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무선 MAN에서 Best Effort 서비스를 위한 충돌 중재 방식: 설계 및 성능 분석

(Collision Arbitration Rules for Best Effort Service in Wireless MAN: Design and Performance Analysis)

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요 약

IEEE 802.16 무선 MAN 표준안에서 best effort 서비스는 가장 낮은 우선 순위이며 예약 ALOHA 기반의 MAC 방식의 지원을 받는다. 이러한 MAC 방식에서 요청 간의 충돌은 피할 수 없으므로 표준안은 충돌 중재를 위해 이진 지수형 back-off 규칙을 채택하였다. 본 논문에서는 throughput 성능의 향상을 위해 pristine 규칙과 metamorphosed 규칙으로 명명된 *p*-persistence 규칙에 기반한 두 가지 충돌 중재 규칙을 대안으로 제시한다. 또한 각 규칙에서 포화 throughput의 근사값을 계산하는 해석적 방법을 개발한다. 모의 실험 결과와의 비교를 통해 이러한 해석적 방법의 높은 정확성을 확인하고 이진 지수형 back-off 규칙과의 비교하여 pristine 규칙 및 metamorphosed 규칙은 높은 포화 throughput을 가져올 수 있음을 관찰한다.

Abstract

In the IEEE 802.16 Wireless MAN standard, the best effort service class is ranked on the lowest position in priority and is assisted by a MAC scheme based on reservation ALOHA. In such a MAC scheme, a collision among the requests is unavoidable so that the standard adopted a binary exponential back-off rule to arbitrate a collision. Aiming at improving throughput performance, we present two generic collision arbitration rules based on *p*-persistence rule, (identified as pristine and metamorphosed rules), as alternatives in a wireless MAN. For each of these rules, we then develop an analytical method to calculate an approximate value of saturated throughput. In comparison with simulation results, we confirm the high accuracy of the analytical method. Also, the pristine and metamorphosed rules are observed to exhibit higher saturated throughput compared with the binary exponential back-off rule.

Keywords : wireless MAN, best effort service, MAC, collision arbitration rule, saturated throughput

I. Introduction

IEEE 802.16 Wireless MAN standard specifies the air interface of fixed point-to-multipoint broadband wireless access systems providing multiple services in a wireless metropolitan area network[1~3]. Between a base station and subscriber stations, a wireless MAN supports five service classes identified as unsolicited grant service, real-time polling service, non-real-time polling service, extended real-time polling service, and best effort service. Among these service classes, the best effort service class is ranked on the lowest position in priority and is usually assisted by a medium access control (MAC) scheme

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based on reservation ALOHA.

In a wireless MAN operating in time division duplexing (TDD) mode, time is divided into frames and each frame consists of uplink and downlink subframes. In such a time structure, a subscriber using the best effort service delivers a request message during a part of an uplink subframe (identified as opportunity) and informs the base of its demand for the resource to send MAC protocol data units (PDU's). If two or more subscribers attempt to deliver their requests on a same opportunity, a collision occurs among these requests and the subscribers involved in the collision have to attempt again later. To suppress repeated collisions, a collision arbitration rule is necessitated. IEEE 802.16 Wireless MAN standard adopted a collision arbitration rule based on binary exponential back-off rule[4]. A binary exponential back-off rule may be the most famous collision arbitration rule. However, a subscriber need to memorize the results of past attempts to deliver a request. Moreover, it was revealed that a binary exponential back-off rule causes capture and starvation effect, which may deteriorate overall delay and throughput performance [5~7].

Aiming at improving throughput performance, we present two generic rules based on *p*-persistent rule, identified as pristine and metamorphosed rules, as alternatives to arbitrate a collision among requests in a wireless MAN. A *p*-persistence rule is a well known scheme in which a message is sent with a certain probability in each time slot[4]. As a result, a *p*-persistent rule does not necessitates to memorize the results of past attempts to deliver requests. In a wireless MAN, however, two or more opportunities may be consecutively provided in an uplink subframe. Also, a subscriber is not allowed to choose two or more opportunities in an uplink subframe to attempt to deliver requests. Thus, we devise the pristine and metamorphosed rules to adapt the unique features of a wireless MAN.

Since the remaining resource is only available for the best effort service after the resource is preferably allocated to other service users, the subscribers using the best effort service may be granted the scarce resource. The throughput performance is thus an important criterion for choosing a collision arbitration rule. To evaluate the throughput performance of pristine and metamorphosed rules, we develop an analytical method to calculate an approximate value of saturated throughput. Using the analytical method, we also optimize design parameters to maximize the request rate.

In section Ⅱ, we construct a MAC scheme for the best effort service in the wireless MAN. In section Ⅲ, we present two collision arbitration rules based on p-persistence rule, (identified as pristine and metamorphosed rules), for arbitrating a collision among the requests. In section Ⅳ, we develop an analytical method to calculate an approximate value of the saturated throughput for each of pristine and metamorphosed rules. In section Ⅴ, we compares the pristine and metamorphosed rules with the binary exponential back-off rule in throughput performance.

Ⅱ. MAC Scheme for Best Effort Service

Consider a wireless MAN operating in TDD mode. In the wireless MAN, time is divided into frames and each frame consists of uplink and downlink subframes. A downlink subframe is used to carry MAC PDU's of the base. Also, the broadcast control field of downlink subframe is used to announce the information about the frame format and the resource grant. On the other hand, an uplink subframe delivers MAC PDU's of subscribers. An uplink subframe

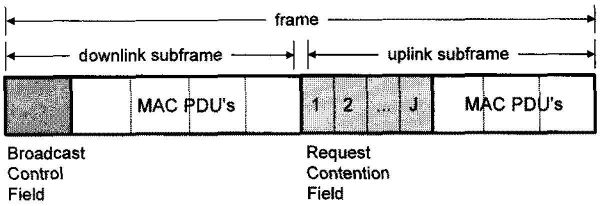

그림 1. 무선 MAN의 프레임 구조
Fig. 1. Frame Structure in wireless MAN.

contains the request contention field, which consists of a number of opportunities. An opportunity is used to deliver a request for resource. Figure 1 shows a simplified frame structure in the wireless MAN.

Prior to sending a MAC PDU, a subscriber chooses an opportunity and attempts to deliver a request which demands an amount of resource to send MAC PDU's. If the subscriber fails in the attempt (due to collision), the subscriber attempts later after intentionally denying a number of opportunities according to a collision arbitration rule. If the subscriber succeeds in the attempt, the base stores the request at the bottom of its buffer and positively acknowledges in the upcoming broadcast control field. In each frame, the base grants an amount of resource to a request residing in the buffer as far as there remains the available resource for the best effort service. Once the base granted a request, the subscriber having delivered the request receives the information about the resource grant via broadcast control field and sends MAC PDU's using the resource.

A MAC scheme for the best effort service must include a number of details, while many of them are not specified in the standard[3]. In this paper, referring to the details of a MAC scheme in [8~9], we construct a MAC scheme as follows:

1) A subscriber is allowed to attempt to deliver a request after the base acknowledges on the previous attempt.

2) Whenever a subscriber attempts to deliver a request, the subscriber demands as much resource as it can send the all MAC PDU's that it has.

3) To grant an amount of resource, the base selects a request in its buffer according to first come first served (FCFS) service discipline.

4) As far as the available resource remains, the base grants a request as much resource as it demands. If the available resource in an uplink subframe is insufficient to satisfy a request, the base deficiently grants the request only the remaining available resource.

Ⅲ. Collision Arbitration Rules

In this section, we describe two generic collision arbitration rules based on p-persistence rule; pristine and metamorphosed rules.

3.1 Pristine Rule

Suppose that a subscriber is ready to attempt to deliver a request. Then, the subscriber sequentially chooses an opportunity independently and identically with opportunity nomination probability, denoted by α. Once the subscriber chose an opportunity in an uplink subframe, the subscriber is not allowed to choose any more opportunity in the same uplink subframe. Note that a subscriber may not choose any opportunity in an uplink subframe.

3.2 Metamorphosed Rule

Suppose that a subscriber is ready to attempt to deliver a request at the start of an uplink subframe. Then, the subscriber first chooses the uplink subframe with frame nomination probability, denoted by β. Once the subscriber chose the uplink subframe, the subscriber equally likely chooses an opportunity among the all opportunities provided in the uplink subframe.

Ⅳ. Throughput Analysis

In this section, we calculate an approximate value of the throughput in the saturated environment where each subscriber always has infinite number of MAC PDU's to send. To calculate such an approximate avlue, we first obtain the exact value of the request rate in the saturated environment. Using the request rate, we then present an approximate saturated throughput while assuming K subscribers reside in the network and J opportunities are given in each frame.

4.1 Request Rate

The request rate is defined as the average number of requests which are successfully delivered to the base from a subscriber per unit time. For $m \in \{0, 1, \cdots\}$, let S_m denote the index of the frame in which a subscriber succeeds in an attempt to deliver a request for the mth time. (We set $S_0 = 0$ almost surely.) Set the inter-success time T_m to be

$$T_m = S_m - S_{m-1} \tag{1}$$

for $m \in \{1, 2, \cdots\}$. Then, the request rate, denoted by γ, is expressed as

$$\gamma = \lim_{n \to \infty} \frac{n}{S_n} = \lim_{n \to \infty} \frac{n}{\sum_{m=1}^{n} T_m} \tag{2}$$

For $k \in \{0, 1, \cdots\}$, let A_k denote the index of the frame in which the subscriber attempts to deliver a request for the kth time. (We set $A_0 = 0$ almost surely.) Set the inter-attempt time B_k to be

$$B_k = A_k - A_{k-1} \tag{3}$$

for $k \in \{1, 2, \cdots\}$. Let U_m denote the number of attempts that the subscriber makes until it succeeds in an attempt for the mth time. Set

$$V_m = U_m - U_{m-1} \tag{4}$$

for $m \in \{1, 2, \cdots\}$. Then, the request rate is also represented as

$$\gamma = \lim_{n \to \infty} \frac{n}{A_{U_n}} = \lim_{n \to \infty} \frac{n}{\sum_{m=1}^{n} \sum_{k=U_{m-1}+1}^{U_{m-1}+V_m} B_k} \tag{5}$$

A. Request Rate of Pristine Rule

In the pristine rule, a subscriber sequentially chooses an opportunity independently and identically with opportunity nomination probability α. Also, once a subscriber attempted to deliver a request using an opportunity in a frame, it is not allowed to attempt again using another opportunity in the same frame. Let δ denote the frame denial probability that a subscriber chooses no opportunity in a frame (hence the subscriber does not attempt to deliver any request at all in the frame). Then, the frame denial probability

$$\delta = (1 - \alpha)^J \tag{6}$$

The sequence of inter-attempt times $\{B_k, k = 1, 2, \cdots\}$ is then mutually independent and identically distributed with the shifted geometric distribution characterized by parameter δ. Also, there is a random variable B^P such that

$$B_k = B^P \tag{7}$$

in distribution for all $k \in \{1, 2, \cdots\}$, where

$$P(B^P = i) = (1 - \delta)\delta^{i-1} \tag{8}$$

for $i \in \{1, 2, \cdots\}$. Once a subscriber attempts to deliver a request, it succeeds in the attempt in an independent and identical fashion. Let ε_P denote the failure probability that a subscriber fails in an attempt. Given that a subscriber attempts to deliver a request in a frame, the probability that the subscriber attempts on the jth opportunity is equal to $\frac{\alpha(1-\alpha)^{j-1}}{1-(1-\alpha)^J}$ for $j \in \{1, \cdots, J\}$. For the subscriber to succeed in the attempt on the jth opportunity, other subscribers must choose either another opportunity or no opportunity in the frame. Thus, the failure probability is obtained as

$$\varepsilon_P = 1 - \sum_{j=1}^{J} \frac{\alpha(1-\alpha)^{j-1}}{1-(1-\alpha)^J} [1 - \alpha(1-\alpha)^{j-1}]^{K-1} \tag{9}$$

Note that the sequence $\{U_m, m = 1, 2, \cdots\}$ is i.i.d. with the shifted geometric distribution characterized by the parameter ε, i.e., there is a random variable U^P such that

$$U_m = U^P \tag{10}$$

in distribution for all $m \in \{1, 2, \cdots\}$ and

$$P(U^P = i) = (1 - \varepsilon_P)\varepsilon_P^{i-1} \tag{11}$$

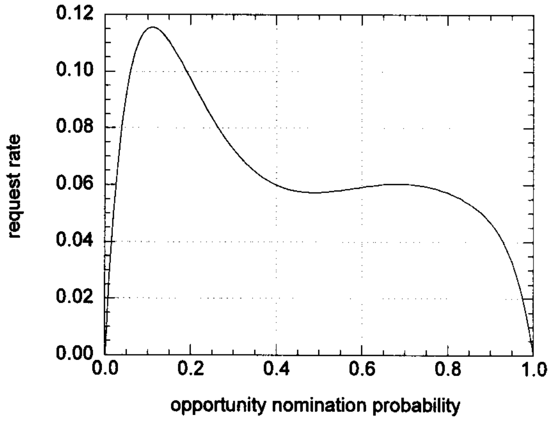

그림 2. 기회 선정 확률에 따른 요청률
Fig. 2. Request rate vs. opportunity nomination probability.

for $i \in \{1,2,\cdots\}$. From the strong law of large numbers, we finally have the request rate, denoted by γ_P, in the pristine rule as

$$\gamma_P = \frac{1}{E(U^P)E(B^P)} = \sum_{j=1}^{J} \alpha(1-\alpha)^{j-1}[1-\alpha(1-\alpha)^{j-1}]^{K-1} \quad (12)$$

Figure 2 shows the request rate (γ_P) with respect to the opportunity nomination probability (α) in the pristine rule. In this figure, we set the number of subscribers $K=10$ and the number of opportunities $J=3$. In figure 2, we observe that there is a non-trivial opportunity nomination probability $\alpha^* \in (0,1)$ which maximizes the request rate.

B. Request Rate of Metamorphosed Rule

In the metamorphosed rule, a subscriber attempts to deliver a request in each frame independently and identically with frame nomination probability β. Thus, the sequence of inter-attempt times $\{B_k, k=1,2,\cdots\}$ is i.i.d. with the shifted geometric distribution characterized by parameter $1-\beta$. Then, there is a random variable B^M such that

$$B_k = B^M \quad (13)$$

in distribution for all $k \in \{1,2,\cdots\}$ and

$$P(B^M = i) = \beta(1-\beta)^{i-1} \quad (14)$$

for $i \in \{1,2,\cdots\}$. Once a subscriber attempts to deliver a request, it succeeds in the attempt in an independent and identical fashion. Let ε_M be the failure probability that a subscriber fails in an attempt. For the subscriber to succeed in the attempt, other subscribers must attempt using another opportunity or not attempt at all in the frame. Thus, the failure probability

$$\begin{aligned}\varepsilon_M &= 1 - \sum_{j=1}^{J}\left[\sum_{l=0}^{K-1}\binom{J}{0}\left(\frac{1}{J}\right)^0\left(\frac{J-1}{J}\right)^l \times \binom{K-1}{l}\beta^l(1-\beta)^{K-1-l}\right]\frac{1}{J} \\ &= 1-\left(\frac{J-\beta}{J}\right)^{K-1} \end{aligned} \quad (15)$$

Note that the sequence $\{V_m, m=1,2,\cdots\}$ is also i.i.d. with the shifted geometric distribution characterized by parameter ε_M. Let V^M be a random variable such that

$$V_m = V^M \quad (16)$$

in distribution for all $m \in \{1,2,\cdots\}$. Then,

$$P(V^M = i) = (1-\varepsilon_M)\varepsilon_M^{i-1} \quad (17)$$

for $i \in \{1,2,\cdots\}$. From the strong law of large numbers, we therefore have the request rate, denoted by γ_M, in the metamorphosed rule as

$$\gamma_M = \beta\left(\frac{J-\beta}{J}\right)^{K-1} \quad (18)$$

Figure 3 shows the request rate (γ_M) with respect to the frame nomination probability (β) in the metamorphosed rule. In this figure, we set the number of subscribers $K=10$ and the number of opportunities $J=3$. In figure 3, we observe that there is a non-trivial frame nomination probability $\beta^* \in (0,1)$ which maximizes the request rate. Also, we notice that $\beta^* \approx 0.3$.

Given K and J, the request rate γ_M is a convex

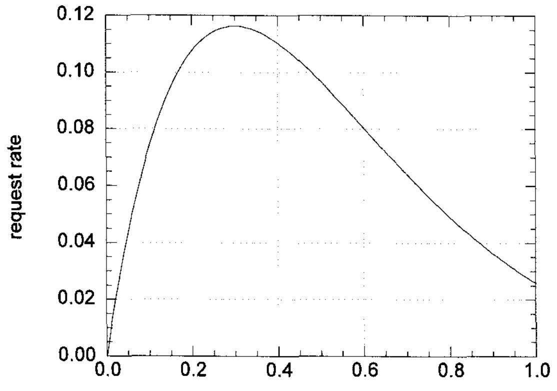

그림 3. 프레임 선정 확률에 따른 요청률
Fig. 3. Request rate vs. frame nomination probability.

and differentiable function of the frame nomination probability $\beta \in (0,1)$. By differentiating γ_M with respect to β, we have a critical point of $\frac{J}{K}$, which is also an extreme point. (The optimal value in figure 3 is 0.3, which coincides with $\frac{J}{K}$.) Thus, we have the maximum request rate, denoted by γ_M^*, as

$$\gamma_M^* = J \cdot \frac{1}{K}(1-\frac{1}{K})^{K-1} \tag{19}$$

From (11), we also have the following relation:

$$\gamma_P \leq \gamma_M^* \tag{20}$$

4.2 Saturated Throughput

Once a subscriber succeeds in an attempt, a request arrives at the base's queueing system. Assume that the number of requests arriving at the queueing system in each frame has the binomial distribution with parameters J and $K\gamma$ independently and identically. Let R_n denote the amount of the available resource for the best effort service in the nth frame. For a random variable R, suppose that $R_n = R$ in distribution for all $n \in \{1,2,\cdots\}$. Let X_n denote the number of requests remaining at the queueing system at the end of the nth frame. Then,

$$X_{n+1} = X_n + M_{n+1} - N_{n+1} \tag{21}$$

where M_{n+1} is the number of requests arriving at the base in the $(n+1)$st frame while N_{n+1} is the number of requests departing from the queueing system, (i.e., being granted an amount of resource) during the $(n+1)$st frame. Note that

$$\begin{aligned} &P(N_{n+1} = 1 \mid X_n \in \{1,2,\cdots\}) = 1 - P(R=0) \\ &P(N_{n+1} = 0 \mid X_n \in \{1,2,\cdots\}) = P(R=0) \end{aligned} \tag{22}$$

since each request demands infinite amount of resource in the saturated environment. Thus, $\{X_n, n=0,1,\cdots\}$ is a homogeneous discrete-time Markov chain on the state space $S=\{0,1,\cdots\}$ with the transition probability function $h : S^2 \rightarrow [0,1]$ such that

$$h(0,j) = \binom{J}{j}(\frac{K\gamma}{J})^j(1-\frac{K\gamma}{J})^{J-j} \tag{23}$$

for $j \in \{0,\cdots,J\}$ and

$$\begin{aligned} &h(i,j) \\ &= \binom{J}{j-i}(\frac{K\gamma}{J})^{j-i}(1-\frac{K\gamma}{J})^{J-i+i} \\ &\quad \cdot P(R=0) \cdot I_{\{j \in \{i,\cdots,J+i\}\}} \\ &\quad + \binom{J}{j-i+1}(\frac{K\gamma}{J})^{j-i+1}(1-\frac{K\gamma}{J})^{J-i+i-1} \\ &\quad \cdot [1-P(R=0)] \cdot I_{\{j \in \{i-1,\cdots,J+i-1\}\}} \end{aligned} \tag{24}$$

for $i \in \{1,2,\cdots\}$.

In the queueing system at the base, let λ and μ denote the arrival rate and the service rate, respectively. Then,

$$\begin{aligned} &\lambda = K\gamma \\ &\mu = 1 - P(R=0) \end{aligned} \tag{25}$$

Let η denote the throughput of the queueing system. Then, $\eta = \lambda \frac{E(R)}{1-P(R=0)}$ if the queueing system is underloaded while $\eta = \mu \frac{E(R)}{1-P(R=0)}$ if it is overloaded. Note that the necessary and sufficient condition for the Markov chain $\{X_n, n=0,1,\cdots\}$ to have the steady state distribution, i.e., for the base's queueing system to stay underloaded is [10~11].

$$\frac{\lambda}{\mu}=\frac{K\gamma}{1-P(R=0)}<1 \tag{26}$$

Thus, we obtain the throughput as

$$\eta=\begin{cases}\dfrac{K\gamma E(R)}{1-P(R=0)} & \text{if } K\gamma<1-P(R=0)\\ E(R) & \text{if } K\gamma\geq 1-P(R=0).\end{cases} \tag{27}$$

Figure 4 shows the saturated throughput (η_P) with respect to the opportunity nomination probability (α) in the pristine rule. In this figure, we set the number of subscribers $K=10$ and the number of opportunities $J=3$. Also, the amount of available resource (measured as the number of MAC PDU's that a subscriber is able to send) has the discrete uniform distribution in $\{0,\cdots,20\}$ independently and identically in each frame. In figure 4, we observe that the approximate value of the saturated throughput is tightly close to the simulation result, which confirms the accuracy of the analytical method to calculate an approximate saturated throughput.

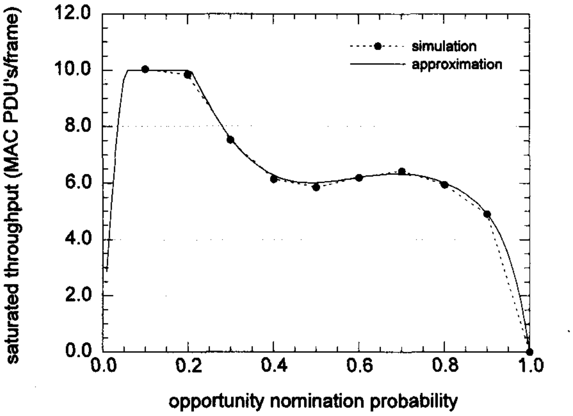

그림 4. 기회 선정 확률에 따른 포화 throughput
Fig. 4. Saturated throughput vs. opportunity nomination probability.

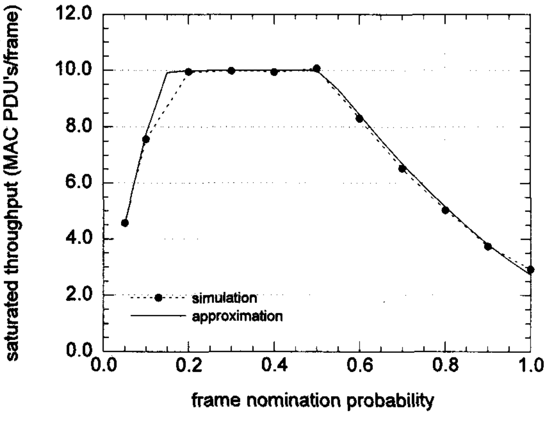

그림 5. 프레임 선정 확률에 따른 포화 throughput
Fig. 5. Saturated throughput vs. frame nomination probability.

Figure 5 shows the saturated throughput (η_M) with respect to the frame nomination probability (β) in the metamorphosed rule. In this figure, we assume the same environment as in figure 4. In figure 5, we notice the accuracy of the analytical method to calculate an approximate value of the saturated throughput as in figure 4.

V. Performance Evaluation

In this section, using the analytical method (presented in section 4) as well as simulation method, we evaluate the throughput performance exhibited by each of the two collision arbitration rules; pristine and metamorphosed rules. The environment assumed in this section is as follows:

1) There are 10 subscribers in the wireless MAN.

2) One minislot is equal to two physical slots.

3) The duration time of each frame is 2000 minislots and the duration times of downlink and uplink subframes are equal to 1000 minislots.

4) The duration time of an opportunity is 8 minislots. Also, 5 opportunities are maximally provided in each frame.

5) 48 minislots are needed to send a MAC PDU.

6) The amount of the available resource (measured as the number of MAC PDU's that a subscriber is able to send) has the discrete uniform distribution in $\{0,\cdots,n\}$ independently and identically in each frame, where $n\in\{1,\cdots,20\}$.

7) In the pristine rule, the opportunity nomination probability (α) is set to maximize the request rate (γ_P).

8) In the metamorphosed rule, the frame nomination probability (β) is set to maximize the

request rate (γ_M).

9) In binary exponential back-off rule, we set the initial support to be $\{0,\cdots,15\}$ to reduce the capture and starvation effects.

10) The propagation delay time between the base and each subscriber is negligibly short.

In figure 6, the pristine and metamorphosed rules are compared with the binary exponential back-off rule in saturated throughput. In this figure, the amount of available resource (for the best effort service) is assumed to have the discrete uniform distribution in $\{0,\cdots,20\}$ independently and identically in each frame. To obtain the saturated throughput, we use the analytical method in the pristine and metamorphosed rules while we use a simulation method in the binary exponential back-off rule. In figure 4, we observe that the pristine and metamorphosed rules produce a superior saturated throughput than the binary exponential back-off rule when a small number of opportunities are provided in each frame. On the other hand, the all rules perform similarly when the number of opportunities is large enough. This phenomenon is due to the fact that the base's queueing system is overloaded when a large number of opportunities are provided so that the saturated throughput is not affected by the collision arbitration rule but determined by the amount of available resource. Also, we notice that the metamorphosed rule exhibits slightly higher saturated throughput than the pristine rule as expected in section Ⅳ.

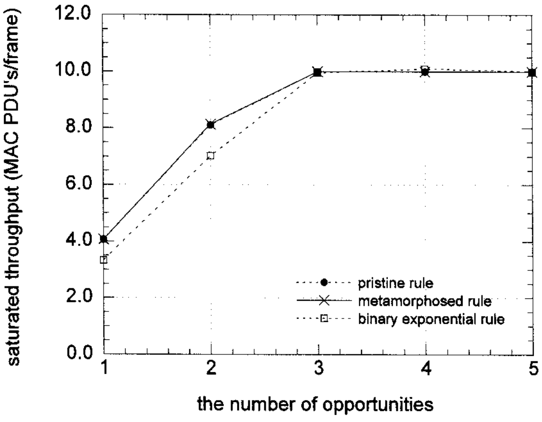

그림 6. 기회의 수에 따른 포화 throughput
Fig. 6. Saturated throughput vs. the number of opportunities.

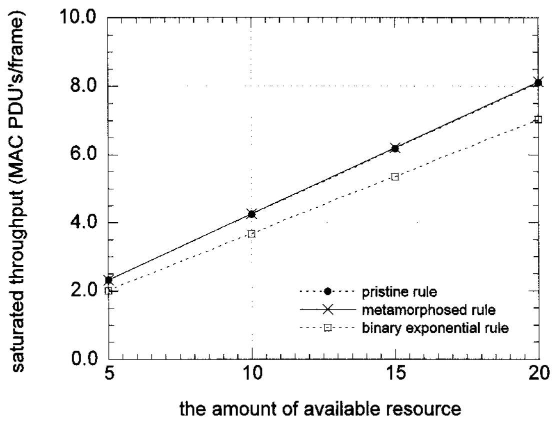

그림 7. 가용 자원의 양이 갖는 support에 따른 포화 throughput
Fig. 7. Saturated throughput vs. the support for the amount of available resource.

Recall that the amount of available resource (for the best effort service) is assumed to have the discrete uniform distribution in $\{0,\cdots,n\}$ independently and identically in each frame. Figure 7 illustrates the effect of n on the saturated throughput. In this figure, we set the number of opportunities $J=2$. In figure 7, we observe that the pristine and metamorphosed rules invoke higher saturated throughput than the binary exponential back-off rule. Also, the difference of saturated throughput between the rules grows as the number n increases, i.e., the support for the amount of available resource expands. Note that the base's queueing system is underloaded in the environment assumed in figure 7. Since the amount of available resource has no effect on the request rate, the request rate is fixed and the saturated throughput, roughly speaking, is thus proportional to the expected amount of available resource.

Ⅵ. Conclusions

In provisioning the best effort service in a wireless MAN, a collision among the requests is unavoidable so that a collision arbitration rule is needed to suppress repeated collisions. In this paper, aiming at improving throughput performance, we presented two generic collision arbitration rules based on p-persistent rule, (identified as pristine and metamorphosed rules), as alternatives to the binary exponential back-off rule. For each of the rules, we developed an analytical method to calculate an approximate value of the saturated throughput. Using the analytical method, we then optimized the design parameters as to maximize the request rate. In comparison with simulation results, the analytical method was evaluated and its high accuracy was confirmed. Also, the throughput performance of the pristine and metamorphosed rules was evaluated in comparison with the binary exponential back-off rule, which revealed that both of the pristine and metamorphosed rules invoke superior saturated throughput to the binary exponential back-off rule.

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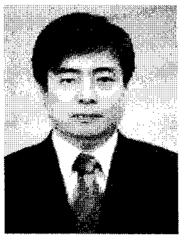

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