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An OFDM-TDMA/SA MAC Protocol with QoS Constraints for Broadband Wireless LANs*

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Abstract. Orthogonal frequency division multiplexing (OFDM) is an important technique to support high speed transmission of broadband traffic in wireless networks, especially broadband wireless local area networks (LANs). Based on OFDM, a new multiple access scheme, called OFDM-TDMA with subcarrier allocation (OFDM-TDMA/SA), is proposed in this paper. It provides more flexibility in resource allocation than other multiple access schemes such as OFDM-TDMA, OFDM-frequency division multiple access (OFDM-FDMA), and orthogonal frequency division multiple access (OFDMA). With OFDM-TDMA/SA, a medium access control (MAC) is designed for broadband wireless LANs. It optimizes bit allocation in subcarriers so that maximum bits are transmitted in each OFDM symbol under a frequency selective fading environment. The OFDM-TDMA/SA MAC protocol also supports three classes of traffic such as guaranteed, controlled-load, and best effort services. Based on the optimum subcarrier bit-allocation algorithm and considering heterogeneous QoS constraints of multimedia traffic, a hierarchical scheduling scheme is proposed to determine the subcarriers and time slots in which a mobile terminal can transmit packets. In such a way, the OFDM-TDMA/SA MAC protocol significantly increases system throughput in a frequency selective fading environment and guarantees QoS of multimedia traffic. Computer simulation is carried out to evaluate the performance of the OFDM-TDMA/SA MAC protocol. Results show that the new MAC protocol outperforms other MAC protocols for OFDM-based wireless LANs.

Keywords: orthogonal frequency division multiplexing (OFDM), time division multiplexing access (TDMA), medium access control (MAC), subcarrier allocation (SA), quality of service (QoS), wireless LANs

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation scheme, which provides a promising solution to the intersymbol interference (ISI) problem in wideband transmission over multipath fading channels [2,17]. It has become an important technique for next generation wireless networks. For example, OFDM has been applied to IEEE 802.11 wireless local area networks (LANs) [3], HiperLan/2 [8], and IEEE 802.16 fixed wireless broadband access systems [7].

Based on OFDM, several multiple access schemes have been proposed:

- *OFDM-time division multiple access (OFDM-TDMA).* In this scheme, OFDM symbols in one time slot is the minimum resource unit that can be allocated to a user [3,17]. Thus, subcarriers of one OFDM symbol cannot be allocated to different users. This limitation reduces the flexibility of resource allocation, especially when the capacity of a time slot is very high.
- *OFDM-frequency division multiple access (OFDM-FDMA).* Subcarriers can be allocated to different users in this scheme [3,17], and are multiplexed as FDMA. In OFDM-interleaved-FDMA [17], the subcarriers allocated to a user do not need to be consecutive, and thus, the subcarriers of different users are interleaved. However, the subcarriers allocated a user are fixed on time axis because no TDMA structure exists. Thus, resource allocation is not flexible in OFDM-FDMA.
- *OFDM-code division multiple access (OFDM-CDMA).* In an OFDM-CDMA system [19], data symbols are first spread across the frequency domain. Then, the spread data symbol is modulated with OFDM technique. OFDM-CDMA can achieve small bandwidth granularity, so the resource allocation can be more flexible than OFDM-TDMA and OFDM-FDMA. OFDM-CDMA has non-zero same-cell interference. Also, high-throughput modulations cannot be applied to uplink CDMA due to limited achievable carrier to interference ratio (CIR) [11].
- *Orthogonal frequency division multiple access (OFDMA).* Subcarrier allocation to a user is allowed in OFDMA. However, subcarriers allocated to a user in a subchannel are selected through a pseudorandom process [11]. This solution does not really improve the flexibility of resource

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allocation, because subcarriers for a user are not necessarily distributed into different groups of subcarriers.

In order to enhance the flexibility of resource allocation for an OFDM-based multiple access scheme, a more effective multiple access scheme is needed. Such a scheme cannot cause too much complexity in resource allocation. With those requirements in mind, a new multiple access scheme, which is called OFDM-TDMA with subcarrier allocation (OFDM-TDMA/SA), is proposed. It has the following features:

- OFDM symbols are organized in a TDMA frame.
- Subcarriers in a OFDM symbol in both uplink and downlink can be allocated to different users.
- Subcarriers allocated to one user do not need to be consecutive in either frequency axis or time axis.
- Subcarriers allocated one user do not need to fixed at different frames.
- Bandwidth granularity can be very small, e.g., as small as one subcarrier per frame.

It should be noted that OFDM-TDMA/SA is different from the multiple access scheme proposed in [2], where different frame structures are used for large radio and small radios resources. Mixed assignment of large and small radio resources under the same frame structure is not investigated in [2].

Two issues in OFDM-TDMA/SA need to be pointed out. First, since the uplink transmission is asynchronous among different mobile terminals, both time and frequency synchronization for those mobile terminals must be guaranteed. To date, several schemes [14,15] have been proposed to solve this problem. In this paper, time and frequency synchronization in the uplink is assumed to be accurate. Otherwise, orthogonality among subcarriers would be destroyed [15]. Second, since subcarrier allocation is also allowed in the uplink, the resource mapping between subcarriers in various time slots and mobile terminals need to be informed to mobile terminals in the downlink. However, the large number of subcarriers in a frame may need a huge resource mapping table, which causes very high overhead. In order to solve this problem, a novel resource mapping scheme is proposed in this paper.

OFDM-TDMA/SA enables flexible resource allocation. However, in order to deliver multimedia traffic with QoS constraints in a broadband wireless LAN, two more issues need to be considered:

- *Frequency selective fading environment.* In a broadband OFDM-based wireless LAN, wide channels have the feature of frequency selective fading instead of flat fading [12]. Thus, subcarriers in different frequency bands experience different channel fading. When a subcarrier experience deep fade, it cannot carry any information bits due to the power constraint. However, as pointed out in [17], it is very unlikely that a subcarrier is in deep fade for all mobile terminals in the same system, because the channel fading of these mobile terminals are mutually independent. Thus, optimum bit allocation in subcarriers is necessary so that maximum bits can be transmitted in an OFDM symbol.
- *Heterogeneous QoS constraints of different services.* In this paper, multimedia traffic is categorized into three services, i.e., guaranteed service, controlled-load service, and best effort service. As specified in IETF standards [13,18], QoS constraints of these three services are much different from one another. Thus, the resource allocation scheme must be carefully designed so that resource can be efficiently utilized and QoS of each service is guaranteed.

To take into account these two important issues, a medium access control (MAC) protocol is designed based on OFDM-TDMA/SA. In this protocol, an optimum subcarrier bit-allocation algorithm is derived to determine the number of bits allocated to each subcarrier. In this algorithm, given the bit error rate (BER) requirement of a service and the maximum allowed transmit power in a subcarrier, the number of bits allocated to all subcarriers is maximized. Thus, it is different from the bit-allocation algorithm in [17], where the transmit power in all subcarriers are optimized. It is also different from the rate adaptation (RA) algorithm [9], which maximize user's minimum throughput subject to power constraints. In the OFDM-TDMA/SA MAC protocol, a hierarchical scheduling scheme is also proposed to allocate subcarriers and time slots to each mobile terminal by considering its QoS constraint. The optimum subcarrier bit-allocation algorithm is embedded in the scheduling scheme. As a result, throughput of an OFDM system under a frequency selective fading environment is increased significantly, and QoS of multimedia traffic is guaranteed. The OFDM-TDMA/SA MAC protocol outperforms other MAC protocols for OFDM systems [1,3].

This paper is organized as follows. The basic operation procedure of the OFDM-TDMA/SA is described in Section 2. The optimum subcarrier bit-allocation algorithm used in the OFDM-TDMA/SA MAC protocol is derived in Section 3, while the hierarchical scheduling scheme is proposed in Section 4. The performance of the OFDM-TDMA/SA MAC protocol is evaluated through computer simulation in Section 5. The paper is concluded in Section 6.

2. The OFDM-TDMA/SA MAC protocol

A broadband wireless LAN based on multiuser OFDM technique is considered in this paper. Channel fading in the broadband wireless LAN is assumed to be frequency selective. In this system, subcarriers of an OFDM symbol of both uplink and downlink can be allocated to different mobile terminals. The number of bits allocated to a subcarrier is dynamically determined according to channel fading experienced by the mobile terminal that owns the subcarrier. Since uplink transmissions from different mobile terminals are asynchronous, frequency and time synchronization schemes such as that in [15] must be used in the uplink.

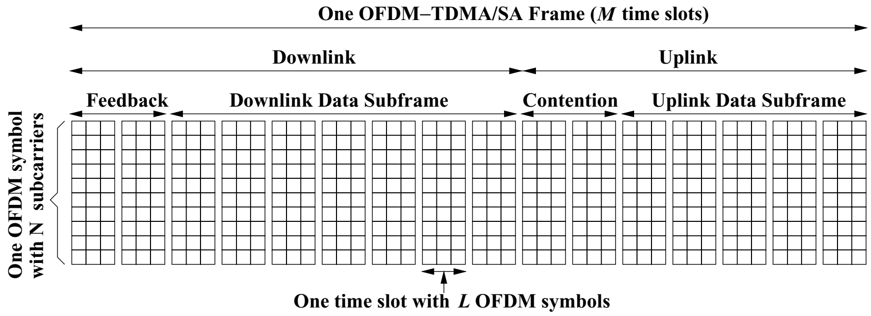

Figure 1. OFDM-TDMA/SA frame structure.

2.1. Frame structure of OFDM-TDMA/SA

In order to achieve flexible resource allocation for both high and low traffic rate applications and implement channel-adaptive subcarrier bit-allocation algorithm for multimedia services under a frequency selective fading environment, OFDM-TDMA/SA is proposed as the multiple access scheme for the broadband wireless LAN under consideration. The OFDM-TDMA/SA frame structure is shown in figure 1. There are M time slots in each frame, L OFDM symbols in each time slot, N subcarriers in each OFDM symbol, and K bits in each subcarrier. Since each mobile terminal experience different frequency selective fading, the subcarrier allocated to a different mobile terminal supports a different number of bits. Thus, K is a parameter that needs to be optimized by the resource allocation algorithm. M, N, and L are system parameters that can be determined in the phase of system design. The OFDM-TDMA/SA is a time division duplex (TDD) system, i.e., uplink and downlink is duplexed in time division. In the first part of downlink is the feedback subframe. The resource allocation information about both uplink and downlink transmissions are transmitted to mobile terminals in this subframe. In the uplink, the first subframe is control subframe in which mobile terminals send request messages such as connection admission requests and packet transmission requests.

Subcarriers in time slots of downlink and uplink data subframes are allocated to mobile terminals according to their QoS requirements. Each subcarrier can be assigned to any mobile terminal and subcarriers allocated to a mobile terminal are not necessarily selected according to a pseudorandom process, which is much different from the subcarrier allocation in OFDMA. The subcarriers allocated to different services in a frame are totally interleaved, and no separate subframe is dedicated to a certain service. Due to this feature, a resource mapping table must be sent to mobile terminals in the feedback subframe. The table needs to have two entries for each subcarrier. One entry is the ID of the mobile terminal that owns a subcarrier, and the other is the number of bits allocated to this subcarrier. Since in a TDD system the power level used by a subcarrier can be determined based on the number of bits allocated to the subcarrier [17], no entry is required in the mapping table to specify the power level of a subcarrier. In an OFDM-TDMA/SA frame, there are $M \times L \times N$ subcarriers, which is a very large number. To convey such information from the base station to mobile terminals will cause a large amount of overhead. In order to reduce the overhead, two schemes need to be used. In the first scheme, continuous subcarriers with similar fading characteristics are considered as one group. Thus, each entry in the resource mapping table corresponds to a group of subcarriers instead of single subcarriers. However, in a frequency selective fading environment, the number of subcarriers in a group is small. Moreover, the small number of subcarriers in a group is preferred in order to achieve good bandwidth granularity. Therefore, the first scheme cannot significantly reduce the overhead. In this paper, an additional scheme is proposed to use one OFDM symbol to convey resource allocation information. The structure of the OFDM symbol for conveying resource allocation information is designed according to figure 2, where a dashed line with arrow illustrates the mapping relationship between an item of resource allocation information in the resource mapping table (i.e. the resource mapping OFDM symbol) and the resource unit. As shown in figure 2, subcarriers of an OFDM symbol are clustered into N_g groups, so the number of subcarriers in each group is $\frac{N}{N_g}$. In addition, subcarriers SC_j of group i in the resource mapping OFDM symbol are used to convey resource allocation information of i-th group of subcarriers in time slot j of the OFDM-TDMA/SA frame, and the overall number of time slots for both uplink and downlink transmission of multimedia traffic is M_t. Given a resource unit (i.e. a group of subcarriers in one time slot such as group i in time slots TS_j), f subcarriers in the resource mapping OFDM symbol are used to convey the resource mapping information. Some bits in the f subcarriers indicate the ID of the mobile terminal (or a traffic flow of the mobile terminal) that owns the resource unit, while the remaining bits specify the number of bits allocated to each subcarrier in the resource unit. Thus, the total subcarriers that are used to convey resource mapping information is $N_t = f \times N_g \times M_t$. If M_t is equal to $\frac{N}{fN_g}$, then $N_t = N$, i.e., one OFDM symbol is consumed to convey the resource mapping information. Thus, the overhead for sending resource mapping information is significantly

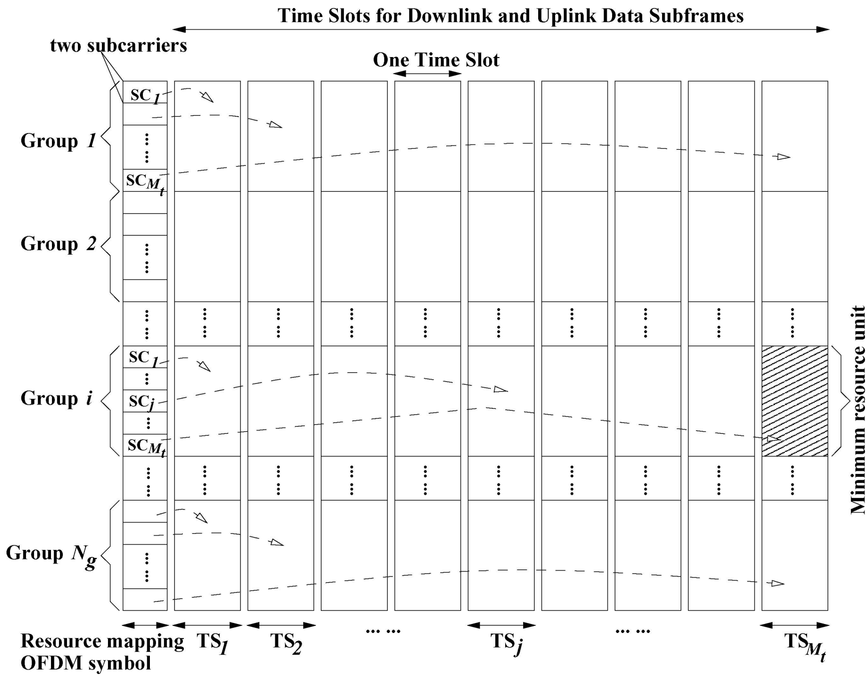

Figure 2. A new resource mapping scheme.

reduced. Considering the variable channel quality, subcarriers in the resource mapping symbol adopt robust modulation scheme. In addition, when BER drops below an acceptable level, higher transmission power is applied as a backup plan.

2.2. *Operation of the OFDM-TDMA/SA MAC protocol*

Based on the frame structure shown in Figure 1, an OFDM-TDMA/SA MAC protocol is proposed. Two important issues are considered in the MAC protocol. One is the optimum bit allocation for each subcarrier of a mobile terminal under frequency selective fading environment. The other is support of multimedia traffic with different QoS constraints. In this paper, the multimedia traffic is categorized into three classes, i.e., guaranteed service, controlled-load service, and best effort service. The operation procedure of the MAC protocol is described as follows. It is focused on the uplink transmission of multimedia traffic. The downlink transmission follows the similar but simpler procedure due to the broadcast nature.

- *Send QoS and traffic specifications.* Before a mobile terminal starts a communication, it needs to send its QoS and traffic specifications to the base station. Such a message is sent in the control subframe in the uplink. In addition to QoS and traffic specifications, the message includes a mobile terminal ID, which is obtained when the mobile terminal subscribes to the network, and service type that the mobile terminal will deliver. The QoS and traffic specifications of guaranteed and controlled-load services are described in [13,18], respectively. In brief, guaranteed service is proposed for real-time applications with tight delay guarantees. Thus, its constant traffic rate must be guaranteed. Controlled-load service is used for adaptive real-time applications, and policing is applied to each traffic flow of controlled-load service. Two requirements must be satisfied for conforming packets after policing: (a) little or no average packet queueing delay over all time scales significantly larger than the burst time, and (b) little or no congestion packet loss. Thus, the traffic rate that is equivalent to the mean rate of policed traffic must be guaranteed. For best effort service, no guarantee is required on traffic rate, but packet loss is not allowed.
- *Send packet transmission request.* For controlled-load and best effort services, the traffic rate changes frame-by-frame. Thus, the packets generated in each frame varies. Such time-varying information is needed by the scheduling scheme at the base station side when performing resource allocation, so it must be sent to base station. In order to reduce signaling overhead, piggyback is used to send such information.
- *Schedule packet transmissions.* The packet transmissions of all service types are scheduled frame-by-frame. In such a way, the subcarrier in each time slot can be utilized as efficiently as possible. In a frequency selective fading environment, a subcarrier experiences different channel fading when it is assigned to different mobile terminals. Therefore, the number of bits that it can deliver varies depending on which mobile terminal it is assigned. When a subcarrier is allocated to a certain mobile terminal, it means that the largest number of bits can be allocated if the assigned mobile terminal uses this subcarrier. Thus, the capacity of the OFDM system is maximized in a frequency selective fading environment. Such bit-allocation is achieved

by an optimum subcarrier bit-allocation algorithm, which will be derived in Section 3. Although optimum subcarrier bit-allocation algorithm maximize the system capacity, it does not guarantee QoS of different services. Thus, a hierarchical scheduling scheme is needed. In the first step, packet transmissions of guaranteed and controlled services are scheduled. The constant traffic rate of guaranteed service and the mean traffic rate of controlled-load service are guaranteed in this step. In the second step, the remaining subcarriers are allocated to controlled-load and best effort services. Thus, the scheduling scheme implies that guaranteed service has highest priority of being serviced and best effort service has the lowest priority.

- *Send resource allocation information.* After scheduling for all services is performed, the resource allocation information is sent back to mobile terminals. The resource mapping table proposed in Figure 2 is used in the feedback subframe to convey such resource allocation information.
- *Transmit packets.* When a mobile terminal receives the information about its allocated subcarriers in various time slots and the number of bits in each subcarrier, it first determines the transmit power of each subcarrier based on the number of bits in the subcarrier and the channel gain estimated through the downlink pilot channel. Then, the mobile terminal transmits packets in allocated subcarriers in various time slots using appropriate power levels. How to convert packets in the MAC layer into bits in subcarriers is part of the functions of OFDM physical layer. However, it is clear this process does not cause overhead.

3. The optimum subcarrier bit-allocation algorithm

As described in the operation procedures of the OFDM-TDMA/SA MAC protocol, an optimum bit allocation algorithm is needed. The objective of such an algorithm is to maximize the number of bits that can be allocated to subcarriers of an OFDM system in a frequency selective fading environment. This algorithm is different from that in [17]. The adaptive subcarrier, bit, and power allocation algorithm in [17] aims to find the optimum assignment of subcarriers so that the overall power consumption of all mobile terminals is minimum. However, the number of bits allocated to subcarriers are not maximized. The optimum subcarrier bit-allocation algorithm is also different from the RA algorithm in [9]. In order to avoid that users in good channels exclude users in bad channels, the maximization of the overall data rates is not considered in the RA algorithm [9]. Therefore, a "max-min" criterion is used, and the optimization becomes a complicated integer programming problem. In addition, the throughput of mobile terminals in good channels is not maximized. In our algorithm, since maximization of the overall data rates is used, system throughput is maximized. In an OFDM-TDMA/SA frame, for a given time slot, if some mobile terminals in bad channels are excluded by other mobile terminals in good channels, they still have the opportunity to try subcarriers in other time slots through a scheduling scheme. Thus, mobile terminals in bad channels are not always excluded, and "max-min" criterion is not used in the optimum subcarrier bit-allocation algorithm.

In this section, the optimum subcarrier bit-allocation algorithm is derived for the uplink access. The same algorithm can be applied to the downlink.

Suppose there are K mobile terminals in a cell of a OFDM-based broadband wireless LAN. Within each OFDM symbol, there are N subcarriers. Given the n-th subcarrier, the magnitude of channel gain experienced by the k-th mobile terminal is assumed to be $\alpha_{k,n}$. In each subcarrier, the modulation scheme is assumed to be QAM with the maximum number of bits equal to M. Thus, 4 QAM, 16 QAM, $\ldots$, 2^M QAM can be used in the OFDM system. Given BER Pe of a mobile terminal, the required power P_s for supporting m bits/QAM symbol is $P_s = \frac{N_0}{3}[Q^{-1}(\frac{Pe}{4})]^2(2^m - 1)$ [17]. Here $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$, and N_0 is the single-sided power spectral density of noise.

Suppose $c_{k,n}$ is the number of bits in the n-th subcarrier when it is assigned to the k-th mobile terminal, and $\rho_{k,n} = 1$ indicates subcarrier n is allocated to mobile terminal k. Since a subcarrier that has been allocated one mobile terminal cannot be allocated to other mobile terminals, so $\rho_{k',n} = 0$ for $k' \neq k$. As a result, the overall bits C_b in each OFDM symbol is

$$C_b = \sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}c_{k,n}, \qquad (1)$$

where

$$\sum_{k=1}^{K}\rho_{k,n} = 1, \quad \text{and} \quad \rho_{k,n} \in \{0, 1\}. \qquad (2)$$

Suppose $f_k(c_{k,n})$ and $P_{k,n}$ are assumed to be the received and transmit power levels, respectively, of the n-th subcarrier allocated to mobile terminal k. Since the transmit power of subcarrier n for mobile terminal k cannot exceed maximum transmit power $P_k^{\max}$, $P_{k,n} = \frac{f_k(c_{k,n})}{\alpha_{k,n}^2} \leq P_k^{\max}$. Note that through this constraint the overall power level of an OFDM symbol is bounded, because the number of subcarriers in an OFDM symbol is a limited number.

When $c_{k,n}$ is transmitted in a QAM symbol, $f_k(c_{k,n}) = \frac{N_0}{3}[Q^{-1}(\frac{Pe_k}{4})]^2(2^{c_{k,n}} - 1)$ must be satisfied, where Pe_k is the BER of mobile terminal k. Therefore,

$$\frac{N_0}{3\alpha_{k,n}^2}\left[Q^{-1}\left(\frac{Pe_k}{4}\right)\right]^2(2^{c_{k,n}} - 1) \leq P_k^{\max}. \qquad (3)$$

Since $c_{k,n}$ is an integer, so

$$c_{k,n} \leq \left\lfloor \log_2\left(1 + \frac{3P_k^{\max}\alpha_{k,n}^2}{N_0[Q^{-1}(\frac{Pe_k}{4})]^2}\right)\right\rfloor. \qquad (4)$$

Define

$$c_{k,n}^{\max} = \min\left\{M, \left\lfloor \log_2\left(1 + \frac{3P_k^{\max}\alpha_{k,n}^2}{N_0[Q^{-1}(\frac{Pe_k}{4})]^2}\right)\right\rfloor\right\}, \qquad (5)$$

then (4) becomes

$$c_{k,n} \leq c_{k,n}^{\max}. \tag{6}$$

In order to maximize overall bits in an OFDM symbol, C_b in (1) is to be maximized. However, $\rho_{k,n}$ and $c_{k,n}$ must satisfy (2) and (6), respectively. Thus, the optimum subcarrier bit-allocation algorithm is formulated as the following optimization problem:

$$\begin{aligned} &\max && \left\{ C_b = \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{k,n} c_{k,n} \right\}, \\ &\text{subject to} && \sum_{k=1}^{K} \rho_{k,n} = 1, \quad \text{and} \quad \rho_{k,n} \in \{0, 1\}, \\ &&& c_{k,n} \in \left\{0, 1, \ldots, c_{k,n}^{\max}\right\}. \end{aligned} \tag{7}$$

Integer programming can be used to solve the problem in (7). However, due to its complexity, it is nontrivial work to include such an optimum subcarrier bit-allocation algorithm in the scheduling scheme of the MAC protocol. In order to avoid the complexity of integer programming, an iterative computation scheme is proposed to solve the optimization problem. The basic idea of such a scheme is that subcarrier n must be allocated to mobile terminal k if $c_{k,n}^{\max}$ is the largest among all the values of $\{c_{k',n}^{\max}, k' = 1, \ldots, K\}$. The procedure of the search scheme is described as follows:

- *Initial step: determine* $c_{k,n}^{\max}$. For the given BER values of all mobile terminals, $c_{k,n}^{\max}$ is calculated for all subcarriers according to (5).
- *Step 1:* Suppose C is the set of $c_{k,n}^{\max}$ of all subcarriers of all mobile terminals. Among all the values in set C, find the maximum value, e.g., $c_{k',n'}^{\max}$, which means that the maximum number of bits is achieved by mobile terminal k' in subcarrier n'. Thus, subcarrier n' must be allocated to mobile terminal k', and the assigned bits in this subcarrier is $c_{k',n'}^{\max}$. In addition, $\rho_{k',n'} = 1$, which means that subcarrier n' cannot be allocated to all other mobile terminals. Therefore, after this step, $\{c_{k,n'}^{\max}, k = 1, \ldots, K\}$ need to be removed from set C.
- *Step i* $(i > 1)$: For the new set C, repeat the same procedure of Step 1 until all the subcarriers are finished.

In order to enhance the speed of the iterative computation, a binary search instead of linear search algorithm can be used to find the maximum value in set C. As illustrated in the procedure, the proposed scheme for the optimization problem is very simple. It will be included in the scheduling scheme in the next section.

4. The hierarchical scheduling scheme

The objective of the scheduling scheme is to guarantee the heterogeneous QoS constraints of multimedia traffic and to utilize the system capacity as efficiently as possible. In this paper, the multimedia traffic is categorized into three classes of services, i.e., guaranteed, controlled-load, and best effort services. Thus, the scheduling scheme must be able to guarantee the constant traffic rate of guaranteed service, mean rate of controlled-load service, and zero packet loss of best effort service.

As shown in figure 1, an OFDM-TDMA/SA frame consists of many time slots. Each time slot has several OFDM symbols, and each of which is comprised of many subcarriers. In order to maximize throughput and efficiently utilize the capacity in each subcarrier, the optimum subcarrier bit-allocation algorithm proposed in Section 3 is embedded in the scheduling scheme to assign subcarriers to mobile terminals and determine the number of bits in each subcarrier. Since BER requirement has been considered in the optimum subcarrier bit-allocation algorithm, BER values of different mobile terminals can always be guaranteed.

Since guaranteed, controlled-load, and best effort services have different QoS requirements, a hierarchical scheduling scheme is proposed to serve these services in a prioritized order. Guaranteed and controlled-load service are serviced first. In this phase, constant rates of guaranteed service need to be satisfied, while only mean rates are guaranteed for controlled-load services. In the second phase, the remaining resources are shared between controlled-load and best effort services. The concept of hierarchical scheduling looks straightforward, but the scheme interacts with the optimum subcarrier bit-allocation algorithm.

The detailed procedure of this scheduling scheme is shown in figure 3 and explained as follows:

- *Step 0: initial settings.* Subcarriers in each time slot of the whole OFDM-TDMA/SA frame is marked as "unused". Based on the estimated channel gain and the BER requirement, the maximum number of bits that can be assigned to each subcarrier for a given mobile terminal is calculated according to (5).
- *Step 1: optimum subcarrier bit-allocation to mobile terminals*[1] *of guaranteed and controlled-load services.* All "unused" subcarriers in the whole frame are assigned to mobile terminals of guaranteed and controlled-load services. A subcarrier is marked as "used" after it is assigned to a mobile terminal. In this step, the optimum subcarrier bit-allocation algorithm is applied in order to achieve maximum system capacity. However, QoS of different services is not taken into account.
- *Step 2: iterative subcarrier and bit allocation to guaranteed and controlled-load services and QoS guarantees.* Based on the optimum subcarrier bit-allocation algorithm, the QoS of guaranteed and controlled-load services is checked. Given a mobile terminal with guaranteed service, the overall bits in the subcarriers allocated to it must achieve its required constant traffic rate in the OFDM-TDMA/SA frame. For a mobile terminal with controlled-load service,

[1] When a mobile terminal has multiple traffic flows, the same procedure is applied separately to each flow. For simplicity of description, we use *mobile terminals* instead of *traffic flows* throughout the paper.

the overall bits in the subcarriers allocated to it must satisfy the mean traffic rate of this mobile terminal. If more subcarriers than required are allocated to a mobile terminal, these unnecessary subcarriers must be released and marked as "unused". After this step, if QoS of guaranteed and controlled-load services is satisfied, scheduling goes to step 3. Otherwise, if "unused" subcarriers are still available in the current OFDM-TDMA/SA frame, steps 1 and 2 are repeated until QoS of guaranteed and controlled-load services is satisfied or no "unused" subcarriers is left. However, if no "unused" subcarrier is left in the current OFDM-TDMA/SA frame, scheduling proceeds to step 4.

- *Step 3: allocation of remaining subcarriers to controlled-load and best effort services.* If no "unused" subcarrier is available in the current OFDM-TDMA/SA frame, scheduling goes to step 4. Otherwise, the remaining "unused" subcarriers are allocated to controlled-load and best effort services according to the following process.
  - *Step 3.1: optimum subcarrier bit-allocation to mobile terminals of controlled-load and best effort services.* For the "unused" subcarriers, optimum subcarrier bit-allocation is performed among mobile terminals that have packets waiting for transmission.
  - *Step 3.2: iterative subcarrier allocation to controlled-load and best effort services.* Based on the optimum subcarrier bit-allocation in step 3.1, each mobile terminal is checked if the number of packets in its buffer is greater than the overall bits in its allocated subcarriers. If the answer is yes, the unnecessary subcarriers are released and marked as "unused" again. After all mobile terminals of controlled-load and best effort services have been checked, if "unused" subcarriers are available, steps 3.1 and 3.2 are repeated until no "unused" subcarrier is left or packets in all mobile terminals are serviced. Then, scheduling proceeds to step 4.
- *Step 4: end of scheduling.* Scheduling is terminated in this step. However, if no "unused" subcarrier is available in the previous step and some packets still wait for transmission in mobile terminals, these packets have to wait for subcarriers in the next OFDM-TDMA frame. If the due time of some packets has passed, they must be dropped. In this situation, packet loss occurs. In order to avoid packet loss in best effort service, the due time for packets of best effort service is assumed to be infinite.

5. Performance evaluation

Computer simulation is carried out to evaluate performance of the OFDM-TDMA/SA MAC protocol.

5.1. System parameters and traffic models

In the OFDM-TDMA/SA-based broadband wireless LAN, channels have the feature of frequency selective slow fading. Thus, the channel model used in simulation is Rayleigh frequency selective fading channel. For subcarrier n of mobile terminal k, the second moment of channel gain, denoted by $E\{\alpha_{k,n}^2\}$, is equal to unity. The frame length of the OFDM-TDMA/SA frame is assumed to be 2 ms, which is similar to that of IEEE 802.16 [5]. There are 16 time slots in downlink and uplink data subframes. Among those time slots, 5 time slots are allocated to uplink traffic transmission. One OFDM symbol is assumed in each time slot, and there are 256 subcarriers in each OFDM symbol. Thus, one time slot is needed in the feedback subframe to send resource mapping table. The number of time slots for contention subframe is assumed to be large enough so that the request access delay is less than one frame. In order to focus on packet access in data subframes, the effect of frequency selective fading on a request transmission in contention subframe is not considered. QAM used in each subcarrier can be 4-QAM, 16-QAM, and 64-QAM. The BER of guaranteed, controlled-load, and best effort services is 10^{-5}, 10^{-4}, and 10^{-9}, respectively. The maximum signal-to-noise ratio (SNR) of transmit signal, i.e., $\frac{P_k^{\max}}{N_0}$ in (5), is assumed to be 26.43 dB, 25.38 dB, and 29.10 dB, respectively, for guaranteed, controlled-load, and best effort services. Such an SNR value ensures that the number of bits in each subcarrier is 6 when $\alpha_{k,n}^2 = 1$.

The traffic of guaranteed, controlled-load, and best effort services is simulated as follows:

- *Guaranteed service.* For each connection of guaranteed service, the traffic rate is assumed to be constant. Moreover, the constant rates of different connections are assumed to be uniformly distributed in $[0, 320]$ kbps. The time out value of a packet of guaranteed service is assumed to be 10 OFDM-TDMA/SA frames. The length of a guaranteed-service connection is exponentially distributed with the average equal to 150 s.
- *Controlled-load service.* Since policing is used for each traffic flow of controlled-load service, the traffic of controlled-load service at the MAC layer is policed traffic that conforms TSpecs of controlled-load service. Thus, for a connection of controlled-load service, its traffic is generated according to a token bucket policing scheme. In this paper, the model described in [16] is used to generate the policed traffic. In this model, the traffic rate of a connection is different in three consecutive durations, i.e., bursty, flat, and off durations. In the bursty duration, the traffic rate is determined by the bucket depth and the input traffic rate. In the flat duration, the traffic rate is equal to the bucket rate, and no traffic exists in the off duration. In this paper, the bucket rate r of a connection is constant. Such rates of different controlled-load-service connections are uniformly distributed in $[0, 160]$ kbps. The bucket depth b of a connection is assumed to be 100 bits. Moreover, the average lengths of bursty, flat, and off durations are assumed to be 0.1, 0.5, and 0.2 MAC frame, respectively. The time out value of a packet of controlled-load service is assumed to be 20 OFDM-TDMA/SA frames. The length of

a controlled-load-service connection is exponentially distributed with the average equal to 150 s.

- *Best effort service*. For a mobile terminal of best effort service, the message is generated according to an exponential random process. The average message size is 200 kbytes. Since best-effort traffic is delay-tolerant and loss-sensitive, it is reasonable to have a large timeout value to avoid packet loss.

In the simulation, the number of information bits in each MAC packet is 16. The call arrival rate of each service is a parameter that adjusts traffic load. As for the relative call composition, guaranteed service, controlled-load service, and best effort service hold 10%, 10%, and 80%, respectively. of all calls in the system.

5.2. Simulation results

The performance of the OFDM-TDMA/SA MAC protocol is presented in this section. In order to show the performance improvement achieved by OFDM-TDMA/SA MAC protocol, comparison with other MAC protocols for OFDM-based system is necessary. It is obvious that the performance of an OFDM-TDMA based MAC protocol is much worse than that of the OFDM-TDMA/SA MAC protocol, because: (a) the minimum resource unit of OFDM-TDMA is one time slot, which wastes resources when it is allocated to a low-rate connection; (b) optimum bit-allocation algorithm cannot be applied to OFDM-TDMA, because subcarrier allocation does not exist. Also, it is easy to show that the performance of an OFDM-FDMA based MAC protocol is much worse than that of the OFDM-TDMA/SA MAC protocol, because the subcarrier allocation is fixed on the time axis. In order to focus on the comparison with OFDMA MAC protocols, comparisons with OFDM-TDMA and OFDM-FDMA MAC are presented in Appendix.

For the purpose of fair comparison, an OFDMA MAC protocol is simulated by considering the features of OFDMA and the concept of hierarchical scheduling scheme. No optimum subcarrier bit-allocation is included in OFDMA MAC.

For guaranteed service, the average packet delay and packet loss ratio of the two different MAC protocols are shown in figure 4. The results of controlled-load services are illustrated in figure 3. The average message delivery time of best effort service is shown in figure 6. No packet loss occurs in best effort service. When OFDM-TDMA/SA MAC protocol is used, no packet loss occurs in guaranteed service, and the average packet delay is 2 ms, as shown in figure 4. For controlled-load service, as shown in figure 5, the average packet delay increases as traffic load becomes higher than 160 guaranteed-service calls/hour. However, both packet loss ratio and average packet delay is relatively low. Therefore, QoS of both guaranteed and controlled-load services are guaranteed. On the other hand, when OFDMA MAC protocol is applied to the same system, the packet loss ratio and average packet delay of controlled-load service is much higher than those of OFDM-TDMA/SA MAC

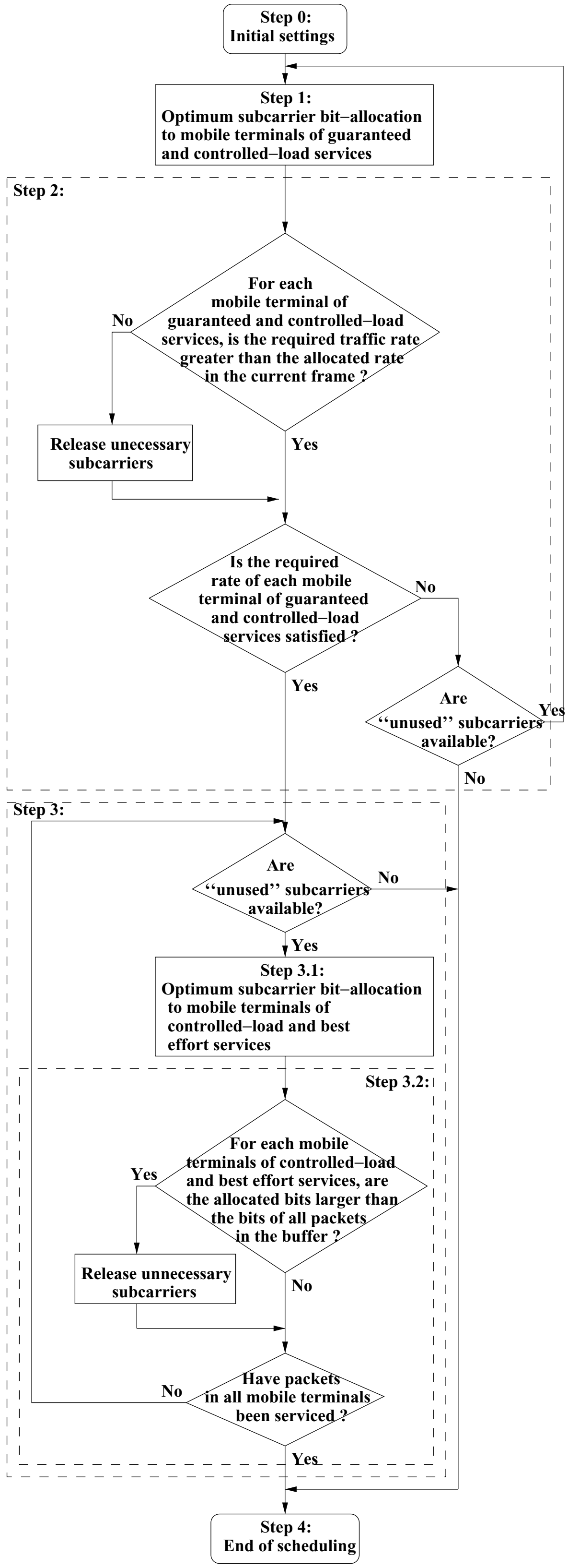

Figure 3. The hierarchical scheduling scheme.

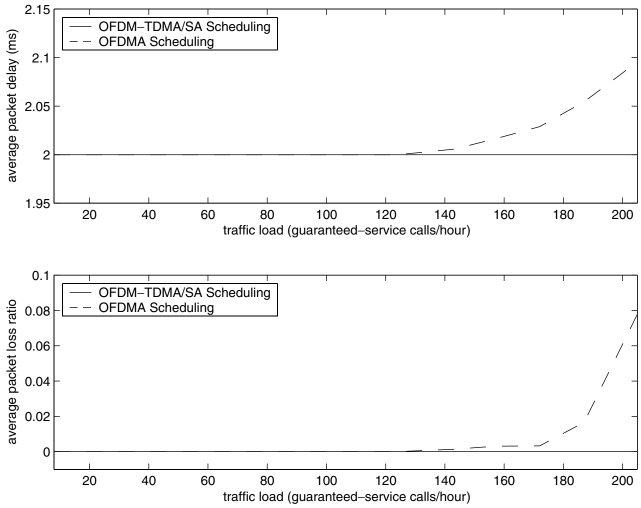

Figure 4. The average packet delay and packet loss ratio of guaranteed service.

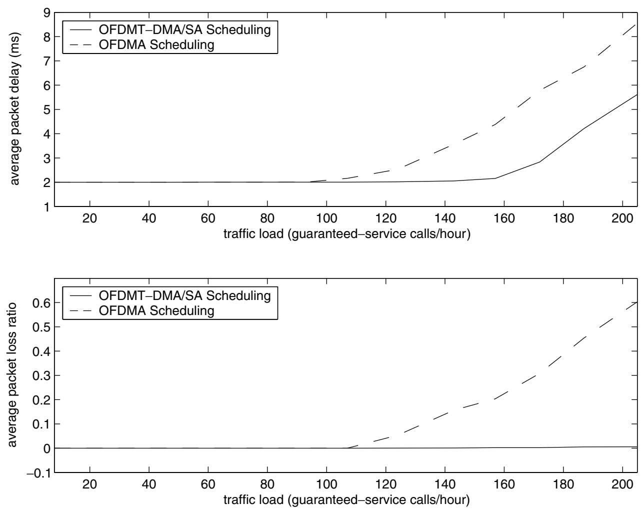

Figure 5. The average packet delay and packet loss ratio of controlled-load services.

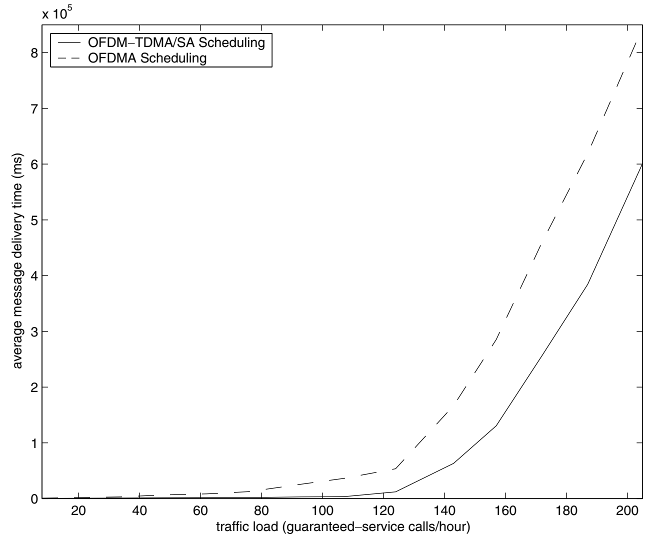

Figure 6. The average message delivery time of best effort service.

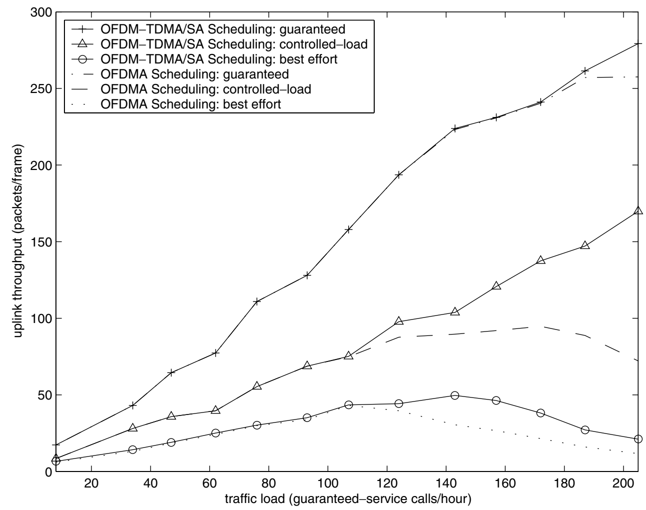

Figure 7. The uplink throughput of different services.

protocol. Moreover, in the OFDMA MAC protocol, packet loss occurs in guaranteed service when the traffic load is higher than 140 guaranteed-service calls/hour. Therefore, QoS of both guaranteed service and controlled-load service is not well guaranteed when an OFDMA MAC protocol is applied. The reason for the performance difference is that subcarrier bit-allocation embedded in the scheduling scheme in the OFDM-TDMA/SA MAC protocol achieves much better resource utilization. In other words, the available capacity for multimedia services in the OFDM-TDMA/SA MAC is always much higher than that in OFDMA MAC. Thus, under the same traffic load, the OFDM-TDMA/SA MAC causes much lower average packet delay and packet loss ratio.

As shown in figure 6, the average message delivery time is much larger than a frame length (i.e., 2 ms). The reason is that the hierarchical scheduling scheme always first satisfy the constant traffic rate of guaranteed service and mean rate of controlled-load service. Thus, A best-effort-service message has to wait for many frames before all packets of a message are serviced. It is also shown in Figure 4 that the average message delivery time achieved by the OFDM-TDMA/SA MAC protocol is lower than that achieved by OFDMA MAC protocol, due to more efficient resource utilization in the OFDM-TDMA/SA MAC protocol.

The throughput of different services are shown in figure 7. For both MAC protocols, the guaranteed service has the highest throughput, although the call arrival rate of this service is not larger than the other two services. The reason is that, on average, the traffic rate of a guaranteed-service call is much larger than that of the other two services. Moreover, as illustrated in figure 7, when traffic load is higher than a certain value, the OFDM-TDMA/SA MAC protocol achieves higher throughput in each service than OFDMA MAC does. For guaranteed service and controlled-load service, QoS is always guaranteed by the OFDM-TDMA/SA MAC protocol at all traffic loads given in Figure 7, so throughput of both guaranteed and controlled-load services increases as traffic load increases. In the OFDMA MAC protocol, when the traffic load is higher than a certain value, the throughput of controlled-load services starts decreasing even if throughput of guaranteed services increases slowly. For example, when traffic load is higher than 175 guaranteed-service calls/hour, throughput of controlled-load service starts decreasing, while throughput of guaranteed services still increases until the traffic load is 187 guaranteed-service calls/hour. Such a difference is because a higher priority is assigned to guaranteed service in the scheduling scheme. In both OFDM-TDMA MAC and OFDMA MAC protocols, the throughput of best effort service decreases when traffic load is higher than a certain value, because best effort service has the lowest priority of being serviced in the scheduling scheme. However, the traffic load at which the throughput of best effort service starts to decreases is lower in OFDMA MAC protocol than that in OFDM-TDMA/SA MAC protocol. The throughput comparisons between two MAC protocols illustrate that the OFDMA MAC protocol outperforms the OFDMA MAC protocol.

6. Conclusion

In this paper, an OFDM-TDMA/SA MAC protocol was designed for broadband wireless LANs, which have the feature of frequency selective fading channels. An optimum subcarrier bit-allocation algorithm was derived to maximize the number of bits that can be allocated to subcarriers in each OFDM symbol. In order to support multimedia services with different QoS constraints, a hierarchical scheduling scheme was proposed based on the optimum subcarrier bit-allocation algorithm. Performance evaluation showed that the OFDM-TDMA/SA MAC protocol guarantees heterogeneous QoS requirements of multimedia traffic. This MAC protocol also outperforms other MAC protocols for OFDM-based wireless LANs.

Future work is needed to derive an optimum subcarrier bit-allocation algorithm that considers the overall power constraint of an OFDM symbol instead of that of a user. A new scheduling scheme based on such an algorithm is also an interesting research topic.

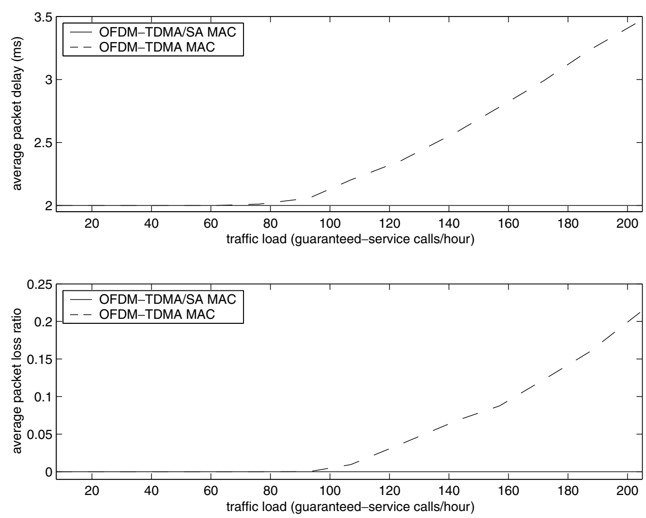

Figure 8. The average packet delay and packet loss ratio of guaranteed service.

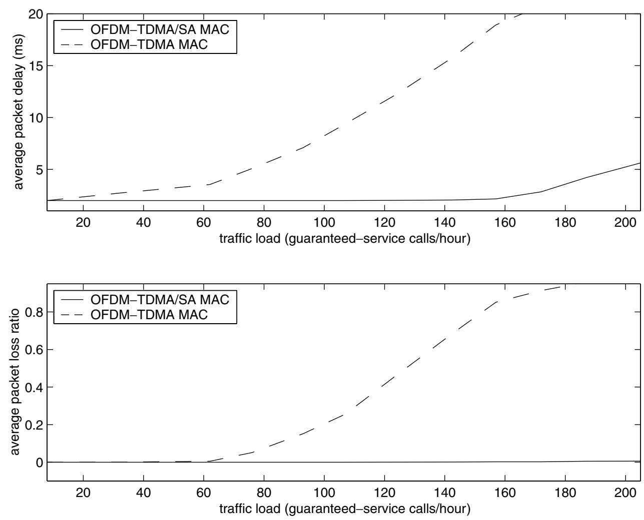

Figure 9. The average packet delay and packet loss ratio of controlled-load services.

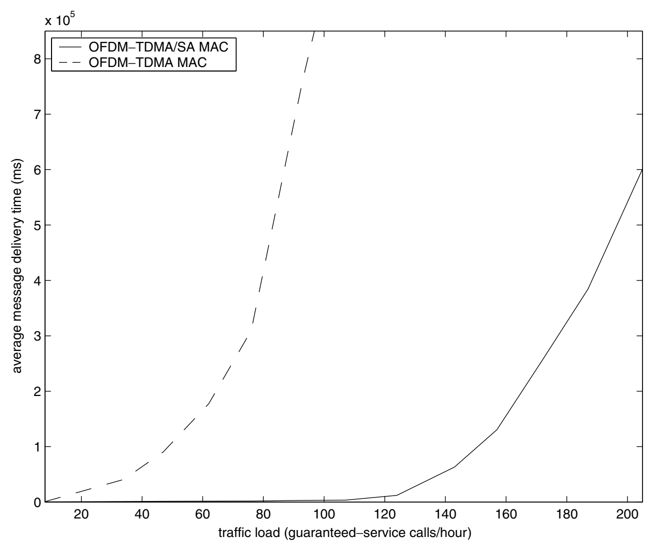

Figure 10. The average message delivery time of best effort service.

Appendix

To have a fair comparison, the packet scheduler in OFDM-TDMA and OFDM-FDMA MAC is also based on hierarchical scheduling scheme. In addition, same system parameters for OFDM-TDMA/SA MAC in Section 5.1 are applied to these two protocols.

The performance comparisons between OFDM-TDMA and OFDM-TDMA/SA MAC are illustrated from figure 8 to figure 11. Due to low resource utilization, OFDM-TDMA MAC produces much higher packet loss ratios in both guaranteed and controlled-load services and much larger packet delay in all services. It also achieves much lower throughput in all services. For best effort services, even starvation occurs as shown by the nearly zero throughput. One reason is due to the overall system capacity achieved by OFDM-TDMA MAC. The other reason is that we assume no minimum resource reservation for best effort services. It should be noted that the same assumption is applied in OFDM-TDMA/SA MAC.

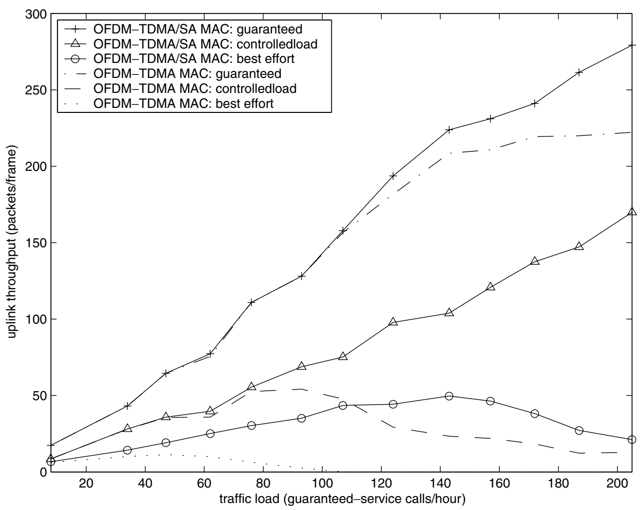

Figure 11. The uplink throughput of different services.

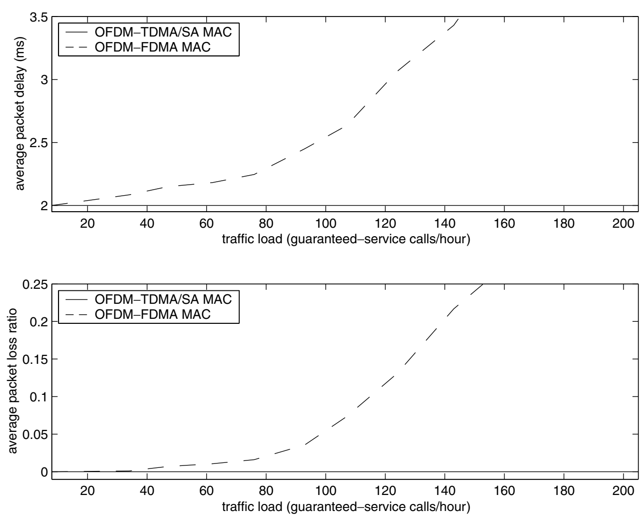

Figure 12. The average packet delay and packet loss ratio of guaranteed service.

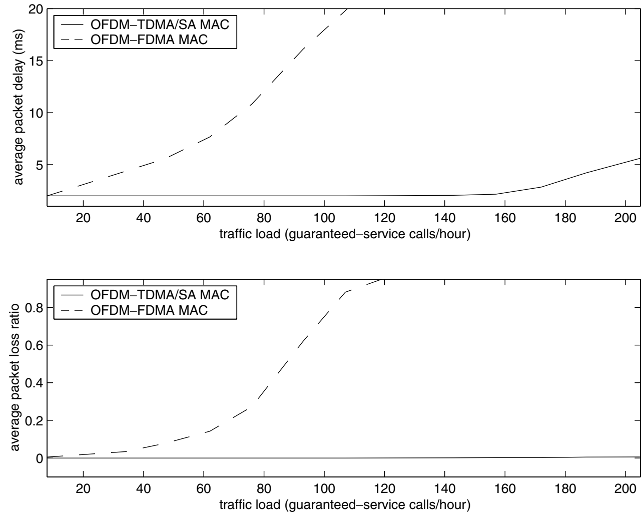

Figure 13. The average packet delay and packet loss ratio of controlled-load services.

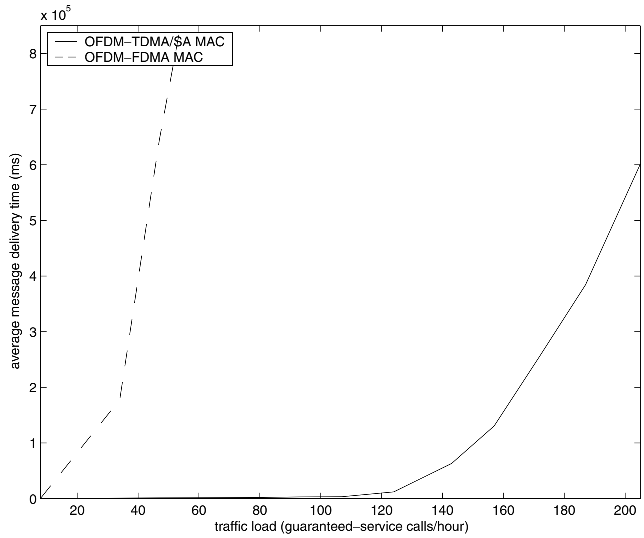

Figure 14. The average message delivery time of best effort service.

The performance comparisons between OFDM-FDMA and OFDM-TDMA/SA MAC are shown in figures 12–15. Again, OFDM-TDMA/SA MAC achieves much higher performance than OFDM-FDMA. It is also interesting to note that the OFDM-TDMA MAC outperforms OFDM-FDMA MAC. The reason is that the resources allocated to a user in OFDM-FDMA MAC are occupied for the lifetime of this users' connection. However, resources allocated to a user in OFDM-TDMA are occupied for just one time slot. Thus, although allocating a whole time slot to the same user in OFDM-TDMA MAC wastes resources,

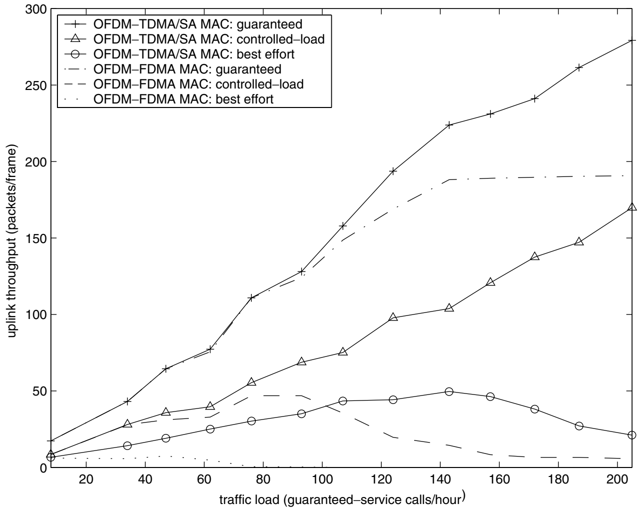

Figure 15. The uplink throughput of different services.

OFDM-TDMA MAC still achieves better resource utilization through TDMA.

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