

FLUID WIRELESS – DYNAMIC SPECTRUM ALLOCATION AND SPECTRUM-MONITORING APPLICATION USING RECONFIGURABLE RADIO AND OFDM

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ABSTRACT

This paper presents a description, further enhancements to, and an analysis of a multi-user Orthogonal Frequency Division Multiplexing (OFDM)-based dynamic spectrum management technique called a Multiple User Data-Enhanced Radio Server (MUDERS). The term 'fluid wireless' is used to describe the discrete-time 'water-flowing around obstacles' interference-avoidance and intentional sub-band avoidance approach used to maximise channel capacity usage. The time-varying radio reconfiguration mechanisms required to implement this technique are also described including a means of indirect spectrum-monitoring. Presented in this paper are results describing how this technique improves data-throughput and robustness of wireless communications links on a common frequency band. In addition, this paper describes how interference-free co-existence of primary and opportunistic secondary users of a wireless medium can be achieved.

1. INTRODUCTION

The rapidly growing popularity of using wireless as the default communications medium is somewhat hampered by the exclusive spectrum-allocation policies currently in place by regulatory bodies and increasingly crowded unlicensed spectrum allocations. Exclusive-use spectrum allocations can experience extremely low duty-cycles by the licensees [1]. Measurements of how spectrum-segments are being used are also highly dependent on temporal, geo-spatial, social, political and economic factors. Taking an opportunistic-usage approach towards how spectrum is used increases the perceived availability of spectrum thus facilitating the increasing trend of wireless as the information-transfer medium.

Dynamic spectrum management [2][3] involves the identification and characterisation of available spectrum,

allocation of this spectrum to one or more users/services, the usage and monitoring of the allocated spectrum and release of this allocated spectrum as each user/service completes their individual information-transfer tasks. The key objective of dynamic spectrum management (DSM) however is the facilitation of interference-free co-existence of services/entities on a common (or multiple) spectrum segments. In this paper, interference is seen as both legitimate primary (and possibly licensed spectrum users) and both natural and artificial interfering sources. These secondary sources of interference include band-limited noise, spurious emissions and other opportunistic spectrum-users. Interference-avoidance benefits both the primary users and the opportunistic secondary user in terms of increasing the robustness and 'good-put' (error-free data-throughput) of the communications links on shared frequency bands.

This paper therefore focuses on the significant wireless communication performance enhancements that may be achieved by taking a highly-reconfigurable approach to the design and implementation of the base-band processing functions of the wireless device as a dynamic spectrum management enabler.

2. ENABLING DYNAMIC SPECTRUM ACCESS

Dynamic spectrum management focusing on interference avoidance necessitates a very high degree of control and manipulation of the spectrum and transceiver signal-chain used by an opportunistic wireless device. The scheme presented in this paper employs a dynamically adaptive Orthogonal Frequency Division Multiplexing (OFDM) [4][5] scheme encapsulated as a highly-reconfigurable software radio [6].

Orthogonal Frequency Division Multiplexing (OFDM) is a spectrally-efficient multi-carrier transmission scheme enabling information to be transmitted at high data-rates with a greater robustness to the effects of noise and fading compared to single-carrier transmission systems. OFDM is

currently used for high data-rate applications including high-speed wireless networking applications such as the IEEE802.16 (WiMax and Wireless Broadband (WiBro) [7][8], IEEE 802.11a/g [9][10], HIPERLAN II [11] standards and high quality digital audio and video broadcasting services such as Digital Audio Broadcasting (DAB) [12], Digital Radio Mondiale (DRM) [13] and Digital Video Broadcasting-Terrestrial (DVB-T) [14]. OFDM is

a frequency-diversity-based transmission scheme and uses closely-spaced orthogonal carrier frequencies. Unlike single-carrier transmission systems, OFDM does not require complex channel equalisation techniques due to the very small bandwidth and resulting flat-fading characteristic models of each OFDM sub-carrier.

Software radio or software-defined radio is the implementation of as much of the traditional transceiver signal-chain as possible in software. Essential hardware including the RF front-end and Analogue to Digital (ADC) and Digital to Analogue (DAC) converters is still required. The emphasis however is on creating a highly-reconfigurable wireless device, which is more feasible using software rather than traditional hardware fixed-architecture systems [15]. Reconfigurable radio is a software radio structured in a way that enables the radio application, application structure and radio parameters to be dynamically modified based on internal and/or external stimuli and policies [16].

Reconfiguration in this context of this paper enables the management of the shared spectrum-usage between multiple users from a common RF-interface. The core of the MUDERS system, as outlined in Fig. 4 is a reconfigurable software radio, implemented on a General-Purpose Processor (GPP) platform. This approach offers a very high degree of reconfigurability regarding the structure, modules and parameters of the software radio application. By dynamically modifying the operation of the radio in response to information from the user, estimated wireless channel activity, number of users requiring access to a spectrum-segment, and desired bandwidths, a superior multi-use wireless communications device can be created.

2. MULTIPLE-USER DATA-ENHANCED RADIO SERVER

5.1. Overview

A Multiple-User Data-Enhanced Radio Server (MUDERS) is a reconfigurable radio that employs an enhanced dynamic adaptive version of OFDM. The reconfigurable radio foundation for the MUDERS system is a general-purpose processor targeted platform called Implementing Radio in Software (IRIS) [17].

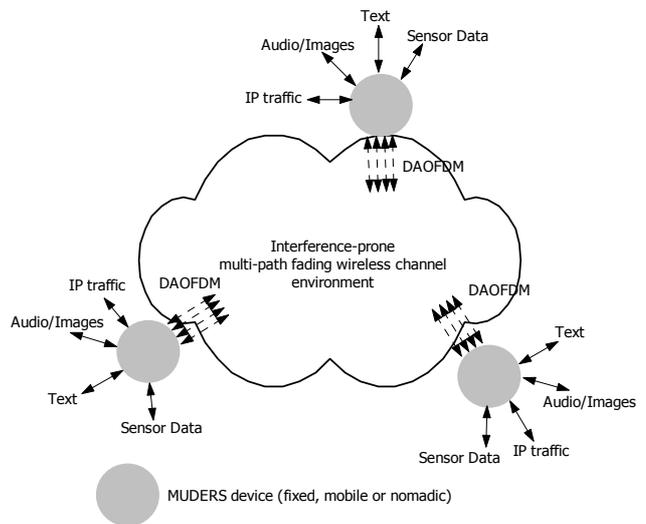


Fig.1. MUDERS: Transmitted information from multiplexed services/users 'flows' around interference and adapts to the time-varying band characteristics .

Designed by the Centre for Telecommunications Value-Chain-Driven Research (CTVR), several users/wireless services can share the desired frequency band using a single MUDERS air-interface as illustrated in Fig. 1. The *data-enhanced* element of the MUDERS system is that increased data-throughput, reduced BER and interference-avoidance capabilities can be achieved. The considerable internal signal-processing complexity of the MUDERS device is effectively hidden by the Man-Machine Interface (MMI) thus significantly reducing the need for manual intervention by the radio user. In addition, the channel awareness and adaptability of this device is designed to facilitate rapid deployment in time-constrained and challenging tactical wireless communications scenarios. The MUDERS system is therefore designed to operate with minimal manual intervention and minimal technical knowledge of the user.

5.2. Orthogonal Frequency Division Multiplexing

OFDM is used because of its ability to both multiplex the information from several users/services in one OFDM symbol and its high-spectral efficiency and ease of frequency-time profile manipulation. An OFDM symbol is a multiplex of orthogonal sub-carriers, created in the frequency-domain and then converted to a time-domain waveform using the Inverse Fast Fourier Transform (IFFT). A data symbol is a point on a constellation diagram of a chosen modulation scheme that represents a modulated grouping of one or binary values depending on the specific modulation scheme. Modulated data relating to each of the p wireless services is denoted by $X(k)$. A modulated data

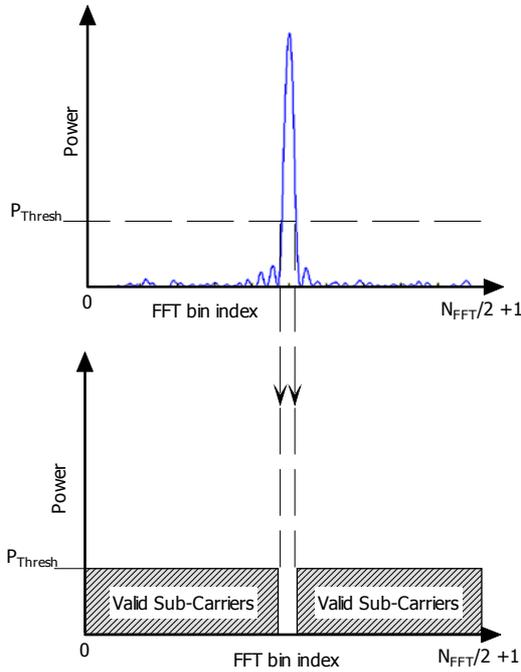


Fig. 2. Frequencies experiencing strong interference are deemed 'unusable' for data transmission.

symbol from one or more of the p sequences corresponding to the wireless services forms the k^{th} modulated sub-carrier value in the desired OFDM symbol. The total number of modulated sub-carrier values depends on the number of valid sub-carriers denoted by N_{SC} where $0 \leq N_{SC} \leq \frac{N_{FFT}}{2} - 1$, where N_{FFT} denotes the size of the FFT.

The OFDM symbols are generated by performing an Inverse FFT (IFFT) on the modulated sub-carriers $X(n)$ and summed to form the k^{th} OFDM symbol as follows:

$$x(k) = \frac{1}{N_{FFT}} \sum_{n=0}^{N_{FFT}-1} X(n) \exp \left\{ j2\pi \frac{nk}{N_{FFT}} \right\} \quad (1)$$

A guard interval is formed by pre-pending the last N_{GI} samples of $x(k)$ to the same OFDM symbol to form a cyclically-extended OFDM symbol s , where $s = \{x[N_{FFT} - N_{GI} - 1 : N_{FFT} - 1]\} \cup x\{[\dots]\}$ and N_{GI} is typically between 10% and 25% of N_{FFT} .

At the receiver, the noise-affected cyclically-extended OFDM symbol is truncated to N_{FFT} samples yielding $r(k)$ where:

$$r(k) = \exp \left(j \frac{2\pi kv}{N_{FFT}} \right) \sum_{q=0}^{L-1} h_q s(k - \eta_q) + n(k) \quad (2)$$

where L is the number of propagation paths (including the direct path signal component), η_q is the q^{th} propagation path delay, h_q is the q^{th} complex-valued path gain, v is the sub-

carrier spacing offset and $n(k)$ is the k^{th} complex-valued zero-mean additive white Gaussian noise sample.

The N_{SC} sub-carrier symbols are extracted from the total set of $N_{FFT}/2 - 1$ sub-carriers by performing a FFT on the recovered OFDM symbol. The value of the k^{th} sub-carrier associated with the p^{th} wireless service/user may be expressed as $Y_p(k)$, where

$$Y_p(k) = \sum_{n=0}^{N_{FFT}-1} r(n) \exp \left\{ -j2\pi \frac{nk}{N_{FFT}} \right\} \quad (3)$$

3. INTERFERENCE AVOIDANCE

A periodogram of the band of interest is the means by which the current spectral-activity is monitored at periodic intervals by the MUDERS system. As the FFT process is an inherent element of the MUDERS receiver, the power spectral density of the band of interest can be extracted without incurring a significant increase in algorithmic complexity. The FFT stage in the receiver yields $N_{FFT}/2$ samples reflecting a snapshot of the frequency band from 0Hz (DC) to $F_s/2$, where F_s is the sampling rate. Periodogram information denoted by $M(k)$ is obtained by calculating L estimates of the Power Spectral Density (PSD) and averaging as described by:

$$M(k) = \frac{1}{L} \sum_{n=0}^{L-1} |Y_n(k)|^2 \quad (4)$$

One of the challenges with this approach is ensuring that the MUDERS wireless device does not misinterpret valid transmissions from another MUDERS as being interference. In order to minimise the possibility of this occurring, periodogram estimates are carried out during the null signal guard interval between OFDM frames in a received MUDERS transmission.

Interference present on the band of interest can be estimated by examining the periodogram information. A specific sub-carrier is used to transmit information if the

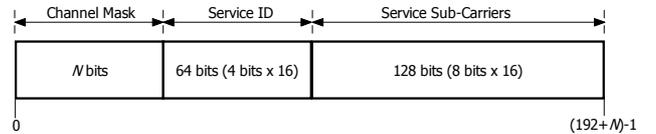


Fig. 3. Channel mask incorporating spectrum-allocation, number of services and individual service sub-carrier allocation information.

received signal power of that sub-carrier does not exceed a specific threshold value, as illustrated by Fig. 2. Prior to the transmission of a MUDERS OFDM frame, the set of N_{SC} valid sub-carriers is obtained by creating a binary channel mask shown in Fig. 3 that describes all of the possible

$N_{FFT}/2$ sub-carriers. The i^{th} channel mask of length $N_{FFT}/2$ is defined using the following rule:

$$\begin{aligned} M(k) &\geq P_{thresh} & c_i &= 0 \\ M(k) &< P_{thresh} & c_i &= 1 \end{aligned} \quad (5)$$

where P_{thresh} is a dynamically variable PSD threshold value.

Referring to Eq. 5, if $c_i(k)=1$, then sub-carrier k is available to convey information. If $c_i(k)=0$, the MUDERS receiver has deemed that sub-carrier k will not be used to transmit information during the next OFDM frame. In order to balance the requirements of maximal channel-capacity usage and increased robustness, sub-carriers which were deemed unusable due to interference or noise levels in excess of P_{thresh} are monitored during subsequent frame guard intervals. The channel mask is updated during each frame guard interval.

The modulated channel mask array forms the pilot values for a blind correlated-based frame synchronisation and carrier-frequency offset estimation scheme based on work by Schmidl and Cox [18][19]. In this implementation, an OFDM frame synchronisation symbol comprises two identical OFDM symbol halves. A carrier frequency offset (CFO) manifests itself as a difference in the pilot values between one half of the OFDM synchronisation symbol and the second half received T/2 seconds later. The CFO can then be measured and compensated for. Upon detecting this frame synchronisation symbol, called an Enhanced Training Symbol (ETS), the channel mask can be extracted by de-multiplexing the ETS.

4. IMPLEMENTATION

The MUDERS system, illustrated in Fig. 4, is implemented using C++ on a General-Purpose Platform. The required modules, which form the transceiver signal-chain are created as Dynamic-Link-Libraries (DLLs) where the parameters associated with this modules are ‘exposed’. This exposure allows the IRIS radio engine to manipulate the parameters in order to reconfigure the radio as required. The IRIS system controls the entire reconfiguration process,

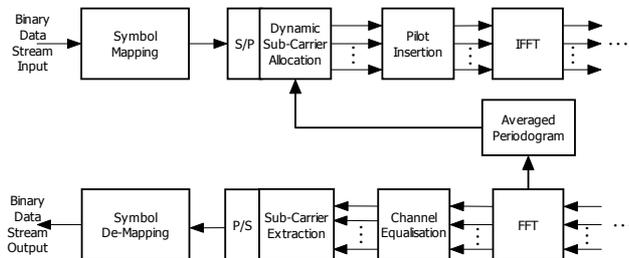


Fig. 4. Block diagram of main MUDERS implementation structure.

encompassing the application, structure, modules and parameters. The RF front-end used for live loop-back testing is a WaveRunner Plus 253 PCI-based radio module operating at a 70MHz Intermediate Frequency (IF). For the purposes of this paper however, baseband simulations are used in order to control the power and type of in-band interference for measurement purposes.

5. EVALUATION

A baseband channel model is used to evaluate the performance of the interference-avoidance dynamic OFDM technique. The channel model experiences interference from a FM transmission comprising three tones of equal power and common to both source and destination MUDERS transceivers. This interference source has a peak power of 2.9dBm and the centre frequency is located within the desired OFDM transmission band. Two scenarios are examined. The first scenario is a traditional static implementation of OFDM using QPSK as the sub-carrier modulation technique. All of the possible $N_{FFT}/2-1$ sub-carriers are employed regardless of the wireless channel conditions. For this test scenario, $N_{FFT} = 128$. The peak power of this OFDM signal is 0.16dBm. The second scenario employs the interference-avoidance sub-carrier allocation technique using 16-QAM on N_{sc} valid sub-carriers. The second scenario involves the same interference-affected AWGN channel model but the OFDM signal is changed. In this case, the threshold value P_{thresh} is equal to approximately 1% of the maximum estimated peak power of the interfering signal.

A graph of the BER vs E_b/N_0 for 1000 OFDM frames for each of the two scenarios is shown in Fig. 5, where the lower-bound graphs for QPSK and 16-QAM for interference-free AWGN channels are also displayed. The

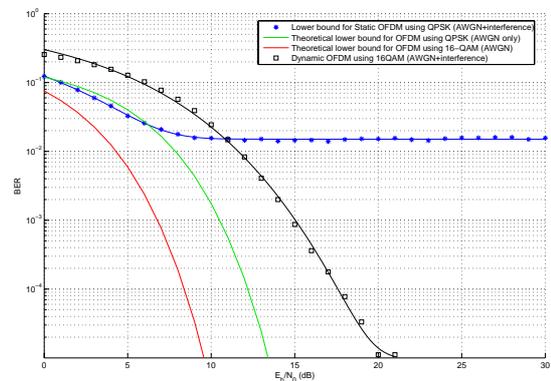


Fig. 5. Graphs of BER vs. E_b/N_0 for statically-allocated and dynamic interference-avoidance MUDERS allocation.

BER for the static QPSK case remains above 10^{-2} due to the interference yet the BER for the dynamically allocated 16-QAM case approaches 10^{-5} . Compared to a 48 sub-carrier fixed allocation OFDM signal, which had a BER of approximately 0.015 where $E_b/N_0 \geq 8$ and a total uncorrected data throughput of 96×10^3 bits per OFDM frame, the dynamically-allocated interference-avoidance OFDM technique achieved a BER of approximately 5.5×10^{-6} for $E_b/N_0 \approx 20$. The total number of uncorrected received data per frame using this technique was significantly increased to 18×10^4 bits.

6. CONCLUSIONS

This paper has presented an interference-avoidance dynamic sub-carrier allocation scheme designed for fair co-existence of several wireless services on a common frequency band. The core transmission technology used for the MUDERS system is OFDM and the reconfigurable radio platform is based on a general-purpose processor. Channel interference assessments are performed periodically during the null signal frame guard interval of the OFDM signal. A single Enhanced Training Symbol (ETS) is used by the receiver to obtain the current sub-carrier allocation information in addition to performing frame synchronisation and carrier frequency offset estimation. Results presented in this paper show that this dynamically-allocated interference-avoidance scheme both significantly increases the data-throughput capabilities and reduces the BER of the received signal compared to traditional fixed-architecture OFDM designs. Future work on this system involves improving spectral-activity awareness using cyclostationary channel estimation techniques to aid the identification of wireless services based on spread-spectrum techniques. Future work also includes evaluating the MUDERS system using a live-test and trial spectrum allocation.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

- [1] <http://www.sharedpectrum.com/?section=measurements>.
- [2] Weiss, T. A. and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency", *Communications Magazine, IEEE*, 2004, 42(3).
- [3] Leaves, P., K. Moessner, et al., "Dynamic spectrum allocation in composite reconfigurable wireless networks.", *Communications Magazine, IEEE*, 2004, 42(5): 72.
- [4] Cimini, L., Jr. "Analysis and Simulation of a Digital Mobile Channel Using Orthogonal Frequency Division Multiplexing." *Communications, IEEE Transactions on* [legacy, pre - 1988], 1985 33(7): 665-675.
- [5] Weinstein, S. and P. Ebert (1971). "Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform." *Communications, IEEE Transactions on* [legacy, pre -1988] 19(5): 628-634.
- [6] Nolan, K. E., "Reconfigurable OFDM Systems", *Ph.D dissertation*, Trinity College, Dublin, Rep. of Ireland, May 2005.
- [7] IEEE Std. 802.16-2001, "IEEE Standard for Local and Metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems". IEEE Std 802.16-2001: pp: 1-322.
- [8] IEEE Std 802.16a-2003, "IEEE Standard for Local and metropolitan area networks --- Part 16: Air Interface for Fixed Broadband Wireless Access Systems--- Amendment 2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11GHz". IEEE Std 802.16a-2003 (Amendment to IEEE Std 802.16-2001) pp:1-292.
- [9] IEEE Std 802.11a-1999, "Supplement to IEEE standard for information technology telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements. Part 11: wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: high-speed physical layer in the 5 GHz band".
- [10] IEEE Std 802.11g-2003, "IEEE standard for information technology-telecommunications and information exchange between systems- local and metropolitan area networks-specific requirements Part II: wireless LAN medium access control (MAC) and physical layer (PHY) specifications".
- [11] HIPERLAN type II, "HIPERLAN type 2 technical specification physical layer". Technical report, ETSI TS 101 475 V1.12.1A, June 2000.
- [12] ETSI EN 300 401 V1.3.3, "Radio Broadcasting Systems; Digital Audio Broadcasting (DAB) to mobile, portable and fixed receivers", May 2001.
- [13] ETSI ES 201 980 V.1.2.2, "Digital Radio Mondiale (DRM) System Specification", April 2003.
- [14] ETSI DVB-T, "EN 300 744 v1.5.1 Digital Video Broadcasting (DVB); Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television," Tech. Rep., June 2004.
- [15] K.E. Nolan, "OFDM Sub-carrier Allocation Scheme for a Multiple User Data Enhanced Radio Server (MUDERS)," in *Proceedings of the 4th Software Defined Radio (SDR) Forum Technical Conference 2004*, Phoenix, Arizona, USA, 2004. vol. A, pp: 71-76
- [16] P. Mackenzie, "Reconfigurable Software Radio Systems", *Ph.D dissertation*, Trinity College Dublin, Rep. of Ireland, Oct. 2004.
- [17] Mackenzie, P., Nolan, K.E., Doyle, L, O'Mahony, D., "An architecture for the development of software radios on general purpose processors," in *Irish Signals and Systems Conference 2002*, 2002, pp. 275--280.
- [18] Schmidl, T. M. and D. C. Cox (1996). "Low-overhead, low-complexity [burst] synchronization for OFDM". *Communications, 1996. ICC 96, Conference Record, Converging Technologies for Tomorrow's Applications. 1996 IEEE International Conference on*.
- [19] Schmidl, M. and D. C. Cox (1997). "Blind synchronisation for OFDM." *Electronics Letters* 33(2): 113-114.