SAMER+: Balancing short term throughput and long term stability in cognitive radio mesh networks

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***Abstract*—A large number of routing protocols for Cognitive radio networks (CRNs) have been proposed recently, each based on different design goals, and evaluated in different scenarios, under different assumptions. In our previous work, we conducted the first extensive empirical performance study of routing protocols for CRNs – Coolest Path, SAMER, and CRP – under the same realistic set of assumptions. Our study revealed that SAMER significantly outperforms the other protocols under low primary user activity but its performance degrades under high PU activity.**

In this work, we introduce an enhanced version of SAMER (SAMER+) that performs consistently well in both low and high PU activity scenarios. The core of SAMER+ is a new path metric that balances short term throughput and long term path stability. We evaluate SAMER+ using extensive simulations and compare it against SAMER and Coolest Path. Our results show that SAMER+ significantly outperforms both protocols in a variety of scenarios.

I. Introduction

In order to satisfy the ever-growing public demand for additional spectrum resources, in November 2008 the FCC issued a ruling permitting unlicensed users (secondary users, SUs) to operate in the so-called white spaces, i.e., unused portions of the TV broadcast frequency band, as long as they do not interfere with licensed users (primary users, PUs). This ruling marks the arrival of cognitive radio networks (CRNs). In CRNs, SUs have the ability to sense a wide spectrum range, dynamically identify currently unoccupied spectrum blocks, and choose the best available block to transmit, ensuring non-interfering coexistence with PUs [6].

Numerous routing protocols for CRNs (e.g., [7], [4], [8], [3], [5], [9], [10], [11], [12], [13], [14], [15], [16], [17]) have been proposed over the past decade. Besides the main goal of protecting PU transmissions, each protocol was proposed based on different design goals, e.g., maximizing spectrum opportunities, maximizing available bandwidth, minimizing hopcount, minimizing end-to-end delay, etc. The performance of each protocol was evaluated with respect to its specific design goals using a different evaluation methodology – different assumptions (e.g., about PU activity), settings, and scenarios, tailored to its specific design goals.

In our previous work [1], [2], we conducted the first extensive empirical performance study of routing protocols for CRNs under the same realistic set of assumptions. We selected three representative CRN routing protocols – Coolest Path [3], SAMER [4], and CRP [5], each taking a different approach with respect to four basic building blocks of a CRN protocol, including 1) how to characterize spectrum opportunities observed locally, 2) how to characterize spectrum opportunities between neighboring SUs, 3) how to define a link metric based on spectrum opportunities and 4) how to select a routing path based on the link metric. Coolest Path aims to find the path with the highest spectrum availability, which results in path stability. SAMER tries to find the path with the highest throughput by taking into account both PU and SU activity, as well as link quality. CRP is designed to either find a path with minimum end-to-end delay and satisfactory PU protection or offer the best protection to PU receivers at the cost of some performance degradation for SUs.

Our study revealed that SAMER significantly outperforms the other protocols under low PU activity, as it takes into account factors considered by traditional wireless mesh routing protocols, such as link quality and interference among neighboring nodes, in addition to spectrum availability. SAMER uses a bottleneck metric which often results in longer paths of higher quality and lower amount of interference from other SU flows. However, the performance of SAMER degrades under high PU activity. In such scenarios, path stability becomes the dominant factor in determining throughput, and Coolest Path with an additive path metric outperforms the other protocols, as it selects short paths with a lower probability to be impacted by PU activity.

In this paper, we introduce an enhanced version of SAMER (SAMER+) that performs consistently well in both low and high PU activity scenarios. The core of SAMER+ is a new path metric for CRNs that balances short term throughput and long term path stability. Our metric is inspired by WCETT [18], the state-of-the-art routing metric in traditional multi-channel mesh networks, but takes into account the special characteristics of CRNs. WCETT is a weighted sum of two path metrics; an additive metric that limits the hopcount and a bottleneck metric that reflects the set of hops on a path that have the highest impact on the path throughput. Our proposed metric is called Cognitive Radio Weighted Cumulative Expected Transmission Time (CR-WCETT) and, similar to WCETT, it combines two metrics: a bottleneck metric derived directly from the metric used in SAMER which aims at maximizing short term throughput and an additive metric that limits the hopcount resulting in higher path stability. We evaluate SAMER+ using extensive simulations following the

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methodology of [1], [2] and compare it against SAMER and Coolest Path. Our results show that SAMER+ consistently outperforms both protocols in a variety of scenarios.

II. Background

In this section, we provide a brief description of SAMER and Coolest Path.

Coolest Path [3] tries to find the most stable path, i.e., the path with the most balanced and/or lowest spectrum utilization by PUs. In Coolest Path, a channel's temperature for an SU link is defined as the fraction of time during which the channel is unavailable due to PU activity in the neighborhood of any of the two SUs. The link's temperature is then defined as the minimum channel temperature among all available channels between the two SUs. Coolest Path provides three different definitions of the path temperature based on the link temperature: (i) *accumulated temperature (AT)*, i.e., the sum of the link temperatures along the path, (ii) *highest temperature (HT)*, i.e., the maximum link temperature among the links along the path, and (iii) mixed temperature – a combination of the first two. The protocol selects the path with the minimum path temperature. In this work, we only consider the first metric (and we call the protocol CP-AT) since our evaluation in [1], [2] showed that it outperforms the other two metrics.

SAMER [4] tries to find a high-throughput path by opportunistically utilizing high-throughput links while still guaranteeing a path's long-term stability. To quantify channel availability, SAMER considers both PU and SU activity. Each SU estimates the fraction of time during which a channel can be used, i.e., it is not used by any PU and any other SU. Since two neighboring nodes may estimate different channel availabilities, the channel availability for a link is given by the smallest of the two values. SAMER estimates the expected throughput of a link (i,j) over channel b as the product of channel availability (or fraction of time the link is available) $T_{f,b}$, link bandwidth $B_{w,b}$, and loss rate $p_{loss,b}$

$$Thr_{(i,j),b} = T_{f,b} \cdot B_{w,b} \cdot (1 - p_{loss,b}) \quad (1)$$

The link metric is then defined as the aggregate normalized throughput across all available channels

$$Thr_{(i,j)} = \sum_{b \in B_i \cap B_j} \frac{Thr_{(i,j),b}}{maxThr_{(i,j),b}} \quad (2)$$

Hence, different from Coolest Path's link temperature, which reflects only a link's stability, the link metric in SAMER reflects both link stability (channel availability) and link quality (bandwidth, loss rate). The path metric, called Path Spectrum Availability (PSA), is the minimum aggregate normalized throughput among all links along a path P, i.e., a bottleneck metric

$$PSA = \min_{(i,j)\in P}\{Thr_{(i,j)}\} \quad (3)$$

Since a bottleneck metric may yield very long paths, [4] uses a heuristic which selects the path with the smallest possible number of hops that has a cost lower than or equal to a maximum cost C_{max}. In [2], we found that it is impossible to select a C_{max} value that works well for all scenarios. Instead, we controlled the path length by limiting it to $2 \cdot SPC$, where SPC is the hopcount of the shortest path between a source-destination pair.

Due to the bottleneck metric, SAMER typically chooses longer paths than CP-AT. Our results in [1], [2] showed that, under low PU activity, SAMER yields higher throughput than CP-AT for two reasons. First, shorter paths typically consist of long links, which result in low signal strength and higher loss rate. This is also true in traditional mesh networks [19]. Further, under low PU activity, there may be several paths with the same low temperature. CP-AT chooses randomly among them while SAMER takes into account the achievable throughput of each path through the link loss rate and bandwidth in (1). Second, in the presence of multiple flows, SAMER tries to select disjoint paths for different flows, since it takes contention from other SUs into account when it calculates link availability. In contrast, CP-AT only considers PU activity in the estimation of link availability and often selects overlapping paths for multiple flows, resulting in high contention and reduced throughput. On the other hand, under high PU activity, long paths result in a large number of link and route breaks due to frequent PU appearances. In such scenarios, link stability becomes more important than link loss rate and bandwidth, and [1], [2] showed that CP-AT, which prefers shorter, low temperature paths, leads to overall better path stability and higher throughput.

III. CR-WCETT Design

The design of CR-WCETT is motivated by the above discussion and satisfies two goals. First, we need a *link metric* that maintains the properties of SAMER's link metric, i.e., it determines a link's cost taking into account not only PU activity but also traditional link quality factors – loss rate, bandwidth, and contention from other SUs; such a metric will select high throughput, diverse paths, under low PU activity. Inspired by the design of WCETT [18], the state-of-the-art metric in traditional mesh networks, we define CR-ETT – the expected time to transmit a packet of size L bits over a link in a CRN – as

$$CR-ETT_{(i,j)} = \frac{L}{\sum_{b \in B_i \cap B_j} Thr_{(i,j),b}} \quad (4)$$

where $\sum_{b \in B_i \cap B_j} Thr_{(i,j),b}$ is the aggregate throughput of link $(i,\ j)$ over all available channels defined in SAMER (2) without the normalization factor $maxThr_{(i,j),b}$. Intuitively, (4) states that the expected packet transmission time over a link depends on the spectrum availability (which in turn is affected by both the PU activity and the contention from other SUs), the link bandwidth, and the link loss rate.

Second, we need a *path metric* that penalizes very long paths, which become unstable under high PU activity. One way to achieve this is using the heuristics in [4] or [2] (limiting the maximum path cost or the maximum hopcount, respectively).

However, in [2], we found that it is hard to choose a threshold that works well for all topologies. A more systematic approach is to introduce an additive component to the path metric, which penalizes long paths regardless of the topology. Inspired again by WCETT, we define CR-WCETT over a path P as:

$$CR-WCETT = \beta \cdot \sum_{(i,j)\in P} CR-ETT_{(i,j)} + \\ + (1-\beta)\cdot \max_{(i,j)\in P} CR-ETT_{(i,j)} \quad (5)$$

where β is a tunable parameter subject to $0 \leq \beta \leq 1$. CR-WCETT consists of two parts. The first part $\sum_{(i,j)\in P} CR-ETT_{(i,j)}$ is the total expected transmission time over path P. Since it is an additive metric, it controls the hopcount, giving preference to shorter paths. The second part is the expected transmission time over the *bottleneck* link. As a bottleneck metric, it gives preference to high throughput paths (i.e., paths with high throughput bottleneck links) but ignores the hopcount. The parameter β balances the two desired properties. A value of β equal to 1 results in an additive metric, similar to CP-AT, although still taking into account link loss rate, link bandwidth, and SU contention, in addition to PU activity. On the other hand, a value equal to 0 results in the (inverse of) the bottleneck metric used in SAMER.

CR-WCETT can be easily incorporated to SAMER since it is based on the same link metric as the original SAMER protocol. We call SAMER with the CR-WCETT metric instead of the original PSA metric SAMER+.

IV. Simulation Methodology

We followed the same methodology as in [1], [2]. We adopted the ns-2 extended framework proposed in [20], which implements all necessary components for SUs in a CRN [21]. Similar to in [5], [20], each SU is equipped with one receiving interface for receiving data packets and sensing the spectrum and one transmitting interface for sending data packets. There is also a third interface fixed on the control channel and used only for transmitting/receiving control packets, e.g., route requests/replies and channel switching notifications.

We model PU activity following an exponential ON-OFF model [22]. Although SUs cannot detect PU activity when they transmit packets, the simulator [20] models the impact of PU activity on SU transmissions by assuming a 20% packet loss probability (due to collision) if a PU is active during a SU transmission.

At the PHY layer, we assume a spectrum band of 11 orthogonal channels – 10 data channels and one common control channel – with the propagation characteristics of 2.4 GHz. The bandwidth of each channel is 6 MHz, which is the same as a TV channel in the UHF band. To simulate different channel qualities, we assume that the packet loss ratio for every channel follows a uniform distribution from 0-0.2.

At the MAC layer, we use 802.11b and disable RTS/CTS. To reflect a channel width of 6 MHz (instead of 20 MHz used in 802.11), we scale down the 802.11b data rates by a factor of 6MHz/20MHz. In our simulations, SUs use the highest data rate of 3.3 Mbps (11 Mbps in 802.11b) to transmit data packets and the basic data rate of 0.3 Mbps (1 Mbps in 802.11b) to broadcast control packets.

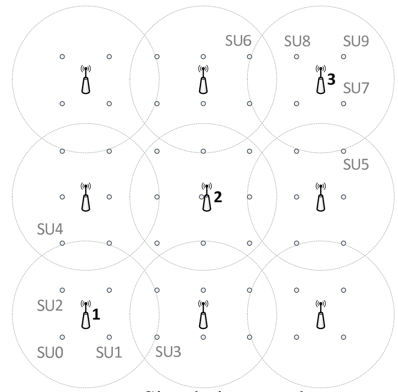


Fig. 1. Simulation topology.

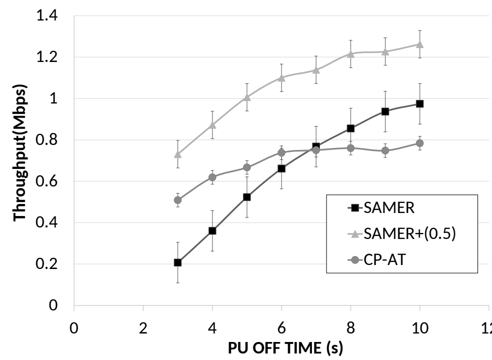
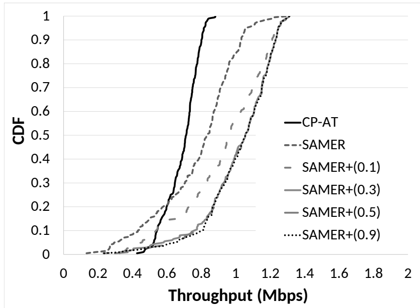


Fig. 2. Baseline throughput comparison.

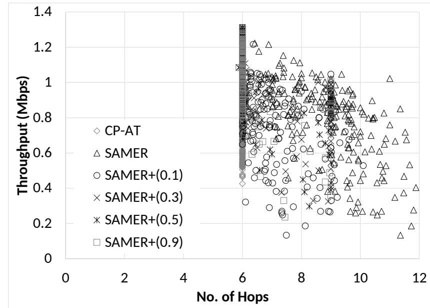
At the network layer, we modified AODV to support the three CRN routing protocols (CP-AT, SAMER, and SAMER+). When the selected channel on a link can no longer be used because of PU activity, i.e, *the link breaks*, the sender-receiver pair tries to repair the link locally by selecting another channel, which is the best among the currently available channels according to the link metric. When no channel is available, the link cannot be used anymore, i.e., *the route breaks*, and a RERR packet is forwarded along the routing path. When the RERR packet arrives at the source node, a new route discovery is initiated by the source node, which buffers packets during this process.

We used the same topology as in [1], [2] (Figure 1), which is similar to the ones used in [7] and [5]. A square region of side 1200 m is divided into 9 square cells of side 400 m. There are 9 PU locations in the centers of the cells. In each location, there are 10 PUs, operating on the 10 channels which can be used for data transmissions; there is no PU operating on the common control channel. Each PU has an interference range of 250 m. 49 SUs are placed on a grid; the distance between any two neighboring SUs is 160 m. Each SU has a maximum transmission range of 250 m on each channel. We use SU0 in cell 1 as the source node and SU9 in cell 3 as the destination node, unless otherwise stated.

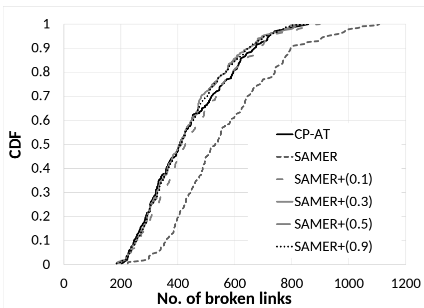
Each simulation runs for 900 sec, during which PUs may become active at any time. In the first 600 sec, SUs only sense the spectrum (during the sensing periods) to learn the statistics



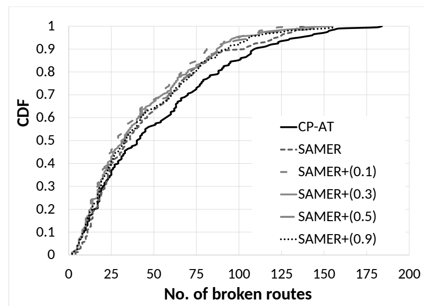
(a) Throughput comparison.



(b) Throughput vs. path length.



(c) Broken links.



(d) Broken routes.

Fig. 3. Localized PU activity.

of PU activity in their neighborhood. The source node starts transmitting data packets at the 600th second and the data transmission period lasts for 300 sec, during which SUs keep sensing the spectrum and updating their observations of PU activity. Each source sends CBR data traffic over UDP at a rate of 3.3 Mbps with a packet size of 1500 Bytes.

V. Performance Evaluation

A. Baseline Scenario

We first compare the throughput of the three protocols in a baseline scenario, in which we assume all PUs have the same average ON and OFF times. In Figure 2, we fix the average PU ON time at 6 sec and vary the average OFF time from 3-10 sec. Each point corresponds to the average throughput over 20 simulation runs and the error bars correspond to the standard deviations. For SAMER+ , we use $\beta = 0.5$. We observe that SAMER+ outperforms SAMER by 30-253% and CP-AT by 44-62% for all PU OFF times. In contrast, SAMER performs better than CP-AT only for low PU activity (OFF times longer than 7 sec).

B. Localized PU activity

We now consider a localized PU activity scenario, using different average OFF times for PUs in different cells. In each cell, all PUs are assigned the same average OFF time, chosen uniformly from the interval 2-11 sec. We use 200 different seeds to select average OFF times and generate PU activity. The performance is shown in Figures 3(a)-3(d). For SAMER+, we use 4 different values for β: 0.1, 0.3, 0.5, and 0.9.

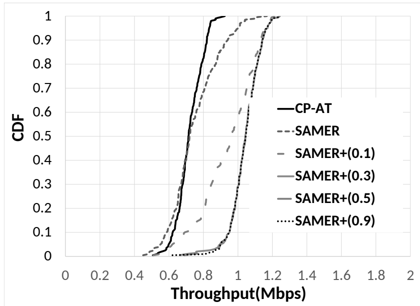
Figure 3(a) plots the Cumulative Distribution Function (CDF) of the throughput for each protocol. We observe that the performance of SAMER+ does not change for $\beta \geq$ 0.3 and is much higher than the performance of CP-AT and SAMER. In the median case, SAMER+(0.9) outperforms SAMER by 27% and CP-AT by 49%. Further, SAMER has lower throughput than CP-AT in 20% of the cases; the percentage reduces to 11.5% for SAMER+(0.1) and to only 3.5% for SAMER+ with higher β values.

Figure 3(b) plots a scatterplot of the throughput against the average routing path length for each of the 200 simulation runs. We observe that, in general, SAMER chooses longer routes than the other protocols, while CP-AT chooses almost always the shortest path (6 hops). The additive component in SAMER+ helps it avoid very long paths (the path length is at most 9 hops for SAMER+(0.9)) while the bottleneck component avoids the shortest path in case a longer path of better quality can be found. As a result, SAMER+ can successfully the two goals of short term high throughput and long term path stability. The latter is shown in Figures 3(c), 3(d) which plot the CDF of broken links and routes due to PU activity for each protocol. We observe that SAMER+ with $\beta \geq$ 0.3 reduces the number of both broken links and broken routes compared to SAMER and CP-AT. CP-AT has a smaller number of broken links than SAMER but a larger number of broken routes.

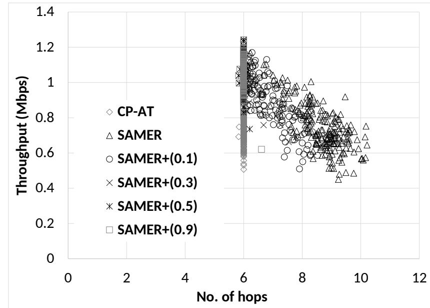
C. Random PU activity

In this section, we simulate a scenario in which the average OFF time for each PU is chosen uniformly from the interval 2-11 sec, independent of its location. We use again 200 different seeds to select average OFF times and generate PU activity. The results are shown in Figures 4(a)-4(d).

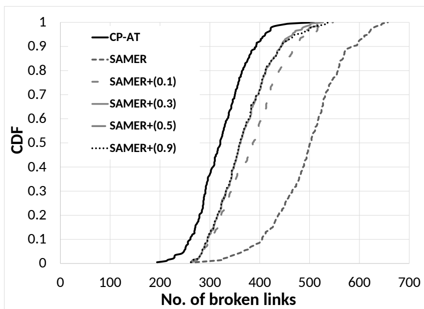
Figure 3(a) plots the CDF of the throughput for each protocol. We observe that this scenario is the most challenging for



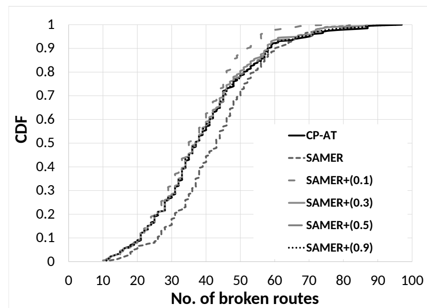
(a) Throughput comparison.



(b) Throughput vs. path length.

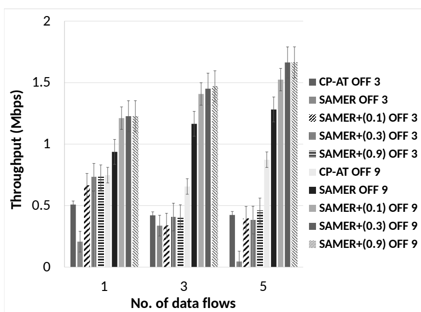


(c) Broken links.

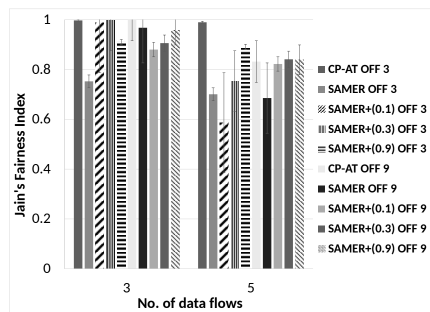


(d) Broken routes.

Fig. 4. Random PU activity.



(a) Throughput comparison.



(b) Fairness comparison.

Fig. 5. Multiple data flows.

SAMER. It only outperforms CP-AT in 55% of the simulation runs. As we found in [2], those are the runs characterized by low PU activity. The shortest path length of CP-AT compared to SAMER (Figure 4(b)) clearly helps much more than in the case of localized PU activity; CP-AT has a smaller number of both broken links (Figure 4(c) and broken paths (Figure 4(d)) compared to SAMER.

In contrast, SAMER+ clearly outperforms both CP-AT and SAMER in all simulated scenarios and for all β values. In particular, for $\beta \geq 0.3$, SAMER+ achieves a median throughput 47% higher than both CP-AT and SAMER. Further, SAMER+ significantly improves the throughput of high PU activity scenarios, which resulted in low throughput for SAMER. The 10-th percentile of throughput with SAMER+(0.9) is 53% higher than with CP-AT and 61% higher than with SAMER. Similar to the localized PU activity scenario, SAMER+ limits the path length in order to improve long term path stability similar to CP-AT; in fact, for $\beta = 0.9$ SAMER+ chooses the shortest path in 199 out of 200 runs. While the number of broken links for SAMER+ is still higher than for CP-AT (although significantly lower compared to SAMER), the number of broken routes is similar for the two protocols. However, in contrast to CP-AT, SAMER makes a wiser channel selection for each link along the shortest path, as it takes into account link loss rate and SU contention in addition to PU activity, achieving much higher throughput than CP-AT.

D. Multiple Data Flows

To study the performance of each protocol with multiple data flows, we conducted simulations with 3 and 5 flows using the baseline scenario. In the topology shown in Figure 1, we selected the source-destination pairs SU0-SU9, SU1-SU8, and SU2-SU7, for the simulations with 3 data flows. For 5 data flows, we added 2 more source-destination pairs - SU3-SU6 and SU4-SU5. We repeated the simulations with the same 20 seeds used in Section V-A for average PU OFF time equal to 3 and 9 sec. Figure 5(a) plots the total throughput, and

Figure 5(b) plots Jain's Fairness Index [23], with 3 and 5 flows.

In Figure 5(a), we observe that SAMER achieves higher throughput than CP-AT regardless of the number of flows under low PU activity (OFF time 9 sec) since it considers interference from neighboring SUs in estimating spectrum availability and selects more disjoint, less interfering paths. In Figure 5(b), we observe that the increase in SAMER's total throughput under low PU activity comes at the cost of reduced fairness; SAMER penalizes some flows by routing them over longer paths in attempt to reduce the amount of SU interference. Finally, SAMER+ improves both throughput and fairness. In particular, the average throughput of SAMER+(0.9) is 30% (64%) higher than SAMER (CP-AT) in the case of a single flow, 26% (123%) in the case of 3 flows, and 30% (91%) in the case of 5 flows. Its fairness index value is similar to SAMER's value (and slightly lower than CP-AT's value) for 3 flows but becomes equal to CP-AT's value for 5 flows.

On the other hand, under high PU activity (OFF time 3 sec) SAMER achieves the lowest performance in terms of both throughput and fairness; in particular, in the case of 5 flows, CP-AT outperforms SAMER by 7.4x in terms of throughput. SAMER+ improves again both throughput and fairness index making their values comparable to those of CP-AT. However, in contrast to the case of low PU activity, we observe here a tradeoff between the two metrics for different values of β. In the case of 3 flows, SAMER+(0.3) offers similar throughput but higher fairness compared to SAMER+(0.9). On the other hand, in the case of 5 flows, SAMER+(0.9) offers 8% higher throughput and 19% higher fairness than SAMER+(0.3).

VI. CONCLUSION

Based on the lessons learned from an empirical performance comparison for CRNs in our previous work, in this paper, we introduced an enhanced version of SAMER (SAMER+) that performs consistently well in both low and high PU activity scenarios. The core of SAMER+ is a new path metric for CRNs, Cognitive Radio Weighted Cumulative Expected Transmission Time (CR-WCETT), that balances short term throughput and long term path stability. Our metric is inspired by WCETT [18], the state-of-the-art routing metric in traditional multi-channel mesh networks, but takes into account the special characteristics of CRNs. Similar to WCETT, it combines a bottleneck metric which tries to maximize short term throughput and an additive metric that limits the hopcount resulting in higher long term path stability, especially in scenarios with high PU activity. Our simulation study showed that SAMER+ significantly outperforms both SAMER and CP-AT in a variety of single-flow scenarios and in multi-flow scenarios under low PU activity; additionally, it achieves similar performance/fairness to CP-AT and much higher than SAMER in multi-flow scenarios under high PU activity.

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