An energy-efficient routing protocol for ad-hoc cognitive radio networks

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Abstract: This paper proposes a routing protocol enriched with an assigning mechanism and a capacity-aware scheme, enabling for efficient data flow coordination and energy conservation, among networking nodes with heterogeneous radio spectrum availability in ad-hoc cognitive radio networks. The proposed assigning mechanism is able to effectively determine efficient routing paths in a distributed networking architecture, designed based on a simulation scenario, where networking nodes operate over television white spaces (TVWS). The main target of routing in this simulation scenario is to provide optimal, high throughput data transfer, by efficiently selecting the best routing paths. Towards enabling Energy-Efficiency in the proposed research approach, a Backward Traffic Difference (BTD) estimation methodology is exploited. The novelty adopted in the proposed capacity-aware scheme arises by the ability to utilize different assignments of sleep-wake schedules, depending on different incoming traffic that each networking node receives through time. The validity of the proposed energy efficient routing protocol is verified, by conducting experimental simulations and obtaining performance evaluation results. Simulation results validate routing protocol efficiency for minimizing energy consumption, maximizing resources exchange between networking nodes and minimizing routing delays in ad-hoc cognitive radio networks.

Keywords: Cognitive Radio; Routing Protocols; TVWS; Energy Conservation.

1. Introduction and research motivation

Cognitive Radio (CR) networks [1] constitute an imminent telecommunications paradigm that enables for the efficient exploitation of radio spectrum resources and the deployment of future sophisticated wireless systems. CR technology is comprised of networking nodes, capable to adapt their physical layer characteristics, based on interactions with the surrounding spectral environment. This capability opens up the possibility to design novel radio spectrum access policies, towards opportunistically reuse under-utilized frequency bands at local level, such as "television white spaces" (TVWS) [2]. TVWS include portions of VHF/UHF radio spectrum, mainly resulted by analogue to digital terrestrial television switchover process, or by completely under-utilized channels due to frequency planning principles ("Interleaved Spectrum") [3], [4], [5]. The flexibility in radio spectrum access phase by CR networks introduces new challenges regarding the design of communication protocols at different layers. More specifically, the design and adoption of efficient routing schemes is vital, since CR networks are characterized by completely self-configuring architectures [6], where spectrum availability highly depends on "primary" networking nodes presence. It is therefore difficult to exploit a Common Control Channel (CCC), towards establishing and maintaining a fixed routing path among "secondary" networking nodes. Furthermore, energy conservation figures a vital aspect for the high performance deployment of CR networks. On one hand, an energy conservation scheme has to be reactive so that the energy levels of networking nodes will be tuned, according to the estimated parameters (i.e. capacity, traffic [7] of the nodes). On the other hand, an energy-efficient scheme has to take into consideration the bounded end-to-end delays of the transmissions.

Conventional routing algorithms exploited in wireless ad-hoc networks, enable for the optimization of network performance metrics, such as end to end delay, switching delay and backoff delay. A rich literature on conventional routing protocols is available based on network-wide broadcast messages, without using any local hops information, towards improving the choice of optimum routing paths. Such approaches are not suited for wireless CR networks, since there is no support for jointly considering radio spectrum availability of "secondary" networking nodes, as well as the effect on other "primary" nodes that share spectrum resources. In a general context, several research approaches have been recently proposed in [8], [9], [10], [11], towards addressing routing issues in CR networking environments. On the other hand, although there are many schemes developed addressing different energy conservation methodologies, the combination of a traffic-aware scheduling scheme with a routing protocol supported by CR networking architectures, has not yet been explored. The latter poses a fertile ground for the development of new approaches with the association of different parameters of communication mechanisms, in order to reduce energy consumption. Mavromoustakis et al. in [12] considers the association of energy conservation problem with different parameterized aspects of the traffic (e.g. traffic prioritization) and enables a mechanism that tunes the interfaces scheduler to sprawl in the sleep state, according to the activity of the traffic of a certain node in the end to-end path in real-time. The scheme takes into consideration the repetition pattern of the traffic, as well as the delay limitation (bounded delay) of each transmission. The proposed scheme then estimates the Backward Traffic Difference for extracting the time duration for which the nodes are allowed to sleep. This mechanism, uses promiscuous caching [13] in an opportunistic manner, to cache the packets destined for the node with turned-off interfaces (sleep state) onto intermediate nodes.

In this context, this paper elaborates on the design, development and performance evaluation of an energy efficient routing protocol for ad-hoc CR network architectures, enabling for the effective communication of "secondary" networking nodes. More specifically, an assigning mechanism combined with an energy efficient scheme is proposed, based on the Backward Traffic Difference estimation [7], [13], [14] in contrast to the end-to-end bounded delay of the transmission. Based on the underlying routing scheme and the volume of traffic that each node receives/transmits, the proposed scheme aims at minimizing the energy consumption, by applying asynchronous, non-periodic sleep-time assignment slot to the secondary wireless nodes. Following this introductory section, Section 2 elaborates on the design and presentation of the proposed routing protocol, enabling for energy-efficient data transition, across "secondary" networking nodes with heterogeneous TVWS availability. Section 3 presents the performance evaluation analysis of the proposed research approach, discussing experimental results and section 4 concludes this paper, by highlighting fields for future research.

2. Energy efficient routing protocol using backward traffic difference estimation

The transmission of "secondary" networking nodes in an ad-hoc CR network is based on radio spectrum opportunity, where routing protocols have to consider the availability of wireless network resources in specific geographical locations. Spectrum awareness, route quality and route maintenance issues are vital to be investigated for different routing schemes, towards enabling for efficient data transfer, across regions with heterogeneous radio spectrum availability. Figure 1 illustrates a simulation scenario, where primary systems base stations operate over specific channels in three geographical areas (i.e. Area A, B and C in Figure 1). Secondary systems base stations opportunistically operate, by utilizing remaining available channels in each geographical area (i.e. TVWS in Figure 1). It has to be noted here that a stable/permanent CCC does not exist between secondary systems base stations, which are located in neighboring geographical areas (i.e. Area A, B and C in Figure 1). In this case, all secondary systems base stations operate as intermediate relay nodes, switching between alternative channels. Therefore, such relay nodes enable for ad-hoc connections among "secondary" nodes, located inside areas A, B and C.

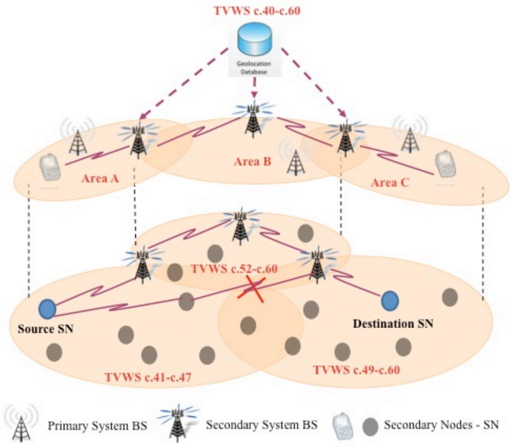

Figure 1: Secondary networking nodes operating over heterogeneous TVWS.

Taking into account this simulation scenario, spectrum awareness and new routing schemes have to be investigated, where "secondary" networking nodes are prohibited to operate on spectrum bands occupied by "primary" networking nodes. The main target of routing in this CR networking environment is to provide optimal, high throughput data transfer by efficiently selecting the best routing paths, among "secondary" networking nodes. Thus, multi-hop connections must be set up between 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" networking nodes behaviour. Furthermore, route maintenance is a vital challenge considering the above mentioned simulation scenario. The unpredictable appearance of a "primary" networking 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.

2.1 – Optimized Signalling Routing Mechanism

Towards enabling for an efficient data transition between source and destination "secondary" networking nodes in the above mentioned simulation scenario, an optimized version of the routing protocol proposed in [15], [16] was designed, implemented and evaluated under controlled simulation conditions. The new version of the proposed routing protocol is based on the exchange of AODV-style messages [17] between "secondary" networking nodes, including two major steps (i.e. route discovery and route reply). During the route discovery step, a RREQ (route request) message, including TVWS availability 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. The proposed assigning mechanism (see *Figure 2*) aims to alleviate the service load of intermediate nodes that are further able to determine if a neighbor node performs better in the routing path. For this scope, the message exchange process of the proposed routing protocol in [15], [16] has been modified/enhanced (see *Figure 2*), in order to consider the new feature of the assigning mechanism.

In this context, when a source node initializes a new flow by sending a RREQ, the intermediate node is informed regarding neighborhood status from geo-location database. It has to be noted here that the proposed approach adopts a protocol (PAWS – Protocol to Access White Spaces Database) [18], which is able to establish efficient and safe communication among geo-location database with secondary nodes. This protocol enables for the support of registration, channel list requests and ID verification of white space devices (e.g. secondary nodes) with geo-location data base. Intermediate node then collects information exploiting PAWS, in order to evaluate the new flow (i.e. performance metrics) and encapsulates the evaluation result in a message that is forwarded to all neighboring nodes, instead of adopting the process proposed in the initial version of routing protocol [15], [16]. This message is the redirecting request signal in *Figure 2*. Once the neighboring nodes receive a redirecting request, they check its validity with the corresponding flow, ensuring that they are not the source/destination nodes or next-hop nodes of that flow.

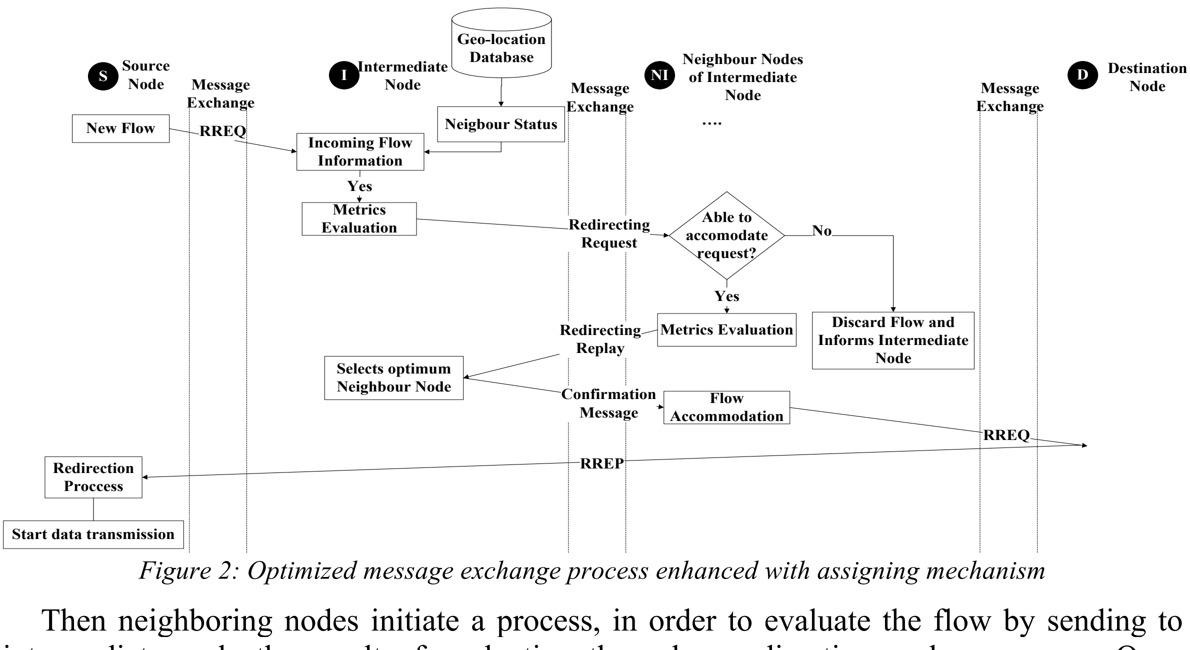

Figure 2: Optimized message exchange process enhanced with assigning mechanism

Then neighboring nodes initiate a process, in order to evaluate the flow by sending to intermediate node the result of evaluation through a redirecting replay message. Once intermediate node receives such reply, it then selects the optimum one, towards serving the incoming flow. Finally, the intermediate node generates a RREP message, in order to inform source node regarding the new candidate intermediate node, while it also sends a confirmation message to the new intermediate node informing that it is chosen to handle the flow. On the side of the source node, once receiving the RREP, it changes the next-hop node and starts data transmission. Also, the enhanced routing protocol in *Figure 2* determines and maintains routes only if it is necessary, on a demand basis, as long as a source node wishes to send a data flow to a destination node. Routing tables are used in order to maintain possible routes, containing information, regarding destination nodes, next hop, number of hops, destination sequence number, active neighboring nodes for this route and expiration time of flow. In the same manner, as it was described in the initial version of routing protocol, the number of RREQ messages carries a time to live (TTL) value that specifies the number of times this message should be re-broadcasted from source node to next hop. This value is set to a predefined value at the first transmission and increased during retransmissions, which occur if no replies are received. In addition, towards enabling Energy-Efficiency in the proposed routing protocol a Backward Traffic Difference (BTD) estimation [12] methodology is exploited. The main additional contribution is that, in the proposed research approach, BTD estimation is bounded by delay limitations of transmission, whereas it considers hop-by-hop link delay, as well as total end-to-end delay of the transmission, where the later should satisfy delay requirements of transmission. In this respect, End-to-End availability of requested resources is guaranteed, while Energy Consumption is significantly reduced and requested scheduled transfers are maintained. Novelty of this scheme is resulted by the ability of each "secondary" node to utilize different assignment(s) of sleep-wake schedules, which depend on different incoming traffic that each node receives through time. Sleep-time duration is assigned according to the BTD scheme in a dissimilar manner, in order to increase nodes lifetime, whereas it avoids mutation, which will result in network partitioning and resource sharing losses.

2.2 –Backward traffic estimation for energy-efficient transmission

The proposed traffic-based scheme is focusing on traffic that is incoming for each node and for a specific time-window *T*. Each node exploits the proposed scheme separately by running the traffic-aware mechanism, using Backward Traffic Difference (BTD). More specifically, the mechanism measures incoming traffic that traverses each node, on a hop-by-hop manner from one to another, until it reaches destination and estimates Sleep-time duration of node, according to the Backward Traffic Difference (BTD) using a specific window frame-size *T*. In case that the node is available and in Active-state for time *t*, it receives the transfer (for example file) whereas, if the node receiving the file is not the destination, it forwards the packet to the destination node via other neighbouring hop-nodes in the path. Alternatively, if the transmission is delayed (i.e. next hop-node is not available) with $d_t > t_{active}$, where t_{active} is active time duration of wireless nodal interface, then nodes may set their interfaces to an Energy Conservation state (Sleep-state), therefore the scheme enables promiscuous caching [13] of the transmitted packet occurs in the path, in order to keep packets in a buffer until to reach destination node. Towards enabling Energy Conservation, as well as greater associativity with the self-similar behaviour expressed in [13], [12], traffic and the monofractal characteristics [13], were considered for a certain time-frame t_w. In this work we consider the window to be

$$t_w(s,d) = \{\lim_{t \to k \cdot t} F_{n(t)} \in t(s,d) : R_N(t) \approx R_N(t - k\tau) \forall k < 2\} \quad (1)$$

where $t_w(s,d)$ is the time window measure for the multipath pair source-destination model and where the limit of it should be bounded into $k\tau$ time duration for the determined window size. k should be less than 2 in order to satisfy the monofractality property of the repetition index $R_N(t)$ of the incoming traffic [13].

The BTD estimation enables the capacity of the traffic $C(t)$ that is destined for the Node i in the time slot (duration) t, and the traffic capacity $C_{N_i(t)}$ which is cached onto *Node (i-1)* for time t, to directly affect the Sleep-time of a node. The one-level Backward Difference of the Traffic is evaluated by estimating the difference of the traffic while the *Node(i)* is set in the Sleep-state for a period, as follows:

$$\begin{aligned} &\nabla C_{N_i(1)} = T_2(\tau) - T_1(\tau-1) \\ &\nabla C_{N_i(2)} = T_3(\tau-1) - T_2(\tau-2) \\ &\vdots \\ &\nabla C_{N_i(n+1)} = T_n(\tau-(n-1)) - T_2(\tau-(n-2)) \end{aligned} \tag{2}$$

where $\nabla C_{N_i(1)}$ denotes the first moment traffic/capacity difference that is destined for *Node(i)* and it is cached onto Node (i-1) for time τ, $T_2(\tau) - T_1(\tau-1)$ is the estimated traffic difference while packets are being cached onto *(i-1)* hop for recoverability as in [12].The Traffic Difference is estimated so that the next Sleep-time duration can be directly affected according to the following:

$$\delta(C(T)) = C_{total} - C_1, \forall C_{total} > C_1, T \in \{\tau-1, \tau\} \tag{3}$$

where the Traffic that is destined for *Node(i)*, urges the Node to remain active for $\frac{\delta(C(T))}{C_{total}} \cdot T_{prev} > 0$, T_{prev} is the previous Sleep-time duration ($\{\tau-1,\tau\}$) of the node. On the contrary with [1], [4] this work measures the BTD within a certain transmission time-frame. This means that each transmission is bounded by a certain delay limitation (time-duration $t_w(s,d)$) which cannot be overtaken. When a node receives traffic, the traffic flow t_f, can be modelled as a stochastic process [12], [19] and denoted in a cumulative arrival form as $A_{t_f} = \{A_{t_f}(T)\}_{T\in N}$, where $A_{t_f}(T)$ represents the cumulative amount of traffic arrivals in the time space [0..T]. Then, the $A_{t_f}(s,T) = A_{t_f}(T) - A_{t_f}(s)$, denotes the amount of traffic arriving in time interval (*s, t*]. Hence the next Sleep-time duration for *Node (i)* can be evaluated as a function of the Traffic that traverses the *Node (i)* provided that the amount of traffic arriving in time interval (*s, t*] is measured according to the total aggregated Traffic/Capacity that the channel can handle at time t. The next Sleep-time duration for *Node (i)* can be defined as:

$$L_i(n+1) = \frac{\delta(C(T) \mid A_{t_f}(s,T))}{C_{total}} \cdot T_{prev}, \forall \delta(C(T)) > 0,\ t_w(s,d) < 2\frac{\delta_{ij}}{\Delta_{\max}} \tag{4}$$

where δ_{ij} is the delay that the transmission experiences to reach destination j, $\Delta_{\max}$ is the max allowed delay-duration that the transmission cannot overtake. The aggregated traffic destined for *Node (i)* should satisfy the $\sup_{s\le T}\left\{\sum_{t_f=1}^{N} A_{t_f}(s,T) - C_{t_f}(T)\right\}$, for traffic flow t_f at time T and $C_{t_f}(T)$ represents the service capacity of the *Node(i-1)* for this time duration. Taking into consideration the above stochastic estimations, the Energy Efficiency EE_{t_f} can be defined as a measure of the capacity of the *Node(i)* over the *Total Power consumed* by the *Node*, as showen in equation 5, that define the primary metric for the lifespan extensibility of the wireless node in the system.:

$$EE_{t_f}(T) = \frac{C_{t_f}(T)}{TotalPower} \tag{5}$$

3. Performance evaluation analysis, experimental results and discussion

Towards verifying the proposed research approach, an urban area of Munich City in Germany (2.2Km x 2.2Km), was selected, as it is depicted in Figure 3 (a), where 50 "secondary" networking nodes are randomly scattered with different TVWS availability, based on measurements performed in [20] populating Geo-location database [21]. "Secondary" networking nodes (i.e. wireless mesh routers) located in this geographical area are possible to act as intermediate nodes, as well as to operate opportunistically utilizing the vacant TV channels, while the remaining channels are dedicated for usage by "primary" networking nodes. Such a mesh-based network incorporates the proposed routing protocol enhanced with an assigning mechanism that enables to determine routing paths between "secondary" networking nodes with different TVWS availability. Nodes in this network have sensing capabilities and are connected with a Geo-location database that includes TVWS availability for all geographical locations. Available TVWS in the area of Munich, based on Geo-location database, vary from one to three, creating inconsistency of spectrum opportunities among "secondary" networking nodes. More specifically, the available TVWS in this location are channels 57, 59 and 60 based on measurements conducted under the framework of COGEU project [21].

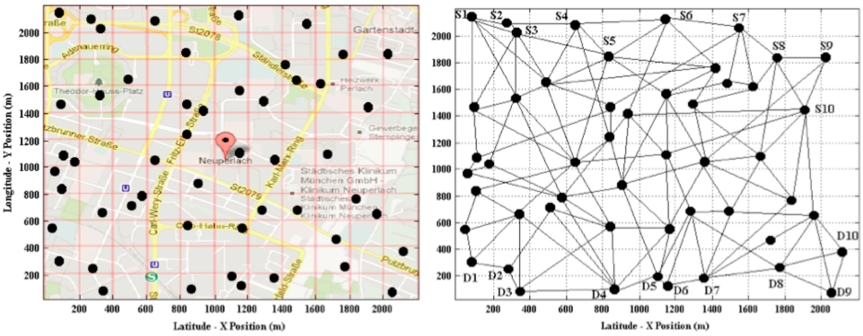

Figure 3: (a) Munich urban-area with secondary network nodes operating over TVWS, (b) Mesh network topology of Munich urban-area

The evaluation topology is shown in Figure 3 (b), where source nodes are on the top and the destination nodes are on the bottom of this networking infrastructure. Pairs nodes from S1 − D1 (source node 1 – destination node 1) to S10 – D10 (source node 10 – destination node 10) represent the concurrent data flows that are initiated in this simulation scenario, in order to evaluate the proposed routing protocol under a heavy load. Experimental simulations are conducted, based on both the previous version of the proposed routing protocol (version presented in [15], [16]), and the version presented in this paper that is enhanced with the assigning mechanism, in order to quantify the evaluation performance. In this context, the experimental tests conducted, evaluate the nodes queue as the load is increasing, considering queuing delay that affect the routing path. Also, a number of delay metrics [22], [23], are compared based on the number of active flows in the simulation area and the activation probability of an idle Primary System. Such delays are the end-to-end delay, backoff delay and switching delay. Finally, the proposed protocol is evaluated, considering the lifespan of "secondary" networking nodes in the transmission path and the fraction of the remaining energy compared with different Energy Conservation schemes.

Towards evaluating nodes queue, a queuing system was set up, exploiting a M/M/1/K Kendall model [24], 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 [25]. The performance evaluation results represent losses rate (see Figure 4 (a)) and mean queuing delay (see Figure 4 (b)), for differed service rate values (i.e. load). It can be observed that both losses rate and queuing delay are increasing when service rate is varied from 0.05 up to 0.45, validating the proper operation of intermediate nodes buffers when the M/M/1/K Kendall model is adopted. The new version of the proposed routing protocol that adopts the assigning mechanism mitigates the service load of intermediate nodes, resulting a routing path that performs better compared to the initial version of the protocol [15], [16].

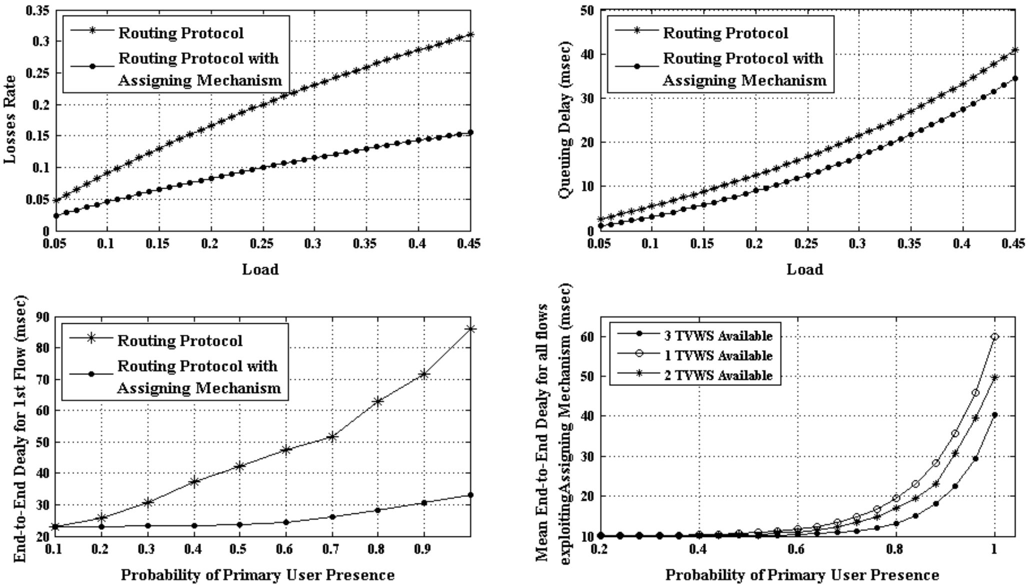

Figure 4: (a) Losses Rate in nodes queues, (b) Queuing Delay in nodes queues, (c) End-to-End Delay for the 1st flow and (d) Mean End-to-End Delay for different TVWS availability versus probability of PU presence

Figure 4 (c) shows simulation results of End-to-End Delay of one flow (i.e. 1st flow S1-D1) when the probability of "primary" networking nodes (i.e. primary user in Figure 4 (c)) presence increases. This figure presents that, as the probability of primary users' presence is getting higher, delay is increasing, while in the initial version of routing protocol, delay increase is more significant. This result is reasonable, since the probability of the presence of an incumbent system is detected as a route failure of the flow, introducing in this way additional delay. Moreover, it is observed that the probability of a primary user presence, affects significant routing procedure in this scenario, as the available TVWS are only 3. This makes difficult to obtain links between secondary intermediate nodes. Therefore, the possible routing paths are high, as the topology of the node is a mesh network, and the assigning mechanism of each node requires enough time to compute delays of all possible routing paths. Moreover, in Figure 4 (d), mean delay is depicted (i.e. for ten concurrent data flows) for different TVWS availability [21], utilizing in all cases the enhanced version of the proposed routing protocol, incorporating the assigning mechanism. In this simulation test, as the number of the available TVWS is getting lower, delays are increasing. It has to be noted here that when the number of primary users is increasing, secondary nodes transmission power has to decrease. This decrease enables secondary nodes to avoid causing possible interference to primary users. However, such limitation affects the efficient secondary nodes operation (i.e. mean End-to-End Delay is increasing), even though the same number of TVWS is available.

Moreover, Figure 5 (a) shows simulation results and performance comparison of mean End-to-End Delay while the number of active flows is increasing. It is clear that when routing protocol incorporates the assigning mechanism, heavy service load is distributed around every intermediate node. It has to be noted here that when the number of active flows in the network is small, assigning mechanism does not show much advantage, since queuing system is just formed or the load is not heavy enough to launch the flow redirection. However, when the number of active flows exceeds 3, intermediate nodes begin to suffer the accumulating queue, and from then on the flow redirection becomes necessary. Also, Figure 5 (b) shows comparison among both versions of routing protocol, under the number of hops that are required, in order to make feasible all paths between the source and the destination nodes, for each flow set. This comparison results that routing protocol, incorporating assigning mechanism performs better. Furthermore, Figure 5 (c) illustrates lifespan of "secondary" networking nodes in transmission path in contrast to the number of hops. The proposed scheme is compared with existing similar schemes [26], showing significant increment in lifespan extensibility, particularly when the number of hops increases. Comparative evaluation illustrates that the proposed routing protocol with assigning mechanism behaves gradually better, and increases lifespan of each "secondary" networking node. The proposed scheme is also compared with other existing schemes, in terms of remaining energy dissipation of each secondary node. Figure 5 (d) shows the fraction of the remaining energy compared with different EC schemes. In the case of periodic sleep and wake methodology, fraction of remaining energy is dramatically dropped whereas, using traffic-aware sleep-scheduling in contrast to the limitations of delay bounds, the scheme offers gradual consolidation of the reduction of nodes remaining energy.

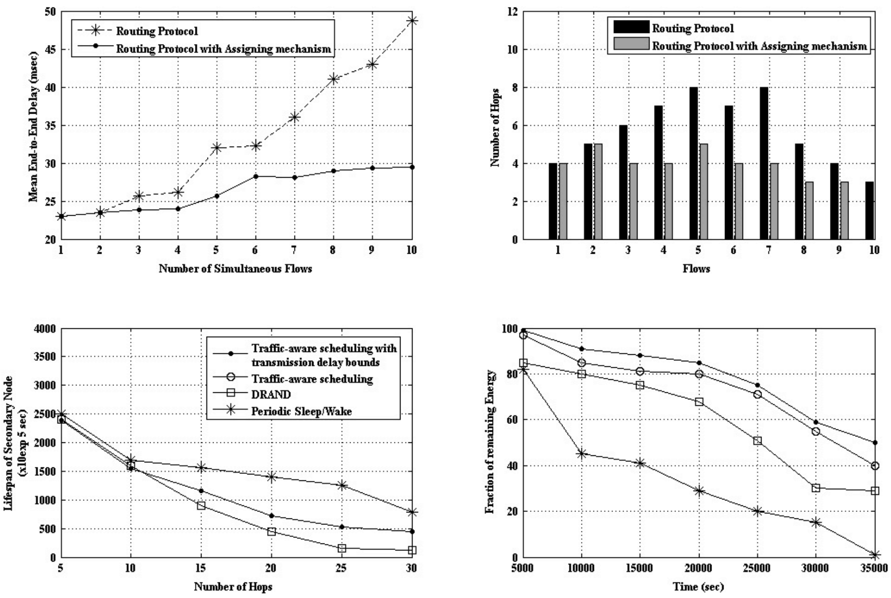

Figure 5: (a) Mean End-to-End Delay for different number of simultaneous flows, (b) Number of Hops per each flow, (c) Network Lifetime and (d) Remaining Energy of each secondary node in the CR system.

4. Conclusions

This paper proposes an enhanced version of a spectrum aware routing protocol for ad-hoc CR networks, adopting two new features. The first one is an assigning mechanism for optimum selection of routing paths and the second one is a BTD scheme that enables energy conservation and reliable data flow among "secondary" networking nodes in a CR networking architecture. The proposed routing protocol establishes an End-to-End optimal path, whereas "secondary" networking nodes can efficiently and, in a collaborative manner, share requested data/resources. Performance evaluation through simulations shows that the proposed routing protocol in collaboration with the assigning mechanism and the BTD mechanism, efficiently coordinates data transfer among "secondary" nodes, operating over TVWS, as well as effectively manipulates their energy consumption. Obtained experimental results verified the validity of the proposed routing protocol, towards enabling for efficient communication between "secondary" nodes located in areas with different TVWS availability. Fields for future research include evaluation, considering performance metrics, such as useful throughput and route stability. Additionally, different optimization methods will be investigated and adopted, towards minimizing delays, occurred during the transition of data flows and maximizing the number of established routing paths.

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