Cognitive Radios and their Role in Efficient Allocationof the Spectrum

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Abstract

Today's wireless networks are characterized by fixed spectrum assignment policy. The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. This new networking paradigm is referred to as Dynamic Spectrum Access (DSA) and cognitive radio networks. Cognitive radio is a paradigm for wireless communication in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently avoiding interference with licensed or unlicensed users. In practice, the spectrum allocated to licensed primary users is not utilized properly. The secondary unlicensed users can sense and utilize the unutilized spectrum.

Keywords: *Wireless, Network, Communication, Cognitive*

Introduction

The idea of cognitive radio was first presented officially in an article by Joseph Mitola III and Gerald Q. Maguire, Jr in 1999. It was thought of as an ideal goal towards which a software-defined radio platform should evolve: a fully reconfigurable wireless black-box that automatically changes its communication variables in response to network and user demands.

Regulatory bodies in various countries (including the Federal Communications Commission in the United States, and Ofcom in the United Kingdom) found that most of the radio frequency spectrum was inefficiently utilized. For example, cellular network bands are overloaded in most parts of the world, but amateur radio and paging frequencies are not. Independent studies performed in some countries confirmed that observation and concluded that spectrum utilization depends strongly on time and place. Moreover, fixed spectrum allocation prevents rarely used frequencies (those assigned to specific services) from being used by unlicensed users, even when their transmissions would not interfere at all with the assigned service. This was the reason for allowing unlicensed users to utilize licensed bands whenever it would not cause any interference. This paradigm for wireless communication is known as Cognitive Radio Spectrum Allocation. More specifically, the cognitive radio technology will enable the users to determine which portions of the spectrum is (1) available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing), (2) select the best available channel (spectrum management), (3) coordinate access to this channel with other users (spectrum sharing), and (4) vacate the channel when a licensed user is detected (spectrum mobility). The main functions of Cognitive Radios are:

(i) Spectrum Sensing: It refers to detect the unused spectrum and sharing it without harmful interference with other users. It is an important requirement of the Cognitive Radio network to sense spectrum holes, detecting primary users is the most efficient way to detect spectrum holes. Spectrum sensing techniques can be classified into three categories:
  - Transmitter detection: Cognitive radios must have the capability to determine if a signal from a primary transmitter is locally present in a certain spectrum, there are several approaches proposed:
    - matched filter detection
    - energy detection
  - Cooperative detection: It refers to spectrum sensing methods where information from multiple Cognitive radio users are incorporated for primary user detection.
  - Interference based detection.

(ii) Spectrum Management: It is the task of capturing the best available spectrum to meet user Communication requirements. Cognitive radios should decide on the best spectrum band to meet the Quality of Service requirements over all available spectrum bands, therefore spectrum management functions are required for Cognitive radios, these management functions can be classified as:
  - Spectrum analysis
  - Spectrum decision

(iii) Spectrum Mobility: It is defined as the process when a cognitive radio user exchanges its frequency of operation. Cognitive radio networks target to use the spectrum in a dynamic manner by allowing the radio terminals to operate in the best available frequency band, maintaining seamless communication requirements during the transition to better spectrum

(iv) Spectrum Sharing: It refers to providing the fair spectrum scheduling method, one of the major challenges in open spectrum usage is the spectrum sharing.

Cognitive radios

Cognitive radios, or “smart radios”, are likely to be constructed from the next generation of software-defined radios. The FCC defines a cognitive radio as “a radio that can change its transmitter parameters based on interaction with the environment in which it operates” . They also point out that “the majority of cognitive radios will probably be SDRs, but neither having software nor being field reprogrammable are requirements of a cognitive radio”. The idea behind cognitive radio is that cognitive users will actively search the spectrum for available frequency bands, dynamically adjusting their transmissions so as to avoid interference with other users. These users could be legacy systems or other cognitive devices. Cognitive radio is frequently cited by policy analysts as a powerful argument against the exclusive-use spectrum model, and it is one of the ideas currently being pursued under the umbrella of DARPA’s Next Generation (XG) program. Nevertheless, fundamental questions of cognitive radio’s practicality still remain open. First, can practical cognitive systems even operate without causing excessive interference to legacy users? Proving so is essential to convincing the FCC to open more spectrums to “flexibly licensed” devices. Second, can useful wireless systems operate under these constraints? In this thesis we target the former issue, focusing on non-interference to the primary system rather than realizable benefits for secondary systems. We show the existence of constraints that allow multiple cognitive radios to transmit at reasonable power levels while maintaining a guarantee of service to legacy/priority users on the same band. We do not consider achievable data rates or necessary protocols for the secondary systems.

Background

Cognitive radio concept

Cognitive radio concept is developed to solve the problem of underutilization of almost completely allocated frequency space. This concept was introduced at 1999 by Mitola. Cognitive radios are intended to have self-awareness and simple intelligence. Cognitive radios are supposed to change their operating band, if the currently used band becomes too occupied or the primary user (PU) takes the band into use. The most important feature of the cognitive radios is the ability to sense the spectrum and find out, if some portion is left underutilized. After the spectrum is sensed, they can make an independent decision based on detection statistics whether to take a certain band into use or not. Since cognitive radios are not the primary users or licensed users, they must ensure not to interfere with PUs' signals. This sets stringent sensitivity requirements for the spectrum sensing of cognitive radios. Cognitive radios are not tied to certain signaling protocols and can adapt to their environment by changing their transmitter parameters to different signaling systems. Depending on the network and cooperation with other cognitive devices, they can exchange information about their location and environment. Cognitive radios can cooperate with other cognitive radios and share information between each other. Prior to the introduction of cognitive radios, reconfigurability was used in radio development. A common radio communication system is implemented in hardware. In software defined radio most of the required hardware and required transmitter and receiver algorithms are implemented in software, thus high reconfigurability is achieved. Cognitive radio is the next step where simple intelligence is added by allowing the radio to sense its environment, track changes and react upon its findings.

Hardware of cognitive radio

The architecture for a generic cognitive radio transceiver is shown in Figure 2(a) . The cognitive radio transceiver unit consists of the radio frequency (RF) front-end and the baseband processing unit. A control bus is used in controlling each component to make the radio adaptive to the RF environment. The RF front-end first amplifies the received signal, then mixes it to a lower band and, finally, the analog signal is converted to a digital signal. The baseband processing unit modulates or demodulates and encodes or decodes the signal depending on whether a signal is transmitted or received. The baseband signal processing unit is similar to common transceivers, but the RF front-end is specifically designed to suit the need of the cognitive radio. Cognitive radio transceiver is required to be capable of sensing over a wide spectrum range and preferably in real time. The wide spectrum range is accomplished by using RF hardware technologies like wideband antennas, power amplifiers, and adaptive filters. The RF hardware is needed to be able to tune in to any part of the frequency spectrum. The main components of the cognitive radio RF front-end are shown in Figure 2(b) and are as follows:

- RF filter: The RF filter selects the desired operating band by band pass filtering the received RF signal.
- Low noise amplifier: The LNA amplifies the received signal without adding remarkable amount of noise.
- Mixer: The mixer is used to mix the received signal with locally generated RF frequency and then convert it to the baseband or the intermediate frequency (IF).
- Voltage-controlled oscillator (VCO): The VCO generates a signal at a specific frequency depending on the control voltage. The generated signal is then used to convert the incoming signal frequency to the baseband or intermediate frequency.
- Phase locked loop (PLL): The PLL makes sure that the signal of VCO is locked accurately on the specific reference frequency.
- Channel selection filter: The channel selection filter selects the desired channel and rejects adjacent channels.
- Automatic gain control (AGC): The AGC is used to keep the gain or output power level of an amplifier constant over a wide range of input signal levels.
- Analog-to-digital converter (ADC): The ADC converts the analog input signal to a digital signal.

Cognitive radio challenges

Common receivers are capable of processing narrowband signals with low complexity and low power processors for digital signal processing. In order to utilize any opportunity, the cognitive radio terminals need to process significantly wider bands. PUs are entitled to claim their frequency bands anytime when cognitive radio is operating at that band. In order to prevent interference to and from PUs, cognitive radio needs to identify the presence of a PU as quickly as possible and vacate the spectrum immediately. Consequently, detection algorithms need to sense the PU during a certain time period. This sets stringent requirement for the sensing method, forming a design challenge for cognitive radios. Challenges of cognitive radio can be listed as follows:

- Designing an efficient spectrum sensing algorithm
- Implementation complexity as cognitive radio has requirement of frequency and system flexibility
- Operation in multiple secondary user environment to not compromise the signaling channel
- Multipath fading and shadowing of user signals
- Designing a resource efficient cooperative scheme for spectrum sensing and information sharing between cognitive radios
- Robustness
- Power consumption

Spectrum sensing theory

Cognitive radios have to sense the spectrum to detect opportunities, and reliably find out if PU signals are present. The spectrum has to be sensed accurately to find out even weaker primary user signals. At the same time, cognitive radios have to respect the needs of the PUs and not to interfere with them. Therefore, the spectrum sensing method has to be very sensitive and distinguish PU signals below the noise floor. Many different spectrum sensing methods have been introduced.

Some methods work for specific signals while others are more generic. Depending on the knowledge of the signal under detection, better performance is usually obtained when detecting specific signals while more generic methods are good for rough estimates on channel usage. One of the more generic spectrum sensing methods is the energy detection. Energy detectors have been introduced nearly half a century ago by Urkowitz, yet they are still researched and new ways to enhance their efficiency are published. Energy detectors do not need any information about the signal under detection; therefore they are able to detect wide variety of signals. However, they cannot differentiate primary users' signals from noise. Other signal detection method exploits the statistical properties of PU signals to detect them. One of these methods is cyclostationary spectrum sensing. Cyclostationary feature detectors can differentiate noise from primary users' signals. Algorithms sensing even more specific signals by matched filtering have been studied from the 1960s, and Middleton introduced a generalized matched filter. Matched filters deliver optimal detection performance; however, each signal under detections needs a specific matched filter. For this reason, matched filter is not widely used. Other way to enhance the detection probability is the cooperation between cognitive radios.

Spectrum sensing challenges

Reliable spectrum sensing has several issues that need to be taken into consideration. Some of the main problems include high hardware requirements needed to operate efficiently with large bandwidths and high resolution. Also signal propagation issues need to consider such as shadowing and severe multipath fading. Depending on the cognitive network in use, there can be weak PUs that may not be detected properly. This is known as a hidden node problem. The hidden node problem is depicted in Figure 3, it shows how node A is not aware of node C and vice versa. In consequence, nodes A and C might transmit simultaneously, and node B would receive corrupt signal. Cooperation improves detection performance for users who are far away from each other, as the other secondary user (SU) might have a better chance of detecting the PU transmission than the other, since a single sensor might suffer from different kinds of interference. In addition, the primary users transmitting a spread spectrum signal or using frequency hopping, where the power of PU signal is distributed over a wide frequency, are difficult to detect.

Statistical modeling of the signal

In order to make the decision whether a PU user is using the spectrum or not, a statistical model is needed for the PU signal for the detection, and then consider the situation without PU. Let us assume a simple received signal is modeled as

$$y(n) = s(n) + w(n) \qquad \text{............(1)}$$

where s(n) is the signal under detection, w(n) is the additive white Gaussian noise (AWGN) sample, and n is the sample index. When there is no PU signal present s(n) = 0. Detection algorithms calculate a detection statistic to be compared with a detection threshold:

$$\rho_x > \lambda_x \qquad \text{...........(2)}$$

in which ρ_x and λ_x are the detection statistic and detection threshold, respectively. Now we can make a decision of the spectrum usage by comparing ρ_x to a fixed threshold value λ_x depending on the detection scheme in use. This can be expressed as a hypotheses comparison

$$H_0 : \quad y(n) = w(n) \qquad \text{...........(3)}$$

$$H_1 : \quad y(n) = s(n) + w(n) \qquad \text{...........(4)}$$

where hypothesis H_0 denotes that no PU is present and hypothesis H_1 that there is PU present. The detection performance can be expressed with two probabilities: probability of detection P_d and false alarm rate P_{fa}. P_d means the probability of detecting a signal on a spectrum band when it really exists. Therefore, a higher Pd equals better performance. P_d can be obtained as

$P_d = Pr(\rho_x > \lambda_x \mid H_1)$ ....(5)

P_{fa} is the probability for the test to falsely indicate that the spectrum is in use when it really is not. P_{fa} can be expressed as

$Pfa = Pr\ (\_X > \_X|H_0)$ ....(6)

P_{fa} should be kept as low as possible to prevent underutilization of spectrum.

Allocation of Cognitive Radio Spectrum

Spectrum allocation model

The spectrum allocation mathematics model is described by several matrix's. In this model, assume that environmental conditions such as user location, available spectrum are static during the time it takes to perform spectrum assignment. The matrix's and parameters needed is shown as follows:

- In a network waiting for spectrum assignment, there are N secondary users indexed from 1 to N competing for M spectrum channels indexed 1 to M.
- Channel availability: $L = \{l_{n,m}\ ,\ l_{n,m}\ \varepsilon\ \{0,1\}\}_{NxM}$ is a N by M binary matrix representing the channel availability. Channel m is available for user n if $l_{n,m} = 1$. And if $l_{n,m} = 0$ the opposite.
- Channel reward: $B = \{b_{n,m}\}_{N\,xM}$ is a N by M matrix representing the channel reward. $b_{n,m}$ represents the maximum bandwidth/throughput that can be acquired by user n using channel m.
- Interference constraint: $C= \{C_{n,m}\ ,\ C_{n,k,m}\ \varepsilon\ \{0,1\}\}_{N\,xNx\,M}$, a N by N by M matrix, represents the interference constraints among secondary users. If $C_{n,k,m} = 1$, users n and k would interfere with each other if they use channel m simultaneously. And $C_{n,k,m} = 1 - l_{n,m}$ if n=k.
- valid spectrum assignment with non- interference : $A = \{a_{m,n}\ ,\ a_{m,n}\ \varepsilon\ \{0,1\}\}_{N\,xM}$ is a N by M binary matrix that represents the assignment. If channel m is assigned to user n. this assignment without interference needs to satisfy all the interference constraints defined by C, that is,

$a_{m,n*}\ a_{m,n} = 0$, if $C_{n,k,m} = 1$,

So abstract the above spectrum allocation problem into a graph coloring problem. We define a bidirectional graph $G=(U,E_C\ ,L_B)$ where U is a set of vertices denoting the users that share the spectrum, L_B represents the bandwidth weighted available spectrum, or the color list at each vertex, and E_C is a set of undirected edges between vertices representing interference constraints between two vertices defined by C. For any two distinct vertices $u,v\varepsilon\in U$, a m-color edge between u and v, is in E_C if and only if $C_{n,k,m} = 1$. Hence, the conditions of the distribution with non-interference satisfied with (7) can be described as: if a color m edge exists between any two distinct vertices, they can't be colored with m simultaneously.

Energy Detection

The radiometer was first proposed by Urkowitz. It relies on discriminating between the binary hypotheses based on the difference in energy levels of the signal of interest and noise. The signal is considered to be deterministic, although unknown in detail. The spectral region to which it is approximately confined is, however, known. The noise is assumed to be Gaussian and additive with zero mean and known power density spectrum σ0. Fig.4 depicts a block-diagram of an energy detector. The input band-pass filter selects the centre frequency and bandwidth W of interest. It is easy to show that the test statistics V follows a central chi-square law (χ2) with 2TW degrees of freedom under hypothesis H0, and a non-central chi-square law (χ2) with 2TWdegrees of freedom and a non-centrality parameter λ given by Es/σ0 under hypothesis H1, Es being the signal's energy. As mentioned above, the unknown signal is considered to be deterministic; however, the result also applies if the signal is random provided the probability of detection is considered a conditional probability of detection, where the condition is a given amount of signal energy. For instance, in and the probability of detection expressions are determined when the signal is of random amplitude. With TW increasing, the statistics V will instead be a normal random variable. For several values of the false alarm probability (Pfa), theoretical graphs of the minimum required SNR (Signal to Noise Ratio) (Es/σ0) versus the time-bandwidth product (TW) are plotted in Fig. 5. For a fixed bandwidth, the SNR required to achieve the desired detection probability−(Pfa) is 1 proportional to T −1/2. Note that 1signals can be detected at a SNR as low as desired, provided the detection interval is long enough and the noise power spectral density (N0) is known. However, realistic limitations on the detector's knowledge of the noise level produce serious degradation in the detector's performance. In almost all practical situations, N0 would need to be estimated by the detector. Denote this estimate by ˆN0 and assume the error in estimating N0 is bounded by

$(1-\varepsilon 1)N0 \leq \hat{N}0 \leq (1+\varepsilon 2)N0$

With $0 \leq \varepsilon 1 < 1$ and $\varepsilon 2 \geq 0$.

Theoretical graphs in Fig. 6 show that, whilst increasing *TW* indefinitely, detection cannot be made at low SNR .Here, *U* denotes the peak-to-peak uncertainty and is defined as:

$U\,(\mathrm{dB}) = 10\log 10\frac{1+\varepsilon 2}{1-\epsilon 1}$

In current telecommunication systems, channel estimation routines also facilitate the estimation of the noise level due to known reference pilot sequences. However, in an opportunistic system, it is not very likely that the cognitive radio has access to the nature of the primary users' emitted signal, hence rendering noise estimation impossible.

Cyclostationary Detection Method

When a cyclostationary model is selected for the searched signal, the detection problem of vacant bands in the spectrum is transformed to the following hypotheses testing problem on the received radio signal x(t):

- Under H0 x(t) is of stationary type and the band is regarded as free;
- Under H1 x(t) is of cyclostationary type and the band is said occupied.

This can be looked upon as a test for presence of cyclostationary rather than a detection of a signal in noise. Theoretically, the obtained solution will be noise-knowledge independent but some knowledge about the searched signal will be required. In a statistical test for the presence of cyclostationary over a candidate cyclic frequency is given. Although it is computationally extensive, this test exhibits good performances and can be applied when the transmission parameters of the primary user are known to the cognitive radio device. As for now, however, let us suppose the worst case of unknown primary user transmission parameters. Then we do not face a single but rather an interval of candidate cyclic frequencies. Following the line of reasoning of , the test will have to be carried out frequency by frequency, which makes the algorithm more computationally complex. In the following, we will present an extension to this monocycle test aiming at simultaneously testing an increasingly important set of cyclic frequencies. Indeed, the more important the number of samples in a segment of data is, plus the set of cyclic frequencies tested is large, the better the performance of the detection.

Vacant Channel Detection within TV Bands

Detection of free channels over TV bands has taken on much interest since the FCC has authorized to cognitive radio devices the right to operate within these bands. In the following we will be interested in SECAM, PAL, NTSC and DVBT TV systems. For each one of them, we determine the characteristic cyclic frequency. In the analog TV systems; the luminance information waveform is random and it exhibits (Fig. 7) synchronizing pulses at the rate of one pulse every TL = 64 µs (63.5 µs for system NTSC). This leads to a cyclostationary video signal although its lower sideband is partially removed (see Fig. 8). Moreover, in the Fourier series development of the covariance function, we obtain the fundamental cyclic frequency (15 625 Hz = 1/64) and its harmonics. In the case of DVBT standard [18], we employ a multi-carrier modulation (OFDM). Cyclostationary in the transmitted video signal arises, due to the guard interval insertion, at cyclic period equal the OFDM symbol period, i.e., in

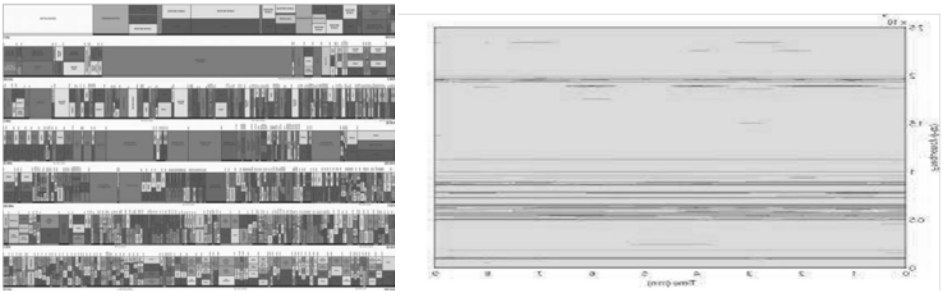
2K mode and for a TV channel of 8 MHz of large, we obtain the data of Table 1.

As for analog TV systems, the Fourier series development of the covariance function of the OFDM signal exhibits lines at the fundamental cyclic frequency (inverse of the cyclo-period) and at its harmonics. Fig. 9 shows the detection results of the multi-cycles detection method when it is applied to detect a noisy OFDM signal. These results are compared with the radiometer detector under the assumption of uncertain noise power indicated by U. From theses curves, it is clear that increasing the number of OFDM symbols used in the calculation of the statistical test leads to an enhanced detection performances for the multi-cycles method. Moreover, this performance remains insensitive, compared to the radiometer, when the noise power uncertainty is varying.

Conclusion

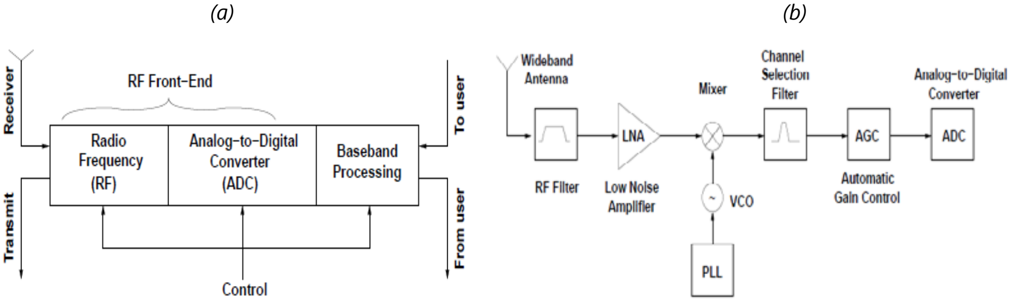
This article has dealt with an opportunistic detection of vacant bands, which is suitable for emerging cognitive radios. Specifically, we have proposed a cyclostationary based detection method. This method, referred to as a multi cycles detector, is based on the estimation of the time varying covariance function of the received signal. It takes advantage of the fact that it tests several cyclic frequencies at the same time. A second advantage can be profited from when the harmonics of the fundamental cyclic frequency exist and in this case the detection performances are enhanced compared to the test of one cyclic frequency. Moreover, this method facilitates the detection of signals the cyclic frequencies of which are unknown; by simply increasing the duration of the segment of data used in the calculation of the correlation function. First simulations of this method for detection of free channels in TV bands prove to be encouraging compared to the simple energy detection.

List of figures



a) The NTIA’s spectrum allocation chart makes available spectrum look scarce.
b) Measurements from the Berkeley Wireless Re-search Center show the allocated spectrum is vastly underutilized.

Figure 1: *There is a great discrepancy between spectrum allocation and spectrum usage.*



(a) *(b)*

Figure 2*: Physical architecture of the cognitive radio :*
(a) Cognitive radio transceiver and (b) wideband RF/analog front-end architecture.

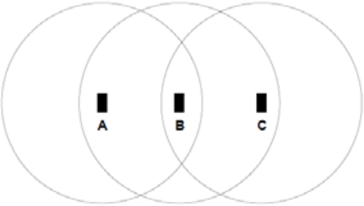


Figure 3*: Hidden node problem.*

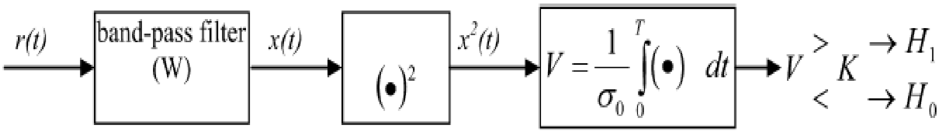


Figure 4: *Typical block diagram of an energy detector*

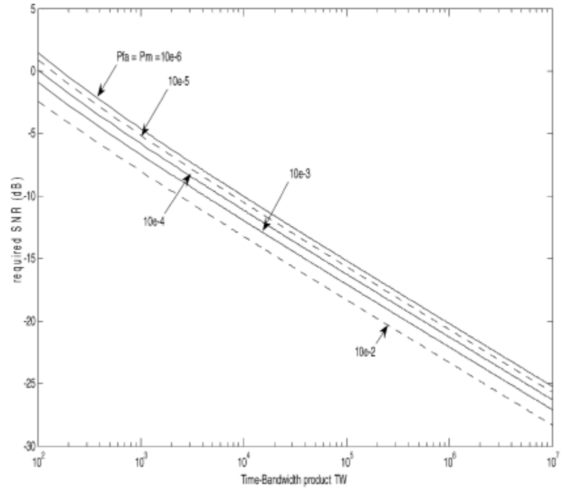


Figure 5: *Required SNR: known noise.*

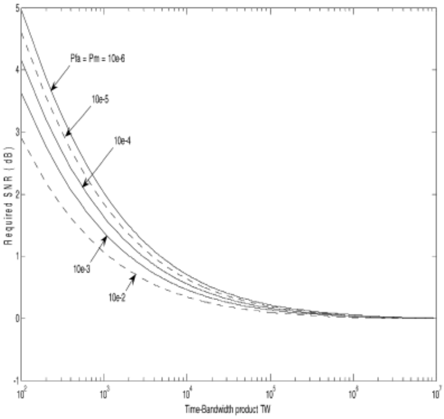


Figure 6: *Required SNR in uncertain noise; U = 3 dB.*

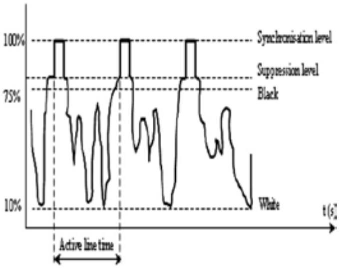


Figure 7: *Video waveform*

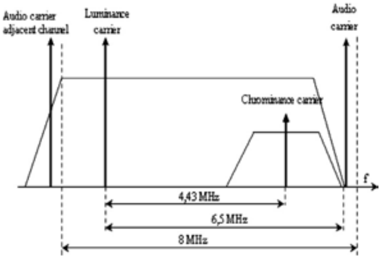


Figure 8: *Analog TV spectrum*

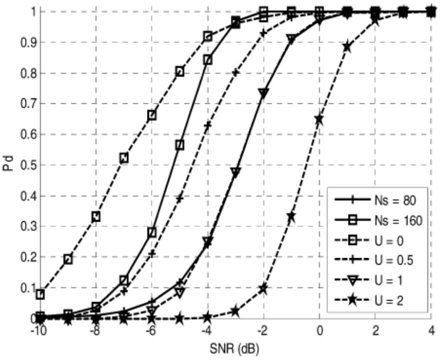


Figure 9: PD= F (SNR). Detection of the numerical signal of TV by the radiometer and the detector multi-cycles.

Table 1. *Data for a TV channel of 8 MHz*

Duration of symbol part *Tu* (µs)	224			
Guard interval *Δ/Tu*	1/4	1/8	1/16	1/32
Cyclic period (µs)	280	252	238 231	

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