mmWave Based 5G Cellular System Design

International Workshop on Cloud Cooperated HetNet

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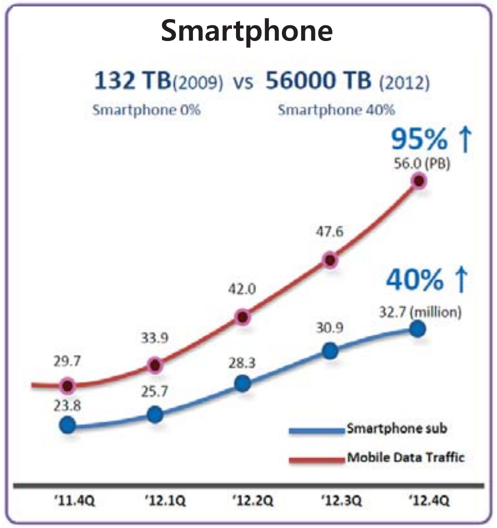
1. 5G Vision

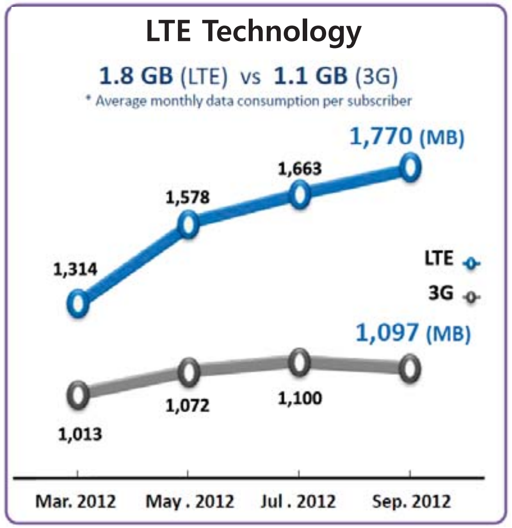
5G Service Vision

Enabling the Immersive Service Experiences

Mobile Traffic Trends

- **Mobile Traffic Explosion in Korean Market**

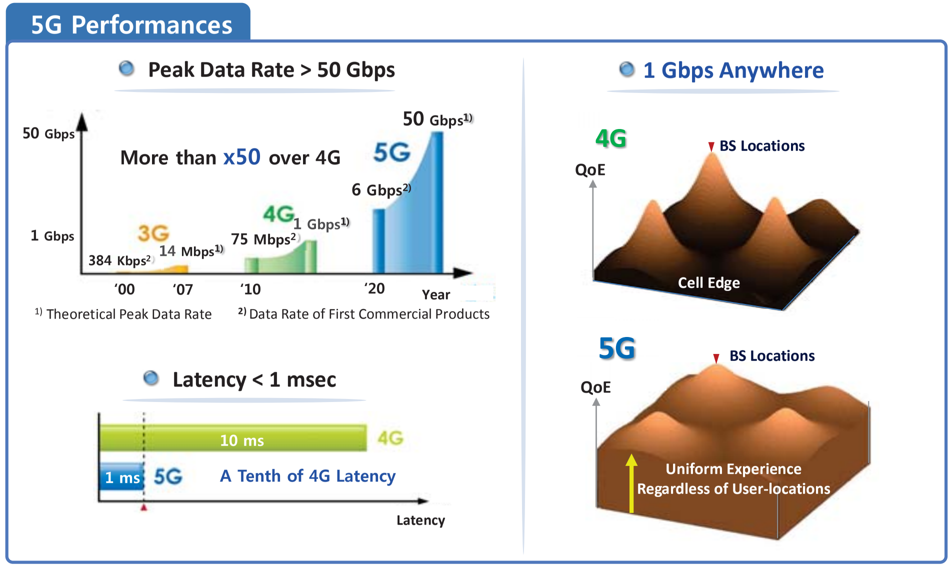




Note : Operators in Korea did not provide "unlimited data plan" for LTE service during this period

5G Key Performance Targets

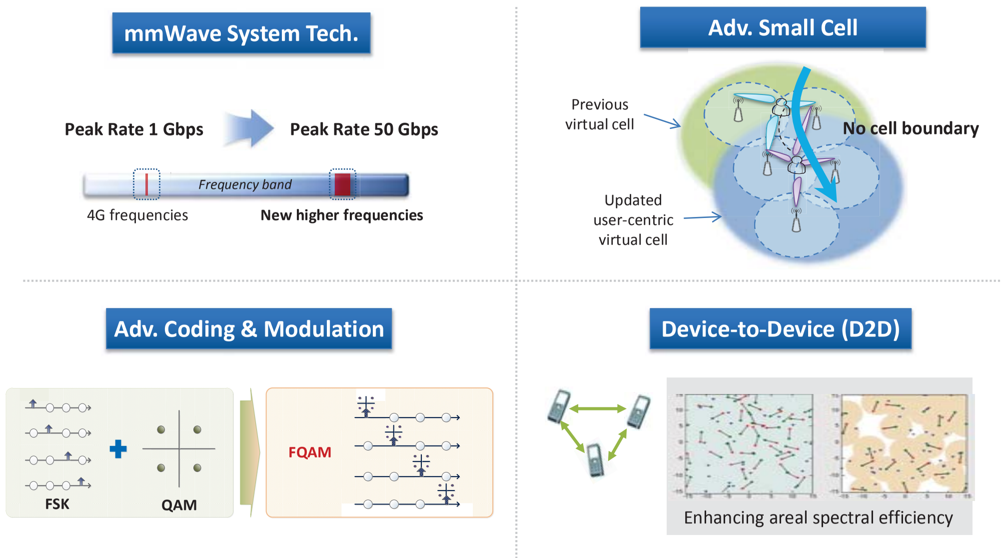
- **Providing Gigabit Experience to Users Anywhere**



2. 5G Key Enabling Technologies

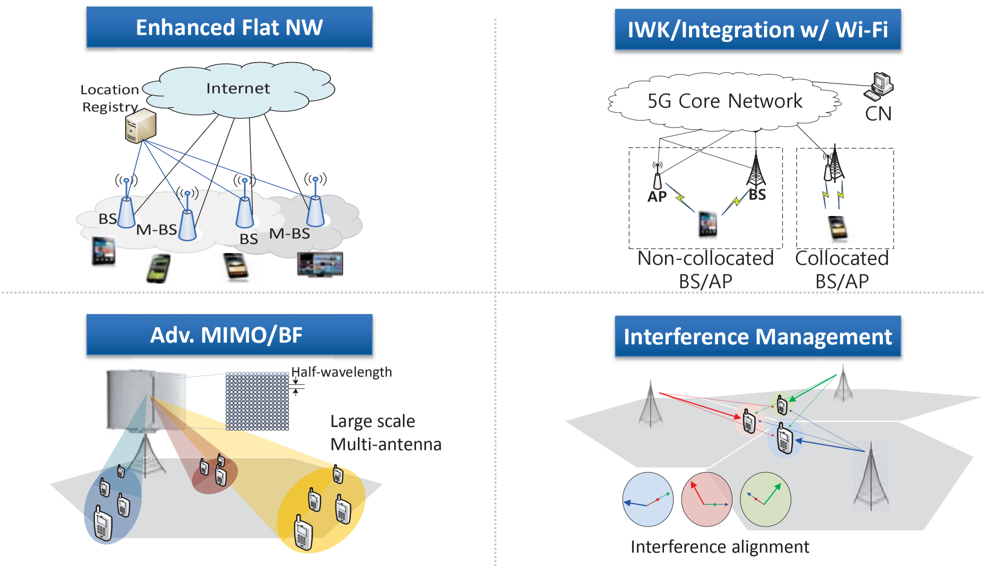
5G Key Enabling Technologies (1/2)

- **Disruptive Technologies for Significant Performance Enhancement**



5G Key Enabling Technologies (2/2)

- **Disruptive Technologies for Significant Performance Enhancement**

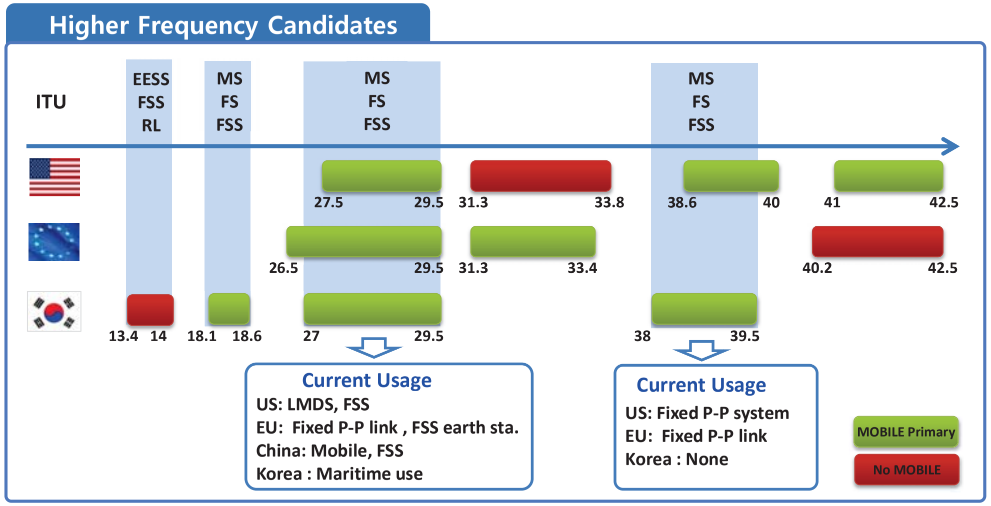


3. MMWAVE TECHNOLOGY

1. mmWave Channel Propagation & Measurements
2. mmWave BF Prototype & Test Results

Spectrum Candidates

- **Candidates for Large Chunks of Contiguous Spectrum**
  - 13.4~14 GHz, 18.1~18.6 GHz, 27~29.5 GHz, 38~39.5 GHz, etc.



EESS (Earth Exploration-Satellite Service) FSS (Fixed Satellite Service) RL (RadioLocation service),
MS (Mobile Service) FS (Fixed Service) P-P (Point to Point) LMDS (Local Multipoint Distribution Services)

Friis' Equation in Free Space (1/4)

Isotropic Tx & Rx

☐ **"Path-loss" is Proportional to Frequency Squared**

$$P_{RX} = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi R}\right)^2$$

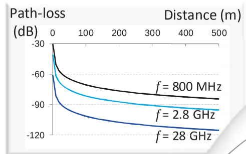
= 1 for Isotropic; Path-loss

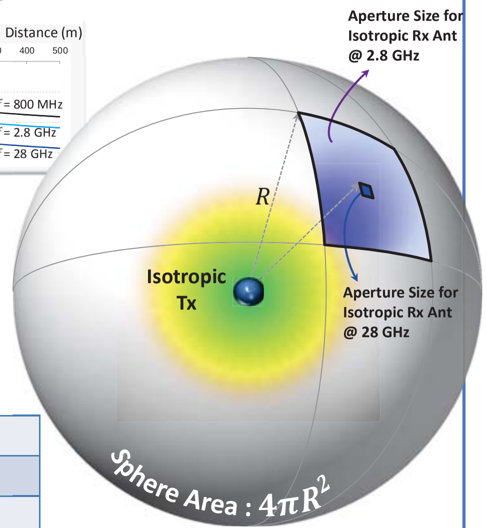
$$= P_{TX} \cdot 1 \cdot 1 \cdot \left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1}{4\pi R^2}\right)$$

Aperture Size; Spherical Area

$$= P_{TX} \cdot 1 \cdot 1 \cdot \left(\frac{c^2}{4\pi \cdot f^2}\right)\left(\frac{1}{4\pi R^2}\right)$$

(c : speed of light)





☐ **Comparison Example**

	2.8 GHz	28 GHz
RX Aperture Size	9.135 cm^2	0.091 cm^2
Path-loss (R=1m)	-41.4 dB	-61.4 dB

-20 dB

Friis' Equation in Free Space (2/4)

Isotropic Tx but Rx Array Antennas

☐ Same Size of Rx Aperture Captures Same Rx Power Regardless of Frequency

$$P_{RX} = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi R}\right)^2$$

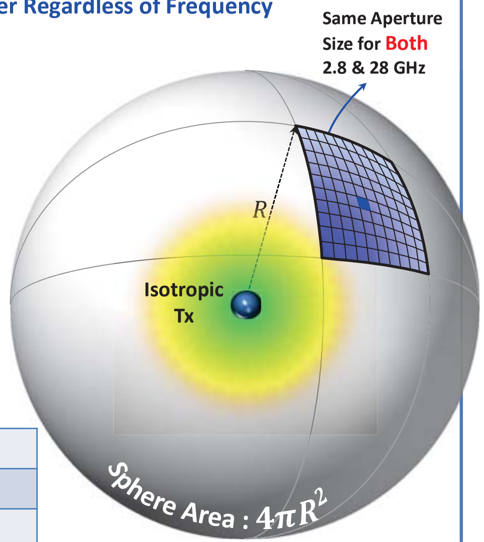
(G_{TX} =1 for Isotropic)

$$= P_{TX} \cdot 1 \cdot G_{RX} \left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1}{4\pi R^2}\right)$$

$\left(G = A_e \frac{4\pi}{\lambda^2}\right)$

$$= P_{TX} \cdot 1 \cdot A_{e,RX} \left(\frac{4\pi}{\lambda^2}\right)\left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1}{4\pi R^2}\right)$$

$$= P_{TX} \cdot 1 \cdot A_{e,RX} \left(\frac{1}{4\pi R^2}\right)$$



☐ Comparison Example

	2.8 GHz	28 GHz
RX Aperture Size	9.135 cm²	9.135 cm²
RX Power	P_{RX}	P_{RX}

Friis' Equation in Free Space (3/4)

Array Antennas for Both Tx & Rx

☐ Rx Power is Even Larger in Higher Frequency with Array Antennas for Both Tx & Rx

$$P_{RX} = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi R}\right)^2$$

$$= P_{TX} G_{TX} G_{RX} \left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1}{4\pi R^2}\right)$$

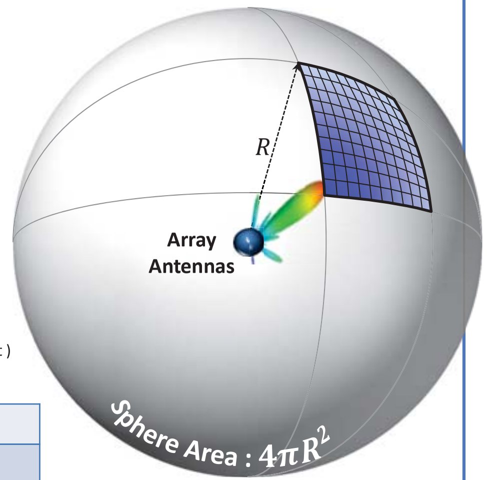
$\left(G = A_e \frac{4\pi}{\lambda^2}\right)$

$$= P_{TX} A_{e,TX} A_{e,RX} \left(\frac{4\pi}{\lambda^2}\right)\left(\frac{4\pi}{\lambda^2}\right)\left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1}{4\pi R^2}\right)$$

$$= P_{TX} A_{e,TX} A_{e,RX} \left(\frac{4\pi}{\lambda^2}\right)\left(\frac{1}{4\pi R^2}\right)$$

$$= P_{TX} A_{e,TX} A_{e,RX} \left(\frac{4\pi f^2}{c^2}\right)\left(\frac{1}{4\pi R^2}\right)$$

(c : speed of light)



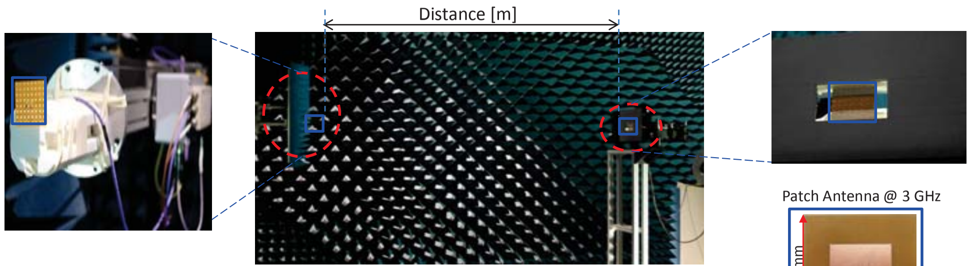
☐ Comparison Example

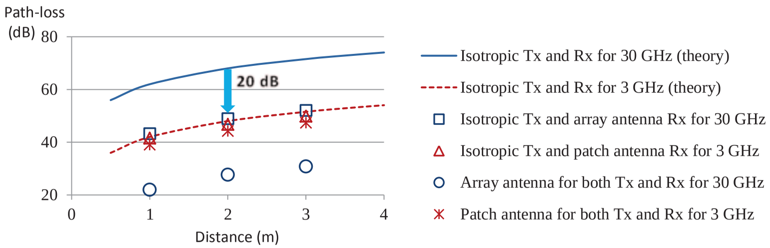
	2.8 GHz	28 GHz
RX Power	P_{RX}	+ 20 dB ⇒ P_{RX} + 20 dB

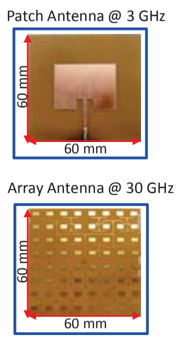
Friis' Equation in Free Space (4/4)

Measurement of Path-loss

☐ Same Size of Rx Aperture Captures Same Rx Power Regardless of Frequency







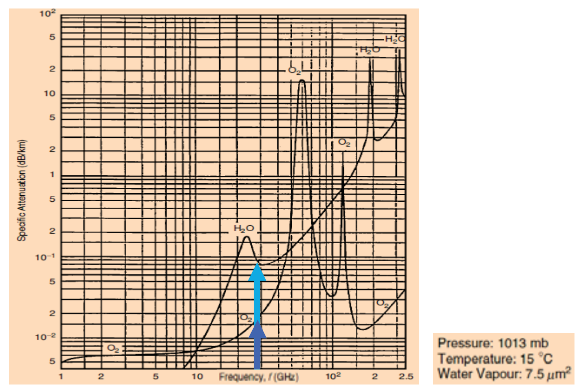
Atmospheric Absorption Loss

- Atmospheric Loss due to H_2O & O_2 at 28 GHz is Negligible

Atmospheric Absorption

☐ H_2O Absorption @ 28 GHz is about 0.09 dB/km (=0.018 dB/200 m)

☐ O_2 Absorption @ 28 GHz is about 0.02 dB/km (=0.004 dB/200 m)



[Specific Attenuation due to Oxygen and Water Vapor] [Conditions]

[Ref.] M. Marcus and B. Pattan. Millimeter wave propagation: spectrum management implications. *IEEE Microwave Magazine*, June 2005.

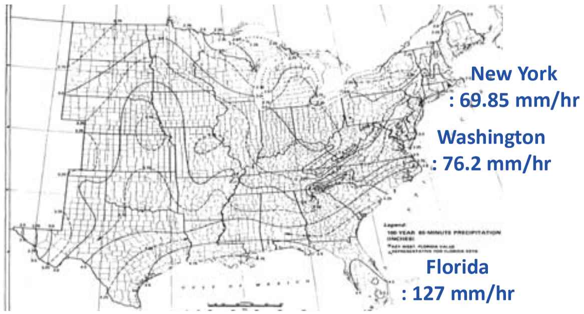
Precipitation Loss

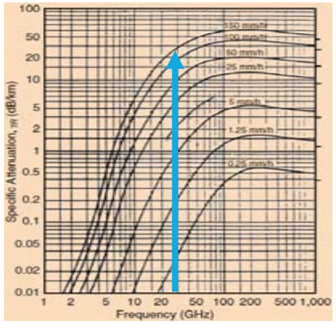
- Rain Attenuation at 28GHz is Approx. 4 dB at 200 m even in 110 mm/hr Intensity

Precipitation Loss

☐ 100-year recurrence 1-hour rain intensity is approx. 110 mm/hr (Seoul, Korea)
☐ 100-year recurrence 1-hour rain intensity is approx. 70 ~ 127 mm/hr (Eastern US)

100 Year Recurrence 1-hour Rain Intensity (Eastern US)





[Attenuation due to Rain]

[Ref.] http://www.nws.noaa.gov/ohd/hdsc/On-line_reports/
[Ref.] M. Marcus and B. Pattan. Millimeter wave propagation: spectrum management implications. *IEEE Microwave Magazine*, June 2005.

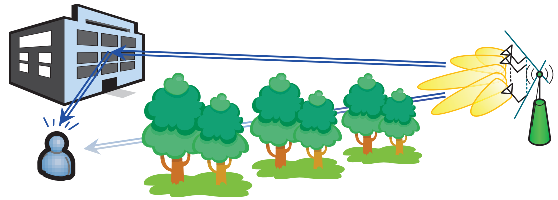
Foliage Loss

- Loss by Dense Foliage is Non-Negligible, But Alternative Paths are Expected in Urban Environments

Foliage Loss

☐ 28 GHz shows ADDITIONAL 3.3 dB loss for 2 m foliage and 8.6 dB for 10 m foliage compared to 2.8GHz

- In urban environments, other reflection paths are highly expected from surroundings



Empirical relationship for loss :

$$L_{foliage} = 0.2 f^{0.3} D^{0.6} \text{ dB}$$

where
f : frequency in MHz,
D : depth of foliage transverse in meters (D < 400 m)

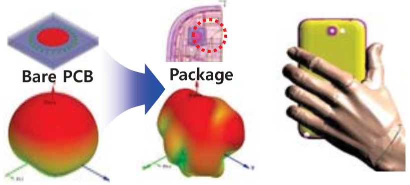
[Ref.] M. Marcus and B. Pattan. Millimeter wave propagation: spectrum management implications. *IEEE Microwave Magazine*, June 2005.

Chassis / Hand / Power Absorption

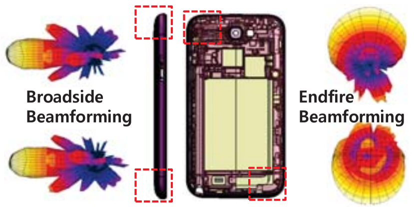
- Effect of Chassis/Hand/Head Could Be Compensated with Beamsteering Array
- High Frequency Beamforming Reduces Power Penetration/Absorption through Skin

Chassis / Hand-held Effect

☐ Chassis/hand impact on gain and pattern



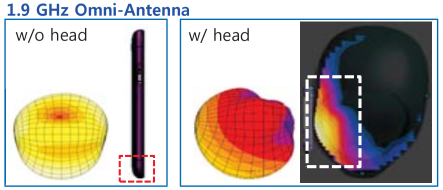
☐ Various antenna locations and BF patterns can overcome these effects



Power Absorption

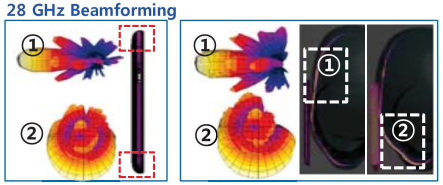
☐ Low penetration and absorption due to high frequency beamforming

1.9 GHz Omni-Antenna



Penetration depth = 40~45 mm, Average = 0.29, MAX = 1 mW/g

28 GHz Beamforming

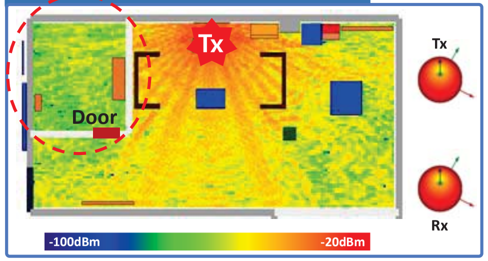


① Penetration depth = 3 mm, Average = 0.15, MAX = 90 mW/g
② Penetration depth = 3 mm, Average = 0.016, MAX = 2.11 mW/g

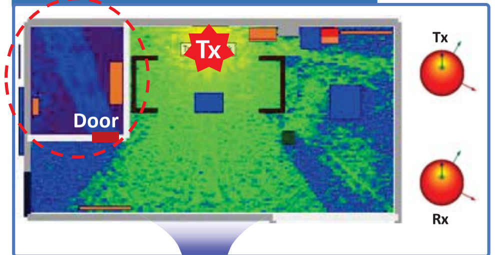
Indoor Propagation

- Beamforming Significantly Improves Indoor Coverage at 28 GHz

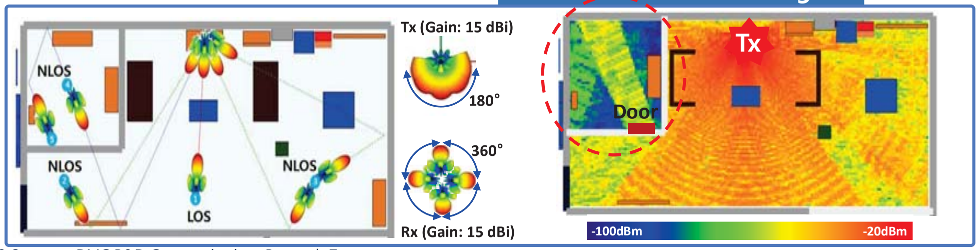
2.4 GHz Omni-directional



28 GHz Omni-directional



28 GHz Beamforming



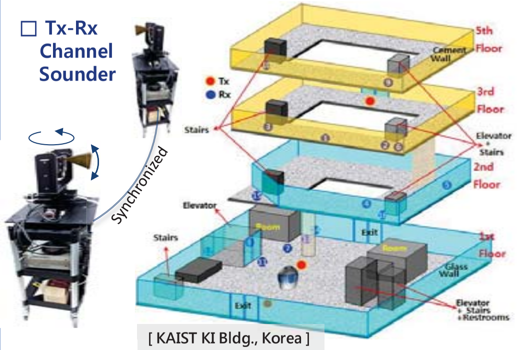
Channel Measurement – Indoor

- **Extensive Channel Measurements have been Conducted and are Continued in Korea**
  - Horn-Ant. based **channel sounder with Tx-Rx Sync.** has been developed
  - **Omni-directional channel modeling** of small scale parameters is underway (e.g. Clustering, AoA/AoD)

Channel Sounder and Structure Map

☐ Measurements at Total 16 Rx Locations
- ✓ Tx-Rx Distance : 10m ~ 40m
- ✓ Max. RMS delay spread : 83.7 [ns] at location 13

☐ Tx-Rx Channel Sounder



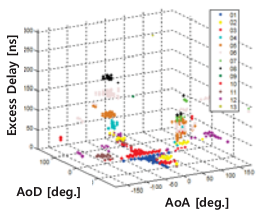
[KAIST KI Bldg., Korea]

Scenery & Exemplary Model at 3rd FL

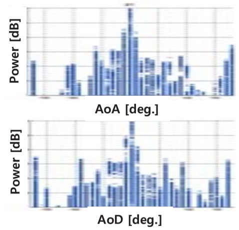
☐ Perspective from the 3rd FL Tx Location

☐ Exemplary Channel Parameter Modeling (location 1)

✓ Clustering



✓ AoA/AoD Power Distribution

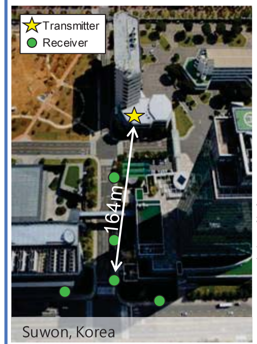


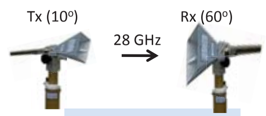
Channel Measurement – Sub-Urban

- **Similar Path-loss Exponent & Smaller Delay Spread Measured** (w.r.t. current cellular bands)
  - Measurements were made by using horn-type antennas at 28 GHz and 38 GHz in 2011

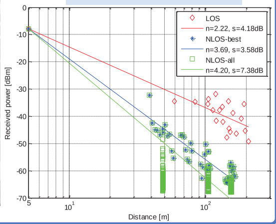
Samsung Campus, Korea

		LoS	NLoS
Path-loss Exponent		2.22	3.69
RMS Delay Spread [ns]	Median	4.0	34.2
	99%	11.4	168.7





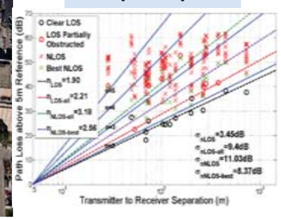
[Received Power]



UT Austin Campus, US

		LoS	NLoS
Path-loss Exponent		2.21	3.18
RMS Delay Spread [ns]	Median	1.9	15.5
	99%	13.7	166

[Path-loss]



* Reference : Prof. Ted Rappaport, UT Austin, 2011

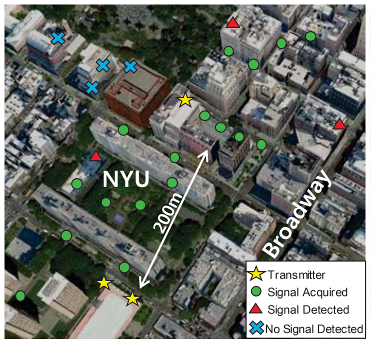
Channel Measurement – Dense Urban

- **Slightly Higher But Comparable Path-loss Measured in New York City in 2012**

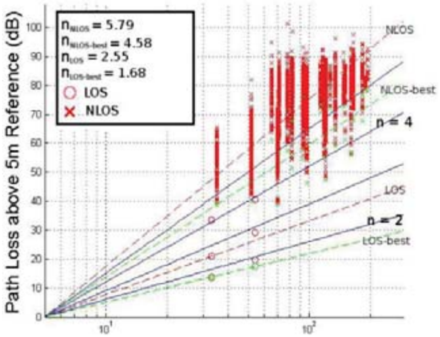
New York, Manhattan, US

- Reference : Prof. Ted Rappaport, NYU, 2012
  - T. S. Rappaport et.al. "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!", IEEE Access Journal, May 2013

	LoS	NLoS
Path-loss Exponent	1.68	4.58
Delay Spread [ns]	Expected to be larger than the previous, But to be still smaller than current bands	



[New York, Manhattan – NY University]



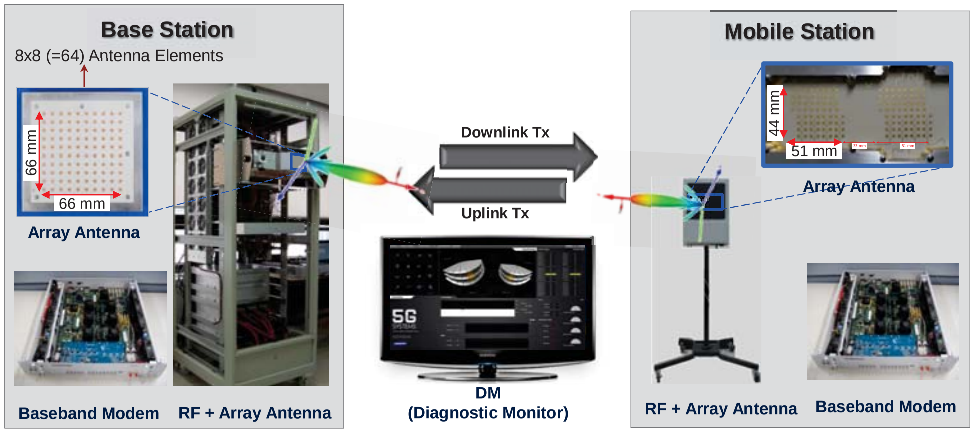
[Path-loss]

mmWave BF Prototype Overview

- **World's First mmWave Mobile Technology**
  - Adaptive array transceiver technology operating in the millimeter-wave frequency bands for outdoor cellular

Carrier Frequency	27.925 GHz
Bandwidth	500 MHz
Max. Tx Power	37 dBm
Beam width (Half Power)	10º

mmWave BF Prototype



Test Results of mmWave BF Prototype

- **Performance Tests of mmWave OFDM Prototype**
  - OFDM system parameters designed for mmWave bands
  - Indoor & outdoor measurements performed for data rates and transmission ranges

System Parameters & Test Results

PARAMETER	VALUE
Carrier Frequency	27.925 GHz
Bandwidth	500 MHz
Duplexing	TDD
Array Antenna Size	8x8 (64 elements) 8x4 (32 elements)
Beam-width (Half Power)	10º
Channel Coding	LDPC
Modulation	QPSK / 16QAM

PARAMETER	VALUE	REMARKS
Supported Data Rates	1,056Mbps 528Mbps 264Mbps	
Max Tx Range	Up to 2km @ LoS	>10 dB Tx power headroom

Test Results – Range

- **Outdoor Line-of-Sight (LoS) Range Test**
  - Error free communications possible at 1.7 km LoS with > 10dB Tx power headroom
  - Pencil BF both at transmitter and receiver supporting long range communications

LoS Range

☐ **Support wide-range LoS coverage**

- ✓ 16-QAM (528Mbps) : BLER 10^{-6}
- ✓ QPSK (264Mbps) : Error Free

BLER : Block Error Rate QPSK : Quadrature Phase Shift Keying QAM : Quadrature Amplitude Modulation

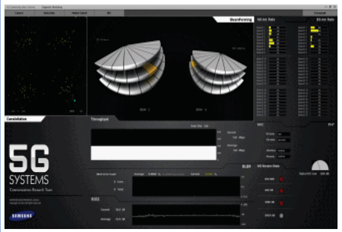
Test Results – Mobility

- **Outdoor Non-Line-of-Sight (NLoS) Mobility Tests**
  - **Adaptive Joint Beamforming & Tracking Supports 8 km/h Mobility even in NLoS**

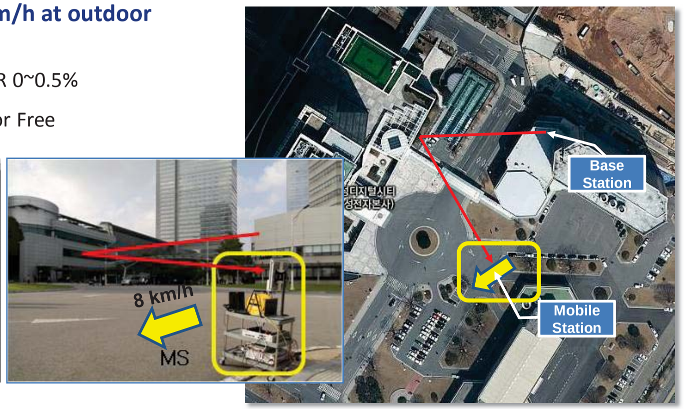
Mobility Support in NLoS

☐ **Mobility support up to 8 km/h at outdoor NLoS environments**

- ✓ 16-QAM (528Mbps) : BLER 0~0.5%
- ✓ QPSK (264Mbps) : Error Free



[DM Screen during Mobility Test]



Test Results – Building Penetration

- **Outdoor-to-Indoor Penetration Tests**
  - Most signals successfully received at indoor MS from outdoor BS
  - Outdoor-to-indoor penetration made through tinted glasses and doors

Outdoor to Indoor #1

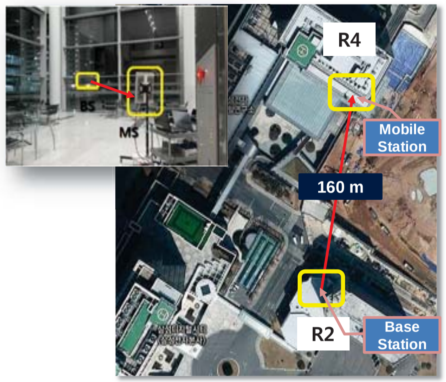
☐ **Signal measured inside office on 7th FL of R2**

- QPSK : BLER 0.0005~0.6% (Target : < BLER 10%)

Outdoor to Indoor #2

☐ **Signal measured inside the lobby at R4**

- QPSK : BLER 0.0005~0.3% (Target : < BLER 10%)

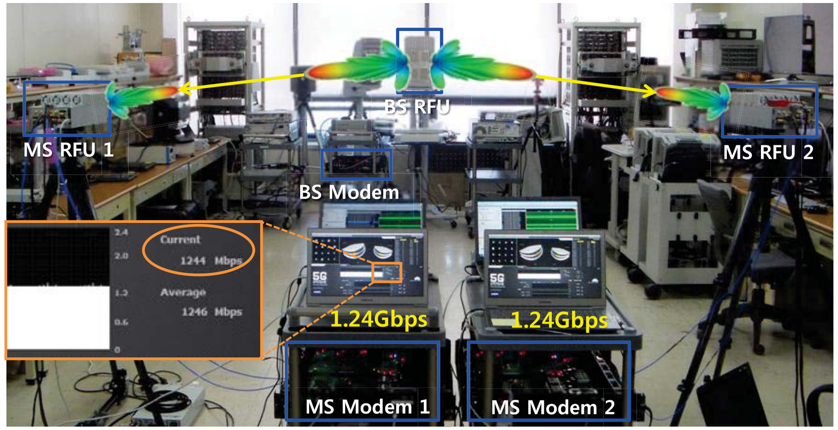


Test Results – Multi-User Support

- **Multi-User Communication Tests**
  - 2.48 Gbps peak data rate in MU-MIMO mode
  - Lab measurements performed using 2 set of MS

Carrier Frequency	27.925 GHz
Bandwidth	800 MHz
Max. Tx Power	37 dBm
Beam width (Half Power)	10º
Multiple Antenna	2x2 MIMO

Test Configuration



Summary

- **Samsung's 5G Goal Is to Maximize Operator & User Benefits by**
  - Order of magnitude improvements in system capacity leading to ***significant cost/bit reduction***
  - Uniform high data rate **(Gbps) experience *anywhere***
- **mmWave BF Technology as a Viable Solution to Provide Gbps Experience**
  - Promising mmWave channel measurement data obtained and modeling to follow
  - Encouraging results of outdoor coverage and indoor penetration tests shown
  - Real-time adaptive beamforming and tracking implemented to show mobility support
  - Advanced hybrid BF algorithms to further performances enhancement
  - More measurement tests, improvements on power/spectral efficiency to ensue