Inter-System Interference Effect on WiMAX Network Performance

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***Abstract*—Systems coexistence is becoming a very challenging issue. Due to the imperfections of the RF (Radio Frequency) front-end filters, the out-of-band spurious emission from the transmitter is occurred, as well as the receiver selectivity inaccuracy. Those two factors cause different interference levels depending on the transmitted power, the duplex mode of the technology, and also on the distance between terminals. We present in this paper an evaluation to the interference caused by the inter-system coexistence using a mathematical model for both the out-of-band spurious emission, and the receiver selectivity. This framework is then used to estimate the inter-system interference impact on the WiMAX CPEs (Customer Premises Equipment), and hence on the performance of a WiMAX network in terms of capacity. Monte-Carlo approach has been used to estimate the WiMAX network capacity using a simple system level simulator. Different simulation scenarios are considered, all in the DL (DownLink) direction. Coexistence with other systems such as Bluetooth is perceived to impact the WiMAX network. The users' applications have also revealed their impact on the capacity.**

Keywords- Technologies coexistence; Inter-system interference; Monte-Carlo simulations; WiMAX capacity.

I. INTRODUCTION

With the increasing demands for higher data rate applications, spectral resources are in crisis. In the actual situation of the spectrum crowd, the case of having different technologies operating in side by side frequency bands is more frequent. We even have different technologies operating in the same band, such as the famous case of WLAN and Bluetooth, sharing the same 2.4 GHz spectrum of the ISM unlicensed band. When different terminals belonging to frequency-neighbor technologies operate in a close geographical nearby, this could be highly risky in terms of interference generation. Such coexistence in close proximity may result in performance degradation. Several coexistence scenarios could be encountered in-between different technologies; the FDD/TDD coexistence in the context of WiMAX [1], the UWB/WiMAX coexistence [2], the inter-operator coexistence for 3G networks [3], and also the FDD/TDD coexistence for 3G networks [10].

Many factors may influence the capability of two systems to coexist while operating in adjacent frequency bands; RF (Radio Frequency) front-end filters' imperfections (transmitter *out-of-band* emission level, and receiver selectivity), antenna polarization, interference cancellation techniques, and deployment factors [1]. The imperfection of the transmitter RF front-end filter causes the signal energy spilling over the spectrum, which is known by *out-of-band* emission. This undesired emission is characterized by the ACLR (Adjacent Channel Leakage Ratio) [3]. Regarding the receiver side; the accuracy of the receiver's RF front-end filter selectivity is an important point of interest. As the transmitter case, the imperfection of the receiver's frequency band selectivity results in the reception of an undesired signal from the adjacent frequency band. ACS (Adjacent Channel Selectivity) is a typical measure of the receiver selectivity imperfection [1], [3].

Our concern in this paper is the interference generated by the different systems operating in the adjacent frequency bands to the licensed WiMAX 2.5GHz band. We evaluate the interference affecting WiMAX CPEs (Customer Premises Equipment) and show that the impact of this interference on WiMAX capacity is significant. We mainly study the effect of technologies operating in the ISM unlicensed band; precisely 2.4 GHz band where WLAN, and Bluetooth operate. We also study the effect of WiMAX-d IEEE802.16-d technology. However the used mathematical model could also be used to estimate the interference generated by other systems such as UWB. Table (1) gives different wireless technology examples and their operating spectrum bands. Several scenarios have been simulated, considering different user profiles, applications, and interferers' types, in order to get a fair evaluation for the interference impact.

The rest of this paper is organized as follows. In section II, we demonstrate the interference model used to evaluate the inter-system interference generated due to the RF front-end filters imperfections.

TABLE I. TECHNOLOGY BANDS

Technology	Frequency band (GHz)
UMTS (TDD)	1.92-1.98 and 2.11-2.17
UMTS (FDD)	1.90-1.92 and 2.010-2.025
Bluetooth/WLAN	2.400 – 2.4835
WiMAX	2.500 – 2.690
UWB	3.168 - 4.752

In section III, we present the simulation model. In section IV, we present the obtained results related to the different considered scenarios. And we conclude in section V.

II. Adjacent and Co-Channel Interference Model

In the previous section we have introduced the main factors that participate in causing the envisaged interference. Spectrum crowd, and the RF font-end filters imperfections, are the factors which we see the most interesting. In this section we will then focus on those factors related to the radio equipment itself, so-called in literature 'technology' factors. How these factors are modeled in such a way to estimate interference is also demonstrated.

The two main factors related to the "technology" implementation of the RF filters that may affect the performance in an inter-system coexistence scenario are:

A. *Transmitter out-of-band and spurious emission*

Regarding the transmitter side; the source of adjacent channel interference is the *out-of-band* emissions and spurious signals generated by the transmitter. The imperfection of the transmitter RF front-end filter causes the signal energy to leak out of the desired spectrum. This undesired emission is characterized by the ACLR. Ideally, 100% of the power output by the transmitter should be contained 'in-band'. However, in reality this is not practical due to the limitations of realizable filters [1].

Out-of-band spurious emissions from a transmitter operating on a certain technology could generate interference to a receiver operating on a coexisting technology. A typical measure of the spurious emissions is the ACLR, which is defined in [4] as the ratio of the transmitted power to the power measured after a receiver filter in the adjacent RF channel. Both the transmitted power and the received power are measured within a filter response that is nominally rectangular.

B. *Receiver Selectivity*

Moving to consider the receiver's side; the equivalent to the transmitter's "*spurious emission*" is the receiver selectivity accuracy. Ideally, the receiver filter will pass the wanted band exclusively. However, as the transmitter filter case, this is not practically perfect. Some of the power from the adjacent channel interferer reaches the demodulator. The selectivity of a receiver refers to its ability to suppress out-of-band signals [1].

ACS is essentially defined as the ratio of the receiver filter attenuation on the assigned frequency band to the receiver filter attenuation on the adjacent frequency band [4].

It is apparent that the total adjacent channel interference depends on the transmitter out-of-band emission as well as on the receiver selectivity. As the effects of both ACLR and ACS are composing the entire interference generated in case of systems coexistence, it is valuable to use one parameter merging these values.

ACP (Adjacent Channel Protection) combines both the ACLR and the ACS in one equation as follows;

$$ACP \cong \frac{1}{\frac{1}{ACLR} + \frac{1}{ACS}} \tag{1}$$

ACP is also called ACIR (Adjacent Channel Interference Ratio) [4]. Another form of interference is the CCI (Co-Channel Interference) created by transmitters in the same band.

"Fig. 1" demonstrates the adjacent and co-channel interference concepts in case the transmitter and the victim filter responses overlap. A signal is transmitted with significant out-of-band emission. The output from the transmitter is received in the adjacent band. At the receiver some of the power from the transmitted signal passes through the receiver filter. This undesired received power will reduce the received SINR (Signal to Interference and Noise Ratio) of wanted signal. The transmitter filter response is shown in blue, in the figure, while the receiver's filter response is shown in red.

For example, ACLR demonstrates its outcome, in the defined frequency interval "b" shown in "Fig. 1", as the power ratio of the transmitter mask (in blue) to the receiver attenuation value (in red).

In our case study of the interference affecting the WiMAX terminals, where the interferer might be a WLAN access point or a Bluetooth terminal (transmitting nearby the CPE), the ACS is then a parameter concerning the CPE (the receiver), while the ACLR depends on the type of interferer under study.

The CCI, which is defined as the power ratio of the transmitted power to the power measured after a receiver filter, in the same band defined by the shown frequency interval "a" in the figure. The CCI is not of this paper scope.

Let us consider a signal transmitted with an effective isotropic radiated power; *EIRP*. The received power *Pr* can be written as:

$$P_r = EIRP - FSL + RxGain \tag{2}$$

where *FSL* is the free space loss, and *RxGain* is the gain from the receiver side, i.e. antenna gain.

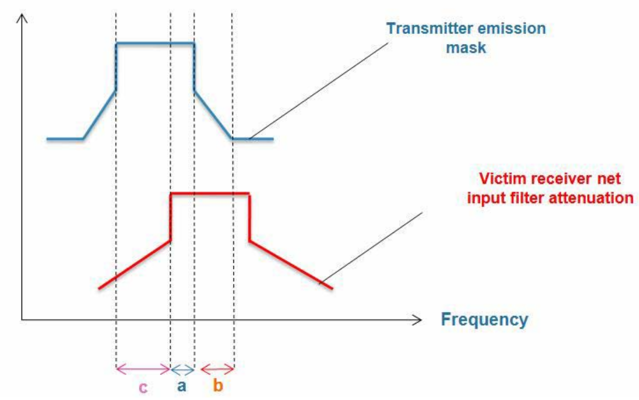

Figure 1. Adjacent channel and CC (Co-Channel) interference.

In case the transmitter and the receiver are not operating on the same band/technology, equation (2) becomes,

$$P_r = EIRP - FSL + RxGain - ACP \quad (3)$$

where *ACP* is the predefined adjacent channel protection parameter.

In a coexistence situation of two systems operating in adjacent bands, the received power *Pr*, due to a transmitted signal by one technology, is seen as interference by the other technology's receiver. The value of this received power is limited, compared to (2), by the factor ACP.

It is relevant to mention that the term "adjacent channel interference" is not restricted to the immediately adjacent channel in the channel raster of the victim's system, but includes any range of spectrum which lies outside the victim's receiver filter.

Table (II) presents the ACLR values for the different technologies used in the paper [8], [15]. The ACS value for the CPE is considered to be 40 dB [8]. The ACLR and ACS values are subject to change according to the different manufactures.

III. SYSTEM MODEL

We perform system level simulations based on Monte-Carlo approach in order to estimate the inter-system interference effect on the WiMAX network capacity.

In this section we will present in details the four main functions/blocks, used to model our WSLS (WiMAX System Level Simulator), as well as the main simulation parameters and assumptions. By the end of this section we will present the used radio resources management technique.

For simplicity we consider a small network consisting of three BS (Base Station), each has an Omni-directional antenna, making each site alike one cell.

The four main functions building the WSLS are:

- The network traffic and load model.
- The channel propagation model.
- The interference distances range model, and finally
- The adjacent channel interference model.

Those four main block functions will be detailed as follows:

TABLE II. ACP VALUES FOR DIFFERENT EQUIPMENT

Radio Equipment	ACLR (dB)
WiMAX-d BS	37
Bluetooth terminal	30
WLAN access point	45

A. Traffic Model

Mobile WiMAX technology supports a wide range of data services and applications with varied QoS (Quality of Service) requirements. According to the IEEE 802.16e standard, QoS profile classes are of four categories [5]:

- UGS (Unsolicited Grant Service)
- RT (Real Time)
- NRT (Non Real Time), and
- BE (Best Effort)

Uniform distribution for the CPEs as well as for the interferers' devices is considered. The users profile-classes distribution in all our simulation scenarios will be as follows; 40% of users will have UGS profile, 10% will have a RT profile, 10% NRT, and 40% of users will have a BE profile class.

The UGS users are served in the first place by the BS, while the BE users are served at last, in case there is available BW (Bandwidth) portion, after serving the RT and NRT users. The scheduler gives the priority to the users according to their profile classes in a descending order.

Each user has also a required application which is independent of his profile class. According to the WiMAX Forum, we have five different application types; each one is specified by its minimum required data rate, maximum latency, and jitter. In this paper we only consider the data rate parameter. Table (III) gives five different applications, as presented in [6], and gives as well their corresponding data rates as simulated in the Monte Carlo simulator.

B. Channel Propagation Model

The COST231 propagation model is used by the WiMAX Forum for system evaluation and testing purposes [14]. We considered the same model for our simulations keeping in mind that our quantitative results would change for other propagation models, but they will not change qualitatively.

C. Interference Range Model

We suppose the coexistence of WLAN access points, or Bluetooth devices, nearby the WiMAX victim terminals. Also WiMAX-d CPE is considered in different scenarios.

The interferer devices are distributed randomly in the WiMAX network grid, as well as the WiMAX CPEs, while the

TABLE III. WIMAX SYSTEM APPLICATIONS AND THEIR SIMULATED DATA RATE.

Application/Service	Required Data Rate
VoIP (Voice over Internet Protocol)	64 Kbps
Multiplayer interactive gaming	50 Kbps
Web browsing and instant messaging	20 Kbps
Streaming media	10 Kbps
Media Content Download	1 Mbps

three BS locations are constants in the grid for each simulation shot. The interferers' number, location, type and their transmitter power, affect the CINR (Carrier to Interference Noise Ratio) value received by the WiMAX terminals. The CPE's location according to its serving BS is also an important parameter, See "Fig. 2". The distance "*d*" shown in "Fig. 2" which represents the WiMAX terminal location parameter, is mutually affecting the CINR value, compared to the distances between the CPE and the interferers; "*d1*", "*d2*",etc…

D. Adjacent Channel Interference Model

Equations (1), (2), and (3) are integrated in the simulator in order to estimate the CINR value for each WiMAX terminal. The measured CINR at each CPE is given by;

$$CINR = \frac{\Pr_{SC}}{\sum_i \Pr_i + NoiseFloor} \tag{4}$$

Where $\Pr_{sc}$ is the received power from the serving cell, $\Pr_i$ is the received power from the interferer network element *i*, and *NoiseFloor* is the receiver's noise floor including the thermal noise. The interferer network elements include all the devices that cause interference containing the neighbor base stations and the near CPEs.

Alike many system level simulators [7], our WSLS has the general model shown in "Fig. 3". Table (IV) gives the main simulation parameters. Different simulation scenarios have been executed. Mobility is not taken into consideration, and subscribers are assumed to be stationary (for each simulation iteration). Adaptive link adaptation is enabled through the selection of the highest modulation scheme (MSC), according the received CINR by each CPE.

For each available Bandwidth, a maximum number of sub-channels exist. For each available BW, and per MSC type, a maximum cell throughput could be achieved. In accordance with the obtained MSC per CPE, the obtained throughput, per each CPE, could be calculated. The user is considered to be "satisfied" if the required throughput (according to both the user profile class and to the required application) is the obtained throughput by the user (occupying one or more sub-channel in the operational band).

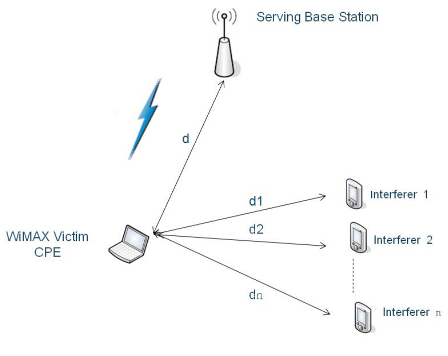

Figure 2. The Interference range model.

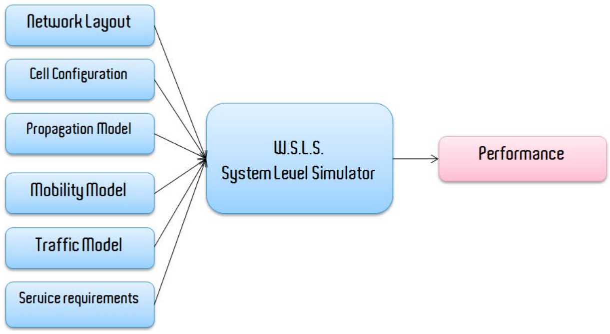

Figure 3. The WSLS general model (Mobility is not considered in our case)

TABLE IV. MAIN PARAMETERS OF THE SIMULATED WIMAX NETWORK

Parameters	Value
Number of cells	3
Antenna configuration	1x1 (Omni)
Frequency band	2.5 GHz
Duplex mode	TDD
Channel Bandwidth	1.25, 5, 10 MHz
DL Permutation	PUSC
Inter-Site distance	4km
BS height	32m
CPE height	1.5m
Propagation model	COST231
Frequency Re-Use mode	3
Power control	OFF

IV. RESULTS

In this section we present the output results from the Monte Carlo simulation for different scenarios. The first scenario aims at estimating the WiMAX network capacity as a function of the different BW values. "Fig. 4" shows the percentage of satisfied WiMAX users when no interferers are induced. The users' profiles classes are distributed as mentioned in section III.

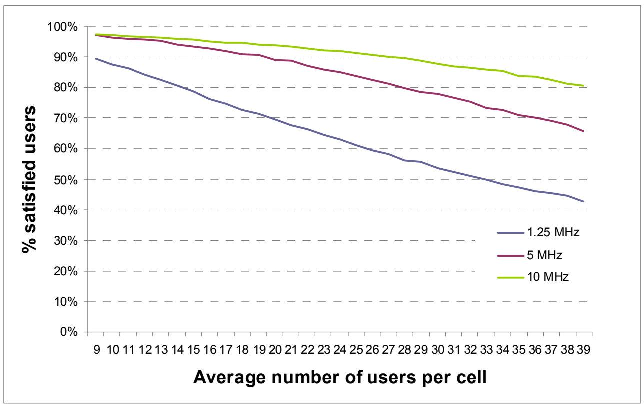

Figure 4. WiMAX network capacity as a function of BW

We can notice that for an average number of users per cell equal to 20, we have;

- 70% of users are satisfied in case the network is deploying 1.25MHz BW, while,
- 90% of users are satisfied when 5MHz BW is used, and
- 95% of users are satisfied when 10MHz BW is deployed.

Two scenarios are demonstrated in “Fig. 5”. In the first one all the users have VoIP application, while in the second; the users are having different applications distributed randomly. For both scenarios, we show three curves, each one presents the percentage of satisfied users in case there is no interferer devices introduced in the network, with 30 WLAN access points, and finally with 70 WLAN access points. Both of the scenarios are having 5MHz of BW.

As expected, the network performance degradation in terms of capacity is observed to be more effectual with the increase of the interferers’ number.

We can notice the effect of the application type on the slop of the curves. The impact of the application type is noticed to be more serious on the network capacity than the interferers in the simulated context.

“Fig. 6” shows different curves for the media content download application, called also FTP (File Transfer Protocol) application. Two scenarios have been simulated, for 5MHz, and 10MHz BW. The “No interferers”, “30 WLAN access points’ interferers”, and “70 access points” cases have been tested for each BW.

We can notice the convergence of the different curves towards a certain point, which means that differentiating between different interfering scenarios vanishes with the increase of users’ number per cell. The number of users per cell becomes dominate over the inter-system interference.

As mentioned in III section C. Different types of interferers have been tested among which WiMAX-d CPE.

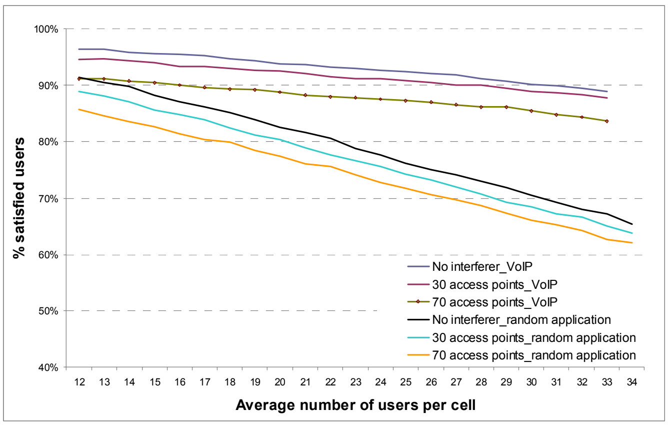

Figure 5. Percentage of satisfied users for VoIP and random application type.

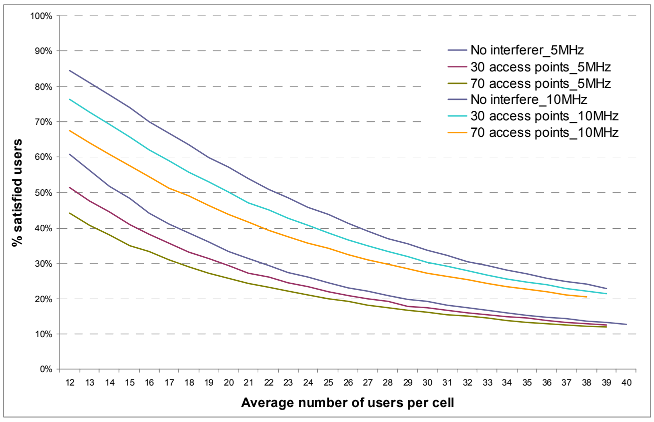

Figure 6. Percentage of satisfied users for FTP application. Comparison between 5MHz, and 10 MHz BW on different interferers conditions.

In “Fig. 7” we present two curves comparing the percentage of satisfied users in case of coexistence with “30 Bluetooth terminals” and with “30 WiMAX-d CPEs”. The curves have been obtained for 5MHz BW, while having the same distribution of user profiles classes as in the previous scenarios. The users have random applications distribution.

We can notice the clear difference between the effect given by the Bluetooth terminals, and that given by the WiMAX-d CPEs. For 11 average number of users about 31.2% of users are satisfied when coexisting with “30 WiMAX-d interferes”, while 66.2% of users are satisfied when coexisting with “30 Bluetooth interferes”. The Bluetooth terminals are considered of class1 transmitting with the maximum power of 20 dBm [9].

V. Conclusion

Inter-system interference is an important issue in nowadays heterogeneous wireless networks. We provided a brief description of the main parameters causing this interference, particularly the technology factors, presented by the ACLR and ACS parameters, and combined into the ACP parameter. We evaluated the effect of the inter-system coexistence on the WiMAX network capacity through the integration of those parameters into Monte-Carlo simulations. Analysis of the results has been demonstrated showing the effect (of WLAN, Bluetooth, and WiMAX-d terminals operational nearby WiMAX CPEs) on a WiMAX network performance. The users running applications are noticed to be a really considerable factor in the WiMAX network capacity evaluation.

Future Work

In the actual situation of spectrum crowd, new techniques as well as new regulator rules are proposed to face such dilemma. The DSA (Dynamic Spectrum Access) topic has been tackled by [11], [12], and others. The need of guard bands are demonstrated in one of the proposed DSA scenarios [13]. We can perceive that in the context of DSA system, the adjacent channel interference becomes a challenging point of interest. This paper work is then a fundamental step when DSA is to be studied. We envisage continue and enhance this work within the actual URC (Urban Planning for Radio Communications) research project. The URC project is

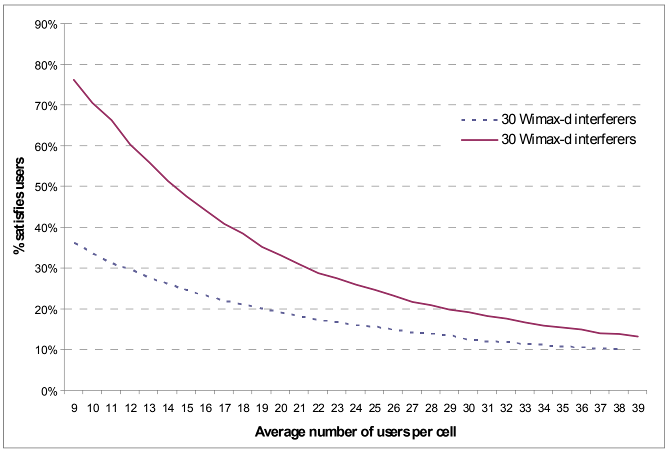

Figure 7. Percentage of satisfied users with the coexistence of Bluetooth and WiMAX-d CPEs interferers. The users access random application types.

investigating a variety of dynamic spectrum access techniques and cognitive radio methods, and developing models and simulation tools for this purpose.

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