Narrowband Signal Detection in OFDM Systems Using Spectral Shaping Techniques

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***Abstract*—Orthogonal Frequency Division Multiplexing (OFDM) allow data to be transmitted efficiently and reliably by using multiple orthogonal subcarriers. It provides robustness against noise and corruption in the channel. The channel can be either wired or wireless depending on the particular application. Due to the close spacing of subcarriers, OFDM is susceptible to corruption caused by various narrowband signals such as Narrowband Interference (NBI). Spectral shaping shapes the Power Spectral Density (PSD) in order to have certain properties. Spectral shaping might improve the effectiveness of OFDM and make it sustainable in the long run for applications beyond the 4th generation of mobile communications (4G) and Long Term Evolution (LTE). We make use of spectral null codes and load them onto OFDM subcarriers. Introducing narrowband signals in the channel degrades the system's performance and also eliminates the designed spectral properties. From this observation we infer that some narrowband noise is present in the channel. Previously, carriers hit by NBI or other narrowband noise had to be switched off manually. We found that combining OFDM with spectral shaping allows the presence of Narrowband signals in the channel to be detected and conclusions can be drawn over the channel quality. This did not improve the system in terms of bit error rate performance.**

***Keywords*—OFDM, spectral shaping, spectral null codes, NBI, power spectral density, wireless communications**

I. Introduction

An increasing demand for broadband wireless access motivates the development of more reliable and efficient techniques to be used in the next generation of communication systems, beyond the 4th generation of mobile communications (4G) and Long Term Evolution (LTE).

Recent developments in integrated circuits (IC) makes the use of multicarrier modulation methods like Orthogonal Frequency Division Multiplexing (OFDM) more economical and feasible. OFDM makes optimal use of the spectrum due to the overlapping of subcarriers. It is robust against many of the multipath effects and corruption typically introduced by the wireless channel [1]. The close spacing of orthogonal subcarriers makes OFDM susceptible to Narrowband Interference (NBI) which degrades the system performance. Further, the out-of-band (OOB) emissions present in OFDM makes it less usable in future applications such as the 5$^{\text{th}}$ generation of wireless communication (5G) [2].

Spectral shaping is a technique where the Power Spectral Density (PSD) is specifically designed in order to have certain properties. It is applied in optical transmission systems such as long distance optical fibre [3], [4], cognitive radio [5], mass storage systems and audio watermarking [6]. Spectral shaping may also be used to improve the effectiveness of OFDM and make it sustainable in the long run. Notch filtering, pulse shaping [7] and coding may be used to design the PSD.

Gorog describes how redundancy may be introduced in order to create codebooks with desired properties in their spectrum [8]. A certain type of spectral shaping code is called a spectral null code which has spectral nulls at selected frequencies. That is, the PSD at designed frequencies is zero. This is applied widely in the field of data storage, for example in magnetic and optical storage systems. A notable application is the inclusion of pilot tones on magnetic storage devices and compact discs (CDs). A pilot tone will provide the hardware with feedback on which physical part of a storage medium is currently being read, for example the current coordinates of a laser on a CD while it is rotating in the CD-ROM. The data on the CD is shaped using spectral null codes, and the pilot tones will coincide with the nulls in the stored data. This prevents pilot tones from corrupting the original data [9]. Gorog described the method for designing and constructing codebooks with codewords which have favourable spectral properties. Specifically, the construction of codebooks which will have spectral nulls at desired frequencies are called spectral null codes [8].

Narrowband signals are estimated to span the length of a single carrier and have an energy which can be an order of magnitude greater than that of the modulator [10], [11]. Various techniques may be used to estimate, cancel or suppress NBI, like cyclic prefix based methods [12], linear minimum mean-square error estimates (LMMSE) [10] and Hanning window estimation [13].

Ouahada proposed loading OFDM subcarriers with spectral null codes and adding a PSD detector at the demodulator.

The PSD detector can be used to detect the disappearance of spectral nulls. If a null disappears it gives an indication of corruption in the channel. An attempt is made to cancel NBI by replacing a corrupted carrier with a codeword from a lookup table containing spectral null codes. This method does not correct any errors. It only provided a substitution of corrupted bits with a code having desired spectral properties [11].

The techniques described by Ouahada can be used to detect subcarriers affected by NBI. For this investigation we make use of spectral shaping techniques (specifically spectral null codes) to achieve a desired spectrum. We investigate how to detect narrowband signals as well as the possibility of applying spectral shaping on OFDM carriers to estimate the channel quality, in terms of BER performance. We explore how spectral null codes can function as a sensor for the state of the channel. A missing spectral null code, where one was expected, indicates the presence of corruption. By sensing the channel and selectively switching off corrupted carriers, an improved BER performance may be achieved. This is investigated by means of simulations.

II. OFDM Simulation

The OFDM simulation consists of three main components namely the transmitter, channel and receiver. A codebook with spectral null codes is constructed and codewords from it is selected as the system's input. The basic design for the OFDM system remains the same for both wired and wireless applications.

A. Transmitter

The serial input data is constructed using codewords from the codebook of spectral null codes. The transmitter modulates and maps the serial input data onto the subcarriers by converting the serial input to a parallel representation. The Inverse Fast Fourier Transform (IFFT) is then applied which simplifies the implementation of the system [14]. An arbitrary modulation scheme may be used, but generally this choice depends on the throughput requirements of the system [15].

B. Channel

A wireless channel is used to investigate the performance of OFDM. During propagation in the wireless environment, the electromagnetic wave can follow a number of N_p unique paths due to various physical phenomena such as reflection and diffraction [1]. Each distinct path might have a different phase, amplitude, some Doppler shift or time delays [1]. This results in small and large scale fading, inter carrier interference (ICI) and inter symbol interference (ISI). The effects present in a channel is unpredictable and random. This channel can be modelled by making use of the Rayleigh fading model [16]. In addition, AWGN will also be present in the channel and we add NBI to investigate its effect.

Figure 1 compares the PSD for an OFDM system where no NBI is present in the channel to one where NBI is present. The addition of NBI resulted in distinct peaks in the PSD for both 16- and 32-QAM OFDM schemes.

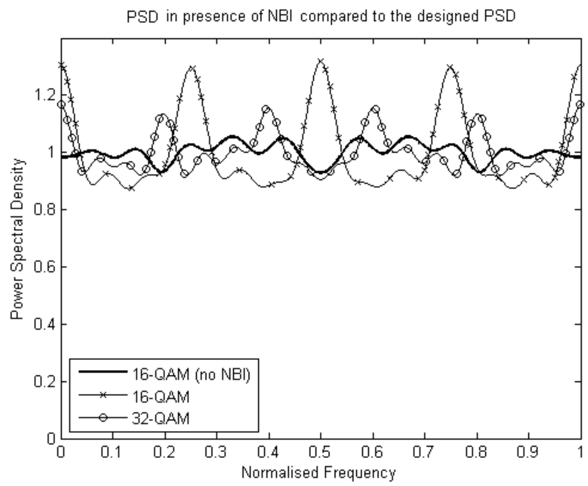

Fig. 1. Power spectral density for OFDM carriers with the effects of the NBI demonstrated

C. Receiver

The receiver will demodulate the transmitted data and analyse the PSD. Performance metrics such as the bit error rate (BER) is used to draw conclusions on the performance of the system as a whole.

III. Spectral Shaping and spectral null codes

Spectral null codes are designed to have a zero power spectral density at certain frequencies. The technique of creating spectral nulls at selected frequencies of the spectrum is called spectral shaping [9]. We create a codebook with spectral null codes which can be used to map data onto the subcarriers in the OFDM system.

A. Codebook

Consider a set S, the codebook of codewords satisfying some spectral null property. Let y be an element within S with $y = (y_1, y_2, \ldots, y_n)$ and $y_i \in \{-1, +1\}$. The codebook contains all symbols of length M having N nulls in the PSD over the normalised frequency. Having spectral nulls is equivalent to equating the PSD function to zero, $H(\omega) = 0$. PSD is defined as [8]

$$H(\omega) = \frac{1}{C_s M} \sum_{i=0}^{M-1} |Y^i(\omega)|^2 \tag{1}$$

where C_s is the cardinality of the codebook and M the length of the codeword. Y is the Fourier transform.

Assign a spectral null at $f = \frac{\omega}{2\pi} = \frac{1}{N}$, thus $\omega = \frac{2\pi}{N}$. From (1) we observe that $H(\omega) = 0$ when $|Y(\omega)| = 0$. Substituting for ω, it can then be noted that $Y\left(\frac{2\pi}{N}\right) = 0$. We apply the Fourier transform in order to obtain [8], [11]

$$\sum_{i=1}^{M} y_i e^{-j2\pi i/N} = 0 \tag{2}$$

Let $M = Nz$, where M is the codeword length and N is an integer representing the number of spectral null groupings. The amplitude of the vector i is denoted by

$$A_i = \sum_{r=0}^{z-1} y_{i+rN}, \qquad i = 1, 2, ..., N \tag{3}$$

By balancing the N vectors, a spectral null code may be constructed. The codebook will be denoted by

$$C_b(M, N) \tag{4}$$

1) Example where N is prime: With $M = 4$ and $N = 2$ we have $z = M/N = 2$. When N is prime, the location of spectral nulls is at

$$f = \frac{1, 2, \ldots, (N-1)}{N} \tag{5}$$

For this example, the null is at $f = \frac{1}{N} = \frac{1}{2}$. From equation (3) we find

$$\begin{aligned} A_1 = \sum_{r=0}^{1} y_{1+rN} &= y_1 + y_3 \\ A_2 = \sum_{r=0}^{1} y_{2+rN} &= y_2 + y_4 \end{aligned}$$

$y_i \in \{-1, 1\}$, but to keep simplicity in the below table we replace -1 with 0.

TABLE I
CODEWORDS WITH $M = 4$ AND $N = 2$

Entry	y_1	y_2	y_3	y_4	A_1	A_2
1	0	0	0	0	-2	-2
2	0	0	0	1	-2	0
3	0	0	1	0	0	-2
4	0	0	1	1	0	0
5	0	1	0	0	-2	0
6	0	1	0	1	-2	2
7	0	1	1	0	0	0
8	0	1	1	1	0	2
9	1	0	0	0	0	-2
10	1	0	0	1	0	0
11	1	0	1	0	2	-2
12	1	0	1	1	2	0
13	1	1	0	0	0	0
14	1	1	0	1	0	2
15	1	1	1	0	2	0
16	1	1	1	1	2	2

From table I the codebook $C_b(4, 2)$ can be constructed. For N prime, the requirement $A_1 = A_2 = \cdots = A_N$ must hold. The entries where $A_1 = A_2$ as indicated by the shaded area will satisfy the spectral requirement. A codebook of codewords obtained is all y_1, y_2, y_3, y_4:

$$C_b(4, 2) = \begin{Bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{Bmatrix} \tag{6}$$

A MATLAB application was developed in order to construct a codebook with any specification and it is used to map data onto subcarriers. Figure 2 shows the PSD for the codebook in (6). The PSD is estimated by making use of the `pwelsh` function in MATLAB [17].

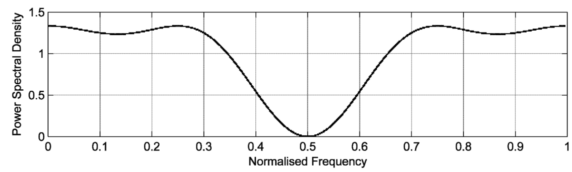

Fig. 2. Power spectral density for the codebook $C_b(4, 2)$ with $M = 4$ and $N = 2$

IV. SHAPED CODES WITH OFDM

In this section, the PSD of an OFDM system where all subcarriers are loaded with codewords having spectral nulls at a selected frequency f_n is investigated. For the purpose of this investigation the standard OFDM system is modified slightly to accommodate the usage of spectral shaped data. The key differences is the usage of a codebook in order to select symbols to be mapped onto the parallel subcarriers. We modify the source to index spectral null coded words which can be mapped directly onto the available subcarriers. The input is modulated and the IFFT is performed. The data is then transmitted through the channel. Suppose NBI is present. This may be caused by a variety of factors such as radio frequency interference emitted by devices such as microwaves or Bluetooth transponders [18]. NBI usually has a power far greater than that of the transmitter and it affects only a few individual subcarriers. NBI and additive white Gaussian noise (AWGN) will be added to the channel for each subcarrier k [19]:

$$r(k) \quad = \quad s_t(k)h(k) + n(k) + i_n(k) \tag{7}$$

s_t is the transmitter output, h is the channel response, n is due to AWGN and i_n represents the noise added due to the presence of NBI. $i_n(k) = \sqrt{10}R_{nbi}(k)$, assuming the NBI is uniformly distributed [20]. R_{nbi} generates a random number.

At the receiver the signal is demodulated and the FFT is performed, yielding bit data used to determine the BER performance of the system. The output is also passed through a PSD scope and analysed.

A. Simulations

Figure 3 shows the PSD for OFDM systems where spectral shaped codewords, as well as non-coded bits (random data) are used. The shaped codewords is selected at random from the codebook $C_b(16, 2)$. These codes are designed to have a null at $f = \frac{1}{2}$ of the normalised frequency, satisfying (5). This is clear when observing the null PSD for the coded input. The random input has a PSD which remains more or less constant throughout the bandwidth.

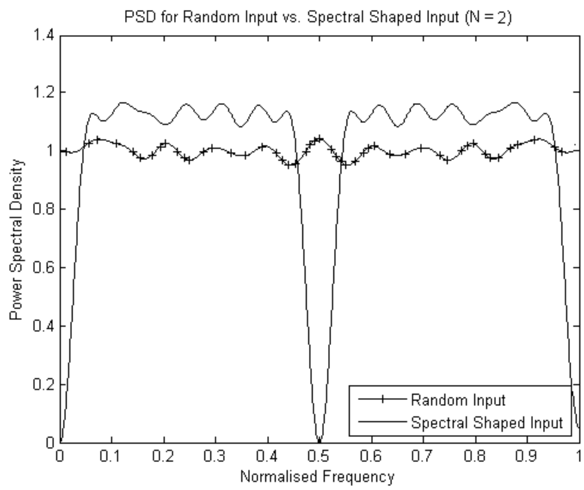

Fig. 3. Power spectral density for OFDM coded with codebook $C_b(16, 2)$ vs. Random input in AWGN channel

Figure 4 shows the PSD for codebook $C_b(16, 4)$ with nulls at $f = \frac{1}{4}$ and $f = \frac{3}{4}$.

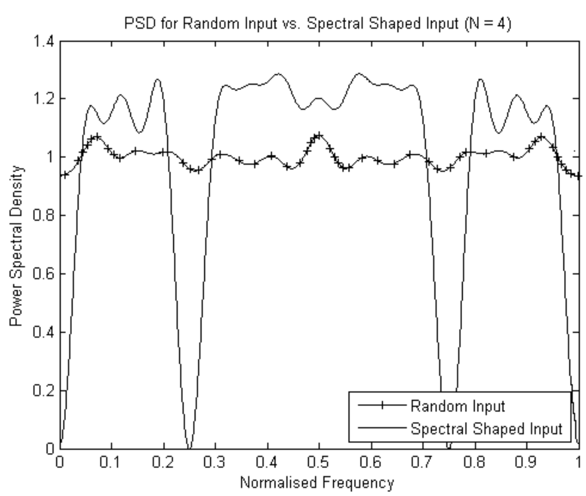

Fig. 4. Power spectral density for OFDM coded with codebook $C_b(16, 4)$ vs. Random input in AWGN channel

Using the spectral null codes and loading them onto OFDM subcarriers resulted in a PSD with nulls at desired frequencies. Both of these cases has AWGN present in the channel, which did not affect the PSD shape in any significant way. This design and the knowledge of the system's spectral properties has some interesting applications. The results are similar to other methods of spectral shaping such as FIR-filtering [2] and notch filtering [21].

V. Results and Analysis

From the previous section we have shown that the OFDM power spectrum may be shaped by loading specially designed spectral null codes onto the subcarriers. Consider figures 5 and 6 showing the PSD for coded data and the effect of NBI on the coded data. The PSD we designed for is the one observed when there is no NBI present in the channel. Observe that the addition of narrowband signals in the channel affects the shape of the PSD. The system does not conform to the designed spectral shape since the PSD at $f = \frac{1}{2} \neq 0$ in figure 5. Similarly we observed that spectral nulls also disappeared in the case where $N = 4$ in figure 6.

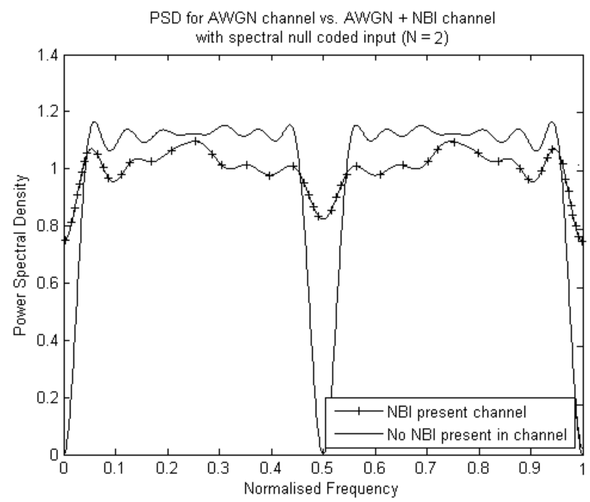

Fig. 5. Power spectral density showing the effect of NBI on spectral shaped data ($N = 2$)

The narrowband signal corrupted a small number of subcarriers. It is assumed that the bits become corrupted in such a manner that they do not adhere to any of the requirements for being a spectral null code. For those subcarriers, the PSD will tend more towards that of random data, diminishing the spectral properties we designed. Figure 7 shows the results of adding NBI to the channel for both random and spectral shaped inputs. These are compared to the designed PSD shape with spectral nulls. The NBI caused the random data to show peaks in its PSD and shaped data does not conform to the designed spectral null shape. Instead the spectral nulls disappeared and the PSD resembles that of random data in an AWGN channel.

The close spacing of subcarriers makes the system susceptible to NBI. Since the power of NBI can be an order

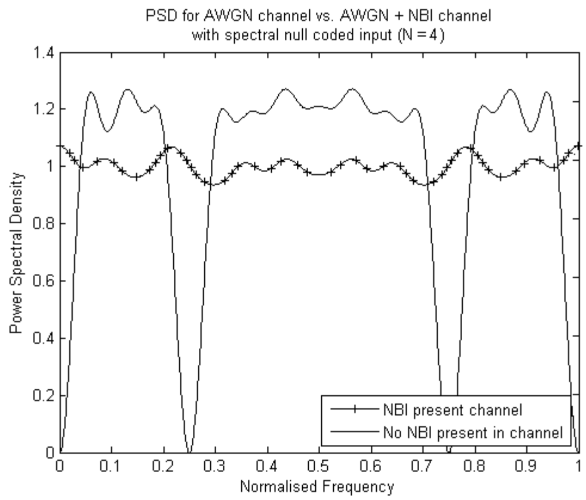

Fig. 6. Power spectral density showing the effect of NBI on spectral shaped data ($N = 4$)

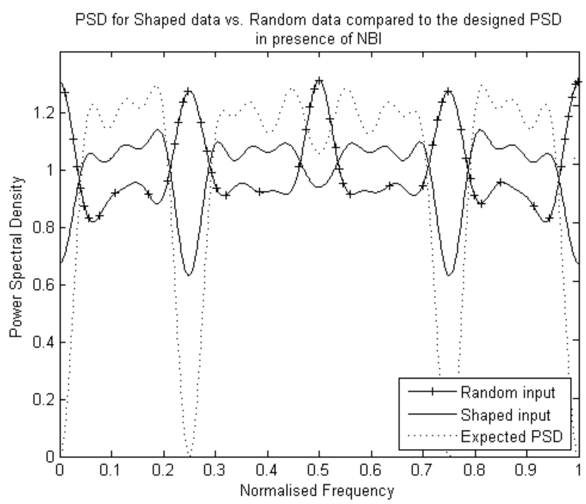

Fig. 7. Power spectral density for random input vs. shaped input in the presence of NBI, compared to the expected (designed) PSD ($N = 4$)

of magnitude higher than that of the signal, an increase in signal power does not improve performance. We note that the use of spectral null codes, even when the NBI coincides with the null frequency, did not improve the system performance. Without mitigation or error correctional techniques the performance of the system is degraded by NBI. Spectral coding therefore does not cancel NBI but rather serves as a sensor.

VI. Conclusion

The effect of narrowband signals on the shape of the PSD is observed. The spectral null is less prominent in the presence of narrowband signals and the spectrum tends more towards that of a random input. Using these observations, we can determine the channel quality and detect narrowband signals which might be present in the channel. However, applying spectral shaping does not yield a better performance in terms of the BER. The carriers loaded with spectral null codes still contained useful bits which became corrupted. The benefit of using spectral shaping techniques lies in the desired spectral shape which can be used to draw conclusions on the state of the channel. The disappearance or diminishing of the spectral null where a null is expected, is indicative of narrowband signals present in the channel. These results holds for both wired and wireless channels.

Future work will be focused on improving the channel quality estimation and more reliably detecting narrowband signals, specifically by loading only selected carriers with spectral null codes. The possibility of automatically cancelling narrow band interference when detected will also be investigated further.

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