Cross-Layer Design for TCP Performance Improvement in Cognitive Radio Networks

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***Abstract*—In cognitive radio (CR) networks, the end-to-end transmission-control protocol (TCP) performance experienced by secondary users is a very important factor that evaluates the secondary user perceived quality of service (QoS). Most previous works in CR networks ignore the TCP performance. In this paper, we take a cross-layer design approach to jointly consider the spectrum sensing, access decision, physical-layer modulation and coding scheme, and data-link layer frame size in CR networks to maximize the TCP throughput in CR networks. The wireless channel and the primary network usage are modeled as a finite-state Markov process. Due to the miss detection and the estimation error experienced by secondary users, the system state cannot be directly observed. Consequently, we formulate the cross-layer TCP throughput optimization problem as a partially observable Markov decision process (POMDP). Simulation results show that the design parameters in CR networks have a significant impact on the TCP throughput, and the TCP throughput can be substantially improved if the low-layer parameters in CR networks are optimized jointly.**

***Index Terms*—Cognitive radio (CR) networks, cross-layer design, transmission control protocol (TCP) throughput.**

I. Introduction

With a variety of existing and emerging wireless applications, the radio spectrum demand has been increased dramatically, and a few available spectrum bands can be allocated. However, as pointed out by the Federal Communications Commission's spectrum report, some spectrum bands are underutilized due to the existing amount of idle spectrum hole at spatial and temporal dimensions [1]. Cognitive radio (CR), which was introduced in [2], is a key enabling technology that allows unlicensed (secondary) users to operate in the licensed spectrum bands. A device with cognitive capability (i.e., secondary user) can sense its surrounding radio environment and adaptively adjust its operating parameters in the physical/data-link layers [3], [4]. For instance, a secondary user can reconfigure the operating frequency, modulation type and coding, transmission power, and the frame size according to its environment [3].

Dynamic spectrum access (DSA) is an important application of CR technologies. Using DSA, secondary users can use the licensed spectrum for wireless communications in the licensed band. Since secondary users are considered lower priority, a requirement is to avoid the interference to primary users in their vicinity. The access opportunities are sensed and used by secondary users in the temporal and spatial dimensions [5]. An optimal spectrum-sensing strategy is proposed in [6] to maximize throughput. A separation principle is established in [7] to decouple the design of the sensing strategy from that of the spectrum sensor and the access strategy. Spectrum opportunity is exploited in the time domain in [8], where an *ad hoc* secondary media-access-control (MAC) layer protocol is presented to facilitate DSA. An effective scheme of discovering spectrum opportunities is proposed in [9]. The authors in [10]–[12] present a cooperative spectrum-sensing method. A game theoretical dynamic spectrum-sharing framework is presented in [13] and [14], where network users' behaviors and efficient dynamic distributed design are analyzed. In [15], three different spectrum-sharing models are presented for different objectives of spectrum trading between spectrum sellers and spectrum buyers. A spectrum-sharing policy is exploited in [16], where power/channel allocation is jointly considered to improve the throughput. The authors in [17] studied the sensing-throughput tradeoff problem in CR networks.

Although some research activities have been conducted in CR networks, most of them consider sensing effectiveness and spectrum utilization as system design criteria. As a result, other performance parameters in the upper layers, such as transmission control protocol (TCP) throughput, are mostly ignored in the literature. However, the TCP is, by far, one of the most important transport protocols that are used by many of the Internet's popular applications, including the World Wide Web, File Transfer Protocol, and some streaming media applications. Therefore, there is a strong motivation to consider TCP performance in CR networks. It is well known that the TCP may suffer from severe performance degradation in wireless networks [18]. This problem may be more severe in CR networks compared with traditional wireless networks since CR-based secondary

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users would have strictly lower quality of service (QoS) than those who enjoy guaranteed spectrum access [19]. Therefore, if the TCP is not carefully considered in CR networks, the perceived TCP performance degradation by secondary users may impede the success of CR technologies.

Recently, many schemes have been proposed to modify the standard TCP taking into account the characteristics of wireless networks to remedy its deficiency [20], [21]. However, the TCP has become the *de facto* standard used in thousands of millions of hosts for many Internet applications. It is very difficult, if not impossible, to modify it according to the characteristics of specific wireless networks, which are merely the access networks in the global Internet. Moreover, it is suggested from the Internet community that wireless networks should be optimized for the standard TCP rather than modifying the standard TCP to adapt to wireless networks [22].

In recent years, researchers have proposed many schemes to improve wireless network performance from a cross-layer design perspective. The authors in [23] jointly consider adaptive modulation and coding (AMC) at the physical layer and automatic repeat request (ARQ) at the data-link layer to maximize the physical throughput. In [24], the authors explore the use of rate adaptation in cellular networks to maximize the TCP throughput. Based on TCP congestion window dynamics and wireless channel conditions, link-layer transmission modes are selected to maximize the TCP throughput in [25]. In [26], the authors propose a general cross-layer TCP modeling framework that considers diverse system characteristics for multiple-input–multiple-output wireless systems, such as fading, the space–time transmission scheme, modulation, channel coding, and ARQ. We are inspired by these previous works to investigate the TCP performance improvement problem over CR networks from a cross-layer design perspective. To the best of our knowledge, CR networks are not considered in the previous works.

In this paper, we take a cross-layer design approach to optimize the TCP throughput over CR networks without modifying the standard TCP. Some distinct features of the proposed scheme are as follows.

- Spectrum sensing, access decision, physical-layer modulation and coding scheme, and data-link layer frame size in CR networks are concurrently optimized to maximize the TCP throughput.
- The time variations of the primary network usage and the wireless channel are modeled as a first-order, finite-state Markov process. With channel miss detection and channel estimation deviation, the state cannot be directly observed. Following the work in [6] and [7], we formulate the CR system as a partially observable Markov decision process (POMDP) [27]. We extend the scheme to jointly optimize the TCP throughput in CR networks.
- Using simulation examples, we show that the design parameters in CR networks have significant impact on the TCP throughput. In addition, we show that the TCP throughput can be substantially improved if the low-layer parameters in CR networks are optimized jointly. A number of interesting observations are presented, which may give insights into the design of future CR networks.

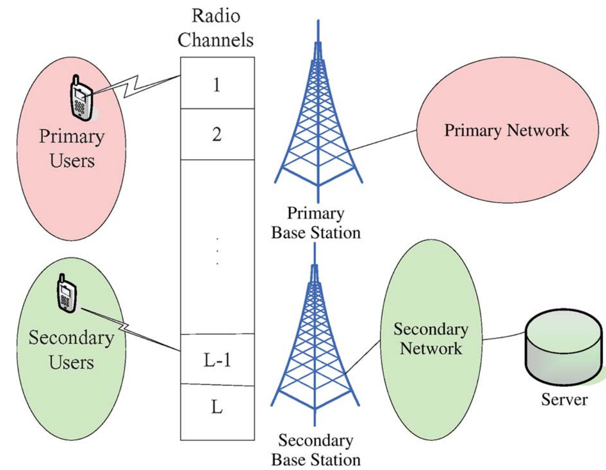

Fig. 1. Network model of a CR network. Primary users and secondary users access their base stations using L-shared radio channels. The primary-based station connects to the primary network, while the secondary base station connects to a server via a secondary network.

The rest of this paper is organized as follows. Section II describes the problem of the TCP throughput in CR networks. Section III presents the proposed scheme. Some simulation results are given in Section IV. Finally, conclusions are given in Section V.

II. Transmission Control Protocol Throughput in Cognitive Radio Networks

Here, we describe the models used in this paper for TCP traffic in CR networks.

A. Network Model

We consider a CR network with primary users and secondary users. Primary users send their data to their corresponding destinations via a primary network. On the other hand, secondary users access a server via a secondary network, as shown in Fig. 1. Both primary users and secondary users share a block of a spectrum consisting of L radio channels, each with bandwidth $W(l)$, $1 \leq l \leq L$. Time is divided into slots with equal length T, and slot k refers to the discrete time period $[kT, (k+1) \cdot T]$. In particular, to address the channel competition among secondary users, we assume that the secondary user obtains the channel access right through the request-to-send–clear-to-send (RTS–CTS) handshake, as proposed in [28]. If a secondary user fails in a slot, its sensing outcome and the corresponding decision result will be saved in the decision system. Hence, the contention problem will not impact the decision in the next slot.

The cross-layer optimization architecture is presented in Fig. 2. Based on the history of observations and action decisions, the secondary user will determine whether to sense the channel. If a sensing action is selected, the cognitive sensor will observe the channel and obtain the sense outcomes. The sensing outcomes are directly sent to the TCP layer. To maximize the TCP throughput, the secondary user will determine whether to access the channel and the corresponding modulation and coding scheme at the physical layer and the frame size at the data-link layer. Consequently, it will feed back the three

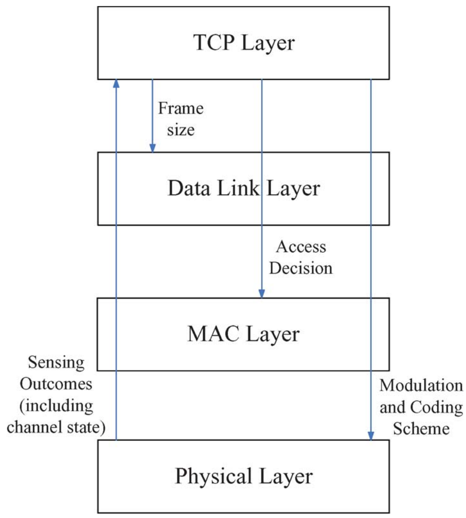

Fig. 2. Cross-layer optimization for TCP flow over CR networks.

decisions to the MAC layer, the physical layer, and the data-link layer, respectively.

B. TCP Throughput Model

The TCP, which is a connection-oriented protocol, provides more facilities for applications than the user datagram protocol, notably, error recovery, flow control, and reliability. It can adapt the sender's rate to network capacity, attempt to avoid potential congestion situations, and further provide reliable end-to-end data transmission [29]. The TCP employs a sliding-window mechanism to control the sending rate at the sender and, consequently, avoid potential network congestion. The size of the sliding window corresponds to the maximum amount of data that the TCP can inject into the network before being acknowledged. It also provides a retransmission mechanism that is used to guarantee the reliability. If the acknowledgment (ACK) is not received within a timeout interval, the TCP packet will be retransmitted. Once the sender identifies loss of data, the TCP immediately reacts to the loss by aggressively reducing its transmission window size before retransmitting.

The TCP congestion control algorithm contains four basic intertwined algorithms: slow start, congestion avoidance, fast retransmit, and fast recovery. These algorithms work together to prevent a sender from overrunning the capacity of the network. Until now, several TCP algorithms have been proposed to improve TCP performance and produce several TCP versions, such as Tahoe, Reno/New-Reno, and Vegas [30], [31]. TCP Tahoe can achieve slow start, congestion avoidance, and fast retransmit. TCP Reno/New-Reno extends Tahoe by adding fast recovery mechanism. TCP Vegas is different from other TCP versions by introducing some recent modifications.

In this paper, we use TCP Reno as the transport layer protocol. The Reno version is similar to Tahoe except for a modified fast retransmit algorithm and a new fast recovery algorithm. In Reno, fast retransmit is entered by a TCP sender after receiving a threshold number of duplicate ACKs. The sender retransmits the lost packet and reduces its congestion window by half. The Reno sender retransmits at most one dropped packet per roundtrip time.

The steady-state performance of TCP flow may be characterized by the throughput, which is the amount of data received by the receiver in unit time. It is one of the important factors that indicate TCP performance. A simple analytical model for the TCP throughput is developed in [32] and [33] as follows:

$$B(\mathrm{RTT}, T_0, b, p) \approx \frac{1}{\mathrm{RTT} \cdot \sqrt{\frac{2bp}{3}} + T_0 \cdot \min\left(1, 3\sqrt{\frac{3bp}{8}}\right) p(1+32p^2)} \quad (1)$$

where p is the packet loss probability, RTT is the roundtrip time, T_0 is the initial timeout, and b is the number of packets that are acknowledged by a received ACK (b is typically 2). In addition, since the TCP throughput is also confined by the maximum congestion window $cwnd$, the TCP throughput B is expressed as

$$B(cwnd, \mathrm{RTT}, T_0, b, p) = \min\left(\frac{cwnd}{\mathrm{RTT}}, B(\mathrm{RTT}, T_0, b, p)\right). \quad (2)$$

Assume that a secondary user would like to access a server in the Internet. In CR networks, the bit error rate (BER) is determined by the sensing selection, access policy, and physical-layer design parameters, such as spectrum sensing, access decision, the modulation and coding scheme, etc. As a consequence, for given sensed outcomes and design parameters in CR networks, the data rate r and BER can be obtained. Furthermore, in wireless TCP networks, the packet loss is mainly due to wireless fading channels, which is a common assumption in the literature [24]. Consequently, the packet loss probability p is approximately equal to the packet error rate, which is a function of BER and data-link layer parameters, such as frame size and ARQ.

To obtain an exact closed-form packet loss rate p under AMC with the ARQ scheme, we adopt the following BER expression [34]:

$$\mathrm{BER} = k_1 \cdot \exp\left(-\frac{k_2 \gamma p_{\mathrm{tr}}}{2^{\rho} - 1}\right) \quad (3)$$

where γ is the channel gain, p_{tr} is the transmit power, ρ is the AMC rate, and constants k_1 and k_2 are related to the specific constellation and code. For example, the parameters $k_1 = 0.2$ (or 2) and $k_2 = 1.5$ for M-order quadrature amplitude modulation, and $k_1 = 0.05$ (or 0.2, 0.25) and $k_2 = 6$ (or 7, 8) for multiple phase-shift keying modulation [35, ch. 9]. When an AMC mode is scheduled for data transmission, it is composed of a modulation scheme with rate ρ^{mod} and a channel code with rate ρ^{cod}, and the AMC rate $\rho = \rho^{\mathrm{mod}} \cdot \rho^{\mathrm{cod}}$ [34].

Furthermore, for a given TCP packet with length L_{TCP}, it will be divided into several smaller frames in the data-link layer over the CR network. Assume that the length of a frame header is L_{frh} and the number of frames per TCP packet is N_{fr}; thus, we can obtain the length of a frame $L_{\mathrm{fr}} = (L_{\mathrm{TCP}}/N_{\mathrm{fr}}) + L_{\mathrm{frh}}$. Hence, the probability of a frame error F_e can be derived, i.e.,

$$F_e = 1 - (1 - \mathrm{BER})^{L_{\mathrm{fr}}}. \quad (4)$$

Under the ARQ scheme, a frame transmission is successful only if the number of retransmissions is less than the maximum. Hence, given the maximum of retransmission number N_{re}, the frame error rate with ARQ is $F_e^{N_{\text{re}}+1}$.

A TCP packet will be successfully transmitted if all frames are received successfully. As a result, the packet error probability P_e can be obtained by the following:

$$P_e = 1 - \left(1 - F_e^{N_{\text{re}}+1}\right)^{N_{\text{fr}}}. \tag{5}$$

Therefore, we can get the approximate packet loss probability $p = P_e$. According to a basic ARQ protocol, each of the ACK frames will be returned to the sender when a frame is received at the corresponding end. Hence, the roundtrip time for a TCP packet can be approximately stated as follows:

$$\text{RTT} = 2 \cdot T_{\text{wired}} + \left(\frac{L_{\text{fr}}}{r} \cdot (N_{\text{ave}} + 1) + \frac{L_{\text{ack}}}{r}\right) \cdot N_{\text{fr}} \tag{6}$$

where T_{wired} is the delay of the TCP packet through the wired path, and r is the data rate of the wireless link. L_{fr} and L_{ack} are the length of data contained in a frame and an ACK frame, respectively. N_{ave} is the average number of retransmissions for one frame, which is determined as follows:

$$\begin{aligned} N_{\text{ave}} &= \left[F_e + 2F_e^2 + \cdots + N_{\text{re}} \cdot F_e^{N_{\text{re}}}\right](1 - F_e) \\ &= \left(F_e - F_e^{N_{\text{re}}+1}\right)/(1 - F_e) - N_{\text{re}} \cdot F_e^{N_{\text{re}}+1}. \end{aligned} \tag{7}$$

From the above equations, we can see that the physical/data-link layer design parameters in CR networks will contribute to the TCP throughput. In this paper, we focus on the two parameters: the modulation and coding scheme at the physical layer and the frame size at the data-link layer. These parameters are adaptively selected to maximize the TCP throughput. This is very different from other existing AMC schemes, such as those described in [35], where the modulation and coding scheme is adaptively adjusted based on the BER.

C. Channel Model

In wireless networks, wireless channels are not stable and often suffer from fading. A finite-state Markov channel (FSMC) model has been widely accepted as an effective approach to characterize the structure of the fading process [36]–[39]. In general, an FSMC model is constructed by partitioning first the range of the channel gain into discrete levels. Then, each level corresponds to a state in the Markov chain.

Let i denote the instantaneous channel state. When the channel is in state i, the corresponding fading gain is γ_i, where $\gamma_i \leq \gamma \leq \gamma_{i+1}$, $1 \leq i \leq S-1$. In CR networks, the state that is occupied by a primary user occurs stochastically, which is similar to fading gain change; thus, we model this state as one of the states in the Markov chain. In other words, when the channel is in state $i = S$, the channel is in use by a primary user.

The S-state Markov channel model is completely described by its stationary distribution of each channel state i, which is denoted by $p(i)$, and the probability of transitioning from state i into state j at the beginning of each time slot, which is denoted by $p(i, j)$, $1 \leq i, j \leq S$. The state-transition probability in the Rayleigh fading channel $p(i, j)$ $(i, j \neq S)$ can be approximated as [39]

$$p(i,j) \approx \begin{cases} \dfrac{\sqrt{\frac{2\pi\Gamma_j}{\Gamma_{\text{Avg}}}}\exp\left(-\frac{\Gamma_j}{\Gamma_{\text{Avg}}}\right)T_p}{\exp\left(-\frac{\Gamma_i}{\Gamma_{\text{Avg}}}\right) - \exp\left(-\frac{\Gamma_j}{\Gamma_{\text{Avg}}}\right)}, & \text{if } j = i+1 \\ & i = 1, 2, \ldots, S-2 \\ \dfrac{\sqrt{\frac{2\pi\Gamma_i}{\Gamma_{\text{Avg}}}}\exp\left(-\frac{\Gamma_i}{\Gamma_{\text{Avg}}}\right)T_p}{\exp\left(-\frac{\Gamma_i}{\Gamma_{\text{Avg}}}\right) - \exp\left(-\frac{\Gamma_j}{\Gamma_{\text{Avg}}}\right)}, & \text{if } j = i-1 \\ & i = 2, 3, \ldots, S-1 \end{cases}$$

where Γ_i and Γ_j are the channel gains corresponding to states i and j, respectively, Γ_{Avg} is the expected channel gain, and T_p is the packet duration. Given the knowledge of the fading process, the transition probability between available states and the busy state, and the probability of the primary user staying in the same state, the stationary distribution $p(i)$ and the channel transition matrix $T = \{p(i, j)\}$ can be derived.

III. Solving the Transmission Control Protocol Throughput Over the Cognitive Radio Problem

Here, we formulate the TCP throughput-optimization problem in CR networks as a POMDP system, which can determine the optimal policy for channel sensing selection, sensor operating point, access decision, selection of the modulation and coding scheme, and the frame size to maximize the TCP throughput in CR networks.

Due to channel sensing and channel state information errors, the system state cannot be directly observed. As a result, we formulate the whole system as a POMDP system [40] following the recent related work in [6] and [41]. Deriving a single POMDP formulation for all policies under the probability of a collision constraint would lead to a constrained POMDP. Constrained POMDPs, however, require randomized policies to achieve optimality, which is often intractable. Hence, we use the separation principle in [41] for the sensor operating point and the access decision. The spectrum sensor operating point is set such that $\sigma = \zeta$, where σ is the probability of miss detection of the busy channel that is used by primary users, and ζ is the required probability of collision.

We assume that the system transitions to a new state at the beginning of each slot. Using a POMDP-derived policy, a channel is selected for spectrum sensing. Based on the sensing observation, an access decision is then made. Then, the system jointly considers the modulation and coding scheme in the physical layer and the frame size in the data-link layer to maximize the TCP throughput. The immediate reward for the time slot is derived based on the previous operations in the slot.

A. State Space, Transition Probabilities, and Observation Space

In each time slot, the system state is characterized by the network usage of a primary user and channel-state information. Let $x(l)$ denote one of the states in the S-state Markov chain for channel l, $x(l) \in X$, where $X = \{1, 2, \ldots, S-1, S\}$. The system with L channels is modeled as a discrete-time homogeneous Markov process with S^L states. The system state in time slot k is given by $V_k = [X_k(1), \ldots, X_k(L)]$. We consider a system with a single channel in the formulation for simplicity of presentation. It can be straightforwardly extended to include multiple channels.

In practice, the channel states always transition independently of the action taken. This is a particular POMDP model. For a system with a single channel, $V_k = X_k$. The transition probabilities of the system state are given by the $S \times S$ matrix T. Moreover, the transition probability is known based on network usage by primary users and channel-fading characteristics determined by the equation of $P(i, j)$.

The observation that is available to the secondary user is the sensed channel outcome, i.e., $\theta_k \in \Theta$, where $\Theta = \{\gamma_1, \ldots, \gamma_{S-1}, \gamma_S \quad \text{(The channel is used by primary users)}\}$ and $\gamma_i < \gamma_j$, $\forall i < j$. Due to channel estimation errors and some mistake of detection, the secondary user cannot have full knowledge of the channel occupancy state and the channel gain in each slot.

The observation is related to the capability of sensor and channel estimation technology. Let $b_{j,\theta}^a = \Pr\{\theta | j, a\}$ denote the probability that the sensor observes θ when the system state is j, and composite action a in the last slot was taken, i.e.,

$$b_{j,\theta}^a = \Pr\{\theta | j, a\} = \begin{cases} 1, & \text{if } \theta = \gamma_S, j = S \\ \epsilon, & \text{if } \theta = \gamma_S, j \neq S \\ P_{\text{ce}}\left(j, v(\theta)\right)(1-\epsilon), & \text{otherwise} \end{cases} \tag{8}$$

where ϵ is the probability of miss detection of the idle channel, and $v(\theta) = i$, $1 < i < S$, given $\theta = \gamma_i$. When the channel is available and accessed, the probability of channel estimation by the receiver is given by $P_{\text{ce}}(x, v(\theta))$.

Using the work in [42], we assume that the channel estimation error has a Gaussian distribution with zero mean and σ^2 variance. At a particular time and channel, the estimated channel gain is

$$\hat{\gamma} = \gamma_i + \omega \tag{9}$$

where σ_i is the actual channel gain, and ω is a Gaussian random variable with zero mean and σ^2 variance. The receiver then quantizes the channel gain to the closest value. The probability that $\hat{\gamma}$ is closest to γ_j is given by

$$P_{\text{ce}}(i, j) = \begin{cases} \frac{1}{2}\left[\operatorname{erf}\left(\frac{\gamma_j+\gamma_{j+1}-2\gamma_i}{2\sqrt{2}\sigma}\right) - \operatorname{erf}\left(\frac{\gamma_j+\gamma_{j-1}-2\gamma_i}{2\sqrt{2}\sigma}\right)\right], & \text{if } j \neq 1, S-1, S \\ \frac{1}{2}\left[1+\operatorname{erf}\left(\frac{\gamma_1+\gamma_1-2\gamma_i}{2\sqrt{2}\sigma}\right)\right], & \text{if } j = 1 \\ \frac{1}{2}\left[1-\operatorname{erf}\left(\frac{\gamma_{s-2}+\gamma_{s-1}-2\gamma_i}{2\sqrt{2}\sigma}\right)\right], & \text{if } j = S-1 \\ 0, & \text{if } j = S \end{cases} \tag{10}$$

where $\operatorname{erf}()$ denotes the error function.

B. Action Space

We will assume that a secondary user is equipped with a single Neyman–Pearson energy detector and can only sense $N_{\text{sense}} = 1$ channel at each time instant. After the state transition of the channel at the beginning of each slot k, the secondary user needs to decide whether to sense, determine which sensor operating point on the receiver operating curve (ROC) to use, decide whether to access the channel, and decide which modulation and coding scheme in the physical layer and which frame size in the data-link layer to use. Therefore, the action space A consists of five parts: a channel-sensing decision $a_s(k) \in \{0(no\_sense), 1(sense)\}$, a spectrum sensor design $(\epsilon(k), \delta(k)) \in A_{\epsilon\delta}$ where $A_{\epsilon\delta}$ are the valid points on the ROC curve, an access decision $a_a(k) \in \{0(no\_access), 1(access)\}$, a modulation and coding-scheme decision $a_m(k)$, and frame size decision $a_{fr}(k)$. The composite action in slot k is denoted by $a_k = \{a_s(k), (\epsilon(k), \delta(k)), a_a(k), a_m(k), a_{fr}(k)\}$.

C. Information State

For a POMDP model, although the system state is not directly known, the agent can use observations to learn the most likely state it is in. Depending on the observation model, directly using the observations can lead to a poor estimate of the current system state. The information state, which is also known as the belief vector, can infer the system state from its decision and observation history encapsulated by the information state.

The information state is a probability distribution over the state space. Let $\pi^k = \{\pi_0^k, \pi_1^k, \ldots, \pi_S^k\}$ denote the information space, where π_i^k represents the probability that we are currently in state i in time slot k. As will be shown later, the knowledge of the system dynamics and the transition probabilities must be known to maintain an information state.

At the end of the time slot, the information state is updated using Bayes' rule, i.e.,

$$\pi_j^{k+1} = \frac{\sum_i \pi_i^k p(i,j) b_{j\theta}^a}{\sum_{i,j} \pi_i^k p(i,j) b_{j\theta}^a}. \tag{11}$$

Given information vector π^k, the distribution of the system state X_k in the time slot k after the state transition is then given by

$$\Pr\{X_k = i\} = \sum_{j \in X} \pi_j^k p(i,j) \qquad \forall j \in X. \tag{12}$$

D. Reward and Policy

In CR networks, from a CR-based secondary user's point of view, the TCP throughput is more important than the QoS at other layers for many Internet applications. Therefore, we model the TCP throughput as the immediate reward in our formulation. The immediate reward in time slot k is defined as

$$R_k = B\left(cwnd, \text{RTT}_{i_k}^{a_k}, T_{0,k}, b, p_{i_k}^{a_k}\right) \tag{13}$$

where $\text{RTT}_{i_k}^{a_k}$ is the roundtrip time, $T_{0,k}$ is the timeout, b is the number of packets that are acknowledged by a received ACK, and $p_{i_k}^{a_k}$ denotes the packet-loss probability when the system is in state i_k, and action a_k is taken in time slot k.

The expected total reward of the POMDP depicts the overall reward over K time slots and can be expressed as

$$J_\mu = E_{\mu_s,\mu_{\epsilon\delta},\mu_a,\mu_m,\mu_{fr}}\left[\sum_{k=1}^{K} R_k\right] \quad (14)$$

where μ_s is a channel-sensing policy that specifies the sensing decision a_s. $\mu_{\epsilon\delta}$ is a sensor-operating policy that specifies a spectrum-sensor design $(\epsilon,\delta) \in \mathbb{A}_{\epsilon\delta}$ based on the system-tolerable probability of collision ζ. μ_a is an access policy that specifies the access decision a_a. μ_m and $\mu_{\rm fr}$, respectively, denote the AMC policy and the frame size policy, which specify the modulation and coding scheme a_m and frame size $a_{\rm fr}$. $E_{\{\mu_s,\mu_{\epsilon\delta},\mu_a,\mu_m,\mu_{\rm fr}\}}$ indicates the expectation given that policies μ_s, $\mu_{\epsilon\delta}$, μ_a, μ_m, and $\mu_{\rm fr}$ are employed.

E. Objective and Constraint

We aim to develop a joint design of an optimal policy for TCP performance improvement in CR networks, i.e., $\{\mu_s,\mu_{\epsilon\delta},\mu_a,\mu_m,\mu_{fr}\}$, that maximizes the expected total reward in K time slots under the collision constraint P_c, i.e.,

$$\left\{\mu_s^*,\mu_{\epsilon\delta}^*,\mu_a^*,\mu_m^*,\mu_{fr}^*\right\} = \arg\max E_{\{\mu_s,\mu_{\epsilon\delta},\mu_a,\mu_m,\mu_{fr}\}}\left[\sum_{k=1}^{K} R_k\right] \quad (15)$$

subject to

$$P_c(k) = \Pr\{a_a(k)=1|X_k=S\} < \zeta, \qquad \forall k \in K. \quad (16)$$

F. Solving the POMDP Problem

The design objective is to determine, in each slot, which composite action is taken so that the expected total reward obtained in K slots is maximized. To effectively calculate (14), we will use dynamic programming to compute the optimal policy. Referred to as the value function, $J_k(\pi_k)$ denotes the maximum expected remaining reward that can be accrued starting from slot k when the current belief vector is π_k. The value function includes two parts: 1) the immediate reward obtained in slot k, which is given by $R_k = B(cwnd, \mathrm{RTT}_k, T_{0,k}, b, p_{i_k}^{a_k})$ when the network is at state j and the user takes composite action a_k and observes θ_k; and 2) the maximum expected remaining reward $J_{k+1}(\pi_{k+1})$ starting from slot $k+1$ given a belief vector $\pi_{k+1} = U(\pi_k|a_k,\theta_k)$, which represents the updated knowledge of the system state after incorporating the action a_k and the observation θ_k in the time slot k. Averaging over all possible network states and observations, we have the following Bellman's equation:

$$J_k(\pi_k) = \max_{a\in A}\sum_{i\in X}\sum_{j\in X}\pi_i^k p(i,j)\sum_{\theta_k=\gamma_1}^{\theta_k=\gamma_S} b_{j,\theta_k}^{a_k} \times \left[R_k + J_{k+1}(U(\pi_k|a_k,\theta_k))\right], 1\le k\le K-1 \quad (17)$$

$$J_K(\pi_K) = \max_{a\in A}\sum_{i\in X}\sum_{j\in X}\pi_i^K p(i,j)\left[\sum_{\theta_k=\gamma_1}^{\theta_k=\gamma_S} b_{\theta_K,j}^{a_K} R_K\right]. \quad (18)$$

This value function with finite action space can be solved using linear programming techniques [27]. Smallwood and Sondik [43] showed that value function $J_k(\pi_k)$ is piecewise linear and convex. The domain of $J_k(\pi_k)$ can be partitioned into a finite number of convex regions $C_1(k),\ldots,C_L(k)$. Associated with each region $C_i(k)$ is a vector $\Upsilon_i(k)$ such that the value function $J_k(\pi_k)$ in this region is given by the inner product of π_i^k ($\pi_i^k \in C_i(k)$) and $\Upsilon_i(k)$. Therefore, we can obtain the following after using this structure:

$$J_k(\pi_k) = \max_{a\in A}\sum_{i\in X}\sum_{j\in X}\pi_j^k p(i,j)\sum_{\theta_k=\gamma_1}^{\theta_k=\gamma_S} b_{j,\theta_k}^{a_k} \times \left[R_k + \left\langle \pi_i^{k+1}, \Upsilon_{i_{\pi(k+1)}}(k+1)\right\rangle\right], 1\le k\le K-1 \quad (19)$$

where $\langle\cdot,\cdot\rangle$ denotes the inner product, and $i_{\pi(k+1)}$ is the index of the region containing the updated belief vector $\pi(k+1) = U(\pi_k|a_k,\theta_k)$. Thus, if the convex regions $\{C_i(k+1)\}$ and the associated Υ-vectors $\Upsilon_i(k+1)$ have been calculated for slot $k+1$, we can obtain from (19) the optimal actions and the corresponding c-vectors for slot t. Note that, in a real system, solving the POMDP can be done offline during system initialization, and the results can be stored in a table. During the TCP flow transmission, a node just needs to find the value for specific information state according to (17) and update the information state according to (11), which introduces little computational complexity.

IV. Simulation Results and Discussions

Here, we illustrate the performance of the proposed scheme by simulations. We use the NS2.29 simulator in our simulations. The TCP version is TCP Reno. The network scenario in the simulations is depicted in Fig. 1. Ten users (including five primary users and five secondary users) are randomly distributed on a 1000×1000 m field. We configure that primary users occupy a wireless channel according to a predefined probability. The bandwidth between a base station and a server is set to 100 Mb/s, and the experienced delay that a packet passes through the wired network is set to be $T_{\rm wired} = 15$ ms. The TCP packet size is $L_{\rm TCP} = 1500$ bytes. The maximum number of retransmissions for a TCP packet is $N_{\rm re} = 5$. The maximum congestion window is $cwnd = 6000$ bytes, and the initial timeout is $T_0 = 2$ s. In the data-link layer, the ARQ protocol is used, and the maximum number of retransmissions is $N_{\rm fr} = 10$ for a frame. The length of the frame header is $L_{\rm frh} = 20$ bits. Moreover, the length of the ACK frame is $L_{\rm ack} = 24$ bits. There are four modulation schemes from which a secondary user can choose: binary phase-shift keying, quaternary phase-shift keying, eight-phase-shift keying, and 16-quadrature amplitude modulation. For simplicity of the presentation, we use one coding scheme, rate 3/4 turbo code, together with four modulation schemes in our simulations. For each wireless channel, the bandwidth is set to be 1 MHz; thus, we can obtain the data rate r for each modulation and coding scheme. After a warm-up time of 100 s, one TCP connection is established over which an FTP is conducted. We assume that the sender always has data to send.

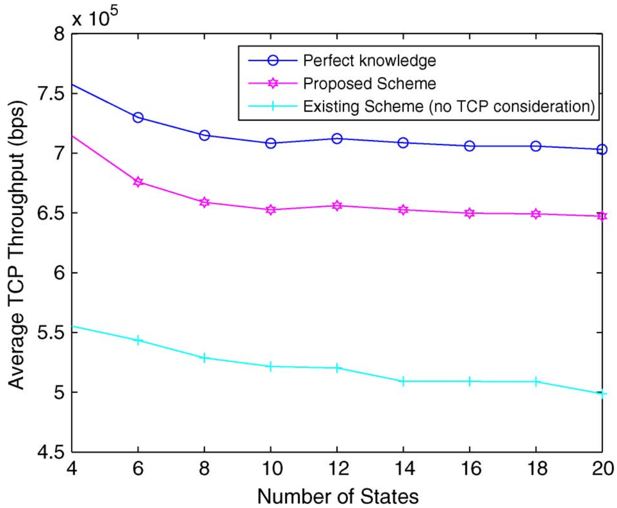

Fig. 3. Average TCP throughput versus the number of states.

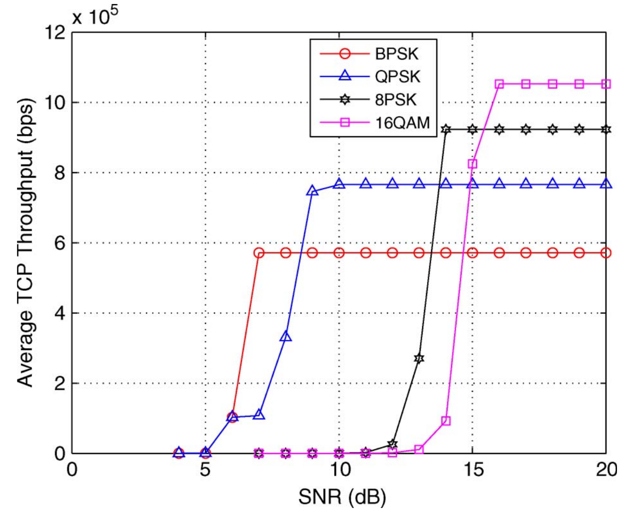

Fig. 4. TCP throughput for different modulation schemes.

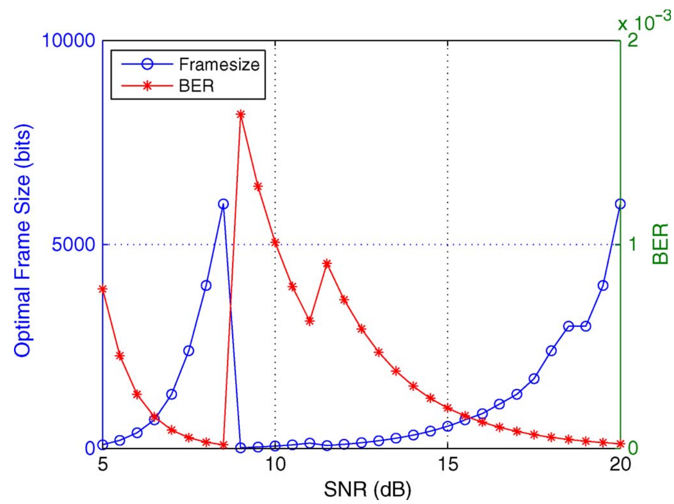

Fig. 5. Optimal frame size for maximizing the TCP throughput.

We consider the system performance in the following three cases: 1) using perfect knowledge of the system and, thus, making perfect decisions, which can obtain the maximum TCP throughput; 2) making decisions based on the most likely state indicated by the information state, which is our proposed scheme; and 3) an existing scheme in which the modulation and coding scheme is adjusted based on the maximum physical-layer throughput rather than the TCP throughput in CR networks [35, ch, 9]. We apply an average TCP throughput metric that refers to the average TCP throughput over the time slots. The choice for the total time slot number K in the dynamic programming depends on the convergence rate of the POMDP program, which is influenced by the state-transition probabilities, observation probabilities, and value functions [27], [40]. In our simulations, the POMDP program is run over a horizon of $K = 300$. We found that it is reasonable to use $K = 300$ to approximate the problem with an infinite horizon.

A. TCP Throughput Performance Improvement

Fig. 3 illustrates the average TCP throughput for different schemes. The number of states refers to $|S| - 1$ quantized channel gains and one busy channel state that is occupied by a primary user. The transition matrix is constructed based on the probability that any available channel state stays in the same state in the next time slot, i.e., $\Pr\{X_{k+1} = v | X_k = v\}$, the probability of transitioning from an available state to the busy state, i.e., $\Pr\{X_{k+1} = z | X_k = v\}$, and the probability of dwelling in the busy state, i.e., $\Pr\{X_{k+1} = z | X_k = z\}$, $\forall v \in \{1, 2, \ldots, S-1\}$, $z = S$, where v and z indicate the available and busy states, respectively. Also, we assume that the probability of transitioning from one available state to another available state $\Pr\{X_{x+1} = v' | X_k = v\}$ is equal among these available states. The following parameter settings are used in this example: $\Pr\{X_{k+1} = v | X_k = v\} = 0.9$, $\Pr\{X_{k+1} = z | X_k = v\} = 0.05$, $\Pr\{X_{k+1} = z | X_k = v\} = 0.1$, $\sigma = 0.5$, $\epsilon = 0.1$.

From Fig. 3, we can see that when perfect knowledge of the channel state is available, perfect decisions can be made for each time slot; thus, the perfect scheme has the highest average TCP throughput. In practice, however, the system cannot obtain perfect knowledge due to the presence of detection error and sensing error. Our proposed scheme uses the information state that is a sufficient statistic for the decision and observation history to select the most likely optimal decisions. This method is quite close to the perfect case. In addition, the scheme without jointly considering the TCP in the CR network has the worse performance, which shows the need to jointly consider parameters in different layers for TCP transmission over CR networks.

B. Effects of Physical and Data-Link Layer Design Parameters

In CR networks, when a secondary user senses that the channel gain is γ, it will decide whether to access this channel. Once an access decision is made, an optimal modulation and coding scheme and an optimal frame size need to be selected to maximize the TCP throughput. Figs. 4 and 5 show the effects of the modulation and coding scheme in the physical layer and the frame size in the data-link layer on the TCP throughput, respectively. Fig. 4 illustrates the change of the TCP throughput under different modulation and coding schemes as the channel gain increases. It is well known that higher order modulation can lead to higher throughput in the physical layer. Nevertheless, it may not result in higher TCP throughput. The reason is that higher order modulation can cause higher bit-error probability and packet-loss probability, which will degrade the TCP throughput performance. As illustrated in Fig. 4, when the channel is in a bad state, using a low-order modulation and coding scheme can obtain higher TCP throughput than that using a higher order modulation and coding scheme. When the channel condition is getting better, the TCP throughput for higher modulation and coding schemes is also increasing due to a lower packet loss probability in this condition. Note that the AMC scheme in traditional physical-layer research may have similar results as those in Fig. 4. However, we consider the TCP throughput in CR networks in this paper and not the physical-layer throughput, which is considered in most existing works. Therefore, the physical-layer design parameter (i.e., which modulation and coding scheme should be selected according to the sensed channel by a secondary user) in our scheme is different from that in most existing works.

Fig. 5 shows the optimal frame size in the data-link layer and its corresponding BER at that moment. For a sensed channel gain, we can obtain an optimal frame size in the data-link layer and the corresponding modulation and coding scheme to maximize the TCP throughput. The smaller the frame size in the data-link layer, the lower the packet-loss probability for a specific modulation and coding scheme under a given channel gain. However, the increase in the number of frames will result in more overhead (e.g., data-link layer headers) and more processing time (e.g., ARQ retransmission), which will degrade the TCP throughput. Hence, an optimal frame size is needed to obtain the optimal TCP performance. As illustrated in Fig. 5, the frame size increases as the channel quality becomes better. However, the frame size steeply drops when the signal-to-noise ratio is better than 9 dB. This is because a new higher order modulation and coding scheme is deployed to get higher TCP throughput. In addition, as shown in Fig. 5, the number of optimal frame sizes gets very large when the BER gets lower. This observation indicates that a larger frame can be formed at the data-link layer to reduce the number of transmissions when the achievable BER is lower.

From these figures, we can see that the design parameters at physical/data-link layers have significant impact on the TCP throughput in CR networks. The TCP throughput can be substantially improved if the low-layer design parameters in CR networks are optimized jointly.

C. Effects of the Parameters in the State Transition Matrix

We evaluate how the parameters in the transition matrix affect the average TCP throughput. Figs. 6 and 7 show the simulation results for the effects of the probability of staying in the same available states, the probability of transitioning from an available state to the busy state, and the probability of dwelling in the busy state, respectively. The probability of transitioning from one available state to another one is equal among these available states. In Fig. 6, there are ten states, and $\epsilon = 0.2$, $\delta = 0.5$, $\Pr\{X_{k+1} = z|X_k = v\} = 0.05$, and $\Pr\{X_{k+1} = z|X_k = z\} = 0.1$. The TCP throughput in our proposed scheme gradually approaches to that in the perfect knowledge case with the increasing probability of staying in the same state. The reason is that it is easier to predict the actual system state as the probability of staying in the same state increases. In Fig. 7, ten states are also used, and $\epsilon = 0.2$, $\sigma = 0.5$, $\Pr\{X_{k+1} = v|X_k = v\} = 0.85$, and $\Pr\{X_{k+1} = z|X_k = z\} = 0.1$. Fig. 7 shows that the probability of transitioning to the busy state has little influence on the TCP throughput of the proposed scheme.

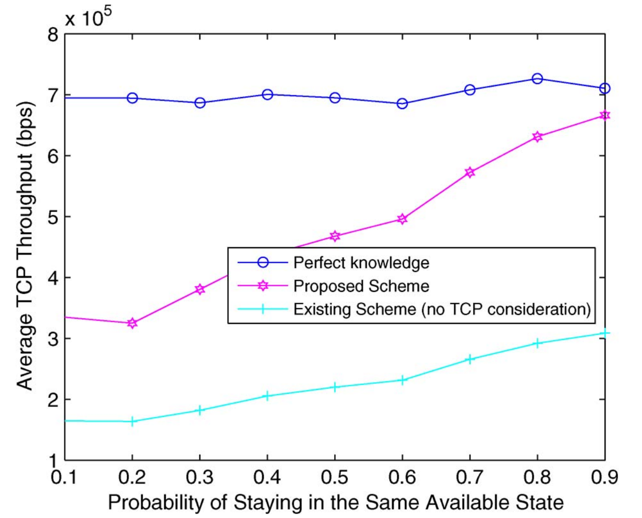

Fig. 6. Average TCP throughput versus the probability of staying in the same state.

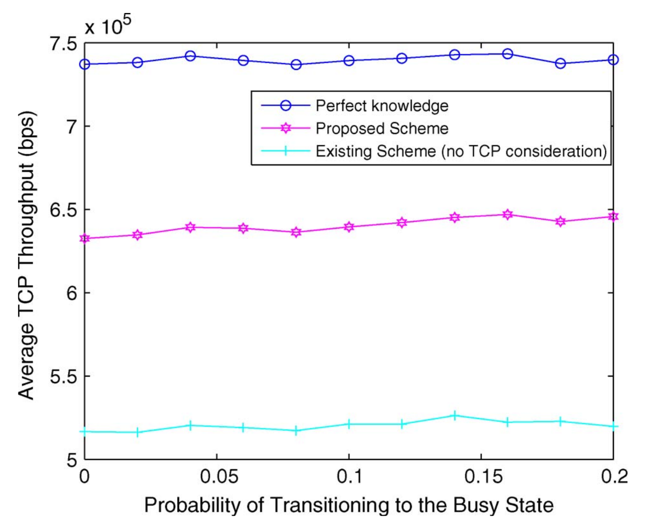

Fig. 7. Average TCP throughput versus the probability of transitioning to the busy state.

D. Effects of the Parameters in the Observation Matrix

The observation matrix is derived from the probability of sensing error ϵ and the standard deviation of the receiver channel-estimation error σ. Figs. 8 and 9 illustrate how ϵ and σ affect the average TCP throughput. ϵ and δ are related based on the sensor ROC, and adjusting ϵ implies a change to the system probability of collision requirement. In Fig. 8,

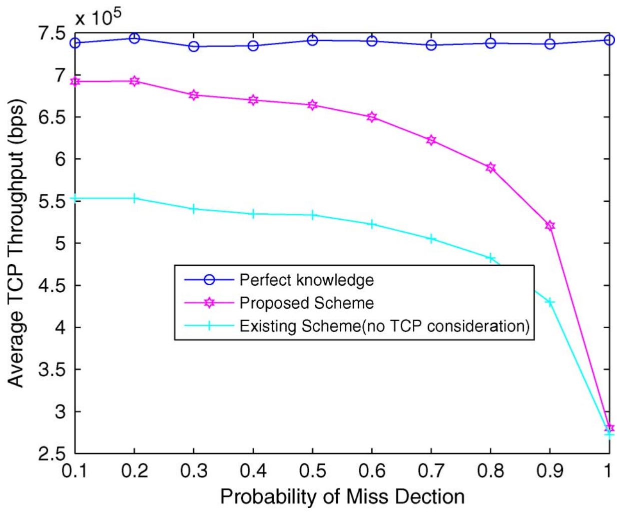

Fig. 8. Average TCP throughput versus the probability of miss detection.

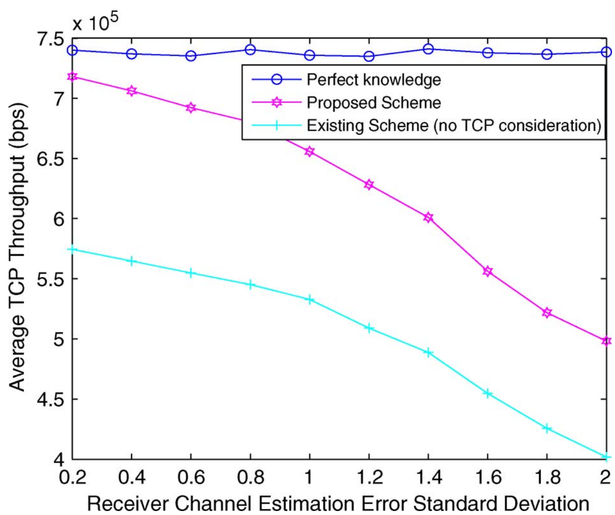

Fig. 9. Average TCP throughput versus channel-estimation error standard deviation.

there are ten states, and $\sigma = 0.5$, $\Pr\{X_{k+1} = v | X_k = v\} = 0.9$, $\Pr\{X_{k+1} = z | X_k = z\} = 0.1$, and $\Pr\{X_{k+1} = z | X_k = v\} = 0.05$. This figure shows that the average TCP throughput decreases as the probability of miss detection increases. It will increase the likelihood that the system makes a wrong decision that the channel is in the busy state as the probability of miss detection increases; thus, the average TCP throughput decreases. In Fig. 9, ten states are used and $\epsilon = 0.2$, and $\Pr\{X_{k+1} = v | X_k = v\} = 0.9$, $\Pr\{X_{k+1} = z | X_k = z\} = 0.1$, and $\Pr\{X_{k+1} = z | X_k = v\} = 0.05$ are also used. We can observe that the average TCP throughput decreases as the receiver estimation degrades. The reduction of receiver estimation performance means increasing the probability of observing that the channel is not in an actual available state. Therefore, the system makes a wrong decision and sequentially takes a wrong action.

E. Spectrum Utilization

Fig. 10 demonstrates the spectrum utilization achieved in the perfect knowledge scheme, the proposed scheme, and the previous ACK-only scheme. In the previous ACK-only scheme, decisions are made solely based on the channel gain provided in the last acknowledgment. The modulation and coding scheme at the physical layer and the frame size at the data-link layer are deployed based on the obtained channel gain at the previous slot. Spectrum utilization is defined as the ratio between the utilized spectrum and the available spectrum. In Fig. 10, $\epsilon = 0.1$ and $\delta = 0.5$. The probability of any available channel state staying in the same state in the next time slot is $\Pr\{X_{k+1} = v | X_k = v\} = 0.9$. The probability of dwelling in the busy state is $\Pr\{X_{k+1} = z | X_k = z\} = 0.15$. The probability that any available channel state stays in the same state in the next time slot is $\Pr\{X_{k+1} = z | X_k = v\} = 0.05$. In Fig. 10, we see that the perfect knowledge scheme can exploit all available spectrum opportunities, and the achieved spectrum utilization is 1. Our proposed scheme selects the access operation according to the most likely state derived from the information state. Therefore, it sometimes makes a wrong decision when the channel is in an available state. As a consequence, the spectrum is underutilized. Nevertheless, the achieved spectrum utilization in our proposed scheme is very close to the perfect knowledge case, which shows the effectiveness of the proposed scheme. The previous ACK-only scheme makes decisions solely based on the channel gain provided in the last acknowledgment. Thus, the spectrum utilization degrades for the channel state changing into a new state, and it has the worst spectrum utilization.

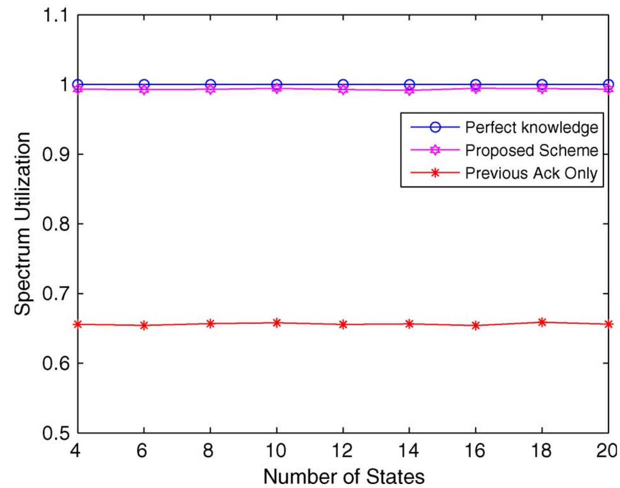

Fig. 10. Spectrum utilization versus the number of states.

V. Conclusion and Future Work

In this paper, we have presented a cross-layer design scheme for TCP performance improvement over CR networks. Spectrum sensing, access decision, the physical-layer modulation and coding scheme, and the data-link layer frame size in CR networks have been jointly optimized to maximize the TCP throughput. We have formulated the CR system as a POMDP to obtain the optimal policy. Simulation results have been presented to illustrate the effectiveness of our proposed scheme. It has been shown that low-layer design parameters have significant impact on the TCP throughput in CR networks, and the TCP throughput can be substantially improved in the proposed cross-layer design scheme.

Future work is in progress to consider other parameters in CR networks, such as energy consumption and security, in the proposed framework.

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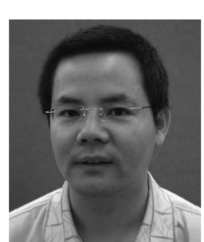

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