Power Allocation Strategy for Cognitive Radio Terminals

E. Del Re, F. Argenti, L. S. Ronga, T. Bianchi, R. Suffritti

CNIT-University of Florence
Department of Electronics and Telecommunications
Via di S. Marta 3, Firenze 50139 Italy
E-mail:{enrico.delre, fabrizio.argenti, luca.ronga, tiziano.bianchi, rosalba.suffritti}@cnit.it
phone/fax: +39 055 4796485

***Abstract*—Traditional communications systems imply an a priori association of the frequency band, the service assigned to it and the used technology. Breaking this static association can provide much more flexible, efficient and easy-to-use dynamic systems able to cope with the requirements and constraints of the environment and the users. *Cognitive Radio* and *Software Defined Radio* modify this current communication paradigm. They provide the enabling technologies to perceive, learn, reason and interact accordingly in open-ended changing environments for the coexistence of different services and systems technologies on the same radio bands. They benefit from the recent advances in digital signal processing, fast computing and advanced reception techniques. This paper evaluates the performances of a cognitive radio approach to the coexistence problem for two application scenarios: a meshed OFDM-based secondary wireless service in coexistence with a primary terrestrial and satellite DVB-SH system.**

I. INTRODUCTION

The term *cognitive radio* (CR) was introduced in [1] with reference to a communication system able to observe and learn from the surrounding environment as well as to implement and adapt its own transmission modalities also to user requirements. The concept of CR is originated from the contrast between an increasing demand of broadband services and the scarcity of radio resources. Recent studies of the FCC Spectrum Policy Task Force demonstrated that a large amount of licensed bands are under-utilized [2], i.e., a lot of spectral resources are reserved for specific services, but, actually, they remain unused for most of the time or unused in several locations. From these studies, the possibility of a CR system is envisaged, i.e., a system able to sense the electromagnetic environment (spectrum sensing), detect the spectral resources actually occupied in a given temporal interval and in a given location, and use the free bands (holes) for its own communication [3]. The search for available resources is not limited to spectrum portions dedicated to unlicensed communications, but is also extended to licensed bands. In this case, a CR system, called the *secondary system*, must coexist with a *primary system*, i.e., the license owner, without producing harmful interference, as shown in figure 1. Both earth and satellite systems can be considered for the role of primary and secondary users.

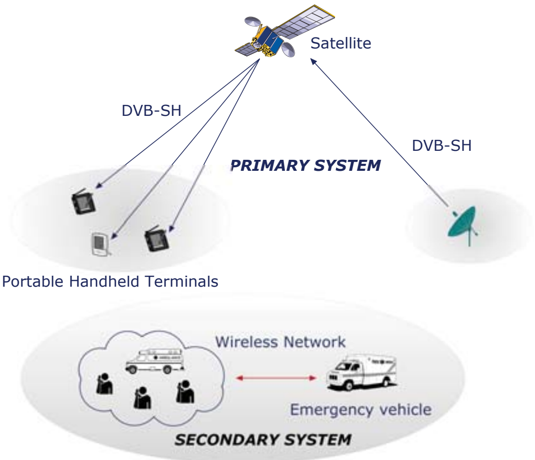

Fig. 1. Cognitive scenario

A CR system assumes that there is an underlying system hardware and software infrastructure that is able to support the flexibility demanded by the cognitive algorithms [4]. In this case the abstraction of hardware capabilities for radio software architecture is a primary design issue because is desirable to isolate the cognitive engine from the underlying hardware. In this context, the Software Defined Radio (SDR) represents the essential enabling technology for its characteristics. SDR is a methodology for the development of applications in a consistent and modular fashion such that both software and hardware components can be promptly reused for different implementations. SDR technology can also provide an advanced management of the available resources and facilitate the definition of interfaces for the coexistence of different communication services. As a potential application, CR systems represents an effective solution to the problem of the deployment of a communication network to face an emergency situation. In such a situation, it may happen that a public mobile network (e.g., GSM or UMTS) is either no more available or overloaded and it can be necessary to provide flexibility to the emergency network where with the term flexibility it is meant the capability to extract information from the environment and the operating context and to adapt accordingly the transmission modality, i.e., the capability of using different carrier frequencies, different bandwidths, even discontinuous, in a time-varying mode and with the possibility to use a variety of communication protocols and standards.

This paper shows the potential benefits of the adoption of a cognitive radio strategy to the coexistence problem. It explores a fully terrestrial and a mixed satellite/terrestrial scenarios, showing the achievable performances in terms of rate spectral efficiency. The paper is organized as follows. In Section II the considered scenarios are presented in detail. In Section III the adopted cognitive strategy is described while in Section IV the simulation results are presented. The concluding remarks are given in Section V.

II. SCENARIOS

CR strategies are strictly related to their operating environment. The considered scenarios have the objectives to investigate on the coexistence problem; i.e. the exploitation of unused radio resources of two different primary systems, a terrestrial infrastructure and a satellite system by a mesh-based terrestrial telecommunication service. All the considered systems are OFDM based, but they exhibit different propagation conditions.

A. All Terrestrial Context

The first analysis has been conducted on a scenario composed by licensed primary system and a "cognitive" secondary system. Both are terrestrial systems and are characterized by a single transmitter and a single receiver. The two systems are not independent since they share the same radio resource. The signal from each transmitter represents a interfering component to the other system receiver. The transmitted signal within an OFDM symbol is represented in the frequency domain by a complex vector of length M equal to 128 that represents the number of the considered subcarriers.

The secondary system operates with OFDM with the same carrier spacing as the primary one. It has, however, a more flexible power allocation scheme. Being *cognitive*, the operating parameters like frequency, modulation and power are modified by its software radio implementation. The possible modulations for the proposed secondary system are QPSK, 16-QAM and 64-QAM. With a constant bit error probability, the minimum required signal-to-noise ratio depends on the modulation order. The actual transmission mode is automatically selected by the secondary device based on the available sensed information.

1) Channel Model: The received signal is corrupted by different phenomena: a *path loss* term due to the transmitted distance calculated at the middle-band frequency, and a *multipath* fading due to the propagation environment and terminal motion.

The path loss is modeled by:

$$L = 10\,log_{10}\left(\frac{4\pi d}{\lambda_0}\right)^{\alpha} dB \tag{1}$$

where the exponent α models the attenuation dependence from the distance, λ_0 is the central frequency wave length and d is the transmitter distance from the receiver. In the time-domain the channel exposes a finite impulse response of L samples, resulting in a frequency selective channel response. A tapped-delay model with Rayleigh distributed coefficients has been adopted. The power delay profile is exponential as follows:

$$\sigma_n^2 = e^{-\beta n} \tag{2}$$

where σ_n^2 is the variance of the n-th coefficient and β is computed for a normalized mean power response.

B. The Mixed Terrestrial/Satellite Context

Differently from the case previously described, the second analysis has been conducted on a mixed scenario characterized by licensed satellite primary system and a terrestrial "cognitive" secondary system. In particular, the primary system is a mobile satellite system based on DVB-SH standard [5], while the secondary one is a terrestrial wireless meshed network that could be used to emergency situations. The two considered systems work in L band (0.39-1.55 GHz) and exploit a context of coexistence in which the secondary one is allowed to take resources from another system without interfering in its normal operations. The representation in the frequency domain of the transmitted signal within an OFDM symbol is the same which is presented for the first scenario but, in this case, the number of considered subcarriers, M, is equal to 853.

The secondary system operates with OFDM with the same carrier spacing as the primary one, but being *cognitive*, it has a more flexible power allocation scheme. The operating parameters like frequency, modulation and power are modified by its software radio implementation. The possible modulations for the proposed secondary system are QPSK, 16-QAM and 64-QAM. The actual transmission mode is automatically selected by the secondary device based on the available sensed information.

1) Channel Model: The propagation channel for the considered mobile satellite channel at L-band is the Lutz (et al.) model [6]. It is based on a two-state (GOOD-BAD) Markov-chain for the fading process. According to this class of models, the amplitude of the fading envelope is divided into fast and slow fading. Slow fading events, normally due to large obstacles, are modelled as a finite state machine. Fast fading events, due to the irregularity of the obstacles (e.g. vegetative shadowing) and to the multipath propagation phenomenon can be additionally represented as superimposed random variations that follow a given probability density function (PDF) for each state. This channel, differently from the previous one, has a flat frequency response.

Also in this case, the *path loss* term due to the transmitted distance calculated at the middle-band frequency, has to be considered in the channel model. It is like that used in the all terrestrial scenario.

III. THE ADOPTED COGNITIVE STRATEGY

The adopted cognitive strategy is derived for a secondary system able to collect all the relevant propagation information of both system. Results are derived also in the case an estimation errors of the sensing process. The power transmitted vector of the primary system, the channel impulse response and the statistical measures of the thermal noise are considered known by the secondary system. The considered system is regulated by (3) and (4):

$$P_{R1} = C_{T1,R1}P_{T1} + C_{T2,R1}P_{T2} + N_1 \tag{3}$$

$$P_{R2} = C_{T2,R2}P_{T2} + C_{T1,R2}P_{T1} + N_2, \tag{4}$$

where P_{Rx} are the received power vector, $C_{Tx,Rx}$ are the instantaneous channel matrices, P_{Tx} are the transmitted power vectors and N_x are the noise power vectors. The solution space is represented by the P_{T2} power vector, obtained by the Cognitive Radio strategy. It is substantially a constrained multi-variable maximum finding. The objective is:

1) Maximize the secondary bit-rate with a maximum tolerable BER
2) Maintain the primary below a target BER

The power allocation procedure for the secondary system is conducted in two phases:

- the computation of the power constraints
- the computation of the power and selection of modulations

2) computation of the power constraints: The first constraint is the total amount of power transmitted by the secondary device. This is ruled by:

$$\sum_{k=1}^{M} P_{T2}(k) \leq P_{T2tot} \tag{5}$$

The power can be arbitrarily distributed among the considered subcarriers. A constraint is derived for the signal to noise and interference ratio at the primary receiver. For each subcarrier k two possible cases are present before the secondary transmission:

$$SINR_{R1}(k) < SINR_{R1min} \tag{6}$$

$$SINR_{R1}(k) \geq SINR_{R1min} \tag{7}$$

In the first case of (6), the primary system does not reach alone an adequate $SINR$ level and the secondary can exploit the carrier. In the second case of (7), the secondary reach the target $SINR$ and potentially provides an useful noise-plus-interference margin to be exploited by the secondary. In the latter case the $SINR$ level must be recomputed after the secondary transmission, in order to verify the primary constraint:

$$P_{T2}(k) \leq \frac{P_{T1}(k)C_{T1,R1}(k) - N_1(k)SINR_{R1min}}{SINR_{R1min}C_{T2,R1}(k)} \tag{8}$$

Also the secondary system has a lower-bound on $SINR$, derived from the desired BER target. Initially the simpler modulation is considered (i.e. QPSK) to compute the lower secondary $SINR$. If possible, a modulation upgrade is performed recursively, maintaining the secondary BER target. The secondary constraint if formally applied as follows:

$$P_{T2}(k) \geq \frac{SIR_{R2min}(P_{T1}(k)C_{T1,R2}(k) + N_2(k))}{C_{T2,R2}(k)} \tag{9}$$

The constraints can sometime be contradictory; in this case the applied rule is to protect the primary service.

A. Secondary power allocation and modulation selection

The underlying idea is the creation of a power allocation matrix for the secondary allocation, iteratively updated until a stop condition is reached (i.e. when the total amount of secondary power is reached). We allocate the power to the secondary subcarrier with an iterative process:

1) The first step creates a $3M$ matrix with the power necessary for the secondary to obtain the minimum $SINR$, for the three modulations. The power values depend only on secondary target BER and the instantaneous channel status. The power allocation scheme follows the general rule of allowing the secondary system the minimum amount of power to obtain the target BER;
2) the next step incorporates the constraints into the allocation matrix. The subcarrier-modulation cells with incompatible constraints are filled with zeros. Where the primary channel status allows it, it may happen that more than a modulation can be used on a carrier;
3) next, a new matrix is computed, containing the power increments which allow a modulation upgrade for the secondary on each carrier. In particular, the first row (QPSK modulation), contains for each carrier the power to allocate to obtain the desired BER with a QPSK modulation. The second row contains the power increment to allocate to the secondary in order to obtain the same BER without violating the primary constraints. The third row as before for the next modulation order;
4) the minimum power of the incremental matrix is selected;
5) the total amount of secondary power is computed, if it is not greater than P_{T2tot} the step 1) is repeated, otherwise the solution is applied.

It is worth noting that at each iteration there are two possible choices: allocate a new carrier to the secondary with a QPSK modulation or perform a modulation upgrade (i.e. QPSK to 16-QAM, 16-QAM to 64-QAM) on a carrier already allocated to the secondary service. The choices are equivalent in term of rate increment and it is selected the one with the minimum required power.

IV. RESULTS

In the next sections the proposed CR strategy is validated through computer simulations for both the considered scenarios. The terrestrial propagation exponent (α) is considered equal to 3, valid for a medium density urban scenario while for the satellite scenario the value of α is assumed equal to 2.

A. All Terrestrial Context

The performance of the proposed CR strategy for the all terrestrial scenario has been evaluated with computer simulations, considering the achieved rate of the secondary system as the main performance index.

Simulations have been conducted for six target BER values of the secondary system in the range $(10^{-3} - 10^{-8})$ and for three E_b/N_0 values for the primary receiver: 10 dB, 15 dB and 20 dB. The primary achieved rate depends only on the primary receiver E_b/N_0, since the cognitive radio strategy always preserve the primary rates.

The considered context has a terminal displacement as in the figure 2. Units are normalized to the primary distances.

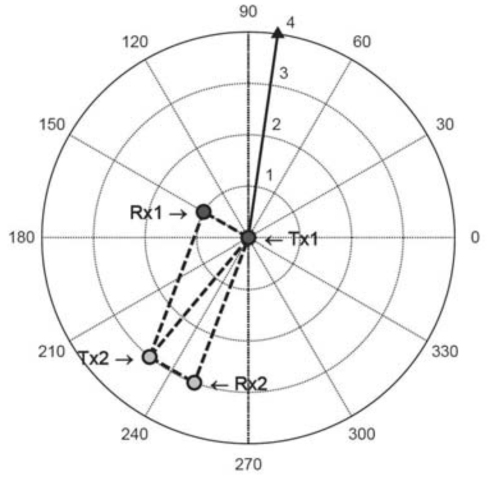

Fig. 2. All terrestrial terminals displacements

The performance of the secondary system heavily depend on the target BER. In figure 3, for each E_b/N_0 value of the primary, it is reported the BER values in log-scale function of the achieved secondary rate. In this case it is worth noting that, for a fixed BER, the achieved rate increases as the primary $SINR$ increases. This is a well known limitation of Cognitive Radio systems, where low $SINRs$ at the primary heavily impair the secondary achievable performances.

Another interesting element is represented by the modification of the experimented $SINRs$ at the primary and secondary receivers before and after secondary transmission. Figure 4 reports for each subcarrier the primary (left) and secondary (right) SNR before and after secondary activation, for a fixed secondary BER.

The primary $SINR$ values are 10, 15 and 20 dB. The secondary BER is fixed to 10^{-3}. The dashed line represents the $SINR$ before the secondary activation. The channel frequency selectivity provide a variable response for both systems. As in the figure 4, the cognitive process places power where the secondary channel is in a good state, and after its activation, the corresponding primary $SINR$ lowers (i.e. the interference from the secondary increases). The larger is E_b/N_0, the larger is the number of carriers where the secondary is allowed to allocate power; this explains the operating point dependence of figure 3.

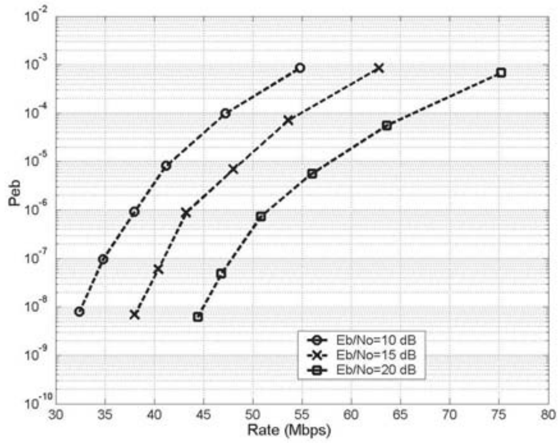

Fig. 3. BER vs. Rate for the secondary system

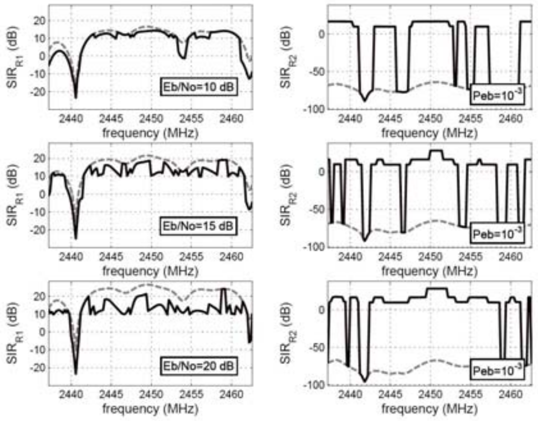

Fig. 4. SINR vs frequency for the primary (left) and secondary (right) systems

B. The Mixed Terrestrial/Satellite Context

Also for the mixed terrestrial/satellite scenario it is considered, as the main performance index, the achieved rate of the secondary terrestrial system. In this case, the six target BER values of the secondary system are different with respect to the all terrestrial scenario and they are in the range $(10^{-2} - 510^{-5})$; the three E_b/N_0 values for the primary receiver are, instead, the same of the previous case: 10 dB, 15 dB and 20 dB. For this context, two different environments, CITY and HIGHWAY, have been considered. The terminal displacements are shown in the figure 5. It is considered that the secondary terminals, T_{X2} and R_{X2}, are fixed and their distance is set to 50 meters while the receiver of the primary system, R_{X1}, approaches the secondary cluster at different distances. The performance have been evaluated for three distance values among the three terminals: $100-100-50$ meters, $70-70-50$ meters and $50-50-50$ meters.

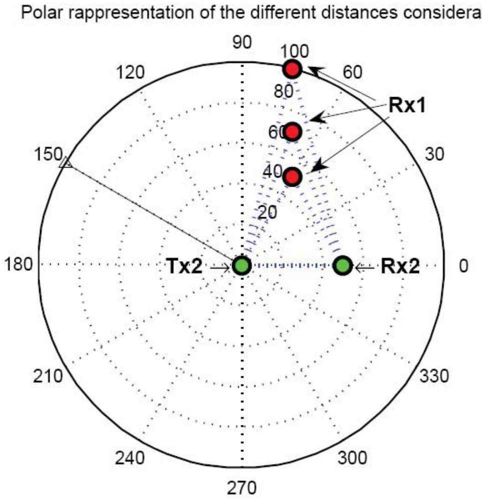

Fig. 5. Terminal displacements

In figure 6, for each distance and for each E_b/N_0 value of the primary, it is reported the rate value in CITY environment with the target BER equal to 10^{-2}. It is important to note that as the distances decreases, the secondary rate decreases as well.

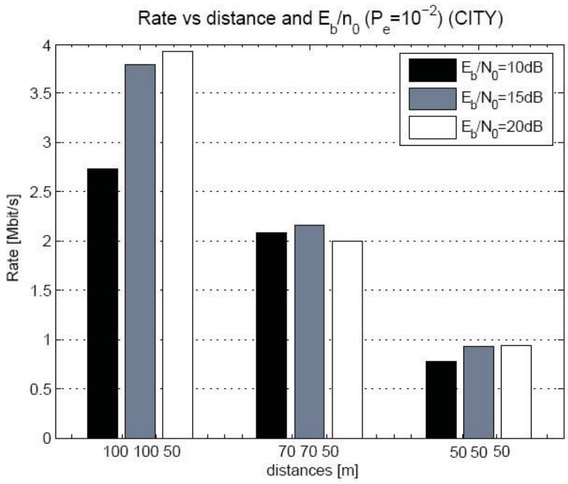

Fig. 6. Secondary Rate vs. Distances (city environment)

Another interesting element is to consider the rate performance for the two analysed environments; in figure 7, we can see that the achieved secondary rate is lower in the CITY case. This is due to the presence of a strong shadowing resulting in a impaired reception of the primary signal. The cognitive strategy has to guarantee the primary rate so the secondary has to minimize its transmission.

V. CONCLUDING REMARKS

Cognitive Radio is one of the most promising solutions to the coexistence problem, the software defined radio being its enabling technology. A practical CR strategy is presented in the paper, where a secondary OFDM system can exploit the radio resources unused by a licensed primary system. Performances in terms of rate for the secondary system show that under the considered scenarios, terrestrial and hybrid satellite/terrestrial, the proposed strategy is able to maximize secondary bitrate by maintaining unchanged the target performances of the corresponding primary service.

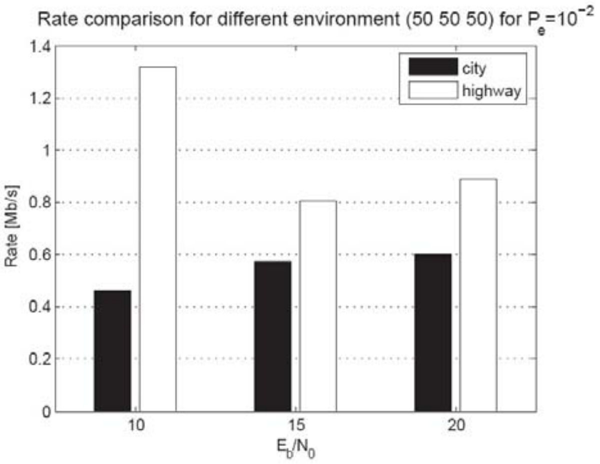

Fig. 7. Rate vs. E_b/N_0 for different environments

ACKNOWLEDGMENT

The authors would like to thank Lorenzo Mayer, Alessandra Romoli and Cristina Bartoloni for their relevant contribution to the work presented in this paper.

REFERENCES

[1] J. Mitola, *"Cognitive Radio: Making software radios more personal"*. IEEE Pers. Commun., Aug. 1999

[2] FCC Spectrum Policy Task Force, *"FCC Report of the Spectrum Efficiency Working Group"*, Nov. 2002, http://www.fcc.gov/sptf/files/SEWGFinalReport1.pdf/

[3] S. Haykin, *"Cognitive Radio: Brain-Empowered Wireless Communications"*. IEEE Journal on Selected Areas in Communications, vol.23, No.2, February 2005

[4] *Cognitive Radio Technology*, Editor Bruce Fette, Newnes, 2006

[5] DVB-SH European Standard,*Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for Satellite Services to handheld devices (SH) below 3Ghz*, Draft ETSI EN 302 583, v. 1.0.0, 2007–08.

[6] E. Lutz,Daniel Cygan, Michael Dippold, Frank Dolainsky, and Wolfgang Papke *"The Land Mobile Satellite Communication Channel-Recording, Statistics, and Channel Model"*, IEEE Transaction on Vehicular Technology, vol.40, No.2, May 1991