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► **To cite this version:**

Wei-Peng Chen, Chenxi Zhu, Takao Naito. Enhanced OFDM Distributed Antenna Systems through Power Redistribution. 9th Wired/Wireless Internet Communications (WWIC), Jun 2011, Vilanova i la Geltrú, Spain. pp.259-271, 10.1007/978-3-642-21560-5\_22 . hal-01583667

**HAL Id: hal-01583667**

**<https://inria.hal.science/hal-01583667>**

Submitted on 7 Sep 2017

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# Enhanced OFDM Distributed Antenna Systems through Power Redistribution

Wei-Peng Chen , Chenxi Zhu, and Takao Naito  
Fujitsu Laboratories of America  
1240 East Arques Ave, Sunnyvale, CA 94085, U.S.A.  
Email: { wei-peng.chen, chenxi.zhu, Takao.Naito@us.fujitsu.com }

**Abstract.** Distributed antenna systems (DAS) have the advantages of achieving low system costs in deployment, operation, and management. While a simple blanket transmission scheme in DAS shows poor performance, several practical limitations prevent the beamforming scheme in DAS from being adopted in the existing systems. By taking advantages of spatial proximity and diversity between different radio equipments (REs) and mobile stations in DAS, we propose a novel approach to enhance the system capacity of orthogonal frequency division multiplexing (OFDM) DAS through power coordination between REs. In comparison with standalone base station deployment, blanket transmission scheme, and beamforming scheme, our proposal achieves higher system capacity by 35.9%, 82.2% and 14.2%, respectively.

**Keywords:** DAS, LTE, OFDM, power redistribution.

## 1 Introduction

A Distributed antenna systems (DAS) is “a network of spatially separated antenna nodes connected to a common source via a transport medium that provides wireless service within a geographic area or structure” [1]. DAS has been broadly adopted in the current wireless cellular communication systems to fulfill numerous challenging deployment requirements [2][3]. In DAS, Radio Equipments (RE) are distributed to different locations and connected to a central control unit, Radio Equipment Control (REC) over optical fiber. Common Public Radio Interface (CPRI) [4] is the industry de facto standard of the interface between REC and RE and the data communicated over CPRI link are in-phase/quadrature (I/Q) samples of baseband signals. REC is the same as a standalone base station (BS) except without the antenna functionalities, whereas the basic functionalities of RE include digital-to-analog (D/A) and analog-to-digital (A/D) conversions, and radio frequency (RF) operations.

The main reason for adopting DAS is to reduce the operation and deployment costs through reduction of radiated power and flexible deployment strategy. To achieve satisfactory coverage, either the sheer number of low power BSs or a few high power BSs are deployed. The total radiated power to cover the same area by many antenna elements (e.g. DAS) rather than a single antenna is actually reduced [5]. In addition, compared to the traditional BS architecture where REC and REs are co-located, operators can adopt a more cost-effective strategy to deploy DAS such that massive RECs can be located at a central office and light-weighted REs can be easily installed at desired locations [6]. The cost of site acquisition to install an RE instead of a BS is much relieved. Yet more benefits of the DAS with multiple REs in contrast with a single RE controlled by an REC are as follows: First, the system cost becomes lower since only one costly REC is used along with multiple inexpensive REs to cover a

wide range of area. Second, less frequent inter-cell handovers are expected because the area covered by different REs under the same REC is considered as the same cell. Third, the management cost is reduced due to less number of cells covering the same area. The amount of control packets exchanged between radio access networks and core networks decreases accordingly with the reduced number of cells and handovers.

The simplest transmission strategy in DAS with multiple REs is called *blanket transmission* [3] where a single set of I/Q samples are transmitted/received by REC to/from different REs on the downlink/uplink (DL/UL) connection, respectively. However, its drawback is that the system capacity is not improved in comparison to distributed standalone BSs because the array gain of multiple antennas in DAS is not fully exploited. On the other hand, in the *beamforming* scheme [8][9], REC exchanges different sets of I/Q samples with different REs. In the ideal beamforming scheme with the knowledge of detailed channel state information (CSI), the signals received from different antennas can be combined coherently to acquire better SINR (signal to interference-plus-noise ratio). Nevertheless, its main drawback is that the detailed CSI at transmitter, receiver, or both is required. Although detailed CSI is assumed available in the previous works [2][3][7][8][9][10], the assumption does not always hold true. RE-specific reference signal is not designed in most standard specifications of cellular radio networks such as 3GPP Long Term Evolution (LTE) [11] or IEEE 802.16 [12] to support multiple REs in DAS. Without RE-specific reference signals, MSs are not aware of the existence of multiple REs. Therefore, estimating each channel response between individual REs and MS is not feasible at MS. Even if RE-specific reference signals are allowed, the overheads of additional reference signals on the control channel are considerable.

In this paper, we propose a novel approach to redistribute power of subcarriers in each RE without the requirement of detailed CSI at either the transmitter side or receiver side. The concept of our proposal is similar to the waterfilling power allocation [16] such that more power is allocated to a subcarrier when its channel quality is good. However, unlike the waterfilling scheme which requires the detailed CSI to decide the power allocations for all the antennas located at the same location, our proposal needs only the approximate estimate of channel response rather than the detailed CSI and it is applicable to DAS with multiple REs. Since REs in DAS are usually placed far apart, there exists a significant difference between the channel gains from different REs to an MS. Therefore, by exploiting the spatial proximity between REs and MS, it is sufficient to estimate the dominant part of channel response, i.e. slow fading, in order to capture the differences of channel responses in different links. In other words, it is no longer critical to learn the volatile component of the channel response, i.e. fast fading, and consequently RE-specific reference signals are not needed in our proposal. Lastly in this paper we focus on orthogonal frequency division multiplexing (OFDM) systems by virtue of the fact that OFDM has become the fundamental technology in the next generation wireless systems such as LTE, IEEE 802.16, and IEEE 802.11n [13].

The rest of the paper is organized as follows. In Sec. 2, we describe the problems and motivations behind the proposal. An overview of the procedures in the proposal is introduced in Sec. 3 followed by the detailed analysis of the baseline schemes and our proposal presented in Sec. 4. Simulation results and performance comparison based on system level simulation are shown in Sec. 5.

## 2 Problems and Motivation

### 2.1 Problems in Blanket Transmission and Beamforming Schemes

In the blanket transmission scheme the same set of I/Q samples is transmitted between REC and REs. In the DL, each RE simply relays the received DL I/Q samples to the next hop RE. In the UL, a RE adds its own I/Q samples to those received from the upstream RE and then send the combined data to its downstream RE (towards the REC). A delay is inserted to compensate for the CPRI propagation and processing delay at each RE. However, a drawback of the blanket transmission is that the array gain of multiple REs in DAS is not fully exploited because the received DL and UL signals are not added up coherently at MS and BS, respectively. In the DL, the channel experienced by an MS is the sum of the channel responses of each individual RE to the MS because the MS cannot estimate the individual CSI between each RE to itself. This is an incoherent operation because no calibration is performed to synchronize the phases of different channel responses. Similarly, the processing of UL signals here is not a coherent operation because REs only compensate the delays caused by both CPRI propagation delay and processing time at REs but not the differences in both magnitude and phase of channels. Consequently the UL array gain of multiple REs in the blanket transmission scheme is not fully exploited.

In the beamforming schemes, different sets of I/Q samples are exchanged between REC and REs. The transmit beamforming scheme [8][9] includes the linear precoding before signals are sent out from the transmitter while the receive beamforming scheme applies the equalization to the received signals at the receiver. The idea of the beamforming schemes is to maximize the array gains of multiple antennas by combining signals of different antennas in a coherent manner. Nevertheless, if each RE does not broadcast its exclusive RE reference signals, the receiver is unable to estimate the individual channel response from different REs. Therefore, the equalization operation cannot be applied at MSs and receiver beamforming is not feasible. Similarly, it is difficult to adopt transmit beamforming in practical systems because the detailed DL CSI is not available at transmitters to compute the precoding matrix. This motivates us to develop solutions not dependent on the detailed CSI.

### 2.3 Motivation of the Proposal

Three key components to determine channel response are path loss, shadowing, and multipath fading [14]. While the first two elements, path loss and shadowing, are considered as slow fading or large scale fading, multipath fading is called fast fading or small scale fading since it can change rapidly in both time and spatial domains. Besides, the magnitude of fast fading is much smaller than that of slow fading [15]. In contrast with the effects of shadowing and multipath fading which are random processes, path loss is the most dominant component in channel response. Moreover, it is a deterministic function of the locations of the transmitter and receiver, and the properties of the antennas and environment. Under the system of DAS with multiple REs, the distances between an MS and different REs are usually different and so are their corresponding channel responses. The differences in the path losses from different REs are even more significant compared to the system with multiple co-located antennas. As the magnitude of the channel gain is dominated by the effect of path loss, higher channel gain is seen between an MS and a closer RE. The main idea

behind our proposal is to take advantage of spatial proximity and diversity by applying different power allocations at different REs based on the estimation of slow fading components rather than detailed CSI. The RE closer to an MS uses higher power in the subcarriers allocated to this MS, whereas the RE further away from the MS reduces the power of these subcarriers and saves the unused power to the subcarriers allocated to other MSs. The traditional OFDM systems adopt uniform power distribution to all subcarriers because there is a limited gain to apply non-uniform power distribution in cellular systems. On the contrary in the system with multiple REs, non-uniform power distribution could enhance DL SINR at MSs because the gain of the power amplification from a closer RE outweighs the loss of the reduced power from a distant RE.

### 3 Overview of the Procedures in the Proposal

The proposed power redistribution scheme consists of 4 stages of procedures.

**Stage 1 - Channel Estimation:** The first stage of our proposal is to estimate the magnitude of DL channel response from the measured magnitude of UL channel response based on the reciprocity principle. The estimation is robust since slow fading does not change rapidly. In FDD systems, the difference in the magnitude of DL and UL path loss is a constant term which is a deterministic function of carrier frequency and antenna settings. Similarly in TDD systems, by assuming that an MS's position does not dramatically change in DL and UL subframe, the difference in the DL and UL path loss is a constant term which is a deterministic function of antenna settings. In our proposal, each RE measures the average received power of the subcarriers allocated to the same MS and deliver this information to REC over CPRI control channel [4].

**Stage 2 - Scheduling:** REC executes a scheduling algorithm to allocate subcarriers in a channel to MSs. Here we decouple the decision of scheduling subcarriers from the problem of subcarrier power redistribution because the joint power and subcarrier assignment problem is NP-hard. Any scheduling algorithm can be used.

**Stage 3 - Power Redistribution Computation:** Based on the measured UL power, REC redistributes the DL power to subcarriers applied in each RE to maximize the system capacity. There could be several strategies to apply power redistribution. One possibility based on maximum ratio combination (MRC) is that the DL power of the subcarriers assigned to an MS at an RE is proportional to the magnitude of the UL channel gain of the same MS measured at that RE. Our proposal is based on maximizing the system capacity. The details of the optimization formulation are presented in Sec. 4.4. A simple example illustrating the main idea of power redistribution is shown in Fig. 1. Suppose that one REC controls two cascaded REs and there are two MSs located in the area served by these two REs. To simplify the scenario, the scheduling algorithm at REC allocates the equal number of subcarriers to these two MSs in a frame. We further assume that the relationship of the magnitudes of channel gain between two REs and two MSs are as follows:

$$RE1 \leftrightarrow MS1 : RE1 \leftrightarrow MS2 = 2 : 1 \text{ and } RE2 \leftrightarrow MS1 : RE2 \leftrightarrow MS2 = 1 : 2$$

Then based on the principle of MRC, the power allocated to MS1's subcarriers by RE1 is boosted from 1/2 to 2/3 of total power while the power allocated to MS2's subcarriers by RE1 is reduced from 1/2 to 1/3 of RE1's total output power. Similarly, the power allocated to MS2's subcarriers by RE2 is increased from 1/2 to 2/3 of

RE2's total output power while the power allocated to MS1's subcarriers by RE2 is decreased from 1/2 to 1/3 of RE2's total output power.

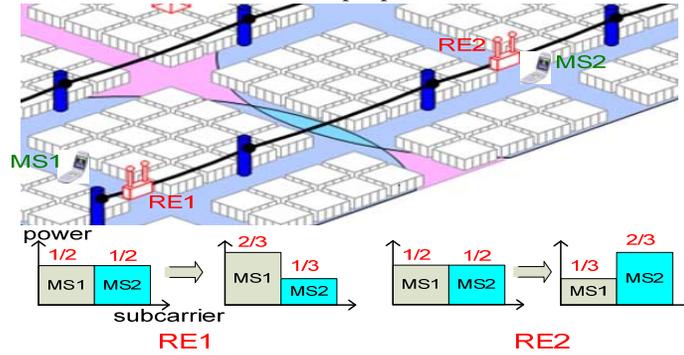


Fig. 1 An example showing the idea of power redistribution.

**Stage 4 – Applying Power Redistribution:** After REC computes each RE's power allocation, power amplification or attenuation is applied to the data in the frequency domain before inverse discrete Fourier transform (IDFT) operation. Traditional OFDM systems apply the same power to each subcarrier. By contrast, in our proposal after DL power redistribution, the signal ( $X^{(i)}$ ) is scaled up or down proportionally subject to the constraint that the total transmission power from each RE remains the same. In the example of Fig. 1, RE1 scales up the signal ( $X^{(i)}$ ) carried on MS1's subcarriers by  $\sqrt{4/3}$  while the signal carried on MS2's subcarriers is scaled down by  $\sqrt{2/3}$  to maintain the same total output power at RE1. Fig. 2 illustrates the operation of power amplification/attenuation.

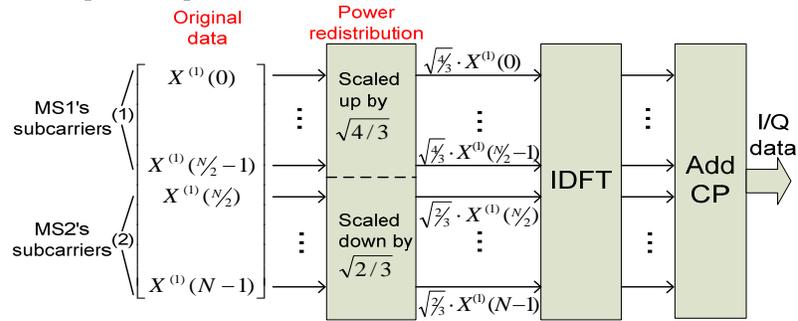


Fig. 2 Power amplification or attenuation at RE1.

#### 4 Detailed Analysis of the Baseline Schemes and our Proposal

The analysis in this paper is based on OFDM systems. In particular we focus on LTE [11]. The DL LTE is based on OFDMA (orthogonal frequency division multiple access) while the UL is based on SC-FDMA (single-carrier frequency division multiple access). We focus on the analysis on the DL in this paper. The detailed analysis on the basic LTE DL processing as well as two baseline schemes of blanket transmission and beamforming will be compared with the proposed scheme.

## 4.1 LTE DL Processing

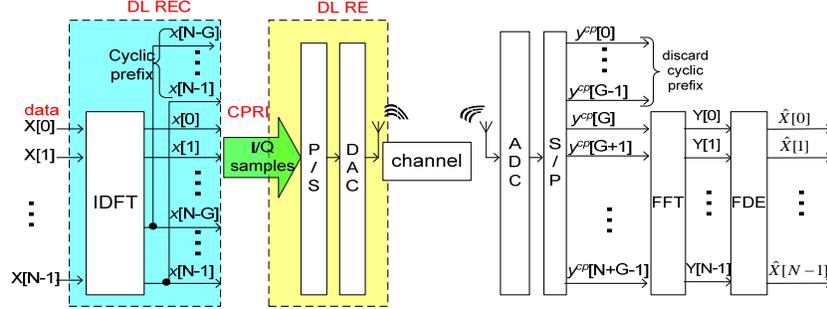


Fig. 3 LTE DL processing

LTE DL processing is shown in Fig. 3. The left and right hand side are the processing at the transmitter (i.e. BS) and receiver (i.e. MS), respectively. REC's DL data at each symbol are  $X[0], \dots, X[N-1]$ . IDFT is applied first to obtain the time domain data:  $x[0], \dots, x[N-1]$ . Then REC sends the time domain data along with the cyclic prefix (CP) in the format of I/Q samples to RE. Then RE transmits the time domain I/Q data over the air to MSs. On the MS side, first  $N+G$  samples are received at each symbol:  $y^{cp}[0], y^{cp}[1], \dots, y^{cp}[N+G-1]$  where  $G$  is the length of CP. After removing CP and applying  $N$ -point FFT (Fast Fourier Transform),  $N$  point frequency domain data,  $Y[0], \dots, Y[N-1]$ , are obtained at MS. Next a frequency domain equalizer (FDE) is applied to  $N$ -point frequency domain data in order to offset the effect of channel response caused to the transmitted data and we obtain:  $\hat{X}[0], \dots, \hat{X}[N-1]$ .

## 4.2 Analysis of DL Processing for Blanket Transmission Scheme

In the blanket transmission scheme the same set of signals is sent from  $N_R$  REs to a MS where  $N_R$  is the number of REs controlled by an REC in a cell. The signal of subcarrier  $k$  received at MS consists of the signals coming from  $N_R$  REs as:

$$Y[k] = \sum_{r=1}^{N_R} \sqrt{\frac{P_{r,k}}{N_T}} H_r(k) \cdot X[k] + \sum_{i=1}^{N_I} \sqrt{\frac{P_{i,k}}{N_T}} H_i(k) \cdot X_i[k] + N[k] \quad (1)$$

where  $N_I$  is the number of interference BSs (including both intra-cell and inter-cell interference) and  $N_T$  is the number of transmitting antennas at each RE.  $N[k]$  is the noise power of subcarrier  $k$ .  $P_{r,k}$  is the received power of the subcarrier  $k$  at the  $r$ -th RE by considering path loss and shadowing:

$$P_{r,k} = P_{r,k}^T \cdot G_r \cdot 10^{X_r/10} / L(d_r) \quad (2)$$

where  $P_{r,k}^T$  is the transmission power assigned to subcarrier  $k$  at  $r$ -th RE,  $G_r$  is the antenna gain (excluding shadowing) between the MS and  $r$ -th RE,  $X_r$  is the lognormal shadowing between the MS and  $r$ -th RE,  $L(d_r)$  is the path loss from  $r$ -th RE to MS at distance  $d_r$ .  $H_r(k)$  in Eq. (1) is the channel response between  $r$ -th RE and MS with inclusion of multipath fading only because both path loss and shadowing have been incorporated into the expression of  $P_{r,k}$ .

As the MS is unaware of the existence of multiple REs, the channel response it sees is the combined channel responses from all REs. Thus, the corresponding FDE for subcarrier  $k$  is:

$$FDE[k] = \Phi[k]^H = \sum_{r=1}^{N_R} H_r[k]^H \quad (3)$$

Lastly, the SINR, the ratio of signal power to interference-plus-noise power, of subcarrier  $k$  can be represented as:

$$SINR(k) = \frac{\sum_{r=1}^{N_R} \frac{P_{r,k}}{N_T} \cdot \|\Phi(k)^H \cdot H_r(k)\|^2}{\sum_{i=1}^{N_I} \frac{P_{i,k}}{N_T} \cdot \|\Phi(k)^H \cdot H_i(k)\|^2 + \|\Phi(k)\|^2 \cdot \sigma^2} \quad (4)$$

Note that the numerator of SINR can be decomposed into two terms: in-phase component  $\sum_{r=1}^{N_R} \frac{P_{r,k}}{N_T} \cdot |H_r(k)|^2$  and out-of-phase component  $\sum_{\substack{i,j=1 \\ i \neq j}}^{N_R} \frac{P_{i,k}}{N_T} H_i(k) \cdot H_j(k)^H$ .

The first term is the sum of Frobenius norm of individual channel responses while the second term is the sum of the interactions between different channel responses of different REs. Since in the blanket transmission scheme MS lacks the information of individual CSI, signals from different REs received at MS cannot be added up coherently. Because the phases of different channel responses,  $H_i[k]$  and  $H_j[k]$ , are not synchronized, the second term causes the destruction of the overall SNR. That is, the transmitter array gain of multiple transmitting antennas at REs is not fully exploited.

### 4.3 DL Processing Equation for Beamforming Scheme

Even though beamforming scheme [8][9] is not considered as a practical method in DAS, for comparison purpose, in this subsection we analyze the DL performance of the beamforming scheme by assuming that the detailed DL CSI and UL CSI are available. The first step in the beamforming scheme is that the transmit weighting coefficient (or precoding) vector  $W_r(k)$  of subcarrier  $k$  at RE  $r$  is applied to input data,  $X[k]$ , before IDFT operation:  $\tilde{X}_r[k] = W_r(k) \cdot X[k]$ . The vector of the precoding coefficients for all the REs,  $W_i(k) = [W_{i_1}(k), \dots, W_{i_{N_R}}(k)]$  can be obtained by computing first  $N_R$  eigenvectors of the matrix  $\Psi_k^H \cdot R_{z,k}^{-1} \cdot \Psi_k$  where  $R_{z,k} = \sum_{i=1}^{N_I} P_{i,k} H_i(k) H_i^H(k) + N_0 \cdot I$  and  $\Psi_k = [\sqrt{P_{1,k}} \cdot H_1(k) \quad \sqrt{P_{2,k}} \cdot H_2(k) \quad \dots \quad \sqrt{P_{N_R,k}} \cdot H_{N_R}(k)]$ . Ideally in the transmit beamforming scheme, both the magnitude and phase are amplified coherently. MS computes the receiver spatial equalizer matrix  $W_r(k)$  as:

$$W_r(k) = \frac{\sum_{r=1}^{N_R} \sqrt{P_{r,k}} H_r(k) W_r^H(k)}{\sum_{r=1}^{N_R} P_{r,k} H_r(k) H_r^H(k) + \sum_{i=1}^{N_I} P_{i,k} H_i(k) H_i^H(k) + N_0 \cdot I} \quad (5)$$

The SINR of subcarrier  $k$  in the beamforming scheme is:

$$SINR(k) = \frac{\sum_{r=1}^{N_R} \frac{P_{r,k}}{N_T} \cdot \|W_r(k)^H \cdot H_r(k)\|^2}{\sum_{i=1}^{N_I} \frac{P_{i,k}}{N_T} \cdot \|W_r(k)^H \cdot H_i(k)\|^2 + \|W_r(k)\|^2 \cdot \sigma^2} \quad (6)$$

Note that the beamforming method considered here is **carrier non-cooperative** approach. That is, each subcarrier is *independently* processed. Therefore, it does not adjust the power allocation similar to waterfilling power allocation [16] across different subcarriers. In DAS, there exists a significant difference in the magnitude of the channel gains of different subcarriers allocated to different MSs. Therefore, the optimization within one subcarrier like the carrier non-cooperative beamforming scheme is not an optimal solution. On the other hand, the carrier cooperative method by considering all subcarriers is computationally prohibitive.

### 4.4 Analysis of the Proposal

The goal of our proposal is to maximize the system capacity of DAS via properly assigning power of subcarriers at different REs. The coefficients of power amplification/attenuation of subcarriers are determined by solving an optimization

problem of maximizing the system capacity. The input of the optimization problem is based on the magnitude of UL power without the requirement of detailed CSI. The output of the optimization problem is the magnitude of power amplification/attenuation of all subcarriers, expressed as  $g_{r,k}$  for subcarrier  $k$  at the  $r$ -th RE. The received signal at MS after FFT operation can be expressed as:

$$Y[k] = \sum_{r=1}^{N_R} \sqrt{\frac{P_{r,k}}{N_T}} H_r(k) \cdot g_{r,k} \cdot X[k] + \sum_{i=1}^{N_I} \sqrt{\frac{P_{i,k}}{N_T}} H_i(k) \cdot g_{i,k} \cdot X_i[k] + N[k] \quad (7)$$

The corresponding FDE at MS side is:

$$FDE[k] = \Phi[k]^H = \sum_{r'=1}^{N_R} g_{r',k} \cdot H_{r'}[k]^H \quad (8)$$

Finally the DL SINR of subcarrier  $k$  in the proposed scheme is:

$$SINR(k) = \frac{\sum_{r=1}^{N_R} \frac{P_{r,k}}{N_T} \cdot \|\Phi(k)^H \cdot g_{r,k} \cdot H_r(k)\|^2}{\sum_{i=1}^{N_I} \frac{P_{i,k}}{N_T} \cdot \|\Phi(k)^H \cdot g_{i,k} \cdot H_i(k)\|^2 + \|\Phi(k)\|^2 \cdot \sigma^2} \quad (9)$$

By comparing the SINR equation of the proposed scheme with that of the blanket transmission scheme shown in Eq. (4), the only difference is the coefficient of power gain  $g_{r,k}$  exists in both numerator and denominator. Based on the information theory, the system capacity of subcarrier  $k$  can be estimated as a function of SINR:  $C(k) = \ln(1 + SINR(k))$ . The objective of the optimization problem is to find out the power amplification gain  $g_{r,k}$  (or square of gain,  $G_{r,k} = g_{r,k}^2$ ) such that the overall system capacity is maximized. Note that the power gain cannot be amplified indefinitely since the total transmission power per RE is limited to its maximum output power,  $P_T$ . Therefore, the constraint function in the optimization problem is that the total transmission power from each RE is less than or equal to  $P_T$ . Besides  $P_T$ , the given inputs of the optimization problem also include  $P_{r,k}^{UL}$ , the received UL power of subcarrier  $k$  at  $r$ -th RE. The DL received power at MS,  $P_{r,k}^{DL} = c \cdot P_{r,k}^{UL}$ , is proportional to the UL received power at RE,  $P_{r,k}^{UL}$ , where  $c$  is a constant factor to calibrate the differences between the antenna gains of DL and UL connections. Thus, the DL SINR formula shown above can be presented as a function of UL received power. Finally, the capacity of subcarrier  $k$  with power amplification can be expressed as:

$$C(k) = \ln\left(1 + \frac{\sum_{r=1}^{N_R} \frac{c \cdot P_{r,k}^{UL}}{N_T} \cdot \|\Phi(k)^H \cdot g_{r,k} \cdot H_r(k)\|^2}{\sum_{i=1}^{N_I} \frac{c \cdot P_{i,k}^{UL}}{N_T} \cdot \|\Phi(k)^H \cdot g_{i,k} \cdot H_i(k)\|^2 + \|\Phi(k)\|^2 \cdot \sigma^2}\right) \quad (10)$$

To simplify the problem, in this paper we only consider the optimization problem without inter-cell interferences:

$$\begin{aligned} \max_{\{g_{r,k}\}} \sum_{k=1}^N c(k) &= \sum_{k=1}^N \ln\left(1 + \frac{\sum_{r=1}^{N_R} \frac{c \cdot P_{r,k}^{UL}}{N_T} \cdot \|\Phi(k)^H \cdot g_{r,k} \cdot H_r(k)\|^2}{\|\Phi(k)\|^2 \cdot \sigma^2}\right) \\ s.t. \sum_{k=1}^N g_{r,k}^2 \cdot P_{r,k}^{TX} &\leq P_T \quad \forall r = 1, \dots, N_R \end{aligned} \quad (11)$$

We can further simplify the objective and constraint functions in Eq. (11) based on the following two arguments:

- First we restrict that the same power amplification gain,  $g_{r,u(k)}$ , is applied to the subcarriers associated with the same MS  $u$ , where  $u(k)$  is the mapping function (i.e.

scheduling) of the subcarrier  $k$  to the MS  $u$ . Such an assumption is reasonable because the path loss between the BS and the MS would not change much in these subcarriers. With this simplification, the number of variables,  $g_{r,k}^2 (=G_{r,k})$ , in the optimization problem is reduced from  $N_R \cdot N$  to  $N_R \cdot N_{MS}$  where  $N_{MS}$  is the number of MSs scheduled to receive data in one frame. Thus, the power gain control parameter for subcarrier  $k$  assigned to MS  $u$  can be represented as  $g_{r,u}$ . Furthermore, before power amplification, uniform power assignment is set to all subcarriers. That is,  $P_{r,k}^{TX} = P_T/N$ . Then the constraint function can be simplified as:

$$\sum_{u=1}^{N_{MS}} S_u \cdot G_{r,u} \leq N \quad \forall r = 1, \dots, N_R \quad (12)$$

where  $S_u$  is the number of subcarriers allocated to MS  $u$  and  $G_{r,u} (=g_{r,u}^2)$  is the square of the power amplification at  $r$ -th RE for all the subcarriers allocated to MS  $u$ .

- Second, we further assume  $H_r(k) = 1$  for all subcarriers. This is equivalent to ignoring the effects of multipath fading in the formulation of optimization problem. With this simplification,  $\Phi(k)$  appearing on both numerator and denominator of the objective function can be cancelled out with each other.

With considering these two simplifications, the optimization formulation becomes a non-linear programming problem which can be solved fast:

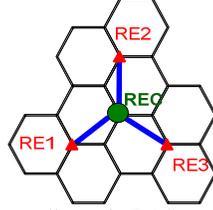
$$\begin{aligned} \max_{\{G_{r,u}\}} & \sum_{u=1}^{N_{MS}} S_u \cdot \ln\left(1 + \frac{\sum_{r=1}^{N_R} \frac{c \cdot P_{r,u}^{UL}}{N_T} \cdot G_{r,u}}{\sigma^2}\right) \\ s.t. & \sum_{u=1}^{N_{MS}} S_u \cdot G_{r,u} \leq N \quad \forall r = 1, \dots, N_R \\ & G_{r,u} \geq 0 \quad \forall r = 1, \dots, N_R; u = 1, \dots, N_{MS} \end{aligned} \quad (13)$$

Because both the objective function and constraint functions are convex (or concave) functions, there exists a global optimization solution by solving the equations of Karuch-Kuhn-Tucker optimality conditions [20].

## 5 Performance Evaluation

In this section we evaluate the DL system performances via a system level simulator which simulates the models of path loss, shadowing, and multipath fading based on system evaluation methodology in [17] and [18]. Both intra-cell and inter-cell interferences are considered in the simulations. Exponential Effective SINR Mapping (EESM) based abstraction [17] of LTE physical layers is implemented in the system level simulator. We compare the performance in two system configurations: macrocell and DAS. In the traditional macrocell deployment (called ‘‘macrocell’’ in the following description), each BS is placed at the center of three hexagons in each cell [18]. On the other hand, in the configuration of DAS we consider, one RE is deployed at the center of three hexagons in each cell, same as the position of BSs. Fig. 4 shows the area of one cell where an REC controlling a set of 3 REs is placed at the center of 9 hexagons. BSs (in the case of macrocell) or REs (in the case of DAS) are located 1 km apart from each other. Mobile stations (MSs) are uniformly distributed in 50 m apart. We focus on a center cell that is surrounded by two tiers of adjacent cells. Frequency reuse 1/3/1 (i.e. the system channel of 10MHz is reused in each of three sectors of each cell) [17] is considered in the simulation. Furthermore, the

MIMO setting in the simulation is 2x2 MIMO with Alamouti transmit diversity [19]. The important system level parameters that we use are summarized in Table 1.



**Fig. 4** Layout of one cell area in DAS controlled by one REC

**Table 1** Important system parameters [17].

Parameter	Value	Parameter	Value
BS (RE) Tx antenna Gain	16 dBi	MS terminal height	2 m
BS (RE) height	32 m	MS noise figure	7 dB
BS (RE) Tx antenna power	43 dBm	Channel bandwidth	10 MHz
BS noise figure	5 dB	FFT size	1024

We compare the proposed power redistribution scheme in Sec. 4.4 against two other DAS schemes, blanket transmission in Sec. 4.2 and beamforming in Sec. 4.3 as well as the setting of macrocell. The effects of the inter-cell interferences are included in the simulation. Table 2 shows the DL sector capacity of these four schemes based on the results of the average of 30 runs (i.e. 30 frames) when the effects of shadowing and multipath fading could be changed at different frames. Note that the cell capacity is three times of sector capacity. Different number of  $N_{MS}$  ( $= 2, 3, 4,$  or  $5$ ) are simulated in our proposal. Besides, the set of MSs to be scheduled in the same frame is randomly chosen. As the performance of the schemes of macrocell, blanket transmission, and beamforming scheme is invariant under different  $N_{MS}$  settings, only one number of these schemes is shown in Table 2. In addition, the proposal with  $N_{MS} = 1$  is equivalent to the blanket transmission scheme.

**Table 2** Comparison of DL sector capacity (unit: Mbps)

Scheme	macrocell	Blanket	Beamforming	Proposal			
$N_{MS}$	1~5	1~5	1~5	2	3	4	5
Sector Capacity	10.82	8.07	12.87	12.03	13.69	14.45	14.70

The simulation results first show that in comparison with macrocell setting, the performance of the blanket transmission scheme is degraded by 34.1% which indicates the great impact of the non-coherent operations in the blanket transmission scheme. The simulation results also show that the performance of the proposed scheme improves as  $N_{MS}$  increases. This is because when  $N_{MS}$  increases, more freedom in the optimization problem of power distribution is created to maximize the system capacity. Our proposal under all the cases of  $N_{MS}$  outperforms the case of macrocell. In addition, the proposed scheme outperforms the beamforming scheme when  $N_{MS} \geq 3$ . As explained in Sec. 4.3 the beamforming scheme evaluated here is a *carrier non-cooperative* approach where each subcarrier is independently processed without the power adjustment across different subcarriers. The result indicates the effectiveness of non-uniform power allocation over carrier non-cooperative beamforming schemes in the DAS environment. In the case of  $N_{MS}=5$ , our proposal improves the DL system capacity by 35.9%, 82.2%, and 14.2% compared to macrocell, blanket transmission scheme and beamforming scheme, respectively.

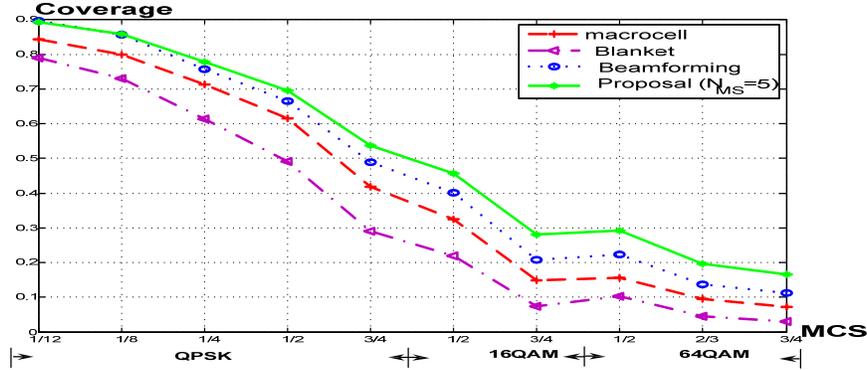


Fig. 5 Comparison of DL coverage.

Fig. 5 compares the coverage performance of various modulation and coding scheme (MCS) shown by the indices on the x-axis. In our study, we define the coverage for a given MCS as the percentage of MSs which have a higher SINR than the required SINR of that MCS over a long duration. It represents the average percentage of MSs that are supported by that MCS level. The system coverage is defined as the coverage on the most reliable MCS. The results in Fig. 5 show the superior coverage performance of our proposal over the other schemes. Not only the system capacity but also the system coverage are improved in our proposal.

Fig. 6 shows the pictorial presentation of DL coverage of macrocell, blanket transmission, beamforming, and our proposal ( $N_{MS}=5$ ). Each small square inside the hexagon indicates the MCS used by the MS located at the position at this square. The yellow color in a square indicates no coverage while the blue color indicates the highest order of MCS, 64QAM with code rate of  $\frac{3}{4}$ . The results show the same trend as the results of DL system capacity. In particular, the coverage of edge user is much enhanced in our proposal.

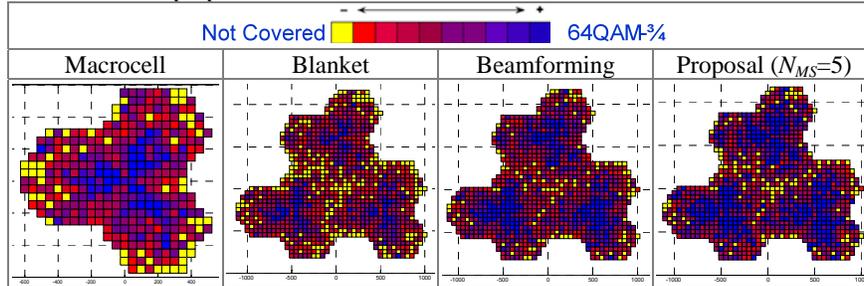


Fig. 6 Comparison of visual presentation of DL coverage.

## 6. Conclusion

In this study we propose a novel approach to enhance the system capacity in distributed antenna systems through redistributing the powers of OFDM subcarriers in the REs. The proposed solution not only maintains the advantages of DAS, which include both low system costs of deployment, operation, and management, and less frequent inter-cell handover, but also improves the performances of system capacity and coverage in DAS compared to other baseline schemes such as the traditional BS

with a single pair of REC and RE, as well as DAS with either blanket transmission or beamforming schemes. The proposal can be easily implemented in the existing OFDM wireless systems such as LTE, WiMAX, or WiFi as well as the next generation wireless systems such as LTE-A and 802.16m. In the future works, we will focus more on optimizing the deployment strategy of the proposal.

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