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Re: N/A

Abstract: In this paper, outdoor double-directional channel measurements in an open square outdoor environment using an in-house developed 300 GHz channel sounder are presented. In the measurements, narrow-beam horn antennas were used at both the transmitter and receiver sides to investigate the scattering processes. The multipath propagation mechanisms were identified by using the angular and delay power spectra obtained from the measurement data. The results reveal that the outdoor terahertz channel exhibits significant sparsity. Finally, the performance of an SU-MIMO transmission to leverage power-significant multipath components was evaluated by Ergodic channel capacity for up to four-stream spatial multiplexing.

Purpose: Information document for IEEE 802.15 SC THz

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Outdoor Double-Directional Channel Measurements in an Open Square Environment at 300 GHz

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Motivation

• Beyond 5G Communication requirements
  – Ubiquitous connection for a heterogenous network
  – Ultra-high data-rate: upwards of 100 Gbps
    • Tens of GHz worth bandwidth available in 0.1-10 THz
  – Ultra-reliable communication for life-critical applications
  – Low latency to support real-time application

• Our Effort
  – Channel measurement at 300 GHz in an open square environment
  – Contribute measurement results
  – Analyze measurement data
  – Path loss and model fitting
  – Ergodic capacity evaluation for MIMO transmission
Outline

• 300-GHz Double-Directional Channel Sounder Development
  – System parameters and specifications
• Channel Measurement and Results
  – Open square
    • Measurement and Post processing
    • Power Spectra and Multipath Propagation Mechanism
    • Path Loss and Model Fitting
    • Ergodic capacity evaluation for MIMO transmission
• Conclusion
• Future Works
Channel Sounder
Sounder System

**Table:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq.</td>
<td>300 GHz</td>
</tr>
<tr>
<td>Signal BW</td>
<td>8 GHz</td>
</tr>
<tr>
<td>Sounding signal</td>
<td>NPM (N=2,560)</td>
</tr>
<tr>
<td>FFT points</td>
<td>20,480</td>
</tr>
<tr>
<td>Sampling rates</td>
<td>64 GSa/s (AWG), 32 GSa/s (Digitizer)</td>
</tr>
<tr>
<td>Delay resolution</td>
<td>125 ps</td>
</tr>
<tr>
<td>Delay span</td>
<td>320 ns</td>
</tr>
<tr>
<td>Horn Ant./Dir Gain</td>
<td>26 dBi</td>
</tr>
<tr>
<td>Horn HPBW</td>
<td>9° @Az, 8° @El</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>60~80 dB</td>
</tr>
<tr>
<td>Polarization</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

1000 snapshots coherent averaging can make 30 dB gain increase

**Diagram:**

- LO Signal: 24.33 GHz
- SG 1
  - 10 MHz Ref.CLK
  - 10 MHz
  - IF Signal: 4~12 GHz
  - 300 GHz (BW= 8 GHz)
  - Rb. Clock
- SG 2
  - LO Signal: 24.33 GHz
  - Down Converter
  - 12 dB F Signal: 4~12 GHz
  - IF AMP
  - 10 MHz Ref.CLK
  - 10 MHz

**Graphs:**

- OTF Magnitude [dB]
  - Without Signal (Single Shot)
  - With Signal (Single Shot)
- 30 dB gain increase

**Slide 6**

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Measurement and Post-processing
Measurement Scenario

- Square dimensions: 30 m × 30 m
- Tx position fixed at the height of 3.1 m, Rx has a fixed height of 1.5 m and moved to 17 different positions at three typical outdoor scenarios: Line-of-sight (LoS), obstructed line-of-sight (OLoS) and non-line-of-sight (NLoS) with the Tx-Rx distance of 12.35 m to 47.5 m, as shown

<table>
<thead>
<tr>
<th>Rx #</th>
<th>2-D Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx-Rx</td>
<td></td>
</tr>
<tr>
<td>Rx01</td>
<td>18.75</td>
</tr>
<tr>
<td>Rx02</td>
<td>18.15</td>
</tr>
<tr>
<td>Rx03</td>
<td>17.45</td>
</tr>
<tr>
<td>Rx04</td>
<td>12.70</td>
</tr>
<tr>
<td>Rx05</td>
<td>14.50</td>
</tr>
<tr>
<td>Rx06</td>
<td>21.35</td>
</tr>
<tr>
<td>Rx07</td>
<td>29.35</td>
</tr>
<tr>
<td>Rx08</td>
<td>26.50</td>
</tr>
<tr>
<td>Rx09</td>
<td>22.00</td>
</tr>
<tr>
<td>Rx10</td>
<td>14.60</td>
</tr>
<tr>
<td>Rx11</td>
<td>14.10</td>
</tr>
<tr>
<td>Rx12</td>
<td>12.35</td>
</tr>
<tr>
<td>Rx13</td>
<td>13.90</td>
</tr>
<tr>
<td>Rx14</td>
<td>31.50</td>
</tr>
<tr>
<td>Rx15</td>
<td>32.50</td>
</tr>
<tr>
<td>Rx16</td>
<td>43.00</td>
</tr>
<tr>
<td>Rx17</td>
<td>46.10</td>
</tr>
</tbody>
</table>
Scanning settings

- Angle scanning – azimuth only

\[ d_t = \frac{\Delta h}{\tan \theta_t} \]
\[ d_1 = \frac{\Delta h}{\tan \left( \theta_t + \frac{\theta_{BW}}{2} \right)} \]
\[ d_2 = \frac{\Delta h}{\tan \left( \theta_t - \frac{\theta_{BW}}{2} \right)} \]

\[ \theta_t = 5^\circ, \theta_{BW} = 8^\circ, \Delta h = 1.6m \]
\[ d_1 = 10.1\ m \]
\[ d_t = 18.3\ m \]
\[ d_2 = 91.7\ m \]
Post – Processing of Measurement Data

- **Obtained Data**
  3-D transfer function data: \( H(\tilde{f}, \tilde{\phi}_T, \tilde{\phi}_R) \)
  3-D impulse response data: \( h(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) \)
  \( h(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) = \mathcal{F}^{-1}\{H(\tilde{f}, \tilde{\phi}_T, \tilde{\phi}_R)\} \)

- **Double-Directional Angle Delay Power Spectrum (DDADPS)**
  \( P(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) = |h(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R)|^2 \)

- **Antenna pattern calibration**
  (after noise reduction)
  \( P'(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) \) [dB] = \( P(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) - G_T(d) - G_R(d) \)

- **Azimuth Delay Power Spectrum (ADPS)**
  Tx: \( \text{ADPS}_T(\tilde{\tau}, \tilde{\phi}_T) = \sum_{n_{\phi_R}} P'(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) \)
  Rx: \( \text{ADPS}_R(\tilde{\tau}, \tilde{\phi}_R) = \sum_{n_{\phi_T}} P'(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) \)

- **Omnidirectional Power Delay Profile (Omni PDP)**
  \( \text{PDP}(\tilde{\tau}) = \sum_{n_{\phi_T}, n_{\phi_R}} P'(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) \)

**Parameters** | **Annotation**
--- | ---
\( d \) | : Tx-Rx distance
\( \tilde{\tau} \) | : delay
\( \tilde{\phi}_T \) | : Azimuth of departure
\( \tilde{\phi}_R \) | : Azimuth of Arrival

**Visualized by Sum-hold**

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Power Spectra and Multipath Propagation Mechanism
Power Delay Profile (PDP)

- Significant clusters clearly visible – the PDP of three scenarios (one Rx position for each is taken as a typical example) are shown as follows
ADPS with panoramic photos and Multipath Propagation Mechanism (Rx07)
Multipath Propagation Mechanisms at OLoS (Rx15) and NLoS (Rx17)

OLoS: Rx15

NLoS: Rx17
Path Loss Model Fitting
Transmission Loss Model

- **Calculation for Path Loss (PL)**
  - LoS best-beam PL (the best LoS beam of Tx-Rx):
    \[ PL_{\text{best-beam}} [\text{dB}] = -10 \log_{10} \left( \sum_{n_{\tau}} P'(\tilde{\tau}, \tilde{\phi}_{T\text{best}}, \tilde{\phi}_{R\text{best}}) \right) \]
  - Omni PL:
    \[ PL_{\text{omni}} [\text{dB}] = -10 \log_{10} \left( \sum_{n_{\tau}, n_{\phi_T}, n_{\phi_R}} P'(\tilde{\tau}, \tilde{\phi}_T, \tilde{\phi}_R) \right) \]

- **Path Loss Models:**
  - Close-in free space (CI) [*]
    \[ L_{CI}(d) [\text{dB}] = 10n \log_{10}(d) + 20 \log_{10} \left( \frac{4\pi f_{\text{GHz}} \times 10^9}{c} \right) \]
  - Floating-intercept (FI) [#]
    \[ L_{AB}(d) [\text{dB}] = 10\alpha \log_{10}(d) + \beta \]

<table>
<thead>
<tr>
<th>PL</th>
<th>CI Model ((n, \sigma))</th>
<th>FI Model ((\alpha, \beta, \sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omni PL</td>
<td>(1.85, 2.08)</td>
<td>(3.28, 64.04, 1.03)</td>
</tr>
<tr>
<td>PL\text{best-beam}</td>
<td>(2.14, 1.92)</td>
<td>(3.01, 71.16, 1.58)</td>
</tr>
</tbody>
</table>

Ergodic capacity evaluation for MIMO transmission
SU-MIMO: streams using the selected beams

- At Rx position #i (i = 1, 2, 3, ..., L), L is the number of measured positions. Based on PDP and ADPS, choose M pairs of Tx and Rx Azimuth angles in power order:

  \[
  [(\varphi_{T,1}, \varphi_{R,1}), (\varphi_{T,2}, \varphi_{R,2}), \ldots, (\varphi_{T,m}, \varphi_{R,m}), \ldots, (\varphi_{T,M}, \varphi_{R,M})]
  \]

- Extract the channel matrix of the \(i_{th}\) Rx position of the \(k_{th}\) sub-carrier (total sub-carrier number is \(K\), e.g. \(K = 4\)) from CTF using the obtained angles index:

  \[
  H_{i,k} = \begin{bmatrix}
  H^i(f_k, \varphi_{T,1}, \varphi_{R,1}) & H^i(f_k, \varphi_{T,1}, \varphi_{R,2}) & H^i(f_k, \varphi_{T,1}, \varphi_{R,3}) & H^i(f_k, \varphi_{T,1}, \varphi_{R,4}) \\
  H^i(f_k, \varphi_{T,2}, \varphi_{R,1}) & H^i(f_k, \varphi_{T,2}, \varphi_{R,2}) & H^i(f_k, \varphi_{T,2}, \varphi_{R,3}) & H^i(f_k, \varphi_{T,2}, \varphi_{R,4}) \\
  H^i(f_k, \varphi_{T,3}, \varphi_{R,1}) & H^i(f_k, \varphi_{T,3}, \varphi_{R,2}) & H^i(f_k, \varphi_{T,3}, \varphi_{R,3}) & H^i(f_k, \varphi_{T,3}, \varphi_{R,4}) \\
  H^i(f_k, \varphi_{T,4}, \varphi_{R,1}) & H^i(f_k, \varphi_{T,4}, \varphi_{R,2}) & H^i(f_k, \varphi_{T,4}, \varphi_{R,3}) & H^i(f_k, \varphi_{T,4}, \varphi_{R,4})
  \end{bmatrix}
  \]
Ergodic capacity evaluation

- For each sub-carrier, $\mathbf{H}^{i,k}$ is normalized by the average Frobenius norm squared value as

$$
\mathbf{H}_{\text{norm}}^{i,k} = \mathbf{H}^{i,k} \left( \frac{1}{KM^2} \sum_{k=0}^{K-1} \left\| \mathbf{H}^{i,k} \right\|_F^2 \right)^{-\frac{1}{2}}
$$

$$
\mathbb{E} \left[ \left\| \mathbf{H}_{\text{norm}}^{i,k} \right\|_F^2 \right] = M^2
$$

- Apply $M\times M$ beam-space MIMO transmission, the Ergodic capacity for the $i_{th}$ Rx is obtained as

$$
C_E^i \text{ [bps/Hz]} = \frac{1}{K} \sum_{k=0}^{K-1} \log_2 \det \left( \mathbf{I}_M + \frac{\rho_i}{M} \cdot \mathbf{H}_{\text{norm}}^{i,k} \left( \mathbf{H}_{\text{norm}}^{i,k} \right)^H \right)
$$
Conclusion

- 300 GHz outdoor ultra-high data-rate wireless access scenario
  - An open square environment (measurement range: 50 m)
  - Availability of using the multipaths
- Radio wave propagation characteristics
  - In addition to the direct wave, single-bounce reflecting is dominant
  - The influence of glass covered walls reflected waves is large.
- Propagation loss
  - Approximately 3 dB improvement over FSPL due to multipath power (omni PL)
- THz SU-MIMO transmission
  - Beamforming is available
  - Up to 4 streams formed by multipath selecting achieve 150 Gbps
Future works

- Efforts to model the stochastic processes in signal propagation at THz band
- Further extensive campaigns with more number of measurement points for evaluation of LSP and generation of transmission loss model
Thank You

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