Distributed Antenna System: Performance Analysis in Multi-user Scenario♣

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***Abstract*—This paper provides a comparative study of the distributed antenna system (DAS) and the conventional co-located antenna system (CAS) in the multi-user scenario. It is demonstrated that thanks to the decrease of the maximum minimum access distance, a tremendous transmission power gain can be achieved by DASs. Besides, the DAS has great potentials to outperform the CAS in terms of multi-user capacity when channel-aware scheduling is adopted. It is proved that the variance of the received power of any given user in a DAS is always larger than that in a CAS, which indicates a higher selective gain. The DAS also has much better interference suppression ability when multiple users are scheduled simultaneously. Substantial capacity gains are shown to be achieved by a DAS over a CAS.**

Keywords- *Distributed Antenna Systems, Capacity, Channel-aware Scheduling, Opportunistic Transmission.*

I. Introduction

The distributed antenna system (DAS) has emerged as a promising candidate for the future beyond 3G or 4G mobile communications thanks to its open architecture and flexible resource management. In DASs, many remote antenna ports are distributed over a large area and connected to a central processor by fiber, coax cable, or microwave link [1]. Recent work has shown that other than a better coverage and lower operation and maintenance costs, the DAS has many attractive advantages over the conventional co-located antenna system (CAS) in terms of system capacity and power efficiency [2-10].

Although it is becoming a common belief that the distributed characteristic of antennas provides a more efficient utilization of space resources, the optimal antenna placement remains unknown. Besides, most of the analytical work is based on the single-user scenario (with multiple antennas at both the transmitter and receiver sides) [5-10]. [2-4] presents the SINR analysis in cellular DASs with no channel-aware scheduling.

In this paper, a comprehensive comparative study of the CAS and the DAS is presented in the multi-user scenario. For a fair comparison, it is assumed that transmission power control is performed so that the mean received power of any user is a constant. It is demonstrated that due to the decrease of the access distance, a huge transmission power gain can be achieved by DASs. This gain, however, is determined by the maximum minimum access distance, which implies that the optimal antenna placement should be as symmetrical and even as possible. In this paper, the QAM constellation is used as the antenna topology. It is shown that with 16 distributed antennas, the sum transmission power of a DAS is less than 5 percent of that consumed by a CAS. Clearly a tremendous transmission power saving is brought by DASs.

Channel-aware scheduling, or opportunistic transmission, was proposed in [11], where the user with the highest instantaneous channel gain is selected for transmission. Because users are expected to experience independent fading, channel-aware scheduling can adaptively exploit the time-varying channel conditions of users and achieve the multi-user diversity gain; the capacity will increase with the number of users [12].

In this paper, the capacity with channel-aware scheduling in CASs and DASs is investigated. It is proved that the variance of the received power of any given user in a DAS is always larger than that in a CAS. This indicates a better selective gain which leads to a higher capacity when single-user scheduling, i.e., the best user is selected for transmission in each time slot, is adopted. The capacity gap is further enlarged when multiple users are scheduled simultaneously. Compared to the single-user scheduling case, although a significant capacity increase can be observed in both the CAS and the DAS, the DAS can better exploit the degrees of freedom via scheduling multiple orthogonal users at the same time. This orthogonality among the selected channel vectors makes it feasible that the selection is performed in a per-antenna manner. A low-complexity selection algorithm for DAS (LS-DAS) is further proposed and the simulation results show that it can indeed achieve the optimal performance.

This paper is organized as follows. The system model is provided in Section II. Section III presents the analysis on the sum transmission power of a DAS and a CAS. The capacity comparison with channel-aware scheduling is shown in Section IV. Finally, Section V summarizes and concludes this paper.

II. System Model

As shown in Fig. 1, consider a DAS with L remote antennas distributed in a circular area with radius R. Assume each user is equipped with one antenna and all the users are uniformly distributed in the whole area with a density ϕ. Consider the uplink transmission. Assume transmission power control is performed so that for any user, at any location, the mean received power at the remote antennas is a constant c. That is,

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$$E\left\{P_{r,k}^{D}\right\}=E\left\{P_{t,k}^{D}\cdot\sum_{i=1}^{L}d_{ik}^{-\alpha}\|h_{ik}\|^{2}\right\}=c \tag{1}$$

where $P_{r,k}^{D}$ and $P_{t,k}^{D}$ represent the received and transmission power of user *k*, respectively. d_{ik} is the distance from user *k* to the *i*-th antenna and α is the path loss exponent. In this paper, the effect of shadowing fading is ignored. h_{ik} represents the small-scale channel coefficient, which is assumed to be a complex Gaussian random variable with zero-mean and unit variance. Under the power constraint of (1), the received power for user *k* is then given by

$$P_{r,k}^{D}=\frac{c}{\sum_{i=1}^{L}d_{ik}^{-\alpha}}\cdot\sum_{i=1}^{L}d_{ik}^{-\alpha}\|h_{ik}\|^{2}=c\sum_{i=1}^{L}\beta_{ik}\|h_{ik}\|^{2} \tag{2}$$

where $\beta_{ik}=d_{ik}^{-\alpha}/\sum_{j=1}^{L}d_{jk}^{-\alpha}$. Obviously we have $\sum_{i=1}^{L}\beta_{ik}=1$, k=1,…,K.

In a CAS, all the antennas are placed together, which implies that $d_{ik}=d_{k}$, i=1,…, L. Therefore, similar to (1), we have

$$E\left\{P_{r,k}^{C}\right\}=LP_{t,k}^{C}d_{k}^{-\alpha}=c \tag{3}$$

where $P_{r,k}^{C}$ and $P_{t,k}^{C}$ are the received and transmission power of user *k*.

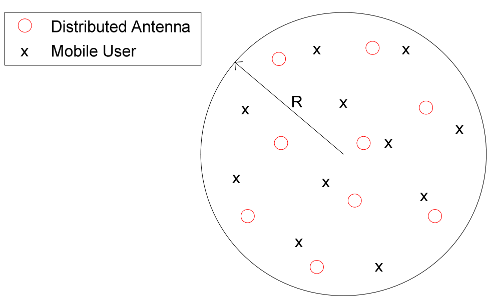


Fig. 1: In DASs, antennas are spread out in the whole area.

III. SUM TRANSMISSION POWER

In this section, the sum transmission power of both systems will be analyzed and a huge power saving will be shown to be achieved by the DAS.

Theorem 1. *The sum transmission power of a CAS is minimized when all the antennas are placed at the center, and the minimum power is* $2\pi R^{\alpha+2}c\phi/L(\alpha+2)$.

Sketch of proof: Assume the antennas are located at (ρ_0,θ_0). The sum transmission power is then given by

$$P_{t}^{C}=\phi\int_{0}^{2\pi}\int_{0}^{R}P_{t,k}^{C}\rho d\rho d\theta=\frac{c\phi}{L}\int_{0}^{2\pi}\int_{0}^{R}(\rho^{2}+\rho_{0}^{2}-2\rho\rho_{0}\cos(\theta-\theta_{0}))^{\alpha/2}\rho d\rho d\theta \tag{4}$$

Let $a=\rho^{2}+\rho_{0}^{2}$, and $b=-2\rho\rho_{0}$. Then we have

$$\int_{0}^{2\pi}(\rho^{2}+\rho_{0}^{2}-2\rho\rho_{0}\cos(\theta-\theta_{0}))^{\alpha/2}d\theta=\int_{-\theta_{0}}^{2\pi-\theta_{0}}(a+b\cos\theta)^{\alpha/2}d\theta \tag{5}$$

It can be easily proved that for any given ρ, (5) is minimized when ρ_0=0. Therefore,

$$\min\left(P_{t}^{C}\right)=\frac{c\phi}{L}\int_{0}^{2\pi}\int_{0}^{R}\rho\cdot\rho^{\alpha}d\rho d\theta=2\pi R^{\alpha+2}c\phi/L(\alpha+2)\cdot \ \blacksquare$$

Theorem 2. *The sum transmission power of a DAS is upper bounded by* $2\pi\tilde{d}_{0}^{\alpha+2}c\phi/(\alpha+2)$, *where* $\tilde{d}_0$ *is the maximum minimum access distance.*

Sketch of proof: Assume *L* antennas are located at (ρ_i,θ_i), i=1,…, L. Then we have

$$P_{t}^{D}=\phi\int_{0}^{2\pi}\int_{0}^{R}P_{t,k}^{D}\rho d\rho d\theta=\int_{0}^{2\pi}\int_{0}^{R}\frac{c\phi}{\sum_{i=1}^{L}d(\rho,\theta,\rho_{i},\theta_{i})^{-\alpha}}\rho d\rho d\theta \tag{6}$$

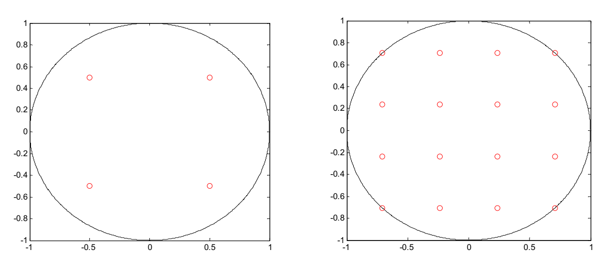
$$\le c\phi\int_{0}^{2\pi}\int_{0}^{R}d(\rho,\theta,\rho_{0}^{*},\theta_{0}^{*})^{\alpha}\rho d\rho d\theta$$

where $d(\rho,\theta,\rho_i,\theta_i)$ represents the distance from (ρ,θ) to antenna (ρ_i,θ_i), and $(\rho_0^*,\theta_0^*)=\arg\min_{i=1,\ldots,L}d(\rho,\theta,\rho_i,\theta_i)$, for each (ρ,θ). Let $\tilde{d}_0$ represent the maximum minimum access distance, i.e., $\tilde{d}_0=\max_{(\rho,\theta)}d(\rho,\theta,\rho_0^*,\theta_0^*)$. From (6), approximately we have

$$P_{t}^{D}\le c\phi\int_{0}^{2\pi}\int_{0}^{\tilde{d}_{0}}\rho^{\alpha}\rho d\rho d\theta=2\pi\tilde{d}_{0}^{\alpha+2}c\phi/(\alpha+2)\cdot \ \blacksquare$$

From Theorem 1 and Theorem 2, it can be seen that the sum transmission power ratio of a DAS and a CAS is upper bounded by $L\cdot\left(\tilde{d}_0/R\right)^{\alpha+2}$. Therefore, the decrease of the access distance can bring a significant transmission power saving. For example, assume L=4 and let $\rho_i=R/2$, $\theta_i=\pi/4+(i-1)\pi/2$, i=1,…,4. Clearly we have $\tilde{d}_0=\sqrt{2}R/2$. In this case, $P_t^D/P_t^C\le L\cdot\left(\sqrt{2}/2\right)^{\alpha+2}$. When α=3, $P_t^D\le\frac{\sqrt{2}}{2}P_t^C$. It is further decreased to $P_t^C/2$ when α=4.

This huge transmission power saving, however, is dependent on the location of the antennas. So a natural question is, with *L* antennas, how should we place them so that the maximum minimum access distance, $\tilde{d}_0$, is minimized? Intuitively, to decrease $\tilde{d}_0$, the antennas should be spread out as evenly as possible. Therefore, the QAM constellation can be used as the antenna topology. As shown in Fig. 2, when L=4 and 16, QPSK and 16QAM will lead to a $\tilde{d}_0$ of $\sqrt{2}R/2$ and $\sqrt{(1-\sqrt{2}/2)^2+(\sqrt{2}/6)^2}R$, respectively. In the latter case, $P_t^D\le 0.045P_t^C$ when α=4, implying a tremendous transmission power saving brought by the DAS.



(a) (b)

Fig. 2: Distributed antenna placement when (a) *L*=4; and (b) *L*=16.

IV. CAPACITY WITH CHANNEL-AWARE SCHEDULING

In Sec. III, it has been demonstrated that the sum transmission power in a DAS is much lower than that in a CAS. In this section, it will be further shown that significant capacity gains can be achieved by the DAS, when channel-aware scheduling is adopted.

A. *Single-user Scheduling*

Assume there are totally K active users and in each time slot the user with the largest received power is selected for transmission. We provide the following lemmas before the capacity comparison.

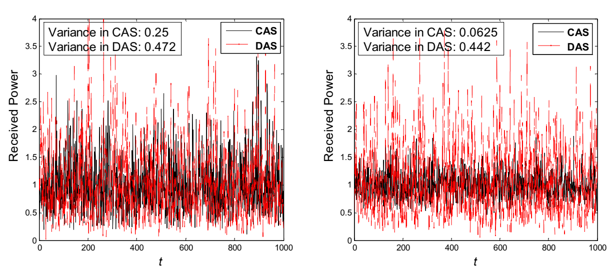
Lemma 1. *For any given user, the variance of the received power in a DAS is no smaller than that in a CAS.*

Proof: From (2) it is clear that

$$\operatorname{var}\left\{P_{r,k}^{D}\right\} = c^2 \sum_{i=1}^{L} \beta_{ik}^2 \geq c^2 / L = \operatorname{var}\left\{P_{r,k}^{C}\right\} \tag{7}$$

because $\sum_{i=1}^{L} \beta_{ik} = 1$ and $\beta_{ik} \geq 0$. ■

From (7) it can be further seen that with an increase of L, the variance of the received power in CASs will decrease, which is not true in DASs. For example, Fig. 3 shows the variance of the received power for user 0 with the location of ($\sqrt{2}$/2, 0) in CASs and DASs when L=4 or 16 and c=1.[1] Clearly in both cases the DAS has a higher variance. When L increases to 16, the variance in CASs is significantly reduced while in DASs it keeps almost unchanged. Therefore, the gap is further enlarged when L=16. It should be also pointed out that in DASs, the variance of the received power of each user is dependent on its location, which is different from the CAS case. The variance is maximized when the user is close to some distributed antenna, i.e., $\beta_{lk} = 1$, and $\beta_{ik} = 0$, i=1,…, L when $i \neq l$.



(a) **(b)**

Fig. 3: Channel fluctuations in a CAS and a DAS when (a) L=4; and (b) L=16.

Lemma 2. *Let* $x_{1,k}$, *k=1,…, K, be i.i.d positive random variables with mean* μ_1 *and variance* σ_1^2. *Similarly,* $x_{2,k}$, *k=1,…, K, are i.i.d positive random variables with mean* μ_2 *and variance* σ_2^2. *Assume* $\mu_1 = \mu_2$, *and* $\sigma_1^2 \geq \sigma_2^2$. *Let* $x_{i,(K)} = \max_{k=1,\dots,K}(x_{i,k})$, *i=1, 2. Then* $E\left\{x_{1,(K)}\right\} \geq E\left\{x_{2,(K)}\right\}$.

[1] In the rest of the paper, we always assume the pass loss exponent α is 4.

Sketch of proof: $E\left\{x_{1,(K)}\right\}$ can be written as $\int_0^1 K u^{K-1} g_1(u) du$, where $g_1(u)$ satisfies $\int_0^1 g_1(u) du = \mu_1$ and $\int_0^1 (g_1(u))^2 du = \mu_1^2 + \sigma_1^2$. $g_1(u)$ is a monotonously increasing function and $g_1(u) \geq 0$ for all $0 \leq u \leq 1$. With $\mu_1 = \mu_2$ and $\sigma_1^2 \geq \sigma_2^2$, we know that $\int_0^1 (g_1(u) - g_2(u)) du = 0$ and $\int_0^1 \left((g_1(u))^2 - (g_2(u))^2\right) du \geq 0$. Therefore, the curves of $g_1(u)$ and $g_2(u)$ must intersect at some point $(u_0, g_1(u_0))$ and

$$\begin{cases} g_1(u) \leq g_2(u) & 0 \leq u \leq u_0 \\ g_1(u) \geq g_2(u) & u_0 \leq u \leq 1 \end{cases} \tag{8}$$

Clearly this implies that $\int_0^1 K u^{K-1} (g_1(u) - g_2(u)) du \geq 0$ (an intuitive explanation is that more weight is given to the points in [u_0, 1] where $g_1(u) \geq g_2(u)$). Therefore, we have $E\left\{x_{1,(K)}\right\} \geq E\left\{x_{2,(K)}\right\}$. ■

Lemma 3. *Let* $x_{1,k}$, *k=1,…, K, be independent positive random variables with mean* μ_1 *and variance* σ_k^2, *k=1,…, K. Assume* $\sigma_0^2 = \min_{k=1,\dots,K} \sigma_k^2$, *and* $x_{2,k}$, *k=1,…, K, are i.i.d positive random variables with mean* μ_1 *and variance* σ_0^2. *Then* $E\left\{x_{1,(K)}\right\} \geq E\left\{x_{2,(K)}\right\}$, *where* $x_{i,(K)} = \max_{k=1,\dots,K}(x_{i,k})$, *i=1, 2.*

Lemma 3 can be easily proved according to Lemma 2. Therefore, we omit the proof here.

Let C^D represent the capacity of a DAS. Then we have

$$C^D = E\left\{\max_{k=1,\dots,K} \log_2(1 + P_{r,k}^D / \sigma_n^2)\right\} \leq \log_2\left\{1 + E\left\{\max_{k=1,\dots,K} P_{r,k}^D\right\} / \sigma_n^2\right\} \tag{8}$$

where σ_n^2 is the variance of Gaussian white noise. From Lemmas 1 and 3, it is clear that

$$\log_2\left\{1 + E\left\{\max_{k=1,\dots,K} P_{r,k}^D\right\} / \sigma_n^2\right\} \geq \log_2\left\{1 + E\left\{\max_{k=1,\dots,K} P_{r,k}^C\right\} / \sigma_n^2\right\} \geq C^C \tag{9}$$

Fig. 4 provides both the upperbound $\log_2\left\{1 + E\left\{\max_{k=1,\dots,K} P_{r,k}^D\right\} / \sigma_n^2\right\}$ and the exact capacity curves of a DAS and a CAS under different values of the average received SNR $\gamma_0 = c / \sigma_n^2$ when L=4 and K=50. Clearly the upperbound can be used as a good approximation of the capacity. Besides, it can be seen that the DAS achieves a much higher capacity than the CAS thanks to a larger variance of the received power.

Even more capacity gains can be obtained when L increases to 16. As shown in Fig. 5, a 1.5 bit/s/Hz capacity gain can be achieved by the DAS over the CAS when K=200. This enlarged capacity gap, however, comes from the decrease of the CAS capacity (which is due to a reduced variance of the received power), rather than the increase of the DAS capacity. From Fig. 5 it can be seen that the capacity of the DAS keeps almost the same when L increases to 16 from 4. Actually it can be proved that with a large K, the capacity of a DAS with single-user scheduling is given by the following theorem.

Theorem 3. *The capacity of a DAS with single-user channel-aware scheduling is given by* $\log_2(1+\gamma_0 \ln(K))$, *where K is the number of users.*

Sketch of proof: With a large *K*, the capacity is determined by those users close to some distributed antenna, i.e., $\beta_{lk}=1$, and $\beta_{ik}=0$, *i*=1,…, *L* when $i \neq l$, as they have the maximum variance of the received power. It can be proved that in that case the capacity is given by $\log_2(1+\gamma_0 \ln(K))$. ■

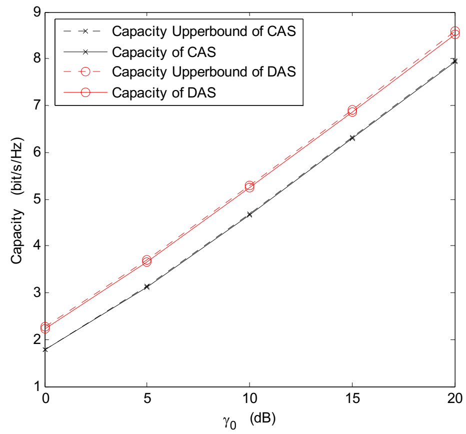


Fig. 4: Capacity vs. γ_0 in a CAS and a DAS with single-user channel-aware scheduling when *L*=4 and *K*=50.

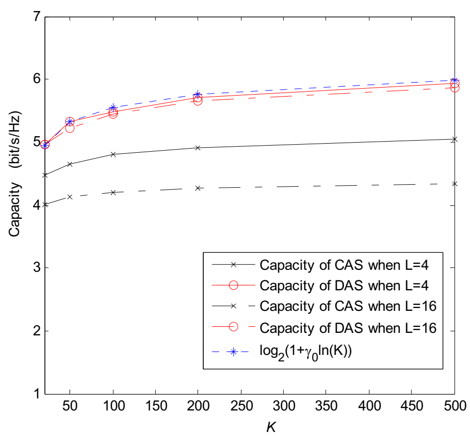


Fig. 5: Capacity vs. the number of users *K* in a CAS and a DAS with single-user channel-aware scheduling when γ_0 =10dB.

A good match of the theoretic and simulation results can be observed in Fig. 5. Theorem 3 indicates that no capacity gain can be achieved when *L* increases. This conclusion, however, is drawn based on the assumption that only ONE user is scheduled in each time slot. In the following we will show that if the best *L*, instead of 1, users are selected for transmission in each time slot, the capacity will increase with *L* dramatically in DASs.

B. Multi-user Scheduling

In Sec. IV. A, it has been shown that an increase of *L* does not improve the capacity when the best user is scheduled in each time slot. This is because only one degree of freedom is used in each transmission whatever *L* is. To fully exploit the degrees of freedom provided by *L* distributed antennas, *L* users should be scheduled simultaneously. Therefore, in this subsection we will further investigate the optimal multi-user scheduling strategy, i.e., the best *L* users are selected for transmission in each time slot.

From (2) it can be seen that for each user *k*, the channel vector is given by $\mathbf{h}_k=[\sqrt{\beta_{1k}}h_{1k},\ldots,\sqrt{\beta_{Lk}}h_{Lk}]^T$. Let $\mathbf{\Omega}$ represent the active user set with size *K*, and $\mathcal{K}$ is an arbitrary subset with size *L*. $\tilde{\mathbf{H}}_{\mathcal{K}}$ denotes the channel matrix which is composed by $\mathbf{h}_k$, $k \in \mathcal{K}$. We aim at finding the optimal $\mathcal{K}^*$ which achieves the maximum capacity. With a high γ_0, $\mathcal{K}^*$ is approximately given by

$$\mathcal{K}^* = \arg\max_{\mathcal{K}\subset\mathbf{\Omega}} \det\left(\tilde{\mathbf{H}}_{\mathcal{K}}^\dagger \tilde{\mathbf{H}}_{\mathcal{K}}\right). \quad (10)$$

and the maximum capacity is $\log_2 \det\left(\gamma_0 \tilde{\mathbf{H}}_{\mathcal{K}^*}^\dagger \tilde{\mathbf{H}}_{\mathcal{K}^*}\right)$.

In a CAS, $\beta_{ik}=1/L$, *i*=1,…, *L*, for any user *k*. While in a DAS, each user has a different $\boldsymbol{\beta}_k$. The difference between the elements of a $\boldsymbol{\beta}_k$ will lead to a much larger variance of the received power than that of a CAS, as we have shown in Sec. IV. A. The difference between $\boldsymbol{\beta}_k$'s, however, can greatly reduce the interference among users, which indicates a significant capacity gain.

Fig. 6 provides the capacity curves of a CAS and a DAS with multi-user scheduling when γ_0=10dB and *L*=4. It can be seen that a much higher capacity is achieved by the DAS, and the capacity gain becomes even larger when *K* increases. Actually in DASs, with a large *K*, it is very likely that $\boldsymbol{\beta}_k$'s of the optimally selected users are mutually orthogonal. That is why substantial capacity gains can be observed in the DAS case. We also provide the capacity curves of DASs and CASs with single-user scheduling. Clearly much more multi-user diversity gain can be achieved by both the CAS and the DAS in the multi-user scheduling case.

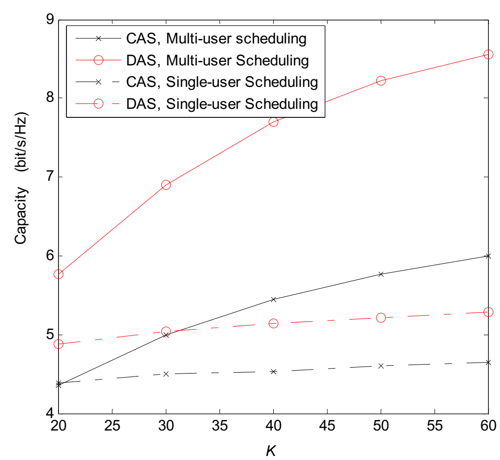


Fig. 6: Capacity vs. the number of users *K* in a CAS and a DAS with multi-user channel-aware scheduling and single-user channel-aware scheduling when γ_0 =10dB and *L*=4.

In a CAS, to find the optimal $\mathcal{K}^*$, an exhaustive search has to be performed, which leads to a prohibitively high complexity level with a large *K* (when *K*=100 and *L*=4, C_K^L =

3921225 comparisons on the determinant of an L by L matrix are required for each channel realization). In a DAS, however, orthogonality among the selected $\boldsymbol{\beta}_k$'s makes it feasible that the selection is performed in a per-antenna manner. A low-complexity selection algorithm for DASs (which is referred to as LS-DAS) is proposed and described as follows.

Initialization: k=L; $\tilde{\mathbf{H}} = \mathbf{H}$. $\mathbf{H}_s$ *is an L by L matrix with zero elements.*

1. *Find the maximal element h* of* $\tilde{\mathbf{H}}$: $\|h^*\| = \max \| \tilde{h}_{ij} \|$. *Let* $(i^*, j^*) = \arg \max_{i=1\ldots L, j=1\ldots K} \tilde{h}_{ij}$.
2. $\mathbf{H}_s(:, i^*) = \mathbf{H}(:, j^*)$.
3. *Set all the elements on the i*-th row and the j*-th column of* $\tilde{\mathbf{H}}$ *to zero, i.e.,* $\tilde{\mathbf{H}}(i^*, :) = zeros(1, K)$ *and* $\tilde{\mathbf{H}}(:, j^*) = zeros(L, 1)$.
4. *k=k-1. If k>0, repeat steps 1-4; Otherwise, output* $\mathbf{H}_s$.

Clearly with LS-DAS, the complexity can be greatly reduced. Only O(L^2K) element-wise comparisons are needed. Fig. 7 shows the superior performance of the proposed algorithm. It can be seen that LS-DAS can indeed achieve the optimal performance.

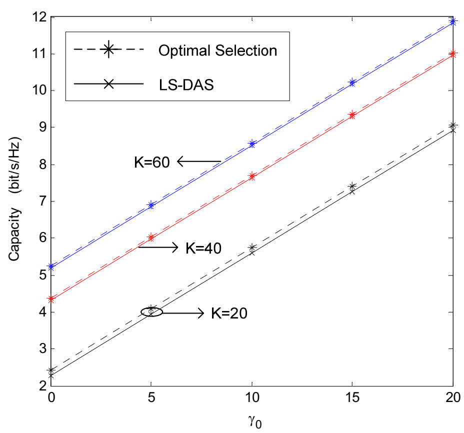


Fig. 7: Capacity of a DAS with the optimal selection and that with LS-DAS when L=4.

Fig. 8 presents the capacity curves of a DAS with multi-user scheduling under different values of L. In contrast to the single-user scheduling case, tremendous capacity gains can be brought when L increases. Actually it can be proved that with a sufficiently large K, the capacity will increase linearly with L. Even with a moderate K, substantial capacity gains can be observed. For example, as shown in Fig. 8, with 500 users, the capacity is doubled when L increases to 4 from 1. Additional 250% gain can be achieved when L further increases to 16.

V. Conclusions

In this paper, we investigated the performance of a DAS in the multi-user scenario and compared to that of a CAS. It was shown that in addition to a tremendous transmission power saving, substantial capacity gains can be achieved by the DAS when channel-aware scheduling is adopted. The analysis demonstrated that the distributed characteristic of antennas actually amplifies the channel fluctuations, which leads to a higher capacity when the best user is selected for transmission in each time slot. This gain, however, cannot be further improved by increasing the number of distributed antennas, L, because only one degree of freedom is exploited with single-user scheduling whatever L is. Therefore, multi-user scheduling was further proposed, where the best L users are selected for transmission simultaneously. Huge capacity gains were shown to be achieved by the DAS thanks to its better interference suppression ability. Besides, LS-DAS was proposed for DASs and the simulation results showed that it can indeed achieve the optimal performance at a much lower complexity cost.

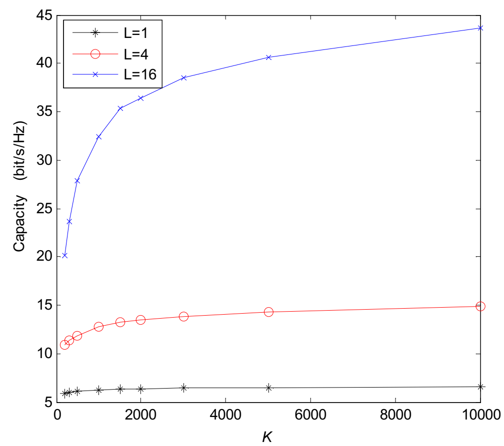


Fig. 8: Capacity vs. the number of users K in a DAS when γ_0 =10dB.

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