# Two Days of Spectrum Use in Europe

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***Abstract*—In this paper we report on spectrum use measurements carried out synchronously over the period of 48+ hours in seven European cities. Special care has been placed on harmonizing the measurement settings and equipment so as to obtain as comparable data as possible. We describe in detail the measurement setup, including the coordinated preparation activities carried out across the different measurement sites. We present preliminary analysis of the obtained data set, and particularly highlight similarities and differences in spectrum use between selected measurement locations. We plan to release later the full data set for research community for the further research.**

## I. Introduction

In recent years there has been significant interest in quantitative studies of spectrum use. Several research groups, companies and regulators have conducted studies of varying time periods on how different radio frequencies are used (see, for example, [1]–[6]). These measurement campaigns have resulted in significant amount of insight on spectrum use at these individual locations. However, it is still very difficult to use existing measurement campaign results to quantitatively study the differences in spectrum use between different countries and environments. There are several reasons for this. First, the measurement campaigns carried out often do not overlap in time, making any detailed comparisons nearly impossible. Second, most studies report very different statistics computed from the measurement data, and the raw data is often not made publicly available, again significantly hindering comparative studies. Third, the equipment and measurement settings used by different groups are highly heterogeneous, often resulting in wildly different results and conclusions especially in time domain analysis.

Based on the above observations, we have carried out a dedicated spectrum measurement campaign specifically targeting the acquisition of data sets of spectrum use from diverse environments that can be also compared scientifically. Seven locations were chosen for the measurements, representing diverse socio-economic environments spread across several countries, and the measurements were carried out in a synchronized manner over the course of two days. The objectives were to gather measurement data on spectrum use both over a wide band (from 75MHz to 3GHz ), as well as with high time resolution. The high time-resolution will contribute also to the secondary aim to understand the traffic patterns in the cellular and ISM bands. For the first of the two days whole 3 GHz bandwidth was swept continuously, whereas for the second day partners with slower spectrum analyzers focused on the cellular and ISM bands. Depending on the availability of the facilities at the different measurement sites, at some locations measurements were also continued over the weekend following the designated days of the measurements. In order to obtain comparable results, the measurement settings were carefully harmonized across all sites. Common data exchange format was also developed to facilitate this approach, and also the sharing of the data later one. This type of spectrum measurements supports better understanding of two different types of objectives. First for the overall spectrum utilization and the white space available around the measurement equipment. Second, for the primary user activity patterns, where the measurement location is important as a primary user activity might not be detected (i.e edge of a cell). In this paper we describe in detail how these two days of measurements were carried out, and discuss the key lessons learned when preparing such a measurement campaign. We also give preliminary results from our analysis of the measurement data, although due to space reasons comprehensive reporting is not possible here. Our plan is to release the full data set by the end of 2012, enabling other research groups to benefit from our measurements.

The rest of this paper is structured as follows. In Section II we discuss the measurement configurations and location in more detail, especially focusing on key lessons learned from this campaign. We then give an overview of selected results first focusing on overall spectrum use over the whole measurement bandwidth in Section III, and then discuss results on cellular bands specifically in Section IV. Finally, we draw conclusions in Section V.

## II. Measurement Settings and Locations

The two days of measurements were carried out during the 13th and 14th of October, 2011 (corresponding to Thursday and Friday on a typical working period week), in the European cities of Aachen, Hannover, Constance, Krefeld, Leuven,

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Fig. 1. The measurement sites for the two days measurement campaign.

TABLE I
SUMMARY OF THE HARDWARE USED AT DIFFERENT MEASUREMENT SITES. (SA: SPECTRUM ANALYZER, SENSITIVITY GIVEN AT 3 GHZ FOR RBW OF 100 KHZ, SL1: ROHDE & SCHWARZ FSL6, SL2:ROHDE & SCHWARZ FSQ-26, SL3:ANRITSU MS2690A, SL4:TEKTRONIX RSA 6100A, AM1:DA 3200 AOR, AM2:DA 753 G)

| City | Latitude | Longitude | SA | Antenna | Sensitivity |
|---|---|---|---|---|---|
| Aachen | 50.7761 | 6.0703 | SL1 | AM1 | -99.5 |
| Maastricht | 50.8428 | 5.7211 | SL1 | AM1 | -101.2 |
| Leuven | 50.8653 | 4.6764 | SL2 | AM2 | -99.0 |
| Skopje | 42.0041 | 21.4125 | SL3 | AM1 | -104.5 |
| Constance | 47.6881 | 9.2014 | SL4 | AM2 | -109.0 |
| Krefeld | 51.4267 | 6.4728 | SL4 | AM2 | -112.5 |
| Hannover | 52.3683 | 6.7711 | SL4 | AM2 | -109.0 |

Maastricht and Skopje. The exact GPS coordinates of the measurement locations are given on Table I, and Figure 1 depicts the measurement locations in Europe.

In the following we go over the measurement setups themselves in detail, first focusing on the used hardware, and then discussing the implications on the measurement equipment on time and frequency domain aspects on the obtained data.

### A. Hardware Setups

The most challenging part for this type of distributed measurement campaign is to control and eliminate the measurement disparities that arise from different measurement setups (mainly due to diverse hardware components and configurations). For that, information on all the hardware components that constituted their measurement setup was gathered beforehand, especially focusing on the following parts:

1) Antenna part (type, input impedance, frequency coverage);
2) Cables (cable types, cables losses and lengths, cable impedance);
3) Spectrum analyzer part (model, supported frequency range, RF input front-end impedance, sweep points, supported resolution bandwidths, detectors, achievable sweep times for given frequency bands, RF attenuation and RF preamplification), sensitivity over different frequency ranges.

A summary of the key hardware characteristics of the measurement setups are given in Table I

Based on the information gathered, common measurement settings were carefully selected, to be:

1) Frequency span: for most sites 75 MHz–3 GHz with Krefeld, Constance and Hannover sites starting from 110 MHz.
2) Resolution bandwidth: 100 kHz which yields a good compromise between the time required to finish a sweep, the accumulated noise (that reduces sensitivity), the frequency resolution, and the typical channel bandwidths of the wireless technologies used at present.
3) Sweep points: this number was selected on the other hand to avoid gaps between the consecutive frequency bins, but also to limit the overlap between the bins. The maximum energy overlap for all the presented sets corresponds to 0.39 dB increase in the measured values only.
4) Detector: the RMS detector was selected as being most appropriate for energy measurements.
5) Cable losses: all the cable losses were measured in order to have accurate understanding of their impact on overall sensitivity.
6) Sensitivity: all spectrum analyzers were tuned to increase their sensitivity by enabling the internal amplifier. In all these spectrum analyzers the frequency specific gains are handled automatically by the device itself, so no more processing is needed to take into account those.

Common binary format was used at all sites for storing the measurement data. That format also included fields for keeping track of overloads and possible hardware failures (such as overloads in the IF or ADC stages of the spectrum analyzer). The overload status and the hardware status fields were checked during the processing of the measurement data, and if a problem was indicated the corresponding sweep was discarded. In the presented sets, the maximum number of dropped sweeps due to overloads was 0.1%.

### B. Time Domain Aspects

The measurements were started slightly before the midnight between 12th and 13th of October, and were stopped (as a minimum requirement) after the 14th of October, 23:59:59. The exact time period for analysis was selected afterwards during the processing part. The clocks at all measurement setups were synchronized with NTP time servers, which results in sufficient precision for type of time domain analysis targeted. All the cities correspond to the same time zone (UTC +1). During the processing phase the time consistency of the consecutive sweeps was also checked. The worst performance in terms of time needed to finish a sweep was 1.7 seconds, including the time period where a computer triggers the sweep to the spectrum analyzer, the spectrum analyzer finishes the sweep and returns the results back to the computer which saves those on the hard disk. In all sweep periods there is always a small drift (the worst observed was $\pm 200$ ms) which usually

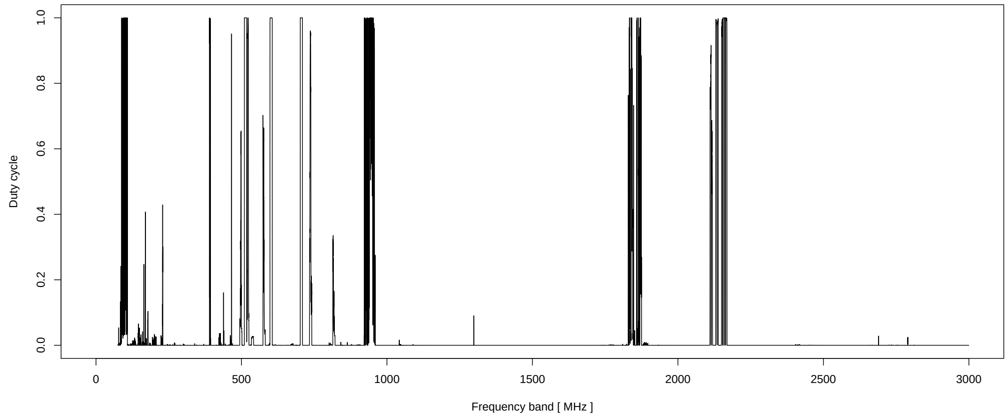


Fig. 2. Overall spectrum use in Aachen (13th-14th of October - Threshold -93 dBm/100 kHz).

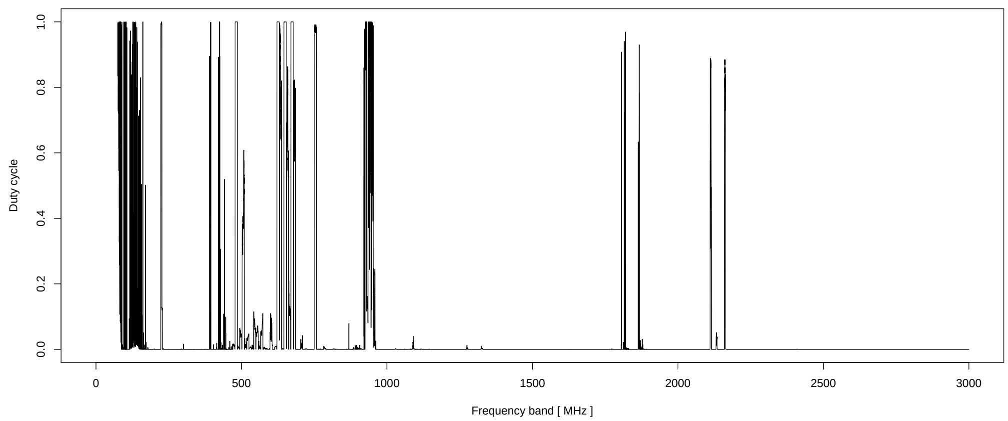


Fig. 3. Overall spectrum use in Leuven (13th-14th of October - Threshold -93 dBm/100 kHz).

is imposed by the operating system and the time a hard disk needs to move the head and write the data.

### C. Overall Sensitivity

The measurement setups have varying sensitivity levels for the different frequency bins (the sensitivity of a spectrum analyzer as well the cable losses are not constant over different frequencies). For assisting the processing of the data the overall sensitivity was calculated that refers to the worst case sensitivity over all the different measurement locations (the worst case sensitivity of a measurement setup being again used). From the information gathered, the value of -99 dBm/100 kHz was obtained. In reality the sensitivity is expected to be slightly less due to unforeseen extra losses one has to take into account, such as induced by cable connections. Because of this, an additional margin of 6 dB was added for most of the processing toolchain to take into account these extra losses.

## III. Results on Overall Spectrum Use

In this section we will report the results of the overall spectrum use for Aachen, Maastricht, Leuven and Skopje data sets (due to space reasons we omit the results from other German cities, focusing on comparisons across countries).

Figure 2 shows the overall spectrum occupancy as measured at the Aachen measurement location during the first day of measurements for the 2011 campaign. For computation of the duty cycle an energy detection threshold of -93 dBm/100 kHz was used, obtained based on the sensitivity of the measurement equipment as discussed above. Unless mentioned otherwise this is also the value, chosen based on the sensitivities of the equipments used by the different partners, that will used in the subsequent results. The figure shows very typical spectrum usage behavior observed in the measurements, and also what would be expected based on earlier measurement campaigns and the regulatory environment. The highest occupancy figures can be seen to correspond to narrowband services used at low

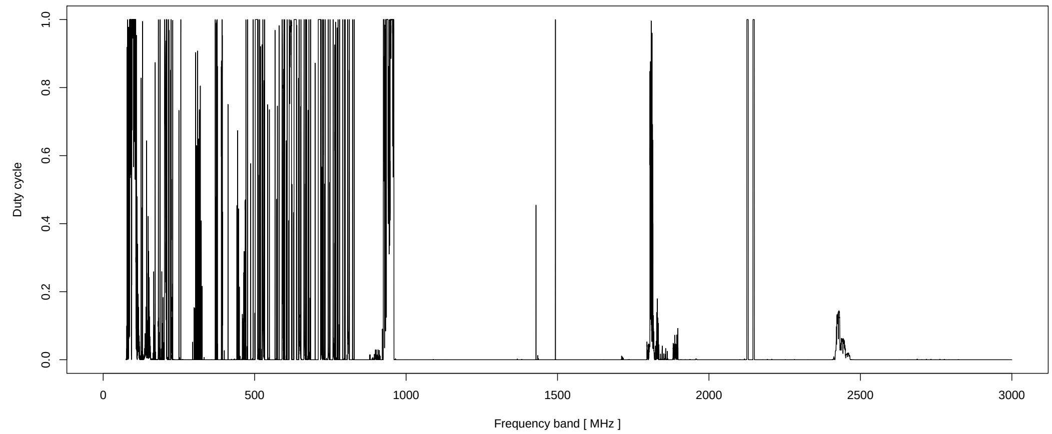


Fig. 4. Overall spectrum use in Skopje (13th-14th of October - Threshold -93 dBm/100 kHz).

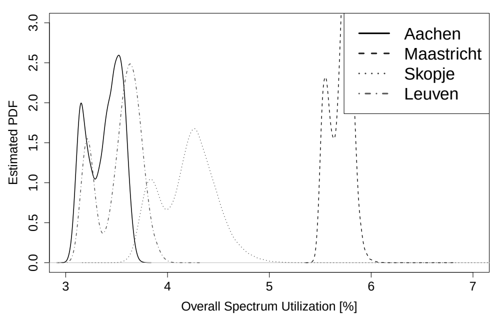


Fig. 5. Comparison of the overall usage of spectrum for four selected measurement sites on the Thursday 13th.

frequencies, terrestrial digital TV in the 470 MHz–790 MHz UHF band, and cellular systems operating on the 900 MHz, 1800 MHz and 2.1 GHz bands. Beyond these, hardly any significant use of spectrum can be seen at the Aachen location. Figure 3 illustrates similar overall spectrum occupancy figure for the case of Leuven measurement location. For higher frequencies very similar behavior compared to the Aachen case can be observed. For frequencies below the DVB-T UHF band slightly higher usage can be seen, and due to differences in the channels assigned to local DVB-T transmitters, the UHF band usage itself is naturally slightly different. Nevertheless, no major changes compared to the Aachen case can be seen at this level.

The situation at the Skopje location is, however, somewhat different. As can be seen from Figure 4, much higher usage of frequencies below 800 MHz was observed (due to large number of neighboring countries each operating their own TV broadcasting systems), and selected higher frequency bands that were almost completely unoccupied in the Aachen and Leuven cases have transmitters present in the Skopje data set. Skopje also has less utilization of UMTS frequencies which is possibly an indicator of slower network evolvement/penetration during the last years. These results emphasize the heterogeneity of Europe also in terms of spectrum regulations and usage, and also highlight the significantly different spectral environments that cognitive radios and systems based on dynamic spectrum access principles must be able to cope with.

Finally, Figure 5 shows the probability density comparison of the overall spectrum use, where the spectrum use refers to power values higher or equal to -93 dBm/100 kHz, for the four selected measurement sites. It is clear that in all cases there is significant underutilization of the available spectrum. The highest utilization is found for the Aachen city and is around 7 percent, in the most extreme case.

## IV. Spectrum use on Selected Bands

In this section we focus the analysis on specific bands, and especially on how the usage of specific wireless technologies differ over different time periods. Due to space reasons we limit our focus here on two time periods, consisting of the time intervals 08:00-15:59 and 00:00-07:59, respectively. We shall refer to these as “day” and “night” in the following. We start by looking the difference in GSM-900 downlink band for the Aachen and Skopje cases, results for which are given in Figures 6 and 7. In both cases the differences in activity between day and night time is easily visible. For the latter case we see that in the 940-948 MHz band the effects of the diurnal cycle are very clearly seen, whereas for the Aachen data set the differences are much more spread out across the entire band. Overall the band features complex dynamics in use, with very small amount of unused spectral resources remaining (however, this might also be due to the threshold used, which is higher than the sensitivity of a typical mobile phone transceiver). Note also that the difference between daytime use and nighttime use can be seen, but is

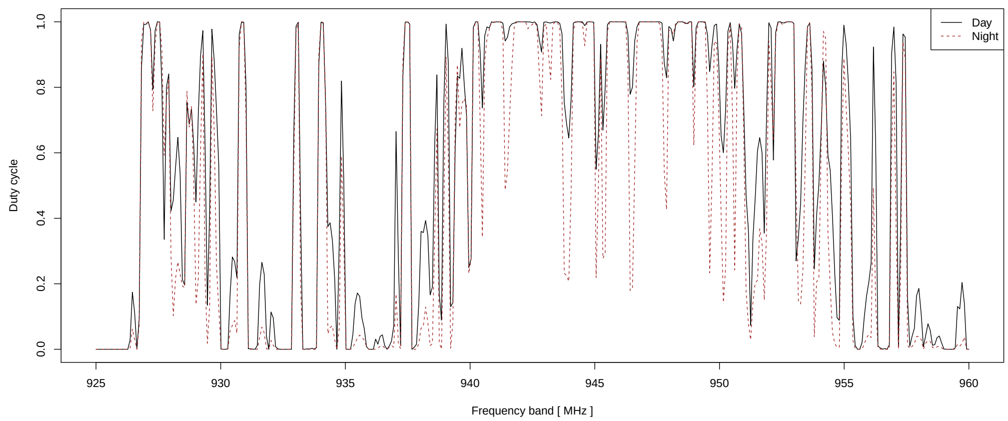


Fig. 6. Usage of the 900 MHz GSM downlink band in Aachen on Thursday the 13th. Day: 08:00-15:59, Night: 00:00-07:59.

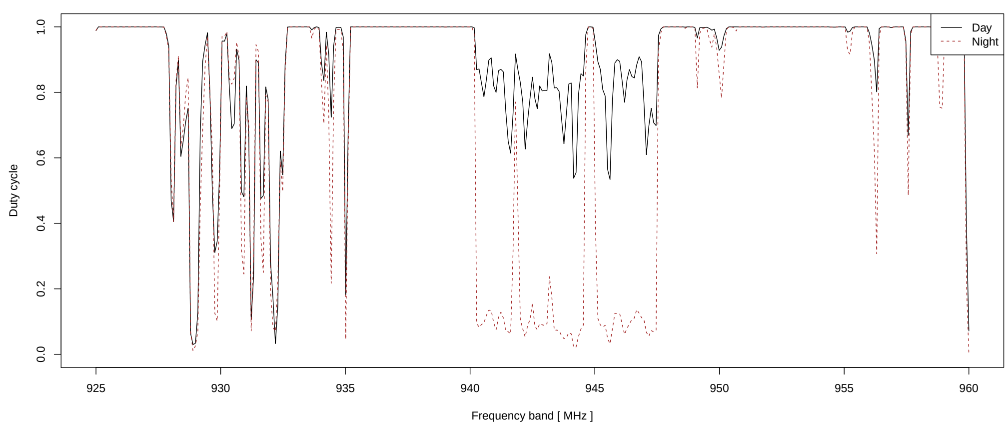


Fig. 7. Usage of the 900 MHz GSM downlink band in Skopje on Thursday the 13th. Day: 08:00-15:59, Night: 00:00-07:59.

not particularly significant except for few very narrow bands around 945 MHz.

Even though the 900 MHz band was very highly utilized at all measurement sites, interestingly the higher cellular bands at higher frequencies showed much greater degree of variability and unused frequencies. An example is given in Figure 8, showing the usage of the 2.1 GHz UMTS downlink band in Aachen. We see that 8 channels each 5 MHz wide are clearly in use. The results also provide an interesting example on how critical it is to interpret the duty cycle values correctly, as the duty cycle metric alone is not enough for interpreting the actual activity patterns of transmitters. The two channels between 2110 and 2120 MHz show less than 100% duty cycle and even visible amount of variation between day and nighttime results, even though UMTS Node B is transmitting continuously due to the CDMA nature of the technology and the presence of the broadcast channel. Therefore all the seen effects of the diurnal cycle and lower duty cycle are caused either by environmental effects, or power control by the Node Bs around the measurement locations which cause the received signal strength to fluctuate around the used threshold of -93 dBm/100 kHz.

We conclude this section by studying in more detail the distribution of the power spectral density values in the measurement data (13th and 14th of October), rather than the aggregate thresholded values the results given above have been based on. Figures 9 and 10 show the estimated probability density functions (PDFs) for the power spectral densities (PSDs) measured at various sites for the DVB-T UHF and GSM900 downlink bands. Due to the lower overall usage of the DVB-T band the PDFs are rather flat with the exception of the prominent peak at low PSD values. The latter arises mainly from the noise and residual interference in the system. The minor modes seen at higher PSD levels then correspond to actually used channels, but since major part of the UHF band in unoccupied especially in the central European data

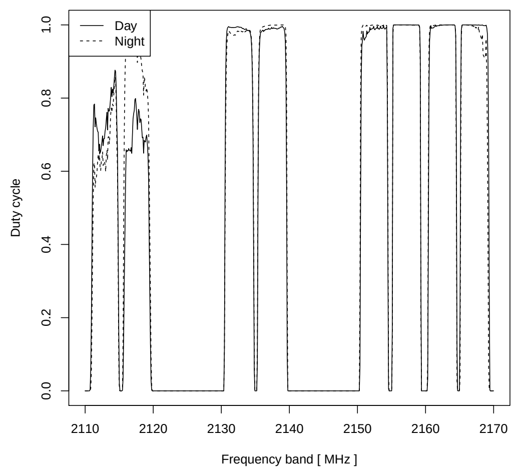


Fig. 8. Usage of the 2.1 GHz UMTS downlink band in Aachen on Thursday the 13th. Day: 08:00-15:59, Night: 00:00-07:59.

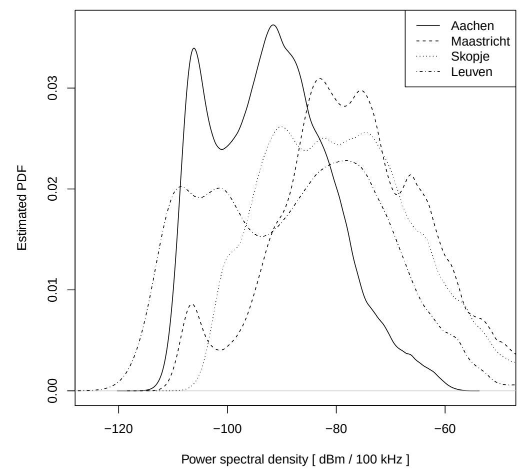


Fig. 10. Distribution of the received power for the 900 MHz GSM downlink band on the Thursday the 13th.

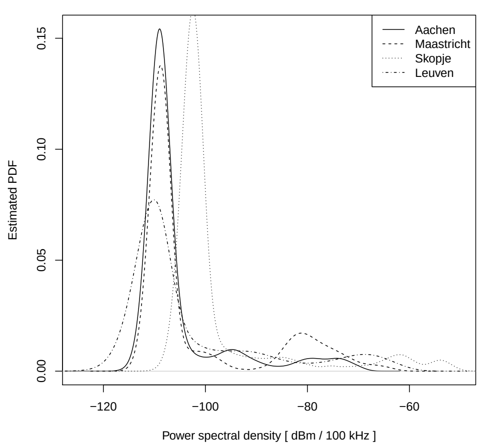


Fig. 9. Distribution of the received power for the 470–790 MHz UHF band on the Thursday the 13th.

sets, these are not as distinct as the peak due to the noise floor. The situation is very different for the highly occupied GSM900 downlink band. For most measurement locations the distributions are clearly multimodal, with the mode at lowest PSD values again corresponding to the noise floor, and other modes roughly corresponding to different base stations around be measurement location. From these results we can see how difficult it is to draw any conclusions on the usage of a band purely from aggregate statistics such as the PDFs, not to mention statistical characteristics of those.

## V. Conclusions

In this paper we have reported on spectrum use measurements carried out in seven European cities over the course of two days or more. The focus of these measurements was specifically on obtaining a data set that is as comparable as possible across the measurement sites, and special care was therefore placed on harmonizing measurement settings and equipment used. We also described in detail the measurement setup itself, and how the preparation work was coordinated across the measurement sites. We have also presented an initial analysis of the obtained data set. Our plan is to release the measurement data and more comprehensive analysis of it to the community by the end of 2012, in order to enable other research groups benefit from these measurements.

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## References

[1] M. A. McHenry, "NSF spectrum occupancy measurements project summary," Shared Spectrum Company, East Lansing, Michigan, Tech. Rep., August 2005.

[2] M. A. McHenry and D. McCloskey, "Multi-band, multi-location spectrum occupancy measurements," in *Proc. of International Symposium on Advanced Radio Technologies (ISART), Boulder, CO, USA*, March 2006.

[3] T. Harrold, R. Cepeda, and M. Beach, "Long-term measurements of spectrum occupancy characteristics," in *Proc. of IEEE DySPAN 2011*, May 2011, pp. 83 –89.

[4] T. Taher, R. Bacchus, K. Zdunek, and D. Roberson, "Long-term spectral occupancy findings in chicago," in *Proc. of IEEE DySPAN 2011*, May 2011, pp. 100 –107.

[5] M. Wellens, J. Riihijärvi, and P. Mahönen, "Evaluation of adaptive mac-layer sensing in realistic spectrum occupancy scenarios," in *Proc. of IEEE DySPAN 2011*, April 2010, pp. 1 –12.

[6] M. Wellens and P. Mahönen, "Lessons learned from an extensive spectrum occupancy measurement campaign and a stochastic duty cycle model," in *Proc. of TridentCom 2009*, April 2009, pp. 1 –9.