

PAPER

An Actual Stadium Verification of WLAN Using a Distributed Smart Antenna System (D-SAS)

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SUMMARY Dense deployments of wireless local area network (WLAN) access points (APs) are accelerating to accommodate the massive wireless traffic from various mobile devices. The AP densification improves the received power at mobile devices; however, total throughput in a target area is saturated by inter-cell interference (ICI) because of the limited number of frequency channels available for WLANs. To substantially mitigate ICI, we developed and described a distributed smart antenna system (D-SAS) proposed for dense WLAN AP deployment in this paper. We also describe a system configuration based on our D-SAS approach. In this approach, the distributed antennas externally attached to each AP can be switched so as to make the transmit power match the mobile device's conditions (received power and packet type). The gains obtained by the antenna switching effectively minimize the transmission power required of each AP. We also describe experimental measurements taken in a stadium using a system prototype, the results show that D-SAS offers double the total throughput attained by a centralized smart antenna system (C-SAS).
key words: WLAN, IEEE 802.11ac, distributed antenna system (DAS), smart antenna system (SAS), antenna switching

1. Introduction

Mobile traffic is increasing massively due to the wide spread use of smart devices such as smartphones and tablet computers [1]. At the same time, the explosive growth of devices in Internet of Things is leading wireless communication systems to high load by mixture of various types of mobile traffic [2]. For stably accommodating such mobile traffic, it is necessary to evolve the current wireless communication systems on the basis of further total throughput improvement. In this regard, particular attention is being focused on spatial domain technologies, which increase the number of spatial streams in a target area without expanding frequency bandwidth.

Spatial domain technologies are classified into centralized and distributed antenna approaches. In the former, it is well known that massive multiple input multiple output (MIMO) enables the spectrum efficiency to be substantially improved by increasing the number of spatial streams [3]–[5]. As Lu et al. reported [4], the benefits of massive MIMO have been maximized by significant additional research work done on channel correlation, hardware implementation and impairments, interference management, and modulation. With regard to the distributed antenna ap-

proach, much research has been made on dense small-cell deployments including coordinated controls between cells in 5G networks [5], [6] and wireless local area networks (WLANs) [7]–[9]. The WLAN approach we focus on is compatible with the distributed approach from the perspective of size and cost of access points (APs).

Many benefits are provided by WLAN AP densification including improvements in spectrum and energy efficiencies, coverage, connectivity, and latency without expanding the frequency bandwidth. However, since there are limited frequency channels available for WLANs, the number of non-overlapping frequency channels will be reduced in crowded environments such as stadiums, shopping malls, and train stations. In these situations, overlapping basic service sets (OBSSs) give rise to inter-cell interference (ICI) that degrades total throughput. Moreover, frequency channel bandwidth is continuing to expand as WLAN standardization advances [10]. Therefore, the number of available frequency channels will also decrease in the future. It is essential to mitigate ICI to achieve dense reuse of frequency channels so that the full potential of dense WLAN AP deployments can be realized.

For mitigating ICI, transmission power control (TPC) has been implemented in various wireless communication systems and its effectiveness has been clarified in actual scenarios [11], [12]. The use of TPC mitigates received power at each station (STA), but it also degrades the transmission quality of cell-edge STAs; therefore, its improvement effectiveness is limited. In a related area, beamforming technologies using an antenna array have been researched for further improving the total throughput [13], [14]. These technologies make it possible to mitigate ICI without significantly lowering the transmission quality by accurately acquiring channel state information (CSI). However, in WLANs based on autonomous distributed control, acquiring CSI with respect to interfered STAs is difficult because the WLAN AP does not have a function to acquire CSI with an unconnected STA.

In our work, we focused on a distributed antenna system (DAS) [15]–[17]. In cellular systems based on frequency division duplex, many research results have clarified the effectiveness of DAS. On the other hand, few practical research reports have been reported on WLANs based on time division duplex. We consider that this is because that compatibility with carrier sense multiple access with collision avoidance (CSMA/CA) applied in WLANs is not good

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when there is considerable ICI. Therefore, to apply DAS to WLAN APs, it is necessary to design while considering up-link and downlink scenarios integrally.

Thus, we proposed the concept of a distributed smart antenna system (D-SAS), which mitigates ICI between OB-SSs for achieving dense WLAN AP deployment, and describe the throughput improvement obtained with it in a fundamental experimental measurement [18]. In the D-SAS, APs transmit with the minimum transmission power gained from the improved received power that can be acquired by using the distributed antennas switched per packet in accordance with STAs for ICI mitigation in the downlink scenario. This control can greatly mitigate ICI while maintaining the received power at each STA by the distributed antenna switching. On the other hand, in the uplink scenario, APs control receiver sensitivity so that the transmit signals from connected STAs in the coverage area can be received. Moreover, to apply the D-SAS proposed in [18] to an actual environment, this paper presents the detailed control procedure of the D-SAS to realize a WLAN protocol that includes carrier sense multiple access with collision avoidance (CSMA/CA), management frame transmission, and data transmission. We also describe the system configuration and cell planning of a WLAN AP using D-SAS and its effectiveness using detailed experimental results obtained in an actual stadium.

The rest of this paper is organized as follows. Section 2 describes the technical classification of the distributed antenna approach and the contributions of this paper. Section 3 describes the D-SAS and presents the system configuration of the proposal. Experimental conditions and evaluation results are shown in Sect. 4, and Sect. 5 concludes the paper with a summary.

2. Related Works and Contributions

Figures 1(a)–(c) show AP configurations based on the DAS approach. In these figures, we assume that each AP has a 4×4 MIMO transmission function to explain them briefly. The type #1 (conventional) configuration in Fig. 1(a) directly connects distributed antennas to each AP antenna port, and all distributed antennas are located in different locations. This configuration can be achieved by mounting distributed antennas without major changes in the AP functions, resulting in lower cost and reduced AP size. For downlink scenarios, the received power at the STA is improved by shortening the distance between each distributed antenna and STA, but the throughput improvement by MIMO transmission is limited because there are distributed antennas at different distances. For uplink scenarios, since ICI is increased by the distributed antennas, the transmission opportunities are greatly reduced.

The type #2 (conventional) configuration in Fig. 1(b) is one that allows the distributed antennas for each AP antenna port to be arbitrarily switched by matrix switch (SW) devices. It is also attenuators (ATTs) connected to each antenna port for mitigating ICI and adjusting the receiver sen-

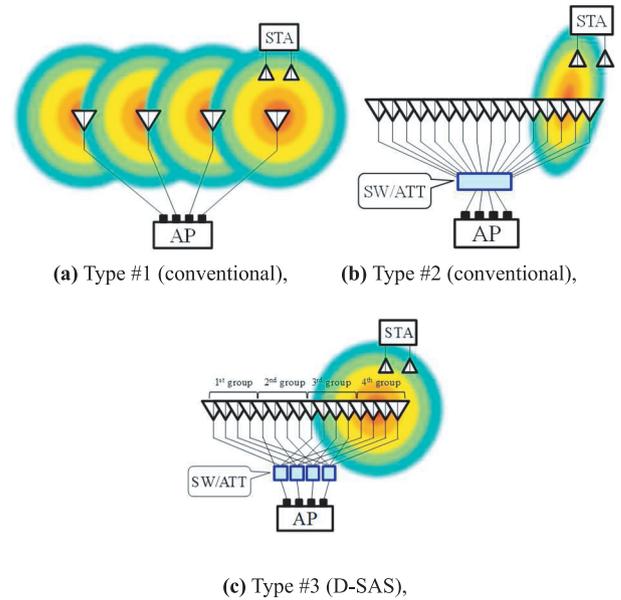


Fig. 1 AP configurations using DAS.

Table 1 Technical classification of AP configurations using DAS.

| | Total throughput | MIMO performance | Cost | Related work |
|-----------------|------------------|------------------|---------|------------------------|
| Type #1 | Limited | Limited | Good | [19], [20] |
| Type #2 | Very good | Very good | Limited | [22] |
| Type #3 (D-SAS) | Good | Good | Good | [18], [21], [25], [26] |

sitivity. The matrix switching makes it possible to maximize not only the received power but also MIMO transmission performance. However, the configuration of the ATT and SW devices becomes complex and insertion loss occur.

The type #3 (D-SAS) configuration in Fig. 1(c) is the one we proposed in which a desired antenna is switched among grouped distributed antennas by SW devices that are not matrix SW devices. Similar to type #2, ATTs are connected to each AP antenna port. In this configuration the limited degree of freedom for antenna switching, results in lower throughput improvement than is obtained with type #2. However, the results are a better MIMO performance than type #1 and better costs than type #3. When using a conventional AP with densely located centralized antennas, the total throughput peaks depend on ICI. Although the transmit power from the AP is reduced to mitigate ICI, total throughput is degraded for STAs at the edge of the coverage area due to insufficient received signal power and the hidden node problem occurs. On the other hand, the proposed D-SAS shortens the distance between AP antenna and STAs in the coverage area and sets the optimum distributed antennas and ATT values for each STA with simple control procedures. As a result, excessive transmit signals can be reduced without reducing the required received power for STAs and ICI can be mitigated.

Table 1 shows the technical classification of AP configurations on the DAS approach based on previous descriptions. As the table shows, D-SAS does not have any ma-

for disadvantages from the viewpoints of total throughput, MIMO performance, and cost. Therefore, we consider that it is suitable for practical use. The table also shows references related to types #1~#3 [18]–[22], [25], [26]. Although there are fewer evaluations of WLAN with DAS than for mobile communication systems, several papers related to type #1 have been reported. However, very few papers have been reported that are related to types #2 and #3, indicating that insufficient study has been done in this field. Moreover, for dense AP deployment expected for practical use, we must consider WLAN protocol that includes including CSMA/CA, management frame transmission, and data transmission and its effectiveness from comprehensive experimental results including a specific cell design.

3. Distributed Smart Antenna System (D-SAS)

This section describes the D-SAS extended from [18] for application in an actual environment.

3.1 System Configuration

Figure 2 shows the system configuration including WLAN AP based on the D-SAS we propose. Our system has a control engine on a network and multiple WLAN APs are connected to the control engine throughout the network. The engine calculates the ICI of the distributed antennas with the maximum ICI between APs and optimizes the allocated frequency channels for each AP in the target area by using the algorithm described by Abeysekera et al. [23] as one example of practical frequency channel allocation.

Figure 3 shows a block diagram of the WLAN AP implemented with a D-SAS unit, which is externally connected to a general WLAN module. The D-SAS unit has M SWs for switching among N ($M \leq N$) grouped distributed antennas. The total number of distributed antennas is MN . The D-SAS unit also has M ATTs for controlling the transmission power and receiver sensitivity. This makes it possible to achieve control on a per-packet basis. Thus, it can be

understood that signal processing enables power control to be achieved. However, since the antenna port units and their control range are restricted, in this configuration, power control is achieved by ATTs that can be externally connected.

3.2 System Flows

Figure 4(a) shows a system flow at the control engine side. The purpose of the flow is to take into account the transmission power mitigations corresponding to the D-SAS under dense frequency channel allocation. As the figure shows, the control engine notifies of the entry of a frequency channel allocation mode for each AP. Then the AP measures the received signal strength indicator (RSSI), $R_{i,j}^{(AP)}[m,n]$ ($m = 1, \dots, M$ and $n = 1, \dots, N$), between the $[m,n]^{\text{th}}$ distributed antenna at AP $_i$ and AP $_j$ ($i \neq j$) by scanning the beacon signal and feeds RSSI information back to the control engine. After acquiring RSSI information from connected APs throughout the network, the control engine calculates ICI, $I_{i,j}$, between AP $_i$ and AP $_j$ by using Eq. (1) and frequency channel allocation by using the algorithm described by [23] as one example of practical frequency channel allo-

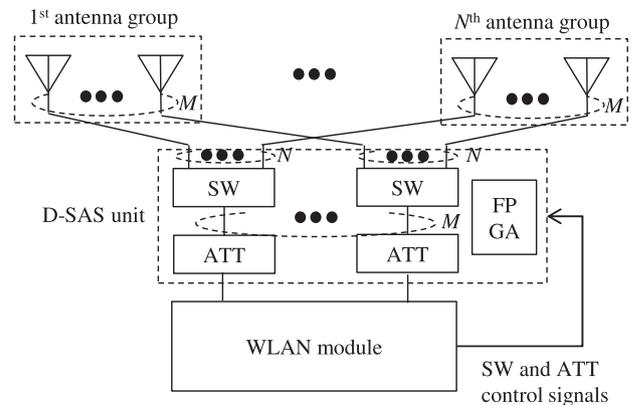


Fig. 3 Block diagram of WLAN AP with D-SAS.

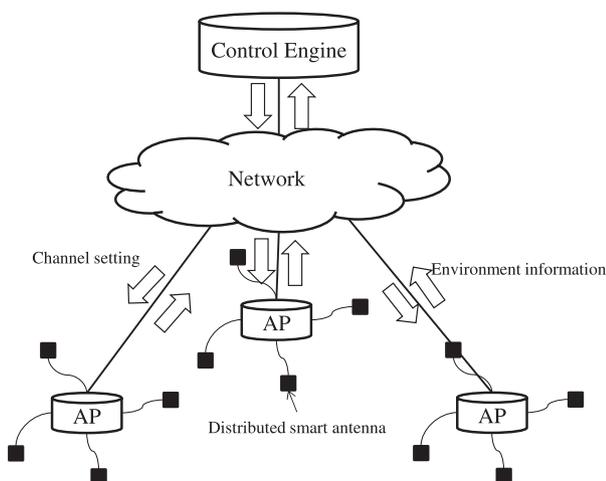
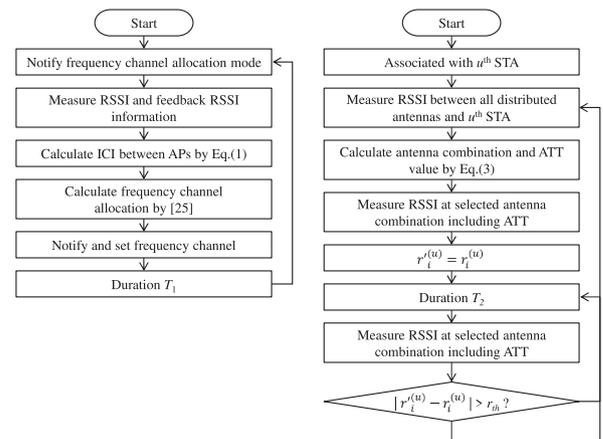


Fig. 2 System configuration.



(a) Control engine side,

(b) AP side,

Fig. 4 System flows.

cation.

$$\begin{aligned} I_{i,j} &= R_{i,j}^{(AP)}[m', n'], \\ [m', n'] &= \operatorname{argmax}_{[m,n]} \left(R_{i,j}^{(AP)}[m, n] \right). \end{aligned} \quad (1)$$

Note that the beacon signal in the proposed system is transmitted from the non-specific antennas $c_1 \sim c_M$, including the non-specific ATT value, A'_i . The non-specific antennas mean one or more selected antennas from each antenna block. The non-specific ATT value calculated from Eq. (2) is used when transmitting downlink signal receiving uplink signal with destination is non-specified. This is because the control information should be shared with all the WLAN devices within a basic service set (BSS) to avoid signal collision.

$$\begin{aligned} A'_i &= \begin{cases} A_{th} - R_{min} & A_{th} - R_{min} > 0 \\ 0 & A_{th} - R_{min} \leq 0. \end{cases} \\ R_{min} &= \operatorname{argmin}_{u, c_m} \left(R_i^{(u)}[c_m] \right) \end{aligned} \quad (2)$$

Here A_{th} is a threshold value of ATT and $R_i^{(u)}[c_m]$ is an RSSI value between the c_m^{th} antenna at AP_i and the u^{th} STA. Then the control engine notifies the calculated frequency channels to each AP and each AP sets the notified frequency channel. After passing duration T_1 , the same flow is performed. T_1 is a value used when the number of unmanaged APs and the setting channel change over time.

Figure 4(b) shows a system flow at the AP side to be independently carried out for each STA. The purpose of the flow is to set specific distributed antennas and ATT values. As shown in Fig. 4(b), when the u^{th} STA is associated with AP_i , AP_i measures RSSI at all distributed antennas $R_i^{(u)}[m, n]$. Then AP_i calculates the antenna combination $\mathbf{M}_{i,u}$ and the ATT value $A_{i,u}$ by using Eq. (3).

$$\begin{aligned} \mathbf{M}_{i,u} &= \left[\operatorname{argmax}_n \left(R_i^{(u)}[1, n] \right) \quad \dots \quad \operatorname{argmax}_n \left(R_i^{(u)}[M, n] \right) \right], \\ A_{i,u} &= A_{th} - \operatorname{argmin}(\mathbf{M}_{i,u}) \end{aligned} \quad (3)$$

After setting $\mathbf{M}_{i,u}$ and $A_{i,u}$, AP_i measures the actual RSSI value $r_i^{(u)}$ for the u^{th} STA and stores it as $r_i^{\prime(u)}$. During periodic intervals T_2 , AP_i measures the RSSI value $r_i^{(u)}$ again. T_2 is a value used when the connected STA moves. If the difference between $r_i^{\prime(u)}$ and $r_i^{(u)}$ is larger than threshold r_{th} , antenna selection and ATT adjustment are carried out again as in the above flow so that the scheme can select optimum antennas and adjust ATT values for each STA in accordance with the mobility of STAs and channel variation.

3.3 Control Procedures for Applying D-SAS

The control procedure for applying the D-SAS to dense WLAN AP environments is classified into four scenarios: downlink scenarios using non-specific and specific antenna combinations, and uplink scenarios using non-specific and specific antenna combinations as shown in Figs. 5(a)–(d). In

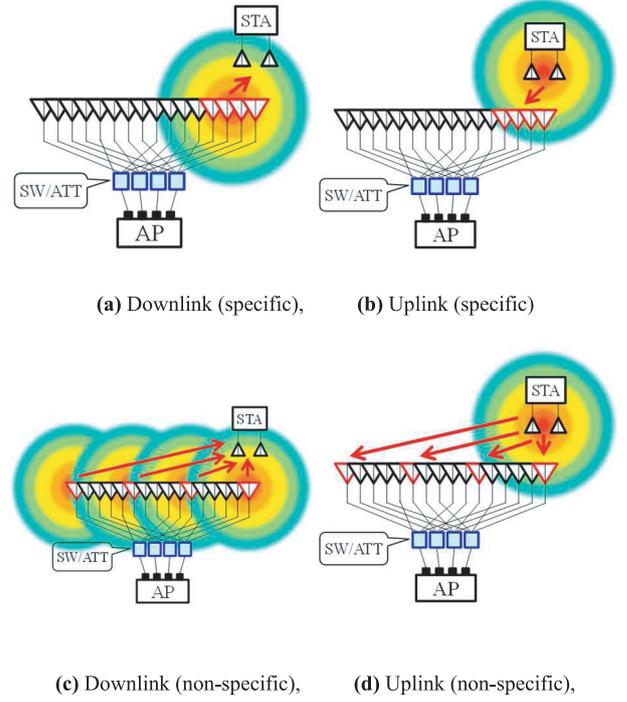


Fig. 5 Control procedures for applying D-SAS.

these figures, selected antennas are marked in red.

Here, (a) shows the downlink scenario in which an AP transmits the broadcast frames to all STAs by using non-specific antenna combinations. The broadcast frames, which transmit to all the STAs existing in the target area, mean the management control frames such as a beacon or CTS (clear to send) frames. Since these frames need to be transmitted to all the STAs within their own cell, the AP transmits using the non-specific antenna combination selected from one or more antennas from each antenna block. Moreover, the ATT values described in Sect. 3.2 are set for ICI mitigation between APs. Next, (b) shows an uplink scenario in which an AP receives interfered signals from other APs and STAs by using the non-specific antenna combination. This procedure is used when receiving signals from non-specified STAs at AP. Non-specific antenna combinations and non-specific ATT values are set so that signals from STAs within the AP cell can be received with minimum receiver sensitivity. By using this control, we expect the signals from each STA can be actively transmitted to their own AP without degrading the transmit quality.

Figures 5(c) and (d) respectively show downlink and uplink scenarios using the specific antenna combinations. The downlink scenario of Fig. 5(c) means the transmission of unicast frames in which an AP transmits signals to a specific STA, the AP transmits the signals after changing the antenna combination and ATT values are calculated by the proposed flow shown in Fig. 4(b). As a result, not only the transmission power but also ICI can be minimized. Moreover, specific antenna combinations can be used not only for transmission but also for reception for response frames for

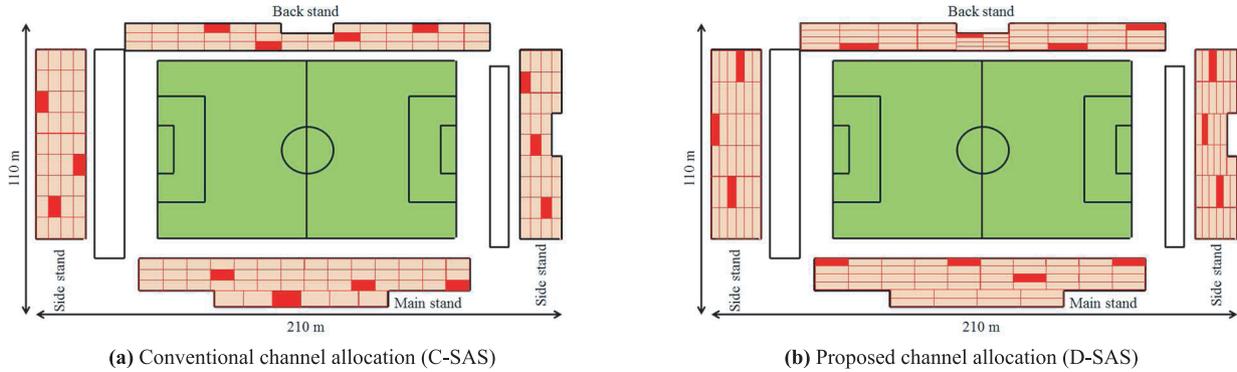


Fig. 6 Measurement environments with the channel allocations we applied.

AP transmission (CTS frame after a request to send a (RTS) frame, an acknowledgement (ACK) frame after data transmission). See. Fig. 5(d).

4. Performance Evaluations

4.1 Experimental Setups and Environments

To clarify the effectiveness of D-SAS, we conducted experimental measurements using our developed WLAN AP with D-SAS prototype at NACK5 Stadium in Omiya, Japan, as a dense WLAN AP deployment environment [24]. Figure 6 shows the stadium’s appearance. This football stadium is 210m × 110m in size and can accommodate up to 15,500 people.

Figures 7(a)–(b) show the WLAN AP with D-SAS and the distributed antennas we developed. Distributed antennas are connected to the external antenna ports of AP. The AP has the general enterprise AP functions specified by IEEE 802.11ac and we used the radio parameters listed in Table 2 in our measurements. The frequency channel and bandwidth were set respectively at 100 ch (5.5 GHz) and 20 MHz. Each AP has 16 planar antenna elements with a half-value angle of 60 degrees. These are grouped into four sets with four elements each. Two sets of external antennas are symmetrically located by using RF cables, where AP and the external antenna set are set 6 m apart for the cost reduction purposes, as shown in Fig. 10. The internal and external antenna gains are 6 dB. The ATT range is 0~20 dB. The AP selects four of the 16 antennas and adjusts four ATT values as described in Sect. 3. Specifically, as shown in Fig. 3, the distributed antenna and ATT are controlled by transferring a switching signal from the WLAN module about 2 μs before the data signal. Figure 8 shows the results obtained for our prototype’s measurement switching signal. Finally, transmit power is 13 dBm without antenna gain or cable loss. We used the Galaxy S5 product (Samsung, Inc.) as the STA. To evaluate in an environment where uplinks and downlinks occur regularly, the traffic is a fully buffered TCP from an AP to an STA that includes an uplink TCP-ACK. Moreover, the uplink CTS frame is always transmitted before the downlink data transmission. Moreover, T_1 and T_2 described in Fig. 4

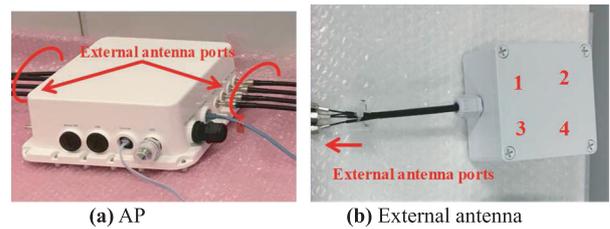


Fig. 7 Photographs of WLAN AP and distributed antenna.

Table 2 Specifications of WLAN AP with D-SAS.

| | |
|--------------------------------|---|
| Standardization | IEEE 802.11ac |
| Frequency channel | 100ch |
| Frequency bandwidth | 20 MHz |
| Number of distributed antennas | 16 planar antennas (4 antenna switches and 4 groups) C-SAS: 16 internal antennas D-SAS: 8 internal antennas and 8 external antennas |
| Antenna gain and beamwidth | 6 dB and 60 deg. |
| RF cable for external antennas | 6 m |
| Range of ATT | 0~20 dB |
| Transmit power | 13 dBm without antenna gain or cable loss |

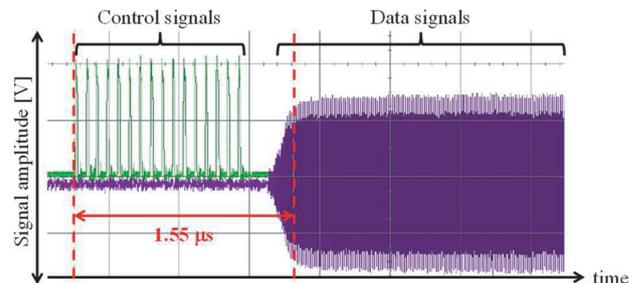


Fig. 8 Measured switching signal.

were set as infinite because they were evaluated in a static environment.

4.2 Cell Planning for NACK5 Stadium

In this subsection, we describe the cell planning (cell shape, distributed antenna/AP arrangements, and channel allocation). We first indicate the cell shape and distributed an-

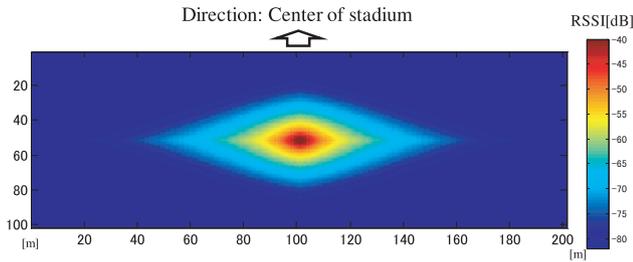


Fig. 9 RSSI characteristic in NAC5 stadium.

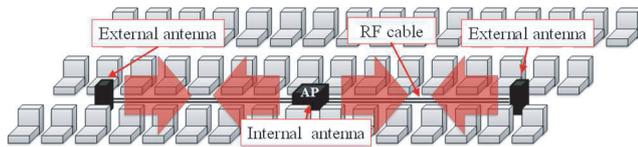


Fig. 10 Coverage area of WLAN AP with D-SAS and antenna locations.

tenna arrangement of each AP. It is generally known that seats are installed in rows that are staggered both horizontally and vertically. Figure 9 shows the results calculated from the transmit power and the propagation loss model using the RSSIs at each seat measured in the stadium. In this measurement, RSSI was measured at each seat of the main stand with the AP installed in the center of the main stand. From the RSSI characteristic we found that RSSI in the vertical direction is lower than that in the horizontal direction. This is because the height of the STAs is different in a stadium. Thus, the interference in the vertical direction is effectively mitigated by the seating arrangement. In the experiments, we exploited this feature and adopted the use of a rectangular cell shape for a WLAN AP with D-SAS (Fig. 10). Furthermore, by devising the antenna directivity, ICI in the horizontal direction was reduced and we were able to set the AP and external antenna sets under the seats.

Figures 11(a)–(c) show the simulation results obtained in ICI analysis on centralized smart antenna system (C-SAS) without/with power control (PC) and D-SAS by using the RSSI characteristic shown in Fig. 9. Note that C-SAS is a type in which the distributed antenna of D-SAS is installed near the AP, and is included in Type #3 of Fig. 1. From Fig. 11(a), we found that RSSI becomes high within the cell we assumed because of maximum transmit power, but ICI also increases. From Fig. 11(b), which is the result obtained by applying power control with RSSI in the cell set to -65 dBm, we found that ICI can be mitigated. Furthermore, we found that by using D-SAS, ICI can be even further mitigated as shown in Fig. 11(c).

Next, we describe the WLAN AP arrangements and frequency channel allocation used for the stadium. Figures 6(a) and (b) show AP arrangements of C-SAS and D-SAS in our measurements. Since it is generally known that enterprise WLAN that each enterprise WLAN connects between 50 and 100 STAs, we assumed 70 STAs per AP. Accommodating 10,000 people (not including those standing) requires 150 WLAN APs. Since the ranges that radio waves

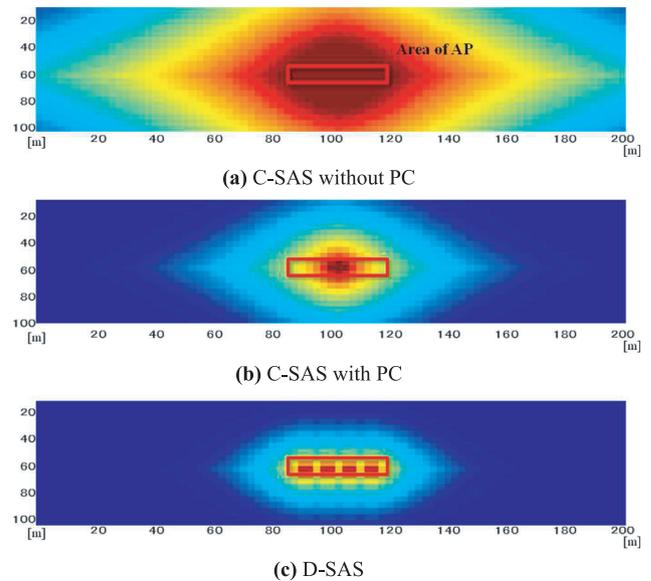
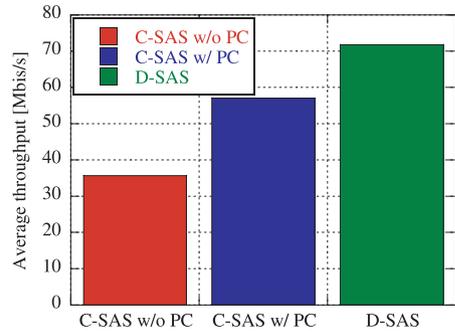


Fig. 11 ICI analysis.

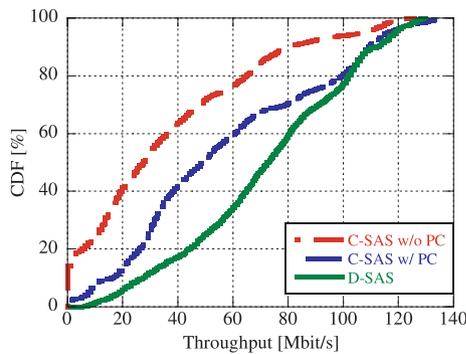
can reach in C-SAS and D-SAS are different, the cell shapes were set so that the area the cell can cover is minimized as shown in Fig. 6. Furthermore, the frequency channel of each AP was calculated by applying the frequency channel allocation method [23]. Since there were 11 available frequency channels at W56 with 20 MHz in our measurements, the number of APs per frequency channel became around 14.

4.3 Experimental Results

Finally, we present the effectiveness of D-SAS by comparing it with the conventional approach of C-SAS without/with PC. In the experimental measurements, after allocating the frequency channel of all the APs described in Sect. 4.2, we used APs with one channel selected from the 11 available frequency channels. Also, each AP was associated with a STA to clarify the effectiveness of the D-SAS for the environment of inter-cell interference we focus on this paper. Conventional APs select four internal antennas with high received power from 16 internal antennas and also use ATTs to control the transmit power and received sensitivity. Conventional AP parameters are the same as those of the D-SAS AP except for the antenna distribution. Figure 12(a) shows the average throughput results for all the STAs using 100 ch (5.5 GHz); we obtained the results in the stadium measurements taken in our experiments. They show that the average throughput of D-SAS was respectively 2.0 and 1.3 times higher than that of C-SAS without/with PC. From these results, it can be seen that the average throughput is improved by mitigating ICI and increasing the transmission opportunity due to ICI mitigation based on the switching of distributed antennas. Moreover, Fig. 12(b) shows the cumulative distribution function (CDF) results for throughput per STA. They show that in all the measurement points with the D-SAS AP, the 10%tile throughput achieves 30.0 Mbit/s



(a) Average throughput of AP.



(b) CDF of throughput.

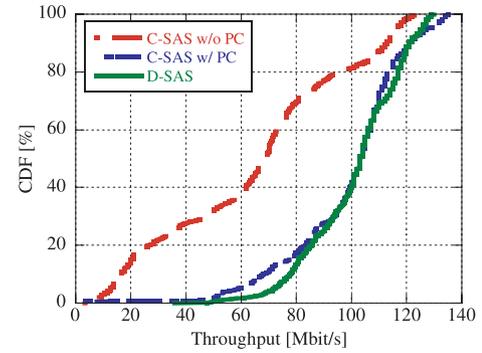
Fig. 12 Throughput results.

although that obtained with the conventional approach becomes nearly zero.

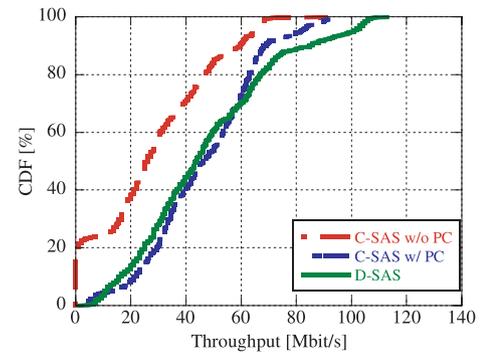
Further, Figs. 13(a)–(c) show the CDF of STA throughputs at the center, middle, and edge locations. These results show higher effect is obtained by controlling ATT at the center and middle locations. However, they also show there is little difference between C-SAS with PC and D-SAS; this is because both reduce ICI by about the same amount. On the other hand, at the cell edge, it can be seen that applying the D-SAS shows a very high improvement effect. This means the proposed scheme can improve the throughput, especially for STAs located at the edge of the service area. This is because the D-SAS can suppress the interference so that the transmission opportunity and the ratio of signal to interference and noise powers are increased.

5. Conclusion

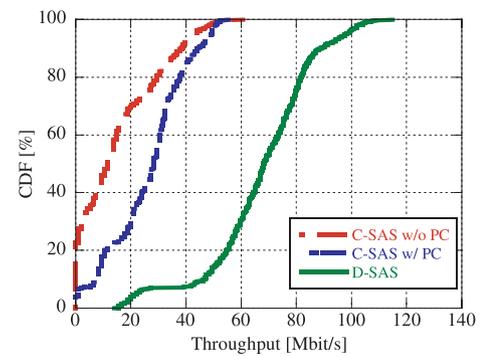
This paper presented a distributed smart antenna system (D-SAS) extended from [18] for dense wireless LAN (WLAN) access point (AP) deployment scenarios and the system configuration (block diagram of WLAN AP and system flows) of D-SAS. The proposed system dynamically switches the best distributed antennas for station conditions (transmission/reception, packet types, and locations) and mitigates inter-cell interference from each AP while improving transmit quality and transmit opportunity. Experimental measurements taken in an actual stadium confirmed that our system prototype achieved twice the average throughput of the



(a) Center



(b) Middle



(c) Edge

Fig. 13 CDF of throughput.

conventional WLAN AP approach with a centralized smart antenna system.

In this paper, we clarified the effectiveness of the proposal assuming a downlink mainstream scenario and a limited number of STAs. For the demand of uplink transmissions, we will clarify its effectiveness in uplink mainstream scenarios and evaluate the effectiveness of the D-SAS in environments with a large number of STAs in our future work.

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