Design and Analysis of Contention-Based Request Schemes for Best-Effort Traffics in IEEE 802.16 Networks

Lien-Wu Chen and Yu-Chee Tseng

***Abstract*—The IEEE 802.16 standard is designed to meet the need of metropolitan-area broadband wireless access. This work studies two collision-resolution requesting schemes for best-effort (BE) traffics in IEEE 802.16 networks. One is the exponential backoff scheme defined in the standard and the other is a piggyback mechanism enhanced by single-frame backoff, called the *Request Piggyback* (RPB) scheme. We analyze and compare their performance in terms of the request success probability and the packet delivery delay under Poisson traffic. The results show that the RPB scheme outperforms the exponential backoff scheme and can reduce request collision.**

***Index Terms*—Contention resolution, IEEE 802.16, Medium Access Control, WiMax, wireless communication.**

I. INTRODUCTION

IEEE 802.16/WiMax has gained a lot of attention recently [1], [2], [3]. WiMax employs a point-to-multipoint (PMP) architecture. Each base station (BS) can serve multiple subscriber stations (SSs). In the MAC part, it adopts Time Division Multiplexing (TDM) for the downlink channel and Time Division Multiple Access (TDMA) for the uplink channel via a request/grant mechanism controlled by the BS.

In IEEE 802.16, a centralized, reservation-based bandwidth allocation mechanism is defined for best-effort (BE) traffics. The uplink channel is modelled as a stream of time slots. SSs must send request messages to the BS to reserve uplink bandwidth. There are three factors that may affect the performance of the uplink channel: (i) the portion of request slots per frame, (ii) the collision-resolving procedure, and (iii) the allocation of slots to SSs' requests. This paper studies the collision-resolution mechanisms for transmitting uplink BE requests to the BS. The request scheme defined in the standard is compared against the proposed *Request Piggyback* (RPB) scheme.

Reference [4] proposes to transmit DL-MAP and UL-MAP control messages on data packets with high data rates to reduce MAC overhead. Optimal contention periods for single and multiple classes of flow priorities are studied in [5], [6]. However, these studies do not study the request scheme itself. Reference [7] models the *truncated binary exponential backoff* (TBEB) scheme in 802.16 assuming that each SS always has traffic to be sent to the BS and each request message only asks for one data slot. The proposed RPB scheme is shown to outperform the TBEB scheme.

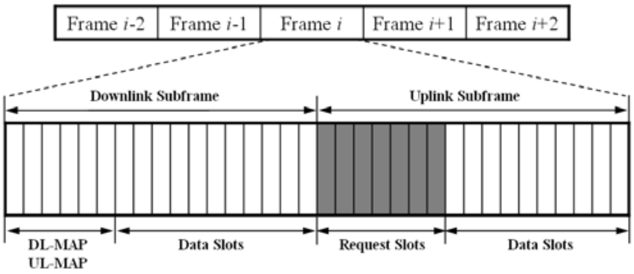

Fig. 1. The TDD frame structure defined in IEEE 802.16.

II. THE REQUEST PIGGYBACK SCHEME

In this section, a new scheme for sending requests of uplink BE traffics is proposed. We first review the TBEB scheme in IEEE 802.16. Fig. 1 illustrates an IEEE 802.16 TDD frame. When a SS has uplink BE traffics, it sets its initial backoff window to W_0 and randomly selects a backoff counter within this window. After the counter expires, it transmits its request. If the request succeeds, the BS will allocate bandwidths to the SS. Otherwise, the SS multiplies its backoff window by a factor of two, as long as it does not exceed the maximum value W_{max}. Then, it repeats the process until either the request succeeds or the maximum number of retries is reached.

The main problem with the TBEB scheme is that the number of waiting frames for a successful request may increase rapidly after consecutive collisions. So SSs may suffer long delay due to accidental consecutive collisions, leading to unfairness of bandwidth allocation. To alleviate this problem, we propose to allow a SS to piggyback its new BE queue length if it still has uplink burst(s) to its BS. This would even reduce the chance of contention. If the SS does not have new buffered packets, the piggyback mechanism is not taken. When an idle SS has new packets to be sent, it has to go through the same backoff and contention procedure as defined in IEEE 802.16.

Since we believe that the above piggyback mechanism can significantly reduce the possibility of collision, we suggest that the backoff window can be kept constant, equal to the number of request slots and does not need to be doubled after each collision. A collided request message can be immediately retransmitted in the next frame. For piggybacking requests, the Grant Management subheader (16 bits) in a generic MAC

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frame can be used. The number of bytes of the bandwidth request is incremental and is limited to 2^{16} bytes.

III. ANALYTICAL RESULTS

This section analyzes the request success probability and the packet delivery delay of the TBEB and the RPB schemes. In our analysis, we assume that a SS sends at most one request in a frame and multiple BE connections in a SS are treated as a single, aggregated connection for simplicity. Suppose that there are n SSs under a BS and s request slots per frame. For TBEB, we set $W_0 = s$ and $W_{max} = 2^m W_0$, where m is the maximum number of retries. This means that in the ith retrial, a SS will send its request randomly from one of the upcoming 2^i frames.

To derive the expected number of contending SSs per frame, we first calculate the probability p_{tx} that a SS will transmit a request message in a frame when it has packets to send. It can be obtained by computing the average number n_{tx} of requests transmitted in a TBEB process and the average period n_{tf} (in unit of frames) of a TBEB process. We have

$$\begin{aligned} n_{tx} &= \sum_{i=1}^{m+1} i \times Prob(\text{request sent exactly } i \text{ times}) \\ &= \sum_{i=1}^{m} i(1-c)c^{i-1} + (m+1)c^m, \end{aligned}$$

where c is the request collision probability. The average period of a TBEB process depends on the number of request retries and the backoff counter which is randomly selected in the beginning of a backoff process. For the ith retry, the backoff window size is $W_i = 2^{i-1}W_0$. The average number of frames n_{af} (which is a function of W_i) that the ith retry needs to be deferred is calculated as

$$n_{af}(W_i) = \frac{1}{W_i}\sum_{j=1}^{W_i} j.$$

Thus, the average period of a TBEB process can be modelled by summing the expected number of deferring frames over all possible numbers of retries:

$$n_{tf} = \sum_{i=1}^{m}(1-c)c^{i-1}\left(\sum_{j=1}^{i} n_{af}(W_j)\right) + c^m \sum_{i=1}^{m+1} n_{af}(W_i).$$

This gives the expected number of contending SSs per frame

$$n_{req}^{\text{TBEB}} = n \cdot p_{tx} \cdot (1 - e^{-\lambda n_{tf} f}),$$

where $p_{tx} = \frac{n_{tx}}{n_{tf}}$, f is the frame duration, and λ is the packet arrival rate with poisson inter-arrival times. The probability that a SS successfully transmits its request in a frame is $p_s^{\text{TBEB}} = (\frac{s-1}{s})^{n_{req}^{\text{TBEB}}-1}$, and the expected number of frames that a SS has to wait before a successful request is submitted is $d_s^{\text{TBEB}} = n_{tf}$. Let M be the number of frames allocated to transmit the data of a request, which is a constant controlled by the BS. The packet delivery delay per data request (in unit of frame) can be written as $d_{pkt}^{\text{TBEB}} = 1 + d_s^{\text{TBEB}} + M = 1 + n_{tf} + M$.

For the RPB scheme, a Markov model is derived. We first define the possible states of a SS:

- $IDLE$: The SS has no BE traffic currently.

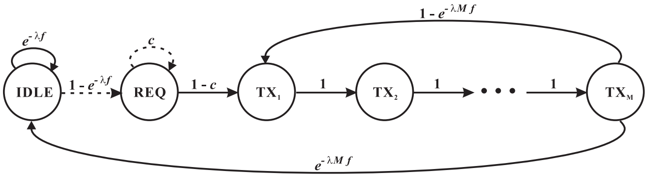

Fig. 2. The state transition diagram of a SS under the RPB model.

- REQ: The SS is contending for a request slot.
- $TX_i, i = 1..M$: Bandwidth has been allocated for the SS and it has been served for i frames.

The state-transition diagram is shown in Fig. 2. The probability associated with each transition can be obtained from the frame duration f, the request collision probability c, and the packet arrival rate λ with poisson inter-arrival times. There are two events which will trigger a SS to contend for request slots: (i) the SS switches from the idle state to the request state as a new packet arrives, and (ii) the SS stays in the request state as a collision was experienced previously. These two events are illustrated in Fig. 2 by dashes.

Next, we compute the probability that the SS will stay in each state. Let $Prob(x)$ be the probability that it is in state x. Since the sum of probabilities over all states must be 1, we have

$$Prob(IDLE) + Prob(REQ) + \sum_{i=1}^{M} Prob(TX_i) = 1.$$

Considering the equilibrium of flows for state $IDLE$, we have

$$Prob(IDLE)(1 - e^{-\lambda f}) = Prob(TX_M) \cdot e^{-\lambda M f}.$$

Similarly, from the equilibrium of flows for state REQ,

$$Prob(REQ)(1-c) = Prob(IDLE)(1 - e^{-\lambda f}),$$

and for state TX_1,

$$Prob(TX_1) = Prob(REQ)(1-c) + Prob(TX_M)(1 - e^{-\lambda M f}).$$

For state TX_i, $i = 2..M$, we have

$$Prob(TX_i) = Prob(TX_{i-1}).$$

There are $M+2$ state probabilities to be determined. From the above equations, we can obtain that

$$\begin{aligned} Prob(IDLE) &= \frac{e^{-\lambda M f}(1-c)}{D} \\ Prob(REQ) &= \frac{(1-e^{-\lambda f})e^{-\lambda M f}}{D} \\ Prob(TX_1) &= \frac{(1-e^{-\lambda f})(1-c)}{D} \\ Prob(TX_M) &= Prob(TX_{M-1}) = \cdots = Prob(TX_1), \end{aligned}$$

where $D = e^{-\lambda M f}(1-c) + (1-e^{-\lambda f})e^{-\lambda M f} + M(1 - e^{-\lambda f})(1-c)$. Thus, the expected number of SSs to contend for request slots per frame can be derived as

$$\begin{aligned} n_{req}^{\text{RPB}} &= n \cdot [(1-e^{-\lambda f})Prob(IDLE) + c \cdot Prob(REQ)] \\ &= n \cdot [(1-c)Prob(REQ) + c \cdot Prob(REQ)] \\ &= n \cdot Prob(REQ). \end{aligned}$$

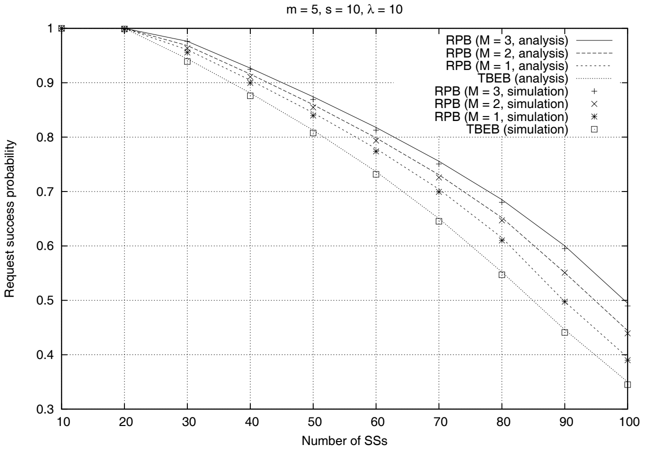

Fig. 3. Comparison of request success probabilities.

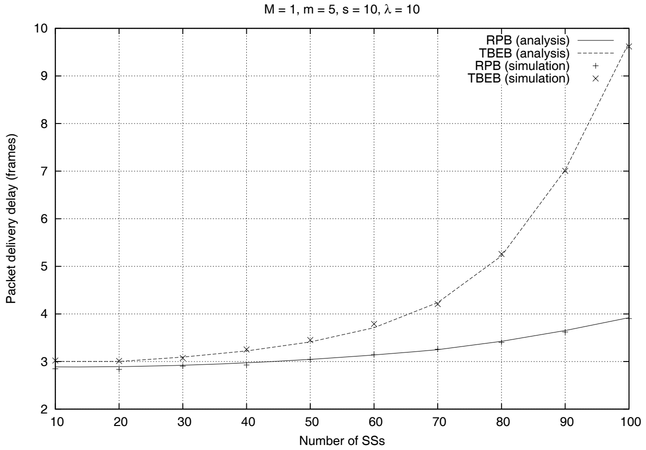

Fig. 4. Comparison of packet delivery delays.

Next, we calculate the expected number d_s^{RPB} of frames that a SS has to wait before a successful request. Let the probability to send a request without collision be p_s^{RPB}. We can derive that $p_s^{\text{RPB}} = (\frac{s-1}{s})^{n_{req}^{\text{RPB}}-1}$ and $d_s^{\text{RPB}} = \frac{1}{p_s^{\text{RPB}}} = (\frac{s}{s-1})^{n_{req}^{\text{RPB}}-1}$.

The delivery delay d_{pkt}^{RPB} of a packet is the period from its arrival at the queue to its complete delivery to the BS. So d_{pkt}^{RPB} consists of three components: (i) the request delay d_{req} (the expected number of waiting frames for a successful request), (ii) the piggyback delay d_{pg} (the expected number of waiting frames for a new bandwidth allocation if the SS is currently in a transmission state TX_i, $i = 1..M$), and (iii) the packet transmission time t_{tx} (M frames controlled by the BS). Component (ii) can be derived as

$$d_{pg} = \sum_{i=1}^{M} i \cdot Prob(TX_{M-i+1}) = \frac{M(M+1)}{2} Prob(TX_1).$$

Summing all three components, the packet delivery delay is

$$\begin{aligned} d_{pkt}^{\text{RPB}} &= d_{req} + d_{pg} + t_{tx} \\ &= \begin{cases} 1 + d_s^{\text{RPB}} + M & \text{the SS is in } IDLE \text{ state} \\ \frac{d_s^{\text{RPB}}}{2} + M & \text{the SS is in } REQ \text{ state} \\ (M+1-i) + M & \text{the SS is in } TX_i \text{ state} \end{cases} \\ &= (1 + d_s^{\text{RPB}}) Prob(IDLE) + \frac{d_s^{\text{RPB}}}{2} Prob(REQ) \\ &\quad + \frac{M(M+1)}{2} Prob(TX_1) + M. \end{aligned}$$

IV. SIMULATION EVALUATION

We verify the derived request success probability and packet delivery delay by a C++ simulator. The frame duration is set to 5 ms, and the request collision probability is obtained through our simulation. In all figures, lines are mathematical results, and symbols represent simulation results. Clearly, the mathematical results fit quite well with the simulation results.

As shown in Fig. 3, when the number of SSs increases, the request success probability decreases. For TBEB, the request success probability decreases rapidly due to more contentions. It can be observed that RPB has a higher request success probability than TBEB. Even with $M = 3$, RPB's request success probability is still about 0.5 when there are 100 SSs associated with the BS.

Fig. 4 shows the packet delivery delay for various numbers of SSs. While the delay of TBEB increases exponentially, the delay of RPB only increases linearly as the number of SSs increases. The same observation holds for all other cases of $\lambda = 10, 20, ..., 100$ and $M = 1, 2, ..., 10$ (due to space limitation, these results are omitted). In Fig. 4, TBEB has a much higher delay than RPB since its number of deferring frames are much higher. RPB produces a lower delay for packet delivery because SSs transmitting data can piggyback their new bandwidth requests without waiting any frame.

From these results, we conclude that the RPB scheme can achieve a higher request success probability and a lower packet delivery delay, leading to more efficient use of wireless bandwidths. On the other word, adopting our scheme in IEEE 802.16 networks can both avoid the BS wasting bandwidth due to insufficient received requests and prevent SSs from buffer overflowing caused by numerous delayed packets.

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