XG Mobile Promotion Forum

6G Radio Technology Project Terminal-Cooperative MIMO Technology WG

September 30, 2025

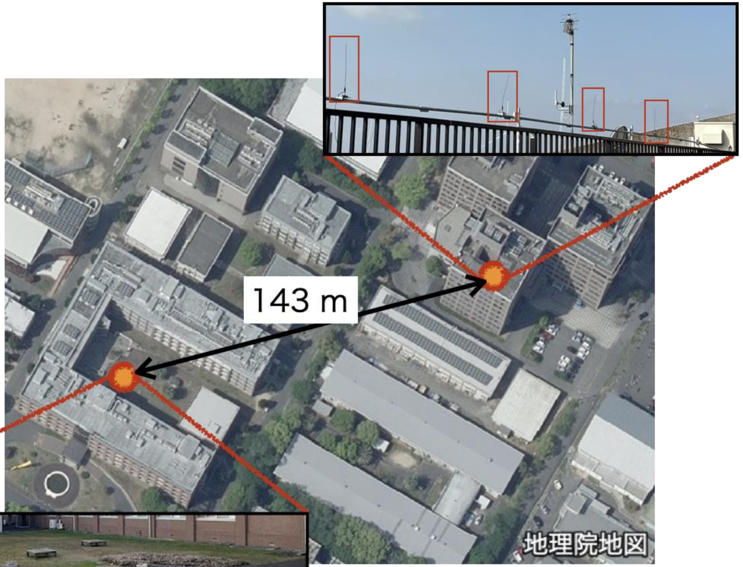
To highlight the importance of joint efforts, we use the term *collaborate* as the principal expression in the following parts.

Field Trial of Terminal-Collaborated MIMO Reception

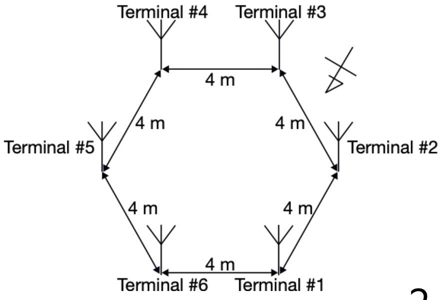
Collaboration with NTT AS

- Four-stream transmission in UHF band
  - 427.2MHz TX from rooftop of 8-story building
  - Received in the courtyard 143 m away
    - Six 1-antenna terminals move slowly around the circumference
    - Obtain RSSI, BER, etc. and record received signal waveforms
- Adaptive collaboration scheme on improved performance
  - Helper terminal that provides the received signal (H)
  - Decision terminal that decides from the collected received signal (D)
  - If the reliability is low, the judgment results of other decision terminals are acquired
  - If the confidence level is still low, D becomes H (H/D)

BS antennas



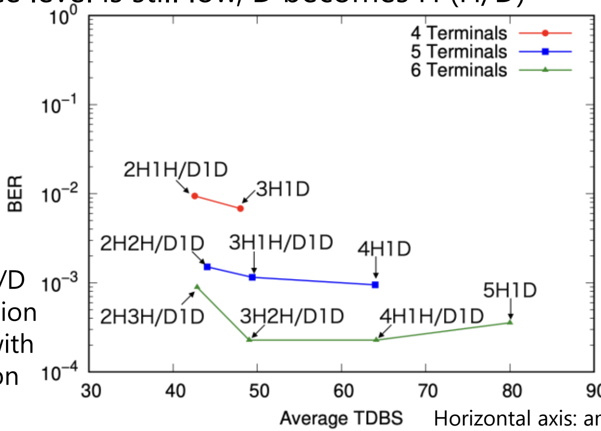
Terminal antennas



Each curve has a fixed total number of terminals

2H starts with overloaded MIMO, thus degrading performance

Increasing the number of H/D terminals in a 3H configuration can improve performance with little increase in collaboration traffic

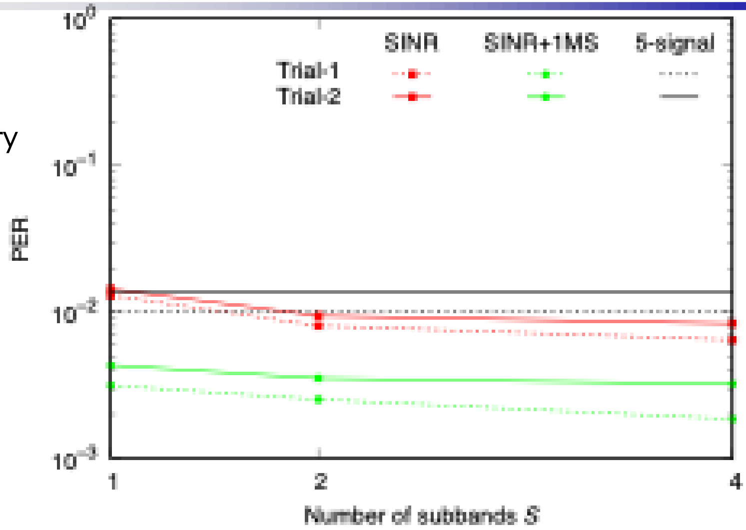


Horizontal axis: amount of collaboration traffic

On Demand Extra Helper Terminal Scheme

Collaboration with NTT DOCOMO

- Transmitting from a UHF 4-stream base station and receiving at 6 terminals
  - 427.2 MHz specific experimental test station, installed on an 8-story rooftop
  - Same setup as before slide
- Effect of improving performance by adding helpers as needed
  - Attempt decoding of a 4-stream transmitted signal with 4 terminals in collaboration
  - 4 terminals in this case are decide by SINR calculated from the MIMO channel matrix
  - Add helpers as needed based on the likelihood information when obtaining decoding results
    - Decoding is performed with 5 terminals in collaboration
  - The collaborating terminals are selected for each subband
  - Helpers to be added are common for all subbands



Received signal waveforms obtained in transmission experiments are used. 2 types: Trial-1 and Trial-2

The horizontal axis indicates the number of subband divisions in the signal bandwidth. Increasing the number of subbands improves the performance.

The proposed SINR+1MS scheme can significantly improve the performance compared to the SINR scheme and the scheme with fixed 5-terminal collaboration scheme.

Filtering-and-Forward (FF) Collaborative Relaying for Higher Spectrum Efficiency

Background & Objectives

- Higer spectrum efficiency is really needed in the next generation cellular system.
- While collaborative relaying achieves high transmission performance, the spectrum efficiency depends on relaying configuration.
- We propose a new collaborative relaying configuration that achieves higher spectrum efficiency.

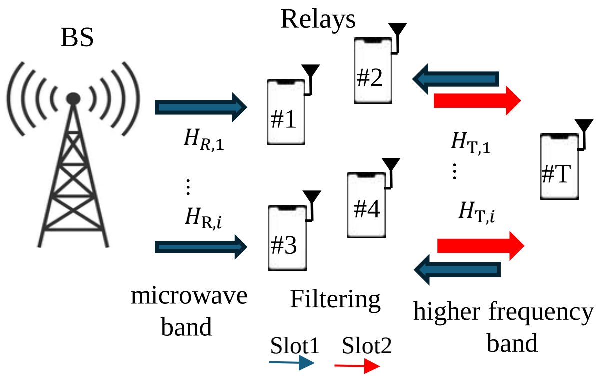


Fig.1 Configuration of FF collaborative Relaying

Proposed Configuration

(A) Relaying in 2-slots

- A BS and a destination terminal send their packets simultaneously in microwave and higher frequency bands for channel estimation, respectively.
- All the selected relays apply filtering signals sent from the base station in the frequency domain, and forward the signal for the destination as shown in Fig.1.

(B) Distributed Relay selection

- Every relay estimates the SNR in the channel from the BS to the destination via only the own relay, and transmits the signal if the SNR is bigger than the threshold.

Results

- The collaborative relaying makes possible in two slots despite of the number of the relays.
- As is shown in the right figures, the proposed relay selection achieves superior performance despite of the number of the candidate relays.

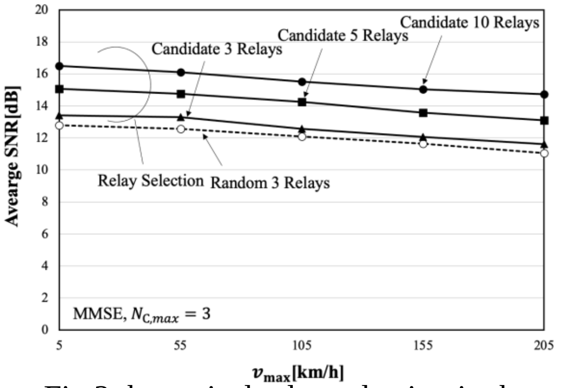


Fig.2 theoretical relay selection in the proposed relaying

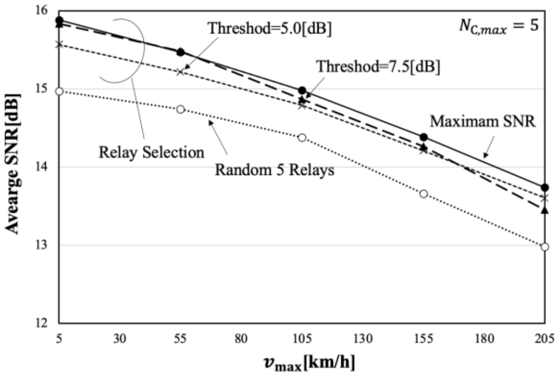
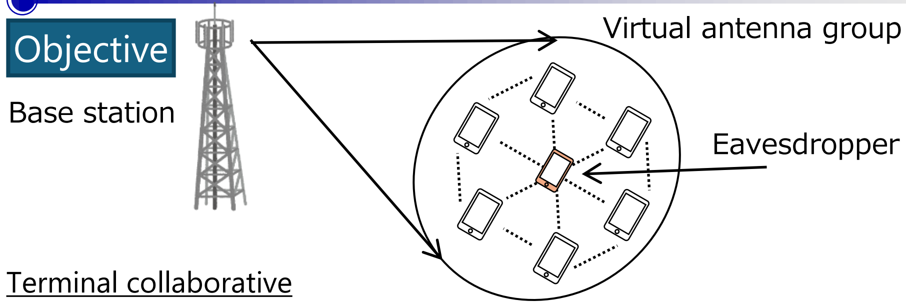


Fig.3 the SNR performance of the proposed relay selection

Physical-Layer Group Security in Terminal Collaborative Communication System

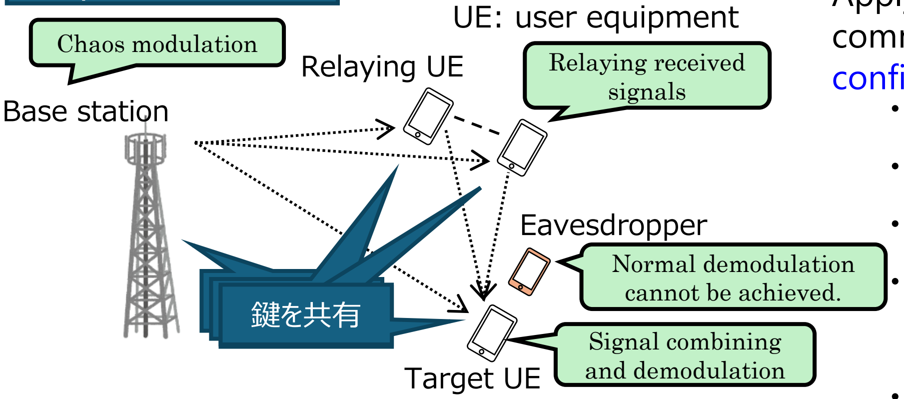
Objective



Terminal collaborative communication system between Terminals (with eavesdroppers)

- A transmission method that ensures group security even if an eavesdropper exists in the virtual antenna group is developed in terminal collaborative communication systems.
- By applying an encrypted modulation and a cooperative relay transmission schemes to the system, the information transmission performance as well as the physical layer security is improved.

Proposed method



Proposed downlink terminal collaborative communication system

Applying radio wave encryption modulation using chaos to obtain communication channel coding effect and physical layer confidentiality.

- A common key signal is shared within a group, assuming ID and pre-authentication, etc.
- Base station transmits the signal to the target UE with chaos encrypted modulation in sub-6 bands .
- Relaying UEs relay the received signal from base station in the millimeter-wave band.
- Target UE combines the received signals from base station and relaying UEs, and demodulates them by maximum likelihood sequence estimation using a common key.

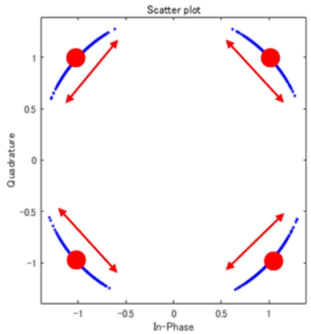
- The group security and quality improvement are achieved by channel coding and the physical layer-encryption effects of chaos modulation, and the diversity effect of cooperative relay transmission.

Study Items: Safety evaluation of group security, transmission performance improvement, application to uplink transmission, common key signal sharing methods and delivery costs

Phase Noise Compensation with Time Window Averaging for CTFI-OFDM

□ Aim:

- OFDM subcarriers are assigned in a narrow bandwidth and are affected by the phase noise (PN) due to phase shift of local oscillator.
- The effect of PN is significant in a high-frequency band, and it also affects terminal coordination.
- The proposed method compensates the PN by the time window averaging (TWA) of pilot signal based on complex time frequency interferometry (CTFI).



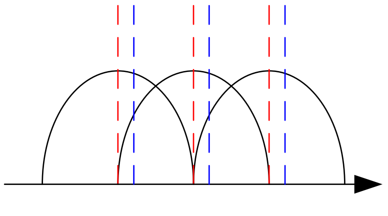


Fig.: Influence of PN

□ Proposed method:

□ TFI:

"1" and "0" are assigned alternately.

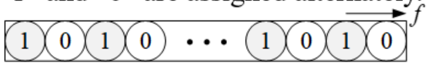


Fig.: TFI

□ CTFI:

"1" and "0" are assigned alternately.

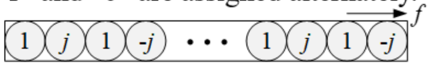


Fig.: CTFI

- Channel estimation (TFI):
- Channel estimation (CTFI):

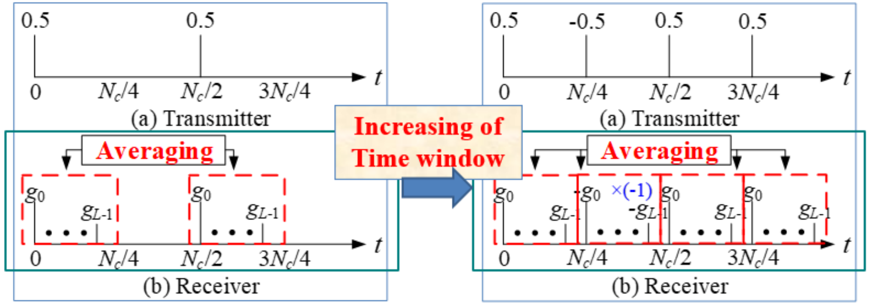


Fig.: TFI (Time domain)

Fig.: CTFI (Time domain)

- Phase noise: $\theta_i = \theta_{i-1} + w$, where w is based on Gaussian distribution.
  ⇒ TW averaging ⇒ Improvement of CSI
- |(CIR bef. TWA)-(CIR aft. TWA)| = Magnitude of PN ⇒ Weight of MMSE

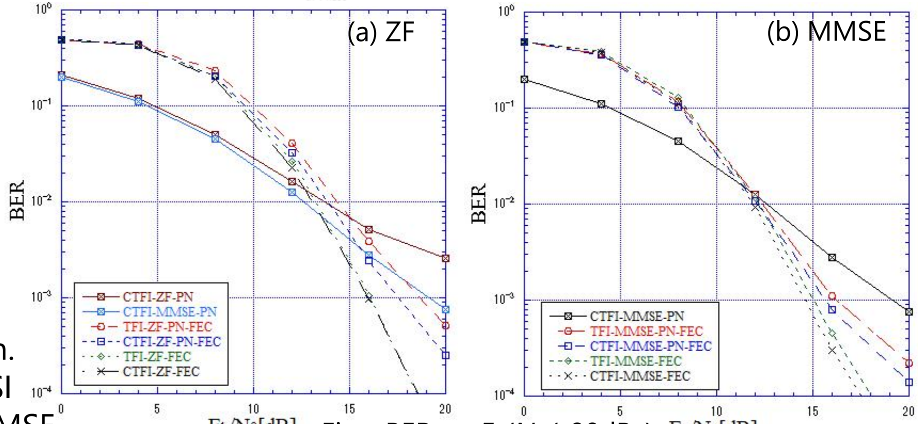


Fig.: BER vs. E_b/N_0 (-80dBc)

[1] S. Okamoto, et al., "Phase Noise Compensation with Time Window Averaging for WHT-CTFI-OFDM," Proc. IEEEGCCE2024, pp. 1392-1393, Oct. 2024.
[2] S. Okamoto, et al., "Phase Noise Compensation with Time Window Averaging for Hadamard Spreading CTFI-OFDM," IEICE Tech. Rep., CS2024-10, pp. 13-14, July 2024.

Cooperative Positioning Techniques with User-terminal Collaboration Over Higher-frequency-bands

- Terminal-collaborative virtual MIMO techniques has been studied, where multiple nearby terminals cooperate in transmission and reception processing.
- By using terminal-collaboration techniques, it is expected to improve not only communication performance but also positioning accuracy.
- In this work, an enhanced cooperative positioning scheme is investigated, where each user terminal information is shared among users through direct inter-user communication at a higher frequency band.

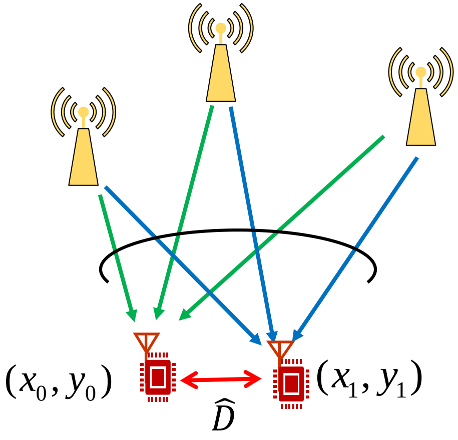


Fig1: Basic concept of cooperative positioning with nearby user-terminal collaboration

- The distance between 2 users can be estimated by $D = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2}$, while it can be also estimated by RSS measurement of direct link, where estimated distance by direct link is $\widehat{D}$.
- Positioning accuracy can be improved by finding a solution that minimizes the weighted sum-of-squares errors of inter-user distance, i.e., $|D - \widehat{D}|^2$.
- Simulation results show that user terminal collaboration significantly improves positioning accuracy in various evaluation scenarios [1][2].

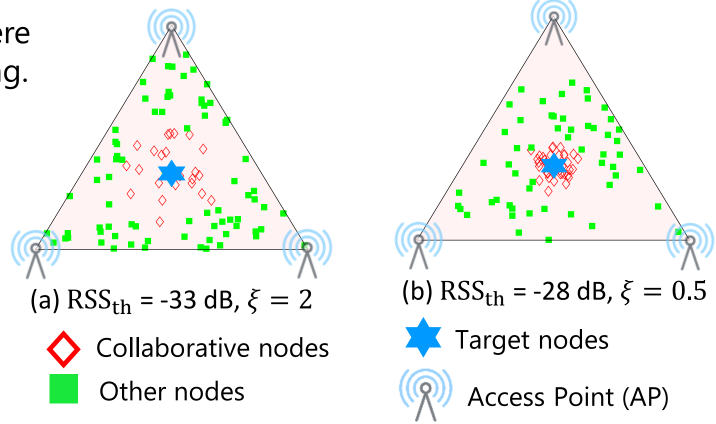


Fig. 2: AP positions and user distributions.

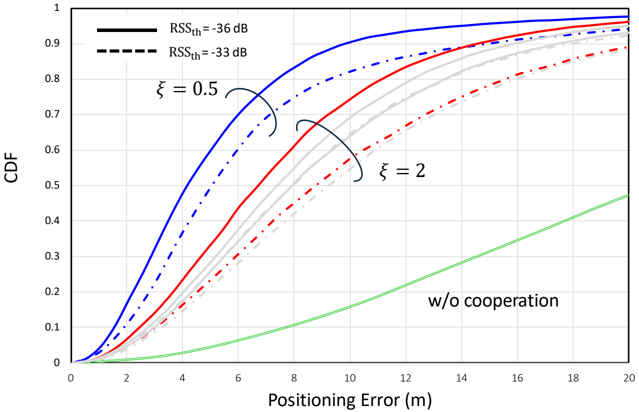
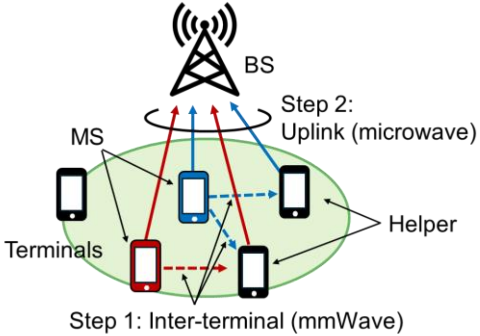


Fig. 3: CDF of positioning errors in case with and without cooperative positioning

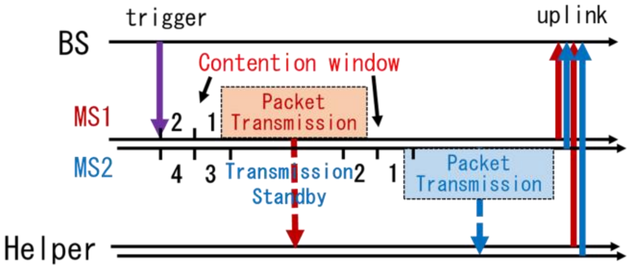
[1] Z. Li, et al., "Performance Evaluation of Cooperative Positioning with User-Terminal Collaboration," Prof. JAC-ECC2023, Dec. 2023.
[2] Z. Li, et al., "Performance of RSS-Based Indoor Cooperative Positioning with Weighted User-Terminal Collaboration," Prof. JAC-ECC2024, Dec. 2024

Access Control for Terminal Collaborative Communication System

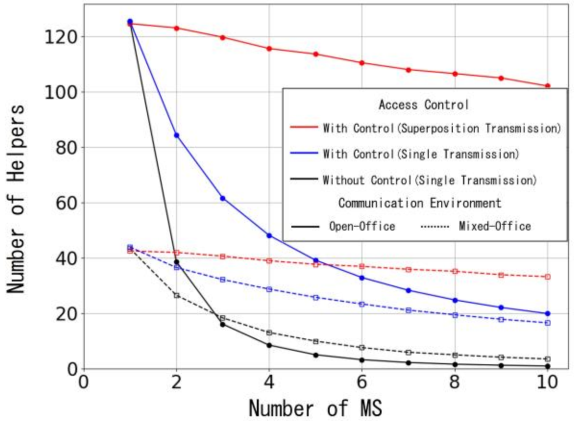
- Uplink terminal collaborative communication system
  - Uplink: sub-6 band, Inter-terminal: mmWave band
- Inter-terminal communication
  - MS broadcasts its data to terminals
  - Terminals that successively receive data becomes Helpers
- Issues and results
  - Evaluation of number of helpers, which affect uplink capacity
  - Performance evaluation considering mmWave indoor propagation model
  - Introduction of access control avoiding interferences



Uplink terminal collaborative communication system



Timing chart of access control

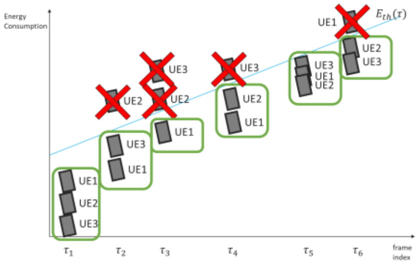


Number of helpers in mmWave indoor environment [1]

[1] Y. Li, et al., "Evaluation of access control mechanisms within inter-terminal cooperation…," IEICE ICETC, 2024.

Grouping Scheme in Terminal Collaborative MIMO

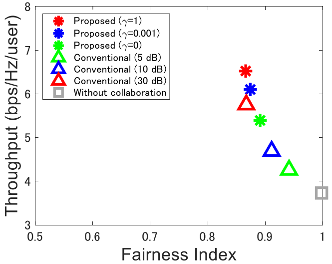
- Donwlink Terminal Collaborative MIMO Reception
  - ➢ Grouping based on instantaneous throughput
    - ⇒ Throughput improvement by a factor of 1.13
- Uplink Terminal Collaborative Bemforming Transmission
  - ➢ Set thresholds on number of assistant UEs in group
    - ⇒ Reduce assist probability of cell-site UE by 1/5 with nearly the same throughput
- Grouping based on Cumulative Energy Consumption
  - ➢ Set thresholds on cumulative energy consumption of each terminal
  - ➢ Threshold based on subframe index
    - Collaboration if energy consumption is less than threshold
    - Leave group if energy consumption is more than threshold
    - Rejoin group if threshold exceeds energy consumption



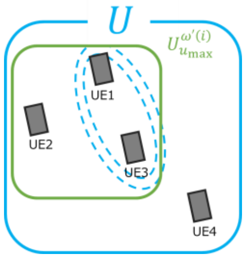
Threshold based on subframe index

Index m	Subgroup	Th	FI
1	(UE1, UE2, UE3)	$\sum T_u^{i(1)}(t)$	$F_{\rm ins}^{i(1)}$
2	(UE1, UE2), UE3	$\sum T_u^{i(2)}(t)$	$F_{\rm ins}^{i(2)}$
3	(UE2, UE3), UE1	$\sum T_u^{i(3)}(t)$	$F_{\rm ins}^{i(3)}$
4	(UE3, UE1), UE2	$\sum T_u^{i(4)}(t)$	$F_{\rm ins}^{i(4)}$
5	UE1, UE2, UE3	$\sum T_u^{i(5)}(t)$	$F_{\rm ins}^{i(5)}$

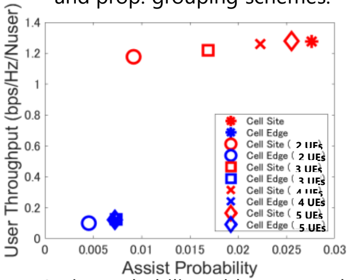
Grouping based on instantaneous throughput.



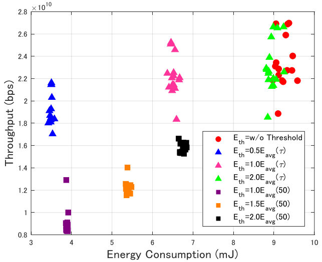
Throughput vs. fairness with conv. and prop. grouping schemes.



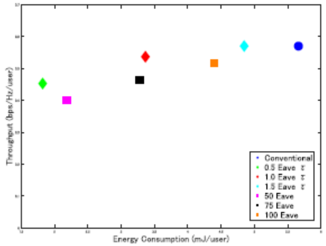
Grouping with limited number of assistant UEs



Assist probability with conv. and prop. grouping schemes.



Throughput vs. energy consumption with thresholds based on subframe index and fixed thresholds.


Throughput vs. energy consumption with thresholds based on subframe index and fixed thresholds.

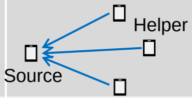
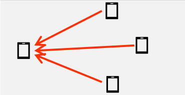
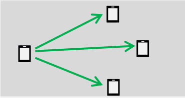
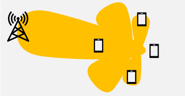
Grouping Scheme in Collaborative MIMO (2)

Objective

- Validate the effectiveness of collaboration while considering the overhead for information sharing
- Organize multiple groups to maximize throughput while targeting considering terminals

Research Direction

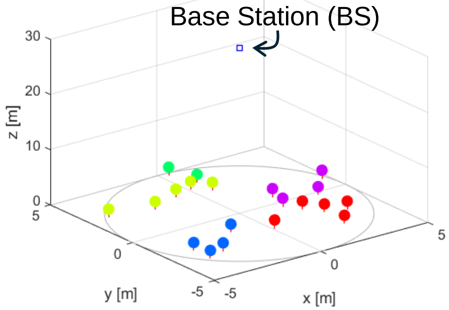
- Formalization of uplink cooperative MIMO transmission considering overhead
- Grouping via clustering (k-means)
- Selection of collaboration terminals (UTs), resource / fairness management considering channel conditions between UTs and BS

1	CSI sharing		$T_{\mathrm{csi}} = \sum_{j=1, j\neq i}^{n_{\mathrm{gr}}} \frac{b_{\mathrm{csi}}}{B_{\mathrm{uu}} C_{ij}}$
2	Data sharing		$T_{\mathrm{dat1}} = \sum_{j=1, j\neq i}^{N_{\mathrm{st}}-1} \frac{b_{\mathrm{dat}}}{B_{\mathrm{uu}} C_{ij}}$
3	Weighted signal dharing		$T_{\mathrm{dat2}} = \sum_{j=1, j\neq i}^{N_{\mathrm{st}}-1} \frac{b_{\mathrm{dat}}}{B_{\mathrm{uu}} C_{ij}}$
4	Uplink trans-mission		$T_{\mathrm{ul}} = \frac{b_{\mathrm{dat}}}{B_{\mathrm{ul}} C_{\mathrm{ul}}}$

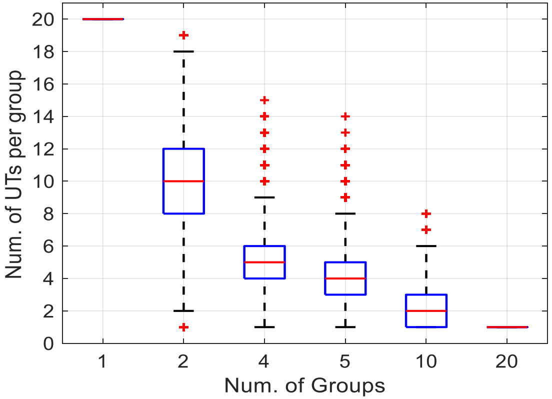
Flow of collab. MIMO uplink

$$\mathrm{TP} = \frac{N_{\mathrm{st}} b_{\mathrm{dat}}}{T_{\mathrm{csi}} + T_{\mathrm{dat1}} + T_{\mathrm{dat2}} + T_{\mathrm{ul}}}$$

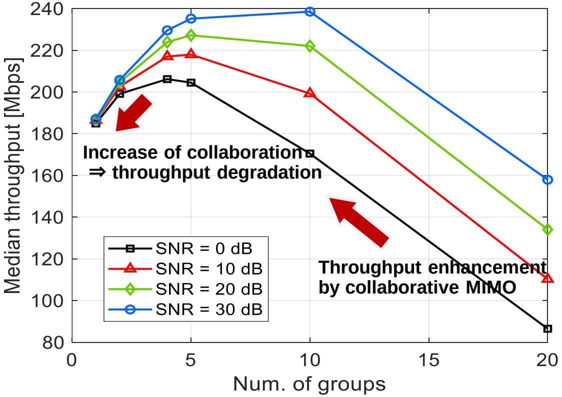
UT – UT : mmW
UT – BS : Sub6



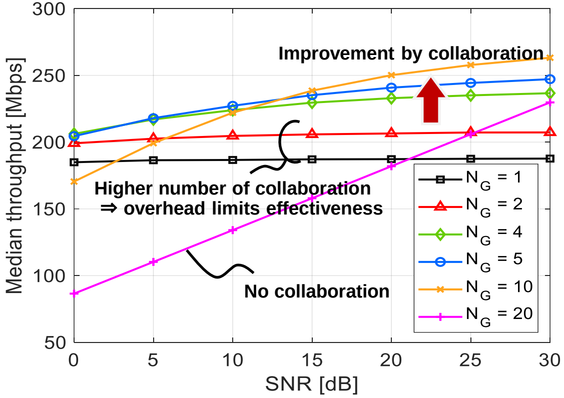
Example of clustering



Number of UEs per Group (Clustering 20 UTs)



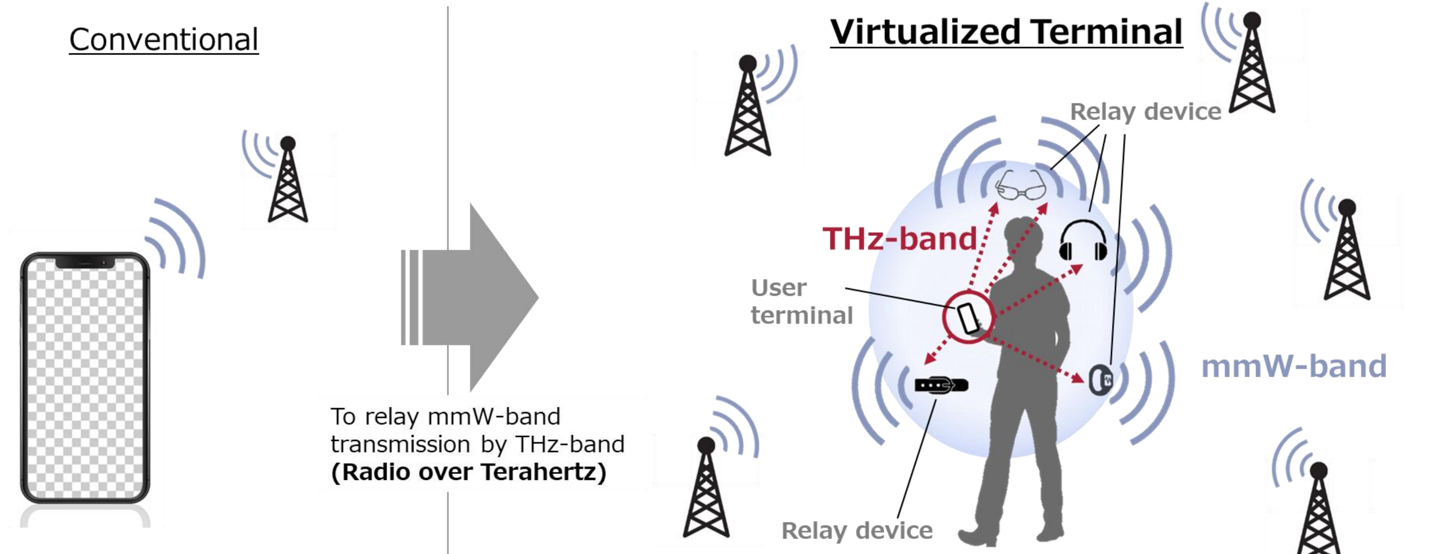
Median Throughput when Grouping 20 Terminal



Median Throughput vs. UT-BS SNR

Virtualized Terminal Technology

- Increasing the number of antennas virtually by wearable devices with mmW-band antennas and connecting them to the user terminal via a terahertz ultra-wideband link.



Limitations to increasing the number of antennas due to constraints on the size of the enclosure
⇒Limitations to improving the uplink

By distributing antennas to wireless devices around the body, the UL throughput is improved through enhanced MIMO performance