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A Spectrum Aware Routing Protocol for Public Safety Applications over Cognitive Radio Networks

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***Abstract*—The paper elaborates on a routing protocol that efficiently coordinates data flows among public safety secondary systems considering the unpredictable availability of TVWS spectrum resources. The proposed application scenario exploits for the communication of the nodes both Ad-hoc and mesh network architectures. Ad-hoc network connections are ideally for emergency situations, when the spectrum resources are pour, while the mesh network architecture addresses the emerging market requirements for building wireless networks that are highly scalable and cost effective, offering a solution for the easy deployment of high-speed ubiquitous wireless access. Efficient protocol operation as a matter of maximum-possible routing paths establishments and minimum delays is obtained by a coordination mechanism. 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.**

Keywords-Ad-hoc Networks, Cognitive Radio, Mesh Networks, Public Safety Applications, Routing Protocols, TVWS.

I. INTRODUCTION

Emerging types of wireless applications and telecommunication services put more and more pressure on the available radio-spectrum that has been nearly fully allocated. Moreover, user and industry demand for wireless services is increasing, thus raising the need for frequency availability (i.e. bandwidth), while creating new challenges in radio-spectrum management and administration. No matter if the utilization of advanced signal processing techniques may enable a very efficient spectrum-usage, there is a worldwide recognition that these methods of spectrum administration have reached their limit and are no longer optimal. In fact spectrum utilization studies have shown the existence of available spectrum [1] when both dimensions of space and time are considered. Such an example of under-utilized spectrum portions is the “television white spaces” (TVWS) [2].

For the exploitation of such spectrum opportunities, a promising solution may be the cognitive radio (CR) technology [3], [4], [5], which is comprised of spectrum-agile devices, capable of changing their technical characteristics based on interactions with the surrounding spectral environment. The advent, however, of CR technology provides tools and solutions for using the spectrum that are flexible, rather than based on the traditional static approach. 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 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.

For the deployment of the above-mentioned issues, new policy models are required for the exploitation of the current CR network architectures. These regulator policies 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 [6]. 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 [7], 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. Another major challenge that faces reliable operation in the white spaces is interference among peer TV band devices given the unlicensed nature of operation in this band. Managing interference between nodes in the same network is generally a difficult problem, and this becomes more challenging when devices belong to heterogeneous networks, using different air interfaces.

In this context, this paper elaborates on the design, development and evaluation of a routing protocol for public safety application scenarios over TVWS, operating under the "Spectrum of Commons" policy. This policy enables for CR Ad-hoc network connections, utilizing a mesh based infrastructure and the proposed routing protocol supports the efficient communication of public safety network nodes, when the available spectrum is limited. 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 public safety nodes 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. Public Safety Application Scenario

The transmission of secondary nodes 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 limited or when an end-to-end path is temporarily unavailable.

Figure 1 illustrates the proposed public safety use-case scenario, where secondary nodes operate opportunistically, by utilizing the remaining (from primary systems) available channels in each geographical area (i.e. TVWS in Figure 1). Ad-hoc network is ideally to be used in emergency situations like natural disasters, military conflicts, emergency medical situations etc. Moreover, an Ad-hoc network is required to support increasing demand for multimedia communications. Maintaining real-time media traffic, such as audio and video in presence of dynamic network topology is particularly challenging due to high data rate requirements and stringent delay constraint, especially when wireless nodes have generally limited network resources.

It has to be noted here that a CCC does not exist between secondary public safety nodes, which are located in neighboring 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.

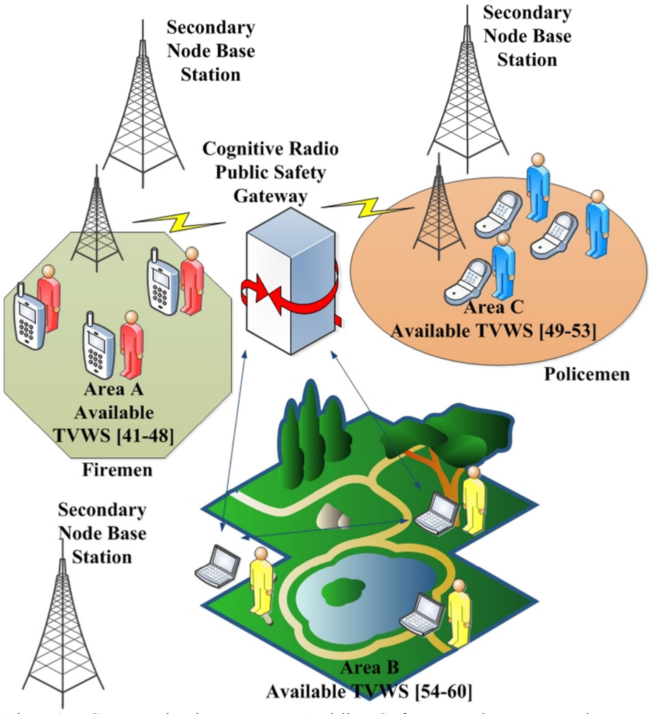

Fig. 1. Communication across Public Safety workers operating on heterogeneous TVWS

In this application scenario, the challenge regarding routing protocols stems from the need to maintain reliable routes with QoS assurance, minimum control overhead and energy consumption from such maintenance. Another goal of routing in such networks is to provide persistent, high throughput communication by optimally selecting the appropriate path between secondary nodes. Thus, multi-hop connections must be set up between secondary nodes 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 behaviors, 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 node 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 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.

Moreover, the public safety secondary nodes communicate utilizing a mesh network infrastructure, which is a fully wireless network that employs multi-hop communications to forward traffic. Mesh based infrastructures are self-configuring and self-healing networks, thus the link failures are limited, as each device has a connection to every other device in its immediate neighborhood. Also, in order to increase capacity and reduce interference, mesh nodes can communicate using multiple radios. Figure 2 illustrates the mesh network architecture, highlighting the different components and system layers.

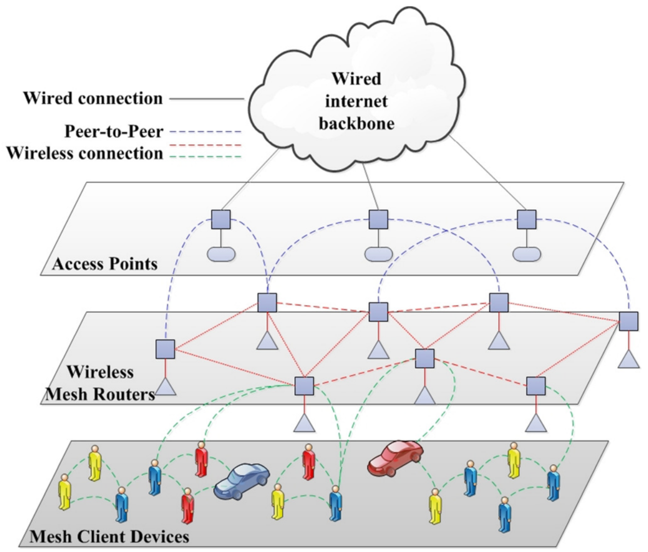

Fig. 2. Mesh network architecture for Public Safety use-case

More specifically, the Ad-hoc extension to the backbone or infrastructure devices consists of clients/users with mesh devices. The mesh client devices can be static or mobile and they interact with the backbone or infrastructure devices, namely wireless mesh routers. The mesh routers communicating among each other and providing wireless transport services to data traveling from mesh clients/users to either other clients or access points, which are special wireless routers with a high-bandwidth wired connection to the Internet backbone. The network of wireless mesh routers consists of a wireless backbone, which provides multi-hop connectivity between mesh clients and wired gateways, thus can save cost by having only a few high bandwidth wired links to the gateways instead of every router having a wired connection.

Meshing among wireless routers and access points creates a wireless backhaul communication system, which provides each mobile user with a low-cost, high-bandwidth, and seamless multi-hop interconnection service with a limited number of Internet entry points and with other wireless mobile users. Backhaul is used to indicate the service of forwarding traffic from the originator node to an access point from which it can be distributed over an external network.

III. DESIGN OF A NOVEL ROUTING PROTOCOL

Figure 3 depicts the area of simulation scenario, where secondary public safety network nodes are scattered in three geographical areas (i.e. A, B and C) of Munich with different TVWS availability. Secondary nodes located in the first geographical area opportunistically operate using channels from 41 up to 48, while remaining channels are dedicated for usage by primary nodes. Also, secondary nodes located in the second and third geographical areas are able to transmit on channels 54-60 and 49-53, respectively. In this simulation scenario, secondary nodes (i.e. Wireless mesh routers) located outside these areas, have greater TVWS availability and is possible to act as coordinator nodes (intermediate secondary nodes in Figure 3). These mesh network nodes are enhanced with a coordination mechanism that enables to determine routing paths between secondary nodes with different TVWS availability in areas A, B and C.

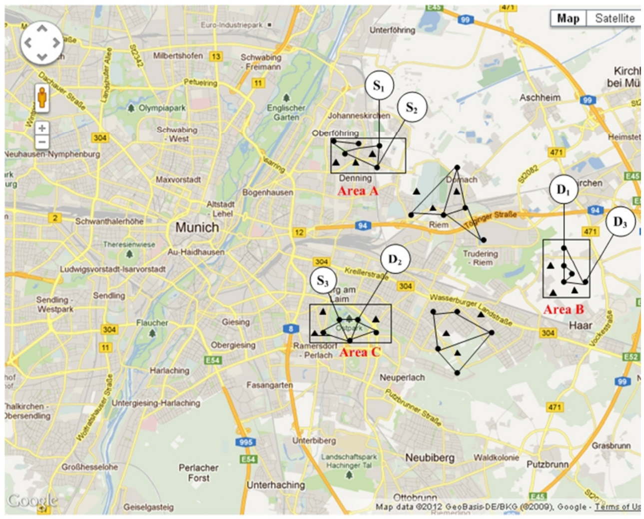

Fig. 3. Munich area with public safety network nodes over TVWS

Coordination mesh 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 mesh 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 has been performed in [8] for the region of Bavaria in Germany.

This simulation scenario includes three source secondary nodes (i.e. S_1, S_2 and S_3 nodes in Figure 3) that wish to deliver data flows to corresponding destination secondary nodes (i.e. D_1, D_2 and D_3 nodes in Figure 3) 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 neighboring areas, prohibiting secondary nodes to communicate since there is no CCC. In such a case, coordination nodes will act as intermediate/bridge nodes between source and destination secondary nodes, coordinating data flows and deciding the most optimum routing path that has to be followed.

Towards enabling for an efficient data transition between source and destination nodes 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 [9] between secondary nodes, 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 node to acquire a possible route up to the destination node. Once the destination node receives the RREQ message, it is fully aware about the spectrum availability along the route from the source node. The destination node 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 node 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 node sends back a RREP (route reply) message to the source node 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 node, it initiates useful data transmission.

Figure 4 presents the detailed process of the proposed routing protocol for handling both RREQ and RREP messages. The source node initiates a flow (i.e. New Flow in Figure 4), transmitting a RREQ message to an intermediate node located in a neighboring location. The intermediate node is updated by Geo-location database about TVWS availability of its neighboring nodes and determines if it is capable or not to accommodate the incoming flow from source node. 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 node. Once the destination node receives RREQ message, it is fully aware of channel availability along the route from the source node. Destination node sends then back a RREP message to the source node. This message contains information regarding channel assignment so that secondary nodes along the route can adjust the channel allocation accordingly. Once the source node receives the RREP, the routing path has been established and useful data transmission is initiated.

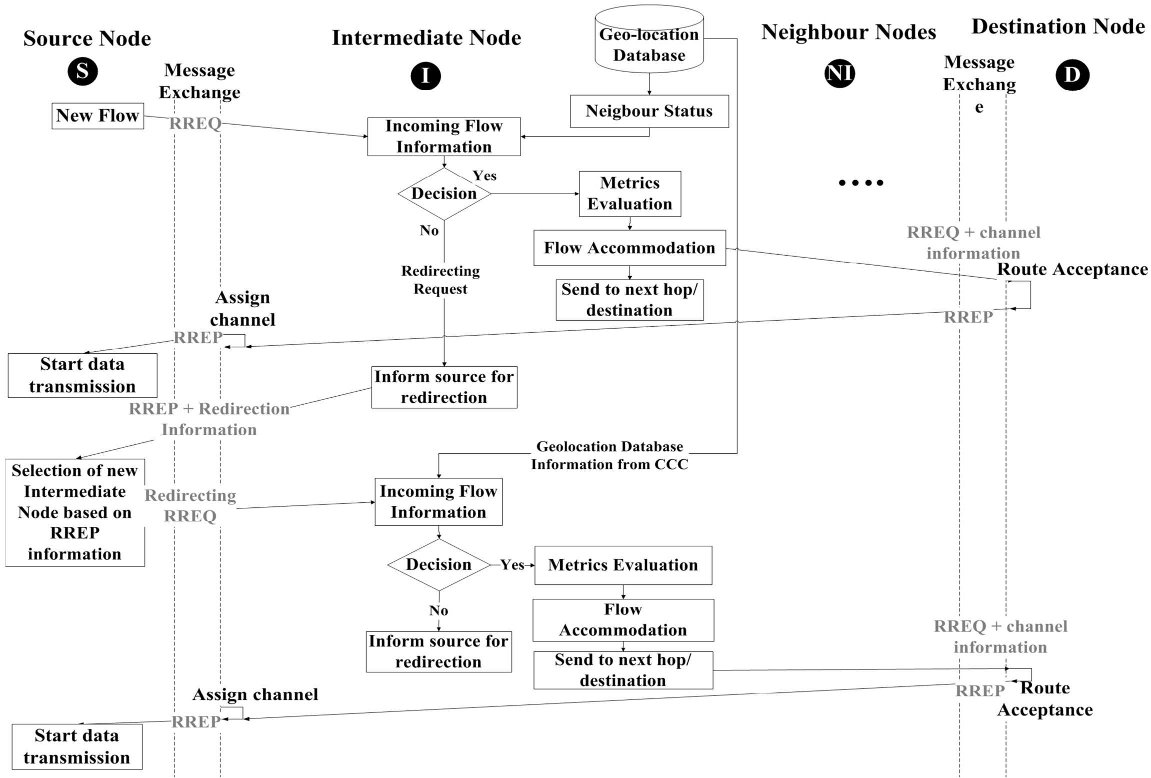

Fig. 4. Message exchange process of the proposed routing protocol

In the case when the intermediate node is not capable to accommodate the incoming flow (i.e. New Flow in Figure 4), a coordination mechanism (redirection process in Figure 4) is in charge of informing the source node, 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 node, including redirection information. As soon as the source node 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 node wishes to send a data flow to a destination node. Routes are maintained as long as they are needed by the source node 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 node, next hop, number of hops, destination sequence number, active neighboring nodes for this route and expiration time of the flow. The number of RREQ messages that a source node 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.

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 mesh nodes are receiving concurrent data flows, stemming from other secondary public safety nodes, resulting to increased delays. According to this simulation scenario, a number of data flows are contending to pass through the same intermediate mesh node, thus evaluation of delays is crucial regarding the efficient performance of the proposed routing protocol. In this context, a number of delay metrics [10], [11], [12], [13], are evaluated, such as switching delay ($D_{switching}$), medium access delay ($D_{backoff}$) and queuing delay ($D_{queuing}$). Switching delay occurs when a secondary node 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 node 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 [14], utilizing 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 [15]. The formulation of mean queuing delay $D_{queuing}$ [16], [17] is depicted below:

$$D_{queuing} = \frac{\rho}{\mu - \lambda} \qquad (1)$$

Additionally, the evaluation of $D_{switching}$ and $D_{backoff}$ [12], [13] is crucial in such simulation scenario. Then, cumulative delay at an intermediate node i is based on them and is computed as follows:

$$NodeDelay = \sum_{1}^{i} (D_{switching} + D_{backoff}) \qquad (2)$$

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

$$D_{End-to-End} = D_{queuing} + NodeDelay \qquad (3)$$

The simulation results that were obtained, provided the routing paths for S_1-D_1, S_2-D_2 and S_3-D_3 communication (see Figure 5). More specifically, when secondary node S_1 wishes to transmit data flows to secondary node D_1, it firstly communicates with an intermediate/coordination on channel 52, which is in charge to route data flows to D_1 by switching to channel 43. Additionally, secondary node S_2 wishes, at the same time to transmit data flows to secondary node D_2. In this case, an intermediate/coordinator located between geographical areas B and C is not able to process data flows from S_2, since it serves at the same time data flows originated from secondary node S3 targeted to secondary node D_3. In such a case, data flows are redirected to an intermediate/coordination, which is then in charge to communicate with D_2 on channel 60. It has to be noted here that all coordination nodes are communicate through the mesh network and are also connected to a TVWS Geo-location database.

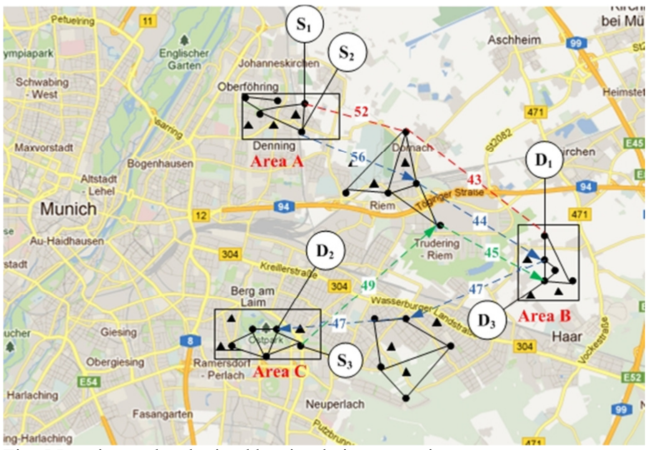

Fig. 5 Routing paths obtained by simulation scenario

Based on the metrics defined above the performance evaluation results (see Figure 6) represent end-to-end delay and node delay for all three data flows of the simulation scenario defined above. 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 node to D_2 secondary node (see Figure 5), includes a higher number of hops, as well as a redirection process is occurred.

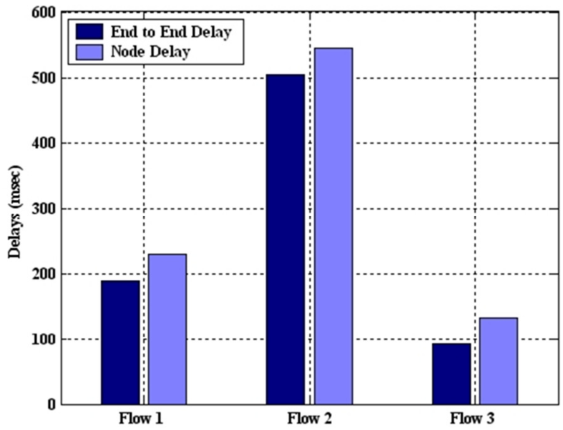

Fig. 6. End-to-End Delay and Node Delay of data flows

V. CONCLUSIONS

This paper discussed a routing protocol for a public safety application scenario that exploits TVWS under the "Spectrum of Commons" regime. It elaborated on the design of a routing protocol, which coordinates data flows among secondary public safety 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 adopted by intermediate mesh routers and 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 public safety secondary nodes 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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REFERENCES

[1] Shared Spectrum Company. New York City Spectrum Occupancy Measurements September 2004.

[2] The Economics of Spectrum management: A Review, Australian Communication and Media Authority (ACMA), 2007.

[3] J. Mitola III and G. Q. Maguire, "Cognitive Radio: Making Software Defined Radio More Personal," IEEE Pers. Commun., vol. 6, no. 4, Aug. 1999.

[4] A. Wyglynski, M. Nekovee, and T. Hou, Eds., Cognitive Radio Communications and Networks: Principles and Practice, Academic Press, 2009.

[5] R. W. Thomas, L. A. DaSilva, A. B MacKenzie, "Cognitive Networks", IEEE DySPAN, First Symposium on Dynamic Access Networks, Baltimore USA, 8-11 November 2005.

[6] A. Bourdena, E. Pallis, G. Kormentzas, C. Skianis, G. Mastorakis, "Real-Time TVWS Trading Based on a Centralised CR Network Architecture", in Proc. IEEE Globecom2011, IEEE International Workshop on Recent Advances in Cognitive Communications and Networking, Texas, Houston, USA, 05-09 December, 2011, pp. 964-969.

[7] E. Hossain, D. Niyato, Z. Han, "Dynamic spectrum access and management in cognitive radio networks", first ed. Cambridge University Press, 2009.

[8] COGEU D6.2: Spectrum-aware routing, transport protocols and negotiation protocols between players for secondary spectrum trading , Initial specification, available on: http://www.ict-cogeu.eu/pdf/COGEU_D6.2%20%20(ICT_248560).pdf

[9] C. E. Perkins, E. M. Royer, "Ad hoc on-demand distance vector routing". In: Proc. of IEEE workshop on mobile computing systems and applications, New Orleans, LA.

[10] H. Ma, L. Zheng, X. Ma, Y. luo, Spectrum aware routing for multi-hop cognitive radio networks with a single transceiver, in: 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom 2008, 2008, pp. 1–6, doi: 10.1109/CROWNCOM.2008.4562509.

[11] G. Cheng, W. Liu, Y. Li, W. Cheng, Spectrum aware on-demand routing in cognitive radio networks, in: 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2007, 2007, pp. 571–574, doi: 10.1109/ DYSPAN.2007.80.

[12] G. Cheng, W. Liu, Y. Li, W. Cheng, Joint on-demand routing and spectrum assignment in cognitive radio networks, in: IEEE International Conference on Communications, ICC '07, 2007, pp. 6499–6503, doi: 10.1109/ICC.2007.1075.

[13] Z. Yang, G. Cheng, W. Liu, W. Yuan, W. Cheng, Local coordination based routing and spectrum assignment in multi-hop cognitive radio networks, Mobile Networks and Applications 13 (1-2) (2008) 67–81. doi: 10.1007/s11036-008-0025-9.

[14] D. G. Kendall, "Stochastic Processes Occurring in the Theory of Queues and their Analysis by the Method of the Imbedded Markov Chain". Annals of Mathematical Statistics 24 (3): 338–354. doi:10.1214/aoms/1177728975. JSTOR 2236285.

[15] J. Van den Berg, F. Roijers, M. Mandjes (2006) Performance modeling of a bottleneck node in an IEEE 802.11 Ad-hoc network. In: The 5th International Conference on Ad hoc Networks and Wireless, Ottawa, August 2006

[16] V. B. Iversen, Teletraffic Engineering Handbook, http://www.tele.dtu.dk/teletraffic/handbook/telehook.pdf

[17] J. Roberts, Traffic Theory and the Internet, IEEE Communications Magazine, Jan. 2001, pp. 94-99 http://perso.rd.francetelecom.fr/roberts/Pub/Rob01.pdf