

# Development of a Software Defined Radio (SDR) for Cognitive Radio (CR) Communication Systems

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**Abstract**— The VHF band is the first choice for the majority of maritime communications because of its affordability, reliability, ease of use and an adequate effective range (up to 30 nautical miles), but expensive satellite links are typically used for all digital communications. However, future navigation and monitoring technologies, such as e-navigation and require high speed (broadband) communication systems, while maintaining affordability. This paper describes the implementation of a prototype cognitive radio communication system, based on software defined radio technology, for opportunistic usage of vacant VHF maritime bands. The implementation focuses three essential components: spectrum sensing (a multichannel energy detector), radio transceiver (which uses non contiguous Orthogonal Frequency Division Multiplexing multicarrier modulation) and a cognitive engine. The implementation uses GNU Radio and Universal Software Radio Peripheral as software tools. The prototype is validated in laboratorial and simulation tests, where it is demonstrated that the system is capable of detecting incumbent user activity and to use vacant spectrum bands without interfering with incumbent users.

**Keywords** — *Cognitive Radio, GNU Radio, NC-OFDM, Software Defined Radio, USRP*

## I. INTRODUCTION

Existing maritime data communication systems are reduced to a small group of options. On the low HF and MF bands, there are some military and amateur digital modes, as well as the well know Navigation Telex (NAVTEX). However, these are mostly dedicated narrowband systems that are not suitable for general purpose communication links. On the VHF band, which is typically the first choice for most line of sight and coastal communications, we have the Automatic Identification System (AIS) and the Digital Selective Calling (DSC). Again, these are application-specific systems (the firsts is for automatic positioning and the second is a paging system for distress alerts and short messaging), that cannot be used for generic data communications. As for terrestrial based communication systems (GSM, UMTS and LTE), since their networks typically don't cover maritime areas, cannot be considered an option for maritime data communications.

On the other hand, SATCOM (Satellite Communications) offers broadband multipurpose data services. With an almost global coverage, it's very reliable and effective, but its installation, maintenance and operating costs are very high (especially for small applications). Furthermore, the overall cost per megabyte of data for SATCOM systems is not expected to decrease, due to the cost of launching and operating satellites and ground control stations. Moreover, SATCOM links are still restricted to few hundreds of kbits per second (at best, a few Mbits per second), which can be a limiting factor for some applications.

The International Maritime Organization (IMO), has been promoting a new concept termed e-navigation (electronic navigation). E-navigation technology will harmonize, integrate and enhance information from legacy and modern navigation systems, improving safety and security in commercial shipping through better organization and exchange of data between ships and shore [1]. However, such complex information systems require more bandwidth and a network infrastructure, which is not currently available, at least for an acceptable cost.

Cognitive radios have been proposed as a solution to overcome spectrum congestion (as a result of static frequency allocation schemes) with a new spectrum utilization paradigm [2, 3], enabling opportunistic use of underutilized bands that are not heavily occupied by licensed users (the case of the VHF maritime band). One of the most prominent cases is the analogue TV switch-off and spectrum refarming [4]— these spectrum opportunities are often called TV white spaces (TVWS). As a matter of fact, regulatory authorities, such as the Federal Communications Commission (FCC), have been developing regulatory efforts to promote and facilitate spectrum usage, allowing operation in the broadcast television spectrum at locations where that spectrum is not being used [5, 6]. Therefore, cognitive radios are a possible solution for future VHF broadband data communications (B-VHF).

There are few works addressing complete cognitive radio implementations. There are various efforts and frameworks working on cognitive radio technology, but most of them are focused in particular sub areas of knowledge, such as, spectrum sensing techniques [7] or radio transceiver techniques [8, 9]. The IEEE 802.22 standard is probably the most complete cognitive radio standardization effort, but it was designed to operate in the TVWS [10] only. In [11], a prototype cognitive radio implementation uses IEEE 802.11 wireless LAN technology, which limits its utilization to the 2.4GHz ISM band. Moreover, the primary user – secondary user scenario is not applicable for the maritime environment.

This paper proposes a cognitive radio solution for new broadband maritime communication systems, taking advantage of vacant VHF bands. VHF incumbent users are detected using spectrum sensing techniques, and then convenient transceiver techniques are used to access those spectrum bands without interfering with incumbent users. Software defined radio technology was used for the implementation because is a proven technology in the communications field [12, 13], and is suitable for flexible and customizable applications.

This paper is organized as follows. Section II provides an overview on cognitive radio technology and how it can seize spectrum opportunities. Section III describes the proposed solution and how the cognitive radio is implemented using

software defined radios. In section IV the prototype cognitive radio is tested and its capabilities demonstrated. Section V is dedicated to conclusions and future work.

## II. COGNITIVE RADIO TECHNOLOGY

The cognitive radio concept was originally proposed by Mitola [3], and since then has been suggested as a possible solution to improve spectrum efficiency [2, 3, 14]. Mitola coined the concept of cognitive radio, bearing in mind that a special type of radio would be up to that task: the software defined radio (SDR). In a dynamic spectrum access (DSA) context, a cognitive radio uses its self awareness and learning capabilities to determine in what conditions the radio spectrum can be accessed [2]. The cognition cycle typically starts with a sensing activity, where spectrum holes are detected. Then, radio scene analysis enables transceiver reconfiguration and continuous learning.

After gathering knowledge on radio spectrum activity, the CR should produce transceiver configuration settings, considering spectrum policies and other sources of information in the decision process. Since the transceiver settings may dynamically change over time, in a network context, all cognitive nodes must be aware of the current settings (the process described in this paper by network synchronization). This series of dependent events is typically coordinated by a management authority, the cognitive engine.

Cognitive radios can be a solution for opportunistic usage of VHF maritime bands. The VHF maritime spectrum is not heavily used by incumbent users, which frequently leads to the existence of spectrum holes, which can be detected and used by secondary cognitive users in an opportunistic basis.

### A. Dynamic Spectrum Access

Dynamic Spectrum Access (DSA) is the generic designation created to address a set of techniques that compose agile and spectrum aware radios. DSA radios utilize the radio spectrum in a dynamic manner, rather than in a fixed approach.

A simple example of a DSA capable system, without cognitive capabilities, is the Digital Enhanced Cordless Telecommunications (DECT<sup>TM</sup>). DECT cordless phones dynamically select vacant channels based on a spectrum measurement [15], which is the simplest form of DSA. Opportunistic spectrum usage is the act of accessing locally / temporally unused spectrum bands that are legally assigned to rightful users – primary users (PU) – by users that do not own the conventional rights to that spectrum - secondary users (SU). As a matter of fact, according to Mitola's work [3], a CR is much more than a DSA device, since it can learn from the environment and adapt behaviors based on observations and previous knowledge.

DSA covers several knowledge areas, including spectrum sensing (detection of radio signals), spectrum shaping (transmitting waveforms and modulations) or network synchronization (dissemination of available spectrum and channel assignment).

### B. Spectrum Sensing

Being aware of the surrounding environment is the first task performed by any cognitive system. For this reason, spectrum sensing is by far the most important component of a cognitive radio application. Spectrum sensing is the process of

detecting primary user activity and determining if the licensed spectrum can be accessed.

The effectiveness of a spectrum sensing framework depends on a number of aspects, such as sensing duration, PU signal strength (signal to noise ratio), previous knowledge about PU features or channel propagation effects. Depending on the application, there is a typical trade-off between speed and accuracy, both critical aspects of spectrum sensing [7].

Network nodes may contribute to a sensing database, with an authority that audits all sensing operations. This type of centralized sensing can also be considered as cooperative sensing, since all network nodes contribute to an enhanced radio picture.

The energy detector (a noise dependent technique) compares the channel energy with a metric that depends on the noise level (decision threshold) to decide if the channel is occupied or not. This technique is a common approach to spectrum sensing since it has low computational complexity [4] and can be implemented in both time and frequency domain. Feature detection techniques require previous knowledge about PU signals and noise. These techniques have the ability to distinguish between different types of signals and high resilience to noise uncertainty [4], but signals must be individually demodulated and analyzed. Blind detection techniques also suffer from the same drawback. Although they seem to be very effective in very low SNR environments [16], they also require channelization and individual analysis.

### C. Spectrum Shaping and Transceiver Techniques

The simplest form of spectrum access consists of utilizing a secondary service that uses the same bandwidth as PU services (the typical case in TVWS). However, for the VHF maritime case, that is not convenient since PU's usually transmit narrowband signals, and the contiguous vacant bands are not wide enough for broadband signals. In Fig. 2.1, five spectrum holes are available, but the largest one is only 120 kHz wide, which is not much bandwidth for a digital communication system.

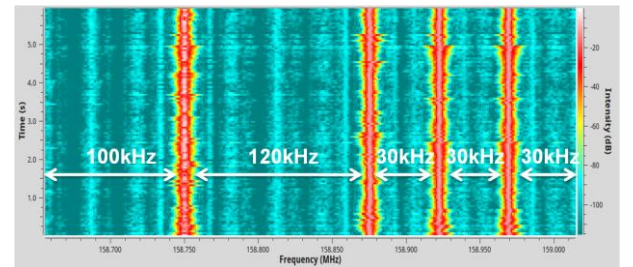


Fig. 2.1 - Spectrogram (time-frequency) plot of PU activity and spectrum opportunities.

Aggregating all five spectrum holes results in 310 kHz of usable bandwidth, which indicates that sub-band aggregation is the path to achieve broadband VHF communications (B-VHF). Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme has been proposed as a possible solution for the aggregation of non-contiguous spectrum bands [8, 9]. Since OFDM sub-carriers are individually assigned and modulated, sub-carriers that superpose PU signals can be turned off, thus achieving some sort of spectrum shaping. This spectrum shaping concept, which can be used as a spectrum

pooling scheme, is often named non-contiguous OFDM (NC-OFDM) (Fig. 2.2).

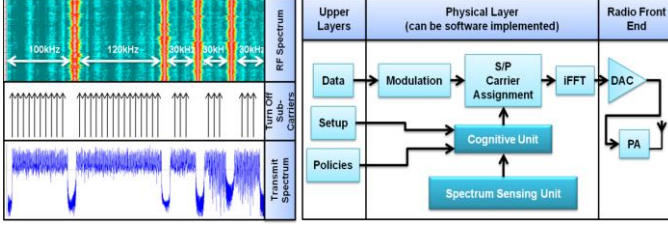


Fig. 2.2 - Basic spectrum shaping using OFDM sub-carrier assignment.

Nevertheless, OFDM systems have some limitations and drawbacks. OFDM suffers from relatively high peak-to-average power ratio (PAPR) and, if not properly contained, high out-of-band (OOB) radiation [17, 18]. NC-OFDM will also suffer from relatively high non-contiguous radiation (for the same reason that has high OOB radiation) [17, 19].

NC-OFDM is easily implemented in software, and GNU Radio already offers a set of tools that facilitate its implementation. In order to use this technique, proper synchronization between transmitters and receivers must also be implemented, assuring both ends use the same settings (sub-carrier allocation, carrier frequency, etc.). Further investigation on both undesired radiation and high PAPR is also provided.

### III. PROPOSED SOLUTION

The reconfigurability characteristics of cognitive radios are easily achieved with software defined radios. GNU Radio is a digital signal processing software toolkit suitable for very fast, real time signal processing. Together with the USRP peripheral, which is a radio frequency digitizer and transceiver, cognitive radio systems can be easily prototyped.

The Maritime Mobile Service (MMS) is a licensed service for the 156 MHz to 174 MHz band, where radio channels are statically allocated and equitably used by PU's. Since VHF systems are used mostly in near shore communications, the B-VHF system can be cellular based, where coastal fixed stations can be gateways to land based fixed networks, as well as base stations (managing sensing activities, network resources and synchronization). This architecture simplifies resource management and network synchronization.

Implementing cutting edge sensing or transceiver techniques or developing new cognitive learning mechanisms is out of the scope of this implementation. Regulatory issues regarding secondary usage of allocated radio spectrum will not be addressed as well.

#### A. Opportunistic Usage of the VHF Maritime Band

MMS PU equipment follows International Telecommunication Union (ITU) recommendations, and the exact spectrum allocation depends on local spectrum management authorities. The most common MMS services are the analogue telephony (Fig. 3.1), DSC (Fig. 3.2) and AIS (Fig. 3.3).

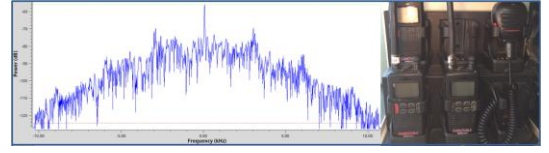


Fig. 3.1 - VHF telephony signal PSD plot (soft speech) of a primary user equipment.

Analogue telephony transceivers use a channel spacing of 25 kHz, where the effective channel bandwidth should not exceed 16 kHz. Signals can be phase or frequency modulated (frequency modulation with a pre-emphasis characteristic of 6 dB/octave).

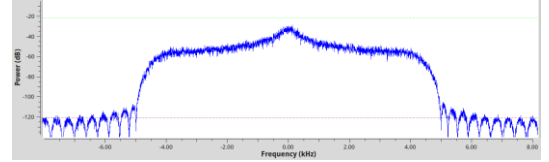


Fig. 3.2 – Digital Selective Call PSD plot.

DSC uses a two level frequency shift keying (FSK) modulated signal that fits the same bandwidth of analogue telephony channels (25 kHz). DSC operates in 156.525 MHz (MMS Channel 70).

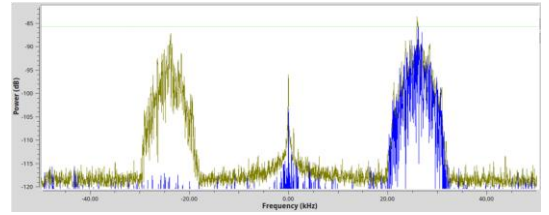


Fig. 3.3 – AIS channels A and B PSD plot (green plot – maximum envelope, blue plot– detected peak).

*AIS transponders operate in two fixed frequencies (161.975 MHz and 162.025 MHz), and use Gaussian Minimum Shift Keying (GMSK) modulation for packet data transmission. Each channel occupies an effective bandwidth of about 12 kHz.*

*Due to the nature of the maritime environment, multiple PU can be in activity at the same time, thus the sensing algorithm must be able to detect multiple transmissions simultaneously (Fig. 3.4).*

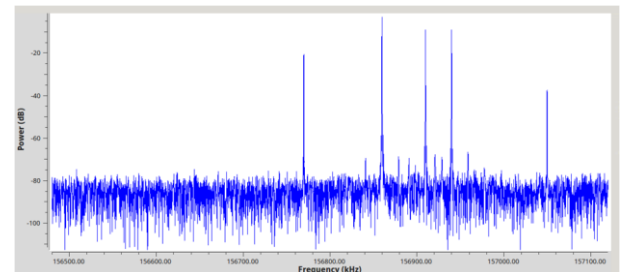


Fig. 3.4 - Typical MMS radio picture with multiple PU's.

As described in section 2, several spectrum sensing algorithms can be used to detect PU activity in the MMS band. However, some sensing algorithms require channel by channel analysis (feature detection and blind detection), which is inadequate for fast detection. The frequency domain energy

detector algorithm can easily detect PU activity in all VHF channels in a single spectrum survey (in a single spectrum measurement) with low computational effort. Moreover, the energy detector is a proven algorithm and easily implementable in software.

### B. Radio Architecture

As stated above, the implementation uses a base station (coastal stations) - mobile station (vessels) approach. Besides being responsible for spectrum sensing management and radio picture compilation, base stations also coordinate network synchronization (dissemination of radio transceiver configuration). The synchronization channel operates in narrowband fixed frequency channel (different from the data channel) that is used for periodic network synchronization and signaling (Fig. 3.5). Every time a new slave joins the cognitive network or an existing slave loses network synchronism, the synchronization channel acts as a rendezvous point.

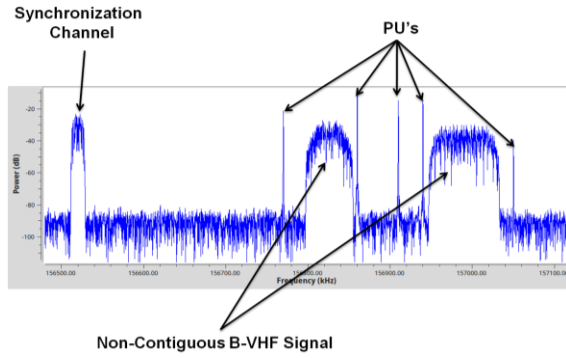


Fig. 3.5 - Proposal for data channels and synchronization channels (synthesized data with GNU Radio).

As for medium access and sharing (among cognitive users), Carrier Sense Multiple Access (CSMA) with collision avoidance (CA) can be easily implemented and requires few signaling operations.

As stated above, the cognitive radio performs several tasks and works in two separate modes (B-VHF and synchronization). The cognitive engine, which operates at the MAC layer level, is the component responsible for coordinating all network operations and interfacing between processing blocks. Fig. 3.6 illustrates the logical connections between the individual components of the radio.

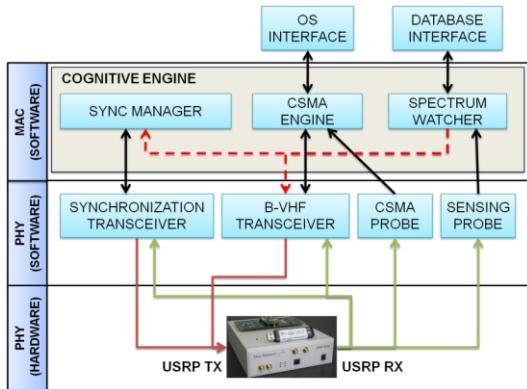


Fig. 3.6 - Cognitive station layer stack for CSMA/CA operation.

On the right side of Fig. 3.6, a spectrum watcher monitors spectrum activity and generates transceiver settings to

reconfigure the local B-VHF transceiver. These settings are also sent to the synchronization manager, which then broadcasts this information to the other network nodes. Since the network stack is software implemented (except from the radio frontend which is implemented by the USRP), the radio is able to reconfigure itself very quickly and adapt to the currently available spectrum bands.

### C. Spectrum Sensor Block

A simple and effective energy detector was implemented to perform multiple PU sensing. Frequency domain energy detectors essentially depend on a spectral estimation, which can be obtained using different techniques. This implementation considered two different spectral estimators. The first technique is based on Welch's method [20], and the other, for comparison, is based on Fast Fourier Transform (FFT) computations.

After performing the spectral estimation, the scanner takes the scanning settings, such as sample rate (total bandwidth), primary user's channel rate (channel spacing) and frequency resolution (FFT length) and performs channel by channel, energy detection (Fig. 3.7).

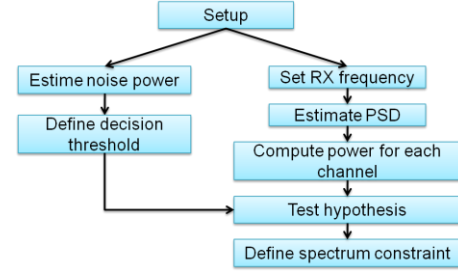


Fig. 3.7 - Workflow of the spectrum sensing framework.

### D. Radio Transceiver Design

On the transmitter side, the cognitive layer gets data packets from the upper network layer (IP layer), appends a cognitive layer header and a cyclic redundancy check (CRC). Then, the frame is inserted into the transmitter flowgraph, which performs physical layer operations, such as, symbol mapping (M-PSK or M-QAM), sub-carrier assignment (where non-contiguous patterns are modeled), OFDM modulation and filtering (Fig. 3.8).

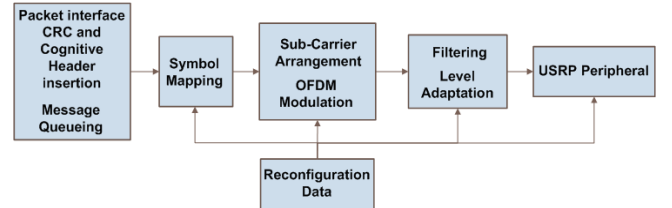


Fig. 3.8 – B-VHF transmitter flowgraph.

GNU Radio's OFDM implementation uses synchronization words and pilot symbols so receivers can detect OFDM frames, correct frequency offsets and perform channel equalization. Reconfiguration data is passed by the cognitive engine and used to update flowgraph setting every time the spectrum availability changes (after the synchronization process).

The transmitter also uses an infinite impulse response (IIR) transmitting filter to reduce OOB radiation. For lower



complexity (low number of coefficients), IIR filters are the adequate choice compared with finite impulse response (FIR) filters.

On the receiver side, the modulation process is reversed after synchronization, frame detection and equalization. Fig. 3.9 illustrates the base receiver implementation, where the integration of reconfiguration data (obtained through the synchronization process) is used to adjust receiver settings.

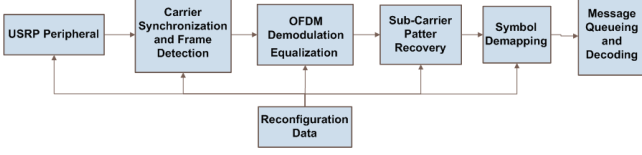


Fig. 3.9 – B-VHF receiver flowgraph.

#### E. Cognitive Engine and Network Synchronization

The cognitive engine manages all radio components. For master stations (base stations) not only the cognitive engine controls the local radio transceiver, but it also remotely controls slave's radio transceivers through the synchronization process.

However synchronization and B-VHF data flow through different physical channels (different carrier frequency, modulation, etc.), the cognitive engine must still be able to reach all network stations despite the current physical channel in use. For this reason, B-VHF data packets have a cognitive engine header, which implements a logic connection between cognitive engines, even in B-VHF operation (Fig. 3.10).

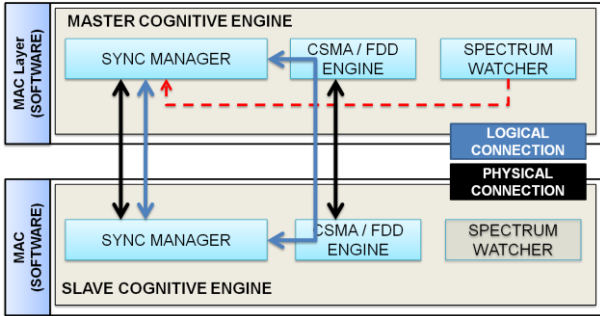


Fig. 3.10 - Cognitive Engine Physical and Logical Channels.

Using this feature, master stations can order slave stations to switch to synchronization mode by including that information in the header of a B-VHF frame. Once all network stations switch to synchronization mode, the synchronization transceiver broadcasts transceiver reconfiguration settings. In the process of generating synchronization data, master stations enforce the current spectrum policy, using local spectrum sensing and cooperative sensing information from slave stations.

The actual synchronization data is based on a spectrum constraint (list of unavailable frequencies), which is converted in OFDM sub-carrier constraint (through a spectrum translator function) and then the synchronization data is produced based in information (Fig. 3.11).

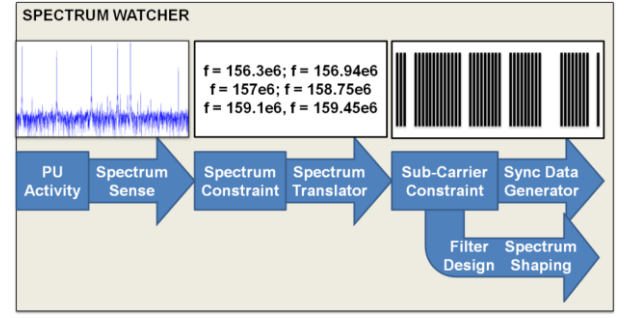


Fig. 3.11 - Synthesizing synchronization data - master stations only.

Master stations run the procedure described above every spectrum survey. However, if the spectrum constraint remains unchanged, the synchronization process is skipped, saving time. Switching between physical channels with a typical acknowledge mechanism can lead to some problems, as illustrated in Fig. 3.12.

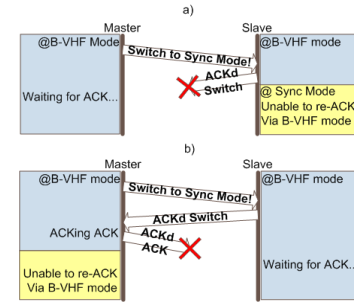


Fig. 3.12 - Switching from B-VHF Mode to SYNC Mode problem when acknowledge messages are lost. a) slave acknowledge only; b) slave and master acknowledge.

Since there is always a chance one of the stations doesn't receive the last acknowledge, this implementation adopts neither of the options illustrated in Fig. 3.12. Instead, no acknowledge mechanism is adopted. However this decision has some obvious drawbacks (slaves can miss the synchronization process), it reduces signaling operations (N slaves would send N acknowledges). Moreover, slave stations have a protection mechanism that prevents them from being in B-VHF mode for too long, forcing a switch to synchronization mode after a certain period of time, which overcomes the fact that a slave might miss the signaling packet ordering a switch to synchronization mode.

This implementation enables host machines to use the designed MAC + PHY layers as a network interface device through which IP traffic can be sent. This functionality is achieved by using Linux's TUN/TAP<sup>1</sup> driver [21], which emulates a virtual network interface card (NIC).

#### IV. TEST AND DEMONSTRATION

Both simulation and laboratorial test were performed to analyse the performance of the cognitive radio and to evaluate its coexistence with primary user signals. For the simulation tests, a channel model emulates the expected conditions of the maritime propagation channel (AWGN and line of sight

<sup>1</sup> TUN/TAP provides packet reception and transmission for user space programs, emulating network devices supported entirely in software.

fading). The different components of the cognitive radio were evaluated and assessed individually, including spectrum performance and coexistence behavior in the presence of primary user signals. Finally a demonstration with IP data is performed to validate the prototype cognitive system.

For laboratorial tests, the USRP's were about 4 m apart from each other, and standard monopole antennas were used, as illustrated in Fig. 4.1.



Fig. 4.1 - Laboratorial setup for over-the-air analysis.

#### A. Spectrum Sensor

In order to establish a baseline for the spectrum sensing framework, benchmark tests were performed using real captured signals and synthesized signals. The overall performance of the spectrum sensor processing block, as a multichannel detector, is highly dependent on the performance of single channel detection. Table 4.1 summarizes the specification used for spectrum sensing analysis.

TABLE 4.1 - SPECTRUM SENSING SETUP.

Parameter	Value
Sensing time	2048 samples = 2.048 ms @ 1MS/s
FFT size	4096 bins $\rightarrow$ 244.1 Hz/bin
Channel spacing	25 kHz
Search bandwidth	12.5 kHz

Fig. 4.2 shows the results from a spectrum scan using the implemented energy detector, allowing a graphical visualization of how the detector measures channel power and performs detection.

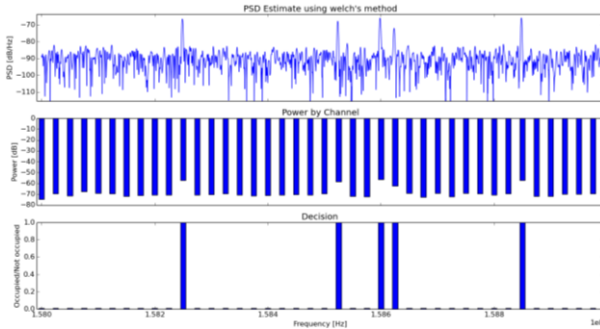


Fig. 4.2 - Spectrum sensing results.

Results demonstrate that the designed energy detector is able to detect multiple narrowband signals in a single spectrum scan, which fulfils the needs of this implementation.

#### B. Transceiver Performance Analysis

This test enables various RF performance and packet measurements, including: spectrum shaping, PAPR,

coexistence between PU and SU and error. Table 4.2 summarizes the adopted settings for the transceiver tests.

TABLE 4.2 - TRANSCEIVER SETUP FOR TRANSCEIVER PERFORMANCE ANALYSIS.

Parameter	Value
System bandwidth	1MS/s
OFDM FFT size	128 bins
OFDM Cyclic Prefix size	32 bins (1/4)
Symbol modulation	QPSK
OFDM Frame size	512 bytes
Cancellation band (per PU)	50 kHz - 7 OFDM bins

By monitoring the CRC errors, one can assess the behavior of the transceiver in the noise + fading channel model. In Fig. 4.3, the total number of sent packets, the number of received packets (% rcvd) and the number of correctly received packets (% ok) is compared.

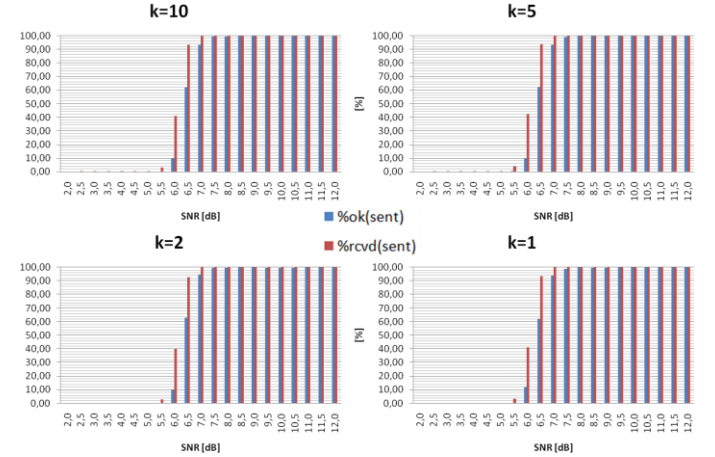


Fig. 4.3 – Percentage of received and correctly received packets vs SNR for different k factors, SNR [2.0 – 12.0] dB.

Results show that the system has a turning point in performance between 5 and 8 dB of SNR, where the receiver is able to start detecting packets and decoding some of them correctly. Results also show that fading has little impact in the overall performance. Some of the fading effects and fluctuations of the received signal are eventually accommodated by the receiver through the automatic gain controller and channel equalizer. For a 7 dB SNR, the percentage of correctly received packets is above 90%, for all fading levels, which is an acceptable loss ratio.

#### C. Spectral Performance

The effect of the transmitting filter can be easily seen in Fig. 4.4, where the OOB radiation level is very low when compared with NC radiation (sub-carrier cancellation only).

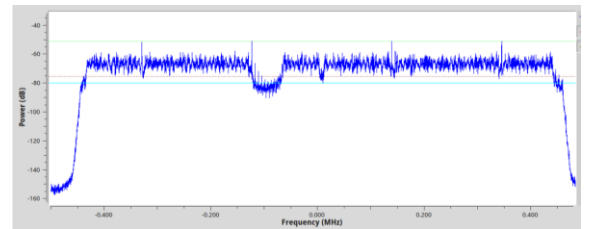


Fig. 4.4 - PSD of the transmitted signal.

In Fig. 4.5, investigation on OOB and NC radiation of the received signal reveals that, in the presence of noise, the signal level is about the same for both cases (from previous tests, with SNR = 7 dB, the system presented acceptable performance).

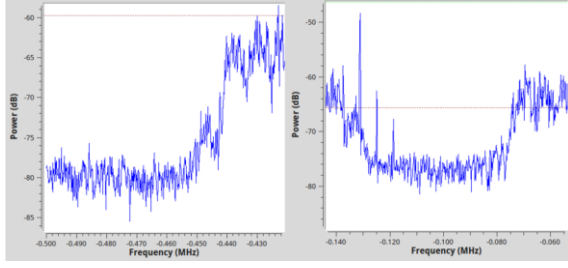


Fig. 4.5 - OOB and NC radiation details from received signal (simulation).

Since the transmitting filter effectively reduces OOB radiation, these results suggest that, as long as the transmitted power is kept to the minimum – SNR = 7 dB was the lowest SNR level for which the system achieved a satisfactory performance – the NC power level is about the same level as background noise.

Fig. 4.6 shows the results for over-the-air transmission, where the NC radiation level is about 5 dB above the OOB radiation level, which confirms the results from the simulations.

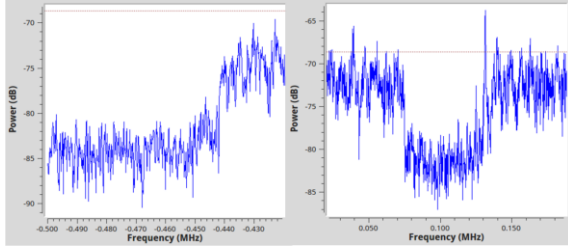


Fig. 4.6 - OOB and NC radiation details from over-the-air received signal.

#### D. Peak-to-average Power Ratio Analysis

PAPR measurements were taken considering the previous settings and with no forced clipping. In order to measure PAPR, the received samples file was analysed with a Python post processing script that computes PAPR and generates the characteristic Complementary Cumulative Distribution (CCD) function. Fig. 4.7 illustrates a comparison of the CCD for various clipping levels (baseline corresponds to no clipping).

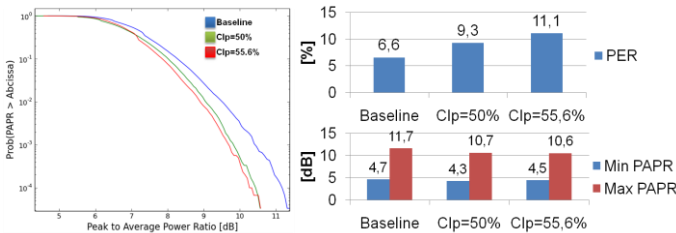


Fig. 4.7 – CCD comparison of results from different clipping levels.

The baseline PAPR level (11.7 dB) is a typical level for OFDM systems. Results also show a reduction of 1dB in PAPR for a 50% clipping factor and a slight increase in PER (9.3 %), which is still below the 10% reference level. As expected, PER increases as the clipping ratio increases. Since the clipping

takes place before filtering, there is no significant impact in the radiation profile (no increase in OOB radiation).

#### E. PU Coexistence Analysis

In order to determine if the transmitted signals interfere with incumbent users, the coexistence limits between PU signals (telephony service) and NC-OFDM signals were subjectively evaluated. To that end, NC-OFDM and PU signals were shifted in frequency across each other using a frequency translating filter, so interference can be percept at different band positions (Fig. 4.8).

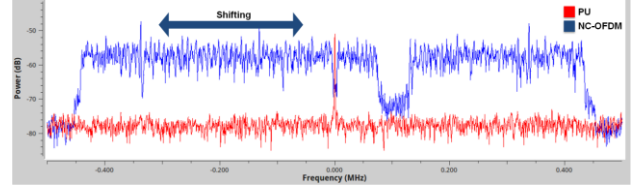


Fig. 4.8 - Subject test signals for subjective analysis.

**Transmitting band:** in this situation the PU signal is totally indistinguishable from background noise and interference (Fig. 4.9).

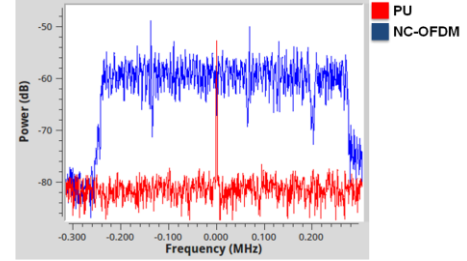


Fig. 4.9 - Interference evaluation at transmitting band.

This scenario represents a total interference situation where the probability of PU service disruption is very high.

**OOB band:** since the OOB radiation is dramatically reduced by the transmitting filter, it is not expected any perceptible interference (Fig. 4.10).

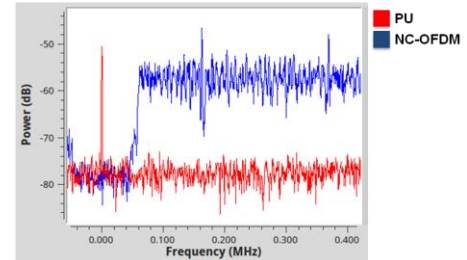


Fig. 4.10 - Interference evaluation at OOB band.

In this scenario, the voice communication is totally perceptible and OOB interference has little impact (almost inexistent) on voice quality.

**NC band:** for this scenario (Fig. 4.11), since the NC radiation level is somewhat above the background noise, it is expected some impact on the communication experience, but with low probability of service disruption.



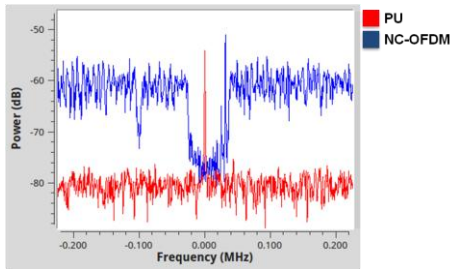


Fig. 4.11 - Interference evaluation at NC band.

Subjective results reveal minor impact in voice perception, but some background interference is noticeable. Even in this condition, the PU service might not be disrupted since it still possible to establish a voice call with acceptable quality. Further analysis revealed that for higher signal levels (relative to the PU level), the background interference increases, but the voice call is still perceptible.

#### F. Demonstration with IP Data Packets

This test demonstrates the transparency of the cognitive MAC + PHY tunneling mechanism. A series of ping requests / responses (ICMP protocol) between two stations (laptop + USRP) is a proof of concept for general data applications (Fig. 4.12).

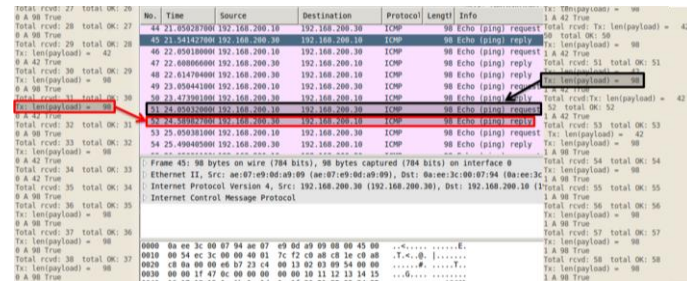


Fig. 4.12 - Packet analysis using station's debugging consoles and Wireshark.

There is a small delay penalty resulting from the physical layer processing, which occurs in software. One of the stations performed 644 ping requests and received 533 ping responses, which yields 17% of packet loss. However, it should be recalled that some packets were lost due to periodic interruptions for network synchronization. The round trip times ranged between 10 ms and 50 ms, which is an acceptable delay for a wireless communication system. Results demonstrate the ability of this implantation to transport generic IP data.

#### V. CONCLUSIONS

This paper demonstrates a prototype solution that can be a viable alternative to SATCOM link for near shore and line of sight communications, where multiple applications can benefit from a broadband system.

There are significant improvements and innovative aspects addressed by this implementation, such as network synchronization and transceiver reconfigurability aspects. A simple but effective synchronization protocol was implemented, which enables transceiver settings to be shared across network nodes, as well as logic connection between network nodes' cognitive engines. A cognitive engine manages sensing activities and enforces spectrum policies, thus the radio transceiver can be dynamically reconfigured to use available vacant sub-bands.

Despite being a prototype, the implemented radio system is fully functional and can be easily deployed in the field. However, some regulatory issues concerning service disruption and coexistence limits between incumbent and opportunistic users [22] and technical issues concerning spectrum shaping (i.e. cancellation of undesired radiation) and spectrum sensing (i.e. sensing periodicity and duration) require further investigation.

Nevertheless, results show an acceptable performance (packet loss rate under 10 %) under low SNR (7 dB) and high fading ( $k=1$ ) environments, which is a good indicator of the receiver's capabilities for maritime applications. Coexistence tests also show that the transceiver induces very low interference in the OOB band, and an acceptable level of interference in the NC band, but not enough to disrupt a PU service. Finally, it was demonstrated the integration and transparency of the entire cognitive radio using IP traffic.

Several improvements can be addressed in future projects, concerning the overall architecture but also in terms of tests and analysis. Other spectrum sensing and cooperative sensing algorithms can be implemented and assessed. The radio transceiver can be improved by applying more effective radiation reduction techniques and blind synchronization methods (which may simplify the synchronization process). Synchronous techniques (such as TDMA) can improve both network synchronization and resource management protocols, as well as sensing activities coordination. Coexistence between incumbent and secondary, spectral efficiency and throughput also need further analysis and testing.

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