MSP: A Routing Metric for Cognitive Radio Networks

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Abstract. The current routing metrics mainly face two inevitable restrictions for Cognitive Radio Networks (CRN) that they are often designed based on routing condition but seldom considering node mobility, and they are always assumed to adapt dynamic spectrum access without considering primary user's activity. In this paper, a novel routing metric called Mobility Success Probability (MSP) is proposed which considers both the mobility model and spectrum available time. Through spectrum access and selection path with mobility success probability, the routing protocol also meets the most essential requirements of optimality. Combined with Dijkstra based routing protocols, optimal expression of the MSP is analytically derived and rigorously proved through CR algebra. The simulation results reveal a good routing performance of adopting MSP for CRNs.

Keywords: Routing metrics · Cognitive radio networks · Optimality

1 Introduction

With the increasing needs for the wireless communication, people require higher data transfer rate as well as more radio spectrum resources. However, many of the licensed spectrums are idle in time and space, which is bound to lead to the lack of spectrum resources fit for wireless communication. Such situation has become a new bottleneck for the further development of wireless communication. CR technology is proposed to efficiently solve the problems mentioned above, by using those idle spectrum resources of licensed users.

Benefits from multiple path and opportunistic routing, current routing solutions for CRN still show some challenges [1]. Specifically, opportunistic routing could exploit next hop forwarding node sets with an expectation metric to promote the overall transmission success probability. However the relay nodes should be selected among all the channels and if PU appears, nodes acting on the same channel would be expired. It is a great burden to recalculate the metric frequently and maintain the node sets. For such a mobile node in wireless networks, up to now there have been many node mobility model researches. Nevertheless, most of the protocol designs such as routing metrics seldom take this node mobility into consideration.

Currently the matric design is conceived mainly from three aspects of integrated information with cross layer interactions, attempting to find optimal available spectrum,

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relay nodes and maintain mechanism. The available spectrum requires a relatively stable PU spectrum occupancy to improve link quality without frequently interruption and spectrum handoff. The matric factor may include minimum transmission time, maximum spectrum available time or handoff. The relay selection would be in favor of those forwarders with a good history forwarding records or have a probability to transmit to the destination successfully. The maintain mechanism is focus on how to deal with handoff and recover transmission when PU appears or connection interrupts.

From above we can see apart from spectrum variability, the forwarder behavior arising from node mobility plays an important role in metric design. Thus, more strict and specific requirements for metric design that need to be considered in routing protocols are concluded as follows [3]. Firstly, fast convergence is a key issue to avoid routing loops and inaccessible destinations especially in a dynamic network topology. Secondly, in a short time span, a fast and effective path is required to adapt mobility without large amount of frequent calculation cost.

There have been a series of newly proposed routing metrics for CRNs [7]. For instance, the author in [2] propose Routing Closeness metric and select path that is far from other paths geographically in order to reduce interference. The author in [4] proposes an approach which aims at balancing the performance of queuing delay, back off overhead and switching cost. The author in [9] proposes a capacity-based routing metric. The metric improves network performance by shifting traffic away from high regions with high density. The author in [8] designs a probabilistic metric that selects path on the basis of the capacity of accessing free channels. The author in [14] computes the transmission time from source to destination and selects the path with minimal value. This metric also takes use of multiple channels, so as to decrease the transmission time. The author in [16] constructs multi-layer relay sets for each sender and when handoff occurs, a backup relay set enables replacing main set to reduce the channel switching and shorten the cost.

This paper explores the mobility application in metric design and introduces a novel routing metric called Maximum Success Probability (MSP), which accounts for both the node mobility and the corresponding spectrum available time of licensed channels. The proposed metric concentrates to maximize the success probability for a CR transmission under node mobility to improve the overall network performance. Based on the mobility features, this paper proposes an efficient opportunistic routing algorithm to select the path with maximum success probability between a CR source and a CR destination. Considering the compatibility between proposed metric and corresponding protocol may degrade network performance if applying an arbitrary routing metric to a CR protocol, CR algebra [10] and basic properties are applied to prove that MSP metric properly works with Dijkstra based routing protocols. Simulation shows throughput of the MSP algorithm outperforms with other two referenced algorithms under different network conditions.

The rest of this paper is organized as follows. Section 2 presents the proposed metric MSP and proves the compatibility of the new metric with Dijkstra based routing protocols. Section 3 gives the simulation results of path section performance in comparison with MTT, MaxPos and MSP metric respectively. Section 4 makes a conclusion and shows further work.

2 MSP Design

2.1 Assumptions

We consider a CRN where n SUs and m PUs co-exist in a limited area. SU can opportunistically access PU's licensed channels in effective transmission range if PUs are not shown in adjacent areas. PU commonly appears and employs its spectrum with Poisson distribution. When a PU becomes active, SU would fast handoff to find a new appropriate channel opportunity and maintain transmission. SU would move with one mobility model depending on a realistic scenario.

Based on the condition above, the CRN in this paper could modeled as a graph $G = (N, E)$, where N stands for the set of CR users and E stands for the set of links in the network. $e_{i,j} = (n_i, n_j)$ is the link between CR users n_i and n_j. It belongs to E only if the CR user n_j is in the transmission range of n_i and there is at least one common data channel between them. However, as there are more than one primary channels, link $e_{i,j}$ consist of several links each of which is working on various primary channels. So, this paper makes $e_{i,j}^{(m)} \in e_{i,j}$ as the link that stands for primary channel m.

This paper assumes that both $T_{on}^{(m)}$ and $T_{off}^{(m)}$ are exponentially distributed [5] with mean equal to λ and μ respectively. The transmission power of each CR user is the same all the time. Moreover, when computing the transmission rate of a CR user over the channel it accesses, Shannon theorem is then used.

2.2 Mobility Detection

There have been many newly investigated mobility models evolved from classic models. The paper [15] proposes backhaul traffic model and energy efficiency model under Gauss-Markov mobility model. In fact, all practical movements show a kind of regularity instead of random activity. Since such a classical random walk model cannot portrait a real scenario with index decay, some human mobility models with social features are emerged to reveal properties as contact duration, inter-contact time or content relevance, such as TVC, SWIM [17] and content popularity framework. Here we briefly apply a simple mobility model as SWIM that shows human common daily trajectory. Generally a handheld node will move to a location in a time period, even along a static route, and then keep still in a range. With respect to such a highly dynamic topology, this process could be viewed as a network sub-graph snapshot which can be represented as time evolving graph with Markov model. However, this topology has an assumption that there is a constant node number C without node expiring or newly joining. For simplicity, we would build a transitional snapshot as a static topology with relatively static neighbor nodes and forwarders. The sequence of graph G can be denoted as following notation:

$$\Gamma = \{G_t = ([n], E_t) : t \in N\}, [\mathrm{n}] = \{1, \ldots, n\} \tag{1}$$

The initial network snapshot at t_0 is represented as G_0. From t_0 if the topology changes, we have a new network snapshot G_t at t_n, so the discrete time sequence snapshot is $G_t = \{\mathrm{G}_0, \mathrm{G}_1, \mathrm{G}_2, \mathrm{G}_3 \ldots\}$. In other words, we suppose the topology keeps stable at time period t. The end to end transmission path from sender to receiver in CRN can be viewed as an edge selection E_t in a snapshot.

Inspired from SWIM mobility model, we define Mobility Trajectory Probability as follows.

For any two neighboring CR users ni and nj, MSP aims to find the path with maximum success probability. The MSP is defined as follows:

$$P_{su}^{\max}\left(e_{i,j}\right) = \max_{m \in M}\{P_{su}\left(e_{i,j}^{(m)}\right)\} \tag{2}$$

2.3 MSP Metric Design

For any two neighboring CRN users n_i and n_j, the MTT metric aims to find the path with minimum transmission time among all the links between them [12], MSAT metric aims to find the link with maximum spectrum available time. The MTT metric only takes the required transmission time between any neighboring CR users into consideration when selecting path from a CR source NS to a CR destination ND. However, spectrum available time of a primary channel may be smaller than the minimum transmission time over the selected path, which means the CR user may be interrupted and lose its traffic once the PU occupies this channel again. Similarly, the MSAT metric only take the spectrum available time between any two neighboring CR users into consideration. However, it will also incorrectly select a bad path if the minimum transmission time over a path is larger than the spectrum available time.

To deal with the above-mentioned problems, this paper introduces a new routing metric called Maximum Success Probability (MSP), which considers both the spectrum available time and CR transmission time.

Success Probability: The notion $P_{su}\left(e_{i,j}^{(m)}\right)$ between any two neighboring CR users n_i and n_j over channel m is given as follows:

$$P_{su}\left(e_{i,j}^{(m)}\right) = P\left[T_{av}\left(e_{i,j}^{(m)}\right) \geq T_{tr}\left(e_{i,j}^{(m)}\right)\right] = e^{-\frac{T_{tr}\left(e_{i,j}^{(m)}\right)}{\mu_{m}(e_{i,j})}} \tag{3}$$

Mobility Success Probability: For any two neighboring CR users n_i and n_j, MSP aims to find the path with maximum success probability. The MSP is defined as follows:

$$P_{su}^{\max}\left(e_{i,j}\right) = \max_{m \in M}\{P_{su}\left(e_{i,j}^{(m)}\right)\} \tag{4}$$

Maximum Path Success Probability: The maximum path success probability between CR source N_S and destination N_D is defined as follows.

$$MaxP_{su}(N_s, N_D) = \max_{l \in L}\{P_{su}^{(l)}(N_s, N_D)\} \tag{5}$$

Where $P_{su}^{(l)}(N_s, N_D)$ is the maximum probability of success on path l. It is computed as follows:

$$P_{su}^{(l)}(N_s, N_D) = \prod_{i=1}^{k-1} P_{su}^{max}(e_{i,i+1}) \tag{6}$$

To correctly find the path with maximum success probability for a CR source N_S and a destination N_D, this paper uses $-log$ function on the success probability to get the final metric value, which means a small metric value refers to a high success probability. The metric value of link m is then defined shown as follows:

$$W(e_{i,j}^{(m)}) = -\log[P_{su}(e_{i,j}^{(m)})] \tag{7}$$

The MSP metric first removes links that are not connected to each other. Then the maximum success probability of each link is computed by Eq. (1). After that, the algorithm computes the metric value for each link using (5). At last, it selects the path with maximum success probability using (2).

2.4 Routing Phrase

Here we design a routing phrase to explain the routing process.

Information exchange: The sender performs spectrum sensing and sends a request to its neighbors on multiple channels. The neighbors response with location and spectrum information. In this stage the topology is build and

Forwarder selection: The sender selects promising neighbors into relay sets on multiple channels for data transmission.

Mobility detection: The sender notifies the nodes in the selected main relay set, assigns them priorities, and applies the opportunistic based routing protocol;

Route maintain: When the transmission fails due to the suddenly active PUs, the sender adjusts the affected main and backup relay sets, and reselects them if necessary (Table 1).

2.5 Compatibility Analysis

In this section we prove the compatibility of MSP and Dijkstra based routing protocols applying mathematical tools called routing algebra. CR algebra can be described as a 4-tuple [11] as follows.

$$C = (S, \oplus, W, \preceq) \tag{8}$$

Table 1. MSP Algorithm.

```
MSP Algorithm
Input: $u(ei,j)$, $C_{S,}$ $C_{D,}$ $G_t$
Output: Path $L$
$T=0;$
1: for each channel $c_m$ do
2:   for each edge $e_{i,j}$ do
3:     Calculate $Psuc_{(}e_{(m)\ i,j\ )}$ with equation (3)
4:   end for
5: Find $Pmaxsuc\ (e_{i,j}) \rightarrow Psuc(e_{i,j})$ with equation (5)
6: Calculate the weight $W_{(e)i,j}$ with equation (7)
7: Path = Dikjstra $(C_S, C_D, W_{(e)i,j})$
8: Assign channel $c$ to $e_{i,j}$
9: if topology $G_t$ changes
10:   repeat from step 1
11: end if
12: store the path $L$ to the history $H_s(t)$
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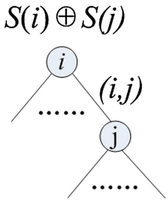

Fig. 1. A simple example for operation of $\oplus$

Where S is the set of CR trees, $\oplus$ is the operator that concatenates two CR trees to a single CR-tree, W is the metric value of a CR tree, and $\leq$ is a preference symbol (Fig. 1).

Combined the Eqs. (4) and (5) above, we can retain the metric value of path l as follows:

$$\begin{aligned} W(P_{su}^{(l)}(N_s, N_D)) &= W[\prod_{i=1}^{k-1} P_{su}^{max}(e_{i,i+1})] \\ &= -log \prod_{i=1}^{k-1} P_{su}^{max}(e_{i,i+1}) = \sum_{i=1}^{k-1} -logP_{su}^{max}(e_{i,i+1}) \\ &= \sum_{i=1}^{k-1} W\left(e_{i,i+1}\right) \end{aligned} \tag{9}$$

Equation (7) shows that the metric value of path l is equal to the sum of metric value of all the links in path l. What's more, as the success probability P_{su} is a value belongs to (0, 1), the metric value $W = -log(P_{su})$ is thus a positive value. And the Dijkstra based routing protocols always prefers links or paths with less metric values. According to these principals, it can be inferred that for $\forall i \in N$ *and* $\forall j \in R(i)$, it has:

$$W[S(i) \oplus S(j)] = \min\{W[S(i)], W[S(j)] + W[(i,j)]\} \qquad (10)$$

Optimality is the most essential requirement to ensure the efficiency and correctness of a routing protocol operation. A CR protocol is optimal if it always routes packets along the path with minimum routing metric value between each source-destination pair in a connected network. According to the works of [10], a Dijkstra-based routing protocol is optimal if its combined CR algebra has the following three properties: Relay-conditionally-beneficial, Strictly preference-preservable and Relay-order-optimal. Based on the above analysis, the proofs of property 1, 2 and 3 are given.

(Proof of property 1). Relay-conditional-benefic: If $W[S(i) \oplus S(j)] = min\{W[S(i)], W[S(j)] + W(i,j)\} \leq W[S(i)]$, it must have $W[S(j)] + W(i,j)] \leq W[S(i)]$. And because $W(i,j) > 0$, $W[S(j)] \leq W[S(i)]$ is then proved. On the other hand, $W[S(i) \oplus S(j)] = min\{W[S(i)], W[S(j)] + W(i,j)\} \leq W[S(i)]$ is obvious. Consequently, MSP algorithm is proved to be relay-conditional-beneficial.

(Proof of Property 2). Strictly preference-preservation: $W[S(i) \oplus S(j)] = min\{W[S(i)], W[S(j)] + W(i,j)\} = W[S(i)]$ or $W[S(j)] + W(i,j)$. Because $W(i,j) > 0$, $W[S(j)] + W(i,j) > W[S(j)]$. And according to the known condition, $W[S(j)] < W[S(i)]$. So, $W[S(j)] < W[S(i) \oplus W(j)]$. Consequently, MSP algorithm is proved to be strictly preference-preservable.

(Proof of Property 3). Relay-order-optimality: $W[S(i) \oplus S(j) \oplus S(w)] = min\{W[S(i)], W[S(j)] + W(i,j), W[S(w)] + W(i,w)\}$. $W[S(i) \oplus S(w) \oplus S(j)] = min\{W[S(i)], W[S(w)] + W(i,w), W[S(j)] + W(i,j)\}$. So, $W[S(i) \oplus S(j) \oplus S(w)]$ equals to $W[S(i) \oplus S(w) \oplus S(j)]$. Consequently, MSP algorithm is proved to be relay-order-optimal.

3 Simulation Results

Our simulations are conducted by MATLAB. In the simulation environment, there are 10 CR users (K = 10) and each node in figure represents a CR user. The index of node is also signed in the figure. Besides, the simulation environment is in a [10 m, 10 m] area and the transmission range of each CR user equals to 5 m. The number of PU channels that can be accessed when they are idle is set to 10 (M = 10). It needs to be mentioned that the 10 PU channels are not visible in the simulation area. The paper takes use of the Rayleigh fading model.

The simulation results of network performance (mainly end-to-end throughput) are shown to identify the impacts of primary user traffic and transmission power. The computation results of MTT, MSAT and MSP are averaged over 100 runs respectively. Analyses of the simulation results are then conducted based on the figures.

3.1 Impact of PU Traffic

This section analyses the impact of the PU traffic on network performance. The PU traffic is reflected by the average PU channel available time μ which continually increases from μ = 0.1 s to μ = 0.8 s with interval 0.1 s. With the increase of average idle time, the PU traffic decreases and CR users are more likely to take use of the PU channel. Two different situations are shown: the simulation results with transmission power P_{tr} = 0.2 W and 0.6 W are shown in Fig. 2.

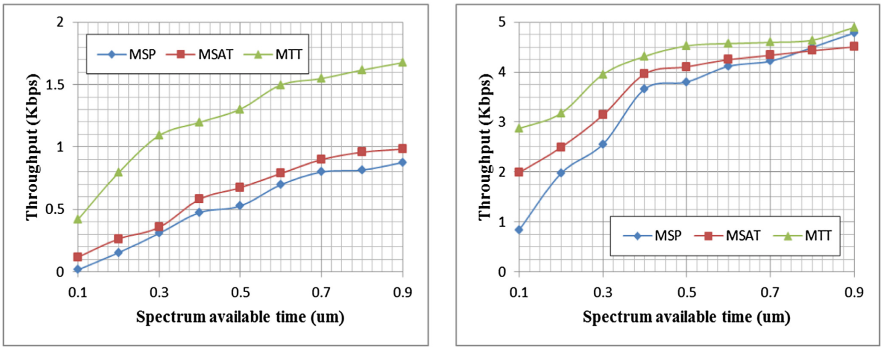

Fig. 2. Throughput of P_{tr} = 0.6 W VS P_{tr} = 0.6 W

It is quite obvious from the figure that with the increment of PU traffic (μ increases), the network throughput increases for all of the MTT, MSAT and MSA metric. This is a common sense because CR users are able to get more opportunities if the PU channel is not busy. But the throughputs computed by MSP are superior to MTT and MSAT metric for MSP metric maximizes the success probability of CR transmission path. This is able to prove the optimality and benefits of adopting MSP metric. Moreover, the MSP metric is able to achieve higher throughput values compared with MTT and MSAT metrics when the transmission power and spectrum available time are relatively small, which is quite essential for energy saving and network operations. More detailed analyzing, with the P_{tr} increases from 0.2 W to 0.6 W the transmission rate R will increase. Consequently, the required transmission time T_{tr} will be shortened and the network throughput then improves.

What's more, as the MTT metric only takes the required transmission time into consideration but ignores the channel available time, so it will achieve high network performance if the PU channels have large values of idle time. Besides, the MSAT metric selects the channel with maximum available time and ignores the required transmission time over each link. So, its network throughput may be less than the MTT metric when the value of μ is relatively large. Figure 2 shows that the MTT metric exceeds MSAT in network performance after the value of μ becomes greater than about 0.75 s, and proves the above mentioned two inferences.

3.2 Impact of Transmission Power

This section analyses the impact of the transmission power on network performance. The P_{tr} is continually increased from $P_{tr} = 0.1$ W to $P_{tr} = 1.5$ W with interval 0.2 W. Two different situations are shown: the simulation results with average available time $\mu = 0.15$ and 0.5 s is shown in Fig. 3.

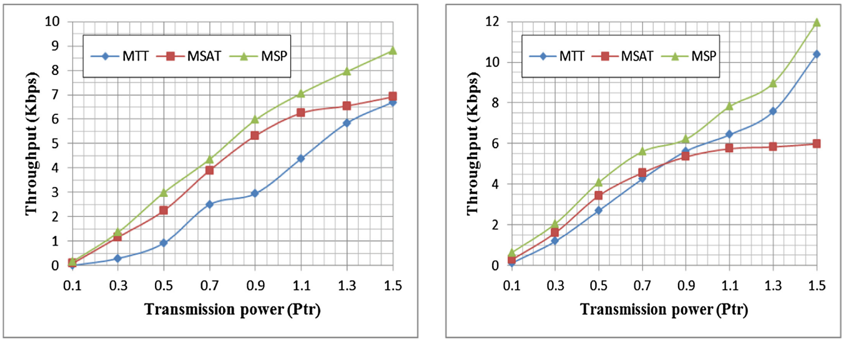

Fig. 3. Throughput of $P_{tr} = 0.6$ W VS $P_{tr} = 0.6$ W

Analyzing Fig. 3, it is quite obvious that with the increment of transmission power (P_{tr} increases), the network throughput increases for all of the MTT, MSAT and MSP metric. This is because the transmission rate R will increase according to Eq. (2). Consequently, the required transmission time T_{tr} will be shorten base on Eq. (1). But the throughputs computed by MSP are significantly superior to MTT and MSAT metric for MSP metric maximizes the success probability of CR transmission path. This is able to prove the optimality and benefits of adopting MSP metric.

More detailed analyzing, with the average idle time μ increases from 0.15 to 0.5 s, CR users have more opportunities to access and take use of the PU channel. As a result, network throughputs of MSP metric are larger than MTT and MSAT.

What's more, the network throughput of MTT metric increases rapidly with the increment of transmission power, while the network throughput of MSAT metric increases slowly after $P_{tr} = 1$ W. Moreover, when the value of transmission power becomes greater than about 0.75 W in Fig. 18, the throughput of MTT metric exceeds the MSAT metric. Three main reasons for such cases are follows. Firstly, the MTT metric only takes the required transmission time into consideration but ignores the channel available time, so it will achieve high network performance if the PU channels have relative large idle time. Secondly, the transmission rate over each link will be improved with the increase of transmission power and the required transmission time will be decreased which is the only factor MTT metric considers. Thirdly, the MSAT metric selects the channel with maximum available time and ignores the required transmission time over each link. So, after reaching a relative high value, its network throughput will change slowly with the variation of required transmission time which is caused by the increase of transmission power.

4 Conclusion

In this paper, a new routing metric for cognitive radio networks called MSP is proposed. MSP selects the path with mobility success probability and then forward data packets along the selected path. MSP is designed to meet two requirements: mobility and otimality. The expression of MSP is analytically derived and proved by applying CR algebra. Simulation results shows that the proposed routing metric MSP obviously outperforms the two reference rouging metrics MTT and MSAT. This conforms that the MSP metric is able to bring benefits to cognitive radio networks. Further researches should focus on different kinds of scenarios, and apply the scheme to improve the network performance.

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