LETTER

Efficient Combining Scheme of Scheduling and Channel Allocation in Multi-Channel Systems

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SUMMARY In this letter, we propose an efficient scheme for combining scheduling and channel allocation functions in multi-channel systems such as an orthogonal frequency division multiple access (OFDMA). In our approach, the scheduling function is embedded in the channel allocation function in an implicit manner, and the implicit scheduler only translates quality-of-service (QoS) requirements into a set of constraints on channel allocation. The channel allocation problem is then formulated as a linear programming (LP) problem, and the optimal solution can be easily obtained through various LP algorithms. Through extensive numerical experiments, it is demonstrated that the proposed scheme can maximize the cell throughput under the given QoS requirements.
key words: *multi-channels, OFDMA, scheduling, channel allocation, RRM*

1. Introduction

Multi-channel systems such as OFDMA systems [1]–[3] have been introduced to increase transmission efficiency in the face of limited radio resources. As a result, it becomes an important task to extend the notion of opportunistic scheduling — one of the key techniques which substantially enhance the capacity of wireless systems — to multi-channel environments. Opportunistic scheduling schemes such as proportional fair (PF) scheduling algorithms [4] take advantage of the flexibility in the service/transmission order of users/packets, and improve the throughput by prioritizing users in better channel condition than usual.

Transmission of a packet in multi-channel systems involves two decision processes; i.e., scheduling and channel allocation. The scheduling function determines the transmission/service time (or frame) of packets/users based on the knowledge of their QoS requirements and channel conditions. The channel allocation function determines the transmission channels of the packet scheduled in a same time-slot or frame. Therefore, compared to single-channel systems, multi-channel systems have another dimension (i.e., channel axis) of flexibility over which multi-user diversity gain can be exploited further. There are recent studies on the optimal channel allocation over multiple channels in the view point of transmission power minimization [1], [2]. These results are then extended in such a way that the error performance can be guaranteed for delay insensitive traffic classes in [3]. On the other hand, the multi-user diversity gain (or the resource efficiency) of multi-channel systems can hardly be maximized when the scheduling and the channel allocation functions are carried out sequentially or separately. This is simply because the scheduling and channel allocation functions require the outputs of each other to carry out their roles efficiently. In other words, for the scheduling function to perform opportunistic scheduling, it requires the state information of the channels over which individual packets will be transmitted. This means that the channel allocation should precede the scheduling for opportunistic scheduling. However the channels allocated to individual packets may vary depending on the set of packets scheduled in a same time-slot or frame, and thus, the channel allocation function cannot provide the scheduler with the accurate channel state information until the scheduling is complete. An easy way to get around such difficulty may be referring to the average state information of the whole channels as the representative channel quality for each user. However, it was shown that this simple approach may result in significant degradation of capacity by overlooking the flexibility in channel allocation at the time of scheduling [5], and this suggests that the scheduling and the channel allocation functions should be combined in such a way that multi-user diversity gain can be maximized along both dimensions of flexibility. (i.e., time- and channel-axis).

In this letter, the scheduling and the channel allocation functions are combined and formulated as an optimization problem. In our approach, the actual scheduling function is embedded in the channel allocation function as illustrated in Fig. 1, and the implicit scheduling block is only responsible for translating various QoS requirements into a set of inequality constraints. The channel allocation block then assigns channels to packets under the set of inequality constraints so that the cell throughput can be maximized by fully exploiting the flexibility (along the time-axis) in meeting QoS requirements.

2. System Model for Channel Allocation

We consider wireless broadband systems where a frame consists of a large number of subchannels. We assume that scheduling and channel allocation are performed on a frame basis. Those subchannels can be divided into a number of groups according to their channel states and each subchannel group has distinctive channel status. It is assumed that the channel status of each subchannel group for each user is maintained as a constant level during the length of a frame. We assume that subchannels can be allocated for a certain

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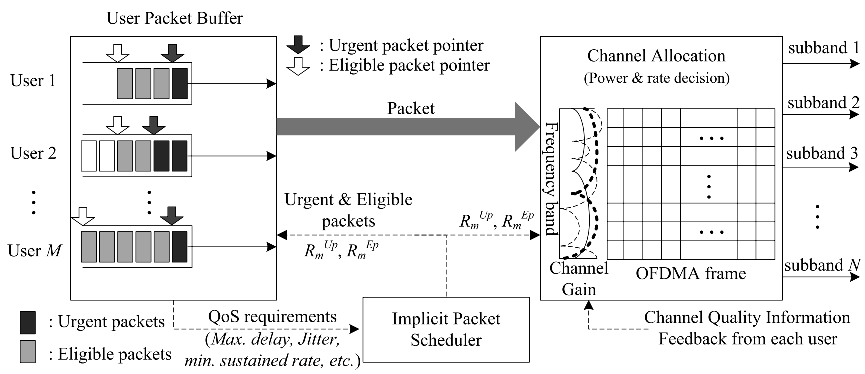

Fig. 1 Combining architecture of the implicit scheduler and the channel allocation block for multi-channel systems.

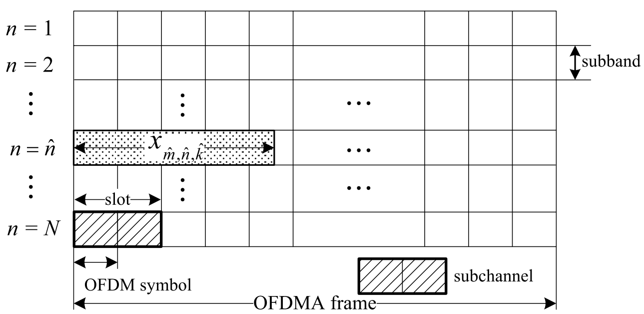

Fig. 2 Example of subband $\hat{n}$ allocated to user $\hat{m}$ with AMC level $\hat{k}$ by using allocation variable $x_{\hat{m},\hat{n},\hat{k}}$.

user with fine granularity neglecting the subchannel boundary. Let us consider an OFDMA system as an example of multi-channel systems [6]. In this case, the subchannel group corresponds to a group of subchannels included in a subband as in Fig. 2. We investigate an OFDMA frame with M users, N subbands in frequency domain and S_{frame} slots in time domain, accordingly there are N times S_{frame} subchannels in an OFDMA frame. It is assumed that a subchannel consists of a frequency subband and a time slot. One time slot is composed of 2 consecutive OFDM symbols as shown in Fig. 2. A subchannel consists of $N_{subcarrier}$ subcarriers.

Let's define the allocation variable $x_{m,n,k}$ as the ratio of the amount of allocated subchannels to the whole amount of subchannels in the nth subband for the mth user with the adaptive modulation and coding (AMC) level of k. As shown in Fig. 2, subchannels can be allocated continuously along the time axis neglecting the time slot boundary according to our assumption. Namely, $x_{m,n,k}$ is a real number and has the range between 0 to 1. We assume that the transmission power of each subband can be different from each other but the sum of the required transmission power is limited by the maximum average transmission power over a frame at the base station (BS). The parameter $p^{tx}_{m,n,k}$ denotes the required transmission power for a subcarrier in the nth subband with the AMC level of k for the mth user. $p^{tx}_{m,n,k}$ is determined by using

$$p^{tx}_{m,n,k} = \frac{(I^{cochannel}_{m,n} + N^{thermal}_{m,n}) \times (SINR)^{k,PER_m}_{required}}{G_{m,n}} \tag{1}$$

where $I^{cochannel}_{m,n}$ is the interference power and $N^{thermal}_{m,n}$ is the thermal noise power for a subcarrier. $(SINR)^{k,PER_m}_{required}$ is the required signal-to-interference-and-noise-ratio (SINR) to transmit a packet with the AMC level of k while satisfying the required packet error rate PER_m. A channel gain $G_{m,n}$ for a subcarrier in the nth subband of the mth user is represented as in

$$G_{m,n} = |H_m(n)|^2 \cdot L^{pathloss}_m \tag{2}$$

where $L^{pathloss}_m$ is the pathloss from the BS to the mth user. $H_m(n)$ is the frequency response of the channel of the mth user at the nth subband. The goal of the proposed scheme is to maximize cell throughput while satisfying the QoS requirements of all users. This problem is formulated as

Objective function:

$$\max \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K} C_k \cdot x_{m,n,k} \cdot (N_{subcarrier} \times S_{frame}) \tag{3}$$

subject to

$$\text{C1}: \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K} p^{tx}_{m,n,k} \cdot x_{m,n,k} \cdot (N_{subcarrier} \times S_{frame}) = P^{Tx}_{max} \cdot N_{symbol} \tag{4}$$

$$\text{C2}: R^{Up}_m \le (N_{subcarrier} \times S_{frame}) \sum_{n=1}^{N}\sum_{k=1}^{K} C_k \cdot x_{m,n,k} \le R^{Up}_m + R^{Ep}_m \quad \text{for all } m \tag{5}$$

$$\text{C3}: 0 \le \sum_{m=1}^{M}\sum_{k=1}^{K} x_{m,n,k} \le 1 \quad \text{for all } n \tag{6}$$

where C_k represents the amount of bits loaded in a subcarrier with the AMC level of k. P^{Tx}_{max} is the maximum average transmission power for transmitting an OFDM symbol and N_{symbol} is the number of OFDM symbols per frame along the time axis. R_m^{Up} and R_m^{Ep} are the amount of urgent packets and eligible packets of the mth user, respectively. These are provided by the implicit scheduler and the details will be explained in Sect. 3. The proposed scheme is accomplished by obtaining the optimal solution of $x_{m,n,k}$ in (3) while satisfying constraints C1, C2, and C3. C1 in (4) is to ensure the sum of the required transmission power should not exceed the maximum average transmission power of the BS. C2 guarantees the total amount of transmitted packets of the mth user must be larger than R_m^{Up} for QoS guarantee. Furthermore, the subchannels can be allocated to the eligible packets to maximize cell throughput until there are no more subchannels left. The channel allocation block should avoid excessive allocation of the subchannels in a frame for each subband. This can be guaranteed by satisfying C3. Equation (3) to (6) forms an LP problem and the optimal solution can be easily obtained through Simplex algorithm.

3. Implicit Scheduling for Guaranteeing QoS

Implicit scheduler divides the packets in the mth user's buffer into urgent and eligible packets based on their urgency. We define the urgent packets as the ones whose QoS requirements will be violated if they couldn't be sent through the current frame. The eligible packets are defined as the ones which are entitled to be sent through the current frame, but their QoS requirements are not violated even though they fail to be transmitted. Implicit scheduler determines R_m^{Up} and R_m^{Ep} in a way that the Service Curve (SC) can be guaranteed [8]. It is possible to satisfy various QoS requirements by guaranteeing the SC established by considering a variety of QoS requirements [8], [9]. We assume the SC reflecting the QoS requirements of each user is provided perfectly to the BS. The busy time t denotes the elapsed time after the moment when the mth user's buffer changes from idle to busy state. If the buffer becomes empty again, t will be reset to zero. The SC $\sigma_m(t)$ defines the minimum amount of traffic that must be offered to the mth user continuously backlogged for the last time t and it is a non-decreasing function [9]. $\rho_m(t)$ denotes the amount of serviced traffic for the last time t. $\rho_m(t)$ must be greater than or equal to $\sigma_m(t)$ at a given time t to satisfy the QoS requirements. To guarantee this, the implicit scheduler calculates the estimated amount of urgent packets $R_m^{Up,est}(t)$ at a given scheduling moment t by using

$$R_m^{Up,est}(t) = \begin{cases} \sigma_m(t+\Delta) - \rho_m(t) & \text{if } \sigma_m(t+\Delta) \geq \rho_m(t) \\ 0 & \text{if } \sigma_m(t+\Delta) < \rho_m(t) \end{cases} \tag{7}$$

where Δ denotes the scheduling interval between the scheduling time t and the next scheduling time $t + \Delta$. Let us suppose that t_1 is the present scheduling moment in Fig. 3. In case $\rho_m(t_1)$ at the time t_1 is less than $\sigma_m(t_1 + \Delta)$ at the next scheduling time $t_1 + \Delta$, the packets equivalent to the amount of the difference between $\sigma_m(t_1 + \Delta)$ and $\rho_m(t_1)$ will violate the QoS requirements unless they are transmitted at the time t_1. Therefore, the urgent packet pointer is set to indicate the amount of $R_m^{Up,est}(t)$ from the beginning of the mth user's buffer. Next, the implicit scheduler calculates the estimated amount of eligible packets $R_m^{Ep,est}(t)$ at the scheduling moment t by using

$$R_m^{Ep,est}(t) = \mu_m(t) - \rho_m(t) - R_m^{Up,est}(t). \tag{8}$$

The maximum traffic bound curve $\mu_m(t)$ in Fig. 3 represents the maximum amount of traffic that can be transmitted to the mth user continuously backlogged for the time t. $\mu_m(t)$ is assumed to be derived by using the minimum latency for guaranteeing jitter requirements. $\mu_m(t)$ must be greater than $\sigma_m(t+\Delta)$ to be valid. Then the eligible packet pointer is set to indicate the amount of difference between $\mu_m(t)$ and $\rho_m(t)$ from the beginning of the buffer. For the traffic without jitter constraints, the eligible packet pointer can simply be located at the end of the buffer so that more eligible packets can have chances to be scheduled. Now the actual $R_m^{Up}(t)$ and $R_m^{Ep}(t)$ are determined according to $\tau_m(t)$ by using

$$\begin{cases} R_m^{Up}(t) = \tau_m(t), R_m^{Ep}(t) = 0 \\ \qquad \text{for } R_m^{Up,est}(t) \geq \tau_m(t) \geq 0 \\ R_m^{Up}(t) = R_m^{Up,est}(t), R_m^{Ep}(t) = \tau_m(t) - R_m^{Up,est}(t) \\ \qquad \text{for } R_m^{Ep,est}(t) + R_m^{Up,est}(t) \geq \tau_m(t) > R_m^{Up,est}(t) \\ R_m^{Up}(t) = R_m^{Up,est}(t), R_m^{Ep}(t) = R_m^{Ep,est}(t) \\ \qquad \text{for } \tau_m(t) > R_m^{Ep,est}(t) + R_m^{Up,est}(t) \end{cases} \tag{9}$$

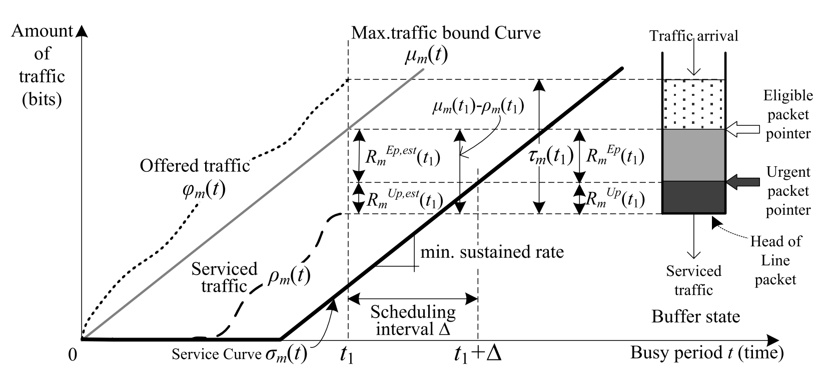

Fig. 3 Example of determining R_m^{Up} and R_m^{Ep} based on SC $\sigma_m(t)$.

where $\tau_m(t)$ represents the total amount of packets in the mth user's buffer at a given time t. $\tau_m(t)$ can simply be obtained by subtracting $\rho_m(t)$ from $\varphi_m(t)$. $\varphi_m(t)$ denotes the actual amount of offered traffic to the mth user for the last time t. Implicit scheduler provides the channel allocation block with R_m^{Up} and R_m^{Ep} as QoS constraints.

If the feasible solution of (3) cannot be found, the implicit scheduler leaves out a user among all users one by one based on the lead index $\delta_m(t)$ of each user. The lead index $\delta_m(t)$ at a given t of the mth user's buffer is defined as

$$\delta_m(t) = \rho_m(t) - \sigma_m(t). \tag{10}$$

If no feasible solution can be found at a given scheduling moment t, the implicit scheduler finds

$$\hat{m} = \arg\max_m \{\delta_m(t)\}. \tag{11}$$

The implicit scheduler leaves out the user $\hat{m}$ among all users. Then, we find the feasible solution of (3) for the remaining users except $\hat{m}$. This operation is performed until the feasible solution can be obtained.

4. Numerical Results

For the performance evaluation, we considered the frame size of 32 subbands and 12 slots based on [6]. Each subchannel has 48 subcarriers. A subband is composed of 24 adjacent subcarriers and the bandwidth of a subcarrier is 9.765625 KHz. An OFDM symbol duration is assumed to be 115.2 μs. Full buffered traffic model was used and the buffer size of each user is assumed to be sufficiently large. We assume that minimum sustained rate r_m and the PER_m of 1% are the QoS requirements for the mth user's traffic. The AMC sets in Table 1 were used to satisfy the PER_m of 1% [7]. We derived average cell throughput when r_m is 0,128 or 256 kbps. We assume that all users have the same QoS requirements. It is assumed the BS perfectly knows the channel conditions of all users. The SC of the mth user is assumed to be

$$\sigma_m(t) = r_m \cdot t. \tag{12}$$

The cell throughput and the cumulative distribution function (CDF) of user throughput of our proposed scheme are compared with those of the MAX-C/I and PF scheduler. The CDFs of user throughput were derived when 10 users are distributed uniformly. The time scale factor† t_c in [4] for the PF scheduler is considered to be 5,000. The r_m of 256 kbps is imposed to the MAX-C/I and PF scheduler. In Fig. 4, MAX-C/I scheduler achieves the highest average cell throughput because it only aims at the maximization of cell throughput by allocating each subchannel to a user with the best channel quality for each subchannel. This leads about 90% of users to violate their QoS requirements as shown in Fig. 5. On the other hand, PF scheduler allocates each subchannel to a user when its channel quality is high relative to its own average channel condition. This makes the fairness among users improved compared to MAX-C/I scheduler. In Fig. 5, the QoS requirements of about 75% of users are guaranteed by PF scheduler but we cannot expect its cell throughput as high as that of MAX-C/I scheduler. In contrast, our proposed scheme guarantees excellently the QoS requirements of all users as shown in Fig. 5. Moreover, the proposed scheme increases the cell throughput drastically as in Fig. 4. In case r_m is 0 kbps, that is, when we have no urgent packets, our proposed scheme operates as MAX-C/I scheduler by allocating each subchannel to a user with the best channel quality for each subchannel. In case of 128 kbps or 256 kbps, the proposed scheme using Simplex algorithm allocates subchannels in a way that the required amount of subchannels for the transmission of the urgent packets is minimized. If we still have unallocated subchannels after completing the allocation of the urgent packets, each surplus subchannel is allocated to the eligible packets of a user in the best channel condition for each subchannel such as MAX-C/I scheduler. For this reason, about 90% of users attain their throughput as much as the minimum sustained rate and the remaining 10% of users achieve much higher throughput than others as shown in Fig. 5.

Table 1 AMC sets@1% packet error rate.

k	Modulation & Coding	C_k	required SINR(dB)
1	QPSK+1/12	1/6	−3.9
2	QPSK+1/6	1/3	−1.6
3	QPSK+1/3	2/3	1.5
4	QPSK+1/2	1	4.3
5	QPSK+2/3	4/3	7.95
6	16QAM+1/2	2	9.3
7	16QAM+2/3	8/3	13.1
8	16QAM+3/4	3	15.8
9	64QAM+2/3	4	18.5
10	64QAM+5/6	5	24.8

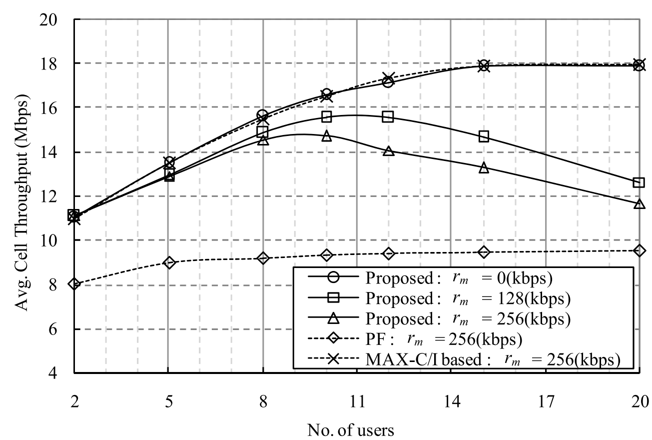

Fig. 4 Average cell throughput according to scheduling schemes.

†This can also be called time window length. t_c is the notation used for the average throughput calculation of the PF scheduling metric in [4].

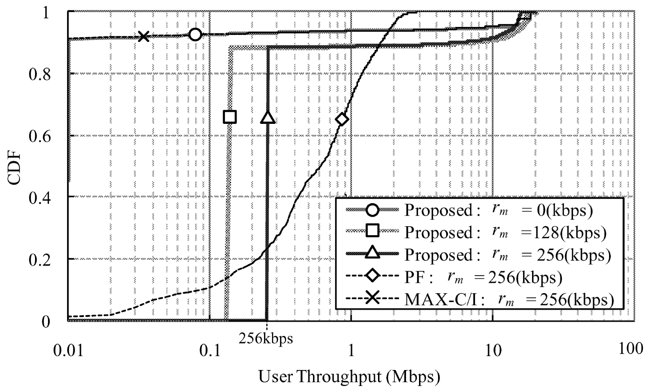

Fig. 5 CDF of user throughput for 10 users.

5. Conclusion

In this letter, the QoS requirement of each user was taken into account in such a way that channel allocation can maximize cell throughput while guaranteeing the QoS requirements through the rate maximization LP problem for multichannel systems. We also suggested the implicit scheduling to meet QoS requirements. Our results show that cell throughput can be maximized efficiently under the given QoS constraints by using the proposed scheme.

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