An Efficient Tool for the Evaluation of the Impact of WiFi Interference on Bluetooth Performance

Madani Zeghdoud¹, Pascal Cordier¹, and Michel Terré²

¹ France Telecom R&D, Issy les Moulineaux, France. ² CNAM, Paris, France

Abstract— IEEE.802.15.1 (Bluetooth) wireless personal area networks and IEEE.802.11b/g (WiFi) wireless local area networks share the same 2.4 GHz unlicensed ISM (Industrial, Scientific and Medical) frequency band. Without any provisions, mutual interference between these two wireless systems may result in performance degradation when devices are co-located in the same environment. In this paper, the Bluetooth and WiFi coexistence issue is addressed. A fast simulation tool that models the PHY and the MAC layers elements of both Bluetooth and WiFi was developed, validated by measurements and used to model interference scenarios.

Index Terms— Bluetooth, WiFi, Coexistence, Interference, Simulation, Measurement

I. INTRODUCTION

Both Bluetooth and WiFi technologies operate in the 2.4 GHz unlicensed ISM (Industrial, Scientific and Medical) frequency band. Mutual interference between these two wireless systems may result in performance degradation when devices are co-located in the same environment.

To model the coexistence of wireless networks sharing a frequency band, both the PHY and the MAC layers elements of the different systems have to be taken into account. Combining a PHY level simulation and a MAC level simulation needs detailed implementations which are relatively difficult when the coexistence scenarios are complex. Furthermore, accurate and complex simulations are very time consuming. Hence, analytical modeling seems to be more suitable for such issue, but deriving mathematical expressions describing complex coexistence scenarios generally needs many simplification hypotheses, and consequently, the results from calculations could be less realistic.

Several previous works have been devoted for the analysis of the WiFi and Bluetooth interference. A detailed analysis has been performed by A. Conti, D. Dardari, G. Pasolini, and O. Andrisano in [9]. An analytical model has been presented by A. Stranne, O. Edfors, and B. -A. Molin in [10], where WiFi and Bluetooth networks interference has been analysed. Bluetooth and WiFi coexistence has been also analyzed by I. Howitt in [6] and in [7], and by Chiasserini and Rao, R.R., in [8].

WiFi and Bluetooth coexistence issue has been addressed by Golmie. In [5], an Analytical analysis has been developed to derive the Bluetooth PER (Packet Error Rate). In [4], a detailed simulation methodology has been developed to evaluate Bluetooth and WiFi interference.

In this paper, the Bluetooth and WiFi coexistence issue is addressed. A simulator that models the PHY and the MAC layers elements of both Bluetooth and WiFi was developed. The same technique as in [4] was used to speed up the simulations at the PHY level. In [4], the PHY level model is combined with OPNET simulator to take into account the upper layers but in our study, the MAC layer elements are implemented in the same tool as the PHY layer, allowing flexible interactions between the two layers. More complex scenarios can then be easily modeled. Furthermore, the simulation methodology was validated by measurements and used in an illustrative example.

The remaining of this paper is organized as follows: section II presents a brief overview of WiFi and Bluetooth protocols. In section III, a short description of the simulator is presented. The measurements are presented in section IV. In section V, an application example is given.

II. SYSTEMS OVERVIEW

A. WiFi

Different versions of IEEE802.11 Physical layer (PHY) are defined for a common Medium Access Control (MAC) sublayer. The MAC sublayer operates by default in Distributed Coordination Function (DCF) mode. DCF is based on Carrier-Sense, Multiple Access/Collision Avoidance (CSMA/CA), which is a contention-based protocol assuring that all stations first sense the medium before transmitting. The main goal is to avoid stations transmitting at the same time, which results in
collisions and consequent retransmissions.

CSMA/CA exploits Binary Exponential Backoff (BEB) mechanism. DCF has two ways to detect the status of the medium, virtual and physical carrier-sense functions. The virtual carrier-sense mechanism uses short frames called Request-To-Send (RTS) and Clear-To-Send (CTS) to announce the time and duration of future data exchanges. In this paper, only the DCF mode with physical carrier-sense is considered. A station wanting to send a frame first senses the medium by performing a Clear Channel Assessment (CCA); If the medium is free for a DCF Inter Frame Space (DIFS), it starts transmission immediately; otherwise, the station waits until the medium is idle, and, if the channel is still idle for a period of DIFS, it goes into a backoff procedure before it sends its frame.

The backoff time is equal to a time slot multiple. This multiple is randomly chosen between 0 and a minimum Contention Window (CWmin) value. If the wireless station has transmitted a packet and has received an acknowledgement (ACK) frame correctly, then the Contention Window (CW) is still equal to CWmin for this station. If the wireless station failed to receive ACK frame, CW is doubled. When CW reaches a maximum bound CWmax, it remains equal to this value. If a packet is not received correctly after a maximal number of retransmissions allowed for a station, the packet is lost.

B. Bluetooth

Bluetooth is a 1-Mbit/s frequency hopping-based (FHSS) system. The physical layer uses 79 channels of 1 MHz-width and hops pseudo-randomly at a nominal rate of 1600 hops/second. Bluetooth supports a master/slave topology referred to as a piconet. The master controls the medium access by polling the slaves for data and using scheduled periodic transmission for voice packets. Between master and slave(s), the following types of links can be established:
- Synchronous Connection-Oriented (SCO) link.
- enhanced Synchronous Connection-Oriented (eSCO) link
- Asynchronous Connection-Less (ACL) link

The SCO link is a symmetric point-to-point link between a master and a single slave in the piconet. The master sends SCO packets to the slave in the reserved master-to-slave slots at regular intervals. The slave is always allowed to respond with a SCO packet in the following slave-to-master slot unless a different slave was addressed in the previous master-to-slave slot. SCO packets are not retransmitted in case of loss or error.

Similar to SCO link, eSCO link reserves slots, but in addition, eSCO supports a retransmission window immediately following the reserved slots. eSCO link may be symmetric or asymmetric.

The ACL link is an asymmetric point-to-multipoint link between the master and all the slaves of the piconet. In the slots not reserved for the SCO link(s), the master can establish an ACL link to any slave. Automatic repeat request (ARQ) is incorporated for ACL links to ensure reliable delivery of data.

III. SHORT DESCRIPTION OF THE SIMULATOR

A simulator that models the PHY and the MAC layers elements of both Bluetooth and WiFi was developed on Matlab software. The same technique as in [4] was used to speed up the simulations at the PHY level. In [4], the PHY level model is combined with OPNET simulator to take into account the upper layers but in our study, the MAC layer elements are implemented in the same tool as the PHY layer, allowing flexible interactions between the two layers. More complex scenarios can then be easily modeled. Bluetooth performance for different interference scenarios can be evaluated by simulations. The performance metric used in this study is the Packet Error Rate (PER) of Bluetooth.

In order to speed up the simulations, the bit error rate (BER) depending on the signal to interference ratio (C/I) is combined with the MAC level simulation to investigate complex scenarios without having to implement signal processing modules which are time consuming.

To simulate an interfering scenario, the user first defines the number and the positions of the interfering stations, the positions of the transmitter and the receiver of the victim link, the propagation model, the PHY layer and the MAC layer parameters of both interfering and victim systems, and traffic parameters.

After the simulation is launched, packets are transmitted by the interfering and the victim networks according to their respective channel access mechanisms described in section II.

Given the transmitted powers, and the channel model, the interfering power and the desired power levels at the victim receiver are calculated.

Collisions between the interfering network stations may occur and are taken into account as depicted on Fig. 1; the interference level value is the sum of all the interfering signals transmitted by different stations.

![Interfering packets and Desired packet with BER values](image-url)
For each transmitted packet of the victim link, binary errors are randomly generated with a probability equal to the average BER for each segment of Bluetooth packet where the C/I is stationary (see Fig. 1). Tables containing the variation of the BER with the C/I variation are loaded in the simulator. Binary errors generation is performed using the same approach than the one used in [4].

Finally, depending on the Bluetooth packet type and the related forward error correction (FEC) specified by the Bluetooth protocol, error correction is applied for each segment of the received packets (header, access code…) and the PER is then computed.

IV. MEASUREMENTS

The aim of the measurements is to validate the simulation methodology. So, to compare the simulation results and the experimental ones, the real parameters of both interfering and victim systems should be measured and used in the simulations.

A. Bluetooth BER as a function of C/I measurement

The key element of the simulations is the curve representing the BER as a function of the C/I at the Bluetooth victim receiver. To measure the BER versus the C/I, the setup depicted in Fig. 2 has been used.

All the measurements were performed in an anechoic chamber to be isolated from external interference.

The equipments used for the experiment are the following:
- CBT : Rohde & Schwarz Bluetooth tester
- Casira DUT: Bluetooth device under test (DUT). The DUT is controlled by a computer and appropriate software.
- AWGN Generator

As described in the Bluetooth test mode specification [1], to measure the BER performance, the DUT shall have a loopback facility.

The DUT is set to its internal test mode and acts as a slave. The CBT acting as a master and using the loopback mode transmits packets. The DUT decodes the received packets and sends back the payload using the same packet type. The CBT compares the sent and looped back payload bits and computes the BER. The payload bits of the packets used in test mode are not protected by any forward error correction (FEC). Here, the used packet type is DH1. The bit error rate is the ratio of the payload bits received in error by the DUT to the total payload bits. The BER is calculated for each packet and a mean value is given and displayed by the CBT.

So the BER can be measured for different values of the C/I at the Bluetooth DUT but the BER measurement is only meaningful under the assumption that the return path from the DUT to the tester (CBT) is perfect and has no impact on the BER. For this aim, the frequency hopping scheme is set to “RX/TX single freq” which is specified in [1]. So, the DUT receives at a constant Rx frequency from the CBT and transmits at a constant Tx frequency. Furthermore, the C/I at the DUT should be sufficient enough in order to maintain the connection with the CBT, so the BER is obtained only for C/I values superior to a given threshold.

For this first experiment, we need a WiFi signal generator transmitting continuously and without incorporating packet structure. Given that IEEE 802.11g signals are OFDM composed of superposition of many sub carriers and the bandwidth of the IEEE 802.11g is much larger than that of the Bluetooth, the WiFi signal generator can be substituted by an Additive White Gaussian Noise (AWGN) generator. Furthermore, IEEE 802.11g (54 Mbit/s) signals have been measured by a Lecroy WaveMaster 8600A digital oscilloscope and treated on Matlab. Using the command “histfit”, the histogram of the measured samples of WiFi signal is compared to a theoretical Gaussian distribution. As illustrated in Fig. 3, the measured and the theoretical histograms are very similar.
To generate the AWGN, Rohde & Schwarz SMIQ, AMIQ and appropriate software were used.

The AWGN bandwidth is set to 20 MHz and its centre frequency is set to 2412. The noise is then similar to WiFi channel 1.

The receiving and the transmitting frequencies of the DUT are set to 2412 MHz and 2477 MHz respectively. So, only the DUT is interfered and the return path from the DUT to the tester (CBT) is not interfered and has no impact on the BER.

The BER measurement results are depicted in Fig. 4.

When the C/I ratio decreases below a threshold value $C/I_{th}$, the link between the Bluetooth tester and the DUT is lost, the measured threshold value is $C/I_{th} = -2.5$ dB.

The BER is given by the CBT for each value of measured C/I. The first measurement was performed for $C/I = 5$ dB corresponding to a very low value of BER which is equal to $10^{-5}$, where the desired and the interference powers were measured at the DUT position. The other values of BER are obtained by decreasing the transmitted power of the CBT by a step of 0.5 dB until reaching $C/I = -2$ dB. $C/I_{th}$ was avoided to keep the connection between the CBT and the DUT.

**Remark:** the interference power (I) and the desired power (C) are measured at the DUT antenna input by using an Agilent E7405A Spectrum Analyzer connected to an Omni directional antenna via a cable of 3 meters long. The measured cable loss is equal to 2 dB.

As we can see it in the following sections, when using the results of this section in the simulations, we consider also the power levels at the antennas inputs and before the receiver filter without applying the spectrum factor.

**B. Simulation methodology validation**

Another experiment was performed in the anechoic chamber to validate the simulation methodology. For this aim, a WiFi network was installed. The test setup is shown in Fig. 5.

The equipments used for this experiment are:
- Bluetooth link CBT-DUT
- 1 WiFi Access Point (LINKSYS AP)
- 2 WiFi Stations (2 LINKSYS Cards)

The Bluetooth link CBT-DUT operates in the same environment as the two WiFi stations communicating with their Access Point (AP).

The geometry of the scenario is depicted in Fig. 5. The relative distances between the different devices were chosen in accordance with the anechoic chamber dimensions; they are the following:
- $d_{AP-DUT} = 2.50$ m = The distance between the WiFi Access Point and the Bluetooth DUT.
- $d_{Sta1-DUT} = 1.80$ m = The distance between the WiFi Station 1 and the DUT
- $d_{Sta2-DUT} = 1.50$ m = The distance between the WiFi Station 2 and the DUT
- $d_{CBT-DUT} = 0.50$ m = The distance between the Bluetooth tester CBT and the DUT.

The same scenario was simulated using the results of the first measurements results (BER versus C/I) and the measured PHY and MAC parameters of the different radio devices.

The Bluetooth PER at the DUT obtained by the simulations tool is compared to the one measured by the CBT.

The WiFi network channel is set to 2412 MHz (channel 1). The transmitted power of the WiFi stations ($P_{Sta1}$ and $P_{Sta2}$) and their Access Point ($P_{AP}$) were measured. The results are the followings:
- $P_{AP} = 10$ dBm
- $P_{Sta1} = P_{Sta2} = 6$ dBm
As an example, the WiFi Access Point spectrum is shown in Fig. 6. The measurement was performed with Agilent E7405A Spectrum Analyzer and an omnidirectional antenna. The antenna was placed 1 meter from the Access Point and connected to the analyzer via a cable of 3 meters long. The cable loss was measured; it is equal to 2 dB.

The maximum transmitted power of the CBT is 0 dBm. To modify the C/I level at the DUT, we had to vary $P_{CBT}$, the transmitted power of the CBT.

The maximum values of C/I are obtained for $P_{CBT} = 0$ dBm. The measured maximum values of C/I caused by the WiFi Access Point, Station 1 and Station 2 are equal to 2 dB, 3 dB and 1.5 dB, respectively.

For each value of $P_{CBT}$ which is decremented by 0.5 for each measurement corresponds a value of the PER at the DUT measured by the CBT. During each measurement, 10000 DH1 packets are sent by the CBT to the DUT.

$P_{CBT}$ is decreased until reaching a minimum value equal to –3.5 dBm which corresponds to the disconnection of the DUT from the CBT because of the interference of WiFi station 2.

Remarks:
- The CBT and its antenna are connected with a cable of 3 meters long. The cable attenuation is measured and is equal to 2 dB.
- Only 2 WiFi stations communicate with their Access Point, so the collisions are neglected.

The packet and ACK durations of WiFi were measured with a Lecroy WaveMaster 8600A digital oscilloscope.

An example of a measured packet followed by an ACK is shown in Fig. 7.

Let’s remind that because of the measurements constraints, the CBT and the DUT frequency hopping scheme is set to “RX/TX single frequency”. The same parameter was then used in the simulations. The CBT receives and transmits at channel 10 and channel 75, respectively (see table I).

The main parameters of WiFi and Bluetooth are summarized on Table I.

Free space propagation model was selected and other MAC and PHY parameters issue from IEEE 802.11 and IEEE 802.15 standards.

The measurements and the simulation results are depicted in Fig. 8.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>BLUETOOTH AND WIFI MAIN PARAMETERS VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluetooth parameters</td>
<td>Values</td>
</tr>
<tr>
<td>Transmitted power</td>
<td>Variable</td>
</tr>
<tr>
<td>Bit rate</td>
<td>1 Mbit/s</td>
</tr>
<tr>
<td>Packet type</td>
<td>DH1</td>
</tr>
<tr>
<td>DUT reception frequency</td>
<td>2412 MHz</td>
</tr>
<tr>
<td>DUT transmission frequency</td>
<td>2477 MHz</td>
</tr>
<tr>
<td>802.11g parameters</td>
<td>Values</td>
</tr>
<tr>
<td>Access Point transmitted power</td>
<td>10 dBm</td>
</tr>
<tr>
<td>Station 1 and Station 2 transmitted power</td>
<td>6 dBm</td>
</tr>
<tr>
<td>$CW_{min}$</td>
<td>31</td>
</tr>
<tr>
<td>$CW_{max}$</td>
<td>1023</td>
</tr>
<tr>
<td>SIFS duration</td>
<td>10 µs</td>
</tr>
<tr>
<td>Bit rate</td>
<td>54 Mbit/s</td>
</tr>
<tr>
<td>Packet duration</td>
<td>250 µs</td>
</tr>
<tr>
<td>ACK duration</td>
<td>30 µs</td>
</tr>
</tbody>
</table>
A good concordance between the simulations and the measurements can be observed in Fig. 8. But in general, the measured PER is a little superior to the simulated one. This can be explained by the WiFi out of band (OOB) emissions which are not taken into account in the simulations.

**V. APPLICATION EXAMPLE**

Based on the good concordance between the experimental and the simulation results, the simulator can be used to model more complex and more realistic interference scenarios between Bluetooth and WiFi. An illustrative example is presented hereafter.

The scenario geometry is the same as the one of Fig. 5. WiFi and Bluetooth parameters are the same as those of Table I except the Bluetooth packet type.

Furthermore, the CBT and the DUT frequency hopping scheme set previously to “RX/TX single freq” because of the measurements constraints is now set to “Europe/USA”, so all the 1 MHz bandwidth channels of the ISM band are used.

eSCO (enhanced SCO) links standardized lately in [1] and SCO links performance are compared. EV3 eSCO packets performance is compared to HV1, HV2, and HV3 SCO packets.

The PER versus the Bluetooth transmitter power is evaluated for the four packet types. The results are depicted in Fig. 9.

The desired power (C) and the interference (I), received at the DUT are very superior to the internal noise and all the equipments are supposed to be in an anechoic chamber. So, an interference limited environment was simulated.

Fig. 9 shows that in this interference limited environment, eSCO links are very preferred over SCO links.

The worst results are obtained using HV3 packets where payload is not protected by forward error correction (FEC). HV1 and HV2 packets protected by 1/3 FEC and 2/3 FEC respectively are better than HV3 packets but FEC is not efficient enough.

For low values of C/I, the correction capacity of the FEC is exceeded and the PER reaches around 19 %. Remind that in this example, Bluetooth hops in the entire ISM band while WiFi uses a fixed 20 MHz bandwidth channel, this explains why the PER is very low compared to the PER in Fig. 8 in section IV where the DUT receiving channel is constant and always overlaps with WiFi channel.

However, this study confirms the efficiency of eSCO links. This is due to packet retransmissions. EV3 packets are not protected with FEC but include a CRC in order to retransmit erroneous packets within a retransmission window and have more chance to be sent in a non overlapped frequency.

So, in this interference limited environment, eSCO links using packet redundancy are very efficient. But WiFi performance (not evaluated in this study) may be better in presence of SCO links than in the presence of EV3 packets because of the increasing of the time channel occupancy by Bluetooth.
VI. CONCLUSION

In this article, we presented a simulation methodology to evaluate the impact of WiFi interference on Bluetooth reception.

A simulator that models the PHY and the MAC layers elements of both Bluetooth and WiFi was developed on Matlab software.

In order to speed up the simulations, the bit error rate (BER) depending on the signal to interference ratio (C/I) is combined with the MAC level simulation in the same tool to investigate complex scenarios without having to implement signal processing modules which are time consuming.

Furthermore, measurements were performed to evaluate the key input parameters of the simulator and verify the simulation results.

Based on the concordance between the simulation and the experimental results, the simulation tool can be used to model more complex and more realistic scenarios. An illustrative example was presented.

The simulation methodology could be extended on other radio networks and further studies including specific radio networks coexistence enhancements could then be carried out on the basis of the simulation tool.

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REFERENCES


