Exploiting Knowledge Management for Supporting Spectrum Selection in Cognitive Radio Networks

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***Abstract*—In order to increase Cognitive Radio operation efficiency, this paper builds up a new knowledge management functional architecture for supporting spectrum management. It integrates the fittingness factor concept proposed by the authors in a prior work and includes a set of advanced statistics capturing the influence of the radio environment. Then, a Knowledge Manager (KM) exploiting these statistics and observed fittingness factor values has been developed to monitor the time-varying suitability of spectrum resources to support heterogeneous services. Based on estimated suitability levels, a new strategy combining Spectrum Selection (SS) and Spectrum Mobility (SM) functionalities has been proposed. Results have shown that the proposed strategy efficiently exploits the KM support at low loads and the SM functionality at high loads to introduce significant gains (ranging from 85% to 100%) w.r.t. a pure random selection while exhibiting substantial robustness to changes in interference levels.**

I. CONTEXT/MOTIVATION

The CR (Cognitive Radio) paradigm has emerged as an intelligent radio that automatically adjusts its behavior based on the active monitoring of its environment [1, 2]. The introduction of cognitive techniques for the management of wireless networks will lead to robustness and the capitalization of the learning capabilities intrinsic to cognitive systems. Strengthening these cognitive techniques would be of great interest for optimizing cognitive management functions. Therefore, technical requirements of new cognitive management systems have been considered in many studies [3–5]. In particular, many recent proposals have tried to develop new models and efficient architectures for introducing cognitive management systems in emerging environments such as the Future Internet [6] or the home environment [7]. The underlying technical challenges have stimulated the initiation of many research projects (e.g. [8–10]) and standardization activities (e.g. [11, 12]) to further strengthen and promote the usage of cognitive management systems.

CR is a key enabling technology for Dynamic Spectrum Access (DSA), a new communication paradigm proposing to use and share the spectrum in an opportunistic manner in order to increase spectrum usage efficiency. The typical DSA scenario is a set of unlicensed users opportunistically selecting unused spectrum portions of licensed users under of the strict constraint of not disturbing them. In this context, the selected spectrum portions should be carefully chosen and vacated whenever the licensed user is detected. Not surprisingly, this topic has received a lot of interest in the recent literature [13–16]. The flexibility provided by spectrum agility has to be materialized in the form of an increased efficiency by means of proper decision-making criteria in the spectrum selection functionality.

In this respect, we have proposed in [17] to strengthen awareness level in cognitive systems by a new fittingness factor concept that captures the suitability of spectral resources exhibiting time-varying characteristics to support a set of heterogeneous services. Motivated by the proven usefulness of the proposed concept to improve spectrum usage efficiency, this paper aims at more focused exploitation of knowledge management for the sake of supporting spectrum selection. Specifically, it is proposed to build up a set of advanced functionalities to efficiently capture unknown changes in radio and interference conditions of available spectral resources. In this perspective, the main contributions of this paper are two-fold: (1) To build up a new knowledge management functional architecture for supporting the spectrum management decision-making process. The proposed architecture integrates the fittingness factor concept and includes a Knowledge Manager (KM) that monitors the time-varying suitability of spectrum resources to support heterogeneous services based on a set advanced statistics and observed fittingness factor values during CR operation, and (2) To develop a spectrum management strategy exploiting the estimated suitability of spectrum resources for supporting both spectrum selection and spectrum mobility functionalities while being robust to unknown changes in interference levels at any traffic load of demanded services.

The remainder of this paper is organized as follows: in Sec. II the system model is presented and the functional architecture of the proposed knowledge management framework for supporting spectrum management is presented. After defining the fittingness factor concept, a set of statistics capturing its behavior are proposed in Sec. III. Based on these statistics and on observed fittingness factor values during system operation, a Knowledge Manager (KM) is built up in order to monitor time-varying suitability of spectrum resources. Then, a new strategy exploiting the estimated fittingness factor values is proposed in Sec. IV in order to support both spectrum selection and spectrum mobility functionalities. Results are presented in Sec. V, firstly evaluating spectrum selection performances in terms of the dissatisfaction probability, and secondly assessing the additional signaling cost the proposed strategy may introduce. Conclusions and future directions are addressed in Sec. VI.

II. SYSTEM MODEL

Let us consider a set of L different radio links that need to be established between pairs of terminals and/or infrastructure nodes. The purpose of each radio link is to support a certain application. The l-th application is characterized in terms of a required bit-rate $R_{req,l}$. The available spectrum is modeled as

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a set of P spectrum blocks (denoted in this paper as "pools") each of bandwidth BW_p. Based on radio link requirements and spectrum pool characteristics, the general aim is to efficiently assign a suitable spectrum pool for each of the L radio links.

In order to accomplish this objective, the functional architecture depicted in Fig. 1 is proposed. It consists in the following entities::

1) The knowledge management entity, which is responsible for storing and managing the relevant knowledge obtained from the radio environment to be used in the decisions made by the decision-making entity. It is materialized by a Knowledge Manager (KM) that monitors the suitability of existing spectral resources to support heterogeneous services based on information retrieved from a Knowledge Database (KD) that stores a set of relevant statistics from the environment.
2) The decision-making entity, which is responsible for assigning the appropriate pools to the different links. For that purpose, it interacts with the KM that will provide the relevant information for the decisions to be made. Decision-making is split into two functional entities: spectrum selection, which will pick up a suitable pool for each communication whenever a new service request arrives, and the spectrum mobility, which will perform the reconfiguration of assigned pools whenever changes occur in the environment and better pools can be found for some services.

In order to assess the suitability of spectral resources to support heterogeneous services, the so-called "Fittingness Factor" ($F_{l,p}$) is introduced in [17] as a metric capturing how suitable each p-th spectrum pool is for each l-th radio link/application. $F_{l,p}$ will particularly assess the suitability in terms of the bit rate that can be achieved operating in the spectrum pool p (denoted as $R(l,p)$) versus the bit rate required by the application l ($R_{req,l}$).

From a general perspective, the fittingness factor can be formulated as a function of the utility $U_{l,p}$ the l-th link can obtain from the p-th pool, where the utility is defined as [18]:

$$U_{l,p} = \frac{\left(\frac{R(l,p)}{R_{req,l}}\right)^{\xi}}{1+\left(\frac{R(l,p)}{R_{req,l}}\right)^{\xi}} \tag{1}$$

where ξ is a shaping parameter that allows the function to capture different degrees of elasticity of the application with respect to the required bit rate. The achievable bit-rate by link l using pool p ($R(l,p)$) will depend on the radio and interference conditions existing in pool p.

Based on the above concept, it is proposed to use the fittingness factor function previously proposed in [17]:

$$F_{l,p}=\frac{1-e^{-\frac{K\times U_{l,p}}{\frac{R(l,p)}{R_{req,l}}}}}{\lambda} \tag{2}$$

where K is a shaping parameter and λ is a normalization factor to ensure that the maximum of the fittingness factor is equal to 1, given by:

$$\lambda=1-e^{-\frac{K}{(\xi-1)^{\frac{1}{\xi}}+(\xi-1)^{\frac{1-\xi}{\xi}}}} \tag{3}$$

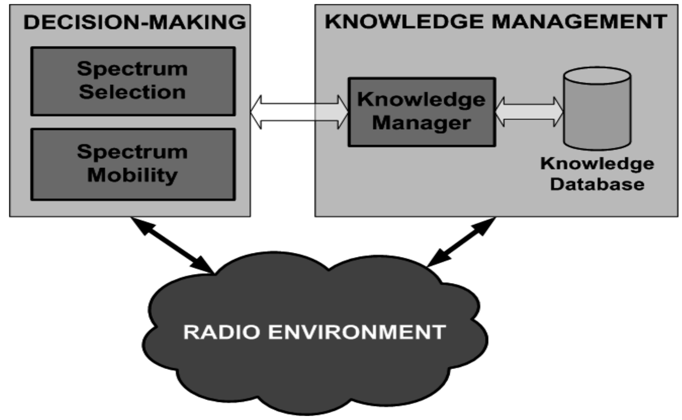


Fig. 1. Functional architecture of the proposed knowledge management framework for supporting spectrum management

The proposed $F_{l,p}$ function increases with $R(l,p)$ up to the maximum at $R(l,p)=\sqrt[\xi]{\xi-1}\times R_{req,l}$. It has been shown in [17] that this formulation of $F_{l,p}$ performs a more efficient usage of spectral resources than just considering $F_{l,p}=U_{l,p}$, thanks to reducing the value of the fittingness factor whenever the available bit rate is much higher than the required one.

III. Knowledge Management

A. Knowledge Database

In order to enable a global characterization of the suitability of a given pool p to a given link l based on the past history when using this pool, the information retained in the KD will be associated to statistics of $F_{l,p}$. The database will be fed by measurements extracted from the radio environment. In particular, the measurement of $R(l,p)$ of active link/pool pairs will be obtained, from which the current value of $F_{l,p}$ will be computed following (2) and will be stored in the database together with the corresponding time stamp.

Considering that $F_{l,p}$ values can be associated to two states: HIGH ($\geq \delta_{l,p}$) or LOW ($< \delta_{l,p}$), the following statistics are also generated and stored in the database:

- The probability $P_L^{l,p}(\delta_{l,p})$ of observing a LOW fittingness factor:
$$P_L^{l,p}(\delta_{l,p})=Prob\left[F_{l,p}<\delta_{l,p}\right] \tag{4}$$
- The probability $P_H^{l,p}(\delta_{l,p})$ of observing a HIGH fittingness factor:
$$P_H^{l,p}(\delta_{l,p})=1-P_L^{l,p}(\delta_{l,p}) \tag{5}$$
- The average of observed LOW fittingness factor values:
$$\bar{F}_L^{l,p}=E\left(F_{l,p}|F_{l,p}<\delta_{l,p}\right) \tag{6}$$
- The average of observed HIGH fittingness factor values:
$$\bar{F}_H^{l,p}=E\left(F_{l,p}|F_{l,p}\geq\delta_{l,p}\right) \tag{7}$$

Furthermore, in order to monitor fittingness factor variability, the following statistical metrics are considered:

- Given $F_{l,p}$ is LOW at a given time instant k, the probability that $F_{l,p}$ will be LOW at each time instant up to time $k{+}\Delta k$ defined as follows:

$$P_{L,L}^{l,p}(\Delta k,\delta_{l,p}){=} \\ Prob\left[F_{l,p}(k+j){<}\delta_{l,p},\forall j{\in}\{1..\Delta k\}|F_{l,p}(k){<}\delta_{l,p}\right] \tag{8}$$

where $F_{l,p}(k)$ denotes the observed $F_{l,p}$ value at time k.

- Given $F_{l,p}$ is HIGH at a given time instant k, the probability that $F_{l,p}$ will be HIGH at each time instant up to time $k{+}\Delta k$ defined as follows:

$$P_{H,H}^{l,p}(\Delta k,\delta_{l,p}){=} \\ Prob\left[F_{l,p}(k+j){\geq}\delta_{l,p},\forall j{\in}\{1..\Delta k\}|F_{l,p}(k){\geq}\delta_{l,p}\right] \tag{9}$$

The proposed fittingness factor variability metrics ($P_{L,L}^{l,p}$ and $P_{H,H}^{l,p}$) can be used to determine to which extent the fittingness factor is not likely to change after a certain time shift Δk.

B. Knowledge Manager

The KM plays a key role between the knowledge management and the decision-making domains of the proposed architecture. In this perspective, it manages the information retained in the KD in order to determine the knowledge about the environment that would be mostly relevant for supporting all decisions made by the decision-making entity.

On one side, the KM keeps an estimation of $F_{l,p}$ values based on the statistics available at the KD. These estimated values, denoted as $\hat{F}_{l,p}$, are obtained following Algorithm 1, and are provided upon request to the decision-making module. The estimate $\hat{F}_{l,p}$ is determined based on whether the $F_{l,p}$ stored in the KD is likely to be the same that was obtained $\Delta k_{l,p}$ time units before (this is checked in the conditions of lines 5 and 11 with respect to the significance thresholds Thr_LOW and Thr_HIGH). In such case, $\hat{F}_{l,p}$ is set to the last measured value $F_{l,p}$ (lines 8 and 14). Otherwise, $\hat{F}_{l,p}$ is randomly set to either $\bar{F}_{L}^{l,p}$ or $\bar{F}_{H}^{l,p}$, the average $F_{l,p}$ values in the LOW and HIGH states, respectively, with probabilities $P_{L}^{l,p}(\delta_{l,p})$ and $1{-}P_{L}^{l,p}(\delta_{l,p})$ (lines 9 and 16). Once all link/pool pairs are explored, the list of all estimated fittingness factor values ($\{\hat{F}_{l,p}\}$) is returned back to the decision-making entity (line 19).

On the other side, the KM captures relevant changes in these estimated values and informs the decision-making module for consideration.

IV. Spectrum Management Decision-Making

In this section, both the spectrum selection and spectrum mobility functionalities of the decision-making process are implemented.

A. Spectrum Selection

Based on the fittingness factor values determined by the KM, the spectrum selection functionality selects a suitable spectrum pool for each radio link according to the Fittingness Factor-based Spectrum Selection algorithm (SS) described in Algorithm 2. Upon receiving a request for establishing a link l, the request is rejected if the set of available pools (Av_Pools) is empty (line 3). Otherwise, an estimation of all $F_{l,p}$ values is obtained from the KM (line 5). Based

Algorithm 1 Knowledge Manager (KM)

1: Function KM()
2: **for** l=1 **to** L **do**
3:   **for** p=1 **to** P **do**
4:     **if** $F_{l,p}$ is LOW **then**
5:       **if** $P_{L,L}^{l,p}(\Delta k_{l,p},\delta_{l,p}){\geq}Thr\_LOW$ **then**
6:         $\hat{F}_{l,p} \leftarrow F_{l,p}$;
7:       **else**
8:         Estimate $F_{l,p}$ as follows:

$$\hat{F}_{l,p}{=}\begin{cases}\bar{F}_{L}^{l,p} & \text{with probability } P_{L}^{l,p}(\delta_{l,p}),\\ \bar{F}_{H}^{l,p} & \text{with probability 1-}P_{L}^{l,p}(\delta_{l,p}).\end{cases}$$

9:       **end if**
10:     **else**
11:       **if** $P_{H,H}^{l,p}(\Delta k_{l,p},\delta_{l,p}){\geq}Thr\_HIGH$ **then**
12:         $\hat{F}_{l,p} \leftarrow F_{l,p}$;
13:       **else**
14:         Estimate $F_{l,p}$ as follows:

$$\hat{F}_{l,p}{=}\begin{cases}\bar{F}_{L}^{l,p} & \text{with probability } P_{L}^{l,p}(\delta_{l,p}),\\ \bar{F}_{H}^{l,p} & \text{with probability 1-}P_{L}^{l,p}(\delta_{l,p}).\end{cases}$$

15:       **end if**
16:     **end if**
17:   **end for**
18: **end for**
19: return ($\{\hat{F}_{l,p}\}$);

Algorithm 2 Fittingness Factor-based Spectrum Selection (SS)

1: **if** service l request **then**
2:   **if** $Av\_Pools{=}\emptyset$ **then**
3:     Reject request;
4:   **else**
5:     $\{\hat{F}_{l,p}\} \leftarrow KM()$ {Call the Knowledge Manager};
6:     $p^{*}(l) \leftarrow \arg\max_{p\in Av\_Pools}\left(\hat{F}_{l,p}\right)$;
7:   **end if**
8: **end if**

on provided $\hat{F}_{l,p}$ values, a greedy algorithm selecting the available spectrum pool $p^{*}(l)$ with the largest fittingness factor is performed (line 6).

B. Spectrum Mobility

In order to further adjust CR behavior to changes in spectrum resources suitability, the spectrum mobility functionality can be executed whenever better pools can be found for some services. Spectrum mobility is considered on a global perspective jointly optimizing all assignments in order to improve the overall pool usage efficiency.

As detailed by Algorithm 3, the proposed Fittingness Factor-based Spectrum Mobility (SM) is triggered whenever a previously selected pool by SS at link establishment is no longer the best in terms of $F_{l,p}$ for the corresponding active link. This may happen whenever some active pools are released or experience some change in their $F_{l,p}$. Following both triggers, the KM is first called in order to get an estimation of all $F_{l,p}$ values ($\{\hat{F}_{l,p}\}$) (line 2). The algorithm then explores the list of currently active links ($Active\_Links$) in the decreasing order of the required throughputs ($R_{req,l}$) in order to prioritize the neediest links. The decision to reconfigure or not each active link is based on a comparison between the actually used pool ($p^{*}(l)$) and the currently best pool in terms of $\hat{F}_{l,p}$ ($new\_p^{*}(l)$) (line 7). Specifically, if $F_{l,p^{*}(l)}$ is LOW and $F_{l,new\_p^{*}(l)}$ is HIGH, a Spectrum HandOver (SpHO) from

$p^*(l)$ to $new\_p^*(l)$ is performed since $new\_p^*(l)$ fits better link l. The same SpHO should be performed in case $p^*(l)$ is no longer available to link l after being preempted during previous reassignments (line 8). Once all active links get explored, the list of assigned pools is updated according to performed SpHOs (line 15).

Algorithm 3 Fittingness Factor-based Spectrum Mobility (SM)

1: **if** (service l^* ends) **or** (change in any active $F_{l,p}$) **then**
2: $\{\hat{F}_{l,p}\} \leftarrow KM()$ {Call the Knowledge Manager};
3: $new\_Assigned \leftarrow \emptyset$;
4: Sort $Active\_Links$ in the decreasing order of $R_{req,l}$;
5: **for** l=1 **to** $|Active\_Links|$ **do**
6: $new\_p^*(l) \leftarrow \arg \max_{p \notin new\_Assigned} \left(\hat{F}_{l,p}\right)$;
7: **if** (($\hat{F}_{l,p^*(l)}$ is LOW) **and** ($\hat{F}_{l,new\_p^*(l)}$ is HIGH)) **or**
8: ($p^*(l) \in new\_Assigned$) **then**
9: $p^*(l) \leftarrow new\_p^*(l)$;
10: $new\_Assigned \leftarrow new\_Assigned \bigcup \{new\_p^*(l)\}$;
11: **else**
12: $new\_Assigned \leftarrow new\_Assigned \bigcup \{p^*(l)\}$;
13: **end if**
14: **end for**
15: $Assigned \leftarrow new\_Assigned$;
16: **end if**

V. Performance Evaluation

A. Simulation Model

To evaluate the effectiveness of the proposed framework in assisting the spectrum management decision-making process, L=2 radio links are considered. The l-th link generates sessions with arrival rate λ_l and constant session duration $T_{req,l}$. Link #1 is associated to low-data-rate sessions ($R_{req,1}$=$64Kbps$, $T_{req,1}$=$2min$) while link #2 is associated to high-data-rate sessions ($R_{req,2}$=$1Mbps$, $T_{req,2}$=$20min$).

Performances are evaluated using a system-level simulator operating in steps of 1s. The radio environment is modeled as a set of P=4 spectrum pools. The available bandwidth at each pool is BW_1=BW_2=$0.4MHz$ and BW_3=BW_4=$1.2MHz$. A heterogeneous interference situation is considered in which the total noise and interference power spectral density I_p experienced in each pool $p \in \{1..P\}$ is assumed to follow a two-state discrete time Markov chain jumping between a state of low interference $I_0(p)$ and a state of high interference $I_1(p)$. It is assumed that interference I_p evolves independently in each pool and that this evolution is independent of the traffic in the radio links. Furthermore, no mutual interference effects between different pools exist. In our specific case, pools #1 and #2 are always in state $I_0(p)$ while pools #3 and #4 randomly alternate between $I_0(p)$ and $I_1(p)$ with transition probabilities for pool #3 P_{10}=55.5×10^{-5} (i.e. probability of moving from state I_1 to I_0 in a simulation step) and P_{01}=3.7×10^{-5} (i.e. probability of moving from state I_0 to I_1) and for pool #4 P_{10}=9.25×10^{-5} and P_{01}=1.32×10^{-5}. Based on these probabilities, the average duration of the high interference state is $0.5h$ for pool #3 and $3h$ for pool #4 while the average duration of the low interference state is $7.5h$ for pool #3 and $21h$ for pool #4.

With this configuration, the achievable bit-rate by one link in pools #1 and #2 is $R(l,3)$=$R(l,4)$=$512Kbps$, while for pools #3 and #4, it alternates between $R(l,3)$=$R(l,4)$=$1536Kbps$ for the $I_0(p)$ state, and $R(l,3)$=$R(l,4)$=$96Kbps$ for the $I_1(p)$ state.

The system is observed during a simulation time of 300 days. Other simulation parameters are ξ=5, K=1, $\delta_{1,p}$=0.2, $\delta_{2,p}$=0.9, Thr_LOW=0.9 and Thr_HIGH=0.9.

B. Benchmarking

In order to assess the influence of the different components of the proposed framework, the following variants will be compared:

- SS+KD: This is the approach considered in [17] consisting in a greedy Fittingness Factor-based Spectrum Selection supported by only the KD (i.e. the decision-making entity of Fig. 1 is assumed to bypass the KM and retrieve only the last measured value $F_{l,p}$ from the KD).
- SS+KM: A greedy Fittingness Factor-based Spectrum Selection supported by the KM module. Compared to SS+KD, the use of KM will allow a better capability to track changes in the interference conditions of each pool, thanks to considering the temporal properties of the $F_{l,p}$ statistics in addition to the last measured values.
- SS+KD+SM: A greedy Fittingness Factor-based Spectrum Selection supported only by the KD (i.e. using only the last measured $F_{l,p}$) and the SM module. As a difference from SS+KD, the inclusion of SM will allow performing pool reallocations for active links when better pools can be found.
- SS+KM+SM: This is the proposed strategy in Section IV implementing a greedy Fittingness Factor-based Spectrum Selection supported by both the KM and SM, so that it incorporates the track-changes benefits of KM together with the reallocation flexibility associated to SM.

Apart from the considered variants, the following reference schemes are introduced for benchmarking purposes:

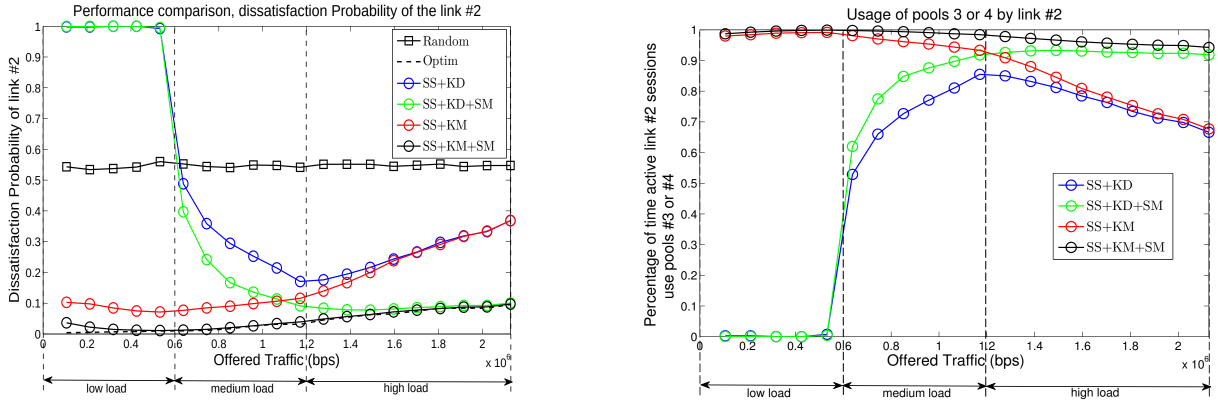
- Rand: This implements only the spectrum selection module of Fig. 1 and performs a random selection among available pools. Neither SM nor KM modules are used.
- Optim: This scheme is an upper bound theoretical reference. In each simulation step, it redistributes all pools among active links to perform the following maximization of the total number of transmitted bits at a given time instant k, defined as:

$$\max \left(\sum_{active(l,p)} \min\left(R_{req,l}, R(l,p,k)\right) \right) \quad (10)$$

where $R(l,p,k)$ is the measured bit-rate $R(l,p)$ at time k.

C. Results

This section presents the performance evaluation of the different schemes introduced in Sec. V.B. The target of the analysis is two-fold: (1) to identify which of the functional elements of the proposed architecture have the most significant impact on performance depending on the system operation conditions, and (2) to benchmark the performance of the proposed spectrum management strategy (SS+KM+SM) with respect to the reference Rand and Optim schemes.



(a) Dissatisfaction probability

(b) Fraction of time that link #2 uses pools #3 or #4

Fig. 2. Spectrum selection performance comparison for link #2

Fig. 2(a) plots the dissatisfaction probability of link #2 (i.e. the most demanding in terms of required bit rate) as a function of the total offered traffic load $\lambda_1 \times T_{req,1} \times R_{req,1} + \lambda_2 \times T_{req,2} \times R_{req,2}$. It is defined as the probability of observing a bit rate below the service requirement $R_{req,l}$. Results for link #1 are not presented since it is all the time satisfied (i.e., the bit rate is always above the requirement of 64Kbps). Fig. 2(b) plots the fraction of time that link #2 uses pools #3 or #4. When using these pools in the low interference state, link #2 will be satisfied. In turn, link #2 will be dissatisfied whenever it is allocated pools #1 or #2 or pools #3 or #4 in the high interference state.

As seen in Fig. 2(a), for low traffic loads below 0.6Mbps, the introduction of KM leads to a very important reduction of the dissatisfaction probability. The reason is that, whenever interference increases in pools #3 and #4 (i.e. they move to state I_1), the corresponding measured value of $F_{l,p}$ will be LOW. As a result, strategies SS+KD and SS+KD+SM that just keep this last measured value of $F_{l,p}$ will decide in the future to allocate only pools #1 and #2, which offers a lower bit rate. Then, the network will not be able to realize the situation when pools #3 and #4 move again to the low-interference state I_0 and become adequate for the link #2 (see in Fig. 2(b) that the fraction of time that these pools are allocated to link #2 is close to 0). On the contrary, the use of the KM component considers the temporal properties of the $F_{l,p}$ statistics to disregard the last measured value and use an estimated value instead whenever a certain amount of time has passed since this last measure was taken (see conditions of lines 5 and 11 in Algorithm 1). Correspondingly, sometime after the interference increase, the network will allocate again pools #3 and #4 to link #2, thus being able to identify if they have re-entered in the low-interference state. Note in Fig. 2(b) that the fraction of time that link #2 uses pools #3 or #4 is close to 1 for strategies making use of KM thus resulting in a better dissatisfaction probability. In summary, for low loads, KM allows a better exploration of the different pools to identify the changes in their interference conditions, and as a result the dissatisfaction probability improves.

When load increases above 0.6 Mbps, pools #1 and #2 will tend to be occupied by link #1 sessions most of the time, which forces the system to assign pools #3 and #4 to link #2 sessions even with reduced $F_{l,p}$. In this case, interference reductions in pools #3 and #4 are detected without the use of KM. This is reflected in Fig. 2(a) where, for high loads, the performances of SS+KD and SS+KM are equivalent, and the same occurs for the performances of SS+KD+SM and SS+KM+SM.

With respect to the role of SM, for low loads, its use leads to small improvements (see the comparison in Figure 2(a) between SS+KD and SS+KD+SM or between SS+KM and SS+KM+SM). The reason is that, for low loads, it occurs very rarely that a link is not allocated to the pool with the highest fittingness factor because of being occupied by another link. Consequently, there is no need to perform SpHOs towards a better pool except in the case when the interference increases in the allocated pool, which justifies the small improvement observed when comparing SS+KM and SS+KM+SM. On the contrary, when load increases, it occurs more often that the preferred pool is occupied by another link and thus a pool offering lower bit rate is allocated. In this case, the execution of SM after the release of the link occupying the preferred pool will lead to improving the performance. Notice in Fig. 2(b) that, with SS+KM+SM, link #2 will be allocated most of the time pools #3 or #4, thus leading to the significant reduction in the dissatisfaction probability achieved by SS+KM+SM with respect to SS+KM in Fig. 2(a) for high loads.

The proposed SS+KM+SM strategy performs very closely to the upper-bound optimal scheme for all load conditions, mainly thanks to the support of the KM and SM components for relatively low and high loads, respectively. The gain observed by SS+KM+SM with respect to the Rand scheme (measured as the reduction in dissatisfaction probability) ranges from 85% to 100% (Fig. 2(a)).

To further assess the proposed strategy in terms of the cost associated to the reconfigurations performed by the SM functionality, Fig. 3 plots the average number of SpHOs per session experienced by SS+KD+SM and SS+KM+SM in both links. For low traffic loads, the joint use of KM and SM causes a small number of SpHOs for link #2, associated to the situations in which the interference in allocated pools #3 or #4 increases. On the contrary, with SS+KD+SM, there are very few SpHO events for low loads mainly because, as discussed previously, pools #3 and #4 are rarely allocated to

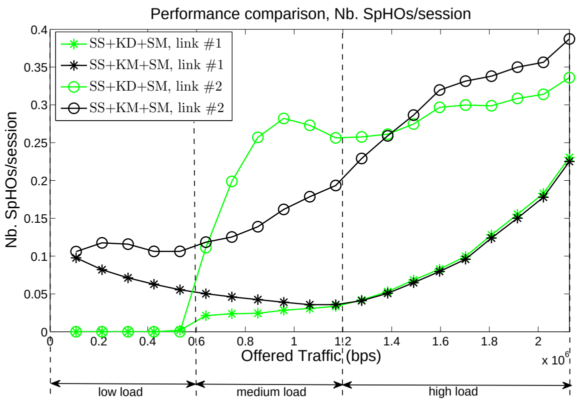


Fig. 3. SpHO performance associated to the SM functionality

link #2. When the offered traffic load increases, link #2 is experiencing more SpHO events with better performance for SS+KM+SM than for SS+KD+SM. This is because the KM support makes less likely to perform unneeded SpHOs due to out-of-date fittingness factor values. For high loads beyond 1.4Mbps, performance of both methods becomes similar.

VI. Conclusions and Future Work

This paper has proposed a new knowledge management functional architecture, based on the fittingness factor concept, for supporting spectrum management to support a set of heterogeneous services. It includes a set of advanced statistics capturing the influence of the dynamic radio environment on the fittingness factor. In particular, a Knowledge Manager (KM) that exploits the proposed statistics and observed fittingness factor values has been developed to monitor time-varying suitability of spectrum resources. Then, a new strategy combining two Fittingness Factor-based Spectrum Selection (SS) and Fittingness-Factor-based Spectrum Mobility (SM) functionalities together with the KM has been proposed. Results have shown that the proposed strategy efficiently exploits the KM support at low loads and the SM functionality at high loads to introduce significant gains (ranging from 85% to 100%) w.r.t. a random selection and to perform very closely to the upper-bound optimal scheme. The associated cost in terms of the rate of SpHOs/session remains bounded below 0.4 regardless of the considered traffic load, which gives a first sketch about the practicality of the proposed strategy.

As part of future work, it is envisaged to further develop the interactions between the different elements of the proposed architecture and to consider other decision-making strategies besides the greedy approach.

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References

[1] J. Mitola III and G. Q. Maguire, Jr., "Cognitive radio: making software radios more personal," *Personal Communications, IEEE*, vol. 6, no. 4, pp. 13–18, Aug. 1999.
[2] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *Selected Areas in Communications, IEEE Journal on*, vol. 23, no. 2, pp. 201–220, Feb. 2005.
[3] R. W. Thomas, D. H. Friend, L. A. Dasilva, and A. B. Mackenzie, "Cognitive networks: adaptation and learning to achieve end-to-end performance objectives," *Communications Magazine, IEEE*, vol. 44, no. 12, pp. 51 –57, Dec. 2006.
[4] J. Kephart and D. Chess, "The vision of autonomic computing," *Computer*, vol. 36, no. 1, pp. 41–50, Jan 2003.
[5] P. Demestichas, G. Dimitrakopoulos, J. Strassner, and D. Bourse, "Introducing reconfigurability and cognitive networks concepts in the wireless world," *Vehicular Technology Magazine, IEEE*, vol. 1, no. 2, pp. 32 –39, 2006.
[6] P. Demestichas, K. Tsagkaris, and V. Stavroulaki, "Cognitive management systems for supporting operators in the emerging future internet era," in *Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops), 2010 IEEE 21st International Symposium on*, Sept. 2010, pp. 21–25.
[7] E. Meshkova, Z. Wang, J. Nasreddine, D. Denkovski, C. Zhao, K. Rerkrai, T. Farnham, A. Ahmad, A. Gefflaut, L. Gavrilovska, and P. Mähönen, "Using cognitive radio principles for wireless resource management in home networking," in *Consumer Communications and Networking Conference (CCNC), 2011 IEEE*, Jan. 2011, pp. 669–673.
[8] The End-to-End-Efficiency (E3) project. [Online]. Available: https://www.ict-e3.eu/
[9] The ICT EU (Opportunistic Networks and Cognitive Management Systems for Efficient Application Provision in the Future InterneT) OneFIT Project. [Online]. Available: http://www.ict-onefit.eu/
[10] The Wireless World Research Forum (WWRF), WG6 (working group 6). [Online]. Available: http://www.wireless-worldresearch.org/
[11] IEEE Standard Coordinating Committee 41 (SCC41). [Online]. Available: http://grouper.ieee.org/groups/scc41/index.html/
[12] ETSI Technical Committee (TC) on Reconfigurable Radio Systems (RRS). [Online]. Available: http://www.etsi.org/WebSite/technologies/RRS.aspx
[13] J. Vartiainen, M. Höyhtyä, J. Lehtomäki, and T. Bräysy, "Priority channel selection based on detection history database," in *crowncom, 2010*, June 2010, pp. 1–5.
[14] P. A. K. Acharya, S. Singh, and H. Zheng, "Reliable open spectrum communications through proactive spectrum access," in *IN PROC. OF TAPAS*, 2006.
[15] Y. Li, Y. Dong, H. Zhang, H. Zhao, H. Shi, and X. Zhao, "Qos provisioning spectrum decision algorithm based on predictions in cognitive radio networks," in *WiCOM 2010*, Sept. 2010, pp. 1–4.
[16] W.-Y. Lee and I. Akyildiz, "A spectrum decision framework for cognitive radio networks," *Mobile Computing, IEEE Transactions on*, vol. 10, no. 2, pp. 161–174, Feb. 2011.
[17] F. Bouali, O. Sallent, J. Pérez-Romero, and R. Agusti, "A framework based on a fittingness factor to enable efficient exploitation of spectrum opportunities in cognitive radio networks," in *Wireless Personal Multimedia Communications (WPMC), 2011 14th International Symposium on*, Oct. 2011, pp. 1–5.
[18] L. Badia, M. Lindström, J. Zander, and M. Zorzi, "Demand and pricing effects on the radio resource allocation of multimedia communication systems," in *GLOBECOM '03. IEEE*, vol. 7, Dec. 2003, pp. 4116–4121.