Research Article
On the Optimality of Generic Rate-Based AIMD and AIAD Congestion Control Schemes in Cognitive Radio Sensor Networks

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Investigating the optimality and the modeling of congestion control schemes is crucial in order to provide quality of service (QoS) for various applications in cognitive radio sensor networks (CRSNs). This paper develops an analytical framework to study the optimality of rate-based generic AIMD and AIAD congestion control schemes. In this way, a congestion model is introduced to describe the congestion behavior of CRSNs. A semi-Markov chain (SMC) is proposed to model the steady-state sending rate distribution of source nodes based on the congestion model. The optimality of generic AIMD and AIAD, based on the proposed models, is analyzed in order to maximize the defined rate-congestion ratio (RCR). The analytical results are verified through various NS2-based simulations in CRSNs.

1. Introduction

Dynamic spectrum access (DSA) is one of the main approaches to have spectrum-efficient wireless networks [1]. Cognitive radio (CR) is frequently used as a capable tool in order to provide dynamic spectrum access in wireless networks. A wireless network with CR nodes is called cognitive radio network (CRN). A wireless node, equipped with CR, operates on the spectrum channels opportunistically based on the CR basic operations: spectrum sensing, decision, and handoff [2]. The CR nodes do not have priority to access the wireless channels in the CRNs because the channels are licensed to some licensed users called primary users (PUs) [1]. The CR nodes can use the licensed channel in the absence of PUs and should leave the channel immediately, if a PU enters in its licensed channel [1]. Cognitive radio technology is widely used in wireless sensor networks (WSNs) to have spectrum-efficient networks and reserve the limited resources of sensors in WSNs. The WSNs with CR-equipped sensors are called cognitive radio sensor networks (CRSNs) [3].

Disregarding the activity of PUs and the unique characteristics of CRSNs (such as spectrum sensing and spectrum mobility) in the protocols of MAC, routing, and transport layers may lead to the violation of the main objectives of CRNs. Hence, studying the optimality of the protocols with regard to CR-related parameters is a crucial task for CRSNs. In this paper, we focus on the optimality of the transport layer protocols in CRSNs. The performance of congestion control schemes is important to provide the QoS of the diverse applications in CRSNs. The performance metrics such as congestion, throughput, and delay should be studied in order to provide various QoS guarantees in CRSNs. In this way, it is needed to tune the basic congestion control schemes in CRSNs in order to reach the QoS objectives. However, there is a limited analytical study on the optimality and performance evaluation of transport layer protocols in CRSNs and also in CRNs.

In [4], a simulation-based study on the performance of existing congestion control schemes is done over CRSNs to reveal the CRSN challenges in transport layer protocols. The challenges of real-time transport over CRSNs in different
spectrum environments of smart grid are studied in [5]. In [6], TCP throughput and efficiency over CRNs are studied. The impact of sensing period, PUs activity, and wireless channels number on the throughput of TCP is investigated in [7]. Authors in [8] study the behavior of TCP throughput, round trip time (RTT), and congestion window size based on the sensing period, the PUs activity, and the heterogeneity of channels. A transport protocol for cognitive radio ad hoc networks is proposed in [9]. Furthermore, the impact of sensing time and the changes of available bandwidth of CR users on the behavior of TCP congestion control is investigated. In [10], a study on TCP performance in CRNs with regard to the congestion window size, RTT behavior, and retransmission timeout (RTO) is done. TCP throughput is evaluated based on PUs activities and the number of available channels in [11]. An equation-based transport protocol for CRNs is proposed in [12]. Authors in [13] evaluate TCP end-to-end throughput, delay, and packet drop probability with regard to packet size, activities of PUs, sensing time, and accuracy.

As described above, most of the previous work on the transport layer of CRNs and CRSNs concentrates on the simulation-based performance evaluation. Furthermore, there is no study on the optimality and the modeling of rate-based congestion control schemes in CRSNs and CRNs. However, study on the optimality of congestion control schemes based on the analytical models is required in order to make better QoS provisioning in different applications. The real time and reliability are two main factors in the delay-sensitive and loss-sensitive applications that should be considered. The type and the parameters of the rate-based congestion control schemes have significant effects on the mean sending rate of source nodes and the congestion level of network. Increasing the sending rate in congestion control schemes leads to higher mean rate. On the other hand, it increases congestion probability of the CR nodes in the network. Hence, it is necessary to find the optimal congestion control scheme in order to provide both the lowest congestion probability and the highest sending rate. To the best of our knowledge, there is no study on the optimality and the modeling of rate-based congestion control schemes for CRNs in the current literature.

In this paper, an analytical study on the optimality of rate-based generic AIMD and AIAD congestion control schemes in CRSNs is presented. The main contributions are the following.

(i) A congestion model is proposed for CRNs.

(ii) A semi-Markov chain (SMC) is proposed to model the steady-state sending rate distribution of source nodes.

(iii) The optimality of rate-based generic AIMD and AIAD schemes is investigated based on the proposed sending rate distribution model of source nodes and the congestion model. In this way, we define the ratio of the mean sending rate to mean congestion probability (RCR) as a metric to measure the balance between mean sending rate and congestion probability. It is deduced by calculation that the optimal scheme to maximize the RCR is the AIMD (1, 3) scheme for the maximum sending rate of 100 packets per time unit.

The rest of this paper is organized as follows. In Section 2, system model of the CRSN is defined. Section 3 presents the proposed congestion model. The steady-state sending rate distribution of source nodes in the CRSN is proposed in Section 4. In Section 5, the optimality of rate-based congestion control schemes is investigated. Simulation results and verifications are presented in Section 6. Finally, the conclusions are presented in Section 7.

2. System Model

We model a cognitive radio sensor network as a collection of CR collecting sensors, CR relay nodes, and a sink station (see Figure 1(a)). The CR collecting sensors sense their event area and send the appropriate sensed data packets toward the sink station. The CR relay nodes do not generate any data and only forward the data packets from the source nodes toward the sink station. Based on the established end-to-end connections between the CR collecting sensors and the sink station, the network can be seen as a set of subnetworks. A subnetwork consists of the end-to-end paths that have at least one common relay node. Each subnetwork can be seen as
a separate system with its own congestion behavior with regard to the sending rate of CR collecting sensors. A subnetwork has a lifetime depending on the network characteristics and established end-to-end paths. We study a subnetwork in its lifetime. In Figure 1(a), such a CRSN with N subnetworks is depicted. Generally, we can consider a sensor network as a set of multiple systems, each with finite sources, and a single sink station. The systematic view of a sensor network is shown in Figure 1(b).

A CR node in this system operates in two main phases: a spectrum sensing phase and a data exchanging phase. In the spectrum sensing phase, the CR node senses spectrum channel to detect the presence of primary users. The CR node enters data exchanging phase after it finds a free channel. It is common in cognitive radio nodes to periodically sense the spectrum with a period of \( \tau_i \). In the sensing phase, a CR node senses the spectrum channel for a duration of \( \tau_i \) time units. Primary users’ activity can be modeled by a two-state ON/OFF Markov model with a mean entrance rate of \( \beta \) and mean departure rate of \( \alpha \) [14]. We assume that the sensing range covers \( K \) wireless channels, licensed for PUs. At each channel a separate and independent primary user operates based on the traffic model of PUs.

### 3. Congestion Model

In wireless sensor networks, congestion control is usually performed by the rate adjustment algorithms [15]. Rate adjustment is to regulate the sending rate of the source nodes according to the congestion notification received from the sink station. Simple rate adjustment and exact rate adjustment are basic rate adjustment algorithms [15]. In the simple rate adjustment algorithms, the rate is controlled based on a single congestion bit. The additive increase multiplicative decrease (AIMD) and additive increase additive decrease (AIAD) are two variations of the simple rate adjustments. On the other hand, in the exact rate adjustment algorithm, the rate is adjusted based on the exact congestion level of the network. In this paper, we investigate the performance and the optimality of the generic AIMD and AIAD rate adjustments as the congestion control schemes which are executed in the sink station. The regulating decisions are made in the sink station and sent to the collecting CR sensors periodically with the period of \( T \) (the sink notification period). The minimum value of the sending rate is assumed to be one packet per second. We assume that the collecting CR sensors have a higher bound of \( R \) packets per second on their sending rate because of the limitations of the sink station.

A cognitive radio sensor subnetwork is considered as a system which receives the traffic of some CR collecting sensors and forwards them toward the sink station. The collecting CR sensors rate is regulated through generic AIMD and AIAD schemes based on the congestion level in the subnetwork. The source nodes rate of the subnetwork can vary between 1 and \( R \) packet per second. Generally, the congestion behavior of a subnetwork can be modeled by the pairs of \( (r, \Omega_r) \), where \( r \) is the source nodes rate of subnetwork \( r = 1, 2, \ldots, R \) and \( \Omega_r \) is the subnetwork congestion probability with regard to the source nodes rate. The trend of \( \Omega_r \) versus \( r \) is a monotonically increasing curve such that, with increasing the collecting CR sensors rate of the subnetwork, the congestion probability will increase. In general, for the rates lower than a specific rate, that is, \( r_l \), there is almost no congestion in the subnetwork. On the other hand, for the rates higher than a specific rate, that is, \( r_H \), the congestion probability is close to one. For the rates between the two thresholds, that is, \( r_l \) and \( r_H \), the congestion probability increases with the rate. The \( \Omega_r \) curve in this region can be approximated by a line. The congestion model of a subnetwork is depicted in Figure 2. Finding the congestion probabilities is subject of a separate research and will not be addressed in this paper. Based on the congestion model, the sending rate distribution of CR collecting sensors, which is regulated by generic AIMD and AIAD schemes, can be calculated (see Section 4).

### 4. Sending Rate Distribution of the Collecting Sensors in CRSNs

The regulated sending rate process of a generic rate-based AIMD scheme can be modeled by a semi-Markov chain (SMC) with the transition probabilities

\[
    r^* = \begin{cases} 
        \max \left( 1, \frac{r}{\text{INC}} \right), & \text{with probability } \Omega_r, \\
        \min \left( r + \text{DEC}, R \right), & \text{with probability } 1 - \Omega_r, 
    \end{cases} \tag{1}
\]

and also of the generic rate-based AIAD scheme:

\[
    r^* = \begin{cases} 
        \max \left( 1, r - \text{DEC} \right), & \text{with probability } \Omega_r, \\
        \min \left( r + \text{INC}, R \right), & \text{with probability } 1 - \Omega_r, 
    \end{cases} \tag{2}
\]

where \( r \) is the current regulated sending rate of source and \( \Omega_r \) is the congestion probability in the subnetwork between the source nodes and the sink station while the sending rate of source nodes is \( r \). The \( r^* \) is the new adjusted sending rate of the source nodes. The AIMD and AIAD increase the rate additively by INC factor if there is not any congested node at the subnetwork at the duration of \( T \). The AIMD/AIAD decreases the sending rate multiplicatively/additively by DEC if a congestion is detected at the subnetwork at the period \( T \). We represent the AIMD and AIAD schemes with the INC...
and DEC factors by AIMD (INC, DEC) and AIAD (INC, DEC), respectively.

A CR collecting sensor regulates its sending rate based on
the AIMD/AIAD algorithm and sends with the regulated rate
for $T$ time units. Hence, sojourn time of being in the various
rates is equal to $T$ and is not exponentially distributed and
we have a semi-Markov chain (SMC). If the behavior of the
SMC is observed at discrete instances that the state transitions
happen, its embedded DTMC will be obtained [16]. In
Figure 3, the embedded DTMC of sending rate process based
on generic AIMD rate adjustment is illustrated for maximum
sending rate $R = 8$, increasing factor INC = 1, and decreasing
factor DEC = 2.

The evolution process of sending rate is a finite state,
aperiodic, and irreducible Markov chain; hence there is a
unique steady-state distribution for this embedded DTMC
[16]. Calculating the steady-state distribution of the embed-
ded DTMC, that is, $\pi = (\pi_1, \pi_2, \ldots, \pi_R)$, can be done by
solving a system of linear equations with $R$ independent
equations and $R$ unknown variables. For the large values
of $R$, the transition matrix will be large. Also, the matrix
is sparse. Hence, we use the LSQR method [17] in order
to solve the system of linear equations. Since the sojourn
time of all states is equal to $T$, the steady-state distribution
of embedded DTMC equals steady-state distribution of the
SMC. The steady-state distribution of SMC can be calculated
through the steady-state distribution of embedded DTMC as
follows:

$$P_r = \frac{\pi_r}{\sum_{r=1}^{R} \pi_r T} = \frac{\pi_r T}{T} = \pi_r, \quad r = 1, 2, \ldots, R,$$

where $(\pi_1, \pi_2, \ldots, \pi_R)$ is the steady-state distribution of
embedded DTMC and $(P_1, P_2, \ldots, P_R)$ is the steady-state
distribution of SMC.

5. Optimality of Rate-Based AIMD and AIAD Schemes

The type of rate adjustment scheme and the increasing and
decreasing factors of scheme, that is, INC and DEC, affect
the sending rate distribution of CR collecting sensors and
congestion probability in CRSNs. Increasing the sending rate
causes the higher mean rate and decreases the delay overhead
of congestion control schemes. On the other hand, it can
increase the congestion probability in CRSNs. Since both of
delay and reliability should be considered in real-time reliable
applications, it is important to establish a trade-off between
mean rate and mean congestion probability in CRSNs. In
this way, we define rate-congestion ratio (RCR) based on
the mean sending rate and mean congestion probability as
follows:

$$\text{RCR} = \frac{\bar{R}}{\bar{\Omega}} = \frac{\sum_{r=1}^{R} P_r (1/r)}{\sum_{r=1}^{R} P_r \Omega_r},$$

where $\bar{\Omega}$ and $\bar{R}$ are mean congestion probability and mean
sending rate of rate adjustment scheme, respectively. Mean
congestion probability is calculated based on the congestion
model. Mean sending rate is obtained based on the steady-
state distribution of the proposed SMC, that is, $(P_1, P_2, \ldots, P_R)$.

Maximizing this ratio will be useful to provide both real
time and reliability in CRSNs. The optimal rate adjustment
scheme and optimal values of rate increasing (INC) and
decreasing (DEC) factors can be obtained based on the
proposed SMC model of sending rate and congestion model.
Our variables are

(i) type of rate adjustment scheme;
(ii) rate increasing factor of the scheme (INC);
(iii) rate decreasing factor of the scheme (DEC).

5.1. Calculation of Optimal Scheme. As noted in Section 4, the
generic AIMD and AIAD rate adjustments are considered.
The INC factor is an integer value at the range of $[1, R − 1]$ for both AIMD and AIAD schemes (minimum rate and
maximum allowable rate of AIMD and AIAD schemes are
1 and $R$ packets per second, resp.). Also, DEC factor is an
integer value at the range of $[2, R]$ for the AIMD schemes
and $[1, R − 1]$ for the AIAD schemes. Hence, search space
size of the optimization problem is $2(R − 1)^2$. Since we do not
have any closed-form formula for the RCR, the optimal values
of INC and DEC factors of AIMD and AIAD schemes can
be obtained through exhaustive search on different values
of INC and DEC factors.

In the congestion model, the value of $r_{hi}$ can be between
1 and $R$; that is, $1 \leq r_{hi} \leq R$, and the value of $r_l$ varies
between 1 and $r_{hi}$; that is, $1 \leq r_{hi} \leq r_{hi}$. Hence, the total
number of possible congestion models is $\sum_{r_{hi}=1}^{R} \sum_{r_{hi}=1}^{R} = R(R + 1)/2$. However, all the congestion models for various
networks are not practical. We can investigate the optimality
of generic AIMD and AIAD rate adjustments for all the
possible models for a given value of $R$. For each congestion
model, in order to maximize the RCR ratio, the optimal
rate adjustment algorithm is obtained through exhaustive
search on the possible values of INC and DEC factors for the
different values of $R$.

In particular, the AIMD scheme with increasing factor of
1 and decreasing factor of 3, that is, AIMD (1, 3), is obtained
as the optimal scheme in order to maximize the RCR ratio while
the value of $R$ is considered as 100 packets per time unit. The
optimal AIAD scheme alters for various congestion models. The
increasing factor of the optimal AIAD scheme is obtained
as 1 and the decreasing factor varies per different congestion
models for the $R$ equal to 100 packets per time unit.

6. Simulation Results and Verifications

The obtained results through models are verified using
simulations by CogNS simulation framework [13] which is
a simulation framework for cognitive radio networks based
on Network Simulator 2 (NS2) [18]. Default simulation
settings and the configuration parameters of the CRSN are
summarized in Table 1. The network area is $400 \times 400 \text{ m}^2$. The
network consists of 5 collecting CR sensors and 12 CR relay
Figure 3: The embedded DTMC of sending rate process based on generic AIMD rate adjustment with maximum sending rate $R = 8$, increasing factor $INC = 1$, and decreasing factor $DEC = 2$. The $\Omega_r$ is the congestion probability in the subnetwork between the source nodes and sink while the sending rate of the source nodes is $r$.

Table 1: CRSN configuration and simulation settings.

| Parameter                              | Value/type                   |
|----------------------------------------|------------------------------|
| Network area                           | $400 \times 400$ m$^2$      |
| The number of collecting CR sensors    | 5                            |
| The number of CR relay nodes           | 12                           |
| The number of wireless channels ($K$)  | 6                            |
| The bandwidth of wireless channels     | 1 Mbps                       |
| PUs’ activity ($\alpha, \beta$)        | (3, 1)                       |
| Sensing time ($t_s$)                   | 0.2 sec                      |
| Sensing period ($r$)                   | 1.2 sec                      |
| MAC protocol                           | Simple CSMA/CA-based multichannel protocol |
| Routing protocol                       | Ad hoc on-demand distance vector (AODV) |
| Queue management strategy              | Droptail                     |
| Transport protocol                     | Generic rate-based AIMD and AIAD schemes |
| Packet size                            | 120 bytes                    |
| Maximum allowable sending rate ($R$)   | 100 packets/sec              |
| Queue size                             | 100 packets                  |
| The queue length threshold for congestion detection | 95 packets                  |

nodes and a sink station. There are 6 wireless channels ($K$) with the same capacity of 1 Mbps. There is one primary user per wireless channel with the entrance rate ($\beta$) equal to 1 and the departure rate ($\alpha$) equal to 3. Sensing time ($t_s$) and sensing period ($r$) are 0.2 seconds and 1.2 seconds, respectively. A simple CSMA/CA-based multichannel protocol is considered as MAC protocol. The AODV is used as routing protocol and queue management in the network layer is done based on droptail strategy. The generic rate-based AIMD and AIAD schemes are considered as transport protocols. The size of packets is 120 bytes. The maximum sending rate of AIMD and AIAD schemes is 100 packets per second. There are different events such as buffer occupancy, packet rate, node delay, channel status, and reliability parameters which are used to detect congestion in WSNs [15]. In our simulations, the queue length (buffer occupancy level) of nodes is assumed as congestion detection parameter. The queue size of nodes is 100 packets and the queue length threshold for the congestion detection is 95 packets.

6.1. The Congestion Behavior of a Subnetwork. In order to show that the congestion behavior of a subnetwork can be generally demonstrated by the proposed congestion model, it is needed to find appropriate thresholds, that is, $r_L$ and $r_H$, in congestion probability curve obtained through simulation for various CRSN configurations so that the curve in the region between $r_L$ and $r_H$ can be fitted by a line. Based on the CRSN configuration described in Table 1, we consider a subnetwork with two collecting CR sensors and six relay nodes. Table 2 shows four different experiments in order to obtain the congestion behavior of the subnetwork. The default parameters (Table 1) are considered in experiment I. In experiment II, PU activity is changed to $(\alpha, \beta) = (1, 3)$. In experiment III, sensing period is set to 0.4 seconds. In experiment IV, we consider traditional wireless sensor networks so that nodes are not CR ($t_s = 0$) and there is not any PU.

In Figure 4, the congestion behavior of the subnetwork is illustrated for experiments I, II, III, and IV. In these figures, the obtained congestion probabilities through simulation for all possible sending rates of collecting CR sensors are demonstrated by the black circle-marker curve. For each curve, the congestion model is fitted on the simulation curve with minimum fitting error and is demonstrated by red curve. The best threshold values of the congestion model are calculated in order to minimize the fitting error. The region between $r_L$ and $r_H$ is depicted by gray region in these figures.
Table 2: Different experiments to show the congestion behavior of a subnetwork through simulation.

| Exp. number | (𝑡, 𝑟)     | (α, β)   |
|-------------|------------|----------|
| I           | (0.2 sec, 1.2 sec) | (3, 1)   |
| II          | (0.2 sec, 1.2 sec) | (1, 3)   |
| III         | (0.2 sec, 0.4 sec) | (3, 1)   |
| IV          | No spectrum sensing | No PU activity |

In Figure 4(a), the values of \( r_L \) and \( r_H \) are obtained to be 42 and 51 packets per second, respectively. In experiment II, the activity of the PUs is increased. Therefore, the subnetwork will be congested with lower sending rates in comparison with experiment I. Consequently, the values of \( r_L \) and \( r_H \) are 34 and 42 packets per second, respectively, in Figure 4(b). Since the sensing period is decreased to 0.4 seconds in experiment III, the overhead of spectrum sensing is increased. Therefore, the capacity of network reduces significantly and the values of \( r_L \) and \( r_H \) are calculated as 24 and 30 packets per second, respectively (Figure 4(c)), which are smaller than the values in experiments I and II. Experiment IV is related to traditional wireless sensor networks. In this experiment, the values of \( r_L \) and \( r_H \) are calculated as 49 and 59 packets per second, respectively. Because the CR nodes can communicate on the channels without the presence of PUs and without spending some portion of time for spectrum sensing, the threshold values are larger than the previous experiments’ thresholds.

With regard to the simulation results, it is reasonable to model the congestion behavior of a subnetwork by the proposed congestion model with some fitting errors. In other words, the simulation results show that we can find two threshold values of the sending rates for each subnetwork and approximate the region between the thresholds with a line.

6.2 Optimal AIMD and AIAD Schemes. In this section, the optimality of AIMD and AIAD schemes in order to maximize the RCR ratio is investigated through simulation for the experiments mentioned in Table 2. In this way, for each experiment, the value of RCR ratio is obtained for all possible AIMD and AIAD schemes. As the default parameters of the CRSN described in Table I, the maximum allowable rate of AIMD and AIAD schemes, that is, \( R \), is 100 packets per second. Consequently, the value of INC factor is at the range of \([1,99]\) packets per second for both AIMD and AIAD schemes. The value of DEC factor is at the range of \([2,100]\) and \([1,99]\) packets per second for AIMD and AIAD, respectively.

In Figures 5, 6, 7, and 8, the value of the RCR is plotted based on the all possible INC and DEC factors for AIMD and AIAD schemes in experiments I, II, III, and IV, respectively. In experiment I, the optimal AIMD scheme is found to be the one with the INC factor of 1 and the DEC factor of 3, that is, AIMD (1, 3) that gives the maximum value of 864.5974 for the RCR (Figure 5(a)). Also, the optimal AIAD scheme in
Figure 5: The value of the RCR based on the all possible INC and DEC factors for AIMD and AIAD schemes in experiment I.

(a) The AIMD (1, 3) scheme is obtained as the optimal scheme to maximize the RCR

(b) The AIAD (1, 32) scheme is obtained as the optimal scheme to maximize the RCR

Figure 6: The value of the RCR based on the all possible INC and DEC factors for AIMD and AIAD schemes in experiment II.

(a) The AIMD (1, 3) scheme is obtained as the optimal scheme to maximize the RCR

(b) The AIAD (1, 26) scheme is obtained as the optimal scheme to maximize the RCR

Figure 7: The value of the RCR based on the all possible INC and DEC factors for AIMD and AIAD schemes in experiment III.

(a) The AIMD (1, 3) scheme is obtained as the optimal scheme to maximize the RCR

(b) The AIAD (1, 18) scheme is obtained as the optimal scheme to maximize the RCR

Figure 8: The value of the RCR based on the all possible INC and DEC factors for AIMD and AIAD schemes in experiment IV.

(a) The AIMD (1, 3) scheme is obtained as the optimal scheme to maximize the RCR

(b) The AIAD (1, 18) scheme is obtained as the optimal scheme to maximize the RCR
experiment I is obtained to be the AIAD (1, 32) scheme with the RCR value of 863.771 (Figure 5(b)). In experiment II, the AIMD (1, 3) and the AIAD (1, 26) are obtained as the optimal schemes with the RCR maximum values of 591.1750 and 589.2905, respectively (Figures 6(a) and 6(b)). The scheme AIMD (1, 3) with the RCR value of 303.1627 and the AIAD (1, 18) with the RCR value of 301.7117 are obtained as the optimal schemes in experiment III which are demonstrated in Figures 7(a) and 7(b). In experiment IV, the scheme AIMD (1, 3) with the RCR value of 1153.4 and the AIAD (1, 37) with the RCR value of 1153.3 are obtained as the optimal schemes (Figures 8(a) and 8(b)).

As it can be seen in the simulation results, the AIMD (1, 3) is the optimal scheme in all experiments. The optimal AIAD scheme is different in various experiments. The INC factor of the optimal AIAD is one in all experiments. However, the value of DEC factor is 32, 26, 18, and 37 in experiments I, II, III, and IV, respectively. Hence, the optimal AIMD and AIAD schemes obtained based on the simulations verify the calculated optimal schemes with regard to the proposed semi-Markov chain (SMC) of the sending rate of the collecting CR sensors and the congestion model.

7. Conclusions

In this paper, we have investigated the optimality of generic rate-based AIMD and AIAD congestion control schemes. In this way, a congestion model is proposed to describe the congestion behavior of CRSNs. Based on the congestion model, the steady-state sending rate of collecting CR sensors has been modeled through the proposed semi-Markov chain (SMC). With regard to the congestion model and the sending rate distribution, we have defined the RCR as the ratio of mean sending rate over mean congestion probability. In order to maximize the RCR, the optimality of AIMD and AIAD schemes has been investigated based on the proposed models. In particular, the AIMD scheme with the rate increasing factor of 1 and rate decreasing factor of 3, that is, AIMD (1, 3), has been calculated as the optimal scheme for the maximum sending rate of 100 packets per time unit. The analytical results have been verified through the NS2-based simulations for CRSNs.

Future study in this research area could be obtaining a closed-form formula for RCR and maximizing it with regard to the parameters such as spectrum sensing time and period of CR nodes.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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