In Proc.of the 6th ACM Intl. Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization (WiNTECH), Las Vegas, USA, September 2011.

Experimental Assessment of Tradeoffs among Spectrum Sensing Platforms

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ABSTRACT

This paper reports experimental results comparing the performance of four platforms employed in spectrum sensing and dynamic spectrum access research: a sensing engine developed at imec and built around a prototype RFIC; the Universal Software Radio Peripheral (USRP) with the Iris software defined radio (SDR) solution; the TelosB sensor network platform; and the Wi-Spy low cost spectrum sensor solution targeted at the ISM band. We use experimental data to derive the receiver operating characteristics (ROC) of each of the four platforms. We observe that for low signal powers, narrow bandwidth signals, high shadowing, or stringent probability of false alarm (PFA) requirements tradeoffs among the platforms tested are most pronounced, whereas for high signal powers, large bandwidths, stable environments, and more flexible PFA requirements less expensive, commercial-off-the-shelf equipment performs sufficiently well.

Categories and Subject Descriptors

B.4.1 [**Input/output and data communications**]: Data Communications Devices; C.4 [**Performance of Systems**]

General Terms

Experimentation, Measurement

WiNTECH'11, September 19, 2011, Las Vegas, Nevada, USA.

Keywords

Spectrum sensing, cognitive radio, comparative analysis, experimental wireless platforms

1. INTRODUCTION

Experimental work on dynamic spectrum access (DSA) and cognitive radio networks requires the deployment of spectrum sensing devices that network nodes can rely on to observe current spectrum utilization and adapt according to channel availability and network conditions. This paper discusses and characterizes the performance tradeoffs among different sensing solutions currently used in wireless network research. Our experiments involve both inexpensive, commercial-off-the shelf (COTS) platforms, such as the Wi-Spy and TelosB devices, and hardware and software solutions developed in-house at our research institutions. The latter include the imec sensing platform and the Iris software defined radio (SDR) solution developed at Trinity College Dublin.

The performance of spectrum sensing solutions has been a topic of investigation since the introduction of dynamic spectrum access networks. Many techniques have been proposed, and some fundamental limits of sensing have been established [11]. Experiments have verified the existence of these limits, often using prototype hardware and expensive processing techniques focusing on sensing a simple known signal [13]. In parallel, many sensing experiments that focus on measuring energy over time for a specific location have been carried out [7]. In the military domain, feature detection techniques are being developed to detect signals with special properties.

The experiments described in this paper were carried out as part of the Cognitive Radio Experimentation World (CREW) consortium, a federation of cognitive radio testbeds formed among academic and industrial research groups in Europe [2]. In the remainder of this section, we discuss some of the relevant literature on the spectrum sensing platforms and their utilization in cognitive radio testbeds. Section 2 describes our experimental set-up, with the results of these experiments presented and discussed in Section 3. Section 4 discusses sustainable comparison through the use of benchmarking. We outline our main conclusions and directions of future work in Section 5.

1.1 Related work

While many sensing techniques have been proposed in the literature, they mostly focus on theoretical or fundamental sensing results that are not specific to any technology or standard [11]. The focus of this paper is not on the measurement or verification of different sensing algorithms, but on comparing the sensing that can be done with a range of existing sensing solutions. The measurement-based verification of sensing results also has a long tradition in the cognitive radio research community. The theoretical work of [8] was verified experimentally in [13] for a pilot signal, experimentally confirming the existence of the SNR wall. Experiments have also been carried out to evaluate the performance of cooperative sensing [7]. These papers focus on the evaluation of sensing information and correlation, and not purely on the evaluation of the sensing performance of the hardware used.

Verification of sensing functionality is often based on the use of spectrum analyzers or expensive power hungry equipment. Alternatively, SDR solutions that have been designed specifically for research purposes are also used [3, 1]. In this paper, we consider sensing solutions that are all part of the CREW federated testbed for cognitive radio experimentation. These include energy and feature detection solutions implemented with USRP radios [3], off-the-shelf sniffers for the ISM band, as well as dedicated sensing and software-defined radio hardware [14].

2. EXPERIMENTAL DESCRIPTION

2.1 Broad Objectives

The primary objective of our experiment is to carry out a simple sensing task that encompassed many different sensing platforms with a view to identifying the similarities as well as the differences in the output of each platform. During this experiment we endeavor to maintain as similar an operating environment as possible between the platforms so that we can say with confidence that the input to each platform was identical and the differences in the outputs are entirely a function of some aspect of the platform, be it the quality of the hardware, the elegance of the design, or the sophistication of the software implementation. We then hope to discover similarities in the outputs and ideally to attribute these similarities to some similarity in the design of the respective platforms. Finally, we compare the performance of the four platforms and assess their strengths and weaknesses.

The hardware and software solutions used in experimental research on spectrum sensing differ in the algorithms employed (energy detection, feature detection, etc.), bands targeted, sensing time and bandwidth, and resulting sensitivity. The experiments described in this paper explore some of this tradeoff space.

The flexibility offered by the hardware and software solutions sometimes translates into an important advantage of one solution over another. Some of the sensing hardware tested was limited to the ISM band, while others could operate in a wider variety of bands. In terms of bandwidth, the systems under test ranged from a 2 MHz sensor node to a flexible front-end that can employ sensing bandwidth from 1 to 40 MHz. In some cases, the hardware provided I and Q samples that can then be processed by the Iris SDR or by a MATLAB script; in others, the hardware provided average energy readings obtained using an internal, proprietary algorithm that is unknown to the end user.

To accommodate the variability in the sensing solutions tested, we chose a common denominator test scenario that allowed us to compare all solutions. This scenario consisted of an 8-MHz DVB-T OFDM signal transmitted over the air in the ISM band. We then derived the Receiver Operating Characteristic (ROC) curve for each of the solutions. This curve characterizes the sensitivity of the sensor, by relating the probability of missed detection to the probability of false alarm in a way that is independent of the energy detection threshold selected.

2.2 Experimental Setups

The spectrum sensing experiments were performed in two setups, where the main difference was how the signal propagated between signal source and spectrum sensing devices. In both setups, a common, OFDM-modulated DVB-T signal with 8 MHz bandwidth was used and will be further referred to as the *test signal*.

Setup 1 - Ideal Channel.

In Setup 1 the wireless channel consisted of coaxial cables and signal splitters, according to Figure 1(a). This setup ensures that all sensing devices receive the same signal and thus allows a reliable comparison of the results, although this method neglects wireless propagation effects.

The test signal was transmitted with a Signalion HaLo 430 signal generator in an infinite loop without frame pause at center frequency 2.45 GHz. From there, it went through a variable attenuator and two stages of T-connectors.

The first measurement was done with maximum attenuation, where only one device could detect the signal. Then, the signal strength was gradually increased until all the devices could detect the emitted test signal.

Setup 2 - Real Wireless Channel.

In the second setup we performed experiments with a real wireless environment between the signal source and the spectrum sensing devices. For this purpose, the hardware was set up in a seminar room, where a signal generator (Anritsu MG3700A) was placed approximately 1 m above the floor on one side, while the sensing equipment was placed at same height on the opposite side of the room. This setup is depicted in Figure 1(b). The distance between the transmit antenna of the signal generator and the receive antennas of the multiple sensing nodes was approximately 9 m.

The test signal was emitted with several transmission patterns in order to compare the sensing nodes with respect to sensitivity and sensing speed. Additionally, all experiments in Setup 2 were performed under two conditions: either in an empty room, or with 10-15 individuals moving randomly between the signal generator and sensing equipment. The objective of the latter experimental condition was to observe the effects of shadowing and multipath.

While Setup 2 allows us to investigate the behavior of sensing devices in a real wireless channel including multi-

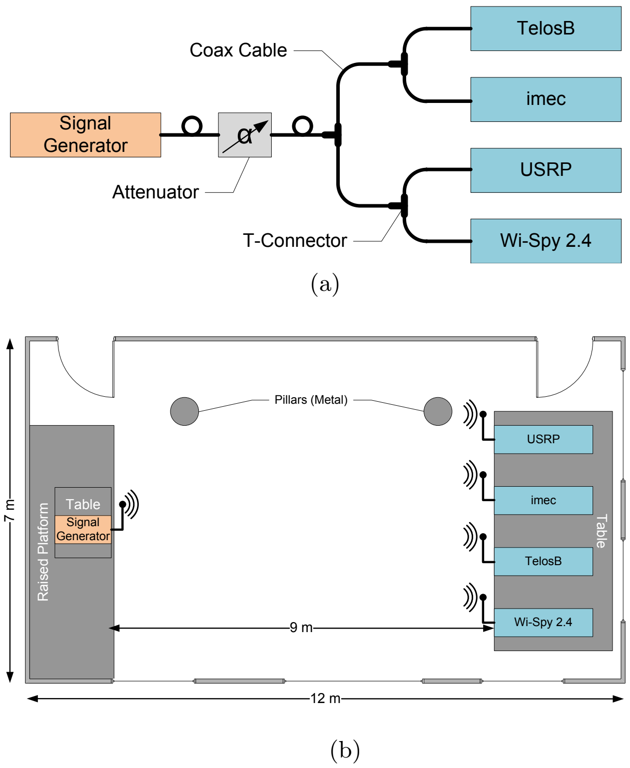


Figure 1: (a) Layout of Setup 1 with coaxial cable connection; (b) Spectrum sensing setup with real wireless channel.

path propagation, fading and shadowing effects, one drawback of this approach is the limited comparability of the results among the sensing equipment employed, as despite the receiving antennas of the devices being located close to each other, the signal paths from the transmitter to the receivers are not identical between sensing devices.

A comparison of the measurement settings in Setups 1 and 2 is shown in Table 1.

Setup	1	2
f_{center}	2.45 GHz	$2.404 \ldots 2.496$ GHz
Tx power	$-20 \cdots -80$ dBm	$\{-4, -15, -30\}$ dBm
Cont. Tx length	∞	$\{60, 0.01\}$ s
Inter-Tx pause	0 s	$\{60, 0.1\}$ s
Distance Tx-Rx	cable	$0.1 \ldots 9$ m
Test signal	8 MHz OFDM-modulated DVB-T signal	

Table 1: Measurement settings for Setup 1 and Setup 2.

2.3 Hardware and Software Platforms

As stated previously, in this paper we investigate the tradeoffs between four of the wireless sensing platforms used in the CREW federated cognitive testbed. Two of these, the imec advanced sensing platform and the USRP with the Iris SDR solution, rely on components developed by member institutions of the CREW project, whereas the other two, the Metageek Wi-Spy 2.4x and the Crossbow TelosB, are low-cost COTS sensing platforms.

2.3.1 *imec advanced sensing platform*

The imec sensing engine is built around an SDR prototype RFIC [4]. The RFIC is a full transceiver in 40nm TSMC technology and is targeted towards low cost and low power handheld devices. The receiver has an RF input frequency range from 100 MHz up to 6 GHz, a programmable channel bandwidth between 1 MHz and 40 MHz, and an onboard 10b 65 MS/s ADC. For testing purposes the RFIC has been mounted on a PCB which connects to an FPGA motherboard. This FPGA motherboard is an HAPS-32 [10] board containing 2 Xilinx Virtex-IV FPGAs. The FPGA board is connected, via a PCI link, to a Linux PC which runs MATLAB to configure the RFIC and implement the signal processing. In subsequent sections this platform will simply be referred to as *imec*.

2.3.2 *TelosB*

Telos [6] is a popular sensor network hardware platform developed at UC Berkeley. The platform uses the IEEE 802.15.4-compliant CC2420 transceiver [12], which enabled us to measure RF energy on different subbands in the 2.4 GHz band. The radio allows the users to adjust the center frequency in steps of 1 MHz, but since an IEEE 802.15.4 channel has a bandwidth of 2 MHz in our measurements we typically sweep over the spectrum in steps of 2 MHz (e.g. 2400 MHz → 2402 MHz → 2404 MHz → etc.). On every channel we take a single RSSI measurement, which represents the signal power averaged over $192\mu s$, and then proceed to the next channel in a round-robin fashion. It takes slightly less than 2 ms to obtain an RSSI sample, to output the data in realtime over the USB interface to a PC and to then switch to the next channel, i.e. the overall sampling frequency is about 500 Hz. In our experiments we used the TelosB variant distributed by Crossbow/Memsic. The software for sampling RSSI was developed by ourselves as a TinyOS 2 [5] application.

2.3.3 *Wi-Spy* 2.4*x*

The MetaGeek Wi-Spy 2.4x is a low cost spectrum sensor designed for use in the ISM 2.4 GHz band. In the experiment the Wi-Spy was interfaced using Kismet Spec-tools for Linux OS. This enabled us to dump power spectral density estimates to a file in a non-proprietary format (a function not available on the standard software *Chanalyzer*). Spectrum dumps are performed as fixed bandwidth sweeps of the entire ISM 2.4 GHz band. The Wi-Spy offers high ease of use.

2.3.4 *USRP*1.0 *with Iris SDR*

The Ettus Research USRP1.0 is a low cost highly flexible transceiver. The RFX2400 daughterboard is operational in the range from 2.3 to 2.9 GHz and the USRP1.0 is capable of bandwidths up to 8 MHz. The Iris reconfigurable SDR, developed by CTVR, The Telecommunications Centre at Trinity College Dublin, makes use of a component-based architecture. As described in [9], users specify which components (such as an OFDM modulator or an RF front-end interface) they would like their radio to make use of and in what order. The user can change exposed parameters of each component in real time, as well as change the components themselves. The flexibility and run-time reconfigurability that are enabled by Iris are not brought into play in this experiment as there is no requirement for the radio to respond to any changes in the surrounding environment. For this reason in this experiment, Iris simply passes I/Q samples from the USRP to a binary file; from here additional processing is performed using MATLAB. When calculating power spectral density (PSD) estimates with this set-up, the bandwidth and the number of FFT bins are both variable; this results in a completely flexible resolution bandwidth. A complete energy detector implementation in Iris is, however, also available which delivers the same level of flexibility as achievable in MATLAB, only in real time. The reason that it wasn't implemented here was to enable the choosing of parameters during post-processing. In subsequent sections this hardware/software combination will simply be referred to as *USRP*.

Table 2 summarizes some properties of note. For further information on the platforms the reader is directed toward the equipment datasheets.

2.4 Expected outcomes

This subsection compares the expected performance of the imec and USRP solutions. Note that the TelosB and Wi-Spy perform energy detection based on proprietary algorithms. The level of internal averaging is not known and we also have no information on any internal filtering of the data. For these reasons theoretical ROC plots for these two platforms are not computed.

To determine the expected performance of the imec platform we start from the noise figure of the RFIC as shown in Table 2. For the imec sensor at 2.4GHz the noise figure is 3.4dB [4] for the RFIC. The USRP RFX2400 has a noise figure of 8dB. Based on the noise figure, the used bandwidth and the RF input power we can compute the received SNR at baseband.

Based on the SNR values computed for the different receivers we can now compute the expected receiver operating characteristic (ROC) curves. The white noise is modeled as a zero-mean Gaussian random variable and the signal is modeled as a Gaussian random variable with a mean value corresponding to the computed SNR. The noise and signal power are averaged over a number of samples equal to the averaging applied in the measurements. For the imec sensor an average over 214 samples is computed and for USRP averaging of 1200 samples is used.

As can be seen in Figure 2, when we allow a maximum probability of false alarm and missed detection of 10% we can see that the imec sensor performs within these specifications up to −106dBm. For the same requirements the USRP works properly up to −108dBm. The USRP based solution achieves better performance than the imec sensor, which has a lower noise figure, by averaging over more samples.

3. RESULTS

In this section, firstly, we compare how the imec platform and USRP with energy detection solution perform compared with the theoretical outcomes presented in the previous section. Secondly, we compare the performance between these two platforms and the COTS equipment introduced in the previous sections, which makes use of unspecified algorithms for energy detection.

The comparison against COTS equipment is done in three ways: Firstly, ROC curves for the different devices are compared. Secondly, we compare the probabilities of detection (PD) that each of the platforms can achieve across varying signal power levels. Both of these first two comparisons were set up over a coaxial cable according to Setup 1 shown in Figure 1(a). Finally we look at the robustness of the detection in the devices subject to shadowing effects created by the presence of people moving in the over-the-air environment shown in Figure 1(b) (Setup 2).

In each experiment each platform senses energy levels within the 8MHz channel in which the test signal is transmitted. As the sensing times of the different platforms are not consistent, readings from platforms with faster sensing times are averaged to achieve a common sensing time for all platforms, within the observed channel. At each point in time each platform reports whether they observe the channel as either free or busy based on energy detection readings with a chosen threshold. Thresholds are chosen to achieve desired probabilities of false alarm (PFA) from measurements where no signal is transmitted over the channel. Based on each threshold a corresponding PD is calculated. Note that the term signal power used in this section refers to the power of the test signal on input to each sensing device.

3.1 Comparison against theoretical optimums

Figure 3(a) shows the ROC of each of the four platforms for a signal power of −74dBm over coaxial cable. If we look at the sensing curves for imec and USRP and compare these to figures 2(a) and 2(b) we can see that the curves deviate from the theoretical estimates. At this signal power the imec curve more closely resembles the curve theoretically possible at −104dBm while the USRP curve more closely resembles that of −108dBm. We suspect that increased noise floor levels were observed in this setup (Setup 1) due to a cumulative amount of leakage from the connected devices. Although theory predicts that, due to a larger number of samples, the USRP solution should result in superior sensing performance than the imec solution, this was not observed in practice.

3.2 ROC comparison against COTS equipment

All four curves in Figure 3(a) remain close to the axes, showing that all four platforms do, in fact, observe the signal.We observe that imec remains tightest to the axes allowing a probability of missed detection (PMD) of 4.4% for a PFA of 0.5%. We see that even though the curve of the TelosB platform lies furthest from the axes it still capable of providing a PD of 88.7% for a probability of false alarm of 15% at this low transmit power. We also see that near perfect detection is achieved by the other two platforms (USRP and Wi-Spy) for PFA above 5%, below which the performance of the platforms deteriorates.

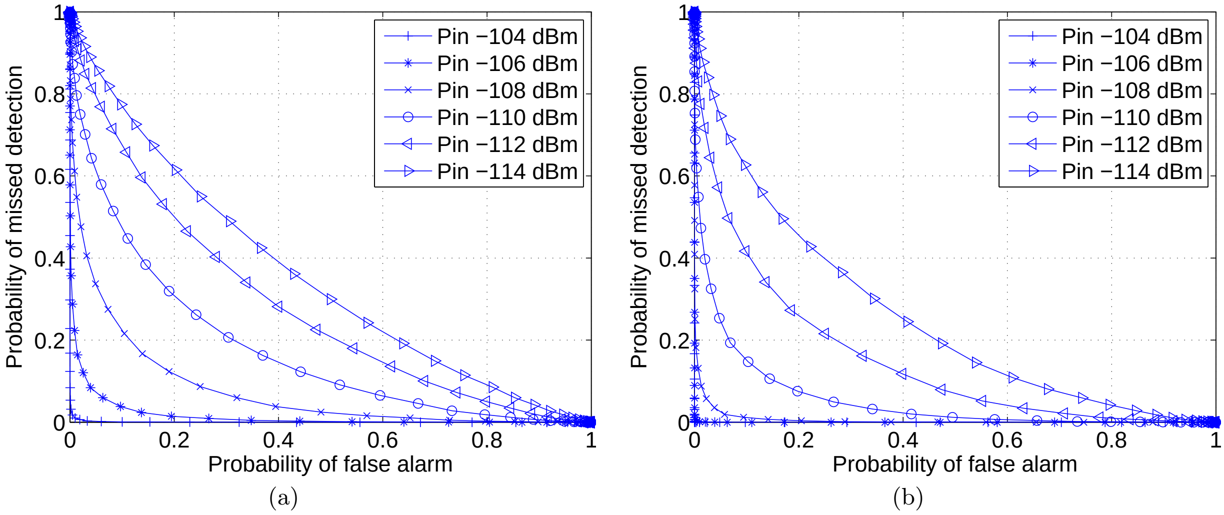
3.3 The effect of signal power

Probability of detection versus signal power is presented in Figure 3(b) for a PFA of 1%. What we first notice about this plot is that below roughly −55dBm the divergences in how well the platforms perform are dramatic. However, above this value all platforms reach PD close to 1. We notice that in this case imec experiences the most stable behaviour, with its PD always remaining above 90%, while Wi-Spy displays more-or-less an ”on-off” behaviour, detecting close to nothing below −55dBm but then performing almost perfectly above this.

From Figure 3(a) we have already seen that for PFAs above 5% the performances of USRP and Wi-Spy are compa-

Table 2: Table of sensing platforms

Platform	Operating Frequencies(GHz)	RBW (Hz)	Noise Figure (dB) [1]	Cost ($)	Datasheet URL
imec	0.1 to 6	any, up to 40M	2.4 to 4	prototype	[4]
TelosB	2.4 to 2.4835	2M	11	<100	www.memsic.com
Wi-Spy 2.4x	2.399 to 2.483	327k	9	<200	www.metageek.net
USRP (RFX2400)	2.3 to 2.9	any, up to 8M	8	<1000	www.ettus.com



(a) (b)

Figure 2: Theoretical ROC curves over a range of input powers (Pin) based on noise figures for: (a) imec advanced sensing platform; (b) USRP with Iris SDR energy detection solution.

rable with that of imec. This means that for these platforms, above this PFA a performance/cost tradeoff no longer exists.

3.4 Robustness in the presence of shadowing

Figure 4(a) shows the ROC produced at $-15dBm$ in a non-changing environment with direct line of sight between Tx and Rx. Figure 4(b) shows the result of the same experiment subject to shadowing and multipath effects created by the movement of people between Tx and Rx to simulate the environment observed in a busy/crowded location.

At first sight we notice that the effect of multipath on imec and Wi-Spy is low and that the PMDs of both devices remain close to 0% regardless. The same cannot be said, however, for TelosB and USRP, which suffer more from the deteriorated propagation conditions. At a PFA of 5% we see an increase of roughly 3% in the PMD of TelosB and almost 24% for USRP in the presence of moving persons in the area where the experiment was performed.

Strangely, we see Wi-Spy performing better in the multipath environment. This is unfortunately due to the unpredictability of the over-the-air channel. It must be also noted that the distance between Tx and Rx for the USRP node was slightly higher than that of the other platforms, hence we see that its overall performance is slightly worse than the others.

Nonetheless, we can conclude that multipath does have an impact on the sensing result which differs from device to device.

4. SUSTAINABLE COMPARISON: A BENCHMARKING APPROACH

While the results from the above comparison may be meaningful to users planning on using one of these devices, the applicability of the results can still be improved by offering a sustainable way to compare these results with results obtained from other experiments. For this purpose, the concept of benchmarking is applied. We define benchmarking as the controlled and comparable evaluation of an experiment relative to a reference evaluation. Comparability is achieved by making an experiment *(i)* repeatable and *(ii)* reproducible. *Repeatability* is a less restrictive requirement than reproducibility, where it is required that the rerun of a benchmark with the same test setup result in the same outcome. *Reproducibility* imposes a sufficiently detailed benchmark description so that the entire experiment can be reproduced by peers in an other location, with the same results.

Comparability is a hard requirement to meet in the experimental environments used in our tests. More generally, any wireless experiment executed in an (open) wireless environment poses great challenges to correctly quantify, due to the unpredictability of the wireless medium. By adjusting the test setup, moving from transmissions over the air

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[1] The noise figure values for TelosB and Wi-Spy 2.4x were calculated by subtracting from the minimum detectable signal power (according to the datasheets: -100 dBm and -110 dBm, respectively) the noise output of an ideal receiver, which is $k \cdot T \cdot B$ (where k = Boltzman constant, T = 290 Kelvin and B = resolution bandwidth).

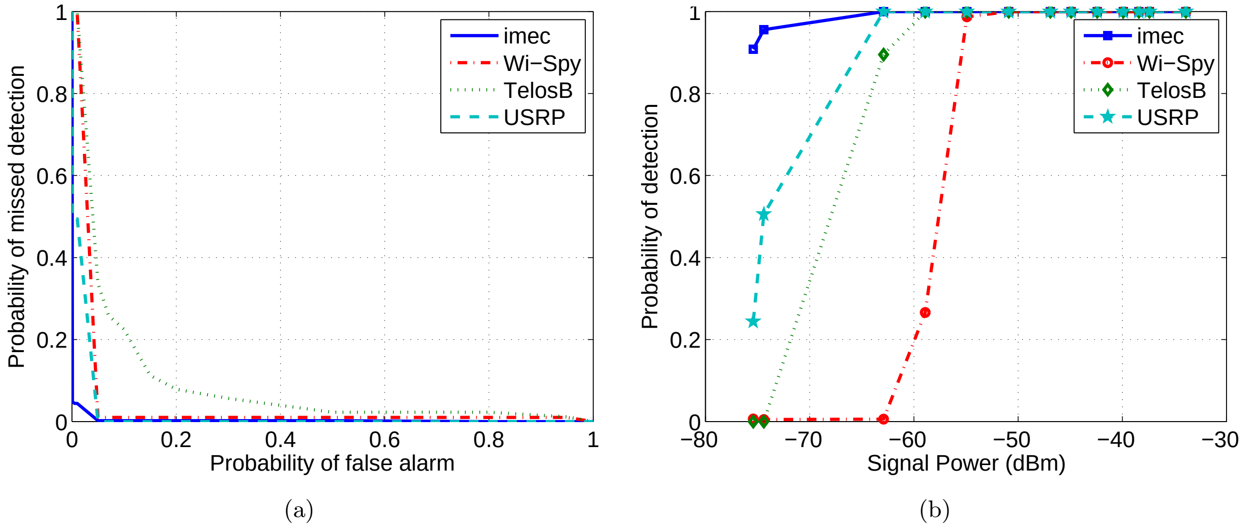


Figure 3: Experiments in Setup 1: (a) Receiver Operating Characteristic (ROC) plot for signal power of -74dBm; (b) Probability of detection of the transmitted signal vs, signal transmit power for probability of missed detection of 1%.

to transmission over coax cable, the influence of the wireless medium was canceled out. However, in order to allow other researchers to perform similar experiments, a detailed benchmarking workflow is necessary describing all facets of the experiment.

The benchmarking workflow is performed in three steps: *(i)* input, *(ii)* processing and *(ii)* output. The *input* consists of a benchmarking scenario, where the behavior of the Systems Under Test (SUT) and the operating environment is fully described. In the case detailed in this paper, the benchmarking scenario would contain the full configuration of the signal generator and the measured attenuation caused by cables and attenuators at the signal input of each SUT. The *processing* step is responsible for translating the values from the individual spectrum sensing tools to performance metrics, using fully described algorithms. Finally, the *output* of our benchmark is the automatic visualization of the metrics results. These graphs simplify result analysis and are based on the selected performance metrics, possibly combined with business metrics, such as the cost of the SUT and the hardware flexibility.

However, the results of the benchmarking approach will not be presented/further elaborated in this paper; they are a subject of future work.

5. CONCLUSIONS AND FUTURE WORK

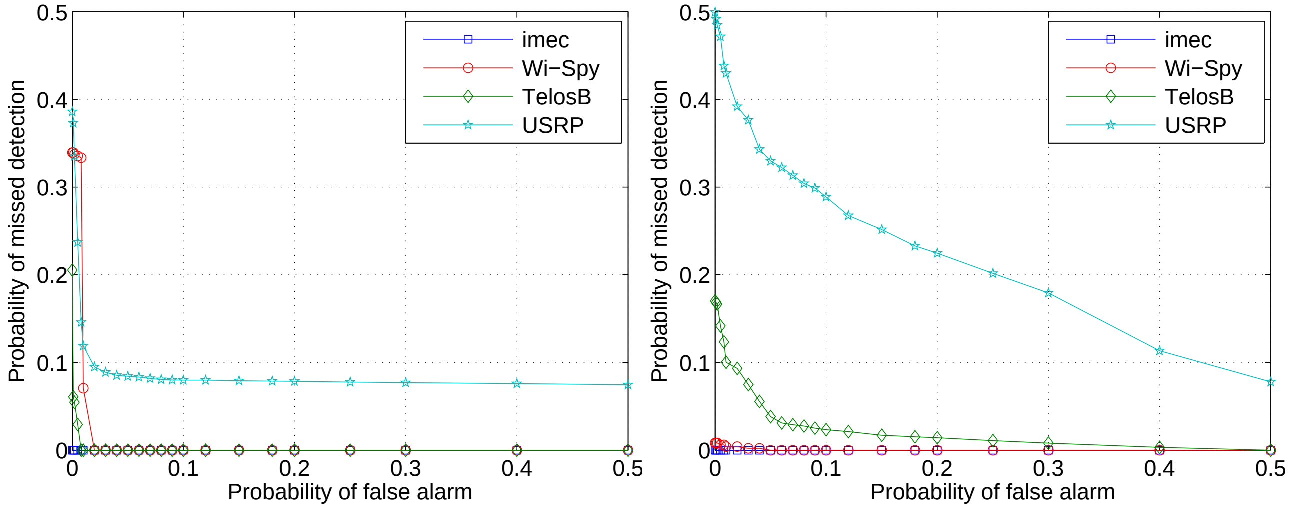
This paper presents the bringing together of four different wireless platforms used/developed in four different research institutions with the future aim of integrating these platforms into a single federated testbed. This enables us to test for tradeoffs between the platforms which would normally not be feasible to perform. We see that a tradeoff between cost and performance does exist, but only under certain conditions. For low signal powers, narrow bandwidths, high shadowing, or stringent PFA requirements more expensive sensing platforms (such as imec and, to a certain extent, USRP) significantly outperform the less expensive platforms. On the other hand, for high signal powers, large bandwidths, stable environments, and more flexible PFA requirements less expensive equipment (e.g. TelosB and Wi-Spy) can be seen to perform as well as more expensive counterparts and be equally effective.

How we can interpret this is that for the majority of nearby ISM traffic (possibly with the exception of Bluetooth) Wi-Spy and TelosB offer reliable detection, at low cost, with great ease of use. Additionally, the built-in Zigbee transceiver in TelosB enables highly reliable detection of Zigbee signals. In detecting further distant signals or non-ISM traffic imec and USRP perform better. For more sophisticated sensing, such as detecting spectrum holes in signals which require synchronization to detect (possibly unused LTE PRBs in a particular area) or difficult to detect signals such as those of wireless microphones, imec would be the chosen platform.

Table 3 presents a final summary of the conditions under which the performance of each platform was observed to deteriorate.

While the experiments described in this paper characterize the performance of each individual platform, one of our current activities is to investigate the gain in sensing accuracy by performing homogeneous and heterogeneous cooperative sensing. Furthermore, we recognize that dynamic spectrum access is expected to rely on geolocation databases, real-time spectrum sensing, or, likely, a combination of both. As the use of geolocation databases requires location awareness, another of our current activities is the integration of assisted GPS into some of the hardware platforms investigated in the paper.

Future research includes building a library containing a set of relevant test signals representing different wireless technologies such as DVB, LTE, Wi-Fi or Bluetooth. Such libraries will allow further characterization of the sensing solutions with respect to their abilities to detect and/or recognize different primary user technologies and transmission patterns. The entire measurement approach is furthermore to be formalized by capturing the entire test set-up (input,



(a)

(b)

Figure 4: Experiments in Setup 2: Reciever Opperating Characteristic (ROC) plot for transmission of -15dBm subject to (a) standard fading of the channel (b) standard fading of the channel plus shadowing effects

Device	PFA (%)	Signal power (dBm)	Multipath environment
imec	< 1	none of those tested	no
TelosB	< 20	< -63	yes
Wi-Spy	< 5	< -55	no
USRP	< 5	< -63	yes

Table 3: Summary of conditions under which performance of the platforms was observed to deteriorate.

processing and output) in publicly shared benchmarking scenarios. We also plan to implement a test facility aimed at enabling repeatable over the air experimentation capable of emulating previously characterized wireless environments, for example mimicking an office or a factory environment. Such environments will also enable performance analysis of distributed sensing approaches.

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 258301 (CREW project).

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