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# A Priority-Based Reservation MAC Protocol in Multi-Channel Cognitive Radio Networks

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**ABSTRACT** Cognitive radio network can improve under-utilized licensed wireless channels called the primary channels where secondary users (SUs) can opportunistically share the primarychannels allocated to primary users (PUs) but which are not used by the PUs. This paper proposes a priority-based reservation medium access control protocol in cognitive radio network where a common control channel is exclusively used for SUs to transmit control packets in order to determine the priority for accessing the primary channels. The position of a control packet that did not collide with others becomes a priority. With the proposed protocol, any new SUs can join the network whenever it wants without knowing any past information. The analytic results show that the number of SUs affects the performance due the collision possibility of random access. However, if the SU can transmit its control packet successfully without collision, then it can transmit its data packet based on its priority without worrying about additional collision.

**INDEX TERMS** Priority-based reservation MAC, cognitive radio networks, multi-channel MAC protocol, common control channel.

## I. INTRODUCTION

Cognitive radio network is the technology to improve the under-utilized licensed wireless channels called primary channels where secondary users (SUs) can opportunistically share the channels that are allocated to primary users (PUs) but are not used by the PUs. In cognitive radio network, an SU senses the primary channels in order to check whether the PUs are using them, and if the channels are sensed to be idle, the SU contends with other SUs in order to use the channels. It is necessary for a medium access control (MAC) mechanism to coordinate between SUs to use primary channels sensed to be idle. In [2]–[5], a number of MAC protocols are proposed for single-channel cognitive radio network.

In [6], a MAC protocol for opportunistic spectrum access is proposed in slotted multi-channel ad-hoc network environment. Here, one channel is used as the common control channel for SUs to transmit control information. All channels are slotted with the size of the data packets transmitted by PUs. Each slot consists of a channel selection phase, sensing phase, and data transmission phase. The channel selection phase of one slot of the common control channel is further divided into several minislots. Here, an SU having data packet to transmit chooses a potential primary channel. And then, it randomly chooses one among the minislots within the channel selection phase and transmits control information containing the chosen primary channel number through the chosen minislot. If the control information does not collide with others, the SU senses the chosen primary channel during the sensing phase to check whether the primary channel is being used by a PU. If the primary channel is sensed to be idle, during the data transmission phase, the SU runs another contention resolution based on backoff mechanism defined in IEEE 802.11 protocol on the chosen primary channel in order to avoid collision that can occur when multiple SUs choose the same primary channel. In this protocol, in order for the SU to transmit its data packet successfully, the following conditions should be satisfied. (1) Control information sent by the SU during channel selection phase should not collide with others. (2) The primary channel that the SU chooses should be idle during the sensing period. (3) Even though the primary channel is sensed to be idle, the SU should win in contention without collision during the data transmission phase. Moreover, the overall network performance can deteriorate when the following cases occur. Assume that 3 SUs try to transmit their data packets and choose the same primary channel. If the chosen primary channel is being used by a PU,

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then all SUs cannot transmit their data packets even though other 3 primary channels are idle. Moreover, even though the chosen primary channel is sensed to be idle, if collision occurs during contention resolution in data transmission phase, none of the SUs can transmit its data packet. Also, even if collision does not occur, at most one SU can transmit its data packet and remaining 2 SUs cannot transmit their data packets even though other 2 primary channels are idle. Therefore, in order to improve the overall network performance, different SUs should be able to transmit their data packets over different primary channels sensed to be idle.

In [7], random access protocol with pre-arbitrated channelization (RawPEACH) protocol is proposed in multi-channel CSMA based cognitive radio network. Here, all channels are slotted with the size of the data packets sent by PUs. When a packet arrives at an SU, the SU selects its backoff counter value from contention window (CW) value. And then, the SU senses all primary channels and if at least one of the channels are sensed to be idle, it decreases backoff counter value by one. If the backoff counter value becomes zero, then the SU chooses one among the primary channels sensed to be idle and transmits its data packet through the chosun primary channel. In this protocol, when several primary channels are idle, if several SUs with backoff counter value equal to 0 choose the same primary channel, then (1) the primary channel can be wasted due to collision between SUs, and (2) other primary channels sensed to be idle can also be wasted because none of the SUs have chosen any channels.

In [8], delay performance is analyzed in multi-channel cognitive radio network where an SU chooses one primary channel independently and uniformly and then transmits its data packet with probability $p$ if the chosen channel is sensed to be idle. Reference [9] analyzes average waiting time by applying M/G/1 preemptive queueing scheme when a single SU opportunistically accesses the multi-channel cognitive radio network allocated to multiple PUs. In [10], there is a dedicated common control channel for SUs in multi-channel ad-hoc network. Here, an SU chooses one primary channel with the (forecasted) highest off period by using the seasonal autoregressive integrated moving average forecasting technique, and then contends over the control channel to use the primary channel by using the IEEE 802.11-based access mechanism.

In [11], a reservation-based MAC protocol is proposed in a single-channel cognitive radio network, where the MAC relies on two stages: contention stage and reservation stage. SUs choose one among CW1 minislots randomly and transmit their own control packets through the chosen minislots during the contention stage, and only the SUs having firstly transmitted their control packets proceed to the reservation stage regardless of the control packet collision. In the reservation stage, if control packet collision occurs, SUs having transmitted the control packets repeat choosing one among CW2 minislots randomly and control packet transmission procedure until the transmitted control packet does not collide with others. Here, the position of the non-collided control packet becomes the priority for the SU to transmit its data packet. In this protocol, network performance can deteriorate due to no data packet transmission during the collision resolution period in the reservation stage. Moreover, in the slotted system with the size of slot equal to the size of the data packet sent by PU, it is reasonable that the number of minislot of one slot should be constant because the size of the control packet is constant. However, in this protocol, the number of minislot varies when the stage changes from contention to reservation.

In [12], non-preemptive MAC protocol is proposed in slotted multi-channel cognitive radio network. Here, one channel is used as the dedicated common control channel to exchange control information between SUs. Each slot of the common control channel is further divided into channel request (CR) part consisting of a number of minislots and channel information (CI) part having as many slots as primary channels. Source SUs randomly choose one of the minislots belonging to the CR part and then transmit their RTS control packets containing information about the number of packet waiting for transmission (queue backlog) through the chosen minislots. Among control packets not colliding with others, only as many control packets as the number of available minislots belonging to CI part are selected. Here available minislots means either no SU are using the corresponding primary channel or the corresponding primary channel is going to be released by an SU. The receiving SU chooses one among available minislots belonging to a CI part and transmits CTS control packet through the chosen minislot. Under the protocol, if the number of available minislot is more than one, then CTS packet collision can occur when receiver SUs choose the same primary channel. Moreover, as an example, consider that only one SU transmits its RTS and there are 3 available minislots in CI part (that is equal to the number of primary channel not used by SUs). Then the receiver SU chooses one among 3 available minislots and sends CTS packet through the chosen minislot. The source SU tries to transmit its data packet through the chosen primary channel. But if the channel is being used by a PU, then the SU cannot transmit its data packet in spite of the fact that other primary channels are sensed to be idle. Therefore, network performance can deteriorate because SU chooses a primary channel first and then senses whether the channel is being used by a PU.

In [13], a fair multi-channel assignment algorithm is proposed in the slotted multi-channel based distributed cognitive radio networks, where a SU tries to transmit multiple data packets through multiple primary channels simultaneously within a slot. Here, all channels are slotted with the size of the data packets sent by PUs. Moreover, one channel is used as a common control channel for SUs to exclusively use for contention resolution. Each slot of the common control channel is divided into (1) channel sensing results period to check whether all primary channel are being used or not by PUs, (2) channel contention phase for SUs to transmit their own control packets by using the slotted ALOHA based access method, (3) channel assignment phase to transmit channel assignment related parameters, and (4) channel grabbing phase to assign primary channels with the round-robin method to provide the fairness between SUs whose control packets have been successfully transmitted without collision. Here, channel contention phase and channel grabbing phase are further divided into a number of minislots, respectively.

In [12] and [13], for example, consider the case that 3 SUs successfully transmitted their control packets without collision but there is no available primary channel in a slot, and none of SUs can transmit their data packets due to collision of control packets even though 3 primary channels are available at the next slot. In this case, there can be a performance deterioration because none of SUs can transmit their data packets during two slots.

In this paper, we propose a priority-based reservation MAC protocol in slotted multi-channel cognitive radio network. One channel is used as the common control channel for SUs to exclusively use without worring about the interference of PUs. In this protocol each SU transmits its control packet through the common control channel and the position of the control packet that does not collide with others becomes the priority to access the primary channel sensed to be idle. Moreover, once the control packet sent by an SU does not collide with others, it can transmit its control packet without worrying about additional collision even when there is no primary channels sensed to be idle. Therefore, with the aforementioned example, when 3 SUs successfully transmitted their control packets without collision but there is no primary channel sensed to be idle in a slot, the SUs can transmit their control packets through the next slot and if the 3 primary channels are not being used by PUs, then 3 SUs can transmit their data packets through the primary channels sensed to be idle. Moreover, with the protocol, only one SU can transmit its data packet through a primary channel sensed to be idle. Therefore, there is no performance degradation either from SU choosing a primary channel sensed to be busy or from collision possibility that can occur when multiple SUs choose the same primary channel sensed to be idle. SUs can operate the proposed protocol in an independent and distributed manner. Also, any new SUs can enter the network at any time. It is because a new SU checks the control channel during one slot and can know the current status of the network.

The paper is organized as follows. The operation of the priority-based reservation MAC protocol is described in detail in Section II. In Section III, we analyze the throughput performance by using a four-state Markov model. We discuss numerical results in Section IV. Finally, we conclude in Section V.

## II. PRIORITY-BASED RESERVATION MAC PROTOCOL

We consider the single-hop distributed cognitive radio networks having $N$ PUs, each of which uses the different non-overlapping licensed primary channels to transmit its data packet. $N$ primary channels have identical bandwidths and propagation characteristics, and guard band between adjacent channels are assumed to be negligibly small [13], [14]. Each of $N$ primary channels can be in either idle or busy state. Therefore, even though $N$ primary channels are allocated for PUs, each primary channel can be used by SUs while the channel is not being used by the PU. It is assumed that there is an additional common control channel for SUs to use without worrying about the interference of the PUs [6], [10], [12]–[14]. Common control channnel is used to determine the access priority between SUs based on slotted ALOHA based random access protocol [6], [10], [12], [13]. All channels are slotted to be the size of the data packets transmitted by PUs [6]–[10], [12], [13]. $\zeta$ be the time that it takes to detect whether a primary channel is idle. Moreover let $\eta$ be the time to take to detect all primary channels [7], [13]. ($\eta$ is equal to the sensing result period in [13].) Then $\eta = N \times \zeta$. One slot of the common control channel is further divided into $\eta$ and $k$ minislots. Here the minislots are used for SUs to transmit their control packets. Moreover, $k$ minislots can be divided into two parts: reservation part and contention part. The number of minislots belonging to the reservation part varies every slot. How to divide $k$ minislots into two parts will be explained later. Control packets are used for determining the priority to sense primary channels by SUs. The source SU address is contained in a control packet and this information is used by the SU to know whether it wins the contention.

There are $M(M > N)$ SUs. SUs are assumed to be equipped with dedicated sensors (DSs) for spectrum sensing [13], [15]. Therefore, with the help of DSs, SUs are assumed to be able to focus on the dynamic channel access mechanism. It is assumed that each SU is equipped with one transceiver. Moreover, it is assumed that each SU can have at most one data packet at a time. The flow chart of the operation of the priority-based reservation MAC protocol of an SU proposed in this paper is shown in Fig. 1. Each SU is assumed to be in one of four states: idle, monitoring, backlogged, or reserved.

(i) Idle
When an SU in idle state (called idle SU) gets a data packet at the beginning of a slot, it changes its state to monitoring.

(ii) Monitoring
An SU in monitoring state (called monitoring SU) tunes its transceiver to the common control channel and counts the number of successful control packets during a slot by monitoring the common control channel and then changes its state to backlogged at the end of the slot. Here, the control packets having successfully transmitted without collision become the successful control packets. If there are $l$ successful control packets in the slot, then the number of minislots belonging to the reservation part is equal to $l$ (that is, 1 through $l$ minislots become the reservation part) and the remaining $(k - l)$ minislots become the contention part in the next slot.

(iii) Backlogged
An SU in backlogged state (called backlogged SU) randomly chooses one among $(k - l)$ minislots belonging

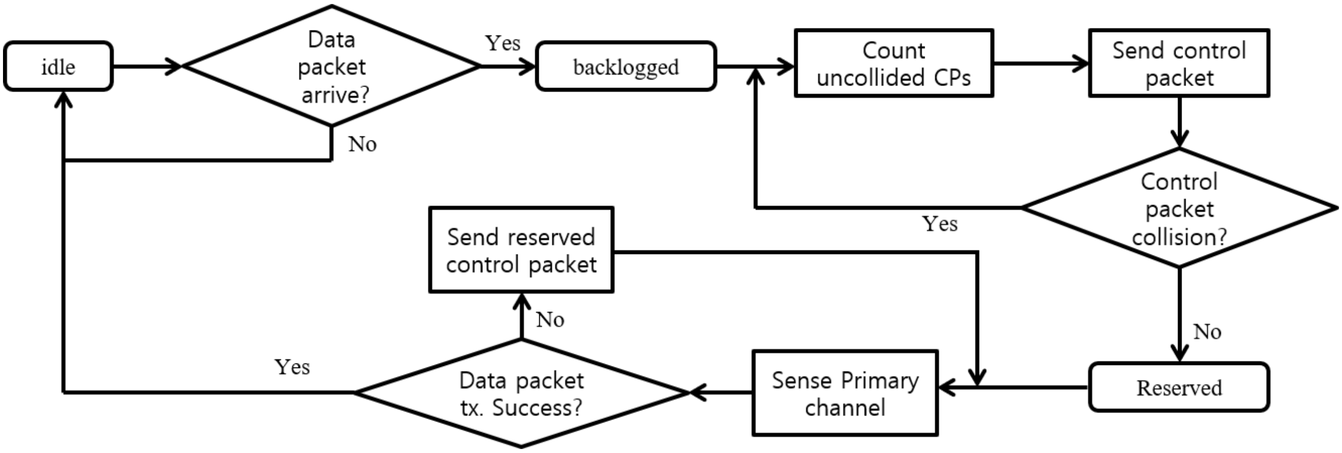

**FIGURE 1.** **Flow chart of the operation of the priority-based reservation MAC protocol.**

to the contention part, and then transmits its control packet through the chosen minislot. It also counts the number of the successful control packets. The SU can know whether its control packet collides with others or not at the end of the slot. If the control packet collides with others, then the SU remains in the backlogged state. The number of successful control packets becomes the number of minislots belonging to the reserved part in the next slot. If the control packet does not collide with others, the control packet sent by the SU becomes the reserved control packet and the state of the SU is changed to reserved. Here, the reserved control packet always becomes the successful control packet.

(iv) Reserved

All SUs in reserved state (called reserved SU) sense primary channels and can transmit their data packets based on the position of the reserved control packets transmitted. That is, the position of the reserved control packet becomes the priority. Let the control packet sent by an SU be the $i$th reserved control packet. Then the SU considers that it has the $i$th priority for transmitting its data packet, and it can transmit its data packet through $i$th primary channel sensed to be idle. If $n(n \leq N)$ primary channels are not being used by PUs, then the maximum $n$ reserved SUs can transmit their data packets. For example, if $n = 3$, then the SU having sent the first reserved control packet can transmit its data packet through the first primary channel sensed to be idle, the SU having sent the second reserved control packet can transmit its data packet through the second primary channel to be idle, and so on. If $n < i$, the SU considers that it cannot transmit its data packet due to low priority and transmits its control packet through $(i - n)$th minislot. The control packet does not collide with others and always becomes the reserved control packet. It is because the control packet transmitted by a reserved SU is located within the reservation part of the common control channel. If the SU successfully transmits its data packet, then its state is changed to idle.

Fig. 2 shows an example of the operation of the proposed protocol. The following is the example of the operation of SUs in monitoring or backlogged state. In Fig. 2, there are 3 primary channels. One slot of the common control channel is composed of $\eta$ and 6 minislots. As described before, the number of minislots belonging to the reservation part in a slot is determined by the number of successful control packets of the preceding slot. Because control packets sent by B, D and A are successfully transmitted without collision at slot $t$, the number of successful control packet is equal to 3 in slot $t$ and 1 through 3 minislots become the reservation part and the remaining 4 through 6 minislots become the contention part in slot $(t + 1)$. The SUs in monitoring or backlogged state monitor the common control channel during slot $t$ and find that there are 3 successful control packets not colliding with others. They can know that the first 3 minislots belong to the reservation part in slot $(t + 1)$. They randomly choose one among remaining 3 minislots belonging to the contention part and transmit their own control packets through the chosen minislots in slot $(t + 1)$. Here, a control packet transmitted by C among backlogged SUs is successfully transmitted without collision. There are 4 successful control packets (including 3 control packets sent by B, D and A) in slot $(t + 1)$. The backlogged SUs consider that the first 4 minislots belong to the reservation part in slot $(t + 2)$. In a similar way, in slot $(t + 2)$, backlogged SUs transmit their control packets through one among 2 minislots belonging to contention part and the control packet transmitted by F is transmitted without collision. In slot $(t+3)$, backlogged SUs transmit their control packets through randomly chosen one among 4 minislots belonging to contention part and control packets transmitted by D, G and B are transmitted without collision.

The following is an example of the operation of the SUs in reserved state. In slot $t$, control packets transmitted by B, D and A become the successful control packets. B, D and A are

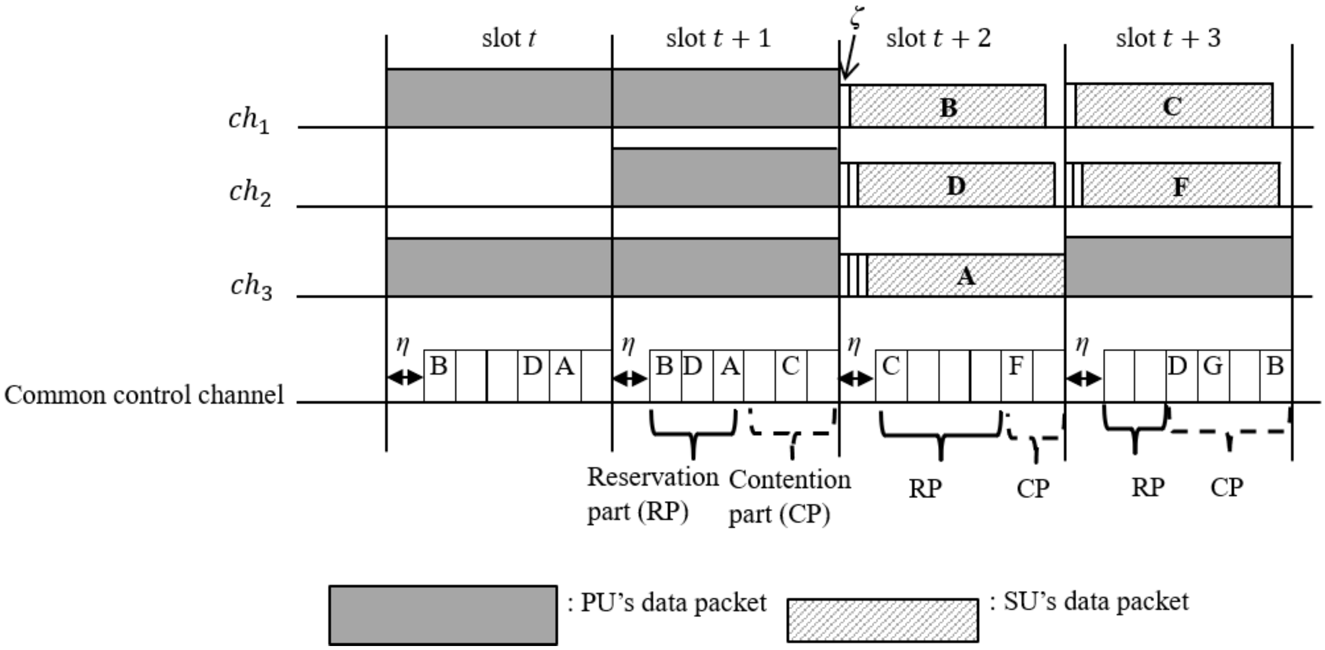

**FIGURE 2.** Example operation of the priority-based reservation MAC protocol.

the reserved SUs whose control packets are the first, second and third successful control packets, respectively. At slot $(t+1)$, all SUs in reserved state (that is B, D and A) sense $ch_1$ during the first $\zeta$ period to know whether the channel is being used by a PU. Because $ch_1$ is sensed to be busy, B, D and A continue to sense $ch_2$ during the second $\zeta$ period to know whether the channel is being used. $ch_2$ is also sensed to be busy and B, D and A continue to sense $ch_3$ during the third $\zeta$ period to know whether the channel is being used. $ch_3$ is also sensed to be busy and there is no more primary channel to sense. Although B, D and A are reserved SUs, because there is no primary channnel sensed to be idle, they transmit their control packets through minislots belonging to the reservation part in slot $(t+1)$. As described before, because the number of successful control packets is 3 at slot $t$, 1 through 3 minislots become the reservation part in slot $(t+1)$. B is the first SU in reserved state and transmits its control packet through the first minislot within the reservation part in slot $(t+1)$. In the similay way, D and A are the second and third SUs in reserved state and transmit their control packets through the second and third minislots within the reservation part in slot $(t+1)$, respectively. At the end of slot $(t+1)$, C also becomes the fourth reserved SU. At slot $(t+2)$, B, D, A and C sense $ch_1$ during the first $\zeta$ period to know whether the channel is being used by a PU. Because $ch_1$ is sensed to be idle, B whose control packet is the first successful control packet can transmit its data packet through $ch_1$ and then changes its state to idle. D, A and C continue to sense $ch_2$ during the second $\zeta$ period and they find that the channel is also idle. D whose control packet is the second successful control packet can transmit its data packet through $ch_2$ and then changes its state to idle. A and C continue to sense $ch_3$ during the third $\zeta$ period and they find that the channel is idle. A, whose control packet is the third successful control packet, can transmit its data packet through $ch_3$ and then changes its state to idle. Although C is also the reserved SU, there is no more primary channel to sense. C defers sensing primary channels and transmits its control packet through the first minislot belonging to the reservation part in slot $(t+2)$. It is because C is the first reserved SU that cannot transmit its data packet through primary channels. Control packets transmitted by C does not collide with others and always becomes the successful control packet. It is because none of the backlogged SUs can transmit their control packets through one of the minislots belonging to the reservation part. In a similay way, in slot $(t+2)$, C and F become the reserved SUs. During slot $(t+3)$, C transmits its data packet through $ch_1$ which is the first primary channel sensed to be idle. Moreover, F transmits its date packet through $ch_2$ which is the second primary channel sensed to be idle.

## III. PERFORMANCE ANALYSIS

The notations used in this paper can be seen in Table 1. Even though the size of the data packet sent by an SU is smaller than the size of the data packet sent by a PU, it is assumed that the size of the SU's data packet is equal to that of PU's data packet to simplify the performance analysis. In order to accurately evaluate the performance of the protocol, $(1-\eta)$ should be multiplied by the result of the performance analysis obtained below.

A new data packet is assumed to arrive at an idle SU with the probability $\lambda$ per every slot. Let $P_{arr}(j|i)$ be the probability

**TABLE 1.** Notations used in this paper.

| Notation | Explanations |
|---|---|
| $N$ | Number of PUs |
| $M$ | Number of SUs |
| $\zeta$ | Time to take to detect whether a primary channel is idle |
| $\eta$ | Time to take to detect all primary channels |
| $k$ | Number of minislots withins a slot of the common control channel |
| $\lambda$ | Probability that an idle SU gets a new data packet per every slot |
| $\mu$ | Probability that each PU transmits its data packet per every slot |
| $P_{arr}(j\|i)$ | Probability that each of $j$ among $i$ idle SUs get a new data packet per every slot |
| $P_{prim}(i)$ | Probability that $i$ among $N$ PUs transmit thier data packets per every slot |
| $Q(i,j,k)$ | Probability that there are only one ball in $i$ boxes when $j$ balls are put into $m$ boxes randomly |
| $P_{succ}(w\|w+x)$ | Probability that $w$ among $(w+x)$ reserved SUs succeed to transmit their data packets |

that each of $j$ among $i$ idle SUs get a new data packet per every slot. Then, $P_{arr}(j|i)$ can be obtained as follows:

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

where

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

Moreover, each PU is assumed to transmit its data packet through a primary channel with probability $\mu$ per every slot. Let $P_{prim}(i)$ be the probability that $i$ among $N$ PUs transmit their data packets per every slot. Then $P_{prim}(i)$ can be calculated as follows:

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

If an SU can successfully transmit its data packet through one of the primary channels sensed to be idle, then the SU is called the transmitting SU. Let $s$, $t$, $u$ and $v$ be the numbers of transmitting SUs, reserved SUs, backlogged SUs and monitoring SUs at the beginning of the first minislot of a slot of the common control channel, respectively. Then the system can be modeled as a four-state Markov chain. Define $\pi_{(s,t,u,v)}$ be the probability that there are $s$ transmitting SUs, $t$ reserved SUs, $u$ backlogged SUs and $v$ monitoring SUs at the beginning of the first minislot of a slot of the common control channel when the system has reached the steady state. Also, let $P_{(w,x,y,z)(s,t,u,v)}$ denote the conditional probability that there are $w$ transmitting SUs, $x$ reserved SUs, $y$ backlogged SUs and $z$ monitoring SUs at the beginning of the first minislot of a slot of the common control channel, given there are $s$ transmitting SUs, $t$ reserved SUs, $u$ backlogged SUs and $v$ monitoring SUs at the beginning of the first minislot of the previous slot of the common control channel. If we can calculate $P_{(w,x,y,z)(s,t,u,v)}$, then $\pi_{(s,t,u,v)}$ can be obtained as follows.

$$\Pi = \Pi P$$

and

$$\sum_{s=0}^{\min(M,N,k)} \sum_{t=0}^{\min(M,k)-s} \sum_{u=0}^{M-s-t} \sum_{v=0}^{M-s-t-u} \pi_{(s,t,u,v)} = 1. \tag{3}$$

where

$$\Pi = \{\pi_{(s,t,u,v)}\} \quad \text{and } P = \{P_{(w,x,y,z)(s,t,u,v)}\}$$

for

$$\begin{aligned} &0 \leq s \leq \min(M,N,k), \quad 0 \leq t \leq \min(M,k)-s, \\ &0 \leq u \leq M-s-t, \quad 0 \leq v \leq M-s-t-u, \\ &0 \leq w \leq \min(M,N,k), \quad 0 \leq x \leq \min(M,k)-w, \\ &0 \leq y \leq M-w-x, \quad 0 \leq z \leq M-w-x-y. \end{aligned}$$

In order to be $w$ transmitting SUs and $x$ reserved SUs at the beginning of the first minislot of a slot, the control packets transmitted from $(w-t+x)$ among $u$ backlogged SUs should be transmitted successfully without collision during the previous slot. Let $Q(m,i,j)$ be the probability that there is only one ball in $i$ boxes when $j$ balls are put into $m$ boxes randomly. Then $Q(m,i,j)$ can be calculated as follows.

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

Then, $Q(k-s-t, w-t+x, u)$ is equal to the probability that the control packets transmitted from $(w-t+x)$ among $u$ backlogged SUs are successfully transmitted without collision when each of $u$ backlogged SUs transmits its control packet through one of the $(k-s-t)$ minislots belonging to the contention part. In this case, the number of SUs that can transmit their data packets is equal to $(w+x)$. (That is, $(w-t+x)+t = w+x$.) Let $P_{succ}(w|w+x)$ be the probability the $w$ among $(w+x)$ reserved SUs succeed to transmit their data packets. If $x$ is not equal to 0, then exactly $w$ primary channels should be idle in order for the number of transmitting SUs to be $w$. Meanwhile, if $x$ is equal to 0, then $w$ reserved SUs can transmit their data packets if at least $w$ primary channels are idle. Therefore, $P_{succ}(w|w+x)$ can be calculated as follows:

$$P_{succ}(w|w+x) = \begin{cases} 0 & \text{if } w > N \\ P_{prim}(N-w) & \text{else if } x! = 0 \\ \{1-\sum_{i=0}^{w-1} P_{prim}(N-i)\} & \text{otherwise} \end{cases}. \tag{5}$$

When $(w-t+x)$ among $u$ backlogged SUs have successfully transmitted their control packets without collision, remaining $\{u-(w-t+x)\}$ backlogged SUs remain in the backlogged state due to collision of control packets transmitted. Moreover, $v$ monitoring SUs change their states to backlogged. Therefore, $y = v+\{u-(w-t+x)\}$. $s$ transmitting SUs transmit their data packets during a slot and change their states to idle at the end of the slot. In order for the number of monitoring SUs be $z$, new data packets should arrive at $z$ among $(M-t-u-v)$ idle SUs. The probability that $z$ among

$(M-t-u-v)$ idle SUs gets new data packets is equal to $P_{arr}(z|M-t-u-v)$. $P_{((w,x,y,z)(s,t,u,v))}$ can be calculated as follows.

$$P_{(w,x,y,z)(s,t,u,v)} = Q(k-s-t,\, w-t+x,\, u) \times P_{succ}(w|w+x) \times P_{arr}(z|M-t-u-v). \qquad (6)$$

Let the system throughput for SUs, $ST_{SU}$, be the average number of slots of the primary channels used by the SUs per slot. Then,

$$ST_{SU} = \sum_{s=0}^{\min(M,N,k)} \sum_{t=0}^{\min(M,k)-s} \sum_{u=0}^{M-s-t} \sum_{v=0}^{M-s-t-u} s \times \pi_{(s,t,u,v)}. \qquad (7)$$

## IV. NUMERICAL RESULTS

In this section, throughput performances are investigated for the proposed priority-based reservation MAC protocol presented in Section 3 and verified by using the simulation. Fig. 3 shows the system throughput for SUs when there are different numbers of minislots. If $N = 3$ and $\mu = 0.3$, $N \times (1-\mu) = 2.1$ primary channels are idle on average. With a low arrival rate, the probability that control packets having transmitted by backlogged SUs collide with others is also low and the system throughput increases as the arrival rate increases. In this paper, in order for an SU to transmit its data packet, the SU randomly chooses one of the minislots belonging to a contention part and then transmits its control packet through the chosen minislot. If the control packet transmits successfully without collision with others, then the SU can transmit its data packet through one of the primary channels sensed to be idle based on its priority. That is, throughput depends on the collision possibility of the control packet at the contention part. In case that $k = 7$ for example, when 2 backlogged SUs successfully transmit their control packets without collision, the first 2 minislots become the reservation part and the remaining 5 minislots become the contention part. If 2 reserved SUs successfully transmit their data packets, then they return to the idle state. However, because backlogged SUs transmit their control packets after having chosen one of the 5 minislots belonging to the contention part randomly, the collision probability of the control packets increases and throughput becomes low. Meanwhile, with the high $k$, even though 2 minislots belong to the reservation part in the previous example, the number of minislots belonging to the contention part is sufficiently large. That is, the collision possibility of the control packets becomes low. If several control packets successfully transmit without collision, then the number of minislots belonging to the reservation part increases to the number of successful control packets. When the number of minislots belonging to the reservation part increases, then the size of the contention part decreases and the collision possibility of the control packet sent by backlogged SUs increases. However, SUs in reserved state can transmit their data packets through the primary channels sensed to be idle. Therefore it can prevent the waste of primary channel sensed to be idle. Moreover, when SUs in reserved state can transmit their data packets, the number of minislots belonging to the reservation part decreases and the number of the minislots belonging to the contention part increases. Then, the number of successful control packet can increase and the SUs in reserved state also increase. That is, if the number of SUs in reserved state is over 2.1 on the average, then we can get the maximum throughput.

Fig. 4 shows the throughput versus arrival rate of SUs for different $\mu$. As described before, with the low arrival rate, the number of backlogged SUs also becomes low.

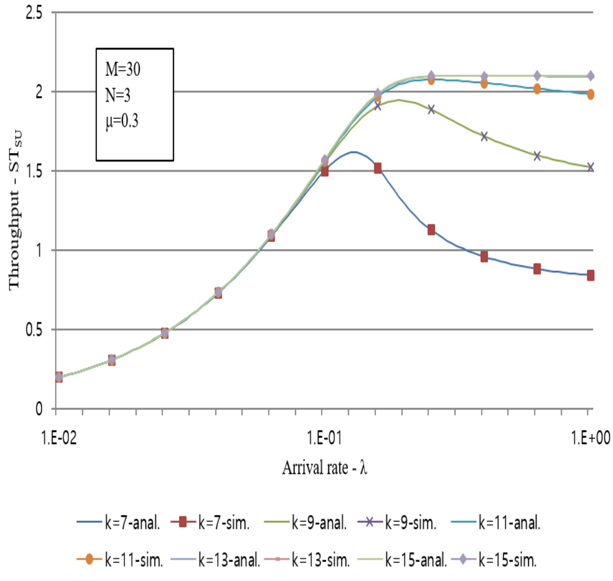

**FIGURE 3.** System throughput versus arrival rate of SUs for different $k$.

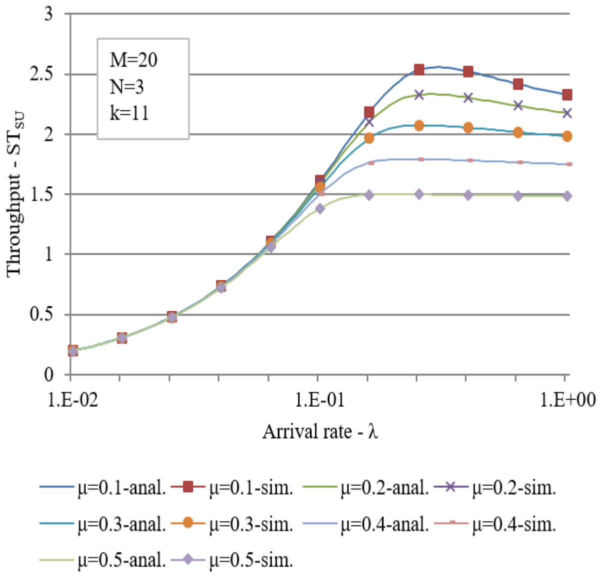

**FIGURE 4.** System throughput versus arrival rate of SUs for different $\mu$.

In this case, the probability that control packets having sent by backlogged SUs collide with others is also low. Therefore, the throughput increases as the arrival rate increases. With high $\mu$, the probability that reserved SUs can transmit their data packets is low due to small average number of primary channels being sensed to be idle. In this case, the number of reserved SUs can exceed the average number of primary channels being sensed to be idle and maximum throughput can be obtained. Meanwhile, with low $\mu$, most of the primary channels are idle. In this case, if control packets having sent by backlogged SUs do not collide with others, then the SUs can transmit their data packets immediately based on their priority. Therefore, throughput depends of how many control packets are successfully transmitted without collision within the contention part.

Fig. 5 shows the throughput for different numbers of SUs. As the number of SUs increases, the number of control packets having transmitted by SUs also increases. With the low $M$, the number of backlogged SUs also low and better throughput can be achieved at higher arrival rate. Meanwhile, with the high $M$, the control packet collision possibility increases, and one can get higher throughput with low arrival rate. With high arrival rate, as arrival rate increases, throughput decreases because the probability that the state of SUs is changed from backlogged to reserved is low due to the control packet collision.

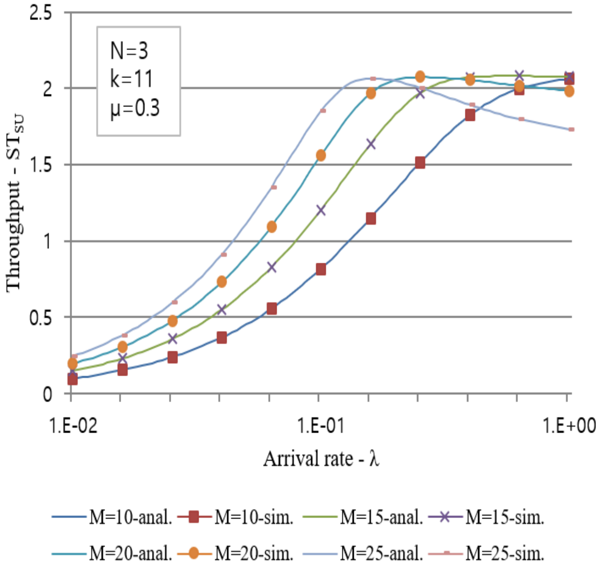

**FIGURE 5.** **System throughput versus arrival rate of SUs for different *M*.**

Fig. 6 shows the throughput when the arrival rate of SUs is 1 (i.e., SUs always have data packets to transmit) after setting the same parameter as in Fig. 6 of reference [12]. Here, when $N = 3$, $k = 13$ and $\mu = 0.4$, then the maximum capacity for SUs is 1.8. Moreover, when $N = 4$, $k = 14$ and $\mu = 0.35$, the maximum capacity for SU is 2.4. When $N = 5$, $k = 15$ and $\mu = 0.3$, the maximum capacity for SU is 3.5. Under the protocol presented in [12], the maximum throughputs are approximately 1.6, 2.3 and 3.05 for $N$=3, 4 and 5, respectively. In this protocol, an SU chooses one of the primary channels before transmitting its control packet. If the control packet does not collide with others, then the SU can transmit its data packet only if the chosen primary channel is idle. Therefore, the throughput performance can deteriorate because primary channels chosen are sensed to be busy. Moreover, when a primary channel is idle, then one slot in between the slots the SU's data packets are transmitted is idle and hence is wasted. Meanwhile, with the protocol proposed in this paper, SUs in reserved state transmit their data packets through the primary channels sensed to be idle based on their priorities. Therefore, there cannot be a case where SU's data packet cannot be transmitted even though there is a primary channel sensed to be idle. If a new data packet arrives at an idle SU, the SU monitors the control channel for a slot to know the number of successful control packet and transmits its control packet after choosing one of the minislots belonging to the contention part. If the control packet has successfully transmitted without collision, then the SU can transmit its data packet at the next slot based on the status of the primary channel and its priority. That is, in the best case, an SU can transmit its data packet per every 3 slots. When $M = 5$, SUs can transmit maximum $5/3 = 1.67$ data packet per every slot when there is no control packet collision. Therefore, the throughput becomes low with the low $M$. However, if $M$ is smaller than $k$, then one can get better performance when different minislots are statically assigned to different SUs. If $M$ is larger than $k$, the number of data packets that can be transmitted by SU also increases and the maximum throughput depends on not $M$ but the maximum available capacity of the primary channels. Therefore, with the large $M$, the throughput performance of the protocol

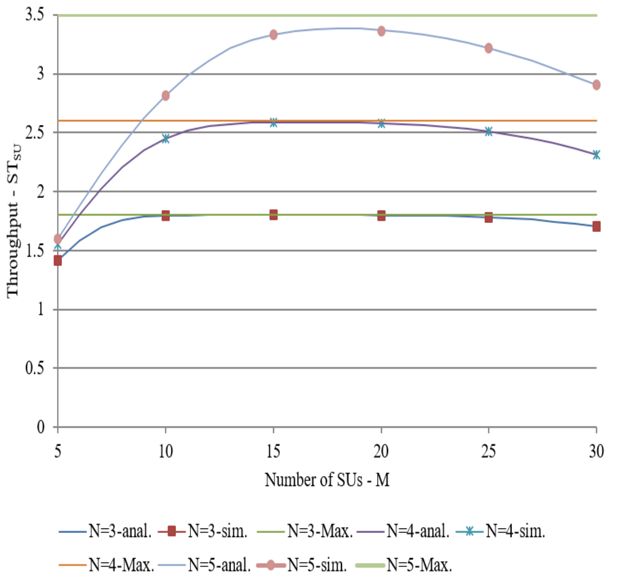

**FIGURE 6.** **System throughput versus the number of SUs by setting same parameters as in Fig. 6 of Reference [12].**

proposed in this paper is superior to that proposed in Reference [12]. When $M = 30$, throughput becomes low compared to the case when $M = 20$. In this case, there can achieve the superior throughput with the lower arrival rate as shown in Fig. 5.

## V. CONCLUSION

In this paper, we have presented a priority-based reservation MAC protocol in slotted multi-channel cognitive radio networks. In this protocol, a common control channel is exclusively used by SUs to determine the access priority of the SUs. A slot of the common control channel is further divided into the time period to sense all primary channels and number of minislots. Moreover, minislots can be divided into two parts: reservation part and contention part. When a data packet arrives at an SU, the SU counts the number of successful control packets by monitoring one slot of the control channel. And then, the SU randomly chooses one of the minislots belonging to the contention part. If the control packet is successfully transmitted without collision, then the SU gets the priority based on the position of the control packet. The SU can transmit its data packet based on its priority without worrying about additional collision possibilities. Therefore, in this protocol, it does not incur performance deterioration due to either (1) choosing the primary channel sensed to be busy or (2) contending to use a primary channel by multiple SUs. The throughput performance of the proposed protocol has been evaluated by using the four-state Markov chain for various system parameters. Performance results show that the proposed protocol can utilize almost maximum available capacity of primary channels. Moreover, there is no need of a central entity and SUs can operate the proposed protocol in an independent and distributed manner. Also, any new SUs can enter the network at any time. It is because a new SU monitors the common control channel during one slot and can know the current status of the network.

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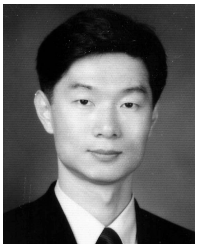

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