A New Medium Access Control Protocol for TDD Mode Wideband CDMA Wireless Local Area Networks *

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ABSTRACT

It is well known that TDD mode wideband CDMA is particularly suited for wireless local area networks (LANs). In this paper a medium access control (MAC) protocol is proposed for wireless multimedia LANs that are based on TDD mode wideband CDMA. In order to minimize interference experienced by a packet and to satisfy bit error rates (BERs) of multimedia traffic, a minimum-power allocation algorithm is derived to determine the received power levels of code channels that are allocated to a mobile terminal. Based on the minimum-power allocation algorithm, the maximum system capacity is investigated, which points out that both rate- and BER-scheduling is required in order to achieve maximum system capacity. Using minimum power allocation and rate- and BER-scheduling, a new packet scheduling scheme is proposed to accommodate packets in time slots. Simulation is carried out to evaluate the proposed MAC protocol. Results show that the proposed MAC protocol greatly improves the performance of TDD mode wideband CDMA wireless multimedia LANs.

1 INTRODUCTION

Wireless Local Area Networks (LANs) have many advantages over legacy wired LANs. However, due to the wireless environment, special design requirements need to be considered for the network protocols of wireless LANs. One of the key tasks is to design a medium access control (MAC) protocol, which delivers multimedia traffic with heterogeneous quality of service (QoS) requirements.

Currently several standards such as IEEE 802.11 [1] and Bluetooth [2] have been developed for wireless LANs. However, none of them is good at QoS support for multimedia traffic. Thus, to develop a wireless LAN that support multimedia traffic with heterogeneous QoS requirements is still an on-going research topic. HiperLAN/2 [3] can support multimedia traffic. However, it is a TDMA network, which lacks the advantages of a CDMA network, especially those of a wideband CDMA network [4]. As specified in the Universal Mobile Telecommunications System (UMTS), time division duplex (TDD) mode wideband code-division multiple-access (CDMA) is well suited for micro- or pico-cell wireless environments with high traffic density [5]. Thus, it can be used as a basic radio access technique for wireless LANs. In this paper, we focus on wireless LANs based on TDD mode wideband CDMA, where time-division-CDMA (TD-CDMA) is used in both uplink and downlink transmissions. In particular we propose a new MAC protocol for uplink transmission in such a wireless LAN.

Recently several MAC protocols [6], [7] have been proposed for TD-CDMA systems. In [6], a wireless multimedia MAC protocol with bit error ratio scheduling (WISPER) is proposed. The scheduling scheme does not consider power control for users in the same time slot because it assumes that the power levels of received signals in one time slot are the same. It contains a novel packet scheduling scheme, which aims to satisfy the heterogeneous bit error rates (BER) of multimedia traffic and improve the system throughput at the same time. Since power control in each time slot is not considered, system throughput is not maximized. In [7], a generic optimal resource management problem for TD-CDMA is defined. Because it is impractical to find the optimal solution to the problem, a sub-optimal algorithm is proposed based on the bin-packing scheme [7]. Compared to WISPER, this algorithm considers different fixed received power levels for different service types. However, it does not minimize the received power level for each mobile terminal.

To develop a new MAC protocol for TDD mode wideband CDMA wireless LANs, we first derive a minimum-power allocation algorithm that minimizes the interference experienced by each packet in a time slot. Different from the power allocation algorithm in [8], our algorithm considers both multiple service types and multiple rates for each service type. The power control of our algorithm is only applied to the uplink received power levels of mobile terminals. The uplink transmitted power level corresponding to the target received power level can be determined by using open- and closed-loop power control schemes [9], [10]. Based on the minimum-power allocation algorithm, the maximum capacity of a time slot is investigated, which points out that both rate- and BER-scheduling is necessary. With rate- and BER-scheduling and minimum-power allocation algorithm, a new packet scheduling scheme is proposed. It maximizes the system

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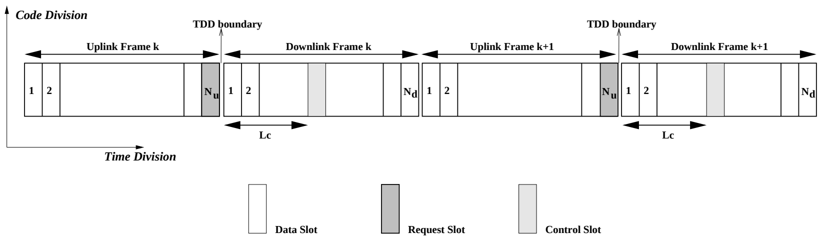

Figure 1: Frame structures of the MAC protocol

capacity, satisfies the heterogeneous BER requirements, and improves the QoS metrics of multimedia traffic.

The paper is organized as follows. In Section 2, we describe the basic MAC protocol for TDD mode wideband CDMA wireless LANs. A minimum-power allocation algorithm is derived in Section 3 where the maximum system capacity is also investigated. A new packet scheduling scheme is proposed in Sections 4. The performance of the proposed MAC protocol is evaluated in Section 5. The paper is concluded in Section 6.

2 The MAC Protocol for Uplink Transmission in a CDMA wireless LAN

We consider a TDD mode wideband CDMA-based wireless LAN. The frame structure of such a network is shown in Figure 1, where uplink and downlink are multiplexed in time division. In the uplink frame, the *request slot* is used by mobile terminals to send requests to the base station. In the downlink frame, a *control slot* is used by the base station to send feedback messages to mobile terminals. The position of the control slot, represented by L_c, depends on the processing power of the base station. Multi-code (MC) operation is used in the uplink., which is the same as UMTS TDD mode [11]. Since each code channel supports one basic rate, in order to achieve multirate, several code channels need to be generated through subcode concatenation [12] for each user. With subcode concatenation, the self-interference among the codes of the same user is avoided [12].

In the MAC protocol, several conflicting QoS parameters such as BER values, average packet delays, and average packet loss ratios are considered. In addition, system throughput needs to be maximized. Since our research is focused on uplink transmission, dynamic TDD is not considered in our proposed protocol.

The new MAC protocol is operated as follows:

- *Request for Transmission.* A mobile terminal sends a transmission request before it transmits a batch of packets. The transmission request can be sent in the request slot or piggybacked in a data time slot. The number of packets and timeout value of this batch of packets are specified in the transmission request.

- *Packet Scheduling.* After the base station collects the transmission requests from all mobile terminals during an entire uplink frame length, it uses a packet scheduling scheme to determine how the packets of multimedia applications are accommodated in each time slot. The packet scheduler is a rate- and BER-scheduling scheme and is also based on minimum-power allocation for each code channel. It maximizes the system capacity and satisfies the heterogeneous BER requirements of multimedia traffic.

- *Downlink Feedback.* After scheduling for packet transmission is completed, the base station sends the results back to the mobile terminals through the control slot in the downlink frame, which is performed by broadcasting. It should be noted that the feedback information for each terminal includes the terminal ID, assigned time slots, the number of packets in each assigned time slot, and the received power level of each code channel.

- *Packet Transmission.* When a mobile terminal gets the permission for packet transmission, it enters the *packet transmission* state and transmits packets in the specified time slots with the allocated power level. When the base station receives such packets, it forwards them to the desired destination. The packets that have not been transmitted in the current frame needs to wait for a permission in the next frame.

As described in the operation procedures of the MAC protocol, new algorithms are required for the packet scheduling scheme.

3 The Minimum-Power Allocation Algorithm

In a time slot code channels of different mobile terminals interfere with each other, so power allocation to these code channels need to be controlled so that BER requirements of different mobile terminals can be satisfied, and that power level of each code channel is minimized. To solve this problem, several algorithms have been proposed. The power allocation scheme proposed in [8] considers only mobile terminals with the same BER requirement. An algorithm is derived in [13] to support mobile terminals with heterogeneous BER requirements in the same time slot. It does not consider subcode concatenation. In this section, we derive a new algorithm that satisfies heterogeneous BER requirements of multimedia services by allocating minimum power level to each code channel. The maximum capacity of a time slot is also investigated.

3.1 SINR of Multimedia Traffic

We assume that K types of services are supported in a TDD mode CDMA wireless LAN, and the target signal to interference-plus-noise ratio (SINR) that satisfies the BER requirement of service k is γ_k. For a mobile terminal supporting service k, the maximum allowed number of code channels is assumed to be M_k. Thus, such a mobile terminal can have m code channels with $m = 1, \cdots, M_k$. Given a mobile terminal that has j code channels and supports service i, the power level for each code channel is denoted by $S_{i,j}$, and the interference level of one out of the j code channel is denoted by $I_{i,j}$. Considering subcode concatenation, the interference experienced by a mobile terminal only comes from the codes of other mobile terminals [12], so $I_{i,j}$ can be expressed by power levels $\{S_{k,m}, k = 1, \cdots, K,\ m = 1, \cdots, M_k\}$ as

$$I_{i,j} = \sum_{k=1}^{K} \sum_{m=1}^{M_k} m T_{k,m} S_{k,m} - j S_{i,j}, \qquad (1)$$

where $T_{k,m}$ is the number of mobile terminals that have m code channels for the transmission of service k. On the right hand side of Equation (1), the summations capture the power levels of the code channels of all mobile terminals in the system, and the second term is the total power level of the mobile terminal under consideration.

In addition to interference, a code channel also experiences noise. We assume that the noise power level of a code channel, denoted by S_N, is the same for all mobile terminals and is given by

$$S_N = N_0 B_s, \qquad (2)$$

where N_0 is the one-sided power spectral density of noise, and B_s is the bandwidth of spread signal.

Since both interference and noise can be approximated by zero-mean Gaussian processes, the SINR for a code channel at the receiver output, denoted by $\lambda_{i,j}$, is [8]

$$\lambda_{i,j} = \frac{S_{i,j}}{\frac{I_{i,j}}{\frac{3}{2}G} + \frac{S_N}{G}}, \qquad (3)$$

where G is the processing gain.

Substituting Equations (1) and (2) into Equation (3), the SINR $\lambda_{i,j}$ is

$$\lambda_{i,j} = \frac{S_{i,j}}{\frac{\sum_{k=1}^{K} \sum_{m=1}^{M_k} m T_{k,m} S_{k,m} - j S_{i,j}}{\frac{3}{2}G} + N_0 B_b}, \qquad (4)$$

where B_b is the bandwidth of the signal with basic transmission rate, and $B_s / B_b = G$.

3.2 The Minimum-Power Allocation Algorithm

The objective of the minimum-power allocation algorithm is to determine the minimum power level of each code channel while BER requirements or target SINRs of multimedia services are satisfied.

In order to satisfy BER requirements of multimedia services, the receiver output SINR $\lambda_{i,j}$ for one out of the j code channel must be larger than or equal to the target SINR γ_i, i.e., $\lambda_{i,j} \geq \gamma_i$. Thus, from Equation (4) we have

$$\frac{S_{i,j}}{\frac{\sum_{k=1}^{K} \sum_{m=1}^{M_k} m T_{k,m} S_{k,m} - j S_{i,j}}{\frac{3}{2}G} + N_0 B_b} \geq \gamma_i. \qquad (5)$$

Define auxiliary variables β_i with $\beta_i \geq 0$ for $i = 1, \cdots, K$. Then, Equation (5) is equivalent to the following equation:

$$\frac{S_{i,j}}{\frac{\sum_{k=1}^{K} \sum_{m=1}^{M_k} m T_{k,m} S_{k,m} - j S_{i,j}}{\frac{3}{2}G} + N_0 B_b} = \gamma_i + \beta_i. \qquad (6)$$

After some algebra, we have

$$(1 - \sum_{k=1}^{K} \sum_{m=1}^{M_k} \frac{m T_{k,m} S_{i,j}}{m + \frac{\frac{3}{2}G}{\gamma_k + \beta_k}})(j + \frac{\frac{3}{2}G}{\gamma_i + \beta_i}) S_{i,j} = \frac{3}{2} G N_0 B_b. \qquad (7)$$

Thus, if the following constraint holds

$$\sum_{k=1}^{K} \sum_{m=1}^{M_k} \frac{m T_{k,m}}{m + \frac{\frac{3}{2}G}{\gamma_k + \beta_k}} < 1, \qquad (8)$$

the power level $S_{i,j}$ of each code channel is given by

$$S_{i,j} = \frac{\frac{3}{2} G N_0 B_b}{(j + \frac{\frac{3}{2}G}{\gamma_i + \beta_i})(1 - \sum_{k=1}^{K} \sum_{m=1}^{M_k} \frac{m T_{k,m}}{m + \frac{\frac{3}{2}G}{\gamma_k + \beta_k}})}. \qquad (9)$$

Otherwise, no solution exists because the power level $S_{i,j}$ must be larger than zero.

By analyzing Equation (9), $S_{i,j}$ is minimized when $\beta_k = 0$ for $k = 1, \cdots, K$. Thus, the minimum power level $S_{i,j}^{min}$ that satisfies the target SINR γ_i is

$$S_{i,j}^{min} = \frac{\frac{3}{2} G N_0 B_b}{(j + \frac{\frac{3}{2}G}{\gamma_i})(1 - \sum_{k=1}^{K} \sum_{m=1}^{M_k} \frac{m T_{k,m}}{m + \frac{\frac{3}{2}G}{\gamma_k}})}. \qquad (10)$$

To guarantee the existence of $S_{i,j}^{min}$, the following constraint must hold:

$$\sum_{k=1}^{K} \sum_{m=1}^{M_k} \frac{m T_{k,m}}{m + \frac{\frac{3}{2}G}{\gamma_k}} < 1. \qquad (11)$$

which comes from Equation (8) when $\beta_k = 0$ for $k = 1, \cdots, K$.

We define $W_{k,m} = \frac{m}{m + \frac{\frac{3}{2}G}{\gamma_k}}$ is the normalized capacity consumed by a mobile terminal that uses m code channels to transmit packets of service k in a time slot. Thus, Equation (11) becomes

$$\sum_{k=1}^{K} \sum_{m=1}^{M_k} T_{k,m} W_{k,m} < 1. \qquad (12)$$

Since $\sum_{m=1}^{M_k} T_{k,m} W_{k,m}$ is the overall normalized capacity consumed by all mobile terminals that support service k, Equation (11) implies that, in order to achieve minimum-power allocation for mobile terminals in a time slot, the overall normalized capacity consumed by all mobile terminals must be less than 1.

3.3 Maximum Capacity of a Time Slot

In this section, we investigate the maximum capacity in terms of the number of code channels that can be supported in a time slot when the minimum-power allocation algorithm is used.

Since $T_{k,m}$ is the number of mobile terminals that use m code channels to support service type k in a time slot, the number of mobile terminals of all service types in the time slot can be described by a vector $[T_{1,1}, \cdots, T_{k,m}, \cdots, T_{K,M_K}]$. If C_t denotes the number of code channels of all mobile terminals in a time slot, it is given by

$$C_t = \sum_{k=1}^{K} \sum_{m=1}^{M_k} m T_{k,m} \tag{13}$$

When minimum-power allocation is used, C_t must satisfy the constraint in Equation (11). As a result, in order to maximize C_t, we need to solve the the following optimization problem: find a positive vector $[T_{1,1}, \cdots, T_{k,m}, \cdots, T_{K,M_K}]$ that satisfies

$$\begin{cases} \sum_{k=1}^{K} \sum_{m=1}^{M_k} \frac{m}{m+\frac{\frac{3}{2}G}{\gamma_k}} T_{k,m} < 1, \\ \\ [T_{1,1}, \cdots, T_{k,m}, \cdots, T_{K,M_K}] \geq \mathbf{0}, \end{cases} \tag{14}$$

and maximizes the objective function C_t in Equation (13).

According to the linear programming theory, C_t is maximized at one of the extreme points of the positive vector $[T_{1,1}, \cdots, T_{k,m}, \cdots, T_{K,M_K}]$. By investigating the constraint in Equation (11), we know the set of extreme points consists of the vectors such as $[1 + \frac{\frac{3}{2}G}{\gamma_1}, 0, \cdots, 0], \cdots,$ $[0, \cdots, 0, \frac{m+\frac{\frac{3}{2}G}{\gamma_k}}{m}, 0, \cdots, 0], \cdots,$ $[0, \cdots, 0, \frac{M_K+\frac{\frac{3}{2}G}{\gamma_K}}{M_K}]$.

Substituting an extreme point, e.g., $[0, \cdots, 0, \frac{m+\frac{\frac{3}{2}G}{\gamma_k}}{m}, 0, \cdots, 0]$, into Equation (13), the value of C_t is $m + \frac{\frac{3}{2}G}{\gamma_k}$. Thus, the maximum value of C_t, denoted by C_t^*, is

$$C_t^* = max\left\{ m + \frac{\frac{3}{2}G}{\gamma_k}, m = 1, \cdots, M_k,\ k = 1, \cdots, K \right\}. \tag{15}$$

From Equation (15), we know that

$$C_t^* = max\{M_k + \frac{\frac{3}{2}G}{\gamma_k}, k = 1, \cdots, K\}, \tag{16}$$

which implies that C_t^* is achieved when all mobile terminals use the maximum allowed number (i.e. M_k) of code channels to transmit packets. This phenomenon can be explained as follows. When mobile terminals use maximum number of code channels, the number of different mobile terminals in a time slot is minimized. Considering subcode concatenation, mutual interference between code channels is also minimized. Within this result in mind, when designing a packet scheduler, we need rate-scheduling, i.e., a mobile terminal must use as many code channels as possible in a time slot to transmit packets.

Also from Equation (15), we know that C_t^* must be achieved at M_{k^*} and γ_{k^*} with $M_{k^*} + \frac{\frac{3}{2}G}{\gamma_{k^*}} = max\{M_k + \frac{\frac{3}{2}G}{\gamma_k}, k = 1, \cdots, K\}$ and the vector $[T_{1,1}, \cdots, T_{k,m}, \cdots, T_{K,M_K}]$ $= [0, \cdots, 0, T_{k^*,M_{k^*}}, 0, \cdots, 0]$. This result implies that service k^* is the only service that can be accommodated in the same time slot; otherwise, the maximum capacity cannot be achieved. In order to guarantee this, BER-scheduling is necessary in the packet scheduler, i.e., packets with different BER requirements must be accommodated in different time slots. It should be noted that k^* is not necessary to be the service with the least stringent BER requirement.

In summary, in order to efficiently utilize the capacity of a time slot in a multi-code TD-CDMA system, both BER- and rate-scheduling are required. With such a scheduling scheme, the optimal result is that mobile terminals transmitting packets in the same time slot have the same BER requirement and use maximum allowed code channels. However, when other QoS parameters such as packet delay and packet loss ratio are considered, the optimal result cannot be always achieved. It is possible that either mobile terminals with different BER requirements transmit packets in the same time slot, or mobile terminals do not use maximum allowed code channels. In such situations, maximum capacity C_t^* cannot be achieved. However, since the minimum-power allocation algorithm is embedded in the scheduler, the capacity of a time slot can still be utilized as efficiently as possible. In the next section, we use minimum-power allocation and the concept of rate- and BER-scheduling to design a packet scheduler for the MAC protocol of TDD mode wideband CDMA wireless LANs.

4 THE PACKET SCHEDULER

The packet scheduler consists of packet prioritizer and rate- and BER-scheduling scheme. The prioritizer is used to determine the priority of each batch of packets according to QoS parameters. Then all batches of packets are serviced from the highest priority towards the lowest priority. After a batch is selected by the packet scheduler, the rate- and BER-scheduling scheme determines the appropriate time slots and the number of code channels to accommodate packets of this batch. The capacity of each time slot and the received power level of each code channel are determined on the basis of the minimum-power allocation algorithm.

4.1 Packet Prioritizer

In order to reduce delay and packet loss ratio, the priority of a batch of packets needs to be inversely proportional to the remaining time of the batch. However, if the remaining time of two different batches is the same, the batch with more packets must have higher priority. It should be noted that a fair queuing algorithm can also be used to determine the priority of each batch. However, its complexity is much higher.

4.2 Rate- and BER-Scheduling Scheme

Suppose that batch i is the first being selected by the packet prioritizer. The scheduling scheme needs to allocate appropriate time slots and code channels to the pack-

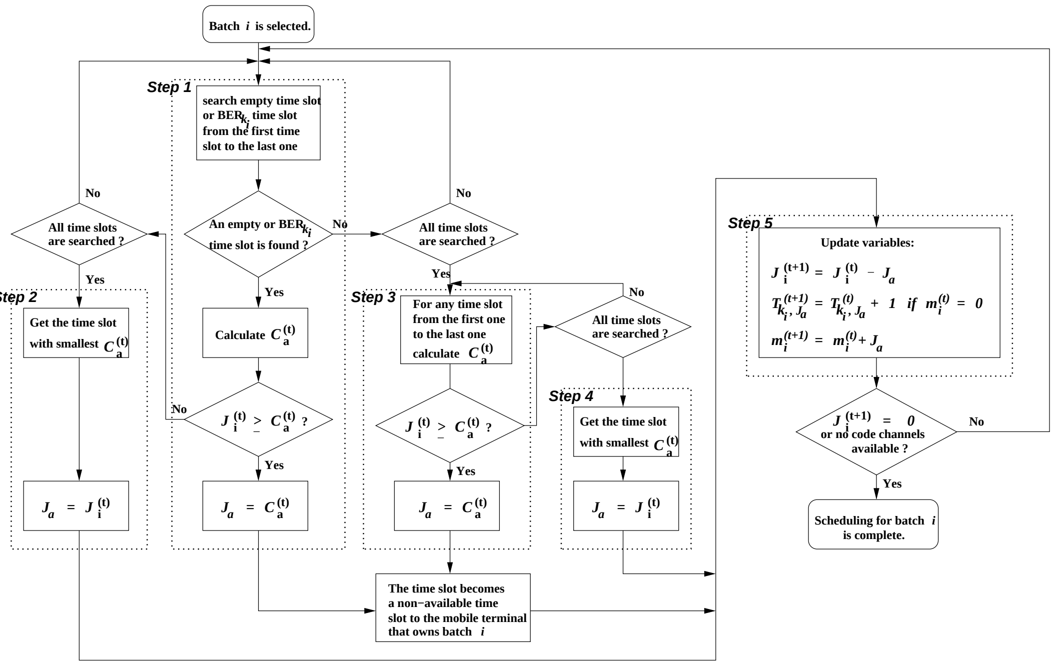

Figure 2: The procedures of the rate- and BER-scheduling scheme.

Table 1: Notations Used in the Scheduling Scheme

t	The iteration number of the scheduling scheme.
$C_a^{(t)}$	The number of code channels that can be used in a time slot for batch i before the t-th iteration.
$m_i^{(t)}, m_i^{(t+1)}$	The number of code channels used by batch i in a time slot before and after the t-th iteration, respectively.
J_a	The number of packets accommodated in an iteration.
$J_i^{(t)}, J_i^{(t+1)}$	The number of packets in batch i before and after the t-th iteration, respectively.
$T_{k,m}^{(t)}, T_{k,m}^{(t+1)}$	The number of mobile terminals using m code channels in a time slot to support service type k before and after the t-th iteration, respectively.

ets of this batch. In order to transmit as many packets as possible in a time slot, the rate- and BER-scheduling scheme is used to allocate code channels in different time slots to batch i.

To simplify descriptions of the scheduling scheme, some notations are defined in Table 1. Several types of time slots are also defined as follows:

- *Empty Time Slot.* If there are no packets accommodated in a time slot, the time slot is called an *empty time slot*. Otherwise, it is a *non-empty time slot*.

- BER_i *Time Slot.* A time slot is called BER_i *time slot* if the most stringent BER required by the packets in this time slot is BER_i.

- *Non-Available Time Slot.* A non-empty time slot is called a *non-available time slot* to a mobile terminal if the mobile terminal has used the maximum allowed number of code channels in this time slot. According to this definition, a *non-available time slot* is not available to a specific mobile terminal instead of to all mobile terminals.

As shown in Figure 2, the rate- and BER-scheduling scheme works iteratively until all packets in batch i are accommodated or no code channel is available for batch i in the current uplink frame. If no code channel is available and there are remaining packets in batch i, these packets are serviced in the next uplink frame. However, if batch i times out in the next frame, the remaining packets must be discarded. As shown in Figure 2, each iteration of the scheduling scheme includes the following steps:

- *Step 1.* An empty or non-empty BER_{k_i} time slot is searched from the first time slot towards the last one of the uplink frame to accommodate packets of batch i so that the packets in the same time slot belong to the same service type. If such a time slot is found, $C_a^{(t)}$ is calculated and compared to $J_i^{(t)}$, i.e., the number of packets in batch i. If $J_i^{(t)} \geq C_a^{(t)}$, $C_a^{(t)}$ packets in batch i are accommodated in the time slot. In such a way, the mobile terminal that owns batch i uses as many code channels in a time slot as possible. If $J_i^{(t)} < C_a^{(t)}$, another empty or non-empty BER_{k_i} time slot is searched until $J_i^{(t)} \geq C_a^{(t)}$ is satisfied. After step 1 succeeds, $J_a = C_a^{(t)}$, i.e., all code channels left for batch i are used, and thus, the corresponding time slot becomes a non-available time slot to the mobile terminal that owns batch i. In this step if some empty or non-empty BER_{k_i} times slots are found, but none of them satisfies $J_i^{(t)} \geq C_a^{(t)}$, the scheduling proceeds to step 2. If neither an empty nor a non-empty BER_{k_i} time slot is found, step 3 is invoked. Step 1 performs both rate- and BER-scheduling.

- *Step 2.* If empty or non-empty BER_{k_i} time slots have been found but $J_i^{(t)} \geq C_a^{(t)}$ is not satisfied, then $J_i^{(t)}$ packets must be accommodated in the empty or non-empty BER_{k_i} time slot in which $C_a^{(t)}$ is the smallest among all empty and non-empty BER_{k_i} time slots. Thus, time slots with larger $C_a^{(t)}$ are reserved for batches with more packets, which is the objective of rate-scheduling. After this step is successfully executed, $J_a = J_i^{(t)}$, i.e., no packets are left in batch i.

- *Step 3.* If neither an empty nor a non-empty BER_{k_i} time slot was found in step 1, all time slots are searched until $J_i^{(t)} \geq C_a^{(t)}$ is satisfied. If a time slot satisfying $J_i^{(t)} \geq C_a^{(t)}$ is found, $C_a^{(t)}$ packets of batch i are accommodated in the time slot. Otherwise, step 4 is invoked. As we can see, only rate-scheduling is performed in this step. After step 3 succeeds, $J_a = C_a^{(t)}$ and the corresponding time slot becomes a non-available time slot to the mobile terminal that owns batch i.

- *Step 4.* If step 3 fails, $J_i^{(t)}$ packets must be accommodated in the time slot in which $C_a^{(t)}$ is the smallest. Thus, $J_a = J_i^{(t)}$.

- *Step 5.* Variables are updated as shown in Figure 2.

In each iteration of the scheduling scheme, $C_a^{(t)}$ is calculated according to the minimum-power allocation algorithm. After rate- and BER-scheduling scheme is completed for the whole uplink frame, the minimum-power allocation algorithm is used to allocate the received power level to each code channel in a time slot.

5 Performance Evaluation

Six traffic models that are the same as those in [6] have been developed to simulate the multimedia traffic.

5.1 System Parameters

- *Input Parameters.* The input parameters are shown in Table 2. In addition, the frame length of both uplink and downlink is 16 $msec$, and the number of slots in the uplink frame is 10. The spreading bandwidth and the spreading gain are 5 MHz and 30.30, respectively, and the basic transmission rate is 16.5 $Kbps$. In Table 2, N_p is the number of total packets that are generated by an email or data message. In simulations, the call composition of different traffic types is the same as that used in in [6].

- *Output Parameters.* Average packet loss ratio r_l, average packet delay d_p, and throughput t_r are the metrics used to evaluate the performance of the protocol. The average packet delay d_p consists of two components, i.e.,

$$d_p = d_r + d_t, \tag{17}$$

  where d_r is the time being spent on allocating time slots to mobile terminals, while d_t is the transmission time of a packet after time slots are allocated.

Table 2: System Input Parameters

Service	t_{out}	BER	γ	M
Voice	2	10^{-3}	4.750	1
CBR Audio	3	10^{-4}	6.910	5
VBR Video	3	10^{-5}	9.090	4
CBR Video	4	10^{-6}	11.295	6
Data	$2N_p$	10^{-9}	17.985	1
Email	$50N_p$	10^{-9}	17.985	1

5.2 Numerical Results

Based on the system input parameters and the traffic models, we have simulated the proposed MAC protocol for TDD mode wideband CDMA wireless LANs. The system output parameters are used to evaluate the performance of the protocol. We also compare our protocol with WISPER protocol [6] and the resource allocation algorithm proposed in [7]. Since WISPER is a FDD mode TD-CDMA MAC protocol, when it is applied to a TDD system in the simulation, its signaling procedures need to be modified as follows: a request transmitted from a mobile terminal in the uplink frame does not receive feedback immediately; the feedback is received in the next downlink frame. However, the packet scheduler of WISPER does not need any change.

The average packet delay of multimedia traffic is shown in Figure 3, and the average packet loss ratios of different types of real time traffic are illustrated in Figure 4. It should be noted that Figure 4 does not include the results of non-real-time traffic because the large timeout values of email and computer data traffic avoid packet loss. The throughput of the system is shown in Figure 5.

In Figs. 3–5, comparisons with WISPER protocol and the resource allocation algorithm in [7] are depicted. Simulation results show that the new protocol not only improves the system throughput but also decreases the packet loss ratio and the average packet delay of each traffic type. As traffic load becomes higher, the improvement becomes more significant. The reason is as follows. By using the minimum-power allocation and rate- and BER-scheduling scheme, the capacity of each time slot is improved. Thus, at the same traffic load the new scheme spends less time to transmits multimedia packets. Also, due to the increase of capacity, more packets can be transmitted within each each frame.

Since there is no packet loss in non-real-time traffic, when the system capacity is not enough to meet the traffic load, the average packet delay is much more significantly increased than that of real-time traffic. In other words, when the system capacity is improved by the new MAC protocol, the average packet delay of non-real-time traffic will be much more significantly reduced by the new scheme than that of real-time traffic. This has been shown in the comparisons of average packet delays in Figure 3 for three different protocols.

6 Conclusions

In this paper, we derived the minimum-power allocation algorithm for mobile terminals that transmit multimedia traffic in TDD mode wideband CDMA wireless LANs. The maximum capacity of a time slot was also in-

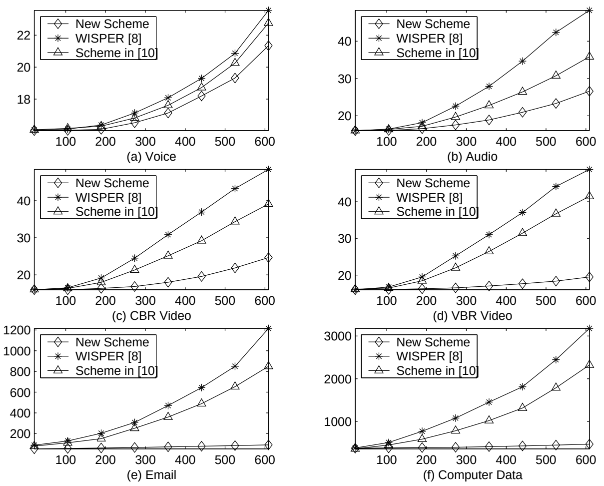

Figure 3: The average packet delay versus call arrival rate. (vertical axis: average packet delay (*msec*), horizontal axis: arrival rate of voice calls (*calls/hour*).)

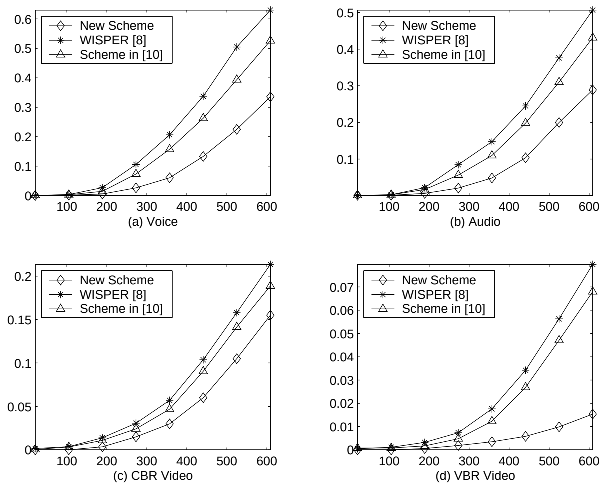

Figure 4: The average packet loss ratio of real-time traffic versus call arrival rate. (vertical axis: average packet loss ratio (percentage), horizontal axis: arrival rate of voice calls (*calls/hour*).)

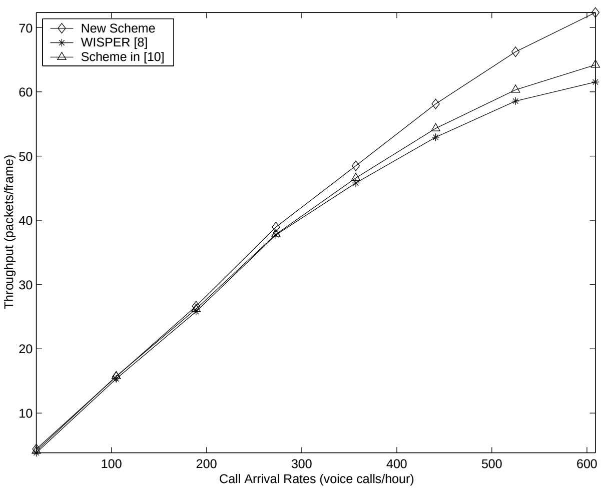

Figure 5: The system throughput versus the arrival rate of voice calls.

vestigated. Then we designed a new packet scheduler for the MAC protocol based on the rate- and BER-scheduling scheme and the minimum-power allocation algorithm. Finally, simulation experiments were thoroughly carried out to evaluate the performance of the new MAC protocol. Results illustrate that our proposed MAC protocol greatly improves the QoS metrics of multimedia traffic and the system throughput.

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