

Adaptive Subcarrier and Power Allocation in OFDM Based on Maximizing Utility *

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Abstract—This paper investigates adaptive resource allocation on the downlink of multiuser OFDM networks to achieve both multiuser diversity and fairness. Utility functions are applied to quantify the level of users' satisfaction derived from the radio resources they occupy. We formulate cross-layer optimization problem as one that maximizes the sum of the utilities over all active users subject to the feasible rate region, which is determined by adaptive resource allocation schemes deployed and the current channel conditions. We present the conditions for optimal subcarrier assignment and power allocation based on utility, and investigate the optimality properties as well. It is also shown that the inherent mechanism of balancing spectral efficiency and fairness is associated with concave utility functions.

I. INTRODUCTION

For wireless Internet services, radio resource allocation has to guarantee both efficiency and fairness. It is worth noting that the problem of how to efficiently and fairly allocate resources and make decisions has been well studied in economics. In economic and decision theories, utility functions are widely used to quantify the benefit values of usage of resources. Recently, wireless resource allocation based on utility and pricing has been received much attention. In wireless networks, pricing of uplink power control in CDMA wireless networks has been presented in [1], [2]. Utility-based power allocation on CDMA downlink for voice and data applications has been proposed in [3]–[5]. However, all of them are concerned only with flat fading environments, which are not capable of supporting high-data-rate services. In this paper, we focus on utility-based resource allocation with *orthogonal frequency division multiplexing* (OFDM) signaling on multiuser frequency-selective fading channels.

OFDM divides an entire channel into many orthogonal narrowband subchannels (subcarriers), and therefore, it supports high peak data rate by reducing the effect of *intersymbol interference* (ISI). Furthermore, in an OFDM system, different subcarriers can be allocated to different users respectively so as to provide a flexible multiuser access scheme [6].

Efficiency improvement needs to exploit adaptive resource allocation techniques. There is plenty of room to exploit the high degree of flexibility of radio resource management in OFDM, in which data rate adaptation over each subcarrier, *dynamic subcarrier assignment* (DSA), and *adaptive power allocation* (APA) can be employed [7], [8]. There are two

important properties in multiuser frequency-selective fading channels. First, different subcarriers of each user suffer from different fading levels, since the channel frequency response is frequency-selective. Second, the channels of different users vary almost independently in a multiuser environment. When the downlink channel state information for each user is fed back to the basestation, dynamic subcarrier assignment, combined with rate adaptation, allocates frequency resources in a dynamic and efficient way by making use of those two characteristics of multiuser frequency-selective fading channels. From a point of view of diversity, the efficiency improvement results from multiuser diversity and frequency diversity. Besides, adaptive power allocation in the frequency domain can also enhance system performance by means of frequency diversity.

With the help of utility functions, cross-layer optimization, including subcarrier rate adaption, dynamic subcarrier assignment and adaptive power allocation, is proposed for OFDM downlink in this paper. It is based on maximizing the sum of the utilities over all active users in wireless environments. This paper mainly focuses on the theoretical results. We present the properties of optimal subcarrier and power allocation associated with utility-based optimization. We use convex analysis to show that concave utility functions make it tractable to search the global optimal point. Furthermore, we point out that utility-based resource allocation has a natural mechanism to guarantee both efficiency and fairness. Therefore, this work provides a framework for efficient and fair resource allocation in multiuser frequency-selective fading environments.

This paper is organized as follows. In Section II, we describe the system model. In Section III, we formulate cross-layer optimization problems and present the optimality conditions of DSA and APA. In Section IV, we prove the convexity of the achievable rate region with continuous frequency assignment and the global optimality. In Section V, we discuss the efficiency and fairness issues. Finally, we conclude the paper in Section VI.

II. SYSTEM MODEL

In this section, we present the channel model, concepts related to utility function, and the model of adaptive modulation and frequency power allocation, which will help formulate utility-based cross-layer optimization problems.

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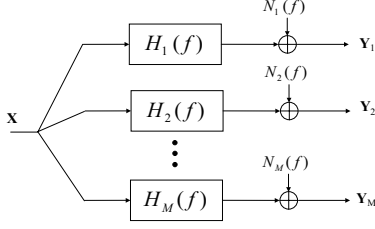


Fig. 1. Multiuser frequency-selective fading channel

A. Multiuser Frequency-Selective Fading Channels

We consider an M -user broadcast channel with frequency-selective fading, in which there are one transmitter (base station) and M receivers (users). For user i , the frequency response of his time-varying frequency-selective wireless channel impulse response is denoted as $H_i(f, t)$. It is assumed that the channel fading rate is slow enough that the channel frequency response has no change during an OFDM block. When we only consider instantaneous channel conditions, the channel frequency response corresponding to user i is denoted by $H_i(f)$.

This M -user frequency-selective broadcast fading channel is shown in Fig. 1. Since different users are located in different positions, their channel frequency responses, $H_i(f)$'s, are independent of each other. There are additive independent one-sided noise power spectral densities, $N_i(f)$'s, as well. The signal \mathbf{X} at the base station has M independent information sources, which are respectively received by M users. Obviously, the quality of each user's channel condition can be indicated by

$$\text{SNR}_i^c(f) = |H_i(f)|^2 / N_i(f),$$

which is called *channel signal-to-noise-ratio (SNR) function* for user i . In this paper, $\text{SNR}_i^c(f)$'s are supposed to be known at the base station.

B. Rate Adaptation and Power Allocation

Using adaptive modulation [9], the transmitter can send higher data rates over the subcarriers with better condition, so as to improve the throughput and simultaneously ensure an acceptable *bit-error-rate (BER)* on each subcarrier.

Let $c_i(f)$ be the achievable throughput per Hz of user i at frequency f under a given BER level and a transmission power density $p(f)$. When continuous rate adaptation is used, $c_i(f)$ can be expressed as [10]

$$\begin{aligned} c_i(f) &= \log_2\left(1 + \frac{\beta p(f) |H_i(f)|^2}{N_i(f)}\right) \quad (\text{bits/sec/Hz}) \\ &= \log_2(1 + \beta p(f) \text{SNR}_i^c(f)) \end{aligned} \quad (1)$$

where β is a constant related to BER by

$$\beta = -1.5 / \ln(5 \cdot \text{BER}).$$

β is usually called SNR gap, which indicates the gap of SNR that is needed to reach a certain capacity between practical implementations and information-theoretical results.

Besides transmission rate adaptation, power allocation at the frequency domain can make further capacity improvement.

C. Utility Functions

Utility function maps the network resources a user utilizes into a real number. In almost all wireless applications, reliable data transmission rate is the most important factor to determine the satisfaction of users. Therefore, the utility function $U(r)$ should be a nondecreasing function of r . In particular, when $U(r) = r$, the utility is just throughput. Furthermore, most traditional system optimization objectives can also be regarded as some special cases of utility functions. Thus, this work can be regarded as a general network optimization theory.

III. ADAPTIVE RESOURCE ALLOCATION IN OFDM

In the paper, we assume that the number of orthogonal subcarriers in all frequency resources is infinite, or the bandwidth of each orthogonal subcarrier $\Delta f \rightarrow 0$, which can be regarded as an extreme situation of OFDM.

Consider a single cell consisting of M users, and let \mathcal{M} denote the set of users, that is, $\mathcal{M} = \{1, 2, \dots, M\}$. Frequency band, $[0, B]$, is divided into several non-overlapping frequency sets that are assigned to different users, where B is the total bandwidth of the system. Define D_i as the frequency set assigned to user i .

Let \mathbf{p} denote a deterministic power allocation $\{p(f), f \in [0, B]\}$. For explicit expression, the achievable data rate function of user i with respect to a given power allocation \mathbf{p} is written as $c_i^{\mathbf{p}}(f)$. Then the transmission throughput of user i can be calculated by

$$r_i = \int_{D_i} c_i^{\mathbf{p}}(f) df. \quad (2)$$

In addition to dynamic subcarrier assignment, transmission power density at different frequencies can also be adjusted to improve network performance, but the total transmission power is constrained by \bar{P} , the total transmission power constraint. Unlike uplink where the limited energy of mobile terminals is a major problem, the objective of resource allocation on downlink is to maximize the total utility of a cell under the overall power constraint.

In this paper, we investigate three kinds of resource allocation schemes: APA, DSA, as well as joint DSA and APA. Here we assume each utility function to be continuously differentiable.

A. Utility-based Dynamic Subcarrier Allocation

DSA optimization problem is described as follows. Given a fixed power allocation, \mathbf{p} ,

$$\text{maximize} \quad \sum_{i \in \mathcal{M}} U_i(r_i) \quad (3)$$

$$\text{subject to} \quad \bigcup_{i \in \mathcal{M}} D_i \subseteq [0, B], \quad (4)$$

$$D_i \cap D_j = \emptyset, \quad i \neq j \quad \forall i, j \in \mathcal{M}, \quad (5)$$

Given a fixed power allocation \mathbf{p} , the optimal subcarrier allocation, D_i^* 's have an important property, which is stated in the following theorem.

Theorem 1: Assume that

$$\mu(\{f \in [0, B] : \frac{c_i^{\mathbf{p}}(f)}{c_j^{\mathbf{p}}(f)} = v\}) = 0 \quad \forall v \in \mathbb{R}_+ \text{ and } i \neq j, \quad (6)$$

where $\mu(\cdot)$ is Lebesgue measure. Given a fixed power allocation \mathbf{p} , if the set of r_i^* , $i \in \mathcal{M}$ is optimal, then the optimal frequency set for user i , D_i^* , satisfies

$$D_i^* = \bigcap_{j \in \mathcal{M} - \{i\}} \{f \in [0, B] : U_j'(r_j^*)c_j^{\mathbf{p}}(f) \leq U_i'(r_i^*)c_i^{\mathbf{p}}(f)\}. \quad (7)$$

where $r_i^* = \int_{D_i^*} c_i^{\mathbf{p}}(f) df$.

The proof is presented in [11]. Note that if channel fading processes have continuous density functions, continuous rate adaptation lets $c_i^{\mathbf{p}}(f)$'s have continuous probability density functions as well. Due to the independence of users' channel conditions and frequency-selective fading, continuous rate adaptation makes (6) valid with probability 1.

B. Utility-based Adaptive Power Allocation

Given a fixed subcarrier allocation, D_i for all i , APA optimization problem is expressed as

$$\text{maximize} \quad \sum_{i \in \mathcal{M}} U_i \left(\int_{D_i} \log_2[1 + \beta p(f) \text{SNR}_i^c(f)] df \right) \quad (8)$$

$$\text{subject to} \quad \int_0^B p(f) df \leq \bar{P} \quad (9)$$

$$p(f) \geq 0. \quad (10)$$

To achieve its optimality, utility-based multi-level water-filling is needed, which is described in theorem 2.

Theorem 2: For a given fixed subcarrier allocation, D_i for all i , the optimal power allocation, $p^*(f)$, satisfies

$$\begin{cases} p^*(f) = \left[\frac{U_i'(r_i^*)}{\lambda} - \frac{1}{\beta \text{SNR}_i^c(f)} \right]^+ & f \in D_i \\ \int_0^B p^*(f) df = \bar{P}. \\ r_i^* = \int_{D_i} \log_2[1 + \beta p^*(f) \text{SNR}_i^c(f)] df, \end{cases} \quad (11)$$

$$\text{where } [x]^+ = \begin{cases} x & x \geq 0 \\ 0 & x < 0 \end{cases}.$$

Proof: To use variation of functions in the case of a given fixed subcarrier allocation D_i for all i , we divide the entire $p(f)$ into a group of $p_i(f)$ for $i \in \mathcal{M}$, which is the one-sided power density function for user i . Manifestly,

$$p_i(f) = \begin{cases} p(f) & f \in D_i \\ 0 & \text{otherwise} \end{cases}. \quad (12)$$

Using Lagrangian method, the above optimization problem with the power constraint becomes the following one.

$$\begin{aligned} \text{maximize} \quad & \sum_{i \in \mathcal{M}} \{U_i \left(\int_{D_i} \log_2[1 + \beta p_i(f) \text{SNR}_i^c(f)] df \right) \\ & - \lambda \left[\int_{D_i} p_i(f) df - \frac{\bar{P}}{M} \right]\} \end{aligned} \quad (13)$$

With the Karush-Kuhn-Tucke (KKT) conditions [12], we have

$$\begin{aligned} & U_i'(r_i^*) \frac{\partial}{\partial p_i(f)} \log_2 \{1 + \beta p_i(f) \text{SNR}_i^c(f)\} \\ & - \lambda \frac{\partial}{\partial p_i(f)} p_i(f) \Big|_{p_i(f)=p_i^*(f)} = 0, \text{ for all } i, \quad (14) \\ & \lambda \geq 0, \\ & \lambda \left[\sum_{i \in \mathcal{M}} \int_{D_i} p_i(f) df - \bar{P} \right] = 0. \end{aligned}$$

(14) is equivalent to

$$U_i'(r_i^*) \frac{\beta \text{SNR}_i^c(f)}{1 + \beta \text{SNR}_i^c(f) p_i^*(f)} - \lambda = 0, \text{ for all } i.$$

Then, the optimal power allocation for a fixed subcarrier assignment satisfies:

$$\begin{cases} p_i^*(f) = \left[\frac{U_i'(r_i^*)}{\lambda} - \frac{1}{\beta \text{SNR}_i^c(f)} \right]^+ & f \in D_i \\ \sum_{i \in \mathcal{M}} \int_{D_i} p_i^*(f) df = \bar{P}. \end{cases} \quad (15)$$

which is identical to

$$\begin{cases} p^*(f) = \left[\frac{U_i'(r_i^*)}{\lambda} - \frac{1}{\beta \text{SNR}_i^c(f)} \right]^+ & f \in D_i \\ \int_0^B p^*(f) df = \bar{P}, \end{cases}$$

where $r_i^* = \int_{D_i} \log_2[1 + \beta p^*(f) \text{SNR}_i^c(f)] df$. \blacksquare

Note that usually, we cannot get the optimal power allocation directly from (11), and iterative algorithms are needed to obtain an appropriate λ .

Although (11) is similar to the classical single-user water-filling, there are two major differences. First, the level of water for each user is proportional to its current marginal utility value. In other words, power allocation is also based on utility function. Second, the power constraint is concerned with the total transmission power rather than individual power.

C. Utility-based Joint Dynamic Subcarrier Allocation and Adaptive Power Allocation

The joint DSA and APA optimization problem is given by

$$\text{maximize} \quad \sum_{i \in \mathcal{M}} U_i \left(\int_{D_i} \log_2[1 + \beta p(f) \text{SNR}_i^c(f)] df \right) \quad (16)$$

$$\text{subject to} \quad \bigcup_{i \in \mathcal{M}} D_i \subseteq [0, B], \quad (17)$$

$$D_i \cap D_j = \emptyset, \quad i \neq j \quad \forall i, j \in \mathcal{M}, \quad (18)$$

$$\int_0^B p(f) df \leq \bar{P} \quad (19)$$

$$p(f) \geq 0. \quad (20)$$

Obviously, there are two necessary conditions of optimal points for the joint DSA and APA problem, which is described as follows:

- 1) Fixing the optimal subcarrier allocation, any change of power allocation does not increase the total utility.
- 2) Fixing the optimal power allocation, any change of subcarrier assignment does not increase the total utility.

Therefore, an optimal frequency assignment D_i^* for all i and power allocation $p(f)$ have to satisfy both conditions (7) and (11), which are stated in the following theorem.

Theorem 3: Assume that

$$\mu(\{f \in [0, B] : \frac{c_i^P(f)}{c_j^P(f)} = v\}) = 0 \quad \text{for any } v \in \mathbb{R}_+ \text{ and } i \neq j. \quad (21)$$

If the set of data rates r_i^* , $i \in \mathcal{M}$ is optimal, then the optimal frequency set for user i , D_i^* , and optimal transmit power allocation, $\mathbf{p}^* = \{p^*(f), f \in [0, B]\}$, satisfy

$$\begin{cases} D_i^* = \bigcap_{j \in \mathcal{M} - \{i\}} \{f \in [0, B] : U'_j(r_j^*)c_j^P(f) \leq U'_i(r_i^*)c_i^P(f)\} \\ p^*(f) = \left[\frac{U'_i(r_i^*)}{\lambda} - \frac{1}{\beta \text{SNR}_i^c(f)} \right]^+ & f \in D_i^* \\ \int_0^B p^*(f) df = \bar{P} \\ r_i^* = \int_{D_i^*} \log_2[1 + \beta p^*(f) \text{SNR}_i^c(f)] df. \end{cases} \quad (22)$$

When each utility function is just throughput, $U_i(r_i) = r_i$. The optimal subcarrier assignment is independent of the optimal power allocation, and a subcarrier assignment has no effect on the assignments of other subcarriers. We can write optimal subcarrier assignment and power allocation as the following closed forms from (22).

$$\begin{cases} D_i^* = \{f \in [0, B] : \text{SNR}_i^c(f) = \max_{m \in \mathcal{M}} \text{SNR}_m^c(f)\} \\ p^*(f) = \left[\frac{1}{\lambda} - \frac{1}{\beta \max_{m \in \mathcal{M}} \text{SNR}_m^c(f)} \right]^+ \\ \int_0^B p^*(f) df = \bar{P} \end{cases} \quad (23)$$

which is identical to the result in [13]. It illustrates that FDMA-type systems can achieve Shannon capacity when they are optimized for the sum of throughputs.

It should be noted that conditions (7), (11), and (22) are only necessary for an optimal point and cannot guarantee global optimality. We will discuss the properties of optimality in the next section further.

IV. PROPERTIES OF OPTIMALITY

In this section, we will investigate the convexity of achievable data rate region in the continuous frequency case, and also show that if the utility function is concave, then a local maximum is also a global maximum, and that the necessary conditions in Theorem 1-3 are also sufficient ones.

Data rate vector \mathbf{r} is defined as $\mathbf{r} = [r_1, r_2, \dots, r_M]^T \in \mathbb{R}_+^M$, where M is the number of users.

Definition 1: The *instantaneous data rate region*, \mathcal{C}_π , is a set which consists of total achievable data rate vectors under the constraints of a resource allocation policy π (e.g. DSA, APA, as well as joint DSA and APA).

The instantaneous data rate region, of course, is determined by the channel conditions at that time and resource allocation constraints. It is intuitive that with more adaptive resource allocation techniques, resource constraints are more relaxed, resulting in a larger feasible region.

Define objective function $\mathcal{U}(\mathbf{r})$ as $\mathcal{U}(\mathbf{r}) = \sum_{i=1}^M U_i(r_i)$ which is a function $\{\mathbb{R}_+^M \mapsto \mathbb{R}\}$. Thus, the optimization problem can be regarded as

$$\text{maximize } \mathcal{U}(\mathbf{r}) \quad (24)$$

$$\text{subject to } \mathbf{r} \in \mathcal{C}_\pi \quad (25)$$

We will investigate the impact of properties of achievable rate region and utility functions on optimality. The convexity of the instantaneous data rate region with frequency assignment and power allocation can be described in the following theorem.

Theorem 4: In the continuous frequency case, with DSA and APA, the achievable data rate region is convex.

Heuristically, it is because of frequency sharing. The details of proof is presented in [14].

Applying the same approach, we obtain the following corollary.

Corollary 1: In the continuous frequency case, in using subcarrier allocation with fixed power allocation or adaptive power allocation with fixed subcarrier allocation, the achievable data rate region is convex.

The convexity of achievable data rate region always leads to some elegant results, as known in convex analysis and optimization theory.

Theorem 5: If all $U_i(r_i)$'s are concave functions, then a local maximum of $\mathcal{U}(\mathbf{r})$ is also a global maximum, and conditions (7), (11), and (22) are both sufficient and necessary.

The proof is presented in [14].

The sufficiency of conditions (7), (11), and (22) for global optimality is indispensable for algorithm design. If, in addition, $U_i(r_i)$'s are all strict concave, there is a unique global maximum solution to the optimization problems. Note that the unique global maximum means that there is only single optimal data rate vector, and that frequency and power allocation may have several schemes. It is well known that a utility function is strictly concave if and only if it has a decreasing marginal utility function, which is called elastic traffic in [15]. Consequently, non-decreasing, continuous and differentiable utility functions with non-increasing marginal utility lead to good and tractable optimality properties.

The relation between the feasible data rate region and concave utility functions is shown in Fig 2. An optimal solution is a feasible solution that has the most favorable value. Heuristically, the optimal rate vector should be a point of tangency between the region boundary and a total utility contour.

V. EFFICIENCY AND FAIRNESS

For resource allocations in wireless networks, both efficiency and fairness issues are very important. With the

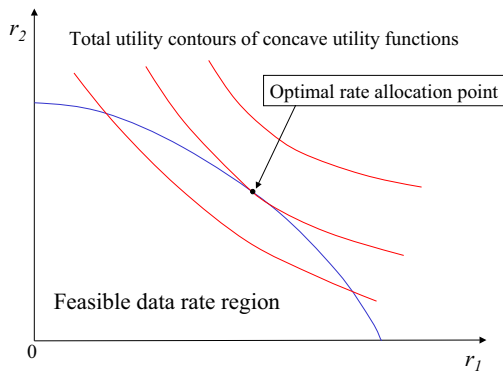


Fig. 2. Feasible data rate region and optimal rate allocation

channel knowledge of each user at the basestation, dynamic subcarrier allocation schemes tend to assign subcarriers to users with better SNR on the corresponding subcarriers, thereby having high spectral efficiency. It is obvious from (7) that the utility-based dynamic subcarrier allocation penalizes poor channel conditions. Due to the independence of users' channel conditions, there is a diversity, called *multiuser diversity*.

Fairness requires fair sharing of bandwidth among competing users and protection of well-behaved connections from aggressive connections. For a concave function $\mathcal{U}(\mathbf{r})$, a feasible rate vector \mathbf{r} , is optimal if and only if

$$\nabla \mathcal{U}(\mathbf{r})^T (\mathbf{r}' - \mathbf{r}) \leq 0 \quad \text{for all } \mathbf{r}' \in \mathcal{C}_\pi. \quad (26)$$

When the logarithmic utility function, $U(r) = \ln(r)$, is used, (26) is identical to

$$\sum_{m \in \mathcal{M}} \frac{r'_m - r_m}{r_m} \leq 0. \quad (27)$$

A resource allocation policy satisfying (27) is said to be *proportionally fair* in [16]. Therefore, the logarithmic utility function is naturally associated with proportional fairness.

It can also be seen intuitively from (7) that increasing utility functions encourage the users having good channel conditions, and decreasing marginal utility functions assign higher priorities to the users with low data rate. Therefore, utility-based resource allocation can guarantee both efficiency and fairness.

VI. CONCLUSIONS

Cross-layer adaptability is needed to optimize new wireless multimedia networks. In OFDM, dynamic subcarrier assignment and adaptive power allocation provide more degrees of freedom of resource allocation. The flexibility of adaptive resource allocation, combined with the ability to deal with ISI, makes OFDM very suitable to support high-data-rate wireless Internet services. On the other hand, utility offers a tangible metric for network provisioning when application performance is the key concern. Utility functions, determined by applications, serve as the optimization objective

of adaptive physical and *media access control* (MAC) layer techniques.

The optimization problem of dynamic resource allocation on the downlink of OFDM networks is formulated on the basis of maximizing the aggregate network utility. We have derived the criteria for utility-based subcarrier assignment and water-filling, and explored the achievable global optimality associated with concave utility functions. Subsequently, utility-based resource allocation is revealed to have the inherent mechanism of maintaining both efficiency and fairness. The fairness is automatically achieved by the behavior of marginal utility functions.

This paper has provided the theoretical framework for utility-based resource allocation in OFDM networks. All implementation algorithms and numerical results will be presented in [17].

REFERENCES

- [1] V. Shah, N. B. Mandayam, and D. J. Goodman, "Power control for wireless data based on utility and pricing," in *Proc., IEEE PIMRC*, 1998, pp. 1427–1432.
- [2] C. U. Saraydar, N. B. Mandayam, and D. J. Goodman, "Pricing and power control in a multicell wireless data network," *IEEE J. Select. Areas Commun.*, vol. 19, no. 10, pp. 1883–1892, October 2001.
- [3] P. Liu, M. Honig, and S. Jordan, "Forward link cdma resource allocation based on pricing," in *Wireless Communications and Networking Conference, 2000. WCNC. 2000 IEEE*, vol. 2, September 2000, pp. 619–623.
- [4] C. Zhou, M. L. Honig, and S. Jordan, "Two-cell power allocation for wireless data based on pricing," in *39th Annual Allerton Conference*, Monticello, IL, October 2001.
- [5] L. Song and N. B. Mandayam, "Hierarchical sir and rate control on the forward link for cdma data users under delay and error constraints," *IEEE J. Select. Areas Commun.*, vol. 19, no. 10, pp. 1871–1882, October 2001.
- [6] J. Chuang and N. Sollenberger, "Beyond 3G: wideband wireless data access based on OFDM and dynamic packet assignment," *IEEE Commun. Magazine*, pp. 78–87, July 2000.
- [7] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1747–1758, October 1999.
- [8] W. Rhee and J. M. Cioffi, "Increase in capacity of multiuser ofdm system using dynamic subcarrier allocation," in *IEEE VTC2000*, 2000, pp. 1085–1089.
- [9] A. J. Goldsmith and S. G. Chua, "Variable-rate variable-power MQAM for fading channel," *IEEE Trans. Commun.*, vol. 45, pp. 1218–1230, Oct. 1997.
- [10] X. Qiu and K. Chawla, "On the performance of adaptive modulation in cellular systems," *IEEE Trans. Commun.*, vol. 47, pp. 884–895, June 1999.
- [11] G. Song and Y. G. Li, "Utility-based joint physical-mac layer optimization in OFDM," in *GLOBECOM 2002*, 2002.
- [12] R. T. Rockafellar, *Convex Analysis*. New Jersey: Princeton University Press, 1970.
- [13] D. N. Tse, "Optimal power allocation over parallel gaussian broadcast channel," in *Proc., IEEE Int. Symp. on Inform. Theory*, Ulm, Germany, June 1997, p. 27.
- [14] G. Song and Y. G. Li, "Utility-based cross-layer optimization in OFDM networks — part I: Theoretical framework," 2003, in preparation.
- [15] S. Shenker, "Fundamental design issues for the future Internet," *IEEE J. Select. Areas Commun.*, vol. 13, pp. 1176–1188, September 1995.
- [16] F. Kelly, "Charging and rate control for elastic traffic," *European Trans. On Telecommunications*, vol. 8, pp. 33–37, 1997.
- [17] G. Song and Y. G. Li, "Utility-based cross-layer optimization in OFDM networks — part II: Algorithms and numerical results," 2003, in preparation.