Link-Adaptation-Enhanced Dynamic Channel Allocation for MIMO-OFDM Wireless Networks

Jia Tang and Xi Zhang
Networking and Information Systems Laboratory
Department of Electrical Engineering
Texas A&M University, College Station, TX 77843, USA
Email: {*jtang, xizhang*}*@ee.tamu.edu*

***Abstract*— We propose a link-adaptation (LA)-based system infrastructure and develop the corresponding dynamic channel allocation (DCA) algorithm for downlink data transmissions over MIMO-OFDM wireless networks. By integrating a set of LA techniques, our system can dynamically select transmit-antennas, modulation-levels, and transmission power for different mobile users. Jointing with the proposed system infrastructure, we develop the DCA algorithm to maximize the total system throughput. In designing the DCA algorithm, we first focus on CDMA-based MIMO-OFDM systems with any given spreading gain G. Deriving the optimal G to achieve the maximum throughput, we prove that the optimal spreading gain is $G = 1$. This implies that the system without using spread spectrum (SS) is optimal in terms of maximizing the throughput. Extensive simulations show that the system throughput increases significantly with the numbers of transmit antennas, receive antennas, and mobile users. Moreover, our DCA algorithm can significantly improve the system throughput performance as compared with the conventional fixed channel allocations (FCA).**

***Index Terms*—Dynamic channel allocation (DCA), transmit antenna selection (TAS), adaptive modulation, power control, OFDM, CDMA, MIMO.**

I. Introduction

THE EXPLOSIVE increase of high-speed wireless networking applications motivates an unprecedented revolution in wideband-wireless communications [1]. This presents great challenges in designing the next-generation wireless networks since the multipath fading channel has a severe impact on reliable transmissions. To overcome these problems, a number of promising schemes are proposed, such as link adaptation (LA) technique [2], multiple-input-multiple-output (MIMO) architecture [3], and orthogonal frequency division multiplexing (OFDM) signaling [4].

Link adaptations (LA) — where the transmission parameters such as power level and constellation size are dynamically adapted to the time-varying fading channel — have emerged as one of the key solutions to increase the spectral efficiency of wireless systems [2], and thus received a great deal of research efforts [5]-[8]. Employing LA, the system can achieve more efficient transmissions to increase the data throughput when the channel condition is good; when the channel becomes bad, the system can decrease its transmission rate adaptively while maintaining the same BER. In contrast, the system without LA can only be designed for the worst channel condition. As a result, LA outperforms the non-adaptive schemes significantly. Due to its great performance, LA is currently part of both W-CDMA and CDMA-2000 standards.

The research reported in this paper was supported in part by the National Science Foundation CAREER Award under Grant ECS-0348694.

While LA can achieve remarkable improvements on spectral efficiency over the non-adaptive schemes, some other interesting techniques can also be integrated with it to further increase the system capacity. In particular, multi-antenna techniques such as MIMO and multi-carrier transmissions such as OFDM, can be combined with LA to achieve the integrated diversities from spatial, temporal, and spectral domains, which will result in significant improvements in supporting QoS requirements of different mobile users for the future wireless networks.

When employing the integrated scheme, the key issue is how to combine these techniques in the most efficient and cost-effective way. In this paper, we propose an LA-based system infrastructure to efficiently integrate a set of adaptation techniques, and develop the corresponding dynamic channel allocation (DCA) algorithm for downlink data transmissions over MIMO-OFDM wireless networks. Specifically, the proposed infrastructure is designed to adaptively select the transmit antenna, constellation size, and power level based on *instantaneous* channel conditions of different mobile users. Based on the proposed system infrastructure, we develop the DCA algorithm to maximize the system throughput. In designing the DCA algorithm, we first focus on the widely employed code division multiple access (CDMA)-based MIMO-OFDM system, i.e., multi-carrier (MC) direct-sequence (DS)-CDMA system [4]. Given the system with any spreading gain of G, we develop the DCA algorithm to maximize the total throughput. Then, we derive the optimal G that can achieve the maximum total throughput. We prove that the optimal spreading gain is $G = 1$, implying that the spread spectrum (SS) always degrades the system performance in terms of total throughput. Extensive simulations verify our analytical analyses and show that the system throughput increases significantly with the numbers of transmit antennas, receive antennas, and mobile users. In addition, our DCA algorithm can significantly improve the system throughput performance as compared to the conventional fixed channel allocation (FCA) algorithms.

The rest of this paper is organized as follows. Section II describes the system model. Section III presents the adaptation schemes used in our system. Section IV focuses on the DCA algorithm for MC DS-CDMA system. Section V derives the optimal spreading gain that can maximize the total system throughput. Section VI conducts extensive simulations to evaluates the performance of our proposed DCA algorithm and compares it with fixed channel allocations (FCA). The paper concludes with Section VII.

II. System Description

A. Transmitter and Receiver Models

We consider the downlink of a single-cell MC DS-CDMA system with a total number of K mobile users. The basestation is equipped with N_t transmit (Tx) antennas and the kth user ($k = 1, 2, ..., K$) is equipped with $N_r^{(k)}$ receive (Rx) antennas. Denote the total transmission power of the basestation by P, the total number of orthogonal subcarriers by U, and the total spread spectrum bandwidth by W. Thus, the bandwidth per subcarrier is equal to $\Delta = W/U$ and the chip duration $T_c = 1/\Delta = U/W$, guaranteeing the orthogonality between different subcarriers. Denote the spreading gain of the system by G. Then, the symbol duration T_s can be expressed as $T_s = GT_c = GU/W$.

First, all mobile users' data streams are fed into the dynamic resource allocation block. According to the channel state information (CSI) and the quality of service (QoS) requirements of different mobile users, the system jointly allocates the system resources including transmit-power, modulation-levels, transmit-antennas to each mobile user. Then, based on the outcomes of the resource allocation, each mobile user's data stream is converted into a number of parallel sub-streams, and then transmitted simultaneously at different subcarriers. The sub-streams at different subcarriers can be assigned with different power-levels and modulated with different constellation sizes, which is obtained by applying the *power control* and the *adaptive modulation* (AM), respectively. Moreover, different sub-streams are sent by different transmit antennas, which is achieved by using *transmit antenna selection* [12]. The details of these LA schemes will be presented in the following two sections.

The rest of the operations at both the basestation and the mobile users are similar to those conventional MC DS-CDMA systems. Specifically, the spreading and de-spreading are performed at the basestation and the mobile users. The modulations at the basestation and the demodulations at the mobile users are implemented by U-point IFFT and FFT processes, respectively. The cyclic prefix (CP) is added at the basestation and removed at the mobile users to eliminate the effect of inter-symbol interference (ISI). When the number of receive antennas $N_r^{(k)} > 1$, the maximum ratio combining (MRC) is assumed to be employed at the kth mobile user.

B. Channel Model

The wireless fading channel is assumed to be frequency-selective. However, the delay-spreads T_m of the channel satisfy $T_m \ll T_c$, making each subcarrier conform with the flat-fading. Moreover, the channel is assumed to be quasi-static so that the channel gains are constant over a burst of symbol intervals but vary from one burst to another. Then, within a burst duration, the channel coefficients between the *i*th transmit antenna of the basestation and the *j*th receive antenna of the kth user at the uth subcarrier can be denoted by $h_{k,u}^{i,j}$, where $k \in \{1, 2, ..., K\}$, $u \in \{1, 2, ..., U\}$, $i \in \{1, 2, ..., N_t\}$, and $j \in \{1, 2, ...N_r^{(k)}\}$.

The additive white Gaussian noise (AWGN) at the receiver is assumed to have the zero-mean and single-sided power spectral density of N_0 for all users. Therefore, the AWGN at each subcarrier can be modelled as having the zero-mean and variance equal to $\sigma_\eta^2 = N_0\Delta = N_0W/U$. The downlink of the system is assumed to be ideally orthogonal and synchronized between users within the cell, i.e., no intra-cell interference is considered in this paper. The inter-cell interference of the kth user at the uth subcarrier has the power denoted by $I_{k,u}$. In addition, the channel state information (CSI) of downlink is assumed to be perfectly known by both the basestation and the mobile user. The CSI at the basestation can be obtained by user's feedback, or, in a time division duplex (TDD) system, the CSI can be obtained directly by the basestation since the channel is reciprocal. It is clear that the CSI feedback will introduce certain amount of overhead. However, such an overhead can be relatively small, especially when the channel changes slowly (e.g., an indoor slow-mobility environment), and the allocation is done once every many symbol intervals [5].

III. Integrated Link-Adaptation Schemes

A. Transmit Antenna Selection (TAS)

In recent years, the transmit diversity technique has received a great deal of research effort. For the open-loop (i.e., without CSI feedback) MIMO system, space-time codes [9] are powerful tools to achieve diversity gain. For the closed-loop (i.e., with CSI feedback) MIMO system, the smart-antenna-based technique using transmit beamforming is shown to be optimal [10]. However, the optimal beamforming imposes high hardware complexity. Moreover, the computational complexity of eigenvalue or singular value decomposition for beamforming also restricts the implementation of transmit smart-antenna. Alternatively, transmit antenna selection (TAS) provides a good tradeoff between complexity and performance.

As compared to space-time codes and smart-antenna-based scheme, transmit antenna selection (TAS) receives relatively low research attention. TAS was first proposed in [11] and thereafter studied in, e.g., [12][13]. The idea of TAS can be briefly described as follows: by using CSI feedback, a single transmit antenna out of all N_t candidates, which maximizes the post-processing SNR at the MRC output, is selected to transmit data for the corresponding user. Since TAS always concentrates all its transmission power to the selected optimal antenna for data transmission, while STBC equally distributes its transmission power over all transmit antennas for data transmission, the performance of TAS is always better than STBC. Meanwhile, the authors in [13] showed that the performance of beamforming is only slightly better than TAS (e.g., 1.5 dB superior than TAS when $N_t = 2$ and $N_r = 1$). It is also interesting to note that when employing TAS, the multiple transmit antennas at the basestation can be considered as "transparent" to the receiver, making TAS very cost-effective to be implemented in practical wireless communications.

All previous work focuses only on TAS applied in single-user communications over flat-fading channel. In this paper, we generalize these results to multi-user multi-carrier communications over frequency-selective channel. Based on the instantaneous CSI, the same user's data at different subcarriers can be transmitted by different antennas. Specifically, the basestation will select the transmit antenna $i_{k,u}$ to send data for the kth user at the uth subcarrier, where $i_{k,u}$ is determined by

$$i_{k,u} = \arg \max_{i \in \{1,2,\cdots,N_t\}} \sum_{j=1}^{N_r^{(k)}} \left| h_{k,u}^{i,j} \right|^2. \tag{1}$$

We assume that a *percentage factor* $\alpha_{k,u} \in [0, 1]$ of the total transmission power P is allocated to the kth user at the uth subcarrier. Thus, after the de-spread and maximum ratio combining (MRC), the post-processing signal-to-noise ratio (SNR) $\gamma_{k,u}$ at the kth user's uth subcarrier can be expressed as

$$\gamma_{k,u} = \frac{GP\,\alpha_{k,u}\,\Omega_{k,u}}{I_{k,u} + \sigma_\eta^2} \tag{2}$$

where $\Omega_{k,u} = \max_{i\in\{1,2,\cdots,N_t\}} \sum_{j=1}^{N_r^{(k)}} \left| h_{k,u}^{i,j} \right|^2$ represents the equivalent channel gain for the kth user at the uth subcarrier when employing TAS.

B. Adaptive Modulation (AM)

Adaptive modulation (AM) is an efficient LA technique to improve the spectral efficiency. Without loss of generality, we employ the adaptive squared QAM modulation. The bit-error rate (BER) for an AWGN channel with QAM modulation is upper-bounded by [7]

$$\text{BER} \leq 0.2 \exp\left(-\frac{1.5\gamma}{2^b - 1}\right) \tag{3}$$

where $0 \leq \gamma \leq 30$ dB is the SNR of the AWGN channel and $b \geq 2$ is the number of bits per symbol. In our MC DS-CDMA system, we assume that different users have different target BER requirements denoted by Γ_k $(k = 1, 2, ..., K)$. Therefore, for the kth user at the uth subcarrier, the maximum number $b_{k,u}$ of bits transmitted in a symbol can be expressed as

$$b_{k,u} = \log_2\Big(1 + \widetilde{\gamma}_{k,u}\Big) \tag{4}$$

where $\gamma_{k,u}$ is given by Eq. (2); $\widetilde{\gamma}_{k,u} \stackrel{\triangle}{=} -1.5\gamma_{k,u} / \log(5\Gamma_k)$ represents the *effective SNR* of the kth user's at the uth subcarrier when employing TAS, using the adaptive QAM modulation, and taking the AWGN σ_η^2, inter-cell interference $I_{k,u}$, and target BER-QoS Γ_k into consideration. As a result, the system throughput R of all users at all subcarriers is determined by

$$R = \frac{1}{T_s}\sum_{k=1}^{K}\sum_{u=1}^{U} b_{k,u} = \frac{W}{GU}\sum_{k=1}^{K}\sum_{u=1}^{U}\log_2\Big(1 + \widetilde{\gamma}_{k,u}\Big). \tag{5}$$

In this paper, we assume that the constellation size is continuous, i.e., the throughput of each subcarrier is based on a *fluid model*.

IV. Dynamic Channel Allocation (DCA)

A. DCA Design Criteria

Based on the proposed system infrastructure, we develop the corresponding DCA algorithm. In designing DCA algorithm, we focus on the quality-of-service (QoS) of maximizing the total system throughput R while guaranteeing different users' target BER requirements. While the fairness is also an important issue for multiuser data networks, it is out of the scope of this paper, and will be discussed in another paper.

The maximization problem is subject to the following two constraints. First, the transmission power of the basestation, which is the sum of the power assigned to all subcarriers for all users, must be upper-bounded by P. This implies that the summation of all percentage-factors $\{\alpha_{k,u}\}$ of the transmission power is upper-bounded by 1, and thus this power constraint can be expressed by

$$\text{CONSTRAINT I:} \quad \sum_{k=1}^{K}\sum_{u=1}^{U}\alpha_{k,u} = 1, \text{ where } 0 \leq \alpha_{k,u} \leq 1. \tag{6}$$

Second, in MC DS-CDMA systems, multiple users can be assigned to a subcarrier at the same time. However, the maximum number of users within a subcarrier is upper-bounded by the spreading gain G of the system to guarantee the orthogonal downlink transmissions. Denote the number of users within the uth subcarrier by K_u. This constraint can be expressed as

$$\text{CONSTRAINT II:} \quad K_u \leq G, \text{ where } u = 1, 2, ..., U. \tag{7}$$

To solve the problem of maximizing R under the above two constraints, we first only consider CONSTRAINT I while ignoring CONSTRAINT II. Then, we find the solutions under both CONSTRAINTS I and II.

B. Step 1: Maximizing R under CONSTRAINT I

Substituting Eq. (2) into Eq. (5), the system throughput R can be derived as follows:

$$R = \frac{W}{GU}\sum_{k=1}^{K}\sum_{u=1}^{U}\log_2\Big(1 + G\delta_{k,u}\alpha_{k,u}\Big) \tag{8}$$

where we define $\delta_{k,u} \stackrel{\triangle}{=} -[1.5\, P\, \Omega_{k,u}]/[\log(5\Gamma_k)(I_{k,u} + \sigma_\eta^2)]$ as the *effective channel quality* of the kth user's at the uth subcarrier. Considering CONSTRAINT I, the problem of maximizing R can be solved by using the Langrange multiplier as follows:

$$\psi = \frac{W}{GU}\sum_{k=1}^{K}\sum_{u=1}^{U}\log_2\Big(1 + G\delta_{k,u}\alpha_{k,u}\Big) + \lambda\left(\sum_{k=1}^{K}\sum_{u=1}^{U}\alpha_{k,u} - 1\right) \tag{9}$$

where λ is the Lagrange multiplier. The *optimal* fraction of power assigned to the kth user's uth subcarrier, denoted by the optimal percentage-factor $\alpha_{k,u}^*$, can be obtained by solving $\partial\psi/\partial\alpha_{k,u} = 0$. The solution of this problem turns out to be the well-known *water-filling formula*, which is given by

$$\alpha_{k,u}^* = \begin{cases} \dfrac{1}{G}\left(\dfrac{1}{\delta_0} - \dfrac{1}{\delta_{k,u}}\right), & \delta_{k,u} \geq \delta_0 \\ 0, & \delta_{k,u} < \delta_0 \end{cases} \tag{10}$$

where δ_0 is the cut-off threshold determined by CONSTRAINT I. The water-filling formula shows that the better the effective channel quality $\delta_{k,u}$, the larger the percentage-factor $\alpha_{k,u}^*$ of the transmission power. When the effective channel quality $\delta_{k,u}$ is smaller than the cut-off threshold δ_0, the kth user cannot use the uth subcarrier for transmission. Plugging Eq. (10) into Eq. (8), the maximum system throughput, denoted by R^*, can be derived as

$$R^* = \frac{W}{GU}\sum_{k=1}^{K}\sum_{u=1}^{U}\left[\log_2\left(\frac{\delta_{k,u}}{\delta_0}\right)\right]^+ \tag{11}$$

where $[x]^+ \stackrel{\triangle}{=} \max\{x, 0\}$. To completely solve the problem, we need to find the cut-off threshold δ_0 in Eq. (10). Sort the effective channel qualities $\{\delta_{k,u}\,|\,k = 1, ..., K; u = 1, ..., U\}$ of all subcarriers for all users into a descending order, i.e., from the best channel quality to the worst channel quality, as

$$\delta^{(1)} \geq \delta^{(2)} \geq \cdots \geq \delta^{(KU-1)} \geq \delta^{(KU)} \tag{12}$$

such that $\{\delta^{(i)}\}_{i=1}^{KU}$ forms the permutation of the original $\{\delta_{k,u}\,|\,k = 1, ..., K; u = 1, ..., U\}$ in a descending order. Correspondingly, we denote the assigned percentage-factors of transmission power by $\alpha^{(1)}, \alpha^{(2)}, ..., \alpha^{(KU)}$, corresponding to $\delta^{(1)}, \delta^{(2)}, ..., \delta^{(KU)}$, respectively.

Assume that among $\delta^{(1)}, \delta^{(2)}, ..., \delta^{(KU)}$, the first M terms is no less than the cut-off threshold δ_0, i.e., $\delta^{(M)} \geq \delta_0 > \delta^{(M+1)}$. Thus, in terms of Eq. (10), the assigned fraction of transmission power $\alpha^{(M+1)}, \alpha^{(M+2)}, ..., \alpha^{(KU)}$ are all zeroes. Then, the first part of Eq. (10) and CONSTRAINT I can be formulated in a matrix form as follows:

$$\begin{pmatrix} 1 & 0 & \cdots & 0 & -1 \\ 0 & 1 & & & -1 \\ \vdots & & \ddots & & \vdots \\ 0 & & & 1 & -1 \\ 1 & 1 & \cdots & 1 & 0 \end{pmatrix} \begin{pmatrix} \alpha^{(1)} \\ \alpha^{(2)} \\ \vdots \\ \alpha^{(M)} \\ \frac{1}{G\delta_0} \end{pmatrix} = -\frac{1}{G} \begin{pmatrix} 1/\delta^{(1)} \\ 1/\delta^{(2)} \\ \vdots \\ 1/\delta^{(M)} \\ -G \end{pmatrix} \tag{13}$$

For a given integer M ($1 \leq M \leq KU$), the solutions of Eq. (13), denoted by $\alpha_M^{(i)}$ ($i = 1, 2, ..., M$) and $\delta_{0,M}$, respectively, can thus be determined by the following equations:

$$\begin{cases} \alpha_M^{(i)} = \dfrac{1}{G}\left(\dfrac{1}{\delta_{0,M}} - \dfrac{1}{\delta^{(i)}}\right), \\ \dfrac{1}{\delta_{0,M}} \quad = \dfrac{1}{M}\left(G + \displaystyle\sum_{j=1}^{M} \dfrac{1}{\delta^{(j)}}\right) \end{cases} \tag{14}$$

Clearly, due to inequality (12), the following inequality always holds $\alpha_M^{(1)} \geq \alpha_M^{(2)} \geq \cdots \geq \alpha_M^{(M)}$. To guarantee all $\alpha_M^{(i)} \geq 0$ ($i = 1, 2, ..., M$), it is sufficient to ensure the smallest term $\alpha_M^{(M)} \geq 0$. Therefore, the optimal M, denoted by M^*, is the largest M such that the inequality $\alpha_M^{(M)} \geq 0$ holds. The optimal value M^* can be expressed as

$$M^* = \max_{\alpha_M^{(M)} \geq 0} \left\{ M \mid 1 \leq M \leq KU \right\} \tag{15}$$

Thus, the corresponding cut-off threshold δ_0 is given by

$$\delta_0 = \delta_{0,M^*}. \tag{16}$$

C. Step 2: Maximizing R under CONSTRAINTS I and II

In the second step, we consider the maximization problem subject to both CONSTRAINTS I and II.

When the total number of users satisfies $K \leq G$, the CONSTRAINT II always holds since we always have $K_u \leq K$ ($u = 1, 2, ..., U$). When $K > G$, at each subcarrier, we sort $\{\delta_{k,u}\}_{k=1}^{K}$ in a descending order, which can be written as

$$\delta_u^{(1)} \geq \delta_u^{(2)} \geq \cdots \geq \delta_u^{(K-1)} \geq \delta_u^{(K)}, \ u = 1, 2, ..., U \tag{17}$$

such that $\{\delta_u^{(i)}\}_{i=1}^{K}$ forms the permutation of $\{\delta_{k,u}\}_{k=1}^{K}$ in a descending order. Since the number of users K_u within the uth subcarrier cannot be larger than G, we only select the first G terms of $\{\delta_u^{(i)}\}_{i=1}^{K}$ as

$$\delta_u^{(1)} \geq \delta_u^{(2)} \geq \cdots \geq \delta_u^{(G-1)} \geq \delta_u^{(G)}, u = 1, 2, ..., U. \tag{18}$$

As a result, the other $(K - G)$ users cannot be assigned to the uth subcarrier. Then, $\{\delta_u^{(i)}\}_{i=1}^{G}$ of all U subcarriers are gathered together and sorted in a descending order as

$$\widetilde{\delta}^{(1)} \geq \widetilde{\delta}^{(2)} \geq \cdots \geq \widetilde{\delta}^{(GU-1)} \geq \widetilde{\delta}^{(GU)} \tag{19}$$

such that $\{\widetilde{\delta}^{(i)}\}_{i=1}^{GU}$ forms the permutation of $\{\delta_u^{(i)} \mid i = 1, 2, ..., G; u = 1, 2, ..., U\}$ in a descending order. Noting that Eq. (19) has the same structure as Eq. (12) except that the number of terms is reduced from KU to GU, we construct a new maximizing problem which is not subject to CONSTRAINT II and can be solved by the same way as the problem only considering CONSTRAINT I. The following proposition ensures that the above allocation algorithm is optimal in terms of maximizing throughput.

Proposition 1: Given any spreading gain G and under the CONSTRAINTS I and II, the total system throughput R is optimal when using the above allocation algorithm.

Proof: The proof is available on-line in [14]. ■

Thus, considering both CONSTRAINTS I and II, we obtain the solutions of the problem for maximizing R.

V. System Throughput Optimization

In Section IV, we develop the algorithm to maximize the system throughput R given a certain spreading gain G. In this section, we further investigate the impact of G on system throughput R.

When the spreading gain G increases, in terms of CONSTRAINT II, the upper-bound of K_u also increases, i.e., we can assign more users within each subcarrier to enhance the total system throughput. However, the throughput of each user decreases as G increases, which can be easily observed from the fact that the throughput $R_{k,u}$ of the kth user at the uth subcarrier given by

$$R_{k,u} = \frac{W}{GU} \log_2 \left(1 + G\delta_{k,u}\alpha_{k,u}\right) \tag{20}$$

is a monotonically decreasing function with respect to the variable G. On the other hand, when the spreading gain G decreases, the throughput of each user increases but the fewer users can share the same subcarrier. Therefore, there is an optimal spreading gain denoted by G^* that can maximize the system throughput. The value of G^* is determined by the following theorem.

Theorem 1: Under CONSTRAINTS I and II, the optimal G^* that maximizes the total system throughput is $G^* = 1$.

Proof: Denote the fraction of power corresponding to $\delta_u^{(1)}, \delta_u^{(2)}, ..., \delta_u^{(K)}$ given in Eq. (18) by $\alpha_u^{(1)}, \alpha_u^{(2)}, ..., \alpha_u^{(K)}$, respectively. Then, the system throughput of the uth subcarrier denoted by R_u can be expressed as

$$R_u = \frac{W}{GU} \sum_{k=1}^{K} \log_2 \left(1 + G\delta_u^{(k)}\alpha_u^{(k)}\right) \tag{21}$$

According to the analyses described in Section IV-C, the number of users assigned to the uth subcarrier is upper-bounded by the smaller one between K and G, which is denoted by $Q = \min\{K, G\}$. Then, Eq. (21) can be rewritten as

$$R_u = \frac{W}{GU} \sum_{k=1}^{Q} \log_2 \left(1 + G\delta_u^{(k)}\alpha_u^{(k)}\right) \tag{22}$$

Since the maximum value of R_u is independent of constants W and U, we define a new variable R'_u given by $R'_u = \frac{1}{G}\sum_{k=1}^{Q} \log_2 \left(1 + G\delta_u^{(k)}\alpha_u^{(k)}\right)$, which has the same maximizer G^* as that for R_u. Then, the following equations hold:

$$
\begin{aligned}
R'_u &= \log_2\left(\prod_{k=1}^{Q}\left(1+G\delta_u^{(k)}\alpha_u^{(k)}\right)^{1/G}\right)\\
&= \log_2\left(\left\{\prod_{k=1}^{Q}\left(1+G\delta_u^{(k)}\alpha_u^{(k)}\right)\underbrace{\times 1\times\cdots\times 1}_{(G-Q)\ \text{terms}}\right\}^{1/G}\right)\\
&\overset{(a)}{\leq} \log_2\left(\frac{1}{G}\left\{\sum_{k=1}^{Q}\left(1+G\delta_u^{(k)}\alpha_u^{(k)}\right)\underbrace{+1+\cdots+1}_{(G-Q)\ \text{terms}}\right\}\right)\\
&= \log_2\left(1+\sum_{k=1}^{Q}\delta_u^{(k)}\alpha_u^{(k)}\right)\\
&\overset{(b)}{\leq} \log_2\left(1+\sum_{k=1}^{Q}\delta_u^{(1)}\alpha_u^{(k)}\right)\\
&= \log_2\left(1+\delta_u^{(1)}\beta_u\right) \qquad (23)
\end{aligned}
$$

where $\beta_u \triangleq \sum_{k=1}^{Q}\alpha_u^{(k)} = \sum_{k=1}^{K}\alpha_u^{(k)}$ is the percentage of power assigned to the uth subcarrier. The first inequality in Eq. (23), denoted by (a), is due to the fact that the geometric average is smaller than or equal to the arithmetical average. The second inequality in Eq. (23), denoted by (b), is due to Eq. (18). The equalities hold in Eq. (23) if one or both of the following two conditions is satisfied:

(i) $G = Q$, i.e., $K \geq G$ and $\delta_u^{(1)} = \delta_u^{(2)} = \cdots = \delta_u^{(G)} \geq \delta_u^{(G+1)} \geq \cdots \geq \delta_u^{(K)}$, i.e., each assigned user has the same *effective channel quality*.

(ii) $\alpha_u^{(1)} = \alpha_u^{(2)} = \cdots = \alpha_u^{(K)} = 0$, i.e., no user is assigned with the uth subcarrier, and thus, $R_u = 0$.

The last part of Eq. (23) corresponds to the maximum throughput of the uth subcarrier, which is achieved when $G = 1$. Thus, the proof follows. ■

According to Theorem 1, the optimal throughput can be achieved when CDMA is not employed in the system, i.e., the optimal system is based on a FDMA-liked scheme with dynamic subcarrier allocation. At each subcarrier, we only select the user which has the best *effective channel quality* as the candidate for sending data. The new transmission scheme (with $G = 1$) is an integrated one based on the well-known multiuser diversity [15] and transmit antenna selection.

VI. Simulation Experiments

We evaluate the performance of our proposed DCA algorithm by simulations. In all simulations, we assume that $\{h_{k,u}^{i,j}\}$ are independent identically distributed (i.i.d.) complex-Gaussian random variables with zero-mean and variance of 0.5 per dimension, respectively. Although our scheme can be applied to heterogeneous mobile users' situation, we simulate homogeneous users for simplicity, i.e., all users have the same number of receive antennas and the same target BER 10^{-3}. For comparison, we also simulate the performance of fixed channel allocation (FCA) using adaptive modulations and equal power assignments. When the number of transmit antennas $N_t > 1$, space-time block codes (STBC) [9] are integrated with FCA in order to compare with our proposed TAS-based scheme. Since it is still unknown whether the full-rate complex STBC exists

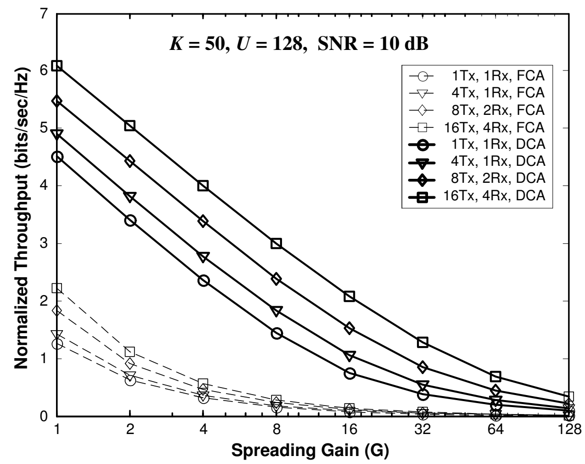

Fig. 1. Normalized throughput versus spreading gain G. The number of users $K = 50$, the number of subcarriers $U = 128$, and the SNR = 10 dB.

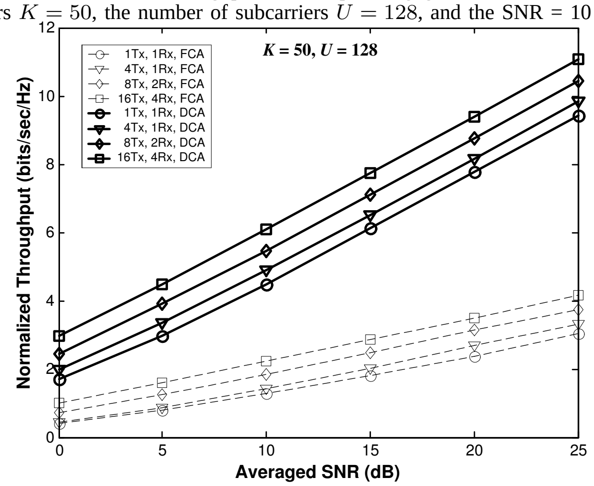

Fig. 2. Normalized throughput versus averaged SNR. The number of users $K = 50$, and the number of subcarriers $U = 128$.

or not when $N_t > 2$, we use full-rate STBC in all simulations, representing the best performance, and we ignore the overhead of cyclic prefix (CP) for simplicity.

Fig. 1 plots the normalized throughputs (the system throughput normalized by the total bandwidth W) versus the spreading gain G employing DCA and FCA with the different numbers of transmit/receive antenna combinations, respectively, where the number K of users is set to $K = 50$, the number of subcarriers $U = 128$, and averaged SNR = 10 dB, respectively. We observe from Fig. 1 that all throughputs are the monotonically decreasing functions with G, which verifies our analytical analyses derived in Section V. Also, Fig. 1 shows that the more the number of transmit/receive antennas, the better the performance of DCA, which is the contribution of our TAS-based scheme. In addition, Fig. 1 shows that our proposed DCA outperforms FCA significantly. Since the smallest G can achieve the maximum throughput, we set $G = 1$ in the rest of simulations.

Fig. 2 depicts the normalized throughput versus the averaged SNR using DCA and FCA with the different numbers of transmit/receive antenna combinations, respectively, where the number of users is set to $K = 50$, and the number of subcarriers $U = 128$. Fig. 2 shows that the higher the averaged SNR, the larger the normalized throughputs. Similar to the conclusion drawn above, increasing the number of

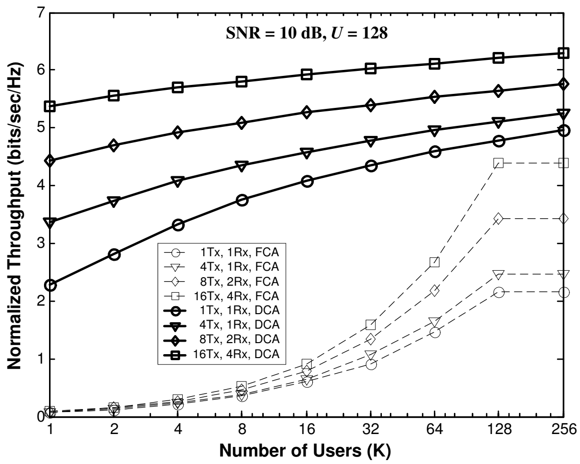

Fig. 3. Normalized throughput versus the number of users K. The number of subcarriers $U = 128$, and the averaged SNR = 10 dB.

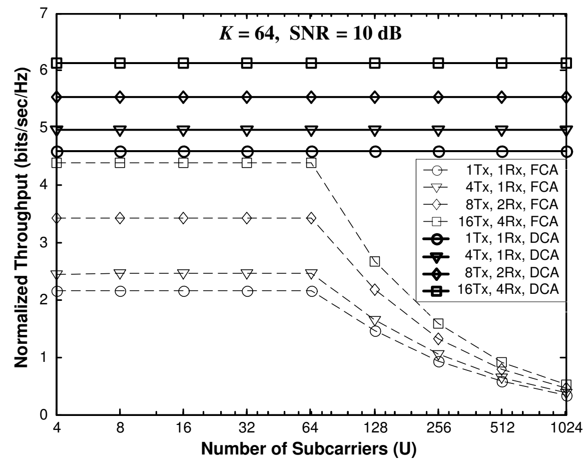

Fig. 4. Normalized throughput versus the number of subcarriers U. The number of users $K = 64$, and the averaged SNR = 10 dB.

transmit/receive antennas improves the performance of DCA significantly. Also, DCA shows a great advantage over FCA. The superiority of DCA over FCA increases as the averaged SNR increases, which is due to the fact that the increasing slopes of throughputs' plots for DCA are higher than those for FCA as shown in Fig. 2.

Fig. 3 presents the normalized throughputs versus the number of users K, where the number of subcarriers is set to $U = 128$, and the averaged SNR = 10 dB. Fig. 3 shows that the throughputs of DCA increases as the number of mobile users increases, which is due to multiuser diversity. In contrast, the throughputs of FCA stop increasing when the number K of users reaches its limit $K = U = 128$, since at most $K = U = 128$ users, regardless of their channel qualities, can be allocated into the FCA system. Once again, the throughput of DCA can be increased by increasing the number of transmit/receive antennas, thus achieving the advantages of both multiuser diversity and transmit antenna selection.

Finally, Fig. 4 plots the normalized throughput versus the number of subcarriers U, where the number of users is set to $K = 64$ and the averaged SNR = 10 dB. Fig. 4 shows that the normalized throughput of DCA never drops regardless of number of subcarriers U. By contrast, the throughput of FCA is a constant when the number of subcarriers $U \leq K$, since only K users are allocated to the system; when $U > K$, the throughput of FCA starts dropping and decreases with U, increasing the throughput superiority of DCA over FCA. Also, based on Fig. 4, we have the same conclusion that increasing the numbers of transmit/receive antennas can significantly increase the throughput, and DCA has much better performance than FCA in terms of throughputs.

VII. CONCLUSIONS

We proposed and analyzed the LA-based system infrastructure and developed the DCA algorithm for MIMO-OFDM systems in multiuser downlink data transmissions. Given the CDMA-based MIMO-OFDM system, we developed DCA algorithm which can maximize the system throughput. Interestingly, we proved that the system without CDMA techniques is optimal in terms of throughput. Thus, our proposed scheme integrates the advantages of multiuser diversity and transmit antenna selection, i.e., at each subcarrier, we only transmit data for the user with the best effective channel quality. We conducted extensive simulations to evaluate the proposed algorithm and to verify our analytical analyses. The obtained simulation results show that the system throughput increases significantly with the numbers of transmit antennas, receive antennas, and mobile users. In addition, our DCA algorithm can significantly improve the system throughput performance as compared with the conventional FCA algorithms.

REFERENCES

[1] T. Rappaport, A. Annamalai, R. Buehrer, and W. Tranter, "Wireless Communications: Past Events and a Future Perspective," *IEEE Comm. Magazine*. May, 2002, pp. 148-161.

[2] S. Catreux, V. Erceg, D. Gesbert, and R. Heath, "Adaptive modulation and MIMO coding for broadband wireless data networks," *IEEE Comm. Magazine*, June, 2002, pp. 108-115.

[3] D. Gesbert, M. Shafi, D. Shiu, P. Smith, and A. Naguib, "From Theory to Practice: An Overview of MIMO Space-Time Coded Wireless Systems," *IEEE J. Select Areas Comm*., vol. 21, no. 3, April 2003, pp. 281-302.

[4] L-L Yang and L. Hanzo, "Performance of Generalized Multicarrier DS-CDMA Over Nakagami-m Fading Channels," *IEEE Trans. Commun*., vol. 50, No. 6, Jun. 2002, pp. 956-966.

[5] C. Wong, R. Cheng, K. B. Letaief, and R. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation," *IEEE J. Select Areas Comm*., vol. 17, no. 10, Oct. 1999, pp. 1747-1758.

[6] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE J. Select Areas Comm*., vol. 21, Feb. 2003, pp. 171-178.

[7] A. J. Goldsmith and S. Chua, "Vairable-rate variable-power MQAM for fading channels," *IEEE Trans. Commmun*., vol. 45, no. 10, Oct. 1997, pp. 1218-1230.

[8] J. Blogh, P. Cherriman, and L. Hanzo, "Comparative study of adaptive beam-steering and adaptive modulation-assisted dynamic channel allocation algorithms," *IEEE Trans. Vehicular Technology*, vol. 50, issue 2, Mar. 2001, pp. 398 - 415.

[9] V. Tarokh, H. Jafarkhani, and A. Calderbank, "Space-Time Block Codes from Orthogonal Designs," *IEEE Trans. Inform. Theory*, Vol. 45, No. 5, Jul. 1999, pp. 1456-1467.

[10] G. Giannakis, Y. Hua, P. Stoica, and L. Tong, *Signal processing advances in communications*, Prentise Hall, New Jersey, 2001.

[11] T. Skinner and J. Cavers, "Selective Diversity for Rayleigh Fading Channels with a Feedback Link," *IEEE Trans. Commun.*, vol. 21, no. 2, Feb. 1973, pp. 117-126.

[12] S. Thoen, L. V. Perre, B. Gyselinckx, and M. Engels, "Performance analysis of combined transmit-SC/receive-MRC," *IEEE Trans. Commun.*., vol. 49, no. 1, Jan. 2001, pp. 5-8.

[13] Z. Chen, B. Vucetic, and J. Yuan, "Comparison of three closed-loop transmit diversity schemes," *IEEE VTC* 2003, Vol. 1, pp. 22-25.

[14] J. Tang and X. Zhang, "Link-Adaptation-Enhanced Dynamic Channel Allocation for MIMO-OFDM Wireless Networks," Networking and Information Systems Labs., Dept. Electr. Eng., Texas A&M University, College Station, Technical Report [Online.] Available: http://ece.tamu.edu/∼xizhang/papers/DCA.pdf, December 2004.

[15] R. Knopp and P. A. Humblet,"Information capacity and power control in single-cell multiuser communications," in *Proc. IEEE ICC 1995*, Seattle, WA, June 1995, pp. 331-335.