TESTS AND TRIALS OF SOFTWARE-DEFINED AND COGNITIVE RADIO IN IRELAND

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ABSTRACT

This paper firstly describes the non-contiguous and reconfigurable orthogonal frequency division multiplexing (OFDM) system designed by CTVR. This was tested April in Dublin, Ireland, using licenced spectrum in the TV and microwave frequency bands. One of the outcomes of these trials, namely the effect of non-contiguous OFDM on the ability to achieve OFDM frame synchronisation at the receiver is presented in this paper. It is shown that frame synchronisation is feasible even when a primary non-cooperative user is sharing that same channel as the secondary opportunistic user.

1. INTRODUCTION

Legacy command-and-control approaches to spectrum management have resulted in largely inefficient spectrum usage resulting in perceived spectrum shortages both in the US and internationally [SSC05]. Dynamic spectrum access networks (DySPANs) have the potential to increase spectrum usage efficiency. DySPANs operate by temporarily using spectrum resources which are not being utilized and using information regarding spectrum usage to ideally avoid the creation of harmful interference. Reconfigurable OFDM technology has been recognized as a key enabler for DySPAN operation through the ability to dynamically adapt waveforms to suit spectrum availability and coexist with other spectrum users [WEI04].

This paper firstly describes the non-contiguous and reconfigurable orthogonal frequency division multiplex (OFDM) system designed by CTVR. This was tested in April using licenced spectrum in the TV and microwave frequency bands. One of the outcomes of these trials, namely the effect of non-contiguous OFDM on the ability to achieve OFDM frame synchronisation at the receiver is presented in this paper

The Irish communications regulator, the Commission for Communications Regulation (Comreg) has established a unique Wireless Test and Trial licencing scheme [COM06]. The main objective of this is to promote innovation in the wireless communications sector and to facilitate trials of new wireless technologies before full deployment. For the month of April 2007, Comreg issued a trial licence to CTVR for the purposes of software-defined radio, cognitive radio, and dynamic spectrum access experiments involving multiple companies and research facilities who were acting in collaboration with CTVR. Comreg has also awarded a year-long test licence to CTVR for dedicated frequency spectrum in the 2.08 GHz and 2.35 GHz frequency ranges. The bandwidth of each of these spectrum segments is 25 MHz.

The initial series of trials were conducted during April 2007, coinciding with the second IEEE symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) [DY07]. For the month of April 2007, these trials availed of a collaborative trial licence also issued by Comreg, permitting the use of a total of 117.5 MHz of non-contiguous frequency spectrum in the UHF and microwave frequency bands. Experiments were carried out to examine the performance of the CTVR reconfigurable OFDM system in terms of the ability to dynamically change the characteristics of the spectrum access scheme, react to changes in estimated spectrum usage in the test and trial frequency bands, and minimise potential interference caused to (and by) designated incumbents were examined. In addition, the ability of two nodes to *rendezvous* in frequency spectrum without *a priori* knowledge of the centre frequency of operation was demonstrated. This system does not require a common control channel thus countering the problem of maintaining a dedicated, interference-free spectrum segment for co-ordination purposes.

Following these trials, CTVR has continued to exploit the ability to reconfigure, react, and rendezvous and is increasing the size of the networks of software-defined and cognitive nodes that can exploit these abilities in collaboration. Current on-going research work is focusing on testing these networks in several other CTVR locations in Ireland for a variety of communications scenarios. The primary scenario focuses on public safety; initiating and maintaining communication between deployed nodes in these locations. Each node may not have *a priori* knowledge of the designated inter-node communications channel; only the spectrum licensing constraints (e.g., permitted bandwidths, effective radiated power, antenna polarization, and locations). The problems of in-band interference in a reconfigurable OFDM context and the resulting challenges of coordinating with other nodes in the network without using a dedicated control channel are also examined.

Section 2 provides an overview of the reconfigurable radio platform. Section 3 introduces the concept of non-contiguous OFDM from a contiguous OFDM starting point. The key receiver issues associated with non-contiguous OFDM are highlighted in Section 4. In Section 5, initial findings from the frame synchronisation tests involving non-contiguous OFDM in both coexistence and sole operator scenarios are discussed. Section 6 concludes.

2. RECONFIGURABLE RADIO PLATFORM

The reconfigurable radio platform used in the implementation of this system is a general purpose processor (GPP) based software radio. It can perform directed and self-reconfiguration in real time in order to respond to changing radio and network resources. The majority of radio functionality is delivered through software. The RF front-end used is the Universal Software Radio Peripheral (USRP) by Ettus Research, LLC [ET07]. Two RF daughterboards were used to access licenced spectrum segments centred at 436.875 MHz (trial licence channel 10) and 2.35 GHz.

This platform comprises two parts:

1. A suite of software components that implement various functions of the radio
2. A mechanism for managing the structure and characteristics of the components and implementation chain.

The radio manager builds a radio configuration chosen by the user/designer using any or all of the available components. The term *manage* encompasses the process of reconfiguring the radio components in response to various triggers and observations throughout its operating lifetime. The platform has been designed to offer the designer/developer a significantly high degree of flexibility and rapid-prototyping capabilities in a wireless platform.

In the tests and trials carried out during April (and continued using additional licenced test frequency allocations in Ireland), dynamic reconfiguration within the communications signal chain facilitated the OFDM spectrum sculpting. The number of OFDM symbols per frame was held constant. As the number of active subcarriers increased and decreased, the resulting length of the OFDM frame also increased and decreased. The effect of this change meant that the components following the OFDM component needed to update their operating parameters (e.g., input/output signal length, storage array sizes) in order to handle this change. The radio manager directed these changes within the components chain.

3. CONTIGUOUS AND NON-CONTIGUOUS OFDM

3.1 Contiguous OFDM

OFDM uses many carriers in parallel, and where the centre frequency of each carrier (or subcarrier) occurs at a null in the spectra of the other OFDM subcarriers. Contiguous OFDM is used in IEEE 802.11a/g, IEEE 802.16 (WiMax), digital audio broadcasting (DAB), digital video broadcasting/digital terrestrial television (DVB/DTT), and digital radio mondiale (DRM), for example. Reconfigurability can add extra value to OFDM-based systems however. OFDM subcarriers may be individually employed to convey different data streams and deactivated if required. Non-contiguous OFDM involves deactivating specific subcarriers to produce nulls in the transmitted signal spectrum. These nulls can help to facilitate coexistence with other users sharing a spectrum segment. Previous work [KN07] by the authors on this topic highlighted that a primary non-cooperative signal and an opportunistic secondary user signal employing this technique helped to facilitate interference-free coexistence between the two.

Fig. 1 is a plot of the power spectral density of a contiguous 2 MHz bandwidth OFDM signal created using a 256 bin FFT. In this case, 200 of the 256 bins are activated. This signal, at a centre frequency of 2.35 GHz was generated using the reconfigurable radio platform and a USRP. The power spectral density plot was captured using an Anritsu Signature spectrum analyser which has a complete in-built Matlab environment. This plot is typical of many of the current OFDM-based standards, except that the occupied bandwidth may be up to ten times greater than illustrated in a standards-based

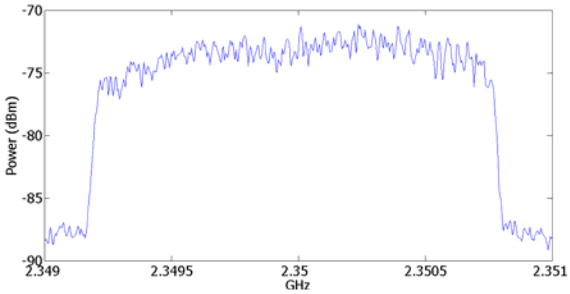

Fig. 1: Power spectral density of a 2MHz bandwidth OFDM signal using 200 active subcarriers.

commercial device.

In a shared spectrum environment, the main problem with contiguous spectrum usage is that other radios within range of the originating signal use the same spectrum segment, and so both may be subject to interference and cause interference to the active user. An ability to ‘sculpt’ spectrum usage and carve opportunities for additional users sharing a common spectrum segment has potential value. The efficiency of how frequency spectrum is utilised can be increased by enabling two or more services to coexistence on an interference-free basis.

3.2 Coexistence

Interference-free coexistence is the ability of two or more wireless communications services to share a common centre frequency or channel without causing interference to each other. The ability of a secondary opportunistic and adaptable user to coexist with primary or legacy users in shared frequency bands can help increase the efficiency of how spectrum is used. Coexistence can also potentially increase the number of users/services that require access to frequency spectrum in order to operate successfully. However, the potential for interference to primary users in the band increases, which is undesirable. In order to increase the viability of this feature, the secondary opportunistic users must be capable of accessing the shared spectrum segments on a non-interference or minimal interference basis. Spectrum usage can be manipulated or ‘sculpted’ in order a adapt spectrum occupancy according to current in-band activity.

3.3 Spectrum Sculpting

Spectrum sculpting is achieved using a channel mask, i.e., a binary array of size N_{FFT}, where a binary one denotes an active subcarrier and a binary zero denotes a deactivated subcarrier. The resultant OFDM signal spectrum is sculpted by performing a logical AND operation on the FFT bin array and the channel mask prior to time-domain transformation using the inverse fast Fourier transform.

4. RECEIVER ISSUES ASSOCIATED WITH RECONFIGURABLE OFDM

The main challenges associated with non-contiguous OFDM lie with the receiver. A receiver requires knowledge of the operating parameters of the transmission source. Among these parameters are the signal bandwidth, subcarrier spacing, cyclic prefix and modulation schemes adopted. In the case of non-contiguous OFDM systems, additional knowledge is required regarding the active subcarrier map in use. However, prior to individual subcarrier symbol demodulation, successful OFDM-based communication links rely heavily on the ability of the receiver to accurately correct timing and carrier frequency offset errors in order to maintain orthogonality between subcarriers and to recover the transmitted information. In order to successfully demodulate a received OFDM signal, frame synchronisation and carrier-frequency offset estimation and correction must be achieved. Typically, a preamble, which precedes an OFDM frame, is used by the receiver to achieve both timing and frequency synchronisation. Known pilot symbols transmitted using designated subcarriers aid equalisation and fine-frequency offset error correction at the receiver.

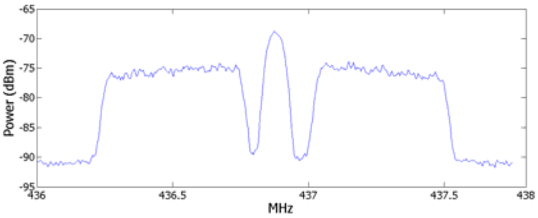

Fig. 2: Power spectral density of a 2MHz OFDM signal with 43 sub-carriers deactivated in order to create a null in the centre of the spectrum for a legacy non-cooperative narrowband user occupying 436.875MHz also.

One of the challenges associated with non-contiguous OFDM is that the ability of the receiver to establish and maintain correct synchronisation may be adversely affected. A preamble used in IEEE 802.16 (WiMax), for example, typically employs the entire frequency bandwidth of the OFDM signal. Pilot carriers may be evenly dispersed within this bandwidth to allow the receiver to estimate the characteristics of the entire bandwidth for equalisation purposes. Deactivated subcarriers can therefore reduce the receiver’s ability to achieve this. Frame synchronisation is achieved using a correlation-based method; the performance of this technique is dependent on the number of active subcarriers within the preamble. As a result, the ability of a receiver to achieve frame synchronisation may be reduced. In the following section, we examine the receiver-centric effects of non-contiguous OFDM on frame synchronisation.

5. FRAME SYNCHRONISATION ANALYSIS

5.1 Experimental Scenario

Fig. 2 is a plot of the averaged power spectral density of a non-contiguous OFDM signal using a bandwidth of 1.6 MHz centred at 436.875 MHz (channel 10 as listed in the

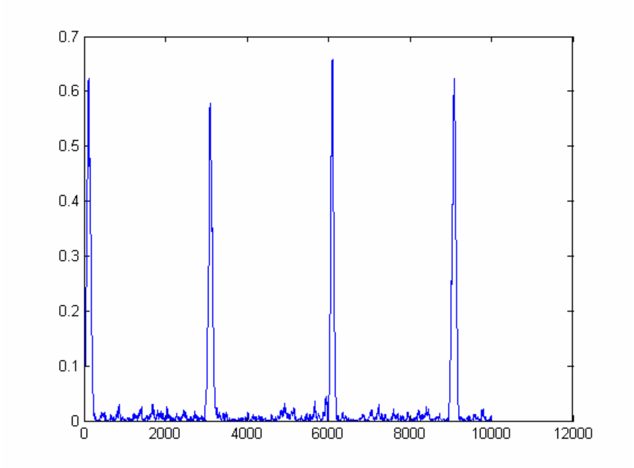

Fig. 3: Frame synchronisation correlation output for the 200-subcarrier OFDM signal illustrated in Fig. 1. Four distinct peaks are shown, corresponding to the preambles preceding four frames.

trial licence issued by Comreg for April 2007). The maximum permitted bandwidth of trial licence channel 10 was 1.75 MHz, whereas the bandwidth of test licence channel 2 is 25 MHz. In this case, a primary non-cooperative user in the form of a 250 kHz bandwidth QPSK transmission, generated using an Anritsu MG3700A vector signal generator, is occupying the same centre frequency. The secondary opportunistic OFDM signal uses a 256 bin FFT. A maximum of 200 subcarriers were made available for use by the reconfigurable radio platform in order to minimise the potential for out-of-band interference and spectral re-growth.

To accommodate the primary non-cooperative signal, the opportunistic OFDM signal must deactivate a contiguous block of subcarriers. The energy detection threshold is -85 dBm in this scenario. An energy detector indicates the power in the bandwidth of the non-cooperative signal exceeding this threshold but in order to minimise potential interference to, and by, the single-carrier non-cooperative signal, adjacent subcarriers must also be deactivated. In this example, 43 subcarriers were deactivated resulting in 157 active subcarriers.

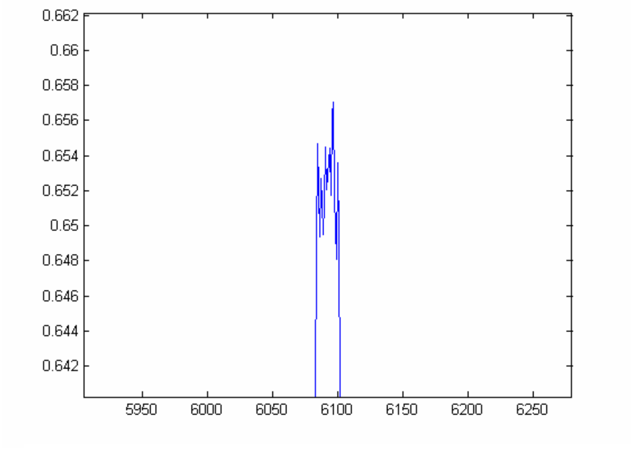

Fig. 4: A closeup of one of the peaks in the correlation output shown in Fig. 2. Each peak is actually an approximated plateau.

At the secondary opportunistic user receiver, the received signal comprises the non-contiguous OFDM signal and the primary non-cooperative user single-carrier signal. Following the passband to baseband conversion, amplification, digital to analogue conversion, and decimation stages, the first key task of the OFDM receiver is to establish frame synchronisation.

5.2 Frame Synchronisation for Contiguous OFDM

The frame synchronisation method employed is based on a technique developed by Schmidl and Cox [SCX]. The OFDM preamble consists of an OFDM symbol with an identical repeated sequence of 128 ($N_{FFT}/2$) samples in this case. These identical half symbols are unique to the preamble. The receiver can therefore identify a preamble by correlating incoming signal samples against those received 128 samples later. The result of this correlation is a distinct peak corresponding to the preamble. Fig. 3 illustrates the output of the frame synchronization process for the contiguous OFDM signal, with the power spectral density shown in Fig. 1. Fig. 4 is a close-up of one of the frame synchronization peaks illustrating that the peak is not a discrete point but it may be approximated as a *plateau*. The receiver can complete the frame synchronization process by estimating the index associated with the start of the frame using a threshold

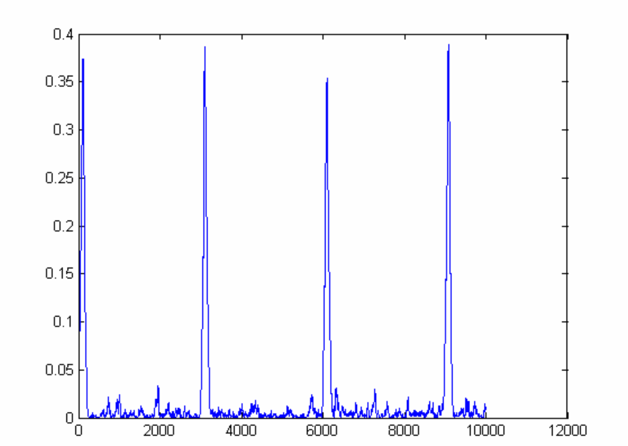

Fig. 5: Output of the frame synchronisation process for the received OFDM signal coexisting with a narrowband user as shown in Fig. 4.

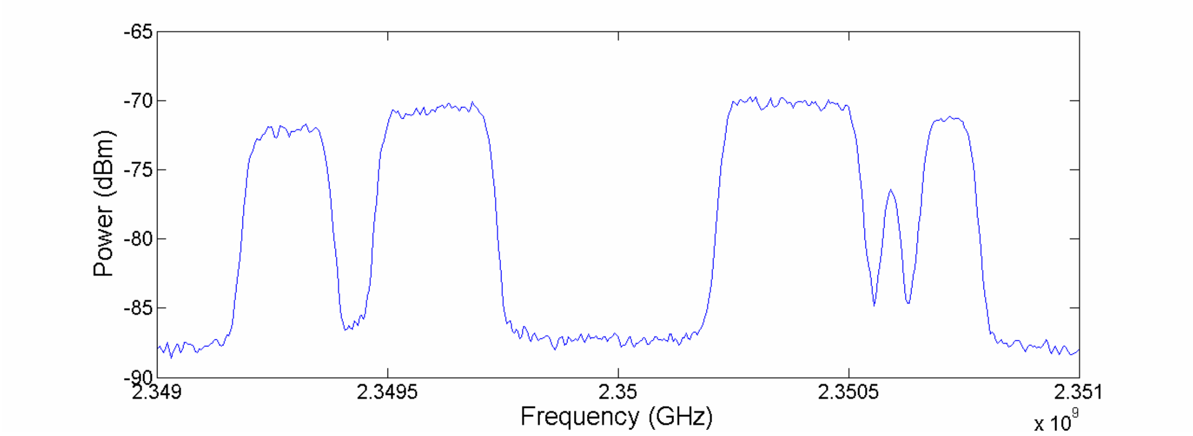

Fig. 6: PSD of a 2MHz OFDM signal with multiple nulls and a total of 103 active subcarriers.

value. The peak output of the frame synchronization technique for this 200 contiguous subcarrier example is approximately 0.6 when a preamble is detected compared to less than 0.025 when the received signal does not contain a preamble. This represents an approximate preamble to non-preamble detection ratio of 240. In this case, the threshold value is chosen to be 95% of the maximum frame synchronization output metric, or plateau.

5.3 Frame Synchronisation for Non-Contiguous OFDM

The key issue with frame synchronisation in a non-contiguous OFDM signal environment is that the number of subcarriers used for synchronisation is reduced as spectral nulls are introduced into the OFDM spectrum.

Fig. 2 illustrates the power spectral density of the received OFDM signal where a spectral null has been created at the centre frequency, 436.875 MHz. A primary non-cooperative user is occupying the same centre frequency. In this scenario, 43 of the original 200 subcarriers were deactivated leaving 157 active subcarriers. The spectral null created as a result is approximately 15 dB down on the power of the adjacent active OFDM signal.

Fig. 5 is a plot of the output of the frame synchronisation block in the OFDM receiver for four received OFDM frames. Four distinct peaks are shown, corresponding to the preambles preceding each of these OFDM frames. The peak correlation output is approximately 0.375. This is almost half of the peak correlation output for the contiguous 200-subcarrier example as shown in Fig. 3. The approximate preamble detection ratio is 150. Despite this reduced correlation output, this result is sufficient to achieve frame synchronisation.

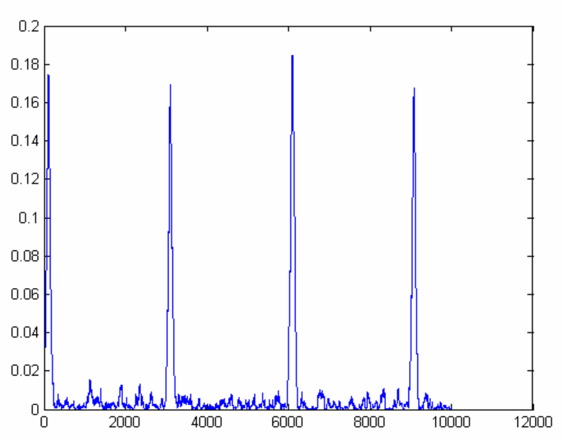

Fig. 7: Output of the frame synchronisation process for the received OFDM signal as shown in Fig. 6.

Further tests were conducted where the number of active subcarriers was reduced even further. The objective of these tests was to examine if the effect of introducing larger nulls in the OFDM spectrum resulted in a reduction in frame synchronisation ability. Fig. 6 illustrates the power spectral density of a received 2 MHz bandwidth OFDM signal with multiple nulls in the OFDM spectrum. The nulls in this spectrum vary in frequency and bandwidth. The aggregate number of active subcarriers in this signal is 103. This is a reduction of 97 subcarriers compared to the original 200-subcarrier signal shown in Fig. 3. Frame synchronisation performance is shown in Fig. 7. The peak output of the correlation process is approximately 0.17, compared to approximately 0.6 for the contiguous 200-subcarrier case. The approximate preamble detection ratio is therefore 68. This represents a reduction of over 170 in the preamble detection ratio compared to the original 200-subcarrier scenario. This result implies that frame synchronisation by the receiver is still possible, however.

6. CONCLUSIONS

These tests indicate the frame synchronisation for non-contiguous OFDM systems, where a second narrow-band user is sharing the same centre frequency is feasible. For a more extreme case where multiple nulls are present in the OFDM spectrum, the frame synchronisation procedure, although affected by a significantly reduced preamble detection ratio, is still deemed feasible. Ongoing work on this topic by the authors is focusing on exploring the relationship between the number of, and distribution of, active subcarriers on this correlation output, especially in the presence of multipath.

7. ACKNOWLEDGEMENTS

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