White Paper on 5G Channel Model for Bands up to 100 GHz

Contributors

Aalto University
BUPT
CMCC
Ericsson
Huawei
INTEL
KT Corporation
Nokia
NTT DOCOMO
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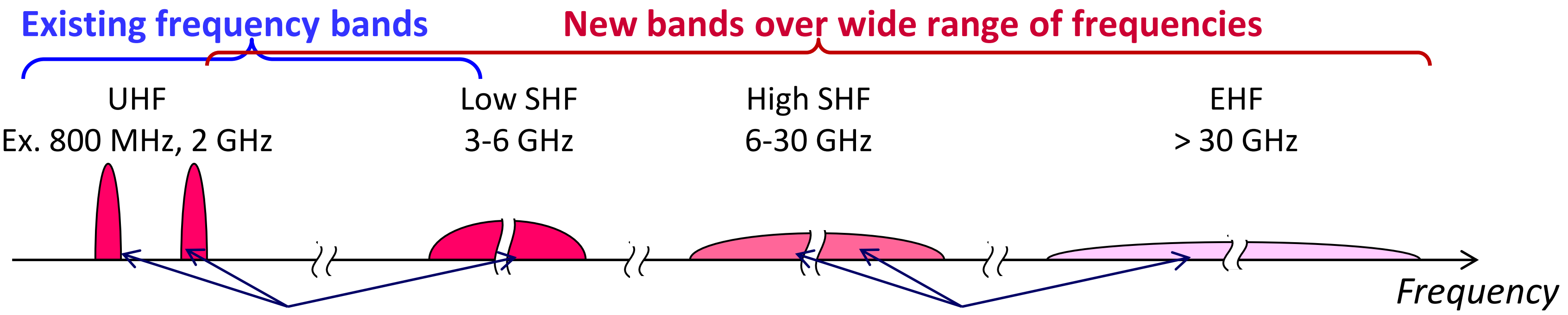
Target Frequency Bands for 5G

5G utilizes wide range of frequency bands
with both frequency-agonistic and frequency-optimized technologies



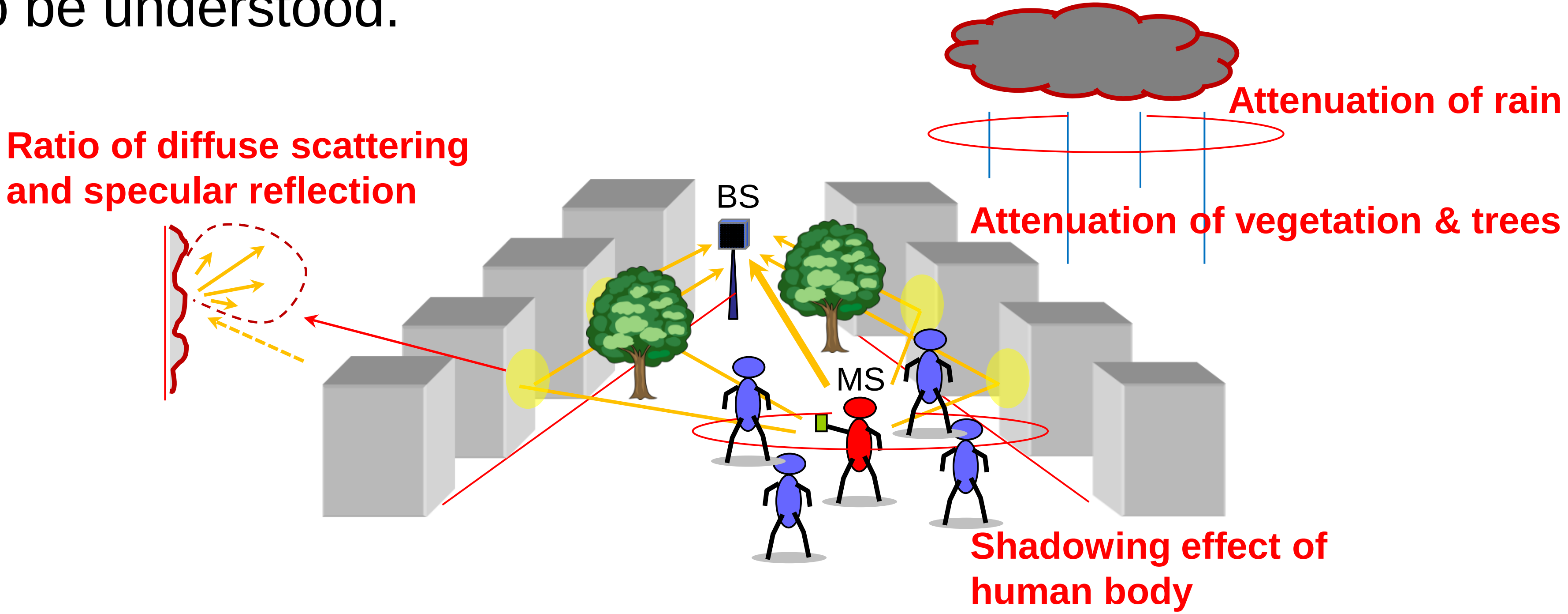
Existing channel models are available for evaluations

Limited channel models/considerations

New channel model is required for frequency range above 6 GHz

Key Propagation Phenomena at Higher Frequencies

To develop channel model for frequency range above 6 GHz, frequency dependency of path loss and channel properties need to be understood.



Efforts for 5G Channel Measurements and Modeling

Many organizations study 5G channel modeling

	Scenarios	Freq. range	Model
IEEE802.11	Indoor	57-64 GHz	Statistical channel model
METIS2020	UMi, UMa, V2V/D2D, Indoor	Up to 86 GHz	GSCM, Map-based, and hybrid
MiWEBA	UMi	60 GHz	Semi-deterministic, semi-stochastic
COST2100	UMi, Indoor	0.3, 3.6-5.3 GHz	GSCM
NYU WIRELESS	UMi, UMa, Indoor	28/38/60/73 GHz	GSCM
QuaDRiGa, Fraunhofer/HHI	UMi, Indoor, O2I, Dense (stadium), Backhaul	10/28/43/60/82 GHz	GSCM

Study on 5G Channel Model in 3GPP

Channel modeling study has been initiated in 3GPP

<u>Objective</u>: Develop a channel model to enable a study on feasibility and framework of 5G using high frequency spectrum of 6-100 GHz

Oct. 2015 | Dec. 2015 | Jun. 2016

<u>Identify Status/expectation of existing information on high frequencies</u>

- Existing/ongoing channel measurements/modeling activities
- Deployment scenarios and their prioritization
- Spectrum bands of interests
- Additional features to be considered for new model

<u>5G channel model development</u>

- Details of the deployment scenarios
- Pathloss/shadowing
- LOS probability
- Small-scale fading
- Additional features required (e.g., Larger band support, blockage loss/ probability, additional loss, spatial consistency, support of 3D beamforming with large array, etc.)

(Ref) RP-151606 – New SID Proposal: Study on channel model for frequency spectrum above 6 GHz

Efforts for 5G Channel Measurements and Modeling

Many companies and academia conducted measurement campaigns for 5G channel modeling

	6 - 20 GHz	20 - 30 GHz	30 - 60 GHz	> 60 GHz
UMi	Aalto Univ., CMCC, Ericsson, Intel/Fraunhofer HHI, Nokia/Aalborg, NTT DOCOMO, Orange	AT&T, Aalto Univ., CMCC, Huawei, Intel/Fraunhofer HHI, Nokia/Aalborg, NTT DOCOMO, NYU, Qualcomm, Samsung, CATT, KT, ETRI, ITRI/CCU, ZTE	AT&T, Huawei, Intel/Fraunhofer HHI, NTT DOCOMO, Qualcomm, CATT, ETRI, ITRI/CCU, ZTE	AT&T, Aalto Univ., Huawei, Intel/Fraunhofer HHI, NYU
UMa	CMCC, Nokia/Aalborg	Nokia/Aalborg	NYU	
Indoor	Aalto Univ., CMCC, Ericsson, Huawei, Intel/Fraunhofer HHI, Nokia/Aalborg, NTT DOCOMO, Orange	AT&T, Alcatel-Lucent, Aalto Univ., BUPT, CMCC, Huawei, Intel/Fraunhofer HHI, Nokia/Aalborg, NTT DOCOMO, NYU, Qualcomm, Samsung, CATT, KT, ETRI, ITRI/CCU, ZTE	AT&T, Ericsson, Huawei, Intel/Fraunhofer HHI, NTT DOCOMO, NYU, Qualcomm, CATT, ETRI, ITRI/CCU, ZTE	AT&T, Aalto Univ., Huawei, Intel/Fraunhofer HHI, NYU
O2I	Ericsson, Huawei, Intel/Fraunhofer HHI, Nokia/Aalborg, NTT DOCOMO, Orange	AT&T, Alcatel-Lucent, Ericsson, Huawei, Intel/Fraunhofer HHI, KT, NTT DOCOMO, NYU, Samsung	AT&T, Ericsson, Huawei, Intel/Fraunhofer HHI, NTT DOCOMO	AT&T, Huawei, Intel/Fraunhofer HHI

White Paper on 5G Channel Model for bands up to 100 GHz

- White Paper titles “5G Channel Model for bands up to 100 GHz” put on this workshop website, http://www.5gworkshops.com/ , was developed by below parties to facilitate development of new channel models for spectrum bands ranging from 6 GHz to 100 GHz
  - Aalto University, BUPT, CMCC, Ericsson, Huawei, Intel, KT Corporation, Nokia, NTT DOCOMO, New York University, Qualcomm, Samsung, University of Bristol and University of Southern California
- The White Paper was developed based on extensive measurement and ray tracing results across a multitude of bands conducted by the parties
- The White Paper has been submitted or will be submitted to standardization forums such as 3GPP and relevant organizations to support their channel modeling activities
- The White Paper will be updated to cover remaining aspects such as details on fast fading models and clustering

Modeling Approaches and Requirements

- It is highly preferable that the new model be based on the existing 3GPP 3D channel model
  - Extensions should cater to 5G modeling requirements and scenarios
- The new model should be
  - Sufficiently accurate for the purposes of 5G evaluation
  - No more complex than it is necessary
- Other considerable requirements

	New channel model	(Ref.) 3GPP 3D channel model
Scenario	5G scenarios	UMi and UMa
Frequency range	Up to 100 GHz	Up to 6 GHz
Bandwidth	Up to 2 GHz	Up to 100 MHz
Support of large antenna array	Finer angular resolution around 1 deg., etc.	N.A.
Mobility	Up to 350 km/h Suitability for dual mobility (D2D/V2V)	Up to 350 km/h
Spatial/temporal/frequency consistency	Spatial consistency, inter-site correlation, correlation among bands, LOS/NLOS state, etc (*)	Partly supported (e.g., spatial consistency of LSPs with fixed BS)

(*) These features could possibly be optional for simpler studies

Typical 5G Deployment Scenarios

- UMi – Street canyon: Urban micro-cellular environment with BSs below rooftop level
- UMi – Open area: Urban micro-cellular environment with BSs below rooftop level and pointing towards open area
- UMa: Urban macro-cellular environment with BSs above rooftop level
- Indoor – Office: Typical office environment comprised of open and closed areas
- Indoor – Shopping mall: Large multiple-story building with open ceiling in the middle.

* Both of outdoor-to-outdoor (O2O) and outdoor-to-indoor (O2I) are considered for UMi and UMa scenarios.

UMi – Street canyon

UMi – Open area

UMa

Indoor – Office

Indoor – Shopping mall

5G Channel Model
Specific Topics

- The following slides provide describe the following:
  (covered in more detail in [5GCM white paper])
  - Urban Micro Environment (UMi)
  - Indoor Hotspot (InH) Environment
  - Urban Macro Environment (UMa)
  - Penetration loss

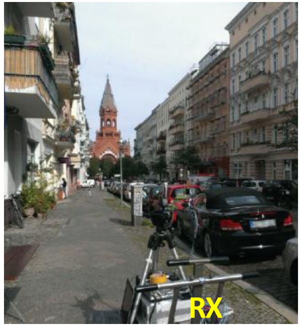
Urban Micro Environment Channel Characteristics

Urban Micro (UMi) – Street Canyon Environment

- Measurement Campaigns by multiple groups : 2 GHz ~ 73 GHz
  - Nokia/Aalborg (2 / 10 / 18 GHz), Qualcomm (2.9 / 29 GHz), CMCC (6 GHz), Intel/HHI (10 / 60 GHz), docomo (26 / 37 GHz), Samsung/KAIST (28 GHz), KT (28 GHz), Huawei (28 / 72 / 73 GHz), NYU (28 / 73 GHz), Aalto Univ. (60 GHz)

New York City & NYU Campus,

Tokyo, Japan



Berlin, Germany

Beijing, China

Daejeon, Korea

Chengdu, China

New Jersey, USA

Pyeongchang, Korea

LoS Probability (based on Ray-tracing) – Street Canyon

Three Models : Current 3GPP / Fitted / NYU

Current model
used in 3GPP / ITU

$$P_{LoS}(d) = \min\left(\frac{18}{d}, 1\right) \cdot \left(1 - \exp\left(-\frac{d}{36}\right)\right) + \exp\left(-\frac{d}{36}\right)$$

Fitted (d1/d2) model
based on 3GPP / ITU Model

$$P_{LoS}(d) = \min\left(\frac{d_1}{d}, 1\right) \cdot \left(1 - \exp\left(-\frac{d}{d_2}\right)\right) + \exp\left(-\frac{d}{d_2}\right)$$

NYU Squared model
proposed by NYU

$$P_{LoS}(d) = \left[\min\left(\frac{d_1}{d}, 1\right) \cdot \left(1 - \exp\left(-\frac{d}{d_2}\right)\right) + \exp\left(-\frac{d}{d_2}\right)\right]^2$$

3GPP/ITU Model sufficient for frequencies above 6 GHz

- Current model has small error over all distances
- LoS probability seems **no** frequency dependent

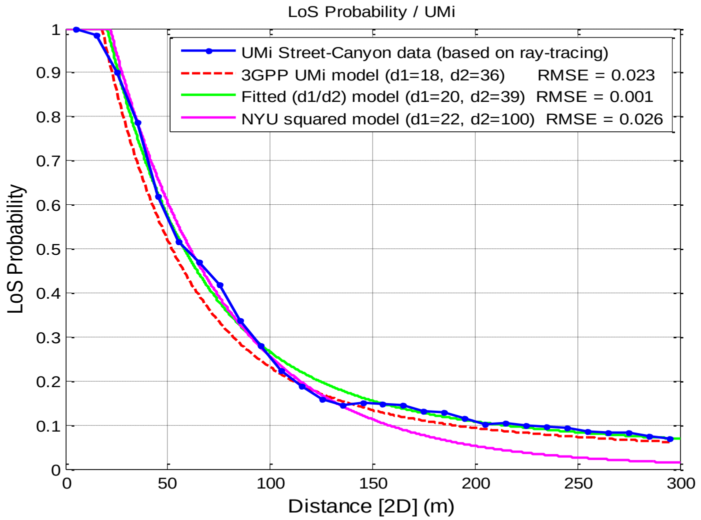
LoS Model Comparison

Models	d1	d2	MSE
3GPP UMi	18	36	0.023
d1/d2 model	20	39	0.001
NYU (squared)	22	100	0.026

Ray-Tracing Simulations

NYU Campus, Manhattan

Tokyo Downtown



LoS Probability Model Comparison

Large-scale Propagation Model : Pathloss / Shadow Fading

Pathloss model based on multiple measurement campaigns

- LoS model – well matched to Friis' free-space pathloss model
- NLoS model – pathloss slope range ($n/\alpha \approx$ 3~4) similar to lower-band, below 6 GHz

Single-slope Baseline Pathloss Model (LoS / NLoS)

Close-in Ref-1m (CI) Model : $\boldsymbol{PL}(d)[dB] = 10\, \boldsymbol{n}\boldsymbol{\log_{10}}(d\ [m]) + \mathbf{32.45} + \mathbf{20}\boldsymbol{\log_{10}}(f_c\ [GHz]) + \boldsymbol{\chi_\sigma}(d)$

α-β-γ Mode : $\boldsymbol{PL}(d)[dB] = 10\, \boldsymbol{\alpha}\, \boldsymbol{\log_{10}}(d\ [m]) + \boldsymbol{\beta} + 10\, \boldsymbol{\gamma}\, \boldsymbol{\log_{10}}(f_c\ [GHz]) + \boldsymbol{\chi_\sigma}(d)$

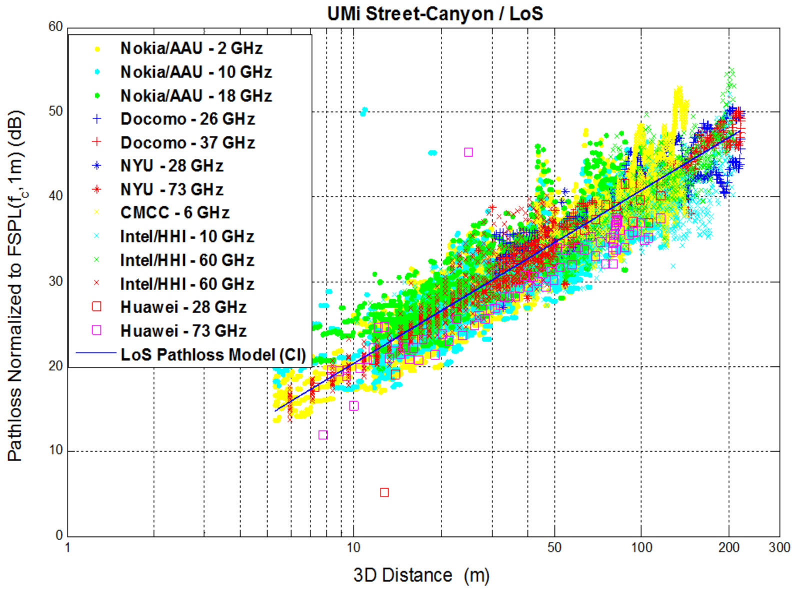
Single-Slope Pathloss Model			Baseline Model : CI model (LoS), CI / α-β-γ model (NLoS)				Valid freq [GHz]	Validity dist. [m]
			n (CI) /	β [dB]	γ	σ_{SF} [dB]	[min ~ max]	[min ~ max]
Street Canyon	LoS		1.98	N/A		3.1	2 ~ 73	5~221
	NLoS	CI	3.19			8.2		10~959
		ABG	3.48	21.02	2.34	7.8		
Open Square	LoS		1.85	N/A		4.2	2 ~ 60	6~88
	NLoS	CI	2.89			7.1		8~605
		ABG	4.14	3.66	2.43	7.0		

UMi Pathloss Model / Street-Canyon : Single-Slope Model

- Baseline LoS Model : CI model / Baseline NLoS Model : CI model and α-β-γ model
- Shadow Fading Model : fixed SF model / distance-dependent SF model is considered with further analysis

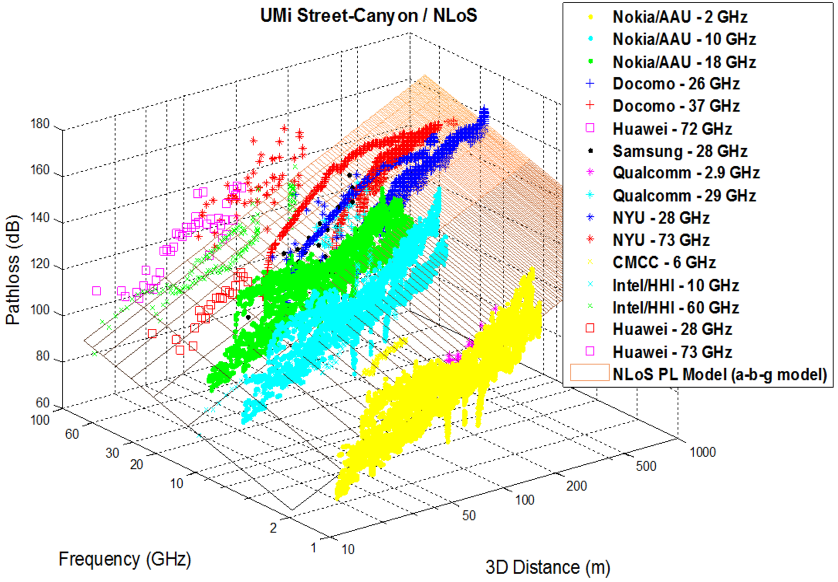
LoS Pathloss Model

- Pathloss Exponent = 1.98



NLoS Pathloss Model

- Pathloss Slope, α = 3.48

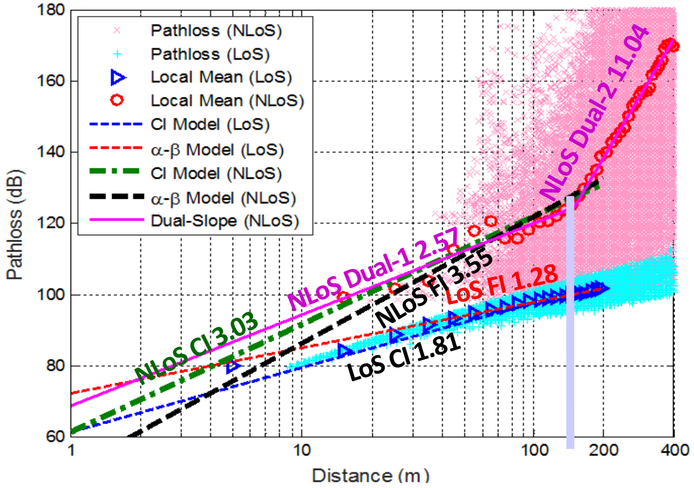


UMi Pathloss Model / Street-Canyon : Dual-slope Model

- Dual-sloped pathloss observed based on ray-tracing simulation, still requires more analysis
  - The median-values of pathloss has different slope in near / far region
  - Due to different propagation characteristics in mmWave, severe diffraction loss / reflection-dominant propagation

Dual-Slope Pathloss Model (NLoS)

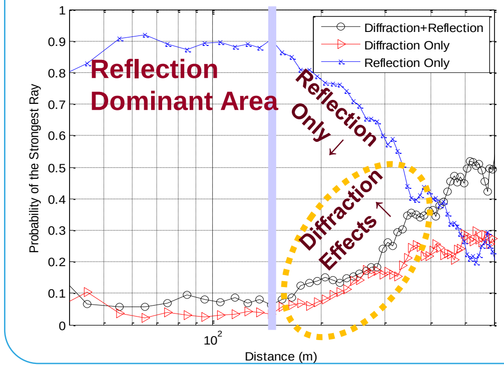
- 1st slope well matched up to 200m range
- 2nd slope of pathloss appeared over 150 m



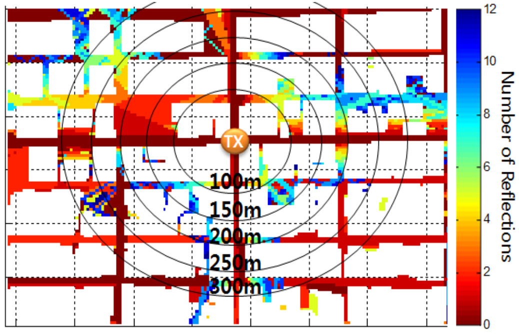
Analysis of mmWave Propagation Characteristics

- Severe diffraction loss / penetration loss
- Mostly reflected paths in NLoS, no twice-penetrated paths
- In far area (over 150 m), the effect of diffracted path is dominant after several reflections

Dominant Path's Propagation in NLoS



Number of Reflection in Street-canyon

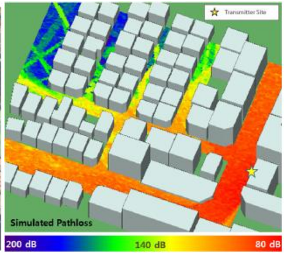


Fast-fading Channel : Extension of Stochastic Channel Model

- Based on the WINNER-like ITU/3GPP model, SCM model extended for mmWave band
- Develop/implement additional features of higher frequency on baseline model

Stochastic Channel Model Approach

- Baseline Model – Extension of the current SCM model
  - Reuse the framework of **double–directional channel model** in standardization [ITU-R M.2135, 3GPP TR36.873]
  - Parameter extraction from Measurement / Ray-tracing simulation over many frequencies

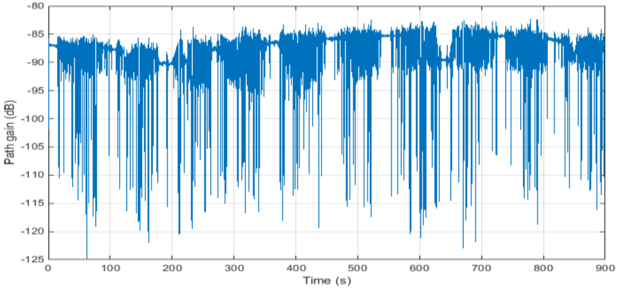


Daejeon Measurement & Ray-tracing @ 28 GHz [1]

NYC @ 73 GHz [2]

Additional Features for Higher Frequency

- **[Ongoing]** Modular Approach added on Baseline Model
- New features can be activated for some scenarios
  - Blockage model from moving vehicles / human body
  - Geometry-induced additional loss in dense urban street-canyon
  - Spatial-consistency for Massive MIMO / MU-MIMO



Example of blockage by moving traffic at 28 GHz

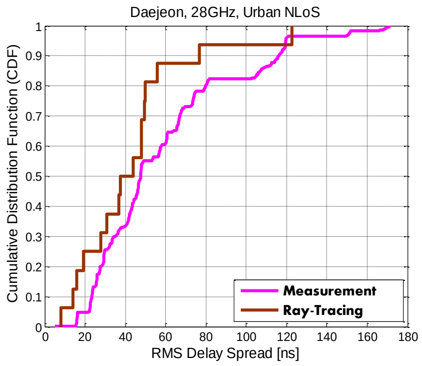
[1] S. Hur, S. Baek, B. Kim, Y. Chang, A. Molisch, T. Rappaport, K. Haneda, and J. Park, "Proposal on Millimeter-Wave Channel Modeling for 5G Cellular System," under review, IEEE JSTSP, May 2015.
[2] M. Samimi and T. Rappaport, "Local Multipath Model Parameters for Generating 5G Millimeter-Wave 3GPP-like Channel Impulse Response," will be presented in EuCAP'2016, April 2016.

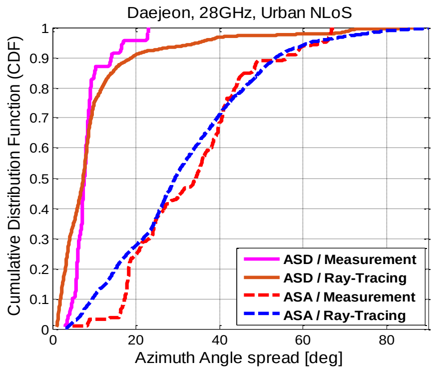
Fast-fading Model : Preliminary Channel Model Parameters

- Delay / angular spreads are frequency dependent
  - Smaller DS/AS in higher frequency, due to highly directional characteristics
  - Measurement and ray-tracing simulation used for extraction of large-scale parameters

Delay / Angular Spreads in mmWave

- DS/ASD/ASA in smaller ranges as frequency increases
- Measurement and ray-tracing shows
  - Mean of RMS delay spread ≈ 50 ns (28 GHz, NLoS)
  - Mean of AS of arrival ≈ 30 deg (28 GHz, NLoS)





Preliminary large-scale Parameters

- Extract large-scale parameters in SCM framework
- 28 GHz (Samsung) and 73 GHz (NYU WIRELESS)

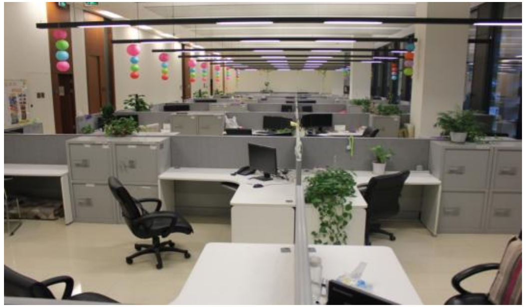
		28 GHz[1]		73 GHz[2]	
		LoS	NLoS	LoS	NLoS
Delay spread (σ_{DS}) $\log_{10}$(seconds)	μ_{DS}	-8.70	-7.39	-7.71	-7.52
	ε_{DS}	0.54	0.31	0.34	0.50
AoA spread (σ_{ASA}) $\log_{10}$(degrees)	μ_{ASA}	-0.49	1.42	1.69	1.45
	ε_{ASA}	0.93	0.29	0.27	0.32
AoD spread (σ_{ASD}) $\log_{10}$(degrees)	μ_{ASD}	-0.40	0.82	1.28	1.32
	ε_{ASD}	1.07	0.38	0.50	0.38
ZoA spread (σ_{ZSA}) (degrees)	μ_{ZSA}	-1.40	0.69	0.60	0.53
	ε_{ZSA}	1.09	0.40	0.09	0.15
ZoD spread (σ_{ZSD}) (degrees)	μ_{ZSD}	-1.25	-0.21	N/A	0.46
	ε_{ZSD}	0.04	0.30	N/A	0.18
Delay distribution		Exponential distribution			
AoD and AoA distribution		Laplacian distribution		Uniform [0, 360]	
ZoD and ZoA distribution		Laplacian distribution		Gaussian distribution	
Delay scaling parameter		4.42	4.82	3.90	3.10

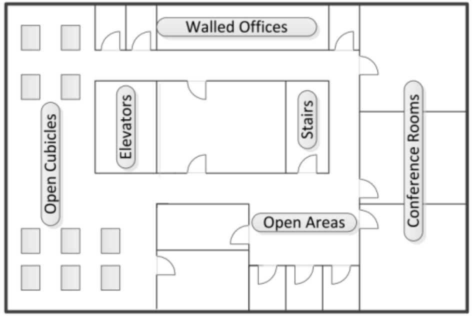
1. From Samsung based on ray-tracing
2. From NYU based on measurement

Indoor Hotspot Environment Channel Characteristics

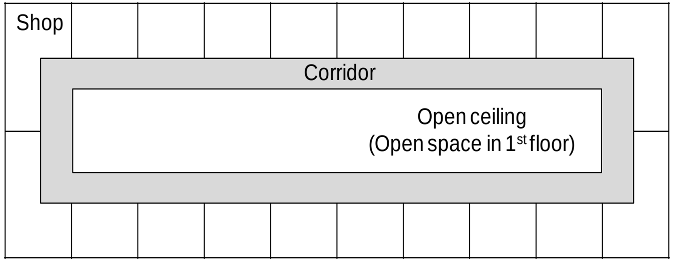
Definition on Scenarios

Considering the possibility of carrying 80% of the MBB traffic, typical indoor hotspot deployment scenarios are worthy of careful investigation.





Typical indoor office



Typical shopping mall

Measurement Campaign for InH

Ray tracing simulation is also important tools for investigating the LOS probability and channel characteristics validation, especially when measurement data is not available.

Contributor	Scenario	Frequency band (GHz)
Aalto University	Shopping mall, LOS/NLOS	28, 60
CMCC	Indoor office, LOS/NLOS	14, 28
DOCOMO	Indoor office, LOS	20
Ericsson	Indoor office, LOS/NLOS	2.44, 5.8, 14.8, 60
Huawei	Indoor office, LOS/NLOS	73, 28
Nokia	Shopping mall, O2I	2, 10, 18
NYU	Indoor office, LOS/NLOS	28, 73
Qualcomm	Indoor office, Shopping mall, LOS/NLOS	2.9, 29, 61
Samsung	Shopping mall, LOS/NLOS	28

InH Channel Characteristics

In LOS conditions, multiple reflections from walls, floor, and ceiling give rise to waveguiding. Measurements in both office and shopping mall scenarios show that path loss exponents, based on a 1 m free space reference distance, are typically below 2, leading to more favorable path loss than predicted by Friis' free space loss formula. The strength of the waveguiding effect is variable and the path loss exponent appears to increase very slightly with increasing frequency, possibly due to the relation between the wavelength and surface roughness.

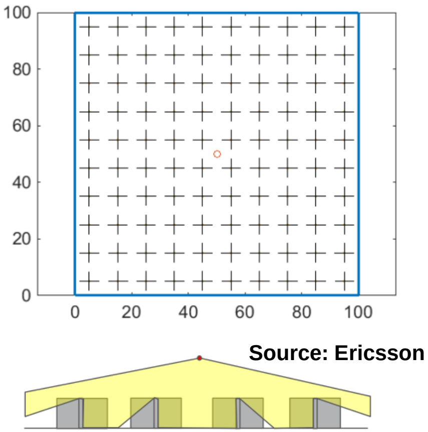
Measurements of the small scale channel properties such as angular spread and delay spread have shown remarkable similarities between channels over a very wide frequency range. It appears as if the main multipath components are present at all frequencies though with some smaller variations in amplitudes.

Recent work shows that polarization discrimination ranges between 15 and 25 dB for indoor millimeter wave channels [Karttunen EuCAP2015], with greater polarization discrimination at 73 GHz than at 28 GHz [MacCartney 2015].

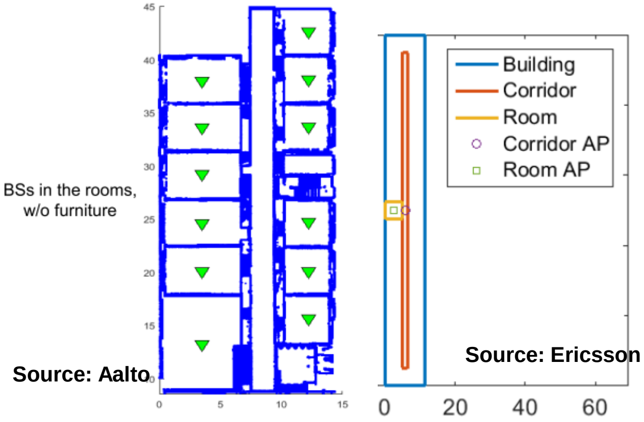
LOS probability (1/2)

Three types of typical indoor office scenarios were investigated with ray tracing:

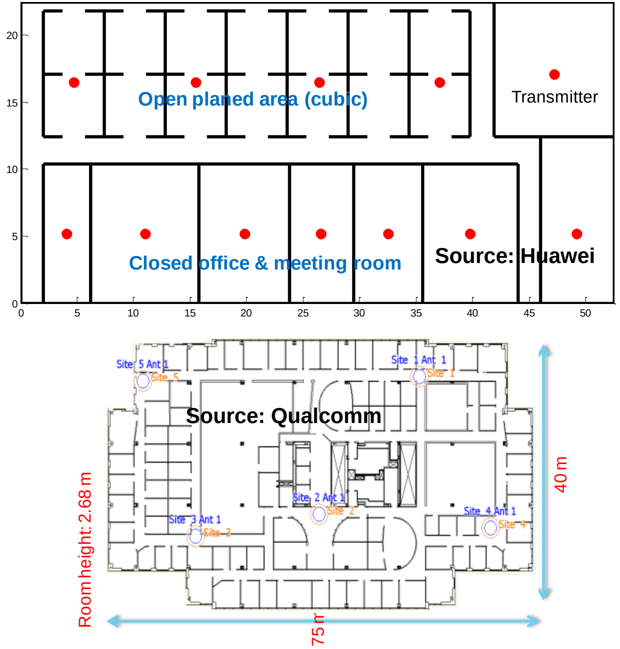
- Open plan office
- Closed plan office
- Hybrid office including both open and closed areas.



Open plan office



Closed plan office

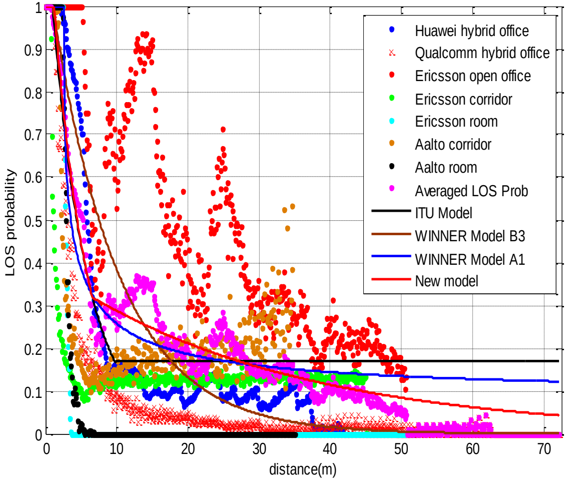


Hybrid office

LOS probability (2/2)

- The modeling results for four models are approaching to the averaged LOS probability samples.
  - The LOS probability model used in ITU IMT-Advanced evaluation and WINNER II are also presented here for comparison.
  - The influence of data set from different types of office scenarios, open or closed, have been merged.
- The results show that the new model has a good fit to the data in an average sense and can be used for 5G InH scenarios evaluation.

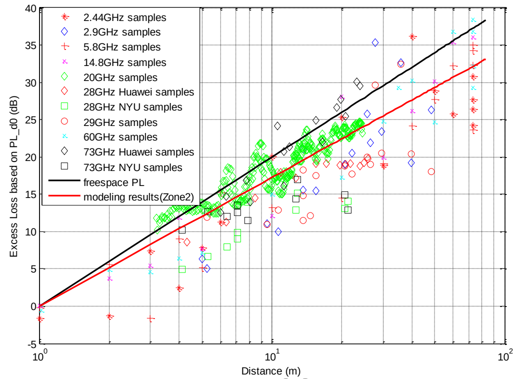
Model	Original	Updated/New	MSE
ITU	$P_{LOS}=\begin{cases}1, & d\le 18\\ \exp\left(-\left(d-18\right)/27\right), & 18<d<37\\ 0.5, & d\ge 37\end{cases}$	$P_{LOS}=\begin{cases}1, & d\le 1.1\\ \exp(-(d-1)/4.9), & 1.1<d<9.8\\ 0.17 & d\ge 9.8\end{cases}$	0.0499
WINNERII B3	$P_{LOS}=\begin{cases}1, & d\le 10\\ \exp(-(d-10)/45), & d>10\end{cases}$	$P_{LOS}=\begin{cases}1, & d\le 1\\ \exp(-(d-1)/9.4), & d>1\end{cases}$	0.0572
WINNER II A1	$P_{LOS}=\begin{cases}1, & d\le 2.5\\ 1-0.9(1-(1.24-0.61\log 10(d))^3)^{1/3}, & d>2.5\end{cases}$	$P_{LOS}=\begin{cases}1, & d\le 2.6\\ 1-0.9(1-(1.16-0.4\log 10(d))^3)^{1/3}, & d>2.6\end{cases}$	0.0473
New model	N/A	$P_{LOS}=\begin{cases}1, & d\le 1.2\\ \exp(-(d-1.2)/4.7), & 1.2<d<6.5\\ \exp(-(d-6.5)/32.6)\cdot 0.32, & d\ge 6.5\end{cases}$	0.0449



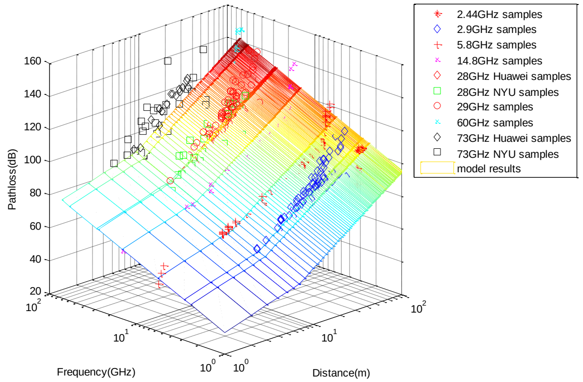
Path Loss Modeling (1/3)

- For LOS
  - Due to strong reflections from walls, ceiling, and floor, wave guide propagation can be observed for both indoor office and shopping mall.
- For NLOS
  - Propagation path loss can be modeled with dual PL slopes along with the propagation distance.
  - Frequency dependency higher than free space can be observed for both scenarios.
  - Single-slope model is FFS
- Shadowing
  - Distance dependency of shadowing can be observed in measurement on some frequency band. But it is still FFS.

Indoor office

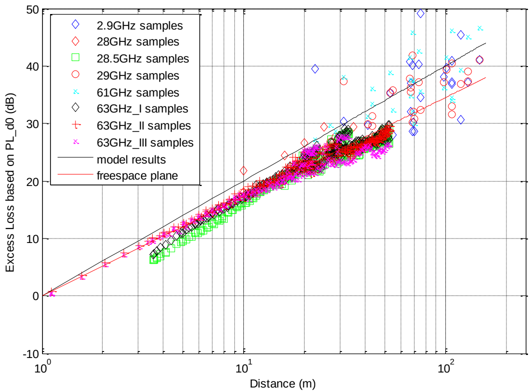


LOS

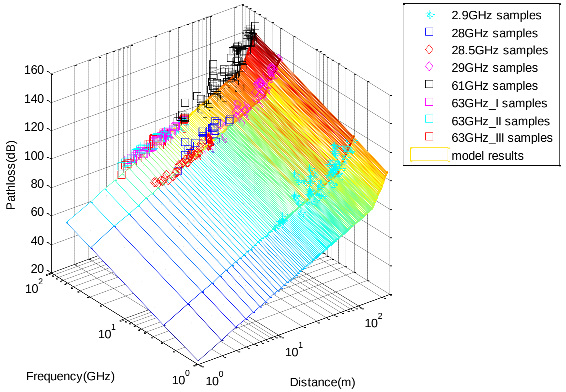


NLOS

Shopping mall



LOS



NLOS

Path Loss Modeling (2/3)

- For LOS, CI model can be adopted.

$$PL_{LOS}(f,d)[dB] = \mathrm{FSPL}(f,1\,m) + 10n\log_{10}\left(\frac{d}{1\,m}\right) + X_\sigma$$

- For NLOS, dual-slope ABG and CIF model can be adopted as two options.
  - Single slope model is FFS.
  - Option 1: ABG

$$PL_{Dual}^{ABG}(d) = \begin{cases} \alpha_1 * 10\log_{10}(d) + \beta_1 + \gamma * 10\log10(f) & 1 < d \le d_{BP} \\ \alpha_1 * 10\log_{10}(d_{BP}) + \beta_1 + \gamma * 10\log10(f) + \alpha_2 * 10\log_{10}(\frac{d}{d_{BP}}) & d > d_{BP} \end{cases}$$

  - Option 2: CIF w/ Free Space Path Loss (FSPL) reference @ 1 m

$$PL_{Dual}^{CIF}(d) = \begin{cases} FSPL(f,1m) + 10n_1\left(1 + b_1\left(\frac{f - f_0}{f_0}\right)\right)\log_{10}(\frac{d}{1m}) & 1 < d \le d_{BP} \\ FSPL(f,1m) + 10n_1\left(1 + b_1\left(\frac{f - f_0}{f_0}\right)\right)\log_{10}(\frac{d_{BP}}{1m}) + 10n_2\left(1 + b_2\left(\frac{f - f_0}{f_0}\right)\right)\log_{10}(\frac{d}{d_{BP}}) & d > d_{BP} \end{cases}$$

, and $f_0 = \frac{\sum_{k=1}^{K} f_k N_K}{\sum_{k=1}^{K} N_K}$

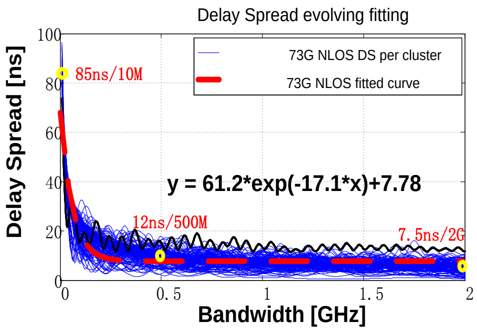
and f_o is the avg. center frequency of input data (K =number of unique frequencies, N_k is # path loss data points at k^{th} frequency f_k).

Path Loss Modeling (3/3)

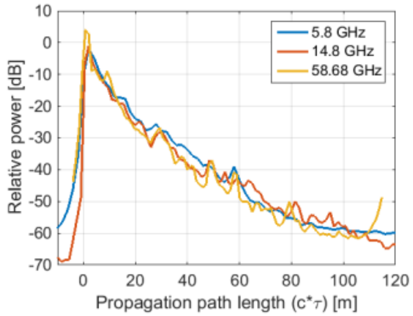
Scenario	**CI/CIF Model Parameters**	**ABG Model Parameters**
Indoor office LOS	n=1.73, σ= 3.02 dB	NA
Indoor office NLoS dual slope	n_1=2.51, b_1=0.12, f_0= 24.1 GHz, n_2=4.25, b_2=0.04, d_{BP} = 7.8 m, σ=7.65 dB	α_1=1.7, β_1=33.0, γ=2.49, d_{BP} = 6.90 m α_2=4.17, σ= 7.78 dB
Shopping Mall LoS	n=1.73, σ= 2.01 dB	NA
Shopping Mall NLoS dual slope	n_1=2.43, b_1=-0.01, f_0= 39.5 GHz, n_2=8.36, b_2=0.39, d_{BP} = 110 m, σ=6.26 dB	α_1=2.9, β_1=22.17, γ=2.24, d_{BP} = 147.0 m α_2=11.47, σ=6.36 dB
Indoor office NLoS single slope (FFS)	n=3.19, b=0.06, f_0= 24.2 GHz, σ=8.29 dB	α=3.83, β=17.30, γ=2.49, σ=8.03 dB
Shopping Mall NLoS single slope (FFS)	n=2.59, b=0.01, f_0= 39.5 GHz, σ=7.40 dB	α=3.21, β=18.09, γ=2.24, σ=6.97 dB

Delay Spread

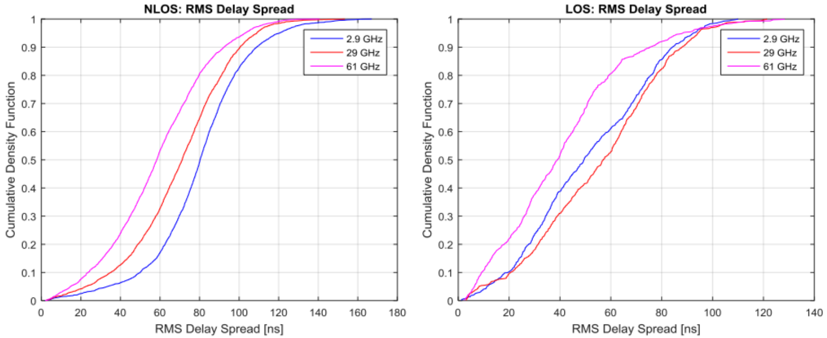
- Frequency dependency on rms DS.
  - In some measurment campaign, delay spread show similarity over a very wide frequency range
  - While in some other measurement campaign, some frequency dependency can be observed.
- Bandwidth dependency on rms DS.
  - In some measurement campaign, bandwidth dependency can observed, considering the possibility of large variance on the system bandwidth may be adopted for above 6GHz system.



DS based on measurement on 73GHz (Huawei)



DS based on measurement on 5.8, 14.8, 60GHz (Ericsson)



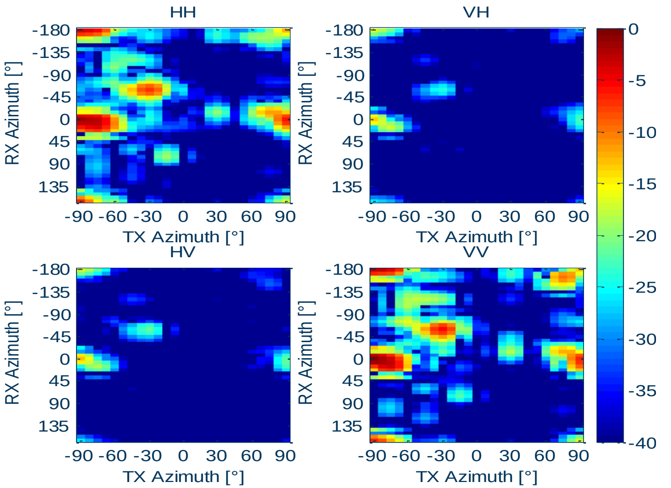
DS based on measurement on 2.9, 29, 61GHz (Qualcomm)

Polarization Modeling

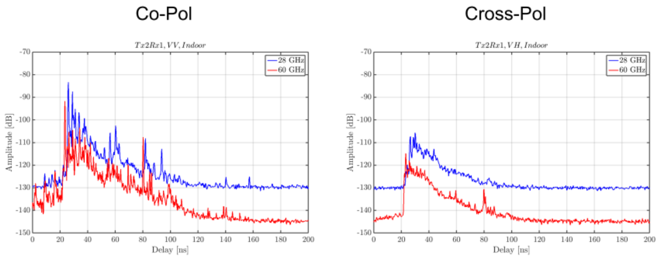
- Polarization has been investigated based on measurement on 28GHz, 60GHz, and 73GHz.
  - If based on 3GPP XPR model, XPR can be decribed in table below. It is still need further investigation on the frequency dependency on the XPR.

Preliminary results on polarization modeling

		28GHz		60 GHz		73GHz
Scenario		Shopping mall		Shopping mall		Indoor office
		LOS	NLOS	LOS	NLOS	Hybrid
XPR (dB)	μ_{XPR}	16.12	14.48	16.85	16.06	11
	σ_{XPR}	6.22	6.26	6.62	5.34	6.5



Polarization measurement on 73GHz (Huawei)



Polarization measurement on 28GHz and 60GHz (Aalto Univ.)

Collection of Results

- For InH scenarios, fast fading channel characteristics have been investigated based on both measurement and ray-tracing.
  - Both indoor office and shopping mall environments have been investigated at frequencies including 20 GHz, 28 GHz, 60GHz, and 73 GHz.
- Some preliminary analysis on large-scale channel characteristics have been collected in table on the right.
- Although it is still too early to apply these results to the full frequency range up to 100 GHz, these preliminary investigations have provided insight into the difference induced by the largely extended frequency range.

		20 GHz[1]	28GHz[2]		60 GHz[2]		73GHz[3]	73GHz[4]
Scenario		Indoor office	Shopping mall		Shopping mall		Indoor office	Indoor office
		LOS	LOS	NLOS	LOS	NLOS	Hybrid	Hybrid
Delay spread (σ_τ) log$_{10}$(seconds)	μ_{DS}	-7.33	-7.52	-7.59	-7.62	-7.45	-8.1	N/A
	ε_{DS}	0.1	0.17	0.33	0.20	0.11	0.4	N/A
Delay distribution		N/A	Exponential				Exponential	N/A
AoA spread (σ_{ASA}) log$_{10}$(degrees)	μ_{ASA}	N/A	1.54	1.57	1.50	1.60	1.6	N/A
	ε_{ASA}	N/A	0.16	0.18	0.16	0.15	0.37	N/A
AoD spread (σ_{ASD}) log$_{10}$(degrees)	μ_{ASD}	1.8	1.44	1.68	1.43	1.72	1.5	N/A
	ε_{ASD}	0.09	0.16	0.19	0.10	0.08	0.26	N/A
ZoA spread (σ_{ZSA}) (degrees)	μ_{ZSA}	N/A	0.87	0.68	0.86	0.67	-0.025d+1.18	N/A
	ε_{ZSA}	N/A	0.45	0.31	0.40	0.23	0.30	N/A
ZoD spread (σ_{ZSD}) (degrees)	μ_{ZSD}	0	0.75	0.95	0.74	0.88	-0.040d+1.45	N/A
	ε_{ZSD}	0.48	0.34	0.22	0.30	0.20	0.33	N/A
AoD and AoA distribution		N/A	Wrapped Gaussian				Uniform	N/A
ZoD and ZoA distribution		N/A	Laplacian				Laplacian	N/A
XPR (dB)	μ_{XPR}	N/A	16.12	14.48	16.85	16.06	15	11
	σ_{XPR}	N/A	6.22	6.26	6.62	5.34	2	6.5
LOS Ricean K factor (dB) *	μ_K	N/A	-0.18	N/A	-1.07	N/A	8	N/A
	ε_K	N/A	2.85	N/A	3.58	N/A	3	N/A

1. From DOCOMO based on measurement
2. From Aalto University based on measurement
3. From Nokia/NYU based on ray-tracing
4. From Huawei based on measurement

Urban Macro Environment Channel Characteristics

5G UMa Environment

- Access points on or above rooftops (25-35 m high), cell radii >= 200 m
- Outdoor-to-outdoor and outdoor-to-indoor (UEs from 1.5-22.5 m)
- UMa characteristics:
  - LOS path loss close to free space
  - NLOS path loss minus free-space path loss at 1 m is very similar across frequency
    - Reflections likely dominate, not diffraction
  - Delay and angle spreads appear to decrease with frequency
  - XPR decreases with frequency according to ray tracing, but measurements have yet to verify this finding

UMa Available Data

- Aalborg University 2, 10, 18, 28 GHz measurements
  - 20 m and 25 m high Tx's
- Ericsson data at 28 GHz
  - Lindholmen (25 m high)
  - Molndal (46 m high)
- NYU 38 GHz measurements, Austin Tx
- Samsung 28 GHz ray-tracing data, Ottawa and NYU-campus
  - 23-35 m high Tx
  - Only data with path loss <= 100 dB minus FSPL(1 m) are used
- Nokia 2, 5.6, 10, 18, 28, 39.3, and 73.5 GHz ray tracing data
  - Same environment as Aalborg data
  - Only data with path loss <= 100 dB minus FSPL(1 m) are used
  - Data not used for path loss and LOS probability since it would be redundant with the Aalborg measured data

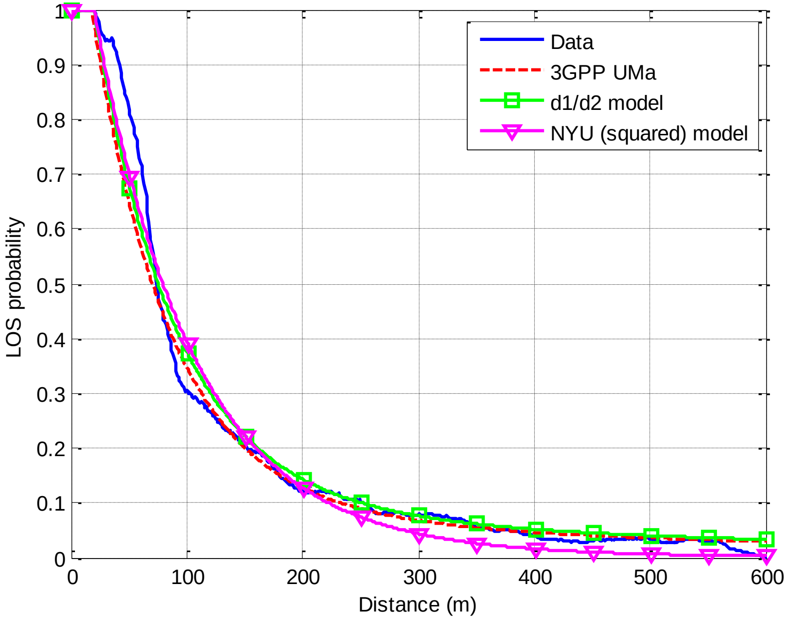
LOS Probability Findings

- UMa, reuse 3GPP definition
  - Good match to new measurements
  - Also already has 3-D UE placement

$$p(d) = \left(\min\left(\frac{18}{d}, 1\right)\left(1 - e^{-d/63}\right) + e^{-d/63} \right)\left(1 + C(d, h_{UT})\right)$$

$$C(d, h_{UT}) = \begin{cases} 0, & h_{UT} < 13m \\ \left(\dfrac{h_{UT} - 13}{10}\right)^{1.5} g(d), & 13 \le h_{UT} \le 23m \end{cases}$$

$$g(d) = \begin{cases} (1.25e^{-6}) d^2 \exp(-d/150), & d > 18m \\ 0, & otherwise \end{cases}$$



Other LOS probability models only slightly improve match to data over 3GPP model

Proposed UMa Path Loss and Shadow Fading Models (<u>Single Slope</u>)

- In all models, d is distance, f is frequency, X is shadow fading Gaussian RV (dB)
- Close-in (CI) reference distance path loss model:

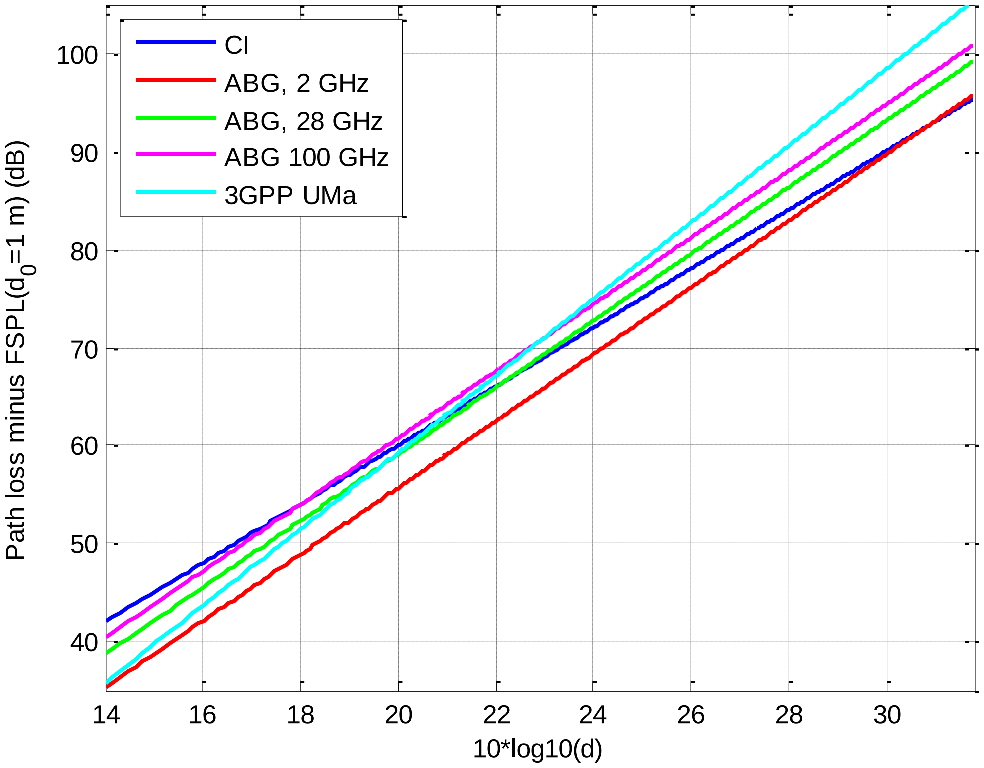
$$\mathrm{PL}^{CI}(f,d)[dB] = \mathrm{FSPL}(f,1\,m) + 10n\log_{10}\left(\frac{d}{1\,m}\right) + X_{\sigma}^{CI} \qquad \mathrm{FSPL}(f,1\,m) = 20\log_{10}\left(\frac{4\pi f}{c}\right)$$

- Alpha-Beta-Gamma (ABG) path loss model:

$$\mathrm{PL}^{ABG}(f,d)[dB] = 10\alpha\log_{10}\left(\frac{d}{1\,m}\right) + \beta + 10\gamma\log_{10}\left(\frac{f}{1\,GHz}\right) + X_{\sigma}^{ABG}$$

Scenario	CI Model Parameters	ABG Model Parameters
UMa- LoS	n=2.0, SF = 4.1 dB	N/A
UMa-nLoS	n=3.0, SF = 6.8 dB	α=3.4, β=19.2, γ=2.3, SF = 6.5 dB

NLOS UMa PL Models Compared to 3GPP UMa Model



Preliminary UMa NLOS Large-Scale Parameters (LSPs)

		5.6 GHz	10 GHz	18 GHz	28 GHz	39.3 GHz	73.5 GHz
Delay spread (s_t) log_{10}(seconds)	m_{DS}	-6.75	-6.80	-6.85	-6.88	-6.89	-6.91
	e_{DS}	0.68	0.88	0.78	0.73	0.73	0.69
AoA spread (s_{ASA}) log_{10}(degrees)	m_{ASA}	1.34	1.14	1.14	1.15	1.14	1.09
	e_{ASA}	0.81	1.14	1.01	0.94	0.91	0.87
AoD spread (s_{ASD}) log_{10}(degrees)	m_{ASD}	0.87	0.67	0.74	0.75	0.78	0.82
	e_{ASD}	0.81	1.35	1.05	1.16	1.06	0.93
ZoA spread (s_{ZSA}) log_{10}(degrees)	m_{ZSA}	0.48	0.31	0.26	0.26	0.24	0.20
	e_{ZSA}	0.75	0.92	0.85	0.81	0.81	0.79
ZoD spread (s_{ZSD}) log_{10}(degrees)	m_{ZSD}	-0.26	-0.24	-0.22	-0.22	-0.20	-0.16
	e_{ZSD}	0.70	0.74	0.78	0.81	0.82	0.83
Shadow fading (dB)		9.82	10.22	10.28	10.12	10.14	9.97
Delay distribution		Exponential	Exponential	Exponential	Exponential	Exponential	Exponential
AoD and AoA distribution		Laplacian	Laplacian	Laplacian	Laplacian	Laplacian	Laplacian
ZoD and ZoA distribution		Laplacian	Laplacian	Laplacian	Laplacian	Laplacian	Laplacian
Delay scaling parameter		TBD	TBD	TBD	TBD	TBD	TBD
XPR (dB)	m_{XPR}	13.87	12.94	10.97	10.76	9.38	7.89
	s_{XPR}	6.12	6.36	6.80	6.57	6.60	6.38

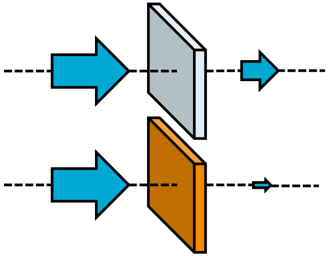
These parameters found using the ray-tracing results in the Aalborg environment

Summary of UMa Trends

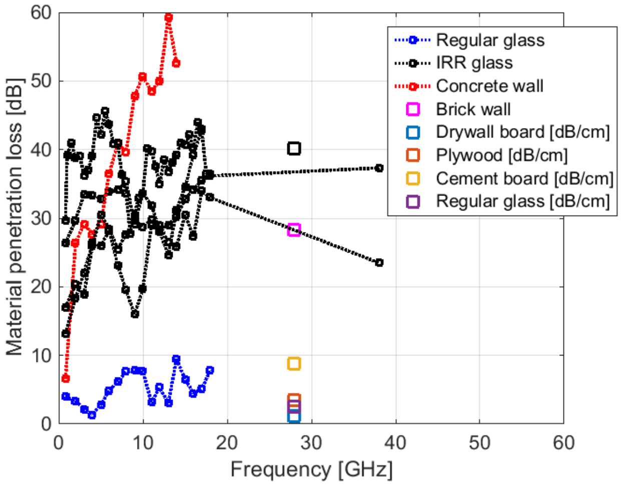
- LOS path loss is very close to free space
- NLOS path loss minus free-space path loss at 1 m (FSPL(1 m)) shows very little change across frequency
  - Aalborg data taken at 2, 10, and 18 GHz in the same environment shows:
    - Path loss minus FSPL(1 m) increases from 2 to 10 GHz, but decreases from 10 to 18 GHz
    - Additional loss from 2 to 10 GHz may be due to diffraction loss, and after 10 GHz (where diffraction is no longer a dominant channel effect) there may be a slight increase in reflectivity in the environment
    - More measurements are needed to confirm a linear trend of path loss minus FSPL (1 m) with the log of frequency (as modeled in the ABG model)
- Delay and angle spreads tend to decrease with frequency
- Although not shown, elevation angle spreads and biases at both the Tx and Rx will have a distance dependence
- XPR appears to decrease with frequency in ray-tracing results due to diffuse scattering model, but measurements have yet to verify this trend

Building penetration loss

Material penetration loss



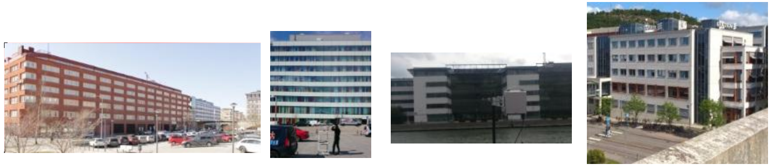
- Penetration loss through a single material slab
  - Depends mainly on thickness and conductivity
  - Approximately linear loss increase with frequency:
    - $L[dB]=a+bf$
- Highly variable among commonly used materials
  - Regular glass 0-10 dB
  - IRR coating adds 20-40 dB
  - Loss through brick and concrete increase strongly with frequency

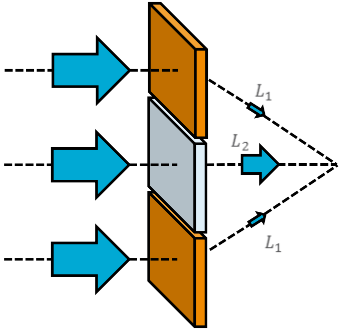


Sources: [Rodriguez VTC Fall 2014], [Zhao 2013], and measurements contributed by Samsung and Nokia

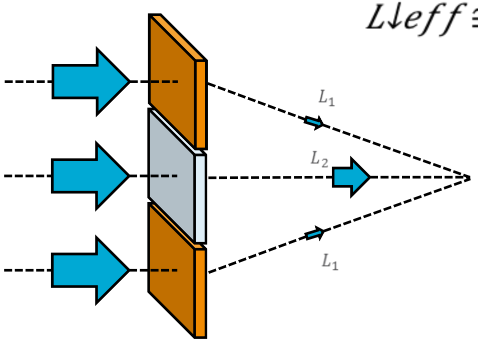
Building penetration loss

- Most buildings have facades made up of multiple materials
  - Windows, concrete, brick, wood, ...
- Very close to the external wall, the loss characteristics of a single material may dominate
- Further into the building the combined loss of multiple materials is experienced



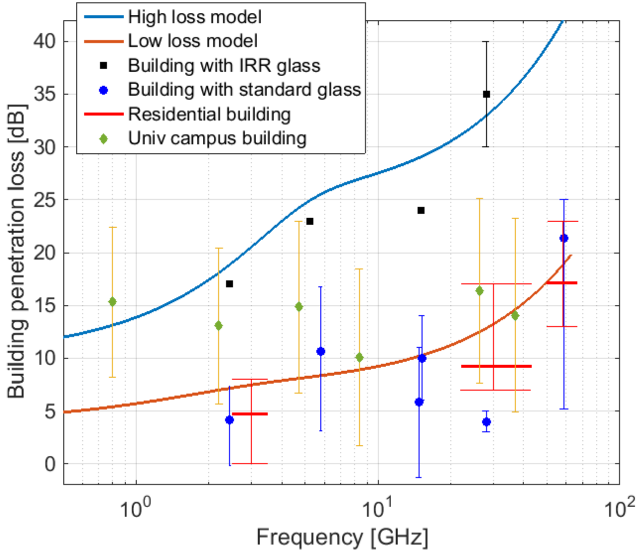


$$L_{eff} \cong L_2$$



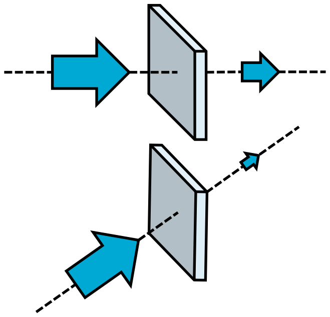
Building penetration Measurements

- Buildings with standard glass have lower loss than buildings with IRR glass
  - Non-linear dependence vs frequency
- For comparison models from [Semaan Globecom 2014] are plotted
  - Low loss model: 30% glass, 70% concrete
  - High loss model: 70% IRR glass, 30% concrete
- Other models have also been proposed, see [5GCM white paper]

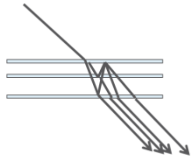


Sources: [Larsson EuCAP 2014] and measurements contributed by Qualcomm, NTT DOCOMO, and Ericsson

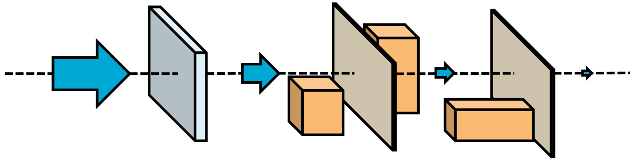
Additional considerations



- Incidence angle to external wall
  - Loss increases by up to 15-20 dB for grazing incidence



- Multiple internal reflections in material
  - Causes frequency-dependent constructive or destructive interference
- Additional loss due to internal walls, furniture, people etc
  - Typically in the order 0.2-2 dB/m with weak frequency dependence



Conclusions

- Building penetration loss tends to increase with frequency
  - Quantified through measurements over a large frequency range
  - Highly variable losses due to differences among building materials
  - IRR coated glass has high loss even at low frequencies
- More details and further model proposals described in the white paper

References

- [5GCM white paper] A. Ghosh, ed., “5G channel model for bands up to 100 GHz”, Globecom 2015. Available for download via: http://www.5gworkshops.com/5GCM.html
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- [Larsson EuCAP 2014] C. Larsson, F. Harrysson, B-E. Olssson and J-E. Berg, "An outdoor-to-indoor propagation scenario at 28 GHz", in Proc. of European Conference on Antennas and Propagation (EuCAP) 2014, pp. 3301-3304.
- [Semaan Globecom 2014] E. Semaan, F. Harrysson, A. Furuskär and H. Asplund, "Outdoor-to-indoor coverage in high frequency bands", Globecom Workshops 2014, pp. 393-398.