Adaptive Priority-Based Downlink Scheduling for WiMAX Networks
Shih-Jung Wu, Shih-Yi Huang, and Kuo-Feng Huang

Abstract: Supporting quality of service (QoS) guarantees for diverse multimedia services are the primary concerns for WiMAX (IEEE 802.16) networks. A scheduling scheme that satisfies QoS requirements has become more important for wireless communications. We propose a downlink scheduling scheme called adaptive priority-based downlink scheduling (APDS) for providing QoS guarantees in IEEE 802.16 networks. APDS comprises two major components: priority assignment and resource allocation. Different service-type connections primarily depend on their QoS requirements to adjust priority assignments and dispatch bandwidth resources dynamically. We consider both starvation avoidance and resource management. Simulation results show that our APDS methodology outperforms the representative scheduling approaches in QoS satisfaction and maintains fairness in starvation prevention.

Index Terms: IEEE 802.16, WiMAX, Resource Management, Quality of Service (QoS)

I. INTRODUCTION

In recent years, wireless broadband networks have undergone significant development. As evidenced by current research interests, next generation wireless broadband networks will combine both wireless and broadband networks [1][2]. The maturation of wireless technologies and development of Internet services have led to an increase in demand for wireless multimedia transmission, data communication, and other mobile services. Many researchers consider the wireless metropolitan area network as a potential solution for mobile communication technology issues. The IEEE 802.16 standard on broadband wireless access is the main technology standard for developing wireless broadband network systems. The purpose of IEEE 802.16 is to build highly stable wireless access networks with high transmission rates and QoS [3][4]. In this paper, we propose an adaptive priority-based downlink scheduling (APDS) algorithm to improve network performance. The algorithm makes dynamic adjustments to bandwidth allocation according to user demand. Moreover, a weight-based proportional fairness scheme has been proposed to decrease starvation of lower level services (i.e., best effort services). The rest of the paper is organized as follows: section 2 presents the scheduling and bandwidth allocation scheme in the proposed APDS; section 3 presents the results of our simulations; and section 4 presents our conclusions.

II. ADAPTIVE PRIORITY-BASED DL SCHEDULING SCHEMES

In general, there are three components in an IEEE 802.16 network: the base station (BS), subscriber station (SS), and mobile station (MS). SS and MS are both clients; the difference is that MS clients are mobile. The objective of this paper is to describe a downlink scheduling scheme that exhibits better performance for the IEEE 802.16 standard. IEEE 802.16 is a connection-oriented wireless communication technology. Each connection in an IEEE 802.16 network is identified by a unique connection ID (CID) that is assigned by the BS. The connection provides bandwidth resources on a downlink or uplink connection. We dynamically adjust the bandwidth allocation for downlinks with downloads to meet QoS restrictions. For each user, we guarantee service quality according to his QoS parameter and avoid starving lower service levels. With these goals, we propose a downlink scheduling scheme called Adaptive Priority-based Downlink Scheduling (APDS). APDS operates in a point-to-multipoint network architecture with time division duplexing technology for data transmission. The proposed algorithm is a service-based centralized scheduling algorithm. It is also a non-work-conserving scheduling algorithm because the scheduling is performed before each frame [5][6]. Admission control [6][7] is not a main consideration in this paper.

A. SYSTEM ARCHITECTURE

In the proposed scheme, each connection will be assigned a priority that identifies the transmission order. APDS improves the QoS guarantee by dynamically adjusting priorities while also taking QoS restrictions into consideration. The QoS parameters defined by the 802.16 standard will be considered and
quantified to allow the scheduler’s adjustments to be more flexible and precise [4,6]. Table I shows the QoS parameter definitions used in this paper.

| Notation | Definition |
|----------|------------|
| \( \Gamma_i \) | Maximum sustained traffic rate of connection \( i \) |
| \( \gamma_i \) | Minimum reserved traffic rate of connection \( i \) |
| \( \zeta_i \) | Maximum latency of connection \( i \) |
| \( \varsigma_i \) | Unsolicited grant interval of connection \( i \) |
| \( \delta_i \) | Tolerated jitter of connection \( i \) |

The five service types defined by IEEE 802.16 are categorized as two services: delay-constrained services (DCS) and throughput-guaranteed services (TGS). DCSs include UGS (un-solicited grant service), ERT-VR (extended real-time variable), and RT-VR (real-time variable rate). TGSs include NRT-VR (non-real-time variable rate) and BE (best effort). With APDS, DCS requests are satisfied before TGS requests. Furthermore, the connection with the lowest priority in the same category promotes its own priority to avoid starvation or connection breakdown. As shown in Fig. 1 for DCSs, an RT-VR can be promoted to an ERT-VR, and the ERT-VR can then be promoted to a UGS. For TGSs, a BE can be promoted to an NRT-VR.

There are two phases included in APDS: priority assignment and resource allocation. As shown in Fig. 2, priority assignment and resource allocation can be divided into two separate operations. The priority assignment phase comprises both connection rankings and priority elevations. Connection ranking determines the priority of connections by their specified parameters. Priority elevation avoids starvation and connection breakdowns by promoting the connection with the lowest priority. For the resource allocation phase, quantification and allocation of bandwidth requirements are performed. Bandwidth requirement quantification calculates the upper and lower bounds of possible bandwidth requests for each connection, allowing dynamic bandwidth allocation by aggregating the upper and lower bounds of all bandwidth requests. Bandwidth requirement allocation allocates bandwidth according to the connection ranking.

**B. Priority Assignment**

As shown in Fig. 3, two types of operations are connection rankings and priority elevations. For connection ranking, we consider two factors: emergent degree and satisfactory degree. The current average latency is calculated as the emergent degree because of the strict latency requests for DCSs. For TGSs, the allocated bandwidth in the last frame is considered as the satisfactory degree for ranking all connections. Moreover, five ranking queues for different service types are used to store ranked connections. To satisfy the QoS requests and avoid lower priority connection break downs in the APDS, we implemented an emergent queue for DCSs and a service interrupt counter for TGSs.

**B.1 Connection Ranking**

**B.1.1 DCS**

We use the symbols \( RQ_{UGS}^{DL} \), \( RQ_{ERT}^{DL} \), and \( RQ_{RT}^{DL} \) to identify the downlink ranking queues for UGSs, ERT-VRs, and RT-VRs. The emergent degree is used to elevate ERT-VR and RT-VR services. For the downlink, an emergent degree is calculated using the tolerable latency (determined by the average remaining wait time). All DCS, UGS, ERT-VR and RT-VR services are viewed as variable bit rate (VBR) for the downlink [4,6]. Here are select parameters that are used in the following algorithms: \( T_{frame} \) represents the length of a frame, \( \zeta_i \) represents the maximum latency of connection \( i \), and \( N_i \) represents the packet size in connection \( i \). \( T^i_a(j) \) is the arrival time of the transferred packet at
the MAC layer. $T^w(i)$ is the wait time of each packet in the MAC layer. This wait time can be calculated using equation (1)

$$T^w(j) = T_c - T^g(j)$$  

$T^g(j)$ is the guard time (tolerable wait time) of each packet, as shown in equation (2). $T_c$ is the current system time. $\zeta_i$ is the maximum latency of connection $i$.

$$T^g(j) = \zeta_i - T^w(j)$$  

$L_i$ is the tolerable latency of connection $i$ and identifies the emergent degree of connection $i$. This latency is calculated by equation (3). We calculate $L_i$ to normalize algorithms 1, 2, and 3. Then, we arrange the order according to this normalized value for every connection.

$$L_i = \sum_{j=1}^{N_j} \frac{T^g(j)}{N_j}$$

-UGS: In Algorithm 1, $N^{DL}_{\text{UGS}}$ represents the number of UGSs in the downlink, and $\Omega^{CID}_{\text{UGS,DL}}$ represents the CID set of the UGSs in the downlink. The ranking is determined by the emergent degree and then sequentially pushed onto the ranking queues, $RQ^{DL}_{\text{UGS}}$.

**Algorithm 1 Priority assignment for a UGS connection**

**Require:** $N^{DL}_{\text{UGS}}$, $\Omega^{CID}_{\text{ERT,DL}} = \{CID_1 \ldots CID_l\}, \forall = 1 \ldots N^{DL}_{\text{UGS}}$

**Ensure:** $RQ^{DL}_{\text{UGS}}$

1: BEGIN
2: for $i = 1$ to $N^{DL}_{\text{UGS}}$ do
3:  
4:  
5:  
6:  
7:  
8:  
9:  
10:  
11:  
12:  
13:  
14:  
15:  
16:  
17:  
18:  
19:  
20: END

-ERT-VR: In Algorithm 2, $N^{DL}_{\text{ERT}}$ represents the number of ERT-VRs in the downlink, and $\Omega^{CID}_{\text{ERT,DL}}$ represents the CID set of the ERT-VRs in the downlink. The ranking is determined by the emergent degree of connection $i$. This wait time can be calculated using equation (1).

$$i^N_{\text{ERT,DL}} = \min(f_i(m-1), \gamma_i T_{\text{frame}}), \forall i = 1 \ldots N^{DL}_{\text{ERT}}$$  

Using equation (4), we can find the minimum bandwidth request for the last frame. Then, the available total bandwidth is divided by the minimum bandwidth request in last frame to find $S_i$. $S_i$
is the ratio that evaluates the satisfactory degree for connection \( i \), as shown in equation \((5)\).

\[
S_i = \frac{b_i^k(m-1)}{b_i^{\text{NRT,low}}(m-1)}, \forall i = 1 \ldots N^\text{DL}_{\text{NRT}}, \forall i \in \Omega^i_{\text{CID}} \tag{5}
\]

Because there is no minimum reserved traffic rate constraint for \( \text{BE} \), we use the number of packets waiting to be served in BS to replace it. We can calculate the satisfactory degree for \( \text{BE} \) with equation \((6)\).

\[
S_i = \frac{b_i^k(m-1)}{b_i}(m-1), \forall i = 1 \ldots N^\text{DL}_{\text{BE}}, \forall i \in \Omega^i_{\text{BE,DL}} \tag{6}
\]

-NRT-VR: In Algorithm 4, \( N^\text{DL}_{\text{NRT}} \) represents the number of NRT-VRs in the downlink, and \( \Omega^i_{\text{CID,DL}} \) represents the CID set of the NRT-VRs in the downlink. The ranking is determined by the satisfactory degree and then sequentially pushed onto the ranking queues, \( RQ^i_{\text{NRT}} \).

**Algorithm 4 Priority assignment for an NRT-VR connection**

**Require:** \( N^\text{DL}_{\text{NRT}} \)

\[
\Omega^i_{\text{CID,DL}} = \{ CID_1 \ldots CID_i \}, \forall i = 1 \ldots N^\text{DL}_{\text{NRT}}
\]

**Ensure:** \( RQ^i_{\text{NRT}} \)

1. BEGIN
2. for \( i = 1 \) to \( N^\text{DL}_{\text{NRT}} \) do
3. \( S_i = \frac{b_i^k(m-1)}{b_i^{\text{NRT,low}}(m-1)} \)
4. end for
5. while \( \Omega^i_{\text{CID,DL}} > 0 \) do
6. \( CID_{\text{min}} = \arg\min S_i \)
7. \( CID_{\text{min}} \) add to \( RQ^i_{\text{NRT}} \)
8. \( \Omega^i_{\text{CID,DL}} = \Omega^i_{\text{CID,DL}} - CID_{\text{min}} \)
9. end while
10. END

-BE: In Algorithm 5, \( N^\text{DL}_{\text{BE}} \) represents the number of BEs in the downlink, and \( \Omega^i_{\text{BE,DL}} \) represents the CID set of the BEs in the downlink. The ranking is determined by the satisfactory degree and then sequentially pushed onto the ranking queues, \( RQ^i_{\text{BE}} \).

**Algorithm 5 Priority assignment for a BE connection**

**Require:** \( N^\text{DL}_{\text{BE}} \)

\[
\Omega^i_{\text{BE,DL}} = \{ CID_1 \ldots CID_i \}, \forall i = 1 \ldots N^\text{DL}_{\text{BE}}
\]

**Ensure:** \( RQ^i_{\text{BE},EQ^i_{\text{BE}},RQ^i_{\text{NRT}}} \)

1. BEGIN
2. for \( i = 1 \) to \( N^\text{DL}_{\text{BE}} \) do
3. \( C_i \geq \eta \) then
4. \( P_j \) Add to \( EQ^i_{\text{BE}} \)
5. end if
6. end for
7. for \( i = 1 \) to \( N^\text{DL}_{\text{BE}} \) do
8. \( S_i = \frac{b_i^k(m-1)}{b_i}(m-1) \)
9. end for
10. while \( \Omega^i_{\text{CID,DL}} > 0 \) do
11. \( CID_{\text{min}} = \arg\min S_i \)
12. \( CID_{\text{min}} \) add to \( RQ^i_{\text{BE}} \)
13. \( \Omega^i_{\text{BE,DL}} = \Omega^i_{\text{BE,DL}} - CID_{\text{min}} \)
14. end while
15. \( EQ^i_{\text{BE}} \) Add to \( RQ^i_{\text{NRT}} \)
16. END

B.2 Priority Elevation

In this paper, we designed a suitable priority elevation mechanism for DCS and TGS. The concept of a virtual emergent queue was proposed by us for ERT-VR and RT-VR in DCS. If the waiting time of packets exceeds the maximum latency, we will elevate the priority for services adaptively. Furthermore, if the services for ERT-VR and RT-VR connections fit equation \((7)\), these services will be put into the emergent queue. The meaning of equation \((7)\) is as follows: the packet can continue waiting, as long as the wait time has been less than \( T_{\text{frame}} \). In fact, the so-called emergent queue inserts ERT-VR and RT-VR connections...
(shown in equation (13)) at the bottom of \( RQ_{DL}^{UGS} \) and \( RQ_{ERT}^{DL} \):

\[
\zeta_i - (T_c - T_i(j)) \leq T_{frame} \quad (7)
\]

We utilize a service interrupt counter to observe the status of every connection in TGS and let the service interrupt connections elevate priorities to BEs. The service interrupt counter \( \varphi_i \) will be used to elevate the priority of BE services. For BE services, the quality of the transmission rate is the most important factor. The service interrupt counter checks the transmission rate in the last frame. If the transmission rate is 0, \( \varphi_i \) is incremented by 1. If \( \varphi_i \) exceeds threshold \( \eta \), the connection is presumed to be starving and has its priority elevated. That is, insert BE connections with transmission rates that exceed \( \eta \) into the bottom of \( RQ_{DL}^{NRT} \).

### C. Resource Allocation

As shown in Fig. 4, resource allocation is divided into two categories: bandwidth requirement quantification and bandwidth requirement allocation. Fig. 5 depicts a flowchart of resource allocation. We quantify requests to determine the allocation method. There are three cases presented in this paper with different resource allocation methods. Otherwise, we propose a weight-based proportional fairness (WPF) for TGS services to improve fairness and increase the number of served requests.

#### C.1 Bandwidth Requirement Quantification

Unsolicited grant interval, tolerated jitter, minimum reserved traffic rate, and maximum sustained traffic rate are four QoS qualifying parameters that concern DCS services. For NRT-VR services, there are two QoS parameters that need to be considered: minimum reserved traffic rate and maximum sustained traffic rate. The maximum sustained traffic rate is the main consideration for BE services.

##### C.1.1 DCS

The maximum sustained traffic rate is the main factor in determining the downlink upper bound for DCS services. Similarly, the minimum reserved traffic rate is the main factor for the lower bound.

\text{UGS Equation (8)} calculates the upper bound of UGSs for the downlink. The base station allocates bandwidth by comparing the maximum available bandwidth to the number of packets in the buffer for each connection. \( b_{i,DL}^{UGS,max}(m) \) represents the maximum possible bandwidth allocation to connection \( i \) in the \( m \)-th frame, \( \Gamma_i \) represents the maximum sustained traffic rate for connection \( i \), and \( f_i(m) \) represents the number of packets waiting to be sent to the base station.

\[
b_{i,DL}^{UGS,max}(m) = \min(f_i(m), \Gamma_i.T_{frame}), \forall i = 1 \ldots N_{DL}^{UGS} \quad (8)
\]

Equation (9) evaluates the sum of the upper bounds of bandwidth requests for UGSs. \( b_{max}^{UGS,DL}(m) \) represents the sum of the upper bounds of downlink bandwidth requests for UGS services.

\[
b_{max}^{UGS,DL}(m) = \sum_{i=1}^{N_{DL}^{UGS}} b_{i,DL}^{UGS,max}(m), \forall i \in \Omega_{DL}^{CID}^{UGS} \quad (9)
\]

For the lower bound of bandwidth requests, the base station al-
locates bandwidth by comparing the minimum requested bandwidth to the number of packets in the buffer for each connection. Equation (10) calculates the lower bound of the request. \( b_{i_{UGS_{\min}}}^{DL}(m) \) represents the minimum requested bandwidth of connection \( i \) in the \( m \)th frame, and represents the maximum sustained traffic rate for connection \( i \).

\[ b_{i_{UGS_{\min}}}^{DL}(m) = \min(f_i(m), \gamma_i, T_{frame}), \forall i = 1 \ldots N_{DL_{UGS}} \]  

(10)

Equation (11) evaluates the sum of the lower bounds of bandwidth requests for UGSs. \( b_{min_{DL}}^{UGS}(m) \) represents the sum of the lower bounds of bandwidth requests in the downlink for UGSs.

\[ b_{min_{DL}}^{UGS}(m) = \sum_{i=1}^{N_{DL_{UGS}}} b_{i_{UGS_{\min}}}^{DL}(m), \forall i \in \Omega_{DL_{UGS}}^{CID} \]  

(11)

-ERT-VR

For ERT-VR services, the upper and lower bounds are evaluated in the same way as UGSs. In equation (12), \( b_{i_{ERT_{\max}}}^{DL}(m) \) represents the maximum possible bandwidth allocation to connection \( i \) in the \( m \)th frame. In equation (13), \( B_{ERT_{\max}}^{DL}(m) \) represents the sum of the upper bounds of downlink bandwidth requests for ERT-VR services. In equation (14), \( b_{i_{ERT_{\min}}}^{DL}(m) \) represents the minimum requested bandwidth of connection \( i \) in the \( m \)th frame. In equation (15), \( B_{min_{DL}}^{ERT}(m) \) represents the sum of the lower bounds of downlink bandwidth requests for ERT-VR services.

\[ b_{i_{ERT_{\max}}}^{DL}(m) = \min(f_i(m), \Gamma_i, T_{frame}), \forall i = 1 \ldots N_{DL_{ERT}} \]  

(12)

\[ B_{ERT_{\max}}^{DL}(m) = \sum_{i=1}^{N_{DL_{ERT}}} b_{i_{ERT_{\max}}}^{DL}(m), \forall i \in \Omega_{ERT_{DL}}^{CID} \]  

(13)

\[ b_{i_{ERT_{\min}}}^{DL}(m) = \min(f_i(m), \gamma_i, T_{frame}), \forall i = 1 \ldots N_{DL_{ERT}} \]  

(14)

\[ B_{min_{DL}}^{ERT}(m) = \sum_{i=1}^{N_{DL_{ERT}}} b_{i_{ERT_{\min}}}^{DL}(m), \forall i \in \Omega_{ERT_{DL}}^{CID} \]  

(15)

-NRT-VR

For NRT-VR services, the upper and lower bounds are evaluated in the same manner for equations (20), (21), (18), and (19). In equation (20), \( b_{i_{NRT_{\max}}}^{DL}(m) \) represents the maximum possible bandwidth allocation to connection \( i \) in the \( m \)th frame. In equation (21), \( B_{max_{DL}}^{NRT}(m) \) represents the sum of the upper bounds of downlink bandwidth requests for NRT-VR services. In equation (22), \( b_{min_{DL}}^{NRT}(m) \) represents the minimum requested bandwidth of connection \( i \) in the \( m \)th frame. In equation (23), \( B_{min_{DL}}^{NRT}(m) \) represents the sum of the lower bounds of downlink bandwidth requests for RT-VR services.

\[ b_{i_{NRT_{\max}}}^{DL}(m) = \min(f_i(m), \Gamma_i, T_{frame}), \forall i = 1 \ldots N_{DL_{NRT}} \]  

(20)

\[ B_{max_{DL}}^{NRT}(m) = \sum_{i=1}^{N_{DL_{NRT}}} b_{i_{NRT_{\max}}}^{DL}(m), \forall i \in \Omega_{NRT_{DL}}^{CID} \]  

(21)

\[ b_{i_{NRT_{\min}}}^{DL}(m) = \min(f_i(m), \gamma_i, T_{frame}), \forall i = 1 \ldots N_{DL_{NRT}} \]  

(22)

\[ B_{min_{DL}}^{NRT}(m) = \sum_{i=1}^{N_{DL_{NRT}}} b_{i_{NRT_{\min}}}^{DL}(m), \forall i \in \Omega_{NRT_{DL}}^{CID} \]  

(23)

-BE

For BE services, the upper and lower bounds are evaluated in the same manner as UGS and ERT-VR services. In equation (24), \( b_{i_{BE_{\max}}}^{DL}(m) \) represents the maximum possible bandwidth allocation to connection \( i \) in the \( m \)th frame. In equation (25), \( B_{max_{DL}}^{BE}(m) \) represents the sum of the upper bounds of downlink bandwidth requests for BE services. In equation (26), \( b_{i_{BE_{\min}}}^{DL}(m) \) represents the minimum requested bandwidth of connection \( i \) in the \( m \)th frame. In equation (27), \( B_{min_{DL}}^{BE}(m) \) represents the sum of the lower bounds of downlink bandwidth requests for BE services.

\[ b_{i_{BE_{\max}}}^{DL}(m) = \min(f_i(m), \Gamma_i, T_{frame}), \forall i = 1 \ldots N_{DL_{BE}} \]  

(24)
\[ B_{\text{max}}^{\text{DL}}(m) = \sum_{i=1}^{N} B_{\text{max}}^{\text{DL}}(m), \forall i \in \Omega^\text{DL}_{\text{BE}} \] (25)

\[ B_{\text{max}}^{\text{DL}, \text{req}}(m) \] represents the upper bound for total bandwidth requests, and \( B_{\text{max}}^{\text{DL}, \text{req}}(m) \) represents the lower bounds for total bandwidth requests in \( m \) frame of the downlink. Because there is no lower bound constraint for BE services, we use the upper bound to replace the lower bound. According to the results of equation (26) and (27), we can choose an adaptive bandwidth requirement allocation rule dynamically.

\[ B_{\text{max}}^{\text{DL}, \text{req}}(m) = B_{\text{max}}^{\text{DL}}(m) + B_{\text{min}}^{\text{DL}}(m) \] (26)

\[ B_{\text{max}}^{\text{DL}, \text{req}}(m) = B_{\text{max}}^{\text{DL}}(m) + B_{\text{max}}^{\text{DL}}(m) \] (27)

C.2 Bandwidth Requirement Allocation

In Algorithm 6, we first examine DCS services in the proposed mechanism. Then, we examine TGS services. We designed a weight-based proportional fairness (WPF) scheme for situations with insufficient remaining bandwidth for the total lower bound TGS request. To allocate bandwidth, WPF determines a weight from the number of requests and ranking. Starvation is likely to occur in TGSs. Therefore, we hope to serve as many connections as possible while avoiding starvation. We utilize the WPF mechanism and set up weights (\( \omega_1 = 0.6 \) and \( \omega_2 = 0.4 \) in simulation) to increase TGS service connections, decrease starvations and maintain fairness. In Fig. 4., we inspect three cases. In case I, \( B_{\text{total}} > B_{\text{max}}^{\text{DL}, \text{req}} \), we satisfy the upper bound request for all connections first. Then, we allocate the remaining bandwidth according to the ratio of unsatisfied bandwidth for connection \( i \) to total unsatisfied bandwidth while maintaining the fairness principle. In case II, \( B_{\text{total}} > B_{\text{max}}^{\text{DL}, \text{req}} \), we still follow the fairness principle to distribute total bandwidth resources according to the ratio of the difference in the upper bound request and lower bound request for an individual connection \( i \) to the difference in total bandwidth request between the upper bound and lower bound. In case III, \( B_{\text{min}}^{\text{DL}, \text{req}} > B_{\text{total}} \), we satisfy the lower bound bandwidth for DCS service connections according to the queue priority first. Then, two subcases, \( B_{\text{rem}} > B_{\text{min}}^{\text{NRT}} \) and \( B_{\text{rem}} \leq B_{\text{min}}^{\text{NRT}} \), are considered. \( B_{\text{rem}} \) represents the remaining bandwidth, and the \( B_{\text{min}}^{\text{NRT}} \) represents the total lower bound request for all NRT-VR connections. If \( B_{\text{rem}} > B_{\text{min}}^{\text{NRT}} \), we will satisfy the lower bound request for all NRT-VR connections first. Then, we allocate the remaining bandwidth to BE connections according to every BE connection request and priority. Otherwise, we allocate the remaining bandwidth to NRT-VR connections directly according to the bandwidth request and priority. Detailed procedures are shown for Algorithm 6.

**Algorithm 6 Bandwidth allocation scheme**

**Require:** \( B_{\text{total}} \)

\( RQ_{\text{UGS}}^{\text{DL}}, EQ_{\text{ERT}}^{\text{DL}}, RQ_{\text{RT}}^{\text{DL}}, RQ_{\text{VR}}^{\text{DL}}, RQ_{\text{BE}}^{\text{DL}} \)

**Ensure:** \( b_{\text{rem}}^i = 1 \ldots N \)

1: BEGIN
2: Calculate \( B_{\text{max}}^{\text{DL}, \text{req}} \) and \( B_{\text{min}}^{\text{DL}, \text{req}} \), \( B_{\text{rem}} = B_{\text{total}} \)
3: if \( B_{\text{total}} < B_{\text{max}}^{\text{DL}, \text{req}} \) then
4: if \( B_{\text{total}} < B_{\text{min}}^{\text{DL}, \text{req}} \) then
5: /* Allocate bandwidth for fine real-time services by Ranking Queue. The priority is as follows: \( RQ_{\text{UGS}}^{\text{DL}} \rightarrow RQ_{\text{ERT}}^{\text{DL}} \rightarrow RQ_{\text{RT}}^{\text{DL}} */
6: for \( i = 1 \to N_{\text{fine-real-time}} \) do
7: if \( B_{\text{rem}} > 0 \) then
8: \( b_i^U = b_{\text{rem}}^U \)
9: \( B_{\text{rem}} = B_{\text{rem}} - b_i^U \)
10: end if
11: end for
12: if \( B_{\text{rem}} > 0 \) then
13: if \( B_{\text{rem}} > B_{\text{min}}^{\text{NRT}} \) then
14: for \( i = 1 \to N_{\text{NRT}} \) do
15: \( b_i^B = b_{\text{rem}}^B \)
16: \( B_{\text{rem}} = B_{\text{rem}} - b_i^B \)
17: end for
18: end if
19: /* Make use of WPF scheme to allocate the remaining bandwidth for BE services by \( RQ_{\text{BE}}^{\text{DL}} */
20: for \( i = 1 \to N_{\text{BE}} \) do
21: \( b_i^B = \left[ \frac{B_{\text{max}}^{\text{DL}, \text{req}}}{\omega_1 \sum_{i=1}^{N_{\text{BE}}} \omega_1} \right] + \right[ \frac{\phi_i}{\sum_{i=1}^{N_{\text{BE}}} \phi_i} \right] * B_{\text{rem}} \)
22: end for
23: else
24: /* Make use of WPF scheme to allocate the remaining bandwidth for NRT services by \( RQ_{\text{NRT}}^{\text{DL}} */
25: for \( i = 1 \to N_{\text{NRT}} \) do
26: \( b_i^B = \left[ \frac{B_{\text{max}}^{\text{DL}, \text{req}}}{\omega_2 \sum_{i=1}^{N_{\text{NRT}}} \omega_2} \right] + \right[ \frac{\phi_i}{\sum_{i=1}^{N_{\text{NRT}}} \phi_i} \right] * B_{\text{rem}} \)
27: end for
28: end if
29: end if
30: for \( i = 1 \to N_{\text{DCS}} \) do
31: \( b_i^B = b_{\text{rem}}^B \)
32: \( B_{\text{rem}} = B_{\text{rem}} - b_i^B \)
33: end for
34: if \( B_{\text{rem}} > 0 \) then
35: for \( i = 1 \to N_{\text{NRT}} \) do
36: \( b_i^B = b_{\text{rem}}^B \)
37: \( B_{\text{rem}} = B_{\text{rem}} - b_i^B \)
38: end for
39: end if
40: else
41: for \( i = 1 \to N_{\text{NRT}} \) do
42: \( b_i^B = b_{\text{rem}}^B \)
43: \( B_{\text{rem}} = B_{\text{rem}} - b_i^B \)
44: end for
45: for \( i = 1 \to N_{\text{NRT}} \) do
46: \( b_i^B = b_{\text{rem}}^B \)
47: \( B_{\text{rem}} = B_{\text{rem}} - b_i^B \)
48: end for
49: if \( i = 1 \to N_{\text{NRT}} \) do
50: if \( SDU - b_{\text{max}}^B > 0 \) then
51: \( b_i^B = b_{\text{rem}}^B \)
52: \( B_{\text{rem}} = B_{\text{rem}} - b_i^B \)
53: end if
54: end for
55: end if
56: end if
57: end for
58: end if
59: end if
60: end if
III. SIMULATION RESULTS

A. Environment and Parameters

A.1 Scenario

The simulation used a point-to-multipoint network architecture that comprised one base station (BS) and nine mobile stations (MS), as shown in Fig 6. Table 2 shows the service type and CID of each mobile station.

A.2 Assumptions

- A TDD-based model was used.
- Scheduling was decided by the BS, taking into consideration the downlink.
- In the BS and MS, packets were dropped if the queue was full.
- All connections were set up after call admission control.
- Connections were not made or canceled during the simulation.

A.3 Parameters

Table 3 shows the simulation parameters, as well as the WPF weight setting (the sum of all weights is 1) and the service interrupt counter threshold \( \eta \). The total number of connections was 45. We defined the queue size and packet size for different types of services. The total amount of bandwidth was 10 Mbps, and the frame duration was 5 ms. Simulation time was 10 sec (2000 frames). The service interrupt counter threshold \( \eta \) was 50.

B. Simulation Results and Analysis

We will now subject APDS to average delay and average throughput comparisons with other related standard scheduling schemes: first in first out (FIFO), deficit fair priority queue (DFPQ) [16], and single-carrier scheduling algorithm (SCSA) [20, 21].

Table 2. THE SERVICE TYPE AND CID OF EACH MOBILE STATION

| MS1  | Services Type | CID  | Services Type | CID  | Services Type | CID  | Services Type |
|------|---------------|------|---------------|------|---------------|------|---------------|
| CID1 | UGS-DL        | CID6 | UGS-DL        | CID11| UGS-DL        |
| CID2 | ERT-VR-DL     | CID7 | ERT-VR-DL     | CID12| ERT-VR-DL     |
| CID3 | RT-VR-DL      | CID8 | RT-VR-DL      | CID13| RT-VR-DL      |
| CID4 | NRT-VR-DL     | CID9 | NRT-VR-DL     | CID14| NRT-VR-DL     |
| CID5 | BE-DL         | CID10| BE-DL         | CID15| BE-DL         |

| MS4  | Services Type | CID  | Services Type | CID  | Services Type | CID  | Services Type |
|------|---------------|------|---------------|------|---------------|------|---------------|
| CID16| UGS-DL        | CID21| UGS-DL        | CID26| UGS-DL        |
| CID17| ERT-VR-DL     | CID22| ERT-VR-DL     | CID27| ERT-VR-DL     |
| CID18| RT-VR-DL      | CID23| RT-VR-DL      | CID28| RT-VR-DL      |
| CID19| NRT-VR-DL     | CID24| NRT-VR-DL     | CID29| NRT-VR-DL     |
| CID20| BE-DL         | CID25| BE-DL         | CID30| BE-DL         |

| MS5  | Services Type | CID  | Services Type | CID  | Services Type | CID  | Services Type |
|------|---------------|------|---------------|------|---------------|------|---------------|
| CID31| UGS-DL        | CID36| UGS-DL        | CID41| UGS-DL        |
| CID32| ERT-VR-DL     | CID37| ERT-VR-DL     | CID42| ERT-VR-DL     |
| CID33| RT-VR-DL      | CID38| RT-VR-DL      | CID43| RT-VR-DL      |
| CID34| NRT-VR-DL     | CID39| NRT-VR-DL     | CID44| NRT-VR-DL     |
| CID35| BE-DL         | CID40| BE-DL         | CID45| BE-DL         |

| MS6  | Services Type | CID  | Services Type | CID  | Services Type | CID  | Services Type |
|------|---------------|------|---------------|------|---------------|------|---------------|
| CID17| UGS-DL        | CID17| UGS-DL        | CID22| UGS-DL        |
| CID18| ERT-VR-DL     | CID23| ERT-VR-DL     | CID28| ERT-VR-DL     |
| CID19| RT-VR-DL      | CID24| RT-VR-DL      | CID29| RT-VR-DL      |
| CID20| NRT-VR-DL     | CID25| NRT-VR-DL     | CID30| NRT-VR-DL     |
| CID21| BE-DL         | CID26| BE-DL         | CID31| BE-DL         |

Table 3. QOS PARAMETERS

| Parameter                  | Value            |
|----------------------------|------------------|
| Number of Connections      | 45               |
| Number of MSs              | 9                |
| Queue Size                 | 100              |
| Packet size of UGS         | 160 Byte         |
| Packet size of ERT-VR      | 160 Byte         |
| Packet size of RT-VR       | 240 Byte         |
| Packet size of NRT-VR      | 120 Byte         |
| Packet size of BE          | 120 Byte         |
| Total amount of bandwidth  | 10 Mbps          |
| Frame duration             | 5 ms             |
| Simulation time            | 10 sec (2000 frames) |
| Service Interrupt Counter (\( \eta \)) | 50 (250 ms) |
| \( \omega_1 \)             | 0.6              |
| \( \omega_2 \)             | 0.4              |
| \( \omega_3 \)             | 0.6              |
| \( \omega_4 \)             | 0.4              |

B.1 UGS

In Fig. 7 we can see that the average throughput of APDS is better than the other methods for efficient scheduling. The average delay of UGSs in the downlink is shown in Fig. 8. Because APDS considers the average delay as a main factor in its scheduling algorithm, APDS has shorter average delays compared to the other methods.
B.2 ERT-VR

Fig. 9 and 10 show the average throughput and average delay, respectively. APDS considers the average delay as a main factor in its scheduling algorithm and utilizes an emergent queue to increase the emergent packet transfer probability. As shown in the results, the performance of APDS is better than the other methods.

B.3 RT-VR

Fig. 11 and 12 show the average throughput and average delay for the downlink, respectively. APDS considers the average delay as a main factor in its scheduling algorithm and utilizes an emergent queue to increase the emergent packet transfer probability. As shown in the results, the performance of APDS is better than the other methods.
### B.4 NRT-VR

Fig. 13 and 14 show the average throughput and average delay in the downlink, respectively. For the NRT-VR services, APDS uses a performance provision for ranking to increase network performance and utilizes WPS in resource allocation to decrease the probability of service interrupts. As shown in the results, the performance of APDS is better than the other methods.

### B.5 BE

Fig. 15 and 16 show the average throughput and average delay in the downlink, respectively. APDS uses a performance provision for ranking to increase network performance and utilizes a service interrupt counter to avoid BE service interrupts. For resource allocation, WPF increases the priority of services to avoid interrupts. As shown in the results, the performance of APDS is better than FIFO and SCSA. The round-robin method is used for fairness in DFPQ. For this reason, DFPQ has better performance than APDS in the downlink for BE services.
This paper proposes an adaptive priority-based downlink scheduling framework for multilevel downlink traffic in IEEE 802.16 networks. Our APDS framework introduces beneficial schemes to not only rank the connections of the separate service types based on the determined priority, but also to achieve QoS guarantees and starvation prevention. Additionally, the proposed bandwidth allocation scheme is well designed for QoS differentiation and satisfaction. The simulation results reveal that APDS has significant performance advantages over FIFO, DFPQ, and SCSA. We will extend this work to the uplink and consider IEEE 802.16j in the future.

REFERENCES

[1] ITU Telecommunications indicators update 2006, http://www.itu.int/ITU-D/ict/statistics/
[2] In-stat Report. Paxton. The broadband boom continues: Worldwide subscribers pass 200 million, No. IN0603199MBS, March 2006.
[3] Jeffrey G. Andrews, Arunabha Ghosh, Rias Muhamed, Fundamentals of WiMAX -Understanding Broadband Wireless Networking. Prentice Hall, 2007.
[4] IEEE Standard 802.16 Working Group, IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Broadband Wireless Access Systems (P802.16Rev2/D3), Feb. 2008.
[5] Hossam Fattah, Cyril Leung, “An overview of scheduling algorithms in wireless multimedia networks,” IEEE Wireless Communications, vol. 9, no. 5, pp. 76–83, Oct. 2002.
[6] Claudio Ciconicetti, Luciano Lenzini, Enzo Mingozzi, “Quality of Service Support in IEEE 802.16 Networks,” IEEE Network, vol. 20, Issue. 2, pp. 50–55, March 2006.
[7] Chingyao Huang, Hung-Hui Juan, Meng-Shiang Lin, Chung-Ju Chang, “Radio Resource Management of Heterogeneous Services in Mobile WiMAX systems,” IEEE Wireless Communications, vol. 14, Issue. 1, pp. 20–26, Feb. 2007.
[8] Zakbia Abichar, Yanlin Peng, J. Morris Chang, “WiMAX: The Emergence of Wireless Broadband,” IT Professional, vol. 8, Issue 4, pp. 44–48, July 2006.
[9] Carl Eklund, Roger B. Marks, Kenneth L. Stanwood, Stanley Wang, “IEEE Standard 802.16A Technical Overview of the WirelessMAN Air Interface for Broadband Wireless Access, IEEE Communications Magazine,” vol. 40, Issue 6, pp. 98–107, June 2002.
[10] Arunabha Ghosh, David R. Wolter, Jeffrey G. Andrews, Runhua Chen, “Broadband Wireless Access with WiMAX/802.16: Current Performance, Benchmarks and Future Potential,” IEEE Communications Magazine, vol. 43, Issue 2, pp. 129–136, Feb. 2005.
[11] Qiang Ni, Alexey Vinel, Yang Xiao, Andrey Turlakov, Tao Jiang, “WIRELESS BROADBAND ACCESS: WIMAX AND BEYOND- Investigation of Bandwidth Request Mechanisms under Point-to-Multipoint Mode of WiMAX Networks,” IEEE Communications Magazine, vol. 45, Issue 5, pp. 132–138, May 2007.
[12] Yaxin Cao, Victor O. K. Li, “Scheduling Algorithms in Broad-Band Wireless Networks,” IEEE Proceedings of The IEEE, vol. 89, no. 1, pp. 76–87, Jan. 2001.
[13] Mohammed Hawa, David W. Petr, “Quality of service scheduling in cable and broadband wireless access systems,” Tenth IEEE International Workshop on Quality of Service, pp. 247–255, May 2002.
[14] Kitti Wongthavarawat, Aura Ganz, Packet Scheduling for QoS Support in IEEE 802.16 Broadband Wireless Access Systems, International Journal of Communication Systems, vol. 16, pp. 81-96, May 2003.
[15] Jonny Sun, Yanling Yao, Hongfei Zhu, “Quality of Service Scheduling for 802.16 Broadband Wireless Access Systems,” IEEE Vehicular Technology Conference (VTC), pp. 1221-1225, May 2006.
[16] Jianfeng Chen, Wenhua Jiao, Hongxi Wang, “A Service Flow Management Strategy for IEEE 802.16 Broadband Wireless Access Systems in TDD Mode,” IEEE International Conference on Communications (ICC), pp. 3422–3426, May 2005.
[17] Haidar Safa, Hassan Artail, Marcel Karam, Rawan Soudah, Samar Khayat, “New Scheduling Architecture for IEEE 802.16 Wireless Metropolitan Area Network,” IEEE/ACIS International Conference on Computer Systems and Applications (AICCSA), pp. 203-210, May 2007.
[18] Daniele Tarchi, Romano Fantacci, Marco Bardazzi, “Quality of Service Management in IEEE 802.16 Wireless Metropolitan Area Networks, IEEE International Conference on Communications (ICC), pp. 1789–1794, June 2006.
[19] Dusit Niyato, Ekram Hossain, “Queue-Aware Uplink Bandwidth Allocation and Rate Control for Polling Service in IEEE 802.16 Broadband Wireless Networks,” IEEE Transactions on Mobile Computing, vol. 5, no. 6, pp. 668–679, June 2006.
[20] Xiaofeng Bai, Abdallah Shami, Khilam Amjad Meerja, Chadi Assi, “New Distributed QoS Control Scheme for IEEE 802.16 Wireless Access Networks,” IEEE Global Telecommunications Conference (GLOBECOM), pp. 1–5, Nov. 2006.
[21] Xiaofeng Bai, Abdallah Shami, Yinghua Ye, “Robust QoS Control for Sin-
kle Carrier PMP Mode IEEE 802.16 Systems, IEEE Transactions on Mobile Computing, vol. 7,” Issue 4, pp. 416–429, April 2008.

[22] Alexander Sayenko, Olli Alanen, Juha Karhula, Timo Hämäläinen, “Ensuring the QoS Requirements in 802.16 Scheduling,” ACM international symposium on Modeling analysis and simulation of wireless and mobile systems (MSWiM), pp. 108–117, Oct. 2006.

[23] Ellen Louise Hahne, Robert G. Gallager, “Round Robin scheduling for fair flow control in data communication networks,” IEEE International Conference on Communications (ICC), pp. 103–107, June 1986.

[24] Naian Liu, Xiaohui Li, Changxing Pei, Bo Yang, “Delay Character of a Novel Architecture for IEEE 802.16 Systems”, International Conference on Parallel and Distributed Computing, Applications and Technologies (PDCAT), pp. 293–296, Dec. 2005.

[25] Leonidas Georgiadis, Roch Guérin, Abhay Parekh, “Optimal multiplexing on a single link: delay and buffer requirements,” IEEE Transactions on Information Theory, vol. 43, Issue 5, pp. 1518–1535, Sep. 1997.

[26] Qingwen Liu, Xin Wang, Georgios B. Giannakis, “A Cross-Layer Scheduling Algorithm With QoS Support in Wireless Networks,” IEEE Transactions on Vehicular Technology, vol. 55, no. 3, pp. 839–847, May 2006.

[27] Lihua Wan, Wenchao Ma, Zihua Guo, “A Cross-layer Packet Scheduling and Subchannel Allocation Scheme in 802.16e OFDMA System,” IEEE Wireless Communications and Networking Conference (WCNC), pp. 1865–1870, March 2007.

[28] A. Jalali, R. Padovani, R. Pankaj, “Data Throughput of CDMA-HDR, a High Efficiency High Data Rate Personal Communication Wireless System,” IEEE Vehicular Technology Conference (VTC), pp. 1854–1858, May 2000.

[29] Mehri Mehrjoo, Mehrdad Dianati, Xuemin (Sherman) Shen, “Kshirasagar Naik, Opportunistic Fair Scheduling for the Downlink of IEEE 802.16 Wireless Metropolitan Area Networks,” The Third International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QShine), pp. 54–67, Aug. 2006.

[30] Mehri Mehrjoo, Xuemin (Sherman) Shen, and Kshirasagar Naik, “A Joint Channel and Queue-Aware Scheduling for IEEE 802.16 Wireless Metropolitan Area Networks,” IEEE Wireless Communications and Networking Conference (WCNC), pp. 1877–1885, March 2007.

[31] Haiying Julie Zhu, Roshdy H.M. Hafez, “Novel Scheduling Algorithms for Multimedia Service in OFDM Broadband Wireless Systems,” IEEE International Conference on Communications (ICC), pp. 772–777, June 2006.

[32] Fen Hou, Pin-Han Ho, Xuemin Shen, An-Yi Chen, “A Novel QoS Scheduling Scheme in IEEE 802.16 Networks,” IEEE Wireless Communications and Networking Conference (WCNC), pp. 2457–2462, March 2007.

[33] Wha Sook Jeon, Dong Geun Jeong, “Combined Connection Admission Control and Packet Transmission Scheduling for Mobile Internet Services, IEEE Transactions On Vehicular Technology,” vol. 55, no. 5, pp.1582–1593, Sep. 2006.

[34] 3GPP, Physical Layer Aspects of UTRA High Speed Downlink Packet Access (Release 4), March 2001, 3G TR25.848 V4.0.0.

[35] Hui Zhang, “Service Disciplines for Guaranteed Performance Service in Packet-switching Networks,” Proc. IEEE, vol. 83, pp. 1374–1396, Oct. 1995.

[36] Haitang Wang, Wei Li, Dharma P. Agrawal, “Dynamic admission control and QoS for 802.16 wireless MAN, in IEEE Wireless Telecommunications Symposium,” pp. 60–66, Apr. 2005.

[37] Bo Rong, Yi Qian, Hsiao-Hwa Chen, "Adaptive power allocation and call admission control in multisevice WiMAX access networks," IEEE Wireless Communications, vol. 14, no. 1, pp. 14–19, Feb. 2007.

[38] Claudio Cicconetti, Alessandro Erti, Luciano Lenzini, Enzo Mingozzi, “Performance evaluation of the IEEE 802.16 MAC for QoS support, IEEE Transactions on Mobile Computing,” vol. 6, no. 1, pp. 26–38, Jan. 2007.

[39] Dongmei Zhao, Xuemin Shen, “Performance of Packet Voice Transmission Using IEEE 802.16 Protocol, IEEE Wireless Communications,” vol. 14, no. 1, pp. 44–51, Feb. 2007.

[40] Jayaparvathy R., Sureshkumar G., “Performance Evaluation of Scheduling Schemes for Fixed Broadband Wireless Access Systems, IEEE Malaysia International Conference on Communication Networks,” pp. 16–18, Nov. 2005.

Shih-Jung Wu was born in Taipei, Taiwan (R.O.C.), on October 25, 1976. He received his B.C. degree from Department of Business Administration, Yuan Ze University, Taiwan (R.O.C.) in 1998. He received M.S. degree from Department of Computer Science and Information Engineering, Tamkang University, Taiwan (R.O.C.) in 2001. And he received his Ph.D. degree in the Department of Computer Science and Information Engineering, Tamkang University, Taiwan (R.O.C.) in 2006. Presently, he is working at Department of Innovative Information and Technology, Tamkang University in Taiwan (R.O.C.). His major research interests in high speed communications, QoS guarantees, parallel algorithms and data mining.

Shih-Yi Huang She received M.S. degree from Master’s Program in Networking and Communications, Department of Computer Science and Information Engineering, Tamkang University, Taiwan (R.O.C.) in 2007. And he received his Ph.D. degree in the Department of Computer Science and Information Engineering, Tamkang University, Taiwan (R.O.C.) in 2011. Presently, he is working at Department of Information Technology and Mobile Communication, Taipei College of Maritime Technology. His major research interests in wireless network.

GKuo-Feng Huang He received M.S. degree from Department of Computer Science and Information Engineering, Tamkang University, Taiwan (R.O.C.) in 2007. And he received his Ph.D. degree in the Department of Computer Science and Information Engineering, Tamkang University, Taiwan (R.O.C.) in 2011. Presently, he is working at Department of Information Technology and Mobile Communication, Taipei College of Maritime Technology. His major research interests in wireless network.

Tamkang University
This figure "SJW.jpg" is available in "jpg" format from:

http://arxiv.org/ps/1210.3768v1
