Computer Communications 31 (2008) 2350–2359

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Energy-efficient packet scheduling algorithms for real-time communications in a mobile WiMAX system

Shiao-Li Tsao *, You-Lin Chen

Department of Computer Science, National Chiao Tung University, Room EC426, No. 1001 Ta Hsueh Road, Hsinchu 300, Taiwan, ROC

ARTICLE INFO

Article history:
Received 17 March 2007
Received in revised form 23 February 2008
Accepted 23 February 2008
Available online 7 March 2008

Keywords:
Mobile WiMAX
Energy efficiency
Power saving
Packet scheduling

ABSTRACT

Broadband wireless access systems usually provide flexible sleep-mode operations for mobile stations to conserve their energy during idle or active mode. For example, Mobile WiMAX, i.e. the IEEE 802.16e, offers several power-saving classes that can be associated with different types of network connections to minimize power consumption of mobile stations. Unfortunately, previous studies did not fully utilize the sleep-mode features to save the energy of a mobile station with multiple real-time connections, and power consumption of a mobile station is not yet optimized. In this work, two energy-efficient packet scheduling algorithms for real-time communications in a Mobile WiMAX system are proposed. The schemes not only guarantee the quality of services (QoSs) of real-time connections but also minimize power consumption of mobile stations. Simulation results demonstrate that the proposed schemes outperform the traditional approach.

1. Introduction

One of the essential features for a broadband wireless access (BWA) system which is designed for portable and battery-operated devices is the power-saving function. For example, the IEEE 802.11, i.e. WLAN, defines a power-saving mode which can be utilized to improve energy efficiencies for web accesses, voice over IP (VoIP), and other applications over WLAN [7,8]. The IEEE 802.16e, so called Mobile WiMAX, that has been newly developed also provides flexible power-saving classes to facilitate mobile stations to conserve their energy during active and sleep mode [1,2,4]. According to the specification, an IEEE 802.16e mobile station can switch to sleep mode for a sleep period, and wakes up to send or receive packets in a listen period. During sleep periods, a base station (BS) must buffer incoming packets sent to the mobile station, and then after the mobile station switches to listen periods, the base station sends the queued packets to the mobile station. To accommodate different characteristics of applications and services, the IEEE 802.16e specifies three power-saving classes and each power-saving class implies a particular sleep and listen behavior for a mobile station. A mobile station can thus associate a power-saving class with a connection and negotiates the parameters of the power-saving class such as the time to sleep and listen, and the length of each sleep and listen period with the base station for the connection. Obviously, the parameters of a power-saving class associated with a network connection should be carefully decided in order to maximize the energy efficiency of a mobile station without violating the QoS requirements of that connection.

Admission control schemes and scheduling algorithms are designed to offer QoS services in wireless networks, and a number of studies have investigated these issues in IEEE 802.16/802.16e networks [3,5,9,10]. For example, Wongthavarawat and Ganz [12] proposed the architecture of the uplink scheduler. They assign different service types with strict priorities, and schedule each service type by using a particular scheme. Unfortunately, these scheduling algorithms do not consider the power consumption of a mobile station. Several studies [6,13,14,16] investigated the power consumption issues of IEEE 802.16e and suggested algorithms to determine the sleep interval in improving its energy efficiency. However, above studies mainly consider non-real-time connections in IEEE 802.16e networks. Shi et al. [15] proposed a burst scheduling mechanism which guarantees the minimum data rates of mobile stations and schedules packets in a busty basis so that it can maximize the sleep time of mobile stations. Unfortunately, the burst scheduling approach may not be suitable to these delay sensitive applications and services. Although a number of energy saving mechanisms have been proposed for the IEEE 802.16e, to minimize power consumption of IEEE 802.16e mobile stations with multiple real-time connections has not yet been investigated. In this paper, we study this problem and propose two packet scheduling schemes to maximize sleep periods of a mobile station without violating the QoS requirements of the real-time connections.

* Corresponding author. Tel.: +886 3 5712121x54717; fax: +886 3 5721490.
E-mail address: sltsao@cs.nctu.edu.tw (S.-L. Tsao).

0140-3664/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.comcom.2008.02.030

The rest of the paper is organized as follows. The IEEE 802.16e sleep-mode operations and the power consumption problems for a mobile station with multiple real-time connections are described in Section 2. The proposed scheduling schemes, called periodic on–off scheme (PS) and aperiodic on–off scheme (AS), are presented in Section 3. The simulation environment and simulation results are discussed in Section 4, and finally, Section 5 concludes this study.

2. The IEEE 802.16e sleep-mode operations and power consumption problem

In a Mobile WiMAX system, a mobile station can switch to sleep mode if there is no packet to send or receive in order to save power. The IEEE 802.16e defines three power-saving classes to accommodate network connections with different characteristics. According to the specification, each connection on a mobile station can be associated with a power-saving class, and connections with a common demand property can be grouped into one power-saving class. The parameters of a power-saving class, i.e. the time to sleep and listen, the length of a sleep period and a listen period can be negotiated by a base station and a mobile station.

The type-one power-saving class specifies that a mobile station sleeps for a period, wakes up to listen for incoming packets, and repeats sleep and listen operations. If there is no packet to send or receive during a listen period, a mobile station doubles the period for the next sleep. This power-saving class is suitable for the connections of web browsing or data access services. The type-two power-saving class requires a mobile station to repeat the sleep and listen on a round-robin basis, and the sleep and listen period are fixed. This sleep mode is appropriate for real-time connections such as VoIP and video streaming services that have packets to send or receive periodically. Based on the type-two sleep mode, a mobile station only needs to wake up to send or receive packets in those listen periods without violating the QoSs of the real-time connections. The type-three power-saving class defines the length of a sleep period, and a mobile station sleeps for that period and then returns to the normal operation. Fig. 1 illustrates examples for the three power-saving classes.

If a mobile station establishes multiple connections with different demand properties, the periods that a mobile station can sleep are determined by the sleep-mode behaviors associated with all connections. Fig. 2 shows an example that a mobile station has three connections. The connections have different demand properties, and associate with their preferred power-saving classes and parameters. It can be seen that the actual periods that a mobile station can sleep are the slots that three connections are all in a sleep period. Obviously, without a proper schedule of the sleep-mode operations for multiple real-time connections on a mobile station, the power consumption of a mobile station might not be reduced even the sleep mode is applied.

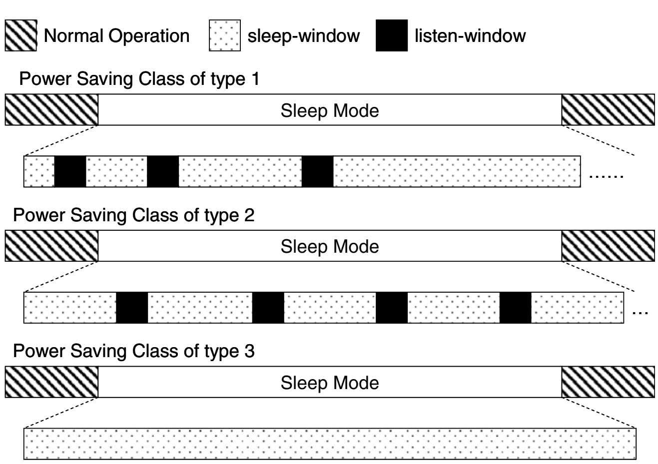

Fig. 1. Power-saving classes defined in the IEEE 802.16e.

In this work, only packet scheduling issues for mobile stations with multiple real-time connections are considered. Non-real-time packets that can tolerate delays could be scheduled in any listen period with available radio resources for a mobile station.

3. Energy-efficient packet scheduling algorithms

3.1. Periodic on–off scheme (PS)

The idea behind the first proposed approach, called periodic on–off scheme (PS), is to allow a mobile station to sleep for a fixed period and then to listen for another fixed period on a round-robin basis. The concept of on–off scheduling algorithms has been applied to wireless devices in reducing the power consumption [17,18]. In this study, we extend the concept and apply it to Mobile WiMAX system. Our scheme maximizes the length of a sleep period in the type-two power-saving class defined in the IEEE 802.16e without violating QoSs of all connections. During listen periods, a mobile station transmits and receives packets, and on other hand, the mobile station sets the interface idle to conserve the energy during sleep periods. Fig. 3 gives an example of a packet schedule for two real-time connections by applying the PS approach.

The PS is performed in two steps. The first step is to compute the length of a sleep period and a listen period for a mobile station. The second step is to let a mobile station enter a periodical sleep mode and schedule the packets according to the parameters obtained in the first step. A mobile station stays idle during sleep periods, and only wakes up to transmit data in listen periods. Packets sent to the mobile station during sleep periods are buffered at the base station and are delivered to the mobile station till listen periods. In other words, the mobile station only needs to receive and transmit data in listen periods and stay idle to conserve energy during sleep periods. The next paragraphs describe the detail of the first-step procedures of the PS. Also, notations used in this paper are summarized in Table 1.

To minimize power consumption of a mobile station with multiple real-time connections, the PS determines the length of a sleep period and a listen period under the radio resource and QoS constraints. Considering a mobile station with N real-time connections, the QoS parameters of connection i can be denoted as $Q_i\{S_i, TI_i, D_i\}$, where D_i is the delay constraint in milliseconds of any two consecutive packets for connection i, S_i is the average packet size in bytes for connection i, and TI_i is the average inter-packet arrival time in milliseconds for connection i. In this paper, these connections could be either downlink from a base station to a mobile station or uplink from a mobile station to a base station. To schedule downlink packets, the proposed algorithms should be implemented on base stations. On the other hand, the proposed mechanisms have to be realized on both base stations and mobile stations if the proposed methods are applied to the uplink packet scheduler. The base station can know the resource requirements of all mobile stations by negotiations in advanced or bandwidth requests from the mobile stations. Thus, the base station scheduler can determine the uplink packet schedule according to the proposed algorithms, and provides transmission opportunities to mobile stations. Then, mobile stations transmit uplink packets through the given OFDM frames. Without loss of generality, this study considers the above-mentioned QoS parameters to present the basic idea behind the proposed scheduling schemes. Other parameters such as delay jitters can be also