Maximizing Energy Conservation in a Centralized Cognitive Radio Network Architecture

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Abstract-**This paper proposes two energy-aware algorithms exploited for optimal resources administration and maximum energy conservation of secondary communication nodes in a centralized cognitive radio network architecture. The proposed algorithms optimally enable efficient TV White Spaces exploitation, through a radio spectrum broker that administrates the resources trading process, based on real-time secondary spectrum market policy. In addition, both algorithms adopt a joint path lifetime and utility maximization scheme, which encompasses a capacity-aware policy for achieving minimum energy consumption and reliability during the resource sharing process. Validity of both algorithms is verified through several sets of extended experimental/simulation tests, carried out under controlled conditions.**

Keywords: Energy-Efficient Algorithms, Radio Resource Management, Cognitive Radio Networks, TV White Spaces

I. INTRODUCTION

Increasing demand for ubiquitous multimedia services provision over mobile computing systems, results to higher radio spectrum needs and creates new challenges in wireless networks resources management. Several radio spectrum exploitation studies verify that a large number of licensed spectrum units is under-utilised [1] and considerable parts of it, such as TV White Spaces (TVWS) are available in specific geographical locations. TVWS consists of VHF/UHF channels that are released after the process of digital terrestrial television switchover, as well as interleaved channels, which are available due to frequency planning issues [2]. Such parts of radio spectrum (i.e. TVWS) are suitable for the deployment of future mobile computing systems (e.g. LTE-Advanced networks [3]), towards providing ubiquitous multimedia based content and services. TVWS can be efficiently exploited based on the real time secondary spectrum market (i.e. RTSSM) policy [4], as the most suitable solution particularly for secondary communication systems deployment, requiring access to radio spectrum with high QoS requirements. RTSSM policy permits primary communication systems (i.e. licensed spectrum holders) to trade rights of radio spectrum access with other secondary communication systems, towards establishing secondary spectrum trading markets. In such cases, primary systems adopt admission control algorithms to permit secondary systems accessing radio spectrum, only when QoS is satisfactory. Spectrum trading markets among primary and secondary communication systems can be established, exploiting a radio spectrum broker, as well as radio resource management (RRM) algorithms [5], [6] in order to optimally administrate TVWS trading processes [7], [8]. This approach enables secondary systems for dynamically requesting access to TVWS only when radio spectrum is needed. TVWS usage is then charged based on a channel utilization basis, as a matter of access characteristics, provided services types and QoS priority level requirements [9], [10]. In this context, an important enabler towards deployment of LTE-Advanced systems over TVWS is Cognitive Radio (CR) technology [11], [12], by using centralized network architectures [13]. Such CR network architectures effectively enable for radio spectrum exploitation, towards increasing income of spectrum suppliers (e.g. primary communication systems or spectrum brokers).

Moreover, as wireless devices have finite capacity on their energy storages, there is a need for data and bandwidth-aware configuration, in order to provide energy efficient communication [14], [15]. The network lifetime comprises of a critical design issue for uninterrupted information flow in CR network architectures. CR nodes are draining to the less the available energy, by using -on a continuous basis- their communication interfaces to exchange resources with other nodes. In addition, CR nodes operate on limited energy resources, whereas the replacement or recharging of these nodes is rarely feasible. The fact that mobile devices change in time their location, there is no guaranteed QoS level during the resource exchange process, resulting to significant reduction on the performance responsiveness, under such conditions. Energy harvesting is important to be applied for CR systems, where network partition can frequently occur, since nodes move freely. As energy conservation poses an important trade-off for high performance deployment in CR networks, the supporting energy efficient schemes have to be reactive so that energy levels of wireless nodes will be tuned, according to associated parameters (i.e. capacity, traffic [15], [17] and remaining supporting energy of the nodes).

In this context, this paper is making progress beyond the current state-of-the-art, by proposing two energy-efficient RRM algorithms for optimum TVWS exploitation and maximum energy conservation through the Path Lifetime Maximization (SPLM) scheme, over a centralised CR network architecture. Operation of such network architecture, energy-efficient control issues, as well as optimal TVWS management, are orchestrated via a spectrum broker. Following this introductory section, section 2 discusses the design of a spectrum broker, incorporated into an energy-efficient CR network architecture and presents both the proposed algorithms. Section 3 elaborates on performance evaluation providing and discussing simulation results, while section 4 concludes the paper, by identifying fields for future research.

II. ENERGY-EFFICIENT SPECTRUM ALLOCATION ALGORITHMS

This section presents a broker-based CR network architecture for efficient TVWS exploitation, under the RTSSM policy. The overall network architecture is depicted in Figure 1, comprising of a spectrum broker that coordinates TVWS management, a number of LTE based secondary systems, as well as of a Geo-location database. An energy controller, incorporated in spectrum broker is responsible to assign energy-efficient paths to Secondary Nodes (SNs) resource exchange requests. This is measured through SPLM model, which is evaluated, by each secondary subsystem energy module, in order to conserve energy, allocating optimal energy-aware path, either through RRM module or utilizing a peer-to-peer resource exchange process.

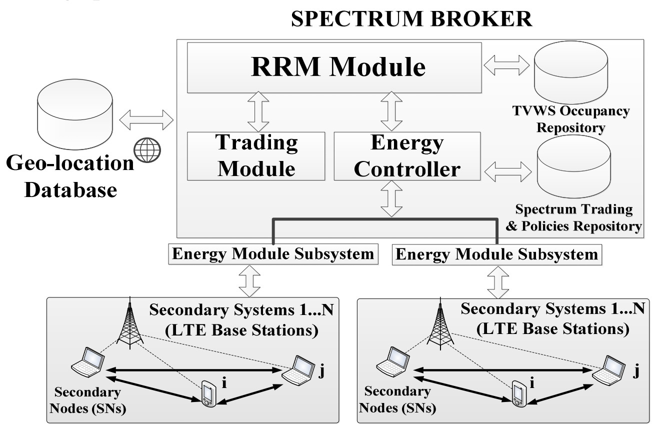

Fig. 1. Broker-based cognitive radio network architecture

An optimised solution is feasible to be achieved, by enabling spectrum broker to assign TVWS to secondary systems. Choice of optimal solution can be obtained based on an optimization procedure [18], aiming either to decrease spectrum fragmentation, avoiding small ineffective "chunks" of spectrum that minimise spectrum utilization (i.e. fixed-price algorithm in Table 1) or to maximise spectrum broker profit (i.e. auction-based algorithm in Table 2), by collecting bids from secondary systems and subsequently determine allocation solution along with price for each spectrum portion.

TABLE 1: FIXED-PRICE ALGORITHM PSEUDO-CODE

1: **Inputs:** $TVWS_{pool}$, Location(x,y), $Power_{max}$, $Demand_{SS}$
2: Update TVWS repository from Geo-location database
3: Estimate the spectrum-unit price
4: Create and advertise price-portfolio
5: Set m the number of slots //Slot named the combination of time and frequency domains
6: Receive secondary systems request R= $\{R_1,\ldots, R_I\}$, where $R_i = \{x_i, t_i\}$
7: **for** all Requests **do**
8: Sort R_i in descending order based on priority and update the price-portfolio
9: **end for**
10: Calculate the minimum fragmentation (Frag(i,f)) for all secondary system requests
11: Create initial solution S
12:for i =1 to m **do //** Iteration process in order to find the best solution
13: Generate a new solution S_i
14: **if** (Objective_function(S) ≤ Objective_function(S_i))
15: **then** save the new allocation solution S_i to best found S
16: **end if**
17: **end for**
18: **find a path** T_{SPLM_i} with $\min(T_R, T_{i\to j})$
19: if $T_R < T_{i\to j}$ and $B_{i\to j} \le B_R$
20: **estimate** $\arg\max_{\delta_{ij}<d_p} \Theta(t_s)\big|T_i\ \forall \min(T_R, T_{i\to j}), \max\sum_{r\in R} U_r(\chi_r)\forall A_\chi \le C$
21: **allocate** S_i for $t_s, \forall t < S_i(t)$
22: **return** Best Allocation Solution

TABLE 2: AUCTION-BASED ALGORITHM PSEUDO-CODE

1: **Inputs:** $TVWS_{pool}$, Location(x,y), $Power_{max}$, $Demand_{SS}$
2: Update TVWS repository from Geo-location database
3: Estimate the spectrum-unit price
4: Create and advertise price-portfolio
5: Receive secondary systems bids $P^{(b)} = \{P_1^{(b)},\ldots, P_I^{(b)}\}$, where $P_i^{(b)} = \{x_i, t_i\}$
6: **for** all Bids **do**
7: Sort $P_i^{(b)}$ in descending order based on price and create the auction-portfolio
8: **end for**
9: Calculate the highest valuation S[i,s] for all TVWS slots (i,s) ∍ {1, 2,…, m}
10: set $S_{optimal}$ = S[i,s] //Random solution for algorithm initiation
11: **for** slot =1 to m **do** //Iteration process in order to find the best solution
12: **if** (S[i,s]) ≤ (S[i+1, s+1]) // Check if the current solution is better or not to the neighbor solution
13: **then** save the new allocation solution (S[i+1, s+1]) to the best found
14: **end if**
15: **end for**
16:**find a path** T_{SPLM_i} with $\min(T_R, T_{i\to j})$
17: if $T_R < T_{i\to j}$ and $B_{i\to j} \le B_R$
18: **estimate** $\arg\max_{\delta_{ij}<d_p} \Theta(t_s)\big|T_i\ \forall \min(T_R, T_{i\to j}), \max\sum_{r\in R} U_r(\chi_r)\forall A_\chi \le C$
19: **allocate** S_i for $t_s, \forall t < S_i(t)$
20: return Best Solution

This work elaborates on the exploration of the energy energy-efficient path in secondary wireless nodes, using Energy Module Subsystem as shown in Figure 1. The scenario used utilises Secondary Nodes (SNs) deployed in a certain geographic area. SNs are recipients of a common broadcasting resource exchange S application for which, there is a time transfer limitation that is bounded within $t_1 < S_i(t) < t_2$. SNs terminals are able to simultaneously access multiple heterogeneous wireless networks. The multi-radio access scenario used in this work utilises a resource exchange policy in which, SNs can download and upload streams, according to the temporally (time-oriented) assigned bandwidth. Each SN can access multiple SNs and transfer simultaneously requested contents through parallel transmission [15]. In case of fading characteristics, the instantaneous Channel State Information (CSI) synchronises states of each channel and updates information periodically in presence of feedback collaboration and provision among channels. The proposed system comprises of a model, which considers the above configuration, using the SNs and CR technology through the spectrum broker (i.e. Figure 1). SNs are contiguously requesting (at no regular intervals) delay constrained/sensitive resources/data, which is demanded within a specified amount of time, otherwise they will be rejected. In this work, M devices of SNs type are used, requesting delay sensitive and transmission bounded delay services; and R Cognitive Radio Access Technology terminals (R<N) are set (i.e. LTE Base station(s)). The main objective is to find the transmission power allocation of cooperative SNs, which can maximise their lifetime. In a general context, for a wireless network, the network lifetime is defined as the time when the first node is depleted with energy [15]. If residual energy and transmission power consumption of node i in the set of M ($i \in M$) are Ej and Pj respectively, then lifetime of node i is measured as:

$$T_i = \frac{E_i}{P_i} \qquad (1)$$

In this context, SPLM strategy is used to allocate a certain path, in such a way that it maximises lifetime of SNs by utilizing R(k) and cooperative k-hop relay path. Spectrum broker receives resources requests, by SNs terminals, in order to find the available energy efficient path. In turn, the Energy Controller assigns to SNs an energy-efficient resource exchange path, according to the associated subsystem energy module that the SNs belongs. The energy efficiency is estimated, by each energy module subsystem, using SPLM scheme, in order to conserve energy. This is achieved, by allocating optimal energy-aware path, either through RRM module or by utilizing peer-to-peer resource exchange process. In the case of losses during resource exchange process -as in [19]- a backup node can be set in the vicinity of SN_i such that SN_{i+1} can claim chunk streaming resources, according to promiscuous caching policy [20]. Therefore, SPLM can be defined as:

$$T_{SPLM_i} = min(T_R, T_{i\to j}) \qquad (2)$$

where $T_R = {E_R}/{P_R}$ and $T_i = \sum_i^j {E_i}/{P_i}$ are the lifetime metrics of each SN through R_i and SN_{i+1} for k-hops from which SN_i can claim chunk streaming sharing resources, according for promiscuous caching purposes, respectively. SPLM is effective from the perspective of uninterrupted data flow through the streaming path. To this end, power allocation problem can be formulated, under Bit-Error-Rate (BER) constraint as:

$$n_i \,\forall\, R_i > T_R \quad (3.1) \qquad n_i \,\forall\, min\left(\sum_i^j {E_i}/{P_i}\right) \in M \quad (3.2)$$

where n_i is the BER for using Radio Access Technologies (Eq. 3.1) and the BER when using peer accessing nodes SN_i to SN_{i+1} via k-hop SNs, respectively. In order to obtain a specified level of desired Throughput $\Theta(t_s)$, for a given nodal lifetime T_i, where for all the k streaming pieces it stands that $S_i = \{\sum_1^k S_k\} \,\forall\, k \in j, R$ and $S_i(\mathrm{t})$, $\forall\, t_1 < S_i(\mathrm{t}) < t_2$, then Θ(ts), can be evaluated via the:

$$\theta(t_s)|T_i = \max\left(\sum_i^{j,R}(1-n_i)\sigma_i B_{i\to j}\log_2\left(1+\frac{g_{ij}P_{ij}}{B_{i\to j}}\right)\right)\forall_{S_i \in j,R} \qquad (4)$$

$B_{i\to j}$ is frequency bandwidth allocated to SN_i from Radio Access Technology or to nearby SN_i peer, σ_i is the streaming parameter as in [20], n_i is the BER for using the Radio Access Technologies and Access Points and the peer accessing nodes SN_i to SN_{i+1} via k-hop SNs, P_{ij} is the transmission power from and, to each SN_i, where it stands that $\forall\, P_i = 1 - T_{SPLM_i}, i \in M$, and g_{ij} is the channel gain. The transmission power P_{ij} can be evaluated as the total path transmission power with $P_{ij} = \sum_i^j 1 - T_{SPLM_{ij}}$. The P_{ij} is estimated when the best path in terms of remaining energy is evaluated ($T_{SPLM_{ij}}$). In order to enable Link Utility Maximization (LUM) which is based on the link that each SN_i can claim chunk streaming sharing resources, the utilisation degree should satisfy the following:

$$\Lambda_{LUM} : \max\sum_{r\in R} U_r(\chi_r) \forall \mathrm{A}_\chi \le C, \chi \ge 0 \qquad (5)$$

where r denotes the index of the SN_i source node, χ_r represents the transmission rate of $\mathrm{SN}_i(r)$, C is a vector containing the associated capacities of all links of $\mathrm{SN}_i(r)$ and $U_r(\chi_r)$ is the utility of node r when transmitting at rate χ_r. According to the work done in [21], the link utility represents the availability degree of a node as a function of the transmission rate. In Eq. (5) the $\mathrm{A}_{\chi(r)}$ is a matrix containing the associated paths (from and to $\mathrm{SN}_i(r)$) which are denoted as 1 if there is such route (via R_i and SN_{i+1}) and 0 otherwise.

The delay that the transmission experiences δ_{ij} should satisfy the $\delta_{ij}<d_p$, where d_p is the maximum delay in the end-to-end path from a source to a destination and can be is evaluated as:

$$d_p = \sum_{i=0}^{i-1}\delta_i + T_i \quad \forall \max\sum_{r\in R} U_r(\chi_r) \qquad (6)$$

where δ_i is the duration where requested data was hosted onto *i-node* and T is transmission delay. Then for obtaining minimised energy consumed in the path E_{C_t} the following should be satisfied:

$$\arg max_{\delta_{ij}<d_p}\,\theta(t_s)|T_i = \{\delta_{ij} < d_p : \theta(t_s)\}\,|T_i = minf(T_{SPLM_i}) \qquad (7)$$

III. Performance Evaluation Analysis, Experimental Results and Discussion

Performance evaluation results encompass comparisons with other existing schemes for offered throughput and reliability degree, regarding delay-bounded transmissions, as well as for EC efficiency. The mobility model used is based on probabilistic Fraction Brownian Motion (FBM) [15], where nodes are moving, according to certain probabilities, location and time. Towards implementing such scenario, the spine model [22] was used, exploiting a common look-up application service for resource sharing among SNs. Topology of a 'grid' based network was modelled, according to the grid approach described in [19]. Each node directly communicates with other nodes, if the area situated is in the same (3x3 center) rectangular area of the node.

The Successful packet Delivery Ratio (SDR) with the number of concurrent flows-requests of the Secondary System is presented in Figure 2 under different LUM parameter values. The LUM parameter is based on the link, through which each SN_i can claim file-chunk sharing resources. This is performed through the LUM policy which enables a vector which reveals the associated capacities of all links. It is important to mark-out that by using *R(k)* resource exchange policy in the presence of high LUM values for low concurrent transfer measures, the SDR is kept in relatively in lower levels. On the contrary, by utilising joint *R(k)* and *SNs* resource exchange SDR increases significantly. Network size with the number of completed files/streaming file chunks and the end-to-end latency with the number of mobile users (*SNs*) during simulation is presented in Figure 3. The upper-level Figure 3 shows associated network size and Throughput response (vertical dashed lines) of the Secondary System with the number of completed files and network size. When network size increases, Throughput response increases accordingly with the number of completed files. This occurs due to LUM indicated policy, which enables under-utilised links (according to their offered data rates) to contribute to the resource sharing policy. In turn the End-to-End latency is reduced when the number of *SNs* in the system increases. This is due to the joint *R(k)* and *SNs* resource exchange which enables alternative paths and as Figure 3 shows, the latency is reduced for both mobility models used.

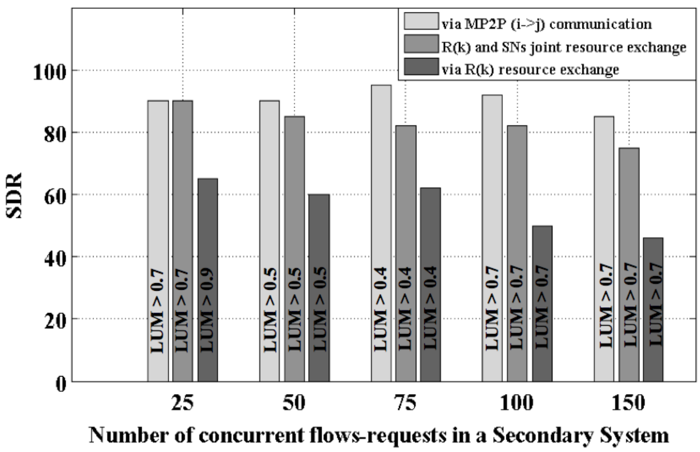

Fig. 2. SDR with the number of concurrent flows-requests in a Sec. System

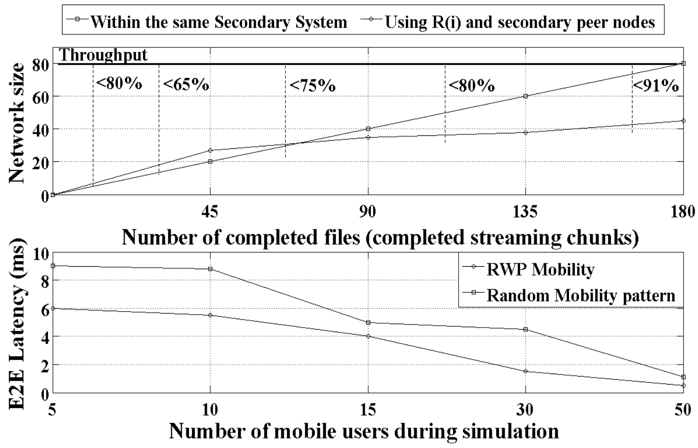

Fig. 3. Network size with the number of completed files/streaming file chunks and end-to-end latency with number of mobile users during simulation

Moreover, the offered throughput response of the system in contrast to the SNR (dBm) and the simulation duration time for two different evaluated schemes, is presented in Figure 4. It can be observed that throughput response can be significantly increased via the proposed methodology for assigning the energy efficient path to the SNs' resource exchange requests, which is measured through the joint LUM estimations and the SPLM approach indicated earlier.

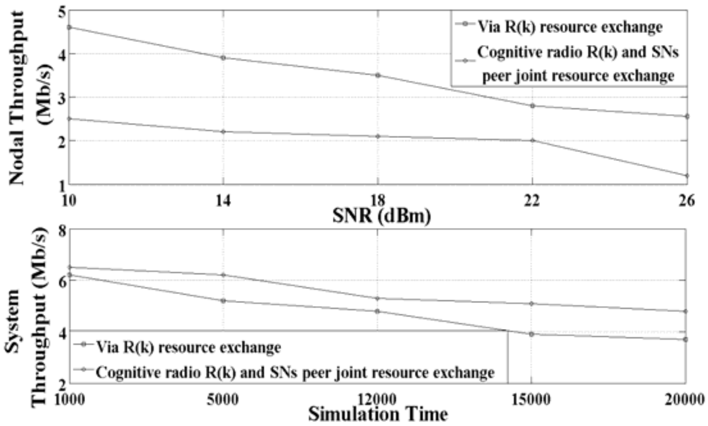

Fig. 4. Nodal and system Throughput with SNR (dBm) during simulation

In addition, the overall energy consumption with the participating number of SNs for four evaluated schemes is shown in Figure 5. It is undoubtedly true that the energy consumption is significantly reduced when both the R(k) through CR and the SNs resource exchange are utilized, whereas when the P2P methodology is used, the energy consumption is slightly increased. When the LUM policy is used the overall energy consumption is further minimized as the link utility represents the availability degree of a node as a function of the transmission rate. The final set of comparisons examines the Energy Efficiency (bytes/mW) which is defined as the service capacity/total energy consumed. The Energy Efficiency (bytes/mW) was measured in contrast to the remaining energy onto each node as shown in lower Figure 5, for four different schemes. The proposed framework is eliminating the severe energy consumption of each node in the system whereas, compared to the joint resource exchange *R(k)* and *SNs* (LUM enabled) scheme, it exposes an improvement on the energy consumption in contrast to the evaluated Energy-Efficiency for each device. The proposed scheme shows to offer optimized behaviour in terms of energy consumption, as it allows greater Energy-Efficiency in contrast to the remaining energy on each node.

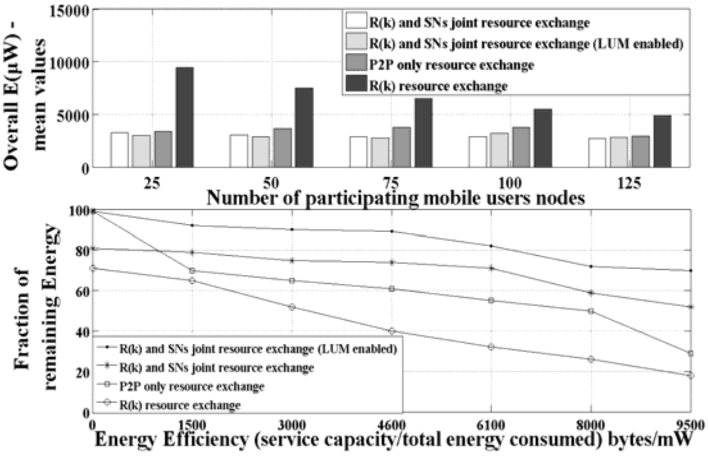

Fig. 5. Overall energy consumption for each SN for three different schemes and Energy Efficiency with fraction of the remaining energy onto each node

IV. Conclusions

This paper proposes two Energy-Efficient algorithms that operate in a CR network architecture, providing effective TVWS exploitation and reliable resource exchange. Both algorithms host a mechanism for minimizing the energy consumption, using a joint methodology for path lifetime and path utility maximization scheme. The joint scheme encompasses a capacity-aware policy for achieving the minimum energy consumption, while it offers high successful delivery rates during the resource exchange process. Towards evaluating performance of both algorithms, a number of experimental tests was conducted under controlled simulation conditions. Obtained experimental results verified the efficiency of spectrum broker, in terms of optimal energy-efficiency during resource exchange process of SNs. In this respect, fields for future research include the expansion of this model into a green motion-aware streaming policy, using both the CR and P2P resource exchange manner.

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