Experimental assessment of the coexistence of Wi-Fi, ZigBee, and Bluetooth devices

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***Abstract*—Many wireless technologies used to build local or personal area networks (WLANs, WPANs) operate into the 2.4 GHz ISM band. Due to the mutual interference, the coexistence of such devices working at the same time in the same area can be troublesome. This paper reports the result of an extensive experimental study on the performance of three popular technologies (ZigBee, Wi-Fi, and Bluetooth), under their mutual disturbance. In addition to assessing the effect of the interference between pairs of technologies, we also analyzed the simultaneous interference among the three systems, a scenario that has never been studied before. Our work partly confirms previous findings, but also reveals some unexpected behaviors, imposing to reconsider some assumptions about the supposed interference-free ZigBee and Bluetooth channels.**

I. Introduction

Many wireless technologies, especially those used to build local or personal area networks (i.e. WLANs or WPANs), operate into the unlicensed frequency bands, which can be exploited by multiple users and networks at the same time. For example, the 2.4 GHz ISM band is used worldwide by several technologies, such as Wi-Fi, ZigBee, and Bluetooth[1].

However, due to the mutual interference, the coexistence of different devices operating in proximity of each other can be troublesome. As proved by many authors [1], [2], this is especially true for ZigBee networks, whose performance is heavily influenced by the presence of Wi-Fi devices. While it is sometimes feasible to avoid the interference among devices sharing the same spectrum and implementing the same standard (e.g. collision avoidance schemes might work across separate networks), the use of incompatible modulations and channel access schemes makes it virtually impossible to ensure the coexistence among devices belonging to different technologies.

Historically, this class of problems has been solved by licensing frequency bands to authorized users, which are thus the sole users allowed to transmit in that frequency range. Yet, in addition to be excessively costly (especially with respect to the cost of the devices), this approach could bring to low utilization of the licensed band, and therefore cannot be regarded as an efficient and viable solution for standards like the above mentioned ones.

More recently, there has been a growing interest in cognitive radio techniques, which allow single devices and even whole networks to monitor the environment in order to dynamically select and use the channel that offers the least interference. However, though this approach has been widely studied [3], [4], its practical and large scale deployment is yet to come.

Therefore, assessing the mutual interference of coexisting systems is still a topical issue. The paper reports the outcome of an extensive experimental study involving Wi-Fi, ZigBee, and Bluetooth devices. The goal of such analysis is to characterize not only the reciprocal interference when pairs of technologies share the same spectrum, but also the coexistence of the three systems when they are all active in the same time and space, an aspect that has always been neglected. The outcome of our study is partly a confirmation of previous results, but more remarkably it brings to light some unexpected findings about the supposed (and no longer such) interference-free ZigBee channels and the coexistence among Wi-Fi and Bluetooth. Note that even techniques, such as cognitive radios, that could be assumed to not need these information, may in fact take advantage of these findings, as they can be used for building a better characterization of the interference phenomenon, and thus improve their ability to avoid the interference of external devices.

II. Related Work

Numerous simulation studies can be found about the performances of ZigBee under the interference of Wi-Fi and Bluetooth. Just to cite one, Shin *et al.* developed a very accurate analytic model to compute the packet error rate (PER) of ZigBee, and validated the results via simulations [5]. However, since no validation is performed through experimental activities, both approaches (i.e. analytical and simulation) remains into the theoretical domain and no measure of their actual utility can be drawn. Clearly, due to the very complex nature of the wireless channel and environment, this shortcoming is pretty common to all those works that do not provide an experimental evidence of the analytical and simulation parts.

Sikora and Groza experimentally obtained the PER of a ZigBee system under the interference of Wi-Fi devices,

[1]Wi-Fi, ZigBee, and Bluetooth are the commercial names for devices using the radio specifications defined by the IEEE in its 802.11, 802.15.4, and 802.15.1 standard suites, respectively. Throughout the paper, with a slight abuse of notation, we will use the standard names (e.g. IEEE 802.11) and the commercial names (e.g. Wi-Fi) interchangeably.

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Bluetooth devices, and also of a microwave oven [2]. However, the study is limited to a single source of interference (e.g. either Wi-Fi or Bluetooth), and also the analysis of the coexistence of ZigBee and Bluetooth is not complete, since the (actually very few) results have been collected in one direction only (i.e. Bluetooth over ZigBee). Neverhteless, an interesting observation in Sikora and Groza's paper is about the presence of notable discrepancies between the collected experimental data and the simulation results provided by the IEEE 802.15.4 task group.

A similar experimental study was led by Musăloiu and Terzis, who evaluated the loss rate of a ZigBee system under Wi-Fi interference [1]. Starting from this result, they developed interference estimators and distributed algorithms to dynamically change the ZigBee operating channel. This approach was proved to drastically reduce the loss rate of ZigBee networks.

The authors of [6] present the results of an empirical study on the coexistence between IEEE 802.11b and Bluetooth devices. However, the primary objective was to develop an analytical model to estimate the mutual interference, rather than characterizing it in real world scenarios. Hence, to build such models, the experiments were controlled through the use of attenuators, signal generators, and coaxial cables, thus resulting in a rather idealistic environment.

Finally, Tang *et al.* obtained a ZigBee channel characterization through a series of field measurements, but without interference of other devices working in the same ISM [7].

From the analysis of the cited works, it emerges a common aspect. In all cases, even in [2], the authors studied the interference of no more than two systems at a time. Therefore, to the best of our knowledge, the literature is still missing a combined, two way, experimental analysis of the simultaneous interference among Wi-Fi, Bluetooth, and ZigBee. With this paper we aim at filling this gap.

III. System Architectures and Channels

In this section we first give a quick overview of the three technologies we used for our experiments, i.e. Wi-Fi, ZigBee, and Bluetoooth. Note that we do not mean to provide a detailed overview of the various aspects of the standards, such as the access schemes, the frame formats, the network topology, etc. For these details, the interested reader is addressed to the respective standard documents or tutorial papers. Rather, we just outline those aspects that are necessary for the full comprehension of the tests we performed, for example the type and number of channels, the transmission power, and the basics of the access schemes.

Secondly, we outline how these standards exploit the 2.4 GHz band and interact in this part of the spectrum.

A. Wi-Fi

The latest IEEE 802.11 standard [8] defines two medium access schemes: a random CSMA/CA (carrier sense multiple access with collision avoidance) scheme and a polled scheme. In practice, however, the latter is not implemented by any card manufacturer, thus leaving the former as the sole scheme actually employed by Wi-Fi devices.

In short, according to the CSMA/CA algorithm, every Wi-Fi device shall listen to the medium before transmitting. The transmission is allowed only if the medium has been sensed idle for a pre-defined time period. In case the medium is sensed busy, or after a collision, the device shall refrain from transmission for a period whose length is determined by a random variable (exponential backoff).

An IEEE 802.11 network can operate over one of the 14 channels defined for the 2.4 GHz ISM band[2]. Each channel is 22 MHz wide, and, since the overall ISM bandwidth is just above 80 MHz, the channels are partially overlapped. Therefore, no more than three networks can be contemporaneously operated in the same area in order to keep the transmissions of each free from interference from the others.

The operative channel and the transmission power are generally set statically (e.g. by the manufacturer or by the user at configuration time), even though dynamic channel selection (DCS) and transmit power control (TPC) routines have been defined for operations in the 5 GHz band. In the 2.4 GHz band the maximum transmission power is 100 mW (20 dBm) in Europe, and 1 W (30 dBm) in North America; in Japan, where power is measured in relationship to bandwidth, the maximum allowed power is 10 mW/MHz.

Finally, the modulation scheme is either a DSSS (direct sequence spread spectrum) for the lower bit rates, or an OFDM (orthogonal frequency division multiplexing) for the higher ones. A third scheme, FHSS (frequency hopping spread spectrum), though defined by the standard, is not implemented in practice.

B. ZigBee

The IEEE 802.15.4 standard [9] specifies the physical and medium access control layers for low-rate wireless PANs, targeting a 10 meter communication range with a transfer rate of up to 250 kb/s.

Similarly to 802.11, also 802.15.4 devices employ the CSMA/CA channel access algorithm and the DSSS modulation (actually, the latest release of the standard defines four modulation schemes, but in the 2.4 GHz band only the DSSS modulation is allowed).

Sixteen channels are defined for worldwide use in the 2.4 GHz band. However, differently from 802.11, they are much narrower (just 2 MHz) and do not overlap, so that up to sixteen 802.15.4 networks can easily coexist in the same area. When starting a new network, an Energy Detection (ED) functionality is used to determine the activity of other systems and thus decide the operating channel; yet there is no support for dynamic channel selection.

[2]Actually, the 14^{th} channel is defined for operations in Japan only. In the rest of the world, 13 channels are usually available, apart from North America, where operations are allowed only in the first 11 channels.

The latest ZigBee release has introduced the support for frequency hopping in the "ZigBee Pro" standard. In this way a PAN coordinator can move the whole PAN to another channel if the one in use is overloaded. However this is not a fast, reliable, and energy saving way to solve the problem. In addition it is not mandatory to implement.

Finally, it should be noted that the ZigBee Alliance, even in its latest specification (October 2007), still refers to the first IEEE 802.15.4 standard, i.e. the one published in 2003. For the purpose of our work, however, there are no fundamental changes between these two versions, given that most of the novelties address the 868/915 MHz bands.

C. Bluetooth

Similarly to IEEE 802.15.4, Bluetooth is a standard communication protocol designed for connection-oriented services such as voice, with low power consumption and short range operations. The range and output power depend on the device-class (see Table I), even though ranges in practice is highly variable.

Table I
BLUETOOTH OUTPUT POWER AND THEORETICAL RANGE.

Device Class	Output Power [mW]	Range [m]
Class 1	100	100
Class 2	2.5	10
Class 3	1	1

Bluetooth transmits on up to 79 channels in the 2402-2480 MHz range. Each channel is 1 MHz wide, and one guard channel is used at the lower and upper band edges. In order to reduce the interference from external sources, frequency hopping (FHSS) is used to spread the signal across all the 79 channels. Thus a single Bluetooth network uses the full available 2.4 GHz ISM band, even though different networks can coexist in the same area by employing different hopping patterns or a time-shifted version of the same pattern. Since specification v1.2, Bluetooth also includes an adaptive frequency hopping (AFH) scheme, which reduces the number of employed channels to further improve its robustness against the interference.

The Bluetooth channel access procedure is based on a master-slave scheme, which is built on top of a time division duplex (TDD) transmission scheme. The master shall always start transmitting at even numbered slots, and the slave shall always start at odd numbered slots. Transmissions can extend over more consecutive slots (up to five).

The basic modulation is Gaussian frequency-shift keying (GFSK), which allows a transfer rate of up to 1 Mb/s. Since the introduction of the enhanced data rate (EDR) with specification v2.0, π/4-DQPSK (differential quadrature phase shift keying) and 8-DPSK modulations may also be used between compatible devices, bringing the data rate to 2 and 3 Mb/s respectively.

D. Channels, Frequencies and Modulations

Figure 1 shows the allocation of the ZigBee and Wi-Fi channels over the 2.4 GHz ISM band. Bluetooth channels are not reported, since we may assume that, because of the high frequency hopping rate, Bluetooth devices cover the whole available spectrum. Each ZigBee channel is 2 MHz wide, whereas each Wi-Fi channel is 22 MHz wide. Note that a single 802.11 channel completely overlaps with four ZigBee channels.

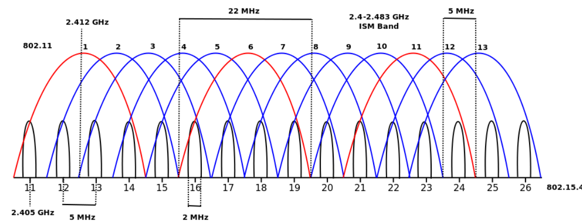

Figure 1. Channel Occupancy of 802.11 and 802.15.4 systems.

The three most used non-overlapping Wi-Fi channels are 1, 6, and 11. In this case, two ZigBee channels should be free from interference from Wi-Fi transmissions, i.e. ZigBee channels 25 and 26 (the two rightmost ones). However, there is no assurance that using channels 25 and 26 solves the interference problem. For example, two channels might not be enough to allow the coexistence among several geographically overlapping PANs. In addition, though in North America ZigBee channels 25 and 26 can be really assumed free from interference (see note 2), in other regions such as Europe and Asia all Wi-Fi channels can be used, thus covering the complete set of ZigBee channels.

A further aspect making the coexistence of Wi-Fi and ZigBee difficult is the different allowed transmission power. In fact, the maximum Wi-Fi output power can be up to 100 times higher than the maximum allowed ZigBee transmission power (100 mW vs. 1 mW). The same consideration holds, at least theoretically, for Wi-Fi and Bluetooth devices belonging to Classes 2 and 3.

IV. TESTBED CONFIGURATION AND TOOLS

In this section, we first give a brief description of the hardware employed in our tests. Then we describe the considered test scenarios, methodologies, and software tools.

A. Hardware

1) ZigBee: To set up a ZigBee network, we made use of the Freescale MC1322x board, which incorporates a complete, low power, 2.4 GHz transceiver, and a 32-bit ARM7 core based MCU. Among the various available stack profiles, we chose the IEEE 802.15.4 Standard-Compliant MAC, which provides all the basic transmission functionalities. The integrated Power Amplifier (PA) provides programmable output power from -30 dBm to +4 dBm, and the receiver

LNA offers -96 dBm of sensitivity. In our test we set the output power to 1 mW (0 dBm).

2) Wi-Fi: The IEEE 802.11 network was built with a commercial Access Point (HP ProCurve 420), and with a HP Compaq tc4200 Tablet PC acting as a Station. The former is equipped with an Atheros AR5212A chipset, whereas the latter employs an Intel PRO/Wireless 2200BG card. Thus, the system operates according to the "g" specification with a maximum output power of 100 mW (20 dBm).

3) Bluetooth: On the Bluetooth side, we used two Hama Bluetooth adapters connected to two laptop PCs via USB ports. Both adapters embed a version 2.0 compliant chipset supporting the EDR feature and belong to Class 2, therefore their output power is 2.5 mW (4 dBm) and they can reach an approximate range of 10 meters.

B. Test Scenarios

The coexistence tests were performed in our research laboratory. We believe this is a realistic indoor scenario, as one might indeed expect to find in it several devices using different radio technologies to work at the same time. A plan of the laboratory is reported in Figure 2. The test devices were placed in the two opposite sides of the room (say *left* and *right*), at a distance of about 9 meters from each other. All devices are therefore within their operation range. At each site we placed either the transmitter or the receiver of each technology. We then varied the combinations of transmitter/receiver pairs. The full set of tested patterns is reported in Table II, in which we use the following intuitive terminology: BT stands for Bluetooth, WF for Wi-Fi, and ZB for ZigBee; the suffixes "T" and "R" stand respectively for transmitter and receiver. For example, BT-T indicates the Bluetooth transmitter. As shown in the table, we tested all possible combinations with two and also with three systems.

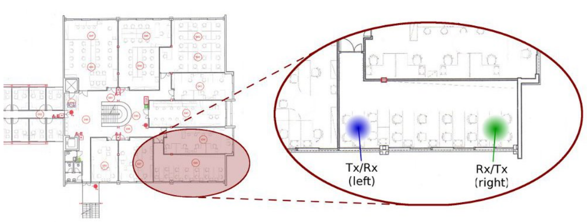

Figure 2. Map of the Laboratory where the tests have been performed.

To monitor the activity on the 2.4 GHz spectrum, and also possible external interference sources that might be present in the test area, such as other Wi-Fi networks, we used the AirView2-EXT ISM-band spectrum analyzer[3]. This consists of a USB dongle with an external antenna plus the related graphical software. An example screenshot produced by AirView2-EXT is presented in Figure 3. The plot reports the registered power level (in dBm) in three forms: the blue area represents the maximum level, the green area the average level (both computed over 1000 seconds of observation), and the yellow line is the instantaneous measurement. All the 2.4 GHz band is in use, with peaks around 2412 and 2462 MHz, the positions of Wi-Fi channels 1 and 11.

One such screenshot has been taken before performing every experiment, in order to check whether external interferences are present, thus avoiding biased results.

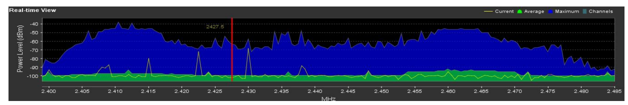

Figure 3. Screenshot of the spectrum occupancy.

C. Configuration and traffic parameters

1) ZigBee: To measure the frame error rate (FER) over the ZigBee connection, we set up a unidirectional data transfer over a single channel. The data frames were made of 8 bytes of data, and 9 octets of MAC header and footer (which includes the frame check sequence, FCS), for a total of 17 octets (23 including the physical preamble and header). This translates into an effective time on air of about 0.8 ms. Each transmission was considered successful if the frame passed the cyclic redundancy check (CRC) provided by the IEEE 802.15.4 layer. No confirmation (ACK) was enabled, so that each frame is transmitted exactly once. Therefore the 1-FER was computed just as the number of correct-CRC received frames over the total number of transmitted frames.

To carry out the ZigBee measurements we adopted the following procedure. A very similar procedure was applied also to the other systems.At first, the PAN coordinator starts the network on the configured channel and waits for the other node to establish a connection with it.

Once the end device is connected, it starts sending data frames. Therefore, in our tests, the transmitter is the end device and the receiver is the coordinator. The interval between two successive frame transmissions is 50 ms, as also used in previous works [7]. Once the predefined number of test frames is reached, the end device transmits a "stop frame", which shall be acknowledged and is used to tell the PAN coordinator to compute the statistics for the measurement session and to prepare for another session (e.g. by resetting its counters). Every session has been performed on 50 seconds time intervals for a total number of 1000 data frames.

2) Wi-Fi: For Wi-Fi too, we generated unidirectional traffic, with the the 802.11 station acting as the source of data and the AP being the sink. The test procedure was very similar to the one illustrated in the previous section, with the obvious technology-specific name changes. Each test session lasted for 50 seconds.

[3]http://www.ubnt.com/airview

Table II
LIST OF TESTED TRANSMITTER/RECEIVER COMBINATIONS.

Position	Exp. #1	Exp. #2	Exp. #3	Exp. #4	Exp. #5	Exp. #6	Exp. #7	Exp. #8	Exp. #9	Exp. #10
Left	WF-T ZB-T	WF-T ZB-R	BT-T ZB-T	BT-T ZB-R	BT-T WF-T	BT-T WF-R	BT-T WF-T ZB-T	BT-T WF-T ZB-R	BT-T WF-R ZB-T	BT-R WF-T ZB-T
Right	WF-R ZB-R	WF-R ZB-T	BT-R ZB-R	BT-R ZB-T	BT-R WF-R	BT-R WF-T	BT-R WF-R ZB-R	BT-R WF-R ZB-T	BT-R WF-T ZB-R	BT-T WF-R ZB-R

Traffic has been generated by means of the MGEN traffic generator[4], and has the following features: UDP at 1.2 Mbps, with two different payload sizes, 64 or 640 octets, which correspond, respectively, to 2359 and 236 frames per second (fps). This means keeping the medium busy for longer or shorter time intervals, and thus affecting more or less heavily the other networks. The exact channel occupancy time cannot be computed, due to the rate adaptation policy enforced by the card drivers. In the most favorable condition that only the 54 Mbps modulation is employed and no retransmissions occur, when the 64-byte payload is used, the channel is busy for about 65% of the time (8.5% for the 640-byte payload). Note that the payload length can also affect the performance of Wi-Fi, since longer frames are more prone to bit errors than shorter ones.

In the case of Wi-Fi, it was not possible to prevent the retransmission of frames, since all unicast frames are acknowledged (and, if necessary, retransmitted) by default. Therefore, instead of measuring the FER, we considered a different performance metric: we counted the number of received UDP packets per second.

3) Bluetooth: The measurement procedure and setup for Bluetooth was in all aspects similar to the ones for ZigBee and Wi-Fi. The traffic was generated by means of a file transfer, and the payload of each frame was automatically set by the Bluetooth devices to 1022 bytes. The frames are acknowledged by default, with the ACK mechanism handled directly by the MAC layer. Therefore, also the performance of Bluetooth was measured in terms of achieved goodput (in this case, the number of transferred bits per second). To collect the data traces and compute the performance, we used hcidump (a software tool for Unix systems that reads the raw Bluetooth data[5]), the popular Wireshark traffic analyzer[6], and a simple C-language program that we developed.

D. Graph Format

Before entering the details of the measurement tests, it is useful to explain the format of the graphs used to show the performance figures previously described (i.e. 1-FER for ZigBee, goodput in pkt/s for Wi-Fi and in Mbit/s for Bluetooth[7]). In each plot, the horizontal axis reports the test session number. As already explained, in each session we collected the statistics for a 50 seconds measurement interval. Therefore each point of the graphs represents the value achieved in a 50 second test (and not in every single second). In practice, due to the longer observation times, momentary anomalies are smoothed out, thus allowing to better catch the global behavior of the tested systems.

V. EXPERIMENTAL RESULTS

A. Wi-Fi and ZigBee

Our analysis started from verifying the impact of Wi-Fi on an ongoing ZigBee transmission. The ZigBee network was set up on channels 11-14 and the Wi-Fi network on channel 1. Thus the two networks used the same spectrum. The Wi-Fi transmitter was placed close to the ZigBee receiver and vice-versa ("crossed" configuration, i.e. experiment #2 with reference to Table II). Wi-Fi carried 64-byte payload frames.

Figure 4 reports the 1-FER of ZigBee during this experiment. The Wi-Fi connection was activated on the 21st session and turned off at the 41st session. Its impact on the ZigBee connection is apparent. As soon as the Wi-Fi transmission starts, the 1-FER of ZigBee drops from almost one to a value between 0.45 and 0.73, with channel 13 being the less impaired (0.69 on average) and channel 14 the most impaired (0.52). Note that these drops (on average 40% of the frames are lost over the four channels) are less than the percentage of time the Wi-Fi connection occupies the channel (at least 65%, see Section IV-C2). Hence the presence of Wi-Fi is not completely destructive (differently from the result obtained by Sikora and Groza [2], but coherently with the one by Musăloiu and Terzis [1]). Very similar results have been registered for other channel combinations, such as WF6 and ZB16-ZB19, and WF11 and ZB21-ZB24[8].

An analogous trend, but with a much less marked impact, was registered for the "parallel" communication, i.e. when the two transmitters are near each other and the two receivers are at the other end of the room (experiment #1). As shown

[4]http://cs.itd.nrl.navy.mil/work/mgen/
[5]http://www.bluez.org
[6]http://www.wireshark.org

[7]Given the use of unacknowledged constant bit rate data transmission for ZigBee, showing the FER is of more immediate impact than the goodput. However, the "translation" from 1-FER to goodput is straightforward: goodput = payload (64 bits) · frame rate (20 fps) · 1-FER.

[8]To simplify the text, we use a concise and intuitive notation to indicate the various channels: WFn represents the nth Wi-Fi channel, and ZBm is the mth ZigBee channel.

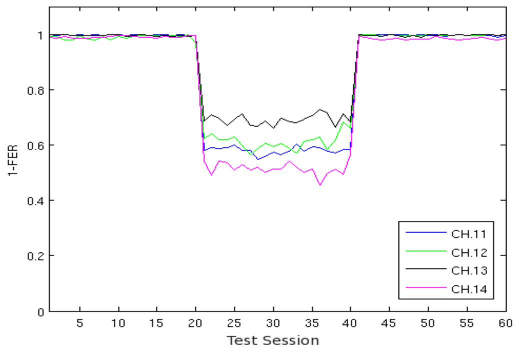

Figure 4. 1-FER of ZigBee under the interference of Wi-Fi – crossed configuration.

in Figure 5, ZigBee now looses only a few percent of the frames (no more than 2.4%, and 1.4% on average). Therefore, the reciprocal positions of the devices seem to play a major role in determining the performance degradation.

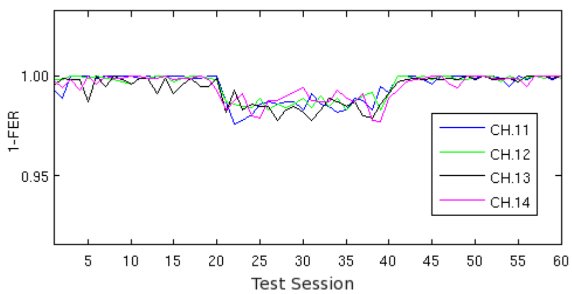

Figure 5. 1-FER of ZigBee under the interference of Wi-Fi – parallel configuration.

Figure 6 reports the outcome of the reverse experiment, i.e. the impact of ZigBee on a Wi-Fi connection, for the crossed configuration. Notwithstanding the presence of the ZigBee transmitter close to the Wi-Fi receiver (between sessions 21 and 40), Wi-Fi is practically unaffected by the activity of ZigBee. The case of parallel configuration yielded the same result (not reported for conciseness).

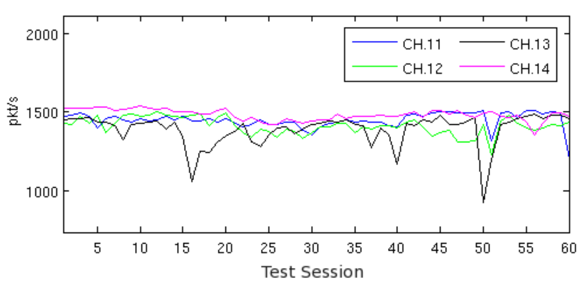

Figure 6. Goodput of Wi-Fi under the interference of ZigBee – crossed configuration.

A second test consisted in evaluating the influence of a Wi-Fi communication on the performance of ZigBee working on the various channels. The Wi-Fi system was still set on channel 1, while the ZigBee network used all channels from 11 to 26. Note that ZigBee channels from 11 to 14 are covered by the spectrum of WF1, whereas the other channels should be free from interference.

Figure 7 shows the 1-FER registered for the first ten ZigBee channels during a Wi-Fi data transfer. It can be seen that ZigBee channels from 11 to 14 are indeed penalized by the presence of the Wi-Fi transmission (as already seen in Figure 4). Surprisingly, however, the test showed that also channels from ZB15 to ZB19 were not free from interference. In fact, ZB15 was even more affected by Wi-Fi than the others. ZB16 to ZB19 are still lightly hampered by WF1, whereas only ZigBee channels from 20 onward can be assumed free from interference (the 1-FER of channels beyond 20 are all like ZB20, and thus not reported for cleanness of the figure).

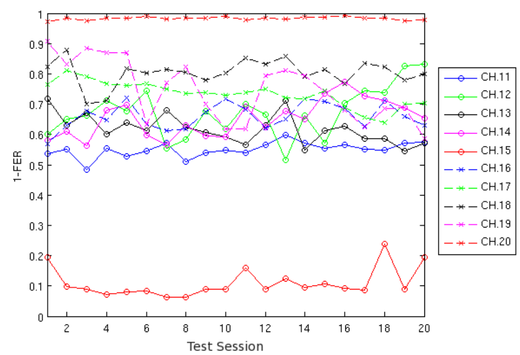

Figure 7. 1-FER of the first ten ZigBee channels under the interference of Wi-Fi channel 1 – crossed configuration.

To verify that the poor performance of ZB15 was not a sporadic occurrence, we repeated this experiment for similar channel combinations, such as WF6 and ZB20, and WF11 and ZB25. The results confirmed that potentially interference-free ZigBee channels (i.e. ZB15, ZB20, ZB25, and ZB26) are in fact the most penalized. The average FER of ZB15 under the influence of WF1 is 89% (as already shown in Figure 7), the FER of ZB20 (interfered by WF6) is 83%, and the one for ZB25 (WF11) is 61%. ZB26 (still interfered by WF11) performs slightly better, with FER around 24% (roughly in line with the performance of ZB16 when hindered by WF1, i.e. 34%).

A more detailed analysis of this phenomenon was lead by means of the AirView tool. The screenshot in Figure 8 shows that the spectrum of Wi-Fi devices operating on channel 1 also occupies the 2.425 GHz band employed by ZB15. Such Wi-Fi spectrum is not illegal, since the IEEE 802.11 standard specifies a transmit power reduction of 30 dB for frequencies farther than 11 MHz from the central frequency, and this is indeed achieved. Yet it is not enough from preventing a heavy interference on ZigBee networks. Also note that the spectrum around the 2.425 GHz is the most used (the predominance of red dots indicates this), coherently with the fact that ZB15 is the most penalized channel.

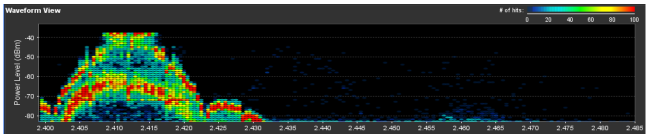

Figure 8. Spectrum of Wi-Fi activity on channel 1.

The high error rate of ZigBee also depends on the packet size (and consequently the "duty cycle") of Wi-Fi. A test run with both 64 and 640 bytes of Wi-Fi payload shows that in the 64-byte case ZigBee is much more hampered. Figure 9 reports the outcome of such test. The Wi-Fi connection is activated at the 21st run with 640 byte payload, the payload is lowered to 64 bytes at run 41, and the Wi-Fi is turned off at run 61. The effects on the 1-FER of ZigBee are apparent.

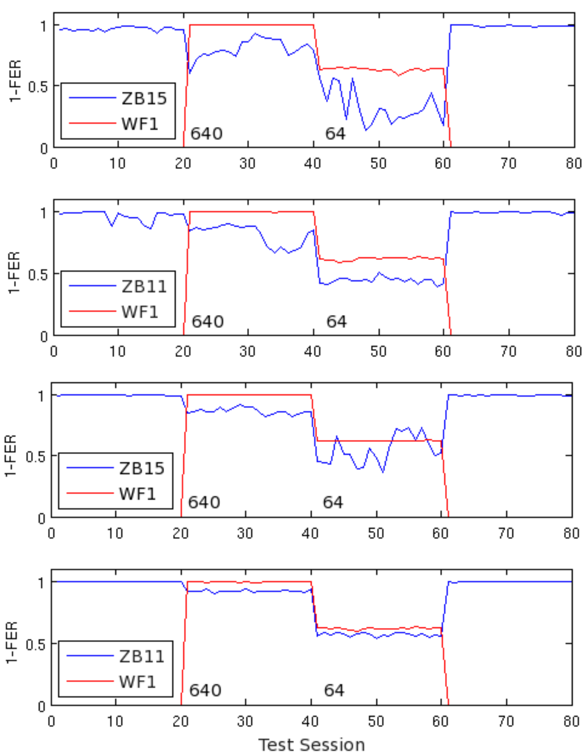

Figure 9. 1-FER of ZigBee (channels 11 and 15) under the interference of Wi-Fi (channel 1, varying payload size) for the crossed (top two) and parallel (bottom two) configurations.

B. Bluetooth and ZigBee

The interference of Bluetooth over a ZigBee connection is shown in Figure 10. It refers to the crossed configuration with ZigBee working on channel 18 (actually, since Bluetooth spans over the whole 2.4 GHz ISM band, the ZigBee channel is scarcely relevant). We can state that ZigBee is not heavily affected by Bluetooth, as its 1-FER is reduced by less than 10% (a result that confirms the one by Sikora and Groza [2]).

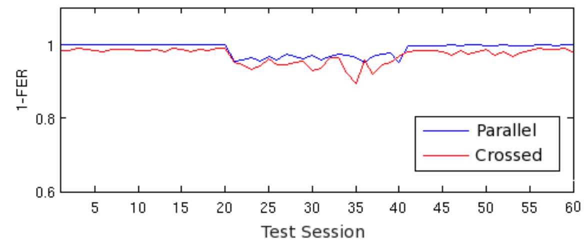

Figure 10. 1-FER of ZigBee under the interference of Bluetooth for both crossed and parallel configurations.

The outcome of the reverse test, i.e. the interference of ZigBee over a Bluetooth connection, is reported in Figure 11. In this case, though the goodput of the Bluetooth network is rather unstable[9], we can hardly appreciate any degradation during the interference phase (i.e. from session 21 to 40). This is also shown by the average goodput values for the three phases of the crossed and parallel configurations, which are reported at the bottom of the figure.

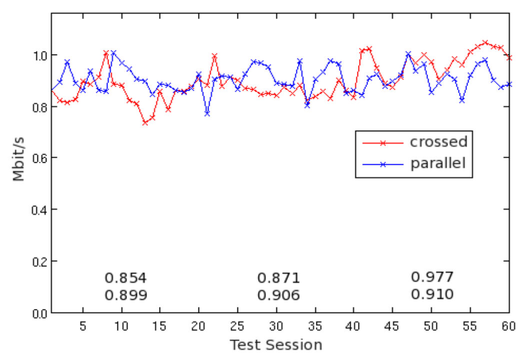

Figure 11. Goodput of Bluetooth under the interference of ZigBee for both crossed (red) and parallel (blue) configurations.

C. Wi-Fi and Bluetooth

To complete the series of two-technology tests, we assessed the mutual interference of Bluetooth and Wi-Fi. Figure 12 shows that the impact of Wi-Fi over Bluetooth is quite strong, as the goodput decreases significantly in both configurations, dropping from an average 1.12 Mbps to 0.59 Mbps for the parallel scenario, and from 0.95 Mbps to 0.30 Mbps for the crossed one.

[9] Even under no interference, Bluetooth always has this kind of oscillating behavior. Investigating this aspect, which might be due to adaptive data rate algorithms employed by the devices, is out of the scope of our work, since it is not an interference-related issue.

This result highlights an interesting aspect. The FHSS technique employed by Bluetooth seems to be less effective than one might expect from a preliminary analysis. It is well known that when Bluetooth hops on channels occupied by a concurrent Wi-Fi transmission it suffers a very high frame loss. Yet the rapid and scattered hopping over the whole set of channels should guarantee a good amount of “clean” transmission opportunities. Since the ratio of interfered versus clean channels corresponds to roughly 28% (i.e. 22 out of 79), one would expect a result in line with this figure. Conversely, the actual goodput reduction is between 47% and 68%, which is far more than 28% (and could be even worse, given that the Wi-Fi “duty cycle” is lower than one). Furthermore, differently from ZigBee, the position of the Bluetooth terminals is less influential, since a heavy performance reduction is registered for both topology configurations. As a consequence, the use of smart and adaptive hopping patterns (AFH) and / or scheduling techniques could indeed be a major (and probably indispensable) contributor towards the achievement of robust Bluetooth connections in vicinity of active Wi-Fi devices.

On the other hand, Wi-Fi is essentially unaffected by the presence of Bluetooth, as shown by Figure 13.

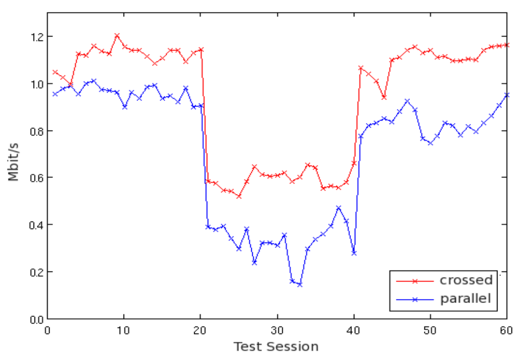

Figure 12. Goodput of Bluetooth under the interference of Wi-Fi.

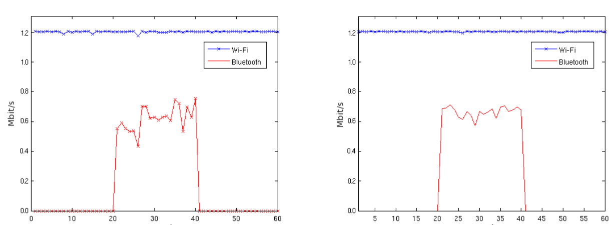

Figure 13. Goodput of Wi-Fi (in Mbit/s) under the interference of Bluetooth.

D. Wi-Fi, ZigBee, and Bluetooth

The last test was about the simultaneous coexistence of the three networks. In a first trial we configured the systems with all transmitters on one side and all receivers on the other. Wi-Fi operated on channel 6, ZigBee on channel 18. Figure 14 shows the performance of ZigBee, Wi-Fi, and Bluetooth. At the beginning, only the ZigBee devices are active, and thus almost no FER is recorded. At the 21st session we started the Bluetooth data transfer. Similarly to the result in Section V-B, ZigBee is lightly affected by Bluetooth, loosing a few percent of frames, and the goodput of Bluetooth oscillates around the usual value (1.02 Mbps). When Wi-Fi is activated, at session 41, employing 640-byte payload frames, the effect on both existing connections is a slight performance reduction. The FER of ZigBee passes from 3.3% to 6.6%, whereas the goodput of Bluetooth goes down to 0.85 Mbps. Wi-Fi works at its full potential with no apparent frame retransmissions. When the Wi-Fi payload is reduced to 64 bytes (at session 61), Bluetooth immediately suffers this change, its goodput dropping to 0.53 Mbps. Conversely, ZigBee does not seem to be much affected.

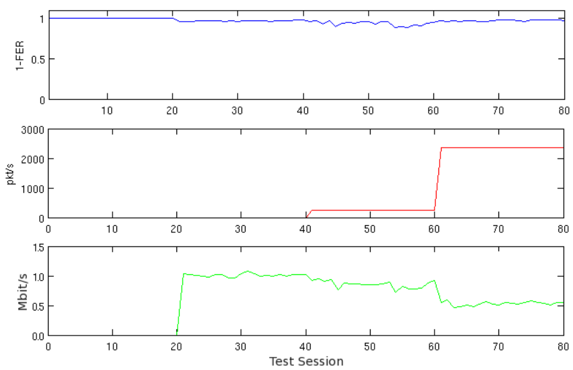

Figure 14. 1-FER of Zigbee (top) and goodput of Wi-Fi (center) and Bluetooth (bottom) – parallel configuration.

The second trial consisted in inverting the position of the ZigBee devices. The loss registered by ZigBee (see Figure 15) is now much more conspicuous, especially in the last part of the test, when the Wi-Fi payload is set to 64-bytes (the registered FER is 41.2%). As for Wi-Fi and Bluetooth, they replicate the result achieved in the previous tests, confirming their insensitiveness to the presence of ZigBee.

We then assessed the behavior of the three systems when Wi-Fi is reversed (i.e. configuration #9 in Table II). The plots in Figure 16 shows that both ZigBee and Bluetooth are heavily hampered by the Wi-Fi connection, especially when this one employs the small 64-byte payload frames (the last 20 test sessions). Also, in both Figure 15 and Figure 16 we can observe that the highest performance degradation for Bluetooth occurs as soon as Wi-Fi is activated, whereas for ZigBee it occurs only when the Wi-Fi frame rate is increased.

The last experiment, i.e. the one with Bluetooth in the crossed configuration, confirms the results achieved so far, and therefore is not reported due to space constraints.

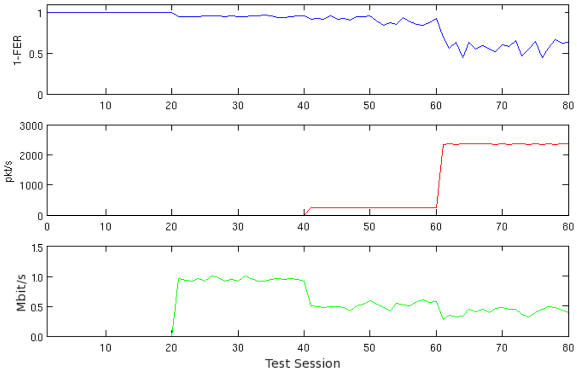

Figure 15. 1-FER of Zigbee (top) and goodput of Wi-Fi (center) and Bluetooth (bottom) – ZigBee-crossed configuration.

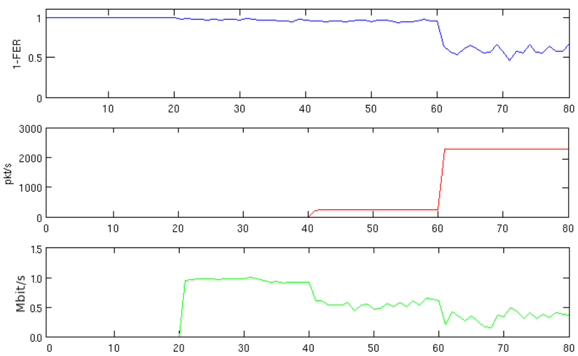

Figure 16. 1-FER of Zigbee (top) and goodput of Wi-Fi (center) and Bluetooth (bottom) – Wi-Fi-crossed configuration.

VI. Conclusions

The paper reported an extensive study on the coexistence of Wi-Fi, ZigBee, and Bluetooth over the shared 2.4 GHz ISM band. Though similar tests have been performed in the past, our work presents a more complete approach, which examines all possible interactions, including the simultaneous activity of all networks. In addition, it reveals some new and remarkable insights.

To summarize, Wi-Fi is scarcely affected by the presence of the other two systems. Even in the crossed configuration with both ZigBee and Bluetooth transmitters working near the Wi-Fi receiver (worst case), Wi-Fi did not show any noticeable loss. Conversely, both ZigBee and Bluetooth suffered conspicuously from the presence of Wi-Fi. ZigBee registered a highly variable performance drop (41% on average) while Bluetooth showed an even more noticeable degradation (up to 68%).

These results are essentially in agreement with previous studies, but there are also some unexpected findings. At first, even ZigBee channels deemed to be interference free, are in fact heavily influenced by Wi-Fi, whose actual spectrum covers more than the classic four ZigBee channels. This result, which was never highlighted before, sheds new light on the ZigBee – Wi-Fi coexistence, as the planning and deployment of ZigBee networks can no longer rely on the supposedly "safe" channels such as ZB15, ZB20, ZB25 and ZB26.

Secondly, the FHSS technique used by Bluetooth did not reveal to be very effective in contrasting the Wi-Fi interference, given that we registered a greater performance drop-off than we would expect from assuming as unavailable just the 22 Bluetooth channels covered by a single Wi-Fi channel.

Finally, the ZigBee system is much more sensitive to the position of the Wi-Fi transmitter than Bluetooth. This means that, while ZigBee networks can be deployed in a shared area by having ZigBee devices placed far from Wi-Fi radios, this is not true for Bluetooth networks, which instead require a more drastic separation from Wi-Fi polluted areas.

The good news is about the coexistence between ZigBee and Bluetooth, as our results showed that these two networks are able to work simultaneously with almost no impairment.

References

[1] R. Musaloiu-Elefteri and A. Terzis, "Minimising the effect of WiFi interference in 802.15.4 wireless sensor networks," *IJSNet*, vol. 3, no. 1, pp. 43–54, 2008.

[2] A. Sikora and V. Groza, "Coexistence of IEEE 802.15.4 with other systems in the 2.4 GHz-ISM-Band," in *IEEE Instrumentation and Measurement Technology Conference (IMTC)*, vol. 3, May 2005, pp. 1786–1791.

[3] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys and Tutorials*, vol. 11, no. 1, pp. 116–130, 2009.

[4] A. He, K. K. Bae, T. Newman, J. Gaeddert, K. Kim, R. Menon, L. Morales-Tirado, J. Neel, Y. Zhao, J. Reed, and W. Tranter, "A survey of artificial intelligence for cognitive radios," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 4, pp. 1578–1592, may 2010.

[5] S. Y. Shin, H. S. Park, S. Choi, and W. H. Kwon, "Packet error rate analysis of zigbee under wlan and bluetooth interferences," *IEEE Transactions on Wireless Communications*, vol. 6, no. 8, pp. 2825–2830, 2007.

[6] I. Howitt, V. Mitter, and J. Gutierrez, "Empirical study for IEEE 802.11 and Bluetooth interoperability," in *IEEE Vehicular Technology Conference, Spring*, vol. 2, May 2001, pp. 1109–1113.

[7] L. Tang, K.-C. Wang, Y. Huang, and F. Gu, "Channel characterization and link quality assessment of IEEE 802.15.4-compliant radio for factory environments," *IEEE Transactions on Industrial Informatics*, vol. 3, no. 2, pp. 99–110, 2007.

[8] "IEEE Standard 802.11-2007," Dec. 2007.

[9] "IEEE Standard 802.15.4-2006," Sept. 2006.