A Framework Based on a Fittingness Factor to Enable Efficient Exploitation of Spectrum Opportunities in Cognitive Radio Networks

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Abstract—**In order to increase CRs (Cognitive Radios) operation efficiency, there has been an interest in increasing awareness level about spectrum utilisation. In this respect, this paper proposes a new fittingness factor concept that captures the suitability of spectral resources exhibiting time-varying characteristics to support a set of heterogeneous CR applications. Different fittingness factor functions to track unknown variations of interference levels are formulated and analysed. First, the dependency with traffic load is studied and second, the impact over the spectrum selection decision-making process in a multi-service CR context is evaluated. Results show that, even with a simple greedy approach, the fittingness factor concept can result in an efficient matching of spectral resources to the requirements of CR applications, thus resulting in significant reduction in the user dissatisfaction probability.**

I. CONTEXT/MOTIVATION

The CR (Cognitive Radio) paradigm has emerged as the solution to the problem of spectrum scarcity for wireless applications [1, 2]. It is a key technology that enables flexible, efficient and reliable spectrum use by adapting the radio operating characteristics to the real-time conditions of the environment.

In this context, the introduction of cognitive techniques for the management of wireless networks will lead to robustness and the capitalization of the learning capabilities that must be intrinsic to cognitive systems. Strengthening these cognitive techniques would be of great interest for optimising cognitive management functions. Therefore, technical requirements of new cognitive management systems have been considered in many studies [3–5]. 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 [11, 12] to further strengthen and promote the usage of cognitive management systems.

Radio Resource Management (RRM) functions are prime important in the specific context of CR and Dynamic Spectrum Access (DSA). 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 increased efficiency by means of proper decision-making criteria in the spectrum selection functionality.

In this respect, the main objective of this paper is to further strengthen awareness level in a cognitive system by proposing a new fittingness factor concept that captures the suitability of spectral resources exhibiting time-varying characteristics to support a set of heterogeneous CR applications. Then, different fittingness factor functions able to track changes in the radio conditions (e.g. interference levels, propagation, etc.) of a set of candidate spectrum pools are introduced. Finally, a first insight of the usefulness of the proposed fittingness factor functions as a driver of the spectrum selection decision-making process is analysed by means of simulations.

The remainder of this paper is organized as follows: in Sec. II the system model is presented. In particular, two different fittingness factor functions are proposed. They are exploited in Sec. III in a spectrum selection decision-making process using a greedy algorithm. Results are presented in Sec. IV, firstly focusing on the capability of fittingness factor to track changes in interference levels, and secondly comparing the performance between the two functions. Conclusions and future directions are addressed in Sec. V.

II. SYSTEM MODEL

Let us consider a set of L different radio links that need to be established between pairs of terminals. The purpose of each radio link is to support a certain CR application. The l-th application is characterised in terms of a required bit-rate $R_{req,l}$ and a temporal duration $T_{req,l}$. The available spectrum is modeled as a set of P pools. The p-th spectrum pool is composed of a number N_p of spectrum blocks each one with bandwidth BW_p. The maximum transmit power in one spectrum block available at all terminals involved in the l-th CR application is denoted by $P_{max,l}$. The "spectrum selection functionality" aims at efficiently selecting a suitable spectrum pool for each of the L radio links based on link requirements and pool characteristics. It is worth noting that this functionality could be properly integrated in an extension of the recently proposed functional architecture for the management and control of ETSI RRS (Reconfigurable Radio Systems) [17].

A. Fittingness Factor definition

Given that the problem in general involves several radio links and several candidate spectrum pools, it is proposed to introduce the so-called "Fittingness Factor" as a metric to capture how suitable a specific spectrum pool is for a specific radio link/application. $F_{l,p}$ denotes the fittingness factor for the l-th radio link with respect to the p-th candidate spectrum pool. The proposed fittingness factor will assess the suitability in terms of the bit rate that can be achieved operating in the spectrum pool versus the bit rate required by the application.

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]:

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

ξ is a shaping parameter that allows the function to capture different degrees of elasticity of the application with respect to the bit rate. In turn, $R(l,p)$ denotes the achievable bit-rate using the p-th pool, which is given by the link capacity:

$$R(l,p) = N_p \times BW_p \times \log_2\left(1+\frac{\min(P_{max,l}, P_{max,p})}{L_{max,p} \times I_p \times BW_p}\right) \tag{2}$$

where $P_{max,p}$, $L_{max,p}$ and I_p respectively denote the maximum allowed transmitted power (in a band BW_p), the maximum propagation loss and the noise and interference power spectral density in the p-th spectrum pool.

Based on the above concept, two different fittingness factor functions are defined. The first one is the utility itself, that is:

$$F_{l,p} = f_1(U_{l,p}) = U_{l,p} \tag{3}$$

Let us notice that with this function, the fittingness factor increases as $R(l,p)$ increases with respect to $R_{req,l}$. In turn, a second function is defined as:

$$F_{l,p} = f_2(U_{l,p}) = \frac{1-e^{-\frac{K \times U_{l,p}}{\frac{R(l,p)}{R_{req,l}}}}}{\lambda} \tag{4}$$

where K is another shaping parameter and λ is a normalization factor to ensure that the maximum of the fittingness factor is equal to 1. Specifically, after some algebraic computations it can be easily obtained that:

$$\lambda = 1 - e^{-\frac{K}{(\xi-1)^{\frac{1}{\xi}}+(\xi-1)^{\frac{1-\xi}{\xi}}}} \tag{5}$$

Note that the second function (4) targets a more efficient usage of pools by penalizing the fittingness factor if $R(l,p)$ is much larger than $R_{req,l}$.

B. Fittingness Factor computation and update

According to the previous definitions, fittingness factors can be computed either by an estimation of the different parameters involved in (2) or by an actual measurement of the achieved bit rate on the radio link. At initialization, the computation of $F_{l,p}$ needs to be based on estimated values of the different parameters. Nevertheless, the proposed approach is to take advantage of previous experience, when available, to update the value of the fittingness factor in accordance with the actual conditions of an assigned pool p^*. Therefore, the update of the fittingness factor can be based on a reward r_{l,p^*} capturing the actual bit rate $R_{meas}(l,p^*)$ measured in the assigned pool p^* as follows:

$$r_{l,p^*} = F_{l,p^*}|_{R(l,p^*)=R_{meas}(l,p^*)} \tag{6}$$

Based on the obtained reward, a possible updating rule is:

$$F_{l,p} \leftarrow F_{l,p} + \beta \times (r_{l,p^*} - r_{acc,l,p^*}) \tag{7}$$

where r_{acc,l,p^*} is the accumulated reward computed as the exponential average of the series of reward values:

$$r_{acc,l,p^*} \leftarrow \gamma \times r_{acc,l,p^*} + (1-\gamma) \times r_{l,p^*} \tag{8}$$

The next section will detail how the overall updating is carried out in the framework of the spectrum selection decision-making process.

III. FITTINGNESS FACTOR IN SPECTRUM SELECTION DECISION-MAKING

The proposed fittingness factor function claims to have applicability in the spectrum selection decision-making process. In general, this decision whose aim is to decide which spectrum pool is allocated to each application is needed in different events: (1) when a new CR application starts, a spectrum pool has to be assigned for the corresponding wireless communication, (2) when a channel pool in use is no longer available to support the CR application. In this case, a spectrum HandOver (HO) is required and, therefore, an alternative channel pool should be assigned to seamlessly continue the CR application or (3) when the quality perceived by the application in the spectrum pool currently in use is not satisfactory and, therefore, a spectrum HO is also required.

In any of the above events, the procedure to establish a radio link for application l is detailed in the following:

1) Obtain from a spectrum opportunity identification functionality the set of candidate spectrum pools that can be assigned to this radio link. If there is no pool available, the request is rejected.
2) Obtain all fittingness factors $F_{l,p}$ for the different pools. If a given pool p has never been used yet by application l, the value of $F_{l,p}$ is computed based on estimations of the different parameters according to (3) or (4). On the contrary, if pool p has already been used, $F_{l,p}$ will result from the update based on the actual experienced bit rate as detailed in step 4.
3) Perform spectrum selection based on $F_{l,p}$ in accordance with some decision-making criterion. Here, different possibilities arise. The simplest one is to consider a greedy algorithm that selects the spectrum pool p^* with the largest fittingness factor:

$$p^* = \arg\max_{p}(F_{l,p}) \tag{9}$$

In order to get a first insight into the relevance of the fittingness factor concept, the greedy algorithm is considered, while it is envisaged as part of future work to consider other possibilities such as Softmax decision-making, multi-objective optimisation, etc.

4) After having allocated pool p^*, the following steps are performed every $\triangle T$ until the application ends:
   a) Measure the actual obtained bit rate $R_{meas}(l, p^*)$.
   b) Update the reward r_{l,p^*} according to (6) and $R_{meas}(l, p^*)$.
   c) Update the fittingness factor F_{l,p^*} according to (7).
   d) Update r_{acc,l,p^*} according to (8).

IV. SIMULATION RESULTS

In order to illustrate the capabilities of the proposed fittingness factor functions, this section firstly makes an analysis of the ability to capture interference variations in different pools. Secondly, a comparison between the two fittingness factor functions is performed in terms of spectrum selection performance.

A. Assumptions

The considered scenario assumes a set of P=4 spectrum pools. They are built from blocks of BW=$200KHz$, and the number of blocks of each pool is N_1=N_2=2 and N_3=N_4=6. The maximum allowed power is P_{max}=$2W$ for all the pools and it coincides with the maximum power of the terminals (i.e. $P_{max,p}$=$P_{max,l}$=P_{max} for all l, p). The propagation loss is also assumed be equal for all pools and is computed using a free space model at distance 50m and frequency 2.4GHz.

Each pool is assumed to experience a different amount of interference I_p, following a daily temporal pattern as described by Fig. 1. Notice that a constant interference power spectral density (PSD) I_1=I_2=$3.10^{-13}W/Hz$ is considered for pools 1 and 2 while a two-level PSD pattern alternating between $I_{3,min}$=$I_{4,min}$=$3.10^{-13}W/Hz$ and $I_{3,max}$=$I_{4,max}$=$70.10^{-13}W/Hz$ is considered for pools 3 and 4. With these interference levels it is obtained that $R_{meas}(l,1)$=$R_{meas}(l,2)$=$512Kbps$, while $R_{meas}(l,3)$=$R_{meas}(l,4)$=$1536Kbps$ for low interference levels, and $R_{meas}(l,3)$=$R_{meas}(l,4)$=$96Kbps$ for high interference levels. L=2 radio links are considered. 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 ($R_{req,2}$=$1Mbps$, $T_{req,2}$=$20min$). Independent traffic loads are considered for each link, λ_l being the arrival rate over the l-th link that is varied during the simulations.

As far as spectrum selection is concerned, the greedy decision making approach explained in Sec. III is considered. The focus is on spectrum assignments performed at initial access. This means that no spectrum HOs is performed even if the quality perceived by the application in the pool currently in use is not satisfactory. Instead, a dissatisfaction metric is collected to benchmark the performance attained. It is specifically measured as the probability of experiencing a bit rate below the requirement $R_{req,l}$.

Performance is obtained with a system-level simulator during a simulation time of 2 days (where in each day the same daily pattern of Fig. 1 is repeated) with $\triangle T$=$0.01s$. All updates/estimations are made using ξ=5, β=0.2, γ=0.2 and K=1.

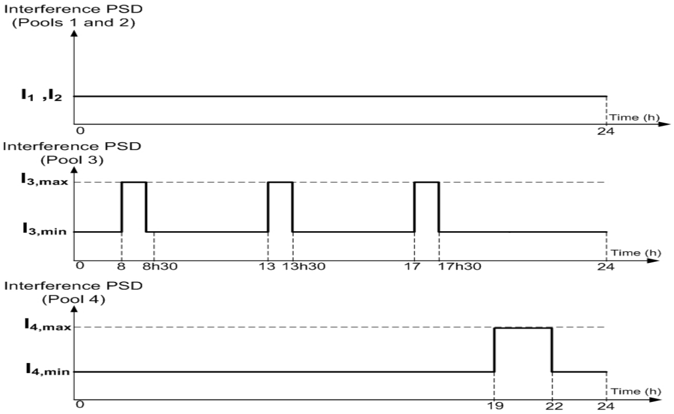


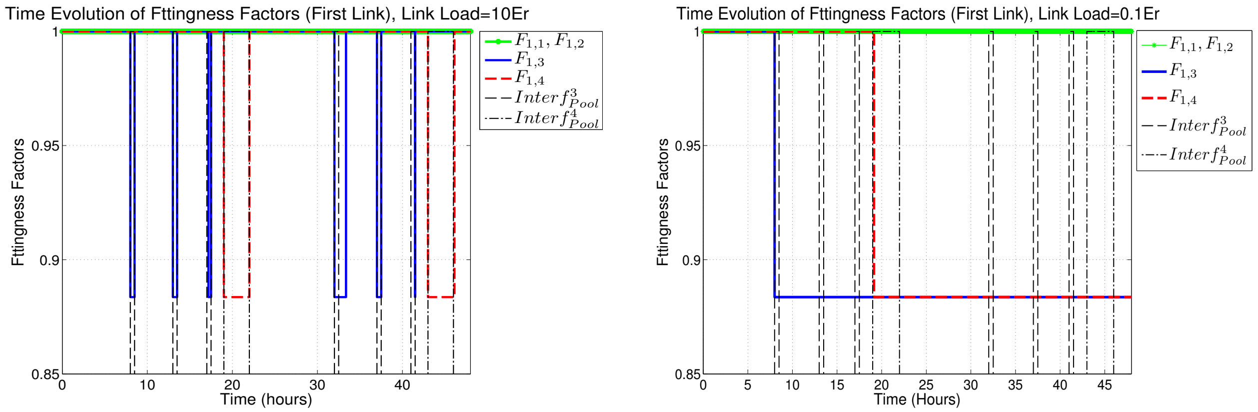
Fig. 1: Daily pool interference patterns

B. Evaluation of Fittigness Factor capability to track changes

The analysis of the capability of fittingness factors to track changes in interference levels is carried out using the first function in which fittingness factor equals the utility.

Fig. 2 and Fig. 3 respectively illustrate the time evolution of fittingness factors of each pool for the first and second links under different traffic loads. Discontinuous black lines represent the instants when the interference conditions change in the third and forth pools. For high load conditions -Fig. 2(a) and Fig. 3(a)- it is observed that fittingness factors of both links react fast to changes in interference levels. The reason is that, once interference level increases for one pool (e.g. at t=$8h$ for the third pool), there is always an active link on that pool due to the high traffic load which makes the corresponding $F_{l,p}$ be quickly reduced. Then, once the interference burst is over, (e.g. at t=$8h30m$ for the third pool), the pool would initially keep the low value of $F_{l,p}$ associated to the case when interference was present (i.e. $F_{1,3}$=0.88 for link 1 or $F_{2,3}$=0 for link 2) and correspondingly the greedy algorithm will tend to exclude it from the assignment. Nevertheless, due to the considered high traffic load, in a future spectrum decision it will happen that all pools with high fittingness factor values will be occupied and e.g. the third pool will eventually be assigned again to a given link. When this happens, the measured quality over the radio link will reveal that the third pool is again providing good performance and, correspondingly, its $F_{l,p}$ will get eventually increased. Notice that some interference change events of the third pool are missed by the second link meaning that they occur without any change in fittingness factor values (see e.g. Fig. 3(a) during the interference change at 13h that is missed during the first day while it is captured in the second day). This can occur whenever there is no active link during the periods when the interference increases in a pool.

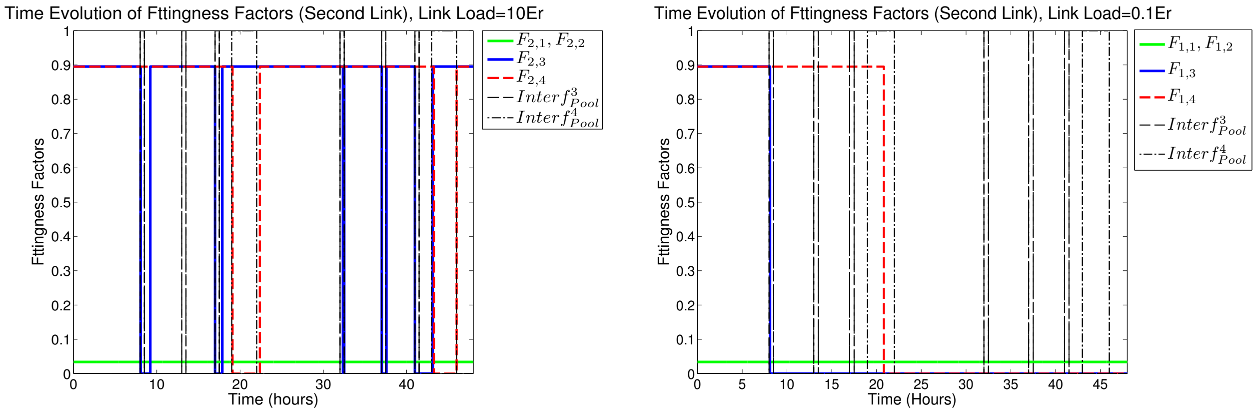
In turn, Fig. 2(b) and Fig. 3(b) illustrate the case of low traffic loads. The main observation is that, once interference level increases for the first time for a given pool, the fittingness factor associated to both links (both CR applications) is reduced and then kept unchanged during the remaining simulation time. The reason is that, under such low traffic load, the greedy approach is preventing accessing again the pool whose fittingness factor has been reduced since there is always another available pool with higher fittingness factor.



(a) High Traffic load ($\lambda_l \times T_{req,l}$=$10Er$)

(b) Low Traffic load ($\lambda_l \times T_{req,l}$=$0.1Er$)

Fig. 2: Time evolution of fittingness factors of the first link



(a) High Traffic load ($\lambda_l \times T_{req,l}$=$10Er$)

(b) Low Traffic load ($\lambda_l \times T_{req,l}$=$0.1Er$)

Fig. 3: Time evolution of fittingness factors of the second link

Even though the observed behavior tracks well changes in interference levels, it does not efficiently manage available spectral resources. To illustrate this fact, let consider for instance the low traffic load case and the first link in Fig. 2(b). Before the interference increases, at t<$8h$ the third and forth pools are preferred since $F_{1,3}$=$F_{1,4}$>$F_{1,1}$=$F_{1,2}$. Correspondingly, the low-data-rate sessions tend to be allocated in pools 3, 4 (that provide a bit rate of 1536Kbps), although their required bit rate of 64Kbps could also be achieved on pools 1 and 2 that provide 512Kbps. Such allocation will impact on the high-data-rate sessions of link 2 that can only be successfully served when using pools 3 and 4 and will find these pools many times occupied by link 1.

C. Comparison between the two Fittingness Factor functions

Fig. 4 illustrates a comparison between link dissatisfaction probabilities for the fittingness factor functions 1 and 2 as far as the second link is concerned. Link dissatisfaction probability is defined as the probability of observing a bit rate below the CR application requirement $R_{req,l}$. Results for the first link are not presented since it is all the time satisfied because the achievable bit rate is always above the requirement of 64Kbps regardless the allocated pool and its interference conditions.

Results show that function $f_2(U_{l,p})$ is outperforming $f_1(U_{l,p})$ for all traffic loads with the gain reducing as traffic load increases. The observed reduction in the dissatisfaction probability ranges from 65% for medium traffic load (1Er) to 15% for high traffic load (5Er). This is basically justified by the intuition behind $f_2(U_{l,p})$ trying to assign just the required resources to a given link. As a matter of fact, $f_2(U_{l,p})$ tends to assign as much as possible pools 1 and 2 to the first link since they can support the required throughput ($R_{meas}(1,1)$=$R_{meas}(1,2)$>$R_{req,1}$) with the minimum resources ($R_{meas}(1,1)$<$R_{meas}(1,3)$=$R_{meas}(1,4)$). This tends to leave pools 3 and 4 available for the second link that would not be served adequately with the pools 1 and 2.

This situation is clearly illustrated by Table I that gives the distribution of pool usage by both links for both fittingness factor functions for a traffic load of 1 Er. For $f_1(U_{l,p})$, the first link uses 71% of the time pools 3 and 4, which forces the second link to access pools 1 and 2 during 55% of the time. This significantly increases the dissatisfaction probability since $R_{meas}(2,1)$=$R_{meas}(2,2)$<$R_{req,2}$. As far as $f_2(U_{l,p})$ is concerned, the first link uses only 8% of the time pools 3 and 4 which keeps them for the second link usage (82% of the time). This reduces the dissatisfaction probability since $R_{meas}(2,3)$=$R_{meas}(2,4)$>$R_{req,2}$.

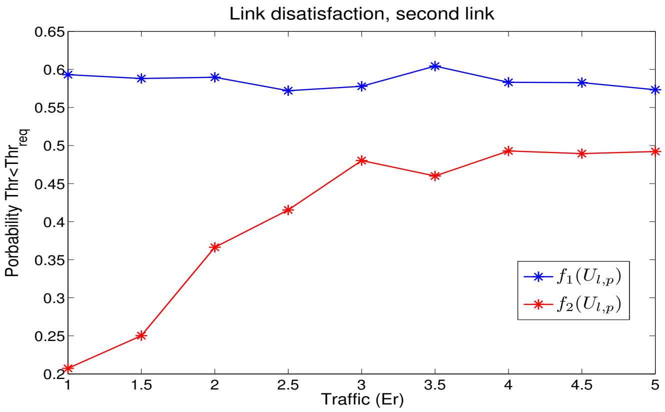


Fig. 4: Link dissatisfaction of the second link

TABLE I: Pool usage distribution for traffic=1Er

	$f_1(U_{l,p})$				$f_2(U_{l,p})$			
	Pool 1	Pool 2	Pool 3	Pool 4	Pool 1	Pool 2	Pool 3	Pool 4
link 1	0.14	0.14	0.25	0.46	0.45	0.46	0.03	0.05
link 2	0.31	0.24	0.34	0.10	0.10	0.06	0.37	0.45

V. CONCLUSIONS AND FUTURE WORK

This paper has proposed a new fittingness factor concept that captures the suitability of spectral resources exhibiting time-varying characteristics to support a set of heterogeneous CR applications. Two different fittingness factor functions have been proposed and analysed in a scenario with unknown interference variations in certain spectrum pools. The capability of these functions to track the fittingness of spectral resources has been first analysed. Thanks to the inclusion of a reward-based fittingness factor update, fittingness factors have been proven to efficiently capture interference variability for medium-to-high traffic loads. Then, the impact of fittingness factors over the spectrum selection decision-making process in a multi-service context has been evaluated. Results show that, even with a simple greedy approach, an efficient matching of spectral resources to the requirements of CR applications can be achieved, thus resulting in significant reduction in the dissatisfaction probability. Motivated by the proven usefulness of fittingness factor, as future work we intend to explore other strategies for spectrum decision in addition to the greedy approach that has been considered. Besides, the proposed fittingness factor framework is envisaged to be extended with learning mechanisms aiming at consolidating the observations gained with its adaptability.

ACKNOWLEDGEMENTS

This work is performed in the framework of the European-Union funded project OneFIT (www.ict-onefit.eu). The project is supported by the European Community's Seventh Framework Program (FP7). The views expressed in this document do not necessarily represent the views of the complete consortium. The Community is not liable for any use that may be made of the information contained herein. The work is also supported by the Spanish Research Council and FEDER funds under ARCO grant (ref. TEC2010-15198)

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 *PIMRC Workshops*, 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. Mahonen, "Using cognitive radio principles for wireless resource management in home networking," in *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. Akyldiz, "A spectrum decision framework for cognitive radio networks," *Mobile Computing, IEEE Transactions on*, vol. 10, no. 2, pp. 161–174, feb. 2011.
[17] "Reconfigurable Radio Systems, functional architecture for the management and control of reconfigurable radio systems," ETSI TR 102 682, Tech. Rep.
[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.