TR 5.1

COGNITIVE RADIO

Editor: Luis Moreno

Abstract

This document aims at the most flexible spectrum usage while allowing the widest possible ranges of uses and technologies. The aims is to define a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment and to dynamically adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives. This device has to learn from the results obtained subject to being satisfied that they will not cause harmful interference to incumbent radio services in this band.

This report define what is named Cognitive radio systems (CRS) in the 'white spaces' of the frequency band 470-790 MHz to ensure the protection of incumbent radio services.

This first part is mainly an technological study while in a second part using trials undertaken a more detailed explanation of the technique used are explained.

1 INTRODUCTION

'White Space' is a label indicating a part of the spectrum, which is available for a radio communication application (service, system) at a given time in a given geographical area on a non-interfering basis with regard to other services with a higher priority.

Cognitive radio system (CRS) is defined as a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state and to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives and to learn from the results obtained.

White space devices or CRS use sensing and/or geo-database [and/or beacon] in order to use White Space spectrum.

The foreseeing applications of CRS are many. One possibility is allow users the ease of installation and configuration of at home devices. The use of white spaces may enable access to high quality video services as well as sharing/navigation of content stored locally within the home or office. Another important category of device may be as an access point or base station, providing a gateway to the Internet.

Three techniques have been proposed to assist the white space devices in finding unoccupied channels.

With spectrum sensing, devices try to detect the presence of protected services in each of the potentially available channels. Spectrum sensing essentially involves conducting a measurement within a candidate channel, to determine whether any protected service is present. When a channel is determined to be vacant, sensing is typically applied to adjacent channels to determine what constraints there might be on transmission power, if any. Some channels may be excluded, because the occupying service is not amenable to protection by sensing.

In the Geo-location approach, cognitive devices measure their location and make use of a "geo-location" database to determine which channels they can use at their current location. They are unable to transmit until they have successfully determined from the database which channels, if any, are available in their location. In this case parameters such as location accuracy and frequency of database enquiry are important.

Finally the Beacons method uses signals which can be used to indicate that particular channels are in use by protected services. The use of beacons can ease the performance requirements on devices that use spectrum sensing, by increasing the likelihood of detection at higher threshold values. The interference protection provided to licensed users comes at a cost in spectrum capacity as well as the cost of purchasing and operating the beacons.

2 REQUIEREMENT

2.1 ESTIMATION OF WHITES SPACES

White spaces are available for a radiocommunication application (service, system) at a given time in a given geographical area with regard to other services with a higher priority on a national basis. On the second part of the project it is aimed to perform an estimation of white spaces. As we will see further in detail in next chapters a geolocalization database allows the receiver to detect wheter to transmit or not. One main objective of this project is to construct one or several geolocalization databases. This will allow us to analyse further in detail de actual spectrum. The database may have information related to position, threshold to transmit etc...

2.2 EMISSION PROTECTION

Many ways to protect signal are available but the most important thing to determine in all of them is the electric field.

The electric field strength available may not be a fixed value. The maximum allowable interfering field strength and received power are calculated according to some complex equations. The estimation of the amount of spectrum available as white space depends on several factors, as the White Space Device (WSD) characteristics, the topology of the area, the national rules governing the use of channels adjacent to those used by DTT, and many others. As some of these factors still have to be defined by national or international regulators, a possible approach to estimate the amount of white space is to make several assumptions whenever needed.

Estimation of the amount of spectrum potentially available for WSD depends on rather a geolocation database and/or sensing approach is adopted.

2.3 DESCRIPTION OF REGULATORY ISSUES

The main issue is how to protect licensed services from non-licensed services.

3 DESCRIPTION OF TECHNOLOGIES

The main idea under each of the following techniques are presented. In any case much further studies must be carried on, on let´s say real life or real world to have a more realistic approach.

3.1 OPERATIONAL AND TECHNICAL REQUIREMENTS FOR WHITE SPACE DEVICES IN THE BAND 470-790 MHZ

3.2 SENSING

This approach is based on listening for the signals from primary and other licensed services in the band before transmitting. The reliability of the spectrum sensing technique is defined by the detection threshold set in the cognitive radio device. The detection threshold of electric field strength available for transmitting is then the key point. This method allows for dynamics protection against interference. The device must be sensing in a continuously way while in other methods may not be necessary.

Key parameters for spectrum sensing include:

- The sensing threshold
- Periodicity of re-sensing on channels that have been detected as vacant
- Sampling duration

The sensing techniques used so far are LBT and DAA.

Sensing methods can be in general divided to two categories: energy detection and feature detection. The energy detection is to detect the signal power in the channel under study. The detector can be either wide band matching the channel bandwidth or narrow band with a possibility to slide it across the channel. Advantage of an energy detector is that it is independent of the radio system to be detected and as such future proof and capable of adapting to any new system introduced into the band. Disadvantage is low sensitivity due to the noise floor and possibility to false alarms. An energy detector alone is not a feasible solution, but can perhaps be used as one element in the detection process.

Feature detector is trying to use certain known characteristics of the signal that is to be detected. This may be some specific pilot carrier signal, preamble, continual or scattered pilots in OFDM signal, certain periodicity (GI) or sequence in the signal or in it's spectrum. Using these features will result in a processing gain, which will enable detection below the noise floor in the usual sense. Drawback in the feature detector is that it is dependent on the specific features and may have difficulties to adapt to any new radio system introduced later in the band. To some extent this may be solved by designing some flexibility to the detector.

3.3 GEOLOCATION

This approach is based on a database in order to determine which are the conditions for the WSD. The database must provide enough information for the device in order to start transmit. The threshold of electric field strength for transmission must be one of this information. The important or key points are that the receiver must know its location in a quite precisely and quickly way and secondly how accurate is the database. The database must be done in advanced by multiple measurement but must be also upgrade frequently with new subscribers.

They different method but one is the Ask-Before-Talk frequency scheme (WSD connects to database) the device can conveniently register their locations in the database. The question of how frequently the database should be updated, and how often WSD should query it is of great interest to study.

3.4 BEACON

Beacons method uses signals to indicate that particular channels are in use by protected services. The use of beacons can ease the performance requirements on devices that use spectrum sensing, by increasing the likelihood of detection at higher threshold values. The interference protection provided to licensed users comes at a cost in spectrum capacity as well as the cost of purchasing and operating the beacons.

There are different Beacon setups possible.

Enable beacon: If the beacon is detected, channel can be used. With enabling beacons, a network of beacon transmitters covering an entire country or region in which WSD are allowed to operate would be required. The devices would only function when they received authorization from one of these beacons. Each device would need to be fitted with a beacon receiver, and fine-grain control over individual devices would not be possible without a back-end database.

Disable beacon: If the beacon is detected; TV channel is occupied. The concept was based on enhancing detection of wireless microphones through the operation of low powered beacons to provide a “bubble of protection” in locations where PMSE equipment is in use.

Beacon as pilot channel: identifies locally used TV channels, i.e. local database. A single beacon operating in a locally unused TV channel where this beacon would carry a list of channels in use by all PMSE systems at that location.

Distributed geolocation database:
A transmitter network is used to distribute the information given in a database to regional transmitting ‘databases’.

3.5 COMBINED

The combination of different techniques like sensing and geo location database techniques may allow a cross checks of the information obtained by sensing techniques with a database and vice versa.

In the first case the distance from the DTT station and form the broadcasting coverage may be determined accurately and thus reduce

In the second case, sensing technique will complete the information of the users of the spectrum with the unlicensed users and thus protect the transmission.

4 PART II

For next deliverable version.

5 SENSING TECHNIQUES

5.1 Definition

5.2 Equipment

The following chapters are describing an experimental implementation of a sensing device in a mobile computer.

5.2.1 Spectrum sensor embedded to a mobile device

In order to conduct field tests using a device with realistic form factor a spectrum sensor was embedded into a Nokia N900 mobile computer with all functionalities. The choice caused some extra challenges since the N900 has not been designed for a mobile TV receiver. Spectrum sensor hardware has been designed on a separate printed circuit board (PCB) and it has been equipped with hardware which enables to receive desired frequency bands and realize all spectrum sensor functionality, see Figure 1. Figure 2 shows the two complete signal paths that have been implemented on the PCB from an antenna element to a FPGA. Two separate RF frontend chips were required: one for UHF frequencies and one for IEEE802.11a/b/g (2.4/5.8 GHz). The used RF receivers are commercial RFIC and they are controlled by the FPGA. The analogue baseband data is digitized for the FPGA using two dual 10 bit AD converters operating at maximum rate of 80 MHz, depending on the system under detection. Feature detector algorithms for spectrum sensing have been implemented on the FPGA.

Figure 1. The spectrum sensor detector board inside N900 mobile phone.

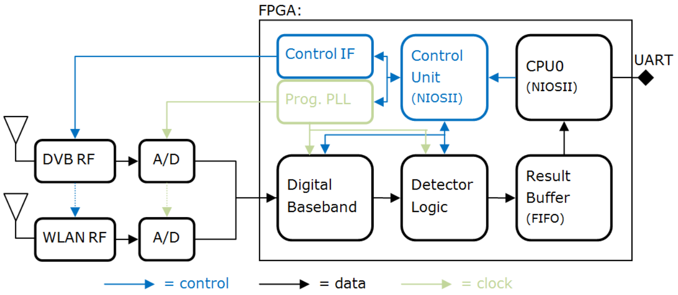

Figure 2. Blocks on the detector board.

Communication between sensor board and the mobile device is done using a universal asynchronous receiver/transmitter (UART). The data rate between the sensor board and mobile device is 1 Mbit/s.
The spectrum sensor board is located inside the display slider case of the device. A custom plastic riser, see Figure 3 was required between the display and the bottom of the case to allow sufficient space for the board. Sensor board is located just behind of the display and on top of the slider mechanic. The slider mechanic is made of metal, as is the background of the display element. To ensure sufficient antenna efficiency both antennas had to be placed to the fin of the plastic riser that is outside the metal frame. It should however be noted that this is only due to the fact that the device has not been designed for spectrum sensor use.
Antenna design, especially at UHF band, is the utmost challenge in a spectrum sensor design. Best efficiency can be achieved with external antennas but for consumer devices embedded antennas have become de facto solutions. Relative bandwidths of the both antennas, UHF and WLAN, are reasonably high. Size and the location of the antennas inside the mobile device limit their efficiency and matching as well as the surrounding mechanics. Sizes of the antennas has been tried to keep as small as possible without losing performance too much. Antenna miniaturization in a mobile device scale is more problematic for an UHF antenna due to its longer electrical (and physical) length compared to a WLAN antenna.

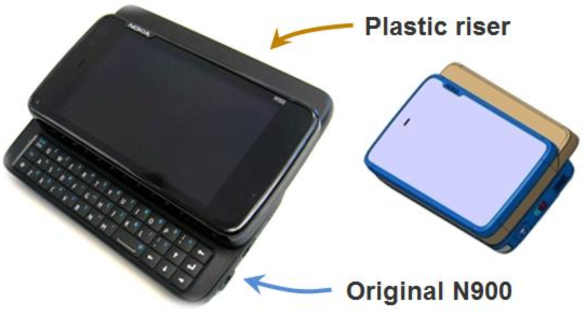

Figure 3. Spectrum sensor prototype implementation on N900 mobile phone.

5.2.2 System requirements related to spectrum sensing

Two very different kinds of target systems were addressed: DVB-T as an example of rather static TV primary system and 802.11a/g as an example of system having very dynamic traffic characteristics. Goal was to implement sensing strategy to measure both temporal and spectral characteristics of target systems. Another aspect was to measure spatial channel utilization in the field. We ended up in this phase to traditional channel numbering instead of generalized notation for cognitive radios in order to simplify control.
TV primary sensing requirement by FCC is -114 dBm sensitivity level averaged over a 6 MHz channel. This corresponds to -112.7 dBm averaged over a 8 MHz DVB-T channel. In order to measure UHF channel utilization, selected strategy is to make single detection per channel at each studied location. This requires quite low false alarm rate e.g. 1% and high probability of detection e.g. 99%. Excluding antenna losses, the sensor prototype presented in this work could reach these requirements with a sensing time of approximately

115 ms. However, for the longest detection time, i.e. 460ms, the headroom for antenna losses is only about 5dB.

In order to understand practical limitations of the platform and analyze filed test properly the prototype and its core entities were characterized both separately and as a complete system.

5.2.3 Antenna

Two antennas were implemented inside the presented mobile spectrum sensing device. For UHF frequencies a commercial antenna based on planar technology has been used. Dimensions of the antenna are 45 mm x 5 mm and it has been designed to work at frequency range from 470 to 750 MHz (DVB-H EU). Antenna for 802.11a/b/g has been realized as a wideband structure which covers frequency range from 2 to 6 GHz. It has been implemented directly to the same PCB than the spectrum sensor. It requires slightly more area than the UHF antenna (32 mm x 8 mm).

Both antennas were measured with and without the device mechanics to understand differences compared to conventional stand-alone antenna testing, and to evaluate actual performance in the field. Measurement results for the UHF antenna are presented in Figure 4 (left) and wideband antenna in Figure 4 (right). Deterioration of the efficiency of the UHF antenna due to mechanics is significant (6-8 dB) at low frequencies. The wideband antenna behaves better and its efficiency deterioration due to mechanics is only 1-2 dB over the whole band. The efficiencies of the antennas are -18-(-7)/-3/-6-(-4) dBs at UHF/2.4/5 GHz bands, respectively, depending on the specific channel. The results clearly indicate the issue of antenna performance at UHF band in small devices.

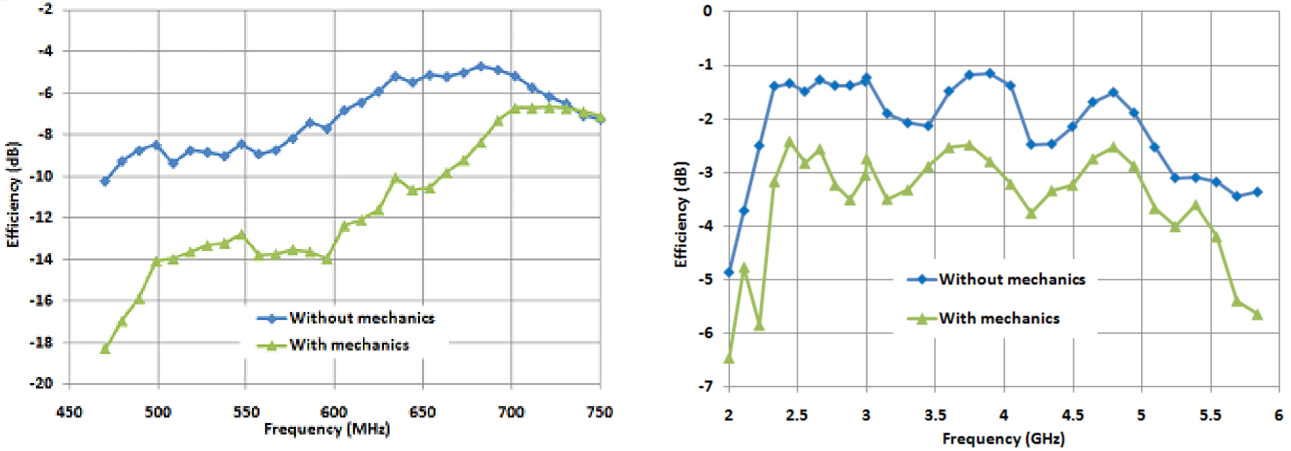

Figure 4. Efficiency of the UHF antenna (left) and for comparison the WLAN-antenna (right).

5.2.4 RF-parts

The used RF receivers are commercial RFIC and they are based on a direct-conversion architecture. Baseband filters are adjustable and they support several bandwidths used in different standards. Block diagrams of the receivers are presented in Figure 5. Typical noise figure (NF) of all receivers without front-end filter is around 4 dB depending on the band. Typical insertion-losses of front-end filter are 1.8 dB at UHF/2.4 GHz bands and 1.4 dB at 5 GHz band.

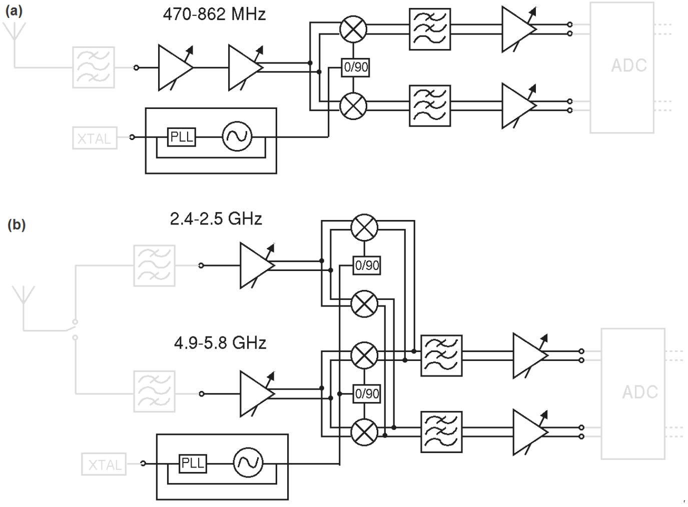

Figure 5. Block diagram of the UHF (a) and 802.11 a/b/g (b) receiver.

5.2.5 Detector

Detector core on the FPGA is developed from the FFT-based cyclostationary feature detector formerly presented by the authors in [1]. The structure of the detector is shown in Figure 6. The fixed-size-FFT implementation utilizes decimation after autocorrelation to control the detection time. Test for the presence of cyclostationary at given cyclic frequency (α) is performed from the FFT of the decimated autocorrelation signal.

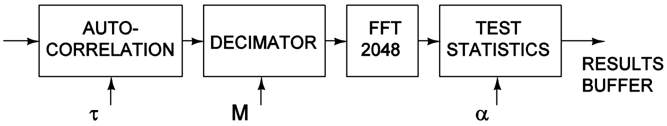

Figure 6. Structure of the implemented cyclostationary feature detector.

In this implementation, the range of selectable decimation ratios is extended up to M=2048 to support longer detection times. Similarly, the maximum autocorrelation delay (τmax) is increased to 8192. The modifications were required to enable detection of very long OFDM symbols used in DVB-T signals. The detector implementation utilizes 16k logic elements, 406k memory bits and 84 9-bit multiplier elements. The figures are 10.2%, 13.7% and 14.6% of all available resources on the FPGA, accordingly.

Detector sensitivity was measured for a WLAN signal at 2.4 GHz ISM band and for a DVB-T signal at the UHF band. Parameters related to modulation, signal bandwidth and transmit frequency of both systems are summarized in Table 1. During the measurements, the antennas were bypassed and the signal generator was connected directly to the RF receiver inputs, therefore the results exclude any antenna effects. The RF receivers operate at maximum gain. Detection times for WLAN and DVB-T were set to 0.8 ms and 460ms, accordingly. False alarm rate is 5%.

Table 1. Specifications of the primary signals used in detector performance measurements.

	WLAN	**DVB-T**
Modulation:	OFDM	OFDM
FFT-size (N_{FFT})	64	8192
Length of cyclic prefix (N_{CP})	16	1024
No. of non-zero subcarriers	52	6817
Subcarrier modulation	16-QAM	16-QAM
Transmit frequency	2437 MHz	670 MHz
Bandwidth	20 MHz	8 MHz

The measured sensitivities are presented in Figure 7 (left) for DVB-T and in Figure 7 (right) for WLAN signal. DVB-T detection reaches 95% probability of detection when the received power is about -117 dBm, while for the WLAN detection received power of -102 dBm is required. Both figures are below the thermal noise floor. Figure 7also show ideal simulation results for the same signals. The differences between simulated and measured probability of detections almost entirely match and are accounted by the non-zero noise figures of the RF receivers. The primary reason that DVB-T detection outperforms WLAN detection by such a large margin is the longer detection time that can be utilized in DVB-T detection. WLAN detection time is limited on the other hand by implementation, where larger FFT would be required to keep the cyclic frequency under the Nyquist frequency for larger decimation ratios, and on the other hand by duration of WLAN signal bursts which is already on the same scale with the detection time.

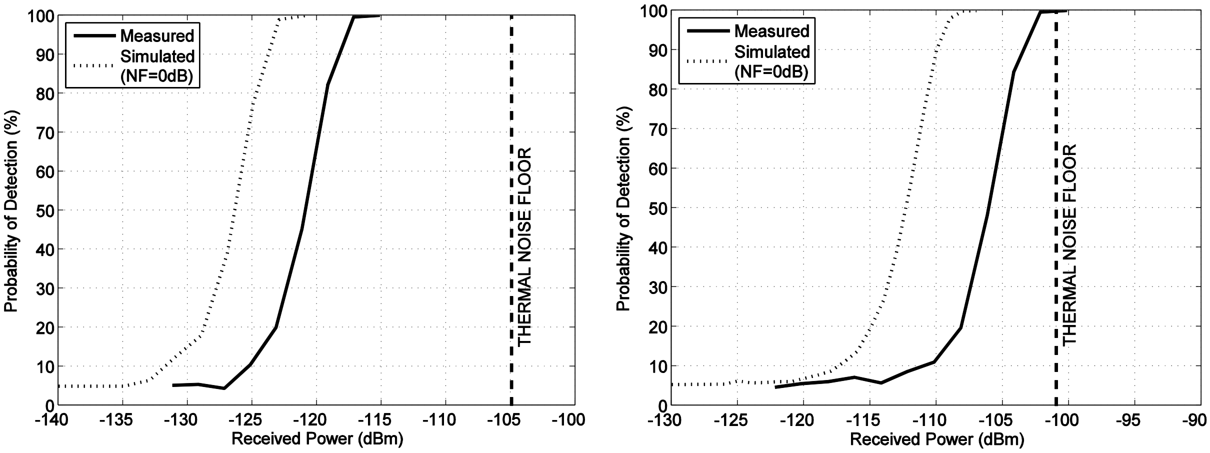

Figure 7. Measured DVB-T (left) and WLAN (right) probability of detection compared to simulated performance. Simulation utilizes ideal receiver (NF=0dB).

5.2.6 Platform Performance

Overall performance for the spectrum sensor hardware has been determined in the laboratory measurements. A 5 dB NF for UHF receiver path was measured at 660 MHz and it is only 1 dB more than NF of the pure UHF receiver. For dual-band 802.11a/b/g receiver, 5 dB and 6.5 dB NF at 2.427 and 5.130 GHz were measured, respectively. IIP3 of –10 dBm, -1 dBm and -1 dBm were measured for UHF, 2.4 and 5 GHz bands, respectively.

When combined with antenna results the overall sensitivity of the signal detection for DVB-T signals at UHF band will be from –100 to –108 dBm depending on the channel of interest. This is significantly higher than FCC requirements but shows feasible values for small devices if the integration time of the detection is kept reasonable. IIP3 of the UHF receiver with antenna corresponds 8 - (-3) dBm compared to 0 dB antenna in the field tests, At some channels platform noise caused by processors and other noisy components in the device will further deteriorate the performance. However, those could be mostly avoided with proper design when UHF band requirements will be taken into account initially in the design of the device and its mechanics. For WLAN OFDM signal detection, the sensitivities using parameters given earlier in this paper will be –101 and –98 dBm (2.4 /5 GHz) including the antenna.

5.3 Measurements

Two sets of field tests were carried out in capital area in Finland using the device described in 5.2. First measurement set was done mostly outdoors in urban Ruoholahti area in Helsinki. Two sensors were used, both using internal antennas. The measurement set consists of spectral samples from 37 different locations, shown in Figure 8. One spectral sample includes detection time, GPS location, band, channel, received signal strength in dBm and DVB-T detection statistics from UHF channels 34 to 60 (578 – 784 MHz). Detection time was set to 460 ms and detection statistics positive detection threshold to produce constant false alarm rate of 1%. Measured signal strengths are shown in Figure 9. Corresponding estimated probabilities of DVB-T detections on different channels are shown in Figure 10. There is DVB-H repeater in the area, detected on channel 35. Espoo TV transmitter station is transmitting on channels 32, 35, 44, 46, and 53.

Table 2. DVB-T transmitter parameters.

DVB-T transmitters	Espoo	Tallinn
Latitude:	60.1778	59.4713
Lognitude:	24.6403	24.8875
Mast heigth:	313 m	272 m
Transmission power:	47 dBm	42 dBm
Occupied channels	32, 35, 44, 46, 53	45, 59, 64

TV transmissions on measurement range are detected with high probability. Channel 59 is occupied by Tallinn TV transmitter on average 78 km away. Open source Splat! [2] radio propagation calculation tool, using Longley-Rice Irregular Terrain Model [3] and NASA SRTM-3 Version 2 Elevation Models [4], was used for field strength estimation. Used transmitter parameters are shown in Table 2. , receiver was assumed to be 3m above sea surface. Estimated field strength, shown in Figure 11. in Ruoholahti area is 20-60 dBµV/m. Field strength has large variation within 1 km radius in urban area. With measured prototype antenna efficiency of -7.5 dB, it corresponds -123 – (-83) dBm signal input power at the receiver. Taking measured detector sensitivity into account we end up 0.6 to 1 detection probability of Tallinn TV transmitter in Ruoholahti, Helsinki. Tallinn transmission on channel 45, adjacent to much stronger Espoo TV transmitter on channel 44 and 46, is masked and it cannot be detected. One must remember that transmissions from Tallinn are out of the reach for typical TV reception setups in Helsinki households.

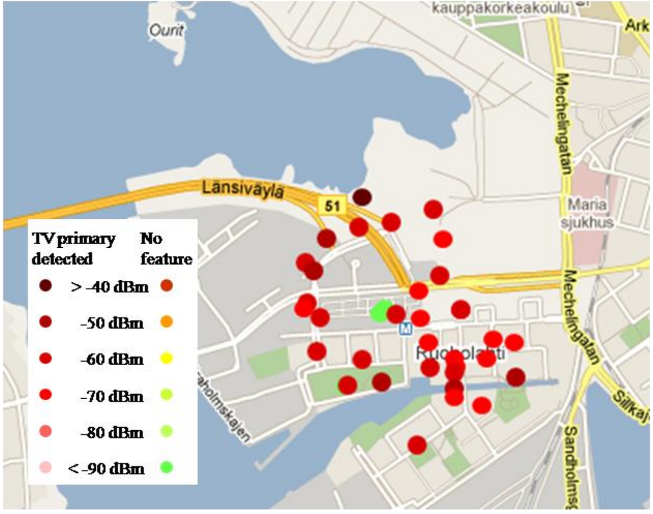

Figure 8. Measurements results on UHF channel 44 (658 MHz) in Ruoholahti, Helsinki.

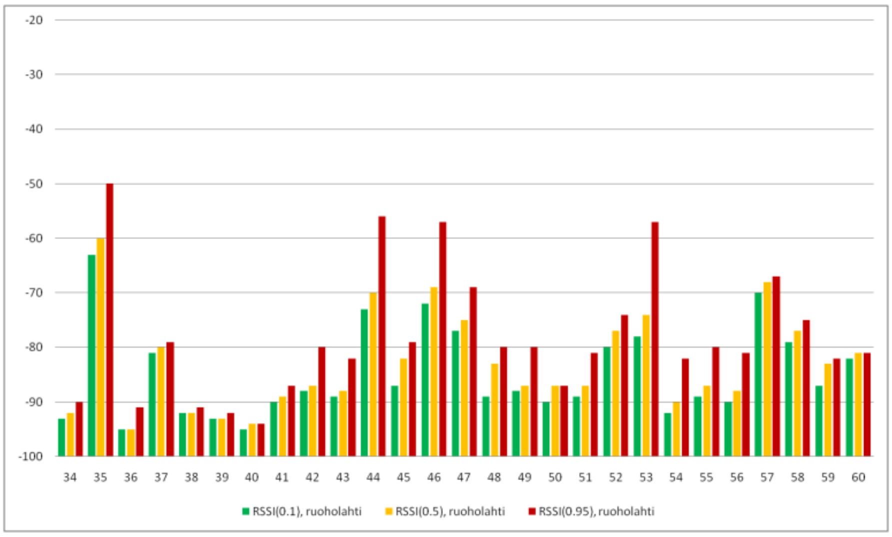

Figure 9. Received signal strength (RSSI[dBm]) upper limit for 10%, 50% and 95% of measured samples in Ruoholahti.

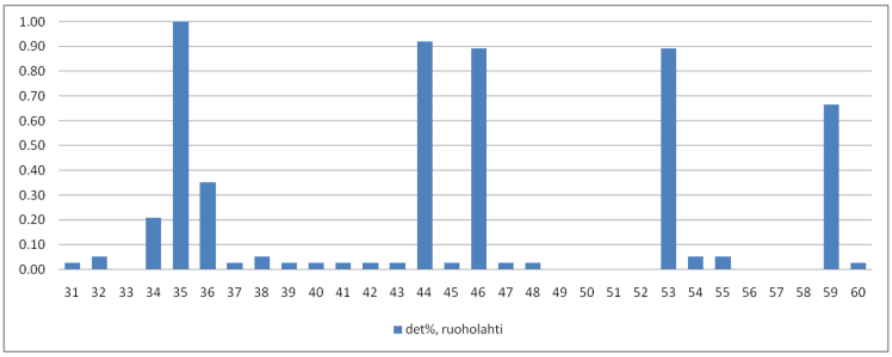

Figure 10. Measured probability of DVB-T detection, n = 37 per UHF channel, average distance to Espoo transmitter 15 km and 78 km to Tallinn transmitter.

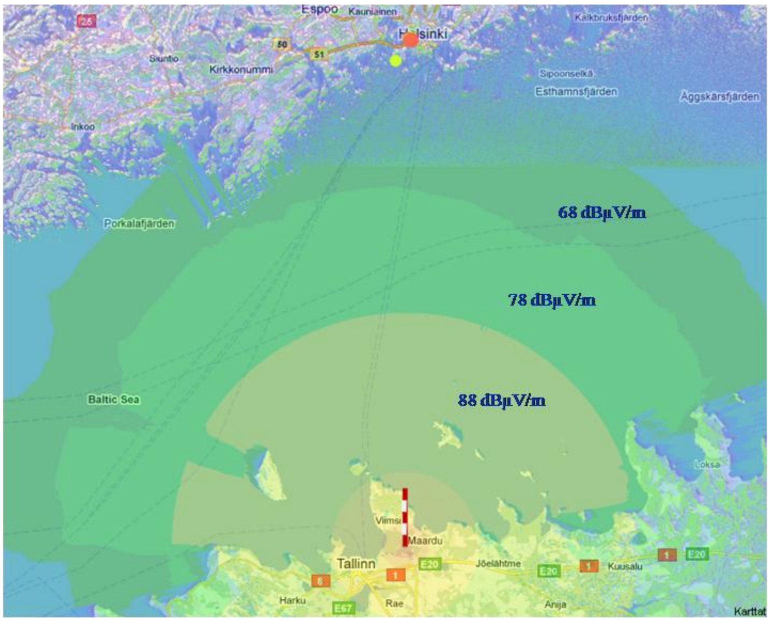

Figure 11. Simulated field strengths on UHF channel 59 (778 MHz) from Tallinn TV tower, distance to Helsinki 77 km.

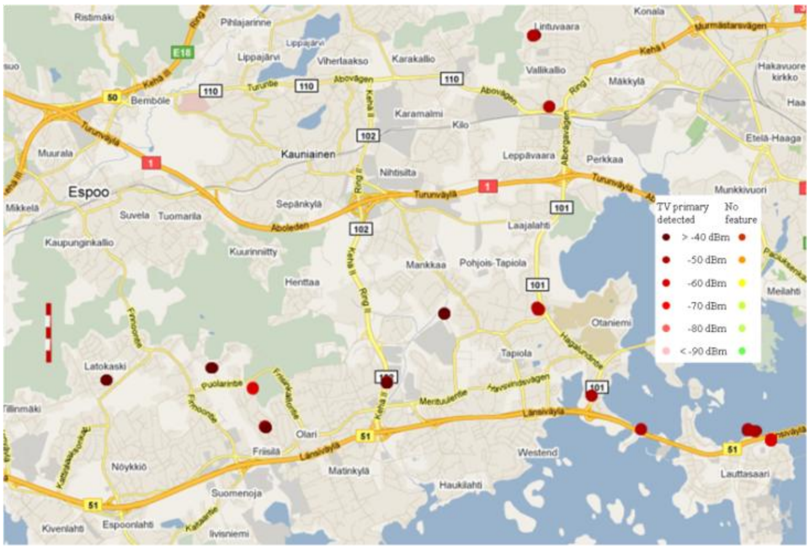

Figure 12. Results on UHF channel 44 (658 MHz) in Espoo, average distance to Espoo TV tower is 8 km.

Second set was measured outdoors in suburban Espoo and target was to evaluate performance of the spectrum sensor in the vicinity of strong TV transmitter. Measurements were done using two sensors one with internal antenna and another with external reference dipole. Measurement locations and results for occupied channel 44 (658 MHz) are shown in Figure 12. Measured signal power on occupied channels was from -65 dBm up to -32 dBm, when using external reference dipole, as shown in Figure 13. The RSSI[dBm] limits tell how many percent of measurement samples have smaller RSSI value than presented. Basically this presents values of observed cumulative distribution function with 10%, 50% and 95% probabilities. TV signal strength is from 10 to 30 dB more than in the Helsinki measurement set. Main difference between results measured using internal and external antennas is that antenna efficiency of internal antenna is on average 7.5 dB lower than external reference dipole. Results using internal antenna are shown in Figure 14. Difference in antenna efficiency means additional noise figure of 7.5 dB, which decreases sensitivity and increases linearity of receiver. In addition there is also device induced noise in internal antenna measurements.

Figure 15 shows the detection results over all channels with external and internal antennas. The antenna performance difference is very clear. Overall it can be seen that a high number of false detections happen due to the IM-products. There is also clear tradeoff between sensitivity and linearity. This is evident with the lower false alarm rate of the internal (lower gain, less signal power) antenna.

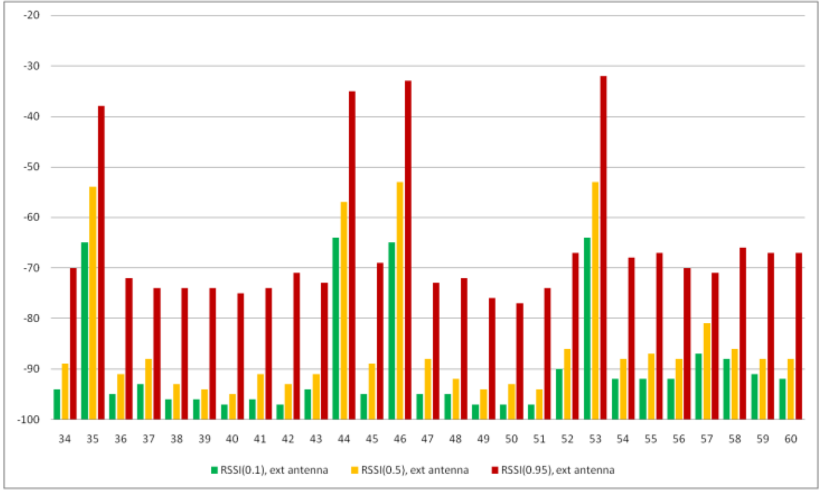

Figure 13. Received signal strength (RSSI[dBm]) with external antenna, upper limit for 10%, 50% and 95% of measured samples in Espoo.

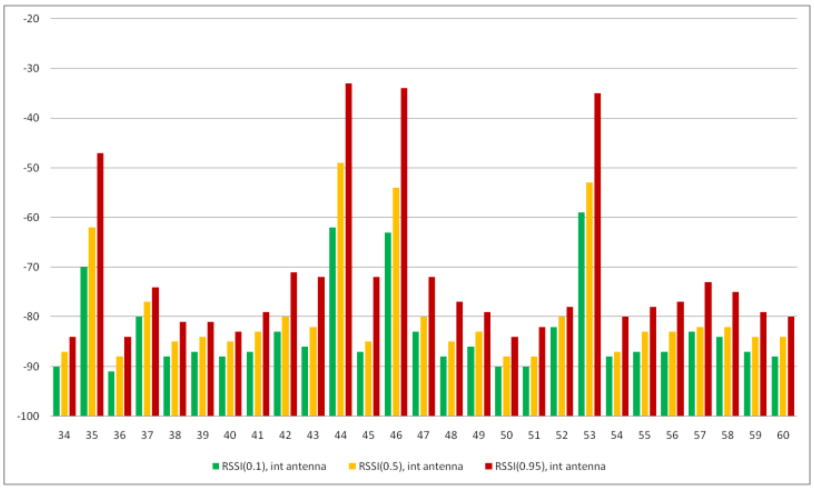

Figure 14. Received signal strength (RSSI[dBm]) with internal antenna, upper limit for 10%, 50% and 95% of measured samples in Espoo.

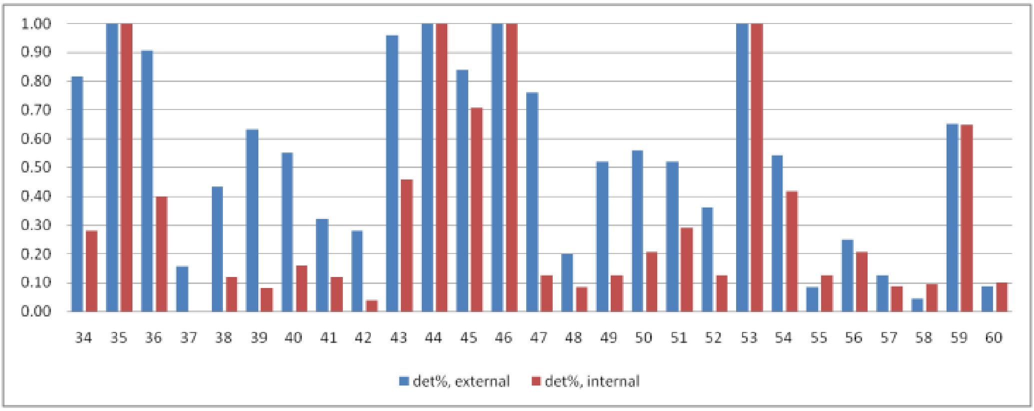

Figure 15. Measured probability of DVB detection, number of detections is 26 per channel, average distance to Espoo transmitter 9km and 78 km to Tallinn transmitter.

5.3.1 Conclusions

A practical spectrum sensor has been implemented in a mobile device. Key performance tradeoffs have been shown in the laboratory tests and functionality proven in the field with TV-signals. The key challenge is antenna integration and the strictest sensing requirements cannot be met using a single device and especially single shot decisions. However by collecting more samples, position information and combining the results from several devices better results could be expected.

Single device single snapshot detection is too unreliable due antenna gain minima, interference, and fading to protect primary users. Just tightening of sensitivity requirement does not help, because IM-products cause desensitization, masking, and false alarms, thus reducing available capacity for secondary users. Methods like geo location databases have to be used for reliable operation. Collaborative sensing averages antenna gain and radio propagation problem. However presented trade-offs between sensitivity in sensor linearity requirement and sensitivity has to be taken into account in algorithm development.

6 GEOLOCATION TECHNIQUES

6.1 Definition

6.2 Equipment

6.3 Measurements

7 BEACONS TECHNIQUES

7.1 Definition of a possible network

7.2 Topology and Network

7.3 Measurements

8 USING LTE WITH RADIO COGNITIVE

For next deliverable version.

8.1 LTE Device

8.2 LTE Interference

9 SERVICE DEFINITION

10 REFERENCES

[1] SE43 Technical and operational requirements for the possible operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz.

[2]