Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

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

Date Submitted: January 2024

Source: Minghe Mao, Riku Takahashi, Minseok Kim, Shigenobu Sasaki
Graduate School of Science and Technology, Niigata University, 8050 Ikarashi 2-no-cho, Nishi-ku, Niigata, Niigata, Japan
Voice:+81-25-262-7478, E-Mail: meika@eng.niigata-u.ac.jp, mskim@eng.niigata-u.ac.jp

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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

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

Minghe Mao, Riku Takahashi, Minseok Kim, Shigenobu Sasaki

Niigata University, Japan

Motivation

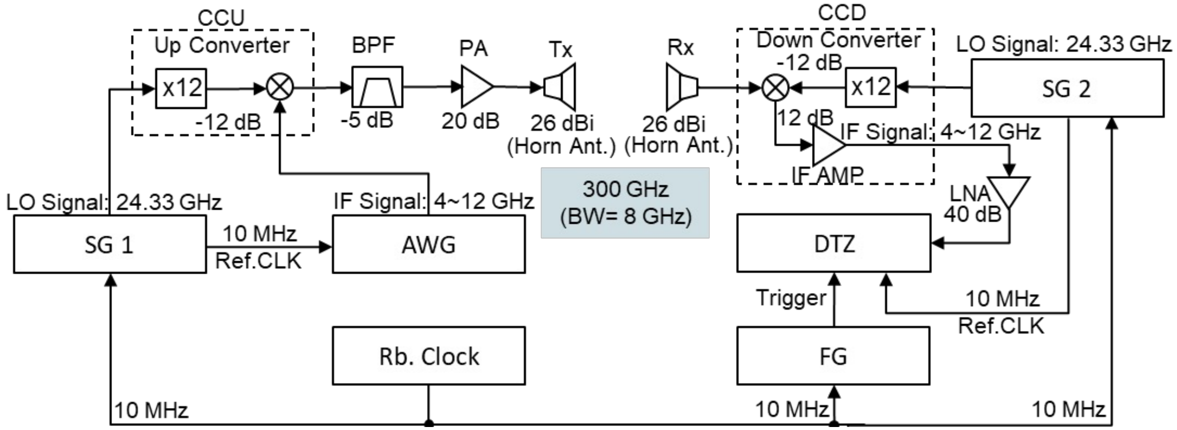
- Beyond 5G Communication requirements
  - Ubiquitous connection for a heterogenous network
  - Ultra-high data-rate: upwards of 100 Gbps
    - Tens of GHz worth bandwidth available in 0.1-10 THz
  - Ultra-reliable communication for life-critical applications
  - Low latency to support real-time application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

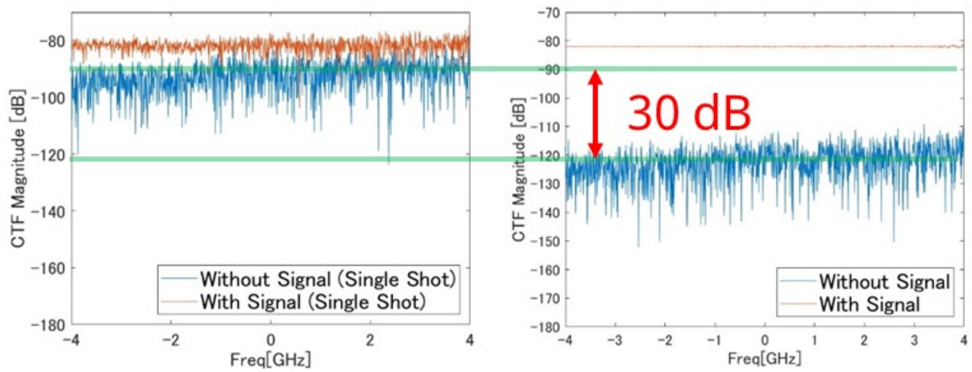
- 300-GHz Double-Directional Channel Sounder Development
  - System parameters and specifications
- Channel Measurement and Results
  - Open square
    - Measurement and Post processing
    - Power Spectra and Multipath Propagation Mechanism
    - Path Loss and Model Fitting
    - Ergodic capacity evaluation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

Channel Sounder

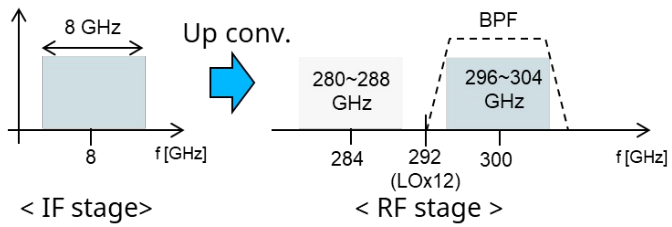
Sounder System



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



1000 snapshots coherent averaging can make 30 dB gain increase



300 GHz Freq. Conversion

Measurement and Post-processing

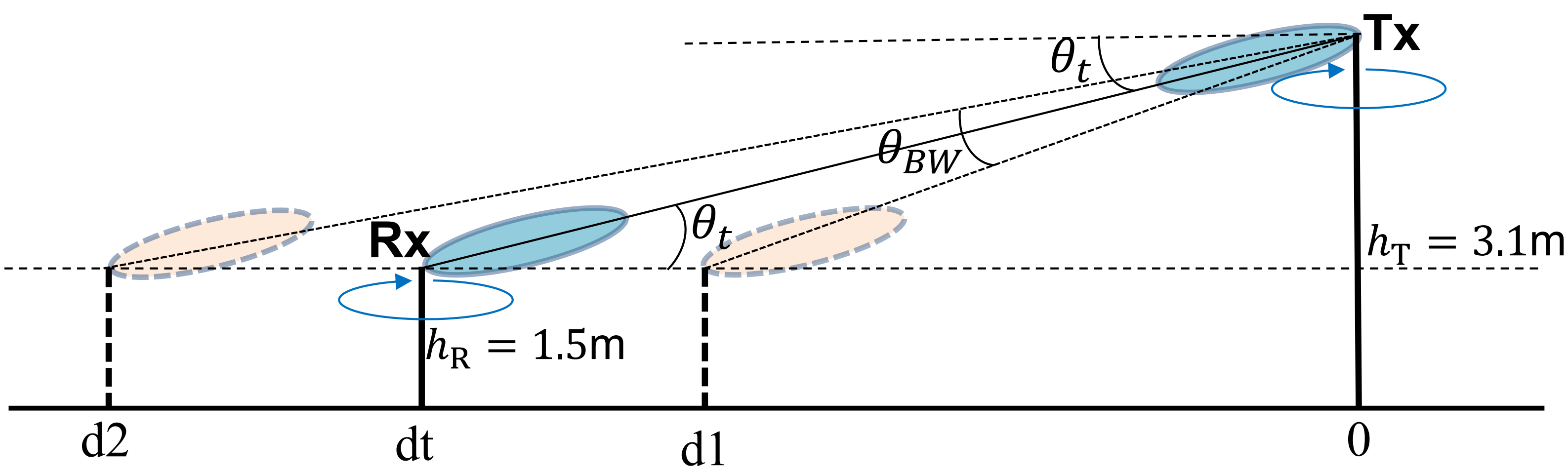
Measurement Scenario

- 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

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

Scanning settings

- Angle scanning – azimuth only



$$d_t = \frac{\Delta h}{\tan \theta_t}$$

$$d_1 = \frac{\Delta h}{\tan\left(\theta_t + \frac{\theta_{BW}}{2}\right)}$$

$$d_2 = \frac{\Delta h}{\tan\left(\theta_t - \frac{\theta_{BW}}{2}\right)}$$

$\theta_t = 5°, \theta_{BW} = 8°, \Delta h = 1.6$m

$d_1 = 10.1$ m

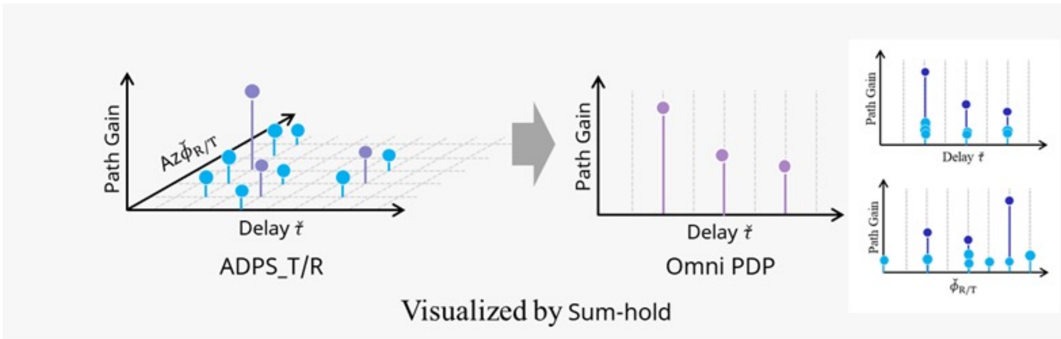
$d_t = 18.3$ m

$d_2 = 91.7$m

Post – Processing of Measurement Data

- Obtained Data
  3-D transfer function data : $\mathrm{H}(\check{f}, \check{\phi}_T, \check{\phi}_R)$
  3-D impulse response data : $h(\check{\tau}, \check{\phi}_T, \check{\phi}_R)$
  $h(\check{\tau}, \check{\phi}_T, \check{\phi}_R) = \mathcal{F}^{-1}\{\mathrm{H}(\check{f}, \check{\phi}_T, \check{\phi}_R)\}$
- Double-Directional Angle Delay Power Spectrum (DDADPS)
  $P(\check{\tau}, \check{\phi}_T, \check{\phi}_R) = |h(\check{\tau}, \check{\phi}_T, \check{\phi}_R)|^2$
- Antenna pattern calibration (after noise reduction)
  $P'(\check{\tau}, \check{\phi}_T, \check{\phi}_R)$ [dB]= $P(\check{\tau}, \check{\phi}_T, \check{\phi}_R) - G_T(d) - G_R(d)$
- Azimuth Delay Power Spectrum (ADPS)
  Tx: $\mathrm{ADPS}_T(\check{\tau}, \check{\phi}_\mathrm{T}) = \sum_{n_{\phi_R}} P'(\check{\tau}, \check{\phi}_\mathrm{T}, \check{\phi}_\mathrm{R})$
  Rx: $\mathrm{ADPS}_R(\check{\tau}, \check{\phi}_\mathrm{R}) = \sum_{n_{\phi_T}} P'(\check{\tau}, \check{\phi}_\mathrm{T}, \check{\phi}_\mathrm{R})$
- Omnidirectional Power Delay Profile (Omni PDP)
  $\mathrm{PDP}(\check{\tau}) = \sum_{n_{\phi_\mathrm{T}}, n_{\phi_\mathrm{R}}} P'(\check{\tau}, \check{\phi}_\mathrm{T}, \check{\phi}_\mathrm{R})$

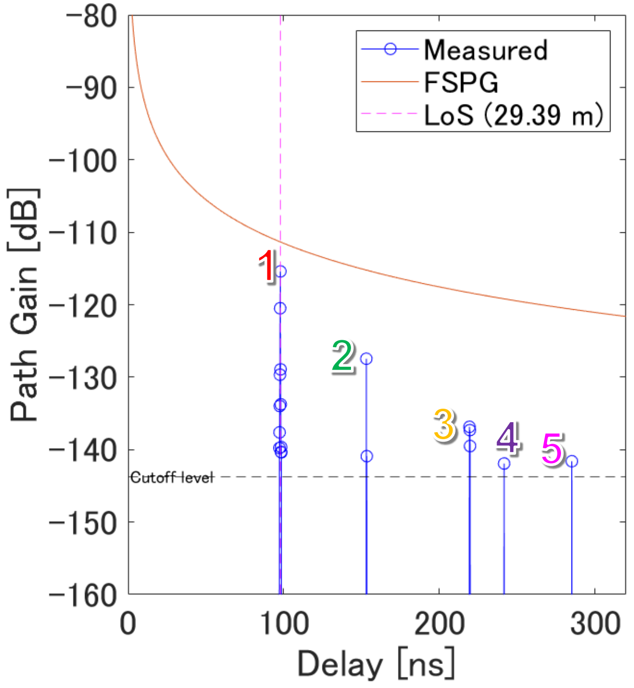
Parameters	Annotation
d	: Tx-Rx distance
$\check{\tau}$	: delay
$\check{\phi}_T$	: Azimuth of departure
$\check{\phi}_R$	: Azimuth of Arrival



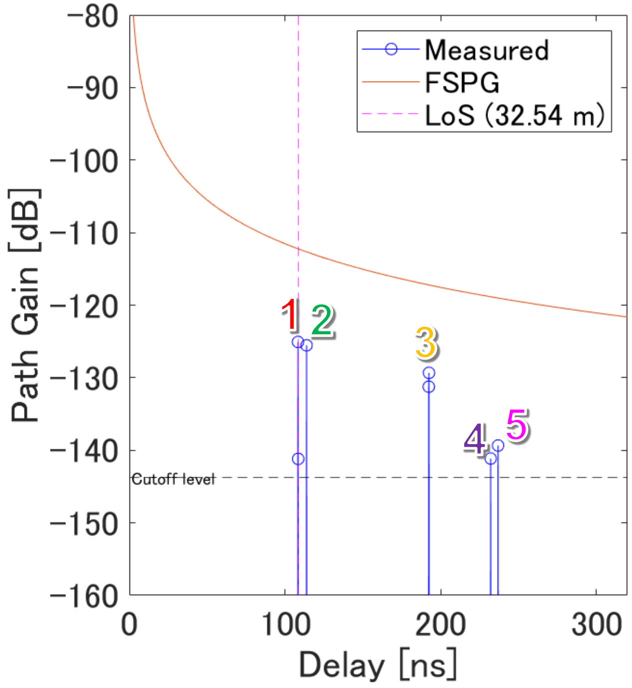
Power Spectra and Multipath Propagation Mechanism

Power Delay Profile (PDP)

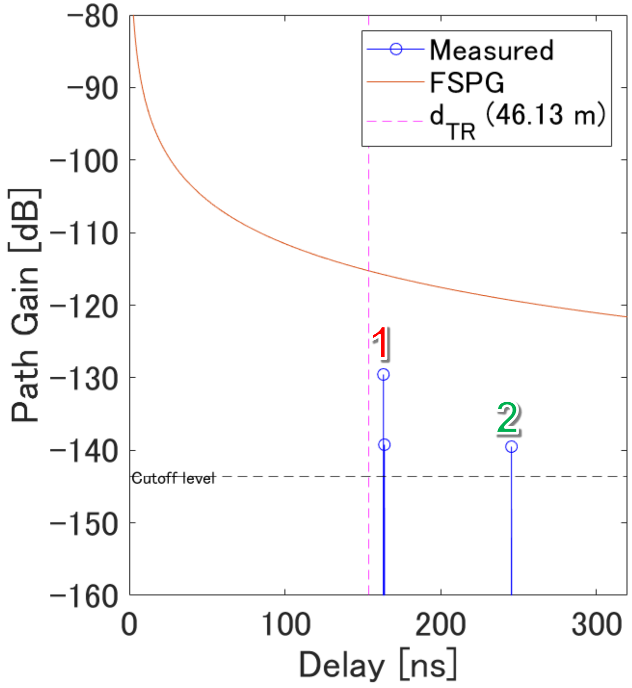
- Significant clusters clearly visible – the PDP of three scenarios (one Rx position for each is taken as a typical example) are shown as follows



LoS: Rx07

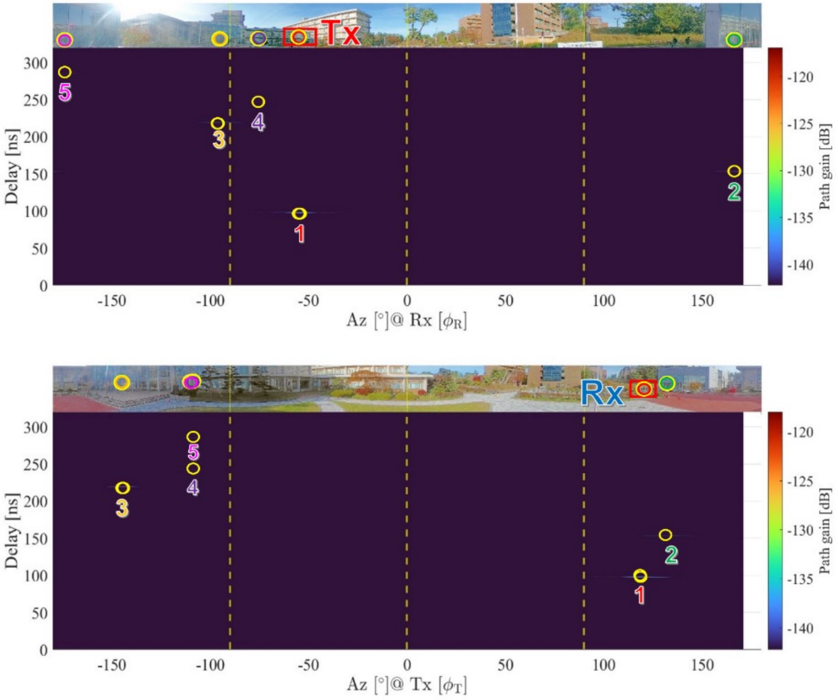


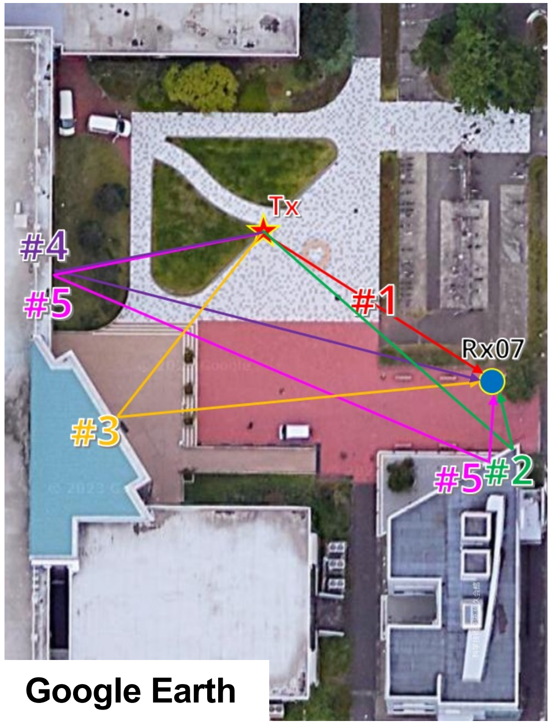
OLoS: Rx15

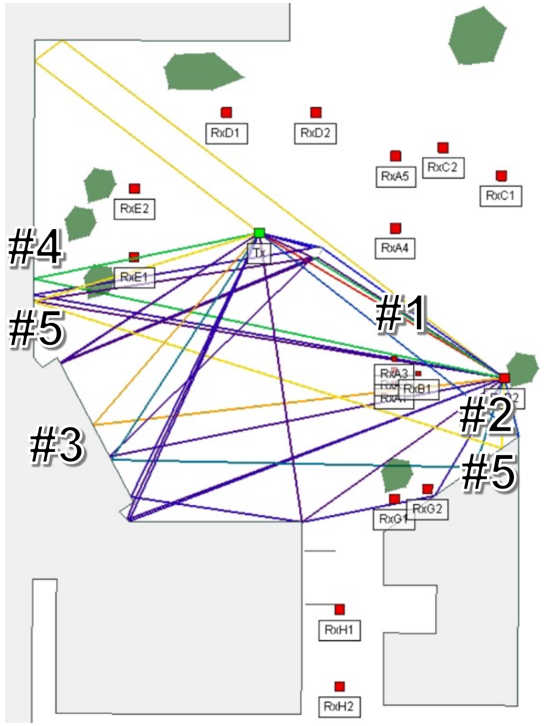


NLoS: Rx17

ADPS with panoramic photos and Multipath Propagation Mechanism(Rx07)

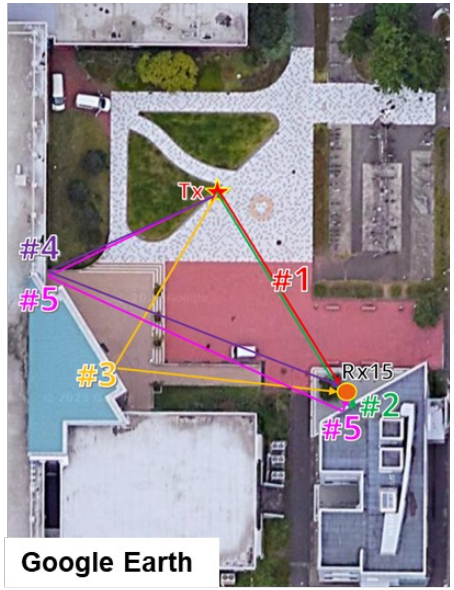




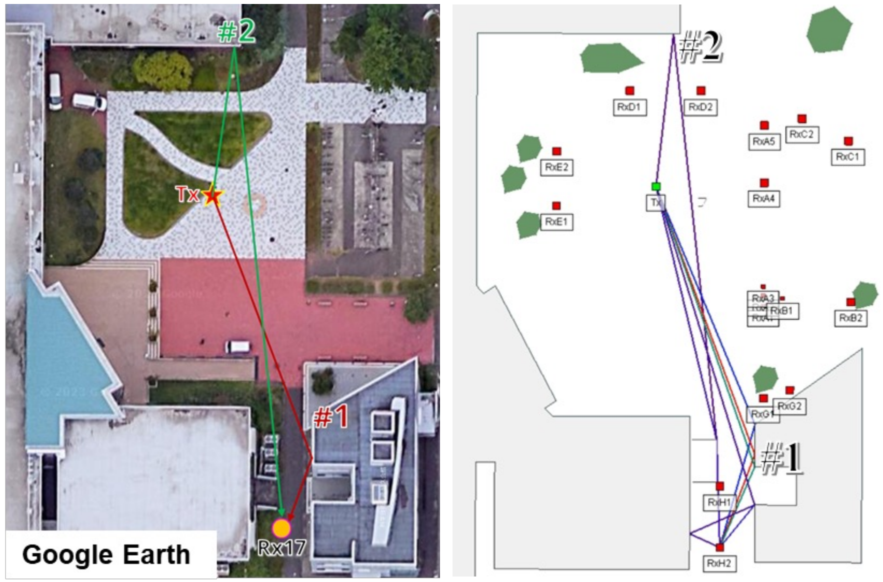


Multipath Propagation Mechanisms at OLoS (Rx15) and NLoS (Rx17)

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):

$$\mathrm{PL}_{\text{best-beam}}[\mathrm{dB}] = -10\log_{10}\left(\sum_{n_\tau} P'(\check{\tau}, \check{\phi}_{\mathrm{T}_{\text{best}}}, \check{\phi}_{\mathrm{R}_{\text{best}}})\right)$$

  - Omni PL:

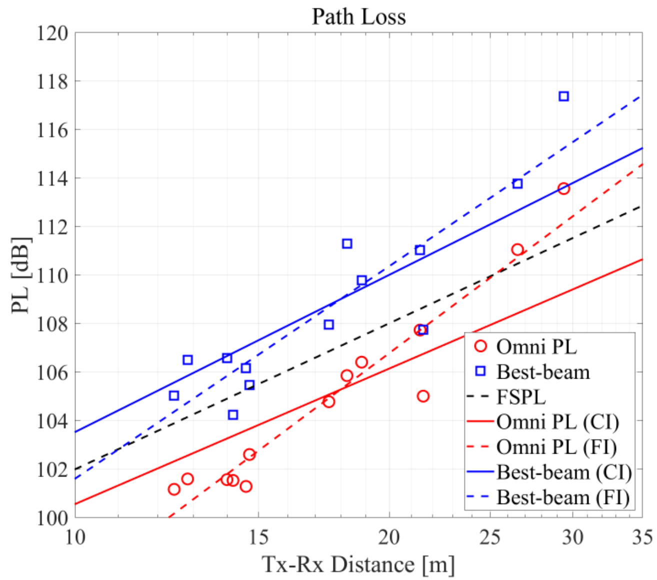
$$\mathrm{PL}_{\text{omni}}\,[\mathrm{dB}] = -10\log_{10}\left(\sum_{n_\tau, n_{\phi_\mathrm{T}}, n_{\phi_\mathrm{R}}} P'(\check{\tau}, \check{\phi}_\mathrm{T}, \check{\phi}_\mathrm{R})\right)$$

- Path Loss Models:
  - Close-in free space (CI) [*]

$$L_{\mathrm{CI}}(d)\ [\mathrm{dB}] = 10n\log_{10}(d) + 20\log_{10}\left(\frac{4\pi f_{\mathrm{GHz}}\times 10^9}{c}\right)$$

  - Floating-intercept (FI) [#]

$$L_{\mathrm{AB}}(d)\ [\mathrm{dB}] = 10\alpha\log_{10}(d) + \beta$$



PL	CI Model (n, σ)	FI Model (α, β, σ)
Omni PL	$(1.85, 2.08)$	$(3.28, 64.04, 1.03)$
$\mathrm{PL}_{\text{best-beam}}$	$(2.14, 1.92)$	$(3.01, 71.16, 1.58)$

[*] K. Haneda et al., “5G 3GPP-Like Channel Models for Outdoor Urban Microcellular and Macrocellular Environments”, 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring), Nanjing, China, 2016, pp. 1-7.
[#] G. R. MacCartney et al., “Path loss models for 5G millimeter wave propagation channels in urban microcells,” 2013 IEEE Global Communications Conference (GLOBECOM), Atlanta, GA, 2013, pp. 3948-3953.

Ergodic capacity evaluation for MIMO transmission

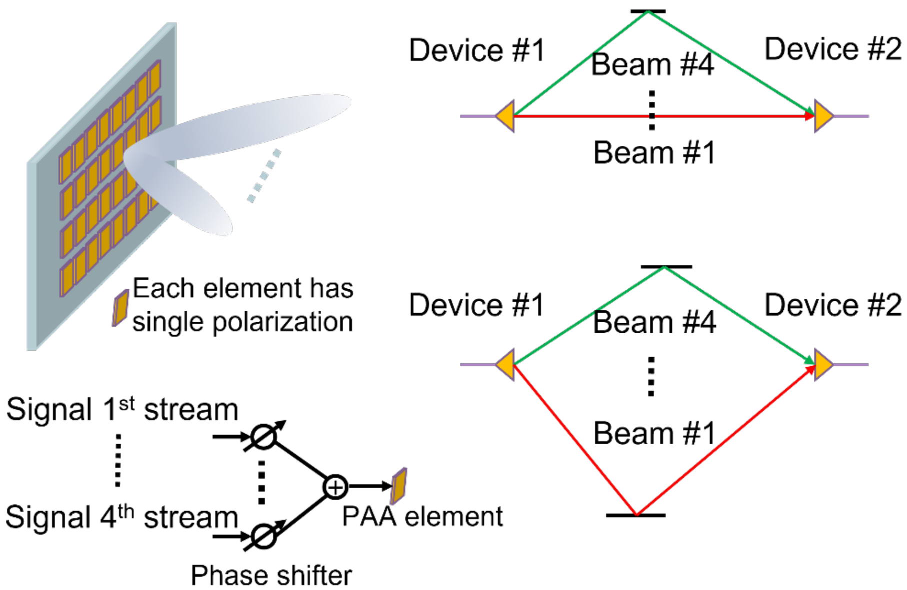
SU-MIMO: streams using the selected beams

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

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

- 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:

$$\mathbf{H}^{i,k} = \begin{bmatrix} H^i(f_k,\varphi_{\mathrm{T},1},\varphi_{\mathrm{R},1}) & H^i(f_k,\varphi_{\mathrm{T},1},\varphi_{\mathrm{R},2}) & H^i(f_k,\varphi_{\mathrm{T},1},\varphi_{\mathrm{R},3}) & H^i(f_k,\varphi_{\mathrm{T},1},\varphi_{\mathrm{R},4}) \\ H^i(f_k,\varphi_{\mathrm{T},2},\varphi_{\mathrm{R},1}) & H^i(f_k,\varphi_{\mathrm{T},2},\varphi_{\mathrm{R},2}) & H^i(f_k,\varphi_{\mathrm{T},2},\varphi_{\mathrm{R},3}) & H^i(f_k,\varphi_{\mathrm{T},2},\varphi_{\mathrm{R},4}) \\ H^i(f_k,\varphi_{\mathrm{T},3},\varphi_{\mathrm{R},1}) & H^i(f_k,\varphi_{\mathrm{T},3},\varphi_{\mathrm{R},2}) & H^i(f_k,\varphi_{\mathrm{T},3},\varphi_{\mathrm{R},3}) & H^i(f_k,\varphi_{\mathrm{T},3},\varphi_{\mathrm{R},4}) \\ H^i(f_k,\varphi_{\mathrm{T},4},\varphi_{\mathrm{R},1}) & H^i(f_k,\varphi_{\mathrm{T},4},\varphi_{\mathrm{R},2}) & H^i(f_k,\varphi_{\mathrm{T},4},\varphi_{\mathrm{R},3}) & H^i(f_k,\varphi_{\mathrm{T},4},\varphi_{\mathrm{R},4}) \end{bmatrix}$$



Ergodic capacity evaluation

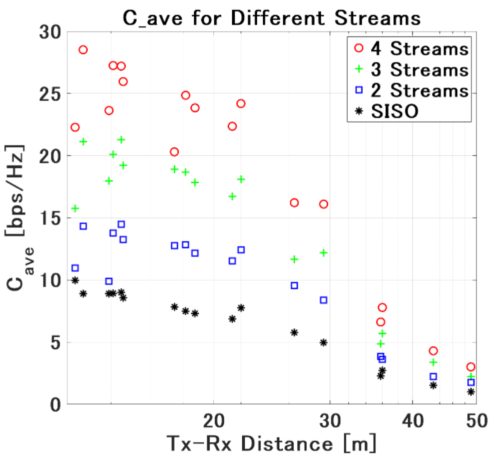
- For each sub-carrier, $\mathbf{H}^{i,k}$ is normalized by the average *Frobenius* norm squared value as

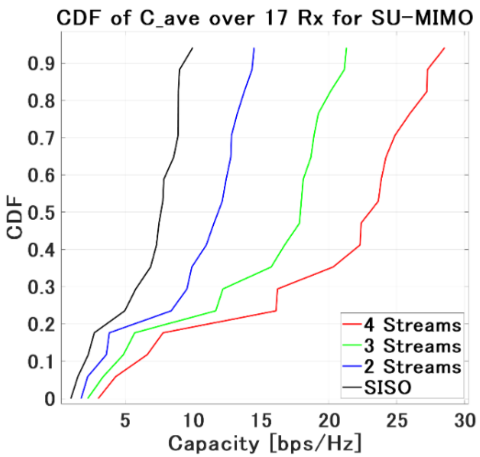
$$\mathbf{H}_{\mathrm{norm}}^{i,k} = \mathbf{H}^{i,k}\left(\frac{1}{KM^2}\sum_{k=0}^{K-1}\left\|\mathbf{H}^{i,k}\right\|_{\mathrm{F}}^{2}\right)^{-\frac{1}{2}}$$

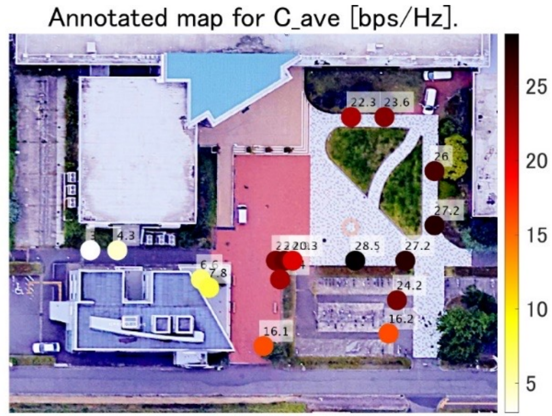
$$\mathbb{E}\left[\left\|\mathbf{H}_{\mathrm{norm}}^{i,k}\right\|_{\mathrm{F}}^{2}\right] = M^2$$

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

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







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

http://radio.eng.niigata-u.ac.jp/

mskim@eng.niigata-u.ac.jp

+81 – 025 – 262 – 7478

This work includes the research results conducted under the National Institute of Information and Communications Technology (NICT) Beyond 5G R&D Promotion Program (Grant No. 02701).