Comparison of Angle-of-Arrival Characteristics at 2.4 GHz and 60 GHz Bands

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Abstract: For seamless communication in millimeter-wave (mm-wave) transmission systems, the robustness against link blockage and user mobility should be guaranteed. Cooperative joint network design over conventional microwave bands and mm-wave bands is essential in future mm-wave WLANs (e.g., IEEE 802.11ay) and 5G cellular networks, and hence understanding the discrepancy between the propagation properties at those frequency bands is crucial. In this letter, the angle-of-arrival characteristics at mm-wave band (60 GHz) and microwave band (2.4 GHz) in indoor environments are presented. From the measurement results, it was seen that the line-of-sight and first-order reflected paths agree well each other, but diffraction and scattering are observed only at microwave band. It was also shown that the angular spreads at mm-wave band was about 25 degrees smaller than those at microwave band.

Keywords: fast session transfer, millimeter wave, microwave, channel sounding, angle-of-arrival, angle spread, antenna array

Classification: Antennas and propagation

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1 Introduction

Recently, the demand for ultra high-speed wireless data transfer for various new applications such as ultra-high definition (4K/8K) and virtual/augmented reality (VR/AR) technologies is increasing. The technical standard for multi-gigabit WLANs at 60 GHz millimeter-wave (mm-wave) band has developed in IEEE 802.11ad [1] and the advanced version is currently being developed in IEEE 802.11ay [2] which can support up to 30 Gbps throughput. However, the propagation loss at mm-wave bands is significantly large and the attenuation by diffraction and penetration is also very large. In this regard, the functionality of fast session transfer (FST) is seriously considered in IEEE 802.11ad [1] to seamlessly switch to Wi-Fi (2.4/5 GHz) when the mm-wave link becomes unavailable due to blockage or beam misalignment. However, existing FST techniques need time-consuming sector sweep and power-consuming mm-wave channel monitoring, thus various multiband techniques have been studied for more efficient FST [3, 4]. In order to design multiband WLANs the discrepancy between the propagation characteristics of different frequency bands should be investigated. Especially, the angular properties such as power spectra of angle-of-arrival (AoA) and angle-of-departure (AoD), are important to apply spatial transmission techniques such as beamforming and MIMO (multiple-input-multiple-output).

In order to compare the angular channel characteristics at different frequency bands, they should be measured by using the identical measurement conditions. Several super-resolution parameter estimation methods such as SAGE and RIMAX [5] which can extract the multi-path components (MPCs) where the entire response of the measurement system including the antennas can be removed. These parametric methods are based on the assumption that the radio channels can be decomposed by a set of discrete plane waves and diffuse scattering. However, since we may have ambiguous decomposition of the channel components due to the signal processing limitation in treating the diffuse scattering, the angular power spectrum (APS) is more appropri
ate way for the comparison purpose [6, 7]. In this letter, we compared the AoA properties at two different frequency bands from the APS where angular scanning of high-gain horn antenna and virtual cylindrical array were employed for mm-wave band and microwave band, respectively. It should be noted that the half-power beamwidth (HPBW) of the virtual cylindrical array was designed equal to that of the horn antennas as much as possible to achieve identical angular resolution. The observation from the measurement results and discussion on the discrepancy of the propagation mechanisms and angular characteristics are presented.

2 APS Measurement Methods

2.1 Millimeter wave band

For mm-wave band, a full polarimetric $2 \times 2$ MIMO channel sounder at the center frequency exactly of 58.5 GHz was used [8]. Rotating highly directive horn antennas with a gain of 24 dBi (HPBW of 12 degrees) at both transmitter (Tx) and receiver (Rx), the 5-dimensional channel transfer functions (CTFs) of 256 sub-carriers over 400 MHz bandwidth as

$$H_{qp}(f_k, \theta_i' , \phi_{j'} , \theta_i , \phi_j)$$

were measured by transmitting an unmodulated multitone signal where the subscript $p, q \in \{\theta, \phi\}$ denote polarization for Tx and Rx antennas, respectively, and $\theta_i'$ and $\phi_{j'}$, and $\theta_i$ and $\phi_j$ indicate the $i'$-th pointing co-elevation (zenith) and the $j'$-th pointing azimuth angle at Tx, and the $i$-th pointing co-elevation and the $j$-th pointing azimuth angle at Rx, respectively. The double-directional angle delay power spectrum (DDADPS) is given by

$$P_{qp}(l, i', j', i, j) = |h_{qp}(\tau_l, \theta_i', \phi_{j'}, \theta_i, \phi_j)|^2$$

(2)

where the channel impulse response $h_{qp}$ is obtained by inverse Fourier transform of (1). From DDADPS, the polarization combined APS is synthesized by

$$\text{APS}(\theta_i, \phi_j) = \frac{1}{2} \sum_{p,q=\{\theta, \phi\}} \sum_{i',j'} P_{qp}(l, i', j', i, j)$$

(3)

where the angle sampling interval is typically 12 degrees.

2.2 Microwave band

For microwave band, a software radio based narrowband channel sounder [9] having 400 kHz bandwidths at center frequency exactly of 2.425 GHz was used. In Fig. 1(a), the cylindrical antenna array structure having half-wavelength element spacing is shown where the APS was synthesized by beamforming with the patch antenna element of 7.3 dBi gain. The response function at the position $(m, n)$ for $m = 1, \cdots, M$, and $n = -N, \cdots, N$ can be expressed as

$$A_{n,m}(\theta, \phi) = A_{n,m}^{\text{uca}}(\theta, \phi) A_{n}^{\text{ula}}(\theta) U_m(\theta, \phi)$$

(4)
where $A_{m}^{\text{uca}}$ and $A_{m}^{\text{ula}}$ denote the circular and linear array responses, respectively, which are expressed as

$$A_{m}^{\text{uca}}(\theta, \phi) = \exp\left(\frac{2\pi}{\lambda} r \sin \theta \cos \left(\phi - \frac{2\pi}{M}(m - 1)\right)\right),$$

(5)

$$A_{n}^{\text{ula}}(\theta) = G_{n} \exp(j2\pi d_{n} \cos \theta)$$

(6)

where $r$, $\lambda$, $M$ and $N$ denote the radius, wavelength, and the numbers of antennas in the circular and linear arrays, respectively. $U_{m}(\theta, \phi)$ and $G_{n}$ denote the patch element pattern and the Dolph-Chebyshev coefficients [10], which result in sidelobe reduction in horizontal and vertical planes, respectively. As shown in Fig. 1(b), it is seen that the cylindrical array beampatterns synthesized by the patch elements ($M = 25$ and $N = 7$) are well matched to the horn antenna patterns. The APS($\theta, \phi$) for $i$-th pointing co-elevation and the $j$-th pointing azimuth angle at Rx is obtained by the beamforming as

$$\text{APS}(\theta_{i}, \phi_{j}) = \mathbf{w}^{H}(\theta_{i}, \phi_{j}) \mathbf{R}_{xx} \mathbf{w}(\theta_{i}, \phi_{j})$$

(7)

where the correlation matrix $\mathbf{R}_{xx} = E[\mathbf{x}(t)\mathbf{x}^{H}(t)] \in \mathbb{C}^{M(2N+1) \times M(2N+1)}$ defining $\mathbf{x}(t) \in \mathbb{C}^{M(2N+1)}$ by the input signal vector, and the element of the weight vector $[\mathbf{w}(\theta_{i}, \phi_{j})]_{M(N+n)+m} = A_{n,m}(\theta_{i}, \phi_{j})$. Here, (7) is calculated every 12 degrees as in (3).

2.3 Angle spread

The angular channel characteristics at different frequency bands are compared using the azimuth angle spread calculated with the azimuth power spectrum as $\text{AzPS}(\phi_{j}) = \sum_{i} \text{APS}(\theta_{i}, \phi_{j})$. The azimuth angle spread distribution is usually modeled as Wrapped-Gaussian distribution. The angle spread is calculated by

$$\sigma = \min_{\Delta} \sqrt{\frac{\sum_{j} \left(\phi_{j}(\Delta)\right)^{2} \cdot \text{AzPS}(\phi_{j})}{\sum_{j} \text{AzPS}(\phi_{j})} - \left(\frac{\sum_{j} \phi_{j}(\Delta) \cdot \text{AzPS}(\phi_{j})}{\sum_{j} \text{AzPS}(\phi_{j})}\right)^{2}},$$

(8)
\[ \hat{\phi}_j(\Delta) = \text{mod} (\phi_j + \Delta, 360^\circ) \]  

(9)

where \text{mod()} denotes the modular operator, and \( \Delta \) indicates an offset angle.

3 Measurement Results

3.1 Measurement Scenarios

We conducted the measurement campaign at a conference room environment which is a typical usage scenario in IEEE 802.11ad and 802.11ay. The Tx as an access point (AP) was set on the television at a height of approximately 2.1 m close to the wall where the antenna radiation pattern covers the front side of the wall. The channel responses were measured at the five Rx positions (denoted by Rx1–Rx5) where the Rx was assumed to be a station (STA), e.g., a laptop PC. The STA antenna was located from 3.12 to 5.65 m away from the AP at the height of 0.9 m from the floor (15 cm from the table). As can be seen, the LoS between Tx and Rx was available in all Rx positions. This refers to the setup of the STA-AP conference room sub-scenario in [1].

3.2 Results and Observation

Fig. 2 shows the measured APS at Rx5 as an example where the ray tracing simulation result is also presented with circular markers in Fig.2(a) as a reference. In addition, Fig.3 illustrates the identified propagation mechanisms which were confirmed by the ray tracing results. It is noted that the APS is normalized by the maximum power and the values larger than \(-25\) dB are only considered. It is seen that the LoS (#1) and first-order reflected paths (#2, #3 and #4) are well observed at both frequency bands. However, the higher-order reflected paths (with diffraction) and diffuse scattering around window frames and metallic chairs (e.g., #5) are observed only at microwave band. The interpretation is as following. At microwave band, it is well known that the scattering objects such as furniture mainly acts as scatterers rather than reflectors due to their size comparable to the wavelength, but the specular reflection is mainly generated by the large object such as walls, ceiling and floors. However, at mm-wave band, it can be expected that even small objects may behave as specular reflector due to the very short wavelength, and hence diffuse scattering was reduced.

In order to quantify the above mentioned discrepancy, angle spread which is one of widely accepted parameters is employed. Fig.4 shows the angle spread at all Rx positions which are also indicated in the same figure. As shown in this figure, the correlation of angle spread between the two frequencies are not clearly shown because the number of measurements is limited and hence the environment-dependency could not be perfectly eliminated. However, it can be seen that the average angle spread \( \sigma_{\text{mmwave}} \) at mm-wave band is significantly smaller (about 25 degrees) than \( \sigma_{\text{mwave}} \) at microwave band. That can be explained as the most propagation mechanisms are specular reflection and there is little contribution of the higher-order reflection (with diffraction) and diffuse scattering at mm-wave band.
4 Conclusin

In this letter, we conducted dual-frequency channel measurements at mm-wave band (60 GHz) and microwave band (2.4 GHz) in an indoor environment to evaluate the AoA characteristics. From the measurement results, it is seen that the LoS and first-order reflected paths agree well each other, but diffraction and diffuse scattering at mm-wave band were not so significant. The angular spread which is calculated by assuming Wrapped-Gaussian distribution was highly environment-dependent, and the correlation between the two frequencies was not clearly shown. However, it was observed that the average angle spread at mm-wave band is significantly smaller (about 25 degrees) than that at microwave band. These results should be utilized for cooperative joint network design using microwave and mm-wave bands for future wireless systems.

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