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Abstract: [In this work, channel measurement at 140 GHz in a conference room is reported, with detailed data processing and channel characterization. Moreover, indoor blockage effects caused by walls and human bodies are analyzed. In light of these, moment generating functions of the aggregated interference and theoretical expressions for the mean interference power are derived. As a result, the approximated coverage probability and average network throughput are thoroughly studied.]

Purpose: Information of IEEE 802.15 SC THz

Channel Measurement and Coverage Analysis in the Terahertz Band

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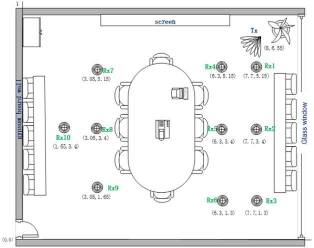
November 10^{th}, 2020

Outline

Measurement Campaign: Scenario and Deployment

Z. Yu, *et. al.*, "Wideband Channel Measurements and Temporal-Spatial Analysis for Terahertz Indoor Communications", in *Proc. of IEEE ICC Workshop on Terahertz Communications*, June 2020.

- A 10m × 8m meeting room
  - Height of 4m
  - A 5m × 2m desk with a height of 0.77m in the center
- Tx fixed and directed to the Rx
  - Height of 2m
- 10 Rx measurement positions
  - Height of 1.4m
  - Sweep in the azimuth plane with the step of 10°



Measurement Campaign: Measurement Parameters

MEASUREMENT PARAMETERS

Parameter	Symbol	Value
Start frequency	f_{start}	130 GHz
End frequency	f_{end}	143 GHz
Bandwidth	B_w	13 GHz
Sampling points	N	1301
Sampling interval	Δf	10 MHz
Average noise floor	P_N	-120 dDm
Test signal power	P_{in}	1 mW
HPBW of transmitter	$HPBW^{Tx}$	30°
HPBW of receiver	$HPBW^{Rx}$	10°
Antenna gain at Tx	G_{t}	15 dBi
Antenna gain at Rx	G_{r}	25 dBi
Time domain resolution	Δt	76.9 ps
Path length resolution	ΔL	2.3 cm
Maximum excess delay	τ_m	100 ns
Maximum path length	L_m	30 m

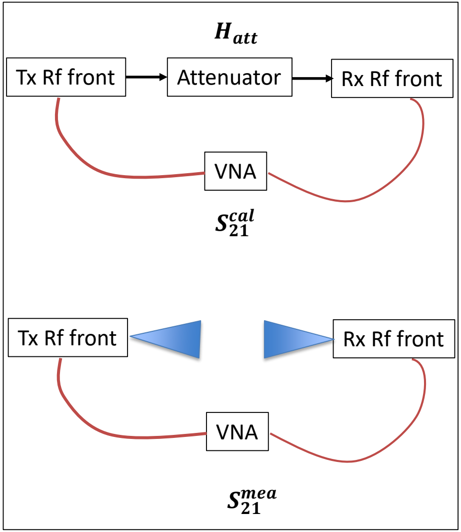
Vector network analyzer (VNA)

- Sweep the frequency band between 130 GHz and 143 GHz

- First remove the antennas at Rx and Tx and connect an attenuator to the RF fronts with the known channel transfer function, H_{att}.
- Measure the S21 parameter get S_{21}^{cal}.
- Use S_{21}^{cal} to calibrate the measured S21 parameter during the channel measurement campaign, S_{21}^{mea}, to get realistic channel transfer function, $H(f)$

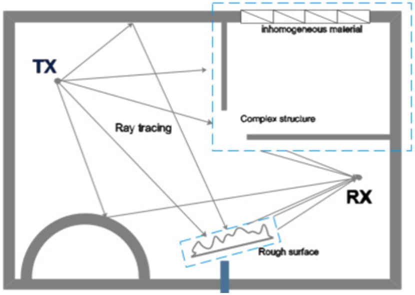
$$H(f) = \frac{S_{21}^{mea} \cdot H_{att}}{S_{21}^{cal} \cdot G_t \cdot G_r}$$

where G_t and G_r are the antenna gain at Rx and Tx, respectively.



Ray tracing is a geometric-optic method to characterize the EM propagation.

- Trace the LoS path, reflected paths, scattered path, penetration and diffracted paths based on the geometry of the propagation environment.



We use ray tracing to simulate the channels in the channel measurement campaign.

- Channel measurement can only tell us the power, delay, angle information of the multipath components (MPCs).
- Help us know the path propagation in the environment which is missing in the channel measurement.

Data Postprocessing: MCD-based Multipath Matching

- Multipath component distance (MCD)-based matching algorithm to match the MPCs extracted from ray tracing and channel measurement.
- MPCs information of the path extracted from ray tracing

$$l_1 \in \mathcal{L}_s \quad : [\alpha_1^s, \tau_1^s, \phi_1^s, \theta_1^s]$$

- MPCs information of the path extracted from measurement

$$l_2 \in \mathcal{L}_m \quad : [\alpha_2^m, \tau_2^m, \phi_2^m, \theta_2^m]$$

- The MCD between two paths is defined as $\mathrm{MCD} = \sqrt{\left\|\mathrm{MCD}_{\mathsf{AoA}}^2\right\| + \mathrm{MCD}_\tau^2}$ with

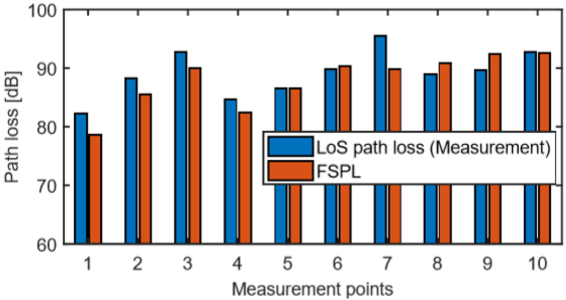
$$\mathrm{MCD_{AoA}} = \frac{1}{2}\left|\begin{pmatrix} \cos(\theta_1^s)\cos(\phi_1^\alpha) \\ \cos(\theta_1^s)\sin(\phi_1^s) \\ \sin(\theta_1^s) \end{pmatrix} - \begin{pmatrix} \cos(\theta_2^m)\cos(\phi_2^m) \\ \cos(\theta_2^m)\sin(\phi_2^m) \\ \sin(\theta_2^m) \end{pmatrix}\right|, \mathrm{MCD}_\tau = \frac{\tau_{std}}{(\Delta\tau_{\max})^2}\cdot|\tau_1^s - \tau_2^m|$$

- If the MCD between two paths is less than a threshold we can regard that the two paths are matched.

Free-Space Path Loss (FSPL)

- FSPS is calculated by Friis' law and shows good agreement with the LoS path loss in the measurement.

$$\mathrm{FSPL[dB]} = -20\log_{10}\left(\frac{c}{4\pi f d}\right)$$

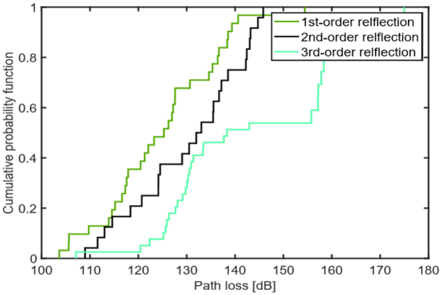


- Some deviations
  - Elevation angle misalignment (Rx1-Rx3)
  - Obstruction by the chair (Rx7)

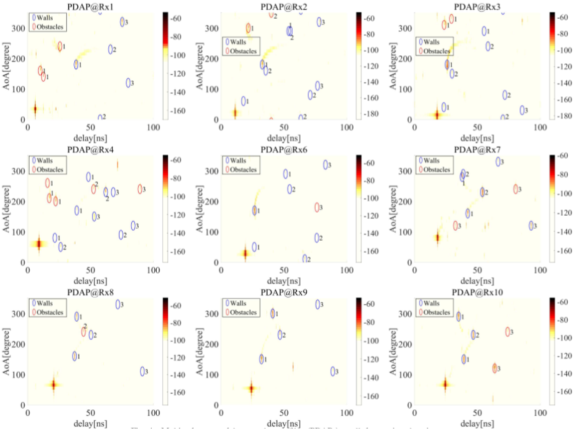
Reflection Loss

Path loss of reflected paths

- 1^{st} order: 124.2 dB
- 2^{nd} order: 129.2 dB
- 3^{rd} order: 138.6 dB



Higher reflection order → Higher propagation loss + Higher reflection loss → Higher path loss.



The THz indoor channel is sparse in both temporal and spatial domains, while the number of MPCs is less than 10.

K factor

The ratio between the power of LoS path and NLoS paths.

Delay spread

Power dispersion in the time domain.

Angular spread

Power dispersion in the angular domain.

STATISTICS OF MPCS FOR EACH RX.

RX	Distance [m]	K-factor	DS [ns]	AS [°]
1	1.43	9059.87	3.58	25.23
2	3.16	807.38	1.9	20.45
3	5.26	410.73	2.95	33.97
4	2.20	462.09	5.72	20.95
6	5.52	39.49	1.17	26.27
7	5.14	101.55	10.02	39.23
8	5.87	109.20	1.62	16.67
9	6.97	18.21	3.95	29.12
10	7.12	17.36	5.87	31.54

CORRELATION MATRIX AMONG THZ MULTIPATH CHARACTERISTICS.

	d	N	K	DS	AS	$\frac{P_{\text{Wall}}}{P_{\text{Obstacle}}}$
Distance	1.00	-	-	-	-	-
Number of MPCs	-0.70	1.00	-	-	-	-
K-factor	-0.67	0.02	1.00	-	-	-
Delay spread	0.04	0.00	-0.09	1.00	-	-
Angular Spread	0.37	-0.20	-0.13	0.66	1.00	-
$\frac{P_{\text{Wall}}}{P_{\text{Obstacle}}}$	0.41	-0.42	-0.15	-0.02	0.11	1.00

- Number of MPCs and K-factor are negatively correlated to distance. The distance positively affects the angular spread and ratio between the wall-reflected power and obstacle-reflected power.
- The number of MPCs has no correlation to K factor, delay spread and angular spread. However, it is negatively related to the ratio between the wall-reflected power and obstacle-reflected power.
- Delay spread and angular spread are positively correlated.

Learnt Lessons on THz Indoor Propagation

- The THz indoor channel is sparse in both temporal and spatial domains, while the number of MPCs is less than 10.
- Although the transmitter directs a narrow beam to the receiver, the existence of MPCs is still not negligible, especially when receivers are far from Tx.
- The long propagation distance, additional reection loss, and beam misalignment of NLoS MPCs cause a very high K-factor and dominant role of the LoS path.
- Wall-reflected MPCs contain considerably higher power than other obstacle-reected MPCs in THz indoor environment.
- Delay spread can be very sensitive NLoS MPCs that arrive shortly after the LoS path, and is positively correlated to angular spread.

Parameterized statistical channel model

The power loss for the EM wave propagation in the THz band is described by

$$L(u_0) = K\left(u_0\right) g\left(u_0\right),$$

where the large-scale fading $K\left(u_0\right)$ equals to $K_L(u_0) = \left|H_{\text{spr}}\left(v_0\right) H_{\text{abs}}\left(v_0\right)\right|^2$ for the LoS case. The large-scale fading $K\left(u_0\right)$ boils down to $K_N(u_0) = \left|H_{\text{spr}}\left(v_0\right) H_{\text{abs}}\left(v_0\right)\right|^2 \mathbb{E}\left[R_c^2\right]$ in the NLoS case.

The path loss due to the small-scale fading caused by the multi-path effect, $g\left(u_0\right)$, follows a distribution with distance-dependent parameters.

- LoS case: we assume that g is a Gamma random variable with the shape parameter $a(u_0)$ and the rate parameter $b(u_0)$, which is expressed as $g_L \sim \text{Gamma}\left(a, b\right)$, where $a = \frac{\mathbb{E}[L(u_0)]^2}{\text{var}(L(u_0))}, b = K_L\left(u_0\right)\frac{\mathbb{E}[L(u_0)]}{\text{var}(L(u_0))}$.
- NLoS case: g is assumed to follow an exponential distribution with the rate parameter $\mu(u_0)$, $g_N \sim \text{Exp}\left(\mu\right)$, where $\mu = \frac{K_N(u_0)}{\mathbb{E}[L(u_0)]}$.

Accuracy of the Proposed Statistical Model

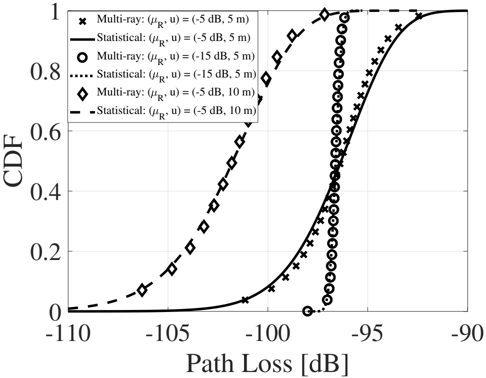


Figure: Comparison between the multi-ray model and the equivalent statistical model: LoS case.

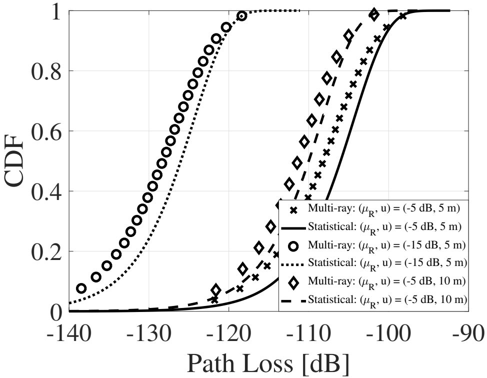


Figure: Comparison between the multi-ray model and the equivalent statistical model: NLoS case.

Outline

C. Han, *et. al.*, "Terahertz Communications (TeraCom): Challenges and Impact on 6G Wireless Systems", arXiv preprint:1912.06040, Dec. 2019.

Terahertz Wireless Local Area Network (Tera-WLAN)

- Motivation: realization of Terabit links between access points (APs) and users equipments (UEs), such as mobile phones and laptops.
- Applications: bandwidth-intensive applications, e.g., virtual reality and 3D holographic calls.

Network-Level Analysis

- Tera-WLANs need to be well designed in terms of the coverage probability.
- The interference still limits significantly the coverage of the THz networks.

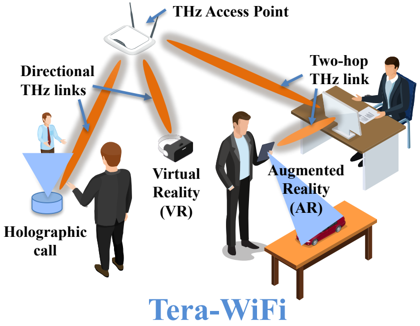


Figure: Tbps WLAN System (Tera-WiFi).

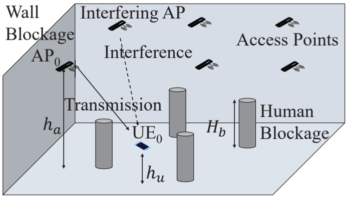
Challenges of Analyzing Tera-WLAN

- The THz channel is more complicated compared to the microwave channel, which may cause NO closed-form expressions for communication metrics (interference distribution, coverage probability, average achievable data rate).
- Rayleigh fading has good properties for the derivation of interference distribution. However, better statistical fading model is required for network-level analysis.
- We need to model the antenna radiation pattern of directional transmission instead of omnidirectional transmission.
- In an indoor environment, two typical blockages, human bodies and walls, should be considered. Both line-of-sight (LoS) and non-line-of-sight (NLoS) transmissions should be considered.
- The assumption of the user association scheme needs to be revisited in the THz networks.

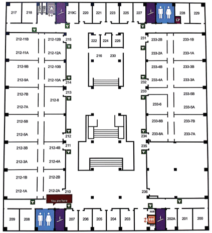
The THz channel has distinctive features (propagation losses, multi-path propagation, blockage effects, directional transmission) from the microwave spectrum. Hence, we need new models and methods of interference and coverage analysis in the THz band.

System Model and Wall Blockage

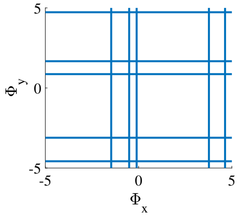
Y. Wu, *et. al*, "Interference and Coverage Analysis for Terahertz Networks with Indoor Blockage Effects and Line-of-Sight Access Point Association", *IEEE Transactions on Wireless Communications*, 2020.



(a) The downlink of the indoor Tera-WLANs scenario in one room.

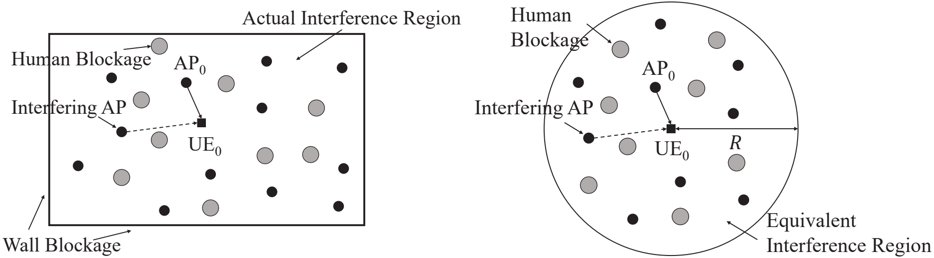


(b) The top view of a realistic indoor environment.



(c) An illustration of a MPLP wall blockage model.

- The indoor environment is usually divided into a number of subspaces by the walls with two orientation angles that are perpendicular to each other in most cases.
- The walls are assumed to be oriented perpendicular to the coordinate axes and modeled as two independent Manhattan Poisson line processes (MPLPs).



(d) The shape of an actual interference region.

(e) Approximate interference region: an equivalent circle.

Figure: Simplification of the rectangular interference region as an equivalent fixed circle.

Modeling Criterion

The average number of the APs in the equivalent circle is equal to that in the actual rectangular interference region. $\rightarrow R = \frac{2}{\sqrt{\pi}\lambda_W}$.

- When the intense signal attenuation caused by human bodies leads to disconnection of the communication link between AP and UE, it will turn to transmission via NLoS paths.
- Human bodies: modeled as cylinders.
- Human position: homogeneous PPP Φ_b with intensity of λ_b.
- LoS and NLoS probability
  - $P_L(u) = P[\text{No human in blockage zone}] = e^{-\beta u}$
  - $P_N(u) = 1 - e^{-\beta u}$

  where $\beta = 2\lambda_b R_b (H_b - h_u)/(h_a - h_u)$ is the parameter determined by the heights of AP and UE, and the size and the density of human bodies.

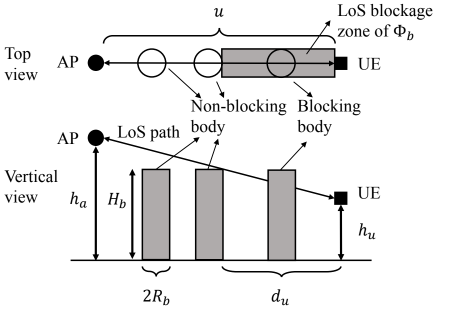


Figure: Top and vertical views of the human-blocking scenario for an AP-UE link.

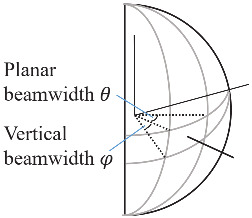


Figure: A pyramidal shape model of the antenna beam.

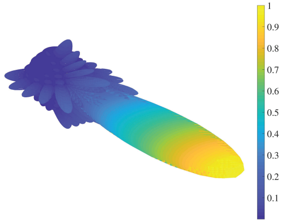


Figure: The simulated antenna beam.

Pyramidal model for the antenna beam

The antenna gain as a function of the angles θ and φ is given by

$$G_{\mathsf{MB}}(\theta,\varphi)=\frac{\pi}{\arcsin\left(\tan\frac{\theta}{2}\tan\frac{\varphi}{2}\right)},$$

Y. Wu, and C. Han, "Interference and Coverage Analysis for Indoor Terahertz Wireless Local Area Networks", in *Proc. of IEEE GLOBECOM Workshop on Terahertz Communications*, December 2019.

Distribution of Interference

The aggregated interference at Rx_0 is the sum of signal power from interfering APs,

$$I = \sum_{i=1}^{N} I_i = \sum_{i=1}^{N} \left(\frac{c}{4\pi f}\right)^2 P_a G_{\mathsf{Tx}} G_{\mathsf{Rx}} g_i e^{-\kappa v_i} v_i^{-\alpha_i}$$

The interference distribution is determined by several random variables (number of interfering APs, transmitting and receiving antenna gains, small-scale fading, interfering distances, NLoS/LoS indicators). $\Rightarrow$ The closed-form expression for the interference distribution is intractable.

Moments of Aggregated Interference

- The first (mean) and second moments (variance + mean^2) of interference can be calculated by the conditional expectation formula (CEF).
- Any order moment of interference can be calculated by the moment generating function (MGF).

Proposed Model

The distribution of interference is approximated as *modified log-normal model*

$$\text{Interfernce distribution} := \begin{cases} \text{extremely weak interference with prob. } p_0 \\ \text{log-normal distribution with parameters } \mu, \sigma \end{cases}$$

Approximated Distribution

The distribution of aggregated interference at Rx_0 is approximated as

$$p_I(t) = \begin{cases} p_0 = \frac{e^{-\lambda_a \pi R_A^2 (1-p_c)^2} - e^{-\lambda_a \pi R_A^2}}{2p_c - p_c^2} + e^{-\pi \lambda_a R_A^2}, t = 0 \\ (1-p_0) \frac{1}{t\sigma\sqrt{2\pi}} e^{-\frac{(\ln t - \mu)^2}{2\sigma^2}}, t > 0 \end{cases}$$

Parameter Estimation

The parameters μ and σ can be estimated by three ways:

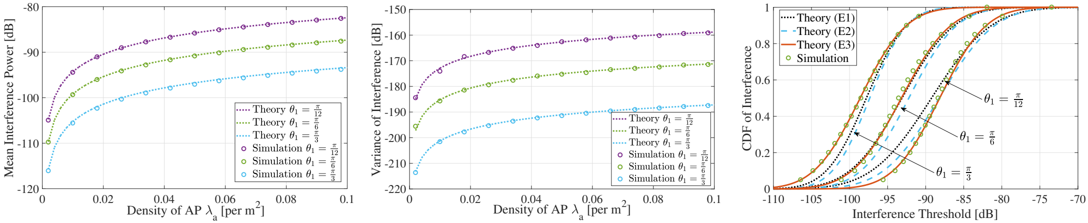
- E_1: with the first two moments of interference;
- E_2: with the first three moments of interference;
- E_3: with simulated data.

$$E_1 : \begin{cases} \mu + \frac{1}{2}\sigma^2 = \ln \frac{\mathrm{E}[I]}{1-p_0} \\ 2\mu + 2\sigma^2 = \ln \frac{\mathrm{E}[I^2]}{1-p_0} \end{cases}$$

$$E_2 : \begin{cases} \mu + \frac{1}{2}\sigma^2 = \ln \frac{\mathrm{E}[I]}{1-p_0} \\ 2\mu + 2\sigma^2 = \ln \frac{\mathrm{E}[I^2]}{1-p_0} \\ 3\mu + \frac{9}{2}\sigma^2 = \ln \frac{\mathrm{E}[I^3]}{1-p_0} \end{cases}$$

The interference distribution can be parameterized from the moments of interference.

Numerical Results: Interference



(a) Mean interference power versus the density of AP, varying θ_1.

(b) Variance of interference versus the density of AP, varying θ_1.

(c) Interference CDF with three ways of parameter fitting, varying θ_1, $\lambda_a = 0.06$ per m^2.

Distribution of Interference

- Derived moments of interference are accurate.
- Accuracy of approximated distribution of interference: $E_3 \geq E_1 \approx E_2$.

SINR distribution

The signal-to-interference-plus-noise (SINR) at Rx_0, which communicates with the associated AP (A_0), is

$$\mathsf{SINR} = \frac{S}{\sigma_n^2 + I}$$

The SINR distribution is determined by the distributions of received signal S and the interference I, and the noise power.

Coverage probability

The coverage probability is interpreted as the probability that an arbitrarily chosen user can achieve target SINR T,

$$\mathrm{P}_c(T) = \mathrm{P}(\mathsf{SINR} > T)$$

- The complementary cumulative distribution function (CCDF) of SINR.
- The average fraction of the network area that is in “coverage” at any time.

Motivation

- The nearest-AP association is based on the fact that the LoS probability is maximized as the dynamic human blockers move. Due to high reflection loss in the THz band, the nearest LoS AP is more likely to provide better SINR than the nearest AP that is NLoS.

User Association Schemes

- Nearest-AP User Association: the user selects the *nearest AP* to associate with and the interfering AP are all further than the associated AP. The distribution of horizontal distance between the UE and the associated AP is

$$f_1(u) = 2\pi\lambda_a u e^{-\lambda_a \pi u^2}, 0 \le u \le R.$$

- LoS-AP User Association: the user selects the *nearest LoS AP* to associate with. If the LoS link is blocked by the moving blockages, the user switches to another LoS AP. The distribution of horizontal distance between the UE and the associated AP is

$$f_2(u) = 2\pi\lambda_a u e^{-\beta u - \frac{2\pi\lambda_a}{\beta^2}(1-\exp(-\beta u)-\beta u\exp(-\beta u))}.$$

Coverage Probability for Weak Reflection Loss

Nearest-AP user association

The coverage probability $P_c\left(T\right)$ is

$$P_c\left(T\right) = \int_0^R \left(p_L\left(u\right) P_{c,L}\left(T\right) + p_N\left(u\right) P_{c,N}\left(T\right)\right) f_1\left(u\right) du$$

where $P_{c,L}(T)$ and $P_{c,N}(T)$ are the conditional coverage probabilities given that the user connects to a LoS or NLoS AP with the 2D distance u.

LoS-AP user association

The coverage probability $P_c(T)$ is given by

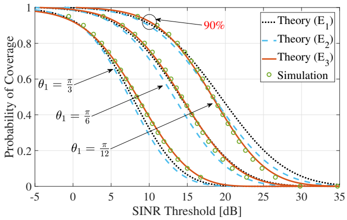
$$P_L\left(T\right) = \int_0^R f_2\left(u\right) \sum_{n=1}^{\infty} \left(-1\right)^{n+1} \binom{a\left(u\right)}{n} e^{-\frac{nTP_N b(u)\epsilon(u)}{P_t G_{\mathrm{MB}}^2 K_L(u)}} \cdot \mathcal{M}_{I_L}\left(-\frac{nTb\left(u\right)\epsilon\left(u\right)}{P_t G_{\mathrm{MB}}^2 K_L\left(u\right)}\right) \mathcal{M}_{I_N}\left(-\frac{nTb\left(u\right)\epsilon\left(u\right)}{P_t G_{\mathrm{MB}}^2 K_L\left(u\right)}\right) du.$$

Coverage Probability for Strong Reflection Loss

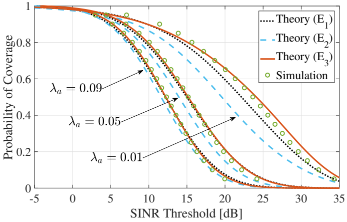
- Strong reflection loss: When the reflection loss is large, the signal power of the NLoS rays can be neglected, compared to that of the LoS ray.
- Dominant interfering AP analysis: We define the dominant interferers as the APs with the antenna gain of the interfering signal equal to $G_a G_u$. We introduce the probability that the number of the dominant interfering APs in the region bounded by two concentric circles of radii $u (0 < u < R)$ and R is equal to k as $P_k(u) = \frac{1}{k!} e^{-\lambda_a p_A p_U \pi (R^2 - u^2)} \left(\lambda_a p_A p_U \pi (R^2 - u^2)\right)^k$. Since $P_0(u) + P_1(u)$ is close to 1 when $\lambda_a p_A p_U$ is small, the number of the dominant interfering APs is not more than one with high probability close to one.
- Closed-form expression of the coverage probability: When $\beta = 0$, the optimal AP density can be efficiently calculated by the coverage probability

$$P_c(T) = e^{-\lambda_a p_A p_U \pi R^2} \frac{1 - e^{-(1-p_A p_U)\pi \lambda_a R_1^2}}{1 - p_A p_U} + \lambda_a \pi p_A p_U e^{-\lambda_a p_A p_U \pi R^2} \frac{1 - e^{-(1-p_A p_U)\pi \lambda_a R_2^2}}{1 - p_A p_U} \left(R^2 - (T-1)(h_a - h_u)^2\right)$$
$$- T p_A p_U e^{-\lambda_a p_A p_U \pi R^2} \left(\frac{1 - e^{-(1-p_A p_U)\pi \lambda_a R_2^2}}{(1 - p_A p_U)^2} - \frac{\pi \lambda_a R_2^2}{1 - p_A p_U} e^{-(1-p_A p_U)\pi \lambda_a R_2^2} \right).$$

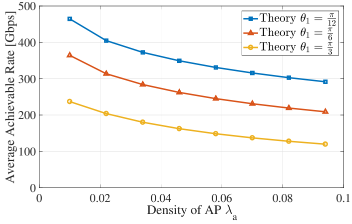
Coverage using Approximated Interference Model



(d) Coverage with three ways of parameter fitting, varying θ_1, $\lambda_a = 0.06$ per m^2.



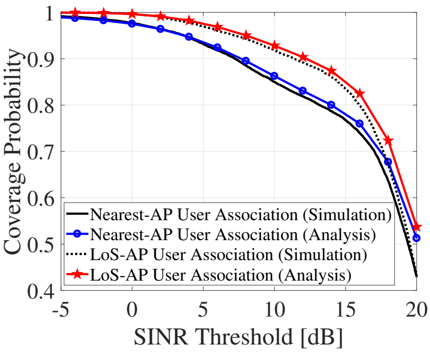
(e) Coverage with three ways of parameter fitting, varying λ_a, $\theta_1 = \frac{\pi}{6}$.



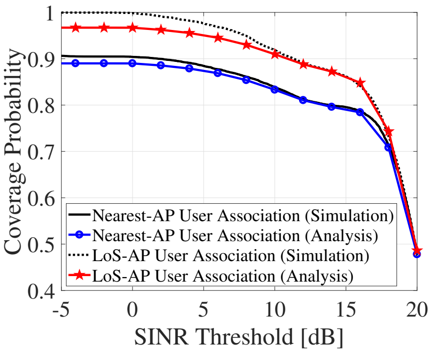
(f) Average achievable rate, varying λ_a and θ_1.

Coverage Probability and Achievable Rate

- The coverage probability for 10 dB SINR can be over 90% under the conditions of 6 APs per 100 m^2, 15-degree beam-width and 50 GHz bandwidth.
- Mean achievable rate can reach level of 250 Gbps with directional antennas and the bandwidth of 50 GHz.



(g) Weak reflection loss, $\mu_R = -5$ dB.



(h) Strong reflection loss, $\mu_R = -15$ dB.

Figure: We validate the accuracy of the analytical expressions for the coverage probability by the simulations and compare two user association schemes. There is a good agreement between the analysis and the simulation.

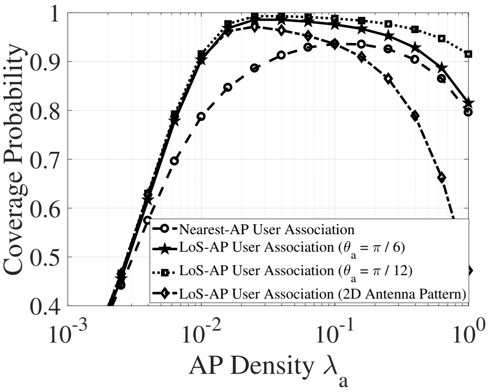


Figure: Coverage probability versus the AP density for SINR threshold $T = 5$ dB.

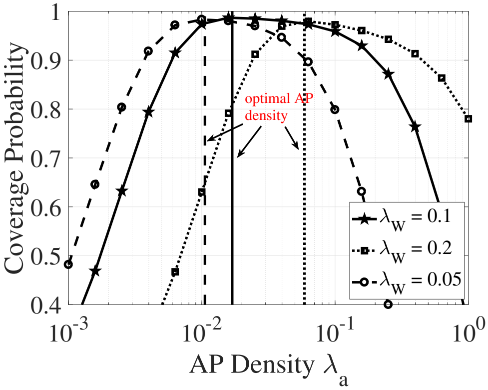


Figure: The optimal AP density versus the wall density.

Outline

Summary

- Conduct 140 GHz indoor channel measurement, with thorough characterization and development of a statistical model.
- Coverage analysis for the indoor Tera-WLANs includes:
  - Geometry model, indoor blockage effects, multi-path fading, directional antenna radiation pattern, user association schemes.
- Learnt lessons
  - For the nearest-AP user association scheme, the optimal AP density to maximize the coverage probability at 5 dB of SINR threshold is nearly 0.15 m^{-2}.
  - In this case, the coverage probability is about 93% and the average network throughput is approximately 30 Gbps/m^2.
  - The LoS-AP user association can improve the coverage probability by 3 percent and the average network throughput by 2 Gbps/m^2.

THANK YOU!

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