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Abstract

When installing a Digital Terrestrial Television (DTT) receiver in a household, it is important to have a measure of how far the reception conditions are from those leading to errors being noticed on the decoded picture or system failure point. Usually the installer has no means of either evaluating the quality of the transmission channel or estimating the carrier to noise ratio at the input to the receiver. Therefore the noise margin of the DTT installation is unknown.

Channel State Information (CSI) is crucial for any DTT receiver to work properly under poor reception conditions. This paper shows how an estimate of the average CSI can be effectively used to characterise the performance of a DVB-T system subject to different types of impairment. A thorough comparison between CSI and other performance indicators gives support to the use of CSI to estimate the noise margin in a DTT installation.

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USING CHANNEL STATE INFORMATION (CSI) TO CHARACTERISE DVB-T RECEPTION

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ABSTRACT

When installing a Digital Terrestrial Television (DTT) receiver in a household, it is important to have a measure of how far the reception conditions are from those leading to errors being noticed on the decoded picture or system failure point. Usually the installer has no means of either evaluating the quality of the transmission channel or estimating the carrier to noise ratio at the input to the receiver. Therefore the noise margin of the DTT installation is unknown.

Channel State Information (CSI) is crucial for any DTT receiver to work properly under poor reception conditions. This paper shows how an estimate of the average CSI can be effectively used to characterise the performance of a DVB-T system subject to different types of impairment. A thorough comparison between CSI and other performance indicators gives support to the use of CSI to estimate the noise margin in a DTT installation.

INTRODUCTION

When it comes to installing a Digital Terrestrial Television (DTT) receiver in a household, it would be useful to have a measure of how far the reception conditions are from those leading to errors being noticed on the decoded picture or system failure point. In other words, we would like to have an estimate of the noise margin[1] of a certain DTT installation.

Usually the installer has no means of knowing how good or bad the transmission channel is in a given location and neither an estimate of the Carrier to Noise Ratio (C/N) at the input to the receiver is available. Moreover, depending on the precise nature of the most likely impairment to adversely affect the reception of DTT signals in a particular installation (e.g. additive Gaussian noise or co-channel analogue interference) the noise margin may be fully determined by a totally different measurable parameter (C/N in a Gaussian channel or Carrier to Interference Ratio (C/I) for co-channel analogue interference).

Channel State Information (CSI) is crucial for any DTT receiver to work properly under poor reception conditions (1). Although its precise silicon implementation may vary between receivers from different manufacturers, the working principle behind it is roughly the same. Since the CSI is affected by not only the additive noise present in the channel (irrespective of where it originates) but also by the shape of the channel frequency response, it may prove quite effective in helping to characterise DTT reception.

The aim of this paper is to show how CSI can be used as a performance indicator for DVB-T systems. First, we present the theory behind Channel State Information so as to gain some more understanding about how it actually works. We then compare CSI measurements with

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[1] This is the term normally used in practice, though in principle the nature of the impairments does not have to be noisy.

those obtained with two other performance indicators — namely, Bit Error Ratio (BER) after the Viterbi decoder and BER before the Viterbi decoder (so-called Channel BER or CBER). This is done for several impairments typically found in practical scenarios. A subsequent analysis of the advantages and disadvantages of each measuring method will give support to the idea of using the CSI to estimate the noise margin in a typical household DTT installation.

THE THEORY BEHIND CSI IN COFDM

Any Coded Orthogonal Frequency Division Multiplex (COFDM) system must rely on the use of some kind of CSI in the receiver to attain close-to-optimal decoding performance. In DVB-T in particular (2), CSI is used to obtain the bit metrics which are fed to the Viterbi decoder. Roughly speaking the CSI associated with a particular carrier measures the reliability of that carrier and constitutes an a priori probability that the corresponding received data symbol is wrong.

Typically the CSI for each carrier is calculated as a properly defined distance *D* between the received data symbols and the constellation points. Namely, given the *k*-th channel equalised data carrier within the *l*-th OFDM symbol $\tilde{Y}_{l,k} = Y_{l,k} / \hat{H}_{l,k}$, where $Y_{l,k}$ is the received carrier and $\hat{H}_{l,k}$ is an estimate of the channel frequency response at the carrier's frequency, $H_{l,k}$, the CSI can be expressed as

$$\mathrm{CSI}_{l,k} = \underset{A \in S}{D} \left(\tilde{Y}_{l,k}, A \right). \tag{1}$$

D represents the 'metric' between the pair of points, whilst S denotes the set of all points A in the transmitted constellation. From the equation above it is clear that the higher the CSI the less reliable carrier k is.

What we define in this paper as average CSI corresponds to a quantised average of the CSI in Eq. 1 taken over the index k. This average ranges from 0% (totally reliable carriers) to 100% (totally unreliable carriers). It is worth pointing out that 0% is unlikely to be achieved in practice. Also note that the precise range of values is implementation-dependant.

In order to get a deeper understanding of how the CSI as defined in Eq. 1 works, let us assume that the received carriers are corrupted by additive white Gaussian noise. Then, we can write

$$\tilde{Y}_{l,k} \approx A_{l,k} + \frac{N_{l,k}}{\hat{H}_{l,k}}, \tag{2}$$

where $A_{l,k}$ denotes the constellation point transmitted on carrier k, $N_{l,k}$ is an additive complex white Gaussian noise with zero mean and power σ^2 , and the 'approximately equal to' sign accounts for any errors introduced by the channel estimation process.

Depending on the actual silicon implementation of the block that calculates the CSI, the final result will vary slightly but in general the average of Eq. 1 over the OFDM symbol index l is directly related to the Carrier to Noise Ratio at that frequency

$$\mathrm{C/N}_k = \frac{\left|\hat{H}_k\right|^2}{\sigma^2}. \tag{3}$$

Note that this C/N is almost identical to the average C/N measured in the time domain with a power meter when the channel frequency response is flat (numerator in Eq. 3 constant).

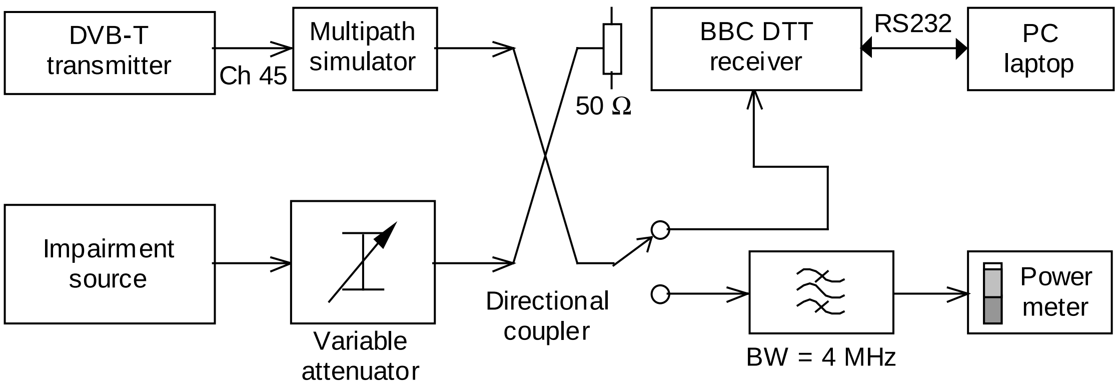


Figure 1: Lab set-up used to measure DVB-T performance**.**

LABORATORY SET-UP USED TO COMPARE DTT PERFORMANCE INDICATORS

The equipment used to record average CSI, post-Viterbi BER and pre-Viterbi CBER values for different types of impairments was set up as shown in Figure 1. A clean DVB-T transmitter produces a DTT signal according to the UK mode configuration — 2K FFT, 64 QAM constellation, rate 2/3 and guard interval 1/32 (2). The transmitter is fed with an external MPEG-2 source. The baseband signal is further up-converted to UHF channel number 45, whose nominal centre frequency is 666 MHz.

The channel simulator takes this RF signal and emulates its transmission through a multipath channel with up to 6 rays (main path and five echoes) whose relative delay and amplitude with respect to the main path, and type of fading (phase, Doppler or Rayleigh) can be varied independently.

The impairment source can be any of the following: wideband white Gaussian noise, co-channel analogue or DTT signals, and upper or lower adjacent analogue and DTT signals. A variable attenuator allows changing the power of the interferer in 0.1 dB steps. The useful DTT and interfering signals are then combined using a directional coupler whose non-used second output is assumed perfectly matched.

A switch is used to feed the resulting signal to either a DVB-T receiver or to a calibrated thermal power meter. The purpose of the 4 MHz bandwidth filter placed at the input to the power meter is first to reject all spurious out-of-band contributions to the measured average power and second to establish the bandwidth over which the power of the wideband Gaussian noise source is integrated. The actual shape of the filter is not important as long as it is used to filter both the useful DTT signal, which to a certain extent resembles narrowband Gaussian noise, and the noise-like interferers (Gaussian noise and DTT). This ensures an accurate measure of the C/N, despite of the absolute C and N values not being correct.

The DTT receiver is controlled and monitored by a software application running on a PC laptop. Since this application in turn averages the BER, CBER and CSI reported by the receiver, the variances of the resulting estimates are significantly smaller.

PRACTICAL RESULTS

In the following we present the BER, CBER and CSI results obtained for different types of channels and/or different sources of interference. To simplify the nomenclature, we will refer to the ratio between the DTT power and the interference power as C/I, regardless of the nature of the interference. A subsequent analysis of all this data will determine the feasibility of the average CSI as a measuring instrument in DTT.

Type of impairment	C/I_{REF} (dB)	CBER $\times$ 100	Average CSI (%)
Gaussian noise	18.9	5.1	47.4
Co-channel PAL	–2.1	6.5	32. 9
Upper adjacent PAL	–43.7	5	42.7
Lower adjacent PAL	–42	4.7	42.6
Upper adjacent DTT	–30.8	5	41.3
Lower adjacent DTT	–30.1	4.8	48.4

Table 1: C/I_{REF}, CBER and CSI for different types of interference.

Gaussian noise, analogue PAL and DTT interference

In Table 1 we show the C/I_{REF} (defined as the Carrier to Interference Ratio corresponding to a reference BER_{REF} of 2×10^{-4} after the Viterbi decoder) for several types of impairment. Also shown are the BER before the Viterbi decoder (CBER) and average CSI, both measured at the same reference level C/I_{REF}.

Curves of BER and CBER versus C/I are plotted in Figure 2a and Figure 2b for the six impairments of Table 1. The label on the x-axis Δ denotes the change in C/I relative to C/I_{REF} and represents a measure of the noise margin of the DVB-T system. An analogous plot for the average CSI is that shown in Figure 3.

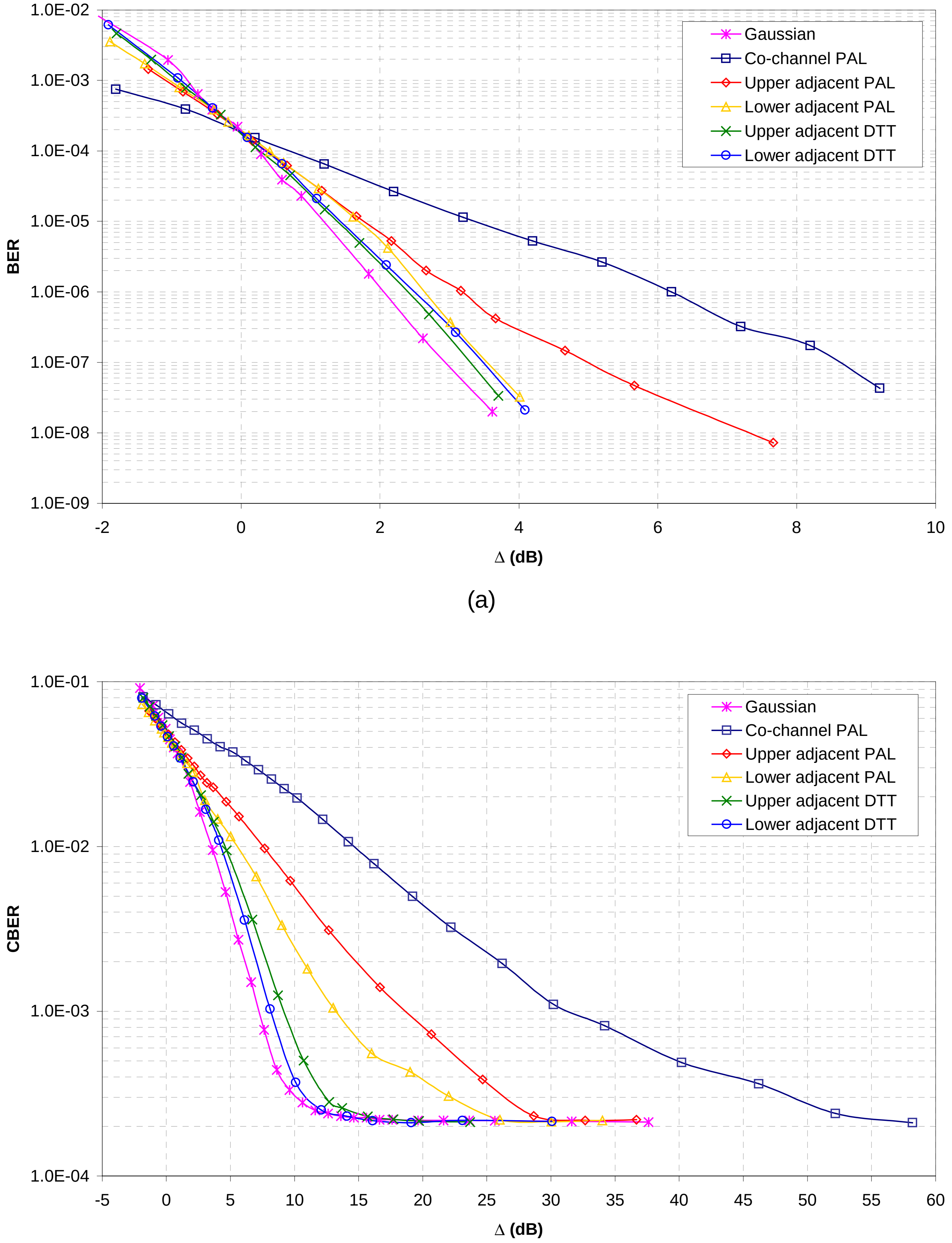
Except for co-channel and upper adjacent PAL, the BER curves in Figure 2a are fairly similar. However the range of C/I values over which the BER is non-zero and therefore can be used as a measuring instrument is rather limited (roughly 6 dB between the point at which the BER reads 10^{-3} and that at which it virtually vanishes). This, together with the fact that the BER curves in the presence of a PAL interferer behave differently, advises against the use of this parameter to measure the noise margin of a DVB-T receiver.

The CBER curves of Figure 2b are much shallower than the corresponding BER curves. For a PAL interferer these curves roll off very smoothly, especially in the co-channel case. For the other interferers the range of C/I values corresponding to discernible CBER values spans almost 15 dB. Although this may look like an improvement with respect to the BER plots, the use of the CBER as a performance indicator is hindered by the fact that PAL interference is still not properly accounted for.

The drawbacks pointed out above are totally overcome by using the CSI to estimate the noise margin. As it can be clearly seen in Figure 3, for any noise margin $\Delta > 8$ dB the spread of all the CSI curves is less than 5%. Thus for the six types of impairment shown in the inset box of Figure 3, the average CSI provides a good estimate of how far the receiver is from the point of failure. In fact for any given CSI the range of feasible Δ is always less than 5 dB wide. For all impairments except co-channel PAL, a rule of thumb valid in the linear region (between C/I_{REF}, where $\Delta = 0$ dB, and $\Delta \approx 7$ dB) is that a 1 dB increase in noise margin is accompanied by a decrease in CSI of 2.5% to 2.7%.

Multipath channels

From all the different types of impairments, multipath propagation is the most difficult to characterise, partly because its effects may range from relatively benign (a high amplitude echo within the guard interval) to catastrophic (the same echo being received outside the guard interval). A more thorough analysis of the impact of multipath propagation on the performance of a practical DTT receiver can be found in (3).



(a)

(b)

Figure 2: BER (a) and CBER (b) for the six types of impairment shown in the inset boxes. The variable Δ is the variation in C/I with respect to C/I_{REF} for each impairment.

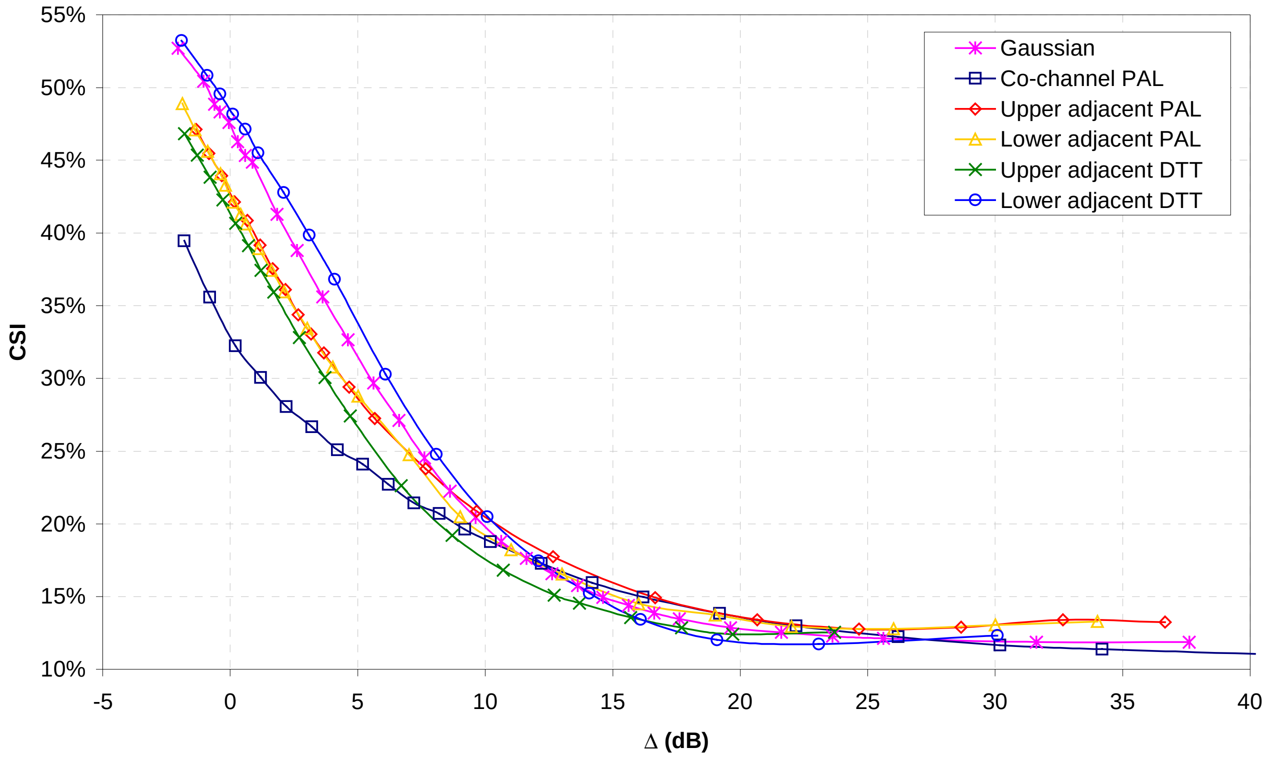


Figure 3: Average CSI for the six types of interference shown in the inset box. The variable Δ is the variation in C/I with respect to C/I_{REF} for each impairment.

Multipath channels with echoes resolvable by a DTT receiver introduce frequency-selective fading[2]. As a result the C/I for two sufficiently distant carriers may vary considerably. The CSI averaged over all carriers might then poorly represent the set of statistics describing the random vector $\{\mathrm{CSI}_{l,k}, \forall k\}$, suggesting that the mean CSI may not be telling the whole story.

Apart from greatly impinging on the performance of the receiver's time synchronisation, frequency synchronisation and channel estimation algorithms, multipath propagation may have both a *multiplicative* and an *additive* effect on the received DTT signal (3). The former is caused by echoes falling inside the receiver's time interpolation window, which add coherently to introduce a ripple in the channel frequency response. The latter is due to echoes arriving outside the guard interval, which cause InterSymbol Interference (ISI).

Figure 4 shows the echo attenuation (dotted lines) and average CSI (solid lines) measured at BER_{REF}[3] as a function of the echo delay for a 2-path channel. The echo was modulated with a Doppler frequency of 2 Hz, which stirs its phase relative to the main path. A time-varying frequency-selective channel is thus created without compromising the performance of the channel equaliser.

The effect of introducing some Gaussian noise into the system can be observed in the curves labelled Equivalent Noise Degradation (END) = 3 dB and END = 6 dB. The END represents the difference between the C/I measured when noise is present in the system and the C/I_{REF} for a Gaussian channel (see Table 1). An infinite END implies that no noise is added to the system.

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[2] As opposed to time-selective fading, in which the total received power fluctuates but any two frequencies within the channel undergo the same attenuation.

[3] In all cases BER_{REF} corresponds to an approximate CBER of 5×10^{-2}.

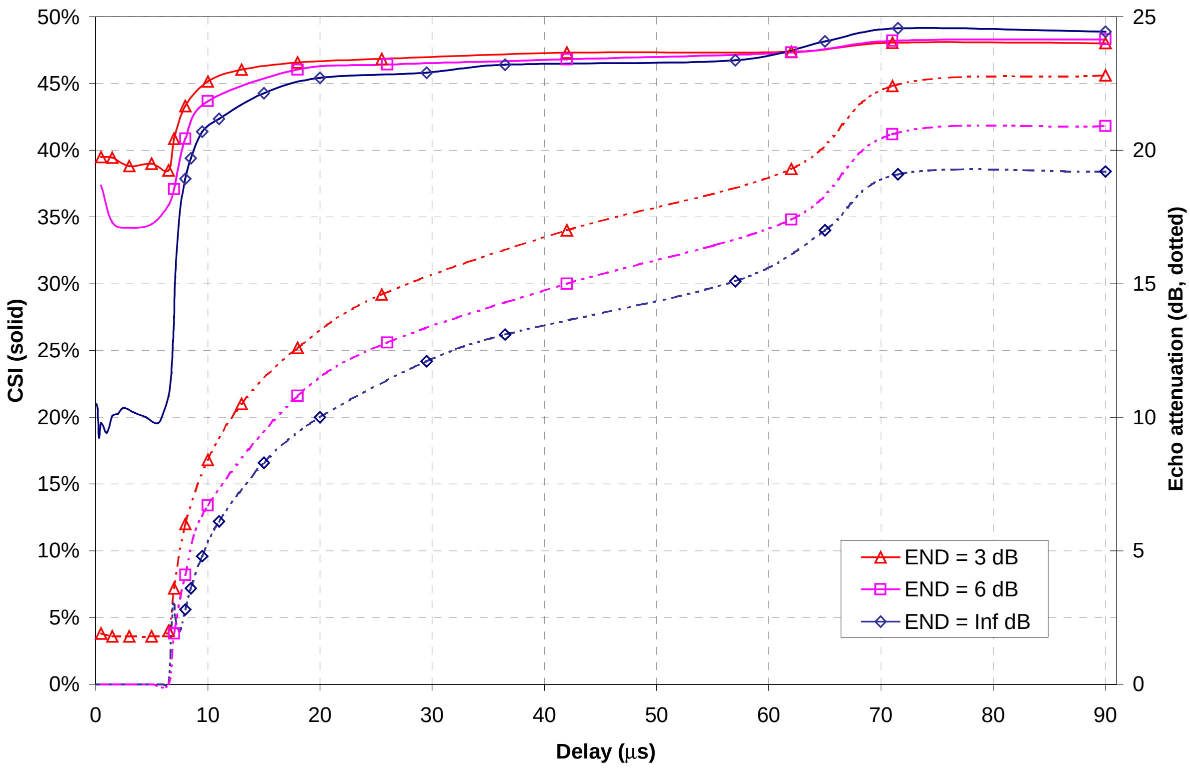

Figure 4: Average CSI and echo attenuation corresponding to BER_{REF} for a 2-path channel plotted as a function of the echo delay and the Equivalent Noise Degradation (END).

For 0 dB echoes inside the guard interval (7 μs for the UK mode) and low levels of Gaussian noise (END = 6 dB and ∞ dB) the BER stays always well below BER_{REF} (chart markers are used to indicate where BER_{REF} is actually achieved). The BER is logically higher for END = 6 dB due to the extra noise also responsible for the greater CSI level (20% versus 34%). For a 3 dB END the echo has to be attenuated 2 dB for the receiver to work. This has a small impact on the measured average CSI, which just rises from 34% to 39%.

Irrespective of the level of additive noise, a considerable number of carriers always fall into the deep spectral notch introduced in the channel frequency response by the 0 dB echo. These badly impaired data carriers lift the residual CSI floor from that measured for a noise-like disturbance (11% as shown in Figure 3) to approximately 19%.

As it might be expected, when the echo leaves the guard interval and ISI becomes dominant, the performance of the system approaches that for a Gaussian channel. For delays lower than 65 μs, which is roughly the maximum delay the channel estimator can handle and where part of the delayed signal still adds coherently, the CSI rapidly increases up to 46.5%, which is close to the CSI measured for a Gaussian channel (Table 1). Within this range of delays the more Gaussian the channel is (echo more attenuated and lower END) the higher the CSI, although this difference tends to vanish for increasing delays.

The gap between the 3 dB END and 6 dB END echo attenuation curves is around 1.8 dB, regardless of the echo delay. Similarly the 6 dB END curve lies 1.5 dB above the ∞ dB END curve. These values agree with predictions made using the empirical model proposed in (3).

When the echo delay is greater than 65 μs, it falls out of the time interpolation window and the channel estimator can no longer equalise it. This causes a slight boost in the average CSI, which is more noticeable (approx. 2%) when no extra Gaussian noise is added (END = ∞ dB). For the other two END values, there is just a 1% increase. For even longer delays the CSI remains approximately constant at a level which, apart from any experimental errors, should not depart much from that measured for a Gaussian channel.

CONCLUSIONS

In a DVB-T system the CSI constitutes a measure of the C/I level affecting every transmitted data carrier. In practice, this measure is typically related to the inverse of the average power of the equalised noise at each carrier position (Eq. 3). Therefore, the CSI is affected not only by the noise present in the channel but also by the shape of the channel frequency response.

For noise-like disturbances such as Gaussian noise and PAL and DTT interferers, the CSI proves a quite effective tool in helping to characterise DTT reception. In households with poor reception conditions leading to noise margins of less than 10 dB, a 1 dB decrease in C/I approximately corresponds to a 2.6% increase in CSI.

For multipath channels, unless additional information is available, it seems rather difficult to separate the contributions to the CSI arising from the channel frequency response and the equalised additive noise. In principle, we could use the estimated channel frequency response for that purpose, thus enabling the use of a suitably modified CSI as a measuring instrument in multipath scenarios.

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