Performances and Feasibility of mmWave Beamforming Prototype for 5G Cellular Communications

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1. 5G Vision

5G Service Vision

Enabling the Immersive Service Experiences

Ubiquitous Health Care

Wearable/Flexible Mobile Device

Mobile Cloud

UHD Video Streaming

Smart Map/Navigation

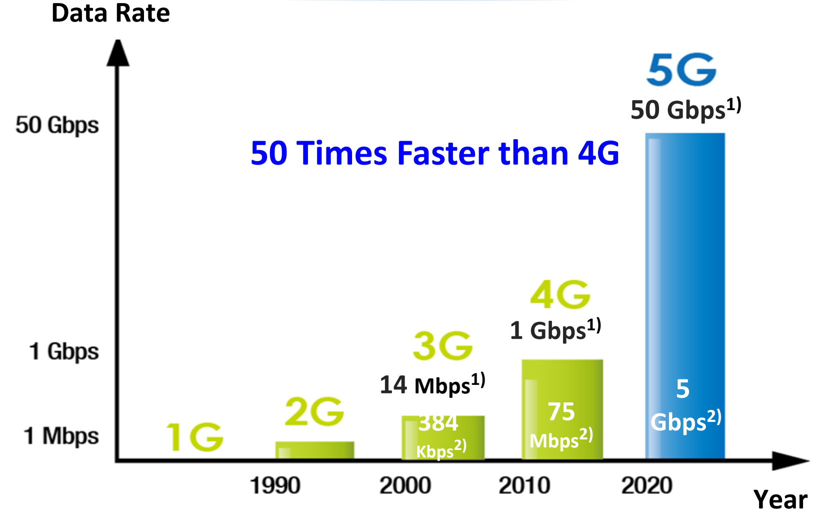
Real-Time Interactive Game

5G Key Performance Targets

- **Providing Gigabit Experience to Users Anywhere**

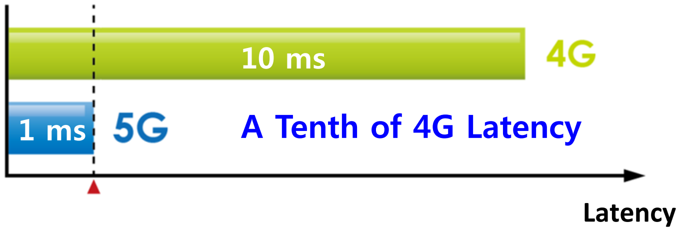
5G Performances

Peak Data Rate > 50 Gbps

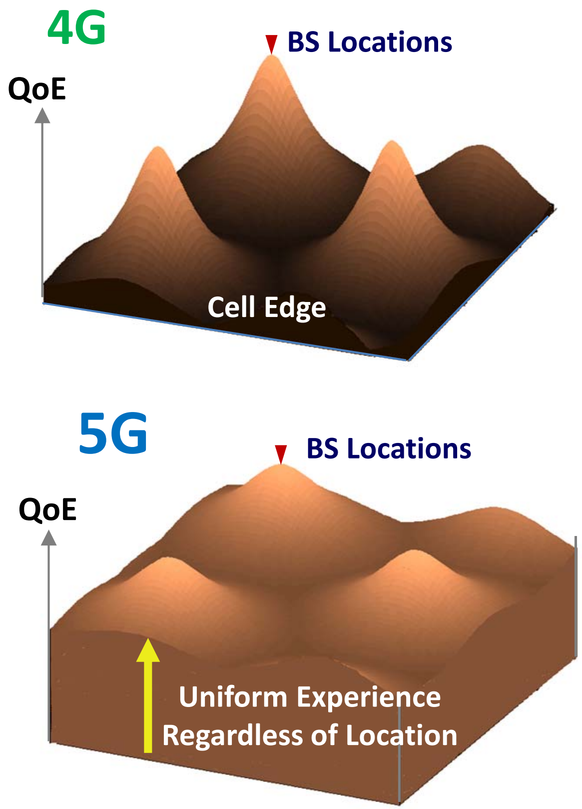


[1] Theoretical Peak Data Rate [2] Data Rate of First Commercial Products

Latency < 1 msec



Anywhere 1 Gbps

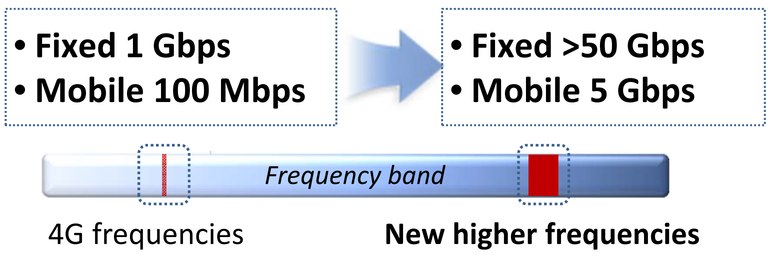


2. 5G Key Enabling Technologies

5G Key Enabling Technologies (1/2)

Disruptive Technologies for Significant Performance Enhancement

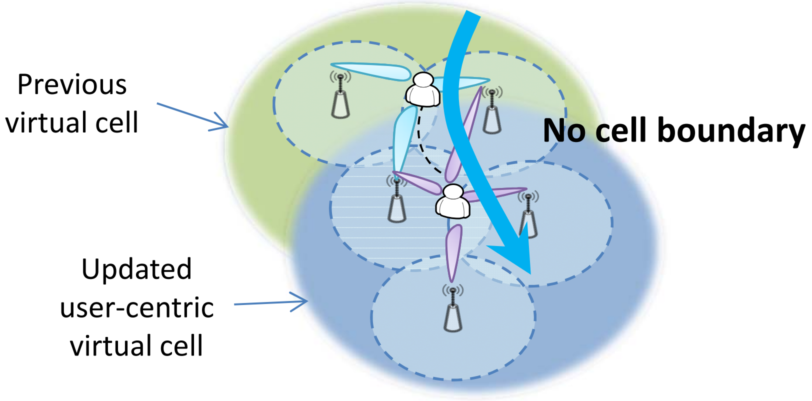
mmWave System Tech.



- **Fixed 1 Gbps**
- **Mobile 100 Mbps**

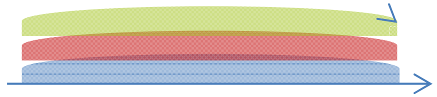
- **Fixed >50 Gbps**
- **Mobile 5 Gbps**

Adv. Small Cell



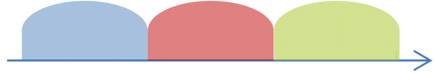
Adv. Coding & Modulation

Non-orthogonal Multiple Access

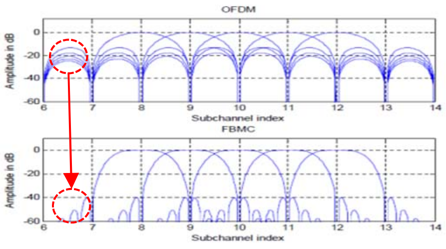


Time/Frequency/Space

Orthogonal Multiple Access

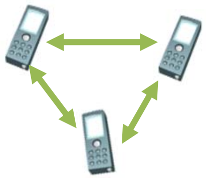


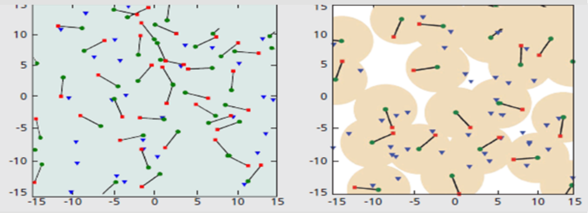
Time/Frequency/Space



Filter-bank Multi-carrier

Device-to-Devie (D2D)



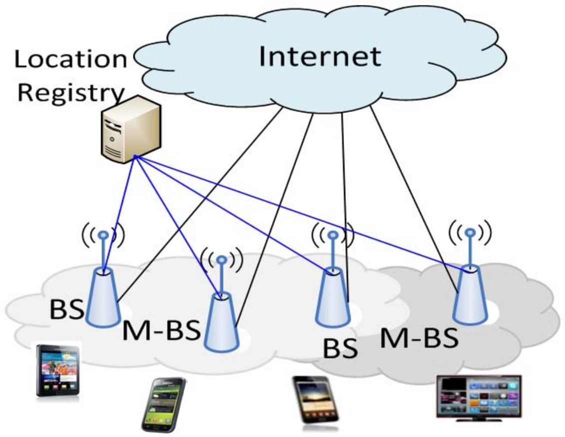


Enhancing areal spectral efficiency

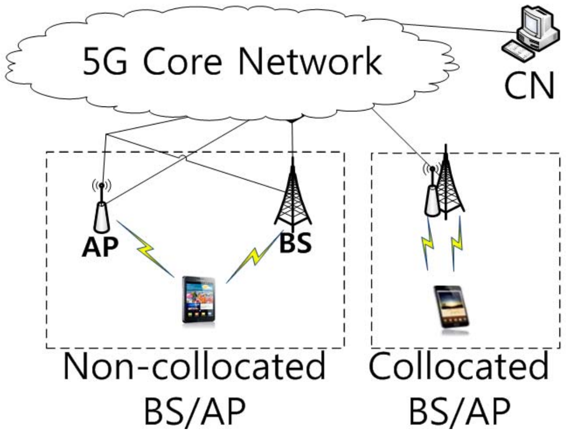
5G Key Enabling Technologies (2/2)

Disruptive Technologies for Significant Performance Enhancement

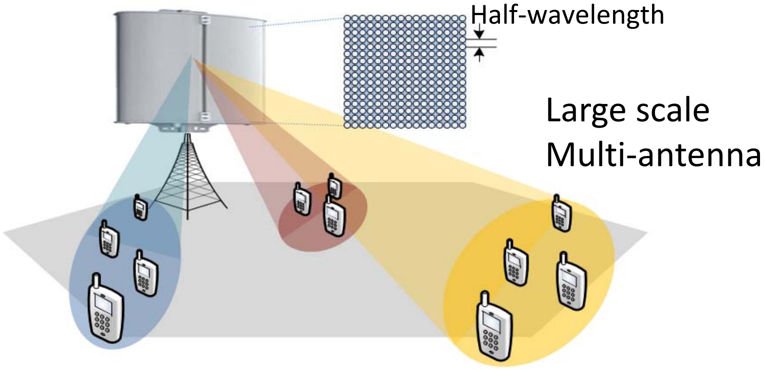
Enhanced Flat NW



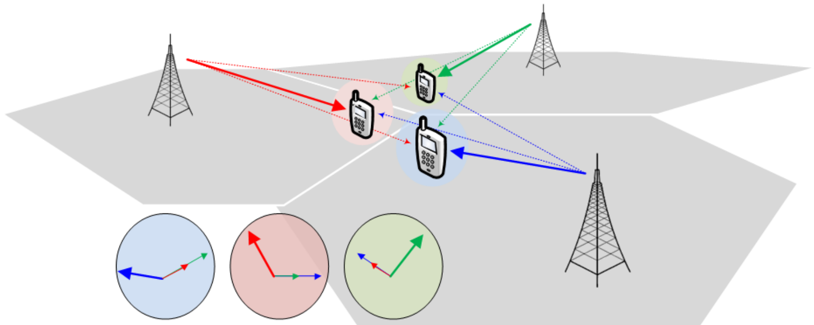
IWK/Integration w/ Wi-Fi



Adv. MIMO/BF



Interference Management



Interference alignment

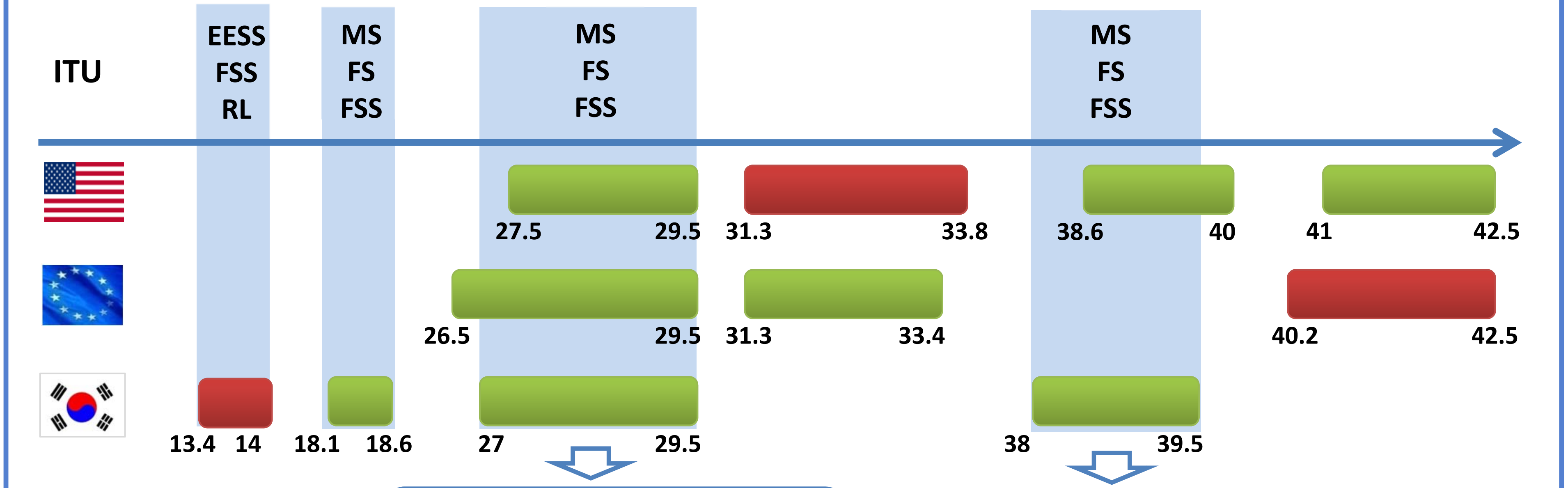
3. mmWave Channel Propagation & Measurements

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.

Higher Frequency Candidates



Current Usage

US: LMDS, FSS
EU: Fixed P-P link , FSS earth sta.
China: Mobile, FSS
Korea : Marine time use

Current Usage

US: Fixed P-P system
EU: Fixed P-P link
Korea : None

🟩 MOBILE Primary
🟥 No MOBILE

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

Friis' Equation in Free Space (1/3)

Isotropic Tx & Rx

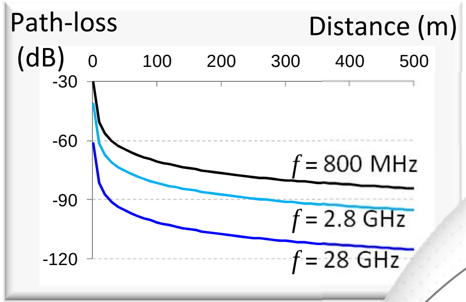
☐ "Path-loss" is Proportional to Frequency Squared

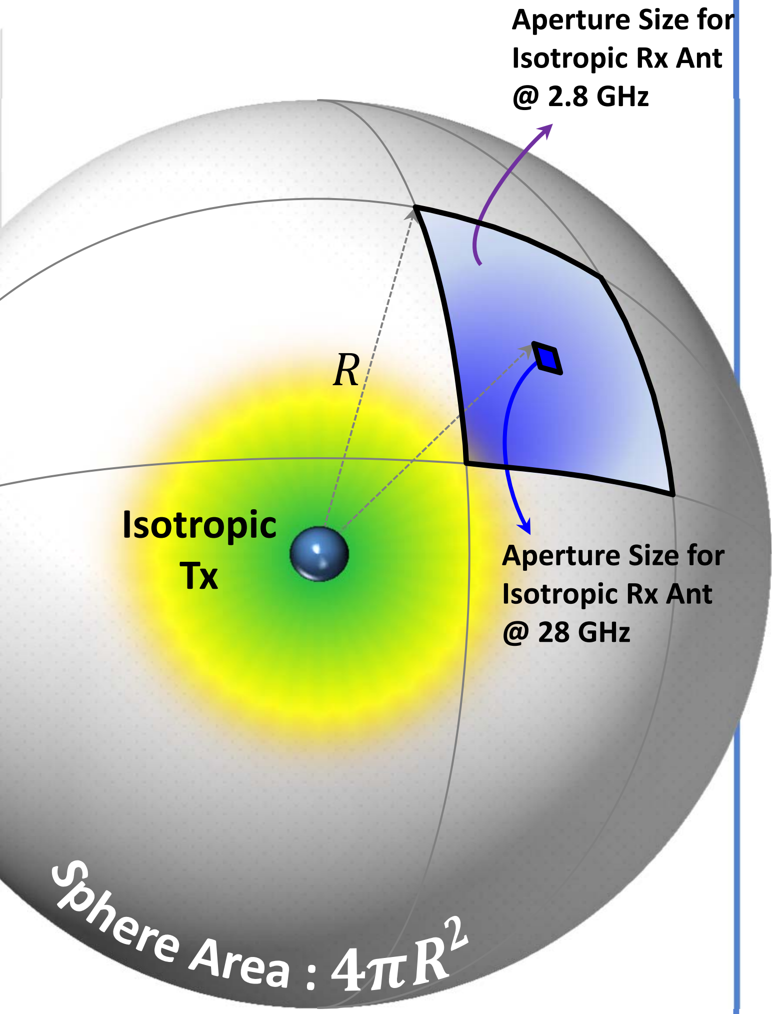
$$P_{RX} = P_{TX}\underbrace{G_{TX}G_{RX}}_{=1 \text{ for Isotropic}}\underbrace{\left(\frac{\lambda}{4\pi R}\right)^2}_{\text{Path-loss}}$$

$$= P_{TX}\cdot 1\cdot 1\cdot \underbrace{\left(\frac{\lambda^2}{4\pi}\right)}_{\text{Aperture Size}}\underbrace{\left(\frac{1}{4\pi R^2}\right)}_{\text{Spherical Area}}$$

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

(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 (2/3)

Isotropic Tx but Rx Array Antennas

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

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

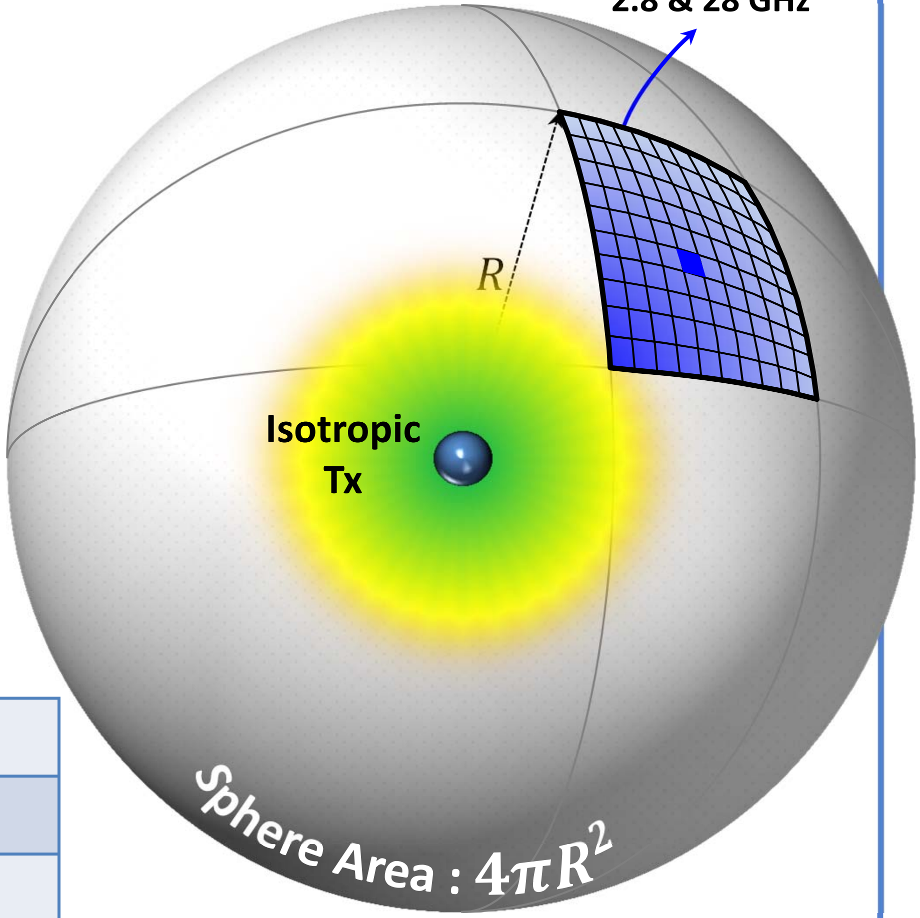
$$= P_{TX}\cdot 1\cdot G_{RX}\left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1}{4\pi R^2}\right)$$

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

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

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

Same Aperture Size for **Both** 2.8 & 28 GHz



☐ **Comparison Example**

	2.8 GHz	28 GHz
RX Aperture Size	9.135 cm^2	9.135 cm^2
RX Power	P_{RX}	P_{RX}

Friis' Equation in Free Space (3/3)

Array Antennas for Both Tx & Rx

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

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

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

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

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

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

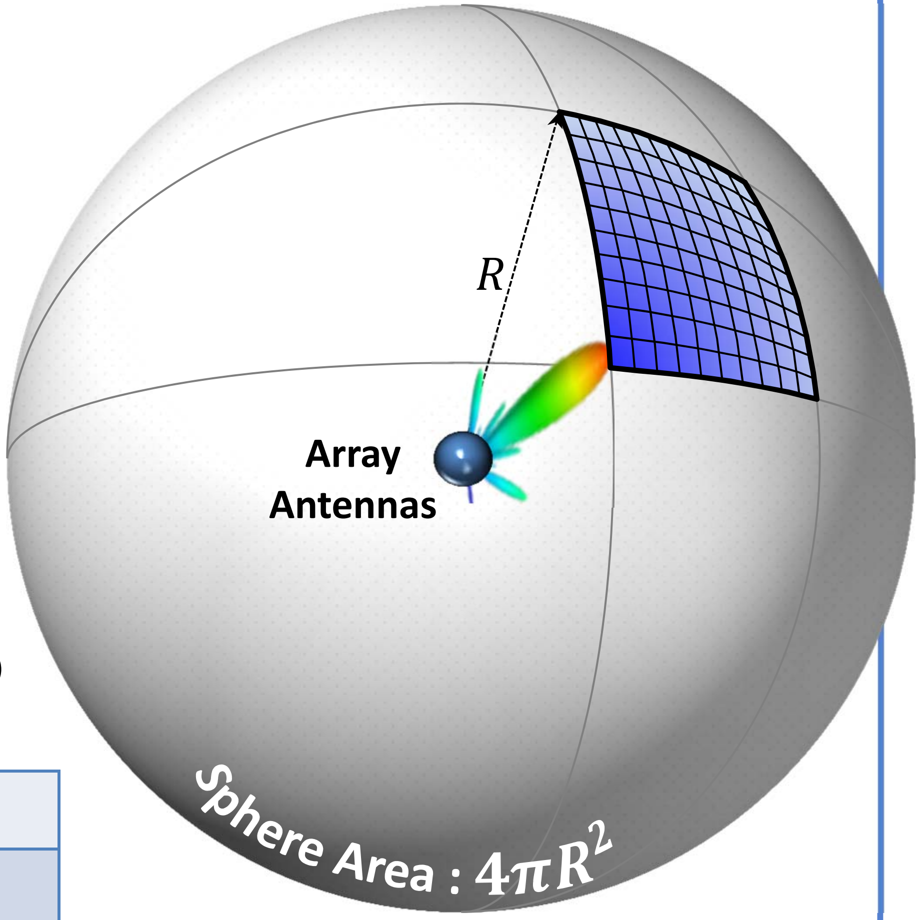
$$= P_{TX} A_{e,TX} A_{e,RX} \left(\frac{4\pi \boxed{\cdot f^2}}{c^2} \right) \left(\frac{1}{4\pi R^2} \right)$$

(c : speed of light)

☐ **Comparison Example**

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

+ 20 dB



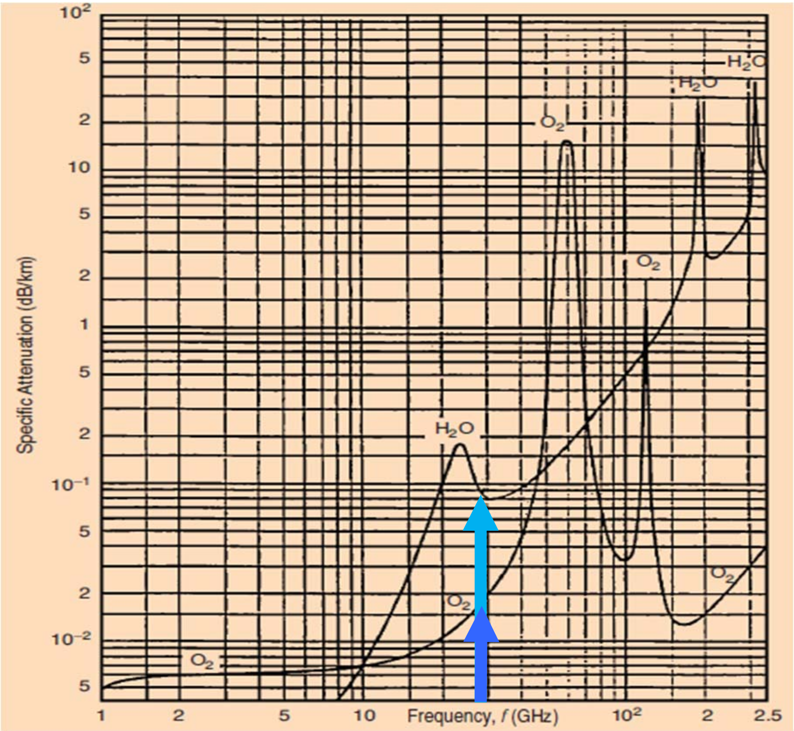
Atmospheric Absorption Loss

- **Atmospheric Loss due to H2O & O2 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)**



Pressure: 1013 mb
Temperature: 15 °C
Water Vapour: 7.5 μm^2

[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.

Rain Attenuation

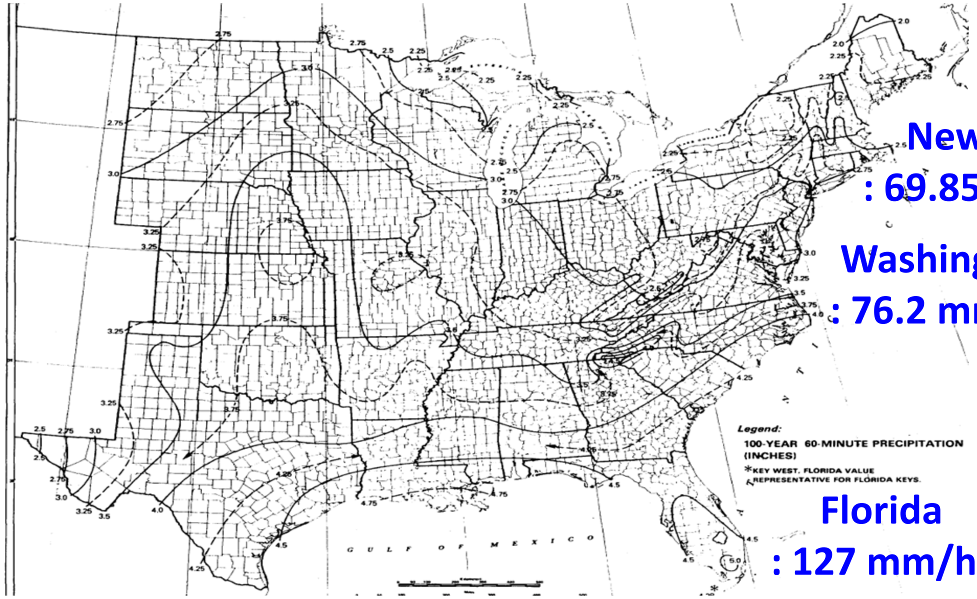
- **Rain Attenuation at 28GHz is Approx. 4 dB at 200 m even in 110 mm/hr Intensity**

Precipitation

□ 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 (US Eastern)

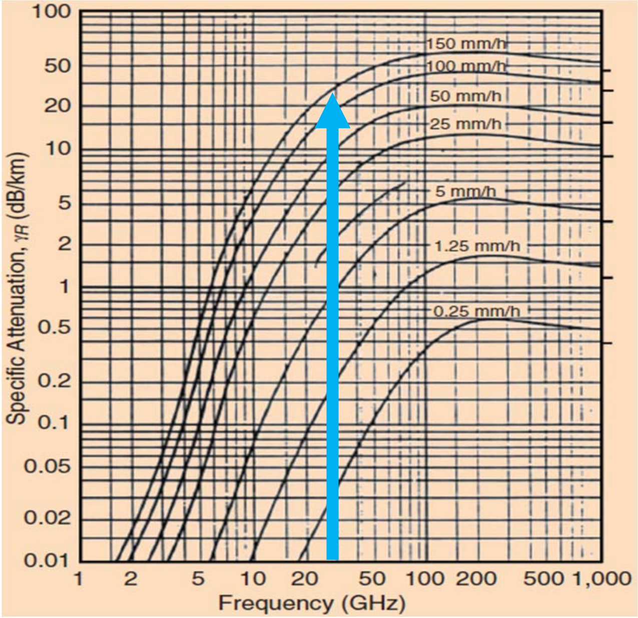
100 Year Recurrence 1-hour Rain Intensity (US Eastern)



New York : 69.85 mm/hr

Washington : 76.2 mm/hr

Florida : 127 mm/hr



[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.

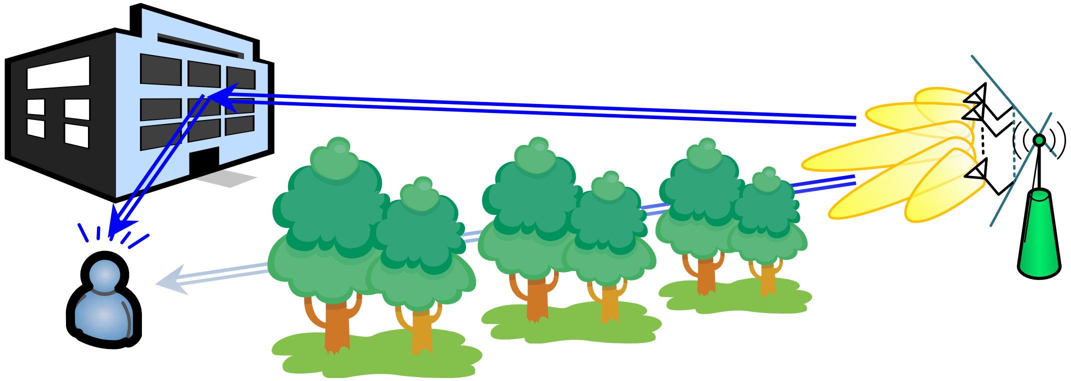
Foliage Loss

- **Loss in Dense Foliage Is Non-Negligible, But Other 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)

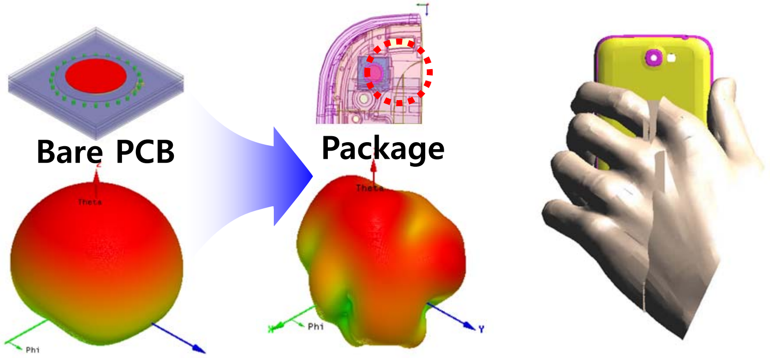
[Ref.] M. Marcus and B. Pattan. Millimeter wave propagation: spectrum management implications. *IEEE Microwave Magazine*, June 2005.

Chassis / Hand / Power Absorption

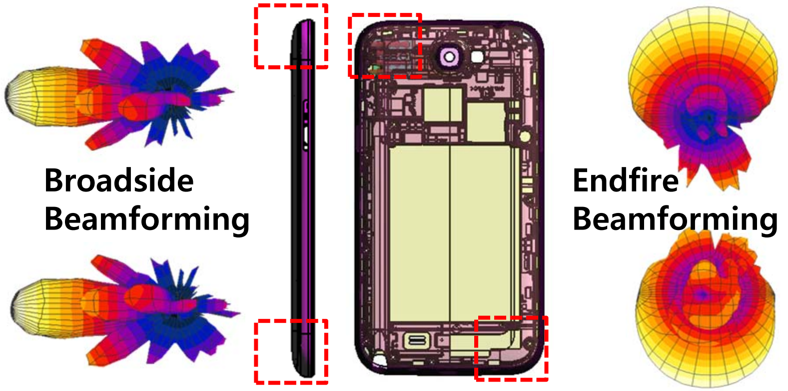
- **Effect of Chassis/Hand/Head Could Be Compensated with Beamsteering Array**
- **High Frequency Beamforming Reduces Power Penetration/Absorption through Skin**

Chassis / Hand-held Effect

☐ **Chassis/hand impact on gain and pattern**



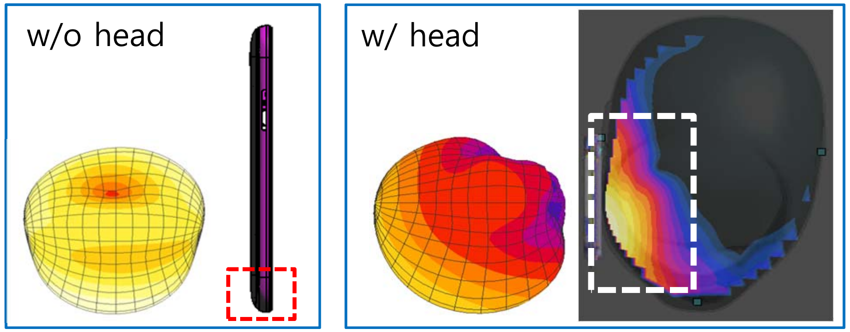
☐ **Various antenna locations and BF patterns can overcome these effects**



Power Absorption

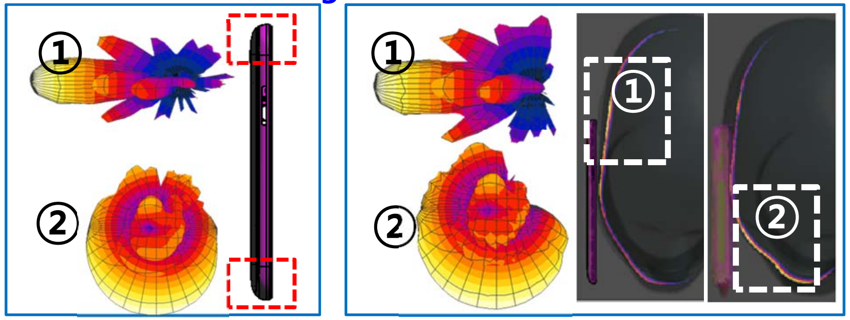
☐ **Low penetration and absorption due to high frequency beamforming**

1.9 GHz Omni-Antenna



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

28 GHz Beamforming

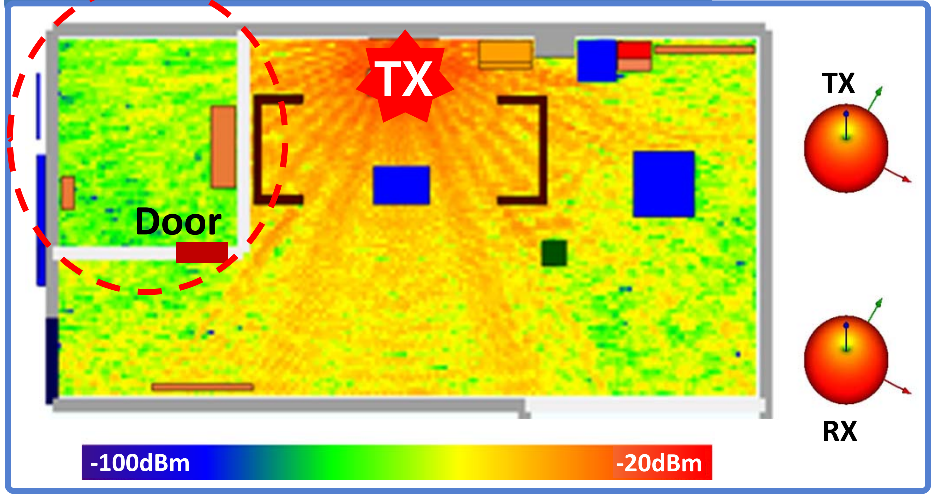


① Penetration depth = 3 mm, Average = 0.15, MAX = 90 mW/g
② Penetration depth = 3 mm, Average = 0.016, MAX = 2.11 mW/g

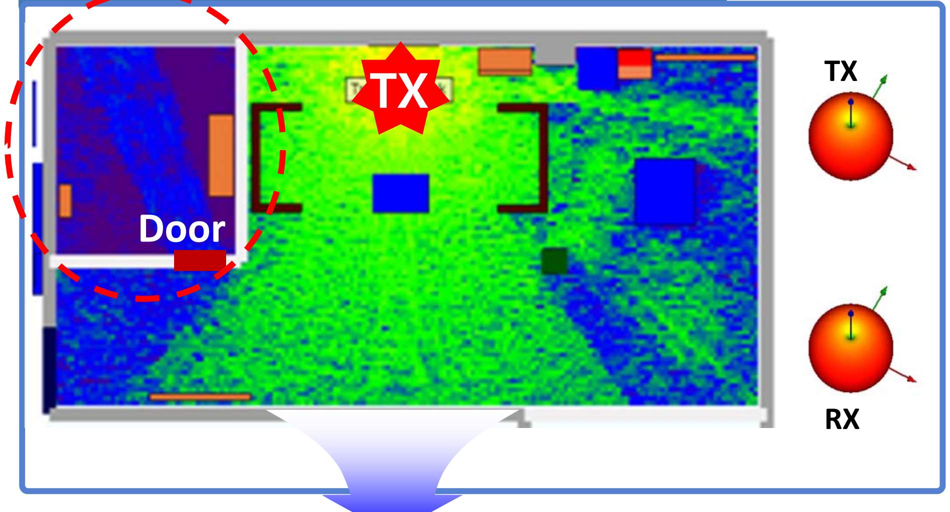
Indoor Propagation

- **Beamforming Significantly Improves Indoor Coverage at 28 GHz**

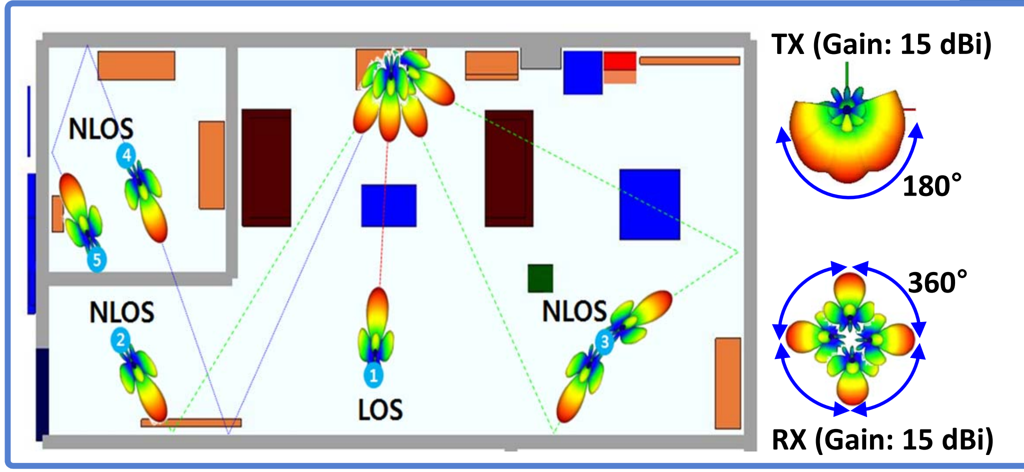
2.4 GHz Omni-directional

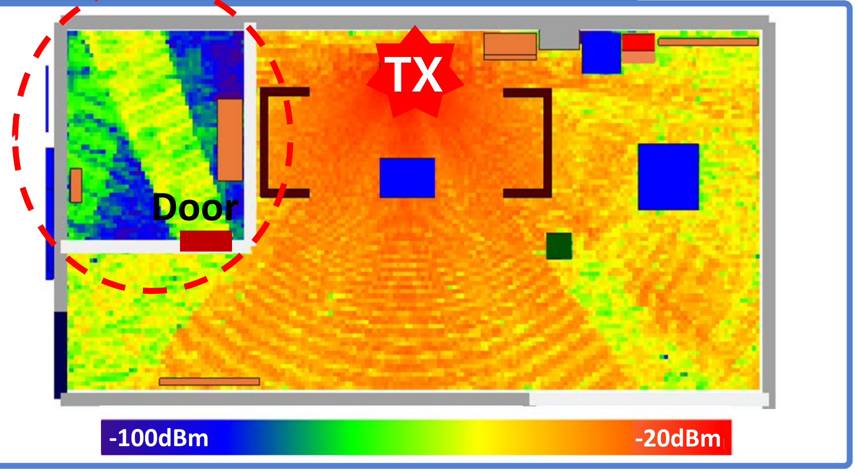


28 GHz Omni-directional



28 GHz Beamforming



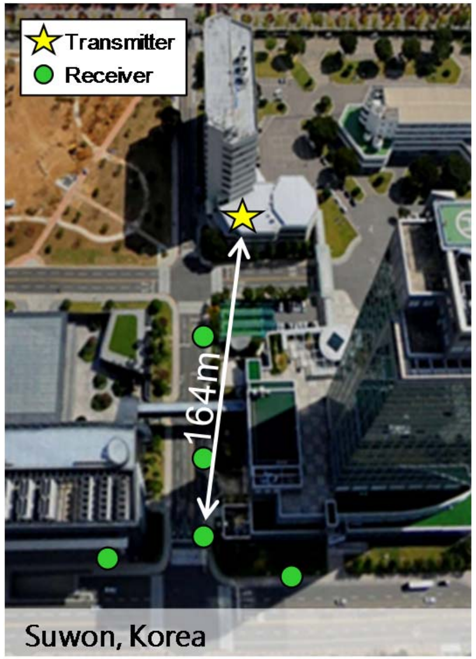


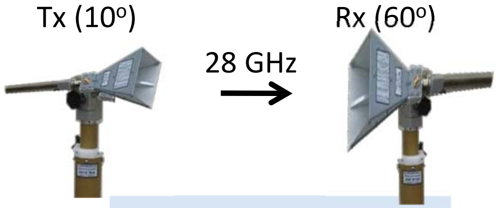
Channel Measurement – Sub-Urban

- **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

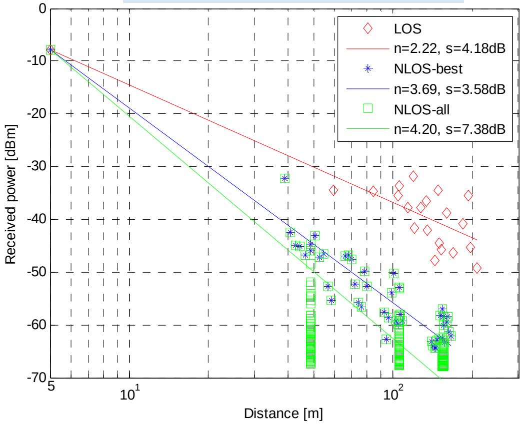
Samsung Campus, Korea

		LOS	NLOS
Path Loss Exponent		2.22	3.69
RMS Delay Spread [ns]	Median	4.0	34.2
	99%	11.4	168.7





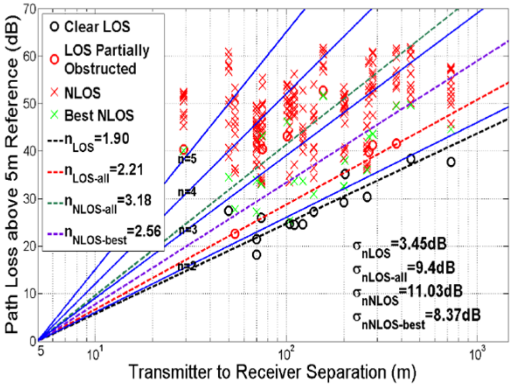
[Received Power]



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

[Received Power]



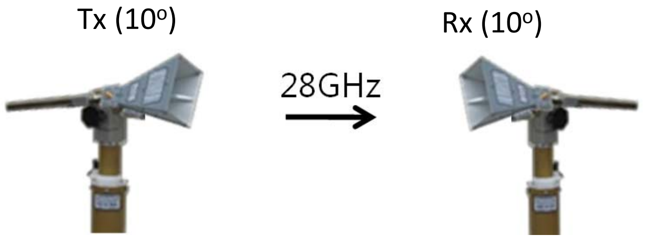
*** Reference : Prof. Ted Rappaport, UT Austin, 2011**

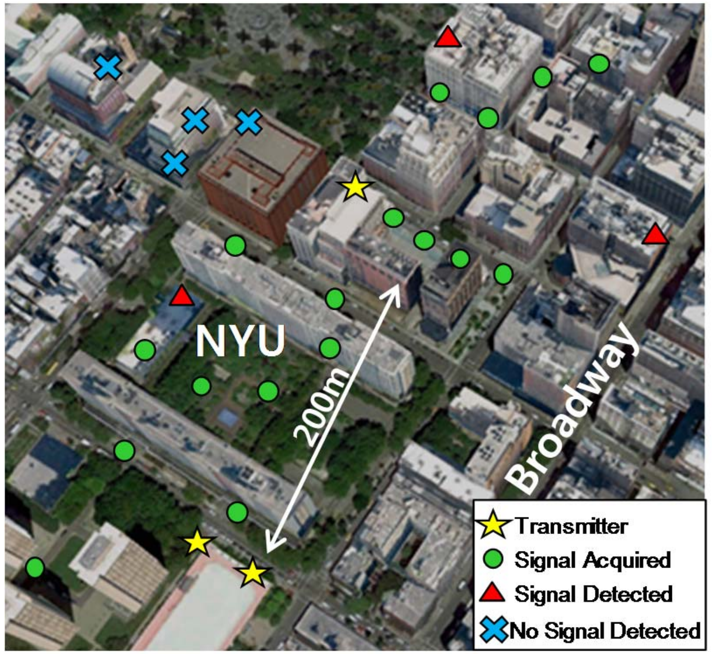
Channel Measurement – Dense Urban

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

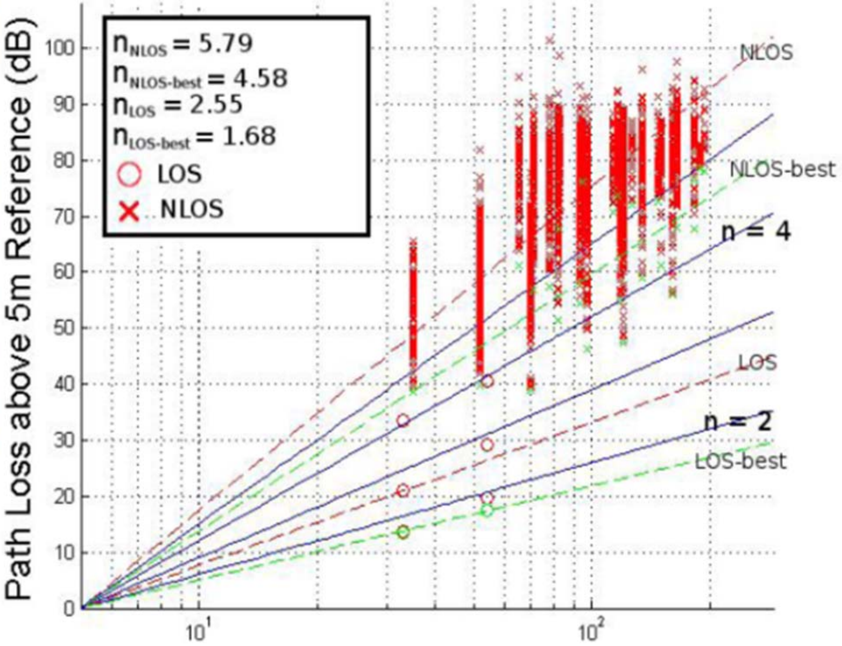
New York, Manhattan, US

	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]

*** Reference : Prof. Ted Rappaport, NYU, 2012**

4. mmWave BF Prototype & Algorithm

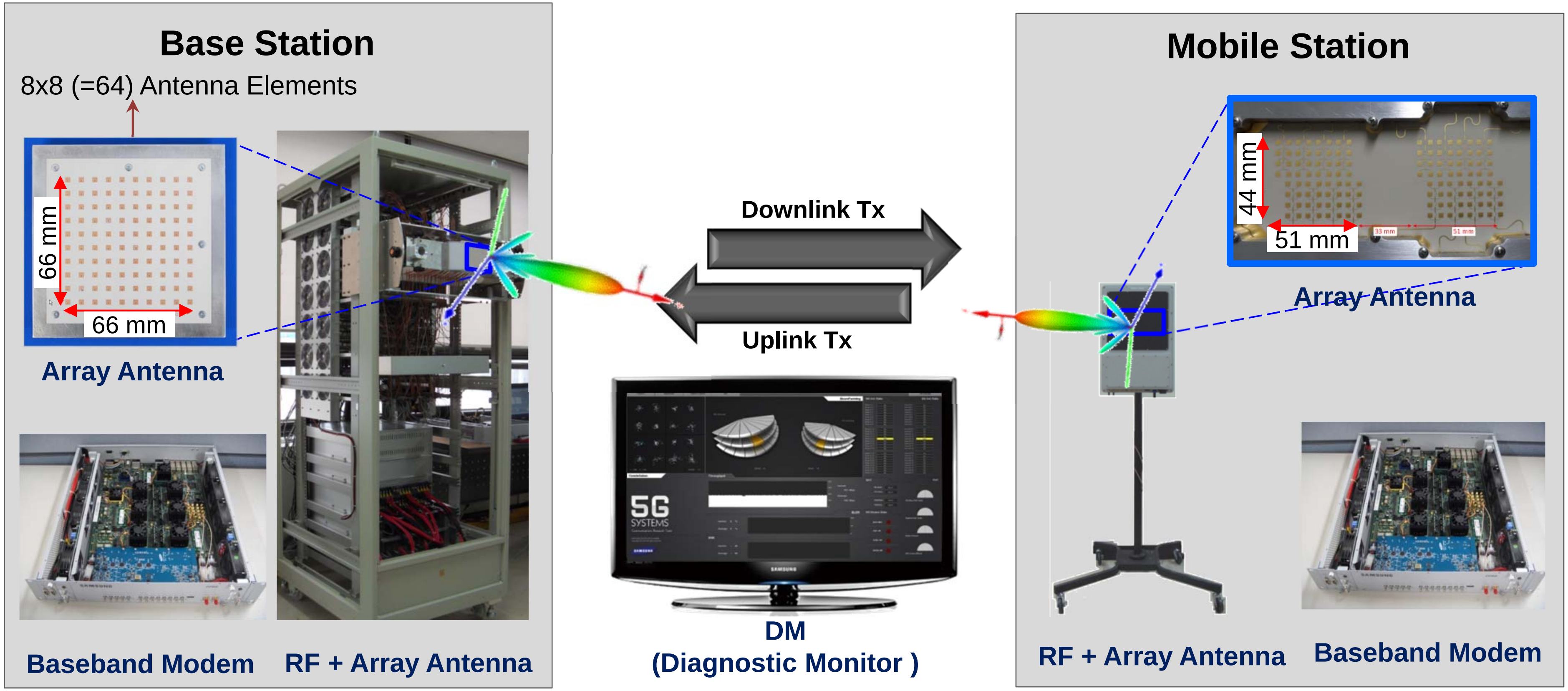
mmWave BF Prototype Overview

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

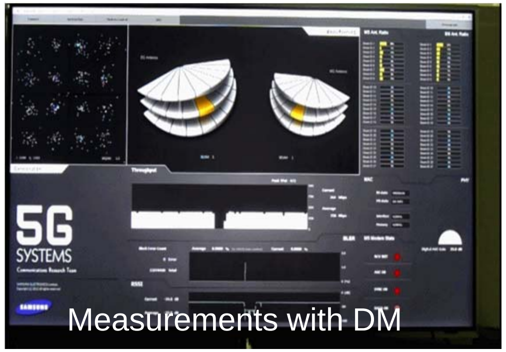
- OFDM system parameters designed for mmWave bands
- Indoor & outdoor measurements performed for data rates and transmission ranges

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)	10^{o}
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

Full-HD Video Streaming Test



Measurements with DM

Test Results – Range

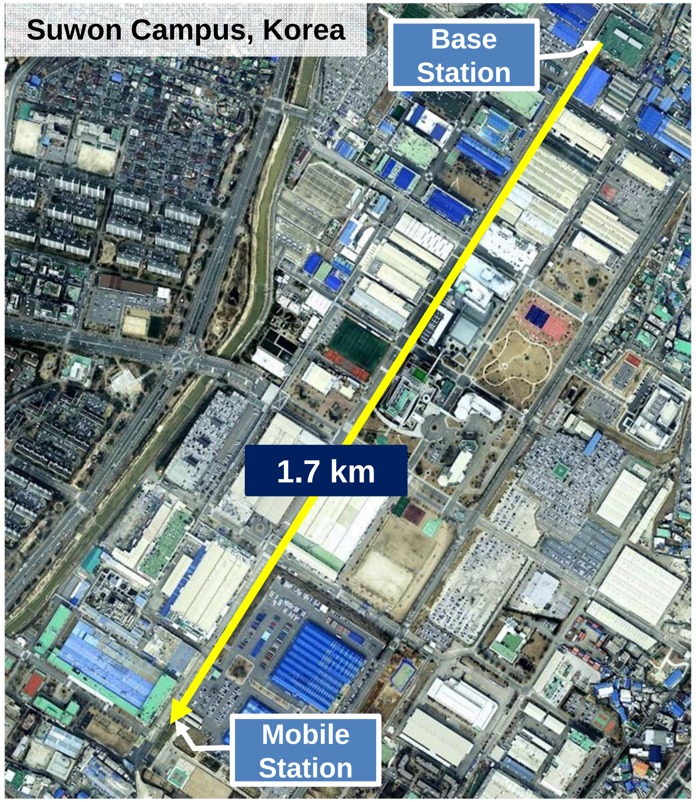
Outdoor Line-of-Sight (LoS) Range Test

- 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

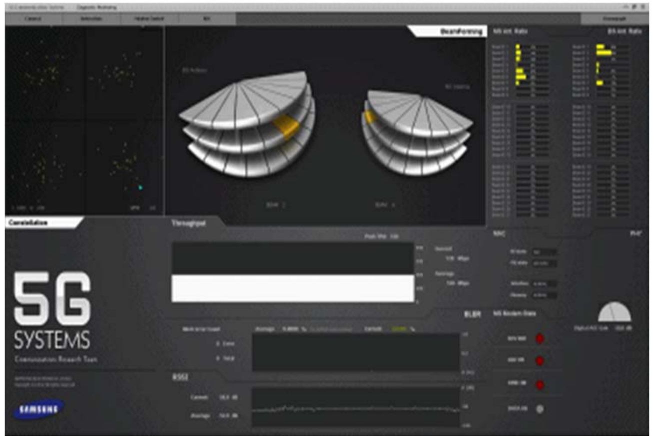
Outdoor Non-Line-of-Sight (NLoS) Mobility Tests

- **Fast Joint Beamforming & Tracking Supports 8 km/h Mobility even in NLOS**

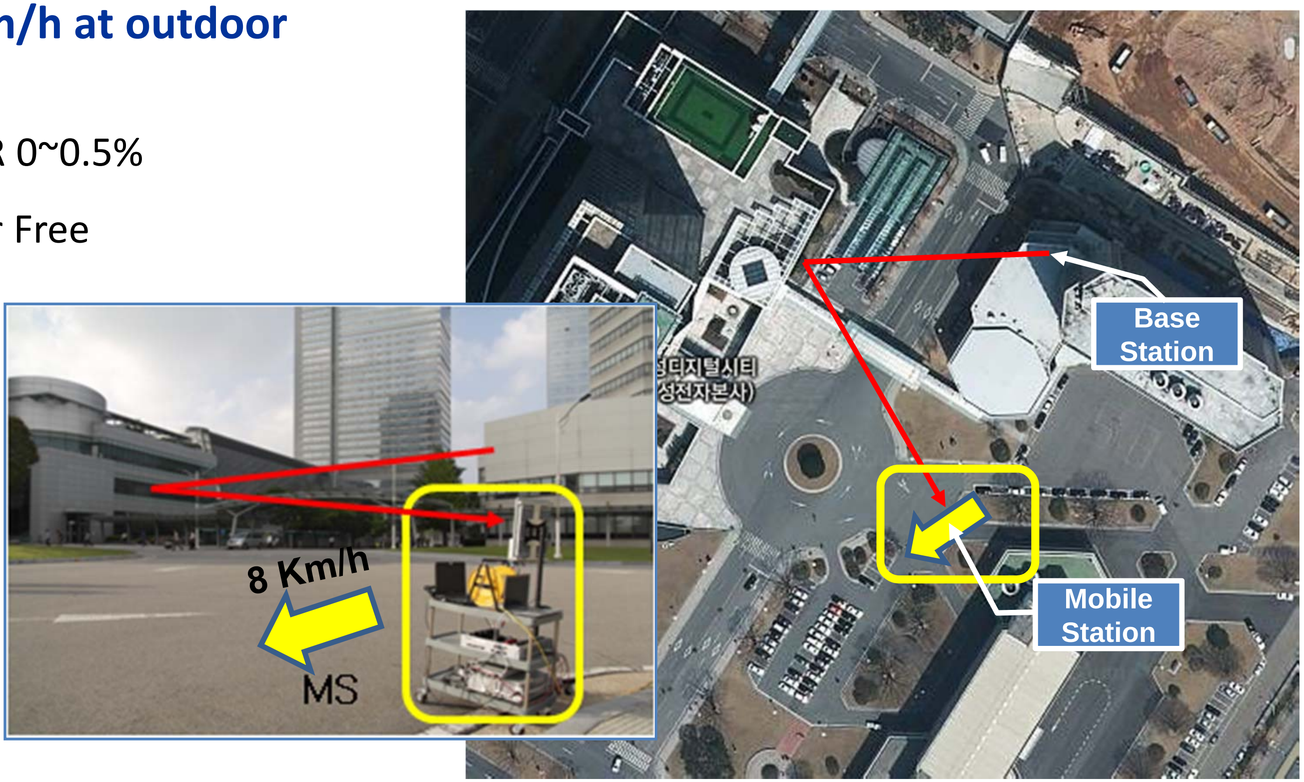
Mobility Support in NLoS

☐ **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]



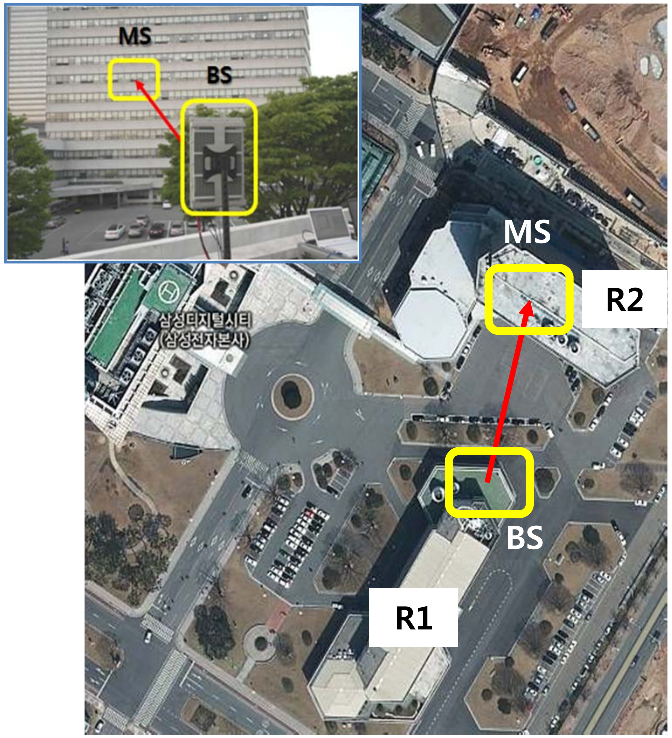
Test Results – Building Penetration

- **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**

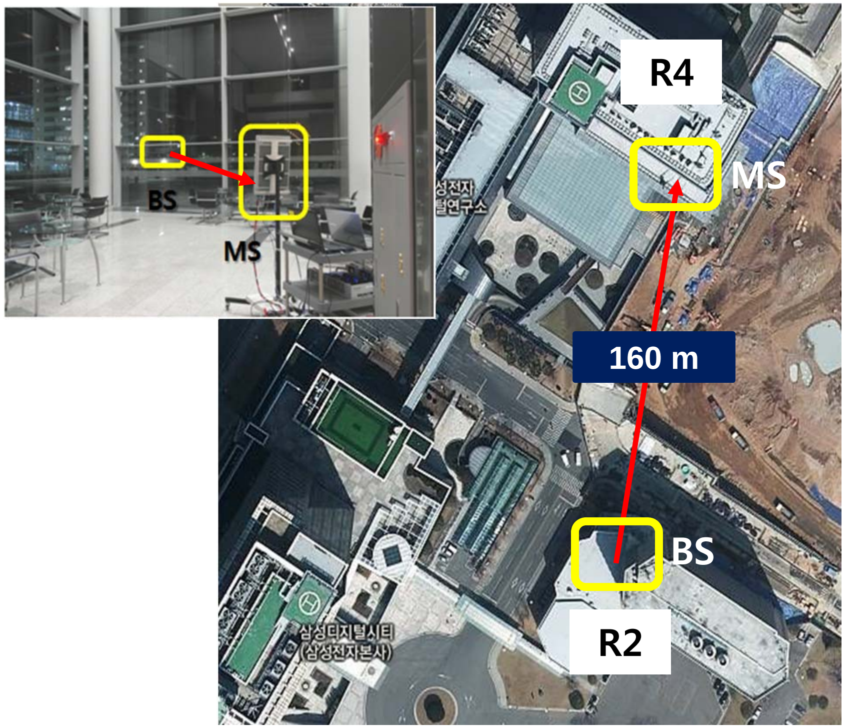
- QPSK : BLER 0.0005~0.6% (Target : < BLER 10%)



Outdoor to Indoor #2

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

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

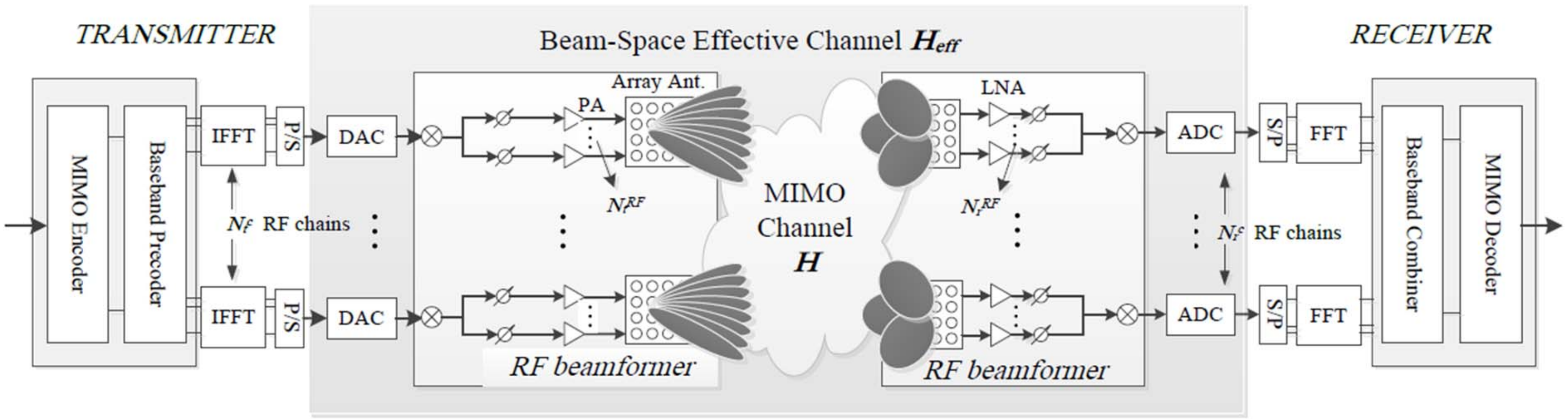


Hybrid BF Architecture

- **Hybrid use of Analog Beamforming and Digital Precoding**
  - Analog Beamforming : To overcome higher path-loss with beamforming gain
  - Digital Precoding : To optimize capacity using various MIMO techniques
- **High performance with Low complexity for mmWave Systems**

Hybrid Beamforming Architecture

• Massive Array Antennas	➔ Large Array Beamforming Gain
• Array Weighting with Phase Shifters	➔ Adaptive Analog Beam Steering
• Multiple RF Chains Linking Array Antennas	➔ Adaptive MIMO/BF Precoding



Hybrid BF Link-level Analysis

Hybrid Beamforming Offers A Good Compromise between All Digital and All Analog

- Performance improvement through digital MIMO precoding on selected multiple analog beams, approaching full digital performance

Link Performance Analysis

- **Analog BF**: Focusing BF gain to the single dominant channel path
- **Digital BF** : Matching dispersive channel paths with full flexibility up to the number of antennas
- **Hybrid BF**: Focusing BF gains to a few dominant channel paths by combining multiple analog beams with limited RF chains

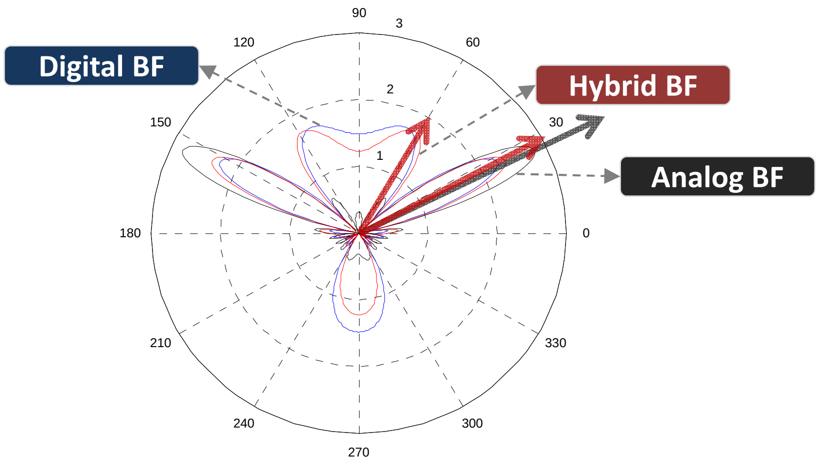


Fig.1: Instantaneous beam patterns for a given dispersive channel

- Hybrid BF Tx : 8 elements/antenna, 2 RF chains
  Rx: 4 elements/antenna, 1 RF chain
- Digital BF Tx: 16 elements (1 RF chain/element)
  Rx: 4 elements (1 RF chain/element)

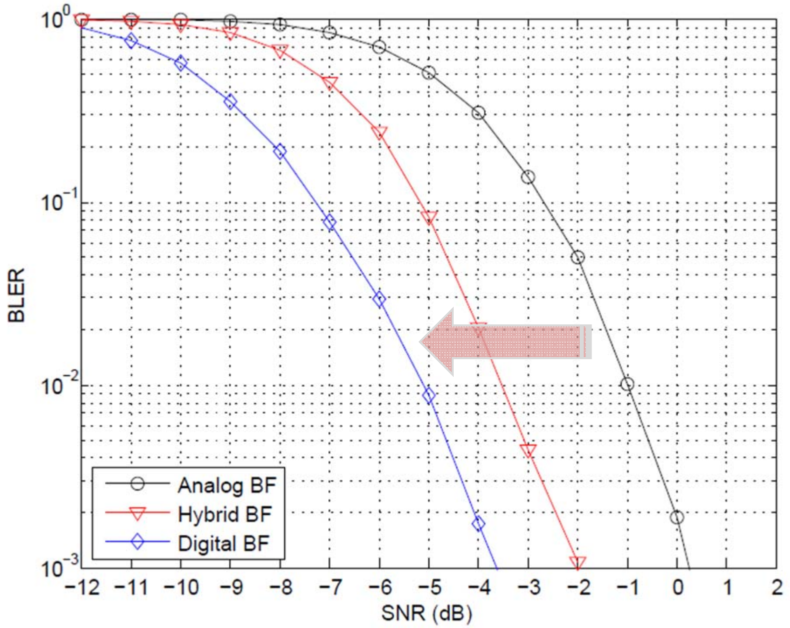


Fig.2: Link performance comparison

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***
- Support of cost-efficient wireless backhaul for ***network scalability***

◆ **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 enhance performances
- More measurement tests, improvements on power/spectral efficiency to ensue