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Dynamic beam steering using directional antennas in mmwave wireless networks

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Abstract: This paper proposes the use of a beam steering scheme for establishing multicast communication between millimeter-wave devices in 60 GHz wireless networks. It should be noted that beam steering is a key technique for the millimeter-wave multicast devices scattered omni directionally. We derive the analytical expression for the dynamic beamforming, and we observe the impact of the number of beams. Extensive simulation results show that dynamic beam steering enable more efficient sectoring than fixed beam steering.

Keywords: millimeter wave network, directional antenna, multicast
Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Millimeter-wave (mmWave) wireless networks are well known for their very high data rate service, which enables them to support many applications such as VoD streaming, wireless display, and the transfer of large files. It should be noted that the use of a multicast communication and directional antennas is highly recommended for applications that require a high data rate. However, the multicast communication is primarily used for broadcasting, where data is simultaneously transmitted to multiple receiving devices; on the other hand, the main function of directional antennas is to transmit a signal in a specific direction. In order to determine the data rate for transmission, the multicast communication involving the use of directional antennas generally considers the device with the lowest data rate (i.e., the most distant device) among all the devices scattered omni directionally. However, this technique has a problem in that even the devices near the transmitting device have to use a low data rate for data transmission. In addition to this problem, directional multicast communication has various other problems, and researchers have been expending efforts to solve these problems. In [1], a beamcast is proposed that ensures omnidirectional transmission to the devices that are close to the transmitting device and directional transmission to the devices that are away from the transmitting device. In [2], an online routing through multicast communication is proposed in order to maximize the lifetime of a network. In [3], a multicast model is defined using a composite beam pattern, which is defined depending on whether the beam's transmission power is equally split or asymmetrically split.

Existing researches have not considered the dynamic sectoring and the mmWave network with frequency model. This paper makes three contributions: 1) A directional multicast communication that considers the 60 GHz channel model is discussed, unlike existing researches that considered low data rate in IEEE 802.11. 2) The problem associated with multicast communication involving the use of a fixed beam is pointed out, and a new standard for dynamic beamforming is considered. 3) A mathematical calculation method is presented for dynamic beamforming that considers the location of the devices scattered omni directionally, and an easy-to-implement method is proposed for easy application without changing the structure of the standard.

2 Dynamic beam steering for multicast communication between millimeter-wave devices

Existing millimeter-wave networks, such as IEEE 802.11ad [4], do not involve a concrete scheme for multicast communication. Therefore, we explain the steps involved in directional multicast communication. First, a beacon frame is transmitted in a common mode (MCS 0) by the sender (i.e., in the case of IEEE 802.11ad, the sender is generally called PCP (personal base service set central point), so that it can be heard/overheard by all devices. After the transmission of the beacon frame, multicast beamforming is carried out

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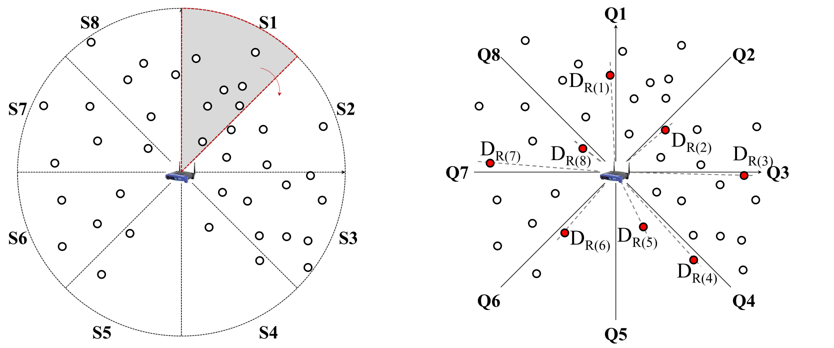

(a) fixed beam steering with 45° (b) finding the reference devices

Fig. 1. Compared with fixed & dynamic beam steering.

through the process of association beamforming training (A-BFT)[1]. During beamforming, if multicast communication is to be established, the PCP sends a request frame to the multicast devices; in response to this request frame, the multicast devices then send an acknowledgement to the PCP by way of an association response and send information regarding whether or not they support multicast communication. In this step, the PCP is involved in the internal process of obtaining the distances between devices, the beamwidth, and the most suitable data rate so that it can perform beam steering. As shown in Fig. 1 (a), the omni-area is divided into 8 sectors (45°), and the sender of the center establishes multicast communication through fixed sectors. The proposed scheme, called the dynamic beam steering (DBS) scheme, involves the use of a sectored beam. As shown in Fig. 1 (b), reference devices are first selected so that dynamic beam control can be applied. The reference device for each sector shown in the figure is one of the devices in each sector and is the closest to the corresponding reference line segment. For example, with Q1 as the reference line segment, $D_{R(1)}$ is the closest to this line segment and therefore serves as the reference device. Thus, the first step is to determine the reference device for each reference line segment.

We assume that the accurate position values of each device can be obtained by a direction of arrival (DoA) estimation technique. Under this assumption, the coordinates are generated with the PCP as reference in order to decide the direction of communication. The PCP can determine the distance from every device (i.e., from D_1 through D_n). After the PCP determines the distances of each device from itself, it then identifies the distances between devices on the basis of the Euclidean distance. Let S be the PCP of $< x_p, y_p >$ and D_i be a terminal device of $< x_i, y_i >$. The distance of each device from S is the length of the path connecting them. As shown in Fig. 2 (a), the distance between vectors $< x_p, y_p >$ and $< x_i, y_i >$ is given by the Pythagorean theorem,

$$\delta(i) = \sqrt{(x_i - x_p)^2 + (y_i - y_p)^2}, i = 1, 2, \cdots, n. \quad (1)$$

In general, the distance between vectors $\mathbf{d}(i)$ and $\mathbf{d}(j)$ in Euclidean space $\mathbf{R}^n$

[1]To achieve multicast communication, the A-BFT period generally involves sectored beamforming using the lowest data rate available.

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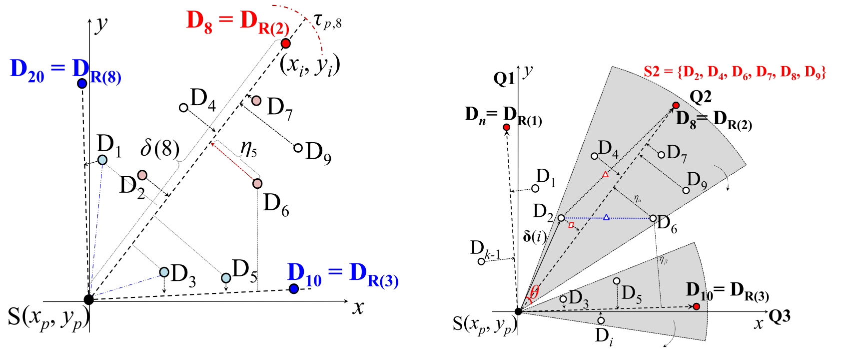

(a) Calculated the distance (b) Generated the beamwidth

Fig. 2. The dynamic beam steering scheme.

is given by

$$\Delta_{(ij)} = |\mathbf{d}(i) - \mathbf{d}(j)| = \sqrt{\sum\nolimits_{i=1}^{n-1} |\delta(i) - \delta(j)|^2}, j = i + 1, \tag{2}$$

where $\mathbf{d}(i)$ and $\mathbf{d}(j)$ are the vectors from S to D_i and D_j, respectively. Once the distances between each device have been determined, it is now necessary to calculate the perpendicular distance between D_i and $D_{R(m)}$ in order to find the adjacent devices. $D_{R(m)}$ denotes the reference device in the mth quadrant. The value of perpendicular distance here indicates the close degree to scattered devices as height of vector projection. The perpendicular distance can be determined using Heron's formula.

$$\eta_i = \frac{1}{2\delta(i)}\{4\delta(i)^2\Delta(ij)^2 - (\delta(i)^2 + \Delta(ij)^2 - \delta(j)^2)\} \tag{3}$$

Now, after the distances between devices have been determined, an adequate sector is generated by combining only those devices whose perpendicular distances from $D_{R(1)}$ are close, while classifying the other devices into different sectors with reference $D_{R(2)}$. After generating adequate sectors, it is necessary to determine the most suitable data rates for multicast communication. For this purpose, the beamwidth of each adequate sector is calculated. The beamwidth can be obtained using the second spherical law of cosine, since it is possible to know the vector values of the devices that are located at the edges of the both sides of the sector. For example, as shown in Fig. 2 (b), it is possible to know $\mathbf{d}(2)$ and $\mathbf{d}(6)$ as the vector values and accurate beamwidth can be calculated using (4).

$$\theta = \left\lfloor \cos^{-1}(\mathbf{d}(i) \cdot \mathbf{d}(j)/|\mathbf{d}(i)| \cdot |\mathbf{d}(j)|) \right\rfloor, \tag{4}$$

where $\mathbf{d}(i)$ and $\mathbf{d}(j)$ are the vector values of $D_i =< x_i, y_i >$ and $D_j =< x_j, y_j >$. In addition, $\mathbf{d}(i) \cdot \mathbf{d}(j) = x_i x_j + y_i y_j$ is the inner product value, and $|\mathbf{d}(i)| = \sqrt{x_i^2 + y_i^2}$ and $|\mathbf{d}(j)| = \sqrt{x_j^2 + y_j^2}$ are the magnitudes of the vectors, respectively. After the beamwidth of each adequate sector has been obtained in this way, it becomes possible to obtain the most suitable data rate for multicast data transmission. The most suitable data rate can derived by

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using the relation formula between beamwidth and average received power [5], is given by

$$R_m = \frac{\kappa W}{N} \log_2 \left(\frac{\alpha (2\pi\eta/\theta)^2 P_T(l) \tau_{TR}^{-\beta}}{N_0 W} + 1 \right). \quad (5)$$

Using the Friss transmission formula of the free space path loss model, the average transmitting and receiving power of a flow can be calculated as $P_R(l)/P_T(l) = G_R(l)G_T(l)(\lambda/4\pi\tau_{TR})^2$, where $G_T(l)$, $G_R(l)$, and τ_{TR} are the antenna gains of the transmitter and the receiver of flow l, and the decodable distance of propagation arrival between the transmitter and receiver, respectively. In addition, the following values are considered; κ is a coefficient related to the efficiency of the transceiver, N_0 is the one-sided spectral density of white Gaussian noise, $\alpha \propto (\lambda/4\pi)^2$ is a constant coefficient depending on the wavelength, β is pass loss exponent, θ is the antenna beamwidth, and η is the antenna's radiating efficiency, respectively.

This process continues until the directional multicast communication is performed from the first quadrant (Q1) to the mth quadrant (Qm) by generating the adequate sectors.

3 Results and discussion

In order to perform the simulation according to the environment of millimeter wave network, we define parameters as shown in [4]. The environment of a conference room, which is one of the target usages of IEEE 802.11ad, is assumed; therefore, the number of devices is fixed to 50, of which the number of multicast devices is varied from 5 to 45. The transmission power of the devices is fixed at 10 mW, while the beamwidth and the distance are varied according to simulation topology. The parameters used are $W = 2,160\,MHz$, $\kappa = -51\,dB$, $N_0 = -114\,dBm/MHz$, and $G_0 = 10^{-2}$. It is assumed that active flows are distributed randomly in a square room with side S, where $S = 7 \times 7\,m^2$ and $5 \sim 45$ active flows are deployed. The numerical results show that $\theta = 30^\circ \sim 90^\circ$, $\eta = 0.7 \sim 1$, and the path loss $\beta = 2$.

Figure 3 (a) shows the difference in throughput between the DBS scheme and the fixed beam steering scheme with $\theta = 30^\circ$, 60°, and 90°. For example, when the number of devices is 30, the DBS scheme shows an improvement in performance by approximately 570 Mbps as compared to the fixed beam steering scheme with $\theta = 30^\circ$. This discrepancy can be explained by two reasons: 1) the fixed beam steering scheme applies the lowest data rate every sector, whereas the DBS scheme uses the most suitable data rate to e obtained beamwidth. 2) the DBS scheme saves time by omitting the sector for which no beam is formed based on the reference device. In addition, since the average latency is inversely proportional to the throughput, the latency can be remarkably reduced when the number of devices is large in Fig. 3 (b). Figure 3 (c) and Fig. 3 (d) show the result of the analysis of the difference in the runtime performance between each of the fixed beams and the DBS scheme. The result of the performance analysis is presented in terms of the mean value measured every second. Results of comparison between the

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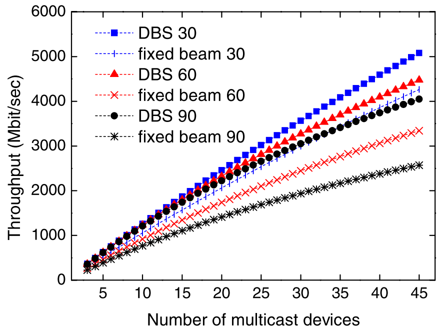
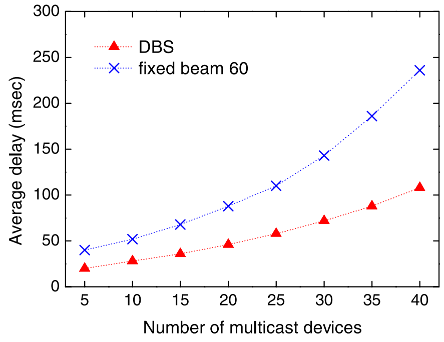
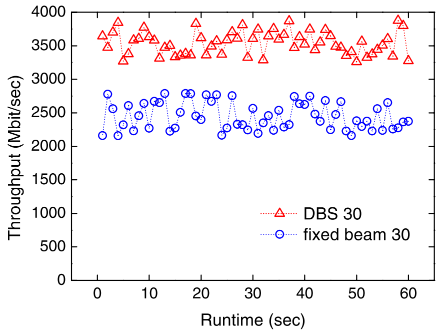


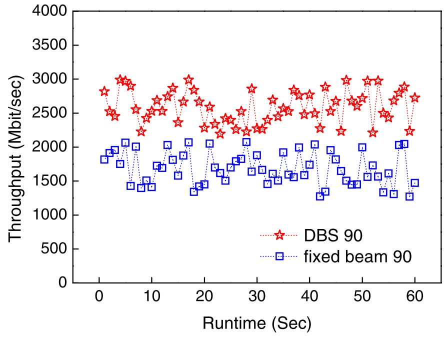
(a) Throughput under different beamwidth and the DBS scheme



(b) Average latency under fixed & dynamic beam steering



(c) Throughput vs. runtime with 30°



(d) Throughput vs. runtime with 60°

Fig. 3. Simulation results.

DBS scheme and the fixed beam steering scheme with $\theta = 30°$ show that the throughput value is stable in the course of runtime. The reason for this stability in the throughput value is that the probability is low that the randomness of the devices that are covered by the 30° beam is dynamic. In contrast, Fig. 3 (d) shows that the fluctuation of throughput is large when $\theta = 90°$, owing to the fact that the devices covered by the 90° beam are more probable to be dynamic in their locations than those covered by the 30° beam. This implies that the performance is better when the devices are randomly clustered in a specific area than when all the devices are uniformly dispersed. Thus, in the case of a random topology, a fixed beam with a narrower angle shows a higher throughput. The DBS scheme also is affected by the randomness of the locations of devices, and this is the reason why its throughput evidently fluctuates when the reference angle is wide.

4 Conclusion

In this paper, we propose a new multicast scheme for controlling the location and angle of a beam, without changing the structure of the fixed beam steering scheme. Compared to the existing scheme, the proposed scheme showed a greater improvement in the throughput performance. It should be noted that the proposed scheme does not involve serious overheads, since it does not require the modification of the PHY or MAC level; however, it involves

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only some more calculations during the beamforming process.

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