Performance Evaluation of Downlink Multi-User Massive MIMO with Configurable Active Antenna System and Inter Access Point Coordination in Low-SHF-Band

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SUMMARY Massive multiple input and multiple output (Massive MIMO) is a key technique to achieve high system capacity and user data rate for the fifth generation (5G) radio access network (RAN). To implement Massive MIMO in 5G, how much Massive MIMO meets our expectation with various user equipment (UEs) in different environments should be carefully addressed. We focused on using Massive MIMO in the low super-high-frequency (SHF) band, which is expected to be used for 5G commercial bands relatively soon. We previously developed a prototype low-SHF-band centralized-RAN Massive MIMO system that has a flexible active antenna system (AAS)-unit configuration and facilitates advanced radio coordination features, such as coordinated beamforming (CB) coordinated multi-point (CoMP). In this study, we conduct field trials to evaluate downlink (DL) multi-user (MU)-MIMO performance by using our prototype system in outdoor and indoor environments. The results indicate that about 96% of the maximum total DL system throughput can be achieved with 1 AAS unit outdoors and 2 AAS units indoors. We also investigate channel capacity based on the real propagation channel estimation data measured by the prototype system. Compared with without-CB mode, the channel capacity of with-CB mode increases by a maximum of 80% and 104%, respectively, when the location of UEs are randomly selected in the outdoor and indoor environments. Furthermore, the results from the field trial of with-CB mode with eight UEs indicate that the total DL system throughput and user data rate can be significantly improved.

key words: 5G, Massive MIMO, low-SHF-band, MU-MIMO, beamforming, C-RAN, CB, CoMP

1. Introduction

Fifth generation (5G) commercial services are expected to launch around 2020. Typical scenarios are classified as enhanced Mobile Broad Band (eMBB), Ultra-Reliable and Low Latency Communications (URLLC), and massive Machine Type Communications/massive Internet of Things (mMTC/mIoT). Compared to Long Term Evolution (LTE), these scenarios require, for example, 1000 times the system capacity, delivery of 10-100 times the user experienced data rate, reduction in system latency to 1 ms, and serving 10-100 times the number of terminals with low power consumption [1].

Among these requirements, a high system capacity and ever-increasing user data rate are two of the most well-known challenges. Massive multiple input and multiple output (Massive MIMO) has attracted significant attention as one of the most promising approaches to increase system capacity and meet user data rate demands of 5G. It uses a very large number of antenna elements at access points (APs) or base stations and simultaneously serves several users with the same time and frequency resources.

Dense small-cell deployment is considered a key strategy for the 5G network. In such deployment, additional APs are deployed in hot spots where high system capacity and improved user data rate are required. A combination of small cells and Massive MIMO would further meet the requirements in the hot spots. Moreover, multiple neighboring hot spots form a hot zone, expanding coverage. However, such deployment would lead to a severely interference-limited system, requiring careful attention to interference management. If the transmission of neighboring APs can be coordinated, the inter-cell interference among APs can be mitigated.

Although there are many publications on the field trials in the low super-high-frequency (SHF) band, which is the potential candidate frequency band for early commercial services of 5G, [2], [3] focused on the high rank MIMO of a single user equipment (UE), and [4] addressed the throughput performance with fixed TRXs at BS. Some studies, such as [5] and [6], have been made on the performance of coherent joint transmission (JT). In the coherent JT, the antennas used in the beamforming are not colocated but correspond to the locations of APs, and data is transmitted from these non-colocated antennas. [7] mainly discussed a precoding matrix generation algorithm that eliminated the need of channel state information (CSI) exchange between the base stations. However, in with coordinated beamforming (CB) mode of our system, each AP received the SRS not only from its own serving UEs but also the from the CB target UEs which were serving by other AP, therefore, the CSI exchange was not necessary. We have developed a prototype low-SHF centralized radio access network (C-RAN) Massive MIMO system [9]–[16]. This system has a flexible active antenna system (AAS) configuration in which the number of antennas is configured based on use cases and requirements, such as required cell capacity, communication quality, and UE density per cell.

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Fig. 1 Block diagram of low-SHF-band C-RAN massive MIMO system.

The C-RAN composition can facilitate advanced radio coordination features, such as coordinated beamforming (CB), Dynamic point selection (DPS), JT, and joint reception (JR) coordinated multi-point (CoMP). In our previous studies, we presented the performance improvement of CB CoMP with up to four UEs in an outdoor environment and evaluated downlink (DL) multi-user (MU)-MIMO performance by using two AAS units in two different outdoor and indoor scenarios [17], [18].

To address the performance of the different scenarios we first evaluated the DL MU-MIMO performance by using our low-SHF-band C-RAN Massive MIMO system with 1 AAS unit and 2 AAS units in outdoor and indoor environments. We then studied the system capacity through simulation based on a real propagation channel. The channel estimation data were measured with 2 AAS units per AP. To confirm throughput enhancement, the field trial on the inter-AP CB with up to eight UEs was conducted.

The rest of this paper is organized as follows. In Sect. 2, we give an overview of our low-SHF band C-RAN Massive MIMO system and the experiment configuration. In Sect. 3, we present the evaluation of the DL MU-MIMO by using our system with 1 AAS and 2 AAS units in outdoor and indoor environments. In Sect. 4, we present the system capacity of CB CoMP using the real propagation channel and present the results of this field trial. The conclusion is given in Sect. 5.

2. Low-SHF-Band C-RAN Massive MIMO System

Figure 1 illustrates a block diagram of our prototype developed low-SHF-band C-RAN Massive MIMO system, and Table 1 lists its specifications. This system consists of a central unit (CU), APs, and UEs. An AP consists of one or more AAS units and digital part (DP) that are connected by multicore multimode optical fibers. The AAS has 64 antenna elements. By connecting two vertical elements to one TRX, 32 transceivers (TRXs) per 1 AAS unit are used. In addition, multiple AAS units can be concatenated vertically and/or horizontally, increasing the number of antenna

Table 1 Specifications of prototype low-SHF-band C-RAN Massive MIMO system.

Common	Center frequency	4.55 / 4.65 / 4.75 GHz
	Bandwidths	100 MHz
	Duplex	TDD, DL:UL = 9:1
	Multiple access	OFDM
	Num. of Subcarriers per PRB	12
	Num. of PRBs	125
	Subcarrier spacing	60 kHz
	Transmission Time Interval (TTI) period	0.25 msec
	Modulation scheme	QPSK, 16QAM, 64QAM
	Coding rate	Max. 0.93
CU	DL link control function	H-ARQ, AMC (w/ OLLA)
AP-AAS	Num. of antenna elements	1 AAS: 4 (V) x 8 (H) x 2 (Pol.), 2 AASs: 4 (V) x 16 (H) x 2 (Pol.)
	Element spacing	0.52 λ (H), 0.61 λ (V)
	Max. Tx power	+25 dBm / polarization
	Antenna polarization	± 45 degrees
AP-DP	DL beamforming algorithm	ZF
	Inter AP coordination algorithm	CB
UE	Antenna configuration	2 Omni antennas w/ 3 λ Spacing
	Max. Tx power	+24 dBm / antenna
	Num. of receiver (Rx) layer	Max. 2

elements. The increased number of antenna elements makes the angle resolution of the beam peak and beam null higher. The calibration of the radio frequency chains of the transmitter and receiver at AAS is described in [11] and Inter-AP calibration is not required in the case of CB CoMP. The DP processes the digital signal processing of beamforming and Layer 1 functions. Spatial multiplexing of up to eight UEs, and 16 layers are supported in the field trial. The Uplink (UL) sounding reference signal (SRS) is used by the DP for channel estimation. The channel estimation obtained from the SRS is used for beamforming (BF) weight generation exploiting UL and DL channel reciprocity. Zero-forcing (ZF) precoding is selected as a DL beamforming algorithm [12] and the DL beamforming weight is calculated per physical resource block (PRB). Suppose one AP transmits data sig-

nal to K UEs. The number of transmit antennas is N_T and each UE is equipped with N_R antennas. Let H_k denote the channel estimation matrix of the k th UE, where $1 \leq k \leq K$. The channel covariance matrix is $\mathbf{H}_k^H \mathbf{H}_k$, where $\cdot^H$ is Hermitian transpose and its eigenvector is given by $\mathbf{v}_{k,l}$, where $1 \leq l \leq N_r$. The $N_T \times L$ matrix $\mathbf{V}$ is denoted by

$$\mathbf{V} = [\mathbf{v}_{1,1}, \mathbf{v}_{1,2}, \dots, \mathbf{v}_{1,L}, \dots, \mathbf{v}_{K,1}, \mathbf{v}_{K,2}, \dots, \mathbf{v}_{K,L}, \dots] \quad (1)$$

and with ZF precoding, we get

$$\mathbf{W}_{ZF} = [\mathbf{w}_1 \mathbf{w}_2 \dots \mathbf{w}_L] = \mathbf{V}(\mathbf{V}^H \mathbf{V})^{-1} \quad (2)$$

where $L = K \cdot N_r$ is the number of Tx layers. The precoding weight is normalized and given by

$$\mathbf{W} = [\mathbf{w}_1 / \|\mathbf{w}_1\| \mathbf{w}_2 / \|\mathbf{w}_2\| \dots \mathbf{w}_L / \|\mathbf{w}_L\|] \quad (3)$$

The CU processes Layer 2 and Layer 3 functions. As the interface between the CU and AP is MAC-PHY split and Layer 1 functions are moved from CU to AP, the required front haul bandwidth between CU and AP is reduced to allow 10G Ethernet interface [8], [9]. The CU controls multiple APs located on geographically different points called “sites”. The CU schedules the radio resource space domain and controls the hybrid automatic repeat request (H-ARQ) and adaptive modulation and coding (AMC). In AMC, the CU configures the modulation and coding scheme (MCS) that would result in a block error ratio (BLER) of 10% on the basis of the outer loop link adaptation (OLLA) in DL.

When inter AP coordination is enabled, APs receives SRS from all UEs involved in the coordination. In the case of DPS, APs calculate the signal-to-interference-plus-noise ratio (SINR) of the received SRS, and sends to CU. The AP with higher received SRS power is selected as the severing AP for the corresponding UE by CU. In the case of CB, the CU sends the MU-MIMO indication message to the APs. This message indicates the target UEs with and without data transmission. The beamforming weight is calculated for all target UEs. Suppose that the number of target UEs without data transmission is K' , L in Eq. (2) becomes $(K + K') \cdot N_r$.

A UE consists of TRXs and DP. The antenna spacing is configurable, and in the field trial it is set as 3 wavelengths, as shown in Table 1. Physical uplink shared channel (PUSCH), physical uplink control channel (PUCCH) and SRS are transmitted by UE. In the DL, UE processes signal reception, demodulation, layer separation (up to two layers per UE) and decoding functions. DL channel estimation is calculated per each PRB.

3. Performance Evaluation of MU-MIMO with 1 AAS Unit and 2 AAS Units

We used 64 antenna elements (1 AAS unit) or 128 antenna elements (2 AAS units) on the AP-AAS, as shown in Table 1. Note that the transmission power per layer was fixed regardless of the number of multiplexed UEs, and the number of transmission layers per UE was fixed as two. The evaluation was conducted in two different scenarios. One is an outdoor

Fig. 2 AP and UE locations in outdoor environment.

parking lot, and the other is an indoor office building. The outdoor environment can be perceived as a large-space outdoor scenario with few reflectors and the indoor environment as a small-space indoor scenario with many reflectors.

3.1 Outdoor Environment

The AP (AAS) and UE locations in the outdoor environment are shown in Fig. 2. The UEs were set in a fan-like shape about 20m from the AP. On the basis of the estimated UL channel, the AP calculated the DL BF weights and carried out DL MU-MIMO transmission by changing the number of multiplexed UEs. The time fluctuation in a channel was ignored because UEs were assumed to be stationary. Only one active UE was allocated to location UE #0, and for the other locations, i.e., UE #1–7, the AP calculated the DL BF weights by using the estimated UL channel measured respectively beforehand.

Figure 3 shows the averaged received SINR and DL throughput of UE #0 in DL MU-MIMO transmission by adding UE #1 (the farthest from UE #0) to UE #7 (the nearest to UE #0) in ascending order. The X axis is the number of multiplexed UEs and the left and right Y axes indicate the averaged received SINR and DL throughput of UE #0, respectively. For both 1 AAS unit and 2 AAS units, the DL throughput of UE #0 was around 705 Mbps, which is the maximum throughput per UE in this system design, even when the number of multiplexed UEs was eight. Note that the DL throughput of UE reached maximum when the modulation scheme is 64QAM and the coding rate is 0.93. Although the averaged received SINR of UE#0 was degraded, it was still high enough to configure the highest modulation order and coding rate. Regarding the received SINR of UE #0, when the number of multiplexed UEs was one, the SINRs of the 1 AAS unit case and the 2 AAS units case are 29.7 dB and 30.9 dB, respectively. When the number of multiplexed UEs was eight, the SINRs of the 1 AAS unit case and the 2 AAS units case were 23.2 and 26.5 dB, respectively. The maximum difference between the two cases was 3.3 dB when the number of multiplexed UEs was eight. The reason is that since the number of antenna element of 2 AAS is twice more than 1 AAS unit, 3 dB beamforming gain is predictable. Besides, with the double number of antennas, higher degrees of

Fig. 3 Averaged received SINR and DL throughput of UE #0 for 1–8 multiplexed UEs in DL MU-MIMO transmission in outdoor environment.

Fig. 4 Averaged received SINR and DL throughput of each of eight multiplexed UEs in DL MU-MIMO transmission in outdoor environment.

freedom can be used for beamforming in the DL MU-MIMO transmission.

We also measured each UE's DL throughput in eight multiplexed UEs case with the same settings. Figure 4 shows the averaged received SINR and DL throughput of each UE in the eight multiplexed UEs DL MU-MIMO case for both the 2 AAS units and the 1 AAS unit. The X axis is UE index, and the left and right Y axes indicate the averaged received SINR and the DL throughput of each UE, respectively. The total DL system throughput (i.e. sum of eight UEs) of the 1 AAS unit and the AAS units were 5.4 and 5.6 Gbps, respectively. All UEs reached the maximum throughput per UE (705 Mbps) in this system design for 2 AAS units, while the DL throughput of UE #6 and #7 degraded for 1 AAS unit. We can confirm that 2 AAS units mitigated the remaining inter-user-interference because of its narrower beamwidth than that of 1 AAS unit, even when the UEs were closer such as UE #6 and #7. In the case of 1 AAS unit, although UE #0 and #7 are as close as UE #6 and #7, the channel correlation between UE #0 and #7 (−16.8 dB) was about 7 dB lower than that between UE #6 and #7 (−9.6 dB). Such relatively high channel correlation caused more remaining inter-user interference during the precoding. This is one of reasons why the performance of UE #0 is better than that of UE #6

Fig. 5 AP (AAS) and UE locations in indoor environment.

and #7.

3.2 Indoor Environment

The AP (AAS) and UE locations in the indoor environment are illustrated in Fig. 5. UE #0, #2, #3, #4, and #6 were located in the same room with the AP. UE #0, #3, #4, and #6 were located in the perspective of AP (LOS), and UE #2 was located outside the perspective of AP (NLOS). The other UEs (UE #1, #5, and #7) were located outside the room with the AP.

Figure 6 shows the average received SINR and DL throughput of UE #0 in DL MU-MIMO transmission by adding UE #1 to #7 in ascending order. The X axis is the number of multiplexed UEs, and the left and right Y axes indicate the averaged received SINR and the DL throughput of UE #0, respectively. For 2 AAS units, the DL throughput of UE #0 remained at about 705 Mbps even when the number of multiplexed UEs increased up to eight. The average received SINR of UE #0 varied from 30.9 to 24.6 dB as the number of multiplexed UEs increased. Although the averaged received SINR of UE #0 degraded, it was still high enough to configure the highest modulation order and coding rate. For 1 AAS unit, however, the DL throughput of UE #0 decreased to 564 Mbps, and the average received SINR changed from 29.7 to 20.4 dB. The difference in the average received SINR tended to become large with the increase in the number of multiplexed UEs, and the maximum difference between the two cases is 4.2 dB when the number of multiplexed UEs was eight.

Figure 7 shows the averaged received SINR and DL throughput of each UE of the eight multiplexed UEs in DL MU-MIMO transmission. The X axis is UE index, and the left and right Y axes are the averaged received SINR

Fig. 6 Averaged received SINR and DL throughput of UE #0 for 1–8 multiplexed UEs in DL MU-MIMO transmission in indoor environment.

Fig. 7 Averaged received SINR and DL throughput of each UE in eight multiplexed UEs DL MU-MIMO transmission in indoor environment.

and the DL throughput of each UE, respectively. The total DL system throughput (i.e. sum of eight UEs) was 5.4 Gbps (about 96% of the maximum total DL system throughput in this system design) for 2 AAS units and 4.8 Gbps for 1 AAS unit. We could confirm a greater performance improvement with 2 AAS units compared with that of 1 AAS unit. For 2AAS units, the DL throughput of UE #2 was higher than that of UE #3. Since the distances between the AAS and the UEs were relatively small, the transmission power was strong enough to reach the maximum DL throughput if the number of multiplex UE was 1 and the free space propagation was not the main impact on the performance. For instance, although UE #3 was closer to the AAS than UE #2, the DL throughput of UE #3 was lower than that of UE #2. The similar phenomena was observed at UE #1 compared to the UE indoors, such as UE #0, #2, #3 and #6.

We now consider the DL MU-MIMO evaluation results of both the outdoor environment and indoor environment. Table 2 shows the delay spread of each UE and averaged delay spread over all UEs of the outdoor environment and indoor environments. We also analyzed the averaged channel correlation of each UE, as shown in Table 3. For an instance, for UE#0, it is the average of the channel correla-

Table 2 Delay spread of outdoor and indoor environment [ns].

UE	#0	#1	#2	#3	#4	#5	#6	#7	Ave.
outdoor	35.3	34.7	58.5	33.9	38.7	37.2	44.4	51.7	41.8
indoor	41.8	45.5	49.0	50.6	51.1	72.0	50.0	45.6	50.7

Table 3 Averaged channel correlation between UEs [dB].

UE	#0	#1	#2	#3	#4	#5	#6	#7	Ave.
outdoor									
1 AAS	-18	-18	-20	-17	-19	-20	-16	-16	-18
2 AAS	-22	-20	-20	-19	-21	-25	-20	-19	-20
indoor									
1 AAS	-17	-15	-14	-15	-16	-15	-18	-16	-16
2 AAS	-20	18	17	-17	-21	-18	-20	-19	-19

tions between UE#0 and any other UE, #1-#7. In the indoor environment, delay spread was larger than in the outdoor environment, and channel correlation was higher by about 2 dB than the outdoor environment. Due to the larger area in the outdoor environment, the locations of UE can be selected with lower channel correlation, even in 1 AAS unit, about 96% of the maximum total DL system throughput was reached, whereas about 86% of the maximum total DL system throughput was reached in the indoor environment. We confirmed that our prototype low-SHF-band Massive MIMO system can optimize the DL throughput performance with the minimum configuration of AAS units by changing the configuration appropriately depending on the environment.

4. Performance Evaluation of Inter AP Coordination

4.1 Simulation Results of Channel Capacity with Real Propagation Channel Estimation Data

In this section, the number of AAS units per AP during channel measurement in both outdoor and indoor environments are two. Two APs and one UE were used. The coverage of two APs can be perceived as a two-site deployment scenario. During the measurement, the SRS was received by both AP#1 and #2 to allow for APs to estimate the propagation channel. The channel-estimation data were recorded at both APs and used as the input for the simulation. The locations of UEs were chosen randomly in the simulation, i.e., no scheduling algorithm for UE combinations was included. Before BF weight calculation, additive white Gaussian noise (AWGN) of a signal-to-noise ratio (SNR) = 20 dB was added to the measured channel data to simulate the channel-estimation error using UL/DL reciprocity and AAS calibration error. In our prototype system, the maximum DL throughput per UE can be achieved when the SNR is higher than 20 dB. The channel capacity was calculated using Shannon's theorem.

The following four modes were simulated. In the multi-AP mode (mode 1 and 2 below), one AP is selected as the serving AP, in which the received power SRS is higher. Only the serving AP transmits DL data to the UE. 1) CB mode (w/ CB): both APs calculate the ZF BF weights for all UEs. Therefore, the DL interference from the non-serving

Fig. 8 APs and UEs locations in simulations and the filed trial of CB.

AP is reduced. However, more freedom of BF weights is consumed than that in non-CB mode. 2) non-CB mode (w/o CB): each AP calculates the ZF BF weights for serving UEs only. Therefore, the interference from the non-serving AP is not reduced. 3) AP#1 only mode: all UEs are served by AP#1 and AP#2 is not used. 4) AP#2 only mode: All UEs are served by AP#2 and AP#1 is not used.

4.1.1 Outdoor Environment

The height of the AAS and the antennas at the UE were 3 and 1.7m, respectively. Figure 8 illustrates an overview of the measurement area and orientations of the AAS. The UE was located with LOS to the AAS. About 9×1200 points in the blue area are measured and the interval between two adjacent points in the direction of 20m is about 2m while about 0.03m in the direction of 40.5m. The channel capacity (bps/Hz) vs. the number of UEs in AP#1 only, AP#2 only, w/o CB and w/ CB is shown in Fig. 9. Compared to AP#1 only, AP#2 only and w/o CB, the channel capacity in w/ CB increases 46% (AP#1 only), 39% (AP#2 only) and 80%, respectively. The system capacity reached maximum when the number of UEs was 18. Figure 10 illustrates the cumulative distribution function (CDF) of the received signal-to-interference power ratio (SIR) when the number of UE was 18. The SIR was the highest in w/ CB.

4.1.2 Indoor Environment

The height of an AAS and the antennas at the UE were 2.5 and 1.7m, respectively. Figure 11 illustrates APs and UE locations in the indoor environment for channel-capacity simulation. The orientations of the APs are shown as green dotted lines. About 3275 points in the blue area are measure and the interval between two adjacent points is about 0.02m. Both LOS and NLOS conditions existed. Figure 12 illustrates channel capacity (bps/Hz) vs. the number of UEs in AP#1 only, AP#2 only, w/o CB and w/ CB. Compared to AP#1 only, AP#2 only and w/o CB, the channel capacity in w/ CB increases 37% (AP#1 only), 26% (AP#2 only) and 104%, respectively. The system capacity reached maximum when the number of UEs was 22. Figure 13 illustrates the

Fig. 9 Estimated channel capacity for AP#1 only, AP#2 only, w/o CB and w/ CB in outdoor environment.

Fig. 10 CDF of received SIR in AP#1only, AP#2 only, w/o CB and w/ CB when number of UEs was 18 in outdoor environment.

Fig. 11 APs and UE locations in simulation in indoor environment.

CDF of received SIR when the number of UEs was 22.

Additionally, we illustrated the maximum channel capacity for the case of 1 AAS unit per AP in both outdoor and indoor environment and compared it with the case of 2AAS units per AP. The comparison results are shown in Fig. 14. The numbers on the top of each bar indicate the number of multiplexed UEs in each different cases. As 2AAS units employed twice more antenna elements, the number of multiplexed UE that it can support will be doubled. In both outdoor and indoor environments, the maximum estimated channel capacity of 2 AAS units is about 1.8-1.9 times more

Fig. 12 Estimated channel capacity in AP#1 only, AP#2 only, w/o CB and w/ CB in indoor environment.

Fig. 13 CDF of received SIR in AP#1 only, AP#2 only, w/o CB and w/ CB when number of UEs is 22 in indoor environment.

Fig. 14 Comparison of maximum estimated channel capacity with 1 AAS and 2 AAS units.

than that of 1 AAS unit, as we expected. Besides, the maximum estimated channel capacity of w/ CB in the outdoor environment is about 1.6-1.8 times than that of w/o CB, while it is about 2 times in the indoor environment. The reason is that because of different directions of two AASs, the inter-cell interference area between two APs is wider in the indoor environment than in the outdoor environment, therefore the enhancement from w/ CB is larger in the in-

Table 4 DL throughput (TP) in AP#1 only, AP#2 only, w/o CB and w/ CB [Mbps].

DL TP	#0	#1	#2	#3	#4	#5	#6	#7	Total
w/ CB	654	519	702	681	703	705	576	701	5241
w/o CB	562	555	594	627	501	559	585	560	4543
AP#1 Only	612	486	664	627	557	243	189	139	3517
AP#2 Only	151	154	129	91	701	686	538	641	3091

Table 5 Averaged received SINR in AP#1 only, AP#2 only, w/o CB and w/ CB [dB].

Averaged Received SINR	#0	#1	#2	#3	#4	#5	#6	#7
w/ CB	22	19	24	22	24	24	21	25
w/o CB	19	20	20	21	17	19	20	21
AP#1 Only	21	17	22	21	19	8	5	4
AP#2 Only	4	4	3	0	24	23	18	23

door environment. Moreover, in both cases of 1 AAS unit and 2AAS units, the maximum estimated channel capacity of the outdoor is smaller than that of the indoor. The reason is that generally the number of multipath components was large in the indoor environment, so that the channel correlations between UEs are relatively low and the antenna degrees of freedom can be used more efficiently even without the deliberate selection of multiplexed UEs. Besides, we can observe that in the 1 AP only (2AAS/AP) mode, the maximum channel capacity is larger than in w/ CB (1AAS/AP) mode.

4.2 Field Trial of Inter-AP Coordination in Outdoor Environment

Due to the hardware constraints on the number of UEs, the performance evaluation of inter-AP coordination was conducted with up to eight UEs. Two APs and one AAS per AP were used. All APs and UEs were active and stationary during the measurement. The orientations of the AAS are the same as in 4.1.1, as shown in Fig. 8. Similar with the simulations, the following four modes, w/ CB, w/o CB, AP#1 only and AP#2 only were evaluated. In the modes of w/ CB and w/o CB, UE #0-#3 were served by AP#1 while UE #4-#7 were served by AP#2. All UEs were served by AP#1 and AP#2 was not used in the AP#1 only mode, while all UEs were served by AP#2 and AP#1 was not used in the AP#2 only mode.

The DL throughput in w/ CB, w/o CB, AP#1 only, and AP#2 only is shown in Table 4. In w/ CB, the total DL throughput was about 5.2 Gbps, while the maximum throughput of one UE reached around 705 Mbps. Compared with the w/o CB, the total DL throughput increase was about 700 Mbps, which is an increase of about 15%. Table 5 shows the average received SINR at each UE. The average received SINR of all UEs except UE#1 increased in w/ CB, and the maximum enhancement per UE was up to 6.5 dB. We also calculated channel capacity based on the received SINR of each layer of each UE by using Shannon's theorem and the enhancement of channel capacity in w/ CB increased

by about 15%, which is consistent with that of the total DL throughput. Such enhancement of channel capacity (15%) in the field trial is smaller than that of the simulations. The reason is that the UE locations was just one snapshot sample during the field trial while they were several snapshot samples and the channel capacity was averaged in the simulations. For the same reason, the total DL throughput in 1AP only is lower than in w/o CB in the field trial.

We also observed that the averaged received SINR of UE #1 slightly degraded in w/ CB compared to that in w/o CB. The reason is that the reduction of S was larger than that of $I+N$. Since the spatial channel correlations of UE #1 and #6 and UE #1 and #7 were relatively high, some of the transmission signal power was used to remove the interference signal from UE #1 in the ZF precoding. This decreased the transmission power to the direction of UE #1 (eigen vector direction of UE #1) in w/ CB. The reason that the enhancement in the average received SINR of UE #6 was relatively small is similar. Due to the high spatial channel correlation of UE #6 and #0, the transmission power toward to UE #6 also decreased in w/ CB.

5. Conclusion

In this paper, we evaluated the performance of DL MU-MIMO by using a prototype low-SHF-band C-RAN Massive MIMO System. The field trials were conducted in the outdoor and indoor environment. We confirmed that with 1 AAS unit in the outdoor and 2 AAS units in the indoor environment the total DL system throughput achieves 5.4 Gbps which is about 96% of the maximum total DL throughput in the system design with the bandwidth up to 100 MHz. The prototype system can optimize the performance of DL throughput and user data rate with the minimum configuration of AAS units by changing the configuration appropriately depending on the environment. We also investigated the channel capacity using a real propagation channel through the simulations. In the case of 2AAS units per AP, the channel capacity in CB increases by a maximum of 80% and 104% with random UE locations selections, compared to w/o CB in the outdoor and indoor environment, respectively. The maximum estimated channel capacity of 2 AAS units per AP is about 1.8-1.9 times more than that of 1 AAS unit per AP. Moreover, the maximum estimated channel capacity of the outdoor is smaller than that of the indoor. In the indoor environment, the antenna degrees of freedom can be used more efficiently even without the deliberated selection of multiplexed UEs. Furthermore, for the field trial w/ CB, the results show that the DL throughput at each UE can be improved greatly.

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