Primary User Activity Prediction Based Joint Topology Control and Stable Routing in Mobile Cognitive Networks

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***Abstract*—The stability of links in mobile cognitive networks (MCNets) is significantly affected by primary user activities and node mobility, which makes topology control and stable routing more challenging than that in traditional wireless networks. In multi-channel multi-hop MCNets, it will become worse. In this paper, we propose a primary user activity prediction model to reveal channel utilization patterns of primary users. Next, we put forward a novel routing metric *Primary user activity Prediction based Stability Metric (PPSM)* to quantitatively capture the affect of primary user activities and node mobility. Finally, we propose and implement a *Primary user activity Prediction based Joint Topology Control and Stable Routing (PP-JTCSR)* protocol for maximizing network throughput based on our primary user activity prediction model, which can find out the most stable and the shortest path between a source and a destination. NS2-based simulation results demonstrate that our PP-JTCSR protocol can generate stable topology through predicting link and path duration quantitatively, and outperforms related proposals in terms of path stability and average throughput.**

I. INTRODUCTION

The stable routing is one of the most fundamental techniques in mobile cognitive networks (MCNets) because the network performance quite depends on the stability of pathes. Compared with classical mobile networks, a path in MCNets is more unstable since it is affected by not only the mobility of nodes but also activities of primary users (PUs) [1]. User activity patterns have been preliminarily investigated in recently years. Most of them estimated channel usage using Markovian model [2] [3]. Instead of traditional Markovian models, Sung et al. [4] used ON/OFF traffic models for PU activity prediction. [5] proposed a PU traffic prediction algorithm for dynamic spectrum access based on estimated PU traffic state transition probabilities. On the other hand, topology control and routing have also been studied in cognitive networks [6] [7] [8]. However, these work did not predict PU activities so that they can not use channels of PUs efficiently. For example, [7] tried to set up "robust route" through assuming the PU activity probability in advance. In conclusion, existing work did not jointly design routing and topology control on the basis of PU channel usage prediction. In Fig. 1(a) and 1(b), the

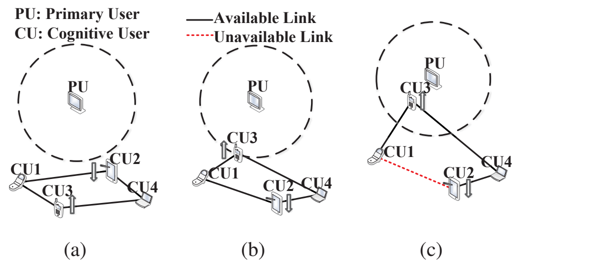

Fig. 1. Motivation Scenario. (a) initial scenario; (b) after 5s, CU_3 arrives at the boundary of the interference range of PU; (c) after 10s, the link $CU_1 \rightarrow CU_2$ fails and CU_3 enters the interference range of PU.

stability of links mainly depends on the movement of CU_2 and CU_3 and the communication of the PU. In traditional scheme like PCTC [1], CU_1 will select CU_2 because CU_3 moves toward to the PU. Suppose after 10s, the network topology changes into the state shown in Fig.1(c). At this moment, CU_3 enters the interference range of the PU; the link between CU_1 and CU_2 fails because the distance between them exceeds the maximum transmission distance while the link between CU_1 and CU_3 is still available. Although the PU is not busy (Fig.1(c)) currently, PCTC relinquishes the free time when PU is idle.

Motivated by the above analysis, we in this paper propose a *Primary user activity Prediction based Joint Topology Control and Stable Routing (PP-JTCSR)* protocol. Although PUs don't use the licensed spectrum evenly, the occupation of their channels has inherent patterns. We can predict activity patterns of PUs through learning the history data of PU channel usage.

Our PP-JTCSR approach quantitatively measures the channel occupation patterns of PUs, and then uses a cross-layer design to explore pathes as stable as possible in MCNets. To the best of our knowledge, this is the first paper that has addressed the PP-JTCSR problem in multi-channel multi-

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hop mobile cognitive networks. Our main contributions in this paper are summarized as follows.

- We propose a primary user activity prediction model to quantitatively capture channel utilization patterns of PUs in future time, based on Probabilistic Suffix Tree (*PST*) [4] [9]. It significantly benefits to topology control and path selection.
- We propose a novel routing metric *Primary user activity Prediction based Stability Metric* (*PPSM*) to quantitatively measure the link stability suffered from PU activity and the node mobility.
- Based on our routing metric PPSM, we propose and develop a joint topology control and stable routing protocol based on our PU activity prediction model. Simulation results demonstrate that our PP-JTCSR protocol can generate stable topology through predicting link and path duration quantitatively, and outperforms related proposals.

The rest of the paper is organized as follows. Section II briefly reviews related work. Section III presents the system model. In Section IV, we present the PU activity prediction model and propose the PPSM routing metric and the PP-JTCSR protocol. Section V evaluates our PP-JTCSR protocol through NS2-based simulations. Finally, we conclude this paper in Section VI.

II. Related Work

Topology control and routing has been studied recently [1] [6] [7] [8]. [1] and [7] are the most related our work. In [1], Guan et al. introduced PCTC scheme that provides cognition capability to routing in MCNets. Based on the link prediction, PCTC captures dynamic changes of the topology and constructs an efficient and reliable topology. Shih et al. [7] introduced the concept of "route robustness" for path selection in multi-hop cognitive radio networks. They select some routes from robust route set and determine the spectrum to be allocated on each link along these routes such that the system throughput is maximized.

In the aspect of predicting channel usage [2] [3] [4] [5], Devanarayana et al. [3] introduced a predictive channel usage which is capable of reducing the interference caused by increasing the data rated and unlicensed users experience through the reduction of the idle channel identification delay. They learned the traffic characteristics of the channels by PST. An et al. [2] adopted discrete-time Markov chain to analyze and model the spectrum usage in time-slotted cognitive radio networks. [4] used ON/OFF traffic models for prediction. Knowledge about the elapsed OFF period of the primary user is exploited to obtain a prediction of the remaining OFF duration that controls the secondary user behavior. [5] proposed a PU traffic prediction algorithm dynamic spectrum access based on estimated PU traffic state transition probabilities, which are obtained by constrained-time PU traffic parameters estimation assuming exponentially distributed PU ON/OFF channel utilization intervals. All of these prediction schemes are used for spectrum access and channel selection and some schemes rely on the certain traffic model of PU. In conclusion, existing related schemes did not solve the PP-JTCSR problem.

III. Network Model

We model a MCNet as an undirected graph $G = (V, E)$ where V is the union of CU set (represented as V_C) and PU set (represented as V_P) such that $V = V_C \cup V_P$; E is the union of E_C (the set of links among CUs) and E_P (the set of links among PUs) such that $E = E_C \cup E_P$.

In a cognitive network, there is a *Cognitive Network Station (CNS)* which controls the behavior of CUs. Each CU is equipped with a traditional wireless interface, which forms a Common Control Channel (CCC) to exchange control messages, such as routing packets. The CCC does not interfere with any data channels. Every CU sends own information such as speed and location to the CNS periodically.

We divide continuous time into a series of discrete time slots. Let $AC_{u,v}$ be the available channel set of a link $\ell_{u,v}$, which changes with time slots. For any pair of $u, v \in V_C$, we use $d_{u,v}(t) = \|u - v\|$ to denote the distance between u and v in a time slot t. Let R_T and R_I be the transmission and interference ranges of a CU, where $R_I = \xi R_T$ ($\xi \geq 2$).

A link $\ell_{u,v} \in E_C$ is available only when $d_{u,v}(t) \leq R_T$. We define the distance between two links $\ell_{u,v}$, $\ell_{u'v'} \in E$ as $d_{\ell_{u,v},\ell_{u',v'}}=\min\left\{d_{u,u'}\left(t\right), d_{u,v'}\left(t\right), d_{v,u'}\left(t\right), d_{v,v'}\left(t\right)\right\}$ At a time slot t, $\ell_{u,v}$ and $\ell_{u'v'}$ interfere with each other (marked by $\ell_{u,v} \otimes \ell_{u'v'}$) if they use the same data channel and $d_{\ell_{u,v},\ell_{u',v'}} \leq R_I$.

IV. PU Activity Prediction Based Joint Topology Control and Stable Routing

In this section, we firstly propose a link stability model and a new routing metric focusing on primary user activity prediction. Then, we present a model for predicting primary user activity patterns. Finally, we propose a joint topology control and stable routing protocol based on the proposed routing metric.

A. Link Stability Prediction

If velocities of nodes u and v stay constant during any epoch, it is obvious that $\partial^2 d_{u,v} / \partial t^2 = 0$ [10] [11]. Thus, distance between u and v can be expressed as $d^2{}_{u,v}(t) = at^2 + bt + c$ where t is the time interval; a, b and c are adjustable coefficients.

Let each CU be equipped with a GPS and always can communicate with adjacent CUs on the CCC channel using the beacon mechanism. It is easy to know the distance between u and v at any time slot t. Given three measurements $(t_0, d_0), (t_1, d_1)$ and (t_2, d_2), a, b and c can be figured out. Let $d_{u,v}(t) = R_T$. We can calculate the link duration $T_{u,v}$ determined by the relative movement between u and v.

In reality, however, nodes may randomly change their velocities. Similar to [10] [11], we use $P(T_{u,v}) \approx e^{-\lambda T_{u,v} e^{-\lambda\tau}} + \zeta(1 - e^{-\lambda T_{u,v}})$ to estimate the probability that $\ell_{u,v}$ may really last by the end of $T_{u,v}$. The parameters τ, ζ can be obtained by measurement. The pair of $[T_{u,v}, P\left(T_{u,v}\right)]$ is used to predict the link duration corresponding to the node mobility.

B. Routing Metric Based on Primary User Activity Prediction

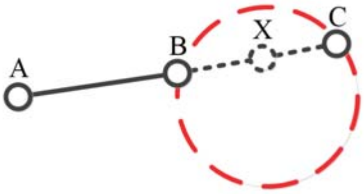


Fig. 2. CU's movement and interference with a PU, where the larger dashed circle represents the interference range of the PU. CU is at place A initially and arrives at B and C after $T_{A,B}$ slots and $T_{A,B}+\Delta t$ slots. At place X, the PU starts communication.

The link stability significantly depends on the PU activities except the relative movement. Most existing routing schemes in MCNets are not efficient in terms of the channel utilization because they cannot predict the activities of PUs. In Fig.2, for example, existing schemes including [1] only use the channel c_{PU} of the PU during $T_{A,B}$ while we use the c_{PU} until $T_{A,X}$=$T_{A,B}+T_{B,X}$ since our model can quantitatively predict when the PU will activate.

Thus, we propose a novel Primary user activity Prediction based Stable routing Metric (*PPSM*), formulated as follows.

$$PPSM^{c}_{\ell_{u,v}}(t) = \min_{u,v\in V_C, i\in\{u,v\}, j\in V_P} \{T_{u,v}\times P(T_{u,v}), T_{i,j}\times P(T_{i,j})\} \tag{1}$$

$PPSM^{c}_{\ell_{u,v}}$ is a metric for $\ell_{u,v}$ on channel c. $T_{u,v}$ is the time when u moves out of the transmission range of v such that $d_{u,v}(T_{u,v}) = R_T$, described above. $T_{i,j}$ is the predicted time when a CU moves into the interference area of any PU_j and the PU_j becomes active at that moment, i.e., $T_{A,X}$ in Fig.2. $P\left(T_{i,j}\right)$ is the probability that $\ell_{u,v}$ may really last by the end of $T_{i,j}$ to capture possible PU activities. The following section will present how to predict when a PU will activate, which is at the core of our routing metric PPSM.

C. PU Activity Pattern Learning

Primary user activities generally are described as a binary string. 0 and 1 represent idle and busy states, respectively. The goal of our PU activity learning is to gain a state vector $\overrightarrow{S}$, and a transition-probability matrix P_t. The key is to reduce the size K of the state vector as much as possible.

We use the PST algorithm [9] to learn PU's activities. The states in leaf nodes of the PST tree compose the state vector $\overrightarrow{S}$. According to $\widetilde{P}(0|s)$ and $\widetilde{P}(1|s)$ of for each leaf node, we can obtain transition-probability matrix P_t.

D. PU Activity Prediction Model

We use a probability vector $\overrightarrow{L} = [P_1, P_2, \ldots, P_k, \ldots, P_K]$ to denote the probability that a PU is under different states $S_k \in \overrightarrow{S}$ such that P_k=$P(S_k)$. Assume the initial probability vector of the PU be $\overrightarrow{L_0}$ when a CU is at the location A, shown in Fig.2. The CU will arrive at B after $T_{A,B}$ slots and at this moment the probability vector of the PU becomes $\overrightarrow{L_0} \times P_t^{T_{A,B}} = [P_1, P_2, P_3 \ldots P_K]$. Further, suppose the CU arrive at C after $T_{A,B}+\Delta t$ slots.

Suppose that after CU arrives at B, PU will keep idle for t slots and will become active from the next slot $t+1$. If the state of PU is S_k when CU is at B, the probability $P_{k,t}$ that PU keeps idle for t slots can be formulated as follows.

$$P_{k,t} = P_k \times \left(\prod_{i=0}^{t-1} P(0|S_k \underbrace{0...0}_{i})\right) \times P(1|S_k \underbrace{0...0}_{t}) \tag{2}$$

Thus, the probability that the PU becomes busy at every state in the period of $[T_{A,B}, T_{A,B}+\Delta t]$ is:

$$(P_{i,j})_{K\times(\Delta t+1)} = \begin{bmatrix} P_1 & 0 & \ldots & & \\ 0 & P_2 & 0 & \ldots & \\ \ldots & 0 & \ldots & 0 & \ldots \\ & & \ldots & 0 & P_K \end{bmatrix} \times$$
$$\begin{bmatrix} P(1|S_1) & .. .. & \left(\prod\limits_{i=0}^{\Delta t-1} P(0|S_1 \underbrace{0...0}_{i})\right) \times P(1|S_1 \underbrace{0...0}_{\Delta t}) \\ P(1|S_2) & & \\ \ldots & .. .. & \ldots \\ P(1|S_K) & .. .. & \left(\prod\limits_{i=0}^{\Delta t-1} P(0|S_K \underbrace{0...0}_{i})\right) \times P(1|S_K \underbrace{0...0}_{\Delta t}) \end{bmatrix} \tag{3}$$

where $S_1, S_2 \ldots S_K$ are K states in $\overrightarrow{S}$.

The element $P_{i,j}$ in the above matrix is the probability that the PU is idle from $T_{A,B}$ slot under S_i to $T_{A,B}+(j-1)$ slot. Summing each column in the above matrix, we have

$$\begin{bmatrix} \sum\limits_{i=1}^{K} P_i \times P(1|S_i) & .. & \sum\limits_{i=1}^{K} \left(\begin{array}{l} P_i \times \prod\limits_{j=0}^{\Delta t-1} P(0|S_i \underbrace{0...0}_{j}) \\ \times P(1|S_i \underbrace{0...0}_{\Delta t}) \end{array} \right) \end{bmatrix} \tag{4}$$

The i^{th} item in the above array represents that the CU can consecutively use PU channel for $(i-1)$ time slots, i.e. PU is inactive during this period.

Obviously, the CU will not interfere with the PU any more after $T_{A,B}+\Delta t$ slots when it leaves from the interference range of PU. The probability that the CU may continuously use the PU's channel since $T_{A,B}$ can be formulated as follows.

$$\begin{aligned} P_{out} = 1 &- \sum_{i=1}^{K} P_i \times P(1|S_i) \\ &- \sum_{t=1}^{\Delta t} \left[\sum_{i=1}^{K} \left(P_i \times \prod_{j=0}^{t-1} P(0|S_i \underbrace{0...0}_{j}) \times P(1|S_i \underbrace{0...0}_{t}) \right) \right] \end{aligned} \tag{5}$$

Thus, the probability distribution function that CU can use the PU's channel is:

$$P(t) = \begin{cases} \sum_{i=1}^{K} P_i \times P(1|S_i) & \text{if } t=0 \\ \sum\limits_{i=1}^{K} \left(\begin{array}{l} P_i \times \prod\limits_{j=0}^{t-1} P(0|S_i \underbrace{0...0}_{j}) \\ \times P(1|S_i \underbrace{0...0}_{t}) \end{array} \right) & \text{if } 1 \le t \le \Delta t \\ P_{out} & \text{if } t > \Delta t \end{cases} \tag{6}$$

where t=0 means that the CU is at B (i.e., the interference boundary of the PU) in Fig.2.

$P_{out} > 0$ means that the PU does not activate probabilistically during $[0, \Delta t]$. We set up a threshold θ. If $P_{out} \geq \theta$, the CU can use the PU's channel continuously in a high probability. In this case, the link duration is estimated as ∞. Otherwise, the time that the CU may use the PU's channel (i.e., the location of X in Fig.2) can be calculated through following formula.

$$\begin{aligned} T_{B,X} &= 1 \times \sum_{i=1}^{K} P_i \times P(0|S_i) \times P(1|S_i 0) + ... \\ &+ \Delta t \times \sum_{i=1}^{K} \left(P_i \times \prod_{j=0}^{\Delta t-1} P(0|S_i \underbrace{0...0}_{j}) \times P(1|S_i \underbrace{0...0}_{\Delta t}) \right) \\ &= \sum_{t=1}^{\Delta t} t \times \left[\sum_{i=1}^{K} \left(P_i \times \prod_{j=0}^{t-1} P(0|S_i \underbrace{0...0}_{j}) \times P(1|S_i \underbrace{0...0}_{t}) \right) \right] \end{aligned} \quad (7)$$

From the above analysis, we can have the time $T_{i,j}$ that the CU may use the PU's channel.

$$\begin{aligned} T_{i,j} &= T_{A,B} + T_{B,X} = T_{A,B} + \\ &\sum_{t=1}^{\Delta t} t \times \left[\sum_{i=1}^{K} \left(P_i \times \prod_{j=0}^{t-1} P(0|S_i \underbrace{0...0}_{j}) \times P(1|S_i \underbrace{0...0}_{t}) \right) \right] \end{aligned} \quad (8)$$

Both $T_{A,B}$ and $P(T_{i,j})$ can be obtained by formulas in Section IV.A.

E. Joint Topology Control and Stable Routing

Based on the above PPSM, we propose a topology control and stable routing protocol PP-JTCSR to discover the stable path for a data flow $f_k = (s_k, d_k)$.

1) PPSM of the most stable path: To find out the most stable path between a source and a destination, we firstly explore the PPSM of this most stable path using Algorithm 1. For a pair of given source s and destination d (s, d), there may be multiple pathes $\mathrm{P_{s,d}}$. Now, we introduce the following three definitions.

Definition 1 (Link PPSM): For a link ℓ_i,$\exists c_j \in AC_{\ell_i}$, $PPSM_{\ell_i}$=$PPSM_{\ell_i}^{c_j} \geq PPSM_{\ell_i}^{c_k}$ ($\forall c_k \in AC_{\ell_i}$ and $j \neq k$). We call such the $PPSM_{\ell_i}$ as the *PPSM of the link* ℓ_i.

Here, AC_{ℓ_i} is the available channel set of link ℓ_i.

Definition 2 (Path PPSM): For a path $p_i \in \mathrm{P_{s,d}}, \exists \ell_j \in p_i$, $PPSM_{p_i}$=$PPSM_{\ell_j} \leq PPSM_{\ell_k}$ ($\forall \ell_k \in p_i$ and $j \neq k$). We call such the $PPSM_{p_i}$ as the *PPSM of the path* p_i.

Definition 3 (Min-Max PPSM): $\exists p_i \in \mathrm{P_{s,d}}$, $PPSM_{min-max}$ = $PPSM_{p_i} \geq PPSM_{p_j} (\forall p_j \in P_{s,d}, i \neq j)$. $PPSM_{min-max}$ is called as the *min-max PPSM of* (s, d).

The CNS maintains a matrix W^c for each $c \in C$ and a matrix $Weight$. W^c consists of $PPSM^c_{\ell_{i,j}}$ of all links $\ell_{i,j}$ ($\forall i, j \in V_C$) on the channel c. $Weight$ includes *min-max PPSM* of all source and destination pairs in a MCNet.

In Algorithm 1, the indicator $\Im^c_{u,v} = 1$ means that the channel c has been assigned to $\ell_{u,v}$; otherwise, $\Im^c_{u,v} = 0$.

Algorithm 1 Calculate min-max PPSM

Input: Matrix $W^c (\forall c \in C)$
Output: Matrix $Weight$
for $c \leftarrow C$ **do**
  if $\Im^c_{u,v} \neq 1$ **then**
    update $PPSM^c_{\ell_{i,j}}$ in W^c using formula (6)
  else $PPSM_{\ell^c_{i,j}} = 0$
  endif
  $Weight_{i,j} = \max(Weight_{i,j}, W^c_{i,j})$
endfor
set $n = rows[Weight]$
for $k = 1$; $k \leq n$; $k++$ **do**
  for $i = 1$; $i \leq n$; $i++$ **do**
    for $j = 1$; $j \leq n$; $j++$ **do**
      $Weight_{i,j} = \max(Weight_{i,j}, \min(Weight_{i,k}, Weight_{k,j}))$
    end for
  end for
end for
return $Weight$

2) PP-JTCSR algorithm: Our joint topology control and stable routing approach is presented in Algorithm 2, where $\pi[u]$ records u's next hop in the selected path p_π and $NSet[u]$ is the next hop set of u.

V. Simulation and Performance Evaluation

We developed a simulation system, which was built on the NS2 simulator to evaluate our PP-JTCSR protocol. Firstly, we describe the simulation system setting and experiment method. We, then, comprehensively evaluate various performance of our PP-JTCSR by comparing it with the most related and recent proposals.

A. System Setting

In our system, both cognitive and primary users were randomly deployed in an area of 1000m×1000m. IEEE 802.11 was adopted for the MAC layer. PUs and CUs move at a speed randomly distributed in [0, V_{max}] with a direction uniformly distributed in [0, 2π]. We used Two-Ray Ground Reflection propagation model and OmniAntenna antenna model. PUs and CUs have the same transmission radius R_T=100m and interference range R_I=200m. Each PU was assigned a fixed data channel. In the experiments, we tested different performance metrics for 500s. We generated and recorded the channel usage data of PUs and analyzed their channel usage patterns. Exponential ON/OFF generator was used as the flow generator to simulate flows of PUs. Other parameters of the simulated flows of PUs was set as follow: packet size= $1000B$, rate= $8kbps$, burst time= $0s$, idle time= $4s$. Parameters for PST was set as follow: D =10, P_{min} =0.006, α =0, r =1.05 and γ =0.0006. To predict activity of PUs, we learn their history data in last 500000s. During our experiment, we find that 500000s is enough to learn the activity of PU because the state vector $\overrightarrow{S}$ and transition-probability matrix P_t will not change when longer history data was provided.

Algorithm 2 Joint Topology Control and Stable Routing

Input: $W^c(\forall c \in C)$, $Weight$, source s and destination d
Output: path p_π with assigned channels, and $NSet$

for each $u \in V_S$ **do**
  COLOR(u,WHITE)
end for
COLOR(d,GRAY), $\pi[d]$ =NIL and INSERT(d,NIL)
$Q = \emptyset$
ENQUEUE(d)
while Q is not empty **do**
  u=DEQUEUE, COLOR(u,BLACK)
  if u=s **then** break **endif**
  for $v \in N(u)$, $c \in C$ **do**
    if $Weight_{s,d} \leq W^c_{u,v}$ and $v's$ color is not BLACK **then**
      INSERT(v, u) $AC_{v,u} = AC_{v,u} \cup \{c\}$
      if $v's$ color is WHITE **then**
        COLOR(v,GRAY), ENQUEUE(v), $\pi[v]$=u
      end if
    end if
  end for
end while
$u \leftarrow s, v \leftarrow \pi[u]$
while u $\neq$NIL **do**
  for $\forall c \in AC_{u,v}$ **do**
    if $\exists \ell^c_{u',v'}, d_{\ell_{u',v'},\ell_{u,v}} \leq R_I$ **then**
      $AC_{u,v}$-=$\{c\}$
    end if
  end for
  $c_{u,v} \leftarrow$ first channel in $AC_{u,v}$
  p_π = $p_\pi \cup \{\ell^{c_{u,v}}_{u,v}\}$
  $\Im^c_{u,v} = 1$, $u = v$, $v = \pi[u]$
end while

B. Performance Evaluations

We evaluate our *PP-JTCSR* through comparing it with the following related protocols.

- *PCTC* [1]. It is the most related to our PP-JTCSR. PCTC selects the path with the maximum link duration to reduce rerouting frequency based on link-availability prediction.
- *ROBUST ROUTE* [7]. This protocol tries to discover robust routes in multi-hop cognitive radio networks. Route robustness is related to the probability that no PU appears on links involved in a path.

We use following performance to evaluate our protocol. Firstly, we compare generated topology by different schemes and link duration prediction results of PP-JTCSR and PCTC. Then, we evaluate average throughput under different parameters.

1) Topology control: Fig.3(a) shows the initial topology with 50 CUs and 1 PU. Let (s, d) be a pair of source and destination nodes. We respectively use s_x and d_x to denote the X-coordinate of s and d; and s_y and d_y to denote the Y-coordinate of s and d. Given a pair of nodes s at (100, 900) and d at (700, 700), PCTC generated a topology shown in (Fig.3(b)), where CUs in the interference range of the PU were completely removed from the initial topology. Instead, our PP-JTCSR generated the topology in Fig.3(c), which did not completely remove CUs in the interference of the PU by learning and predicting activities of the PU. Consequently, our PP-JTCSR can improve the channel utilization rate for data transmission than PCTC when CUs locate in the interference range of PU. The reason is the our PP-JTCSR can make full use of the idle channel of the PU even CUs lie in the interference range of the PU, through quantitatively predicting of PU activities. Fig.3(d) is generated by our PP-JTCSR for a pair of nodes at (100,900) and (900,100), whose result and reason are similar to those in Fig.3(c).

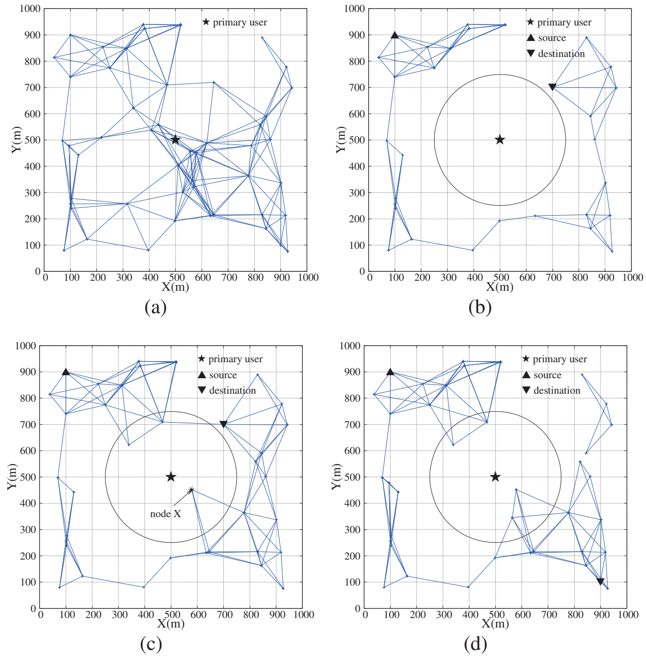
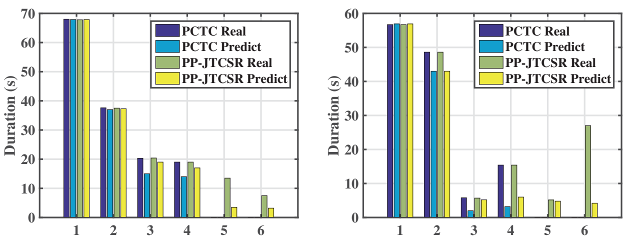


Fig. 3. Topology control. (a) Initial topology; (b) Resulting topology of *PCTC* for $s = (100, 900)$ and $d = (700, 700)$; (c) Resulting topology of our *PP-JTCSR* for $s = (100, 900)$ and $d = (700, 700)$; (d) Resulting topology of our *PP-JTCSR* for $s = (100, 900)$ and $d = (900, 100)$.



(a) Path duration with one PU

(b) Path duration with two PUs

Fig. 4. Path duration (s).

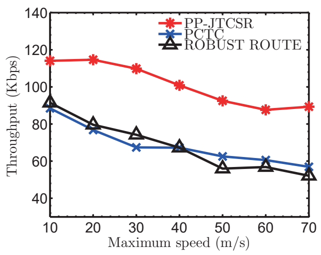
2) Path duration: We tested the predicted path duration from the both schemes and the real path duration that were analyzed from trace files to evaluate their prediction precision.

We conducted three types of experiments to evaluate our PP-JTCSR and PCTC.

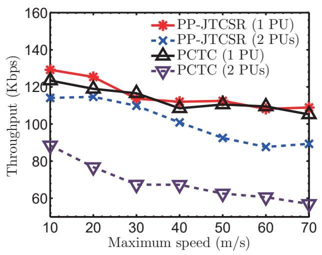
In the first case (1st and 2nd groups in the Figs.4(a) and 4(b)), a link became unavailable only due to relative movement of the associated two CUs. We can observe that the predicted time in PP-JTCSR almost equals to that in PCTC. The reason is the link duration mainly depends on the node mobility in this case and both PP-JTCSR and PCTC can control the mobility well.

In the second case (3rd and 4th group in the Figs.4(a)) and 4(b)), a link fails because one CU enters the interference range of the PU during the transmission. The predicted time of PP-JTCSR is more accurate than that of PCTC. This results from the fact that PP-JTCSR can predict and exploit the idle time of the PU after a CU enters the interference range of the PU. In Fig.2, for example, PCTC and PP-JTCSR predict the available time are $T_{A,B}$ and $T_{A,B} + T_{B,X}$, respectively.

The third case (5th and 6th group in the Figs.4(a) and 4(b)) describes the scenario that a source node is in the interference range of the PU when it needs to transmit a data flow. In this case, the real time and predicted time of PCTC are all zero but PP-JTCSR still can utilize the channel. Under the link duration calculation framework of PCTC, source node is not allowed to send any data. Instead, in our PP-JTCSR, the source node can obtain a nonzero link duration through predicting the PU activities. From Fig.4, we can observe that the path duration predicted by our PP-JTCSR is a little shorter than the real path duration, which means our PP-JTCSR does not interfere with any PU. In conclusion, our PP-JTCSR can predict path duration more accurately than PCTC so that it provides more opportunities to send data without interfering PUs.



(a) Throughput vs speed



(b) Throughput vs speed and PU

Fig. 5. Throughput performance.

3) Average throughput: We compare average throughput of PP-JTCSR, PCTC and ROBUST ROUTE. As shown in Fig.5(a), average throughput of three protocols decreases as the movement speed increases. However, our PP-JTCSR always outperforms PCTC and ROBUST ROUTE. The reason is our PP-JTCSR selects a stable next hop and utilizes the free time of PUs more efficiently.

Next, Fig.5(b) reveals the change of PUs numbers have a significant affect on throughput for PCTC. Throughput in our PP-JTCSR slightly decreases when the number of PU increases while under the same condition, throughput in PCTC decreases sharply. When the PU number increases, it means that each CU will have more opportunities to interfere PU. PCTC selects the path with shorter link duration than PP-JTCSR.

VI. Conclusions

We have formulated and addressed the PP-JTCSR problem. Our PP-JTCSR approach has the following advantages. Firstly, PP-JTCSR can quantitatively capture channel utilization patterns of PUs based on the PPSM proposed in this paper. Next, since our PP-JTCSR can quantitatively predict PU's activities, it allows CUs use the PU's channel even the CU enters the interference range of the PU. Thirdly, our PP-JTCSR can find out the most stable and the shortest path and improve channel utilization rate of PUs significantly. NS2-based simulation results demonstrate that our PP-JTCSR approach can accurately predict path duration, generate stable and efficient topology, and outperform related schemes in terms of path stability and average throughput.

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