A Cross-layer Resource Allocation Scheme with Guaranteed QoS in Multiuser OFDM Systems

Feng Han Yingzhuang Liu* Guangxi Zhu
Department of Electronics and Information
Huazhong University of Science and Technology
Wuhan, China

Abstract—Adaptive resource management has become a key technique for the next-generation wireless systems. In this paper, we propose a cross-layer adaptive resource allocation and scheduling approach for downlink multiuser OFDM systems. Different from adaptive resource allocation schemes proposed earlier, the distinctive feature of the cross-layer optimization methodology is the joint design of the multiuser subcarrier, bit and power allocation in the physical layer along with the packet scheduling in the data link layer. Simulations results show that the proposed cross-layer optimization and design approach achieves significant gains in both throughput and average packet delay compared to the traditional resource allocation scheme without consideration of the cross-layer interactions.

I. INTRODUCTION

The allocation and management of resources are crucial for wireless networks, in which multiple users share the scarce wireless radio resources and stringent energy constraints. However due to the inherent time-varying characteristic of wireless channels, the traditional layered networks architecture in which each layer is designed and operated independently, results in inefficient resource use in wireless networks. So, it is necessary to implement more efficient protocols through a cross-layer approach [1].

Recently, orthogonal frequency division multiplexing (OFDM) has attracted significant research interest for supporting high-speed transmission for future wireless communications. OFDM is demonstrated as an efficient way to mitigate the negative effects of frequency selective fading associated with multi-path fading by transmitting over flat faded parallel narrow-band channels. The inherent multi-carrier nature of OFDM also allows the use of subcarrier allocation, adaptive modulation, and power distribution to significantly enhance the system performance [2-5]. Besides, packet scheduling at the data link layer is another critical component which allocates the bandwidth resources at a packet level to provide QoS guarantees as well as fairness among users [6-8].

In the literature, there have been many works on adaptive resource allocation in multiuser OFDM system [2-5]. However, these algorithms are mainly confined to the physical layer without considering the queuing behaviors and traffic arrival observed in the data link layer. It should be mentioned that a cross-layer link-adaptive packet scheduling for real-time traffics in multiuser OFDM network is introduced to provide QoS guarantees [9]. However this algorithm simplifies the problem only considering per-link throughput maximization under constraint of transmission power of each user. Similarly, a joint MAC-PHY layer resource allocation algorithm for delay insensitive services is proposed in [10] and it is only confined to a fixed capacity in the physical layer by performing fixed modulation level.

In this paper, we are motivated to propose a cross-layer adaptive resource allocation algorithm with QoS guarantee for OFDM downlink systems. The adaptive subcarrier, bit, and power allocation at the physical layer and packet scheduling at the data link layer are jointly designed to take advantage of inter-dependencies between these two layers. The main goal of this algorithm is to maximize the sum rate of OFDM system under the constraints of the total power and the maximum bit error rate as well. Specially, based on the exact instantaneous channels status information, an adaptive multiuser subcarrier, bit, and power allocation under total power constraint and bit error rate for each user is performed in the physical layer. The allocation results are then passed up to the data link layer. The scheduler in the data link layer then schedules packets of different user queue, which takes the allocation results, quality of service (QoS) requirement and user fairness into consideration. After that, the physical layer reallocates the resources dynamically to guarantee QoS. To provide attractive tradeoff between throughput maximization and fairness among users, we extend PF scheduler much used in single carrier environment into the multi-carrier system. Simulation results confirm that our cross-layer scheme performs better than the traditional one.

The remainder of this paper is organized as follows. The system model and frame structure of the proposed algorithm is described in the next section. In section 3, the detailed adaptive resource allocation scheme is presented. In section 4, we investigate the performance of the proposed system and compare with the traditional resource allocation scheme. Finally, we conclude the paper.

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II. SYSTEM MODEL

We consider a downlink OFDM system where the base station (BS) serves M users. And we assume that the overall bandwidth B is divided into N orthogonal narrow-band subcarriers. At data link layer, a separate queue is maintained for each user at the BS which is assumed to have infinite lengths. Within each queue, packets are served in an FIFO (First in first out) order. Across queues, PF scheduler determines service discipline based on the allocation results in the physical layer, QoS requirement and packet arrival. At the physical layer, the channel state information (CSI) is assumed to be delivered to BS through an error-free feedback channel. According to the PF scheduling results, the physical layer reallocates radio resources accordingly. The modulated signals are transmitted after inverse fast Fourier transform (IFFT), parallel to serial (P/S) conversion, and guard interval insertion. The time axis is divided info frames and a frame is further divided into a control part and a data part which contains S OFDM symbols.

III. ALGORITHM DESCRIPTION

The cross-layer resource allocation scheme may include three phases as follows.

A. Resource Allocation in Physical Layer

Here we assume that each subcarrier is narrow enough to undergo flat fading. The goal of resource allocation is to allocate the subcarriers and transmission power so that the system throughput is maximized, while the QoS requirements of each user are satisfied. Here we consider one QoS requirement: bit error rate (BER). Under the assumptions above, the received signal-to-noise ratio (SNR) of the nth subcarrier signal for the m th user at the s th OFDM symbol can be expressed by $\gamma_{m,n}(s)=\dfrac{p_{m,n}(s)\cdot g_{m,n}(s)}{N_0B/N}$ where $p_{m,n}(s)$, $g_{m,n}(s)$ and N_0 are the allocated transmission power, the channel gain, and power spectral density of AWGN, respectively. Assuming that QAM modulation and ideal phase detection are used, the instant service rate at the nth subcarrier for the m th user by the upper bound on BER can be expressed as $c_{m,n}(s)=\dfrac{B}{N}\log_2(1+\dfrac{r_{m,n}(s)}{\Gamma_m})$ where $\Gamma_m=-\ln(5BER_m)/1.5$. Noting that Γ_m is usually called SNR gap, as it is caused by the gap between practical implementations and information-theoretic results [11].

Let us introduce $\alpha_{m,n}(s)$, referred to as the subcarrier allocation indicator, to show whether the nth subcarrier of the s th OFDM symbol is allocated to the k th user or not.

$$\alpha_{m,n}(s)=\begin{cases}0 & if\ c_{m,n}(s)=0\\ 1 & else\end{cases} \qquad (1)$$

As in [3], we assume that each subcarrier can be allocated to only one user. This implies that $\alpha_{m,n}(s)$ satisfies $\sum_{m=1}^{M}\alpha_{m,n}(s)=1$ for all subcarriers and OFDM symbols. In this case, the achievable data rate of the m th user in a frame can be calculated as $R_m=\sum_{n=1}^{N}\sum_{s=1}^{S}\alpha_{m,n}(s)\cdot c_{m,n}(s)$ and the system throughput in a frame is given as $T=\sum_{m=1}^{M}R_m$.

In summary, the resource allocation considered in this paper can be formulated as

$$\max_{\alpha,p}\frac{B}{N}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{s=1}^{S}\alpha_{m,n}(s)\cdot\log_2(1+\frac{p_{m,n}(s)\cdot g_{m,n}(s)}{\Gamma_m N_0 B/N}) \qquad (2)$$

where the maximization is subjected to the constraints of

C1 total power constraint: $\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{s=1}^{S}p_{m,n}(s)\le P_T\ \&\ p_{m,n}(s)\ge 0$

C2 $\forall n\in\{1,2,\cdots N\}, s\in\{1,2,\cdots S\}$, if m' with $\alpha_{m',n}(s)\neq 0$ exists, then $\alpha_{m,n}(s)=0, \forall m\neq m'$

C3 BER requirement: $BER_m, m=1,2,\cdots M$.

As in [3], the subcarrier should be allocated only one user who has the best channel gain for that subcarrier to maximize the system throughput. By using the Lagrange multiplier method similar to that in [3], we can conclude the allocated power as

$$p_{m',n}(s)=\frac{N_0B\Gamma}{N}\left[\frac{1}{\lambda_0}-\frac{1}{g_{m',n}(s)}\right]_+ \qquad (3)$$

where the subscript $m'=\arg\max_m\{g_{m,n}(s)\}$ and $[x]_+\triangleq\max\{x,0\}$. The Lagrange multiplier λ is determined by C1. Then R_m, the allocated bits per frame for user m can be achieved and passed up to the data link layer for PF scheduler.

It should be noted that the adaptive resource allocation is solved assuming a continuous rate adaptation, i.e., $c_{m,n}(s)$ is a continuous nonnegative variable. However, in realistic system, $c_{m,n}(s)$ is restricted to a fixed set of nonnegative integer values according to different modulation types. Due to this additional constraint, no closed-form solution is available. In this case, the optimal resource allocation can be achieved by a greedy solution, which initially assigns zero bits to all subcarriers and then allocates bit by bit to the subcarrier that requires the least additional transmission power. The process is repeated until the upper bound of the total transmission power is reached. We use this greedy algorithm for each OFDM symbol frame.

B. *Packet Scheduling in Link Layer*

The resource allocation results in the physical layer reflect the multiuser diversity and high frequency efficiency. However, it only considers the characteristic inherent in physical layer without considering the link layer traits. To optimize the system performance, the scheduler in the data link layer should take these allocation results into consideration, so that more packets can be scheduled when the channel condition is good and vice versa as well as fairness is guaranteed. In this paper, we adopt proportional fair (PF) schedule in the data link layer to improve system efficiency.

As part of HDR of HSDPA standards, PF scheduler can provide reasonable tradeoff between throughput, delay jitter, and fairness [6]. According to the PF scheduling policy, the user selected to receive a transmission from the BS in the nth time slot is decided by $J = \max_{1 \le m \le M} \frac{K_m}{K_m^{avg}}$ where K_m is the instantaneous rate of the m th user and K_m^{avg} is the average throughput which is updated as $K_m^{avg}(t+1) = (1-\frac{1}{t_c})K_m^{avg}(t) + \frac{1}{t_c}K_m(t)$. Of them $K_m(t) = K_m$ if the k th user is chosen for transmission during time slot t and $K_m(t) = 0$ otherwise. By adjusting t_c, the desired tradeoff between throughput and fairness can be adjusted. In general, the higher the value of t_c, the larger is the total achieved throughput and the more is the unfairness among users and vice versa [6].

Here we extend PF scheduling to multi-carrier system as follows:

Step 1: According to R_m which is conveyed from the physical layer, the J user can be selected to receive transmission. Assuming the m th user is selected, N_m packets can be scheduled and N_m is given as $N_m = \min([\frac{R_m}{L_m}], q_m)$ where L_m is the packet length of the m th user, and $[x]$ means the integer number no larger than x. And q_m is the queue length of the user m.

Step 2: For residual users, step 1 is repeated until the maximized physical rates are reached. That is to say, only $\sum_{i=1}^{M'} N_i L_i \le \sum_{m=1}^{M} R_m$ is satisfied, step 1 is repeated where i is the user who is scheduled by the PF scheduler and M' is the number of them.

C. *Resource Reallocation in Physical Layer*

With the scheduling results, N_m packets for each user should be transmitted in a frame. So one additional constraint is needed for the original problem. C4 $R_m \ge N_m \cdot L_m \quad \forall m$

Due to the additional constraints, the resource reallocation becomes more complicated. Here we bring out a suboptimal algorithm. Similar to the first resource allocation in the physical layer, we adopt greedy algorithm for each user to allocate subcarrier and power and check if C4 is satisfied. If C4 is not satisfied for the m th user, we stop the subcarrier allocation for the user, and continue this process again to allocate the residual subcarriers to the residual users until all the packets or subcarriers are allocated completely. Two cases in the end may happen as follows:

(1) All packets are allocated completely and unused subcarriers still exist. In this case, more packets can be selected to transmit by the PF scheduler. Here we only schedule the packets passed down from the data link layer due to the simplification of the algorithm.

(2) All subcarriers are allocated completely. This means that the reallocation results may be larger than the scheduling results. Then the packets including the redundant bits are sent back to the specified user's queue.

IV. NUMBERICAL RESULTS

In this section, we present simulation results to show the performance of the proposed resource algorithm. Table I shows the simulation parameters. The wireless channel is modeled as a frequency-selective channel consisting of six independent Rayleigh multipaths. Each multipath component is modeled by Clarke's flat fading model. It is assumed that the power delay profile is exponentially decaying with e^{-2l}, where l is the multipath index. And the user location is assumed to be uniformly distributed. In the following, we define the total SNR as $P/(N_0 B)$ and evaluate the average system throughput through 200 independent simulation runs. For all users, we assume that $BER_m = 10^{-4}$. In the data link layer, we assume there are infinite packets waiting to be scheduled, and the packet size is fixed as 100 bits for all users for simplicity. In our simulation, we assume $t_c = 1000$ just as [6].

The number of subcarriers	64
Guard interval	8
Channel	6-paths Rayleigh fading exponential decaying channel
Bandwidth	10MHz
User number	6
Packet length	100bits
Round trip time(RTT)	500ns

TABLE 1: simulation parameters

In contrast to our cross-layer design, traditional design conducts no communication between the physical layer and the link layer. So in traditional design, the scheduler schedules the packets in a predetermined time interval regardless of the capacity change of the physical layer although it performs resource allocation in physical layer. The same packets for each user are assumed to transmit.

In Fig. 1, we show the average throughput of the proposed cross-layer algorithm for various total SNR, and compare it with that of the traditional algorithm. The proposed algorithm is shown that higher average system throughput is achieved than the traditional one especially when total SRN is high. At low SNR, the difference of average system throughput is small since the available power is small. As the total SNR becomes higher, the proposed algorithm performs apparently better than the traditional one. The reason is that, for high transmitting power, it is desired to transmit more packets as possible. However link layer scheduler of traditional algorithm still schedule fixed packets as well regardless of the capacity change of physical layer. Hence, the performance of cross-layer algorithm achieves higher average throughput due to the interaction of link layer and physical layer.

Fig 2 shows the performance of the average packet delay for the proposed algorithm and the traditional one. At low SNR, the cross-layer scheme achieves much shorter delay than the traditional one. This is because at low SNR, a large number of retransmissions will occur due to the lack of interactions between the link layer and physical layer. Specially, the scheduler in link layer still schedules the packets in a predetermined time interval even if the link is in poor conditions. It can be seen that until SNR is 15 dB or so, the packet delay becomes stable for traditional one. At this time, the packets scheduled by the link layer are all transmitted successfully. However, as the SNR is high, the traditional algorithm achieves shorter packet delay. This is mainly because that more packets can be transmitted and more time is needed by cross-layer scheme.

V. CONSLUSIONS

In this paper, we introduce a novel cross-layer scheme for multiuser OFDM downlink system. This design jointly implements the scheduling in the link layer and the multiuser adaptive subcarrier, bit and power allocation in the physical layer. In addition, we extend the PF scheduler to multi-carrier system in the data link layer that provides a good tradeoff between throughput and fairness. Simulation results show that the proposed cross-layer algorithm can achieve significant improvement in packet delay and throughput than the traditional layered one.

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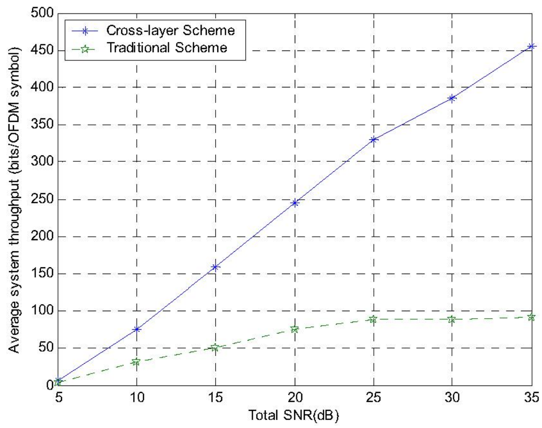

Fig1. Average system throughput versus total SNR

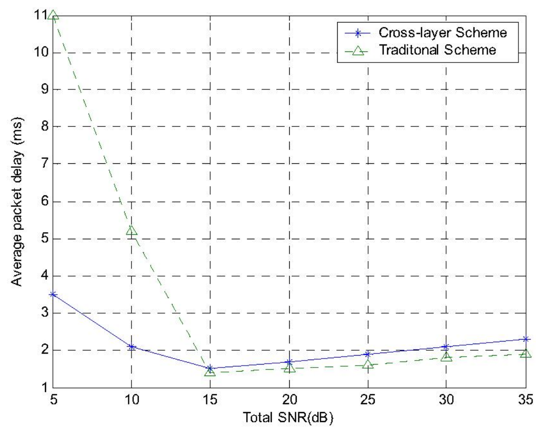

Fig2. Average packet delay versus total SNR