IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 4, 2020, accepted October 6, 2020, date of publication October 9, 2020, date of current version October 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3029843

An Efficient Reservation-Based MAC Protocol for Multi-Priority Traffic in Slotted Multi-Channel Distributed Cognitive Radio Networks

JAEHWOON LEE, (Member, IEEE)
Department of Information and Communication Engineering, Dongguk University, Seoul 04620, South Korea
e-mail: jaehwoon@dongguk.edu

This work was supported by the Institute for Information and Communications Technology Promotion (IITP) funded by the Korea Government (MSIT) under Grant IITP-2018-0-00846.

ABSTRACT Cognitive radio network (CRN) is developed to improve the scarce but under-utilized wireless spectrum due to rapidly developing wireless networks. This paper proposes a reservation-based MAC protocol for traffic having multiple classes of priorities in CRN. One channel called control channel is used for contention resolution between secondary users (SUs). In this protocol, an SU having data packets with different class of priorities transmits its control packet containing the priority value through the control channel. The order of access to primary channels is determined based on the priority of the data packet and the position of the non-colliding control packet. The access order determines the idle primary channel that an SU uses to transmit its data packet. In this protocol, there is no performance degradation either from SUs choosing a busy primary channel or multiple SUs choosing the same idle primary channel. Moreover, even though the SU cannot transmit its data packet because there is no idle primary channel that the SU can utilize, it can re-transmit its control packet without having concern over additional collision. Multi-state Markov chain is used to analyze the throughput and performance of the proposed protocol and the analytical results show that higher priority traffic can be transmitted first ahead of the lower priority traffic. Notwithstanding the above, the maximum sum of the throughput of SUs with different classes of priorities is almost equal to the available capacity, and therefore the proposed protocol can take advantage of almost all of the available portion of primary channels.

INDEX TERMS Reservation MAC, multi-priority traffic, cognitive radio networks, multi-channel MAC protocol, common control channel.

I. INTRODUCTION

Cognitive radio network (CRN) is developed to improve the scarce but under-utilized wireless spectrum due to rapidly developing wireless networks [1]. In CRN, licensed users called primary users (PUs) and unlicensed users called secondary users (SUs) can both utilize the wireless spectrum. Here, wireless spectrum is assigned to PUs, but a number of SUs will try to utilize the wireless spectrum when the spectrum is not in use by PUs. Therefore, a medium access control (MAC) protocol is necessary in order for SUs to use the available wireless spectrum. In [2]–[6], A number of MAC protocols in distributed CRN are proposed for a wireless spectrum composed of a single-channel [2]–[6].

A number of MAC protocols in distributed CRN are proposed for wireless spectrum divided into a number of slotted non-overlapping channels [7]–[11]. In [7], a protocol is proposed for SUs to share the spectrum opportunistically in multi-channel distributed CRN. Here, a PU can transmit its data packet whenever it wants through a primary channel that is dedicated to itself. SUs will try to use the primary channels while the channels are not used by PUs. It is assumed that each SU has two transceivers, and exchanges its control packet on an additional dedicated control channel by using one transceiver. Moreover, it is assumed that time is slotted with beacon intervals. In this protocol, an SU chooses a primary channel and then transmits the control packet containing

The associate editor coordinating the review of this manuscript and approving it for publication was Noor Zaman.

the chosen channel number through the control channel. The SU then tries to resolve the collision possibility when multiple SUs choose the same primary channel, by using the CSMA/CA based contention resolution protocol defined in IEEE 802.11. That is, in order for an SU to successfully transmit its data packet, the chosen primary channel should be idle, and the SU should also win the contention. In this protocol, there is performance degradation due to the lack of coordination between SUs. In other words, SUs cannot know which primary channel will be used by other SUs to transmit their data packets. Therefore, even though there are several idle primary channels, an SU cannot transmit its data packet either (1) when the SU chooses a busy primary channel, (2) when the SU loses the contention, or (3) when control packet collision occurs. In [8], a random access protocol based on multi-channel CSMA/CA is proposed in multi-channel distributed CRN. Here, for the same reason as mentioned above, there is no coordination between SUs to use the idle primary channel. Therefore, performance can be degraded either (1) when collision occurs due to several SUs contending to utilize the same idle primary channel, or (2) when an SU that loses the contention cannot transmit its data packet despite there being several idle primary channels. In [9], non-preemptive MAC protocol is proposed in slotted distributed CRN. In [7]–[9], an SU chooses a primary channel first and then senses the status of the channel, which incurs performance degradation. That is, there is no coordination between SUs as described earlier. In [10], a fair multi-channel assignment algorithm is proposed where an SU tries to transmit multiple data packets through multiple idle primary channels at the same time within a slot. In [9], [10], if an SU transmits its control packet with no collision but there is no idle primary channel, the SU should re-transmit its control packet during the next slot, but when control packet collision occurs, it cannot transmit its data packet even though there are idle primary channels. In [11], a MAC protocol is proposed that determines the order of access based on the position of the non-colliding control packets in a slotted multi-channel distributed CRN. That is, SUs with the first, second and third order can transmit their data packets through the first, second and third idle primary channels, respectively. Therefore, in this protocol, performance does not degrade since (1) SUs will not choose a busy primary channel, and (2) several SUs will not choose the same idle primary channel. Moreover, when an SU transmits its control packet without collision and there is no primary channel that is idle, then SU will re-transmit its control packet which will not collide with others. In [12], a dynamic common control channel based MAC protocol is proposed in the centralized CRN. Here, when SUs transmits primary channel information to Cognitive Radio Base Station (Co-BS), Co-BS allocates one channel as a common control channel and assigns one idle primary channel to an SU.

The protocols proposed in [7]–[12] assume that data packets transmitted by SUs have a single priority. However, for example, if SUs try to transmit both (relatively) time-sensitive traffic and non-time-sensitive traffic, then it is necessary for a protocol to transmit data packets having traffic with higher priority first ahead of those having traffic with lower priority. A number of protocols are proposed to transmit data packets having traffic with multiple classes of priorities in slotted multi-channel CRN [13]–[18]. In [13], a mixed preemptive/non-preemptive M/G/1 queueing model is proposed in CRN. Here, interruption-based priority is considered to characterize the spectrum usage with multiple handoffs in a multi-class SUs. In [14], a dynamic load-balancing spectrum decision mechanism is proposed in which a load-balancing controller allocates packets with 2 different classes of priority transmitted by SUs to available primary channels. In [15], an energy-efficient dynamic channel access mechanism is proposed in which the cluster header in cognitive radio sensor network (CRSN) allocates one of the idle primary channels to a sensor node based on the priority of its data packet and energy consumption. In [16], a reservation channel access scheme and channel aggregation method is proposed to minimize starvation of low-priority SUs. Here, PUs have preemptive priority over SUs, and high-priority SUs have preemptive priority over low-priority SUs. In this paper, in order to minimize starvation, (1) a low-priority SU can aggregate a certain number of idle primary channels to transmit its data packet and (2) a certain number of channels are reserved for low-priority SUs. In [17], a scheduling algorithm is proposed in vehicular ad hoc network (VANET). Here, a road-side unit (RSU) allocates the whole dedicated short range communication (DSRC) spectrum channel to high-priority traffic such as safety traffic approaching the expiration time and then allocates an idle cognitive channel to low-priority traffic such as the infotainment traffic. In [18], a spectrum handoff prioritization using preemptive/non-preemptive based dynamic spectrum access is proposed. However, the protocols proposed in [13]–[18] consider the transmission of data packets having traffic with multiple classes of priorities in a centralized CRN environment. In a centralized environment, each SU is connected to a central controller based on a one-to-one connection forming a star topology. Therefore, data packets transmitted by an SU do not collide with others and the central controller stores the data packets sent by SUs based on their priority. After that, the controller transmits stored data packets through idle primary channels based on the priority. Therefore, such protocols cannot be applied to the distributed CRN where there is no such central controller. In a distributed cognitive radio network, there are few mechanisms for SUs to transmit data packets with multiple classes of priorities. In [18], a dynamic spectrum access (DSA) protocol is proposed for SUs to transmit data packets having traffic with two different classes of priorities in the distributed slotted multi-channel CRN. Here, SU chooses one of the idle primary channels (similar to method proposed in [8]). The SU then proceeds with contention resolution to avoid any collision possibility that may arise when other SUs have chosen the same primary channel. Here, SUs having high-priority data packets use shorter arbitration inter-frame sequence (AIFS) and smaller counter window (CW) than that of the SUs having low-priority data packet. In this protocol, for example, if there are 2 idle primary channels and 2 SUs choose the same channel, there is performance degradation in the following two cases. First, when collision occurs at the channel, none of the 2 SUs can transmit their data packets. Second, when an SU wins the contention, the other SU cannot utilize any other idle primary channel to transmit its data packet.

In this paper, we propose a reservation based MAC protocol in order to transmit data packets having traffic with multiple classes of priorities in a slotted multi-channel distributed CRN by extending the protocol proposed in [11]. Here, one channel called control channel is used for contention resolution between SUs. In this protocol, an SU having a data packet transmits its control packet containing the priority value of the data packet through the control channel. The order of access to primary channels is determined based on the priority and the position of the non-colliding control packet. The advantages of the protocol proposed in this paper are as follows: First, data packets having traffic with higher-priority can be transmitted first over those having traffic with lower-priority. Second, there is no performance degradation either from SUs choosing a busy primary channel or from collision possibility of multiple SUs choosing the same idle primary channel. Third, if SU transmits its control packet without collision but there is no idle primary channel, then the SU can re-transmit its control packet through the control channel without the concern over additional collision at the control channel. Finally, a new node can enter the network at any time and can know the status of the network by monitoring the common control channel during one slot.

The paper is organized as follows. Section II describes the operation of the proposed reservation protocol. The throughput and delay of the proposed protocol are analyzed by using a multi-state Markov chain in Section III. Section IV describes numerical results and Section V concludes the paper.

II. RESERVATION-BASED MAC PROTOCOL FOR TRAFFIC WITH MULTI-PRIORITY

In this paper, we consider a single-hop network with $N+1$ non-overlapping channels having identical bandwidths and propagation characteristics [10], [19]. N number of different primary channels are used for N number of different PUs to transmit their data packets. Every primary channel is either in an idle or a busy state according to whether a PU uses the channel to transmit its data packet. Therefore, an SU can utilize a primary channel while it is not being used by a PU. There is one additional channel functioning as a common control channel [7], [9]–[11], [20]. All channels are slotted, and the size of a slot is equal to the size of the data packet sent by PUs [7]–[11], [20]. Let ζ be the time spent to sense a primary channel. Let η be the time spent to sense all primary channels [8], [10], [11]. Then, $\eta = N \times \zeta$. η is equal to "sensing result period" defined in Reference [10]. One slot of the control channel is comprised of η and k minislots. Whenever a data packet arrives at an SU, the SU transmits its control packet through the control channel based on a slotted ALOHA protocol to determine the access order. The data packet is used to transmit the upper layer traffic with different classes of priorities. An SU can transmit its control packet through one minislot. The source address of the SU and the priority value are contained in a control packet. The control packets sent by SUs are used to determine the order of access to primary channels based on the priority and position.

It is assumed that SUs are equipped with dedicated sensors (DSs) that are solely used to sense the spectrum [10], [20]. This enables SUs to focus on a dynamic channel access mechanism. Moreover, it is assumed that each SU is equipped with two transceivers: one for data transmission and the other is tuned to primary channels during η period and then tuned to the control channel during the remaining time of a slot. Moreover, SU is assumed to have no more than one data packet at a time. Figure 1 shows the flow chart of the operation of the protocol for transmitting data packets having traffic with different classes of priorities proposed in this paper. Each SU can be in one of the five states: idle, sensing, sending and sensing, reserving and sensing, and transmitting.

(1) Idle
When a data packet arrives at an SU in idle state at the beginning of a slot, the SU changes its state to the sensing state.

(2) Sensing
An SU in a sensing state monitors the control channel, counts the number of non-colliding control packets within a slot, and then changes its state to sending and sensing state. Here, non-colliding control packet is defined as a control packet not colliding with others. Whether or not a control packet collides with others can be determined, for example, through the calculation of cyclic redundancy check (CRC) included in the control packet. Assume that there are l non-colliding control packets in a slot.

(3) Sending and sensing (S&S)
An SU in a sending and sensing state (called S&S SU) senses primary channels during η period of a slot to check how many primary channels are idle. Here, $n(n \leq N)$ primary channels are assumed to be idle. Then, the SU can know that the first $m(m = max(0, l-n))$ minislots are used by SUs in the R&S state, as defined below. The SU chooses one of the remaining $(k-m)$ minislots randomly and then transmits its control packet through the chosen minislot of the control channel. Moreover, the SU monitors the control channel during the slot to know the status of its control packet. If the control packet collides with others, then the SU remains in this state and repeats the operation described herein. Otherwise, the SU counts the number of non-colliding control packets with higher priorities than the priority value contained in the control packet sent by the SU, and also counts

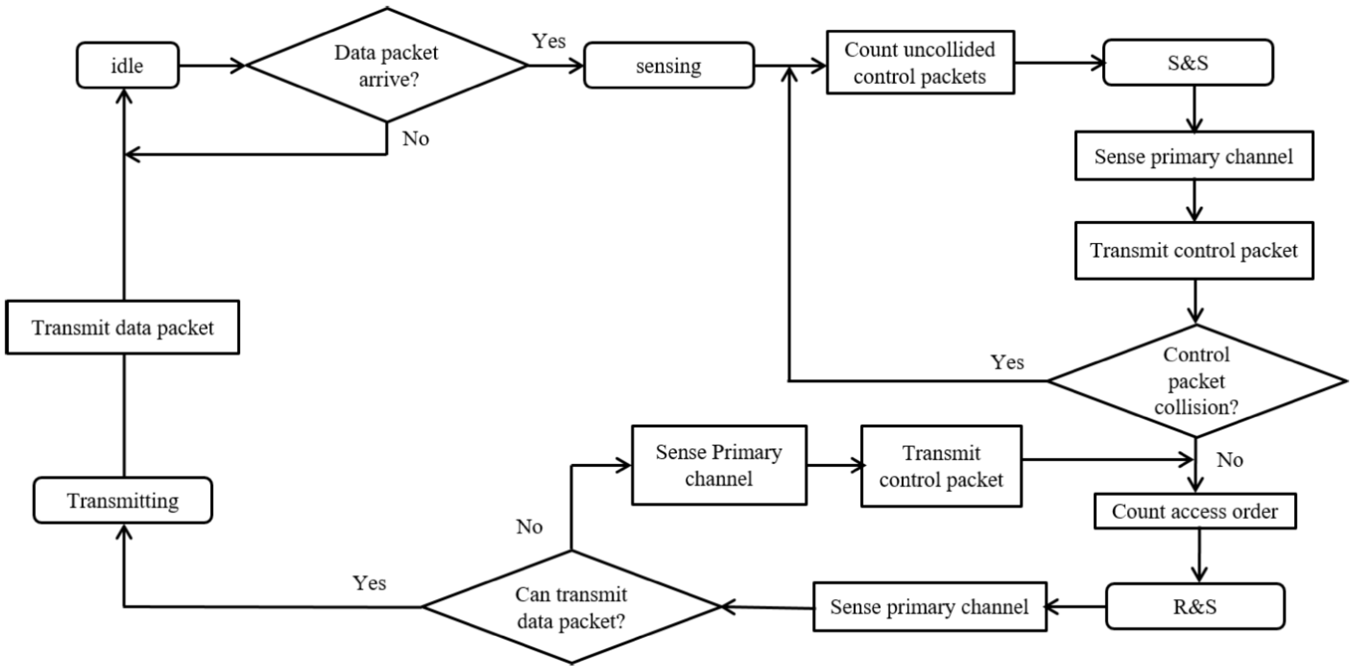

FIGURE 1. Flow chart of SU's operation to support multi-priority traffic.

the order of the control packet transmitted by the SU among control packets having the same priority.

Assume that there are a non-colliding control packets with higher priorities and the control packet sent by the SU is b-th non-colliding control packet among those having the same priority. Then, the SU considers that it is given $j(j = (a + b))$-th order of access to primary channels. It then changes its state to the reserving and sending state.

(4) Reserving and sensing (R&S)

An SU in reserving and sending state (called R&S SU) with j-th access order senses primary channels during η period to check how many primary channels are idle. Here, assume that n primary channels are idle. Then at most n R&S SUs can transmit their data packets based on the order of access. For example, the SU having the first order of access can transmit its data packet through the first idle primary channel, and the SU having the second access order can transmit its data packet through the second idle primary channel, and so forth. If $n < j$, the SU knows that it cannot transmit its data packet because its access order falls behind. Then the SU transmits its control packet through $(j - n)$-th minislot of the next slot. And this control packet always becomes a non-colliding control packet. Otherwise, the state of the SU is changed to a transmitting state.

(5) Transmitting

An SU in transmitting state (called transmitting SU) transmits its data packet through j-th primary channel and then changes its state to an idle state.

Fig. 2 shows an example of the operation of the protocol for transmitting multi-priority data packets proposed in this paper. In Fig. 2, there are 3 primary channels. ch_i represents i-th primary channel. One slot of the control channel is comprised of η and 6 minislots. At the beginning of slot t, when a data packet arrives at an SU in an idle state, the SU changes its state to Sensing state and monitors the control channel during slot t in order to count the number of non-colliding control packets. At slot t, there are three non-colliding control packets. The source addresses included in the non-colliding control packets are D, B and A, and their priorities are 3, 2 and 1, respectively. Therefore, the order of access to the primary channels becomes A, B and D based on the priority and the position of the non-colliding control packets, and their states become R&S state. At slot $(t+1)$, SUs in S&S or R&S state sense ch_1 during the first ζ period to find out whether the channel is idle or not. Because ch_1 is sensed to be busy, they proceed to sense ch_2 during the second ζ period. Because ch_2 is also busy, SUs in S&S or R&S state proceed to sense ch_3 during the third ζ period. ch_3 is also busy and it is the last primary channel. SUs in R&S state transmit their control packets based on the access order at the next slot. That is, SUs A, B and D transmit their control packets through the first, second and third minislots in slot $(t + 1)$, respectively. SUs in sensing state count the number of non-colliding control packets during slot t and can know that there are 3 non-colliding control packets. They change their states to S&S state. SUs in S&S state check how many primary channels are idle by sensing the primary channels during η period of slot $(t + 1)$. Because there is no idle primary channel, they can know that the first 3 minislots are reserved by SUs in

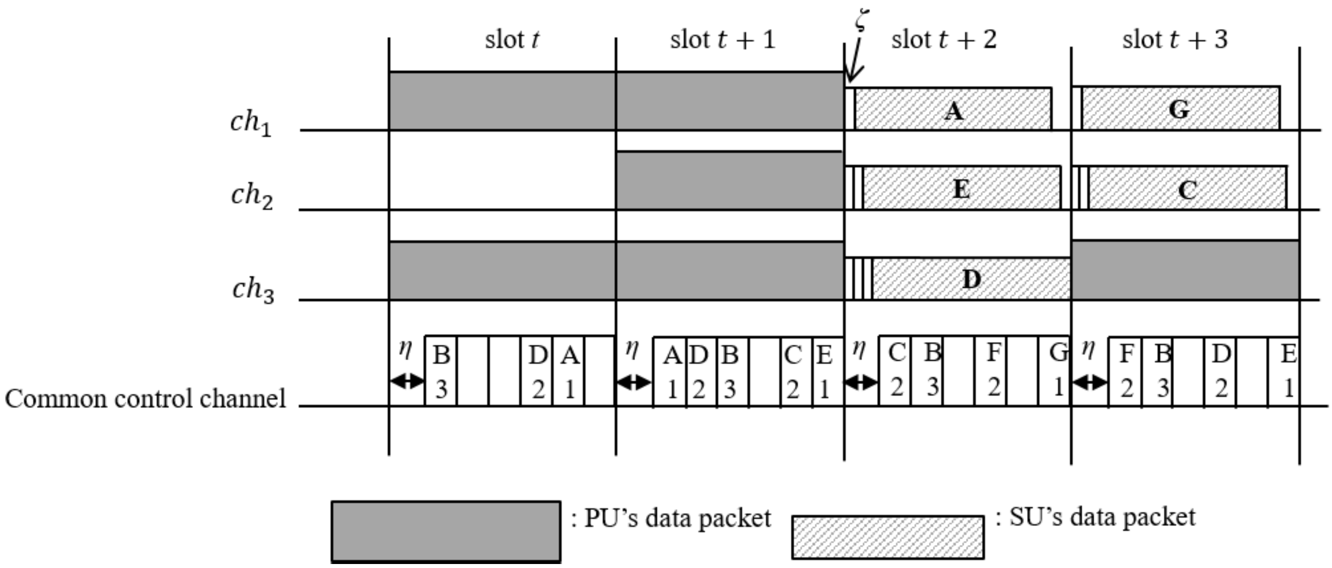

FIGURE 2. Example operation of the reservation MAC protocol for supporting multi-priority traffic.

R&S state. Each of SUs in S&S state randomly chooses one of the remaining 3 minislots and transmits its control packet through the chosen minislot. Two control packets transmitted by SUs in S&S state do not collide in slot $(t+1)$. Their state is then changed to R&S state. Their source addresses are C and E and priorities are 2 and 1, respectively. Control packet transmitted by E is the second control packet among those having 1st priority, and therefore SU E can transmit its data packet through the second idle primary channel. Meanwhile, there are 2 SUs having higher priority than C (that is, A and E) and control packet transmitted by C is the second control packet among those having the same priority. Therefore, SU C can know that it is given 4th access order. That is, the order of access to primary channels becomes A, E, D, C and B. These five SUs (including SUs in S&S state) sense all primary channels from the first to the last, to know how many channels are idle during η period of slot $(t+2)$. In this slot, all primary channels are idle. Therefore, SUs A, E and C transmit their data packets through the first, second and third primary channels, respectively. SUs C and B can know that SUs A, E and D can transmit their data packets, and that SUs C and B cannot transmit their packets because their access orders fall behind. SUs C and B transmit their control packets through the first (that is $4-3=1$) and second (that is $5-3=2$) minislots, respectively. Those control packets will always be non-colliding control packets. The reason is as follows. There are 5 non-colliding control packets at slot $(t+1)$ and 3 idle primary channels at slot $(t+2)$. Therefore, three SUs in R&S state can transmit their data packets during slot $(t+1)$ and remaining 2 SUs will transmit their control packet through the first 2 minislots of the same slot. At slot $(t+2)$, each of SUs in S&S state randomly chooses one of the remaining 4 minislots (that is, 3rd to 6th minislots) and transmits its control packet through the selected minislot. Here SUs F and G can successfully transmit their control packets without collision and their priorities are 2 and 1, respectively. Then, the order of access to primary channels becomes G, C, F and B at the end of slot $(t+2)$. At slot $(t+3)$, two primary channels are idle. SUs G and C can transmit their data packets and SUs F and B transmit their control packets through the first and second minislots, respectively. By using the operation described above, SUs having data packets with higher priority can transmit their data packets first, among SUs whose control packets are non-colliding control packets.

III. PERFORMANCE ANALYSIS

Even though the size of SU's data packet is smaller than the size of one slot η, in order to simplify the throughput analysis, it is assumed that the size of the SU's data packet is equal to that of one slot. The accurate throughput of the protocol can be calculated by multiplying the result of the throughput obtained below by $(1-\eta)$ [11]. Moreover, it is assumed that an SU transmits data packets having a specific class of priority. There are $M_i (i = 1, \cdots, p)$ SUs that try to transmit data packets having i-th priority. Here, 1 means highest priority and p represents the lowest priority. Moreover $M = \sum_{i=1}^{p} M_i$. Table 1 shows the notations used in this section.

Assume that λ is the probability that an SU in an idle state can get a new data packet per each slot. Moreover, let $P_{arr}(i|j)$ be the probability that new data packets arrive at i among j SUs in idle state per each slot. Then, $P_{arr}(i|j)$ can be calculated as follows:

$$P_{arr}(i|j) = \binom{j}{i} \lambda^i (1-\lambda)^{j-i}. \tag{1}$$

where

$$\binom{j}{i} = \frac{j!}{i!(j-i)!} \quad \text{for } j \geq i \geq 0.$$

TABLE 1. Notations used in this paper.

Notation	Explanations
N	Number of PUs (that is, number of primary channels)
M_i	Number of SUs having i-th priority
M	Number of SUs (that is, $M = \sum_{i=1}^{p} M_i$)
ζ	Time spent to sense a primary channel
η	Time spent to sense all primary channels
k	Number of minislots within a slot of the control channel
λ	Probability that a new data packet arrives at an idle SU per each slot
μ	Probability that a primary channel is busy per each slot
$P_{arr}(i\|j)$	Probability that new data packets arrive at i among j idle SUs per each slot
$P_{prim}(i)$	Probability that i primary channels are busy per each slot
$P_{prio}(x_1, \cdots, x_p\|j)$	Probability that there are x_i SUs having i-th priority ($i = 1, \cdots, p$) among j SUs
$Q(m, i, j)$	Probability that only i control packets become non-colliding control packets when j control packets are transmitted through m minislots randomly
$P_{succ}(i\|j)$	Probability that i among j SUs become transmitting SUs that transmit their data packets

Each primary channel is assumed to be busy with probability μ per each slot. Let $P_{prim}(i)$ be the probability that i primary channels are busy per each slot. Then $P_{prim}(i)$ can be obtained as follows:

$$P_{prim}(i) = \binom{N}{i} \mu^i (1-\mu)^{(N-i)}. \tag{2}$$

Let $P_{succ}(i|j)$ be the probability that i among j SUs become transmitting SUs that transmit their data packets. Then, $P_{succ}(i|j)$ can be obtained as follows:

$$P_{succ}(i|j) = \begin{cases} 0 & \text{if } i > min(k, N, j) \\ 1 & \text{else if } j = 0 \\ P_{prim}(N-i) & \text{else if } i < j \\ \{1 - \sum_{l=0}^{i-1} P_{prim}(l)\} & \text{otherwise.} \end{cases} \tag{3}$$

Moreover, let $Q(m, i, j)$ be the probability that only i control packets become non-colliding packets when j control packets are transmitted through m minislots randomly. Then $Q(m, i, j)$ can be obtained as follows:

$$Q(m,i,j) = \frac{1}{m^j} \times \binom{m}{i}\binom{j}{i} i! \sum_{s=0}^{\min(m-i,j-i)} (-1)^s \times \binom{\text{m-i}}{s}\binom{\text{j-i}}{s} s!\,(m-i-s)^{j-i-s}. \tag{4}$$

Let a_i, b_i, c, d be the numbers of SUs having i-th priority in transmitting state, the number of SUs having i-th priority in R&S state, SUs in S&S state and SUs in sensing state just before the first minislot within a slot of the control channel, respectively. Then the system can be modeled as a multi-state Markov chain. Define $\pi_{(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}$ be the probability that there are a_1 SUs having the first priority in transmitting state, $\cdots$, a_p SUs having the p-th priority in transmitting state, b_1 SUs having the first priority in R&S state, $\cdots$, b_p SUs having the p-th priority in R&S state, c SUs in S&S state and d SUs in sensing state just before the first minislot within a slot of the control channel when the system has reached the steady state. Also, let $P_{(e_1,\cdots,e_p,f_1,\cdots f_p,g,h)(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}$ denote the conditional probability that there are e_1 SUs having the first priority in transmitting state, $\cdots$ e_p SUs having the p-th priority in transmitting state, f_1 SUs having the first priority in R&S state, $\cdots$, f_p SUs having the p-th priority in R&S state, g SUs in S&S state and h SUs in sensing state just before the first minislot within a slot of the control channel, given that there are a_1 SUs having the first priority in transmitting state, $\cdots$, a_p SUs having the p-th priority in transmitting state, b_1 SUs having the first priority in R&S state, $\cdots$, b_p SUs having the p-th priority in R&S state, c SUs in S&S state and d SUs in sensing state just before the first minislot within the previous slot of the control channel. If we can calculate $P_{(e_1\cdots,e_p,f_1,\cdots f_p,g,h)(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}$, then $\pi_{(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}$ can be calculated as follows.

$$\Pi = \Pi P \quad \text{and}$$
$$\sum_{a_1=0}^{\min(M_1,N,k)} \cdots \sum_{a_p=0}^{\min(M_p,N-\sum_{i=1}^{p-1} a_i,k-\sum_{i=1}^{p-1} a_i)} \sum_{b_1=0}^{\min(M_1-a_1,k-\sum_{i=1}^{p} a_i)} \cdots \sum_{b_p=0}^{\min(M_p-a_p,k-\sum_{i=1}^{p} a_i-\sum_{i=1}^{p-1} b_i)} \sum_{c=0}^{M-\sum_{i=1}^{p}(a_i+b_i)} \cdots \sum_{d=0}^{M-\sum_{i=1}^{p}(a_i+b_i)-c} \pi_{(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)} = 1 \tag{5}$$

where

$$\Pi = \{\pi_{(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}\} \quad \text{and}$$
$$P = \{P_{(e_1,\cdots,e_p,f_1,\cdots f_p,g,h)(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}\}.$$

SUs in transmitting state transmit their data packets in a slot and then their states are changed to idle state at the end of the slot. Therefore, SUs in transmitting state can be treated as SUs an in idle state. In order to be h sensing SUs at the next slot, each *of h SUs* among $(M - b_1 - \cdots - b_p - c - d)$ idle SUs should get a data packet and the probability becomes $P_{arr}(h|M - b_1 - \cdots - b_p - c - d)$. The state of d sensing SUs in a slot is changed to S&S state at the next slot. Moreover, SUs among c SUs in S&S state remain in the S&S state when the control packets sent by SUs collide with others. Therefore, in order to be g S&S SUs at the next slot, control packets transmitted by $(g - d)$ SUs among c sensing SUs should collide with others, and remaining $(c-(g-d))$ control packets should not. Because there are $(b_1 + \cdots + b_p)$ SUs in R&S state, each of the SUs in S&S state can randomly choose one among remaining $(k - b_1 - \cdots - b_p)$ minislots. Therefore, when each of c sensing SUs chooses one among $(k - b_1 - \cdots - b_p)$ minislots randomly and transmits its control packet through the chosen minislot, the probability that $(c-(g-d))$ control packets become non-colliding control packets is equal to $Q(k-b_1-\cdots-b_p, c-(g-d), c)$. When there are b_i SUs having i-th $(i=1,\cdots,p)$ priority in R&S state, the number of SUs with i-th priority among $(c-(g-d))$ SUs whose control packets are non-colliding should be $(e_i+f_i-b_i)$, in order for the number of SUs having i-th priority in transmitting or R&S states to be (e_i+f_i). Let $P_{prio}(e_1+f_1-b_1,\cdots,e_p+f_p-b_p|c-(g-d))$ be the probability of the number of SUs having i-th priority to be $(e_i+e_i-b_i)(i=1,\cdots,p)$, out of $(c-(g-d))$ SUs whose control packets are non-colliding packets. $P_{prio}(e_1+f_1-b_1,\cdots,e_p+f_p-b_p|c-(g-d))$ can be calculated as follows. Assume that there are b_i SUs with i-th priority in R&S state just before the first minislot of a specific slot of the control channel. Then, there are (M_i-b_i) SUs having i-th priority not in R&S state. The probability of (M_i-b_i) SUs among $(M_1-b_1+\cdots+M_p-b_p)$ SUs not in R&S state to be SUs having i-th priority is equal to $(M_i-b_i)/(M_1-b_1+\cdots+M_p-b_p)=(M_i-b_i)/(M-b_1-\cdots-b_p)$. Therefore,

$$\begin{aligned}
&P_{prio}(e_1+f_1-b_1,\cdots,e_p+f_p-b_p|c-(g-d))\\
&\quad=\frac{(c-(g-d))!}{(e_1+f_1-b_1)!\cdots(e_p+f_p-b_p)!}\\
&\qquad\times\Big(\frac{M_1-b_1}{M-b_1-\cdots-b_p}\Big)^{(e_1+f_1-b_1)}\\
&\qquad\cdots\\
&\qquad\times\Big(\frac{M_p-b_p}{M-b_1-\cdots-b_p}\Big)^{(e_p+f_p-b_p)}
\end{aligned}\tag{6}$$

where

$$c-(g-d)=\sum_{i=1}^{p}(e_i+f_i-b_i).$$

Moreover, $(e_1+\cdots+e_p)$ among $(b_1+\cdots+b_p+c-(g-d))$ SUs in R&S states can be SUs in transmitting state with the probability of $P_{succ}((e_1+\cdots+e_p)|(b_1+\cdots+b_p+c-(g-d)))$. Here, f_p should be equal to $(c-(g-d)+\sum_{i=1}^{p}(b_i-e_i)-\sum_{i=1}^{p-1}f_i)$ because the number of SUs in R&S with higher-priority is equal to $\sum_{i=1}^{p-1}f_i$. Moreover, in case that $f_i(i=1,\cdots,p-1)$ does not equal to 0, SUs having lower priority than i-th priority in R&S state should not transmit their data packets. That is, either $f_i(i=1,\cdots,p-1)$ or $e_j(j=i+1,\cdots,p)$ should be equal to 0.

$P_{(e_1,\cdots e_p,f_1,\cdots f_p,g,h)(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}$ can be calculated as follows:

$$\begin{aligned}
&P_{(e_1,\cdots e_p,f_1,\cdots f_p,g,h)(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}\\
&\quad=P_{arr}(h|M-b_1-\cdots-b_p-c-d)\\
&\qquad\times Q(k-b_1-\cdots-b_p,c-(g-d),c)\\
&\qquad\times P_{prio}(e_1+f_1-b_1,\cdots,e_p+f_p-b_p|c-(g-d))\\
&\qquad\times P_{succ}((e_1+\cdots+e_p)|(b_1+\cdots+b_p+c-(g-d))).
\end{aligned}\tag{7}$$

Let ST_i be the system throughput for SUs having i-th priority that is defined by the number of data packets having i-th priority transmitted in a slot. Then,

$$\begin{aligned}
&ST_i\\
&=\sum_{a_1=0}^{\min(M_1,N,k)}\cdots\sum_{a_p=0}^{\min(M_0,N-\sum_{i=1}^{p-1}a_i,k-\sum_{i=1}^{p-1}a_i)}\\
&\quad\sum_{b_1=0}^{\min(M_1-a_1,k-\sum_{i=1}^{p}a_i)}\cdots\sum_{b_2=0}^{\min(M_2-a_2,k-\sum_{i=1}^{p}a_i-\sum_{i=1}^{p-1}b_i)}\\
&\quad\sum_{c=0}^{M-\sum_{i=1}^{p}(a_i+b_i)}\cdots\sum_{d=0}^{M-\sum_{i=1}^{p}(a_i+b_i)-c}\\
&\quad a_i\pi_{(a_1,\cdots,a_p,b_1,\cdots,b_p,c,d)}.
\end{aligned}\tag{8}$$

Let D_i be the average delay of the data packets transmitted by SUs having i-th priority. then D_i can be calculated as follows:

$$D_i=\frac{M_i}{ST_i}-\frac{1}{\lambda}+1.\tag{9}$$

IV. NUMERICAL RESULTS

In this section, we investigate the performances for the proposed protocol presented in Section 3 and simulation programmed in C language was used to verify the results of the analysis. Table 2 shows the simulation parameters used in this section. We assume that the value of $M_i(i=1,\cdots,p)$ is the same in order to compare the throughput and delay performance between SUs having i different priorities. That is, $M=\sum_{i=1}^{p}M_i$. Fig. 3 shows the throughput and delay performance for various N. In Fig.3, "high" stands for high-priority SU and "low" stands for low-priority SU. Moreover, "anal" and "sim" stand for the results of analysis and simulation, respectively. If $N=1$ and $\mu=0.3$, then the maximum capacity that SUs can utilize is 0.7. Under a low load, there is small number of SUs that transmit control packets, and therefore the probability of control packets colliding with others is also small. Therefore, if there is any primary channel that is idle, an SU can transmit its data packet irrespective of the priority. As the arrival rate increases, the number of control packets that SUs transmit also increases. In this case, even though control packets transmitted by SUs can be transmitted with no collision, not all SUs in R&S state can transmit their data packets due to the limited available capacity of the primary channel. In such case, high-priority data packets can be transmitted first ahead of those that have low-priority. Hence, low-priority SUs have to defer the attempt to transmit their data packets. The high-priority SUs, therefore, can get higher throughput performance over low-priority SUs. At the high load, the difference in the throughput between SUs having different priorities decreases. The reason is as follows. Assume that $k=5$ and there are 2 low-priority SUs in R&S state that failed to send data packets at a certain slot. Those SUs would then transmit their control packets through the first 2 minislot of the next slot. Here, assume that each of the remaining 8 SUs selects one of the remaining 4 minislots randomly and transmits its control packet through the minislot

TABLE 2. Simulation parameters.

Figure number	No. of SUs (M)	No. of primary channels (N)	No. of minislots (k)	P[slot is busy] (μ)	Simulation time (No. of slots)
Fig. 3	10	1. 3	5	0.3	5,000,000
Fig. 4	10	3	5	0.3	5,000,000
Fig. 5	10	3	5, 7	0.3	5,000,000
Fig. 6	8, 14	3	5	0.5	5,000,000
Fig. 7	10	3	5	0.1, 0.3	5,000,000
Fig. 8	16	3	10	0.3	5,000,000

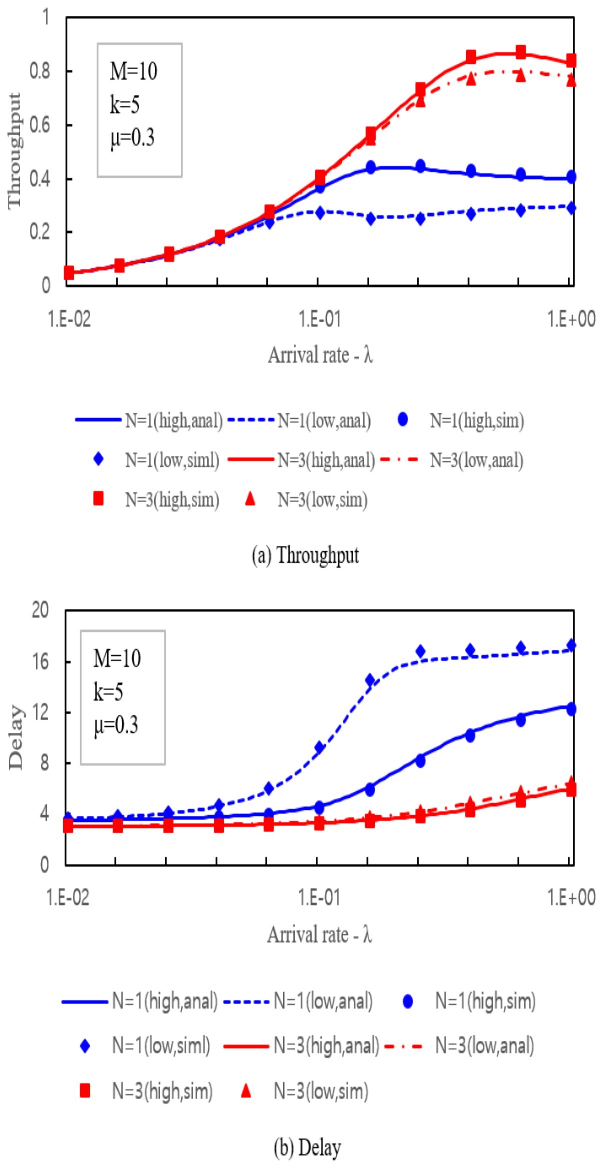

FIGURE 3. Throughput and delay versus λ for various N.

that was chosen. In this case, the probabilities that 1 or 2 control packets are transmitted without collision are 0.417 and 0.0256 by the Q function, respectively. If we ignore the probability of 2 control packets being successfully transmitted, then with the probability of 0.417, only one control packet will become a non-colliding control packet. The probability that the SU is a high-priority SU is 5/8. That is, the probability that one of the high-priority SUs can transmit its control packet without collision is about 0.26. Moreover, with the probability of 0.74, either one of control packets transmitted by low-priority SUs becomes non-colliding control packet, or all control packets sent by 8 SUs collide with each other. In this case, with the probability of 0.74, one of the SUs in R&S state can transmit its data packet through the idle primary channel even though it is a low-priority SU. Notwithstanding the above, the maximum sum of the throughput of high-priority SUs and that of SUs with low-priority is almost 0.7, and we can utilize almost all of the available capacity of the primary channel. In the meantime, when $N = 3$, more data packets can be transmitted, and the number of SUs in R&S state decreases. Therefore, among SUs in R&S state, the number of SUs remaining in the R&S state again decreases. In this case, the number of available minislots that SUs in S&S state can choose increases. In such case, the number of non-colliding control packets sent by SUs also increases and SUs can transmit their data packets. Therefore, high-priority SUs get higher throughput than the low-priority SUs but the difference decreases.

Fig. 3(b) shows the delay versus arrival rate for various number of primary channels. When $N = 3$, having an average number of idle primary channels of 2.1 is relatively sufficient. Therefore, if the control packet transmitted by an SU does not collide with others, then the SU can transmit its own data packet regardless of the priority of the data packet. In this case, the difference in delay performance between high-priority SUs and low-priority SUs is not large. On the other hand, when $N = 1$ and in high load region, even though the control packet transmitted by an SU does not collide with others, the SU may remain in the R&S state due to the lack of primary channels sensed to be idle. Therefore, higher priority SUs can transmit its data packet first before the ones with lower priority as long as there is an idle primary channel, and therefore, higher priority SU can get lower delay performance.

Fig. 4 shows throughput and delay comparisons between the protocol proposed in this paper (represented by RbMAC) and the protocol presented in Reference [18] (represented by DSA). The throughput and delay of DSA are obtained by using a simulation. "Sum" stands for the sum of the throughputs of high-priority SUs and low-priority SUs. In [18], one slot of a primary channel is sub-divided into multiple subchannels. However, here we assume that an SU can transmit only one data packet per slot for the purpose of performance comparison. Moreover, in [18], AIFS = 1 and CW = 2 for

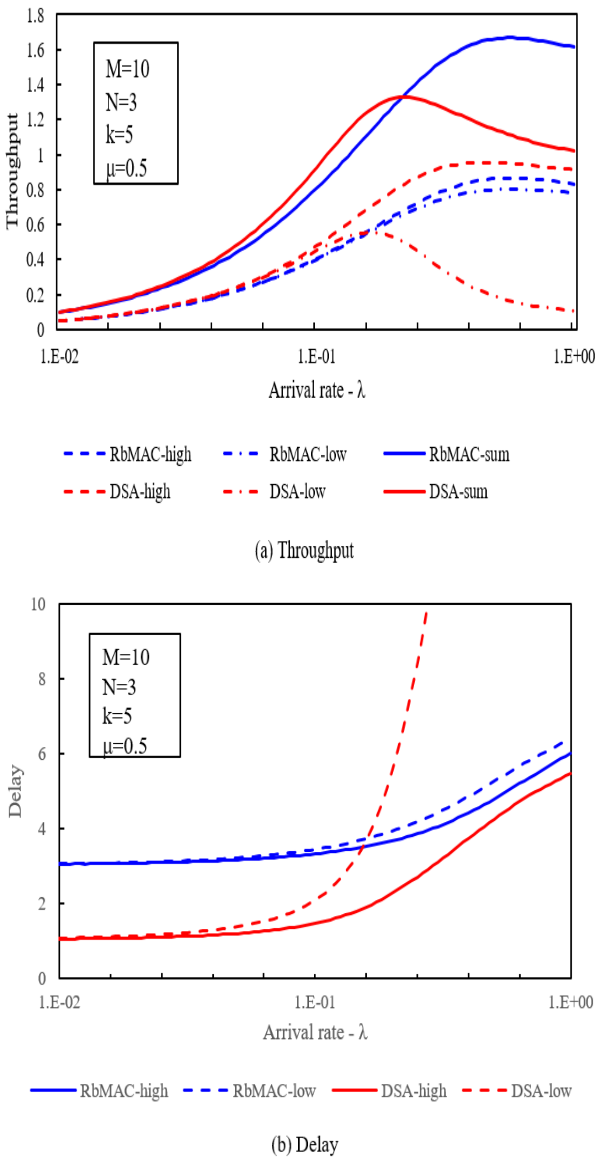

FIGURE 4. Throughput and delay comparisons between protocol proposed in this paper and the protocol presented in Ref. [18].

high-priority SUs, and AIFS=2 and CW=3 for low-priority SUs. That is, one slot of a primary channel is comprised of η period, 5 minislots and the size of the data packet sent by SUs. However, for throughput comparison, we assume that throughput is defined as the number of data packets transmitted by SUs per slot. As shown in Fig. 4(a), in low load region, DSA shows higher sum of throughput of high- and low-priority SUs compared to that obtained in RbMAC. The reason is as follow. In the low load region, the probability of SU's packet collision is also low. In DSA, when a data packet arrives in an SU at the beginning of a slot, the SU can transmit its data packet within the same slot through one of the idle primary channels, and the data packet can be transmitted without collision. On the other hand, in RbMAC, when a data packet arrives in an SU at the beginning of a slot, the SU monitors control channel during the same slot, transmits its control packet at the next slot, and then at the next slot, can transmits its data packet through one of the idle primary channels. That is, in RbMAC, if a data packet arrives at an SU, the SU can transmit its data packet only after two slots have passed. Therefore, RbMAC incurs lower throughput performance compared to that of DSA. On the other hand, as load increases, collision possibility at a primary channel becomes a dominant factor. In DSA, data packet can collide in the primary channel, but in RbMAC, data packet collision does not occur in the primary channel. Therefore, the RbMAC obtains higher throughput compared to DSA. Moreover, the maximum sum of throughput in case of RbMAC is much higher than that in the case of DSA. In the meantime, difference between the throughput of high-priority SUs and one of low-priority SUs in case of RbAMC is not large compared to DSA. The reason is that in RbMAC, an SU transmits its control packet through the control channel in order to transmit the data packet, and control packet collision is independent of the priority level. On the other hand, in DSA, SU with different priority uses different AIFS and CW values and therefore throughput difference between high-priority SUs and low-priority SUs is quite large. Figure 4(b) shows the delay comparison between the two protocols. As explained above, under a low load region, data packets in the case of DSA mechanism can be transmitted within an earlier time than that of RbMAC. Therefore, DSA can obtain lower delay performance compared to RbMAC. However, as the load increases, the delay experienced by the low-priority SU in the case of DSA mechanism increases rapidly. Also, in the high-load region, low-priority SUs in case of DSA mechanism suffer from starvation. In the meantime, in RbMAC, the SUs transmit control packets through a common control channel regardless of priority. Only SUs having transmitted control packets without collision can transmit data packets over the idle primary channels according to the priority and order of the non-collision control packets. Therefore, the delay difference experienced between the high priority SUs and the low priority SUs is much smaller than that of the DSA.

Fig. 5 shows the throughput for SUs for a number of minislots in a single slot. Fig. 5 also shows the throughput for SUs with a single priority presented in Reference [11]. The number of minislot is closely related to whether the transmitted control packets become non-colliding or not. A small number of minislots means higher chances of collision, and large number of minislots means that control packets can be transmitted without collision. As the number of non-colliding control packets increases, the number of high-priority SUs that transmitted control packets without collision also increases. High-priority SUs in the transmitting state return to the idle state after having transmitted their data packets, and also change to the sensing state when data packets arrive. Therefore, as the number of minislots increases, the probability of high-priority SUs transmitting their data packets first ahead of low-priority SUs also increases and the

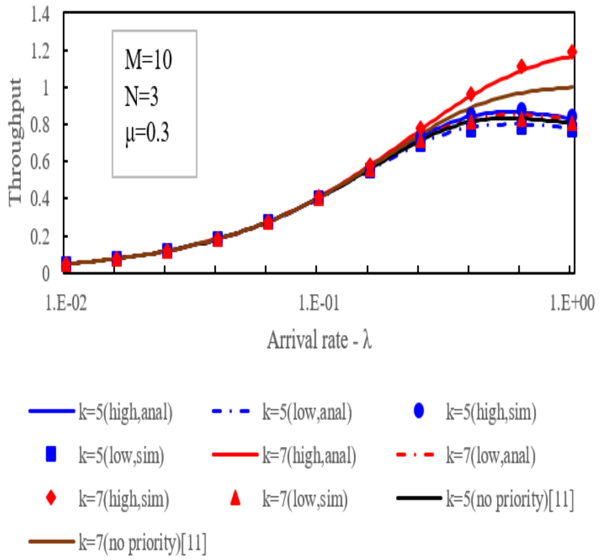

FIGURE 5. System throughput versus λ for various k.

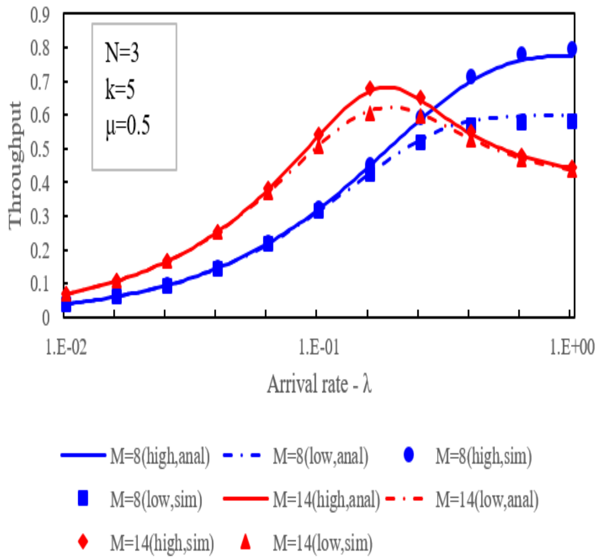

FIGURE 6. System throughput versus λ for various M.

throughput difference becomes larger between high-priority SU and low-priority SU.

Fig. 6 shows the throughput for SUs for various M. As M increases, the number of control packets transmitted also increases. As the number of control packets transmitted increases, the collision possibility also increases and the number of non-colliding control packets decreases. That is, in this case, whether or not the control packets transmitted are non-colliding packets becomes the dominant factor. Therefore, the throughput difference is reduced between SUs having different priorities in a low load where number of control packets transmitted is small, and in high load where

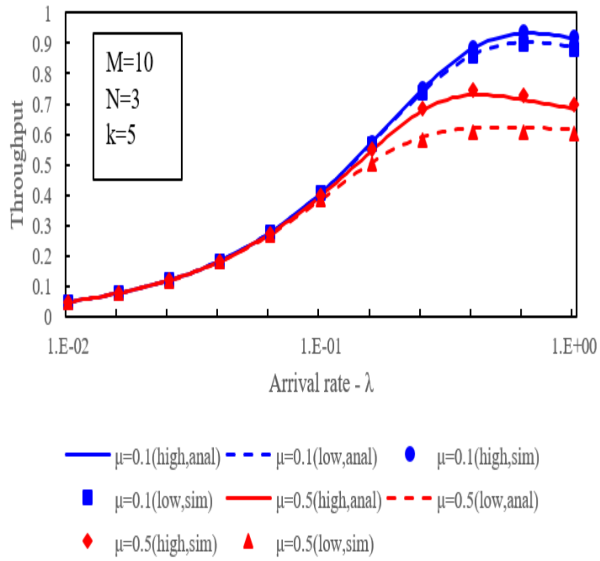

FIGURE 7. System throughput versus λ for various μ.

collision occurs across control packets. Only under the middle load, high-priority SUs can get higher throughput than SUs with low-priority. In the meantime, when M is small, the probability that control packets collide with others is also small, and data packets of high-priority SUs can be transmitted before those of low-priority SUs. However, as described earlier, when low-priority SUs in R&S state cannot transmit their data packets due to small number of idle primary channels, they will transmit their control packets at the next slot. In this case, the probability that control packets transmitted by SUs in S&S state collide with each other increases due to the reduced number of available minislots. The control packet is transmitted based on a slotted-ALOHA protocol and high-priority SUs can transmit their data packets only when their control packets are non-colliding control packets. Therefore, high-priority SUs cannot always transmit their data packets first over low-priority SUs.

Fig. 7 shows throughput for SUs for different μ. When $\mu = 0.1$, most of the primary channels are idle. That is, when control packets sent by SUs in S&S state are non-colliding control packet, they can transmit data packets through idle primary channels. Therefore, the throughput difference between SUs with different priorities is small. Meanwhile, when $\mu = 0.5$ and $N = 3$, on average 1.5 primary channels are idle. That is, on average 1.5 SUs in R&S state can transmit their data packets. Therefore, high-priority SUs among SUs in R&S state can transmit data packets first and high-priority SUs can get higher throughput than low-priority SUs.

Fig.8 shows the throughput and delay performance obtained by using a simulation when there are 4 classes of priorities (that is, $p = 4$). Whenever an SU with higher priority transmits its control packet without collision, the SU can firstly transmit it data packet through one of the idle

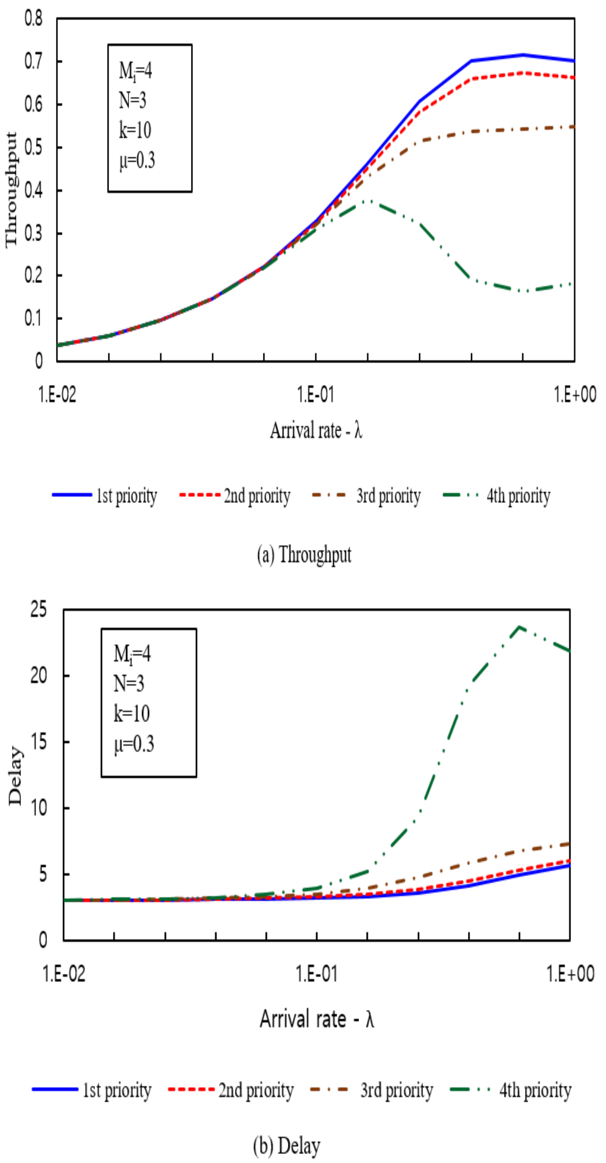

FIGURE 8. Throughput and delay versus λ for 4 classes of priorities.

primary channels. In the meantime, an SU with the lowest priority can transmit its control packet by using ALOHA protocol, and whether or not the control packet collides with others is independent of the priority level. However, even though the control packet transmitted does not collide with others, since the SU has lowest priority, it also is given the lowest order to access the primary channels. Therefore, in the low load region, as there are small number of SUs that try to transmit their data packet, any SU can transmit its data packet through one of idle primary channels independent of its priority. However, as the load increases, SU with higher priority can first transmit its data packet once its control packet does not collide with others. Therefore, In the high load region, SU having the lower priority incurs lower throughput and higher delay.

V. CONCLUSION

In this paper, a reservation MAC protocol was presented for transmitting data packet having traffic with multiple classes of priorities in a slotted multi-channel distributed CRN. In this protocol, SUs use an additional control channel to coordinate the order of access to primary channels between SUs. A slot of common control channel is further comprised of the time spent to sense all primary channels and a number of minislots. When a data packet arrives at an SU, the SU counts the number of non-colliding control packets by sensing one slot of the control channel. Moreover, the SU senses primary channels and counts the number of idle primary channels. The SU randomly chooses one of the minislots among those that are not reserved by SUs in R&S state. If the control packet is a non-colliding packet, then the SU is given the order of access based on the priority of data packets and the position of the control packet. The access order determines the idle primary channel that an SU uses to transmit its data packet. In this protocol there is no performance degradation either from SUs choosing the busy primary channel or multiple SUs choosing the same idle primary channel. Moreover, even though the SU cannot transmit its data packet because there is no idle primary channel that the SU can utilize, it can re-transmit its control packet without the concern over additional collision. We analyzed the throughput and delay of the proposed protocol by using the multi-state Markov chain and derived the numerical results for various system parameters. Numerical results show that high-priority data packets can be transmitted first ahead of the lower-priority ones. Notwithstanding the above, the maximum sum of the throughput of SUs with different classes of priorities is almost equal to the available capacity, and therefore the proposed protocol can take advantage of almost all of the available portion of primary channels. The future work will involve extending the protocol so that higher priority SUs can have access priority to the common control channel over lower priority SUs.

REFERENCES

[1] "Report of the spectrum efficiency working group," FCC Spectrum Policy Task Force, Washington, DC, USA, Tech. Rep., Nov. 2002.

[2] B. Dappuri and T. G. Venkatesh, "Design and performance analysis of cognitive WLAN MAC protocol," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2261–2272, Sep. 2018.

[3] Y. H. Bae, A. S. Alfa, and B. D. Choi, "Performance analysis of modified IEEE 802.11-based cognitive radio networks," *IEEE Commun. Lett.*, vol. 14, no. 10, pp. 975–977, Oct. 2010.

[4] P. Ren, Y. Wang, Q. Du, and J. Xu, "A survey on dynamic spectrum access protocols for distributed cognitive wireless networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2012, no. 1, pp. 1–21, Dec. 2012.

[5] D. Jung, Y. Kim, and H. Lim, "Energy-efficient MAC protocol for IEEE 802.11-based cognitive radio networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, San Diego, CA, USA, Dec. 2015, pp. 6–10.

[6] M. Luis, R. Oliveira, R. Dinis, and L. Bernardo, "A novel reservation-based MAC scheme for distributed cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 4327–4340, May 2017.

[7] L. Le and E. Hossain, "A MAC protocol for opportunistic spectrum access in cognitive radio networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Las Vegas, NV, USA, Mar./Apr. 2008, pp. 1426–1430.

[8] J. W. Chong, Y. Sung, and D. K. Sung, "RawPEACH: Multiband CSMA/CA-based cognitive radio networks," *J. Commun. Netw.*, vol. 11, no. 2, pp. 175–186, Apr. 2009.

[9] M. Luis, R. Oliveira, R. Dinis, and L. Bernardo, "A non-preemptive mac protocol for multi-channel cognitive radio networks," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, New Orleans, FL, USA, Mar. 2015, pp. 9–12.
[10] Z.-H. Wei and B.-J. Hu, "A fair multi-channel assignment algorithm with practical implementation in distributed cognitive radio networks," *IEEE Access*, vol. 6, pp. 14255–14267, 2018.
[11] J. Lee, "A priority-based reservation MAC protocol in multi-channel cognitive radio networks," *IEEE Access*, vol. 6, pp. 57536–57544, 2018.
[12] K. G. M. Thilina, E. Hossain, and D. I. Kim, "DCCC-MAC: A dynamic Common-Control-Channel-Based MAC protocol for cellular cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3597–3613, May 2016.
[13] A. Y. Zakariya and S. I. Rabia, "Analysis of an interruption-based priority for multi-class secondary users in cognitive radio networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 23–27.
[14] H. Cao, H. Tian, J. Cai, A. S. Alfa, and S. Huang, "Dynamic load-balancing spectrum decision for heterogeneous services provisioning in multi-channel cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 9, pp. 5911–5924, Sep. 2017.
[15] H. Yang and H. Chen, "Energy-efficient channel access considering data priority in cognitive radio sensor networks," in *Proc. 11th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Xi'an, China, Oct. 2019, pp. 23–25.
[16] A. T. El-Toukhy and H. Arslan, "Enhancing the performance of low priority SUs using reserved channels in CRN," *IEEE Wireless Commun. Lett.*, vol. 9, no. 4, pp. 513–517, Apr. 2020.
[17] R. Pal, A. Prakash, R. Tripathi, and K. Naik, "Scheduling algorithm based on preemptive priority and hybrid data structure for cognitive radio technology with vehicular ad hoc network," *IET Commun.*, vol. 13, no. 20, pp. 3443–3451, 2019.
[18] V. K. Tumuluru, P. Wand, D. Niyato, and W. Song, "Performance analysis of cognitive radio spectrum access with prioritized traffic," *IEEE Trans. Veh. Technol.*, vol. 61, no. 4, pp. 1895–1906, May 2012.
[19] Y. Li, L. Zhao, C. Wang, A. Daneshmand, and Q. Hu, "Aggregation-based spectrum allocation algorithm in cognitive radio networks," in *Proc. IEEE Netw. Operations Manage. Symp.*, Apr. 2012, pp. 506–509.
[20] S. Debroy, S. De, and M. Chatterjee, "Contention based multichannel MAC protocol for distributed cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 12, pp. 2749–2962, Dec. 2014.

JAEHWOON LEE (Member, IEEE) received the B.S. degree in electronic engineering from Hanyang University, Seoul, South Korea, in 1985, and the M.S. and Ph.D. degrees in electrical and electronics engineering from the Korea Advanced Institute of Science and Technology (KAIST), South Korea, in 1987 and 1995, respectively. From 1987 to 1990, he was a Researcher in line of packet switching network protocols with DACOM. From 1990 to 1999, he was with Samsung Electronics, where he was also with the Network Systems Group. Since March 1999, he has been with Dongguk University, where he is currently a Professor of information and communications engineering. His research interests include internet protocol, IP mobility, and high-speed networks.