The Analysis of the Optimal Contention Period for Broadband Wireless Access Network

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Abstract

In IEEE 802.16 MAC protocol, the performance of the system is affected by the size of the contention period, since bandwidth request messages are collided during a contention period allocated by a bandwidth allocation MAP message. We stochastically analyze the performance of the system to find the optimal size of the contention period in this paper. To obtain the optimal contention period according to the number of users, we define the cost function using the channel throughput and delay of the system. We also verify the analytic results using OPNET simulator. As the analytic results, it shows that the optimal size of the contention period is about two times of the number of users.

1. Introduction

Demands for a mobile communication and a high quality service such as video streaming or VoIP have been increasing in recent years [1]. According to these social environments, many research groups have been studying to provide a high quality service and trying to do the protocol standardization for occupation the market of related technologies. IEEE(Institute of Electrical and Electronics Engineers) 802.16 standard for fixed BWA(Broadband Wireless Access) systems supports a metropolitan area network architecture. Specifically, IEEE 802.16e standard supports the mobility in wide area. In 2004, Intel and Samsung have proposed together WiBro(Wireless Broadband Internet) domestic standard based on IEEE 802.16e.

IEEE 802.16 standard assumes a point-to-multipoint topology, with a controlling BS(Base Station) that connects SS(Subscriber Station) to various public networks linked to the BS. The access mode for the upstream channel is based on TDMA(Time Division Multiple Access) and each upstream channel is composed of fixed-size time minislots. According to a bandwidth allocation MAP message, the upstream channel is divided into concatenate frames, and each frame is made up of the contention period, the data transmission period, and the initial ranging period[2],[3]. In IEEE 802.16 MAC(Medium Access Control) protocol, the performance of the system is affected by the size of the contention period. If the size of the contention period is much smaller than the number of users, then the packet transmission delay is longer than the normal case due to the collision generated by bandwidth request messages. Also if the size of the contention period is larger than the number of users, then the packet transmission delay is longer than the normal case due to the delay of waiting for the next frame. For the related works, Benelli analyzed the optimal frame size according to the number of users, but it is difficult to apply the equation to a real system because the equation contains the variable of the number of collided packets in a frame [4]. Vogt also found the optimal frame size, but he did not derive the exact equation of the optimal frame size for the number of users [5]. Therefore we stochastically analyze the throughput and delay of the system. After that we define the cost function including the throughput and delay, and then derive the equation of the optimal size of the contention period for the number of users.

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IEEE 802.16 standard assumes a point-to-multipoint topology, with a controlling BS that connects SSs. BS transmits a packet to SS through the downstream channel, and SS transmits a packet to BS through the upstream channel. The access mode for the upstream channel is based on TDMA [6]. Each upstream channel is made up of frames, which are composed of fixed-size time minislots. Each frame in the upstream channel is divided into the contention period, the data transmission period, and the initial ranging period according to a bandwidth allocation MAP message that BS transmits to SSs through the downstream channel. When SS enters into the transmission range of BS, BS and SS operate ranging and registration. Ranging use the power to include a distance measurement mechanism and a synchronization process between BS and SS. Registration is the process by which SS registers the connection parameters of SS with BS. Many SSs transmit bandwidth request messages to BS in the limited contention period over the upstream channel, so that collisions may be generated during the contention period. If a bandwidth request message is successfully transmitted during a frame then the data that corresponds to the bandwidth request message is transmitted during the data transmission period allocated by the next bandwidth allocation MAP message. The collided bandwidth request message retransmits after waiting for random slot(s) according to binary truncated exponential backoff [6].

IEEE 802.16 standard supports the service flows to guarantee the QoS(Quality of Service). The four service flows are defined as follows [2].

- UGS(Unsolicited Grant Service): UGS is generated to support real-times service flows that generate fixed-size data packets on a periodic basis, such as Voice over IP.
- rt-PS(real-time Polling Service): rt-PS is designed to support real-time service flows that generate variable-size data packets on a periodic basis, such as MPEG video.
- nrt-PS(non-real-time Polling Service): nrt-PS is designed to support non-real-time service flows that require variable-size data grants on a regular basis, such as high bandwidth FTP.
- BE(Best Effort): Neither periodic polls nor periodic data grants will be sent by the BS unless they are needed to satisfy the minimum reserved bandwidth for that service.

When more than two bandwidth request messages are concurrently transmitted in a minislot during the contention period by SSs, a collision is generated in the slot. The collided bandwidth request messages are retransmitted during a random slot in the next frame. For the performance analysis of the system according to the number of users, we assume that the concatenated frames are consecutively arranged contention periods as shown in Fig. 1. In Fig. 1, users randomly choose a slot at the beginning of a frame, then transmit a bandwidth request message in the slot. To analyze the performance of the MAC protocol, we assume as follows.

- The fixed-size bandwidth request message is uniformly distributed during a frame.
- The frame size is F [slots], and the total number of users is M.
- A user transmits only one bandwidth request message.
- BS knows the number of users within its transmission range through ranging and registration.
4. The Performance Analysis

The throughput and delay should be considered in order to optimize the performance of the system, however it is difficult to find the optimal point since the throughput and delay are trade-off of each other. Therefore we will define the cost function that includes the throughput and delay factors, and derive the optimal size of the contention period from the cost function.

4.1. Throughput Analysis

Let $r$ be the number of users who choose the same contention slot among $M$ users. Request messages are uniformly distributed in a frame. The probability that $r$ users are in a contention slot is

$$P[X = r] = \binom{M}{r} \left( \frac{1}{F} \right)^r \left( 1 - \frac{1}{F} \right)^{M-r} . \quad (1)$$

The expected value of the number of slots with $r$ users in a slot[5],[7] is

$$E[X = r] = F \binom{M}{r} \left( \frac{1}{F} \right)^r \left( 1 - \frac{1}{F} \right)^{M-r} . \quad (2)$$

Denote by $C_r$ equals the number of slots being filled with exactly $r$ users. So the average number of collided request messages($\Lambda$) is derived as follows.

$$\Lambda = \sum_{r=2}^{M} \sum_{C_r=1}^{F} rP(X = C_r)C_r = \sum_{r=2}^{M} rE[X = C_r]$$

$$= \sum_{r=2}^{M} rF \binom{M}{r} \left( \frac{1}{F} \right)^r \left( 1 - \frac{1}{F} \right)^{M-r}$$

$$= M - M \left( 1 - \frac{1}{F} \right)^{M-1} . \quad (3)$$

The throughput is defined as the ratio of the number of successfully transmitted request messages and the total number of transmitted request messages.

$$Throughput = \frac{M - \Lambda}{M} = \left( 1 - \frac{1}{F} \right)^{M-1} . \quad (4)$$

4.2. Delay Analysis

The delay is the time spent until a bandwidth request message successfully transmits.

$$Delay = \text{The number of retransmission} \times \text{frame size}. \quad (5)$$

To obtain the delay, we need to find the number of retransmission. We derive the number of retransmission as follows.

$$P_{\text{another slots}} = \left( 1 - \frac{1}{F} \right)^{M-1} . \quad (6)$$

So, the probability of successfully transmitting a bandwidth request message during a slot ($P_{\text{suc,1}}$) is given by

$$P_{\text{suc,1}} = \frac{1}{F} \times \left( 1 - \frac{1}{F} \right)^{M-1} . \quad (7)$$

Since the frame size is $F[\text{slots}]$, the probability of successfully transmitting a bandwidth request message during a frame ($P_{\text{suc}}$) is

$$P_{\text{suc}} = \frac{1}{F} \left( 1 - \frac{1}{F} \right)^{M-1} \times F = \left( 1 - \frac{1}{F} \right)^{M-1} . \quad (8)$$

The probability of unsuccessfully transmitting a particular bandwidth request message during a frame is given by

$$P_{\text{col}} = 1 - \left( 1 - \frac{1}{F} \right)^{M-1} . \quad (9)$$

Let $P_{\text{suc}}(k)$ be the probability of the successfully transmitting a request message in the $k^{th}$ frame. Using geometric distribution, $P_{\text{suc}}(k)$ can be derived as

$$P_{\text{suc}}(k) = (1 - P_{\text{col}}) P_{\text{col}}^{k-1} . \quad (10)$$

The average number of retransmission for a bandwidth request message is

$$E[X = k] = \sum_{k=1}^{\infty} kP_{\text{suc}}(k) = \frac{1}{(1 - \frac{1}{F})^{M-1}} . \quad (11)$$

Therefore, we can derive the delay from (5) and (11) given by (12)

$$Delay = \frac{F}{(1 - \frac{1}{F})^{M-1}} . \quad (12)$$

4.3. The Optimal Size of the Contention Period

Since the throughput and delay are trade-off of each other, we define the cost function in order to optimize the size of the contention period using the throughput and delay. Let us denote that the cost function equals $\theta(M, F)$, then it can be defined as

$$\theta(M, F) = \frac{Throughput}{Delay} = \frac{(1 - \frac{1}{F})^{2(M-1)}}{F} . \quad (13)$$
\( \theta(M, F) \) indicates the optimal value when the throughput is large and the delay is small. Therefore, we can obtain the optimal size of the contention period when \( \theta(M, F) \) is a maximum value. We differentiate (13) with respect to \( F \), and then we can find the optimal size of the contention period for the number of users. Finally, the optimal size of the contention period is \( 2M - 1 \).

5. Numerical and Simulation Results

In this chapter we analyze the mathematical results for the throughput, delay, cost function, and the optimal size of the contention period and verify the mathematical results by using OPNET simulator.

Fig. 2 shows the throughput for the various contention periods and number of users. In Fig. 2, the \( x \) axis indicates the size of the contention period, and the \( y \) axis indicates the throughput. The lines are the mathematical results, and the symbols show the simulation results. The simulation results are measured using OPNET simulator. Fig. 2 shows that the mathematical results are very close to the simulation ones. In Fig. 2, as the contention period increases, the throughput increases. However, it is difficult to find the optimal contention period because the delay factor also impact on the optimal contention period.

In Fig. 3, the \( x \) axis indicates the size of the contention period with log scale, and the \( y \) axis indicates the delay [slots] with log scale. When the number of users increases until 30 users, the delay decreases because of the reduction of the average number of collided request messages. On the other hand, the delay increases during the size of the contention period is larger than 30 slots because the delay is affected by the size of the contention period more than it is affected by the collision probability of bandwidth request messages. As the cost function increases, the system shows better performance since the cost function is correlated to the throughput and delay.

In Fig. 4, the \( x \) axis indicates the size of the contention period, and the \( y \) axis indicates the cost function. There is a line that indicates the optimal size of the contention period in fig. 4. We can find the optimal size of the contention period when the cost function indicates a maximum value. Because the maximum value of the cost function represents the optimal performance of the system. As the number of the users becomes larger, the slope of the cost function curve becomes smaller. The reason is that the delay rapidly decreases to the minimum value and then slowly increases, while the throughput continuously increases as the contention period increases. In Fig. 4, we can find the optimal size of the contention period more clearly when the number of users is small.

In Fig. 5, the \( x \) axis indicates the number of users, and the \( y \) axis indicates the optimal size of the contention period [slots]. Fig. 5 shows that the line of the optimal contention slot size is linear and its slope is 2. So we can conclude that the optimal contention slot size is two times of the number of users (exactly \( 2M - 1 \)).
6. Conclusion

The performance of the system is affected by the size of the contention period due to the collision probability of bandwidth request messages in IEEE 802.16 MAC protocol. Since SSs send a bandwidth request message in the limited contention period which is allocated by a bandwidth allocation MAP message. In this paper, we analyzed stochastically the throughput and the delay. We defined the cost function in order to find the optimal size of the contention period, and derived the optimal size of the contention period from the cost function. Finally, we found that the optimal size of the contention period is two times of the number of users.

The analytic models and results in this paper can be used to optimize the parameters of the reservation ALOHA based protocols such as IEEE 802.15, IEEE 802.20, DOCSIS, and WiBro MAC protocol.

References