Distributed Optimal Relay Selection for Improving TCP Throughput in Cognitive Radio Networks: A Cross-Layer Design Approach

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Abstract—In cognitive radio (CR) networks, cooperative relaying is emerging as a key technology to improve the performance of secondary users (SUs), while ensuring the quality of service of primary users. Most previous work considers maximizing physical layer throughput as a design criterion. However, the end-to-end Transmission Control Protocol (TCP) performance perceived by SUs is largely ignored. In this paper, we take a cross-layer approach to jointly consider optimal relay selection strategy, adaptive modulation and coding and data-link layer frame size to maximize the TCP throughput in CR networks. Specifically, we formulate the CR relay network as a restless bandit system, where the finite-state Markov channel model is used to characterize the time-varying channel state. With this stochastic optimization formulation, the optimal relay selection policy has indexability property that dramatically reduces the computation and implementation complexity. Simulation results show the effectiveness of the proposed scheme.

I. INTRODUCTION

Cognitive radio (CR) is a key technology to achieve high spectrum utilization in wireless networks [1]. The secondary user (SU) and the primary user (PU) can simultaneously access a licensed spectrum as long as the interference caused to PU is below a predefined threshold [2]. Besides, cooperative communications is an emerging and powerful solution to significantly combat channel fading and improve system performance, e.g., capacity increase, power saving and coverage extension [3]. Intermediate relay nodes are assigned to help source nodes forward information to destination nodes, hence forming a virtual distributed antenna array to enable space diversity.

Recently, cooperative communications in CR networks, which is capable of improving the performance of SUs without affecting the quality of service (QoS) experienced by PUs, have raised great research interest. In [4], the authors employed cooperative relaying to improve spectrum sensing capability in a multi-user CR system. In [5], a transmit power allocation scheme in relay-assisted CR systems was proposed to maximize the signal-to-interference-and-noise-ratio (SINR) at secondary destinations, while limiting the interference at the primary receiver. In [6], the authors discussed the impact of the spectrum acquisition capability on the outage performance in CR networks, where a group of relay nodes at different locations assist secondary source nodes transmitting information to destination nodes only when the PUs are idle.

Although some work has been conducted for cooperation transmissions in CR relay networks, most of the previous work considers optimizing the performance in the physical layer, e.g., achievable data rate, as the design criterion. However, the end-to-end performance of Transmission Control Protocol (TCP) over CR relay systems as well as the effect of relay selection strategy on TCP throughput have not yet been addressed. TCP is by far the dominant transport protocol used by contemporary multimedia applications over the Internet [7]. Besides, increasing physical layer data rate may bring about high packet losses in the upper layer, and thus degrade the TCP performance, which directly affect user application. It is well known that TCP suffers from severe performance degradations in wireless environments due to its inability to distinguish packet losses caused by network congestion from those caused by transmission errors.

In this paper, we present a distributed optimal relay node selection scheme to improve the TCP performance in CR relay networks without modifying standard TCP. The distinct features of our proposed scheme include: a cross-layer approach to maximize TCP throughput by jointly considering physical layer adaptive modulation and coding (AMC) and data-link layer adaptive frame size (AFS) in the process of relay selection optimization; formulation of the CR relay networks as a restless bandit system [8], [9], using the finite-state Markov channel (FSMC) model, which has been widely applied to model Rayleigh fading channels [10], to predict the upcoming channel condition for the subsequent packets transmission; that it is fully scalable and distributed, and thus there is no need for a centralized coordinator; the relay node can join and leave from the candidate relay set freely.

The rest of this paper is organized as follows. In Section II, the TCP throughput and system models are analyzed. Section III formulates the problem as a restless bandit problem, which is solved through the primal-dual priority-index heuristic. In
Section IV, we present the distributed relay selection process. Simulation results are presented and discussed in Section V. Section VI concludes the paper.

II. TCP THROUGHPUT IN COGNITIVE RADIO RELAY NETWORKS

As shown in Fig. 1, we consider an underlay CR system with the coexistence of primary and secondary networks. In the primary network, a primary transmitter (PT) sends data to a primary receiver (PR). Meanwhile, in the secondary network, a secondary source (S) communicates with a secondary destination (D) assisted by the intermediate relay nodes Rn, n ∈ N = {1, 2, · · · , N}, over the same band that is licensed to the primary network. To guarantee the QoS of primary transmissions, the interference caused to PT by S should be below a predefined threshold. A large data file is transferred from S to the fixed peer host (PH) through a single TCP connection. We assume that D and PH are connected via a wired path. As we are only interested in the TCP performance in the wireless CR relay networks, we assume that there is no congestion or packet losses in the wired path.

Throughout this paper, we consider block-Rayleigh fading channels, such that the channel gain remains unchanged during the transmission of one block. We consider the decode and forward (DF) relaying strategy with a two-time-phase implementation. Assume that S and D have perfect knowledge of the complex channel gains hSD, hSR, and hRR,D associated with links S-D, S-Rn and Rn-D, respectively. Receiver noise is assumed to be AWGN with power spectral density N0. The transmission time for a large data file is partitioned into T time slots with equal length, i.e., T = [0, 1, · · · , T − 1]. At the beginning of each slot, spectrum sensing and decision is executed by each SU. For simplicity, we assume the sensed outcome (either “Idle” or “Busy”) is the same within the coverage area of the secondary network. Besides, we denote the action of each relay node Rn in time slot t ∈ T as a(t), a(t) ∈ {0, 1}, where 0 means idle and 1 means active for the corresponding relay node in the respective time slot. Assume that a single relay node is selected from the candidate relay set, i.e., ∑Nn=1 a(t) = 1. In order to satisfy the primary networks QoS requirement, the transmit power of both S and Rn, i.e., Ps and Prn, should be limited by the interference-power constraint of PT. Consequently, in the underlay CR paradigm, we have

\[
\begin{align*}
\{ P_S = P_S^{\text{max}}, P_{Rn} = P_{Rn}^{\text{max}}; \text{the spectrum band is "Idle"} \\
\{ P_S = \frac{I_{th}}{h_{\text{SP}}}, P_{Rn} = \frac{I_{th}}{h_{\text{RP}}}; \text{the spectrum band is "Busy"}
\end{align*}
\]

where Pmax and Pmax denote the maximum transmit powers of S and Rn, respectively, and Ith represents the interference-power threshold.

A. TCP Throughput Model

Assume that each TCP packet with length LTCP is divided into Nfr link-layer frames, and the length of each frame is assumed to be Lfr long bits. We apply TCP Reno as the transport layer protocol, and use the analytical model for TCP throughput in [11], given by

\[
T = \min \left( \frac{W_m}{\text{RTT}}, \frac{1}{\text{RTT} \sqrt{2kp + T_0 \min \left(1, 3 \frac{3bp}{s} \right) p(1 + 32p^2)}} \right)
\]

where Wm is the maximum transmission number for the link layer automatic repeat request (ARQ) mechanism, such that a frame is discarded if the number of retransmissions exceeds Nre. Note that a TCP packet transmission is successful only when all Nfr frames are correctly received. Thus, we can obtain the packet loss probability p as

\[
p = 1 - (1 - F_e^{N_{fr}+1})^{N_{fr}}
\]

RTT can be approximately expressed as

\[
\text{RTT} = 2 \cdot T_w + N_{fr} \cdot \left[ \frac{L_{fr} \cdot (N_{fr} + 1) + L_{ack}}{r} \right]
\]

where T_w is the delay over the wired path, Lack is the length of an ACK frame, r denotes the data rate in the wireless link S-D assisted by relay node Rn, and Nre represents the average number of retransmissions for one frame, given by:

\[
N_{re} = \sum_{i=1}^{N_{fr}} i \cdot F_e^{N_{fr}} \cdot (1 - F_e) = \frac{F_e - F_e^{N_{fr}+1}}{1 - F_e} - N_{re} \cdot F_e^{N_{fr}+1}
\]

B. Channel Model

As mentioned earlier, we consider block Rayleigh fading channels. The FSMC model has been widely accepted as an effective approach to characterize the time-varying behavior of fading [10]. In this paper, the FSMC model is constructed by partitioning the range of continuous average channel gain into discrete levels, each corresponding to a state of the FSMC. For the considered links S-D, S-Rn, Rn-D, S-PR and Rn-PR, the
average channel gain, $\sigma_{ij}(t) = \mathbb{E}[h_{ij}(t)]$, is modeled as a random variable evolving according to a $L$-state Markov chain, which has a finite state space denoted by $\mathcal{C} = \{C_0, C_1, \ldots, C_{L-1}\}$. Here, $\mathbb{E}[\cdot]$ represents expectation. Let $\phi_{a_t,b_t}(t)$ be the probability that $\bar{\sigma}_{ij}(t)$ transits from state $g_n$ to $h_n$ at epoch $t$. The channel state transition probability matrix can be expressed as:

$$
\Phi(t) = [\phi_{R_t,\sigma_t}(t)]_{L \times L},
$$

(7) where $\phi_{a_t,b_t}(t) = \text{Pr}\{\bar{\sigma}(t+1) = h_n | \bar{\sigma}(t) = g_n\}$, for $g_n, h_n \in \mathcal{C}$.

C. Spectrum Usage Model

Since ideal spectrum sensing is assumed, there is no missed detection and false alarms. We use a two-state Markov model to represent the spectrum usage in time slot $t$ denoted by $X(t) \in \mathcal{X} = \{0(Idle), 1(Busy)\}$, where “0(Busy)” denotes the spectrum band being in use by PUs, and “1(Idle)” represents the spectrum being idle from PU activity. The spectrum state transition probability matrix can be written as follows:

$$
\Theta(t) = [\theta_{ij}(t)]_{2 \times 2},
$$

(8) where $\theta_{ij}(t) = \text{Pr}\{X(t+1) = j | X(t) = i\}$, for $i, j \in \mathcal{X}$.

III. Problem Formulation

A. State Space and Transition Probabilities

In time slot $t \in [0, 1, \ldots, T-1]$, the state of candidate relay node $R_n$, denoted as $i_n(t)$, is characterized by S-D channel state $\bar{\sigma}_{SD}(t)$, S-R channel state $\bar{\sigma}_{SR}(t)$, R-D channel state $\bar{\sigma}_{RD}(t)$, S-P_R channel state $\bar{\sigma}_{SP_R}(t)$, R-P_R channel state $\bar{\sigma}_{RP_R}(t)$, and $X(t)$. Consequently, state $i_n(t)$ can be expressed as the combination

$$
i_n(t) = [\bar{\sigma}_{SD}(t), \bar{\sigma}_{SR}(t), \bar{\sigma}_{RD}(t), \bar{\sigma}_{SP_R}(t), \bar{\sigma}_{RP_R}(t), X(t)].
$$

(9) In practice, $\bar{\sigma}_{SD}(t)$, $\bar{\sigma}_{SR}(t)$, $\bar{\sigma}_{RD}(t)$, $\bar{\sigma}_{SP_R}(t)$, $\bar{\sigma}_{RP_R}(t)$, and $X(t)$ are independent with each other. Therefore, relay state $i_n(t)$ will change in a Markovian fashion, and the corresponding finite-state space can be represented as $\mathcal{J}_n$, $i_n(t) \in \mathcal{J}_n$, with the following transition probability matrix

$$
P_n(t) = \begin{bmatrix}
\phi_{i_n,v_n}(t), & \phi_{i_n,y_n}(t), & \phi_{i_n,z_n}(t), & \phi_{i_n, \sigma_n}(t), & \phi_{i_n, \sigma_t}(t), & \theta_{ij}(t)
\end{bmatrix}_{H \times H},
$$

(10) where $\phi(t)$ and $\theta_{ij}(t)$ are defined in (7) and (8), respectively, $g_n, h_n, v_n, y_n, z_n, \sigma_n, \sigma_t, X(t) \in \mathcal{C}$, and $H = |L|^3 \times 2$. The element of $P_n(t)$ is $p_{i_n,j_n}(t)$, which denotes that the state of $R_n$ changes from $i_n$ to $j_n$, where $i_n, j_n \in \mathcal{J}_n$.

B. Expected System Reward

Since the goal of our scheme is to maximize TCP throughput by optimal relay selection, we define the immediate reward of $R_n$ as

$$
R_{i_n}(t) = T(W_m, \text{RTT}(i_n(t), a_n(t)), T_0, b, p(i_n(t), a_n(t))),
$$

(11) where $\text{RTT}(i_n(t), a_n(t))$ and $p(i_n(t), a_n(t))$, respectively, denote the round trip time and the packet loss probability when $R_n$ with state $i_n(t)$ takes action $a_n(t)$ in time slot $t$.

For a stochastic process, a maximum immediate value is not equivalent to the maximum expected long-term accumulated value. Denote by $u \in \mathcal{U}$ and $0 < \beta < 1$ the admissible policy and the discount factor, respectively. The objective of the restless bandit problem is to find an optimal policy $u^*$ that maximizes the total expected discounted reward during the whole TCP packet transmission period, i.e.,

$$
Z(u^*) = \max_{u \in \mathcal{U}} \mathbb{E}[\sum_{t=0}^{T-1} R_{i_n}(t) \beta^t].
$$

(12)

C. Solution to the Restless Bandit Problem

1) Linear Programming (LP) Relaxation: To formulate the restless bandit problem mathematically, we first introduce the performance measures, $x_{\bar{\sigma}}^n(u) = \mathbb{E}_u[\sum_{t=0}^{T-1} R_{i_n}(t) \beta^{T-t-1}]$, representing the total expected discounted time when relay node $R_n$ in state $i_n$ takes action $a_n \in \mathcal{A}$ under Markovian policy $u$, where $\lambda_{i_n}(t) = 1$ if action $a_n$ is taken at epoch $t$. Otherwise, $\lambda_{i_n}(t) = 0$. Let $X$ denote the performance region spanned by vector $x = (x_{\bar{\sigma}}^n(u))_{u \in \mathcal{A}, i_n \in \mathcal{J}_n}$ under all admissible policies $u \in \mathcal{U}$, i.e., $X = \{x = (x_{\bar{\sigma}}^n(u))_{u \in \mathcal{A}, i_n \in \mathcal{J}_n} | u \in \mathcal{U}\}$.

Since the restless bandit problem is naturally modeled as a discounted Markov decision chain, it can be formulated by the following linear program [8]:

$$
(\text{LP}) \quad Z^* = \max_{x \in X} \sum_{u \in \mathcal{A}} \sum_{i_n \in \mathcal{J}_n} \sum_{a_n \in \mathcal{A}(0,1)} R_{i_n} x_{\bar{\sigma}}^n(u).
$$

(13) As discussed in [8], the corresponding first-order relaxation expression is given by:

$$
(\text{LP}^1) \quad Z^1 \equiv \max_{x \in X} \sum_{u \in \mathcal{A}} \sum_{i_n \in \mathcal{J}_n} \sum_{a_n \in \mathcal{A}(0,1)} R_{i_n} x_{\bar{\sigma}}^n(u) \quad (14)
$$

subject to $x_n \in Q_n^1$, $n \in \mathcal{N}$,

$$
\sum_{n \in \mathcal{N}} x_n = \frac{M}{1-\beta}.
$$

$Q^1$ is precisely the projection of restless bandit polytope [8], denoted as $\mathcal{P}$, over the space of variable $x_{\bar{\sigma}}^n$ for $R_n$.

2) Primal-Dual Priority-Index Heuristic: Under some mixing assumptions on active and passive transition probabilities, they interpreted the primal-dual heuristic as a priority-index heuristic. The dual of linear program (LP$^1$) is

$$
(\text{D}^1) \quad Z^1 = \min_{\lambda \geq 0} \sum_{u \in \mathcal{A}} \sum_{i_n \in \mathcal{J}_n} \lambda_{i_n} x_{\bar{\sigma}}^n(u) + \frac{M}{1-\beta} \lambda
$$

(15) subject to $\lambda_{i_n} - \beta \sum_{j_n \in \mathcal{J}_n} \lambda_{j_n} R_{i_n,j_n} \geq R_{i_n}, i_n \in \mathcal{J}_n, n \in \mathcal{N}$,

$$
\lambda_{i_n} - \beta \sum_{j_n \in \mathcal{J}_n} \lambda_{j_n} R_{i_n,j_n} \geq 1, i_n \in \mathcal{J}_n, n \in \mathcal{N},
$$

$$
\lambda \geq 0.
$$

We denote by $\{\lambda_{i_n}\}$ and $\{\lambda_{i_n}\}$ the optimal primal and dual solution pair to the first-order relaxation (LP$^1$) and its dual ($\text{D}^1$). Let $\{\bar{\lambda}_{i_n}\}$ represent the corresponding optimal reduced cost coefficients, i.e., $\bar{\lambda}_{i_n} - \beta \sum_{j_n \in \mathcal{J}_n} \bar{\lambda}_{j_n} R_{i_n,j_n} - R_{i_n}$ and $\bar{\lambda}_{i_n} = \lambda_{i_n} - \beta \sum_{j_n \in \mathcal{J}_n} R_{i_n,j_n} - R_{i_n}$, which must be nonnegative. Based on this, the index of $R_n$ in state $i_n$ is defined as

$$
\delta_{i_n} = \bar{\lambda}_{i_n} - \bar{\lambda}_{i_n}.
$$

(16)
IV. DISTRIBUTED INDEXABLE RELAY SELECTION SCHEME

In this section, we present the distributed indexable relay selection scheme in CR relay networks. Our scheme is based on the request-to-send/clear-to-send (RTS/CTS) mechanism of collision avoidance, and the current channel states can be estimated via exchanging RTS/CTS packets.

We assume that $N$ intermediate relay nodes depicted in Fig. 1 could decode both RTS and CTS packets successfully. In addition, we further assume that the estimated channel gain in direct link S-D is less than the minimum of the channel gains in the two-hop relaying links S-R$_n$ and R$_n$-D, i.e., $\sigma_{SD} < \min(\sigma_{SR}_n, \sigma_{RD}_n)$, $n \in \mathcal{N}$. As a consequence, the $N$ relay nodes constitute the candidate relay set, denoted by $\mathcal{R} = \{R_n | n \in \mathcal{N}\}$.

The process of distributed relay selection can be divided into the off-line stage and the on-line stage. The specific procedure is given in Algorithm 1.

Algorithm 1 Process of Distributed Relay Selection Scheme

Step 1: Off-Line Computation
1) According to the sensed spectrum usage outcome and the estimated channel condition, the transition probability matrices and state space under different actions are determined:
2) Before TCP data transmission, input the state transition probability $p_{x|x'}^{n}$, the reward $R_{n}^{x}$, the discount factor $\beta$ and the initial state probability vector $\pi_0$, then off-line compute the priority-indices $[\delta_i]$ according to (15-16);
3) The indices $[\delta_i]$ and the corresponding $p_{x|x'}^{n}$, $R_{n}^{x}$ and $\pi_0$ are stored in an index-table.

Step 2: On-Line Selection
1) Each candidate relay node shares its state $i_n$ and the initial state probability vector $\pi_0$ with the others in a distributed way;
2) At epoch $t$, each candidate relay node $R_n \in \mathcal{R}$ looks up the index-table to find out the corresponding index $\delta_i$. After that, $R_n$ broadcasts a priority-index (PI) packet containing its own index, and then arranges the list of indices $[\delta_i]$ from the lowest to the highest. The relay node is set to be active if its index is in the first place.

End

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, we present some simulation results to illustrate the performance of our proposed TCP optimization scheme. The network scenario is depicted in Fig. 1, in which a large FTP file is transferred from S to the fixed peer host (i.e., PH), and TCP Reno is adopted as the transport layer protocol. Without lose of generality, we set the wired network delay to be $T_w=15$ ms. The TCP packet size is $L_{TCP}=1500$ bytes. The maximum congestion window size is $W_{m}=10$ packets, the initial time-out is $T_0=2$ seconds and the discount factor $\beta=0.8$. The length of each ACK frame is $L_{ack}=20$ bits. To guarantee a small buffer size and a low delay, we assume the maximum number of frame retransmission is $N_r=5$.

The channel state transition matrix is made up of the probability that a channel dwells in the same state at the next time slot, i.e., $Pr[S_{t+1} = V | S_t = V], V \in \mathcal{C}$, and the probability of transitioning to other state, i.e., $Pr[S_{t+1} = Z | S_t = V], Z \in \mathcal{C} - \{V\}$. For simplicity, we assume that the probability of the channel changing from one state into another state is the same, i.e., $Pr[S_{t+1} = Z | S_t = V] = Pr[S_{t+1} = Z' | S_t = V]$, for all $Z, Z' \in \mathcal{C} - \{V\}$ and $Z \neq Z'$.

A. Effects of Cross-Layer Design Parameters

In order to highlight the effects of cross-layer design parameters on TCP performance, we consider other two schemes for comparison. The first one is “Optimal Relaying + AFS, w/o AMC” scheme, in which the priority-indexable optimal relaying policy and AFS strategy in data-link layer are employed, but without AMC consideration in physical layer. The second one is “Optimal Relaying, w/o TCP Performance Consideration” scheme, in which the priority-indexable optimal relaying policy and AMC strategy are adopted to maximize physical-layer throughput rather than TCP throughput in CR relay networks ([13], Ch.9).

![Fig. 2. Average TCP throughput vs. simulation time](image)

Fig. 2 illustrates the average TCP throughput under different schemes. Here, we set $N=4$. $Pr[S_{t+1} = V | S_t = V]$ is assumed to be 0.6. The sensed spectrum state transition probabilities are $Pr[X_{t+1} = 0(Busy) | X_t = 0(Busy)) = 0.4$ and $Pr[X_{t+1} = 1(Idle) | X_t = 1(Idle)] = 0.7$. It can be seen in Fig. 2 that the system only takes a few time slots to reach the steady state, which means that the restless bandit decision making approach has good convergence property. Moreover, the proposed scheme has better TCP performance than the “Optimal Relaying + AFS, w/o AMC” scheme. The main reason is that no AMCs consideration at the physical layer could result in high bit error rate and packet loss rate in the upper layer, which will degrade the TCP throughput dramatically. In addition, the scheme without considering TCP optimization has the worst performance. Fig. 2 indicates the need to jointly consider design parameters in different layers for improving TCP transmission over CR relay networks.

B. Effects of Different Relaying Scheme on TCP Performance

In this subsection, we compare our proposed TCP optimization scheme with the random relay selection method and an existing memoryless opportunistic relaying method [14], which use the current observed channel conditions to select the best-relay for subsequent frame transmission. For fair
comparison, the latter two schemes are revised by adding AMCs in physical layer and AFS in data-link layer. Besides, we set the whole simulation time as $T_{\text{sim}} = 180$ slots.

Fig. 3 shows that the average TCP throughput increases as the number of candidate relay nodes increases, and the proposed scheme always has the best performance. It can be observed that when $N$ is bigger than 6, the TCP throughput reaches almost the steady state due to high probability of choosing the best relay node with good channel conditions. In Fig. 3, we take the following simulation parameters: $\Pr[S_{t+1} = V \mid S_t = V] = 0.7$, $\Pr[X_{t+1} = 0(\text{Busy}) \mid X_t = 0(\text{Busy})] = 0.3$ and $\Pr[X_{t+1} = 1(\text{Idle}) \mid X_t = 1(\text{Idle})] = 0.6$.

![Average TCP Throughput vs. Number of Candidate Relay Nodes](image1)

Fig. 3. Average TCP throughput vs. number of coocandidate relay nodes

Fig. 4 demonstrates that the average TCP throughput decreases with the increase of the probability of spectrum state changing from “Idle” to “Busy” (i.e., $\Pr[X_{t+1} = 1(\text{Busy}) \mid X_t = 1(\text{Idle})]$). This is because when the spectrum is occupied by PUs, the transmit power levels at S and R are constrained by the interference-power threshold $I_b$. As $\Pr[X_{t+1} = 1(\text{Busy}) \mid X_t = 1(\text{Idle})]$ increases, S and R transmit data with lower power for a higher fraction of the time, and thus the TCP throughput is degraded. Again, our proposed scheme outperforms the other two schemes. In this example, we assume $\Pr[S_{t+1} = V \mid S_t = V] = 0.5$ and $\Pr[X_{t+1} = 0(\text{Busy}) \mid X_t = 0(\text{Busy})] = 0.6$.

![Average TCP Throughput vs. Probability of Spectrum State Changing from Idle to Busy](image2)

Fig. 4. Average TCP throughput vs. the probability of spectrum state changing from Idle to Busy

VI. CONCLUSION

In this paper, we have proposed a cross-layer design for improving TCP performance over underlay CR relay networks, while guaranteeing the QoS of primary transmissions. With link layer ARQ, AMC at the physical layer and AFS at the data-link layer are jointly considered in the process of cognitive relay node selection. Specifically, we formulate the TCP throughput optimization as a restless bandit problem, where the channel and spectrum-usage state transitions are characterized by FSMCs. The optimal relay selection policy is obtained by a primal-dual priority-index heuristic, which can dramatically reduce the computation and implementation complexity. Simulation results demonstrate that physical and link layer parameters have substantial impact on the TCP performance. In all scenarios considered, results show that the proposed optimization scheme can improve TCP throughput significantly.

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