Modelling of Differentiated Bandwidth Requests in IEEE 802.16m Systems

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Abstract

In order to support a large number of mobile stations (MSs) with statistical multiplexing in cellular networks, a random access scheme is widely used for uplink (UL) bandwidth request (BR). In the design of a random access based BR scheme, there are two important requirements: short connection delay and diverse Quality of Services (QoSs) support. Such requirements are crucial for IMT-Advanced systems like IEEE 802.16m to provide various types of fourth generation (4G) data services. IEEE 802.16m provides advanced UL BR schemes for non-real time polling service (nrtPS) and best-effort (BE) service to meet the requirements of short connection time and multiple QoS level support. In order to provide short connection time and multiple QoS support, three-step and differentiated BR procedures are adopted. In this paper, a novel modelling of IEEE 802.16m contention based BR scheme is proposed that uses a 2-dimensional discrete time Markov chain. Both the short access delay three-step BR procedures and normal five-step BR procedure are considered in the model. Our proposed model also incorporates the IEEE 802.16m differentiated BR procedure. With the proposed model, we extensively evaluate the performance of IEEE 802.16m BR for two different service classes by changing QoS parameters, such as backoff window size and BR timer. Computer simulations are performed to corroborate the accuracy of the proposed model for various operation scenarios. With the proposed model, accurate QoS parameter values can be derived for the IEEE 802.16m contention-based BR scheme.

Keywords: IMT-Advanced, IEEE 802.16m, bandwidth request, Markov chain, quality-of-service (QoS), random access, service differentiation.

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1. Introduction

In recent years, the explosive increase of demand for higher data rate and interactive multimedia applications in mobile environments has accelerated the development of new network architectures for fourth generation (4G) cellular systems. The International Telecommunication Union Radio Section (ITU-R) has commenced the process of developing ITU-R Recommendations for the terrestrial components of the International Mobile Telecommunications-Advanced (IMT-Advanced) radio interface to enable high-quality mobile services. IMT-Advanced systems are 4G cellular systems that offer significant enhancements over IMT-2000 third generation (3G) systems. IMT-Advanced systems are designed to provide significant improvement in performance and Quality of Service (QoS). As one of the IMT-Advanced systems, the enhanced air interface specification for the Wireless Metropolitan Area Network (WirelessMAN), Institute of Electrical and Electronics Engineers (IEEE) Std 802.16m™-2011(IEEE 802.16m) [1] has been developed by the IEEE 802.16 Task Group m (TGm). IEEE 802.16m, which is the WirelessMAN-Advanced air interface and specifies physical (PHY) and Medium Access Control (MAC) layers for high data rate and QoS enhancement, is designed to meet and in many cases exceed the requirements of the IMT-Advanced system [1], [2].

Cellular networks employ statistical multiplexing to share limited wireless resources with a large number of Mobile Stations (MSs). In point-to-multipoint (PMP) mode, a central Base Station (BS) controls all wireless resources which are used for communications between MSs and a BS. Under a centralized architecture, MSs share uplink (UL) resources statistically on a demand basis by sending a request [3]. A random access scheme is widely used to provide statistical multiplexing in cellular networks. The random access scheme provides a way to request UL bandwidth allocation to MSs with UL packets to transmit. IEEE 802.16 MAC layer provides differentiated services among different service flows with individual QoS requirements [4]. To meet the random access requirements of 4G cellular systems: high data rate through short connection time and QoS enhancement through multiple QoS level support, IEEE 802.16m provides advanced UL bandwidth request (BR) schemes called a contention-based BR scheme with BR preamble sequence and a quick access message scheme for non-real time polling service (nrtPS) and best-effort (BE) service flows [1], [5]. Such random access schemes support a expedited BR procedure providing short connection delay. Moreover, IEEE 802.16m BR scheme provides service differentiation to support multiple QoS levels among service flows. Since a random access scheme utilizes decentralized and implicit coordination, MSs competing to transmit BRs may experience collisions during a random access operation. In order to resolve such collisions, a backoff process is employed in IEEE 802.16m. A different access priority can be given to each service flow by differentiating backoff values used in a collision resolution procedure and by controlling the BR timer values used for retransmission.

There have been several studies on the performance of the IEEE 802.16e random access scheme [6]. An analytical model of the IEEE 802.11 distributed coordination function backoff process using a Markov Chain (MC) model was proposed in [7]. Based on a similar approach to [7], the IEEE 802.16e backoff process was firstly investigated in [8]. Since IEEE 802.16 employs a request based allocation procedure and does not consider Carrier Sense Multiple Access (CSMA), [8] adopted additional idle states to model the IEEE 802.16e random access. [9] examined the performance of backoff algorithms which can be applied to the study of the

3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) and the IEEE 802.16 random access schemes. In order to analyze prioritized random access schemes in multiservice cellular networks, the authors in [10] considered and mathematically modelled slotted ALOHA, which is one of random access strategies widely used in cellular network. ALOHA and its variants including slotted ALOHA are widely used as a random access scheme because of its simplicity without requiring any information on channel conditions [10].

In [11], the capacity of the contention slots used to deliver bandwidth requests and the average access delay were derived by using an MC-based analytical model considering collision and timeout. The authors in [12] and [13] provided the subchannelization analysis in order to model multiple concurrent BR transmissions based on the proposed MC model in [11]. [14] presented a comprehensive study of both unicast polling and contention resolution in IEEE 802.16e standard with a retry limit based on [11] and proposed some scheduling policies. [15], [16] and [17] presented an analytical model for the IEEE 802.16e contention-based BR scheme along with performance estimation of the network capacity and delay in a saturated access mode. Most of the previous researches on IEEE 802.16 random access focused on the legacy IEEE 802.16 BR schemes [6]. As far as we are aware, there has not been any study on the IEEE 802.16m contention-based BR scheme. The objective of this paper is to provide a thorough performance analysis of the IEEE 802.16m contention-based BR scheme with different service flows. To the best of our knowledge, performance analysis of the IEEE 802.16m contention-based BR scheme with different service flows has not been studied.

In this paper, we propose a novel analytical model of the IEEE 802.16m contention-based BR scheme using a 2-dimensional discrete time MC model. The proposed model is based on the analytical framework used in [11]. Based on [11], the subchannelization parameters were added in [12] and [13] for more accurate modelling of the legacy IEEE 802.16 BR scheme. In [11], [12], and [13], the authors assumed that before a expiration of a BR timer a BS tried to send an UL grant to a target MS upon receiving a BR message without collision. However, in the emerging IEEE 802.16m contention-based BR scheme, a BS is able to allocate bandwidth to MSs after successfully receiving a quick access message or a BR header from an MS during a BR procedure. Furthermore, in IEEE 802.16m, fast three-step and normal five-step BR procedures can be provided depending on the result of detection and decoding of a BR message (a BR preamble sequence and a quick access message), which do not exist in the legacy IEEE 802.16 BR scheme. Since BR schemes considering fast three-step and normal five-step BR procedures have not been analyzed in the previous studies, these models cannot be used for modelling the IEEE 802.16m contention-based BR scheme with a BR message containing a BR preamble sequence and a quick access message. A BR message with a BR preamble sequence and a quick message is newly adopted Random Access Channel (RACH) structure in IEEE 802.16m.

In order to accurately model the IEEE 802.16m contention-based BR scheme, we particularly consider the following five aspects which are the main contributions of this paper.

1) *Grouping of states*: In order to present backoff and resource allocation processes in one MC model, states in [11] are classified into two groups: backoff states and waiting states. Based on the classified states, new IEEE 802.16m's collision and BR timeout cases can be modeled successfully. However, since these models are not able to provide modelling of three-step and five-step BR procedures, three new sub-groups of waiting states are further added in the proposed model for accurate modelling of the IEEE 802.16m contention-based BR scheme.

2) *Three-step BR procedure with consideration of differentiated BR timers*: State transition to three-step BR states with transition probability of a BR transmission without contention is newly introduced. In three-step BR procedure, an MS tries to retransmit a BR message if a differentiated BR timer expires before receiving an UL grant for transmitting data to a BS. Different BR timer values are utilized to provide different QoS levels. Differentiated BR timers for QoS are fully considered in the proposed model.

3) *Five-step BR procedure with consideration of differentiated BR timers*: State transition to five-step BR states with transition probability of a BR message collision (only data portion) is newly introduced. In five-step BR procedure, an MS tries to retransmit a BR message in either of two BR timer expiration cases : a fixed BR timer before receiving a BR header grant or a differentiated BR timer before receiving an UL grant. Different BR timer values are also utilized to provide different QoS levels. Similar to three-step BR procedure, differentiated BR timers for QoS are fully considered in the proposed model.

4) *Transmission failure states*: In IEEE 802.16m, when more than two MSs transmit a same BR preamble sequence using a same BR channel, BR transmission fails due to collision. In this case, an MS needs to restart BR procedure with next backoff stage after expiration of a fixed or differentiated BR timer. In order to model this feature in our proposed model, state transition to transmission failure states with transition probability of BR message collision (both preamble and data portions) is newly introduced and such new collision case of IEEE 802.16m BR is fully considered. Similar to three-step and five-step BR procedures, in case of transmission failure, differentiated BR timers are also employed to provide different QoSs. Differentiated BR timers for QoS are also fully considered in the proposed model.

5) *Service differentiation in the IEEE 802.16m contention-based BR scheme*: In our performance analysis, we consider actual service differentiation parameters, such as backoff and BR timer values and present transition probabilities to sub-groups of waiting states influenced by different BR parameters in order to clearly show how different QoSs of service flows are guaranteed.

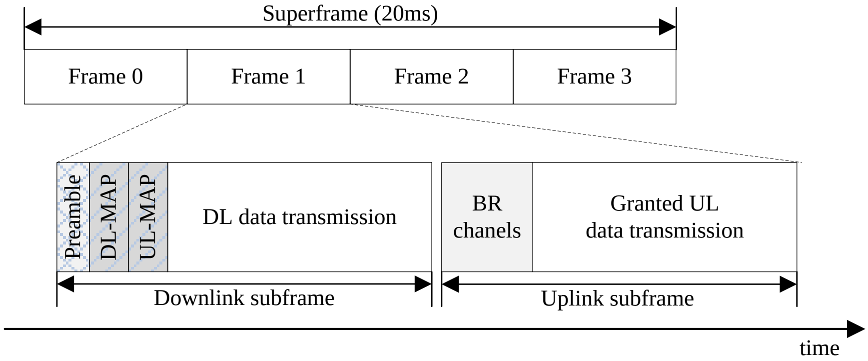
The rest of this paper is organized as follows. Section 2 provides detailed operation of the IEEE 802.16m contention-based BR scheme and differentiated BR parameters. The proposed analytical model is described in Section 3. In Section 4, first performance comparison between IEEE 802.16e random access and IEEE 802.16m random access is provided in order to highlight the benefits of new IEEE 802.16m random access features and then the proposed model is validated through simulations. In Section 5, we conclude our discussion.

2. Random Access Scheme in IEEE 802.16m

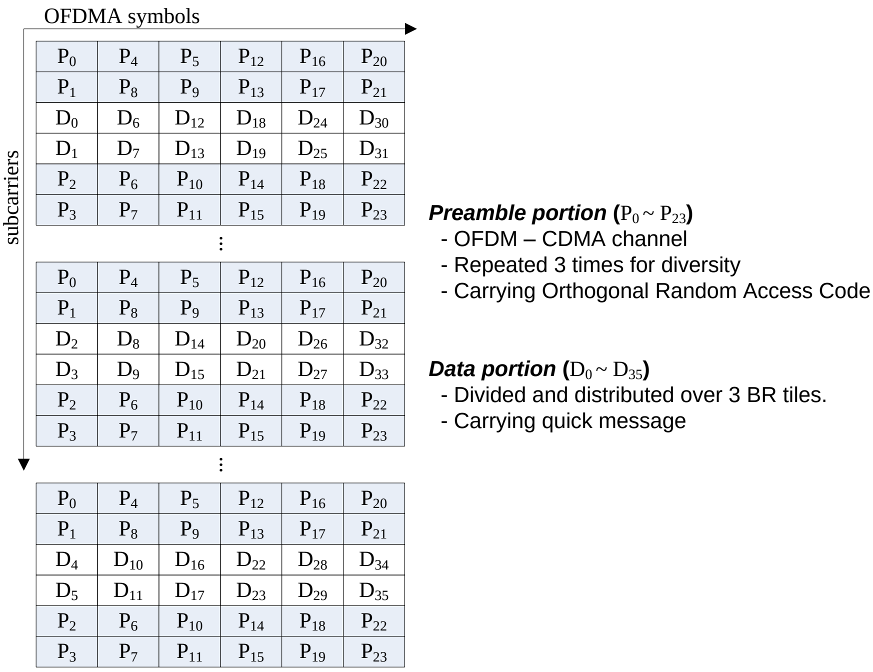
2.1 Contention-based Bandwidth Request

In the contention-based BR scheme, as a random access scheme of the IEEE 802.16m, BR channels are used for RACHs. Each BR channel indicates a BR opportunity and a BS determines the number of BR channels per one UL frame, N_{bwr}, for MSs to transmit a BR message. **Fig. 1 (a)** shows the time-division duplexing (TDD) MAC frame structure defined in the IEEE 802.16m standard [2].

Like other IEEE 802.16m control channels, BR channels are designed to be very robust to wireless channel errors. Each BR channel is comprised of three distributed BR tiles for frequency diversity as shown in **Fig. 1 (b)**. The BR tile is a resource block which is defined as six contiguous subcarriers by six OFDMA symbols. Each BR channel consists of two parts:



(a) Basic frame structures for TDD mode in IEEE 802.16m



(b) IEEE 802.16m BR Channel Structure

Fig. 1. IEEE 802.16m basic frame structure (TDD) and BR channel structure.

a preamble part and a data part.

The preamble part carries the selected BR preamble sequence. The preamble part of the BR tile spans four subcarriers by six OFDMA symbols. Each BR preamble sequence consists of 24 bits which is modulated by binary phase shift keying (BPSK). All MSs share the same BR preamble sequence pool with a finite number of BR preamble sequences, N_{seq}. The 802.16m standard defines 24 orthogonal access sequences as preamble sequences [1]. The selected BR preamble sequence is repeated in the same location of three BR tiles for frequency diversity gain. Basically, the preamble part in BR channels is equivalent to an Orthogonal Frequency Division Multiplexing-Code Division Multiple Access (OFDM-CDMA) [9]. Therefore, similar to the CDMA based random access scheme, as long as different BR preamble sequences are transmitted by MSs through a single BR channel, a BS is able to detect transmitted multiple BR preamble sequences and distinguish indices of the detected BR pre-

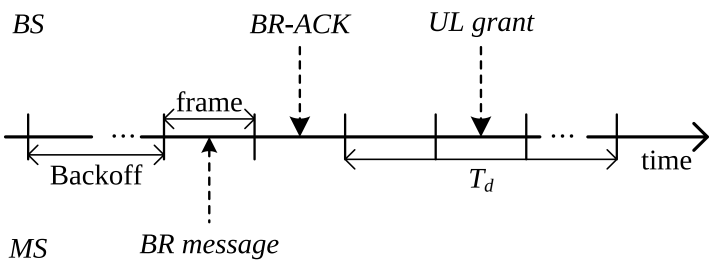


Fig. 2. Three-step contention-based BR procedure.

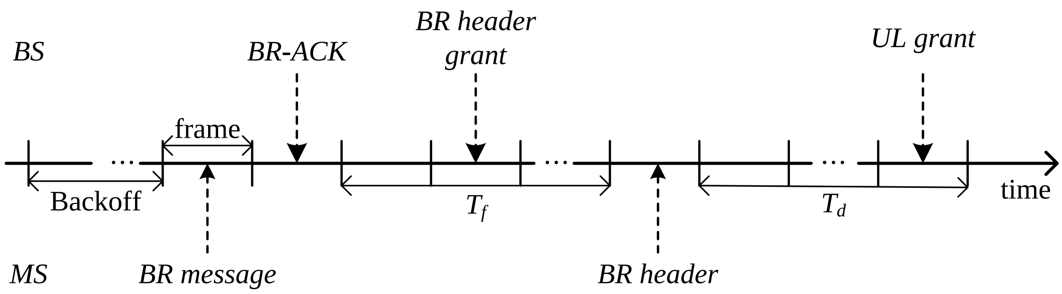


Fig. 3. Five-step contention-based BR procedure

amble sequences. If more than two MSs choose the same preamble sequence, such MSs' preamble sequence cannot be properly handled by a BS, which is referred as a collision in the preamble part. Even though such collision happens, a BS considers collided preamble sequences as a successfully received BR preamble sequence, since a BS cannot notice multiple receptions of the same BR preamble sequences.

The data part of BR channels carries the quick access message. The data part of the BR tile spans two contiguous subcarriers by six OFDMA symbols. The 16-bit information in the quick access message is encoded into 72 bits using tail-biting convolution code. The 72 coded bits are modulated by quadrature phase shift keying (QPSK) to generate 36 data symbols. In contrast to the preamble sequence, a BS is able to decode only one quick message in a single BR channel. Even though a BS is able to correctly detect multiple BR preamble sequences transmitted in a BR channel, multiple quick messages from multiple MSs cannot be decoded, which is referred as a collision in the data part.

Before transmitting a BR message using the contention-based BR scheme, an MS starts a backoff process. Each MS randomly selects a backoff counter value within its current backoff window (*CW*) in the range of [0,*CW*-1]. Whereas the backoff counter decreases during idle channel in IEEE 802.11 wireless local area networks (WLANs) [7], the IEEE 802.16m backoff process decrements a backoff counter at the beginning of every BR channel regardless of channel condition [9]. After the backoff process, an MS transmits a BR message containing a BR preamble sequence randomly selected from N_{seq} sequences and a quick access message with its station identifier (ID), BR size, and QoS level through a BR channel. If a BS detects at least one BR preamble sequence in BR channels, it transmits a BR acknowledge (BR-ACK) in the next download (DL) frame. A BR-ACK includes the indices of all correctly received BR preamble sequences in the previous UL subframes and the decoding status of the quick access message for each correctly received BR preamble sequence. If an MS's transmitted BR preamble sequence is not included in the BR-ACK, an MS considers such status as receiving a

Negative-ACK (NACK). MSs, whose indices of the transmitted BR preample squences are included in the BR-ACK, start BR timers.

The contention-based BR procedure is classified into two types: 1) three-step and 2) five-step BR procedures. Upon successful transmission of a BR preamble sequence and a quick access message, an MS enters the three-step BR procedure, as shown in **Fig. 2**. In the three-step BR procedure, a BR timer value is set to be a *differentiated* BR timer, T_d. The BR timer is stopped upon reception of an UL grant. If a BS is unable to decode a quick access message, BR procedure is switched to the five-step BR procedure. **Fig. 3** illustrates an example of the five-step BR procedure. Because of collision in the data part, a BS may provide a BR header grant to acquire BR information from MSs. In this case, MSs set the BR timer value to be a *fixed* BR timer, T_f. A BR header contains the same information of 48 bits as in a quick access message [6]. After transmitting a BR header, an MS starts a BR timer of T_d. Similar to the three-step BR procedure, the BR timer is stopped upon reception of an UL grant.

A BS may defer transmitting an UL grant for the next frame when bandwidth is not available. Therefore, the BR timer may expire before receiving an UL grant from the BS. If either a NACK is received or a BR timer expires, an MS increases its backoff window and restarts the backoff process. After successful reception of an UL grant, an MS transmits UL data on its granted UL frame.

2.2 Differentiated Bandwidth Request Parameters

Since contention-based BR is a decentralized scheme, it is typically unsuitable for services with high QoS requirements. In order to provide differentiated QoS levels in random access, IEEE 802.16m provides service differentiation in its BR mechanism by separating service flows into *k* different service classes (*k* different priorities). Each service flow is able to have a differentiated BR channel access priority by controlling the backoff and BR timer values [2].

The backoff value means the number of BR channels that an MS waits before transmitting a BR message. A different priority can be given to each service class with initial backoff window size (W_0^k), maximum backoff window size ($W_{\max}^k$) and backoff scaling factor (s^k). At the first BR transmission, *CW* is set to be W_0^k. After each unsuccessful BR transmission, an MS increases its backoff window by s^k up to $W_{\max}^k = (s^k)^m \cdot W_0^k$, where m is the maximum backoff stage. W_0^k and $W_{\max}^k$ range between 0 to 15 expressed as a power of 2 [1] and usually $s^k = 2$, which is called the binary exponential backoff algorithm. For different connection priorities $k<k$\`, at least one or more of the following backoff parameters are set to be $W_0^k < W_0^{k'}$, $W_{\max}^k < W_{\max}^{k'}$, or $s_k < s_{k'}$. Since MSs with a higher connection priority of service flows have a shorter average backoff time than the other MSs, they have a better chance of accessing BR channels.

A BR timer is a number of frames before the contention-based BR procedure is re-attempted for the service flow. There are two types of BR timer: a fixed BR timer (T_f), and a differentiated BR timer (T_d^k). Priorities can be defined with differentiated BR timer values (T_d^k), where T_d^k is an UL grant reception timeout value and ranges between 1 to 64 frames [1]. After successful reception of a quick message or BR header, a BS should try to allocate an UL grant within this parameter value during the contention-based BR procedure. For different priorities $k<k$\`, BR timers are set to be $T_d^k \le T_d^{k'}$. If a certain MS's BR message is dropped due to collision or congestion in the networks, the MS cannot notice the loss of the BR message

until its BR timer expires. Thus, for the purpose of fast retransmission, MSs with higher connection priority of service flows set shorter T_d^k than the other MSs.

BR timer and backoff timer parameters are based on QoS parameters, e.g. UL scheduling type, latency and so on. BR timer and backoff timer parameters are negotiated during service flow setup and can be different in each frame. A BS is able to update parameters via control messages.

3. Analytical Modelling of the IEEE 802.16m Random Access

In this section, description of the proposed analytical model of the IEEE 802.16m contention-based BR scheme is provided. In [7], Bianchi presented an accurate model to compute the throughput of a saturated IEEE 802.11 distributed coordinate function under ideal channel conditions using an MC model. Based on [7], Fallah et al. [11] modeled a contention-based BR scheme considering collision and BR timeout in the legacy IEEE 802.16 [6]. However, since Fallah et al.'s model focused on the legacy IEEE 802.16 BR scheme, performance of the new IEEE 802.16m contention-based BR scheme using BR preamble sequences, quick messages, and different service flows cannot be analyzed by their model. Therefore, based on the analytical framework in [11], we propose a novel analytical model of the IEEE 802.16m contention-based BR scheme for extensive study of the performance.

Several assumptions are made in the proposed model. MSs are assumed to be under saturation condition, which means each MS always has available data for transmission. Under such condition, each MS’s behavior with different connection priority is extensively analyzed in order to see how different QoS is guaranteed with random access QoS parameters. By considering a saturation condition, the upper bound of the system performance can be analyzed [15] as shown in the results of [11]. Since the one of main objectives of this paper is to understand the maximum system performance for two different services classes, the assumption of saturation condition is adequate. The BR channel can be assumed to be ideal, i.e., error free because IEEE 802.16m BR channels are designed to be very robust to channel errors and also MSs transmit BR messages with maximum transmission power to be error free. Under ideal channel assumption, like other prior works on random access including [7], we are able to focus on the system behaviour of the IEEE 802.16m differentiated BR procedure. Therefore, unsuccessful BR transmission only occurs in case of a BR timer expiration or collision in both parts of a BR message. For simplicity, we only consider two types of service flows, nrtPS and BE with two different connection priorities. High connection priority is referred as class 1 service flow and low connection priority is referred as class 2 service flow. Service flows of each class are assigned to N_1 and N_2 numbers of MSs, respectively. Each service flow achieves a differentiated BR channel access priority by controlling the backoff and BR timer values. Our model can be extended very easily with more service flows of different connection priorities.

3.1 Markov Chain Modelling for Contention-based Bandwidth Request Scheme

The contention-based BR procedure is classified into two groups of states: back-off states and waiting states. The backoff states group describes the binary exponential backoff procedure. After transmitting a BR message, an MS goes into waiting state and starts a BR timer after receiving a BR-ACK.

Let $b(t)$ be a stochastic random process representing a current backoff value for an MS. The backoff value decreases only at the beginning of BR channels. Therefore, a time scale is dis-

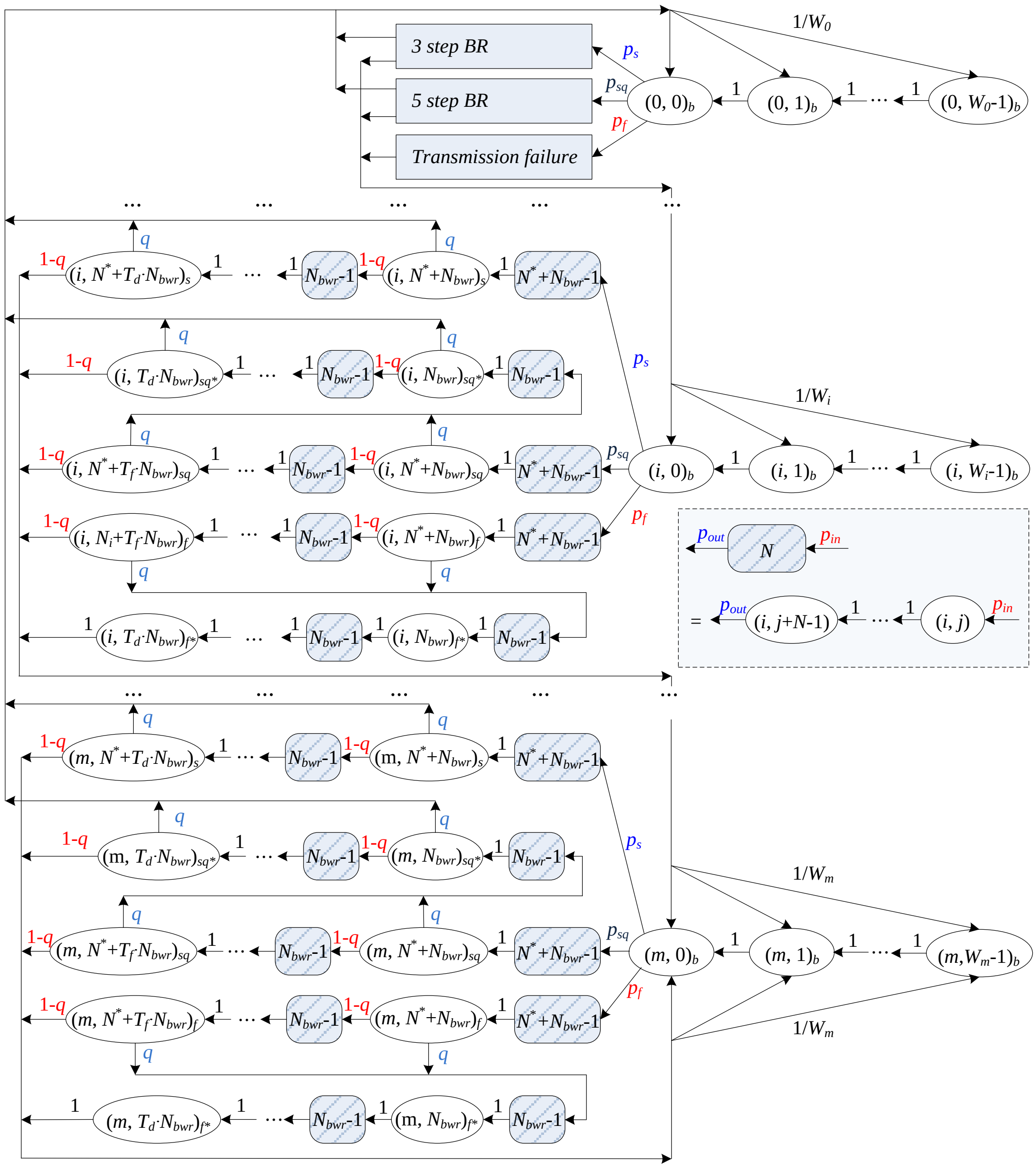


Fig. 4. Markov chain modelling for contention-based BR procedure

crete and integer and is not directly related to system time. An MS's backoff window size can be modeled as $W_i = 2^i \cdot W_0$ after ith unsuccessful BR transmission. Let $s(t)$ be a stochastic random process representing a current backoff stage of an MS. Using these two random processes, we can represent the IEEE 802.16m backoff procedure in a 2-dimensional Markovian process $(s(t), b(t))_b$. Transmission of a BR message occurs whenever a backoff value $b(t)$ reaches zero.

Let N^* be the average number of remaining BR channels until the end of the current UL frame after an MS's BR message transmission. N^* can be found by using the average number of the contention window size $\bar{W}$ [11]. Under the ideal BR channel assumption, an MS is able to receive a BR-ACK in the next DL frame, i.e., after N^* BR channels after transmitting its BR message with probability 1. Let $w(t)$ and $w(t)$' be a stochastic random process representing the current waiting time of a BR header grant and an UL grant for an MS, respectively.

An MS can be notified whether a BS has received its BR message correctly or not at the next DL frame via a BR-ACK message. In order to differentiate waiting state in accordance with BS's detecting and decoding status of received BR messages, waiting states are further partitioned into three sub-groups of states with different transition probabilities.

1) *3-step BR states* : If a given MS transmits a BR message, while none of the other MSs transmit BR messages, a BS is able to detect a BR preamble sequence and decode a quick message correctly in a received BR message. In this case, states of the MC model transit to the three-step BR procedure with probability p_s and are tagged as $(s(t), w(t)')_s$.

2) *5-step BR states* : Even though a given MS and one or more MSs transmit BR messages simultaneously, a BS is able to distinguish a BR preamble sequence among received BR messages if a given MS uses a different BR preamble sequence from BR preamble sequences used by other MSs. In this case, collision occurs in the data part. States of the MC model transit to the five-step BR procedure with probability p_{sq} and are tagged as $(s(t),w(t))_{sq}$. After an MS receives a BR header grant, states are tagged as $(s(t),w(t)')_{sq*}$.

3) *Transmission failure states* :If a given MS and one or more of the other MSs transmit BR messages using the same BR preamble, collision in a BR preamble part occurs. The MC model transits into transmission failure states with probability p_f and are tagged as $(s(t),w(t))_f$. After MS receives a BR header grant, states are tagged as $(s(t),w(t)')_{f*}$.

In waiting states, if an UL resource is available, a BS transmits a grant for a received BR message to a corresponding MS in one of the DL frames before a BR timer expires. We model this procedure with probability q, which is the probability to transmit a BR header grant or an UL grant for a received BR message within the T_f or T_d frames before expiry of BR timer. It is reasonable to assume that q is a constant value for all waiting states [11], [14]. q can be used to represent the status of bandwidth resources and can be controlled by admission control or scheduling policy.

Since the backoff value of each MS depends on its previous retransmission history, the stochastic process, $(s(t),b(t))_b$ is non-Makovian. By referring to [7] and [11], we can assume that p_s, p_{sq} and p_f are constant and independent of number of collisions. Under such assumption, it is possible to model the contention-based BR scheme in a 2-dimensional discrete-time MC as shown in **Fig. 4**.

Assuming knowledge of p_s, p_{sq}, and p_f, nonnull one-step state transition probabilities are shown below:

$$\begin{cases} P\{(i,j)_b \mid (i,j+1)_b\} = 1 \\ P\{(i,1)_s \mid (i,0)\} = p_s \\ P\{(i,1)_{sq} \mid (i,0)\} = p_{sq} \\ P\{(i,1)_f \mid (i,0)\} = p_f \end{cases}, \qquad i \in [0,m],\ j \in [0, W_i - 2] \tag{1a}$$

$$\begin{cases} P\{(i,1)_{sq*} \mid (i, N^* + j \cdot N_{bwr})_{sq}\} = q, & i \in [0,m],\ j \in [1, T_f] \\ P\{(0,j')_b \mid (i, N^* + j \cdot N_{bwr})_s\} = q/W_0, & i \in [0,m],\ j \in [1, T_d],\ j' \in [0, W_0 - 1] \\ P\{(0,j')_b \mid (i, j \cdot N_{bwr})_{sq*}\} = q/W_0, & i \in [0,m],\ j \in [1, T_d],\ j' \in [0, W_0 - 1] \end{cases} \tag{1b}$$

$$\begin{cases} P\{(i, N^* + j \cdot N_{bwr} + 1)_s \mid (i, N^* + j \cdot N_{bwr})_s\} = 1 - q, & i \in [0, m], j \in [1, T_d - 1] \\ P\{(i, N^* + j \cdot N_{bwr} + 1)_{sq} \mid (i, N^* + j \cdot N_{bwr})_{sq}\} = 1 - q, & i \in [0, m], j \in [1, T_f - 1] \\ P\{(i, j \cdot N_{bwr} + 1)_{sq*} \mid (i, j \cdot N_{bwr})_{sq*}\} = 1 - q, & i \in [0, m], j \in [1, T_d - 1] \end{cases} \tag{1c}$$

$$\begin{cases} P\{(i+1, j)_b \mid (i, \bar{N} + T_d \cdot N_{bwr})_s\} = (1-q)/W_{i+1} \\ P\{(i+1, j)_b \mid (i, \bar{N} + T_f \cdot N_{bwr})_{sq}\} = (1-q)/W_{i+1}, & i \in [0, m-1], j \in [0, W_{i+1} - 1] \\ P\{(i+1, j)_b \mid (i, T_d \cdot N_{bwr})_{sq*}\} = (1-q)/W_{i+1} \end{cases} \tag{1d}$$

$$\begin{cases} P\{(i,1)_{f*} \mid (i, N^* + j \cdot N_{bwr})_f\} = q, & i \in [0, m], j \in [1, T_f] \\ P\{(i, N^* + j \cdot N_{bwr} + 1)_f \mid (i, N^* + j \cdot N_{bwr})_f\} = 1 - q, & i \in [0, m], j \in [1, T_f - 1] \\ P\{(i+1, j)_b \mid (i, N^* + T_f \cdot N_{bwr})_f\} = (1-q)/W_{i+1}, & i \in [0, m-1], j \in [1, W_{i+1} - 1] \\ P\{(i+1, j)_b \mid (i, T_d \cdot N_{bwr})_{f*}\} = 1/W_{i+1}, & i \in [0, m-1], j \in [1, W_{i+1} - 1] \end{cases} \tag{1e}$$

$$\begin{cases} P\{(m, j)_b \mid (m, N^* + T_d \cdot N_{bwr})_s\} = (1-q)/W_m \\ P\{(m, j)_b \mid (m, N^* + T_f \cdot N_{bwr})_{sq}\} = (1-q)/W_m \\ P\{(m, j)_b \mid (m, T_d \cdot N_{bwr})_{sq*}\} = (1-q)/W_m, & j \in [0, W_m - 1] \\ P\{(m, j)_b \mid (m, N^* + T_f \cdot N_{bwr})_f\} = (1-q)/W_m \\ P\{(m, j)_b \mid (m, T_d \cdot N_{bwr})_{f*}\} = 1/W_m \end{cases} \tag{1f}$$

The first equation in (1a) is a transition probability in backoff procedure before transmitting a BR message. The rest of the probabilities in (1a) are transition probabilities from the end of backoff states, $(i, 0)_b$, to three sub-groups of waiting states after transmitting a BR message.

The probabilities in (1b), (1c), and (1d) describe transitions in the 3-step and 5-step states respectively. A BS assigns a BR header grant or an UL grant with probability q. The last two probabilities in (1b) mean that an MS starts a new backoff process to send a next BR message with uniformly chosen backoff value in the range of [0, W_0-1]. On the other hand, the BS defers a BR header grant or an UL grant with a probability of 1-q if the BR timer has not yet expired (1c). (1d) accounts for unsuccessful allocation of a BR header grant or an UL grant due to BR timeout. When BR timeout occurs, an MS restarts a backoff process with a uniformly chosen backoff value in the range of [0, W_{i+1}-1].

(1e) represents transitions in the transmission failure states. The probabilities in (1e) are the same as the ones used in the 5-step states except for the last probability. In contrast to the 5-step states, multiple MSs transmit a BR header simultaneously after receiving a BR header grant because they used the same BR preamble sequence in a previously transmitted BR message. In this case, a BS is not able to decode BR headers from them due to collision. Consequently, a BS is not able to transmit an UL grant. However, the MSs have to wait to retransmit BR messages until the differentiated BR timer expires because they do not know whether the BS has received their BR header or a collision has occurred. Thus, the BR timer is decremented at the beginning of each frame with probability of 1 in $(i, j)_{f*}$ states.

The probabilities in (1f) represent special cases of (1a)-(1e). If a BR timer expires and the current backoff stage is the maximum value m, a backoff value is chosen in the range of [0,W_m-1].

Let us denote the stationary distribution of each state with $b_{i,j}^{b}$, $b_{i,j}^{s}$, $(b_{i,j}^{sq}, b_{i,j}^{sq*})$ and $(b_{i,j}^{f}, b_{i,j}^{f*})$. First, we note the following relationships among backoff states and each waiting state from the global balance equation:

$$b_{i,j}^{s} = \begin{cases} p_s \cdot b_{i,0}^{b}, & i \in [0,m], j \in [1, N^*] \\ (1-q)^k \; p_s \cdot b_{i,0}^{b}, & i \in [0,m], j \in [N^* + k \cdot N_{bwr} + 1, N^* + (k+1) N_{bwr}], k \in [0, T_d - 1] \end{cases} \tag{2a}$$

$$b_{i,j}^{sq} = \begin{cases} p_{sq} \cdot b_{i,0}^{b}, & i \in [0,m], j \in [1, N^*] \\ (1-q)^k \; p_{sq} \cdot b_{i,0}^{b}, & i \in [0,m], j \in [N^* + k \cdot N_{bwr} + 1, N^* + (k+1) N_{bwr}], k \in [0, T_f - 1] \end{cases} \tag{2b}$$

$$b_{i,j}^{sq*} = (1-q)^k \cdot \left\{ 1 - (1-q)^{T_f} \right\} \cdot p_{sq} \cdot b_{i,0}^{b}, \quad i \in [0,m], j \in [k \cdot N_{bwr} + 1, (k+1) \cdot N_{bwr}], k \in [0, T_d - 1] \tag{2c}$$

$$b_{i,j}^{f} = \begin{cases} p_f \cdot b_{i,0}^{b}, & i \in [0,m], j \in [1, N^*] \\ (1-q)^k \; p_f \cdot b_{i,0}^{b}, & i \in [0,m], j \in [N^* + k \cdot N_{bwr} + 1, N^* + (k+1) N_{bwr}], k \in [0, T_f - 1] \end{cases} \tag{2d}$$

$$b_{i,j}^{f*} = \left\{ 1 - (1-q)^{T_f} \right\} \cdot p_f \cdot b_{i,0}^{b}, \qquad i \in [0,m], j \in [1, T_d \cdot N_{bwr}] \tag{2e}$$

The transition to the next backoff stage means an unsuccessful BR transmission due to expiration of BR timers. Thus, from (2), we can define the probability of retransmission, p_{rts}, as $p_{rts} = p_f + (1-q)^{T_d} \cdot p_s + (1-q)^{T_f} \cdot p_{sq} + (1-q)^{T_d} \cdot \left\{ 1 - (1-q)^{T_f} \right\} \cdot p_{sq}$. Using p_{rts}, relationships between stationary distributions of backoff stages for the $(i, 0)_b$ states, $i \in (0,m]$, are

$$\begin{aligned} & b_{i,0}^{b} \cdot 1 = p_f b_{i-1,0}^{b} + (1-q)^{T_d} \; p_s b_{i-1,0}^{b} + (1-q)^{T_f} \; p_{sq} b_{i-1,0}^{b} + (1-q)^{T_d} \left\{ 1 - (1-q)^{T_F} \right\} p_{sq} b_{i-1,0}^{b} \\ & \rightarrow b_{i,0}^{b} = (1 - p_{rts})^i \, b_{0,0}^{b}, \quad i \in [0, m-1] \end{aligned} \tag{3a}$$

$$\begin{aligned} & b_{m-1,0}^{b} \cdot p_{rts} = (1 - p_{rts}) \cdot b_{m,0}^{b} \\ & \rightarrow b_{m,0}^{b} = \frac{(p_{rts})^m}{1 - p_{rts}} b_{0,0}^{b} \end{aligned} \tag{3b}$$

Due to the chain regularities for each $j \in [0, W_i - 1]$ and considering $\sum_{i=0}^{m} b_{i,0}^{b} = b_{0,0}^{b} / (1 - p_{rts})$, we can express the relationships between stationary distributions of neighboring backoff states in the same backoff stage as follows.

$$b_{i,j}^{b} = \frac{W_i - j}{W_i} \cdot b_{i,0}^{b}, \qquad i \in [0, m], j \in [0, W_i - 1] \tag{4}$$

By considering the relationships among (2), (3) and (4), all stationary distributions are expressed as functions of the $b_{0,0}^{b}$ and a solution $b_{0,0}^{b}$ is found in terms of p_s, p_{sq}, p_f, and constant variables of W_0, m, q, T_d and T_f by utilizing the normalization condition.

$$\begin{aligned} 1 &= \sum b_{i,j} \\ &= \sum_{i=0}^{m} \left[\sum_{j=0}^{W_i - 1} b_{i,j}^{b} + \sum_{j=1}^{N^* + T_d \cdot N_{bwr}} b_{i,j}^{s} + \left(\sum_{j=0}^{N^* + T_f \cdot N_{bwr}} b_{i,j}^{sq} + \sum_{j=1}^{T_d \cdot N_{bwr}} b_{i,j}^{sq*} \right) + \left(\sum_{j=0}^{N^* + T_f \cdot N_{bwr}} b_{i,j}^{f} + \sum_{j=1}^{T_d \cdot N_{bwr}} b_{i,j}^{f*} \right) \right] \end{aligned} \tag{5}$$

$$b_{0,0}^{b}=\frac{1}{\frac{1}{2}\left\{W_0\left(\frac{1-(2p_{rts})^m}{(1-2p_{rts})}+\frac{(2p_{rts})^m}{(1-p_{rts})}\right)+\frac{1}{(1-p_{rts})}\right\}+\frac{N_{bwr}}{(1-p_{rts})}\left\{\frac{N^*}{N_{bwr}}+A\cdot p_s+(1+A\cdot q)B\cdot p_{sq}+(1+T_d q)B\cdot p_f\right\}} \quad (6)$$

where, $A=\left\{1-(1-q)^{T_d}\right\}/q$ and $B=\left\{1-(1-q)^{T_f}\right\}/q$.

An MS transmits a BR message whenever backoff value $b(t)$ reaches zero. Therefore, we can express the probability τ that a given MS transmits a BR message in a given BR channel using the solution $b_{0,0}^{b}$ and (3).

$$\tau=\sum_{i=0}^{m}b_{i,0}^{b}=\frac{b_{0,0}^{b}}{\left(1-p_{rts}\right)} \quad (7)$$

3.2 Transition Probabilities to Waiting States Sub-groups

In this section, state transition probabilities from $(i,\ 0)_b$ to $(i,\ 1)_s$, $(i,\ 1)_{sq}$ and $(i,\ 1)_f$ are formulated as conditional probabilities, when a given MS transmits a BR message. MSs in class k have W_0^k, $W_{\max}^k$ backoff values and T_d^k BR timer value. Probabilities in different classes are also discriminated with k.

First, we define the conditional probability of a BR transmission without any collision for a given MS in class k as p_s^k. p_s^k stands for the probability that none of the other MSs transmit a BR message when a given MS transmits. Therefore, p_s^k is formulated as in (8), where $k\in[1,2]$, $k'\in[1,2]$ and $k\neq k'$. In this case, a BS correctly receives a BR message and starts the three-step BR procedure.

$$p_s^k=\left(1-\tau_k\right)^{N_k-1}\left(1-\tau_{k'}\right)^{N_{k'}} \quad (8)$$

If a given MS chooses a different BR preamble sequence from the other MSs', a BS can distinguish a BR preamble sequence in a BR message and starts the five-step BR procedure for the MS. On the other hand, since a BS cannot distinguish BR messages using the same BR preamble sequence, the BR messages have to be retransmitted later.

Let N_u be the number of MSs transmitting BR messages simultaneously when a given MS transmits a BR message, where $N_u\in[1,N_1+N_2-1]$. N_u consists of n_1 and n_2 numbers of MSs for each class. To discriminate these two types of events, we calculate the probability that $N_u = n_1 + n_2$ MSs transmit BR messages at the same time when a given MS transmits. This probability is formulated by the sum of the probability of all possible subset (n_1, n_2).

$$p_{tr}^k(N_u)=\sum_{i=1}^{N_u}\left[\binom{N_k-1}{N_u-i}\tau_k^{(N_u-i)}\left(1-\tau_k\right)^{((N_k-1)-(N_u-i))}\binom{N_{k'}}{i}\tau_{k'}^{\ i}\left(1-\tau_{k'}\right)^{(N_{k'}-i)}\right] \quad (9)$$

where, $\binom{n}{r}=\frac{n!}{r!(n-r)!}=1$ when $r=0$.

The conditional probability that a BR preamble sequence of a given MS is distinctively distinguished at a BS, when a given MS and one or more of the other MSs simultaneously transmit BR messages, p_{sq}^k, is the sum of probabilities that N_u MSs transmit BR messages at the same time and none of N_u MSs uses the same BR preamble sequence as the given MS for all $N_u\in[1,(N_1+N_2-1)]$.

$$p_{sq}^k = \sum_{N_u=1}^{N_1+N_2-1}\left[\left(\frac{N_{seq}-1}{N_{seq}}\right)^{N_u} p_{tr}^k(N_u)\right] \tag{10}$$

From (10), the conditional probability that BR preamble cannot be distinguished, when a given MS and one or more the other MSs simultaneously transmit BR messages, p_f^k, is expressed by

$$p_f^k = \sum_{N_u=1}^{N_1+N_2-1}\left[\left\{1-\left(\frac{N_{seq}-1}{N_{seq}}\right)^{N_u}\right\} p_{tr}^k(N_u)\right] \tag{11}$$

Equations from (6) to (11) represent a nonlinear system with τ_k, p_s^k, p_{sq}^k, and p_f^k unknown values. These values can be obtained by solving nonlinear equations based on the known values of $(W_0^k, W_{\max}^k)$, (T_f, T_d^k), and q, using numerical techniques.

3.3 Performance Metric of Contention-Based Bandwidth Request

Using τ_k, p_s^k, p_{sq}^k and p_f^k, we can analyze the performance of the contention-based BR scheme. We define the number of successful BR transmissions as the number of transmitted BR messages leading to successful UL grant reception. The probability of successful BR transmission for a given MS in a BR channel, P_{suc}^k, contains the following probabilities: when a given MS transmits a BR message, 1) no other MSs transmit and successfully receive an UL grant within T_d^k frames after a BR message transmission, or 2) a BS is able to distinguish the BR message of a given MS from received multiple BR messages by using a BR preamble sequence and as a consequence a BR header grant and an UL grant are successfully received by the MS within T_f and T_d^k respectively. P_{suc}^k describes the efficiency of a BR channel for an individual MS.

$$P_{suc}^k = \tau_k \cdot \left\{ p_s^k\left(1-(1-q)^{T_d^k}\right) + p_{sq}^k\left(1-(1-q)^{T_d^k}\right)\left(1-(1-q)^{T_f}\right)\right\} \tag{12}$$

Since a BS can distinguish more than one BR message by using BR preamble sequences, the system capacity for a single BR channel can be expressed by the average number of successful BR transmissions in a BR channel, N_{suc}^k, and simply expressed by multiplying N_k by P_{suc}^k as follows.

$$N_{suc}^k = N_k \cdot P_{suc}^k = N_k \cdot \tau_k \cdot \left\{ p_s^k\left(1-(1-q)^{T_d^k}\right) + p_{sq}^k\left(1-(1-q)^{T_d^k}\right)\left(1-(1-q)^{T_f}\right)\right\} \tag{13}$$

When collision occurs in the preamble part, an MS cannot be notified of the collision until its BR timer expires. Thus, the MS has to wait until a differentiated BR timer or fixed BR timer expires in order to attempt to retransmit a BR message. Let us define the ratio of waiting frame for an individual MS in class k as R_w^k. R_w^k means that when collision occurs in the preamble part, each MS spends R_w^k portion of time out of the whole system time waiting for a BR message re-transmission on average. Since the steady state probability represents stationary behavior of an MS in MC modelling [18], R_w^k can be expressed by the sum of the following steady state probabilities in the transmission failure states.

$$R_w^k = \sum_{i=0}^{m} \left\{ \sum_{j=\bar{N}+1}^{N^* + T_f N_{bwr}} b_{i,j}^{f} + \sum_{j=\bar{N}+1}^{T_d^k N_{bwr}} b_{i,j}^{f*} \right\} = \left[\frac{1-(1-q)^{T_f}}{q} + T_d^k \left\{ 1-(1-q)^{T_f} \right\} \right] N_{bwr} \cdot p_f^k \cdot \tau_k \tag{14}$$

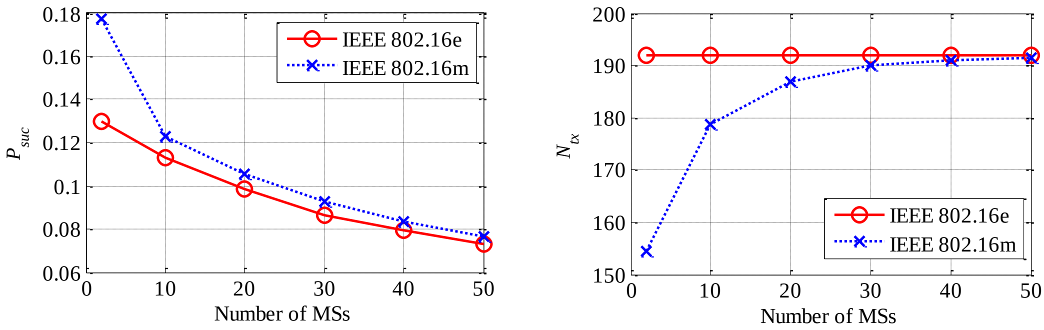
4. Model Validation and Numerical Results

In this section, extensive study on the performance of the IEEE 802.16m contention-based BR scheme is presented. In order to validate the proposed analytical model, we also compare the numerical results calculated using the model with the simulation results. We use a discrete event driven simulator for the IEEE 802.16m contention-based BR scheme written in the MATLAB programming language. Each simulation run is carried out for 50,000 frames. The exact behaviour of the IEEE 802.16m contention-based BR scheme is implemented including the details of the binary exponential backoff and BR timer operation. A decision procedure for a collision by using BR preamble sequences in a BS is also implemented. Each MS generates a new BR message after receiving a successful UL grant for the previous BR message. Using this simulator, extensive study on the performance validation of the proposed MC model with different sets of random access parameters is performed. The performance metrics introduced in Section 3.3. are used in this study.

Before performing the performance validation of the proposed MC model of the IEEE 802.16m BR procedure, in order to provide better understanding of the IEEE 802.16m BR mechanism, we compare the performance of the BR procedures of IEEE 802.16e [6] and IEEE 802.16m [1] through simulation. IEEE 802.16e only provides normal five-step BR procedure because an MS is able to transmit only a BR code which is similar to a BR preamble sequence in IEEE 802.16m. IEEE 802.16e standard specifies that a subset of ranging codes is used as BR codes [6]. The length of a IEEE 802.16e BR code is 144 bits and a BR code is modulated by BPSK. After successful transmission of the BR code, the MS is able to transmit BR information to the BS by transmitting a BR header of 48 bits via the allocated UL resource. A BS allocates UL resource requested by an MS and the MS is able to transmit UL data using the allocated UL resource. The operation of BR timer is same as the IEEE 802.16m normal five-step BR procedure except service differentiation using differentiated BR timers. In order to see the benefit of fast three-step BR procedure, a typical fixed value, q = 0.7 is used and all BR parameters are fixed with constant values, W_0=2, W_{max}=8, T_f = 5, T_d = 10, N_{bwr} = 2, and N_{seq} = 24.

The simulation result for P_{suc} is shown in **Fig. 5 (a)**. In case of IEEE 802.16m, since a BS is able to allocate an UL grant without receiving a BR header by just decoding a quick access message, connection delay is shorter than that of the IEEE 802.16e based BR scheme. Therefore, in general, the IEEE 802.16m BR scheme shows better performance in terms of P_{suc} than the IEEE 802.16e BR scheme. However, since the three-step BR procedure can only be provided when there is only one MS transmitting a BR message in a single BR channel, the benefit of three-step BR decreases as the number of MSs, N_u, increases.

Fig. 5 (b) shows the result of average transmitted bits by an MS when an MS succeeds a BR procedure, N_{tx}. Since IEEE 802.16e only provides normal five-step BR procedure, an MS needs to transmit 192 bits, a CDMA ranging code (144 bits) and a BR header (48 bits), in order to transmit an UL data packet in IEEE 802.16e systems. However, there are two cases for an MS to transmit an UL data packet in IEEE 802.16m systems: fast three-step BR procedure and normal five-step procedure. In IEEE 802.16m BR procedure, an MS transmits a BR message



(a) P_{suc} **(b)** N_{tx}

Fig. 5. The performance comparison of BR scheme of IEEE 802.16e and IEEE 802.16m.

containing a BR preamble sequence and a quick message. A BR preamble sequence has a length of 24 bits and is repeated three times (72 bits) and a quick message of 16 bits is encoded into 72 bits using convolution code. Therefore, an MS transmits 24 * 3 + 72 = 144 bits if fast three-step BR procedure is successful. On the other hand, if BR procedure is switched to the five-step BR procedure because a BS is unable to decode a quick access message, an MS needs to transmit a BR header of 48 bits which is the same length as the IEEE 802.16e BR header. As shown in **Fig. 5 (b)**, an MS using IEEE 802.16m BR scheme transmit fewer bits than IEEE 802.16e up to 24.28% when there are only two MSs because of three-step BR procedure. Although N_{tx} increases as N_u increases, the number of transmitted bits converges toward 192 bits which is the same value as IEEE 802.16e.

Now, the effect of backoff window size is examined. In order to see the effect of backoff window size differentiation, other service differentiation parameters are fixed with constant values, $T_f = 5, T_d^k = 10$ and $N_{bwr} = 2$. The ratio of each class MSs is set to be 50%. In the case of $W_{\max}^k$ with $W_0^k = 2$, we can see that P_{suc}^k and N_{suc}^k of both classes are identical for differentiated maximum backoff window size sets: (4,8), (4,16) and (8,16).

The results of P_{suc}^k and N_{suc}^k, according to initial backoff window size W_0^k, are shown in **Fig. 6**. A typical fixed value, $q = 0.7$ and the maximum value, $W_{\max}^k = 16$ in the standard [1] are used. The differentiated initial backoff window size sets (W_0^1, W_0^2): (2,4), (2,8) and (4,8) are considered. As shown in **Figs. 6 (a)**, **(b)** and **(c)**, each MS's P_{suc}^k decreases as the number of MSs increases. Since it is assumed that MSs always have data to transmit under the saturation condition, the probability of a BR transmission without collision, p_s^k decreases as N_u increases. This means that an MS needs to commence the five-step BR procedure or the BR re-transmission procedure in the transmission failure states due to the collision in the preamble part or data part.

Collision leads to performance degradation of the contention based BR scheme since MSs have to suffer from long connection delay and retransmit BR messages frequently. However, in the IEEE 802.16m BR scheme, since a BS is able to distinguish more than one BR message by using preamble sequences, N_{suc}^k increases as the number of MSs increases as shown in **Figs. 6 (d)**, **(e)**, and **(f)**. A larger W_0^k means that an MS should wait for more BR channels (opportunities) before transmitting a BR message. Consequently, the probability of BR transmission decreases as W_0^k increases. Since we set BR timer values to be the same value, a

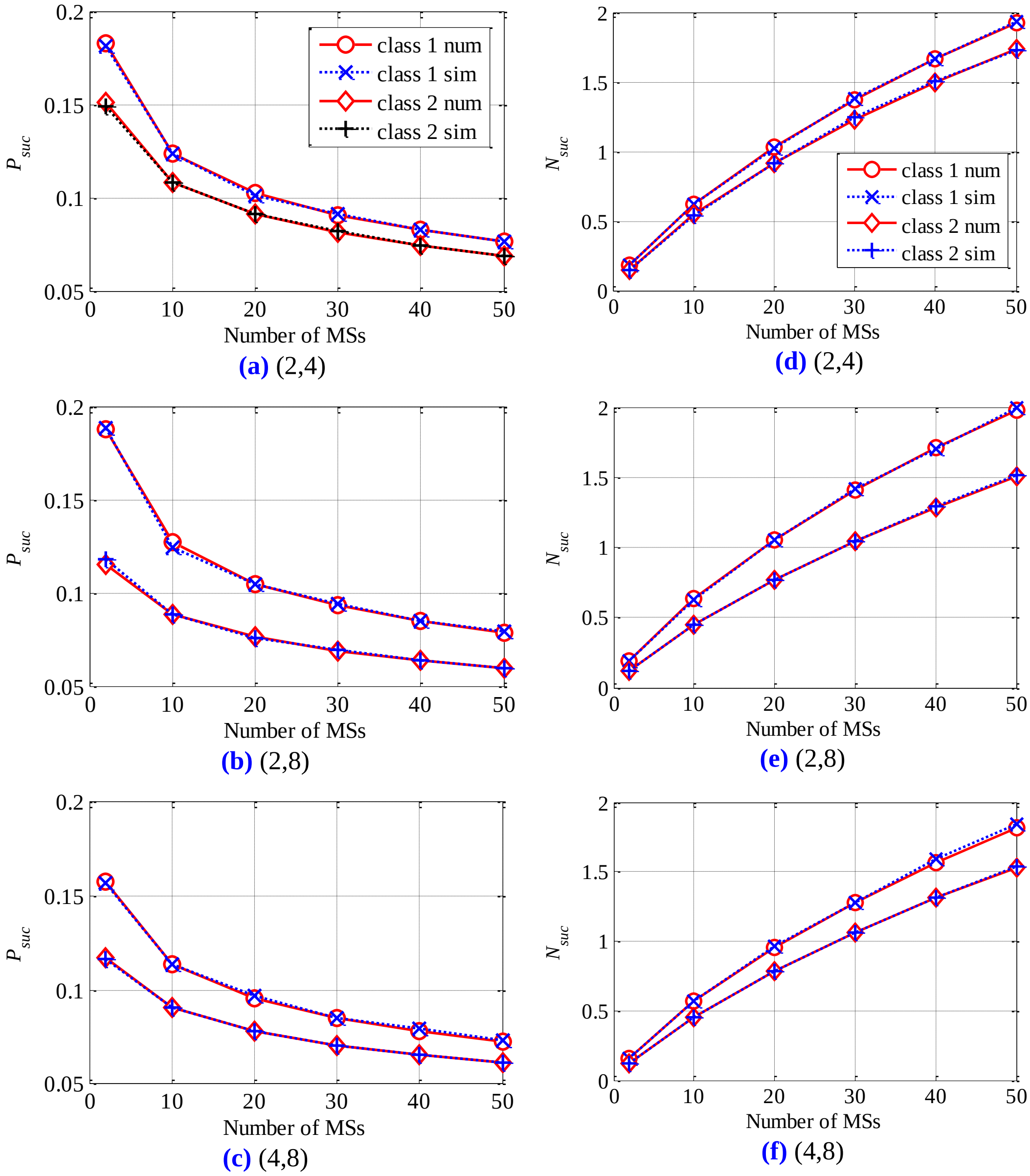
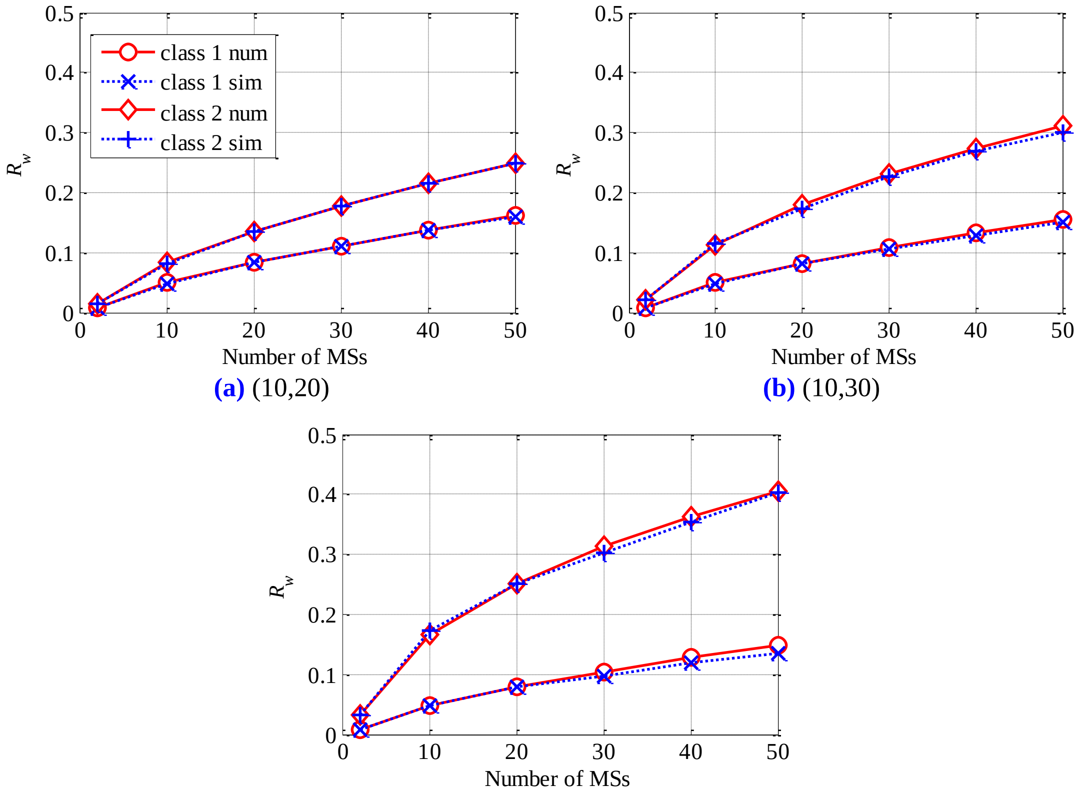


Fig. 6. Service differentiation with different (W_0^1, W_0^2): **(a)** - **(c)** P_{suc}^k and **(d)** - **(f)** N_{suc}^k.

larger P_{suc}^k means that MSs in class k have better chances to access BR channel and shorter connection delay than the other MSs with different service flow of lower priority. As we can see in **Fig. 6**, a smaller W_0^k leads to more frequent BRs with larger P_{suc}^k and N_{suc}^k values. The service differentiation becomes more significant with increasing difference between W_0^1 and W_0^2.

Next, the performance of service differentiation with differentiated BR timer, T_d^k, is investigated. The analytical performance results are compared with the simulation results for validation. In order to see the effect of BR timer differentiation, $(W_0^k, W_{\max}^k) = (2,8)$ is fixed for both classes. A BS may use a scheduling algorithm or admission control to enhance QoS for



(a) (10,20) **(b)** (10,30) **(c)** (10,50)

Fig. 7. Ratio of waiting frame with different (T_d^1, T_d^2)

higher priority MSs and it may affect q. However, since the purpose of this paper is to study the effectiveness of the service differentiation parameters, a typical fixed value $q = 0.7$ is used, and differentiated BR timer sets (T_d^1, T_d^2) : (10, 20), (10,30) and (10,50) are considered.

When collision occurs in the preamble part, an MS has to wait until one of its BR timers, T_d or T_f, expires in order to attempt to retransmit a BR message. Thus, each MS spends R_w^k portion of time out of whole system time waiting for a BR message re-transmission on average. As shown in **Fig. 7**, in the case of transmission failure, larger T_d makes an MS wait more frames to retransmit a BR message. Consequently, the probability of BR transmission decreases as T_d increases.

As expected, a larger T_d results in performance degradation of the contention-based BR scheme as shown in **Fig. 8**. Each MS attempts to transmit a BR message after receiving an UL grant for the previous BR message or its BR timer expiration. Before those events, the MSs remain in waiting states. Thus, MSs assigned with larger T_d^k have to wait more frames than others assigned with smaller T_d^k and this leads to smaller P_{suc}^k and N_{suc}^k. Therefore, a smaller T_d^k allows MSs in class k to have better chances to access a BR channel and increases the efficiency of the BR channel. The service differentiation in the capacity of the system for a single BR channel also becomes more significant with increasing difference between T_d^1 and T_d^2 as shown in **Fig. 8**. Compared to backoff parameters, the adjustable range of the BR timer is wider than that of the backoff timer. The average number of successful BR transmissions of

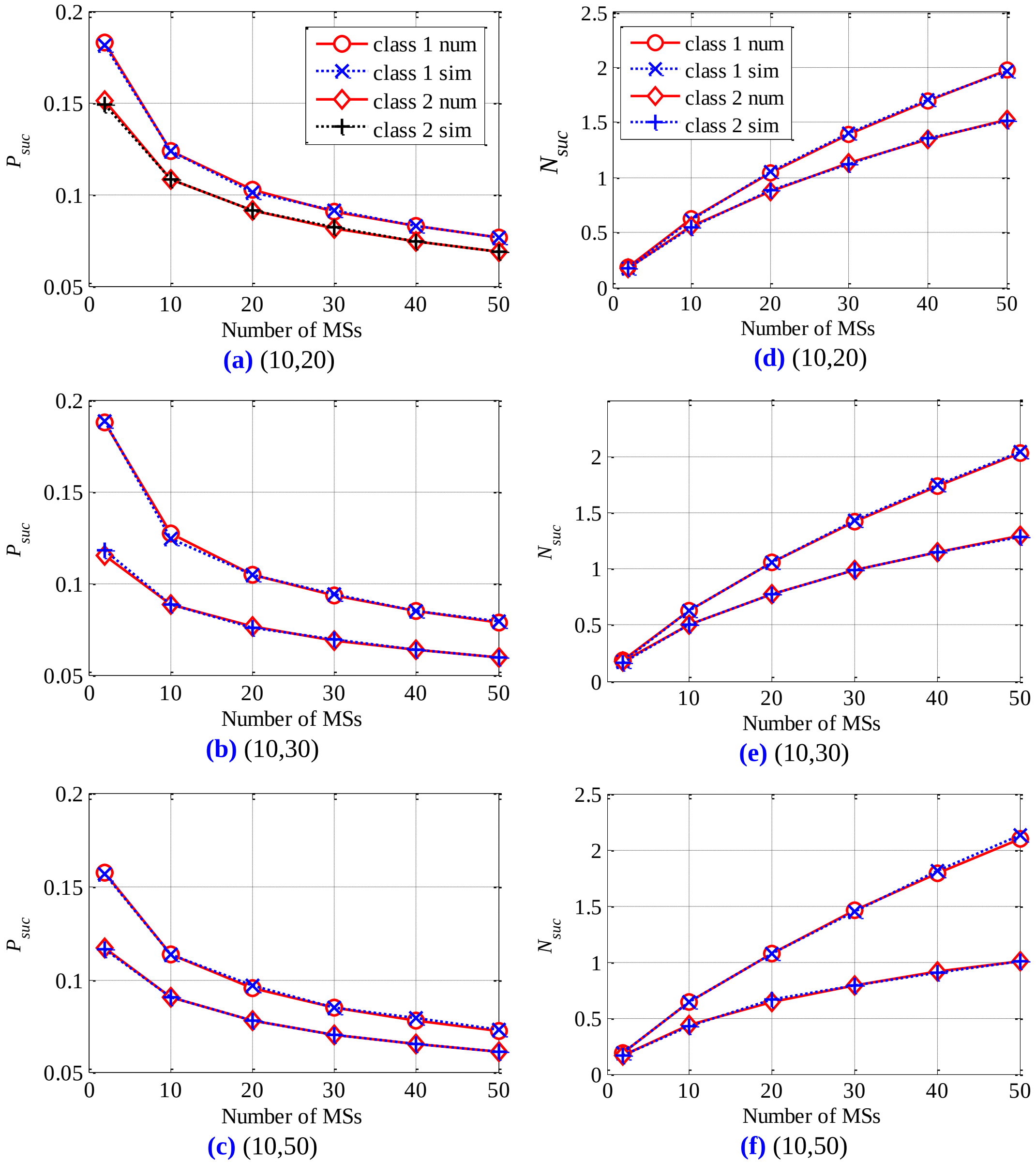


Fig. 8. Service differentiation with different (T_d^1, T_d^2) : **(a)** - **(c)** P_{suc}^k and **(d)** - **(f)** N_{suc}^k .

class 1 is more than twice that of class 2 in the case of $(T_d^1, T_d^2) = (10,50)$.

According to the results, we can notice that smaller W_0^k and T_d^k values are the key factors to the service differentiation of the IEEE 802.16m contention-based BR scheme. Through comparison with the simulation results, we can also see that the proposed MC model is highly accurate.

5. Conclusion

This paper has presented a performance analysis of the contention-based BR scheme in IEEE

802.16m networks with two different service flows. We have proposed a new analytical model for evaluating the contention-based BR in a saturated 802.16m network with a 2-dimensional discrete time MC model. The proposed model considers both the three-step and five-step procedures, preamble sequences as random access code, a quick access message, and actual service differentiation parameters, such as backoff and BR timer. Furthermore, in order to analyze interaction between the two classes, high and low, we have represented the transition probabilities to the waiting states sub-groups which are influenced by MSs in both classes. We have used this model to study the effect of the backoff and BR timer configuration on service differentiation. Through comparison study with the simulation results, we have validated the proposed model and confirmed its accuracy.

We have investigated the service differentiation for the contention-based BR and found that the initial backoff window sizes have a major effect on service differentiation by influencing the BR transmission probability rather than the maximum backoff windows size. Moreover, we have found that a smaller BR timer value helps fast retransmission and enhances the efficiency of the system. The proposed model provides an accurate predictive tool for use in QoS provision with different MAC parameters for contention-based BR method of the 802.16m system.

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