Electromagnetic Compatibility from a Time-Frequency Perspective

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***Abstract*— In wireless communication, interference between two radio systems may occur when they operate at close frequency bands, sharing the same environment at the same time. Such systems coexist if both of them perform correctly in the presence of the other. To ensure their coexistence, Electromagnetic Compatibility (EMC) is used to specify rules within standardization bodies. According to current EMC standards, the radio spectrum has been divided into non-overlapping bands often with exclusive access. However, nowadays there is a proliferation of new digital systems sharing common frequency bands because the spectrum is a limited resource. Many of them are operating in unlicensed bands regulated by The International Telecommunications Union (ITU), for example the 2.45 GHz Industrial, Scientific and Medical (ISM) band. The frequency allocation is also changing with the emergence of digital systems and this is the case for white spaces in the broadcast television (TV) spectrum. To avoid high interference levels, it is necessary to consider some parameters related to signal variations, representing more accurately the environment. Some techniques have been proposed in the literature to reduce interference levels but they are applied to specific sharing studies. Hence, we evaluate in this paper the impact of time-frequency considerations for radio coexistence. We show that EMC studies are more precise and more representative of the reality when additional parameters relevant to the time domain are taken into account in the analysis framework. We illustrate these concepts through a specific study case. We evaluate the results for different system parameters, first considering that both of them occupy the same band and then assuming that they use overlapping but non-equal frequency bands.**

***Index Terms*— Radio coexistence, electromagnetic compatibility, frequency-domain analysis, time-domain analysis.**

I. Introduction

Two radio systems can coexist in the same environment if both of them perform correctly in the presence of the other. The electromagnetic compatibility (EMC), which studies this phenomenon, is an important condition to be satisfied before the deployment of any radio system. It should operate correctly in its environment but should not cause harmful interference on present legacy systems[1].

Some rules have been established within standardization organizations to guarantee EMC. To ensure successful coexistence, current EMC standards usually require a frequency separation in order to respect the receiver sensitivity while taking into account system frequency ranges, power levels, occupied bandwidths and spectral masks. As a consequence, the radio spectrum has been divided into distinct frequency bands mostly with exclusive access.

The spectrum is becoming scarce as more and more digital systems are being deployed to provide various services requiring higher and higher data rates. The International Telecommunications Union (ITU) has kept some bands for unlicensed use to allow the development of new digital technologies. Systems operating in these bands are foreseen to use simultaneously the same or nearby frequency bands. This is the case of wireless systems in the 2.45 GHz ISM (Industrial, Scientific, Medical) band [1] *e.g.* IEEE 802.11 b/g/n (Wi-Fi) [2], IEEE 802.15.1 (Bluetooth) [3] and microwave ovens [4].

The frequency allocation is also changing with the emergence of digital systems. As a matter of fact, the radio environment is becoming complex not only because of technology improvements but also frequency allocation changes and electronics evolution. This is the case of converged wireless communication devices such as laptops and smart phones which are likely to have multiple technologies. In these devices, antennas and radio circuitry for each radio is in a fixed location very close to other radio systems. Because of antennas proximity, out-of-band signal levels are much higher than traditional EMC requirements and it is not possible to move the antennas or change their relative orientation. Antenna arrays, which consist of groups of antennas, are also more and more used in modern communication systems to offer more flexibility and space diversity.

Radio systems are likely to suffer from interference and this is critical for their coexistence. Mitigation techniques are mentioned in the literature (frequency hopping [5], spectrum sensing before transmission [6],...) but they are applied to specific spectrum sharing studies. From a standardization perspective, the ITU recommends to refine the compatibility criteria based on link budget considerations for systems allocated in adjacent or nearby bands [7] and systems operating at the same frequency [8]. Consequently, it is fundamental to consider additional parameters to represent more accurately the propagation environment. Time-domain parameters are interesting because the information within digital systems is transmitted through pulsed signals, different from analog systems that were based on continuous transmission.

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[1]Legacy systems have been using the spectrum for a long time so that it seems hard to change their standards. They continue to be used as they still work satisfactorily even though newer technologies have been deployed.

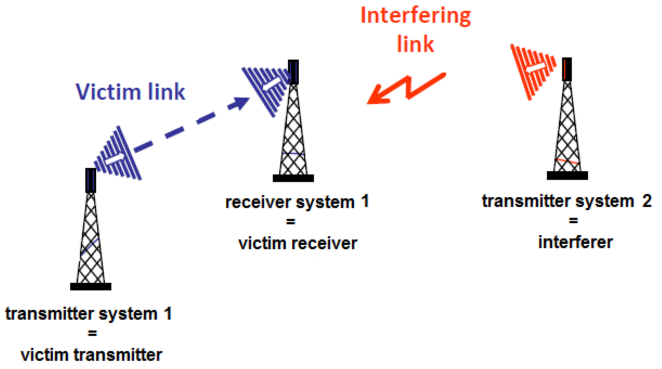

Fig. 1. RFC System model: transmitter, interferer and victim.

In this paper, we emphasize the importance of time-domain considerations for EMC analysis between systems sharing the same spectrum. Including time-frequency aspects (discontinuous transmission, symbol rate,...) as well as technology properties (modulation scheme, coding gain,...) into spectrum sharing studies can make easier the coexistence. We will apply this so-called time-frequency approach to a simplified study case. We evaluate the results for different offsets between systems center frequencies, first considering that both of them occupy the same band and then assuming that they use overlapping but non-equal frequency bands.

The paper is organized as follows. In section II, we summarize the principle and main parameters used in current EMC standards. Then, in section III, we explain why time-domain parameters are important for EMC analysis. Finally, in section IV, we emphasize through a study case the effect of system parameters on the coexistence problem.

II. Current EMC approach : frequency domain analysis

Let us consider two radio systems, system 1 and system 2, operating in the same environment. Interference between these systems may occur if they transmit at the same time using overlapping frequency bands[2]. For the rest of this work, we assume that system 1 is the victim and system 2 the interferer. We illustrate in Fig. 1 the EMC scenario where the victim receiver gets an interfering signal from the interferer.

We denote the useful signal power level at the victim's antenna input by S_{dB}, the interference power level at the victim's antenna input by I_{dB} and the noise level by N_{dB}. The expression of S_{dB} (in dBm) is given by

$$S_{dB} = P_s + G_s(-\theta_s, -\phi_s) + G_r(\theta_s, \phi_s) - L(r_s, \theta_s, \phi_s), \quad (1)$$

where P_s (in dBm) is the power transmitted by the victim's transmitter, G_s (in dBi) is the transmitter's antenna gain in the victim's antenna direction and G_r (in dBi) the receiving antenna gain in the transmitter's antenna direction. r_s, θ_s and ϕ_s are respectively the distance, azimuth angle and elevation angle and L_s (in dB) is the propagation path loss. The study here does not take into account multi-path propagation environment.

[2]It is important to take into account Out Of Band (OOB) radiations of the interfering terminal to determine the actual interference level. OOB radiations quantify the emitted power outside the interfering bandwidth.

Similarly, I_{dB} (in dBm) is given by

$$I_{dB} = P_i + G_i(-\theta_i, -\phi_i) + G_r(\theta_i, \phi_i) - L(r_i, \theta_i, \phi_i) + H_{dB}, \quad (2)$$

where P_i (in dBm) is the power transmitted by the interferer, G_i (in dBi) is the interferer's antenna gain in the victim's antenna direction and G_r (in dBi) the victim antenna gain in the interferer's antenna direction. r_i, θ_i and ϕ_i are respectively the distance, azimuth angle and elevation angle of the interferer relatively to the victim and L_i (in dB) is the propagation path loss from the interferer to the victim. H_{dB} (in dB) is the result of the superposition between the interferer's transmitting mask M_i and the victim's receiving filter F_r. H_{dB} is obtained by the convolution product of M_i and F_r, calculated as follows:

$$H_{dB} = 10 \cdot \log_{10}\left(\int_{-\infty}^{+\infty} M_i(f) \cdot F_r(f)\, \mathrm{d}f\right). \quad (3)$$

For EMC purpose, if the interference I_{dB} is lower than the noise N_{dB}, the compatibility is considered guaranteed. For all the other cases, the compatibility is determined based on the signal to interference plus noise ratio $SINR$ that should satisfy a certain threshold that depends on the system technology. This approach requires a link budget analysis and provides information about the frequency margin that protects the victim from the presence of interference. The result depends on several parameters, mainly:

- Distance between interferer and victim;
- Frequency range and separation between carriers;
- Transmission power;
- Interferer signal bandwidth and frequency mask;
- Victim receiver's bandwidth and frequency filter;
- Antenna parameters (gain, polarization, radiation pattern);
- Signal to Noise Ratio SNR at the receiver.

Based on spectrum sharing studies, rules and regulations have been established within standardization bodies to organize the access to the radio spectrum so that the EMC is satisfied. In conventional EMC testing, the interfering field strength at the victim receiver is required to be less than the regulatory levels recommended by the ITU. As a consequence, spectral masks have been specified for each system to limit power levels of emissions on frequencies outside its allowed band (out of band emissions [9] and spurious emissions [10], see Fig. 2). Selectivity masks have also been defined for radio receivers to reject unwanted signals in adjacent frequencies. Radio system specifications have to respect these masks to enable coexistence with other systems sharing the same frequency band. For example, systems using ISM bands have to follow limitations of transmission power densities and peak power.

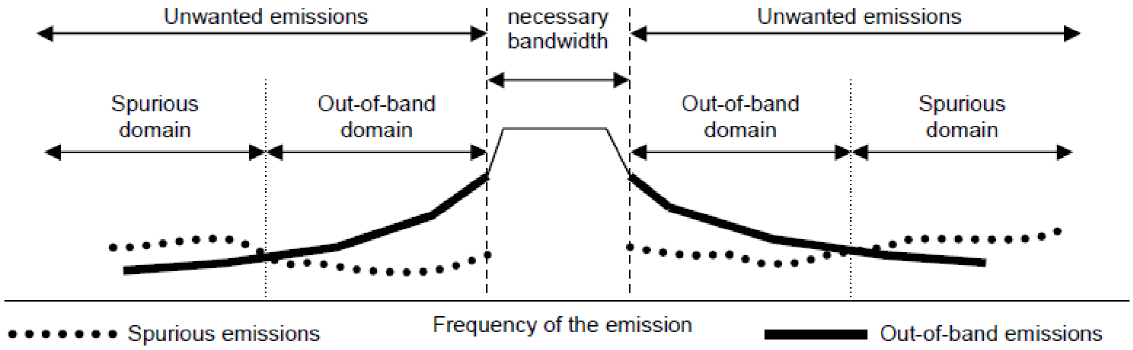

Fig. 2. Unwanted Emissions description.

III. From EMC to radio coexistence : time-domain perspective

Current EMC analysis in the frequency domain deals with worst case scenarios, where the victim receiver is getting interference all the time. In existing EMC standards, the interference level is computed with respect to the propagation environment (power, spatial separation, antenna characteristics) taking into account frequency domain parameters such as spectral masks, carrier separation, range and bandwidth (see [11] for more details). The interferer is assumed to transmit continuously and the potential victim receiver is likely to intercept interfering signals continuously.

With the development of wireless systems, duplexing has been introduced to enable two way communication. Systems use either Time Division Duplex (TDD) approach, where the user and the base transmit at the same frequency during disjoint time intervals, or Frequency Division Duplex (FDD), where the two devices transmit simultaneously using two different carriers. Furthermore, radio equipments are becoming smaller and usually they host different technologies, which means that coupling between components should appear.

Moreover, many wireless and mobile systems are emerging nowadays, enabling point to multipoint communications [12]. The transmitted information by these systems is encoded to discrete values and through bursted signals. Terminals in the same environment use the radio frequency (RF) channel during smaller periods of time such that they could share the resource. Multiplexing has been considered as a solution to share the resource between them. The most common multiplexing techniques are :

- Frequency Division Multiplexing (FDM): each user is allocated to a fraction of the available spectrum. Such a technique is widely used for radio spectrum management;
- Time Division Multiplexing (TDM): each user occupies the available spectrum during a time slot. Such a technique used by many schemes such as ALOHA protocols, and Channel Sensing Multiple Access (CSMA) schemes;
- Code Division Multiplexing (CDM): users employ simultaneously the same frequency channel but using different codes. Two common types of codes are direct sequence spread spectrum and frequency hopping;
- Space Division Multiplexing (SDM): signals are transmitted through antennas pointing to different directions such that users could employ the same frequency channel simultaneously.

The trend to use digital communication systems has also engendered frequency allocation evolutions. Indeed, these systems require higher data rates and more bandwidth so that the radio spectrum tends to saturation. Diverse solutions are being proposed to reorganize more efficiently the radio spectrum [13],[14]. Nowadays the switch to digital television frees up a large spectrum opened to unlicensed use in the United States in 2010 [13]. This spectrum could provide high speed broadband internet access according to the White Spaces Coalition (Microsoft, Google, Dell, HP, Intel, Philips, Earthlink, and Samsung Electro-Mechanics). In Europe, the Analogue Switch Off (ASO) process would be finalized in 2012 and the resulting digital dividend may be used for many services (broadcast services, converged television and phone services, wireless broadband services...) [14].

In addition, wireless systems are evolving and becoming very flexible and adaptable. We can mention here the example of decentralized wireless networks (also named ad-hoc networks). These networks are interesting because they do not require a special infrastructure setup and claim to provide enough capacity to guarantee quality of service for all users [15]. Ad-hoc networks are a suitable option for emergency situations such as natural disasters but they have to meet number of challenges like device heterogeneity, variable traffic profiles, user mobility and power conservation [16]. One key element in the design of ad-hoc networks is Software Defined Radio (SDR) which is based on a software architecture [17], [18]. SDR uses cognitive radios (CR) which are smart radios that are able to adapt their technologies depending on the user demand, the traffic load and propagation conditions.

Because of the rapid development in multimedia and wireless systems, it is necessary to develop EMC standards suitable to the emerging technologies [20]. By considering only link budget parameters, it seems very difficult to ensure systems coexistence under the scenarios described above. It becomes important to take into account new parameters for more elaborated spectrum sharing analysis between radio systems, more particularly those sharing the same spectrum. A different kind of electromagnetic compatibility evaluation has been proposed in [20]. The idea is to focus on the performance degradation of the radio link due to interference, with respect to the $SINR$ instead of analyzing the interfering electromagnetic field strength. Under this methodology, the two systems could coexist if the quality of the communication in the presence of the interference remains above a minimum required level. Additional system parameters are needed to compute more accurately the $SINR$ and so to evaluate more precisely the systems coexistence. Hence, we propose herein to study the coexistence using time-frequency characteristics of both systems. From now on, the EMC is referred to the time-frequency approach and it takes into account system parameters (discontinuous transmission, instantaneous power variation, number of users, etc.) and technology properties (modulation scheme, coding gain, subcarrier repartition for multi-carrier modulations, etc.).

IV. Coexistence from a time-domain perspective : A study case

In this section, we propose to study the influence of time-domain parameters on the coexistence between radio systems sharing the same spectrum. The idea is to analyze the effect of channel occupation rates of both systems assuming a victim system and an interferer. To this end, we consider two radio systems that operate in the same environment (see Fig. 1).

A. System performance evaluation

We call the respective bandwidths of interferer and victim by B_1 and B_2. In addition, we denote by P_1 and P_2 the power of the victim's signal (in its necessary bandwidth, see Fig. 2) and the interference signal (in its necessary bandwidth) at the victim's receiver. We also define the receptively channel occupation rates of both signals by R_1 and R_2. Finally, we suppose that both signals are independent and we call $H_1(f)$ and $H_2(f)$ respectively the transmission mask of system 1 and the reception filter of system 2.

In this work, we focus on the influence of channel occupation rates of both systems on the $SINR$, for different values of B_1 and B_2. Let us first compute the $SINR$ before taking into account the channel occupation rates. The general expression of the $SINR$ is :

$$SINR = \frac{S}{N+I} = \frac{1}{(\frac{N}{S}) + (\frac{I}{S})} = \frac{1}{(\frac{1}{SNR}) + (\frac{1}{SIR})}, \quad (4)$$

being SNR and SIR :

$$SNR = \frac{S}{N}, \quad (5)$$

$$SIR = \frac{S}{I}. \quad (6)$$

S and I are the powers received by the victim from the victim transmitter and the interferer, respectively, both computed in the victim system bandwidth. S and I are computed similarly to equations (1) and (2) and are given by:

$$S = \int_{B_1} \frac{P_1}{B_1} \cdot H_1(f)\,\mathrm{d}f \quad (7)$$

and

$$I = \int_{-\infty}^{+\infty} \frac{P_2}{B_2} \cdot H_1(f) \cdot H_2(f)\,\mathrm{d}f. \quad (8)$$

In addition, N is the noise level in the victim system bandwidth, related to the Boltzmann constant k and the temperature T (in K) by :

$$N = k \cdot T \cdot B_1. \quad (9)$$

Consequently, the $SINR$ can be written as :

$$SINR = \left[\frac{\int_{B_1} \frac{P_1}{B_1} \cdot H_1(f)\,\mathrm{d}f}{(\int_{-\infty}^{+\infty} \frac{P_2}{B_2} \cdot H_1(f) \cdot H_2(f)\,\mathrm{d}f) + (kTB_1)}\right] \quad (10)$$

For the performance evaluation, we will consider the outbreaking work of Shannon [19] which provides the error-free capacity under gaussian noise interference. We assume from now on that interference plus noise could be modeled as a white gaussian noise and the system performance is derived based on the following theorem:

Theorem 4.1: (Shannon-Hartley Theorem [19]) The error-free capacity that can be transmitted over a additive white gaussian channel is

$$D_{max} = B \cdot \log_2(1 + SNR). \quad (11)$$

In our case, we denote by C (which is given in bits/channel access) the capacity of a system in the presence of noise plus interference. Three cases are possible :

- In the first situation, we consider the capacity (C) without taking into account the channel occupation rates;
- In the second situation, we consider the capacity (C') based on the average $SINR$ ($\widehat{SINR}$);
- In the third situation, we consider the average capacity (C'') based on the instantaneous $SINR$ ($SINR(t)$).

In the first case, the capacity of the victim system is written as (11),

$$C = R_1 \cdot \log_2(1 + SINR) \quad (12)$$

which means that :

$$C = R_1 \log_2 \left(1 + \left[\frac{\int_{B_1} \frac{P_1}{B_1} H_1(f)\,\mathrm{d}f}{\int_{-\infty}^{+\infty} \frac{P_2}{B_2} H_1(f) H_2(f)\,\mathrm{d}f + kTB_1}\right]\right) \quad (13)$$

In the second case, we take into account $\widehat{SINR}$. The corresponding capacity C' is then

$$C' = R_1 \cdot \log_2(1 + \widehat{SINR}), \quad (14)$$

being

$$\widehat{SINR} = E\{SINR\} = \frac{E\{S\}}{E\{N\} + E\{I\}}, \quad (15)$$

given that S, I and N are independent. Therefore, the capacity of the victim system is written as

$$C' = R_1 \log_2 \left(1 + \left[\frac{R_1 \int_{B_1} \frac{P_1}{B_1} \cdot H_1(f)\,\mathrm{d}f}{R_2 \int_{-\infty}^{\infty} \frac{P_2}{B_2} H_1(f) H_2(f)\,\mathrm{d}f + R_1 kTB_1}\right]\right) \quad (16)$$

In the third case, we consider the expected system capacity (C'') taking into account $SINR(t)$. The result is :

$$\begin{aligned} C'' &= E\{C\} = E\{\log_2(1 + SINR)\} \\ &= \lim_{T\to\infty} \frac{1}{T} \cdot \int_T \log_2(1 + SINR(t))\,\mathrm{d}t, \end{aligned} \quad (17)$$

being p_1 and p_2 the instantaneous powers of the victim system and the interferer. The integral in equation (17) can be divided into three integrals depending on the presence of useful signal, noise and interference. Hence, equation (17) can be rewritten as follows :

$$\begin{aligned} C'' = &\lim_{T\to\infty} \frac{1}{T} \int_{T,S=0} \log_2(1)\,\mathrm{d}t \\ &+ \lim_{T\to\infty} \frac{1}{T} \int_{T,S\neq 0,I=0} \log_2(1 + SNR)\,\mathrm{d}t \\ &+ \lim_{T\to\infty} \frac{1}{T} \int_{T,S\neq 0,I\neq 0} \log_2(1 + SINR)\,\mathrm{d}t. \end{aligned} \quad (18)$$

The first one represents the situation where the victim system is not transmitting. The second one corresponds to the case where the victim system is transmitting without interference and the third one represents the situation where both systems are transmitting.
The parameters $SINR$ and SNR are constant, so we obtain

$$\begin{aligned} C'' = &\, 0 + \log_2(1 + SNR) \lim_{T\to\infty} \frac{1}{T} \int_{T,S\neq 0,I=0} \mathrm{d}t \\ &+ \log_2(1 + SINR) \int_{T,S\neq 0,I\neq 0} \mathrm{d}t \\ &= \log_2(1 + SNR) p(S \neq 0, I = 0) \\ &+ \log_2(1 + SINR) p(S \neq 0, I \neq 0), \end{aligned} \quad (19)$$

where $p(x, y)$ is the joint probability of the variables x and y. Using conditional probability formulae and assuming that p_1 and p_2 are independent, the probabilities can be written as

$$\begin{aligned} &p(S \neq 0, I = 0) \\ &\quad = p(S \neq 0, I = 0/I = 0).p(I = 0) \\ &\quad = p(S \neq 0).p(I = 0) = R_1(1 - R_2), \end{aligned} \quad (20)$$

and

$$\begin{aligned} &p(p_1 = P_1, p_2 = P_2) \\ &\quad = p(S \neq 0/I \neq 0).p(I \neq 0) \\ &\quad = p(S \neq 0).p(I \neq 0) = R_1 R_2. \end{aligned} \quad (21)$$

The average capacity of the victim system in the presence of the interferer considering $SINR(t)$ is

$$\begin{aligned} C'' &= R_1 \cdot (1 - R_2) \cdot \log_2(1 + SNR) \\ &\quad + R_1 \cdot R_2 \cdot \log_2(1 + SINR) \\ &= R_1 \cdot (1 - R_2) \cdot \log_2 \left(1 + \frac{\int_{B_1} \frac{P_1}{B_1} \cdot H_1(f)\,\mathrm{d}f}{kTB_1}\right) \\ &\quad + R_1 \cdot R_2 \cdot \log_2 \\ &\quad \left(1 + \left[\frac{\int_{B_1} \frac{P_1}{B_1} \cdot H_1(f)\,\mathrm{d}f}{\int_{-\infty}^{+\infty} \frac{P_2}{B_2} H_1(f) H_2(f)\,\mathrm{d}f + kTB_1}\right]\right), \end{aligned} \quad (22)$$

B. Results analysis

1) Simulation parameters: We illustrate in the following some results based on the expressions presented on Section IV-A. For this, we set the SNR to $20dB$ and we compute the capacities C, C' and C'' for different values of the powers ratio $\frac{P_1}{P_2}$, channel occupation rates R_1 and R_2 and bandwidths B_1 and B_2 of both systems, and considering different values of the systems frequency offset δ.

We present hereafter three types of results. We first compute the three capacities with respect to the ratio of system powers $\frac{P_1}{P_2}$. We then study the variations of C, C' and C'' with respect to the interference channel occupation rate R_2. We finally analyze the three capacities with respect to the channel occupation rate R_1.

For the first type of results, we calculate the capacity considering $\frac{P_1}{P_2}$ values between $-20dB$ and $10dB$, for $R_1 = 1$ (continuous transmission by the victim) and two values of the channel occupation rate by the interferer: R_2 = 1 (continuous interference) and R_2 = 0.5 (half-time interference).

For the second type of results, then fix $R_1 = 1$ and we compute the capacities for $\frac{P_1}{P_2} = 5dB$ and $\frac{P_1}{P_2} = -5dB$, considering $B_2 = 1$, two values of the interfered system bandwidth: $B_1 = 0.5$ and $B_1 = 0.1$ and two values of the frequency offset $\delta = 0$ and $\delta = \frac{B_1+B_2}{4}$.

For the third type of results, we set $R_2 = 0.5$ and we calculate the capacities for the same parameters as for the previous type of results.

2) Study case simplification: To simplify the study, we assumed that both system masks ($H_1(f)$ and $H_2(f)$) are ideal, *i.e.* that they are expressed by :

$$H_1(f) = \begin{cases} 1 & F_1 - \frac{B_1}{2} \leq f \leq F_1 + \frac{B_1}{2} \\ 0 & otherwise \end{cases} \quad (23)$$

$$H_2(f) = \begin{cases} 1 & F_2 - \frac{B_2}{2} \leq f \leq F_2 + \frac{B_2}{2} \\ 0 & otherwise \end{cases} \quad (24)$$

being F_1 and F_2 center frequencies of system 1 and system 2. System 1 and system 2 use overlapping frequency bands if the frequency offset between them δ

$$\delta = F_2 - F_1, \quad (25)$$

verifies

$$-\frac{B_1 + B_2}{2} \leq \delta \leq \frac{B_1 + B_2}{2}. \quad (26)$$

Assuming that $H_1(f)$ and $H_2(f)$ are ideal, we have:

$$S = P_1 \tag{27}$$

and

$$I = \begin{cases} \frac{P_2}{B_2} \cdot \left(\frac{B_1+B_2}{2} - \delta\right) & B_1 \le B_2 \\ P_2 & B_1 > B_2 \end{cases} \tag{28}$$

Consequently :

$$SINR = \begin{cases} \left(\frac{kTB_1}{P_1} + \frac{P_2}{P_1}\frac{B_1+B_2-2\delta}{2B_2}\right)^{-1} & B_1 \le B_2 \\ \left(\frac{kTB_1}{P_1} + \frac{P_2}{P_1}\right)^{-1} & B_1 > B_2 \end{cases} \tag{29}$$

and

$$\widehat{SINR} = \begin{cases} \left(\frac{1}{SNR} + \frac{P_2}{P_1}\frac{R_2}{R_1}\frac{B_1+B_2-2\delta}{2B_2}\right)^{-1} & B_1 \le B_2 \\ \left(\frac{1}{SNR} + \frac{R_2}{R_1}\frac{P_2}{P_1}\right)^{-1} & B_1 > B_2 \end{cases} \tag{30}$$

3) Results for $B_1 = B_2$ and $\delta = 0$: In this particular case, the interfering system and the victim system use the same frequency band. The signal to interference ratio is equal to the powers ratio $\frac{P_1}{P_2}$. The three capacity cases in this situation are given by:

$$C = R_1 \cdot \log_2\left[1 + \left(\frac{1}{SNR} + \frac{P_2}{P_1}\right)^{-1}\right], \tag{31}$$

$$C' = R_1 \cdot \log_2\left[1 + \left(\frac{1}{SNR} + \frac{R_2}{R_1}\cdot\frac{P_2}{P_1}\right)^{-1}\right], \tag{32}$$

$$C'' = R_1 \cdot (1 - R_2) \cdot \log_2(1 + SNR) + R_1 \cdot R_2 \cdot \log_2\left[1 + \left(\frac{1}{SNR} + \frac{P_2}{P_1}\right)^{-1}\right]. \tag{33}$$

We show in Fig. 3 the capacities C, C' and C'' with respect to the SIR. We notice that when both systems transmit continuously ($R_1 = R_2 = 1$), C, C' and C'' are identical. In this situation, the average SIR and the instantaneous SIR are both equal to the ratio of systems powers. Considering continuous transmission for the victim and discontinuous interference transmission ($R_2 = 0.5$), the capacities C' and C'' increase compared to C. It can be also noticed that if $\widehat{SINR}$ is considered, the capacity gain when compared to the continuous case is more significant for high $SINR$ whereas if $SINR(t)$ is considered, the capacity gain is more important for low $SINR$ values.

We illustrate in Fig. 4 the capacities C, C' and C'' variations with respect to the rate R_2. We see that for a fixed R_1, the capacity C remains constant with respect to the interference channel occupation rate R_2. For both $SINR$ values, we can notice that the capacity C' decreases in logarithmic scale and C" decreases linearly with respect to R_2, but they are both higher than C. More particularly, for $R_2 = 1$ (continuous interference case), we retrieve that the three capacities are identical.

We finally show in Fig. 5 the capacities C, C' and C'' variations with respect to the rate R_1. We see that for a fixed $SINR$, the system capacity C increases linearly with respect

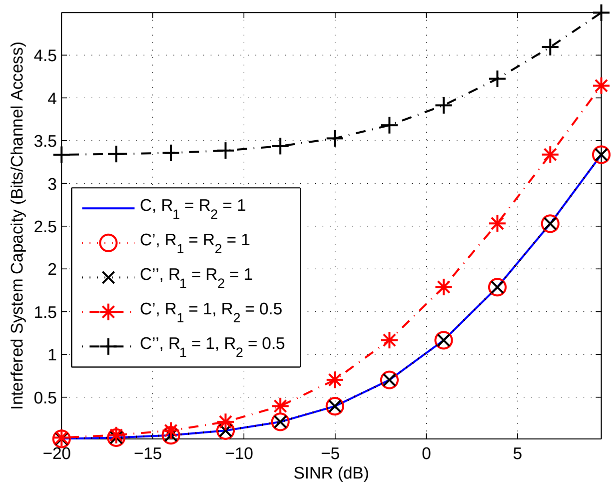

Fig. 3. : Channel capacity in the presence of co-channel interference and noise with respect to the $SINR$, for SNR = 20 dB and for systems using the same frequency band.

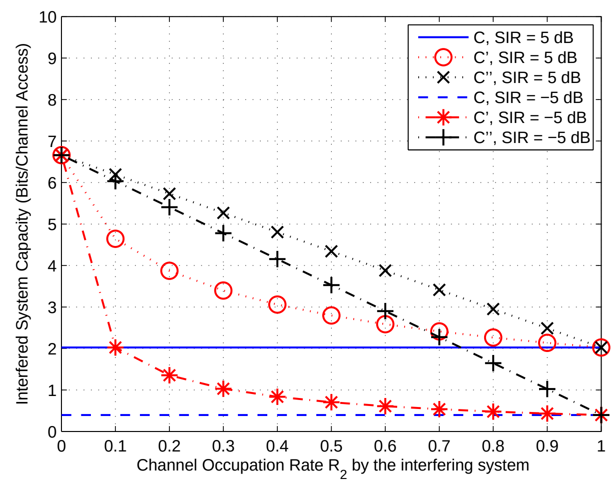

Fig. 4. : Channel capacity in the presence of co-channel interference and noise with respect to the interfering channel occupation rate, for R_1 = 1, SNR = 20 dB and for systems using the same frequency band.

to R_1. As expected in equations (32) and (33), the capacity C'' increases also linearly and C' increases in logarithmic scale with respect to R_1. We note however that for $R_1 < R_2$ the victim system capacity C' considering $\widehat{SINR}$ is lower than the capacity C in the continuous case. The reverse result holds for $R_1 > R_2$ and if $R_1 = R_2$. In all cases, C" remains higher than C and C'.

4) Results for $B_1 > B_2$ and $-\frac{B_1+B_2}{2} \le \delta \le \frac{B_1+B_2}{2}$: In this situation, the interfering system and the victim system use overlapping frequency bands and the interfering signal uses a larger bandwidth than the useful signal. The corresponding capacities have the same expressions as in section IV-B.3.

5) Results for $B_1 \le B_2$ and $-\frac{B_1+B_2}{2} \le \delta \le \frac{B_1+B_2}{2}$: In this case, the SIR depends on the ratio of systems bandwidths, their frequency bandwidths and their frequency offset. The

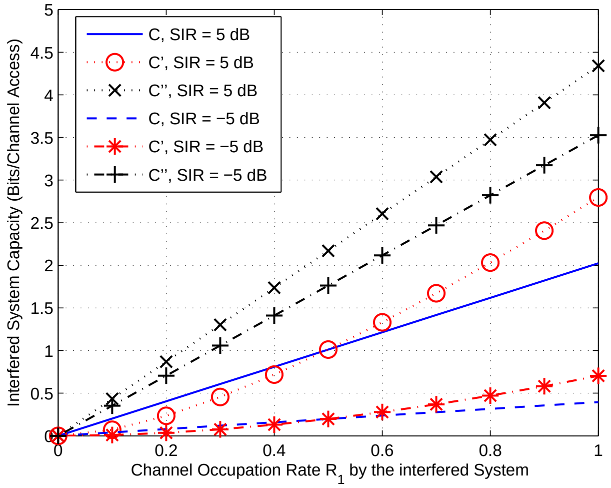

Fig. 5. : Channel capacity in the presence of co-channel interference and noise with respect to the useful channel occupation rate, for R_2 = 0.5, SNR = 20 dB and for systems using the same frequency band.

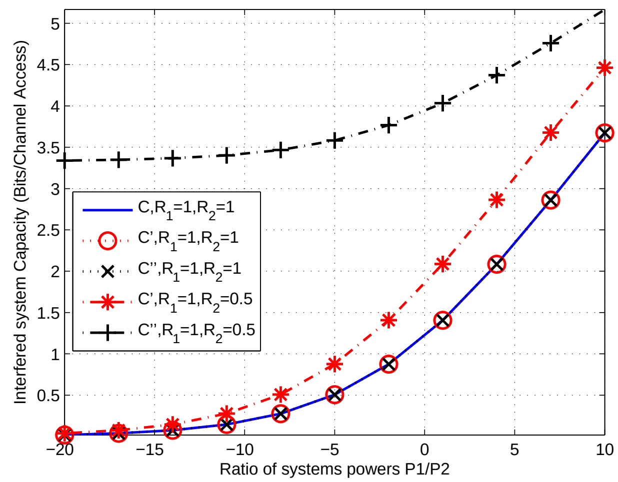

Fig. 6. : Channel capacity in the presence of co-channel interference and noise with respect to the ratio $\frac{P_1}{P_2}$, for SNR = 20 dB, B_1 = 0.5, B_2 = 1 and δ = 0.

expression of the interfered system capacities are given by:

$$C = R_1 \log_2 \left[1 + \left(\frac{1}{SNR} + \frac{P_2}{P_1} \frac{B_1 + B_2 - 2\delta}{2B_2} \right)^{-1} \right], \quad (34)$$

$$C' = R_1 \log_2 \left[1 + \left(\frac{1}{SNR} + \frac{R_2}{R_1} \frac{P_2}{P_1} \frac{B_1 + B_2 - 2\delta}{2B_2} \right)^{-1} \right], \quad (35)$$

$$C'' = R_1 (1 - R_2) \log_2 (1 + SNR) + R_1 R_2 \log_2 \left[1 + \left(\frac{1}{SNR} + \frac{P_2}{P_1} \frac{B_1 + B_2 - 2\delta}{2B_2} \right)^{-1} \right]. \quad (36)$$

We show herein the capacity variations with respect to the power ratio $\frac{P_1}{P_2}$:

- in Fig. 6 for $B_1 = 0.5$ and $\delta = 0$;
- in Fig. 7 for $B_1 = 0.5$ and $\delta = \frac{B_1+B_2}{4}$;
- in Fig. 8 for $B_1 = 0.1$ and $\delta = 0$;
- in Fig. 9 for $B_1 = 0.1$ and $\delta = \frac{B_1+B_2}{4}$.

We notice from Fig. 6 to 9 that when both systems transmit continuously, the capacities C, C' and C'' are identical. When either $\widehat{SINR}$ or $SINR(t)$ is taken into account, the victim system capacity increases compared to C and this holds for all the studied values of systems bandwidths and frequency offsets. We also notice from the four figures that the higher is the power ratio $\frac{P_1}{P_2}$, the more significant is the capacity gain with $\widehat{SINR}$ whereas the capacity gain is the more significant for low values of $\frac{P_1}{P_2}$.

When comparing the results of Fig. 6 and Fig. 8, we see that for a given frequency offset, the capacity gain when considering $SINR(t)$ is the same whereas the capacity gap between C' and C'' decreases with the ratio $\frac{B_1}{B_2}$ for high values of $\frac{P_1}{P_2}$ (*i.e.* high values of the $SINR$). This also holds when comparing the results of Fig. 7 and Fig. 9.

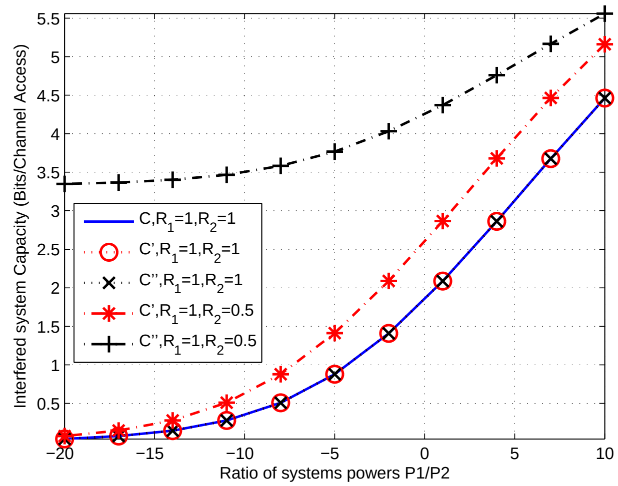

Fig. 7. : Channel capacity in the presence of co-channel interference and noise with respect to the ratio $\frac{P_1}{P_2}$, for SNR = 20 dB, B_1 = 0.5, B_2 = 1 and δ = $\frac{B_1+B_2}{4}$.

In addition, when comparing results of Fig. 6 and Fig. 7, we notice that for a given bandwidth B_2 and a ratio $\frac{B_1}{B_2}$, the capacity gap between C and C'' (as well as between C' and C'') decreases with the frequency offset particularly for high values of $\frac{P_1}{P_2}$ (*i.e.* high values of the $SINR$). This also holds when comparing the results of Fig. 8 and Fig. 9.

We also see that for very low values of $\frac{P_1}{P_2}$, the gap between C" and C is the same for fixed channel occupation rates, independently of systems bandwidths and frequency offset (Fig. 6 to 9).

We then fix $R_1 = 1$ and we study variations of C, C' and C'' with respect to the interference channel occupation rate R_2, as presented on Section IV-B.1. We illustrate the corresponding results in Fig. 10 for $\delta = 0$ and in Fig. 11

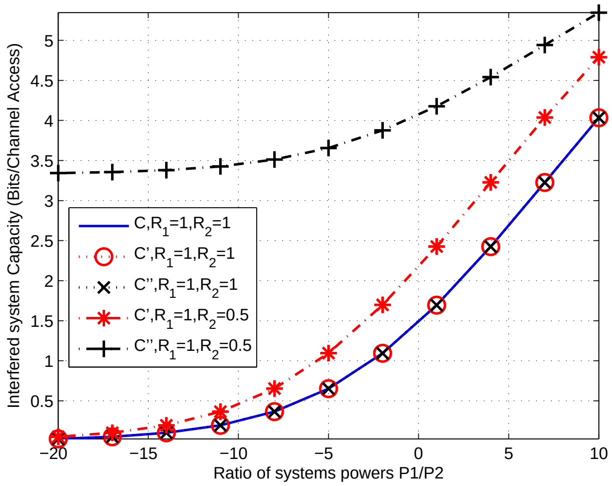

Fig. 8. : Channel capacity in the presence of co-channel interference and noise with respect to the ratio $\frac{P_1}{P_2}$, for SNR = 20 dB, B_1 = 0.1, B_2 = 1 and δ = 0.

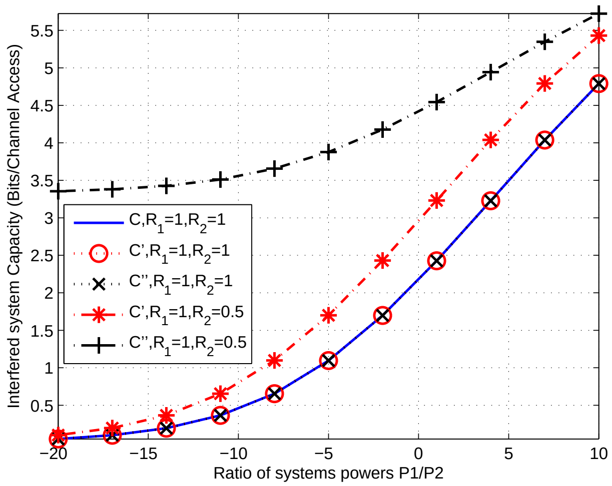

Fig. 9. : Channel capacity in the presence of co-channel interference and noise with respect to the ratio $\frac{P_1}{P_2}$, for SNR = 20 dB, B_1 = 0.1, B_2 = 1 and δ = $\frac{B_1+B_2}{4}$.

for $\delta = \frac{B_1+B_2}{4}$. We see that as in the subsection IV-B.3, C remains constant, C' decreases in logarithmic scale and C'' decreases linearly with R_2 and this occurs for all studied values of B_1, B_2 and δ but in all cases we have $C" \geq C' \geq C$. Moreover, when we compare the results of Fig. 10 and Fig. 10, we notice that for given values of B_1 and B_2, the capacity gain decreases when $\mid \delta \mid$ increases.

We finally set $R_2 = 0.5$ and we analyze the variations of C, C' and C'' with respect to the channel occupation rate R_1 as mentioned in Section IV-B.1. We present the corresponding results in Fig. 12 for $\delta = 0$ and in Fig. 13 for $\delta = \frac{B_1+B_2}{4}$.

We notice from Fig. 12 and 13 that for fixed powers and bandwidths, C and C'' increase linearly and C' increases in logarithmic scale with respect to R_1, for both studied values

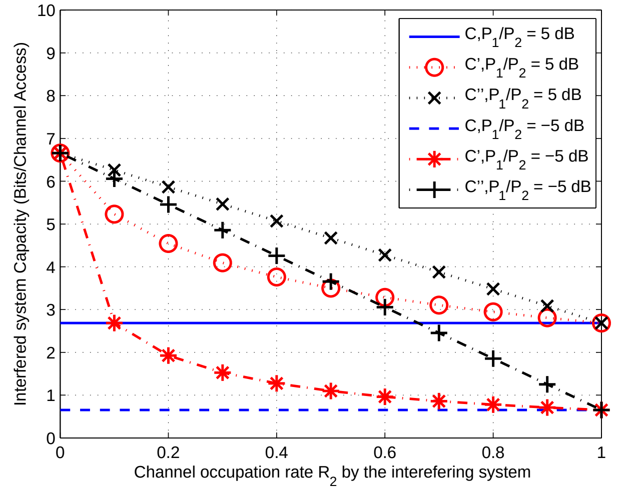

Fig. 10. : Channel capacity in the presence of co-channel interference and noise with respect to the interfering channel occupation rate, for R_1 = 1, SNR = 20 dB, B_1 = 0.1, B_2 = 1 and δ = 0.

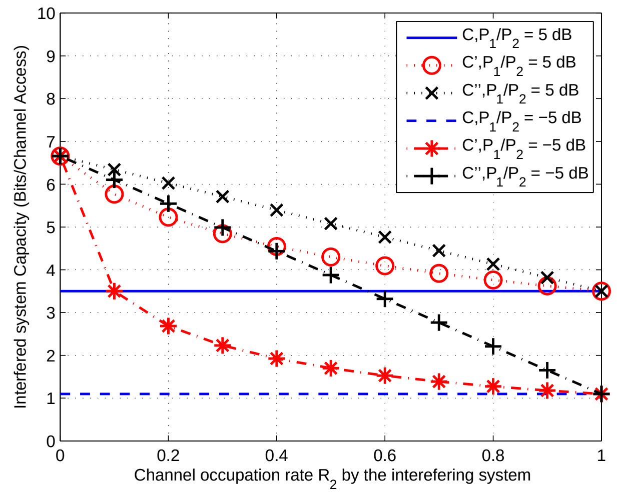

Fig. 11. : Channel capacity in the presence of co-channel interference and noise with respect to the interfering channel occupation rate, for R_1 = 1, SNR = 20 dB, B_1 = 0.1, B_2 = 1 and δ = $\frac{B_1+B_2}{4}$.

of the offset δ. For both offsets, we verify that for $R_1 < R_2$ the victim system capacity C' considering $\widehat{SINR}$ is lower than the capacity C in the continuous case. The reverse result holds for $R_1 > R_2$ and if $R_1 = R_2$, both capacities are identical but lower than the capacity considering $SINR(t)$. In addition, we can notice that when $\mid \delta \mid$ increases, the capacity gain decreases. However, higher capacity of the victim system could be achieved for high values of $\mid \delta \mid$ (*i.e.* when the overlapping between bandwidths of the interfering and the interfered systems is low).

Finally, from Fig. 3 to Fig. 13, we can see that the victim system performance increases significantly when channel occupation rates of both systems are considered. It can be noticed that considering $SINR(t)$ is more realistic because it takes

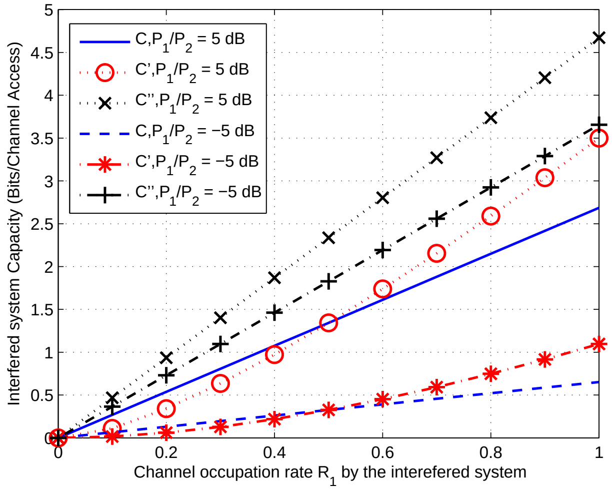

Fig. 12. : Channel capacity in the presence of co-channel interference and noise with respect to the useful channel occupation rate, for R_1 = 1, SNR = 20 dB, B_1 = 0.1, B_2 = 1 and δ = 0.

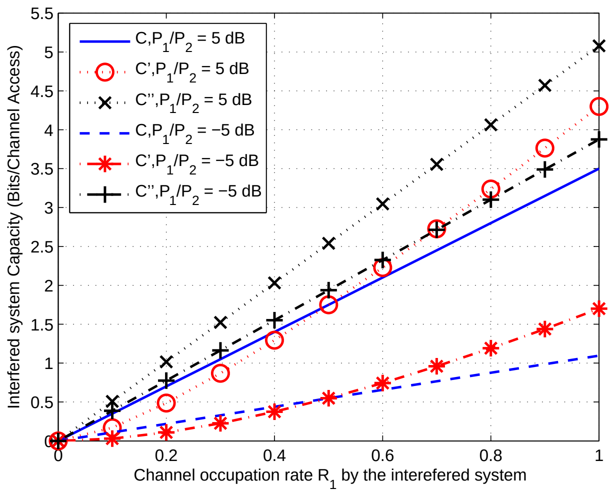

Fig. 13. : Channel capacity in the presence of co-channel interference and noise with respect to the useful channel occupation rate, for R_1 = 1, SNR = 20 dB, B_1 = 0.1, B_2 = 1 and δ = $\frac{B_1+B_2}{4}$.

into account system time-domain aspects with less approximations. As a result, frequency sharing studies could be more precise and systems could be more accurately characterized.

In this case study we made approximations on the propagation environment and we obtained simple expressions for the signal to interference ratio using the channel occupation rates of both systems. We also studied the case where both system masks are ideal and we considered that their antennas are isotropic. More results can be easily obtained using realistic transmission and reception masks as well as antennas radiation patterns by applying equations (2) and (3) into our case study. Moreover, to get more accurate results, additional parameters should be taken into account such as the Inter-Symbol Interference (ISI) and multipath phenomena.

V. Conclusion

In this paper we showed the importance of time-domain considerations to improve the spectrum sharing between radio systems. Current EMC frequency domain analysis provides worst-case results (the involved systems are assumed to transmit continuously), whereas the time-frequency approach seems to be more accurate. It takes into account time-frequency aspects and technology properties. We analyzed a study case in a simplified propagation environment, which allowed us to emphasize that considering channel occupation rates of both systems affects the EMC result and provides more realistic results under certain conditions. On the other hand, the time-domain analysis seems to be more complex as the instantaneous actual interference level may depend on additional parameters of the systems physical layer (power variations, modulation schemes...) and upper layers' parameters (coding schemes, channel access methods...). For the future, we would like to evaluate realistic scenarios taking into account the propagation environment characteristics and specific properties of the signal. In addition, imperfections in the transceiver chain should be taken into account to obtain more representative results. This analysis should be extended to situations where the systems use different channels with overlapping frequency.

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