), the weighted vector of DEV4 is transformed from $W_{4(1)}$ to $W_{4(2)}$ according to **Table 1**, the beam of DEV4 is transformed from pointing to DEV1(the first stage) to pointing to DEV2(Due to adopt predefined beam codebook, the MRA direction of DEV4 maybe not pointing to DEV2, but can ensure DEV2 within the range of beam main lobe). The weighted vector of DEV2 is transformed from $W_{2(1)}$ to $W_{2(4)}$ according to **Table 1**, the beam of DEV2 is from pointing DEV1(the first stage) to pointing DEV4. The DEV1-DEV2 NLOS transmission link is replaced by two-hop LOS transmission link DEV1-DEV4-DEV2 and the continuity of data transmission is ensured.

The solution to solve blockage problem using cooperative link refers to a step which is detecting the LOS path status. Although cooperative communication is likely to improve system performance, but the cooperative node will also consume extra power consumption. So when the blockage of direct path is disappeared, the direct path should be preferentially employed for communication. The recovery test process of LOS path is presented as below:

(1) The beam of DEV1 is transformed from pointing to DEV4 to pointing to DEV2;
(2) The beam of DEV2 is transformed from pointing to DEV4 to pointing to DEV1;

(3) DEV1 sends detection signal, tests the SNR of link DEV1-DEV2;

(4) If the SNR of link DEV1-DEV2 is greater than the predefined threshold, we can predicate the blockage of direct link is disappeared, and LOS path recovered. The beams of DEV1 and DEV2 are re-established to pointing to each other. If the SNR of link DEV1-DEV2 is lower than the predefined threshold, the blockage of direct link is predicated still existing. The beams of DEV1 and DEV2 are both kept with DEV4, system continues to use link DEV1-DEV4-DEV2 for cooperative communication.
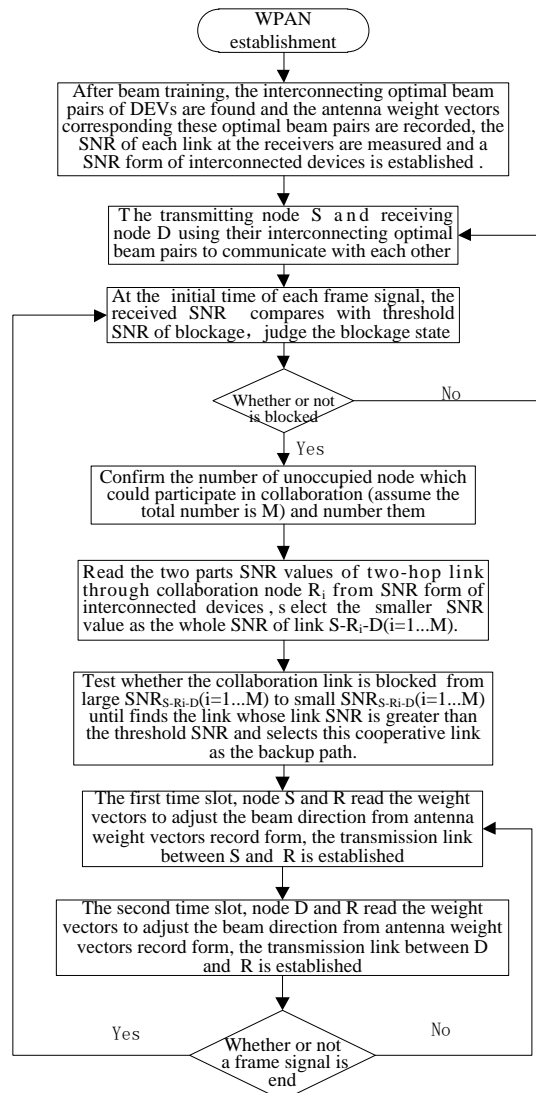
Fig. 3. The integrated flow diagram for 60GHz cooperative communication based on switching beamforming

About the detection cycle of LOS path recovery is set as one superframe. According to 802.15.3c, a superframe duration is about tens of milliseconds for 60GHz communication. The movement speed of human body is about 1 m/s - 5 m/s. Tens of milliseconds detection cycle is enough to meet the detection demand of moving human body. Otherwise it will consume extra power with frequent detection.

5. SER Performance Analysis of 60GHz Directional Cooperative Communication System

60GHz wireless communication is conducive to directional spatial multiplexing for devices due to its directional transmission character. Space-time division multiple access (STDMA) can be adopted and the WPAN system capacity will be improved[22]. So there may be other DEVs working in the same transmission time slot, these DEVs will play an inevitable interference effect for each other in the same transmission time slot[23]. As **Fig. 2**, I_k represents the receiving interference value of cooperative node R from other parallel transmission DEVs in the first time slot, where $k=1,2,……N_{IR}$, N_{IR} indicates the interfering DEVs number of cooperative node R in the first time slot. I_n represents the receiving interference value of destination node D from other parallel transmission DEVs in the second time slot, where $n=1,2,……N_{ID}$, N_{ID} indicates the interfering DEVs number of destination node D in the second time slot. h_{SR} represents the channel impulse response between transmission node S and cooperative node R, h_{RD} represents the channel impulse response between cooperative node R and destination node D. $h_{I_k,R}$ represents the channel impulse response between interference I_k and cooperative node R. $h_{I_n,D}$ represents the channel impulse response between interference I_n and destination node D. Because the interference I_k and I_n also adopt antenna array beamforming for direction transmission, the receiving signal in nodes R and D can be expressed as:

$$y_R = \sqrt{P_s}h_{SR}x_S + \sum_{k=1}^{N_{IR}}\sqrt{P_{I_k}}h_{I_k,R}x_{I_k} + n_R \tag{3}$$

$$y_D = \sqrt{P_R}h_{RD}x_R + \sum_{n=1}^{N_{ID}}\sqrt{P_{I_n}}h_{I_n,D}x_{I_n} + n_D \tag{4}$$

The blocked NLOS S-D link is converted to S-R-D two-hop LOS transmission link, so in this paper channel impulse response h_{SR}、h_{RD}、$h_{I_k,R}$、$h_{I_n,D}$ can be modeled as IEEE 802.15.3c CM1 LOS channel impulse response formula[24].

$$h(t,\phi,\theta) = \beta\delta(\tau,\phi,\theta) + \sum_{k=0}^{K}\sum_{l=0}^{L_k}\alpha_{k,l}\delta(t - T_k - \tau_{k,l})\delta(\theta - \Psi_k - \psi_{k,l}) \tag{5}$$

Where $\beta\delta(\tau,\phi,\theta)$ expresses LOS weight gain. $\delta(\cdot)$ represents impulse function, K represents the number of cluster arriving the receiver, L_k indicates the number of multipath in the kth cluster. α_{kl}, τ_{kl} and ω_{kl} indicate the plural amplitude value, delay and arrival angle in the kth cluster, lth path respectively. T_k and Θ_k represent the delay and arrival angle in the kth cluster respectively. P_S, P_R, P_{I_k}, P_{I_n} represent the transmission power of node S, R, I_k and I_n respectively. x_S, x_R, x_{I_k}, x_{I_n} represent the transmission signal of node S, R, I_k and I_n respectively. n_R and n_D indicate complex gaussian process which submit to zero mean value and N_R, N_D variance respectively. For convenience of calculation and expression, the beam antenna gains of transmission node S, destination node D and cooperative node R are equaled into the channel impulse response of each link. In the calculation process of channel impulse response is expressed as G_{r1} and G_{r1} respectively in formula (6). In the desktop LOS scenario, LOS component can be observed as two paths response due to reflection effect, desktop direct path

and reflection path respectively, as formula (6).

$$\beta\,[\text{dB}] = 20 \cdot \log_{10}\left[\left(\frac{\mu_d}{d}\right)\left|\sqrt{G_{t1}G_{r1}} + \sqrt{G_{t2}G_{r2}}\,\Gamma_0 \exp\left[j\frac{2\pi}{\lambda_f}\frac{2h_1h_2}{d}\right]\right|\right] - PL_d\left(\mu_d\right) \qquad (6)$$

For most of LOS and NLOS environments, $\Gamma_0 \approx 0$, where $PL_d\left(\mu_d\right)$ can be expressed as[25]

$$PL_d\left(\mu_d\right)[\text{dB}] = 20\log_{10}\left(\frac{4\pi d_0}{\lambda_f}\right) + 10 \cdot n_d \cdot \log_{10}\left(\frac{d}{d_0}\right) \qquad (7)$$

Bringing formula (6) into formula (7), $\beta\,[\text{dB}]$ can represent as formula (8)

$$\beta\,[\text{dB}] = 20 \cdot \log_{10}\left(\frac{\mu_d}{d}\right)\sqrt{G_{t1}G_{r1}} - 20\log_{10}\left(\frac{4\pi d_0}{\lambda_f}\right) - 10 \cdot n_d \cdot \log_{10}\left(\frac{d}{d_0}\right) \qquad (8)$$

Where μ_d, G_{t1}, G_{r1}, λ_f, d_0, n_d represent mean distance, transmitting antenna gain in direct path direction, receiving antenna gain in direct path direction, wave length, reference distance and path attenuation exponential, generally d_0=1.
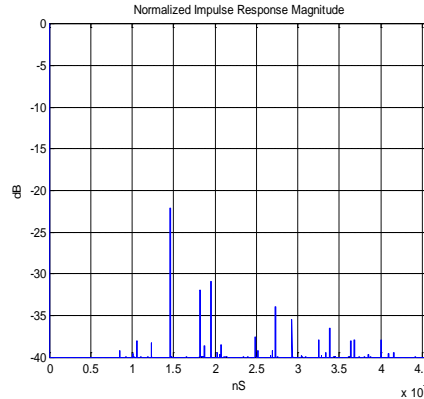
Fig. 4. 60GHz IEEE802.15.3c CM1.3 discrete channel impulse response

From **Fig. 4**, the signal strength of LOS path is over 20dB than the subsequent arrived multipath in LOS environment. 99% of the energy is concentrated in the LOS path[5]. The rest of multipath signal energy is quite little which can be neglected. So the impulse response under LOS channel in formula (5) can be simplified to

$$h(t) = \beta\delta(t) \qquad (9)$$

β is the $\beta\,[\text{dB}]$ in formula (8). Bring $\lambda_f = c/f = 3\times10^8/(6\times10^{10}) = 5\times10^{-3}$ into formula (8). The reference distance d_0 is set as 1m,

$$\beta\,[\text{dB}] = 20\log_{10}\left(\sqrt{G_{t1}G_{r1}}\right) - 20\log_{10}\left(800\times\pi\right) - 20\log_{10}\left(d\right) = \frac{\sqrt{G_{t1}G_{r1}}}{\left(800\times\pi\times d\right)} = kd^{-1} \qquad (10)$$

Where $k = \dfrac{\sqrt{G_{t1}G_{r1}}}{800 \times \pi}$. Bring(10) into (9),

$$h = kd^{-1}\delta(t) \tag{11}$$

The channel impulse response can be considered only associated with sending and receiving antenna gain, the transceiver distance in LOS channel. The instantaneous SNR of link S-R, R-D, I_k-R and I_n-D can be expressed as formula (12)(13)(14)(15)respectively.

$$\gamma_{SR} = \frac{P_s |h_{SR}|^2}{N_R} \tag{12}$$

$$\gamma_{RD} = \frac{P_R |h_{RD}|^2}{N_D} \tag{13}$$

$$\gamma_{I_kR} = \frac{\sum_{k=1}^{N_{IR}} P_{I_k} |h_{I_k,R}|^2}{N_R} \tag{14}$$

$$\gamma_{I_nD} = \frac{\sum_{n=1}^{N_{ID}} P_{I_n} |h_{I_n,D}|^2}{N_D} \tag{15}$$

Assume that all 60GHz signal using same modulation mode in the network, the signal-interference and noise ratio (SINR) in node R can be represented as:

$$\gamma_R = \frac{P_s |h_{SR}|^2}{N_R + \sum_{k=1}^{N_{IR}} P_{I_k} |h_{I_k,R}|^2} = \frac{\gamma_{SR}}{\gamma_{I_kR} + 1} \tag{16}$$

Where γ_{SR} and γ_{I_kR} is shown in (12)(14).

The SINR in node D can be expressed as:

$$\gamma_D = \frac{P_R |h_{RD}|^2}{N_D + \sum_{n=1}^{N_{ID}} P_{I_n} |h_{I_n,D}|^2} + \frac{P_s' |h_{SD}|^2}{N_D + \sum_{m=1}^{N_{ISD}} P_{I_m} |h_{I_m,D}|^2} \tag{17}$$

Where h_{SD} is the channel impulse response of S-D link in the first time slot. Because the LOS path is blocked, so in this paper, h_{SD} is modeled as NLOS CM2 channel impulse response. In the first time slot, there are N_{IR} interference nodes to interfere cooperative node R, there are N_{ISD} interference nodes to interfere cooperative node D. P_{I_m} (m=1,2,……N_{ISD}) is the transmission power of interference node in node D. $h_{I_m,D}$ is the channel impulse response between interference node and node D, which is also modeled as LOS CM1 channel impulse response. Here a limited condition is considered, on the one hand, due to S-D link is blocked, $|h_{SD}|$ is very small; on the other hand, the beam direction is pointing to node R, not pointing to node D, so the array antenna gain is small. Furthermore, due to the high directivity of 60GHz

signal, most of the energy is focused on the beam axis direction within 4.7°. So the transmission power of node S in S-D direction is much less than that in S-R direction, that is $P_s^{'} << P_s$, $\dfrac{P_s^{'}\left|h_{SD}\right|^2}{N_D + \sum\limits_{m=1}^{N_{ISD}} P_{I_m}\left|h_{I_m,D}\right|^2}$ can be ignored. Formula (17) can be rewritten as

$$\gamma_D = \frac{P_R\left|h_{RD}\right|^2}{N_D + \sum\limits_{n=1}^{N_{ID}} P_{I_n}\left|h_{I_n,D}\right|^2} \tag{18}$$

Cooperative communication[26] can be divided into two types: decode-and-forward (DF) and amplify-and-forward (AF) [27][28]. In this paper the theoretical values of SER using DF cooperation and AF cooperation are given respectively when the common channel interference existing.

5.1 DF cooperation performance analysis

Literature [29] gives the SER expression of uncoded system using M-PSK modulation,

$$\psi_{PSK}(\gamma) = \frac{1}{\pi}\int_0^{(M-1)\pi/M} \exp(-\frac{b_{PSK}\gamma}{\sin^2\theta})d\theta \tag{19}$$

Where γ represents SNR, $b_{PSK} = \sin^2(\pi/M)$. If the transmission node S and cooperative node R adopt M-PSK modulation, the decoding error probability of cooperative node R can be expressed as $\psi_{PSK}(\gamma_R)$, the decoding error probability of destination node D can be expressed as $\psi_{PSK}(\gamma_D)$. In the transmission process from node R to node D, if cooperative node R decodes the source symbols x_S correctly, the cooperative node R continues to send the correct symbol to destination node D with the power P_R. Otherwise, the cooperative node R does not forward to destination node D. That is, the forward power P_R=0, then the SER performance of S-R-D link is

$$
\begin{aligned}
P_{PSK}^{S-R-D} &= \psi_{PSK}(\gamma_D)\Big|_{P_R=0}\times\psi_{PSK}(\gamma_R) + \psi_{PSK}(\gamma_D)\Big|_{P_R\neq0}\times[1-\psi_{PSK}(\gamma_R)]\\
&= \psi_{PSK}\left(\frac{P_s^{'}\left|h_{SD}\right|^2}{N_D+\sum\limits_{m=1}^{N_{ISD}}P_{I_m}\left|h_{I_m,D}\right|^2}\right)\Big|_{P_R=0}\times\psi_{PSK}\left(\frac{P_s\left|h_{SR}\right|^2}{N_R+\sum\limits_{k=1}^{N_{IR}}P_{I_k}\left|h_{I_k,R}\right|^2}\right)\\
&\quad + \psi_{PSK}\left(\frac{P_R\left|h_{RD}\right|^2}{N_D+\sum\limits_{n=1}^{N_{ID}}P_{I_n}\left|h_{I_n,D}\right|^2}\right)\Big|_{P_R\neq0}\times\left[1-\psi_{PSK}\left(\frac{P_s\left|h_{SR}\right|^2}{N_R+\sum\limits_{k=1}^{N_{IR}}P_{I_k}\left|h_{I_k,R}\right|^2}\right)\right]\\
&\approx 1\times\psi_{PSK}\left(\frac{P_s\left|h_{SR}\right|^2}{N_R+\sum\limits_{k=1}^{N_{IR}}P_{I_k}\left|h_{I_k,R}\right|^2}\right) + \psi_{PSK}\left(\frac{P_R\left|h_{RD}\right|^2}{N_D+\sum\limits_{n=1}^{N_{ID}}P_{I_n}\left|h_{I_n,D}\right|^2}\right)\Big|_{P_R\neq0}\times\left[1-\psi_{PSK}\left(\frac{P_s\left|h_{SR}\right|^2}{N_R+\sum\limits_{k=1}^{N_{IR}}P_{I_k}\left|h_{I_k,R}\right|^2}\right)\right]\\
&= \frac{1}{\pi}\int_0^{(M-1)\pi/M}\exp\left(-\frac{b_{PSK}P_s\left|h_{SR}\right|^2}{\sin^2\theta[N_R+\sum\limits_{k=1}^{N_{IR}}P_{I_k}\left|h_{I_k,R}\right|^2]}\right)d\theta\\
&\quad + \frac{1}{\pi}\int_0^{(M-1)\pi/M}\exp\left(-\frac{b_{PSK}P_R\left|h_{RD}\right|^2}{\sin^2\theta[N_D+\sum\limits_{n=1}^{N_{ID}}P_{I_n}\left|h_{I_n,D}\right|^2]}\right)d\theta\times\left[1-\frac{1}{\pi}\int_0^{(M-1)\pi/M}\exp\left(-\frac{b_{PSK}P_s\left|h_{SR}\right|^2}{\sin^2\theta[N_R+\sum\limits_{k=1}^{N_{IR}}P_{I_k}\left|h_{I_k,R}\right|^2]}\right)d\theta\right]
\end{aligned} \tag{20}
$$

$\psi_{PSK}(\gamma_D)\big|_{P_R=0} \times \psi_{PSK}(\gamma_R)$ in formula (20) represents the probability that cooperative node R decodes the source symbols x_S incorrectly and does not forward to destination node D. The receiving signal in destination node D only contains the signal from NLOS link S-D. h_{SD} is modeled as NLOS CM2 channel impulse response. As formula(15), the transmitting power of node S in S-D direction can indicated as $P_s' \ll P_s$, it can be reasonably considered that

$$\psi_{PSK}\left(\frac{P_s' |h_{SD}|^2}{N_D + \sum_{m=1}^{N_{ISD}} P_{I_m} |h_{I_m,D}|^2}\right)\Bigg|_{P_R=0} \approx 1 \tag{21}$$

$\psi_{PSK}(\gamma_D)\big|_{P_R\neq0} \times [1-\psi_{PSK}(\gamma_R)]$ represents the decoding error probability of destination node D when the cooperative node R decodes correctly. Introduce the array antenna gain of each node and the distance d between two nodes into the channel impulse response h. Then the theoretical SER using DF cooperation can be derived when the direction path is blocked under 802.15.3c channel.

5.2 AF cooperation performance analysis

For AF cooperative system, the receiving signal at the destination node D can be rewritten as formula (19) from formula (4).

$$y_D = h_{RD}\alpha y_R + \sum_{n=1}^{N_{ID}} \sqrt{P_{I_n}} h_{I_n,D} x_{I_n} + n_D \tag{22}$$

Where α represents the gain control factor of cooperative node R. Assuming the cooperative node power is restricted to P_R, that is $\alpha^2 E(|y_R|^2) = P_R$, then

$$\alpha^2 = \frac{P_R}{E(|y_R|^2)} = \frac{P_R}{P_s|h_{SR}|^2 + \sum_{k=1}^{N_{IR}} P_{I_k}|h_{I_k,R}|^2 + N_R} \tag{23}$$

Introduce the y_R of formula(3) into formula (22),can be rewritten as

$$y_D = h_{RD}h_{SR}\alpha\sqrt{P_s}x_s + \sum_{k=1}^{N_{IR}}\sqrt{P_{I_k}}h_{I_k,R}h_{RD}\alpha x_{I_k} + h_{RD}\alpha n_R + \sum_{n=1}^{N_{ID}}\sqrt{P_{I_n}}h_{I_n,D}x_{I_n} + n_D \tag{24}$$

According to formula(24), the SNR of whole link S-R-D can be expressed as

$$\gamma_{AF} = \frac{|h_{RD}|^2 |h_{SR}|^2 \alpha^2 P_s}{\sum_{k=1}^{N_{IR}} \alpha^2 P_{I_k}|h_{I_k,R}|^2 |h_{RD}|^2 + |h_{RD}|^2 \alpha^2 N_R + \sum_{n=1}^{N_{ID}} P_{I_n}|h_{I_n,D}|^2 + N_D}$$

$$= \frac{|h_{RD}|^2 |h_{SR}|^2 P_R P_s}{(\sum_{k=1}^{N_{IR}} P_R P_{I_k}|h_{I_k,R}|^2 |h_{RD}|^2 + \sum_{k=1}^{N_{ID}} P_s P_{I_n}|h_{I_n,D}|^2 |h_{SR}|^2 + P_R|h_{RD}|^2 N_R + P_s|h_{SR}|^2 N_D + W} \tag{25}$$

$$= \frac{\gamma_{SR}\gamma_{RD}}{\gamma_{RD}\gamma_{I_nD} + \gamma_{SR}\gamma_{I_kR} + \gamma_{RD} + \gamma_{SR} + \gamma_{I_nD} + \gamma_{I_kR} + \gamma_{I_nD}\gamma_{I_kR} + 1} = \frac{\dfrac{\gamma_{SR}}{\gamma_{I_kR}+1} \cdot \dfrac{\gamma_{RD}}{\gamma_{I_nD}+1}}{\dfrac{\gamma_{SR}}{\gamma_{I_kR}+1} + \dfrac{\gamma_{RD}}{\gamma_{I_nD}+1} + 1} = \frac{\gamma_R \cdot \gamma_D}{\gamma_R + \gamma_D + 1}$$

$$\text{Where} \quad W = \sum_{k=1}^{N_{ID}} P_{I_n} \left| h_{I_n,D} \right|^2 N_R + \sum_{k=1}^{N_{IR}} P_{I_k} \left| h_{I_k,R} \right|^2 N_D + \sum_{k=1}^{N_{ID}} P_{I_n} \left| h_{I_n,D} \right|^2 \sum_{k=1}^{N_{IR}} P_{I_k} \left| h_{I_k,R} \right|^2 + N_R N_D \qquad (26)$$

Because the receiving signal of cooperative node R is not decoded and recoded, the cooperative node R influences the system performance simply by changing the signal power of cooperative node. Then we only need to use γ_{AF} to replace γ in formula(19), the theoretical SER using AF cooperation can be rewritten as

$$\psi_{PSK}(\gamma_{AF}) = \frac{1}{\pi} \int_0^{(M-1)\pi/M} \exp(-\frac{b_{PSK}\gamma_{AF}}{\sin^2\theta})d\theta \qquad (27)$$

6. Simulation Results of 60GHz Directional Cooperative Communication under NLOS Channel

After the resolution process for link blockage is confirmed, system performance evaluation and simulation is carried out. System SER performance is selected as the evaluation criteria to verify the validity of this algorithm. The simulation setup and environment are presented as follows.

1) Antenna model.

Assume that all devices in 60GHz-WPAN system are deployed with same antenna equipment. Two antenna patterns are taken into consideration, which are omnidirectional antenna and directional antenna with switching-beam. 802.15.3c beam codebook is used to structure switching-beam [8]. The number of antennas in antenna array is 8 and the number of beam is 16.

2) Channel model.

IEEE 802.15.3c channel model is adopted, which is constructed by the measurement of 60GHz signal propagation characteristics. No matter for DF cooperation or AF cooperation, the channel model between S and D will be modeled as NLOS CM2.3 channel because the link S-D is blocked at this moment. Given cooperative link is not blocked, two-hop cooperative links S-R and R-D are modeled as LOS CM1.3 channel model.

3) Gaussian white noise.

Generally, Gaussian white noise can be calculated by NF=KTBF, where F is the noise factor and which is defined as F=1 here, $K = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, T=17°(290K) is the room temperature, B is the bandwidth of 60GHz signal and is defined by the 802.15.3c as 2.16GHz here. By the given parameter values, we can figure out the noise coefficient of 60GHz communication system under normal room temperature state. So -80dBm～-50dBm is set as the Gaussian white noise range in the simulations.

4) Spatial distribution model of 60GHz-cooperative communication system.

The location distribution of cooperative node used in simulation is presented in **Fig. 5**, 6 cooperative nodes are deployed in this simulation. The distance between cooperative node R_i and S(D) node is presented in **Table 3**. The location of optimal cooperative node is determined through simulation when all of the cooperative links are unblocked. In order to compare the system performance when the cooperative node located in different position, we set the distance sum of two-hop links S-R2-D，S-R3-D，S-R4-D，S-R5-D，S-R6-D are always 6m.
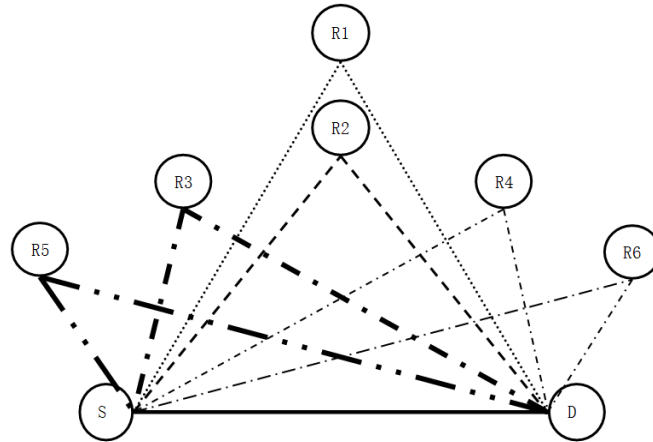
Fig. 5. Different cooperative node distribution diagram

Table 3. Table of distance between cooperative node R_i and $S(D)$

Cooperative node number	the distance to node S (m)	the distance to node D (m)
R1	4.0	4.0
R2	3.0	3.0
R3	2.0	4.0
R4	4.0	2.0
R5	1.5	4.5
R6	4.5	1.5

5) Other simulation parameters.

Considering STDMA is adopted, there may be other DEVs interfering the communication link in same time slot. The number of interference source is set according to literature [30]. Assuming that the obstacle located in the center position of S-D connecting line, the path gain loss of penetrating obstacle is set as 20dB. The power of transmit node S, cooperative node $R_i(i=1…6)$ are both set as 10dBm. QPSK modulation is adopted while channel coding is not adopted in this simulation.

For DF cooperation, the SINR of two-hop links S-R-D is determined by the one link which has smaller SINR, which can be expressed as formula(28)

$$\gamma_{DF} = \min(\gamma_R, \gamma_D) \tag{28}$$

For AF cooperation, the SINR has been given by formula (25). Given all the SINR in formula(25) is positive, $\gamma_{AF} = \dfrac{\gamma_R \cdot \gamma_D}{\gamma_R + \gamma_D + 1} \leq \dfrac{\gamma_R^2 + \gamma_R \cdot \gamma_D + \gamma_R}{\gamma_R + \gamma_D + 1} = \gamma_R$, similarly, $\gamma_{AF} < \gamma_D$, so $\gamma_{AF} \leq \min(\gamma_R, \gamma_D) = \gamma_{DF}$. For 60GHz directional cooperative system, DF cooperation can bring about higher transmission rate and lower BER performance than AF cooperation in the same conditions. When one link transmits with identical communication rate, the outage probability using directional DF cooperation is lower than using directional AF cooperation.

According to formula (25) and (28), if the power of transmission node and cooperative node is fixed, γ_{DF} and γ_{AF} are determined by the channel impulse response of each link under certain noise level. While the channel impulse response of each link mainly depends on two parts:the

distance between transmission node and cooperative node; the distance between cooperative node and destination node. As a result, whether or not the link can maintain normal communication rate without interruption, the position of cooperative node is very important.
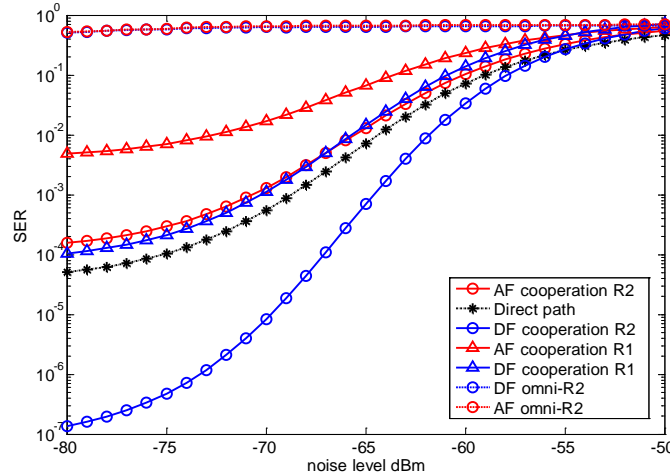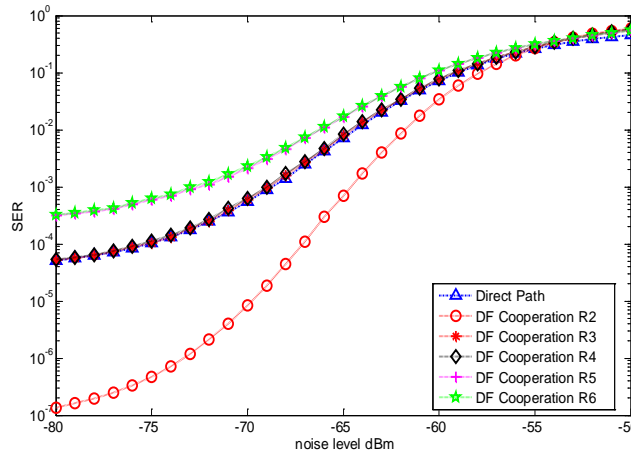

Fig. 6. The SER performance evaluation of 60GHz AF cooperative system and DF cooperative system with different cooperative distance

Fig.6 is the SER Monte Carlo simulation of 60GHz system with DF cooperation and AF cooperation when the S-D link is blocked. The existing researches on relay or cooperation are normally based on omni-directional antenna, while 60GHz systems usually adopt directional transmission. The research on directional transmission relay system is relatively rare. So the simulation comparisons between using omnidirectional antenna cooperation and using directional antenna cooperation based on beamforming are presented in the simulation. As shown in **Fig. 6**, no matter AF or DF cooperation is adopted, the cooperative efficiency is always poor if using omnidirectional antenna for 60GHz communication system. The directional cooperation based on beamforming could dramatically improve the cooperative performance for 60GHz system. The reason for this result is that the energy loss of 60GHz frequency band is huge, if adopting omnidirectional antenna,the cooperative distance is limited. In order to assess the cooperative efficiency, the SER performance simulation of direct path S-D without blockage under directional antenna is also presented in **Fig. 6**. Cooperative node R1 and R2 are adopted in this simulation. As shown in **Fig. 6**, DF cooperation can get more excellent performance than AF cooperation when using same cooperative node under directional antenna, which is in accordance with the proposed theoretical analysis. The reason for this result is that the distance between R2 and D, R2 and S are both less than the distance between R1 and D, R1 and S. So the probability of successful cooperation for R2 is higher than R1 node. To observe the influence of cooperation on system performance, the SER simulation using unblocked direct path link is also joined in this simulation. When the noise level is high enough (-55dbm—-50dbm), the direct path communication has the best performance. But with the decrease of the noise level, the system performance of DF cooperation through node R2 is superior to direct path communication and the advantage is more and more obvious. The heavy path loss of 60GHz frequency band leads to the sensitivity of 60GHz communication system toward communication distance. Assuming the direct path and cooperative link are both unblocked, the distance of each hop in cooperative communication through node R2 is less than the distance between S and D, so the

SER performance of cooperative communication through node R2 is better. Because the distance of each hop in cooperative communication through node R1 is greater than the distance between S and D, the performance of cooperative communication through node R1 is worse than direct path communication. While for AF cooperation, the SER performance is always worse than direct path no matter using cooperative nodes R1 or node R2.
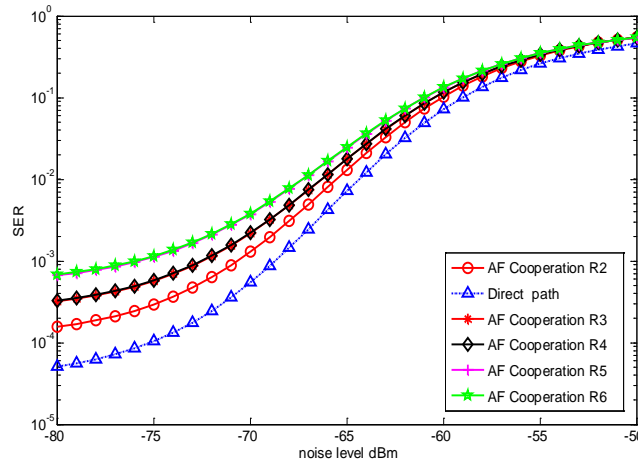
Fig. 7. The SER performance evaluation of 60GHz AF cooperative system under different cooperative node position

Fig. 8. The SER performance evaluation of 60GHz DF cooperative system under different cooperative node position

Fig. 7 presents the SER performance evaluation of 60GHz AF cooperative system under different cooperative node position. While **Fig. 8** presents performance evaluation of 60GHz DF cooperative system under different cooperative node position. The cooperative system using node R2 for cooperative node has the best performance no matter using DF cooperation or AF cooperation. While the cooperative systems using node R3 and node R4 for cooperative node is shown with approximate performance. Close inspection of the simulation curve shows the performance with R3 cooperative node is slightly better than that with R4 cooperative node.

The performances with R5 and R6 cooperative nodes are worst, and the performance with R5 cooperative node is also slightly better than R6 cooperative node. The DF cooperation performance with node R3 or node R4 can get close to but slightly worse than the performance with unblocked direct path. While the AF cooperation performance with node R3 or node R4 is obviously worse than the performance with unblocked direct path. Simulation results indicate that the node which is more closed to the perpendicular bisector of line segment SD can bring about better cooperation performance if the distance sums of two-hop cooperative links and the channel environments are close. If two cooperative nodes are symmetric about perpendicular bisector of line segment SD, the system performances are close.

7. Conclusion

In this paper, a combination of beamforming technology and cooperative technology are proposed for 60GHz NLOS communication. The directional transmission gain from the beamforming technology can make up the path loss, at the same time using cooperative technology of 60GHz WPAN system to overcome link blockage.

Firstly, a 60GHz cooperative communication model is established. Secondly a selection scheme of optimal cooperative node is proposed. Through establishing a WPAN SNR form of interconnected devices to determine the optimal cooperative node, the complex process to find the optimal cooperative node beam pairs can be avoided in case the direct path is blocked. This cooperative method effectively shortens the time of switching the beam and improves the communication efficiency when the link is blocked. Thirdly the resolution process of link blockage is presented. Finally, the SER derivation and simulation of 60GHz directional cooperative communication system under NLOS channel is presented. Simulation results show that DF cooperation can bring about better performance than AF cooperation when using same cooperative node. The node which closing to the perpendicular bisector of line segment SD can get better cooperation performance when the distance sums of two-hop cooperative links are close.

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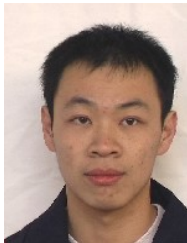
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