The Optimal Employment of CSI in COFDM-Based Receivers

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Abstract: This paper investigates different methods of exploiting the Channel State Information (CSI) available at the receivers of Coded Orthogonal Frequency Division Multiplexing (COFDM)-based wireless communications systems in the equalisation, demodulation and/or decoding processes. The optimal method to be used is defined theoretically and computer simulations prove that the selected method outperforms the other methods by more than 5 dB SNR at 10^{-3} BER.

1. Introduction:

COFDM has been the core technology in the physical layer of many wireless communication standards, including WLAN standards such as IEEE802.11g and HIPERLAN/2, as well as digital broadcasting systems such as Terrestrial Digital Video Broadcasting (DVB-T) [1]. It is also a very powerful candidate for fourth-generation mobile communications systems either by itself or by employing the OFDM principles in other solutions such a Multicarrier CDMA (MC-CDMA) or Multicarrier DS-CDMA (MC-DS-CDMA).

One of the main advantages that make COFDM such an attractive approach is the way it deals with frequency selectivity. In a multipath channel the frequency selectivity of fading within the signal's bandwidth results in a significant increase of complexity at the receiver due to the advanced channel estimation and equalisation techniques that need to be applied. However, in OFDM, by splitting the signal's wideband carrier into several narrow-band subcarriers the channel can be considered to be flat-faded at every subcarrier, resulting in the simplification of the channel equalisation sub-systems into a one-tap equaliser problem. This gives rise to another advantage of COFDM by exploiting the frequency selectivity of the channel to improve the system's performance. By interleaving the relevant encoded bits onto several uncorrelated subcarriers it is less likely that these bits will be severely faded simultaneously. At the receiver, giving every bit a fair weight corresponding to its attenuation level should considerably improve the ability of the decoder to correct errors and enhance the overall system performance.

The weighting of bits relies basically on having a good knowledge of the channel conditions at the subcarriers on which they were transmitted. With this knowledge the Channel State Information (CSI) can be generated for every subcarrier. Many papers have proposed different methods of generating and utilising the CSI at different stages of the receiver. In [2] for example, CSI is considered first for frequency equalisation and then as a weighting parameter for the branch metrics of the Viterbi decoder. Likewise, in [3] CSI is employed in the equaliser and at the output of the demodulator. In [4], however, the division-based equaliser was replaced with the scaling of the demapper's constellation points using the CSI.

In this paper, different methods of employing CSI at different stages of the receiver are investigated, some of which are similar or close to the methods proposed in references [2]-[6]. The performance and complexity of these methods are compared and the optimal method among them is identified.

The rest of this paper is structured as follows: Section 2 describes the COFDM system model used to obtain the performance results presented in the paper. Section 3 summarises the different CSI-employment methods that are under examination. Section 4 provides the computer simulation results. Some complexity issues are discussed in Section 5, and the paper is concluded in Section 6.

2. System model:

At the transmitter side, as shown in Fig.1, N symbols each representing B channel coded and interleaved bits are mapped by an M-point mapper and the output symbols are multiplexed into N parallel branches and modulated each by a subcarrier through the normal OFDM modulation (IFFT) process. The output of the transmitter is the superposition of N signals in the time domain.

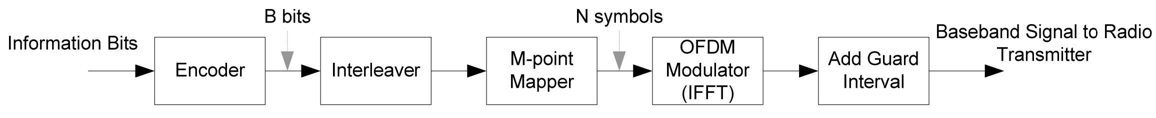

Figure 1: Structure of COFDM Transmitter

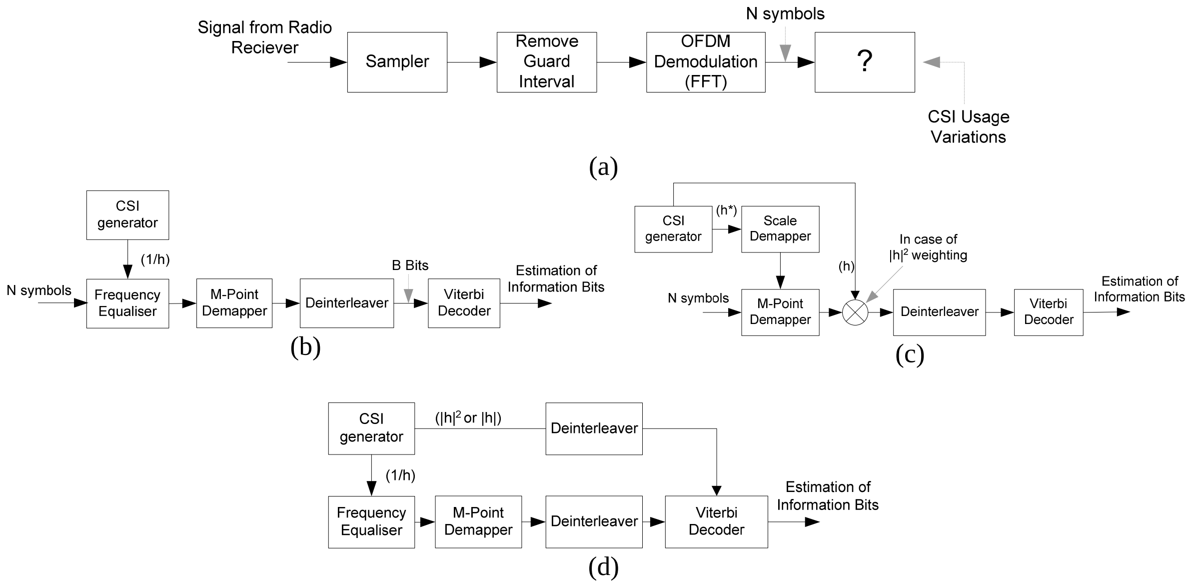

Figure 2: Structure of OFDM Receiver with different CSI Usage Methods

At the receiver (Fig. 2a) the received signal at the generic subcarrier after the FFT stage can be written as:

$$r(n) = h(n)x(n) + w(n) \tag{1}$$

Where $r(n)$, $x(n)$, $h(n)$ and $w(n)$ are the received signal, transmitted signal, complex flat-fading channel response and additive white Gaussian noise (AWGN) all at subcarrier (n), where $n = 1,2,\ldots N$, respectively. The channel is assumed to be perfectly known at all subcarrier positions. The following steps should be to equalise, de-map, de-interleave and decode the received signal. Several methods are available to achieve this; these are summarised in the following section.

3. Methods of Employing CSI:

3.1. Method 1: Conventional Equalisation, Demapping and Decoding

This method (Fig 2.b) is based on the zero-forcing theory. The received data are first equalised by dividing $r(n)$ by $h(n)$ to get the estimated transmitted signal $\hat{x}(n)$ given by:

$$\hat{x}(n) = x(n) + \frac{w(n)}{h(n)} . \tag{2}$$

This is then demapped to get soft values which are de-interleaved and passed to the Viterbi decoder to make its decision on the transmitted bits.

It can be noted here that there will be severe noise enhancement especially at null frequencies due to the division of noise by small values of $h(n)$ at the faded subcarriers, i.e. when $|h(n)| < 1$. This further distortion to the system may lead the decoder to wrong decisions on what the transmitted bits were.

3.2. Method 2: Weighting by $|h|^2$ or $|h|$ at the Demapper

This is basically achieved by first rescaling the demapper constellation points and consequently the threshold levels by multiplying them with $h^*(n)$, where $h^*(n)$ is the complex conjugate of $h(n)$. The soft outputs of the demapper which represent the distances between the received symbols and their respective 'rescaled' thresholds are then further multiplied by $|h|$ (in case of $|h|^2$ weighting) as shown in Fig 2.c. Mathematically, this is equivalent to first applying the previously-described zero-forcing equalisation to the received signal, demapping it, and then weighting the soft outputs by $|h|^2$ (or by $|h|$ if no extra multiplication is applied after demapping) to compensate for the noise enhancement caused by equalisation. This weighting step can be thought of as decreasing the likelihood level between the estimated transmitted signal and the constellation point which could have been modified by noise enhancement while giving more confidence to bits with strong channel conditions.

With this method we have two options; one is to directly apply the weighting by $|h|^2$ (or $|h|$) to all the subcarriers' symbols no matter whether they were faded or not, and the other is to limit the weighting to subcarriers with $|h|<1$, i.e. to faded channels. The demapper output can then be represented as:

$$d'(b,n) = \begin{cases} d(b,n) & ,|h| \geq 1 \\ |h|^2 d(b,n) & ,|h| < 1 \end{cases}. \tag{3}$$

Where $d(m,n)$ is the soft output of the demapper corresponding to the bit number m at subcarrier n, and $m = 1,2, \ldots B = \sqrt{M}$. The symbols at subcarriers with $|h|>1$ will be equalised by h using method (1) without weighting in any further stage of the receiver. It is suggested that weighting by $|h|^2$ should give better performance as it reflects the SNR of the signal at every OFDM symbol.

3.3. Method 3: Weighting by $|h|^2$ or $|h|$ at the Viterbi Decoder

If the outputs of the demapper are of unsigned values ranging between 0 and 1 to represent the closeness to either a 0 or 1 transmitted bit, respectively, then the normal decoding process holds except that when calculating the trellis metrics at the decoder the results will be multiplied by $|h|^2$or $|h|$ as shown in Fig 2.d. This can be written (in case of $|h|^2$) as:

$$z(l) = \sum_{k=1}^{K} (d_i(k) - c(k))^2 \times |h(k)|^2 \tag{4}$$

Where $z(l)$ is the branch metric of uncoded bit l, $d_i(k)$ is the output of the bit interleaver corresponding to the k-th encoded bit representing bit l and $c(k)$ indicates the representation of the codeword. The effect of weighting by $|h|^2$or $|h|$ here is to minimise the contribution of the severely-faded-subchannel bits in the calculation of the metrics. This would counter any noise enhancement caused by the equalisation step. The option of applying the weighting only to bits with $|h|< 1$ can still be considered as in the previous method.

4. Simulation Results

The simulations were run for the multipath-channel environment with RMS delay spread of 175 ns. The modulation scheme used is 16-QAM and the code is rate-½ standard convolutional code with constraint length = 7 followed by bit interleaving.

The performance of methods 2 and 3 (with no restriction on $|h|$) were tested and compared along with the conventional equalisation method (method 1). Also the use of both methods (2 and 3) together was simulated. The BER results are shown in figure 3. The modified method 2 which applies weighting only to subchannels with $|h|< 1$ was then tested and compared with the unconditional method 2. Results are shown in figure 4 where the terms "open" and "restricted" refer to the unconditional and $|h|< 1$ conditional constraints, respectively. The weighting by $|h|^2$ and $|h|$ are compared for both methods 2 and 3. The results of BER performance are shown in figure 5.

Figure 3 shows that both methods 2 and 3 when applied separately to the system significantly improve the performance of the system compared to the conventional equalisation. Their performances are almost the same. However it can be noted that applying both methods together degrade the performance. This can be reasoned as overweighting "strong" bits and underweighting "weak" bits more than their actual relative strengths.

Restricting the application of method 2 to low values of $|h|$ does not seem to have any significant effect on the performance of the system as implied in figure 4.

It can be seen in figure 5 that using $|h|^2$ as a weighting factor instead of $|h|$ in either method 2 or 3 always gives better results. This affirms what has been suggested in section (3) on that weighting by $|h|^2$ reflects the actual SNR of the symbol at every subcarrier, i.e. the relative power contained in that symbol.

5. Complexity Issues

In Method 2 rescaling the demapper with the values of h through multiplication reduces the complexity that would arise if the division-based equalisation was used in either method 1 or 3.

Moreover, using the CSI inside the Viterbi decoder assumes that these CSI values are buffered and then de-interleaved in a way similar to that applied on the demapped bits. This would increase the complexity of the architecture of the receiver as well.

Overall, from a complexity reduction point of view, method 2 with no export of CSI to the decoder is optimal.

6. Conclusion

It can be concluded that weighting by $|h|^2$ at either the demapper or the Viterbi decoder can significantly enhance the overall system's performance. The application of weighting should not be restricted to a range of $|h|$ values and the weighting should not be applied to both the demapper and the decoder at the same time. For complexity reduction reasons, applying the scaling and weighting at the demapper is preferable.

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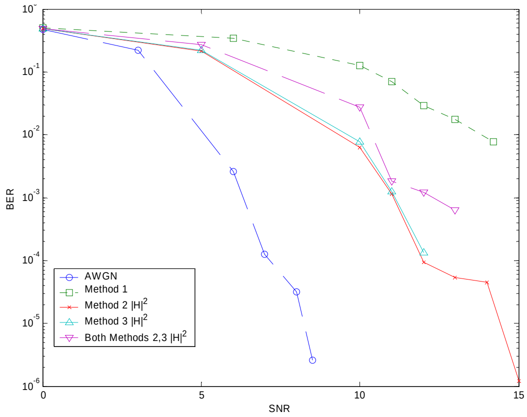

Figure 3: BER Performance of Methods 1,2 and 3

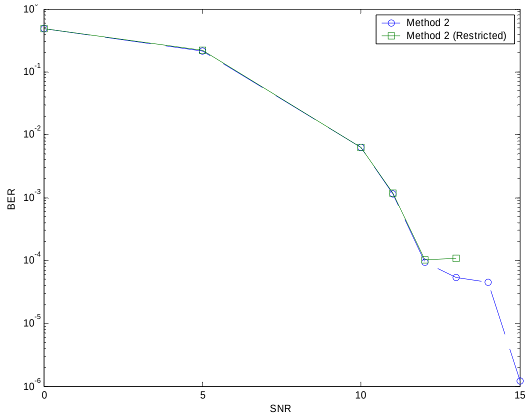

Figure 4: BER Performance of Method 2 (Open & Restricted)

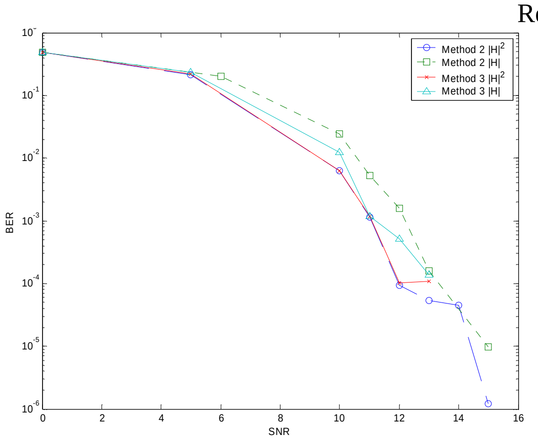

Figure 5: BER Performance of Methods 2 & 3 with $|h|^2$ & $|h|$