Sub-THz Band Transsmission Technology for 6G Wireless Communication

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KAIST
Ju Yong Lee

KAIST

Contents

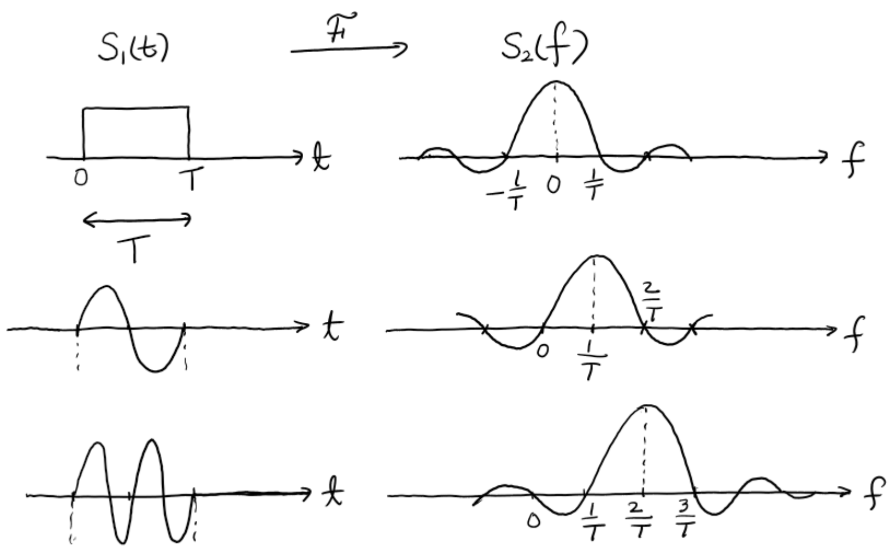
1 Introduction

- 3G wireless communication
  - ✓ Time resource: 2 MHz bandwidth at 1 GHz carrier frequency
  - ✓ Spectral efficiency : 1 bps/Hz, Capacity: 2 Mbps
- 4G wireless communication
  - ✓ Time resource: 20 MHz bandwidth at 2 GHz carrier frequency
  - ✓ Space resource (MIMO): number of antennas = 4
  - ✓ Spectral efficiency : 15 bps/Hz, Capacity: 300 Mbps
- 5G wireless communication
  - ✓ Time resource: 1 GHz bandwidth at 28 GHz carrier frequency
  - ✓ Space resource: number of beams * polarization
  - ✓ Spectral efficiency : 20 bps/Hz, Capacity: 20 Gbps

1 Introduction

- Number of information from time and frequency resource
  - ✓ Time resource: *T*, frequency resource: *W*
  - ✓ Time and frequency have fourier transform relationship.
  - ✓ Number of sinc functions in frequency domain

$$K = \frac{W}{1/T} = WT \text{ (Number of information)}$$



$$S_2(f) = \int_{-\infty}^{\infty} S_1(t)\, e^{-j2\pi f t} dt$$

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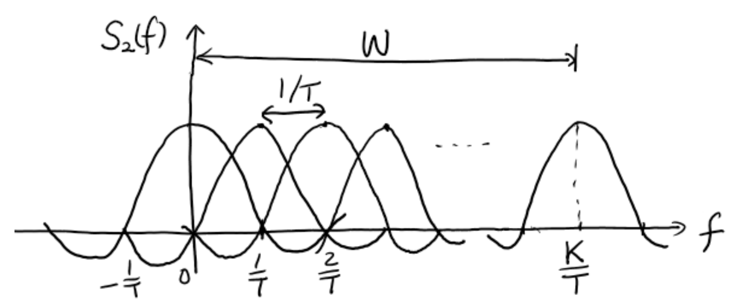


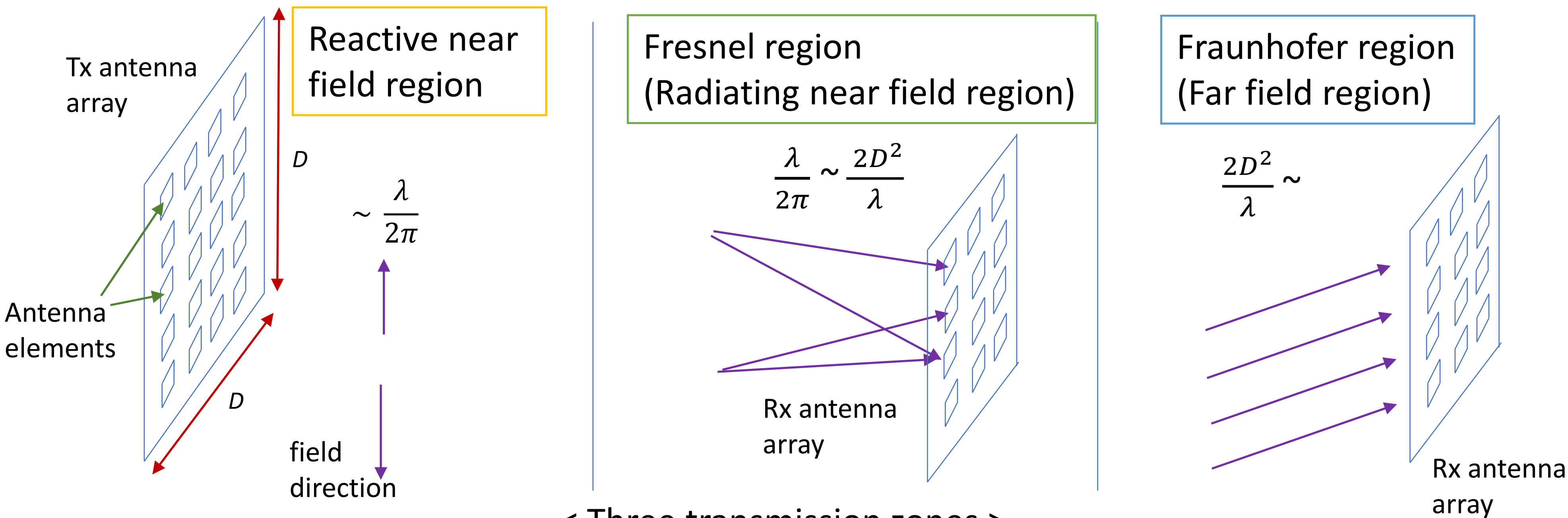
< Utilization of time and frequency resources >

1 Introduction

- 6G capacity requirement
  - ✓ The goal of 6G: 1 Tbps capacity
- 6G frequency resource and capacity
  - ✓ Sub-THz band: 100 GHz~300 GHz
  - ✓ Available bandwidth: 5 GHz~10 GHz
  - ✓ Required spectral efficiency: 100~200 bps/Hz
  - ✓ (64QAM) * (polarization) = (6 bps/Hz) * 2 = 12 bps/Hz
- Can we achieve the spectral efficiency of 100~200 bps/Hz for 6G 1 Tbps capacity?
  - ✓ Yes, capacity can be increased by utilizing spatial resources in the Fresnel region.

2 Fresnel Region Transmission

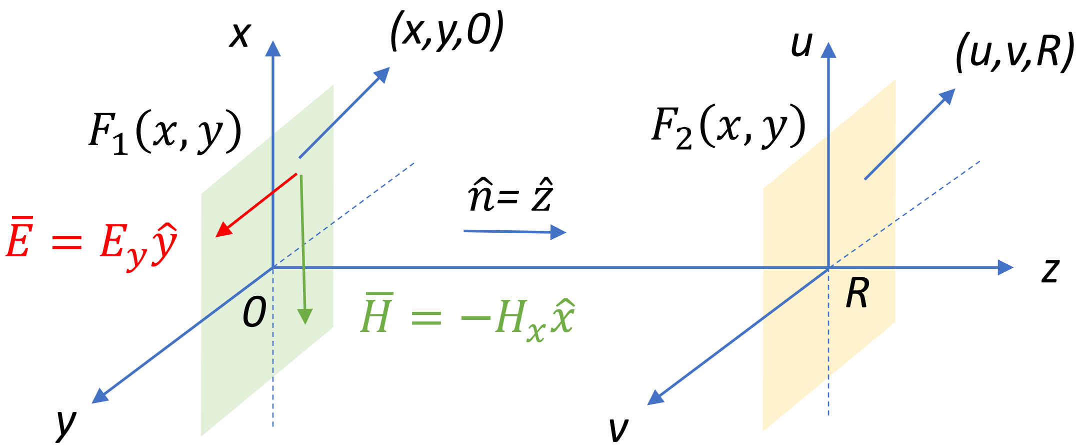
- Transmission region in a LoS (Line-of-sight) environment
  - ✓ Reactive near field region: Energy is stored without radiation.
  - ✓ Fresnel region: Different pairs between Tx antenna elements and Rx antenna elements have different channel characteristics.
  - ✓ Fraunhofer region: The field reaches all receiver antenna elements in the same direction.



< Three transmission zones >

2 Fresnel Region Transmission

- Relationship between Tx field and Rx field (Fresnel approximation)



$\bar{J}(\bar{r})$=$\hat{n}$x$\bar{H}$= $\hat{z}$x$(-H_x\hat{x})$= $-H_x\hat{y}$

$\bar{M}(\bar{r})$=$-\hat{n}$x$\bar{E}$= $-\hat{z}$x$(E_y\hat{y})$=$E_y\hat{x}$

$F_1(x,y)$: Tx field (E or H)

$F_2(x,y)$: Rx field (E or H)

$$\bar{r} = (x,y,0), \bar{r}' = (u,v,R)$$

$$|\bar{r}-\bar{r}'| = \sqrt{(x-u)^2+(y-v)^2+R^2}$$

$$F_2(u,v) = \frac{j}{\lambda}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_1(x,y)\,\frac{e^{-jk|\bar{r}-\bar{r}'|}}{|\bar{r}-\bar{r}'|}dxdy$$

$$\approx \frac{je^{-jkR}}{\lambda R}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_1(x,y)\ exp\left(-\frac{jk}{2R}(u-x)^2-\frac{jk}{2R}(v-y)^2\right)dxdy$$

$$= \frac{je^{-jkR}}{\lambda R}e^{-\frac{jk}{2z}(u^2+v^2)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_1(x,y)\ e^{-\frac{jk}{2R}(x^2+y^2)}e^{\frac{jk}{R}(ux+vy)}dxdy$$

2 Fresnel Region Transmission

- Transformation from signals to fields

$S_1(x,y)$: Tx signal, $S_2(u,v)$: Rx signal

$$F_1(x,y) = S_1(x,y)\ e^{\frac{jk}{2R}(x^2+y^2)}, \qquad F_2(u,v) = S_2(u,v)\ e^{-\frac{jk}{2R}(u^2+v^2)}$$

- Relationship between Tx signal and Rx signal

  ✓ Tx/Rx signals have a 2-dimensional Fourier transform relationship.

$$S_2(u,v) = \frac{je^{-jkR}}{\lambda R}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S_1(x,y)\ e^{j\frac{k}{R}(ux+vy)}dxdy$$

$$= je^{-jkR}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S_1(x,y)\ e^{j2\pi\left[\left(\frac{u}{\sqrt{\lambda R}}\right)\left(\frac{x}{\sqrt{\lambda R}}\right)+\left(\frac{v}{\sqrt{\lambda R}}\right)\left(\frac{y}{\sqrt{\lambda R}}\right)\right]}\frac{dx}{\sqrt{\lambda R}}\frac{dy}{\sqrt{\lambda R}}$$

$$S_1(x,y) = -je^{jkR}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S_2(u,v)\ e^{-j2\pi\left[\left(\frac{x}{\sqrt{\lambda R}}\right)\left(\frac{u}{\sqrt{\lambda R}}\right)+\left(\frac{y}{\sqrt{\lambda R}}\right)\left(\frac{v}{\sqrt{\lambda R}}\right)\right]}\frac{du}{\sqrt{\lambda R}}\frac{dv}{\sqrt{\lambda R}}$$

$$S_1(x,y) \xleftrightarrow{\text{2−dim. Fourier transform}} S_2(u,v)$$

2 Fresnel Region Transmission

- Two one-dim. Fourier transform
  - ✓ If $x' = \frac{x}{\sqrt{\lambda R}}$, $y' = \frac{y}{\sqrt{\lambda R}}$, $u' = \frac{u}{\sqrt{\lambda R}}$, $v' = \frac{v}{\sqrt{\lambda R}}$,

    then $S_2(u', v') = je^{-jkR} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S_1(x', y')\ e^{j2\pi\,(u'x'+v'y')} dx'dy'$
  - ✓ If $S_1(x', y') = S_{1,H}(x')S_{1,V}(y')$, $S_2(u', v') = je^{-jkR} S_{2,H}(u')\, S_{2,V}(v')$,

    then $S_{2,H}(u') = \int_{-\infty}^{\infty} S_{1,H}(x') e^{j2\pi u'x'} dx'$, $S_{2,V}(v') = \int_{-\infty}^{\infty} S_{1,V}(y')\ e^{j2\pi\, v'y'} dy'$
- Spatial resources
  - ✓ Tx array size: $A_1 * B_1$, Rx array size: $A_2 * B_2$, distance: R, wavelength: λ
  - ✓ Tx space resource: $0 \leq x' \leq \frac{A_1}{\sqrt{\lambda R}}$, $0 \leq y' \leq \frac{B_1}{\sqrt{\lambda R}}$
  - ✓ Rx space resource: $0 \leq u' \leq \frac{A_2}{\sqrt{\lambda R}}$, $0 \leq v' \leq \frac{B_2}{\sqrt{\lambda R}}$

2 Fresnel Region Transmission

- Time and frequency resource → Fourier transform relationship
  - ✓ Time resource *T*, and frequency resource *W*
  - ✓ Number of information: *T*W*
- Linear array resource → Fourier transform relationship
  - ✓ Tx array resource $\left(\frac{A_1}{\sqrt{\lambda R}}\right)$, and Rx array resource $\left(\frac{A_2}{\sqrt{\lambda R}}\right)$
  - ✓ Number of modes for linear array: $\left(\frac{A_1}{\sqrt{\lambda R}}\right)\left(\frac{A_2}{\sqrt{\lambda R}}\right) = \frac{A_1 A_2}{\lambda R}$
- Planar array resource → 2-dim. Fourier transform relationship
  - ✓ Number of modes for horizontal(vertical) direction array: $\frac{A_1 A_2}{\lambda R}, \frac{B_1 B_2}{\lambda R}$
  - ✓ Number of modes for planar array: $\left(\frac{A_1}{\sqrt{\lambda R}}\right)\left(\frac{B_1}{\sqrt{\lambda R}}\right)\left(\frac{A_2}{\sqrt{\lambda R}}\right)\left(\frac{B_2}{\sqrt{\lambda R}}\right) = \frac{A_1 A_2 B_1 B_2}{(\lambda R)^2}$

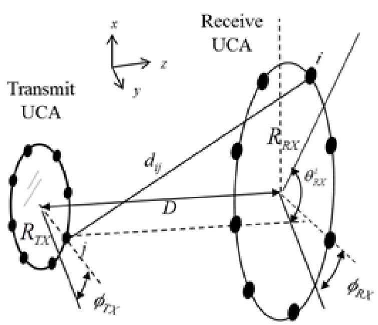
(Example)

Carrier frequency: *150 GHz*, $\lambda = 2\ mm$, $R = 3\ m$, $A_1 = A_2 = B_1 = B_2 = 20\ cm$

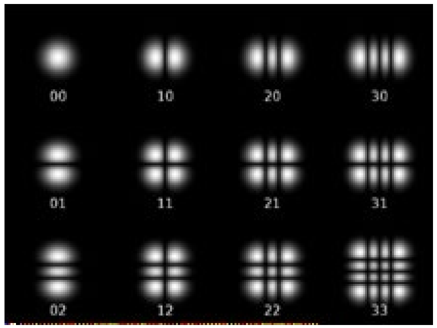
Number of modes: $\frac{20cm*20cm*20cm*20cm}{(3m*2mm)^2} = 44$

Fresnel Region Transmission

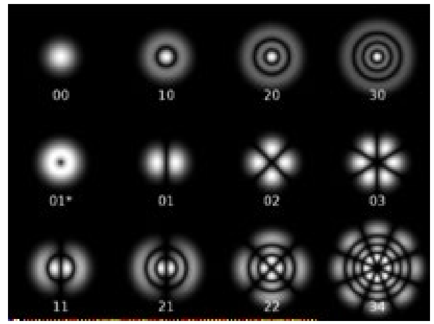
- System design for spatial multimode transmission
  - ✓ Channel environment: LoS environment
  - ✓ In optics, various multi-mode transmission schemes such as OAM, Hermite Gaussian and Laguerre Gaussian modes, have been studied.
  - ✓ In order to apply it to wireless communication environment, it is necessary to develop a transmission scheme that addresses RF impairment problems and supports user mobility.



< OAM mode >



< HG mode >



< LG mode >

3 Beamforming for Mobility

- Beamforming for mobility
  - ✓ 5G beamforming for mobility

    : Far-field region beamforming

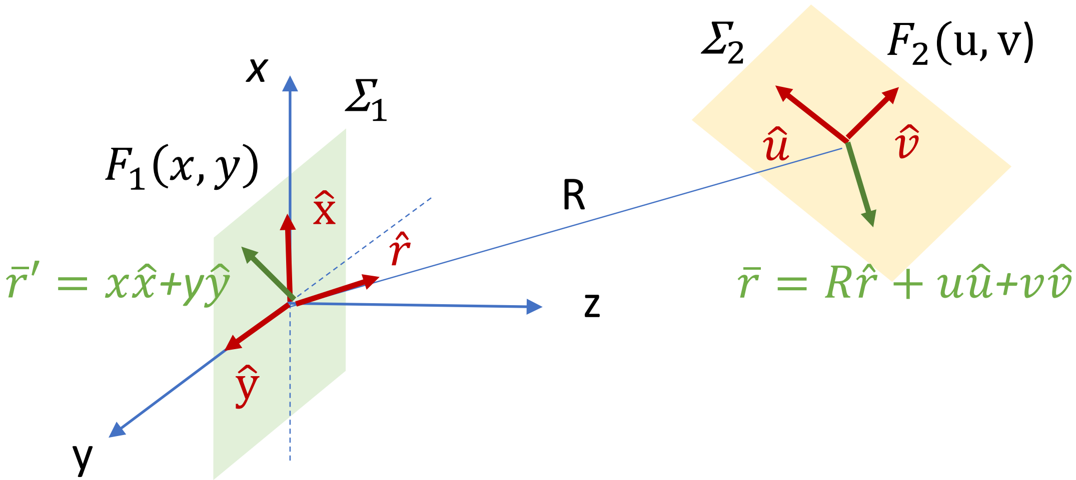
    : Polarized streams can be transmitted in each beam
  - ✓ 6G beamforming for mobility

    : Fresnel region beamforming

    : Multiple modes can be transmitted simultaneously in each beam
- Beamforming for misalignment
  - ✓ When Tx antenna and Rx antenna are not aligned, is it possible to obtain Fourier transform relationship between Tx signal and Rx signal?
  - ✓ Yes, beamforming can make Fourier transform relationship betwen Tx and Rx signals.

Beamforming for Mobility

- Relationship between Tx field and Rx field for misaligned Tx/Rx antenna arrays



$$a_{rx} = \hat{r}\cdot\hat{x},\ a_{ry} = \hat{r}\cdot\hat{y},\ a_{rz} = \hat{r}\cdot\hat{z}$$

$$a_{ru} = \hat{r}\cdot\hat{u},\ a_{rv} = \hat{r}\cdot\hat{v}$$

$$a_{ux} = \hat{u}\cdot\hat{x},\ a_{uy} = \hat{u}\cdot\hat{y}$$

$$a_{vx} = \hat{v}\cdot\hat{x},\ a_{vy} = \hat{v}\cdot\hat{y}$$

$$\bar{r}' = x\hat{x} + y\hat{y},\ (x,y)\in\Sigma_1,\ \bar{r} = R\hat{r} + u\hat{u} + v\hat{v},\ (u,v)\in\Sigma_2$$

$$F_2(u,v) = \frac{j}{\lambda}\iint_{\Sigma_1} F_1(x,y)\frac{e^{-jk|\bar{r}-\bar{r}'|}}{|\bar{r}-\bar{r}'|}a_{rz}dxdy$$

$$\approx \frac{je^{-jkz}}{\lambda R}e^{-jk(ua_{ru}+va_{rv})}e^{-\frac{jk}{2R}(u^2+v^2)}$$

$$\iint_{\Sigma_1} F_1(x,y)e^{jk(xa_{rx}+ya_{ry})}e^{-\frac{jk}{2R}(x^2+y^2)}e^{j\frac{k}{R}(uxa_{ux}+uya_{uy}+vxa_{vx}+vya_{vy})}\,a_{rz}dxdy$$

- Tx/Rx beamforming for mobile users

$S_1(x,y)$: Tx signal $S_2(x,y)$: Rx signal

(1) Tx beamforming

$$F_1(x,y) = S_1(x,y)\underbrace{e^{-jk(xa_{rx}+ya_{ry})}e^{j\frac{k}{2R}(x^2+y^2)}}_{\text{Tx beamforming}}$$

(2) Rx beamforming

$$S_2(u,v) = F_2(u,v)\underbrace{e^{jk(ua_{ru}+va_{rv})}e^{-j\frac{k}{2R}(u^2+v^2)}}_{\text{Rx beamforming}}$$

(3) Relationship between Tx signal and Rx signal

$$S_2(u,v) = \frac{je^{-jkR}}{\lambda R}\iint_{\Sigma_1} S_1(x,y)\, e^{j\frac{k}{R}(uxa_{ux}+uya_{uy}+vxa_{vx}+vya_{vy})}\, a_{rz}dxdy$$

3 Beamforming for Mobility

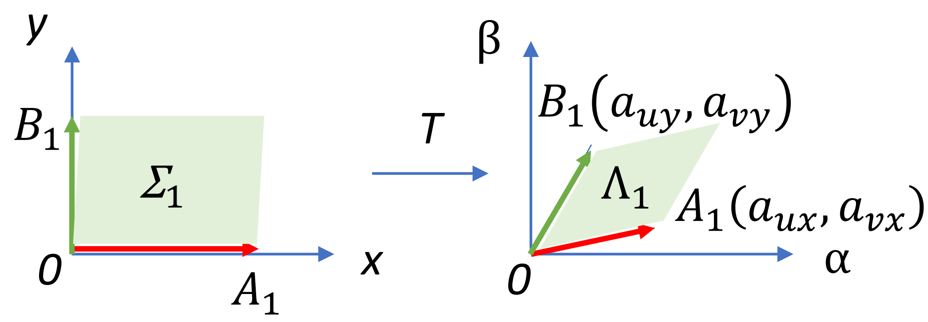
- Coordinate transformation

$$\alpha = x a_{ux} + y a_{uy}$$

$$\beta = x a_{vx} + y a_{vy}$$

$$u x a_{ux} + u y a_{uy} + v x a_{vx} + v y a_{vy} = u\alpha + v\beta$$

$$\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = T\begin{pmatrix}x\\ y\end{pmatrix},\ T = \begin{pmatrix}a_{ux} & a_{uy}\\ a_{vx} & a_{vy}\end{pmatrix}$$



$$\begin{pmatrix}x\\ y\end{pmatrix} = T^{-1}\begin{pmatrix}\alpha\\ \beta\end{pmatrix},\ T^{-1} = \frac{1}{D}\begin{pmatrix}a_{vx} & -a_{uy}\\ -a_{vx} & a_{uy}\end{pmatrix},\ D = \begin{vmatrix}a_{ux} & a_{uy}\\ a_{vx} & a_{vy}\end{vmatrix} = a_{ux}\,a_{vy} - a_{uy}\,a_{vx},\ |D| \le 1$$

$$Q_1(\alpha,\beta) = S_1(x,y) = S_1(T^{-1}(\alpha,\beta)) = S_1\left(\frac{1}{D}(a_{vy}\alpha - a_{uy}\beta), \frac{1}{D}(-a_{vx}\alpha + a_{ux}\beta)\right)$$

$$S_2(u,v) = \frac{je^{-jkR}}{\lambda R}\frac{a_{rz}}{|D|}\iint_{\Lambda_1} Q_1(\alpha,\beta)\, e^{j\frac{k}{R}(u\alpha+v\beta)} d\alpha d\beta$$

$$Q_1(\alpha,\beta) \xleftrightarrow{\text{2-dim. Fourier transform}} S_2(u,v)$$

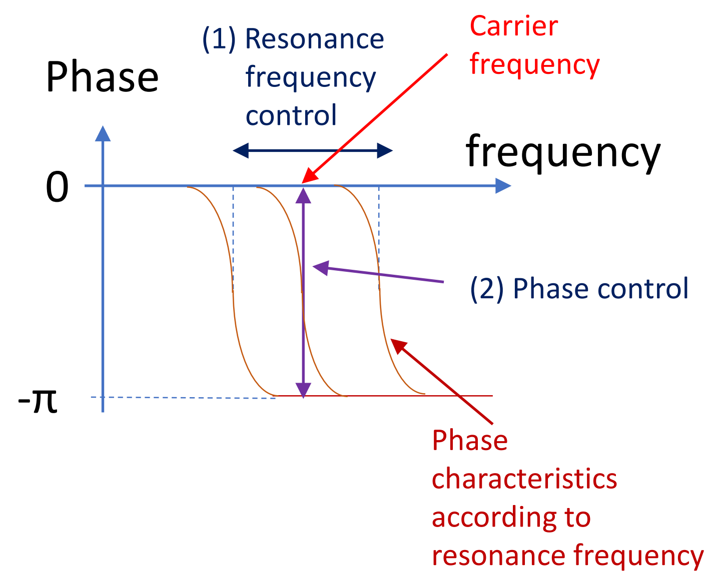
3 Beamforming for Mobility

- Number of modes (rank)
  - ✓ Transmitter antenna array size: $A_1{}^*B_1$
  - ✓ Receiver antenna array size: $A_2{}^*B_2$
  - ✓ Number of modes: $\frac{A_1B_1A_2B_2}{(\lambda R)^2}|D|$, $\quad (D = a_{ux}\, a_{vy} - a_{uy}\, a_{vx})$
- Effect of non-pararell antenna arrays
  - ✓ Capacity may decrease if tx antenna array is not parallel to rx antenna array.
  - ✓ If Tx/Rx antenna arrays are parallel to each other,

    then $|D| = 1$, and the number of modes and capacity are maximized.

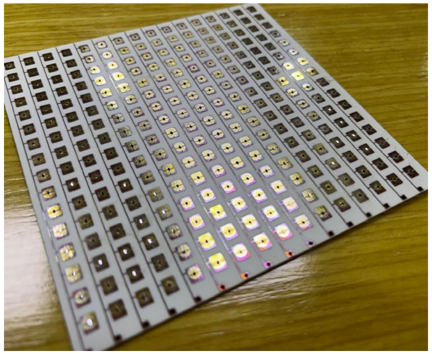
4 Reconfigurable Intelligent Surface

- Reconfigurable intelligent surface
  - ✓ Can overcome the shadowing problem in an NLoS environment.
  - ✓ Can be utilized for beamforming for mobile users.
  - ✓ Reflection type, transmittance type
- What should be considered about RIS?
  - ✓ RIS can be used in beamforming.
  - ✓ You should be able to change phases easily.
  - ✓ Controlling the amplitude is not that important.
- Principle of RIS
  - ✓ RIS can change the phase characteristics at the carrier frequency by controlling the resonance frequency.

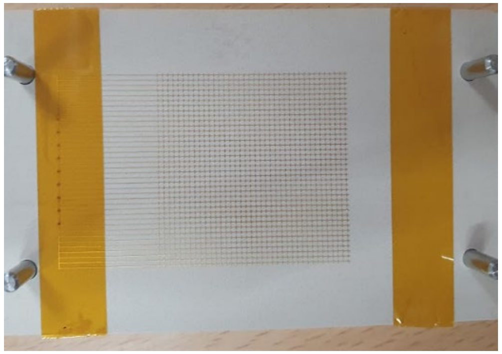


4 Reconfigurable Intelligent Surface

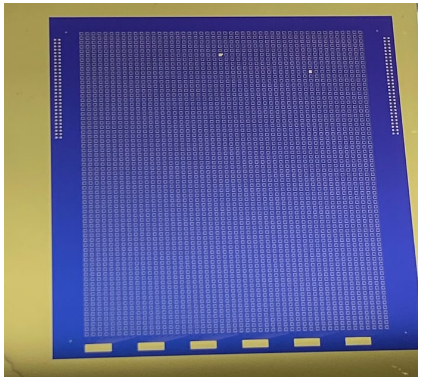
- How to control resonance frequency
  - ✓ Varactor diode: control capacitance (Upper-mid band, 24 GHz)
  - ✓ Graphene: control chemical potential (Sub-THz, 150 GHz, 300 GHz)
  - ✓ Liquid crystal: control permittivity (Sub-THz, 150 GHz, 300 GHz)



< Varactor based RIS >



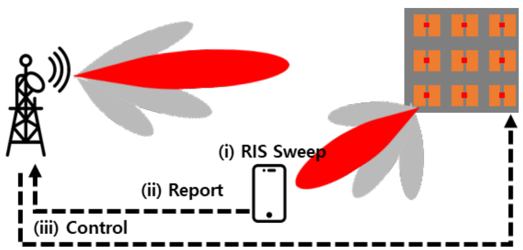
< LC based RIS >



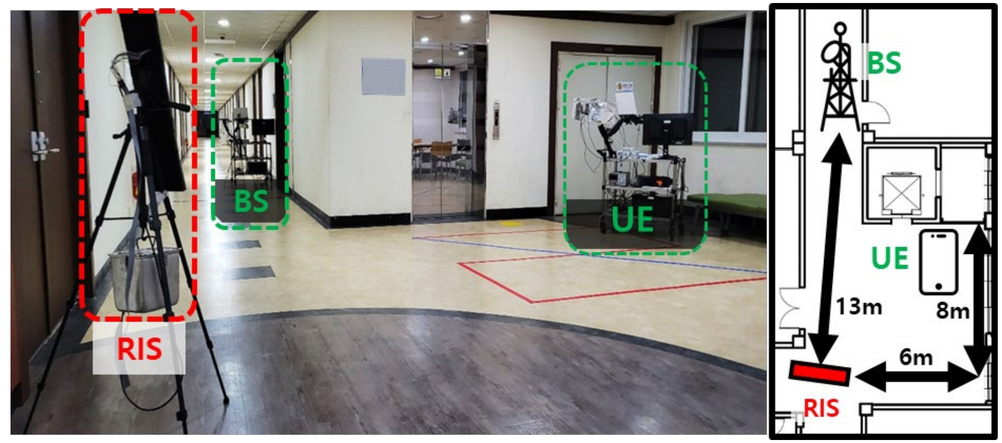
< Graphene based RIS >

4 Reconfigurable Intelligent Surface

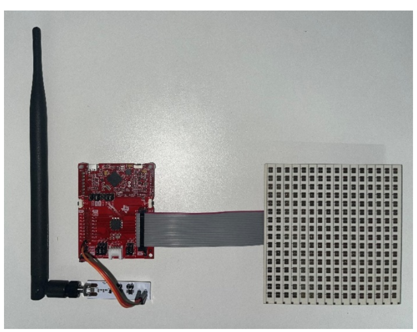
- RIS implementation in 6G upper-mid band (varactor diode)



< Concept of RIS beam control>

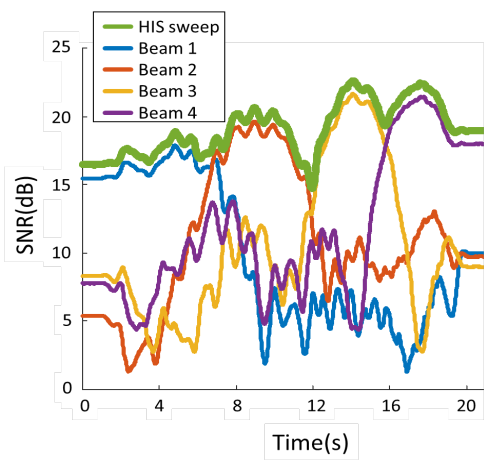


< Real-time RIS operation in indoor environment >



< RIS and RIS controller >

< Tx system (Rx system) >



< Measurement results >

1) Beam 1~4
  - metasurface beamforming pattern 1~4
2) HIS sweep
  - beamforming pattern giving
    the best SNR value

5 Conclusion

- Multi-mode transmission for 6G 1 Tbps capacity
  - ✓ Time and space resources should be utilized effectively.
  - ✓ In sub-THz band, the number of modes and capacity are determined by antenna array size and transmission distance.
  - ✓ Through transmitting multiple modes per each beam, we can achieve 1 Tbps capacity, which is one of the goals of 6G wireless communication.
- Beamforming for mobility
  - ✓ Beamforming is also required to serve mobile users.
  - ✓ There is a need to develop a low complexity method for multi-mode transmission and beamforming.
- RIS for 6G solution
  - ✓ RIS allows you to overcome the shadowing problem.
  - ✓ RIS can be effectively used in low complexity beamforming solutions.

Thank you