Frequency Characteristics of Path Loss and Delay-Angular Profile of Propagation Channels in An Indoor Room Environment in SHF Bands

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Abstract  Comparison of channel characteristics at many frequency bands is necessary to study the frequency-depen
dendency which is important for consistent multi-frequency spatial-temporal channel model. Path loss (PL) and
power spectrum characteristics of the channel measured in a typical classroom line-of-sight (LOS) were presented
at three different bands: 3, 10 and 28 GHz. The results showed that diffuse scattering was more significant in lower
bands, whereas specular reflection was more significant in higher bands. Moreover, PL of 3 and 10 GHz were higher
than their free space PL (FSPL) counterparts. For 28 GHz band, the PL was roughly the same as FSPL.

Key words  Beam forming, Indoor environments, Microwave propagation, Millimeter wave propagation, Propa-
gation losses

1. Introduction

Because of the substantial increase in the mobile data traf-
fi c in recent years, the 5th generation (5G) wireless system
has been researched extensively [1][2]. To accommodate the
vast amount of traffic, 5G is targeting frequency bands higher
than 10 GHz which can provide large bandwidth. Further-
more, massive number of antenna is planned to be utilized
to send massive number of multiple streams simultaneously.
Most researchers have been focusing on 60 GHz band due
to its high priority. However, 28 GHz band has also been
potential candidate and has been extensively investigated re-
cently [3–6]. Even though it is intended that high frequency
system will be deployed in the 5G system, the “fall-back” al-
ternatives in which the system can switch to lower frequency
bands is essential due to many uncertainties of the high fre-
quency bands such as sensitivity to blockage and rapid mo-
bile station (MS) movement [7]. Therefore, for system de-
sign of the wireless systems with high robustness and reli-
ability, it is necessary to characterize the channel not only
at high frequency bands, but also at lower bands. Thus,
some researchers have been starting to focus on analysing the
frequency-dependency channels in many different frequency
bands in the same environment [3,8–12]. To the authors’ best
knowledge, in indoor cases, the frequency-dependency anal-
ysis is still limited with most papers comparing the power
spectrum and delay spread between different bands.

In this paper, the path loss (PL) and power-angle-delay
profile (PAPD) of the channels in an indoor, line-of-sight
(LOS) classroom environment is presented and discussed at
three different bands: 3, 10 and 28 GHz. All three bands
have 2 GHz bandwidth. The beamforming (BF) is used to
obtain the PAPD [13], whereas the power sum of the im-
pulse response is calculated to find the PL of each transmit-
ter (T x) location [14]. The comparison results showed that
more multipaths can be observed at lower bands due to dif-
fuse scattering effect. The PL comparison with free space
PL (FSPL) and PL fit using power law model indicated that
the PL of 3 and 10 GHz bands are higher than FSPL due to
wave guiding effect in a small room, whereas the PL of 28
GHz band is roughly the same as FSPL, indicating that the
wave guiding effect is negligible. Moreover, since the wave
guiding effect at lower bands is stronger, the PL exponent
(PLE) is smaller in those bands.

The rest of the paper is organized as follows: In Section
2, the radio channel measurement is explained. Section 3
brieﬂy describes the BF and PL calculation steps. After
that, Section 4 presents the BF and PL analysis results. Fi-
nally, Section 5 summarizes the ﬁndings of this paper and
provides the future work.

2. Virtual Array Radio Channel Mea-
surement Method

In this paper, the virtual uniform circular array (UCA)
system [8,9] was utilized for the radio channel measurement.
The simpliﬁed system is shown in Fig. 1. This system con-
sist of five main parts: the vector network analyzer (VNA),
LO/IF distribution unit to divide the local oscillator (LO)
signal to mixers, test and reference mixers to down convert
the received and transmitted signal to intermediate fre-
quency (IF) signal, and the automatic rotator to rotate the
antenna after each measurement sweep [8,9]. The single-
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Thus, the SIMO channel transfer function was calculated
from SISO channel transfer function as follows

\[ H = [H_0, H_1, ..., H_l, ..., H_{l-1}] \]

where \( l, H_i \) are the number of Rx antenna locations, channel
transfer function at the −th Rx location, respectively.

3. Beamforming and Pathloss Calculation
Methods

3.1 Beamforming

For simplicity, this paper utilized the BF [13] to estimate
the PADP of the channel. In the ﬁrst step, the array fre-
quency response of the channel was calculated by

\[ Y(f, \phi) = \frac{1}{N} \sum_{i=0}^{N-1} H_i(f) \exp(-j2\pi f (r/c) \cos(\phi - \phi_i)) \]

where \( f, H_i(f), r, \phi, \phi_i, \) and \( c \) are the carrier frequency,
frequency transfer function at the −th Rx location and at car-
rrier frequency \( f \), radius of UCA, angle-of-arrival (AoA) of
the BF, angle of the −th Rx antenna location, and speed of
light, respectively.

After that, the array impulse response (IR) was obtained
by using inverse discrete Fourier transform (IDFT) of this
array frequency response.

\[ y(\tau, \phi) = \sum_{k=0}^{N-1} Y(f_k, \phi) \exp(j2\pi f_k \tau) \]

where \( N, f_k \) and \( \tau \) are the number of frequency bins, the
frequency of the −th frequency bin, and delay, respectively.

Finally, the PADP was calculated by taking the absolute
and square of this array impulse response.

3.2 Path Loss Calculation

There are 2 steps for PL calculation for each measurement
snapshot, which is similar to the calculation in [14]. To re-
duce the effect of large variation of antenna gain across the
wide bandwidth, the PL was calculated only for 400 MHz
bandwidth (150 frequency bins) around the center frequency
of each band. In the ﬁrst step, assuming that the paths
are concentrated in the azimuth plane, the antenna gain
deembedded IR of the −th antenna element was calculated by

\[ h_i[n] = \frac{1}{N} \sum_{k=0}^{N-1} \frac{H[k]}{(G_{Tx}[k]G_{Rx}[k])^{1/2}} \exp(j2\pi kn) \]

where \( H_i[k], G_{Tx}[k], G_{Rx}[k], n \) denote the channel transfer
function, Tx and Rx gain at the −th frequency bin, and de-
lay bin respectively. \( i \) is the array element index. Then, PL
was calculated by

\[ PL = \left( \frac{1}{7} \sum_{i=0}^{l-1} \sum_{n \in U} |h_i[n]|^2 \right)^{-1} \]

where \( U \) is the set of delay bins in which the power is above
the noise level. In case of 3 and 10 GHz, all 150 delay bins
were used for the PL calculation. For 28 GHz, the ﬁrst 75
bins and last 30 bins were used.
4. Results and Discussion

4.1 Measurement Environment and Channel Sounder Specification

The radio channel measurement was conducted in a typical small class room in Aalborg University, Aalborg, Denmark. The classroom environment with Tx and Rx locations, and measurement photographs are shown in Fig. 2 and 3, respectively. Three sides of the room are covered by the concrete walls. The window frames are made from metal and the glass is the energy efficient glass covered with thin metallic layer. The transmitter (T_x) is a single commercial wideband biconical antenna and the Rx is a virtual 360 elements UCA with the radius of 0.24 m utilizing the modified biconical antenna [15]. There are five rows of tables with the height of 0.74 m. A total of 20 spatial snapshots were measured by moving the Tx between the tables. Each Tx in each row was spaced 80 cm apart. Both Tx and Rx were mounted at 1.5 m height.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>3, 10, 28 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Tx antenna</td>
<td>Commercial biconical antenna (A-INFO SZ-2003000)</td>
</tr>
<tr>
<td>Rx antenna</td>
<td>Modified biconical antenna [15]</td>
</tr>
<tr>
<td>Number of Rx elements</td>
<td>360</td>
</tr>
<tr>
<td>UCA radius</td>
<td>0.24 m</td>
</tr>
<tr>
<td>Number of frequency bins</td>
<td>750</td>
</tr>
<tr>
<td>Maximum delay</td>
<td>375 ns</td>
</tr>
<tr>
<td>Tx and Rx height</td>
<td>1.5 m</td>
</tr>
</tbody>
</table>

4.2 Delay-Angle Power Spectrum Comparison

Figs. 4, 5 and 6 (a) shows the PADP results at the third, seventh and twelfth Tx location in which the locations are depicted in Fig. 2. The paths were visually identified and numbered from peaks of PADP and the results were plotted in Figs. 4, 5 and 6 (b) for the third, seventh and twelfth Tx location respectively. From these results it could be seen that PADP suffered from joint angular-delay sidelobe especially the LOS component and strong specular reflected path due to the wide bandwidth and large array size used, which was also observed in [8, 13]. In case of 3 GHz band, the floor and table reflected paths could be seen as shown in Fig. 4 and 5 due to the wide elevation beamwidth. Moreover, more multipaths were detected due to diffuse scattering effect. This effect is from the paths scattered from the small objects in the environment, which is stronger in lower frequency bands. On the other hand, the channels in 10 and 28 GHz bands were sparse and dominated by the specular reflection due to much smaller wavelength. These results also agree with the results in [8] which utilize almost the same measurement system and antennas.

4.3 Path Loss Comparison and Model Fitting

Fig. 7 shows the measured PL compared with the FSPL at the center frequency of each band. As expected, the measured PL at 3 and 10 GHz were smaller than the FSPL in LOS scenario because of the wave guiding effect of a small room, which was similarly observed in [14]. On the other hand, in case of 28 GHz band, the measured PL was roughly the same as FSPL. This is because the LOS component was much more dominant at higher frequency bands, whereas diffuse scattering and specular reflections were more dominant in the lower bands.

Fig. 8 and Table 2 show the power law model PL fitting results and the PL model parameters of all three bands, in which the PL is expressed by

$$PL[\text{dB}] = a \cdot 10 \log_{10}(d[m]) + b + X$$

where $a$ and $b$ represent the PLE and PL at 1 m distance, respectively. $X$ is the shadowing variation, which is represented by the log-normal random variable with mean and...
variance equal to 0 and $\sigma^2$ respectively.

From these results, it could be seen that the PLE of all three bands were smaller than 2 and increases as the frequency increases. This was also due to the stronger wave guiding effect at lower frequency bands. In particular, the 3 GHz had much smaller PLE than the other two bands. One possible explanation is that the strong reflection and diffuse scattering from the concrete wall at the back of the room occurred at larger distances (Tx16-Tx20) since the Tx was very close to the wall. These results contradict to the results in [3, 12] which reported that the PLE decreases with frequency and is higher than 1.5. The possible explanation is that the size of the rooms in [3, 12] were much larger than the class room in this paper and hence the effect of the wave guiding was smaller. Moreover, both papers also measured the channel at larger Tx-Rx distances and have more spatial snapshots.

5. Conclusion
This paper presented the delay-angle power spectrum and PL characteristics of channels in an indoor classroom environment using three SHF bands: 3, 10 and 28 GHz. The channels were measured using the VNA-based channel sounder and rotator to realize virtual UCA. The power spectrum results indicated that the diffuse scattering dominated the lower 3 GHz band and thus more multipaths could be observed, whereas the specular reflection was more significant in 10 and 28 GHz bands. The PL results showed that, as the result of the guiding effect of the small environment in lower bands, the measured PL at 3 and 10 GHz were few dBs lower than the FSPL counterparts and the PLE increased with frequency. In contrast, the measured PL at 28 GHz was almost equal to the FSPL because LOS dominates the channel. These results implied that, in case of small class room environment, the channel characteristics

<table>
<thead>
<tr>
<th>Frequency band (GHz)</th>
<th>$a$</th>
<th>$b$</th>
<th>$\sigma$</th>
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</thead>
<tbody>
<tr>
<td>3</td>
<td>0.886</td>
<td>45.25</td>
<td>0.485</td>
</tr>
<tr>
<td>10</td>
<td>1.183</td>
<td>54.05</td>
<td>0.478</td>
</tr>
<tr>
<td>28</td>
<td>1.300</td>
<td>64.54</td>
<td>0.309</td>
</tr>
</tbody>
</table>

Fig. 4: PADP and identified paths at the 3-rd Tx location ((a) PADP, (b) paths identification).

Fig. 5: PADP and identified paths at the 7-th Tx location ((a) PADP, (b) paths identification).
Fig. 6: PADP and identified paths at the 12-th Tx location ((a) PADP, (b) paths identification).

Fig. 7: Path loss comparison with free space path loss vary significantly across the SHF bands. It is to be noted that the results presented here is specific to the class room environment. Thus, as the future work, it is also necessary to investigate the PADP and PL characteristics carefully in various types of environment. The influence of the antenna pattern on PL characteristics will also be more carefully analyzed. Moreover, the frequency dependent PL will be fitted and analyzed and the multipath will be resolved by using some sidelobe suppression techniques along with the parameter estimation algorithm [16].

References


