

Finding an Immuned Path against Single Primary User Activity in Cognitive Radio Networks

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Abstract – Due to recent crowdedness in unlicensed spectrum, a new technology is introduced which allows unlicensed users, also known as Secondary Users (SUs), to dynamically access licensed spectrum whenever they are not used by their licensed users, also known as Primary Users (PUs). Routing in Cognitive Radio Networks (CRNs) is not as in traditional routing of wireless networks, because it is mandatory for SUs to periodically sense licensed spectrum, channels availability changes over time, knowledge of tolerated interference by PUs.

In this paper, a novel routing discovery technique is proposed to find a primary path, if exist, which is immuned to one PU, such that at most one SU fails (must back off transmission) when a PU becomes active again. Also, a backup path can be discovered using the same technique with the condition that it is channel-link disjoint from the primary path. The problem is modeled using a multi-layer graph where each layer corresponds to a channel in a network. The proposed strategy reduces number of required channel-links maintenance to two, if failed due to one PU activity. As a result, SUs' energy consumption is reduced when re-establishing route connectivity, and therefore, network life time is prolonged.

Keywords: Cognitive Radio, Primary Users, Primary Path, Backup Path, Protection, Energy.

Nomenclature

Abbreviation	Meaning
CR	Cognitive Radio
CRNs	Cognitive Radio Networks
PU	Primary User
SU	Secondary User
E2E	End-to-End
SHRG	Shared Risk Group
IPP-SSF	Immuned Path Protection with Single SU Failure

I. INTRODUCTION

The standards of powerful cooperation, connected in a wireless communications setting, can offer more vigorous and successful correspondence for some difficult and rising situations including networks of distributed wireless nodes [1]-[3]. Amid the most recent decades, the advancement of wireless communication systems has been a gigantically effective undertaking [4]-[5]. Curiously, we have seen a blast or explosion in prevalence of technologies using the permit license-exempt ISM frequency bands [6]-[8].

Typically, licensed spectrum bands are temporally and spatially underutilized while the unlicensed bands are overcrowded, such as ISM bands 900MHz and 2.4GHz. Consequently, the interference, collision, and end-to-end (E2E) delay are substantially increased, while capacity decreased [9]-[12].

A new technology for spectrum access is proposed namely, Cognitive Radio (CR) technology [13]. This enables unlicensed wireless nodes, formally known as Secondary Users (SUs), to dynamically and opportunistically switch to available licensed channels, e.g.; 400-700MHz, which are currently not utilized by their licensees, formally known as Primary Users (PUs) [14], in order to improve their QoS, e.g.; throughput. However, when PUs becomes active again, SUs must leave their channels immediately. Many challenges face this new technology, for instance, spectrum sensing, mobility, routing, allocation, interference, channels heterogeneity, and sharing [15]-[19].

In this paper, the focus on finding a route that is immuned to one PU activity with at most one single SU failure. The rest of this section and section II present the differences between routing in traditional wireless networks and CR Networks (CRNs).

A. Routing in Traditional Wireless Networks

Routing in traditional wireless networks generally requires awareness about neighbor nodes such as their locations, transmission ranges, interference ranges, channel-links bandwidth, etc. Ad-hoc wireless networks

is classified as wireless dynamic networks, in which developing routing protocols is harder than static networks, because wireless nodes may change their locations over time, and hence, routing links fail. Therefore, researchers developed resilient routing protocols that consider nodes mobility, route maintenance in case of links failure, and bandwidth provisioning, where these protocols must have an acceptable overhead.

For ad-hoc networks, eight different routing protocols are evaluated in [20], and also a comparison of their performance metrics is presented. Ad-hoc routing protocols are categorized into two schemes: First, Table driven, e.g.; Destination-Sequenced Distance-Vector Routing (DSDV). Second, source initiated request on demand, e.g.; Ad-Hoc On-Demand Distance Vector Routing (AODV) and Dynamic Source Routing (DSR). An On-Demand Multicast Routing Protocol (ODMRP) for ad-hoc and mobile networks is proposed in [21]. They employ forwarding group notion such that only a subset of nodes forwards the multicast packets, their scheme is dynamic and performs well with dynamic network mobility and limited bandwidth. In wireless mesh networks, a multicasting ring topology is developed [22] such that 802.11 with RTS/CTS scheme is utilized, in order to ensure QoS requirements such as E2E delay and routing capacity.

Reinforcement learning is utilized to obtain routing awareness and dynamic channel selection in wireless networks, [23] presented related work in this direction in order to improve awareness using Reinforcement learning methods. Channel assignment enhancement in wireless LANs is studied in [24] by employing traffic awareness when allocate channels to users, in which predicting future demands for AP and measuring interference are also considered. Authors in [25] propose channel assignment methods for nodes with multi-transceivers under IEEE 802.11s technology, three categories are classified: First, channels assignment at MAC level only. Second, channels allocation performed by an adapted MAC layer coupled with the upper layers. Finally, channels assignment mechanism is developed in an intermediate layer between MAC and network layer. Also, a distributed channels assignment in 802.11 wireless mesh networks for nodes with multi-radios is discussed in [26], in their approach channel selection and data forwarding are decoupled.

B. Routing in Cognitive Radio Networks

Routing in CRNs is not as in conventional wireless network, due to many reasons such as spectrum availability changes over time, SUs must be aware about spectrum availability and the tolerated interference threshold by PUs. When SUs use PUs channels, they must periodically sense PUs activity; therefore, SUs overall transmission time is reduced. Section II explains in details literature work for routing in CR networks.

The rest of this paper is organized as follows: Section II, discuss related literature work. System model, motivation, and developed protocol are presented in Section III. Results and their insights are discussed in Section IV. Conclusions are illustrated in Section V.

II. RELATED WORK

Routing is an important feature in wireless networks, however, due to new characteristics of CRNs compared to traditional wireless networks; new routing protocols is needed to solve routing challenges of CRNs [27]-[36]. Also, SUs protection against PUs' emulation attack is studied in [37]-[41], PU attacker may jam licensed channels and makes them seem busy or cause a harmful interference.

Interference cancellation methods are proposed in [42], [43], in order to reduce received bit error rate. Moreover, attacker may flood the common control channel of SUs for long time, and consequently, SUs cannot cooperate and exchange control information. The following subsections show some state-of-art literature work for routing in CRNs organized based on considered performance metrics.

II.1. Routing with Minimum E2E Delay

CRN routing protocols aim to find a route with a minimum (E2E) delay, maximum links' stability, maximum throughput, and minimum link-hops to the destination [44], [45]. An efficient Fault-Tolerant Cognitive Ad-hoc Routing Protocol (FTCARP) is studied in [46] that discovers primary and backup paths where their throughput, packet loss, and E2E delay are better than Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) studied in [47].

A multi-path routing protocol for CR network, named MACNRP, is proposed in [48]. A set of node-disjoint routes from source to destination are established, depending on channels availability. They compared their work with FTCARP [46] and D2CARP [47] using a mathematical model and OPNET tool. Results demonstrate higher capacity and better resiliency against route failures.

In [49], a multicast routing tree is constructed with objective of minimizing the maximum route with E2E delay, in addition to minimizing number of used channel-links and increasing transmission rate. Authors used two meta-heuristic methods with multiple objectives: First, ant-colony. Second, the simulated annealing based technique.

Authors in [50] propose constructing a routing tree for many-to-many communication, in which data transmission rate and delay are improved, and number of utilized links resources is reduced.

II.2. Routing with Minimum Interference to Primary Users

A distributed and scalable routing protocol for CR ad-hoc networks is developed in [51], called CRP, in which the routes are prioritized and PUs receivers are protected from SUs transmission. Especially, to protect PUs from collision that occurs during the beginning of SUs transmission, because these PUs activities were not detected during dedicated sensing period. Amazingly, this protocol has a novel characteristic, because it invests routing of control packets through common control channel, in order to gather more channels information and network conditions.

A cross-layer protocol is proposed [52], in order to select a route with minimal interference and throughput between a set of candidate routes. Selection is based on a set of metrics: routing overhead, throughput, and packets effective delivery ratio. NS2 simulation tool is employed to assess this protocol performance, results demonstrates that the proposed protocol outperforms traditional CR ad-hoc routing protocol, such as CRP [51] and SEARCH [53].

An interesting routing approach is proposed in [54] that avoids any harmful interference to ongoing PUs transmission. Routes are selected every pre-defined specific period, based on analyzing PUs activity pattern, such that selected routes maintenance is minimized. Route maintenance may include channels or links switching. Moreover, Authors in [55] formulated route selection problem as route selection game, its objective is to reduce interference with PUs activity as well as reduces channels congestion. The solution decides which channels or links should be re-used or even not used. Authors developed their own simulation using MATLAB tool, a detailed simulation code can be found in [56].

II.3. Resiliency- and Stability-based Routing

Authors in [57] proposed a route selection strategy, named coolest path method, which is based on choosing a path with lowest PUs usage, as a consequence, selected route's stability is maintained for longer time. Authors in [58] proposed k-protected routes scheme, such that route major links have a pre-assigned channels in a way a backup path is guaranteed to be found, although when k-PU becomes active again.

A network model using a multilayer hyper-graph is developed [59], in which routing multicast session is presented for protection against channel failures, such that primary and backup paths are shared-risk groups disjoint. A route discovery protocol is proposed in [60] where the selected route has the maximum number of common channels between links; apparently this strategy enhances path stability. In [61], a distributed location-aided routing protocol, called LAUNCH, is proposed, which considers PUs activity and channel switching

delay. Additionally, it provides an efficient route maintenance strategy with less overhead.

For mobile ad-hoc networks, authors in [62] proposed a multicast routing protocol, called Associativity Based Multicast Routing (ABAM), which mainly has two functions: constructing a multicasting tree and its corresponding re-configuration. However, authors in [63] proposed an enhancement for routing resiliency of ABAM protocol, and called the enhanced protocol as EABAM.

EABAM constructs a multicast semi-mesh-tree topology, and also find two routes to each destination. If these routes share links, a maintenance procedure is lunched, called receiver re-join method, in order to re-establish communication with the multicast tree. Authors developed a code for these routing techniques that integrated with OPNET simulation tool. Simulation results reveal that EABAM outperforms ABAM protocol in terms of throughput, E2E delay, and control messages overhead.

Spectrum-aware mesh routing in cognitive radio networks (SAMER) [64] is enhanced in 2016 [65], and called (SAMER+). SAMER+ demonstrates high efficiency in low or even high PUs activities. The developed new metric aims to maximize short period throughput and prolongs path stability. Path stability is achieved by reducing number of utilized channel-links over selected route. Simulation results reveal that SAMER+ is drastically better than both SAMER [64] and coolest path methods [57].

A robust-fair routing protocol is developed [66] to a stable multi-hop route, based on cooperative game and bipartite graphs. Also in [67], centralized and distributed resilient-robust topology control mechanisms are developed which maintain routes connectivity and reduce interference.

A Local Re-routing and Channel Recovery (LRCR) technique is proposed in [68]. Once PU becomes active, SUs which corresponds to failed channel-links search for new routes by lurching LRCR. It is worth to mention that authors developed a discrete-event simulator, in order to evaluate LRCR performance.

A novel routing method for SUs data flow is proposed in [69] and formulated using integer programming optimization problem. The novelty is based on developing a performance metric that finds the optimal sequence of routes selection when PUs becomes active, and thus, current route fails. This metric is a function of channels and links switching cost, as a result selected routes stability is improved. For the sake of stability, a dynamic programming algorithm is developed [70] that finds a k-channels connectivity graph under tree-width degree constraint, if possible. The proposed solution

generates channels spectrum allocation, only if CR network is k-channel connected.

II.4. Routing-based on Underlay Spectrum Access Approach

On the other hand, spectrum access strategies in CRNs can be overlay approach, assumed in this work, or underlay approach [71]. In underlay approach, SUs are allowed to access licensed spectrum with PUs at the same time, under a condition that SUs caused interference does not exceed the tolerable interference threshold at PUs' receivers. Some state-of-art literature work assumes that SUs are empowered by successive interference cancellation (SIC) at physical layer. Consequently, SUs are allowed to utilize licensed channels more efficiently, more importantly, network connectivity becomes stronger, that network topology control becomes more convenient in a way that stabilizes established routes connectivity.

Recently, concurrent PUs and SUs transmission is proposed and studied in [72], where SIC technique is employed by SUs in order to overcome caused interference by PUs, reduce number of used channels, and hence, a durable network structure management.

A key question is raised by researches, which spectrum approach SUs should conduct: underlay or overlay? An analytical model with a closed-form expression is devised in [73]. A novel technique is proposed, in which a decision can be made which spectrum access approach is better to employ.

An underlay dynamic channel access scheme is modeled in [74] which facilitates two outstanding features, such as: First, multiple channels can be used by one SU at the same time, if available. Second, share licensed channels, in other words, one or two SUs transmission may co-exist over single channel with its licensed PU's transmission. Clearly, that what makes this model novel with respect to other existing work, such as [75], [76].

Constructing a primary path and backup in CRNs should be stable in terms of availability time for the selected channels, such that when a PU becomes active again the number of failed channel-links for SUs should be the minimum. Therefore, in this paper we propose a novel path selection model that increases primary and backup paths immunity by decreasing number of failed channel-links to only two, due to one PU activity.

III. PROPOSED SYSTEM MODEL

This section contains three subsections as follows: First, the motivation for our proposed work with an example scenario of CRNs. Second, the proposed system model. Third, the primary path and backup path discovery mechanisms are demonstrated.

III.1. Motivation

The motivation of this work is to find a primary and a backup routing paths, if exist, from a source SU to a destination SU in CRNs, such that when one PU becomes active, at most one SU fails along the selected route (failure means that SU must back-off transmission over the PU's licensed channel).

To show our motivation, let us consider network scenario shown in Figure 1. There are five primary users, PU1, PU2, PU3, PU4, and PU5. Also, a set of SUs are distributed in the area. Using our proposed strategy for route selection, path 1 is selected, {SUs, SU1, SU2, SU3, SUD}, in which when any PU becomes active, say PU2, only one SU fails, SU1, at most. However, if traditional routing protocol is employed, say path 2 is selected, {SUs, SU4, SU5, SU6, SU7, SU3, SUD}, in which if one PU becomes active, say PU4, one or more SUs (SU5 and SU6) must stop transmission over the corresponding PU's licensed channel.

Using the proposed route selection strategy in this work, at most one SU fails when a PU becomes active again. Therefore, routing maintenance requires less time than the case when more than one SU fails, because when one SU may fail at most, only two channel-links fail at most. In fact, this is another major motivation, because route maintenance overhead is significantly reduced. To the best of author knowledge, existing work in literature does not consider how many SUs fail due to a PU activity.

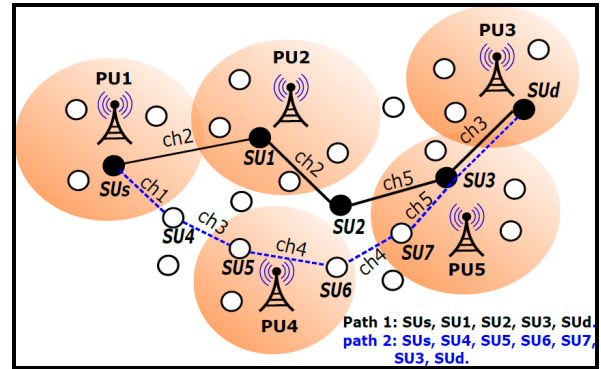


Figure 1. A scenario for two paths: path1 is selected based on the proposed strategy, while path 2 is not selected using the proposed strategy, say based on a traditional approach.

III.2. System Model

In order to explain the proposed model, consider the CR network shown in Figure 2, in which three PUs called PU1, PU2, and PU3. The circular shaded area around each PU transmitter represents its corresponding interference range. Also, there is a set of thirteen SUs including source SU, named SUs, and destination SU, named SUD. Labels on links represent common channels between the corresponding SUs, e.g.; label (i, k) on link

layers and the vertical edges between layers are considered as regular edges which represent channels switching and their cost represents channels switching time delay, moreover, horizontal edges cost represents transmission time delay.

To find the backup path, simply delete all SUs nodes and their incident edges in the selected primary path. After that, just apply the shortest path algorithm again on the reduced graph. The found backup path, if exist, is channel-link disjoint. As a result, a PU activity may cause one or none SU to mandatory evacuate the PU's corresponding channel.

When discovering the primary or backup path, the shortest path algorithm is adjusted, such that when selecting nodes along the path, each node must belong to a different SHRG of SUs. In other words, one SU node at most can be chosen from any SHRG, as a result, this guarantees that one PU activity causes at most one SU to fail or to evacuate the corresponding PU channel.

IV. SIMULATION RESULTS

In the conducted simulation, a group of PUs are scattered randomly within a square area, (0, 0) and (3500, 3500), where distances are in meters. A group of SUs that are placed in a grid-based network, such that the square side length is equal to 500 meter, therefore, the total number of SUs is: $(3500/500) * (3500/500) = 49$. The interference range for each primary user is equal to 650 meter, transmission range for each SU is 500 meter. The parameters of simulation are set as follows, unless mentioned otherwise: The probability of a common channel existence between two adjacent SUs = 0.5. Number of PUs and number of licensed channels are varied throughout the simulation.

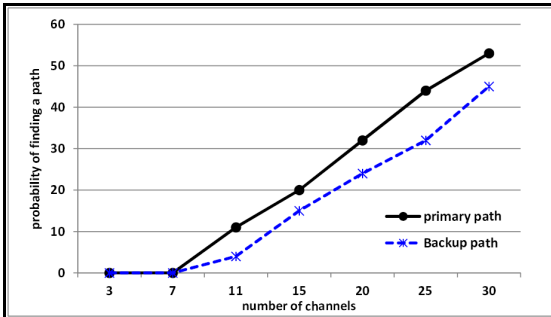


Figure 4: The probability to find a primary and backup path in network with respect to number of channels.

Figure 4 shows the probability to find primary and backup paths in network with respect to number of channels. Obviously, increasing number of channels increases the probability to find a path. Notice that when number of channels is greater or equal to 11, the probability to find a primary path is about 10% higher than the probability to find a backup path.

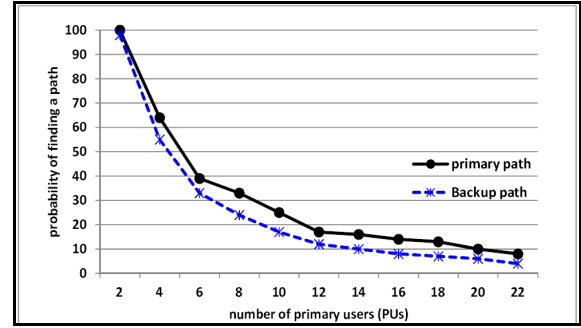


Figure 5: The probability to find a primary and backup path in network with respect to number of primary users (PUs).

Figure 5 shows the probability to find primary and backup paths with respect to number of Primary Users (PUs), which almost follows the probability density function for an exponential distribution. Increasing number of PUs, decreases the probability to find primary or backup path, because PUs are assigned to more channels and their interference ranges affect more SUs' channel-links.

Figure 6 shows the probability to find primary and backup paths with respect probability of a common channel existence between two adjacent SUs, called P_c . Results shows that when P_c is greater or equal to 50%, the probability to find a primary and backup path are at least 65% and 28%, respectively.

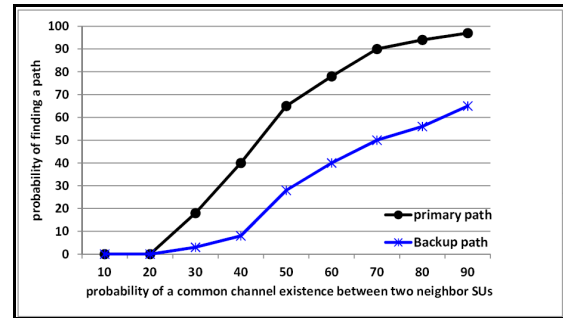


Figure 6: The probability to find a primary and backup path in network with respect to probability of a common channel existence between two adjacent Secondary Users (SUs), P_c .

Let us call our proposed fault tolerance technique as the Immuned Path Protection with Single SU Failure (IPP-SSF), in which at most one SU must evacuate the channel when its licensed PU becomes active again.

In order to evaluate the End-to-End (E2E) delay for the selected path when IPP-SSF scheme routing conditions are applied, e.g.; SHRGs disjointness, simulation parameters are set as follows: PUs are scattered randomly in square area, (0, 0) and (5000, 5000) meter. The SUs are deployed in a grid-based network, such that the square side length is equal to 500 meter, therefore, total number of SUs = $(5000/500) * (5000/500) = 100$. The interference range for each PU is

750 meter, transmission range for each SU is 500 m. We kept the probability of a common channel existence between two adjacent SUs = 0.5.

Assume channels data rate is symmetric and equals to 1Mbps, message segment size = 2,300 bytes, therefore, transmission time delay = $(2,300 * 8 / 1 * 10^6) = 0.018$ sec, and thus, horizontal edges cost in the multi-layer graph = 0.018. Moreover, channels switching time is 1ms/1MHz [77], that is used to find vertical edges cost in the multi-layer graph, e.g.; figure 3.

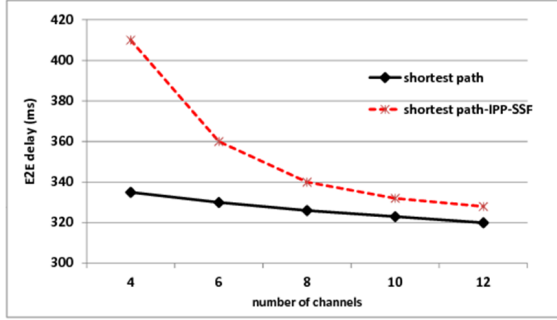


Figure 7: E2E delay with respect to number of channels.

Figure 7 shows the E2E delay with respect to number of channels, the modified shortest path algorithm with our IPP-SSF scheme; call it shortest path-IPP-SSF, shows higher E2E delay than the traditional shortest path algorithm. This completely makes sense, because our scheme conditions enforce the algorithm to search for alternative routes when discovering the path to the destination, in order to maintain the SHRGs-disjointness condition. Clearly, it is a trade-off between the E2E delay and channel-links maintenance cost, such that when our scheme is employed the E2E delay for selected path may increase, however, two channel-links at most may fail (in other words, one SU must back-off transmission, because the PU of currently used channel becomes active again). Note that in figure 7, the maximum percentage for the difference in E2E delay, between the shortest path-IPP-SSF and the traditional shortest path, is equal to 22% when number of channels = 4. While it becomes much less when number of channels = 12 and it equals to 0.025%, which is really minor. That is, when number of channels is increased, e.g.; 10, our scheme employment does not cause a significant increase to the E2E delay.

Figure 8 shows the E2E delay with respect to number of PUs in network. Our proposed shortest path-IPP-SSF scheme has higher E2E delay than the traditional shortest path algorithm, due to the fact that when number of PUs increases in the network area, the probability for a channel-link to be available becomes less, and therefore, the connectivity or channel-links' density becomes also less. As a result, the chance to find a path with a minimum number of hops is reduced, and consequently,

the proposed scheme searches other possible routes, in order to reach the destination.

Note that in figure 8, the minimum percentage for the difference in E2E delay, between the shortest path-IPP-SSF and the traditional shortest path, is equal to 2% when number of PUs = 10. While it becomes greater when number of PUs = 40 and it equals to 15%. This implies an important insight, as large number of PUs is deployed, when the proposed shortest path-IPP-SSF scheme is employed, the E2E delay may increase up to 15%.

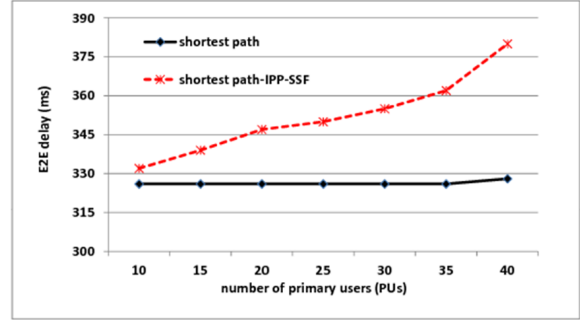


Figure 8: E2E delay with respect to number of primary users (PUs).

Figure 9 shows number of dropped channel-links with respect to number of PUs, when number of channels is fixed to 10.

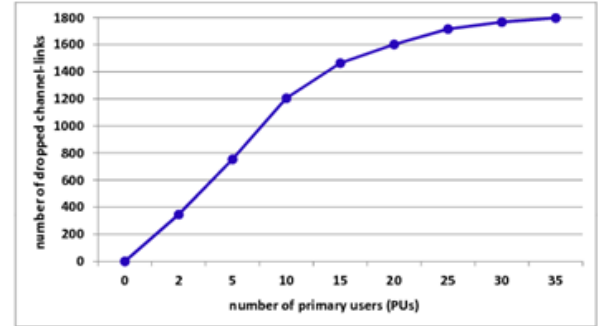


Figure 9: number of dropped channel-links with respect to number of primary users (PUs), where number of channels = 10.

A channel-link is dropped and not considered in the multi-layer graph when running route search algorithm, as explained in Section III, when the corresponding SUs of this link belong to the same SHRG, in which both are affected by the same PU(s)' interference range. Figure 9 results show that increasing number of deployed PUs increases number of dropped channel-links, as a result, the probability to find a path is decreased. For example, for figure 9 when number of PUs = 35, the probability to find a primary path and backup path is reduced to 0.016 and 0, respectively. That is, the network is overwhelmed; and therefore, number of channels must be increased.

On the other hand, if number of channels cannot be increased to improve the probability of finding an Immuned path using the proposed method, the underlay spectrum access approach is employed. In CRNs,

spectrum access strategies can be either overlay, as assumed in this work, or underlay. In overlay, SUs can access licensed channels only when their PUs is currently inactive. However, in underlay approach [71]-[72], SUs can access licensed channels simultaneously with their corresponding PUs, under a condition that SUs caused interference does not exceed the tolerable interference threshold.

It is worth mentioning that when the proposed technique is employed, in order to find a primary or backup path, such that when one PU becomes active one SU at most must back-off PU's channel. That is, at most two channel-links fail for corresponding backed-off SU. As a result, energy consumption is reduced which could be used for repairing more than two failed channel links, including route re-establishment overhead, exchanging control messages, re-transmitting lost data packets. Thereby, CR network life time is prolonged when the proposed shortest path-IPP-SSF method is employed.

V. Conclusions

Routing in cognitive radio networks (CRNs) is not as in conventional networks routing, due to many reasons, e.g.; Secondary Users (SUs) must be aware about spectrum availability. In this paper, a fault tolerant routing discovery mechanism is proposed, in which when a Primary User (PU) becomes active again only one SU fails at most (must back-off data transmission) along the selected route. In other words, at most two channel-links fail when PU becomes active, which reduces used energy for re-routing, and hence, network life time is prolonged. To the best of author knowledge, existing CRNs routing in literature does not consider how many SUs fail (or limit number of failed SUs' channel-links), due to a PU activity.

The proposed routing strategy can also be employed, in order to find a channel-link disjoint backup path, if exist, from the primary path. The problem is modeled using a multi-layer graph where each layer corresponds to one channel. Simulation results show that the probability to find a primary and backup path increases when number of channels is increased or the probability to find common channel(s) between neighbor SUs increases, however, the probability of finding a path decreases by increasing number of PUs. Also, results show employing the proposed scheme does not increase the E2E delay significantly, if number of PUs is not large and there are enough sensed licensed channels.

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