Beam Switching Support to Resolve Link-Blockage Problem in 60 GHz WPANs

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Abstract—In this paper, we propose a solution to resolve link blockage problem in 60 GHz WPANs. Line-of-Sight (LOS) link is easily blocked by a moving person, which is concerned as one of the severe problems in 60 GHz systems. Beamforming is a feasible technique to resolve link blockage by switching the beam path from LOS link to a Non-LOS (NLOS) link. We propose and evaluate two kinds of Beam Switching (BS) mechanisms: instant decision based BS and environment learning based BS. We examine these mechanisms in a typical indoor WPAN scenario. Extensive simulations have been carried out, and our results reveal that combining angle-of-arrival with the received signal to noise ratio could make better decision for beam switching. Our work provides valuable observations for beam switching during point-to-point communication using 60 GHz radio.

I. INTRODUCTION

Millimeter wave (mmWave) radio is a promising technology due to its potential to provide Giga-bps data rate. It fulfills the requirements of emerging wireless multimedia applications like high definition video streaming. Multi-GHz bandwidth around 60 GHz frequency has been allocated worldwide for short range wireless communications. To standardize 60 GHz Wireless Personal Area Networks (WPANs), IEEE 802.15.3 Task Group 3c (TG3c) [1] has been formed since March 2005. Due to the extremely high frequency band, 60 GHz radio experiences higher path loss compared to 2.4 or 5 GHz radio. Directional antennas could provide much higher efficiency to compensate for this high path loss. By thrusting energy on certain direction, directional antennas eliminate interference from other directions and also limit multi-path transmissions, but meanwhile, they make 60 GHz communications highly relying on the Line-of-Sight (LOS) links. Due to the weak penetration and reflection capability of 60 GHz radio, the received signal strength could be shadowed around 20 dB when a person crosses the direct link [2]. Hence, the LOS link is easily broken by a moving person, which is termed as human body blockage effect [3].

The influence of human activity on 60 GHz radio link is fully investigated in [4]. The authors reported that the fading caused by human blockage has several properties: the attenuation speed is fast, the fading duration is long, and the fading amplitude is strong, which means, LOS link blockage could be easily detected by the dramatic reduced signal strength and there is sufficient time to adopt certain anti-blockage mechanisms to maintain connectivity. In [2][5][6], the authors investigated the use of system diversity to reduce link blockage probability. In [7], a multi-hop solution is proposed to circumvent link blockage by using intermediate devices as relays. The IEEE 802.15.3c activities consider the use of beamforming technique to switch the LOS link to a Non-LOS (NLOS) link when the direct link is blocked [8]. In a residential environment, there normally exist one LOS link and several NLOS links which can be used as alternative paths. Therefore, before establishing a link for communication, transmitter and receiver could negotiate a backup choice. Once the LOS link is blocked, they switch to the backup NLOS link together to maintain the connectivity. Being different from relying on system diversity or intermediate relaying devices, beamforming does not require support from other hardware or devices to resolve link blockage problem.

In this work, we are motivated to investigate how to select a backup NLOS link to support high performance beam switching. To the best of our knowledge, this is the first paper working on this subject. The main contribution of this work includes the following aspects. We classify beam switching (BS) mechanisms into two categories: instant decision based BS and environment learning based BS. The instant decision based BS refers to the mechanisms which only use the currently available information to select backup links, for instance, the received Signal-to-Noise Ratio (SNR), Angle-of-Arrival (AoA) of a beam path, etc. The environment learning based BS uses the previous successful or failure BS experiences to assist the backup beam path selection. The environment learning based BS is suitable for the usage model like uncompressed video streaming [1], in which, devices like High-Definition TV (HDTV), Digital Video Recorder (DVR), are always stationed at fixed positions. We evaluate our proposals in a residential environment. Extensive simulations have been carried out. Our work provides valuable insights to support beamforming in 60 GHz WPANs.

The rest of this paper is organized as follows. In Section II, we introduce our work assumptions and system models. In Section III, we classify the BS mechanisms into two categories and explain them in details. By using our simulation model, we compare and discuss the performance of these two BS categories in Section IV. Finally, we conclude our work in Section V.
II. SYSTEM MODEL

A. Work Assumptions

During data transmission, the transmitter and receiver both use directional antennas for transmitting and receiving. The received signal strength from multi-path is negligible. Therefore, when a person passes through the LOS link, the transmission is terminated. When the LOS link is blocked, the transmission pair switches their antenna main lobe pointing directions to an alternative NLOS path according to certain negotiations beforehand. Because the reflections higher than first order normally cannot be used for transmission anymore, only the first order reflection beam paths are considered as the backup candidates. After beam switching, devices should keep probing the channel status of the LOS link. To maximize the system throughput, the moment when the LOS path is unblocked, the link should be switched back to the LOS path. In this paper, we assume that devices equipped with directional antennas that could steer to any directions. In reality, the steering range of directional antennas might be constrained to a certain number, which leads to a reduced number of backup NLOS links.

B. Environment Model

We use the geometrical optics method to compute the significant paths between the transmission pair in a predefined three-dimensional environment with size \( L_x \times L_y \times L_z \), as shown in Figure 1 (a). The coordinates of the transmitter and receiver are \( [t_x, t_y, t_z] \) and \( [r_x, r_y, r_z] \), respectively. According to the scenario in Figure 1 (a), the first order reflections from the four walls and roof, apparently, are significant paths, which are considered as the possible beam paths in the following study. Before data communication starts, devices execute neighbor discovery process to discover surrounding devices and probe channel status. Normally, there is one LOS link between a transmission pair and also several NLOS links with degraded channel quality. Each beam path could be characterized by the received SNR \( \gamma_i \) and the signal’s transmitting and receiving direction. Therefore, we define a three-tuple profile factor \( (\gamma_i, \Delta \beta_{t_i}, \Delta \beta_{r_i}) \) for a certain NLOS path \( i \), where \( \Delta \beta_{t_i} \) and \( \Delta \beta_{r_i} \) are the transmitting and receiving spatial angle differences between the LOS link and the \( i^{th} \) NLOS path, as illustrated in Figure 1 (a).

C. Human Body Blockage Model

In this section, we describe the methodology to model human activity. A person is represented by a cylinder with radius \( r_m \) and height \( h_m \). We assume that the transmitter and receiver are deployed lower than the height of a person, hence the LOS link could be easily blocked by a person. When a person crosses a LOS link, it affects the radio link by the attenuation of the received signal strength and the duration of shadowing. According to the methodology used in [4], a link blockage event is detected when the attenuation is higher than a certain threshold, which means, when a person moves into a certain area, his body shadows the received signal strength and the radio link blockage is detected. This area, which is termed as shadowing area in this work, is defined as a rectangle with length \( d_{tr} \) and width \( \epsilon \) as shown in Figure 1 (b), where \( d_{tr} \) is the distance between the transmitter and receiver on the XY-Plane. By using different modulation and coding scheme, the tolerance of the radio link to the signal strength attenuation is different, which leads to a different length of \( \epsilon \). However, in this work, we define \( \epsilon \) with a fixed value for the sake of simplicity in analysis. The person moves according to the Random Way Point (RWP) mobility model with a certain speed and pausing time.

D. Propagation Model

1) LOS free-space model: In a LOS free-space scenario, the received power (in dB) at the receiver side, which is \( d \) meters away from the transmitter, is represented as,

\[
P_r(d) = P_t + G_t + G_r - (PL_0 + 10n \log(d) + X_{\Omega}) - I_L \quad (1)
\]

where \( P_t \) is the transmitting power, \( G_t \) and \( G_r \) are the antenna gains of transmitter and receiver. \( I_L \) is the implementation loss. \( PL_0 \) is the reference path loss at \( d = 1 m \) and \( n \) is the path loss exponent. \( X_{\Omega} \) is zero mean Gaussian distributed random variable with a standard deviation \( \Omega \), the measured \( \Omega \) is about 1 dB [9].

2) NLOS model: After the first order reflection, the signal strength is degraded due to the reflection loss. The amplitude of the signal response after reflection is given as:

\[
\nu = \left( \frac{\lambda}{2\pi \sigma} \right) |\Gamma_0 \sqrt{G_t G_r}| \Gamma_0 = \frac{\cos \theta_1 - \sqrt{\omega - \sin^2 \theta_1}}{\cos \theta_1 + \sqrt{\omega - \sin^2 \theta_1}} \quad (2)
\]

where \( \theta_1 \) is the incident angle, \( \omega \) is dielectric constant which can be set as \( 6.5 - 0.7 j \) for concrete structure [10]. The received power from NLOS link is given as \( P_r'(d) = P_r(d) + 20 \log \Gamma_0 \).
III. PROPOSAL TO RESOLVE LINK BLOCKAGE

To support beam switching during transmission, the transmitter and receiver should negotiate a backup NLOS link before establishing an isochronous link. Devices use directional antennas to detect their surrounding neighbors and probe corresponding channel state. They specify a weight factor $\xi$ for each possible beam path, and select a path with the highest weight factor as the backup choice. In this section, we introduce several beam switching mechanisms.

A. Beam Switching Mechanisms

1) Instant Decision based Beam Switching: The most straightforward way is to select an alternative path with the highest SNR, because intuitively, this path could provide the best channel quality. Hence we use the measured SNR $\gamma_i$ (in dB) on each beam path $i$ to compute the weight factor $\xi_i$ as

$$\xi_i = 1 - \left| \frac{\gamma_i - \gamma_o}{\gamma_o} \right|, \quad (3)$$

where $\gamma_o$ is the measured SNR from the LOS link. We denote this mechanism as SNR based Beam Switching (SNR-BS).

In certain circumstances, if the NLOS link is geographically close to the LOS link, the selected backup link is probably also blocked by the same person. Therefore, to involve spatial diversity in the alternative path selection process, the weight factor is adjusted as:

$$\xi_i = \left( 1 - \left| \frac{\gamma_i - \gamma_o}{\gamma_o} \right| \right) \sin \left( \frac{\Delta \beta_t}{2} \right) \sin \left( \frac{\Delta \beta_r}{2} \right), \quad (4)$$

where $\Delta \beta_t$ and $\Delta \beta_r$ are within the range $[0, \pi]$. This method involves beam path spatial property by taking the AoA of a beam path into consideration. Therefore, we denote this mechanism as Directional-SNR based Beam Switching (DSNR-BS).

2) Environment Learning based Beam Switching: In a residential environment, the consumer electronic devices, like HDTV, DVR, are always placed at fixed positions. Hence, they could learn from the beam switching successes and failures to assist antenna beamforming. One simple approach that can be easily implemented is the Exponential Moving Average (EMA) technique. By using this approach, the weight factor of each NLOS path candidate is computed based on the previous weight factor as

$$\xi_i(n+1) = [(1-\alpha)\xi_i(n) + \alpha M_i(n)]_{M_i(n) \neq \phi}, \quad (5)$$

where $\alpha$ is a constant smoothing factor, which influences the learning rate by characterizing the importance of the recent measurement data. $M_i(n)$ is the $n^{th}$ beam switching result by using beam path $i$, where

$$M_i(n) = \begin{cases} 1 & \text{switching success} \\ 0 & \text{switching failure} \\ \phi & \text{path } i \text{ is not selected} \end{cases} \quad (6)$$

When $M_i(n) = \phi$, the initial value of $\xi_i$ could be got by using SNR-BS or DSNR-BS.

B. Visibility Test

In this section, a geometric approach is used in our simulations to test the visibility of the beam paths. If the LOS link and NLOS link cannot be shadowed by a person at the same time, it is defined as a successful beam switching. We use different methods to test the visibility of the paths reflected via the walls and the roof, which are illustrated in Figure 1 (b) and (c), respectively.

As shown in Figure 1 (b), it is the plan view of the indoor scenario, in which the transmitter and receiver are on the line $l_1: y = k_1x + b_1$, and $l_1$ separates the room into two parts: Area 1 and Area 2. A person moves from $A$ to $B$ according to the trajectory $l_2: y = k_2x + b_2$, and he crosses $l_1$ at point $O$. Take the tangents from transmitter and receiver to circle $A$ and $B$, they enclose two triangles $\Delta T x R x M$ with angles $(\theta_{t1}, \theta_{r1})$ and $\Delta T x R x N$ with angels $(\theta_{t2}, \theta_{r2})$, which are considered as the influenced area by the person. Hence if a NLOS path $i$ within Area $\omega$ is reflected via a wall, where $\omega \in [1, 2]$, and it satisfies $\Delta \beta_t \leq \theta_{t\omega}$ or $\Delta \beta_r \leq \theta_{r\omega}$, this NLOS path is also blocked by the same person. The threshold angles are given as

$$\theta_X = \arcsin \left( \frac{d_m}{(d^2 + (0.5e + r_m)^2)^{\frac{1}{2}}} \right) + \arctan \left( \frac{(0.5e + r_m)}{d_X} \right), \quad (7)$$

where

$$X = \begin{cases} t1: d_{t1} = d_{t0} + \kappa \\ t2: d_{r2} = d_{r0} - \kappa \\ r1: d_{r1} = d_{r0} - \kappa \\ r2: d_{r2} = d_{r0} + \kappa \end{cases},$$

in which, $d_{t0}$ denotes the distance between $T x$ and crossing point $O$ at XY-plane, $\kappa = (0.5e + r_m) \cot(\vartheta)$, and $\vartheta$ is the angle between $AB$ and $TxRx$.

As shown in Figure 1 (c), we plot the plane that is perpendicular to the XY-plane and intersects with XY-plane in line $l_1$. It illustrates the NLOS path reflected via the roof. According to the reflection law, the position of the reflection point via roof is influenced by the heights of the transmitter and receiver. If the person’s crossing point is within the range of $d_s$ as shown in Figure 1 (c), he does not block the NLOS path reflected from the roof, which is considered as a successful beam switching. If the crossing point is uniformly distributed on the LOS link, the beam switching successful ratio $p$ by using the path reflected via the roof is obtained as

$$p = \frac{2(L_z - h_m)}{2L_z - (r_z + L_z)} - \frac{2r_m}{((x_z - r_x)^2 + (y_z - r_y)^2)^2}, \quad (8)$$

Based on the above equation, we can also conclude that putting the transmitter and receiver at higher positions could help to decrease the probability of link blockage.

IV. PERFORMANCE EVALUATION

A. Simulation Specifications

We have developed a MatLab based simulation environment to model our proposed scenario. The related simulation parameters are listed in Table I. The radio propagation model...
mentioned in Section II.D is used to compute the received SNR from different beam paths. In one run of a simulation, a person moves according to the RWP mobility model, and he crosses the LOS link for 10000 times in total. All the depicted simulation results are based on the average value of the 10000 iterations. We define the link visibility $p_s$ as the proportion of the successful switching in one run of the simulation. To model the capacity of NLOS links, we use the specifications as listed in Table II, in which, 25.3 Mbps is considered as the basic rate used to transmit command packets to probe channel status. Therefore if the received signal strength from a NLOS link is lower than -61 dBm, it cannot be used as a backup link. According to the received signal strength at beam path $i$, the achievable data rate $D_i$ could be estimated based on Table II. We define the achievable capacity by using NLOS path $i$ as $C_i = D_i \times p_s$.

B. Simulation Results

1) Performance comparison between different beam paths: Figure 2 depicts the link visibility by using all the first order reflection paths with variant transmitter and receiver positions. In Figure 2 (a) and (b), the receiver is fixed at $[5, 9.5]$ and transmitter is put at $[t_x, t_y]$, in which, $t_x$ varies from 0.5 to 9.5 with step size 1, and $t_y$ is set as 0.5 and 5.5 in different scenarios. As shown in Figure 2 (a) and (b), the beam paths reflected from wall 1, wall 2, wall 3 and roof exhibit the best performance alternately at different positions. In Figure 2 (c) and (d), we vary the receiver position at $[2, 9.5]$ and $[8, 9.5]$, respectively. For the transmitter, its y-coordinate is fixed at 3.5 and $t_x$ varies from 0.5 to 9.5 with step size 1. In sub-figure (c) and (d), the reflection via the roof exhibits the best performance in most of the tested positions.

The performance of the capacity for different beam paths is shown in Figure 3, in which, the reflection from roof is superior than the others in all the examined positions although its link visibility is not always the highest. What should be notice is that compared to the LOS link, the achievable capacity is degraded due to the path loss and reflection loss. Therefore, for certain bandwidth-constrained application, like video streaming, the video format should be adapted to a lower bandwidth requirement format. This involves cross-layer optimization which is out of the scope of this paper.

Another interesting observation is that, according to (8), the switching success ratio by using the path reflected via the roof should not be influenced by the transmitter and receiver’s position. However as shown in Figure 2, the link visibility for the reflection via the roof varies with different positions. This is because, (8) is derived based on the assumption that a person crosses the LOS link uniformly. However, by using the RWP model, the spatial positions of a person are not uniformly distributed. For instance as shown in Figure 4, it
records the y-coordinate of the person’s crossing points in one run of a simulation. The crosses are the data collected from the simulation, and the line is the fitted curve, which shows that by using the RWP model, the person has a higher probability to be in the middle of the room than the margin of the room.

2) Performance comparison between different BS mechanisms: In Figure 5, we compare the overall beam switching performance by using instant decision based BS (SNR and DSNR) and the environment learning based BS (SNR-EMA and DSNR-EMA). The receiver is put at [5, 9.5] and transmitter has a variable position as illustrated in Figure 5. We observe that for the instant decision based mechanisms, D-SNR has a better link visibility than the SNR based BS, which indicates the benefit of involving directional information to make beam switching decision. For the environment learning based mechanisms, SNR-EMA and DSNR-EMA have similar performance, but DSNR-EMA is slightly superior than SNR-EMA. In an unknown environment, they are envisioned to trace the beam path that has a high link visibility, which will be further tested in a more complex environment in future work. By using the EMA approach, the beam path selection is controlled by the smoothing factor $\alpha$. In Figure 6, we compare the smoothing capability with different $\alpha$. Each simulation point is averaged over 10000 runs of the simulations. A smaller $\alpha$ has a higher dependency on previous beam switching performance, which leads to a faster convergence to the stable status if the environment is fixed. Finally, we can conclude that, for the devices with fixed positions, long-term environment learning is robust to the instant decision. For the portable devices without fixed positions instant decision based BS is a better choice, and D-SNR could provide better performance than SNR based BS.

V. CONCLUSION

In this work, we investigated several Beam Switching (BS) mechanisms to support high performance beamforming. We classify the BS mechanisms into two categories: instant decision based BS and environment learning based BS. Instant decision based BS uses currently available information, like received SNR and Angle-of-Arrival (AoA), to select a NLOS link that has the highest SNR (denoted as SNR-BS) or select a NLOS link which is geometrically far away from the LOS link, but meanwhile, keeping the SNR as high as possible (denoted as DSNR-BS). Environment learning based BS uses the earlier switching experiences to make a BS decision. We assessed

the link visibility and the achievable system capacity by using different BS mechanisms, and we conclude that combining the directional information of a beam path with the received SNR could make better decision for beam switching. In future work, a more complex indoor environment will be designed and constructed in our simulation to test and improve our proposal.

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