

MIMO Throughput Enhancement by NRNT and its Evaluation in Digital Twin Simulator

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Abstract—In this paper, we propose a multiple-input multiple-output (MIMO) system that utilizes metasurfaces and reconfigurable intelligent surfaces (RISs), and we evaluate its throughput enhancement effect using a system-level simulator modeling a real-world environment. Although MIMO is widely known as a technology that improves throughput proportionally to the number of antennas by deploying multiple antennas at both the base station (BS) and the user equipment (UE), a wide spacing between the BS antennas must be maintained to achieve this enhancement. Therefore, we propose a configuration that employs metasurfaces and RISs as extended antennas for the BS. By distributing metasurfaces and RISs in space, the proposed configuration makes it easy to maintain a wide spacing between the BS antennas, which is expected to enhance the MIMO capacity across the entire coverage area. To verify the effectiveness of the proposed configuration, we captured a real-world environment as point cloud data using LiDAR. Based on this data, we developed a simulator capable of evaluating the throughput performance of the RIS/metasurfaces aided MIMO by integrating ray-tracing-based radio propagation calculations with system-level simulations. Simulation results confirmed that adding one RIS and one metasurface to a base station with a maximum MIMO rank of 2 in the 28 GHz band resulted in a throughput improvement of 783 Mbps at the 80th percentile (approximately 18.6% of the maximum throughput), and 1,133 Mbps at the 85th percentile (approximately 26.8% of the maximum throughput). This demonstrated that MIMO throughput can be improved by using RIS and metasurfaces.

Keywords—6G, Distributed MIMO, New Radio Network Topology (NRNT), RIS, metasurface

I. INTRODUCTION

The millimeter-wave (mmW) band introduced in fifth-generation mobile communications (5G) has wide bandwidth and high maximum throughput, but significant free-space and shielding losses of mmW make securing communication areas difficult. Therefore, as one of the technical concepts for sixth-generation mobile communications (6G), NTT DOCOMO is proposing New Radio Network Topology (NRNT), which expands transmission distance and enhances robustness against shielding by increasing the number of wireless paths through the deployment of multiple devices in space that assist radio wave propagation between base stations and terminals, such as wireless relay stations, Reconfigurable Intelligent Surfaces (RIS), and metasurfaces [1].

Fig. 1 shows an overview of NRNT that consists of devices that assist radio wave propagation and various physical layer-based controls, such as beam direction control for maximizing received power and avoiding interference.

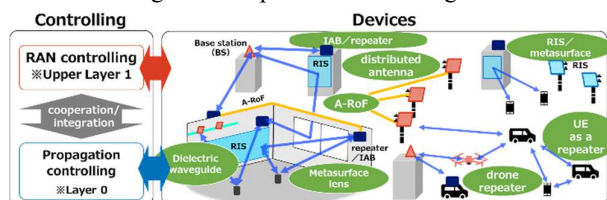


Fig. 1 NRNT (New Radio Network Topology)

NTT DOCOMO has been conducting demonstration experiments on devices that assist radio wave propagation, including beamforming wireless repeaters that enable signal coverage behind walls using a two-stage donor service configuration [2], glass-type metasurfaces that control the direction of reflection while maintaining sufficient transparency for deployment on building windows [3], and dielectric waveguides that can function as antennas at arbitrary points by bending a portion of the waveguides [4]. Other technologies such as non-terrestrial network (NTN) platforms (e.g., HAPS, LEO, and GEO), and analog Radio over Fiber (A-RoF) are also being investigated.

On the other hand, 6G requires communication speeds exceeding 100 Gbps and a capacity more than 100 times greater [1]. To achieve these requirements, it is considered essential to deploy even more antennas in space and to improve frequency utilization efficiency through MIMO spatial multiplexing [5]. Therefore, as an application of NRNT, the authors are investigating methods to increase the number of wireless propagation paths using numerous devices to increase MIMO capacity. Fig. 2 shows an example of the basic configuration, which consists of a BS, a RIS, and a MS. We proposed and verified a cooperative beamforming control method for the BS antennas and the RIS. The results confirm that, under a line-of-sight (LOS) condition with an unknown MS location, two paths are formed: a direct path between the BS and the MS and a reflected path via the RIS. Consequently, the throughput is improved compared to the case of BS alone because of the MIMO effect [6].

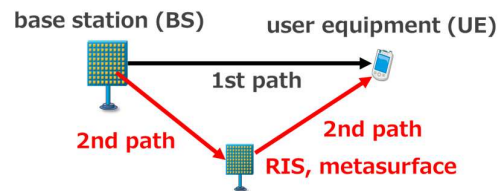


Fig. 2 RIS/metamaterial aided MIMO system

However, it is unclear whether throughput will improve when evaluated in a real-world environment compared to when RIS or metasurfaces are not present.

In this paper, we used LiDAR to acquire point cloud data from a real environment, constructed a 3D map, and built a simulator combining ray tracing-based radio wave propagation calculations with system-level calculations. We then verified the throughput improvement effect of using one RIS and one metasurface in an indoor environment.

II. OVERVIEW OF THE DIGITAL TWIN SIMULATOR AND THE ENHANCEMENT OF THE SIMULATOR

This simulator is based on the digital twin simulator described in [7]. This section provides an overview of the existing simulator and additional features for this study.

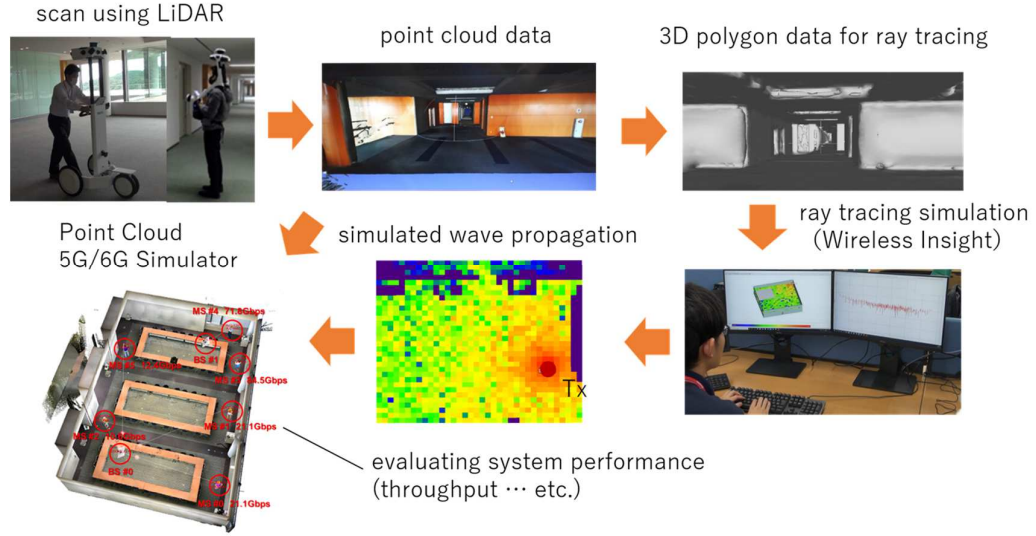


Fig. 3 The flow of the Point Cloud 5G/6G simulator

A. The existing Simulator

The existing simulator was designed to evaluate wireless system performance in specific environments.

Fig. 3 shows the flow of this simulator. Step 1) Using LiDAR, surrounding objects (including floors, walls, and ceilings) are acquired as point cloud data (real-world data) and converted into 3D polygon data. Step 2) The coordinates of the BS and MS are set within the 3D polygon data obtained in Step 1, and a ray-tracing simulation is performed to obtain radio wave propagation parameters (path loss, Direction-of-Departure (DoD), Direction-of-Arrival (DoA), angular spread, and delay spread) between the BS and each MS position. Step 3) A link-level simulation (LLS) is conducted using the propagation channel generated by applying the radio wave propagation parameters obtained in Step 2, along with the pre-set BS and MS antenna configurations, to the Spatial Channel Model (SCM) specified in 3GPP TR 38.901 [8]. The BLER and throughput at each MS position are then obtained.

Furthermore, we are also investigating a feedback loop to the physical space using this digital twin simulator to maximize the performance of mobile communication systems. Our research group has implemented an AI-based blockage prediction and avoidance technology via serving BS switching control on the digital twin simulator, and we are investigating approaches to mitigate the throughput degradation caused by vehicular blockages in the mmW [9].

B. The developed Digital Twin Simulator

To analyze the throughput enhancement effect of RIS- and metasurface-assisted MIMO transmission, we extend the simulator by introducing RIS and metasurface devices into the simulation space. The equivalent transmit power of each device is determined according to the path loss between the device (RIS or metasurface) and a predefined BS antenna. That is, when the transmission power of the BS antenna is $P_{t,BS}$ and the path loss between the BS antenna and RIS is L_{RIS} , the transmission power of RIS, $P_{t,RIS}$, is given by

$$P_{t,RIS} = P_{t,BS} - L_{RIS}. \quad (1)$$

The transmission power of the metasurface is calculated in the same manner. The beam direction control (beamforming) is possible for the BS and RIS, but the beam direction of the metasurface is fixed.

Although simplified, this model captures the essential impact of RIS/metamaterial deployment on the propagation environment and allows efficient evaluation of its contribution to MIMO throughput improvement.

C. The method of calculating path loss

If the far-field condition in (2) holds for the aperture diameter A_{BS} of the BS array antenna, the aperture diameter A_{RIS} of the RIS, the distance R between the two apertures, and the wavelength λ , then the path loss L_{RIS} between the two points can be calculated using the gain G_{BS} of the BS array antenna and the gain G_{RIS} of the RIS with Friis transmission formula in (3). Note that G_{BS} and G_{RIS} represent the gains of the BS antenna and RIS.

$$R > \frac{2A_{BS}A_{RIS}}{\lambda}, \quad (2)$$

$$L_{RIS} = G_{BS}G_{RIS} \left(\frac{\lambda}{4\pi R} \right)^2. \quad (3)$$

However, in indoor deployments, the BS-RIS distance is often short and the array/aperture size is not negligible compared with the wavelength. In such cases, the far-field condition (2) does not necessarily hold, and the path loss should be estimated by near-field calculation.

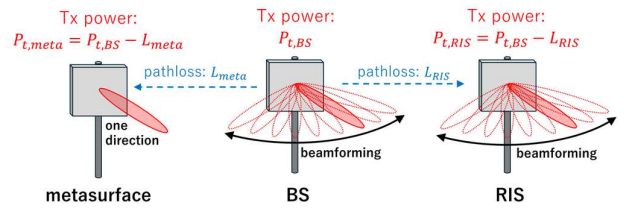


Fig. 4 The relation between the Tx power and the path loss

Let the aperture coordinates of BS antenna at the wavefront be (y, z) , and the aperture coordinates of the observation surface (RIS) be (y', z') , with the distance between them being x . Then the Rayleigh-Sommerfeld diffraction operator H is expressed as in (4). If the aperture distribution of the BS array antenna is f_{BS} and that of the RIS is f_{RIS} , the path loss L_{RIS} can be calculated as (5). $r := \{x^2 + (y' - y)^2 + (z' - z)^2\}^{1/2}$ is the distance. $\Delta y, \Delta z, \Delta y',$ and $\Delta z'$ are the spacings between elements. λ is the wavelength. $\|f\|_2$ is the 2-norm of the aperture distribution f (note that $f = f_{BS}$ or f_{RIS}).

$$H = \frac{e^{j2\pi r \lambda^{-1}}}{r} \cdot \frac{x}{r} \left(\frac{1}{2\pi r} + \frac{1}{j\lambda} \right) \Delta y \Delta z, \quad (4)$$

$$L_{RIS} = \frac{f_{RIS}^* H f_{BS}}{\|f_{RIS}\|_2 \|f_{BS}\|_2} \Delta y' \Delta z'. \quad (5)$$

The calculation results for L_{RIS} are shown in Fig. 5. When the distance R is large, it matches Friis transmission formula and attenuates at -20 dB/dec. On the other hand, when the distance is short, it is smaller than the value obtained by Friis transmission formula. Furthermore, when the antenna sizes of BS and RIS are equal, it can be seen that it converges to 0 dB in the limit as $R \rightarrow +0$.

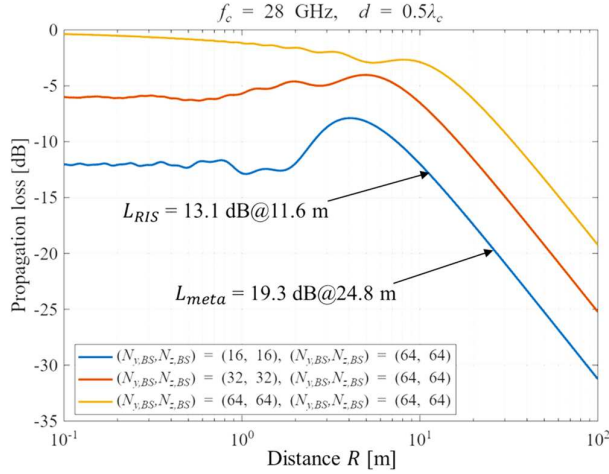


Fig. 5 Propagation loss between BS and RIS/metasurface

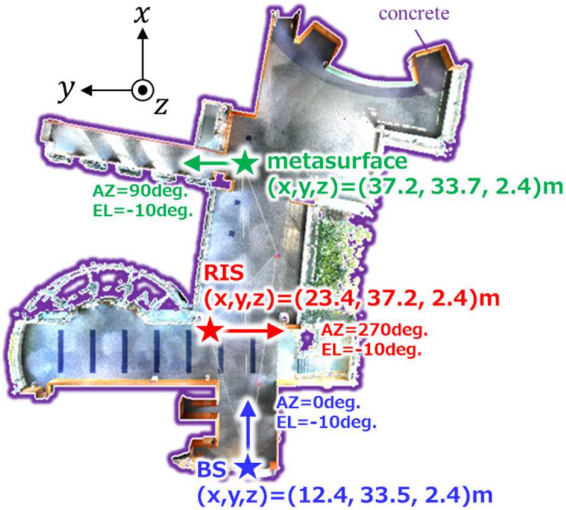


Fig. 6 Position of the BS, RIS and metasurface

III. SIMULATION CONFIGURATION

A. 3D map and deployment

To evaluate the MIMO capacity improvement effect achieved by the RIS and metasurface, a throughput area map was generated using the Digital Twin Simulator in an indoor environment where a base stations, a RIS, and a metasurface were deployed. For this purpose, point cloud data was acquired using LiDAR from a floor of the NTT DOCOMO R&D Center and converted into a 3D model. The resulting model is shown in Fig. 6.

The BS is located at the bottom of the map, and due to the layout of the environment, there are multiple blind spots seen from the BS. We investigate whether placing a metasurface in the blind spot of the corridor in the upper left of the map can improve the received power in this area. On the other hand, the RIS is installed so that its LOS range from the BS overlaps with that of the BS. This allows us to investigate whether throughput can be improved through the MIMO effect of the RIS and metasurface.

In the simulation, the placement and orientation of the BS, RIS, and metasurface are marked in Fig. 6. In the ray tracing, all surfaces within the target region are assumed to be made of concrete, and the space inside and outside the region is assumed to be vacuum. The antenna configuration is summarized in Table 1. Each parameter corresponds to the locations shown in Fig. 7. Since neither the BS-RIS link nor the BS-metasurface link satisfies the far-field condition of (2), the path loss between the BS and the RIS/metasturface is calculated using the near-field method described in Section II-C.

Table 1 Configuration of the array antennas of BS, RIS, metasurface, and UE

Parameter	BS	RIS	metasurface	UE
subarray size, (M_y, M_z)	(2, 1)	(1, 1)		(2, 1)
subarray spacing, (D_y, D_z)	$(2\lambda, -)$	$(-, -)$		$(\lambda, -)$
array size, (N_y, N_z) , [values in SLS]	(8,16)	(64, 64) [(32,32)]		(2, 2)
array spacing, (d_y, d_z)	(0.5 λ , 0.5 λ)			
directivity of each element	Omni			
path loss between BS (values in SLS)	—	13.1 dB (7.1 dB)	19.3 dB (13.3 dB)	—

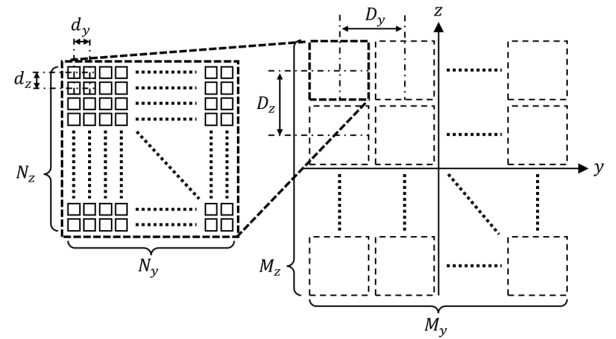


Fig. 7 Configuration of the array antennas

While the RIS and metasurface were initially designed with a 64 by 64 element configuration, this was reduced to 32 by 32 for system-level simulation (SLS) due to computational complexity. Therefore, the path loss value is reduced by 6 dB.

B. Simulation parameters

The specifications for ray tracing and system-level simulation are shown in Tables 2 and 3.

Table 2. The specifications for ray tracing

parameter	specification
center frequency	28 GHz
BS and UE antenna height	2.4 m, 1.5 m
BS and UE antenna	omni (0 dBi)
calculation algorithm	ray launching
ray launching interval	0.1°
number of reflections	10
number of diffractions	none
material	concrete

Table 3. The specifications for system level simulation

parameter	specification
center frequency	28 GHz
bandwidth	400 MHz
No. of used MIMO rank	1 or 2
Tx power of BS, $P_{t,BS}$	30 dBm
azimuth beam range of BS and RIS	$-90^\circ \leq \varphi \leq 90^\circ$
azimuth beam number	36
elevation beam range of BS and RIS	$-90^\circ \leq \theta \leq 0^\circ$
elevation beam number	36
MIMO precoder	SVD

MIMO rank adaptation is not applied. Simulations are performed separately for the cases of rank 1 transmission and full rank (2 ranks) transmission. During MIMO transmission simulations, the channel matrix $\mathbf{H}$ is assumed to be known. A precoder based on singular value decomposition (SVD) is applied to the BS antennas, including RIS and metasurfaces if used. At the UE, MIMO signal detection based on MMSE-IRC (Minimum Mean Squared Error Interference Rejection Combining) is performed, and the throughput is calculated.

IV. SIMULATION RESULTS

Based on the conditions in Section III, simulations were performed in four cases, corresponding to combinations of: 1) with or without RIS/metasurface, and 2) rank 1 only or full rank transmissions. The results are shown in the following subsections.

A. Received power and the throughput with MIMO rank 1

Figs. 8(a) and (b) show the received power and the throughput at MIMO rank 1 without RIS and metasurface ,

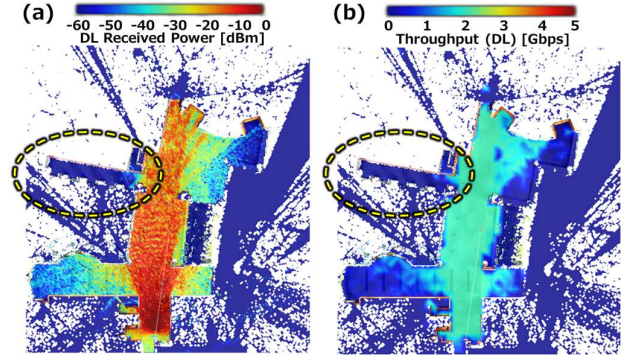


Fig. 8 (a) received power and (b) throughput at MIMO rank 1 without RIS and metasurface

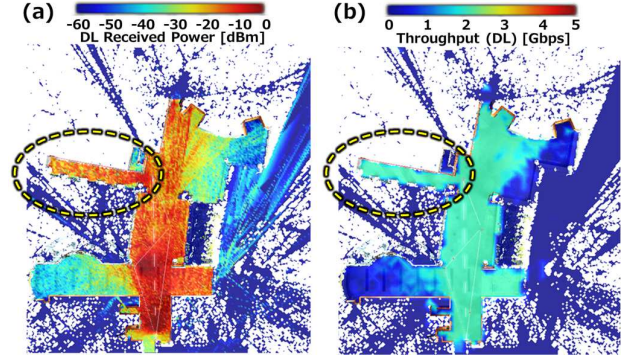


Fig. 9 (a) received power and (b) throughput at MIMO rank 1 with RIS and metasurface

while Figs. 9 (a) and (b) show the received power and throughput at MIMO rank 1 with RIS and metasurface.

Comparing Figs. 8 and 9, it can be seen that when RIS and metasurfaces are used, the received power and throughput in the corridor, which is a blind spot from BS (the area enclosed by the yellow dashed line in the figure), are improved compared to when they are not used.

Fig. 10 shows the cumulative distribution function (CDF) curve of throughput in MIMO rank 1 transmission. This curve shows an improvement in coverage area. Specifically, it can be confirmed that there is a 6.2% improvement in coverage area at 1 Gbps (approximately half of the maximum throughput) and a 5.0% improvement at 2 Gbps.

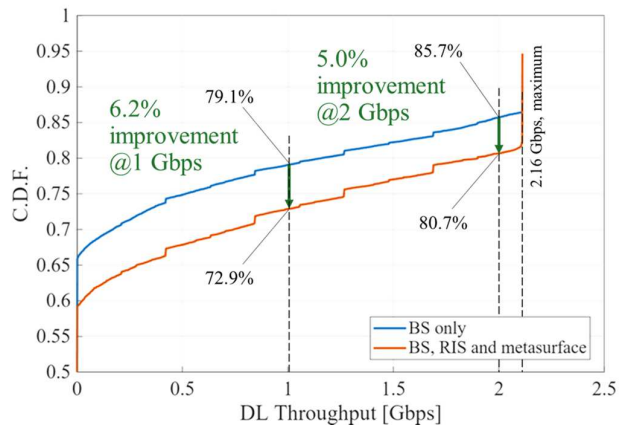


Fig. 10 CDF of the throughput (rank 1 transmission)

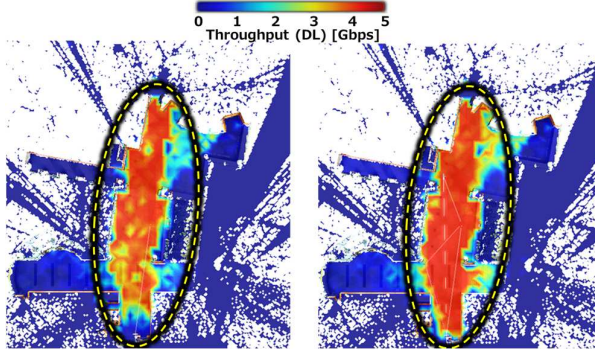


Fig. 11 Throughput in MIMO full rank transmission: (a) without and (b) with RIS and metasurface (right side)

B. Throughput with MIMO rank 2

Figs. 11(a) and (b) show the throughput in MIMO full rank transmission without and with RIS and metasurface, respectively.

Comparing the two, it can be seen that when using RIS and metasurfaces, the throughput in the central part of the room (the area enclosed by the yellow dashed line in the figure), which is directly in front of the base station, is improved compared to when they are not used. From Fig. 11(a), it can be seen that when using only BS, the throughput decreases even near the BS where the received power is high. This indicates that in order to communicate will full MIMO rank,

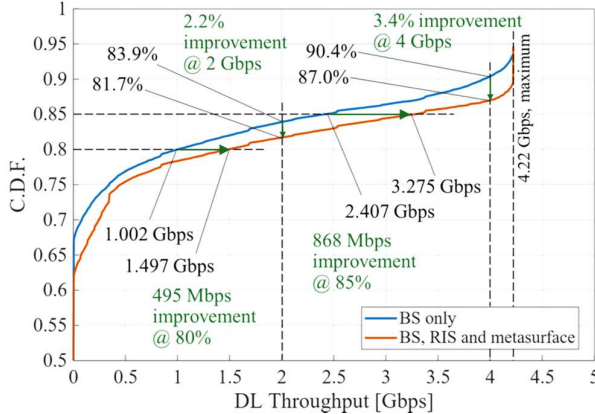


Fig. 12 CDF of the throughput (full MIMO rank transmission)

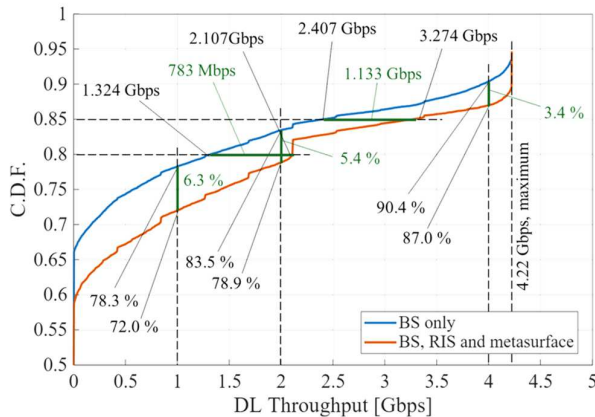


Fig. 13 CDF of the throughput when MIMO rank adaptation is virtually applied.

sufficient received power alone is not enough; it is also necessary to enhance the MIMO effect. As shown in Fig. 11(b), this is achieved by reducing the spatial correlation among antennas through the spatially distributed placement of the RIS and metasurface. In addition, the throughput in the corridor area cannot be improved by increasing the transmission ranks, even when a metasurface is employed.

Fig. 12 shows the CDF curve of throughput in full MIMO rank transmission. This curve shows an improvement in throughput. Specifically, it can be confirmed that there is a 495 Mbps improvement in throughput at 80th percentile and a 868 Mbps improvement at 85th percentile.

C. Throughput with virtual MIMO rank adaptation

By calculating the maximum throughput characteristics at each UE point for MIMO rank 1 or full rank transmission, as shown in subsections IV-A and IV-B, respectively, the throughput characteristics under MIMO adaptation can be obtained. Fig. 13 shows the CDF of throughput under MIMO rank adaptation.

Fig. 13 shows the improvement in throughput under rank adaptation. Specifically, it can be confirmed that there is a 783 Mbps improvement in throughput at 80th percentile and a 1,133 Mbps improvement at 85th percentile. Based on the above considerations, it has been shown that throughput can be improved by using RIS and metasurfaces.

V. CONCLUSION

In this paper, we propose a RIS/metasurfaces aided MIMO configuration for improving the system throughput.

To evaluate the effectiveness of the proposed system, we developed a simulation to perform propagation simulations and 5G system-level simulations under conditions close to those of a real environment. The developed simulator can calculate radio wave propagation information at arbitrary frequencies by performing ray tracing using the surrounding environment acquired as point cloud data using LiDAR. Furthermore, it can perform a 5G-compliant system-level simulation using this radio wave propagation information, and acquire transmission characteristics such as received power and MIMO throughput at each point on a 3D map.

Using the developed simulator, we evaluated the MIMO throughput improvement provided by RIS and metasurfaces in a 28 GHz band MIMO system with maximum 2 ranks within the indoor environment of the NTT DOCOMO R&D Center. The evaluation results showed a throughput improvement of 783 Mbps at the 80th percentile, which is approximately 18.6% of the maximum throughput (4.22 Gbps), and 1,133 Mbps at the 85th percentile, which is approximately 26.8% of the maximum throughput. These results demonstrate that RIS and metasurfaces not only contribute to area expansion as in conventional uses, but also contribute to improving MIMO throughput.

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