Primary Weight Measure and its Support in Stochastic Routing for Dynamic Cognitive Radio Networks

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ABSTRACT

In dynamic cognitive radio mesh networks the variation in spectrum diversity and availability is high due to the presence and the sojourn time of primary users. In this research, we develop a Primary Weight Measure (PWM) metric that measures the uniformity of spread of primary users around a particular node. This metric approximates the expected spectral stability and availability around a node. In addition, we consider the stochastic availability of resources in a cognitive radio network environment, and propose a decentralized routing algorithm called *Primary Spread Aware Routing Protocol* (PSARP). The PSARP is an adaptive per-hop routing scheme that, unlike the predecessor schemes, is nondeterministic. The traffic from a source to a destination is modeled by a Markov process, and packets are forwarded hop by hop based on transition probabilities that reflect the next hop spectral availability as well as the entire path quality. The PWM metrics of the nodes are relayed via back-pressure and are used in the construction of transition probabilities. On a cognitive-based NS2 network simulator, we compare the performance of PSARP with two previously developed routing protocols for dynamic environment. We also develop a Cognitive Stochastic Routing (CSR) protocol based on the PSARP stochastic framework that uses backlogged queue capacity instead of PWM. Our results show higher throughput in PSARP and CSR, which indicate the advantage of stochastic-based routing in a dynamic environment. In addition, PSARP with its PWM measure is more successful in choosing the best path due to the correct identification of the primary users' distribution, and performs substantially better than CSR at high rates.

Categories and Subject Descriptors

C.2.2 [**Computer-Cpmmunication Networks**]: Network Protocols—*Routing Protocols*

Keywords

cognitive radio, network, stochastic

1. INTRODUCTION

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Secondary cognitive radio networks are born from the advanced rendezvous capability of cognitive radios. These radios exploit the vacancies of the spectrum bands dedicated to other users (primary users), and utilize the remaining available spectrum resources. Based on an FCC report, these resources are quite large and up to 85% of the available spectrum [1]. The presence of primary users affects the performance of the secondary network (the network formed by secondary users). Whenever primary users return to their dedicated spectrum band, secondary network packets are lost or corrupted, and secondary users should switch to another channel, which introduces back-off and switching delay. Therefore, it is critical for a secondary user to learn of the primary users' influence in the vicinity of the secondary user's transmission environment. Understanding the spread of availability of channels helps in efficient decision making of MAC and routing layers. For instance, if the channels surrounding a node are affected uniformly by primary users, using a channel selection mechanism is not necessary. This information could be given to the cognitive engine of the cognitive radio nodes to save energy and computational cost by disabling a channel selection mechanism. In addition, in the routing layer, a path that is less frequently influenced by primary users is preferred.

We consider a cognitive radio mesh network operating in a *dynamic* environment, where the variation of the primary users' arrival rate is high, altering the stability of available spectrum blocks. Therefore, communication links are stochastic in nature and highly dependent on primary users' nondeterministic behavior. We develop a new metric called Primary Weight Measure (PWM) to capture the uniformity or diversity of availability in the channels of different spectrum bands. The primary weight measure is a metric with nonnegative values. Small values of PWM indicate uniformity while large values of PWM indicate diversity. PWM is constructed by using two probability distributions, say P and Q. The probability distribution P statistically targets a channel with the highest idle frequency (number of times that a secondary user senses that a channel is unoccupied), while Q points to the one with the minimum idle frequency. *Uniformity* occurs when P and Q are close together, and *diversity* happens when P and Q are a considerable distance apart. Thus, from a theoretical point of view, to construct the PWM we need the probability distributions P and Q and a metric to measure the distance between them. Soltani and Mutka introduce the ArgMax probability distribution in [2], which is statistically able to identify the channel with the maximum idle frequency among other channels. Naturally, we take P to be the ArgMax distribution. We select ArgMin probability distribution, to act for Q. The ArgMin distribution statistically determines the channel with the minimum idle frequency.

There are plenty of metrics for measuring the distance between two probability distributions. The Kullback-Leibler divergence (K-L) is a popular and effective metric. It is widely used in information theory. In principal, it measures the information lost when Q is used instead of P. PWM measure is constructed by measuring the distance between P (the ArgMax probability distribution) and Q (the ArgMin probability distribution) by the K-L measure. In addition, we take into consideration the stochastic nature of a dynamic Cognitive Radio Network (CRN) and propose a new routing protocol called Primary Spread Aware Routing Protocol (PSARP). The PSARP is based on nonhomogeneous Markovian transitions that give priority to the paths with the minimum expected frequency presence of primary users. The next hop is selected probabilistically. The probability of selection depends on both the next hop's ability to transfer a packet to a particular destination and also the stability of the links connecting it to the sender nodethat uses stochastic system tools to route packets in the network. PSARP uses PWM metric in order to assess the suitability of the links that are one hop away from a sender node. In summary, the contribution of this work is as follows:

- We develop a new computationally efficient routing metric called PWM that identifies the diversity of the spread of availability of channels around a particular node.

- We introduce the Primary Spread Aware Routing Protocol (PSARP) that routes the packets in a CRN operating in a highly dynamic environment.

In order to evaluate the PWM metric and the performance of PSARP, the protocol is implemented by the NS2 network simulator that is enhanced with a cognitive medium access layer. We implemented another protocol called Cognitive Stochastic Routing (CSR) that is based on PSARP stochastic framework but uses backlogged queue capacity instead of the PWM metric to find the best route. Moreover, we compare the PSARP with the Local Coordination Based Routing and spectrum assignment (LCBR) [3], and OSDRP [4]. The LCBR is an AODV based protocol that uses the summation of frequency switching and back off delay at a node on top of the number of hops as its routing metric. The protocol also identifies traversing flows at each node and calculates the active frequency bands taken, which are used for multi-flow multi-frequency scheduling. Many other schemes that are designed for the dynamic environment adopt the same approach. The OSDRP estimates the route lifetime based on the channel availability, as well as channel switching and queuing delays, and adjusts the time of a flow according to the route lifetime. In addition, it controls the transmission power and selects the nearest forwarding SUs to the SU destination node to support QoS. The results of our comparison suggest that PSARP and CSR are more robust to the variation of available links caused by random interruptions of primary users than LCBR and OSDRP because of their underlying stochastic modeling. However, PSARP performs better than CSR because it is using PWM metric that is based on statistical learning of its surrounding environment.

The organization of this paper is as follows. In Section 2, we review related research on CRN routing protocols and routing metrics that are designed to characterize primary users' effect. The primary weight measure metric is introduced in Section 3. The theoretical basis and algorithm of PSARP protocol and its underlying assumptions are presented in Section 4.2.4. Some features of PSARP are presented in Section 5. Section 6 demonstrates the evaluation results, and Section 7 concludes the paper.

2. RELATED WORK

Recently, more attention is being made towards developing new metrics that would capture the effect of primaries in routing layer. In works of [5], [6] and [7], spectrum utilization is modeled as a new metric to enhance the selection mechanism in traditional routing schemes. In [8], [9] and [10], the problem of routing, scheduling and interference awareness is formulated into different forms of an optimization problem. These studies'underlying assumption is that the behavior of primary users are fairly predictable. In [11], authors look at the average of the on and off times of a particular channel to capture the probability of bandwidth availability by using the odds-on-mean probability distribution.

Protocols such as LCBR [3], CODV [12], OSDRP [4] and [13] adopt the framework of ad hoc or wireless sensor networks to overcome the unpredictable behavior of primary users. The channels stability is mapped into nodes availability in these protocols. The summation of frequency switching and back off delay at a node is considered in [3] as an indication of a reliable link and ultimately the node's priority in routing. In [14], the queueing delay is also added to the above delays to include the effect of network traffic. The airtime cost is used with the available time of the spectrum band utilized by the link in [5]. However, authors in [15] the traffic is distributed on links based on a probability that is formulated by odds-on-mean probability distribution and feedback from the gateway node. In this paper, we focus on developing a stochastic protocol. Our work is different from these previous studies because first, the transition probabilities are found based on the ArgMax probability distribution. In [2] authors show that the ArgMax distribution is very different from Odds-On-Mean even in the case of an exponential arrival pattern of primary users and is more accurate. Second, we develop the PWM metric, that measures the nature of frequency and distribution of primaries around a particular node. There is no knowledge of the location of the primary users transmitters or receivers since we assume a dynamic operational environment for the network. Third, the evaluation of transition probabilities is completely decentralized.

3. PRIMARY WEIGHT MEASURE

The PWM metric is evaluated by measuring the distance between the two probability distributions: ArgMax and ArgMin.

The ArgMax probability distribution points to the channel that at an instant of time appears to have the maximum idle frequency. Assume a node i is connected to j via a set of N_t available channels at time t. A channel between node i and j is stable if it is less prone to the arrivals of primary users. We let the random variable $u_{ij}[k,t]$ represent the link (i,j) utilization via channel k at time t; defined as the average frequency that a channel, sensed by the node i, is available without any interruption from primary users. We suppress the time index t from our notations whenever there is no ambiguity. In our simulation, we record the number of times that a channel is sensed idle over a period of time and then use it for $u_{ij}[k]$. The probability that the channel n between node i and j has the maximum utility is modeled by the ArgMax probability distribution as follows:

$$P_{ij}(n) = Pr\{k^* = n\} = Pr\left\{u_{ij}[n] = \max\{u_{ij}[k],\ u_{ij}[k] \in E[i,j:t]\}\right\}, \tag{1}$$

where k^* is the channel between nodes i and j with maximum utilization at time t, and $E[i,j;t]$ is the set of all available channels between nodes i and j at time t. $Pr(A)$ stands for the probability of event A.

Following the same analogy the ArgMin measure points to the channel that is less stable and is highly exposed to the presence of primary users. Therefore, the probability that the channel h between node i and j has the minimum utility is

$$Q_{ij}(h) = Pr\{k^* = h\} = Pr\,\{u_{ij}[n] = \min\{\ u_{ij}[k],\ u_{ij}[k] \in E[i,j:t]\}\} \tag{2}$$

where k^* is the channel between i and j with minimum utilization at time t. More comprehensive definitions of ArgMax and ArgMin probability distributions is presented in the Appendix.

Monitoring the ArgMax and ArgMin probability distributions provides interesting information on the utilization of channels. If the primary users arrive frequently, the channels will be affected almost uniformly by the primary users arrival. Therefore, the probability that a channel n has the maximum idle frequency is close to the probability that the same channel has the minimum idle frequency. Therefore the difference between $P_{i,j}(n)$and $Q_{i,j}(n)$ is small. Large gap between the two probability distribution P and Q imply a nonuniform spread of primary users on channels; and hence, there exists a channel whose utilization is substantially larger. We measure the distance between the distribution functions ArgMin and ArgMax by the Kullback-Leibler divergence (K-L) [16] measure.

The K-L divergence is a non-symmetric measure of the difference between two probability distributions F and G. In probability theory, F represents the “true" distribution of data, observations, or a precisely calculated theoretical distribution. The distribution G represents a theory, model, description, or approximation of F. It also can be interpreted as the opportunity lost for implementing G instead of F.The K-L divergence for two discrete probability distributions F and G is defined to be

$$D_{KL}(F\|G) = \sum_k F(k) \log \frac{F(k)}{G(k)}. \tag{3}$$

It requires that $G(k) > 0$ for all the values of k for which $F(k) > 0$. It possesses the properties that

- $D_{KL}(F\|G) \neq D_{KL}(G\|F)$.
- $D_{KL}(F\|G) \geq 0$.
- $D_{KL}(F\|G) = 0 \ \Leftrightarrow\ F = G$.

In the context of a cognitive network, with $F = P_{i,j},\ G = Q_{i,j}$, and channel utilization as the average frequency that a channel is idle without any interruption from primary user, we have following interpretations for the K-L divergence.

- $D_{KL}(P_{i,j}\|Q_{i,j})$: The expected utility acquired by transferring packets through channels with maximum utilizations, instead of employing channels with minimum utilizations.
- $D_{KL}(P_{i,j}\|Q_{i,j})$: The expected utility lost by transferring packets through channels with minimum utilizations, instead of employing channels with maximum utilizations.

Primary Weight Measure (PWM) at node i is denoted by $\delta_{i,j}$ defined by taking the average of the above measures.

$$\delta_{i,j} = \frac{1}{2}\{D_{KL}(P_{i,j}\|Q_{i,j}) + D_{KL}(Q_{i,j}\|P_{i,j})\}. \tag{4}$$

The K-L divergence is not symmetric. However, the $\delta_{i,j}$ is symmetric in i, j and indicates the degree of the nonuniform spread of primaries in channels between nodes i and j. When there is no primary user around a particular node, $P_{i,j} = Q_{i,j}$ and the $\delta_{i,j} = 0$. However, if primary users are present, channel utilizations follow a continues random variable and $D(P_{i,j}\|Q_{i,j}) > 0$ and consequently $\delta_{i,j} > 0$. For $\delta_{i,j} > 0$, the larger the value of $\delta_{i,j}$, the more the channels that are less occupied by primary users, and thus have priority over the other channels in the vicinity of the node i. When $\delta_{i,j}$ approaches zero, primary users are spread uniformly, and consequently there is no privilege to any transition. Note that when primary users are present, the $\delta_{i,j}$ could be near zero but not exactly equal.

To show how the PWM represents the nature of the spread of primary users on channels around a node, let us look at the following numerical example.

Example 1. Assume there are two nodes 1 and 2, each one has 5 different channels available to its neighbor j. Primary users arrive at each of these channels randomly. The ArgMax probability distribution $P_{1,j}$ indicates the channel that is more likely to stay stable among the other channels. For instance, if channel 3 has been idle the most during N sensing periods, then the $P_{1,j}(3)$ has the maximum value. Now if the primaries are affecting all the channels with the same rate channel 3 might also be the channel that has been idle the least among other channels. Therefore, the difference between $P_{1,j}(3)$ and $Q_{1,j}(3)$ is small. As explained above, the PWM measure quantifies this difference. Bellow, the primaries are spread around node 1 according to normal distribution and around node 2 following a uniform distribution. After evaluating ArgMax and ArgMin probability densities for all channels, we have the following results for each node respectively:

$$\begin{array}{ll} & \begin{array}{ccccc} ch1 & ch2 & ch3 & ch4 & ch5 \end{array} \\ node\ 1; \begin{array}{c} P \\ Q \end{array} & \begin{pmatrix} 0.26 & 0.21 & 0.28 & 0.12 & 0.13 \\ 0.17 & 0.22 & 0.12 & 0.2 & 0.29 \end{pmatrix}, \end{array}$$

$$\begin{array}{ll} & \begin{array}{ccccc} ch1 & ch2 & ch3 & ch4 & ch5 \end{array} \\ node\ 2; \begin{array}{c} P \\ Q \end{array} & \begin{pmatrix} 0.13 & 0.18 & 0.25 & 0.19 & 0.25 \\ 0.16 & 0.24 & 0.24 & 0.19 & 0.17 \end{pmatrix}. \end{array}$$

The $\delta_{1,j}$ is 0.17 but the $\delta_{2,j}$ is 0.02. As a result, the PWM is substantially lower when the channels are affected uniformly by the arrivals of primary users.

4. PRIMARY SPREAD AWARE ROUTING PROTOCOL

We observed that the transition of packets from a source to a destination in a cognitive radio network is a stochastic process since the random arrival of primary users on channels make the next state of the system (next hop) in the path indeterministic. Packets may be sent to a next hop but never reach that hop due to the arrival of primary users. Therefore, we develop a stochastic routing scheme that uses the transitional probabilities to find the most stable path. Our protocol is different in nature from all other previous work since it is not deterministic.

We consider a mesh network of secondary users in the downtown area of a city, where there are heterogenous primary users with a variety of spectrum availability. Secondary users may choose their particular destinations randomly. We also assume that all users in our system have little to no mobility. A number of primary users are randomly deployed throughout the network. Therefore, the secondary channel availability is not consistent. Some secondary users might be affected by more primary users than others. Primary users access their dedicated channel anytime they desire without notifying other secondary users on the channel. The secondary users have access to a number of channels from different spectrum bands. The medium access is CSMA. Hence, once a channel is available, other secondary users compete to access the channel and transfer their packets when the channel is sensed idle. If a secondary users senses a primary user transmission, it interrupts its transmission, queues up its packet, and waits for the next channel availability. Secondary users are equipped with two radio interfaces with omni directional antennas. A control channel is dedicated to the exchange of control packets and is monitored by one interface. Due to the irregular arrival of primary users, a dedicated control channel is necessary for the reliable transfer of control packets. The other interface monitors the data channels. The wireless channel has the Rayleigh fading model. According to [17], Rayleigh fading is appropriate for an urban area, where there is no line of sight between the sender and the receiver.

4.1 Theory

The flow of packets initiated from a sender to a receiver can be modeled by a Markov process with time dependent transition probabilities, because the transitions are step wise from one node to another [18]. All the *nodes* of a particular flow form the transient *states* of the Markov chain except the receiver, which is absorbing. Let us consider a secondary network. At a time epoch t, a secondary user sender i chooses any of its neighboring nodes j, $\{j \neq i, j \in M_{i,t}\}$ ($M_{i,t}$: total number of neighboring nodes of i accessible from i at time t) to send its packets to the destination d via channel k, $k = 1, \cdots, N_{ij}$ based on the transition probabilities $p_{t[ij;d]}(k)$. The variable N_{ij} represents the total available channels between nodes i and j at time t. The time index t is suppressed from now in our notations whenever there is no ambiguity.

To have a reliable transmission, from a local perspective, the node i at time t looks for a neighboring node j with a reliable link connection. In a global view however, the neighboring node j should be able to forward received packets to the desired destination. In other words, node j should be on a valid path to the destination. Therefore, in any formulation for $p_{t[ij;d]}(k)$, the neighbor's forwarding ability and the neighbor's link quality must be addressed.

4.1.1 *Neighbor's forwarding ability*

To model a node's forwarding ability, a selection probability $g_d(j)$ is assigned to each neighbor node j based on its PWM value δ_{ij}, for a specific ultimate destination d at time t. Probabilistically, the transition must go through the nodes that have maximum PWM meaning they are less affected by the primary users. Therefore, $g_d(j)$ is found based on the odds on PWM probability distribution as follows.

$$g_d(j) = \frac{\delta_{ij}}{\sum_{m \in M_{i,d}} \delta_{i,m}},\ j \in M_{i,d} \tag{5}$$

where $M_{i,d}$ consists of the node i neighbor nodes that could be chosen for the ultimate destination d at time t. The set $M_{i,d}$ is identified in the initial setup phase of the PSARP protocol. As explained in the previous section, when $\delta_{ij} = 0$, there are no primary users around the node j. Therefore, $g_d(j) = 1$.

4.1.2 *Link reliability*

A link between node i and node j is stable if it is less interrupted by the primary users. When a primary user is absent, the channel is used by other secondary users. A link reliability metric should also capture other secondary users traffic load on the channel. We use the ArgMax probability distribution to characterize the channel that has the maximum utility among the set of all available channels. Therefore, the probability that channel n at node i has the maximum utility is $P_{ij}(n)$, evaluated using equation (1).

4.1.3 *System Transitional Probabilities*

let us summarize the probabilistic dynamics of transitions. A node i seeks an accessible node with maximum PWM through a link with maximum utilization at a given epoch. The system has stochastic dynamics; consequently, the desirable nodes and links are subject to change. The transition has two stages: the selection of the desirable neighboring node for the ultimate destination d, and the selection of the desirable link. The tree diagram with root i and branches $[i \to j, j \to k_j]$, $j = 1, \cdots, M_{i,d}$, $k_j = 1, \cdots, N_{ij}$, shown in Figure 1, depicts the transitions from i to j through channel k. Thus, the transition probability from i to j through the channel k at time t is

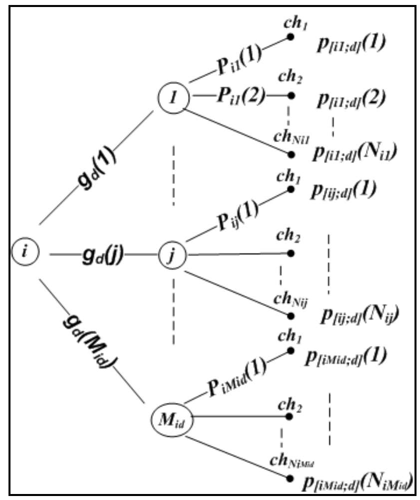

Figure 1: Transition probabilities tree diagram

$$p_{[ij;d]}(k) = g_d(j) P_{ij}(k). \tag{6}$$

Therefore the transition is from i to any of the states in $\{(j,k) : j = 1, \cdots, M_{i,d},\ k_j = 1, \cdots, N_{ij}\}$ The following matrix governs the transition probabilities.

$$T_{id} = \begin{pmatrix} p_{[i1;d]}(1) & p_{[i2;d]}(1) & \cdots & p_{[iM_{i,d};d]}(1) \\ p_{[i1;d]}(2) & p_{[i2;d]}(2) & \cdots & p_{[iM_{i,d};d]}(2) \\ \vdots & \vdots & \ddots & \vdots \\ p_{[i1;d]}(N_{i1}) & p_{[i2;d]}(N_{i2}) & \cdots & p_{[iM_{i,d};d]}(N_{iM_{i,d}}) \end{pmatrix}, \tag{7}$$

The number of columns of T_{id}, $M_{i,d}$, is the number of neighbors available to node i leading to destination d at time t, and the number of rows, N_{ij}, is the number of channels available between node i and its neighbor j at time t. Clearly, $\sum_{jk}^{N_{i,j} M_{i,d}} P_{ij,d}[t; ch_k] = 1$. We see this is satisfied since the elements of the transition matrix T_{id} are the ending branches of the conditional tree diagram in Figure 1. In the next subsection, we present the framework and forwarding mechanism based on the transition matrix T_{id} of PSARP.

4.2 PSARP Implementation

In this section we layout the implementation of the stochastic protocol. First, we list different routing components that are used to make the protocol reliable and sustainable in actual implementation. Second, we explain how these components are constructed. Finally, we explain the adaptive per-hop forwarding procedure by following packets from a source to a destination. We categorized the routing components into tables, control messages and transition probabilities.

4.2.1 PSARP Tables

Two tables are held and maintained at each CR nodes.

• Neighbor table

Similar to AODV based protocols [19], CODV [12], OSDRP [4], each node holds a table to store some attributes of its neighbors. These attributes will eliminate the count to infinity and the discontinuity problems that are usually present in a decentralized decision making protocols. A neighbor table entry corresponding to a neighbor j is shown in table 1. The channel utilization effect is captured

Table 1: An entry of the neighbor Table

Neighbor Id (j)
Destination Id (d)
Number of hops
Authorization index (connectivity attribute)
Time to live (Expiration time for this node)
PWM, δ_{ij}
Reception channel k^*.

in evaluating the channel k^* that has the maximum utility around neighbor j by using equation (1).

• Forwarding table

The entries in the forwarding table construct the sets of candidates among the neighbors that are suitable to receive packets for a specific destination. See Table 2. Each node uses the forwarding table information to construct its transitional probabilities. This process is explained in detail in the following subsections. Active neighbors are those with a lower number of hops and a valid Authorization index; this information is obtained from the neighbor table. Note that the forwarding table also exists in the other routing protocols.

Table 2: An entry of the forwarding Table

Destination
List of authorized neighbors
$p_{[ij;d]}(k)$ transition probabilities for all authorized neighbors

4.2.2 Control Messages

In order to update the entries of the neighbor table and forwarding table according to the system dynamics, neighbors exchange two types of control messages.

• HELLO Packet

Similar to decentralized protocols, HELLO packets are responsible to update the neighbor and forwarding table of each node. A Hello packet carries the destination of the next packet waiting to be transmitted. The HELLO packet is generated when a node does not have an entry for a particular destination or when the transition probability update period is reached. HELLO packets are broadcast to neighbors on the common control channel with the following information:

- Destination
- Number of hops
- PWM, δ_{ij}
- received channel ID

Upon receiving the HELLO packet, the node updates the corresponding information in its Neighbor table. In order to avoid HELLO packet collisions, nodes send HELLO packets in random time slots.

• Destination Acknowledgment DACK Packet

In order to avoid isolated nodes, the neighbors are authorized for a specific destination. To set the Authorization index in the neighbor table, when destination receives a message, it will generate the DACK message. Instead of acknowledging each path, which

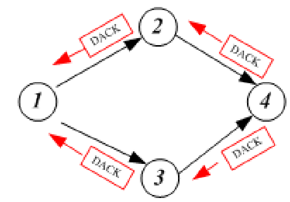

Figure 2: Simple topology, node 4 is the destination, generating DACK messages.

may introduce overhead for long packet headers, we authorize each neighbor via back-pressure. See Figure 2. Node 1 wants to send to node 4. Once node 4 receives a packet, node 4 authorizes 2 and 3, letting them know that they can reach node 4. Then, nodes 2 and 3 authorize 1, letting node 1 know that it can reach 4 through 2, 3. The DACK is sent locally. Once a node is authorized, no DACK message will be sent to it. We also authorize all paths with a minimum number of hops to the destination to skip long paths. The DACK messages are only sent in the initial set up. We consider a mesh network where the nodes are stationary with long lasting energy. Therefore, the hop number would not be dynamic. Note that the dynamics of channel availability and node occupancy are included in the T_{id} matrix. Hence, contrary to DSR, DSDV, AODV, and other reactive and proactive protocols, we do not need to repeat this process during network operation.

4.2.3 Transition Probabilities

As mentioned earlier, the next node is found based on the transition probability associated to it. In order to find each entry of the transition matrix $T_{i,d}$, $P_{ij}(k)$ is calculated by both nodes i and j, and the $g_d(j)$ is evaluated by node i based on the values of δ_{ij} that are stored in its Neighbor table.

• Evaluation of Channel Reliability Probabilities

Each node i is aware of its surrounding and gathers the number of times that a channel k is sensed idle ($u_{ij}[k]$, the channel utilization parameter for each channel k). It constructs the following vector for a pre-specified observation period:

$$R_i(t) = [u_{ij}[1] \ldots u_{ij}[k]].$$

Therefore, the node has many realization of vector $R_i(t)$ after t sensing periods. The ArgMax and ArgMin probability distributions corresponding to the channel utilizations are evaluated based on simplified simulation method presented in Algorithm 1. The variable T_{max} corresponds to the maximum number of observations. The variables Max_k and Min_k represent the number of times that channel k has the maximum and minimum utilization respectively.

• Evaluation of Forwarding Ability Probabilities

The δ_{ij} metric of the neighboring node j informs the sender i of the distribution of primary users around its neighbor j. Each node j calculates its δ_{ij} according to equation (4) at each time t that a Hello-reply packet is sent. Based on the δ_{ij} obtained from all the neighbors, $p_{[ij;d]}$ is calculated for each neighboring node j based on equation (5). The index i in the notation of δ_{ij} means that node j evaluates a different PWM for another node that is located in the

Algorithm 1 ArgMax and ArgMin probabilities calculation procedure

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for $t = 1$ to T_{max} **do**
  in $R_i(t)$
  if channel k has the maximum u_{ij} **then**
    $Max_k = Max_k + 1$
  end if
  if channel k has the minimum u_{ij} **then**
    $Min_k = Min_k + 1$
  end if
end for
$P_{ij}(k) = Max_k/T_{max}$
$Q_{ij}(k) = Min_k/T_{max}$

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vicinity of other channels that are not accessible by node i. This is because it is usually the case in the network that node j has access to some channels that are not accessible by node i.

4.2.4 PSARP Forwarding Mechanism

The procedure of forwarding packets from a source to a destination is presented here. In the initial setup the neighbor and forwarding tables need to be constructed. Hence, to identify the authorized neighbors, source nodes broadcast the data packets destined for a particular destination. By simple flooding, the packets are delivered to the destination. The destination generates the DACK messages and the nodes that are authorized by receiving the DACK packet from the destination, will authorize their neighbors as explained in the construction of control messages above. The DACK messages are propagated back to the source so that the source node can update the forwarding table. After this initial setup the forwarding mechanism is as follows:

- The source node i
  1. checks the neighbor table to see if the destination d is in the neighbor table. If not, broadcasts the message (waits for DACK messages to arrive).
  2. sends the HELLO packets and collects the HELLO packets from its neighbors. Hence, the forwarding and neighbor table elements are updated.
  3. computes $p_{[ij;d]}(k)$ for each neighbor based on equation (6).
  4. sends number of packets with the same destination to neighbor j proportional to the value of $p_{[ij;d]}(k)$. Therefore, the neighbor j that has the highest value of $p_{[ij;d]}(k)$ associated to it, is more often the next hop.
- The intermediate node j upon receiving a message, checks the destination of the message and
  1. checks the neighbor table to see if the destination d is in the neighbor table. If not, broadcasts the message (waits for DACK messages to arrive).
  2. looks at the forwarding table, if there is a neighbor h for the destination d, gets the transition probabilities $p_{[jh;d]}(k)$ from the table.
  3. forwards the number of packets destined to d to neighbor h proportional to the value of $p_{[jh;d]}(k)$.
- The destination node d receives the packets and looks up the previous hop from the message header and checks if it is included in the list of the authorized previous hops. If not, the destination gathers a list of the unauthorized previous hops and insert them in the DACK message. The DACK message is then broadcasted. Therefore, all the unauthorized previous hops are authorized with one DACK message.

5. ADDITIONAL FEATURES

Here, we elaborate on some features embedded in PSARP that may be used in other stochastic routing protocols.

5.1 Update Period

Note that the $p_{[ij;d]}(k)$ is highly dependent on how fast $P_{ij}(k)$ and $g_d(j)$ are updated. Currently, the update period is around one second. During this period, we can have 100 samples of R_i matrices to estimate $\hat{P}_{ij}(k)$ and $\hat{g}_d(j)$. From the law of the iterated algorithm proposed by Kolmogorov in [20], the upper and lower bound on the rate of convergence of the estimator of a distribution to its true value are as follows:

$$\limsup_{n\to\infty} \frac{\sqrt{n}\|\hat{P}_n - P\|}{\sqrt{2\ln\ln n}} \leq 1/2$$

$$\liminf_{n\to\infty} \sqrt{2n\ln\ln n}\|\hat{P}_n - P\| = \pi/2$$

where n is the number of samples. From the above we can find the upper bound on the error of the estimator based on n, for large n

$$\|\hat{P}_n - P\| < \frac{\sqrt{\ln\ln n}}{\sqrt{2n}} \tag{8}$$

We can see that by selecting $n = 100$, the error is about 0.15; and as n increases, the rate of convergence will go exponentially to zero. By selecting $n = 200$, the error is 0.004. Therefore, by having our update period around one second, or in other words by collecting 100 to 200 samples, we have a very good estimate for the ArgMax and Odds-on-Mean distributions corresponding to $P_{ij}(k)$ and $g_d(j)$ respectively.

5.2 Channel Selection Mechanism

The process of handshaking with neighbors in CRNs is challenging. For instance, suppose node 1 is choosing channel 1 because the $P_{12}(1)$ is maximum, while node 2 is selecting channel 2 because based on its sensing measurement $P_{2j}(2)$ is maximum, where node j is a neighbor of node 2. Therefore node 1 should check which channel node 2 is on before sending its packet on its decided channel. We have the following mechanism in place to reduce packet loss for such a scenario. This mechanism will also reduce handshaking overhead.

1) Each node chooses its receiving channel according to the values of the ArgMax probability distribution that locates the channel with the maximum idle frequency in the set of available channels. The channel ID is sent to neighbors via HELLO packets and saved in the neighbor table.

2) When node i wants to send its packets, the next hop j is selected based on the transition probability $p_{[ij;d]}(k)$ in equation (6). Then, node i switches to the receiving channel of node j for sending. If the receiving channel of node j is occupied on the side of node i, the next hop is reselected.

3) After sending, node i switches back to its own best receiving channel.

We can see that this mechanism forces the node to choose a link that is reliable at the both sender and receiver side.

6. EVALUATION

We study the effectiveness of PSARP in a dynamic environment through NS2 network simulator.

We focus on a *dynamic* environment. The primary transmitters and receivers locations are unknown and their transmission duration is unpredictable. Therefore, we compare the protocol with the Local Coordination Based Routing and spectrum assignment (LCBR) [3], and OSDRP [4].

Further more, to show that the PWM measure truly has an advantage to show the distribution of primaries around a node, we also compare the PSARP with the Cognitive Stochastic Routing (CSR) protocol, that we developed, which has the same stochastic dynamics as PSARP but uses the backlogged queue capacities as an indication of next node's reliability instead of PWM. The results show that the stochastic approach we proposed is indeed successful in coping with the uncertainties in dynamic environment in both protocols. However, the PSRP performs better because the PWM measure enables it to recognize unstable routes more accurately.

We used different scenarios. In the first scenario a network with 30 nodes with 4 primary users in a $1000X1000$ sq m area is considered. The secondary users are spread randomly throughout the plane. The radio range is 250m and a channel is dedicated to the control channel with the bandwidth of 250kb/sec. Three other channels are available, each with the bandwidth of 2Mb/sec. The secondary nodes are able to switch to another channel when their transmission is interrupted or the channel is occupied. This scenario is similar to the test configuration of the OSDRP protocol.

6.1 Primary Users Traffic Patterns

The distribution of the inter-arrival time of primary users is exponential with a mean of 3.0. As a result, the primary user's traffic follows a Semi-Markov process with an OFF/ON period following the exponential distribution. This illustrates the model presented in the measurement study [21] of the behavior of primary users.

To evaluate PSARP under different primary user patterns, we changed both the distributions and their corresponding mean of the idle period of primary users and kept all the parameters of scenario 1 constant. The average throughput of the protocols is shown in Table 3. With the exponential pattern, all four protocols gain higher throughput. This was expected, since the shape of the distribution is skewed to the right. The average idle period will be higher than the uniform distribution. PSARP and CSR maintain throughput even though the inter-arrival time of primary users is changing from 3 to 30 seconds. When the inter-arrival time of primary users is 3 seconds, the protocols should quickly adapt to the changes in the network dynamics. The PSARP adapts to the primaries' change of behavior. Its good performance is also an indication that the transition probabilities are estimated in a timely manner to cope with the uncertainties. The OSDRP and LCBR are not successful in capturing the randomness effect because of their deterministic framework and frequent calling of route recovery mechanisms. However, as the idle periods increase, meaning the channels are less interrupted by the primary users, the throughput of both protocols improves and approaches that of the CSR and PSRP. This shows that stochastic modeling works better than deterministic modeling when the environment is dynamic.

Table 3: Average throughput (bytes/sec), (30-node network) with different primary users traffic patterns

Average Idle Period (sec)	OSDRP	LCBR	CSR	PSARP
Exponential (mean 3 sec)	2.30E4	3.49E4	5.20E4	5.5E4
Exponential (mean 30 sec)	4.40E4	4.70E4	4.80E4	5.10E4
Uniform (mean 3 sec)	2.20E4	3.3E04	4.50E4	4.80E4
Uniform (mean 30 sec)	3.91E4	4,40E4	4.51E	4.83E4

6.2 Effect of Network Load

We change the sending rate from 81kb/sec to 1638kb/sec in the first scenario. We use the exponential distribution with the mean of 3 for the inter-arrival time for the primary users. We used 15 different random scenarios with the same configuration as the first scenario, the results shown in Figure 3 and Figure 4 are the average of the throughput and end-to-end delay from all the 15 random scenarios. There is a peak around a 409kb/sec rate in all four protocols.

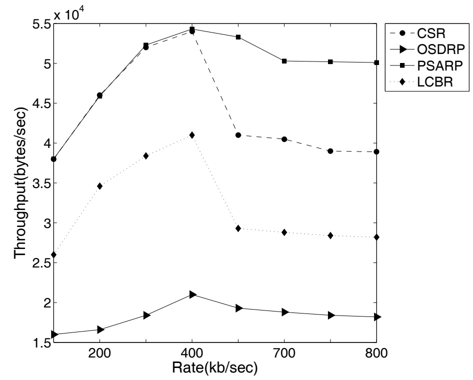

Figure 3: Average throughput under different loading conditions, 30-node network

This was expected since there are 8 CBR connections, meaning 8 sources are sending packets with 409Kb/sec. The channel's bandwidth is 2Mb/sec. If the packets are distributed fairly across all three channels, the network generates high throughput around this rate. However, if the availability of a channel is not determined accurately and packets are sent through an unreliable channel or if the route is not updated on time, a bottleneck is generated. When the sending rate is higher than 409kb/sec, the overall sending rate is more than the channel capacity. As a result, queues fill up quickly. The power of PSARP and CSR are in their stochastic nature. Both protocols benefit from the uncertainty of the network parameters. Hence, while OSDRP and LCBR try to find a new route by unexpected arrival of a primary users, PSARP and CSR stochastic framework have already predicted primary users arrival and chosen an appropriate node for forwarding the packets to. PSARP and CSR learn and adapt to the primary users' behavior more quickly. In OSDRP and LCBR, when a link disappears, the corresponding node is removed from the routing table and the new route discovery mechanism is initiated. Hence, the network operates with less nodes and does not reach its optimal performance and generates less throughput. The LCBR performs better than OSDRP due to its spectrum assignment mechanism that helps a node to forward packets with less channel switching. We can see at higher rates that the network saturates and throughput drops. The sharp decrease in CSR is due to the decrease in queue capacity variation. Hence CSR selection is blind to the behavioral pattern of primary users located one hop away from the intermediate neighbors at high rates. PSARP on the other hand, uses the PWM measure and is able to identify the correct path. In Figure 4, we represent the end-to-end delay comparison. Since the environment is highly dynamic, OSDRP does deliver a substantial amount of packets compared to PSARP and CSR, which adds to end-to-end delay. PSARP and CSR are using ArgMax probability distribution in locating the channel with the maximum utilization. The strength of ArgMax probability distribution is in its accurate identification of the maximum random variable among a set of random variables. Therefore, the channel that is chosen has a higher probability to stay stable and provide stable transmission. Therefore, packets are rarely buffered in the network. This further enhances the performance of the PSARP and CSR and minimizes its end to end delay. Since PSARP chooses the more stable path, its end to end delay is better than CSR. At the rate of 409kb/sec, CSR and PSARP delay are the lowest and the throughput is at its peak value.

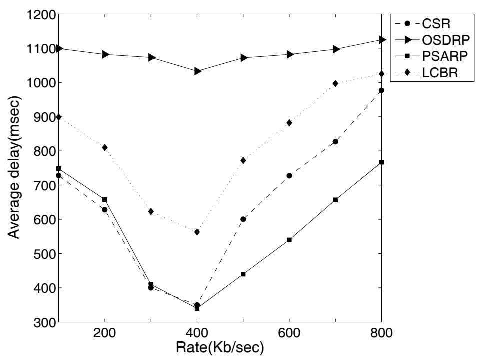

Figure 4: Average end-to-end delay under different loading conditions, 30-node network

6.3 Large Network

We use a network with 70 nodes. The sending rate is $409kb/sec$. The number of primary users are 15, and they choose different channels from the three available channels. There are 8 CBR connections and sources are distributed randomly in a $1500X1500$ sqm field. Since primary users' inter-arrival time is random, learning their behavior and selecting the route adaptively substantially improves the performance of the network. Table 4, shows the simulation results for different distribution for the inter-arrival time of primary users. We can see that OSDRP fails substantially to deliver packets due to the large instability of links and nodes. However, as the idle period of the primaries increases and the network operational environment is closer to a semi-dynamic environment, OSDRP and LCBR throughput increases. On the other hand, PSARP is still successful in maintaining throughput within a range and adapts to the uncertainties. Since PSARP and CSR are stochastic in nature, their throughput degrades as the environment tends to be more static. The reason is that a node in these protocols selects the next hop and the receiving channel probabilistically. It does not stay on a specific best channel or rely on a specific best next hop. Nevertheless, PSARP has a higher throughput than CSR because the PWM measure captures the distribution of primaries more accurately than the queue average backlogged capacity. When the environment is semi-dynamic, PSARP performs slightly better than OSDRP and LCBR because it distributes the packets fairly among the nodes based on its selection probabilities. We also test the performance of PSARP under different loading conditions in the large network. Figure 5 present the average throughput. Although the network size has increased, the PSARP is still successful in maintaining the throughput. The queues have more variations in their capacities, when there are more nodes in the network. Therefore, CSR throughput has less variation and degrades slower compared to the scenario 1. The OSDRP and LCBR are showing the same trends as scenario 1. Maintaining throughput is very useful in applications that require a guarantee of delivery within a certain user defined quality of service range. In the future, it will be interesting to evaluate the lower and upper bound of the PSARP delivery range. Evaluation of the delivery range is useful to control the applications' sending rate in order to have a guaranteed delivery in dynamic CRNs. Finally we present the comparison of the relative overhead frequency of the protocols over the first four hours of the large network operation in Figure 6. The relative overhead frequency is the ratio of the number of overhead packets of each protocol over the total number of overhead packets collected from all four protocols over that particular hour. The relative overhead frequency of PSARP and CSR is larger in the first hour of operation due to the transmission of DACK messages. Recall that the DACK messages are needed in the initial configuration of the network to configure the neighbor and forwarding table. However, the relative overhead frequency decreases substantially after the first hour because only the HELLO messages would provide the information needed to the sender nodes to update their transition probabilities. On the other hand, the relative frequency of LCBR and OSDRP is higher due to the frequent calling the route recovery and spectrum assignment mechanism.

Table 4: Average throughput (bytes/sec), (70-node network) with different primary users traffic patterns

Average Idle Period	DSODV	LCBR	CSR	PSARP
Exponential (mean 3 sec)	1.35E4	2.01E4	3.8E4	3.95E4
Exponential (mean 30 sec)	3.91E4	4.1E4	3.84E	4.10E4
Uniform (mean 3 sec)	1.20E4	1.9E4	3.75E4	3.91E4
Uniform (mean 30 sec)	3.70E4	3.8E4	3.71E4	4.02E4

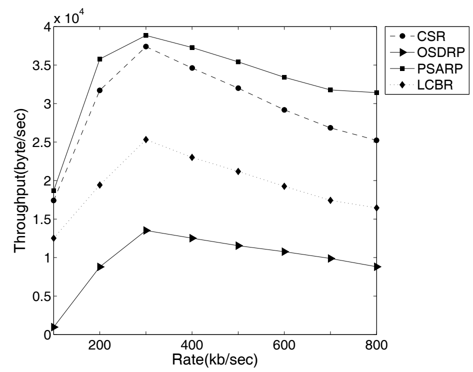

Figure 5: Average throughput under different loading condition, 70-nodes network.

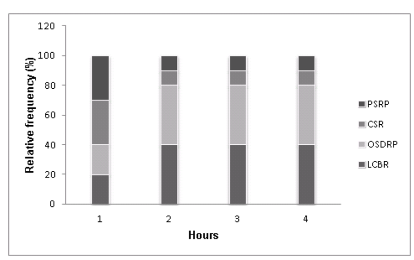

Figure 6: relative frequency distribution of overhead in the first 4 hours of 70-nodes network operation.

7. CONCLUSION

In this research, we introduced an interesting measure called *primary weight measure*, which indicated the frequency and the nature of the distribution of primaries around a particular node. A low value of the primary weight measure metric indicated uniform and frequent primary users interruptions on the channels surrounding a node. With this information MAC and routing decisions are taken more efficiently. In addition we introduced a Primary Spread Aware Routing Protocol (PSARP), which is able to adapt to the uncertainties of spectrum availability in cognitive radio networks. PSARP is based on the Markovian property of a particular flow from source to destination and uses PWM as one of its routing metrics. We demonstrated through simulation that PSARP is robust to the variation of the primary users' activity. Our results confirmed that using a stochastic protocol for a stochastic environment is indeed more cost efficient and suitable than using deterministic protocols that map channels' availability to nodes' availability. We believe this research is the beginning of a new line of work on the development of stochastic routing protocols.

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