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A Spectrum Aware Routing Protocol for Ad-Hoc Cognitive Radio Networks

Athina Bourdena, George Mastorakis, Georgios Kormentzas, Evangelos Pallis

Abstract—**The paper proposes a routing protocol that efficiently coordinates data flows among secondary systems with heterogeneous spectrum availability in an ad-hoc cognitive radio network architecture. Efficient protocol operation as a matter of maximum-possible routing paths establishments and minimum delays is obtained by a coordination mechanism, which was implemented based on a simulation scenario. The simulation scenario includes a number of secondary systems that exploit television white spaces, under the spectrum of commons regime. The validity of the research approach is verified via a number of experimental tests, conducted under controlled simulation conditions, evaluating the performance of the proposed routing protocol.**

Index Terms—**Ad-hoc Networks, Cognitive Radio, Routing protocols, TVWS.**

I. INTRODUCTION

COGNITIVE Radio (CR) technology [1], [2] is a promising solution for efficient spectrum usage and simplified deployment for new wireless networks applications. Cognitive radio networks are comprised of spectrum-agile devices, capable of changing their technical characteristics (operating spectrum, modulation, transmission power and communication technology) based on interactions with the surrounding spectral environment. They can sense a wide spectrum range, dynamically identify locally unused spectrum for data communications, and efficiently (i.e. through Radio Recourse Management algorithms [3]) access it. This capability also opens up the possibility of designing dynamic spectrum access strategies/policies with the purpose of opportunistically reusing under-utilised spectrum at local level. Such an example of under-utilised spectrum portions is the "television white spaces" (TVWS), which consist of VHF/UHF frequencies that are either released by the digital switchover process ("Spectrum Dividend"), or are completely unexploited (especially at local level) due to frequency planning issues and/or network design principles ("Interleaved Spectrum") [4]. Therefore, introduction of CR networks in TVWS currently represents a disruption to the "command-and-control" paradigm of TV/UHF spectrum management, thus the exploitation of the CR technology is highly intertwined with the regulation models that would eventually be adopted.

These regulator models can be utilised by the current CR network architectures, which are categorized among the other to infrastructure-based (i.e. centralized) architectures, as well as to distributed (i.e. ad-hoc) ones. This classification depends on the frequency that the network topology changes. The "Real-time Secondary Spectrum Market - RTSSM" regime can be performed through an infrastructure-based architecture, where a spectrum manager is responsible to orchestrate a secondary market for spectrum leasing and spectrum auction between primary and secondary systems [4]. On the other hand, "Spectrum of Commons" regime is well-suited in distributed CR network architectures, where there is no spectrum manager to preside over the resource allocation. In this case, the communication between secondary users is opportunistic and is assured via sensing techniques.

The flexibility in the spectrum access phase by CR network infrastructures caused new challenges along with increased complexity in the design of communication protocols at different layers. More specifically, the design of effective routing protocols for ad-hoc CR networks is a major challenge in cognitive networking paradigm. Ad-hoc CR networks are characterized by completely self-configuring architectures [5], where routing is challenging and different from routing in a conventional wireless network. A key difference is that spectrum availability in an ad-hoc CR network highly depends on the primary users' presence, thus, it is difficult a Common Control Channel (CCC) to be used in order to establish and maintain a fixed routing path between secondary users.

Moreover, the advent of CR technology provides tools and solutions for using the spectrum in a more flexible manner. Thus, it is important to focus on prospective application areas, in order a number of specific scenarios with good business potential can be envisaged, such as Public Safety use-cases. Moreover, the flexibility of Ad-hoc CR networks capabilities

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Athina Bourdena is with the Department of Information and Communication Systems Engineering, University of the Aegean, Samos, 83200, Greece (Tel: +302273082235, Fax: +302273082009, Email: abourdena@icsd.aegean.gr)

George Mastorakis is with the Department of Commerce and Marketing, Technological Educational Institute of Crete, Ierapetra, 72200, Crete, Greece (Email: gmastorakis@staff.teicrete.gr)

Georgios Kormentzas is with the Department of Information and Communication Systems Engineering, University of the Aegean, Samos, 83200, Greece (Email: gkorm@aegean.gr)

Evangelos Pallis is with the Department of Applied Informatics and Multimedia, Technological Educational Institute of Crete, Heraklion, 71500, Crete, Greece (Email: pallis@epp.teicrete.gr)

appears to have the potential to enhance Public Safety operations.

Cognitive radio operating in the TVWS can facilitate multi-organizational (e.g. fire-brigade and police) interventions at operational level, which would not be based on the need for dedicated and harmonized spectrum assignment to Public Safety systems at the European level. Instead, systems could collectively use possible TVWS spectrum that is available in an open access manner. Furthermore, cognitive radio technologies have the potential to address interoperability issues of emergency communication systems, through two different means. A TVWS gateway could be used to link two different radio communications systems on different frequencies or the cognitive radio system could be used to minimize mutual interference between two communication systems deployed in the same operational crisis site.

In this context, this paper elaborates on the design, development and evaluation of a routing protocol for a TVWS based CR network, enabling for the efficient communication of secondary users (i.e. Public Safety nodes) that operate under the "Spectrum of Commons" regime. Following this introductory section, Section 2 elaborates on routing challenges in ad-hoc CR networks and the definition of the simulation scenario. Section 3 presents the design of a novel routing protocol that enables for the proper data transition across secondary users with different TVWS availability, while section 4 elaborates on the performance evaluation of the proposed research approach. Finally, section 5 concludes the paper by highlighting fields for future research.

II. ROUTING IN AD-HOC CR NETWORKS OPERATING OVER TVWS

The transmission of secondary users in an ad-hoc CR network is based on spectrum opportunity. Therefore, routing in such a network has to take into account the availability of spectrum in specific geographical locations at local level. Spectrum awareness, route quality and route maintenance issues have to be investigated for different routing schemes, in order to enable for the proper data delivery, across regions of heterogeneous spectrum availability, even when the network connectivity is intermittent or when an end-to-end path is temporarily unavailable. Figure 1 illustrates a use-case scenario, where primary users operate on specific channels in three geographical areas (i.e. Area A, B and C in Figure 1). Secondary users in Figure 1 opportunistically operate by utilising the remaining available channels in each geographical area (i.e. TVWS in Figure 1). It has to be noted here that a CCC does not exist between secondary users, which are located in neighbouring geographical areas (i.e. Area A, B and C in Figure 1). In such a case, secondary users that are located outside Areas A, B and C, (i.e. Areas with higher spectrum availability in the region) may act as intermediate bridge/relay nodes, able to switch among multiple channels, towards enabling for an ad-hoc connection between secondary users' pairs with different spectrum availability. In this use-case scenario, links on each path have to be established using different channels, according to the TVWS availability in a specific geographical area and time period.

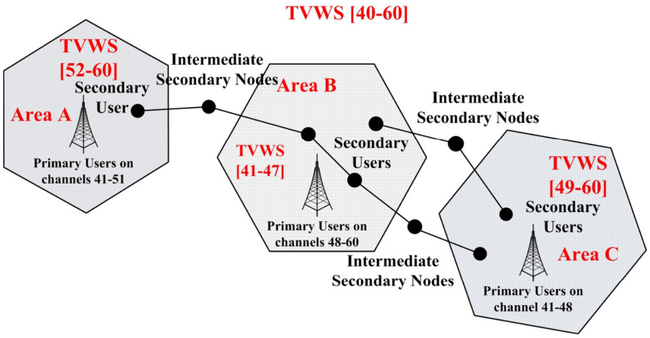

Fig. 1. Routing across regions with heterogeneous TVWS availability

Taking into account the above scenario, spectrum awareness issue has to be investigated, regarding routing in such an ad-hoc CR network, where secondary users are prohibited to operate on spectrum bands occupied by primary users. The goal of routing in such networks is to provide persistent, high throughput communication by optimally selecting the appropriate path between secondary users. Thus, multi-hop connections must be set up between secondary users pairs with different spectrum availability and a new routing protocol has to be designed and adopted, enabling for route discovery capabilities, taking into account spectrum heterogeneity in different geographical locations. Route quality issues have also to be investigated since the actual topology of such multi-hop CR networks is highly influenced by primary users' behaviour, and classical ways of measuring/assessing the quality of end-to-end routes (nominal bandwidth, throughput, delay, energy efficiency and fairness) should be coupled with novel measures on path stability. Furthermore, route maintenance is a vital challenge considering the above mentioned use-case scenario. The unpredictable appearance of a primary user at a specific time period is possible to make a given channel unusable at local level, thus resulting in unpredictable route failures, which may require frequent path rerouting either in terms of nodes or used channels. In a general context, routing in a TVWS based ad-hoc CR network constitutes a rather important but yet unexplored problem, especially when a multi-hop network architecture is considered. The design of a new routing protocol is therefore required, towards overcoming challenges defined above and establishing/maintaining optimal routing paths between secondary users with heterogeneous TVWS availability.

In this context, Figure 2 depicts a simulation scenario, where secondary users are scattered in three geographical areas (i.e. A, B and C in Figure 2) with different TVWS availability. Secondary users located in the first geographical area opportunistically operate using channels from 52 up to 60, while remaining channels are dedicated for usage by primary users. Also, secondary users located in the second and third geographical areas are able to transmit on channels 41-47 and 49-60, respectively. In this simulation scenario, secondary users located outside these areas, are able to operate over all available channels (i.e. channels 40-60) and act as coordinator nodes (intermediate secondary nodes in Figure 2). These nodes are enhanced with a coordination mechanism that enables to determine routing paths between secondary users with different TVWS availability in areas A, B and C.

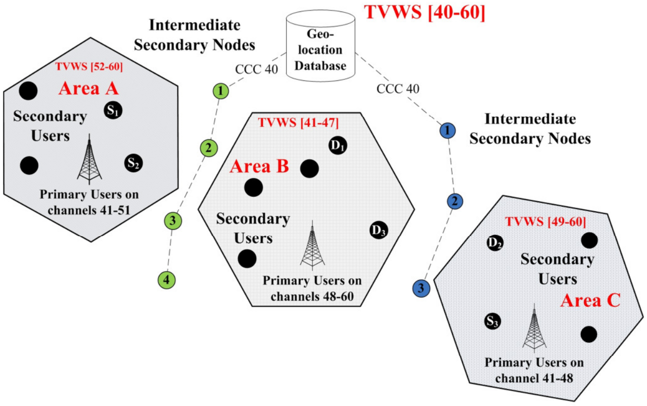

Fig. 2. Simulation scenario of secondary users operating on heterogeneous TVWS

Coordination nodes have sensing capabilities and are connected with a Geo-location database that includes TVWS availability for all geographical locations. The Geo-location database also provides to intermediate communication nodes, data regarding the maximum allowable transmission power that can be used so that no causing interference to primary systems. For this reason an initial study is required, in order to compute the transmission power limitations of communications nodes for each TVWS channel. Such an investigation can be performed, by adopting the method, which is proposed in [6] for the region of Bavaria in Germany.

This simulation scenario includes three source secondary users (i.e. S1, S2 and S3 users in Figure 2) that wish to deliver data flows to corresponding destination secondary users (i.e. D1, D2 and D3 users in Figure 2) located in geographical areas with heterogeneous TVWS availability. The main challenge in such an ad-hoc CR network architecture is the spectrum heterogeneity of the available TVWS between neighbouring areas, prohibiting secondary users to communicate since there is no CCC. In such a case, coordination nodes will act as intermediate/bridge nodes between source and destination secondary users, coordinating data flows and deciding the most optimum routing path that has to be followed.

III. DESIGN OF A NOVEL ROUTING PROTOCOL

Towards enabling for an efficient data transition between source and destination users of the above mentioned simulation scenario, a new routing protocol was designed, implemented and evaluated under controlled simulation conditions. This routing protocol is based on the exchange of AODV-style messages [7] between secondary, including two major steps in the route discovery process (i.e. route discovery and route reply step). This selection was made due to the unpredictable availability of the TVWS that requires hop-by-hop routing, by broadcasting discovery packets only when necessary. During the route discovery step, a RREQ (route request) message, including TVWS availability of nodes is sent by the source user to acquire a possible route up to the destination user. Once the destination user receives the RREQ message, it is fully aware about the spectrum availability along the route from the source user. The destination user then chooses the optimum routing path, according to a number of performance metrics (e.g. backoff delay, switching delay, queuing delay, number of hops, throughput) and assigns a channel to each secondary user along the route. It has to be noted here, that the evaluation of performance metrics is conducted, by each intermediate node during the routing path of the RREQ message. In the next step, destination user sends back a RREP (route reply) message to the source user that includes information regarding channel assignment so that each node along the route can adjust the channel allocation accordingly. Once this RREP is received by the source user, it initiates useful data transmission.

Figure 3 presents the detailed process of the proposed routing protocol for handling both RREQ and RREP messages. The source user initiates a flow (i.e. New Flow in Figure 3), transmitting a RREQ message to an intermediate node located in a neighbouring location. The intermediate node is updated by Geo-location database about TVWS availability of its neighbouring nodes and determines if it is capable or not to accommodate the incoming flow from source user. If this is possible, it then evaluates the performance metrics, accommodates the incoming flow and finally forwards the RREQ message to the next hop or to the destination user. Once the destination user receives RREQ message, it is fully aware of channel availability along the route from the source node. Destination user sends then back a RREP message to the source user. This message contains information regarding channel assignment so that secondary users along the route can adjust the channel allocation accordingly. Once the source user receives the RREP, the routing path has been established and useful data transmission is initiated.

In the case when the intermediate node is not capable to accommodate the incoming flow (i.e. New Flow in Figure 3), a coordination mechanism (redirection process in Figure 3) is in charge of informing the source user, about the neighboring node, which could possibly act as an alternative intermediate node. In such a case, the intermediate node sends a RREP message to the source user, including redirection information. As soon as the source user receives this message, it broadcasts a redirecting RREQ message to the next possible intermediate node, which is then in charge to decide if it is feasible to accommodate the data flow, evaluate the performance metrics and forward it to the next hop. The proposed routing protocol determines a route only when a source user wishes to send a data flow to a destination user. Routes are maintained as long as they are needed by the source user and the exploitation of sequence numbers in the exchange messages guarantee a loop-free routing process. Furthermore, the proposed routing protocol is a reactive one, creating and maintaining routes only if it is necessary, on a demand basis. The routes are maintained in routing tables, where each entry contains information, regarding destination user, next hop, number of hops, destination sequence number, active neighbouring nodes for this route and expiration time of the flow. The number of RREQ messages that a source user can send per second is limited, while each RREQ message carries a time to live (TTL) value that specifies the number of times this message should be re-broadcasted. This value is set to a predefined value at the first transmission and increased during retransmissions, which occur if no replies are received.

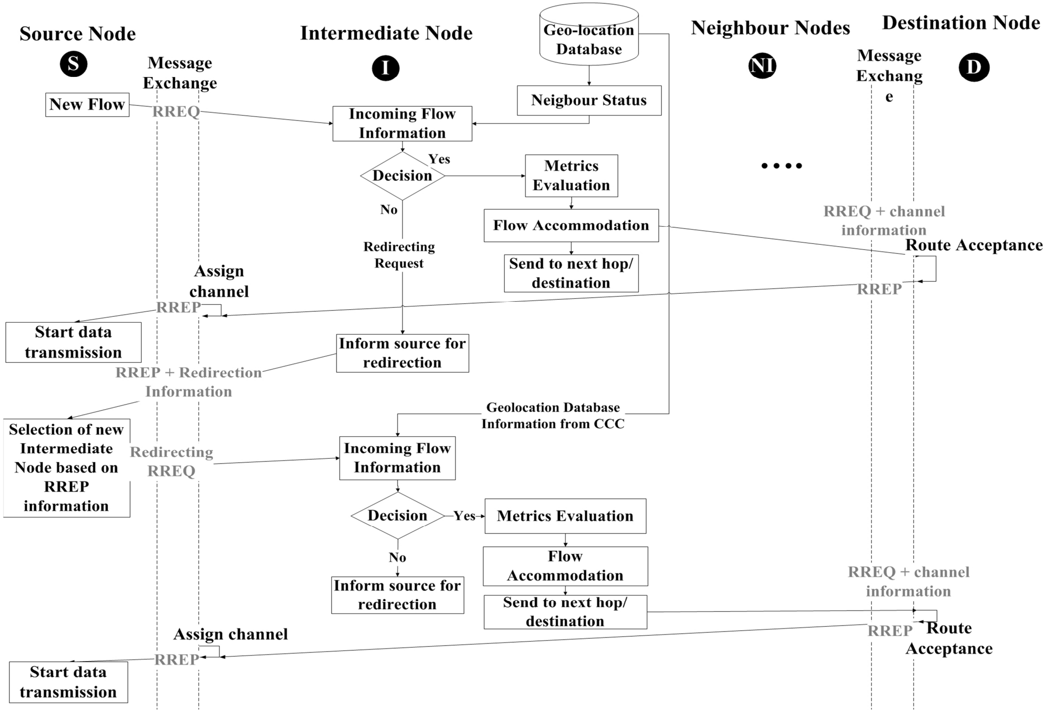

Fig. 3. Message exchange process of the proposed routing protocol

IV. PERFORMANCE EVALUATION

Towards verifying the validity of the proposed routing protocol, experimental tests were conducted, under controlled conditions (i.e. simulations). More specifically, in such use-case scenario intermediate nodes are receiving concurrent data flows, stemming from other secondary users, resulting to increased delays. According to this simulation scenario, a number of data flows are contending to pass through the same intermediate node, thus evaluation of delays is crucial regarding the efficient performance of the proposed routing protocol. In this context, a number of delay metrics [8], [9], [10], [11], are evaluated, such as switching delay ($D_{switching}$), medium access delay ($D_{backoff}$) and queuing delay ($D_{queuing}$). Switching delay occurs when a secondary user during the routing path switches from one channel to another, while the medium access delay, namely backoff delay, is based on the MAC access schemes used in a given frequency band. Backoff delay is defined as the time from the moment that a data flow is ready to be transmitted up to the moment the data transmission is successfully initiated. Queuing Delay is based on the output transmission capacity of a secondary user on a given channel. More specifically, queuing delay represents the time needed for a data flow to wait in a queue until it can be processed.

According to the simulation scenario a queuing system was set up, exploiting a M/M/1/K Kendall model [12], utilising an inter-arrival time (i.e. first M of the M/M/1/K model), as well as an accommodation/serving time (i.e. second M of the M/M/1/K model) following exponential distributions based on the load/service rate (i.e. ρ). The system capacity (or number of flows can be served) was set to K = 1, while the service rate ρ depends on the parameters λ and μ. λ denotes the number of data flows, arriving every second and μ denotes the number of data flows that are accommodated every second. Load/service rate is equal to λ/μ and during the simulation test load was varied from 0.05 to 0.45, towards evaluating the node queue under different loads [13]. The formulation of mean queuing delay $D_{queuing}$ [14], [15] is depicted below:

$$D_{queuing} = \frac{\rho}{\mu-\lambda} \tag{1}$$

Additionally, the evaluation of $D_{switching}$ and $D_{backoff}$ [9], [10] is crucial in such simulation scenario. Then, cumulative delay at an intermediate node i is based on them and is computed as follows:

$$Node\ Delay = \sum_{1}^{i}(D_{switching} + D_{backoff}) \tag{2}$$

Finally, end-to-end delay from the source user up to the destination one is computed as the overall sum of $D_{queuing}$ and ND:

$$D_{End-to-End} = D_{queuing} + Node\ Delay \tag{3}$$

The simulation results that were obtained, provided the routing paths for S1-D1, S2-D2 and S3-D3 communication (see Figure 4). More specifically, when secondary user S1 wishes to transmit data flows to secondary user D1, it firstly communicates with coordination node 2 on channel 52, which is in charge to route data flows to D1 by switching to channel

43. Additionally, secondary user S2 wishes, at the same time to transmit data flows to secondary user D2. In this case, coordinator node 3 located between geographical areas B and C is not able to process data flows from S2, since it serves at the same time data flows originated from secondary user S3 targeted to secondary user D3. In such a case, data flows are redirected to coordination node 2, which is then in charge to communicate with D2 on channel 60. It has to be noted here that all coordination nodes are connected to a TVWS Geo-location database, through a CCC (i.e. channel 40).

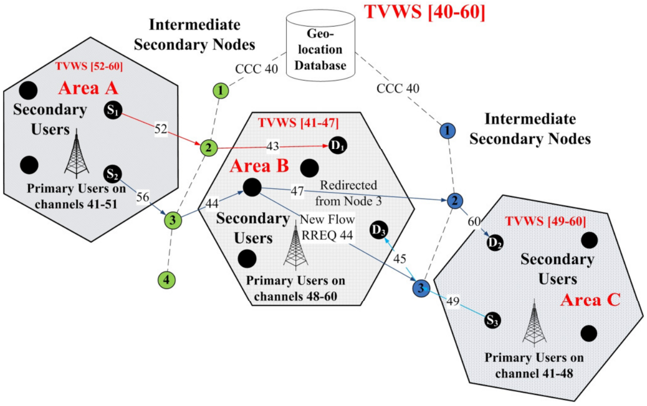

Fig. 4 Routing paths obtained by simulation scenario

Based on the metrics defined above the performance evaluation results (see Figure 5) represent end-to-end delay and node delay for all three data flows of the simulation scenario defined above.

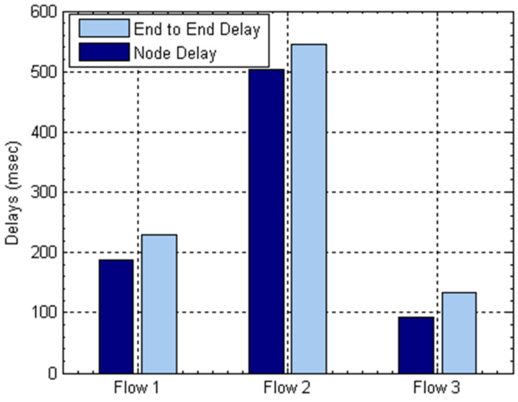

Fig. 5. End-to-End Delay and Node Delay of data flows

It can be observed that end-to-end delay and node delay for data flow 2 is higher in comparison to delays of data flows 1 and 3, since the routing path from S_2 secondary user to D_2 secondary user (see Figure 4), includes a higher number of hops, as well as a redirection process is occurred.

Towards further evaluating the performance of the proposed routing protocol, a discrete time Markov chain process is adopted. The number of active nodes at a given time is defined as the initial state of the system. This number represents the discrete time states of Markov chain, given by a random variable Xt{0,1,2,…,M}. Also, it is assumed that a finite number of M nodes is connected to the coordination node that utilizes the proposed routing protocol. Each secondary node is equipped with a buffer with capacity of a packet. The discrete time is a step in the transition of Markov model analysis. Each secondary node generates packets at the beginning of every timeslot (i.e. per sec) independently of the other nodes with probability of arrival Pa, following independent geometric distribution. In case of unsuccessful transmission (i.e. collision), the packet enters the buffer of the node and is marked as active (i.e. backlogged), while nodes with empty buffer are marked as free (i.e. unbacklogged). Moreover, each secondary node attempts to retransmit a packet with probability Pr, independently from other ones at the beginning of every timeslot (i.e. per sec).

Based on the assumptions defined above, the performance evaluation results (see Figures 6-8) represent a) the percentage of time that a node is occupied/active with a successful transmission of packets and b) the mean delay that is required in order for a packet to be transmitted. In more detail, figure 6 depicts the percentage of time that a node is occupied with a successful transmission of packets over the probability Pa that a node generates a packet. According to the results, it is observed that for low values of Pa the successful transmission of the packets is 37%, while for Pa from 0.04 to 0.3, it is observed a rapidly decrease of the successful transmission, which continues to decrease at a slower rate. As far as the probability increases, the number of conflicts/collisions is getting higher.

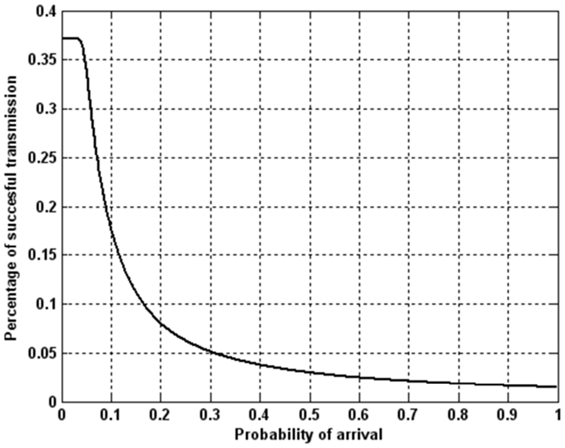

Fig. 6. Percentage of a successful transmission

Figure 7 represents the mean delay that is required in order for a packet to be transmitted. During the initial values of Pa (i.e. up to 0.04), the mean delay is relatively constant due to the maximum percentage of successful packet transmission (see initial values of percentage of successful probability in Figure 6). Then, a steady increase is observed, which is normal since as the probability of each packet to be transmitted is increased, the number of active nodes will be higher in order to send a packet without a collision.

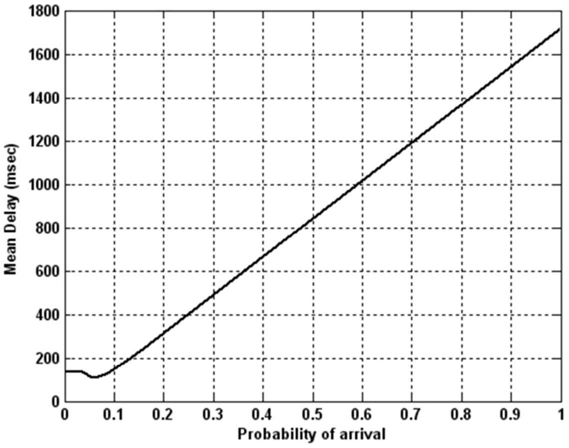

Fig. 7. Mean delay for packet transmission

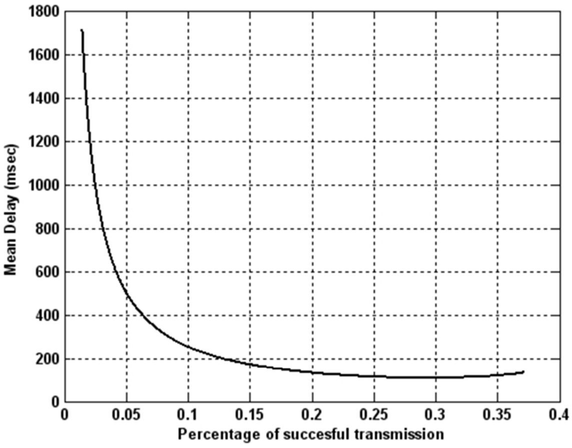

Fig. 8. Mean delay over successful transmission

Finally, Figure 8 represents mean delay over percentage of successful transmission of packets. It is observed that as the percentage of successful transmission increases, the mean delay decreases. This is also verified in Figures 6 and 7.

V. CONCLUSION

This paper discussed spectrum aware routing in an ad-hoc CR network architecture that exploits TVWS under the “Spectrum of Commons” regime. It elaborated on the design of a routing protocol, which coordinates data flows among secondary systems with heterogeneous spectrum availability. Efficient protocol operation as a matter of maximum-possible routing paths establishments and minimum delays was obtained by a coordination mechanism that was implemented based on a simulation scenario. Towards evaluating the performance of the protocol, a set of experimental tests was conducted under controlled simulation conditions, where various secondary systems were concurrently/simultaneously communicating in ad-hoc connections, accessing the available TVWS. The obtained experimental results verified the validity of the proposed routing protocol, towards enabling for an efficient communication between secondary nodes located in areas with different TVWS availability. Fields for future research include the evaluation of the proposed routing protocol, considering performance metrics such as useful throughput, number of hops and route stability. Additionally, different optimization methods will be adopted, towards minimizing delays, occurred during the transition of data flows and maximizing the number of established routing paths.

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