Chapter 2
Dynamic Resource Allocation

Dynamic Resource Allocation is an essential technique to exploit the time-space-frequency variation in wireless channels by adaptively distributing precious radio resources, such as spectrum and power, to either maximize or minimize the concerned network performance metrics. In traditional static resource allocation strategies, subchannels are distributed in a predetermined manner; that is, each user is assigned fixed frequency bands regardless of the channel status. In this case, the resource allocation problem reduces to power allocation or bits loading on each subchannel, which fails to fully exploit the potential of multiuser diversity in wireless environment.

2.1 Resource Allocation in OFDM Systems

In multiuser OFDM systems, a typical resource allocation scheme might be designed to determine the subchannels, the transmission power and the bits allocated to users to optimize the desired performance.

2.1.1 Wireless Channel Characteristics

In wireless signal transmission, multipath reflections from different objects give rise to a common phenomenon-multipath fading. Specifically, the multipath reflections result in the electromagnetic wave travelling along different paths with varying length, and the interaction between those waves causes multipath fading with frequency selectivity.

Another characteristic of the multipath channel is its time-varying nature. This time variation occurs owing to the mobility of either the transmitter or the receiver, and therefore the location of reflectors in the transmission path, which gives rise to multipath, will change over time. Consequently, wireless channel is generally assumed to be wideband time-varying frequency-selective multipath fading.

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The coherence bandwidth, defined as a range of frequencies over which the channel can be considered as flat fading, is a significant parameter to characterize the multipath fading channels in frequency domain [1]. By taking advantage of this property, each OFDM subchannel can be assumed to undergo flat fading as long as the bandwidth of each subchannel is chosen much smaller than the coherence bandwidth of the channel. One of the most popular models to illustrate the statistical nature of flat fading channels is the Clark's model based on scattering [1]. In this model, the fading parameter of the channel is considered to be a random variable with Rayleigh distribution. Besides, it is also assumed that additive white Gaussian noise (AWGN) imposes on all subchannels of all users.

Accordingly, the fading parameters for different users are mutually independent, which implies that it is unlikely for a certain subchannel to undergo deep fading for all users; that is, each subchannel is expected to be in good condition for some users in the system, also referred to as multiuser diversity. One of the crucial principles of dynamic resource allocation is intended to assign each subchannel to the user with the best channel gain on it. The essential premise of such a scheme is the perfect estimation of channel information and feedback to base stations, while the channel information is always available at the beginning of each transmission block. In addition, the fading rate of each channel is supposed to be slow enough that the time-varying channel can be deemed quasi-static where the channel condition does not change within each OFDM transmission block.

The resource allocation schemes discussed in this brief are based on the assumption of perfect channel information at both the transmitter and the receiver sides. While it is rarely possible for the transmitter to obtain perfect channel state information (CSI), typical channel estimation is accurate enough to justify the use of adaptive resource allocation. The channel prediction algorithms have been studied extensively in the past years and recently, more studies have been focused on channel prediction methods in the context of OFDM [2–8].

In a multiuser OFDM system, the subchannel allocation is generally carried out based on the instantaneous channel information and the desired requirements of system. According to the aforementioned analysis about wireless channel characteristics, Figs. 2.1 and 2.2 depict the channel gain of a frequency selective fading with 32 subchannels and the channel gain of a wireless channel with eight subchannels and four users, respectively. These two figures manifest two important properties of channel gains in a multiuser OFDM system: First, different subchannels of a certain user experience different fading levels because of frequency selectivity of a channel, namely, frequency diversity; second, the subchannel gains of users at different locations vary independently, known as multiuser diversity. Taking full advantage of the channel information and its properties, the transmitter performs dynamic subchannel and power allocation to achieve the best performance of the system [9].

2.1.2 FFT-Based Transceiver

Consider the downlink of a multiuser OFDM system, a base station communicates with multiple users with limited resources, such as the given bandwidth and the

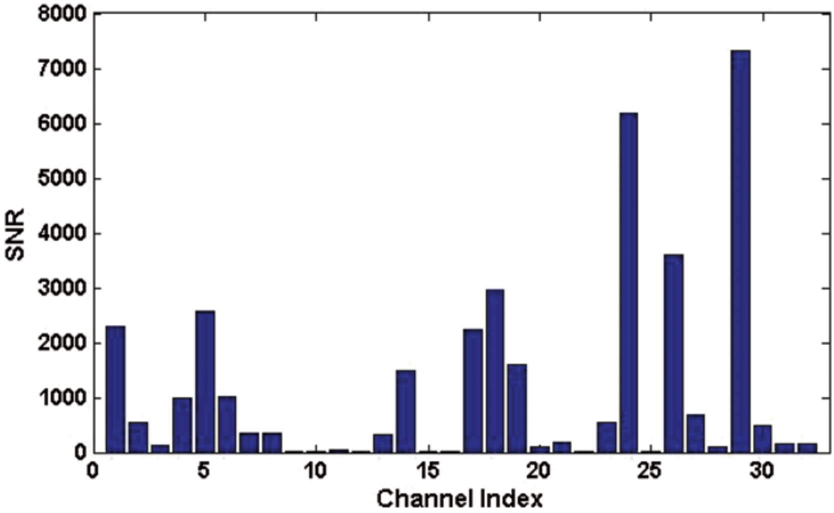

Fig. 2.1 Frequency selective channel with 32 subchannels

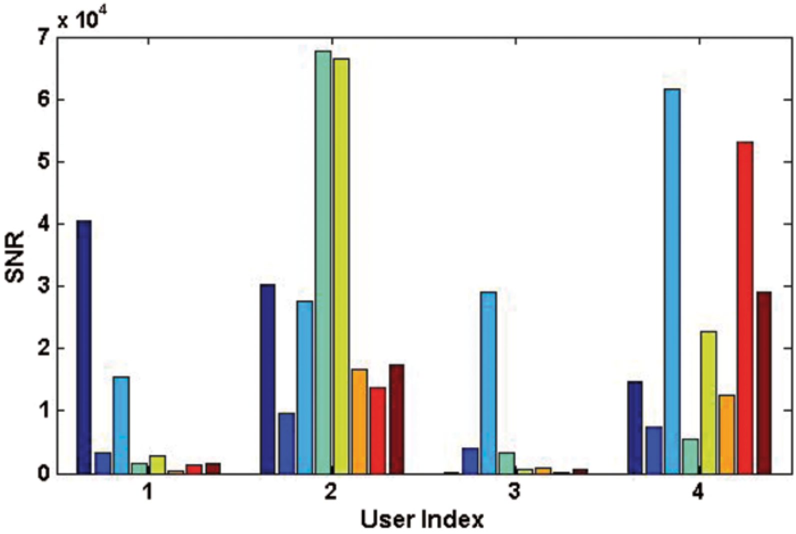

Fig. 2.2 Wireless channel with eight subchannels and four users

transmit power. The framework in a multiuser OFDM transmitter with adaptive resource allocation is illustrated in Fig. 2.3.

The process can be detailed as follows. The transmitter utilizes channel information to perform dynamic resource allocation algorithm, working out the subchannels allocated to each user, the number of bits transmitted and power loaded on each subchannel. At the output of the modulators, the complex symbols are transformed

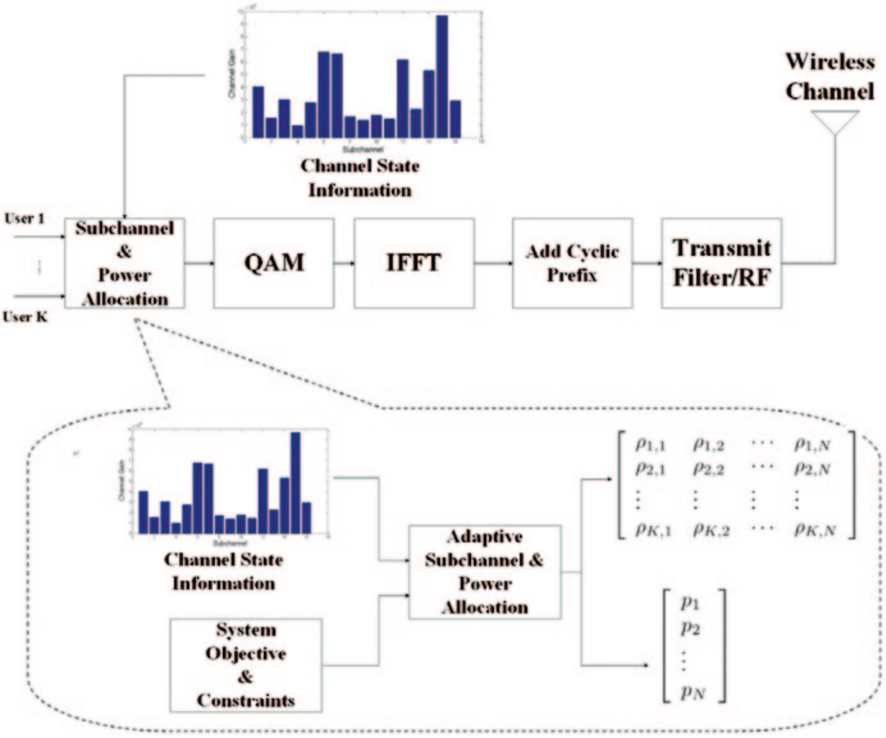

Fig. 2.3 Block diagram of an OFDM transmitter with adaptive resource allocation [9]

into an OFDM symbol by inverse fast Fourier transform (IFFT) in the transmitter. Then, the copy of the last portion of the data symbol is used as a cyclic prefix and added to the samples in time domain, which serves as a guard interval to ensure the orthogonality between subchannels. In this type of multicarrier modulation, also referred to as cyclic prefix OFDM (CP-OFDM), intersymbol interference (ISI) can be eliminated when the amount of time dispersion of the channel is smaller than the duration of the guard interval. The resource allocation information, as well as the OFDM symbols, is then transmitted to the receiver through an exclusive control channel. In the receiver side, the guard interval is removed and the time samples are transformed into modulated symbols by fast Fourier transform (FFT).

Mathematically, the problem of resource allocation with N OFDM subchannels and K users is to determine the subchannel allocation indices $\rho_{k,n}$'s, describing whether the subchannel n should be assigned to user k, and the amount of power should be loaded on subchannel n used by user k, denoted by $\rho_{k,n}$. The detailed block in Fig. 2.1 gives a distinct overview of this problem.

In practical systems, different users are generally not allowed to share the same subchannel to simplify the transceiver implementation; that is, the subchannel allocation indices $\rho_{k,n}$'s are mutually exclusive with binary value $\{0, 1\}$. Theoretically, it has been proved that the overall throughput can be maximized when each subchannel is allocated to only one user who enjoys the best channel gain for that subchannel, along with the optimal power loading on each subchannel [10]. Thus, throughout this brief, we assume that each subchannel can only be occupied by one user.

As the dramatic evolvement of various wireless services, future wireless communication networks are expected be flexible enough to handle myriad quality requirements, e.g., high data rate, fairness and low latency. Therefore, different dynamic resource allocation schemes and optimization techniques will be introduced in this brief in the light of different desired objectives and constraints.

2.1.3 Efficiency and Fairness

Efficiency and fairness are always two pivotal issues for dynamic resource allocation. Given limited resources for a wireless communication system, the concept of efficiency specifies either spectral efficiency (SE) or energy efficiency (EE). Specifically, SE is generally defined as the data rate per unit bandwidth, which can be calculated by dividing the total throughout by the total bandwidth of a system. Note that it considers the total data rate of the system rather than the individual achieved rate of users. Consequently, in order to achieve high SE, users with poor channel conditions might suffer relatively low data rate. On the other hand, EE is defined as the system throughput per unit energy consumption, referred to as "*bits-per-Joule*", which is mostly considered during network operation for resource allocation [11–18]. Most previous research efforts put little emphasis on EE for wireless network design until very recently. It, however, has become an inexorable trend as the blossom of green communication. Unfortunately, the SE and the EE are not always consistent and even conflict with each other sometimes. Hence, how to balance the two metrics deserves deep study to establish a more flexible and intelligent wireless networks.

In terms of fairness, the definition varies with different design criteria, indicating how equally the resources are allocated among users. For instance, it can be defined either with respect to bandwidth with the same number of subchannels assigned to each user [19], or with respect to power where each user is allocated equal portion of power from the total budget [20], or with respect to data rate which tries to achieve the same data rate of each user [21]. Particularly, when the objective is to guarantee the rate proportionality among users, it is called optimization with constrained-fairness. Generally, fairness index for rate proportional constraints is introduced as in to flexibly describe the instantaneous fairness among users. When the fairness index reaches the maximum value of 1, it indicates the fairest case in which all users would achieve the same data rate. An alternative criterion to guarantee absolute fairness among users is the max-min strategy; that is, to maximize the minimal data rate of users ensures that each user shares the equal data rate eventually.

Often, it fails to optimize the efficiency and the fairness simultaneously, since different metrics often lead to different, or even opposite design criteria for network operation. For example, optimal SE may scarify the fairness among users, because users with good channel condition are more preferable to be allocated with more resources to achieve high system throughput. Also, the optimal SE and EE can hardly be achieved at the same time due to the conflict between these two metrics in some cases. Thus, it is of great importance to figure out the trade-offs between these metrics, concerning the sorted requirement of practical systems.

2.1.4 Classes of Dynamic Resource Allocation

As one of the most important issues in OFDM systems, adaptive resource allocation has attracted significant attentions during the past two decades, particularly from the perspective of the SE. A comprehensive survey can be found in and references therein.

Resource allocation in conventional OFDM systems can be classified into two categories, namely margin adaptive [22–24] and rate adaptive [10, 21, 25–32]. The optimization objective of the margin adaptive is generally to minimize the consumed power under given rate requirements of users, while the algorithms for the rate adaptive usually try to maximize the throughput of OFDM systems under transmission power limitation. Particularly, with a given bandwidth, the rate adaptive is equivalent to the SE maximization.

Recently, the increasing awareness of green communication, which emphasizes on the EE, provides a new sight and inspiration for future wireless system design, promoting new waves of research and standard development activities. Compared with a large amount of work has been devoted to enhancing the throughput or the SE of OFDM systems, the EE is not much concerned previously. However, the energy-efficient resource allocation has been put on the agenda in both industry and academia, especially for the OFDM-based system, which serves as the most promising modulation technique for future wireless networks. Thus, an emerging class of resource allocation is catalyzed by the development of green communication, known as energy-efficient resource allocation [13–17, 33–35], which aims to maximize the overall EE of OFDM systems.

2.1.5 General Problem of RA in Multiuser OFDM Systems

Without loss of generality, we consider a multiuser OFDM system with K users denoted by the set $K = \{1, 2, \ldots.., K\}$. The total bandwidth W is divided into N subchannels, denoted by $N = \{1, 2, \ldots.., N\}$. The data rate of the *k*th user, R_k, in bits/s is given by

$$R_k = \frac{W}{N}\sum_{n=1}^{N}\rho_{k,n}\log_2\left(1+\frac{\gamma_{k,n}}{\Gamma}\right), \tag{2.1}$$

where $\rho_{k,n}$ is the subchannel allocation index indicating whether the *k*th user occupies the *n*th subchannel. If subchannel *n* is assigned to user *k*, $\rho_{k,n} = 1$; otherwise, $\rho_{k,n} = 0$. $\gamma_{k,n}$ represents the signal-to-noise ratio (SNR) of the *n*th subchannel used by the *k*th user, which is given by

$$\gamma_{k,n} = p_{k,n}H_{k,n} = \frac{p_{k,n}h_{k,n}^2}{N_0 W / N}, \tag{2.2}$$

where $\rho_{k,n}$ and $H_{k,n}$ denote the amount of power allocated to the *k*th user over the *n*th subchannel and the channel-to-noise ratio of the *n*th subchannel used by the *k*th user, respectively. $h_{k,n}$ signifies the channel gain for the *k*th user on the *n*th subchannel, and $N_0\frac{W}{N}$ is the noise power over each subchannel with N_0 as the power spectral density of additive white Gaussian noise (AWGN). Γ is the SNR gap in practical modulation schemes, where an effective SNR should be adjusted according to the modulation scheme for a desired bit-error-rate (BER). The power loss, defined as the difference between the SNR for achieving a certain data rate for a practical system and that for the theoretical limit, is called the SNR gap. Thus, the SNR gap can be described as a function of BER.

For instance, the BER for an AWGN channel adopting multilevel quadrature amplitude modulation (MQAM) and ideal coherence phase detection is bounded by [36]

$$BER \le 2e^{-1.5\gamma/(M-1)}, \tag{2.3}$$

where $M = 2^r$ with r denoting the number of bits. On condition that $r \ge 2$ and $0 \le \gamma \le 30dB$, BER can be approximated within 1 dB by [37]

$$BER \le 0.2^{-1.5\gamma/(M-1)}, \tag{2.4}$$

and the SNR gap Γ is

$$\Gamma = \frac{-In(5BER)}{1.5}. \tag{2.5}$$

For simplicity, the subchannel and power allocation problem is written into a general form as follows,

$$\begin{aligned}
\min_{\rho_{k,n},P_{k,n}} \quad & f\left(\rho_{k,n},P_{k,n}\right) \\
s.t. \quad & C1:\rho_{k,n}\in\{0,1\},\forall k,n \\
& C2:\sum_{k=1}^{K}\rho_{k,n}=1 \\
& C3:P_{k,n}\geq 0 \\
& C4:\sum_{k=1}^{K}\sum_{n=1}^{N}\leq P_t \\
& C5:User\ \ Rate\,Requirements
\end{aligned} \tag{2.6}$$

where $C1$ and $C2$ indicate each subchannel can be assigned to only one SU. C4 gives the total power limit for the OFDM network. $C5$ implies either fixed or variable rate requirements of users. For instance, $C5$ can be fixed rate requirement of individual or the overall throughput, or it can be proportional rate constraints to preserve the fairness among users.

Concerning the three types of dynamic resource allocation introduced in the previous section, the objective for the subchannel and power allocation can be respectively described as follows,

- Margin adaptive

$$\min_{\rho_{k,n},P_{k,n}} f(\rho_{k,n},P_{k,n})=\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}P_{k,n}.$$

- Rate adaptive (equivalent to Spectral efficient RA)

$$\max_{\rho_{k,n},P_{k,n}} R_T=\frac{W}{N}\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}\log_2\left(1+\frac{P_{k,n}H_{k,n}}{\Gamma}\right),$$

which can be equally written into

$$\min_{\rho_{k,n},P_{k,n}} f(\rho_{k,n},P_{k,n})=-\frac{W}{N}\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}\log_2\left(1+\frac{P_{k,n}H_{k,n}}{\Gamma}\right).$$

- Energy-efficient RA

The metric of EE is defined as the system throughput per unit energy consumption,

$$\eta_{EE}(\rho_{k,n},P_{k,n})=\frac{R_T}{P_T}=\frac{\frac{W}{N}\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}\log_2\left(1+\frac{P_{k,n}H_{k,n}}{\Gamma}\right)}{\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}P_{k,n}}.$$

Thus the objective of optimization problem is

$$\max_{\rho_{k,n},P_{k,n}} \eta_{EE}(\rho_{k,n},P_{k,n}),$$

or

$$\min_{\rho_{k,n},P_{k,n}} f(\rho_{k,n},P_{k,n}) = -\eta_{EE}(\rho_{k,n},P_{k,n}).$$

In short, the problem in each class is formulated accordingly and the optimal solution is obtained by different optimization techniques. Sometimes, suboptimal algorithms are preferred in real-time practical applications, due to the unaffordable computational complexity for achieving optimal solutions.

2.2 Resource Allocation in CR Systems

For the arising OFDM-based CR networks, dynamic resource allocation is of paramount importance because it is the prerequisite to achieve high system performance, such as capacity and quality of service (QoS), with limited resources. Resource allocation in an OFDM-based CR network, however, is more complex than that in a conventional OFDM system since the PUs may not adopt OFDM modulation, leading to the interference between the two systems. Moreover, the unavoidable sensing errors in the CR network can aggravate the interference, and the interference introduced to the PUs must be carefully controlled below a predefined threshold to prevent the unacceptable degeneration of the performance of the PUs.

2.2.1 Primary/Secondary Network Models

From both theoretical and practical perspectives, there are two general types of CR networks. One is the infrastructure-based network where multiple SUs are served by a common access point (AP), as illustrated in Fig. 2.4a; the other is the ad-hoc manner, as shown in Fig. 2.4b, which consists of multiple distributed secondary links.

In the infrastructure CR network, the SUs communicates with the CR AP, to some extent, the CR base station; that is, the common AP is usually correspond to one particular cell in a CR cellular network, coordinating the transmission of secondary system. In this case, the downlink and uplink transmission can be modeled as a broadcast channel and a multiple access channel, respectively. With regard to ad-hoc secondary networks, because a secondary terminal can be both a transmitter and a receiver, it is generally described as an interference channel. For a certain receiver, it will receive the signals from the direct-link channel from its corresponding transmitter, as well as the signals from the cross-link channels from

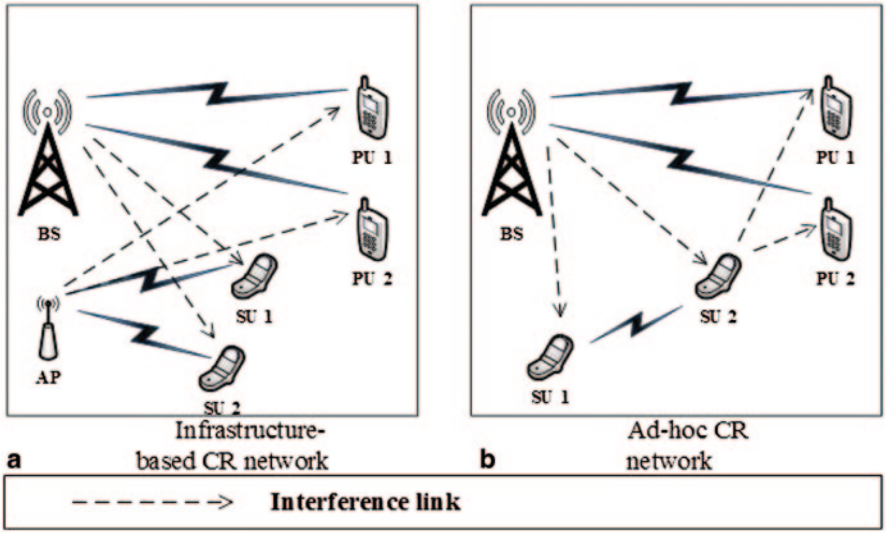

Fig. 2.4 CR networks. **a** Infrastructure-based manner. **b** Ad-hoc manner

other transmitters. In the both types of networks, the mutual interference between primary system and secondary system should be taken into consideration.

In order to perform the dynamic resource allocation based on the CSI of SUs, the channels are assumed constant for a transitory and fixed transmission frame, such as one frequency-bin in OFDM systems. Generally speaking, the secondary transmitting terminal needs to satisfy two types of power constraints for dynamic resource allocation: CR transmission power budget and the limitation of interference level to the PUs.

2.2.2 CR Operation Models

To date, in spite of assorted operation models proposed for CR networks, there is no consensus on the terminology used for the associated definitions yet [38, 39]. By and large, there are two most popular basic operation models for CR: opportunistic spectrum access and spectrum sharing.

Specifically, the former allows SUs to transmit over the non-active frequency bands, namely spectrum holes, where no PUs are transmitting over this band. In this case, spectrum sensing serves as an indispensable technique to enable the implementation of opportunistic spectrum access; that is, the SUs try to detect the active PU transmissions over the band individually or cooperatively, and then decide to transmit on the non-active bands, where the PUs' signals are inactive with a high probability, indicated by the spectrum sensing results. Spectrum sensing is a hot

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