Throughput of Wireless-Powered Massive Distributed Antenna Systems Over Composite Fading Channels

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Abstract —Massive Distributed Antenna System (DAS) with energy harvesting can promisingly satisfy the ever-growing wireless transmission requirements while providing sustainable power supply to the User Equipment (UE). In this paper, we propose a massive DAS with multiple-circle layout, where a large number of Remote Antenna Units (RAUs) are evenly distributed across these circles. Based on the instantaneous channel quality, a RAU is selected for the downlink wireless energy transfer to the UE. Using the harvested energy, the UE transmits information to all the RAUs according to the “harvest-then-transmit” protocol over the uplink. The closed-form asymptotic throughput for an arbitrary UE is derived over composite fading channels, which include the shadowing, fading, and path-loss effects. Subsequently, we analyze the average throughput when the UEs are uniformly distributed in the cell. Performance results are provided to validate our theoretical analysis and reveal the impacts of time allocation, UE locations, and RAU deployment on the system throughput.

Index Terms—Massive distributed antenna system, remote antenna unit, throughput, wireless energy transfer, wireless information transmission

I. Introduction

The fifth-generation (5G) mobile communications systems are expected to satisfy the rapid growth of various wireless services by enhancing the spectral and energy efficiencies [1], [2]. However, since the user equipments (UEs) operate with the capacity-limited batteries, mobile networks cannot realize unstoppable communications [3], [4]. To extend the lifetime of mobile networks, scholars have proposed Energy Harvesting (EH) or Wireless Energy Transfer (WET) technique by enabling the UEs to harvest the ambient Radio Frequency (RF) energy [5], [6]. Nevertheless, the efficiency of WET is low because of the severe path-loss caused by the long distance between transmitters and receivers [7]-[9]. Massive Multiple-Input Multiple-Output (MIMO) technique has been commonly regarded as a promising technique for enhancing the energy efficiency and spectral efficiency by deploying hundreds of antennas at a Central Base Station (CBS) [10]. Beamforming and EH zone have been further used to improve the EH efficiency in massive MIMO and cognitive radio networks, respectively [11], [12]. In general, only the receivers with short distance to the transmitters may harvest sufficient energy for the Wireless Information Transfer (WIT).

As a counterpart of the centralized massive MIMO, massive Distributed Antenna System (DAS) is a potential network to overcome the boundary effect and guarantee the communications fairness of UEs with different locations [13]. Compared with the traditional DAS in which a few Remote Antenna Units (RAUs) are distributed in a cell [14], [15], massive DAS contains hundreds of RAUs which are connected to the Baseband Processor Unit (BPU) via optical fiber. The effects of small-scale fading and the uncorrelated noise can be alleviated in massive DAS with this configuration [16]. Compared with the centralized massive MIMO, massive DAS can achieve the macro-diversity with such flexible structure [17]. The average distance between transmitters and receivers can be shortened in this structure, which can weaken the path-loss and reduce the transmit power [18]. Therefore, it is more feasible to implement the WET in massive DAS. Reference [17] proposed a massive DAS model based on single-circle layout, and the optimal radius of RAU deployment was acquired through maximizing the asymptotic data rate. Li et al. investigated the massive DAS based on multiple-antenna clusters layout, and each cluster equips multiple antennas [19], [20]. The authors of [13] and [16] proposed a massive DAS model with uniformly distributed RAUs, and the average distance between transceivers can be shortened. Unfortunately, these models are either inefficient for the UEs far away from the RAUs to harvest the RF energy nor too complicated in connecting all the RAUs via optical fiber. Therefore, it is desirable to design a feasible massive DAS for simultaneously WET and WIT with less optical fiber. Since the WET technique is sensitive to the distance between transceivers, how to improve the EH efficiency is another urgent issue. One effective approach is to select a suitable RAU for the WET towards the UE, which can reduce the RF chains cost and enhance the EH efficiency [21]. Practically, various RAU selection schemes for the WIT can be also applied to the wireless-power based massive DAS [14]-[24].

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In this paper, we study the massive DAS with multiple-circle layout based on the EH over composite fading channels which include the shadowing, small-scale fading, and path-loss effects. We first propose a circular architecture for the massive DAS, where hundreds of RAUs are deployed over multiple circles. On one hand, this model can shorten the WET distance between RAU and UE. On the other hand, with this circular layout pattern, it is easier to connect RAUs using optical backhaul. To save the signaling overhead and improve the EH efficiency, the RAU with the best channel quality towards the UE is selected for the downlink WET. In addition, the closed-form asymptotic throughput for an arbitrary UE is derived with no shadowing and shadowing. The average throughput for a typical UE in the cell is also developed from the design perspective. Performance results are provided to validate our theoretical analysis and show the impacts of various parameters on the throughput performance, which can provide some guidelines for the network deployment.

The reminder of this paper is organized as follows. Section II introduces the wireless-powered massive DAS with multiple-circle layout. In Section III, we analyze the asymptotic throughput of the RAU selection WET based on the best channel quality. Numerical and simulation results are provided in Section IV. Finally, Section V concludes this paper.

Notation: Boldface lowercase and uppercase letters represent vectors and matrices, respectively. $|\cdot|$ denotes the absolute value, $\mathbf{E}\{\cdot\}$ denotes the expectation, $\mathbf{Pr}\{\cdot\}$ denotes the probability, $\mathrm{tr}(\cdot)$ denotes the trace of a matrix, and $\|\cdot\|_F$ denotes the Frobenius norm of a vector. The operations $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ represent the transpose and conjugate transpose of a vector, respectively. $(m)_n$ is given as $(m)_n = \frac{\Gamma(m+1)}{\Gamma(n+1)\Gamma(m-n+1)}$, where n and m are integers, and $\sum_m \sum_k$ represents $\sum_{m=1}^{M}(-1)^{m-1}\sum_{\kappa=1}^{(M)_m}$.

II. System Model

We consider a wireless-powered massive DAS over composite fading channels, where the energy is harvested in the downlink and the information is transferred in the uplink. As shown in Fig. 1, dozens or hundreds of RAUs are evenly distributed across N circles, and they are all connected to a BPU via optical fiber. The BPU processes signals in a centralized way. Compared with stochastic layout and regular-grid layout, this architecture needs less optical backhaul connection, which can simplify the performance analysis as the topology is equivalent to one dimensional network. Throughout this paper, the Time Division Multiple Access (TDMA) technique is applied in each time block, and the Channel State Information (CSI) of both uplink and downlink is assumed to be available at the RAU. Further, the signals are assumed to experience frequency nonselective fading. Since the zero-forcing decoder can separate data from different UEs, the interference among UEs diminishes in massive MIMO with such a large number of antennas [17]. In this work, to facilitate the analysis, we consider the single user scenario, while we intend to study the multi-user scenario in future work.

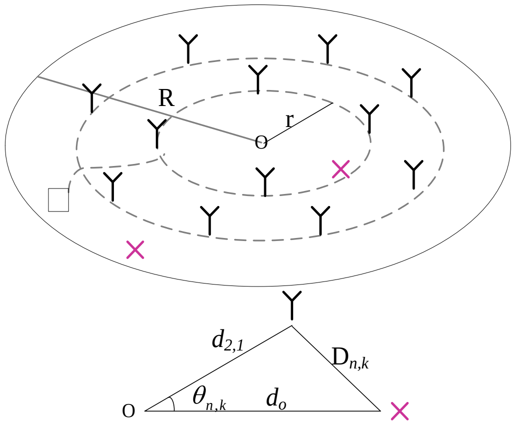

Fig. 1. The system model of wireless-powered massive DAS. In this figure, Y denotes RAU, X denotes UE, the diamond represents the BPU, and the dashed line represents the optical backhaul.

The total number of RAUs in a cell is set to be M . The mth RAU deployed in a cell is denoted as $\mathbf{R}_m$, where $1 \le m \le M$. Each UE and RAU is equipped with one omnidirectional antenna. The downlink and the uplink small-scale fading between the lth RAU and the UE is denoted as h_m and g_m , respectively. The harvest-then-transmit protocol is adopted in the downlink, where in the first τ_0 ($0<\tau_0<1$) time, the UE harvests the RF energy from the selected RAU and saves the energy into battery. In the remaining $1-\tau_0$ time, the UE transmits information data to the RAUs using the harvested energy.

A. Downlink Energy Transfer

In the downlink phase, the optimal RAU, $\mathbf{R}_o$, is selected to transfer the wireless energy to the UE. The baseband signal transmitted by the mth RAU, $\mathbf{R}_m$, is denoted as s_m satisfying $\mathbf{E}\{|s_m|^2\}=1$, the downlink path-loss can be modeled as $L_m = (d_m)^{-\alpha}$, where d_m is the distance between $\mathbf{R}_m$ and the UE, and α is the path-loss exponent. The shadowing from each RAU is independently and identically distributed. In a given time block, the received signal from the selected RAU at the UE is expressed as

$$r_o = \sqrt{S_s P_t L_o} h_o s_o + n_o \tag{1}$$

where P_t is the transmit power of RAU, n_o is the additive white Gaussian noise, and S_s characterizes the lognormal shadowing with the Probability Density Function (PDF)

$$f_{S_s}(s) = \frac{\varpi}{\sqrt{2\pi}\epsilon s}\exp\left[-\frac{(10\lg s-\varepsilon)^2}{2\epsilon^2}\right], \tag{2}$$

where $\varpi = 10/\ln 10$, ε and ϵ (in dB) are the mean and the standard deviation of $10\lg s$, respectively. It is noted that when $S_s = 1$, there is no shadowing during the transmission.

Since the transmit power P_t is sufficiently large, the energy harvested from the noise is negligible. The amount of energy harvested by UE is given by

$$Q = \xi \tau_0 S_s P_t L_o |h_o|^2 \tag{3}$$

where $0 < \xi < 1$ denotes the EH efficiency.

B. Uplink Data Transmission

In the remaining time fraction, the UE sends its data with its achievable rate to the RAUs. The uplink path-loss is denoted as L_m due to the symmetry of the propagation path between uplink and downlink. As the uplink channel fading related to $\mathbf{R}_m$ is g_m, the $M \times 1$ channel vector between UE and RAUs can be written as

$$\mathbf{c} = \left[\sqrt{S_s L_1} g_1 \cdots \sqrt{S_s L_M} g_M \right]^{\mathrm{T}} \tag{4}$$

We define x_m as the transmitted signal from the UE to the *m*th RAU with $\mathbf{E}\{|x_m|^2\} = 1$. The received signal at the BPU can be obtained as

$$y = \sum_{m=1}^{M} \sqrt{S_s P_a L_m} g_m x_m + n \tag{5}$$

Since the energy harvested in the downlink is used for the circuit operation and information transmission, we define $0 < \rho \le 1$ as the proportion of energy used for the information transmission. Then, the available transmit power for the UE is

$$P_a = \frac{\rho Q}{1-\tau_0} = \frac{\rho \xi S_s P_t L_o |h_o|^2 \tau_0}{1-\tau_0}. \tag{6}$$

It is observed from (4) and (5) that the instantaneous SNR at the BPU is given as

$$\gamma = \frac{S_s P_t \rho \xi L_o |h_o|^2 \|\mathbf{c}\|_2^2 \tau_0}{\sigma^2 (1-\tau_0)}. \tag{7}$$

III. Throughput Analysis

In this section, we analyze the throughput of massive DAS over composite fading channels. For the downlink, the RAU with the best channel quality towards the UE is selected for the WET to reduce the signaling overhead and the RF-chain cost. For the uplink, the UE transmits data to all the RAUs simultaneously to fulfill the macro-diversity.

A. RAU Selection for the WET

The RAU with the best channel quality towards the UE is selected for the WET, i.e.,

$$\chi_o = \arg \max_{1 \le m \le M} \{\chi_m\} \tag{8}$$

where $\chi_m = \dfrac{S_s P_t L_m |h_m|^2}{\sigma^2}$.

As h_m is Rayleigh distributed, χ_m follows the exponential distribution and its Cumulative Distribution Function (CDF) conditioned on the given S_s can be written as

$$F_{\chi_m|S_s}(\chi) = 1 - \exp(-\lambda_m \chi) \tag{9}$$

where $\lambda_m = \dfrac{\sigma^2}{S_s P_t L_m \Omega_m}$ and $E\{|h_m|^2\} = \Omega_m$.

Based on (9), the conditional CDF of χ_o is given as

$$F_{\chi_o|S_s}(\chi) = \prod_{m=1}^{M} 1 - \exp(-\lambda_m \chi), \tag{10}$$

where all the RAUs are independently distributed in the cell.

We denote $F_{\kappa,m}$ as the κ th m-subset of F_i that contains m elements, where $\kappa = 1, 2, \ldots (M)_m$. The elements of $F_{\kappa,m}$ are denoted as $\mu_{m,\kappa,l}$ ($l = 1, 2, \ldots, m$), which are related with $\lambda_m = \dfrac{\sigma^2}{S_s P_t L_m \Omega_m}$. According to (19) of [25], (19) can be rewritten as

$$\begin{aligned} F_{\chi_o|S_s}(\chi) &= 1 - \sum_{m=1}^{M} (-1)^{m-1} \sum_{\kappa=1}^{(M)_m} \prod_{l=1}^{m} \exp(-\mu_{m,\kappa,l} \chi) \\ &= 1 - \sum_m \sum_\kappa e^{-\sum_{l=1}^{m} \mu_{m,\kappa,l} \chi}, \end{aligned} \tag{11}$$

The conditional PDF of χ_o can be obtained by taking the derivative of (11) as

$$f_{\chi_o|S_s}(\chi) = \sum_m \sum_\kappa \left(\sum_{l=1}^{m} \mu_{m,\kappa,l} \right) e^{-\sum_{l=1}^{m} \mu_{m,\kappa,l} \chi} \tag{12}$$

B. Throughput of Massive DAS

Theorem 1: As $M \to \infty$, the asymptotic ergodic capacity conditioned on the downlink channel fading, h_o, without considering the shadowing effect can be given by

$$C_{h_o}^{NS} \cong \log_2 \left(1 + \delta P_t M L_o |h_o|^2 \bar{L} \frac{\tau_0}{1-\tau_0} \right), \tag{13}$$

where $\delta = \dfrac{\rho \xi}{\sigma^2}$. In (13), when the number of RAUs tends to be infinity, the average path-loss is given as

$$\bar{L} = \lim_{M \to \infty} \frac{1}{M} \sum_{m=1}^{M} L_m. \tag{14}$$

Proof: Conditioned on the downlink channel fading with no shadowing, the ergodic capacity is given as

$$\begin{aligned} C_{h_0}^{NS} &= \mathbf{E}\left\{\log_2\left(1+\gamma\right)\right\} \\ &= \mathbf{E}\left\{\log_2\left(1+\frac{\delta L_o \mid h_o \mid^2 \tau_0}{1-\tau_0} P_t \| \mathbf{c} \|_2^2\right)\right\}. \end{aligned} \tag{15}$$

We define $\mathbf{g} = [g_1 g_2 \cdots g_M]^{\mathrm{T}}$ as a $M \times 1$ vector. Let $\mathbf{g}/\sqrt{M}$ be a random vector of i.i.d. entries with zero mean and variance $1/M$. The eighth-order moment of the mth fading is expressed as $\mathbf{E}\{\mid g_m \mid^8\}/M^4$ and its order is $\mathcal{O}(1/M^4)$. Let $\mathbf{L} = \mathrm{diag}\{L_1, L_2, ..., L_M\}$ be a $M \times M$ diagonal matrix which is independent of $\mathbf{g}/\sqrt{M}$. According to Lemma 4 of [26], when M is sufficiently large, we have

$$\begin{aligned} &\frac{1}{M}\|\mathbf{c}\|_2^2 - \frac{1}{M}\sum_{m=1}^{M} L_m \\ &= \frac{1}{\sqrt{M}}\mathbf{g}^{\mathrm{H}}\mathbf{L}\frac{1}{\sqrt{M}}\mathbf{g} - \frac{1}{M}\mathrm{tr}\left(\mathbf{L}\right) \\ &\to 0. \end{aligned} \tag{16}$$

Therefore, when $M \to \infty$,

$$M \| \mathbf{c} \|_2^2 \to M\sum_{m=1}^{M} L_m = \bar{L}. \tag{17}$$

Substituting (17) to (15), we can obtain the asymptotic ergodic capacity, as shown in (13).

It is also concluded from (13) that if more time is allocated to the WET, better achievable rate can be obtained. However, if less time is allocated to the information transmission, the throughput gets worse. Hence, there exists a time-allocation tradeoff between the downlink WET and the uplink WIT.

1) Without shadowing

When the number of RAUs grows to be infinity, without shadowing, the system throughput can be derived as

$$\begin{aligned} T^{NS} &= (1-\tau_0)\mathbf{E}_{h_o}\left\{C_{h_o}^{NS}\right\} \\ &= (1-\tau_0)\int_0^{\infty}\log_2\left(1+\frac{\rho\xi M\bar{L}\tau_0}{1-\tau_0}\chi\right) f_{\chi_o|S_s}(\chi)\mathrm{d}\chi \\ &= (1-\tau_0)\sum_m\sum_\kappa\left(\sum_{l=1}^{m}\mu_{m,\kappa,l}\right) \\ &\quad \times\int_0^{\infty}\log_2\left(1+\frac{\rho\xi M\bar{L}\tau_0}{1-\tau_0}\chi\right)e^{-\sum_{l=1}^{m}\mu_{m,\kappa,l}\chi}\mathrm{d}\chi \\ &= \frac{\tau_0-1}{\ln 2}\sum_m\sum_\kappa \exp\left(\Lambda\right)Ei\left(-\Lambda\right), \end{aligned} \tag{18}$$

where $Ei(x) = -\int_{-x}^{\infty} e^{-t}/t\mathrm{d}t$ is the exponential integral function [27], and $\Lambda = \frac{1-\tau_0}{\rho\xi M\bar{L}\tau_0}\sum_{l=1}^{m}\mu_{m,\kappa,l}$.

2) With shadowing

Let $\Lambda' = \frac{\Lambda}{S_s}$, when the number of RAUs tends to be infinity, applying the Gauss Hermite quadrature integration [28], we can obtain the approximate throughput as

$$\begin{aligned} T^{S} &= \int_0^{\infty} T^{NS} f_{S_s}\left(s\right)\mathrm{d}s \\ &= \frac{\varpi(\tau_0-1)}{\sqrt{2\pi}\ln 2\epsilon}\sum_m\sum_\kappa\int_0^{\infty}\frac{1}{s}\exp\left(\Lambda'\right)Ei\left(-\Lambda'\right) \\ &\quad \times\exp\left[-\frac{\left(10\lg s-\varepsilon\right)^2}{2\epsilon^2}\right]\mathrm{d}s \\ &\cong \frac{\tau_0-1}{2\sqrt{\pi}\ln 2}\sum_m\sum_\kappa\sum_{j=1}^{N_j}[\varphi(t_j)]^{\frac{1}{2}} \\ &\quad \times\exp\left(\Delta\right)Ei\left(-\Delta\right), \end{aligned} \tag{19}$$

where $\Delta = \frac{1-\tau_0}{\rho\xi M\bar{L}\tau_0}\sum_{l=1}^{m}\mu_{m,\kappa,l}\varphi(t_j)$, $\varphi(t_j) = 10^{-\frac{\sqrt{2}\epsilon t_j+\varepsilon}{5}}$, H_j is a weight factor, N_j is the Hermite polynomial order, and t_j is the base point.

Intuitively, the throughput gets better with the increase of antenna number. However, for the wireless-powered massive DAS, signals will experience bidirectional path-loss, and the channel gain related to those RAUs far away from the UE can be ignored. As a result, the throughput improves slightly as the number of RAUs increases.

C. Average Throughput of a Typical UE

It is highly challenging to determine the optimal network design and the best time allocation for the downlink WET and the uplink WIT to maximize the average throughput with a large number of RAUs in a cell. However, this issue is tractable with theoretical analysis and numerical results.

It is assumed that M RAUs are evenly distributed across N circles with radius r, $2r$, ..., Nr. Since the radius of each circle is increased by r from the inner ring to the outer ring, the corresponding numbers of RAUs deployed on each circle are set as K, $2K$, ..., and NK, respectively. The total number of RAUs in the cell with radius R is $M = KN(1+N)/2$. The kth RAU deployed on the nth circle is denoted by $\mathbf{R}_{n,k}$, where $1 \le k \le K$ and $1 \le n \le N$. The distance between a typical UE and the cell center is denoted as d_0, the distance between the UE to the kth RAU on the nth circle, $\mathbf{R}_{n,k}$, is denoted as $d_{n,k}$. With this circular pattern layout, the angle between any two adjacent RAUs on the nth circle is assumed to be $\theta_n = \frac{2\pi}{nK}$. Hence, the adjacent RAUs on each circle keep the same distance from each other, and the total number of RAUs in the cell is $M = \frac{KN(1+N)}{2}$. The angle between the direction of the UE to the cell center and $\mathbf{R}_{n,k}$ to the cell center is $\theta_{n,k}$. Without loss of generality, we assume $\theta_{1,1}=0$, therefore, $\theta_{n,k}=\frac{2\pi(k-1)}{nK}$. The distance between the UE and $\mathbf{R}_{n,k}$ is given as

$$d_{n,k}=(nr)^2+d_0^{\ 2}-2nrd_0\cos\theta_{n,k}. \tag{20}$$

According to (34) of [17], when $M\to\infty$, the average propagation path-loss can be derived as

$$\begin{aligned}\bar{L}&=\frac{2}{KN(N+1)}\sum_{n=1}^{N}\sum_{k=n}^{nK}L_{n,k}\\&=\frac{2}{KN(N+1)}\sum_{n=1}^{N}\frac{1}{\Delta\theta}\\&\quad\times\sum_{k=n}^{nK}\left[(nr)^2+d_0^{\ 2}-2nrd_0\cos\theta_{n,k}\right]^{-\frac{\alpha}{2}}\Delta\theta\\&=\frac{2}{KN(N+1)}\sum_{n=1}^{N}Kn\\&\quad\times\int_{-\pi}^{\pi}\left[(nr)^2+d_0^{\ 2}-2nrd_0\cos\theta\right]^{-\frac{\alpha}{2}}\mathrm{d}\theta\\&\cong\frac{2}{N(N+1)}\sum_{n=1}^{N}n\,|(nr)^2-d_0^{\ 2}|^{-\frac{\alpha}{2}}\\&\quad\times P_{\frac{\alpha}{2}-1}\left[\frac{(nr)^2+d_0^{\ 2}}{|(nr)^2-d_0^{\ 2}|}\right],\end{aligned} \tag{21}$$

where $P(\cdot)$ is the Legendre function [29].

Since the UE is uniformly distributed in the cell, the PDF of the UE's position can be written as [30]

$$f_{d_0}(d_0)=\frac{2d_0}{R^2},0<d_0\le R. \tag{22}$$

Applying (20) and (21) into (18) and (20), and averaging over the PDF of d_0 shown in (22), the asymptotic average throughput of a cell with no shadowing is derived as

$$\bar{T}^{NS}=\frac{2}{R^2}\int_0^R d_0\ \ T^{NS}(d_0)\mathrm{d}d_0. \tag{23}$$

Similarly, the asymptotic average throughput of a cell with shadowing is given as

$$\bar{T}^{S}=\frac{2}{R^2}\int_0^R d_0 T^{S}(d_0)\mathrm{d}d_0. \tag{24}$$

Since the mathematical tools such as Matlab include integral and Legendre functions, the analytical expressions of (23) and (24) can be efficiently evaluated. The optimal deployment of RAUs, as well as the best time allocation for the downlink EH and the uplink WIT can be estimated from the analysis.

IV. Numerical Results

In this section, we present numerical results to demonstrate the throughput of wireless-powered massive DAS, and give simulation results to verify the theoretical results. In the simulations, without stated otherwise, the cellular radius is set as $R=500$ meters, the number of circles is *N*, each circle has *K* RAUs, the total number of RAUs is $M=\frac{KN(1+N)}{2}$, the path-loss exponent is $\alpha=3$, the EH efficiency is $\xi=0.9$, the proportion of energy used for the information transmission is $\eta=0.9$, the normalized time fraction is $\tau_0=0.45$, the transmit power of each RAU is $P_t=0.3$ W, the power of noise is $\sigma^2=-80$ dBm, and the angles between the direction of UE to the cell center and horizontal direction is $\theta=\pi/100$. Fig. 2 depicts the throughput versus the normalized time fraction allocated to the downlink WET for the UE at different locations in the cell (*N*=15 and *M*=120) without considering shadowing effect. The theoretical results shown in (18) agree well with the simulation results. When $\tau_0=0$, i.e., there is no time allocated to the WET, the throughput is zero. On the contrary, when $\tau_0=1$, i.e., the time allocated to the WIT is zero. Although the optimal time fraction maximizing the throughput varies across different UEs' locations, the throughput increases as more time allocated to the WET, but it decreases after reaching a peak. This is because the available transmit power of a UE increases if more time is allocated to the downlink WET, whereas if τ_0 exceeds a threshold, the amount of time for information transmission decreases. As a result, the gain caused by WET does not surpass the loss brought by WIT.

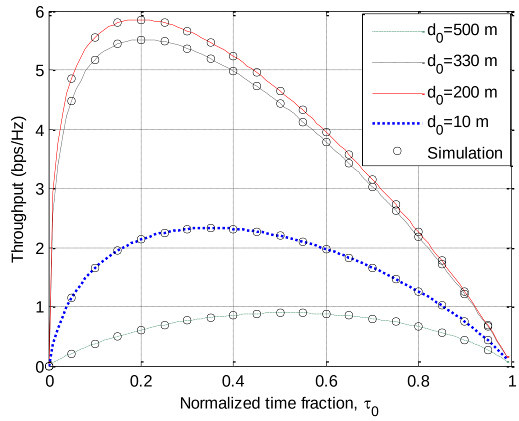

Fig. 2. Throughput versus normalized time fraction for a UE at different positions (*N*=15).

Fig. 3 compares the performance of our proposed RAU selection scheme and the minimized distance (MD) based RAU selection scheme. Both the theoretical results of (18) and (20) with no shadowing and shadowing ($\varepsilon=0$ dB, $\epsilon=5$ dB) match the simulation results. The throughput of all the scenarios can reach a peak value when the UE is located at $d_0=31.25$ m. This is because the radius of the first inner circle is $r=31.25$ m, and when the UE moves to this position a RAU deployed in the circle dominates the performance. Our RAU selection scheme outperforms the minimized distance based RAU selection scheme, especially when the UE departs far away from the circle. When more RAUs (*M*=480) are deployed in the cell, the throughput increases slightly.

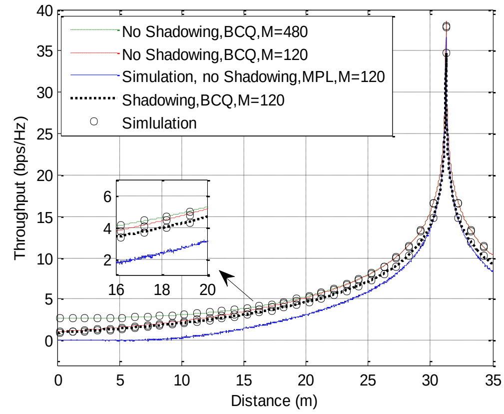

Fig. 3. Throughput versus distance for massive DAS with 15-circle links.

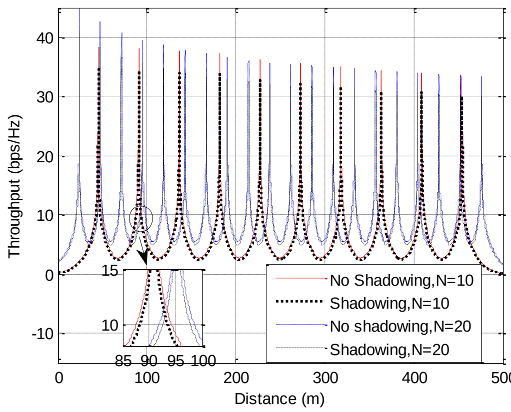

Fig. 4. Throughput versus distance for an arbitrary UE with different deployment (*N*=20 and *N*=10).

Since the theoretical results are verified very tight to the simulation results, the system performance can be estimated efficiently by the theoretical expressions without resorting to the time-consuming simulations. Fig. 4 plots the throughput for an arbitrary UE in a cell based on 10-circle layout and 20-circle layout. Both the two deployments have nearly the same number of RAUs (*M*=220 for *N*=10, and *M*=210 for *N*=20). The throughput of the two deployments appears ten and twenty times peak values around their circles, respectively. The worst throughput is obtained when the UE is located at the midway two adjacent circles.

We further study the massive DAS with 10-circle layout to investigate the impacts of RAU number on the throughput, and compare our massive DAS with the centralized large-scale MIMO (L-MIMO) system at different locations ($d_0 = 25$ m and $d_0 = 100$ m). Fig. 5 shows that the throughput increases with the number of antennas, but it grows slowly when the number of antennas tends to be infinity. Compared with our massive DAS, the centralized L-MIMO system is more sensitive to the UE's locations. For instance, when the UE is located near the cell center ($d_0 = 25$ m), the L-MIMO system outperforms the massive DAS, whereas when the UE departs far away from the cell center ($d_0 = 10$ m), the L-MIMO achieves low throughput. Therefore, compared with the centralized L-MIMO, massive DAS is more applicable for EH to ensure the fairness of the UEs.

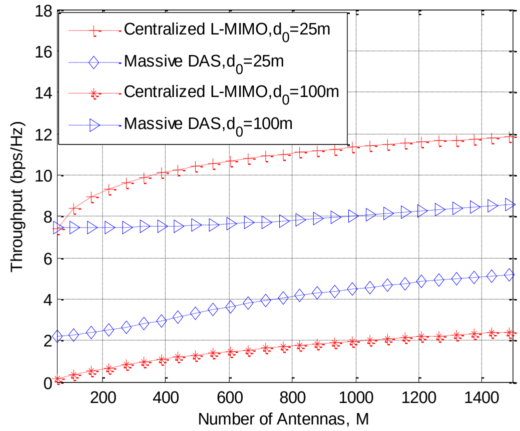

Fig. 5. Throughput versus the number of antennas for massive DAS with 10-circle and centralized L-MIMO ($\tau_0 = 0.2$).

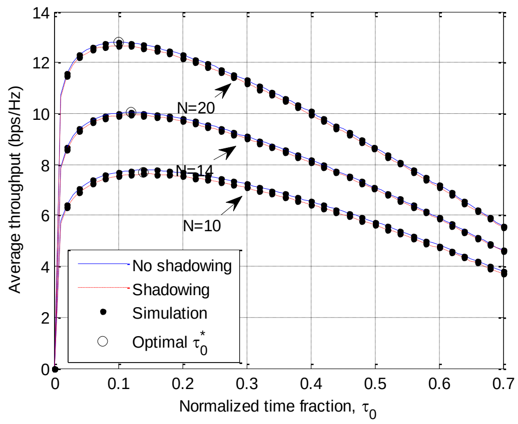

Fig. 6. Average throughput versus the time fraction with different number of circle links.

For a typical UE, the average throughput in a cell reflects the average experience of service. The theoretical results with no shadowing and shadowing are consistent with the simulation results. As can be seen from Fig. 6, the average throughput has the same variation trend as Fig. 2, and the optimal time fraction that can maximize the average throughput varies with different number of circles. For example, the optimal time fractions for massive DAS with 10-circle layout (*M*=220), 14-circle layout (*M*=210), and 20-circle layout (*M*=210) are 0.14, 0.12, and 0.1, respectively. It is concluded from Fig. 5 and Fig. 6 that the number of circles, rather than the number of RAUs, imposes more effects on the system performance.

We then employ the optimal τ_0^* for the network design with different circles layout, and the average throughput with nearly the same number of RAUs versus the transmit power of the RAU is plotted in Fig. 7. We can see that the transmit power of a RAU can be saved for a network with larger number of circles layout. However, with too many circles, the cost of hardware and the optical backhaul installation becomes more expensive, and the total transmit power of the cell increases at the same time. Thus, we can optimize the number of circles and the time allocation between WET and WIT for the network design according to the communication requirement.

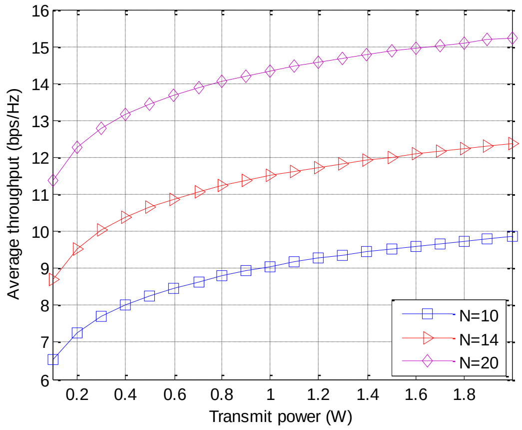

Fig. 7. Average throughput versus transmit power with the optimal time allocation.

V. Conclusions

In this paper, we have analyzed the throughput of the massive DAS based on the WET over composite fading channels. We propose a multiple-circle layout network in which a large number of RAUs are evenly deployed across these circles. Since the average distance between RAUs and UEs can be shortened, the efficiency of WET can be improved. The RAU with the best channel quality is selected for the downlink WET. In the uplink, the received signals can be strengthened by exploring large number of RAUs. The closed-form asymptotic throughput is obtained with shadowing, and the average throughput in terms of single-integral has also been derived. The impacts of various parameters on the throughput have been revealed.

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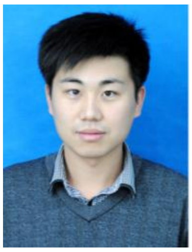

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