XG Mobile Promotion Forum

6G Radio Technology Project
Advanced MIMO WG
— WG Activities and White Paper —

September 30, 2025

Advanced MIMO Working Group

Introduction of Advanced MIMO Working Group

- **Advanced MIMO Working Group (A-MIMO WG)**
  - Chair: Kazushi Muraoka (NEC)
  - Vice chairs: Daisei Uchida (NTT), Shunsuke Kamiwatari (KDDI Research)
  - 40 Members (As of 2025/09)
    - Industry: KDDI, NTT, NTT DOCOMO, Softbank, NEC, Sharp, Ericsson Japan, Panasonic, KYOCERA, Sony, Huawei Japan, NICT, Keysight, DNP,
    - Academia: Hokkaido Univ., Univ. of Electro-Communications, Tokyo Univ. of Science, Tohoku Univ., Fukuoka Univ., Tokyo Univ., Science Tokyo

- **Objectives of WG**
  - Engage in discussions regarding domestic and international technological trends, standardization activities related to Advanced MIMO technologies as well as use cases and scenarios of practical application
  - Propose directions for the Advanced MIMO technologies.

- **Recent Activities**
  - Monthly meeting including discussion on Advanced MIMO related topics
  - White Paper

Outlines

- Introduction of White Paper
  - Preface
  - Section I: Evolution and Challenges of Advanced MIMO Towards 6G
  - Section II: Recent Activities of Advanced MIMO Technologies in Japan

Preface

- **Expectation and requirement for 6G**
  - Foundational infrastructure to build CPS and digital twins in the AI era
  - Cost-effective and sustainable networks
  - Efficient use each frequency bands (Sub6 GHz, mmWave, FR3)

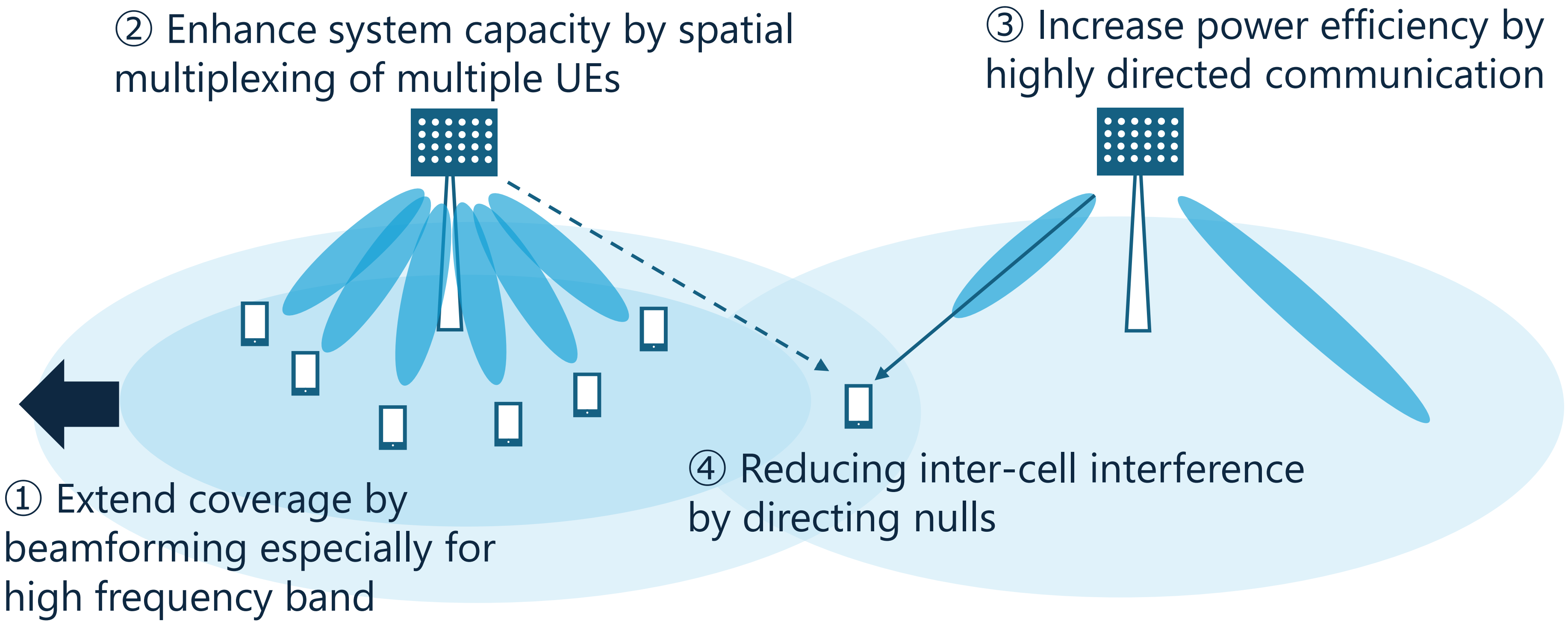
- **MIMO Technology Evolution**
  - From single-user MIMO to multi-user MIMO
  - From MIMO to Massive MIMO
  - From single TRP to multi TRPs (distributed MIMO: D-MIMO)

- **Toward Advanced MIMO**
  - Involving more BSs and UEs, both massive MIMO and distributed MIMO technologies will evolve and be integrated. Ultimately, concept of MIMO expands to optimize spatial transmission for entire systems
  - Evolved MIMO technologies from traditional massive MIMO and multi-TRP are broadly defined as Advanced MIMO technologies in this white paper.

- **Features of Japanese R&D in this area**
  - Many researches and experiments for D-MIMO in broad rage of frequency range (sub6/mmWave/SubTHz)

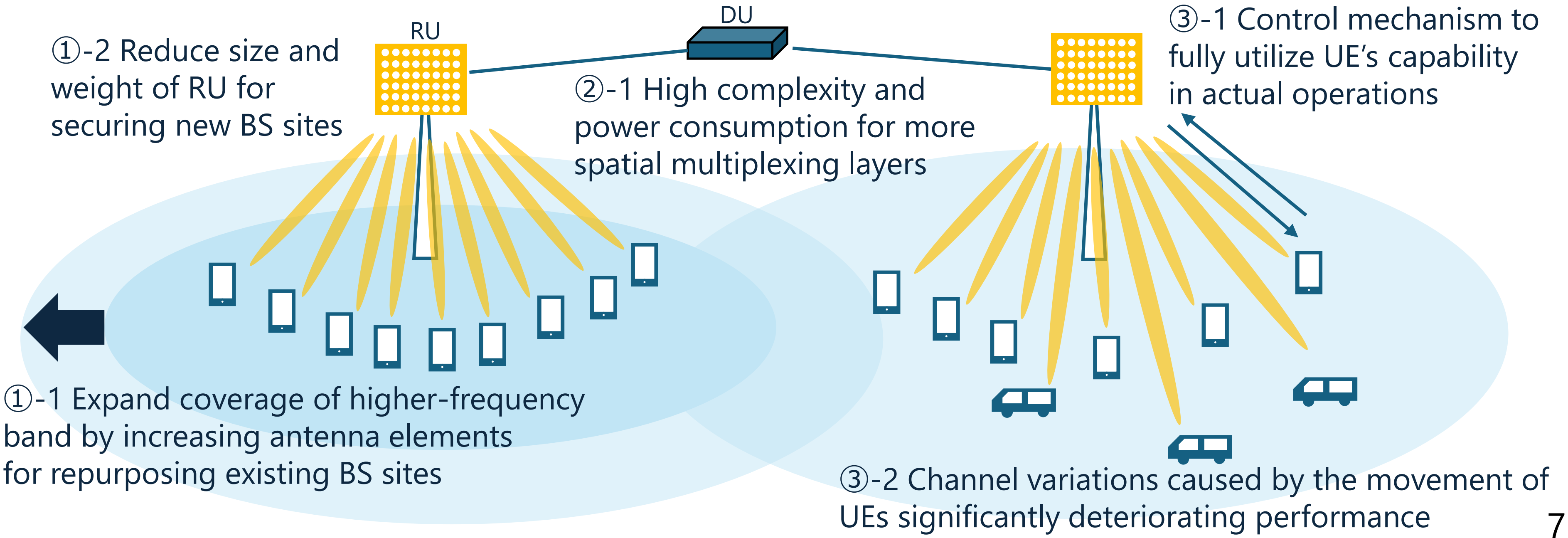
Section I
Evolution and Challenges of Advanced MIMO Towards 6G

Advantages of Massive MIMO



Challenges toward Advanced Massive MIMO

① Challenges related to BS deployment and frequency
② Challenges concerning equipment for BSs and Ues
③ Challenges in transmission methods



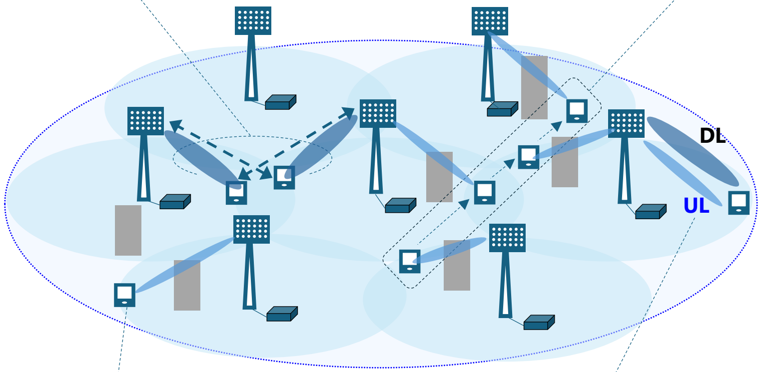
I-1. Current Status and Challenges of Distributed MIMO

Advantages of Distributed MIMO

Cellular Configurtaion

(2)
Low-capacity density
(Interference Inter-cell)

(3)
Low radio quality under shadowing
(without L1 site-diversity)



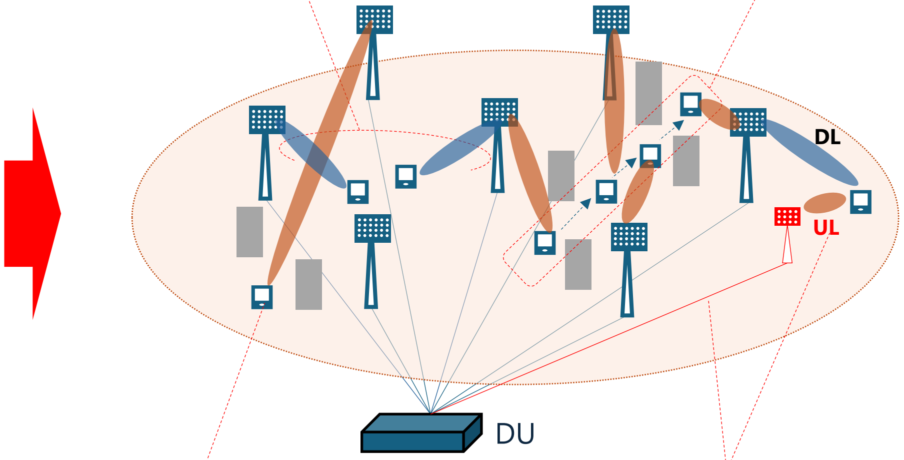
(1)
Low radio quality at cell edge
(in high shadowing direction)

(4)
Low radio quality in UL
(Low link budget due to low transmission power from UE)

Distributed MIMO Configurtaion

(2)
High-capacity density
(MU-MIMO with low spatial correlation)

(3)
High radio quality even under shadowing
(with L1 site-diversity)



(1)
Uniform radio quality in all area
(low shadowing in all direction)

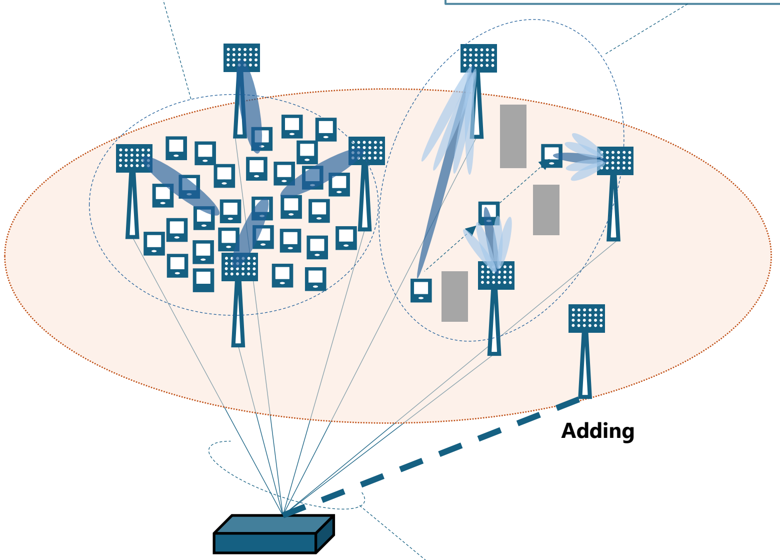
(4)
High radio quality in UL
(with reception only TRP)

Challenges of Distributed MIMO

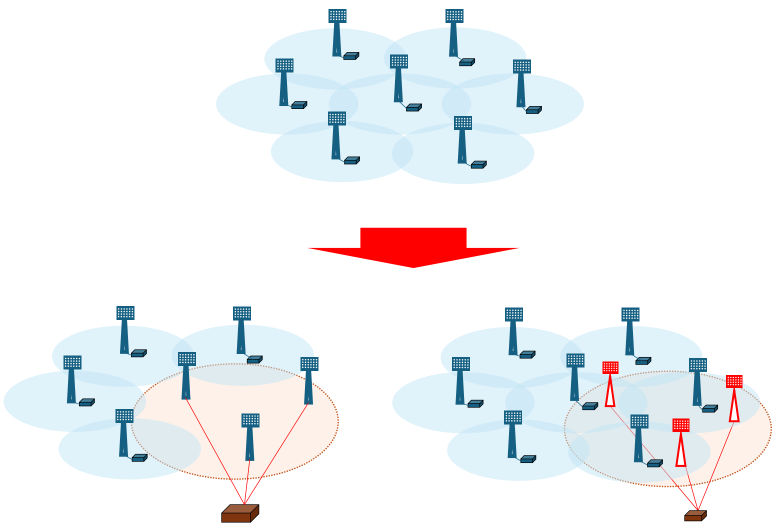
The number of spatial resource increase :
- Schedulers become more complex.
- Reference signals needs flexibility to increase.

Using high-frequency band:
- Optimum selection for combination of TRP/beam
- Proactive selection of TRP under shadowing

How do we evolve from a cellular configuration to a distributed MIMO configuration?



Adding TRP:
- Deployment TRP cost need to be lower
- Fronthaul capacity need to be flexibly expanded



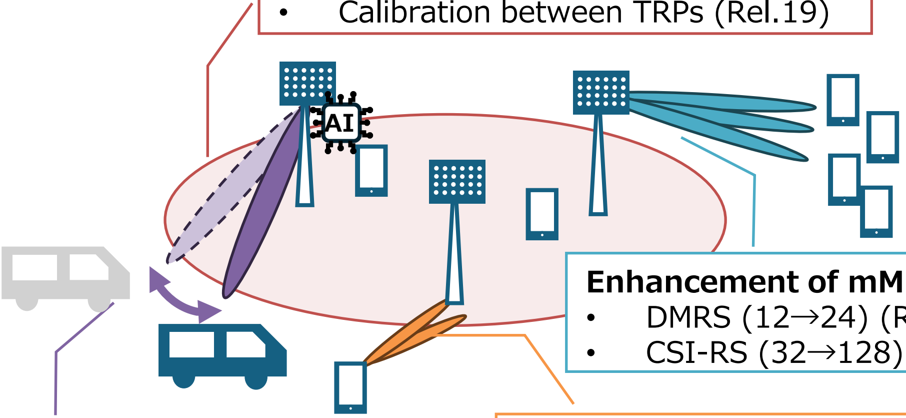
Configuring distributed MIMO with existence TRP

Configuring distributed MIMO with new TRP

I. Evolution and Challenges of Advanced MIMO Towards 6G
I-3. Recent Activities related Advanced MIMO in 3GPP

A-MIMO in 5G-Advanced

Realization of D-MIMO
- DL CJT (Rel.18)
- Calibration between TRPs (Rel.19)

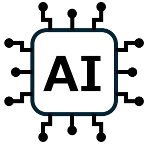


Enhancement of mMIMO
- DMRS (12→24) (Rel.18)
- CSI-RS (32→128) (Rel.19)

Stable communication in FR2
- UE-initiated/Event-driven beam management (Rel.19)
- AI-based beam management (Rel.19)

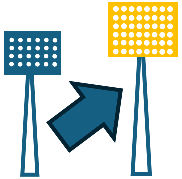
Enhancement of Uplink
- UL Layer/SRS (4→8) (Rel.18)
- STxMP (Rel.18)
- UL-only TRP, 3Tx UE (Rel.19)

Towards 6G



AI/ML-native NW
- AI-based function
- RS enhancement

Energy friendly NW
- Network Energy Saving
- Energy efficient MIMO



Further evolution of MIMO
- More massive antennas
- Practical D-MIMO
- Side systems (RIS, etc.)

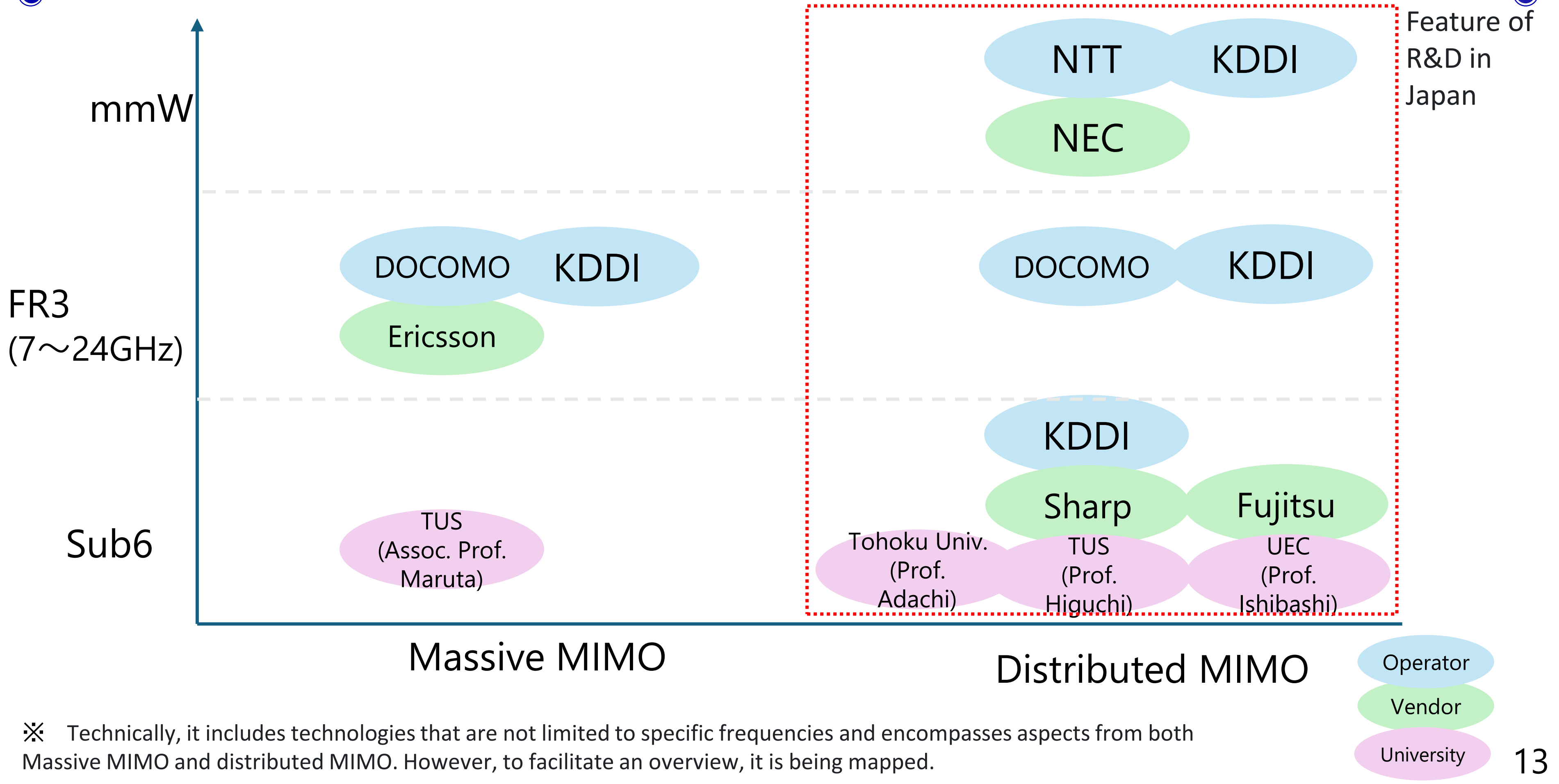
New spectrum
- Frequency Range 3 (FR3)
- Efficient use of FR1-FR3

Section II
Recent Activities of Advanced MIMO Technologies in Japan

Section II Contributions

Contributors (1st)	Title
KDDI Research, Inc.	Research Activities for MIMO Evolution in Each Frequency Range towards 6G
NTT DOCOMO, INC.	Performance Evaluation of FR3 Distributed MIMO Using 6G Simulator
NTT DOCOMO, INC.	Performance Evaluation of FR3 Massive MIMO in Real Urban Areas through Link-Level Simulation
NTT	High-frequency Band Distributed Antenna System
NEC Corporation	Distributed MIMO Technology for Efficient Utilization of Millimeter-Wave Bands
Fujitsu Limited	Distributed Antenna Technology (High-density Distributed Antenna System and Transmission Point Sharing Control)
SHARP Corporation	6G views on Coherent Joint Transmission and Multi-User MIMO
Ericsson Research Japan	A Study on Advanced MIMO Large Arrays in the 7–15 GHz Spectrum for 6G
Tohoku University	User Cluster-centric Approach for Cell-free Massive MIMO Systems
Tokyo University of Science	Low-Complexity User-Centric TRP Clustering Method in Downlink Cell-Free MIMO with Regularized ZF-Based Beamforming
Tokyo University of Science	Robust Massive MIMO Transmission Technology in Mobile Environments
The University of Electro-Communications	Recent R&D Activities of Distributed MIMO (D-MIMO) Technologies in Japan

Main Target of Each Contribution



※ Technically, it includes technologies that are not limited to specific frequencies and encompasses aspects from both Massive MIMO and distributed MIMO. However, to facilitate an overview, it is being mapped.

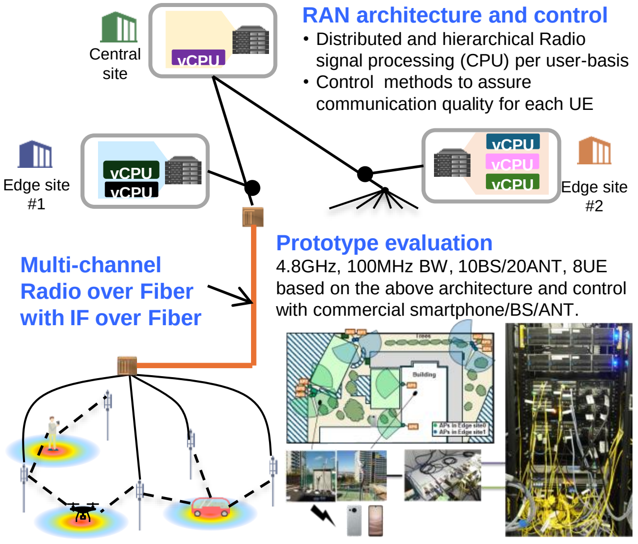
Research Activities for MIMO Evolution in Each Frequency Range towards 6G (KDDI)

Provide dependable wireless quality by integrating diverse frequency ranges

Frequency Ranges (FRs) in 6G

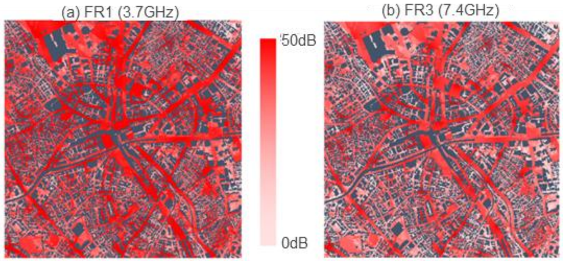
FR1: e.g., 3.5GHz **Further capacity enhancement is necessary**	FR3: e.g., 7, 14GHz **A feasibility study is necessary**	FR2: e.g., 28GHz **Coverage enhancement is necessary**

Developing enable technologies for large-scale CF-mMIMO

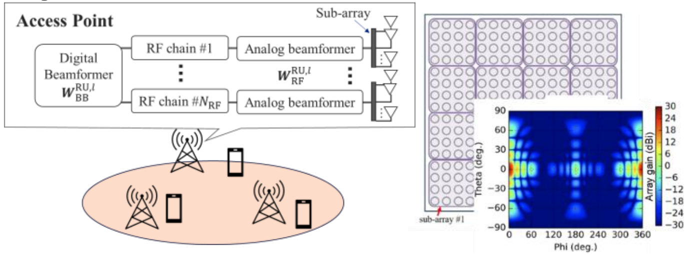


Cell-Free massive MIMO (CF-mMIMO)

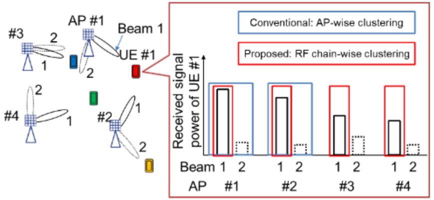
Coverage comparison with FR1



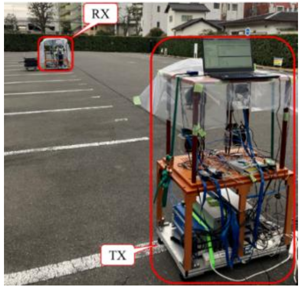
Hybrid BF structure for CF-mMIMO



Clustering scheme for FR2 CF-mMIMO



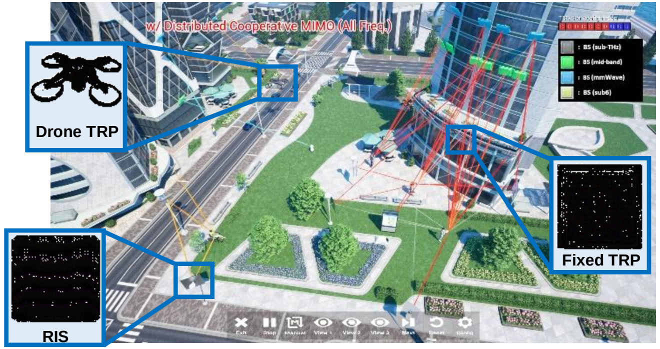
Beamforming (BF) scheme for LoS-MIMO



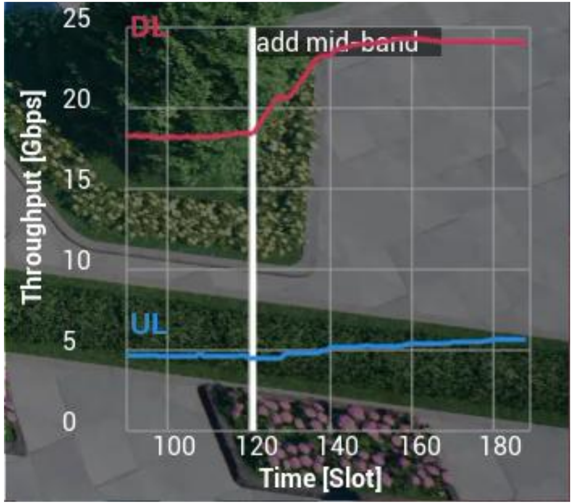
Line of Sight MIMO (LoS-MIMO)

Performance Evaluation of FR3 Distributed MIMO Using 6G Simulator (DOCOMO)

- The frequency band known as mid-band (FR3: 7 to 24 GHz), is being highlighted as a candidate for 6G.
  - ➢ wider bandwidth than Sub-6 used in 5G
  - ➢ lower frequency than the 28 GHz millimeter wave → low propagation loss
- Achieve high-speed, high-capacity communication while ensuring a certain level of coverage
- Enhance the 6G simulator:
  - ➢ implement mid-band in outdoor urban
  - ➢ evaluate distributed MIMO technology



6G Simulator in outdoor urban



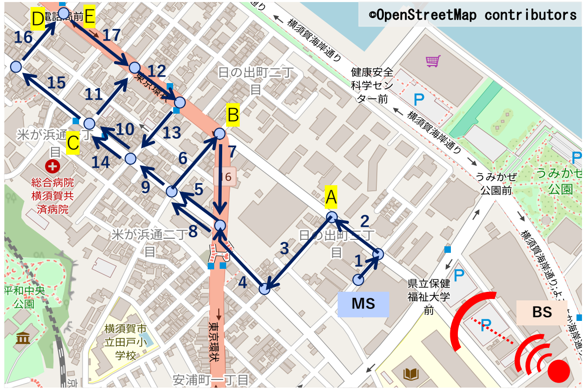
UE throughput (enhanced by mid-band)

Performance Evaluation of FR3 Massive MIMO in Real Urban Areas through Link-Level Simulation (DOCOMO)

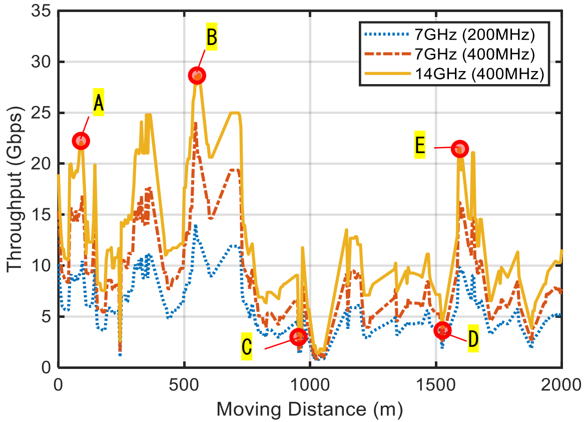
- To evaluate coverage performance under more realistic conditions, we used a radio wave propagation channel obtained by applying **color imaging method** to Yokosuka City.
- Based on the antenna configuration:
  - ✓ the peak data rate exceeds the target values for 5G,
  - ✓ Gbps-level communication can be provided everywhere, achieving the goal of "Gbps Anywhere"

Simulation Parameters

Center frequency [GHz]	7	14
Band width [MHz]	200/400	400
No. of antenna elements (BS)	256	1024
No. of antenna elements (MS)	64	256
No. of digital ports (BS)	64	
No. of digital ports (MS)	16	



Location of BS / paths of MS



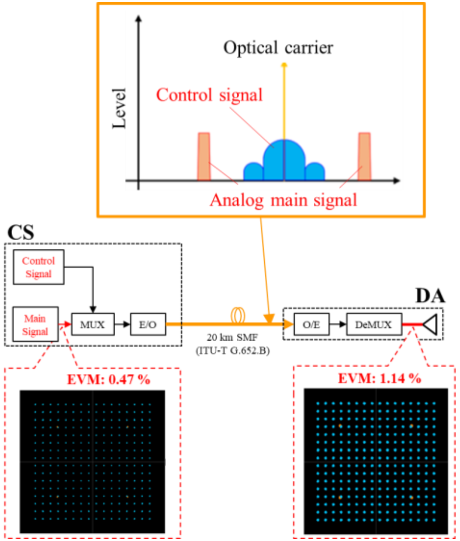
Throughput vs. MS moving

A-RoF and DA/Beam selection Tech. for High-frequency band D-MIMO (NTT)

◆Tech.1 : A-RoF for deployment DA

-Advantage of A-RoF (CS ⇔ DA)
CS can be smaller by reducing digital func.

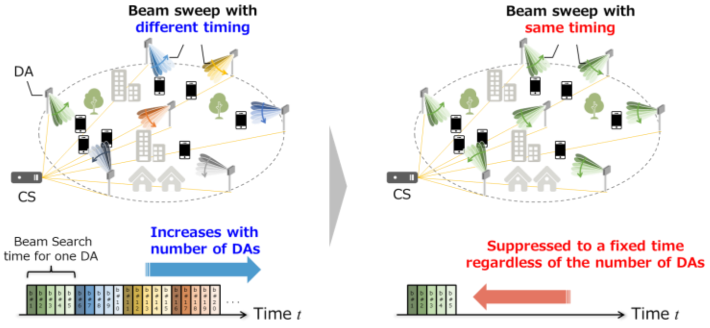
Data and control signals are multiplexed onto one wavelength for optical transmission



EVM is 1.14%
even with 20km optical transmission

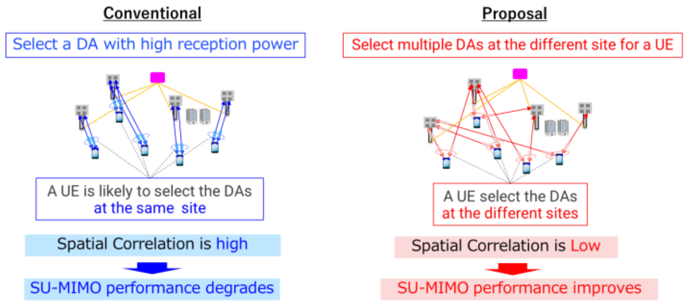
◆Tech.2 : Beam/DA Fast Selection

Simultaneous Beam Search on All DAs



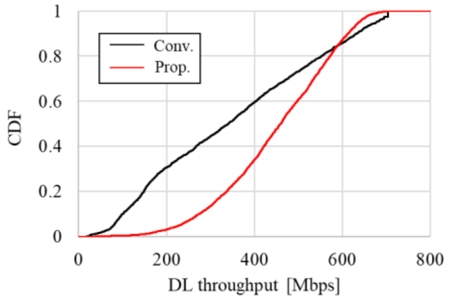
◆Tech.3 : DA Selection for SU-MIMO

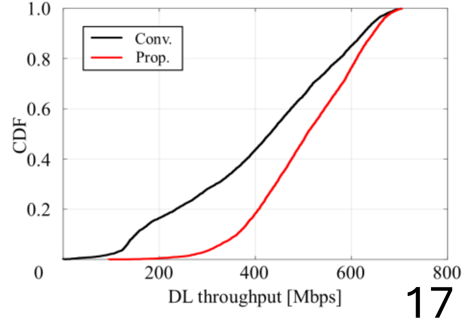
Different DA selection of antennas in the same UE



＜Experimental Evaluation＞

Freq. 40GHz
OBW. 100MHz
4DAs / Indoor (20m x 10m)
UE with moving speed of 4km/h
DA/UE : Using Analog-Beamforming



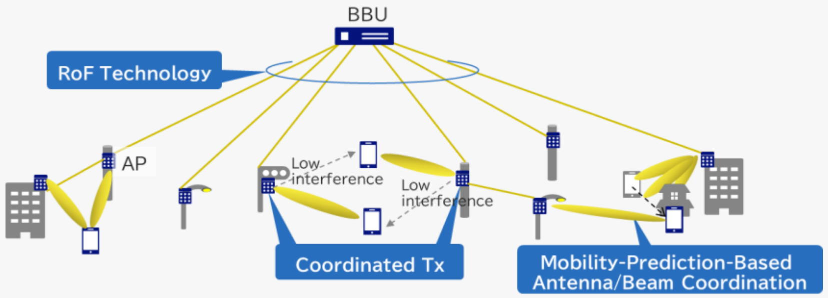


Distributed MIMO Technology for Efficient Utilization of Millimeter-Wave Bands

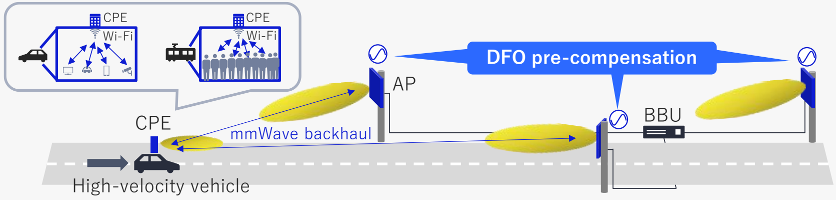
(NEC)

Two use cases for mmWave Distributed MIMO

(a) RAN designed for millimeter-wave band for MT

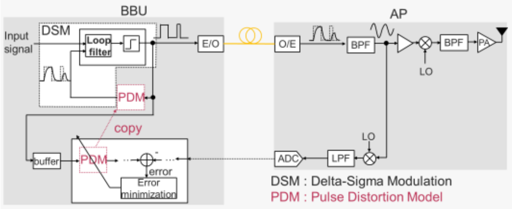


(b) mmWave backhaul for high-velocity vehicles

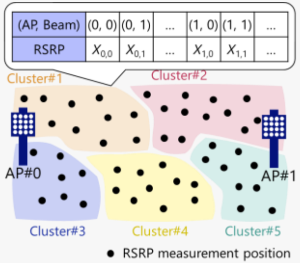


Elemental Technologies to realize two use cases

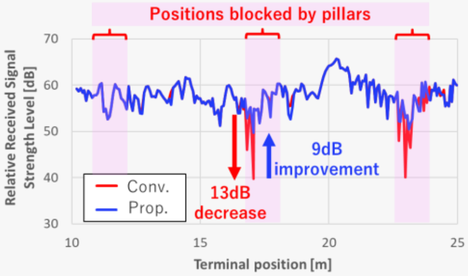
Delta-sigma RoF using COTS optical devices with pulse distortion compensation



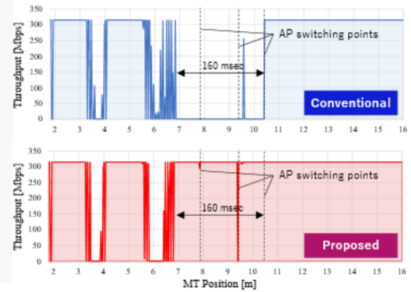
Inter-AP coordinated Tx using RSRP database for interference reduction



Mobility-prediction based antenna beam coordination for avoiding blocking effect

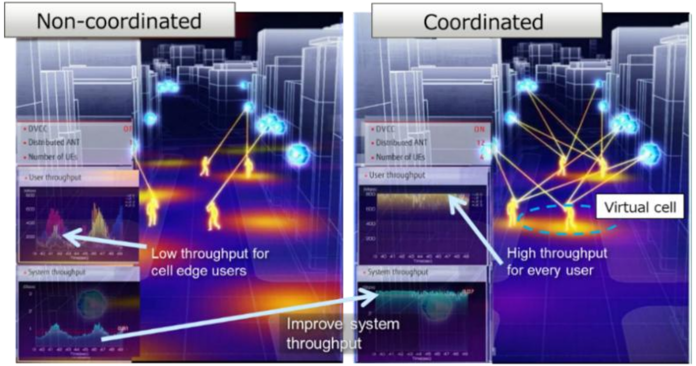


Doppler Frequency Offset Pre-compensation for smooth antenna switching



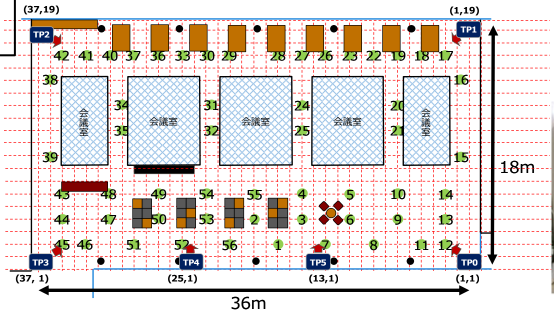
Ultra-High Density Distributed Antenna System (Fujitsu)

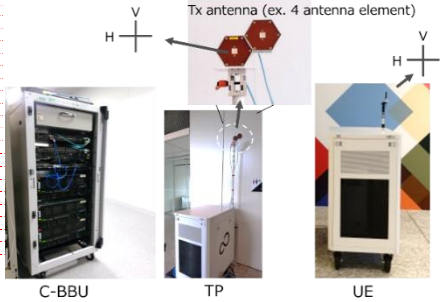
<u>The proposed technology features:</u>
- Dynamic Virtual Cell(DVC) control including following sub feature is implemented in centralized base band unit and control whole area.
- ZF/MMSE based MU-MIMO across 16 distributed TRPs.
- The channel power-based UE selection algorithm that balances high performance and low complexity
- Adaptive over-the-air calibration for achieving precise phase synchronization among TRPs.

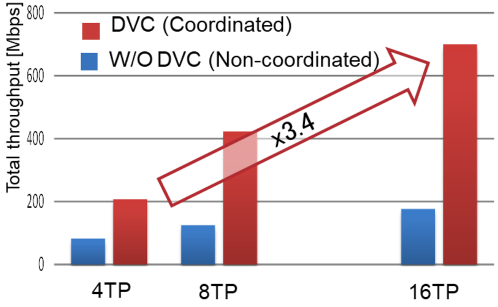


Simulation results, based on a real map and building information from a central Tokyo area, demonstrate the advantages of the proposed HDDA system. A comparison is made against a conventional, non-cooperative cell.
- Significant system throughput gains are achieved.
- The HDDA system provides consistently high throughput performance throughout the coverage area, unlike the conventional cell, which exhibits significant location-dependent variations in UE throughput.

The performance evaluation in the field experiment in real office building:
The large throughput gain is confirmed in the field experiment in the real office building. The throughput of DVC is
3 times larger than the conventional non-coordinated case.

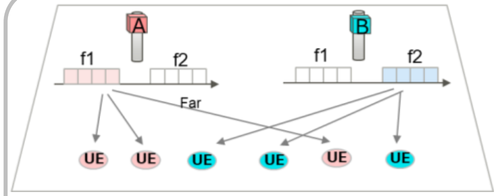




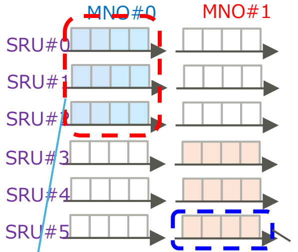


Ultra-High Density Distributed Antenna System (Fujitsu)

Conventional cell/MNO independent deployment



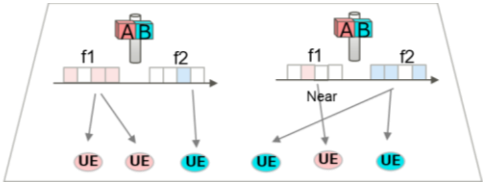
Resource allocation (example: 3 cells x 2MNO is located at different location)



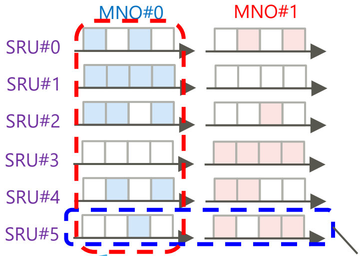
FH traffic volume is proportional to 4 block /RU.

Calculation resource volume is proportional to 12 block.

BS sharing system



Resource allocation (example: Distributing 3cell resource/MNO for 6shared RUs.

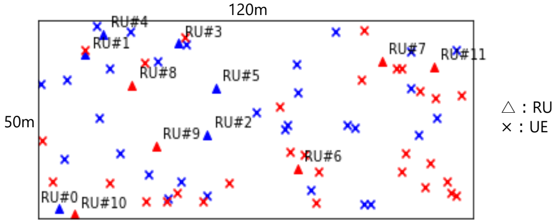


Calculation resource volume is proportional to 12 block.
(same as Non-sharing system)

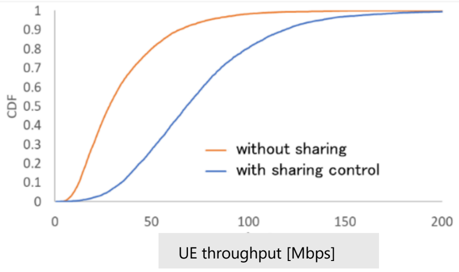
FH traffic volume is proportional to 4 block /RU.
(same as Non-sharing system)

Maximize PF utility function without increasing FH traffic and calculation cost.

Simulation condition amd results asurming indoor use-case.



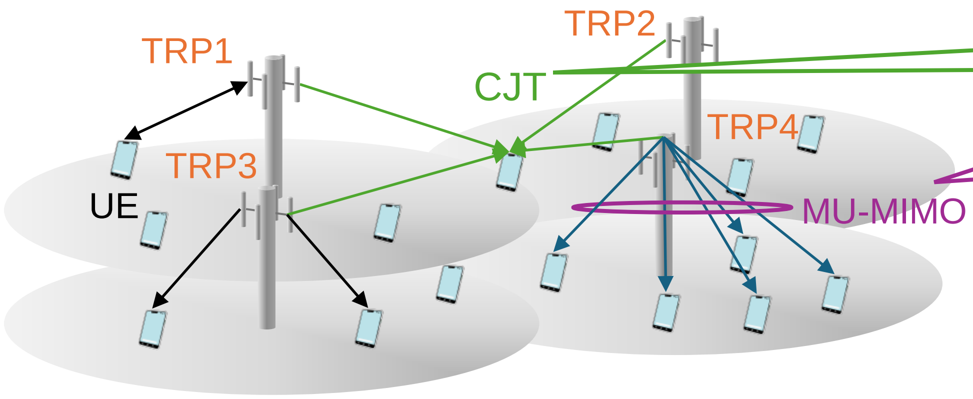
Parameter	Setting
Frequency, bandwidth	3.8GHz, 100MHz/MNO
Room size	120m×50m×3m
RU distribution	Uniform, 3RU/MNO(4MNO)
UE distribution	Uniform, 30UE/MNO
Tx ant. conf., Tx power	2×2, 0.5λ space, 24dBm
Pathloss	$\mathrm{Pr_{LOS}PL_{LOS}} + (1-\mathrm{Pr_{LOS}})\mathrm{PL_{NLOS}}$



6G views on Coherent Joint Transmission and Multi-User MIMO

(Sharp)

Integration of MU-MIMO with Coherent Joint Transmission (CJT) on multi-TRP operation



Improve SINR of cell-edge UEs

Improve capacity within a cell

Resource allocation algorithm is one of challenges

Proposed resource allocation algorithm

PF (Proportional Fairness)-metric-based intra-cell resource allocation

TRP#2	UE#1	UE#1	UE#3	UE#4 UE#5
TRP#3	UE#7	UE#6	UE#8	UE#8
TRP#5	UE#12	UE#13 UE#14	UE#3	UE#15
TRP#7	UE#16	UE#20	UE#3	UE#20

Estimated-SINR-based MIMO scheme selection

$SINR_{\mathrm{MU-MIMO}} > SINR_{\mathrm{SU-MIMO}}$

$SINR_{\mathrm{MU-MIMO}} < SINR_{\mathrm{SU-MIMO}}$

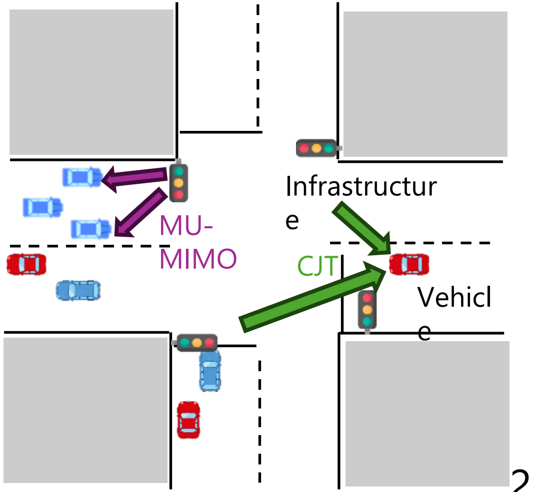
Resource block group

SINR-based inter-cell resource allocation

Freq.

Achieve

6G use case: Cell-free V2X communication

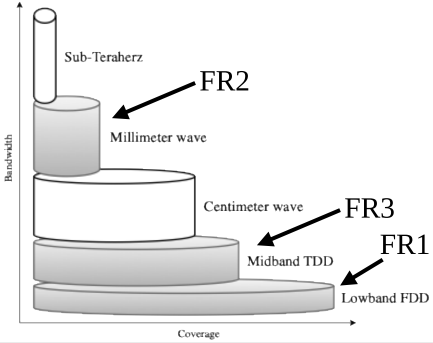


A Study on Advanced MIMO Large Arrays in the 7–15 GHz Spectrum for 6G (Ericsson)

Background

Mobile networks are evolving to boost capacity, energy efficiency and reduce costs. As data demands rise from 5G to 6G, new frequency bands are essential. The **centimeter-wave spectrum** (FR3) is a prime candidate to handle surging data volumes and enhance spectral efficiency.

New Frequency Band for 6G

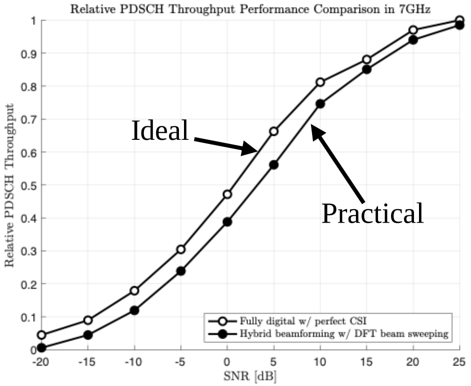


Historically, FR1 delivered wide coverage but limited bandwidth, while FR2 offered high data rates yet poor reach. **FR3 strikes a balance, providing broader bandwidth and favorable propagation**. Integrating these with massive MIMO can support 6G's diverse performance needs.

Hybrid MIMO Arrays

Despite FR3's promise, non-cellular incumbents require spectrum coexistence, and its use raises complexity, cost, beamforming precision, CSI acquisition, element coupling, and eCPRI overhead. We demonstrate the **potential of a straightforward beam-sweeping method** to tackle some of the challenges.

Experimental Result



Link-level simulations of PDSCH throughput with adaptive MCS with a **7 GHz NR-compliant hybrid beamforming** large-array **using beam sweeping and practical channel** estimation is shown in comparison with the ideal fully-digital beamforming. Operating over **100 MHz CP-OFDM (30 kHz SCS)** under the **CDL-B NLoS** model, CSI-RS every five slots configures analog beams, with frequency-domain weights via SRS via reciprocity. A **256-element dual-polarized BS and 32-RF-chain** hybrid array are compared to a fully digital counterpart. Results show **hybrid performance near digital** across SNRs, offering cost-efficient trade-offs.

Conclusion

The cmWave (FR3) spectrum offers broad bandwidth and favorable propagation, bridging sub-6 GHz and mmWave for 6G. **Exploiting its potential requires advanced large-array tech to mitigate path loss despite added CSI, computation, and hardware challenges**; hybrid arrays show near-digital performance.

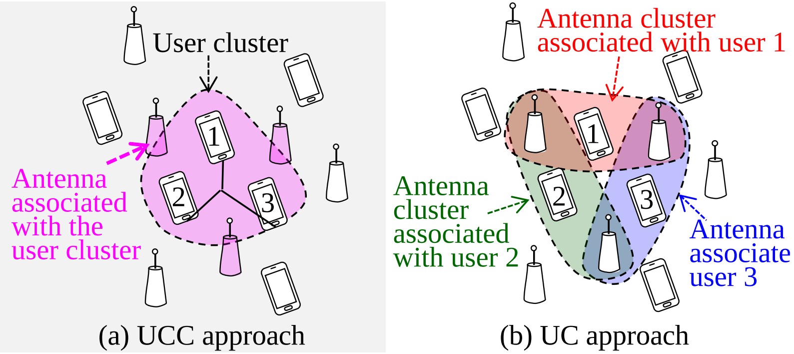
User Cluster-centric Approach for Cell-free Massive MIMO Systems

F. Adachi & R. Takahashi
(Tohoku Univ.)

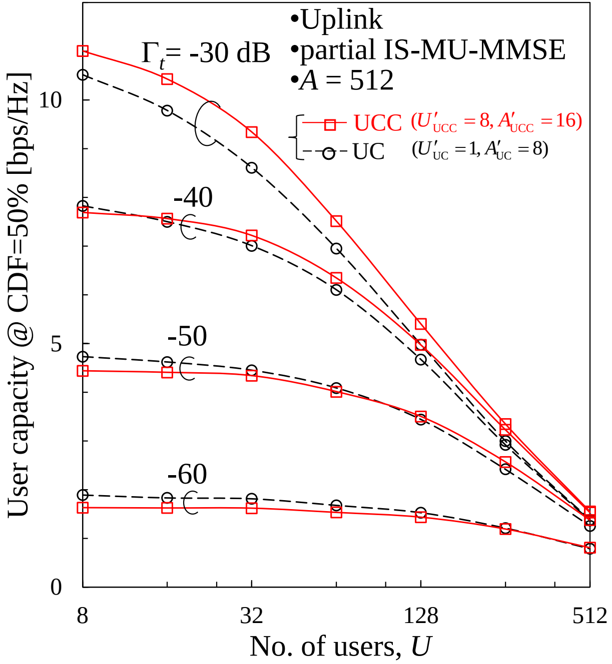
- User-cluster-centric (UCC) approach utilizing partial interference suppression multiuser MMSE/ZF (IS-MU-MMSE/ZF) enhances CF-mMIMO systems [R. Takahashi, 2023]

  - Multiuser spatial multiplexing technique is introduced, which involves forming user clusters (or user-centric virtual small cells) consisting of neighboring users
  - IS-MU-MMSE/ZF is designed to suppress only the dominant interference from the neighboring user clusters
  - UCC approach provides higher capacity than user-centric (UC) approach if the transmit power is sufficiently high

- R. Takahashi, H. Matsuo, S. Xia, Q. Chen, and F. Adachi, "Uplink Postcoding in User cluster-Centric Cell-Free massive MIMO," IEICE Trans. Commun., Vol. E106-B, No. 9, pp. 784-757, Sep. 2023.



Comparison of UCC and UC approaches



Capacity comparison between UCC and UC approaches

User Cluster-centric Approach for Cell-free Massive MIMO Systems

F. Adachi & R. Takahashi (Tohoku Univ.)

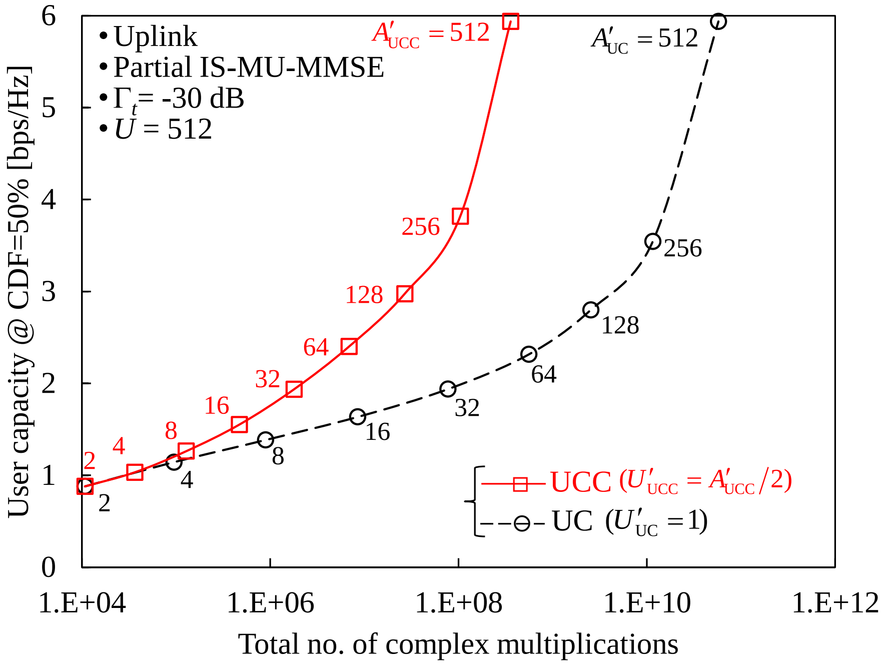
- User-cluster-centric (UCC) approach utilizing partial interference suppression multiuser MMSE/ZF (IS-MU-MMSE/ZF) enhances CF-mMIMO systems [R. Takahashi, 2023]

■ UCC approach achieves higher user capacity than UC approach under the same computational complexity

Computational complexity

LDL^H decomposition for the inverse matrix operation [Björnson, 2017]

Approach	No. of user clusters	The total no. of complex multiplications required for weight computation for all users
UC	$K=\frac{U}{U'_{\mathrm{UC}}}=U$	$\left(\frac{A'^2_{\mathrm{UC}}+A'_{\mathrm{UC}}}{2}\left(\frac{1}{K}\sum_{k=1}^{K}\lvert \mathrm{P}_k\rvert\right)+\frac{A'^3_{\mathrm{UC}}-A'_{\mathrm{UC}}}{3}+A'^2_{\mathrm{UC}}\right)K$
UCC	$K=\frac{U}{U'_{\mathrm{UCC}}}$	$\left(\frac{A'^2_{\mathrm{UCC}}+A'_{\mathrm{UCC}}}{2}\left(\frac{1}{K}\sum_{k=1}^{K}\lvert \mathrm{P}_k\rvert\right)+\frac{A'^3_{\mathrm{UCC}}-A'_{\mathrm{UCC}}}{3}+A'^2_{\mathrm{UCC}}U'_{\mathrm{UCC}}\right)K$



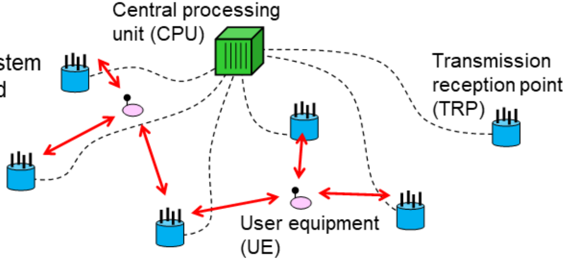
User capacity versus computational complexity

- R. Takahashi, H. Matsuo, S. Xia, Q. Chen, and F. Adachi, "Uplink Postcoding in User cluster-Centric Cell-Free massive MIMO," IEICE Trans. Commun., Vol. E106-B, No. 9, pp. 784-757, Sep. 2023.
- E. Björnson, J. Hoydis, and L. Sanguinetti, "Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency," Foundations and Trends in Signal Processing: Vol. 11, No. 3-4, pp. 154-655, 2017.

Low-Complexity User-Centric TRP Clustering Method in Downlink Cell-Free MIMO with Regularized ZF-Based Beamforming (Tokyo Univ. of Science)

Cell-Free MIMO and User-Centric TRP Clustering

Cell-Free MIMO distributes TRPs throughout the system coverage area and eliminates the cell boundaries.



User-centric TRP clustering methodology is a key to obtaining a sufficient performance gain.

Conventional User-Centric TRP Clustering Methods

◆ Path-loss based method [1, 2]

- determines a set of TRPs in order of the highest average path gain between the target UE and each TRP.

✓ Pros: Low computational complexity due to no need for complex beamforming (BF) matrix calculation

✓ Cons: Poor performance since BF effect is not well considered

◆ Signal-to-leakage-and-noise ratio (SLNR)-based method [3]

- determines a set of TRPs based on the expected SLNR after BF.

✓ Pros: High performance since BF effect is considered

✓ Cons: High computational complexity since complex BF matrix calculation is needed for each candidate cluster

[1] E. Björson and L. Sanguinetti, IEEE Trans. Commun., vol.68, no.7, pp 4247-4261, Jul. 2020.
[2] Mojahedian and A. Lozano, in Proc. IEEE 2021 29th EUSIPCO, Ireland, 23-27, Aug. 2021.
[3] Y. Oshima, A. Benjebbour, and K. Higuchi, IEICE Trans. Commun., vol. E97-B, no. 1, pp. 155-163, Jan. 2014.

Proposed Method

◆ Purpose

- To achieve an improvement in system-level throughput performance through low-complexity TRP clustering

◆ Proposed method

- TRP clustering for each UE is determined based only on the average path gain information between UEs and TRPs. ➔ No BF matrix calculation
- Achievable BF gain and spatial interference levels suitable for Regularized ZF (RZF)-based BF are considered.

RZF-based BF

◆ If a set of TRPs $\mathcal{T}_k$ is selected to transmit a signal to UE k BF vector for UE k is obtained based on the following matrix.

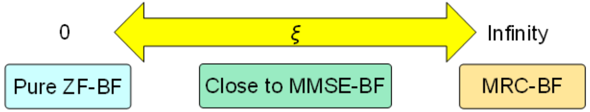
$$\mathbf{M}_k^{\mathrm{RZF}}(\mathcal{T}_k) = \tilde{\mathbf{H}}_k^H(\mathcal{T}_k)\left(\tilde{\mathbf{H}}_k(\mathcal{T}_k)\tilde{\mathbf{H}}_k^H(\mathcal{T}_k) + \underbrace{\xi\frac{N_0}{p_k}\mathbf{I}}_{\text{Normalization term corresponding to noise term}}\right)^{-1}$$

$\mathbf{H}_k(\mathcal{T}_k)$: Channel matrix with the $|\mathcal{T}_k|$-dimensional channel vector of UE k and other UEs aligned in the row direction

p_k : Transmit power of the signal transmitted to UE k

N_0 : Noise power

ξ : Nonnegative parameter to adjust the normalization term



Low-Complexity User-Centric TRP Clustering Method in Downlink Cell-Free MIMO with Regularized ZF-Based Beamforming (Tokyo Univ. of Science)

Proposed TRP Clustering Metric for RZF

- Proposed TRP clustering metric for the UE k is determined to maximize the following metric

$$\lambda_k^{\text{Prop.}}(\mathcal{T}) = \beta\lambda_k^{\text{Prop.ZF}}(\mathcal{T}) + (1-\beta)\lambda_k^{\text{Prop.MRC}}(\mathcal{T})$$

$\mathcal{T}$: The set of candidate TRPs for UE k
β : weight coefficient that ranges from 0 to 1

Proposed method can select based on a metric that adjusts the value of β according to the applied BF

✓ Two metrics suitable for ZF and MRC are defined as

$$\lambda_k^{\text{Prop.}()} = \frac{\text{Expected received signal power after BF}}{\text{Interference power + Noise power}}$$

Proposed method can determine the set of TRPs for UE k based on average path gain assuming RZF

- TRP clustering metric $\lambda_k^{\text{Prop.ZF}}(\mathcal{T})$ suitable for ZF is obtained as

Degrees of freedom of MIMO channel after nulling

$$\lambda_k^{\text{Prop.ZF}}(\mathcal{T}) = \frac{\left\{\left(T - U^{\text{null}}\right)/T\right\}\sum_{l=1}^{T} g_{k,l}\,p_k}{\frac{1}{U}\sum_{j=1}^{U}\sum_{l\in\mathcal{T}\setminus\mathcal{S}_j} g_{j,l}\left(g_{k,l}/\sum_{l=1}^{T} g_{k,l}\right)p_k + \alpha N_0}$$

Expected interference power given by candidate TRPs to UEs with unknown CSI — Noise power

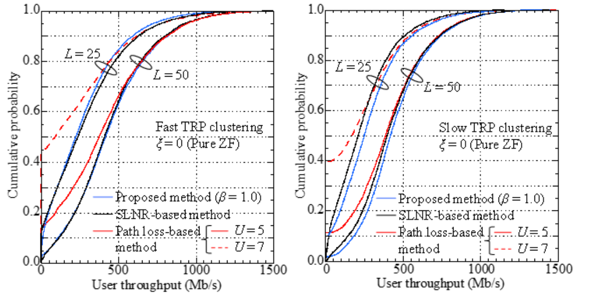
T : Number of transmitting antennas
U^{null} : Number of UEs to null
U : Number of UEs to consider interference power
$\mathcal{S}_j$: Set of TRPs that know instantaneous CSI of UE j
α : Positive coefficient parameter
N_0 : Noise power

- TRP clustering metric $\lambda_k^{\text{Prop.MRC}}(\mathcal{T})$ suitable for MRC is obtained as

$$\lambda_k^{\text{Prop.MRC}}(\mathcal{T}) = \frac{\sum_{l=1}^{T} g_{k,l}\,p_k}{\frac{1}{U}\sum_{j=1}^{U}\sum_{l\in\mathcal{T}} g_{j,l}\left(g_{k,l}/\sum_{l=1}^{T} g_{k,l}\right)p_k + \alpha N_0}$$

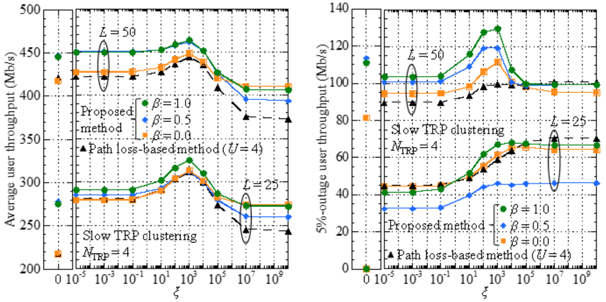
The set of TRPs $\mathcal{S}_j$ interferes to UE j — Noise power

Numerical Results



(a) Fast TRP clustering. (b) Slow TRP clustering.

Figure 1: Cumulative probability of the user throughput when pure ZF is applied to the fast and slow TRP clustering scenarios.



(a) Average user throughput. (b) 5%-outage user throughput.

Figure 2: Average and 5%-outage user throughput as a function of ξ.

Conclusion

- Proposed method achieves higher system-level throughput levels in a realistic scenario than the conventional path loss-based and SLNR-based methods.
- Meanwhile, the computational complexity of the proposed method is very low since complex BF matrix calculation is not needed.

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(Tokyo Univ. of Science)

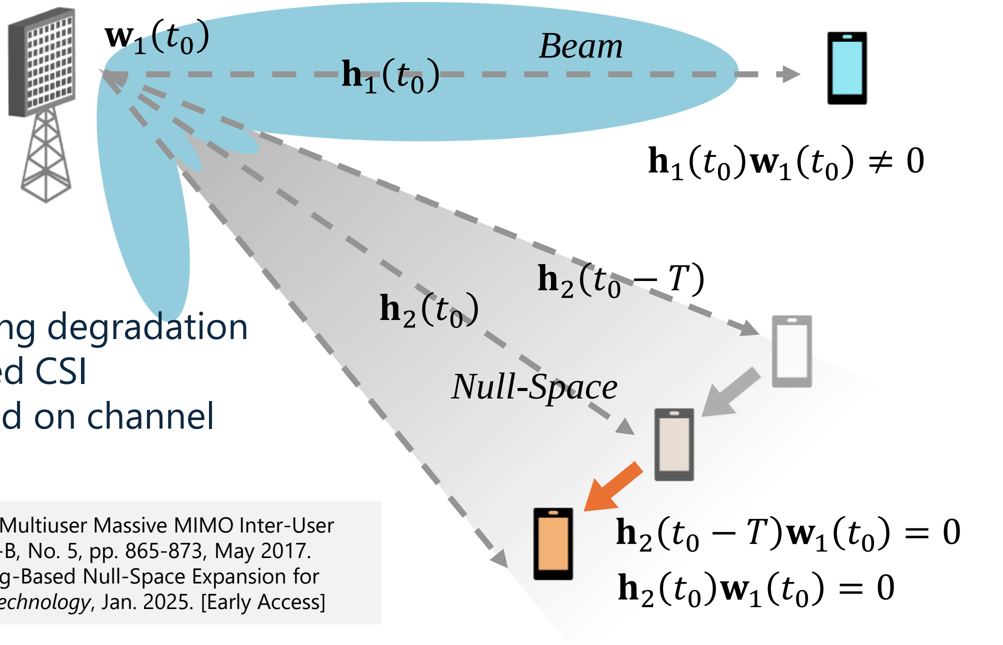
Null-Space Expansion (NSE)

By directing nulls toward both pre- and post-variation channels, the null space is expanded to suppress inter-user interference even in high-mobility environment

$$\mathbf{W}_1(t_0) = \begin{bmatrix} \mathbf{h}_{\color{red}{1}}(t_0) \\ \mathbf{h}_2(t_0) \\ \mathbf{h}_2(t_0 - T) \end{bmatrix}^{-1}$$

$$= [\color{red}{\mathbf{w}_1(t_0)} \quad \mathbf{w}_2(t_0)]$$

Past CSI are available



- ✓ Fully exploits the excessive spatial degrees of freedom in Massive MIMO
- ✓ Compensates for MU-MIMO spatial multiplexing degradation caused by interference leakage due to outdated CSI
- ✓ Outperforms existing precoding schemes based on channel prediction

[a] T. Iwakuni, K. Maruta, A. Ohta, Y. Shirato, T. Arai, M. Iizuka, “Null-Space Expansion for Multiuser Massive MIMO Inter-User Interference Suppression in Time Varying Channels,” *IEICE Trans. Commun.*, Vol. E100-B, No. 5, pp. 865-873, May 2017.

[b] Y. Sasaki, K. Arai, J. Nakazato, K. Maruta, “Receiver Maximum Eigenmode Beamforming-Based Null-Space Expansion for Multi-user Massive MIMO in Time-Varying Channel,” *IEEE Transactions on Vehicular Technology*, Jan. 2025. [Early Access]

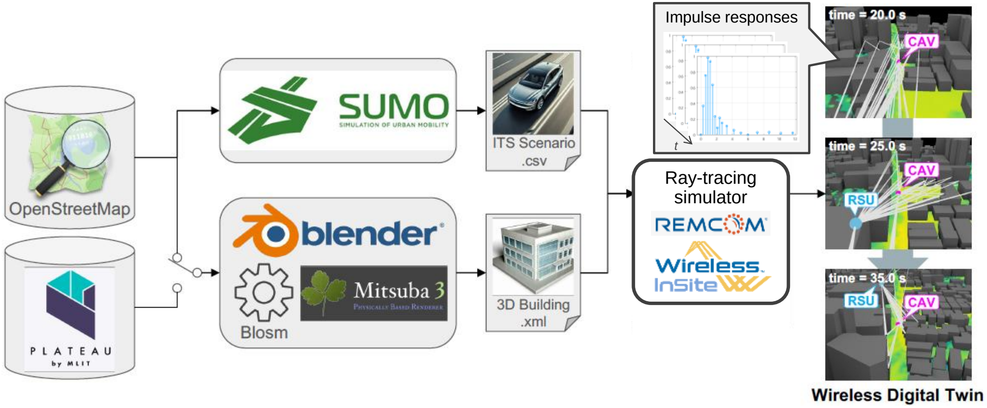
Robust Massive MIMO Transmission Technology in Mobile Environments

東京理科大学 TOKYO UNIVERSITY OF SCIENCE

Application to mmWave V2X (MIC FORWARD)

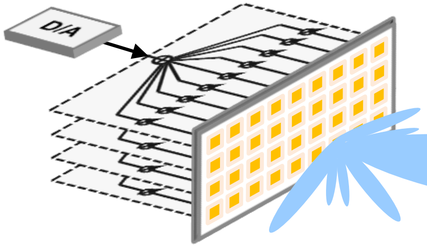
w/KKE

- ✓ Wireless Digital Twin using open platform: **OWDT**
- ✓ High-frequency bands require site-specific models
- ✓ 3D + time domain enables mobile MIMO system evaluation



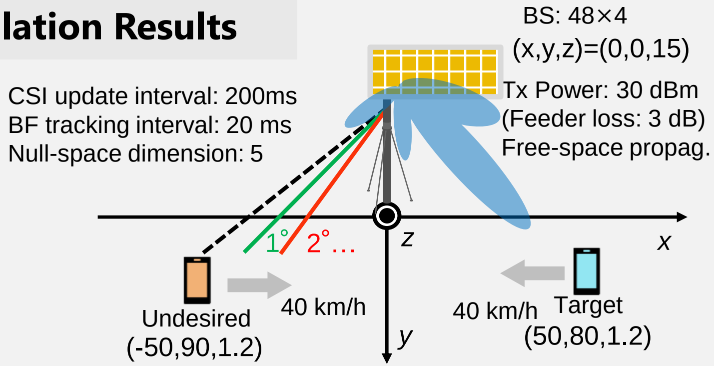
Implementation for Analog Beamforming

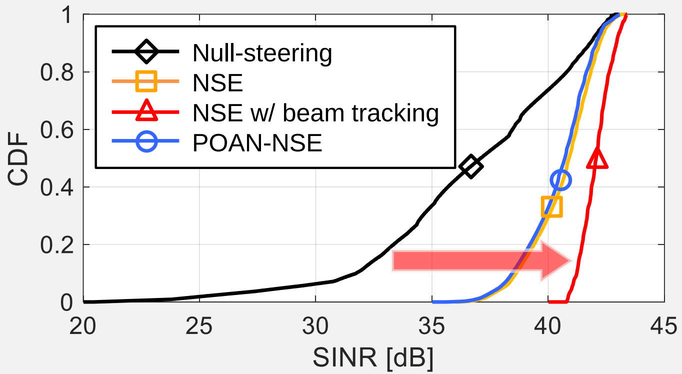
w/KWIC



- ✓ Analog control is more practical from implementation perspective
- ✓ Null-space expansion is realized under the constraint of phase-only control: **Phase Only Adaptive Nulling (POAN)**

Simulation Results

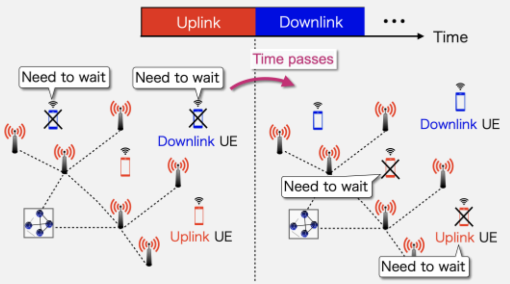




- ✓ NSE greatly outperforms existing null-steering
- ✓ Beam tracking + NSE gives best performance
- ✓ Phase-only control matches basic NSE

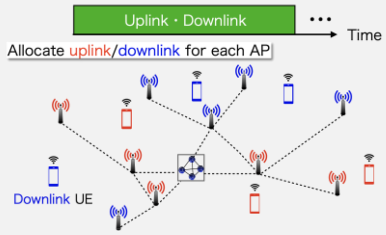
Duplex Design for Scalable Distributed MIMO (D-MIMO) Systems (UEC)

Time Division Duplex (TDD)



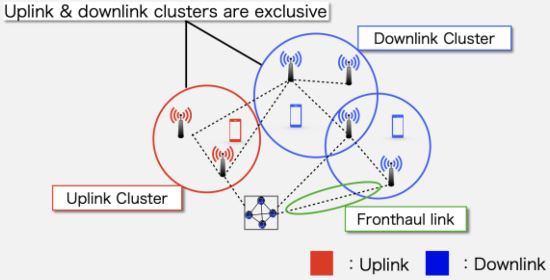
- Network is limited to either Uplink or Downlink

Network-Assisted Full-Duplex（NAFD）[1,2]



- Achieve Full-Duplex in the network
- Achieve high spectral efficiency (SE)
- Need to consider fronthaul limitation and scalability

Scalable NAFD with Fronthaul Capacity Limitation [3]



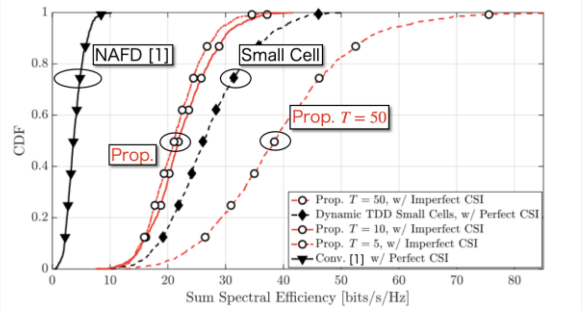
- **Joint design of beam and AP clustering**
  - Achieving high scalability with high spectral efficiency
  - Robustness against fronthaul limitation

[1] S. Fukue, et. al., IEEE Access, 2022.
[2] D. Wang, et. al., IEEE TCOMM 2019
[3] K. Okui, et.al., IEEE VTC-fall 2023

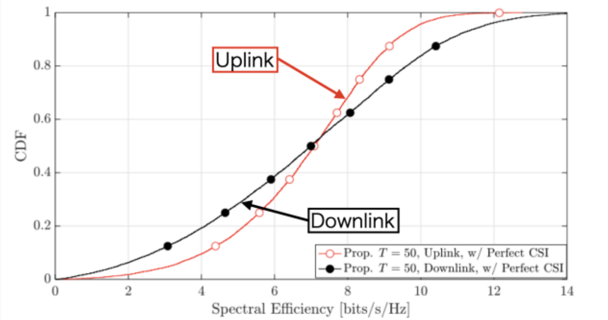
Numerical Results

Num. of APs 50, Num. of uplink UEs 10, downlink UEs
Fronthaul capacity 2bits/s/Hz, Cluster size T=5,10,50

- **Sum spectral efficiency**



- **Spectral efficiency per UE**



Receiver Designs for D-MIMO Systems with Practical Impairments (UEC)

① Uplink signal detection with rate-limited fronthaul [4]

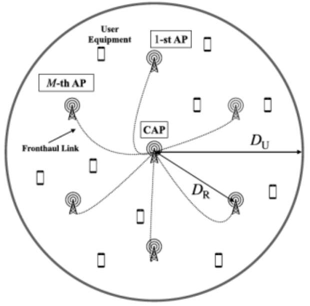


FIGURE 1. Illustration of a local cluster in a scalable CF-mMIMO uplink system, where a common CAP, supported by multiple APs, serves multiple single-antenna UEs distributed within a circle of radius D_U [m].

<Contributions>

I. EP-based robust receiver :

Effective detection method taking into the highly correlated channel conditions and limited fronthaul link capacity, but limited to feasible system size.

II. Low-complexity robust receiver (PDAZF) :

A discrete-aware GLS-based receiver, achieving near performance with significantly lower complexity using proximal gradient method.

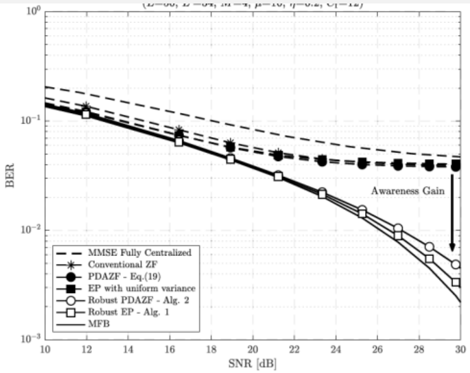


FIGURE 2. BER performances of CF-mMIMO systems with proposed and SotA receivers as a function of SNR, with $L=50$, $L'=34$, $M=4$, $\mu=10$, $\eta=0.2$ and $C_f=12$.

② Bayesian receiver design via bilinear inference with low-resolution ADCs [5]

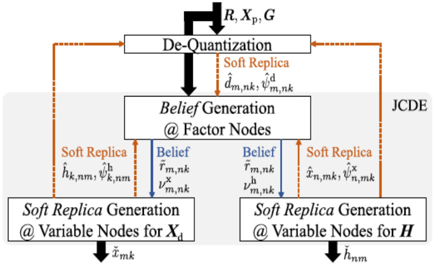


Fig. 2. Schematic of the belief propagation process employed in the proposed DQ-aided BiGaBP algorithm.

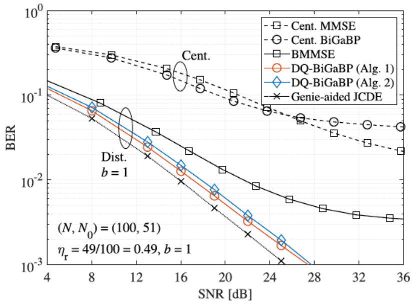
<Contributions>

I. Scalable Bayesian receiver :

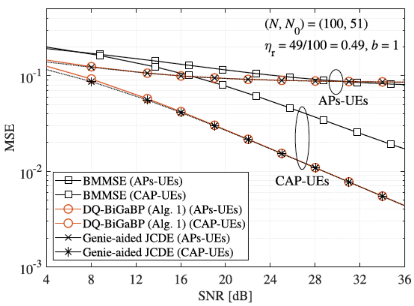
A novel joint channel and detection estimation (JCDE) algorithm, called DQ-aided BiGaBP, extending bilinear message passing framework to multi-dimensional quantized observations.

II. Insight on DoF-ADC resolution trade-off:

A new insight for scalable CF-mMIMO, showing the optimal ratio between CAP-centralized and AP-distributed antennas depend on ADC quality.



(c) $(N, N_0) = (100, 49)$, $\eta_r = 0.49$, $b = 1$.



(c) $(N, N_0) = (100, 49)$, $\eta_r = 0.49$, $b = 1$.

[4] K. Ando, H. Iimori, T. Takahashi, K. Ishibashi, and G. T. F. de Abreu, "Uplink Signal Detection for Scalable Cell-Free Massive MIMO Systems With Robustness to Rate-Limited Fronthaul," *IEEE Access*, vol. 9, pp. 102770 – 102782, July 2021.

[5] T. Takahashi, H. Iimori, K. Ando, K. Ishibashi, S. Ibi, and G. T. F. de Abreu, "Bayesian Receiver Design via Bilinear Inference for Cell-Free Massive MIMO with Low-Resolution ADCs," *IEEE Trans. Wireless Commun.*, vol. 22, no. 7, pp. 4756-4772, July 2023.