Evaluation of Spectrum Occupancy in Indoor and Outdoor Scenario in the Context of Cognitive Radio

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***Abstract*—Dynamic spectrum access is an integral part of the Cognitive Radio paradigm. However, efficient spectrum sensing techniques are crucial on the way towards systems, which use idle spectrum bands opportunistically and increase the overall spectral efficiency. Current spectrum occupancy was evaluated in few measurement campaigns at different locations mostly located in the USA. In this paper we report about an extensive measurement campaign conducted in Aachen, Germany, comparing indoor- and outdoor measurement results. The highly sensitive measurement system enabled us to measure also man-made or ambient noise. Since an energy detector cannot differentiate such noise from other primary user signals we determine a very high spectrum occupancy in the outdoor scenario in the band from 20 MHz up to 3 GHz. Considerably less occupation was measured in the indoor scenario also because of less ambient noise. Our measurements confirm that the spectrum band 3-6 GHz is rarely occupied. We further provide a case study how the amplitude probability distribution can be used together with detailed regulatory information to infer additional information about the spectral usage. Such information is beneficial in order to optimize the spectrum sensing process and identify candidate bands for further investigation and possible secondary usage.**

I. Introduction

Recently, Cognitive Radio (CR) technology has become one of the most rapidly expanding research topics in the field of wireless communication. CRs will dynamically adapt to their environment and combine various information to make intelligent decisions [1]. One of their main features is the ability to choose their working frequency opportunistically based on the results of their own local spectrum occupancy measurements and possibly cooperatively gathered additional information. Such technology is motivated by measurement campaigns comparing the spectrum regulations defined by governmental agencies and the actual usage by the licensees. Several measurement campaigns were conducted at diverse locations, e.g. [2]–[9], showing that large amount of regulated spectrum is not used. However, the coverage of locations is still much smaller than the number of different regulations existent in different countries. In order to develop systems which are not restricted to certain geographical areas further measurements are required. Additionally, the time-span covered by the measurement campaigns until now is not sufficient to analyse also changes over time in detail. Some of these gaps were also determined by other researchers [3].

We report in this paper about an extensive measurement campaign conducted in the city of Aachen located in Germany near to the border to Netherlands and Belgium. The reported work is part of a larger on-going measurement campaign conducted by the RWTH Aachen University in several European countries. The spectrum occupancy of several frequency bands was measured over longer time periods up to seven days. We report about general usage and analyse the spectrum occupancy. Additionally, we present the amplitude probability distribution as a powerful approach how spectrum occupancy data can help to optimize the search for unused spectrum, so called white space. These results are compared to the official spectrum regulation defined by Federal Network Agency (Bundesnetzagentur) [10], the governmental agency dealing among other things with frequency allocations in Germany.

The search for white spaces can be based on different spectrum sensing methods [11]. Depending on how much information is available about the signal used by the regulated services, also known as primary user signals, different performance can be reached. However, in the most general case no prior information is available so that energy detection is the only possibility left. Energy detection compares the received energy in a certain frequency band to a usually predefined threshold. Based on our results we discuss the impact of the decision threshold and also give examples for the importance of the sensing sensitivity in this context.

The remainder of this paper is structured as follows. After commenting on related work we will present our measurement setup in section II. We will discuss our measurement results in section III and also show the impact of the decision threshold. We analyse the results in more detail in section IV and conclude the paper in section V.

A. Related Work

Several researchers have performed similar measurement campaigns as we present in this paper. However, most of them were done in the USA and therefore evaluate the American spectrum regulations and usage. The first larger spectrum occupancy measurement campaign was performed by the NTIA (National Telecommunications and Information Administration), responsible for managing the Federal Governments use of the radio spectrum in the USA, in 1998 [8]. The spectrum occupancy was found to be higher in coastal cities because of the presence of naval radars etc. Marc McHenry et. al. did another large scale spectrum occupancy measurement campaign funded and ordered by NSF [3]. The spectrum occupancy in several American cities was found to be always below 25 %, which is mostly caused by a rather high decision threshold between -90 and -105 dBm. No detailed rationale for this threshold is given. Robin Chiang et. al. report about spectrum occupancy measurements done in New Zealand [2]. They also determine several idle bands by using a similar approach as we apply based on the thermal noise floor of the measurement system for fixing the decision threshold. In [5] a detailed spectrum survey in urban Atlanta and also rural measurement sites is described. In addition to threshold decision a better decision algorithm is explained. The campaigns presented in [9] and [4] cover smaller spectrum bands but still report about large amount of unused spectrum. Also in [6] large amount of unused spectrum band is shown although no details about the measurement setup are provided. To the best of our knowledge, [7] provides the only available spectrum occupancy report based on scientific measurements performed in Germany. It shows vast amount of unused spectrum but does not provide details about the measurement setup or analysis of the measurement result so that the reported received power values cannot be reasonably compared to our results.

II. Measurement Setup

Our measurement setup consists of a laptop, which remote controls an Agilent E4440A high performance spectrum analyzer via cross-over Ethernet cable. Depending on the measured spectrum band we used three different antennas: We used a large discone antenna[1] for the frequency range between 20 MHz and 1.52 GHz. Another much smaller discone antenna[2] covered the frequency range of 1.5 GHz up to 3 GHz and we also deployed a radom antenna[3] specified up to 10 GHz, although we measured only up to 6 GHz. All antennas are vertically polarized, have an omnidirectional characteristic in horizontal plane and have small amount of directivity in the vertical plane. All equipment besides the antennas was enclosed in a weatherproof box made of wood, which was shielded in order not to cause unwanted emissions. Figure 1 shows a photograph of the measurement setup as it was used during the outdoor measurements.

The MATLAB software package and its instrument control toolbox was used to control the measurement, save the data and later on analyze it. The detailed settings used for the spectrum analyzer are listed in table I[4].

Center frequency	Band 1: 770 MHz Band 2: 2250 MHz Band 3: 3750 MHz Band 4: 5250 MHz
Frequency span	1500 MHz
Resolution bandwidth	200 kHz
Number of measurement points	8192
Sweep time	1 s
Detector type	Average detector
Preamplifier	up to 3 GHz: 28 dB gain above 3 GHz: no preamplifier

TABLE I
Spectrum analyser configuration used throughout the measurements

Fig. 1. Setup as used during the outdoor measurement in Aachen, Germany.

A. Geographical locations

We report about two measurement campaigns: The first one was performed indoor in a room located in a modern office building[5]. The second one was run on the roof of a ten story high office building owned by the city of Aachen[6]. It is located next to Aachen main railway station on a hill so that most of the city was below the measurement point. Additionally, all nearby buildings are at maximum eight stories high, so that no other building blocked the radio propagation considerably. Several different transmitters (numerous cellular base stations, FM radio, TV broadcaster, etc.) had direct line of sight connection to the measurement location. The figures 2 to 5 show the view from the roof to different directions and prove that no other building was higher and e.g. figure 4 also shows the roof of the Aachen main station building.

III. Measurement Results

In order to give a general overview of the spectrum usage we start our discussion with the minimum, average, and maximum

[1]Larger discone antenna: AOR DA-5000.
[2]Smaller discone antenna: AOR DA5000JA.
[3]Radom antenna: Antennentechnik Bad Blankenburg AG KS 1-10.
[4]The preamplifier inbuilt in the spectrum analyzer supports only signals up to 3 GHz so that it could not be used for the higher bands.
[5]Latitude: 50° 47' 24.01" North, Longitude: 6° 3' 47.42" East.
[6]Latitude: 50° 46' 6.93" North, Longitude: 6° 5' 28.48" East.

Fig. 2. View to the north from the outdoor measurement location.

Fig. 3. View to the east from the outdoor measurement location.

Fig. 4. View to the south from the outdoor measurement location.

Fig. 5. View to the west from the outdoor measurement location.

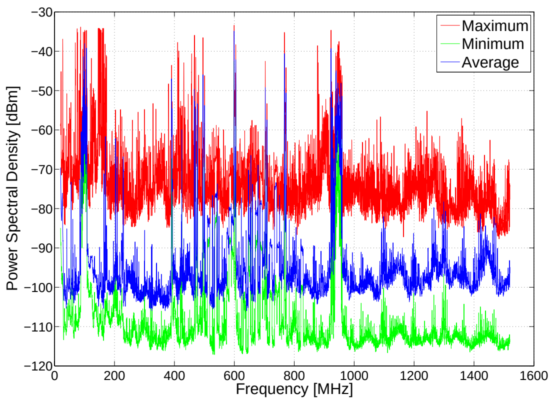

Fig. 6. Minimum, average and maximum PSD measured at the outdoor location in the spectrum band 1 from 20-1520 MHz.

power spectral density (PSD) measured per each band at the outdoor location. Figure 6 shows these results for the lowest measured spectrum band from 20 to 1520 MHz. Some bands such as the FM radio around 100 MHz and the GSM channels around 900 MHz can be clearly identified because in contrast to most of the other spectrum bands also the measured minimum level was above -80 dBm. Another example is the thin peak around 380-390 MHz, which is the uplink channel of the TETRA test network for public safety applications running in the Aachen area. The thermal noise floor and thus the rough sensitivity level of the measurement system is clearly below -110 dBm. As the average PSD is well above -110 dBm we can determine that in all bands actual man-made transmissions were received for considerably long periods. Additionally, the measurement period was about seven days and any signal caused only by thermal noise should average out and lead to a flat spectrum. Such flat subbands are not present so that we can estimate that at maximum only few and narrow bands do not show any signal.

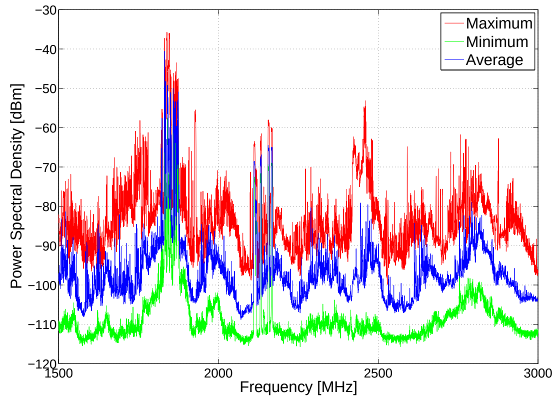

Fig. 7. Minimum, average and maximum PSD measured at the outdoor location in the spectrum band 2 from 1500-3000 MHz.

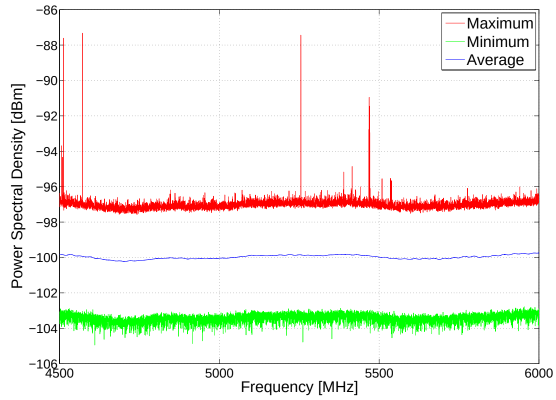

Fig. 9. Minimum, average and maximum PSD measured at the outdoor location in the spectrum band 4 from 4500-6000 MHz.

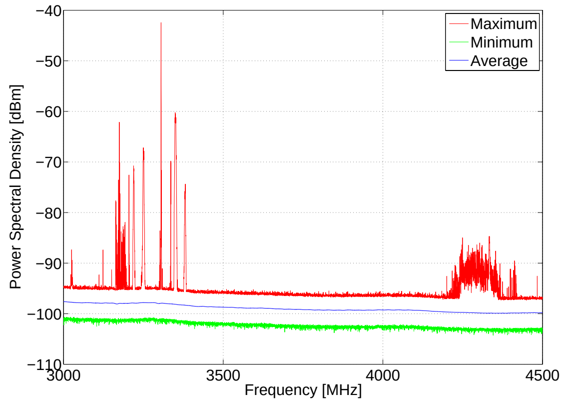

Fig. 8. Minimum, average and maximum PSD measured at the outdoor location in the spectrum band 3 from 3000-4500 MHz.

Similar facts can be derived from the results for the second spectrum band from 1500 to 3000 MHz shown in figure 7. The GSM channels in the band around 1800 MHz and the UMTS system working around 2100 MHz can be clearly identified. The ISM-band at 2400 MHz is recognizable because of the clearly higher peak power measured at some point in time. Only very few bands are found with average PSD below -105 dBm or with a stable and low PSD over larger bandwidth. As for the lowest band we can conclude that nearly no frequency band can be determined idle by only looking at the PSD.

Figures 8 and 9 show the results for the frequency bands 3000-4500 MHz and 4500-6000 MHz, respectively. The preamplifier inbuilt in the spectrum analyzer used during the measurement does only support signals up to 3 GHz so that the sensitivity of the measurement setup for higher frequencies is lowered. However, the average PSD for both higher bands is very flat so that we can assume that these bands are mostly idle. The single peaks measured roughly at 3200-3400 MHz are caused either by military signals or are active radar transmissions emitted by spacecrafts for earth exploration. The peaks measured around 4200-4400 MHz are radar transmissions originated by airplanes for altitude measurements. The ISM-band at 5150-5350MHz is completely empty showing once more the difference in popularity between the 2.4 and 5 GHz ISM-bands.

The average PSD for both bands is about -100 dBm or slightly above. If we compare this value to the plots presented for the two lower bands we find numerous frequency bands with higher average PSD. Therefore, the probability that a high number of primary user signals was not found because of the lower sensitivity is small. Some signals might have been missed but the majority of the frequency band 3-6 GHz is idle and available for opportunistic spectrum usage.

A. Spectrum Occupancy

If an energy detector is used to decide about spectrum occupancy the PSD is compared to some decision threshold, which becomes an important parameter. If the measured PSD in a certain frequency band is above this threshold the energy detector will report this band as occupied. If the measured PSD is below, the frequency band will be reported as idle and could be used by secondary users. In order to determine a realistic threshold we measured the thermal noise of the system using a fitted resistor of 50 Ω. Afterwards we used the distribution of the measured noise samples to determine that a threshold 3 dB higher than the measured noise floor leads to a false alarm probability of about 1 % caused by noise samples with high power. We should note that the threshold is not constant over frequency because the measured noise slightly increases with the frequency. However, the selected margin of 3 dB is fixed throughout the whole investigated spectrum band.

For the indoor measurements this threshold leads to an overall spectrum occupancy of about 32 % for the band of 20-3000 MHz and a measurement time of seven days. Some bands are used with very high percentages, such as bands used

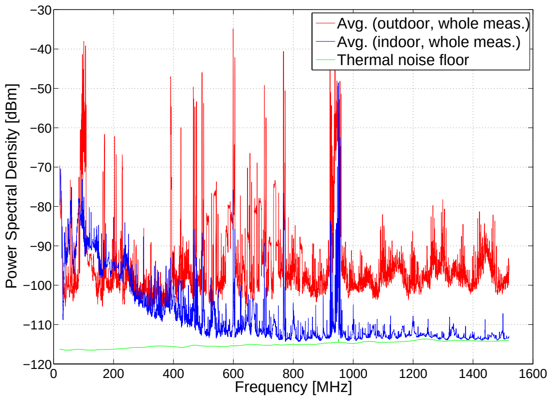

Fig. 10. Comparison of indoor and outdoor measurement results to the measured thermal noise floor for 20 to 1520 MHz.

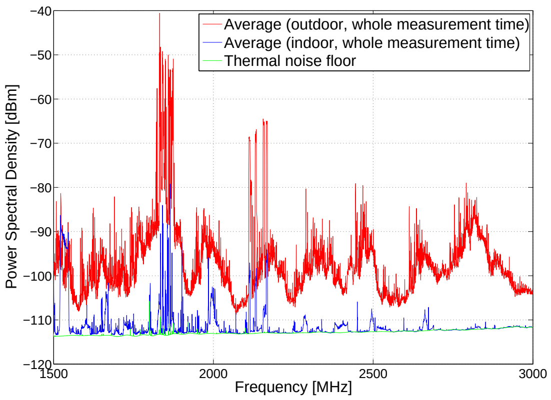

Fig. 11. Comparison of indoor and outdoor measurement results to the measured thermal noise floor for 1500 to 3000 MHz.

for cellular downlink transmissions, point-to-multipoint services, e.g. media broadcasting, or satellite downlink channels. Other bands are rarely used such as some military bands or frequencies reserved for inter-ship communication.

In the case of the outdoor measurements the spectrum occupancy is considerably higher because signals were attenuated less. Several transmitters had direct line of sight to the receiver antennas and the setup was located outdoor on the roof of a high building. Additionally, the measurement site was located next to Aachen main railway station, a location with several additional noise sources. The resulting spectrum occupancy is nearly 100 % measured over a period of seven days for the spectrum band 20-3000 MHz.

Describing spectrum occupancy with a single number is obviously not sufficient. It can only provide a rough impression on the occupancy measured at a single location. Additionally, the reason for determining a frequency band as occupied is not differentiated, it might be because of an intented transmission but might also be caused by man-made noise as it was the

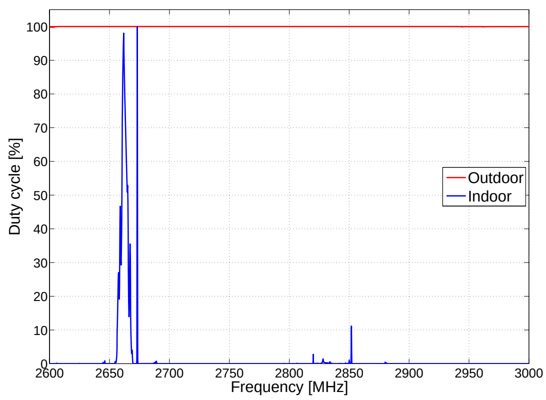

Fig. 12. Comparison of duty cycle based on indoor and outdoor measurement for 2600 to 3000 MHz.

case for several bands during our outdoor measurements. Nevertheless, from our point of view the single number enables to summarize the spectral occupancy to a certain extend. More detailed plots such as the PSD over frequency or also the amplitude probability distribution as presented in section IV can be used for closer investigation of the measurement results.

Figures 10 and 11 compare the average PSD for the indoor and the outdoor case to the thermal noise floor as measured with the fitted match. The reported noise measurements were performed with the same spectrum analyzer settings as used for the spectrum occupancy measurements and are the averages over long enough time periods (longer than six hours) guaranteeing representative results. It is obvious from the figures that the PSD measured in the indoor scenario converges more and more closer to the thermal noise floor the higher the measured frequency gets. These results show expected effects as the attenuation of walls, windows etc. increases with the frequency. We can conclude that some of the higher frequency bands will be determined idle by an energy detector in the indoor scenario for considerable amount of time. In contrast, the average PSD measured in the outdoor scenario is clearly higher leading to the very high percentage of occupation.

This high occupancy rate was not expected because the German frequency spectrum regulations reserve several bands only for passive usage such as radio astronomy etc. We investigated the PSD for some examples of such bands. For instance in the band 1400-1427 MHz, reserved for passive services[7], we found several peaks above -80 dBm which clearly indicate active transmissions in this band. We assume out of band transmissions of other primary user signals to be the main reason for such ambient noise.

Figure 12 shows the duty cycle for the indoor and outdoor measurement calculated using the described margin of 3 dB. We chose the spectrum band 2600-3000 MHz as an example

[7] In Germany 1400-1427 MHz is allocated for three services: Earth exploration, radio astronomy and space research (all passive). This band is protected by recommendation ITU-R RA.769 [12].

since some typical cases of frequency regulation and usage are present in this band. The band 2650-2670 MHz is used by some directive point-to-multipoint services and both measurement setups were obviously covered by one of the deployed directed antennas. The small band 2690-2700 MHz is also reserved for the explained passive services and should therefore not be used by CRs although indoor duty cycle is 0 %. The spectrum band 2900-3000 MHz is an example for possible opportunistic usage. It is allocated for military services but also for radar applications on ships. As Aachen is located neither at the sea nor near to a river such latter applications will never be used in the Aachen area. However, the military allocation will have to be considered so that efficient spectrum sensing is still required. Besides, some of the explained bands are further examples showing that the outdoor measurement results in very high spectral occupation although some of these bands are definitely not used by any active transmitter. Instead, out-of-band transmissions or other ambient noise is received and interpreted as primary user signal because an energy detector is not able to differentiate between primary user signals and ambient noise without further information.

IV. Analysis

Several options exist to combine additional information with the outcome of the energy detector in order to reach a more reliable sensing result. In this paper we present the amplitude probability distribution (APD) analysis method [2], [3] to investigate the primary user activity. Key characteristics such as signal bandwidth, transmitter mobility, number of transmitters, etc. can be very well estimated by evaluating small parts of the amplitude probability distribution.

APD is a three-dimensional histogram with one axis being amplitude, one being frequency span, and another being the probability of each amplitude value throughout the whole measurement period. The underlying principle of APD analysis is that different equipments and devices show distinct behavior in terms of PSD and signal characteristics. Such transmitter characteristics can be deduced from the statistical distribution of the amplitude probability. Figure 13 and 14 show the APD of the outdoor measurements covering the frequency range of 20 MHz to 3 GHz. In figure 13, the density of peaks is very high and these peaks have various kinds of shapes, implying a coexistence of diverse types of services. Comparatively, transmitters residing between 1500 MHz and 3000 MHz as a whole are received with less power and operate with less diversity of service type.

In order to illustrate how APD analysis works, part of figure 13 from 20-150 MHz is taken out and magnified as shown in figure 15. This range is chosen as an example due to the existence of various different types of signals instead of being an ideal band for opportunistic reuse. Note that the PSDs of most bands are well above noise level therefore indicating occupied bands. Some obvious or representative peaks were marked in figure 15 and associated services can be obtained by referring to the German frequency regulations [10]. Between 20 and 30.01 MHz peaks with flat distribution labeled by

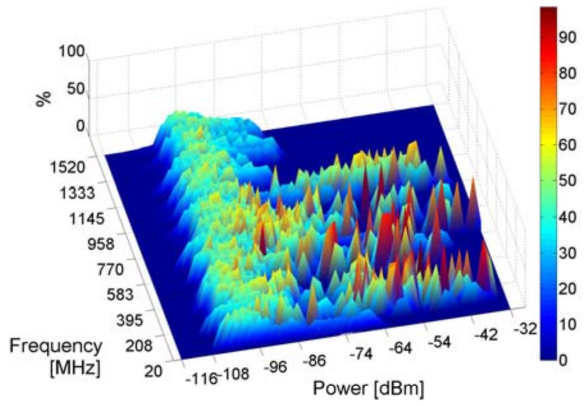

Fig. 13. Amplitude probability distribution of the power levels measured during the outdoor campaign from 05-Feb-2007 11:13:52 to 12-Feb-2007 09:06:42 in the spectrum band 20-1520 MHz.

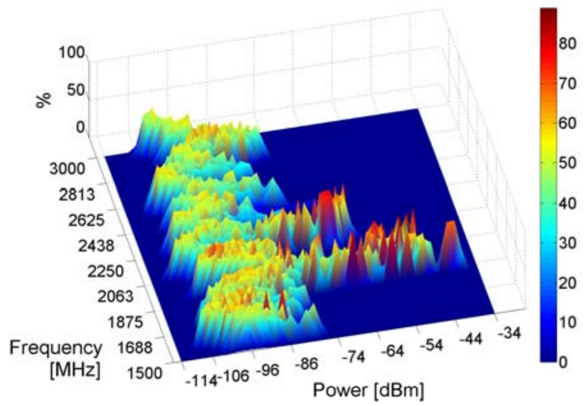

Fig. 14. Amplitude probability distribution of the power levels measured during the outdoor campaign from 12-Feb-2007 09:47:42 to 20-Feb-2007 08:47:28 in the spectrum band 1500-3000 MHz.

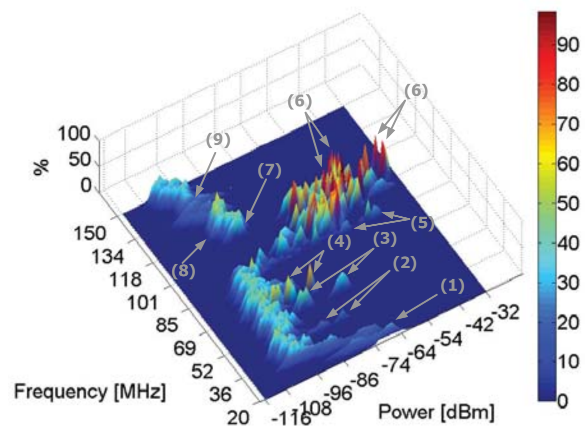

Fig. 15. Amplitude probability distribution of the power levels measured during the outdoor campaign in the spectrum band 20-150 MHz with more details and marks.

marker 1 can be observed with a large variation of the PSD (-108 to -64 dBm). These characteristics imply a coexistence of miscellaneous services[8] with different limitations on transmission power. From 47-68 MHz several peaks (markers 2, 3, and 4) were observed. In Germany this range is allocated for land mobile services, wind profiler radars, and amateur radio. With further magnification of this range, five mobile transmitters, each occupying 0.5 MHz bandwidth, are found operating around 41 MHz. Three additional groups of mobile transmitters (marker 3) were operating around 55 MHz but were received with higher power and show higher mobility due to wider peaks. Between 61 and 62 MHz stand four single peaks (marker 4), which have the typical attributes of fixed transmitters with constant power: sharp, narrow and high peaks. Two single wide peaks (marker 5) residing between 84 and 85 MHz are known as BOS[9] radio transmitters with high mobility. Although a digital TETRA-network is under test in the Aachen area several public safety radios still use analog transmission. Between 87.5 and 108 MHz more than 15 single narrow peaks (marker 6) are observed congregating in high power range. Their amplitudes are the highest ones in the histogram indicating that they were fixed transmitters with very constant transmission power during the whole measurement. It is a typical characteristic for point-to-multipoint services, such as cellular downlinks, media broadcasting services, and satellite downlinks. In this case the peaks are caused by FM radio broadcast stations. The frequency range 108-137 MHz is mainly occupied by aeronautical radio navigation services. Peaks with marker 7 are aeronautical beacons sent by the instrumental land system (ILS) for guidance of aircraft landing and takeoff. The communication between the aircraft and the ground stations led to the peaks labeled by marker 8. Peaks by marker 9 display a disperse power distribution and are supposed to be radio communication between aircrafts or between aircrafts and ground stations. The flat shape indicates many transmitters at many different distances.

From the analysis above general rules for primary user recognition can be concluded and summarized. A single peak with narrow and sharp shape and large amplitude is associated with a fixed transmitter with rather constant power. The height and the width of the peak jointly describe the stability of the transmission power. The higher and the narrower the peak the more constant the transmission power is. A single wide peak with large amplitude represents a transmitter applying amplitude modulation (AM) or a transmitter with mobility. If multiple transmitters are received with similar distribution of received power values a single peak could also represent a group of stations though. Whether the widening of the peak is due to AM or mobility can usually be differentiated by referring to the frequency regulations. If it is a mobile transmitter, the mobility is determined by the width of the peak. The wider the peak the higher the mobility of the transmitter is. A wider distribution with many peaks but small maximum amplitudes is associated with many devices received from different distances, or congregation of various services with distinct power regulations. Again, these cases can be distinguished using frequency regulation information. Finally, the received power allows in some cases to infer the rough operating power of the transmitter directly from the APD histogram.

All this information should be used to improve the CR's search for idle spectrum bands available for opportunistic usage. If the regulatory conditions of a spectral band are known and only few single transmitters were found this band will most probably be idle in case these few transmitters stop their transmission. Determining an idle band in case it is used by multiple services and multiple users will be much more difficult and also much less probable because the number of potential primary users is higher. As sensitive spectrum sensing is energy-intensive because signals near to the thermal noise floor should be reliably detected an efficient sensing strategy will be beneficial. Additionally, a quicker way to find empty spectrum bands will increase the overall system performance. CRs should possess detailed frequency regulation information and combine it with their measurement results analyzed in form of the APD in order to lower the number of candidate bands that should be sensed in detail.

V. Conclusion

Our measurements showed that the spectrum occupancy highly depends on the sensing location and the decision threshold chosen to differentiate idle and used bands. Both facts are to be expected but clearly confirmed by only two measurement locations. We will increase the number of measurement locations also taking into account the differences in frequency regulations between different European countries. In the outdoor campaign unexpectedly high level of ambient or man-made noise led to a spectrum occupancy of nearly 100 % for 20 MHz to 3 GHz. Occupancy in the band of 3-6 GHz was determined to be very low although the sensitivity of the measurement setup was lower. In the indoor case several spectrum bands also between 1 and 3 GHz can be determined to be idle for longer time periods showing possibilities for opportunistic spectrum access. Hence, in the outdoor the main opportunities reside in the frequency bands above 3 GHz and in the case of low-power indoor systems also some lower frequency bands may be usable for secondary access. The location, especially knowledge of being located indoor or outdoor, is a quite important factor and indicates that the future CR systems should be ideally location-aware devices in order to operate efficiently.

In case of the outdoor location sole energy detection will report too high occupation because out of band transmissions of other primary user signals and other noise sources will be interpreted as primary user signals. We gave a detailed example how the amplitude probability distribution and thus information gathered during former spectrum sensing activities can be combined with information about spectral regulation.

[8] In Germany over 33 services are assigned to this range.

[9] Public Safety Authorities and Organizations, in German: Behörden und Organisationen mit Sicherheitsaufgaben (BOS).

Such approaches help to perform spectrum sensing more efficiently and find promising candidate bands for opportunistic access.

As part of our future work we plan to do measurements at further locations and continue to investigate our results statistically in order to develop modeling strategies for spectrum occupancy. We also plan to provide statistical information from the measurement campaign in digital format to interested parties through Internet later in the future.

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