OAM Multiplexing of 5 GHz Band Microwave Signal Propagating Along PVC Pipe Walls for a Buried Pipe Inspection Robot

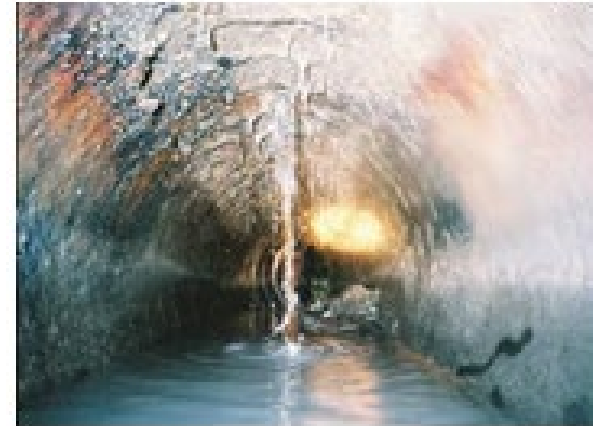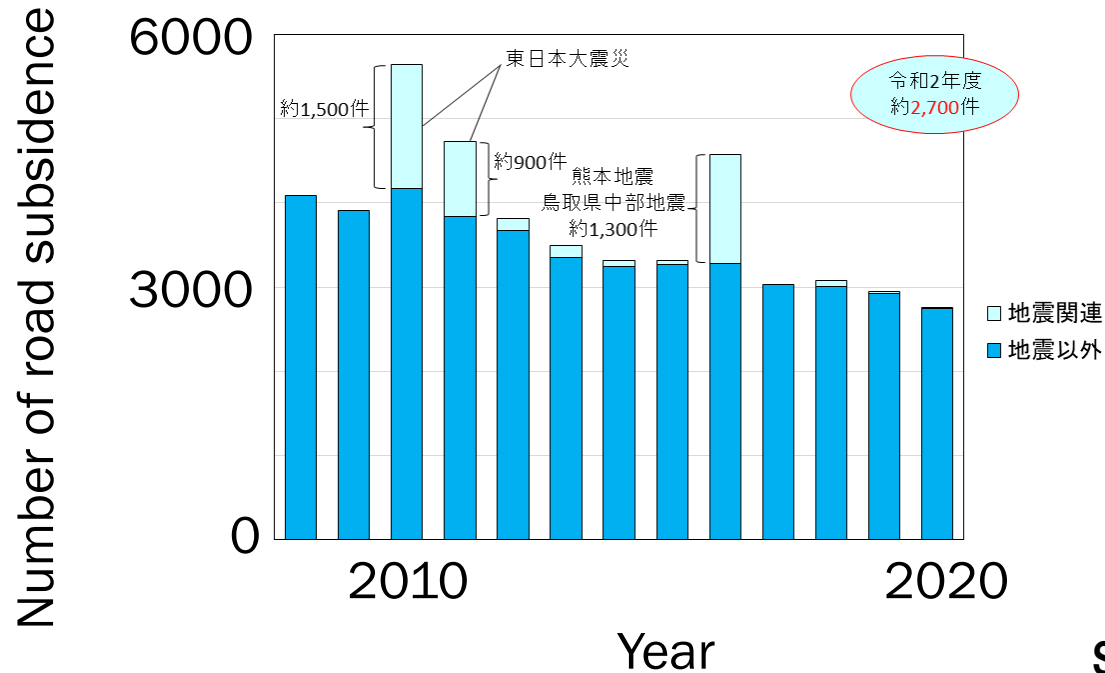A. Hirata[1]

[1]Chiba Institute of Technology, Chiba, Japan

Outline

- Background

- Communication challenges for buried pipe inspection robots

- Microwave signal propagating along PVC pipe walls

- Propagation of OAM mode along PVC pipe wall

- OAM mode multiplexing

- Conclusion

Background

- The number of road subsidence caused by buried pipe is around 3,000 per year
- Systematic maintenance and management is necessary to ensure sustainable infrastructure

Road subsidence caused by buried pipe

東日本大震災

約1,500件

約900件 熊本地震

鳥取県中部地震
約1,300件

令和2年度
約2,700件

地震関連
地震以外

6000

3000

0

Number of road subsidence

2010   2020

Year

Source: Ministry of Land, Infrastructure, Transport and Tourism website
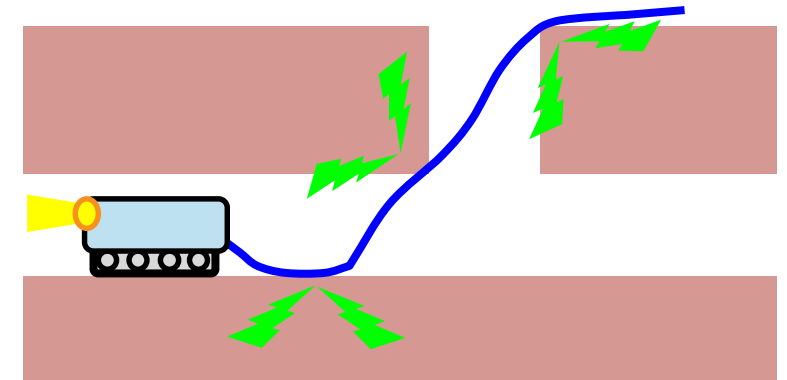
Inspection of buried pipe

- Use of robots considered for inspection of buried pipe interior

- Using wired communication for signal transmission restricts the robot's movement

Current buried pipe inspection

Buried pipe inspection robot

Challenges in wired communication with robots
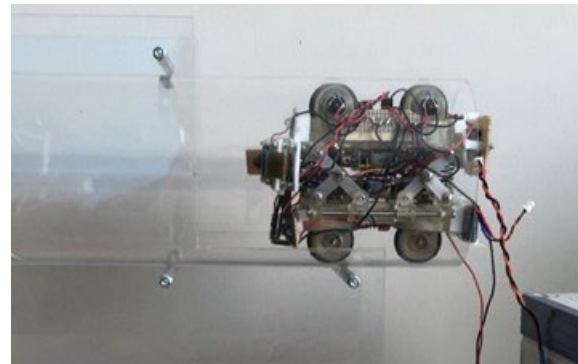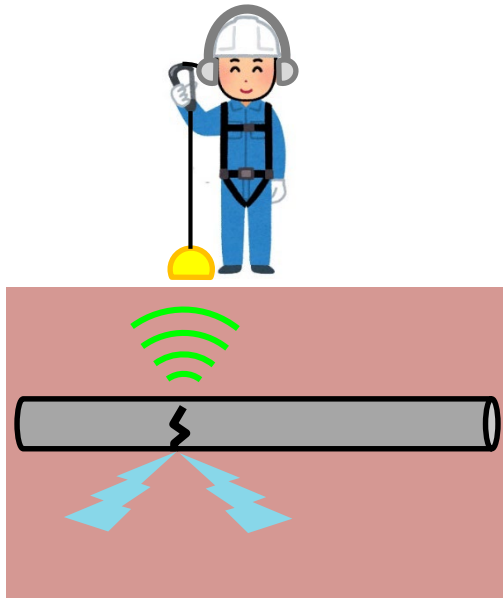
A. Matsuura, et al., ICPE, C007 2022

Microwave propagation along thin pipe

- Microwaves propagating through narrow pipes suffer high loss
- Low loss transmission of microwave signal can be achieved by using microwave guided-modes, which can propagate along pipe walls

**Electric field distribution along 0.5-m PVC pipe**

inside pipe

along pipe wall

pipe wall
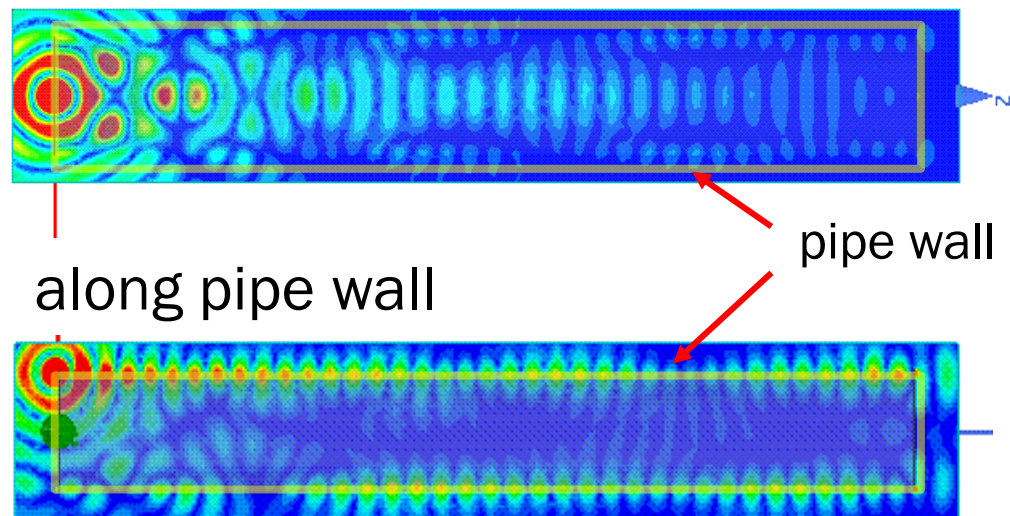
Transmission characteristics along 1-m PVC pipe
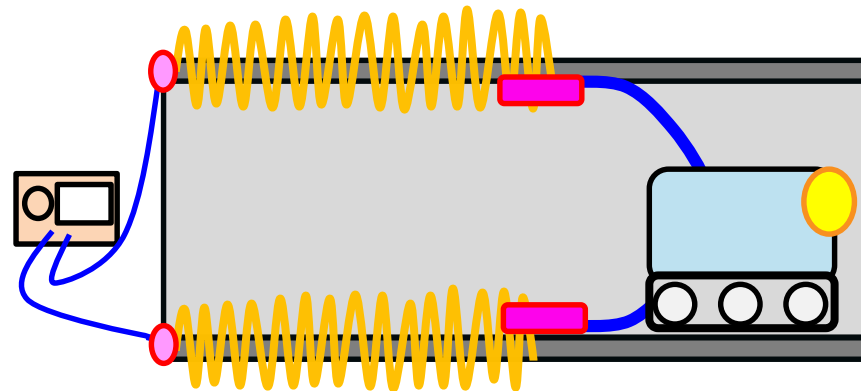
MIMO multiplexing
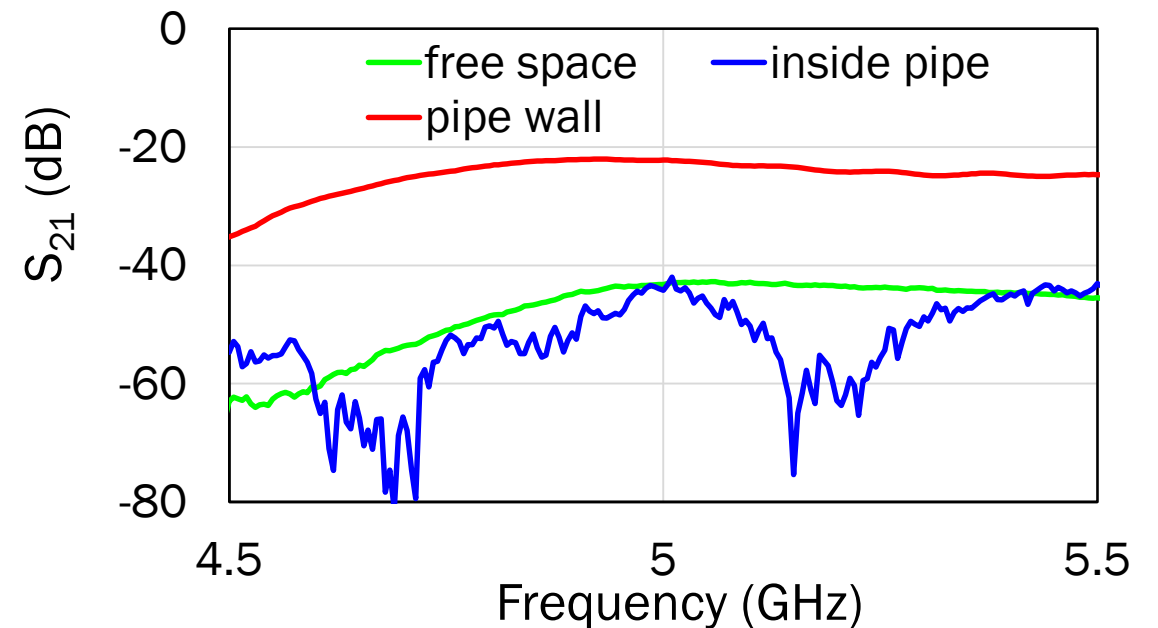
- **Multi-input multi-output (MIMO)** technology has been investigated to increase the communication capacity

- Spatial correlation between antennas increases, which decreases the capacity of the MIMO system in case pipe length increases
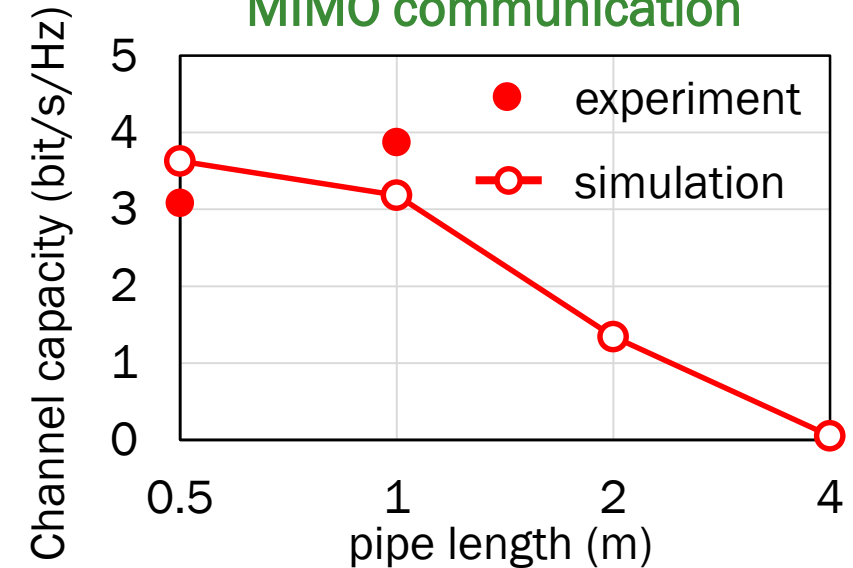
MIMO communication
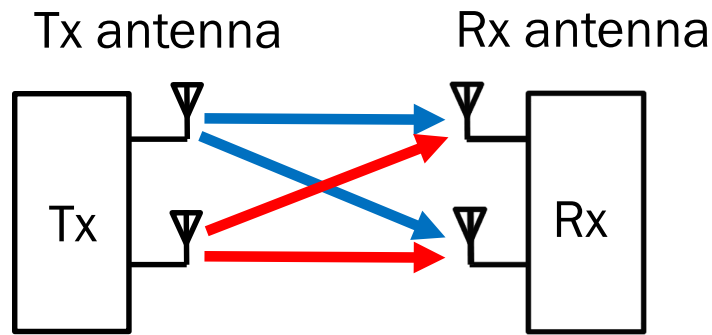
MIMO communication for buried pipe inspection robot

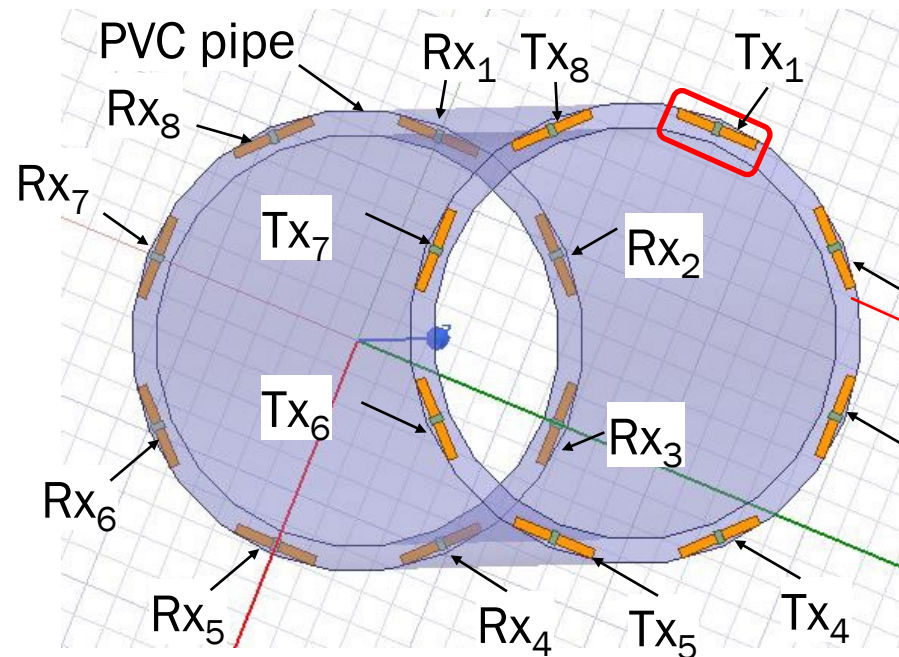Channel capacity of MIMO communication

- Eight Tx and Rx dipole antennas were installed on the ends of the PVC pipe wall at 45º intervals
- 5 GHz signal was input to each Tx antenna with different phases depending on OAM mode
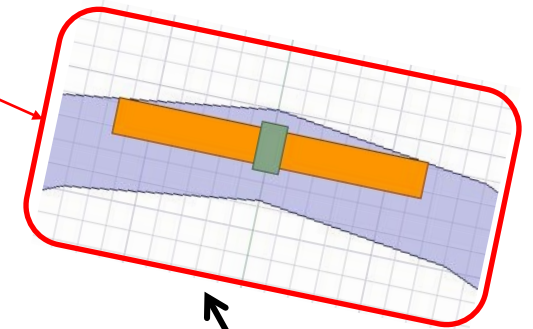
Input signal for Tx$_m$

$$f_{m,l} = \frac{1}{\sqrt{N}} exp\left(j\frac{2\pi l}{N}m\right)$$

l: OAM mode number

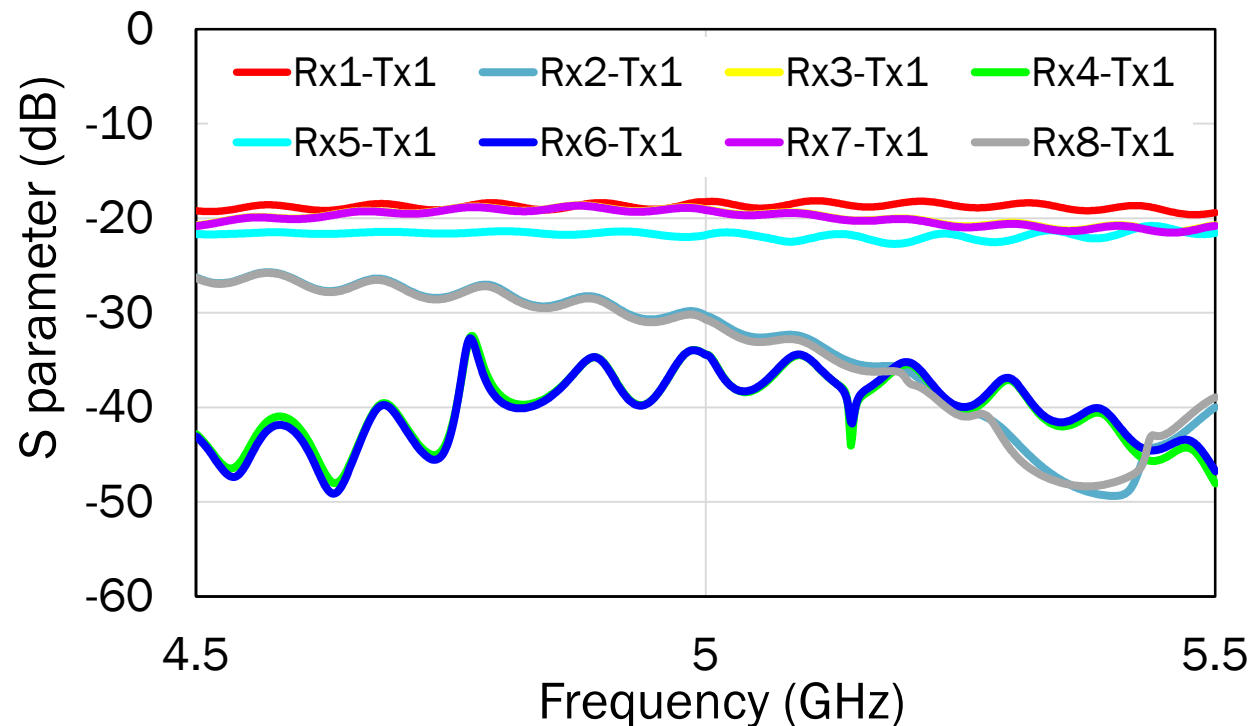*N:* total number of the transmitter antenna (=8)

Inner diameter: 125 mm
Outer diameter: 140 mm
PVC permittivity: 2.7
PVC loss tangent: 0.007

dipole antenna

Transmission loss of OAM mode

- Transmission loss from Tx_1-Rx_1 : 18.3 dB

- Tx_1-Rx_2, Rx_8, Rx_6, Rx_8 : 12–16 dB lower than that of Rx_1

Transmission loss of microwave guided-modes propagating along 1-m-long PVC pipe
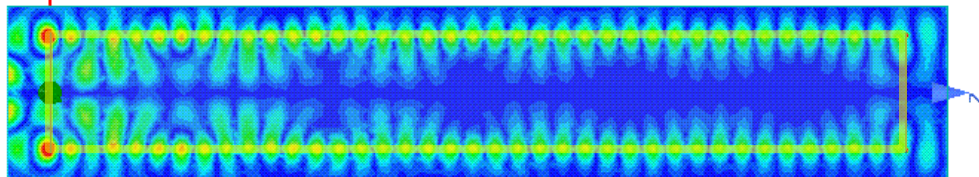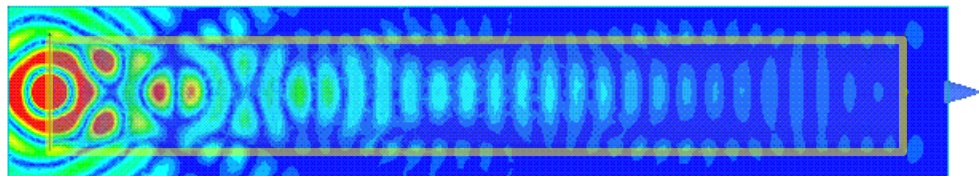
Transmission loss of OAM mode

- Transmission loss of the OAM mode (*l=0*) : 37.6 dB for PVC pipe length of 8 m

- 20 dB smaller than that when only Tx1 and Rx1 were placed at the center of both ends of the pipe
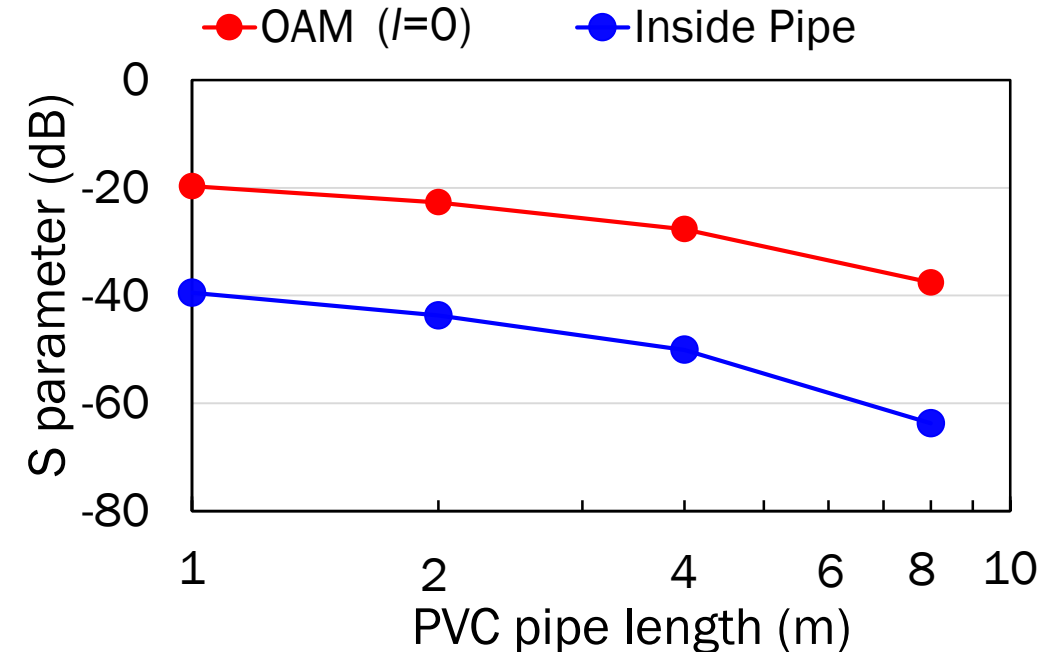
Electric field distribution along 0.5-m PVC pipe

Transmission characteristics of OAM mode

OAM (*l* = 0)

inside pipe

We2E-3

Phase distribution of OAM mode

- *l*-th mode generates *2πl* phase rotations along the pipe
- In modes *+l* and *-l,* the direction of rotation of the phase is reversed

Simulation results of phase distribution

OAM mode

PVC pipe

200 mm
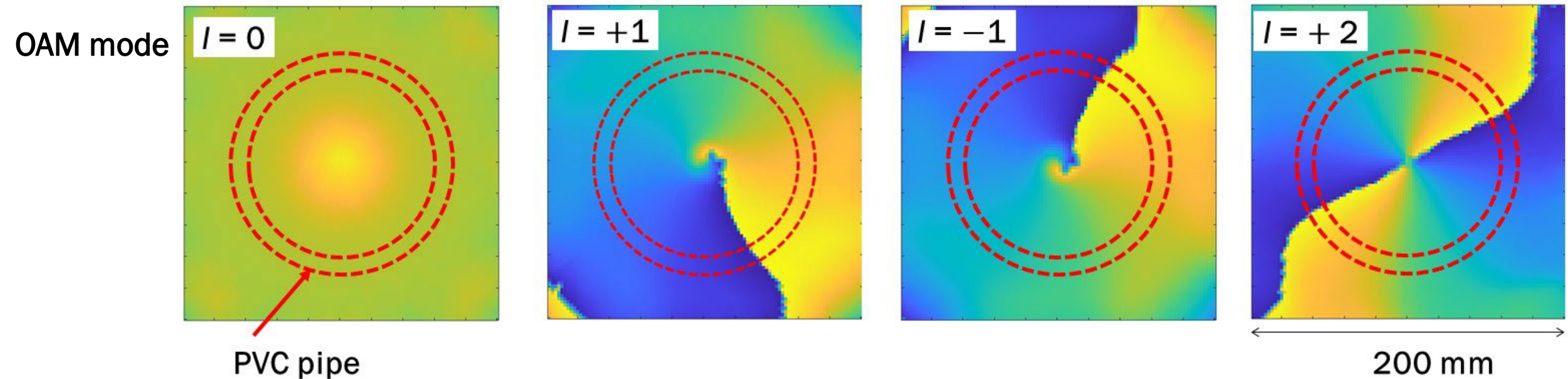
# Electric field vector distribution

- Electric field is concentrated around the pipe wall and propagates while rotating along the pipe wall

- In modes *+l* and *-l*, the direction of rotation of the electric field is reversed

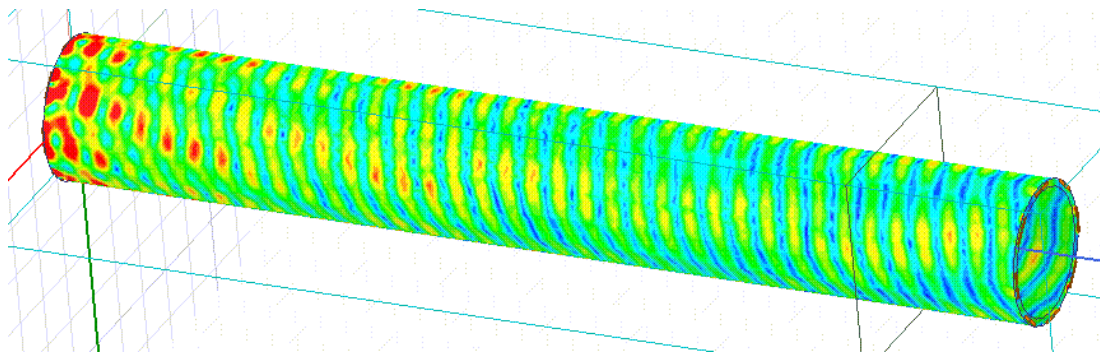Simulation results of electric field vector distribution
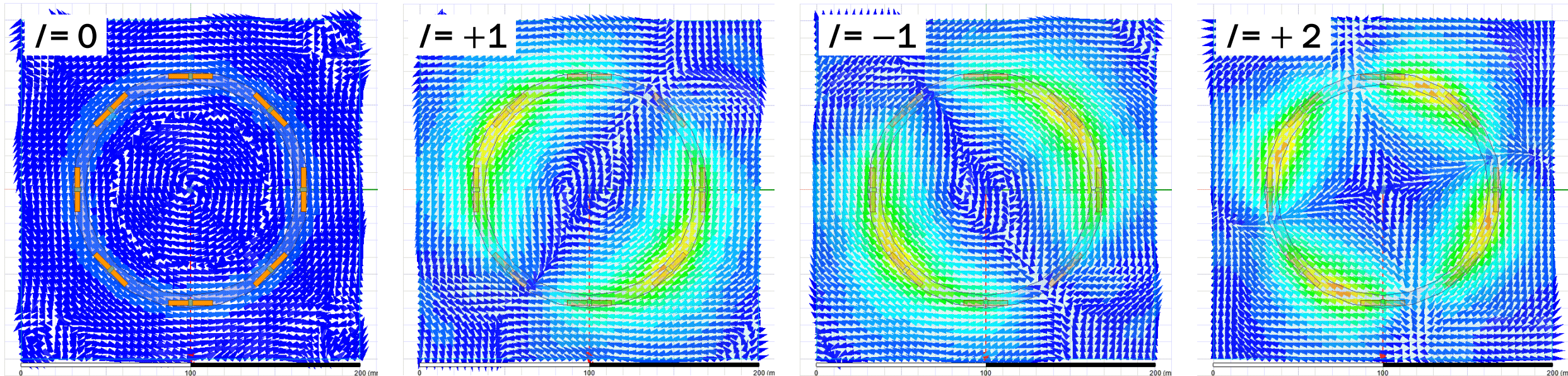
- Twisting of the wavefront of a propagating microwave signal
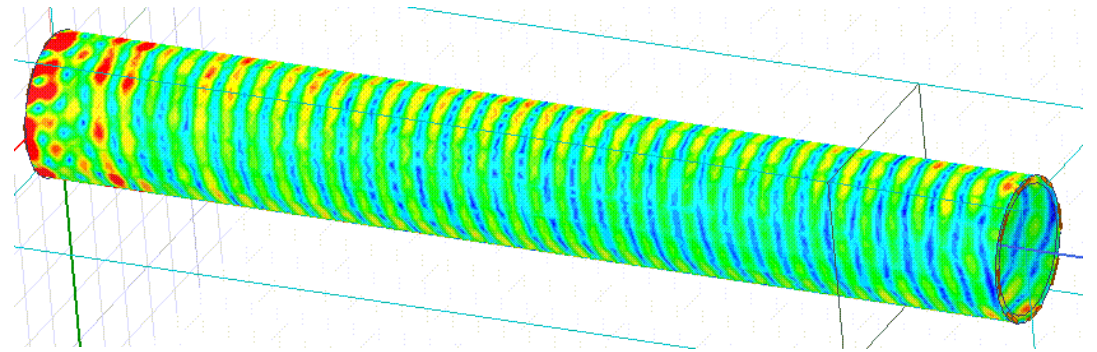- The wavefront phase of an OAM beam can change from 0 to *2πl* azimuthally
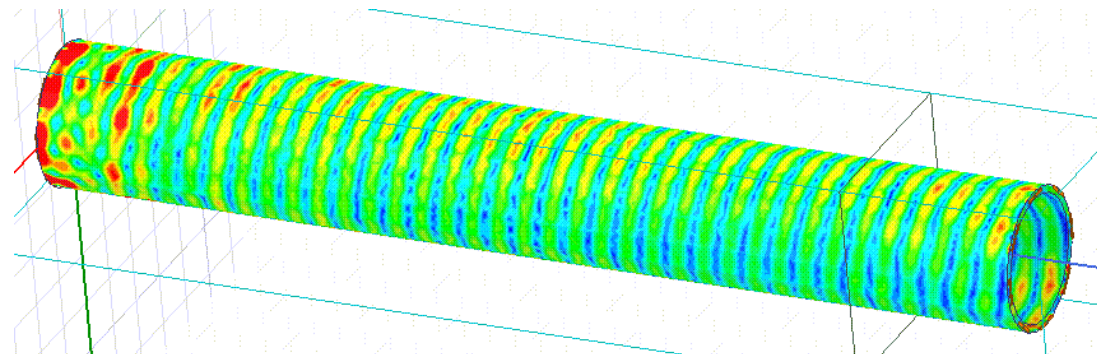
l = 0

l = +1

l = + 2
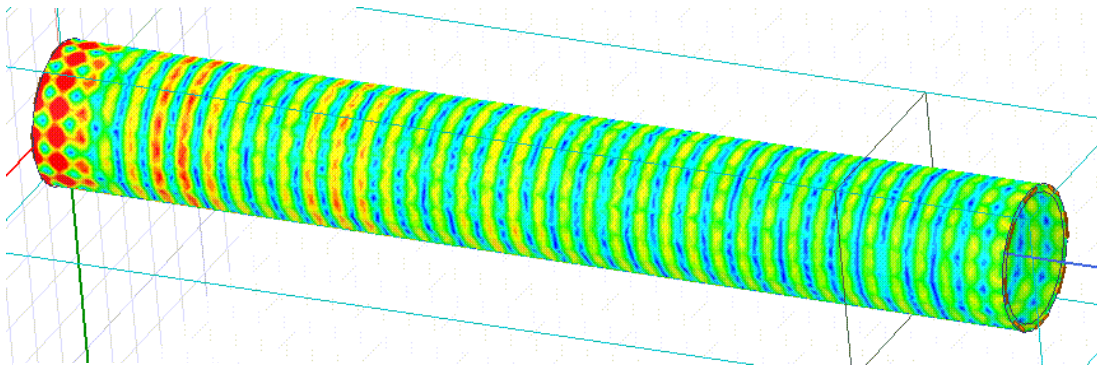
l = −1

- Carrier frequency: 5.0 GHz, Bandwidth: 20 MHz

- Output power of Tx: 5 mW/MHz

- When the mode *l* signal is extracted at the receiver side, each received signal is combined by giving it a phase rotation opposite to that of the transmitted signal

transmitted signal x_m of the antenna Tx$_m$

$$x_m = \sum_{l=-L}^{+L} s_l \frac{1}{\sqrt{N}} exp\left(j\frac{2\pi l}{N}m\right)$$

s_l: transmission signal of OAM mode number *l*

received signal y$_n$ of Rx$_n$

$$y_n = H_{nm}x_m$$

H_{nm}: channel response between Tx$_m$ and Rx$_n$

output $z_{l,l}$ after synthesis in the case of mode l

$$z_{l,l} = \sum_{n=1}^{N} y_n \frac{1}{\sqrt{N}} exp\left(-j\frac{2\pi l}{N}n\right) = s_l \sum_{m=1}^{N} \overline{h_m}$$

intermodal interference signal $z_{l,l'}$ between modes l and l'

$$z_{l,l'} = \sum_{n=1}^{N} \sum_{m=1}^{N} h_{nm} \sum_{l=-L}^{+L} \sum_{l'=-L, l'\neq l}^{+L} \frac{s_{l'}}{N} exp\left(-j\frac{2\pi ln}{N}\right) exp\left(j\frac{2\pi l'm}{N}\right)$$
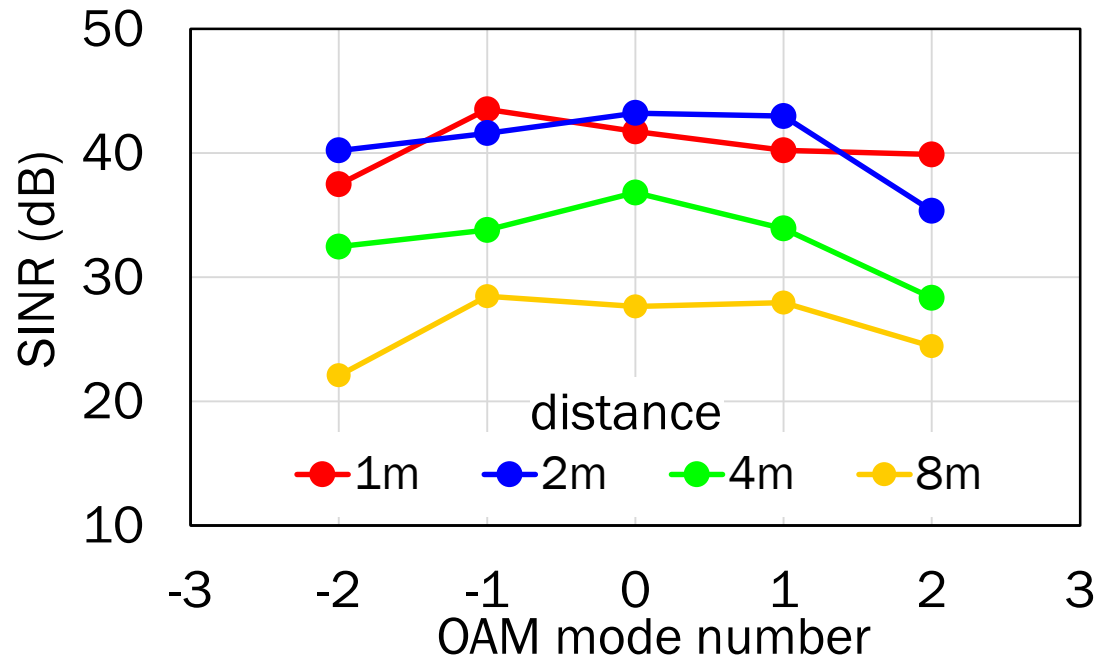
system capacity of OAM transmission

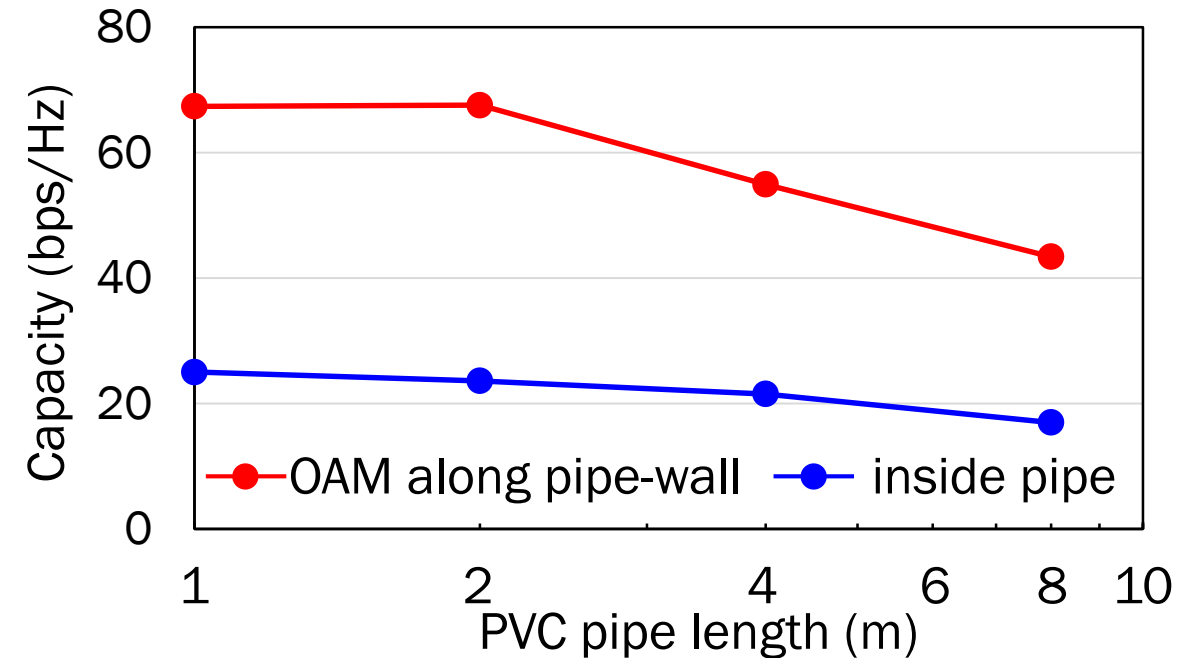$$C_{sum} = \sum_{l=-L}^{L} log_2(1+\gamma_l)$$

SINR of mode l

$$\gamma_l = \frac{E\left[|z_{l,l}|^2\right]}{E\left[\sum_{l',l'\neq l}|z_{l,l'}|^2\right] + E[|\widetilde{n_l}|^2]}$$

- SINR for pipe length of 1m: 37.5 dB to 43.5 dB
- System capacity of OAM multiplexing achieve over 2.5 times the capacity to a system that transmits inside the pipe
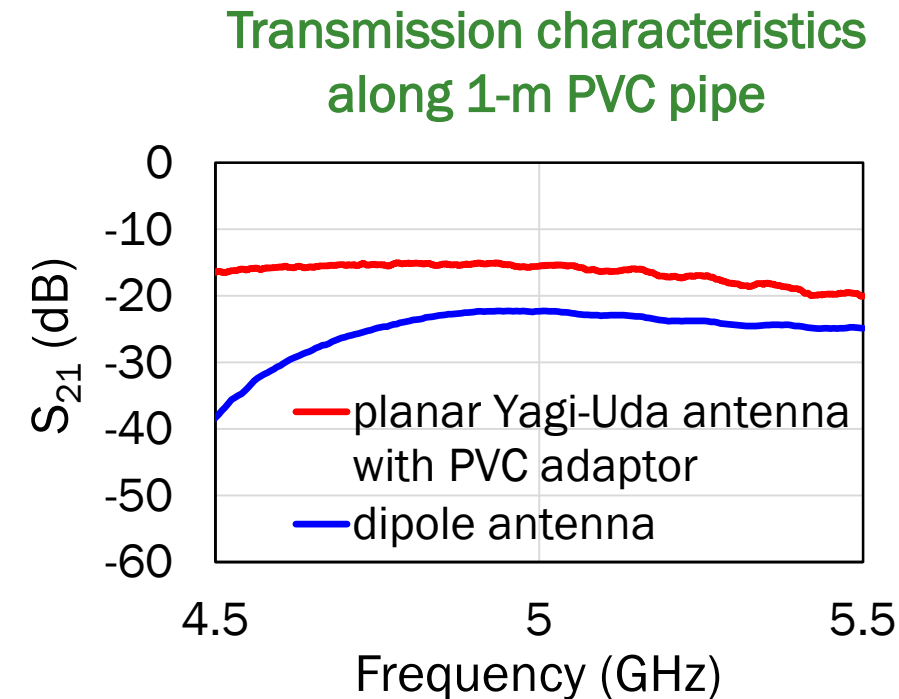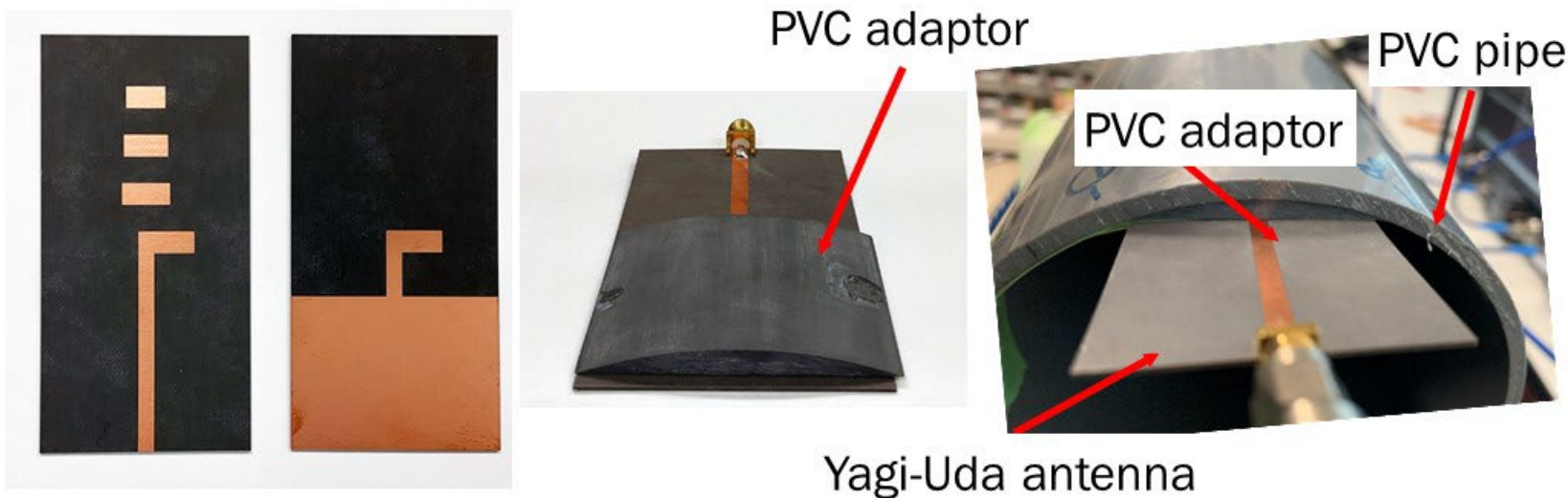

Dependence of SINR on OAM mode number

Dependence of capacity on pipe length

Future development

- Development of Yagi-Uda antenna for contacting the interior of PVC pipe

- Measurement of channel response between Tx_{1-8} to Rx_{1-8} along 1-m-long PVC pipe by VNA

PVC adaptor

Yagi-Uda antenna

PVC adaptor

PVC pipe

Transmission characteristics along 1-m PVC pipe

planar Yagi-Uda antenna with PVC adaptor

dipole antenna

Summary

- OAM multiplexing transmission along pipe wall for communication capacity enhancement for a buried pipe inspection robot

- OAM modes can be generated in the microwave signal that propagates along the pipe wall by giving a phase rotation to the transmitter antennas

- SINR: 37.5–43.5 dB for 1-m-long PVC pipe

- OAM multiplexing system where microwave signal propagates along pipe wall achieved 2.5 times system capacity compared to system where microwave signal propagates inside pipe