Transmission of Hierarchical Broadcast Signals using Multi-Level-Codes

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Abstract. The digitisation of broadcasting media, such as radio and television, often results in the system requirement of reaching receivers operating under varying degrees of received signal strength. Cover (1972???) showed time-sharing to be inefficient, that is transmitting a robust but low quality signal multiplexed with a higher quality but more susceptible one. In this paper we propose the use of Multi-Level-Coding (MLC) in order to incorporate data streams of differing importance into one modulation scheme. MLC with 8-ASK (Amplitude Shift Keying) is chosen as an example and compared against time-sharing.

Zusammenfassung. Die Digitalisierung des Radio- und Fernsehrundfunks führt oftmals zur Forderung nach der Verwendbarkeit von Empfängern, welche bei unterschiedlichen Empfangsfeldstärken arbeiten. Cover (1972???) hat gezeigt, dass das sogenannte Time-Sharing ineffizient ist. Time-Sharing bedeutet hier die abwechselnde Übertragung eines qualitativ hochwertigen Signals und eines in der Dienstequalität verringerten Signals, welches im Gegenzug robuster gegenüber Störungen auf dem Übertragungskanal ist. In diesem Beitrag schlagen wir die Verwendung von Multi-Level-Codierung (MLC) vor, welche es ermöglicht Datenströme unterschiedlicher Priorität innerhalb eines Modulationsverfahrens parallel zu übertragen. MLC unter Verwendung von 8-ASK (Amplitude Shift Keying) wird hierbei als Beispiel gewählt und mit Time-Sharing verglichen.

1 Introduction

The introduction of hierarchical modulation to digital broadcasting systems is driven by two major problems concerning the receivers. Firstly, highly complex systems, such as high definition digital television (HDTV) [???4,6], call for the possibility of having receivers at reduced cost that implement only a subset of the maximum performance in terms of screen size and resolution, thus allowing for portable equipment with antennas of reduced aperture e.g. Secondly, digital radio broadcasting applications have to overcome the annoying effect of the sudden drop out of the program at the receiver due to the fact that the entity of digital modulation and forward error correction performs almost perfect at elevated signal to noise ratios and then degrades to no possible service within a few tenth of a decibel of received signal strength. In such an environment the source decoder is not able to provide graceful degradation and therefore the user has to live with sudden and possibly repeated drop outs. The latter scenario is for example encountered in a mobile reception environment or in digital short wave transmissions over the ionosphere that are currently under investigation by Digital Radio Mondiale (DRM), an international consortium developing digital radio broadcasting to replace analogue AM below 30MHz [3???]. Additionally, a more robust transmission channel could be used to serve an enlarged service area.

For all the above scenarios, hierarchical modulation offers a possibility to provide more flexibility to the receivers, flexibility that was perfectly provided by the old analogue systems. The recently increasing interest in such techniques is mainly due to the fact that source coding is now able to support such capabilities efficiently, the currently evolving MPEG 4 standard e.g. [10???].

2 Multi-Level-Coding

2.1 System overview

The key feature of Multi-Level-Coding (MLC) is the mechanism of splitting the transmission channel into several logical subchannels, with the number of such subchannels depending on the size of the signal constellation of the modulation scheme. A scheme using a signal constellation of 2^l -points can be divided into l subchannels with a maximum capacity of 1bit/s/Hz each. Subsequently, for every subchannel one has to design an individual pair of encoder and decoder. This mechanism is depicted in figure 1, showing MLC for a 2^l-point signal constellation thus having l levels.

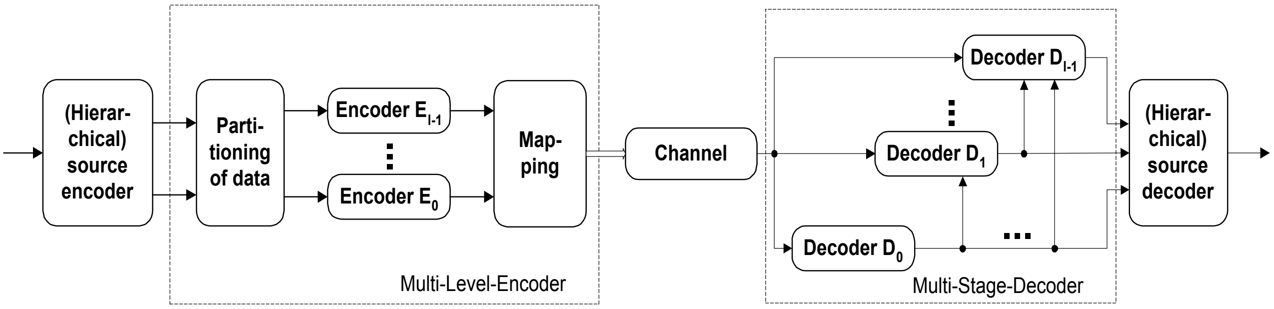

Figure 1. Structure of a Multi-Level-Coding system

2.1.1 Encoder

The encoder can be described with three sequential steps. Firstly, the input data stream is partitioned into l parallel streams that are feed each into its proper encoder. Secondly, every such encoder, operating at a well chosen code rate, adds redundancy to the bitstreams on the individual levels. The details on the demultiplexing of bits to the individual levels and the choice for the code rates are given in section 2.3???. However, we will not compare any particular coding schemes against each other, since the theoretical values for the achievable channel capacities are independent of such a choice. Thirdly, the encoded bitstreams are mapped onto the signal constellation containing 2^l-points and transmitted over the channel. The choices that exist for the partitioning strategies are mainly set by the receiver architecture and will be described in more detail in section 2.3???.

2.1.2 Decoder

The structure of the decoder we use, is the so called multi-stage decoder. It reduces the complexity as compared to a maximum likelihood sequence estimation (MLSE) decoder, that processes the full constellation within one step, by successively decoding the individual binary levels. The decoding of every, but the lowest, level takes into account the results from previously decoded levels. It is important to note (Wachsmann????), that such a decoder structure can achieve the maximum channel capacity derived by information theory.

As it was said before, we will limit our examples to 8-ASK since all major effects can be shown this way. Nevertheless, it has to be noted that this does not result in any limitation for the use of our results in practise, since the constellation most often encountered, namely quadrature amplitude modulation (QAM) is contained within the example of ASK. It can be interpreted as modulating two orthogonal carriers with an ASK constellation each. By doing so, the complexity per decoded bit will also not be increased since the same encoders/decoders are used on the corresponding levels for both the inphase and the quadrature component. In the case that block codes are used as components codes, this is highly desirable as it increases the block length of the codes at a constant delay as compared to encoding the components separately (Fischer et al. ???).
The problem of error propagation that can arise in such a sequential structure is strongly depending on the partitioning strategy.

2.2 Partitioning strategies

The different partitioning strategies for the signal constellations can be divided into three main categories. The classical, so called Ungerböck partitioning (UP) that is known from trellis coded modulation (TCM) and is aimed at maximising the intra subset minimum Euclidean distance. An inverse strategy, that we call block partitioning (BP). This scheme minimises the intra subset minimum Euclidean distance and below will prove to be very helpful for hierarchical systems. Last but not least, a combination of both that we want to call mixed partitioning.

2.2.1 Ungerböck partitioning

This standard way of segmenting a partitioning tree is shown in figure 2 for 8-ASK The individual x^i represent the labels associated with the i^th^ level of the MLC scheme, thus the second point from the left of the constellation has the label **x** = $(x^0\ x^1\ x^2) = (1\ 0\ 0)$ e.g. Stepping trough this binary partitioning tree, it becomes evident that the Euclidean distance between common point of a subset increases towards the higher levels of the mapping scheme. It also becomes clear, that error propagation can become a problem for any such mapping scheme, since an demapping error on a lower levels effects all decisions taken on the following upper levels.

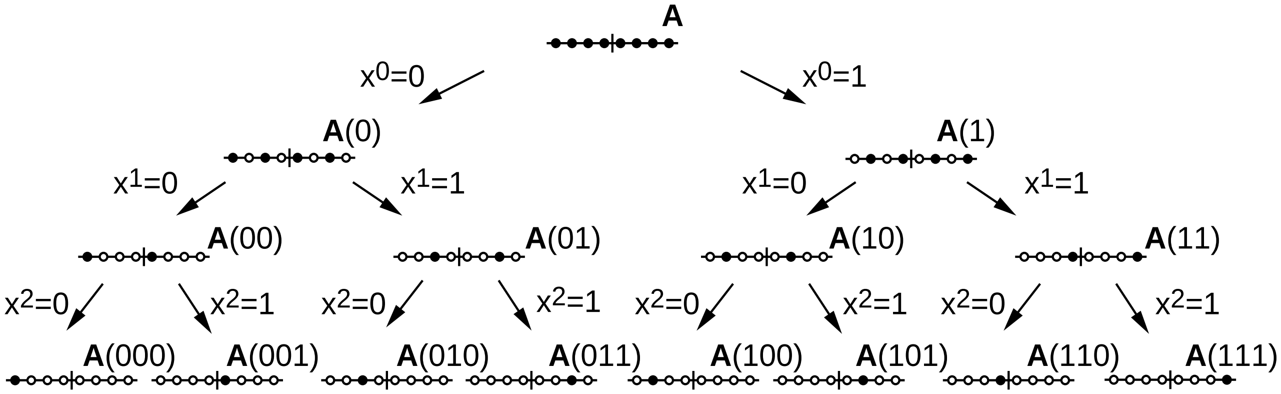

Figure 2. Ungerböck partitioning for 8-ASK

2.2.2 Block partitioning

The inverse strategy to UP, is called block partitioning (BP) (Wachsmann???). As depicted in figure 3, BP minimises the intra subset minimum Euclidean distance. For the decoder this has the advantages that only one comparison against a single threshold has to be taken at every level of decoding. Furthermore it is important to note, that although the channel capacity is independent of the partitioning strategy, it has been found (Wachsmann???) that for a finite block length, UP is more power efficient than BP. Therefore, a level using BP calls for the use of a long and powerful block code, such as a Turbo-Code e.g. We will not further investigate this effect in this paper, since for Turbo-Codes e.g. an increase in block length does not increase decoding complexity but only the necessary memory and decoding delay.

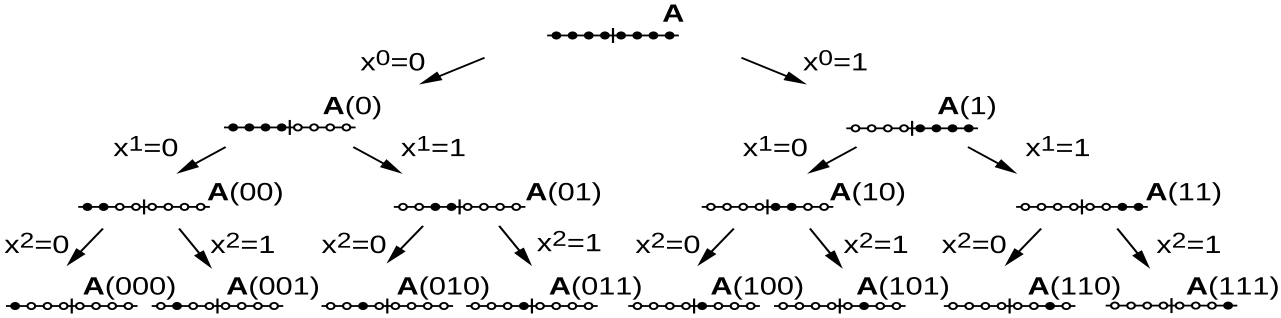

Figure 3. Block partitioning for 8-ASK

2.2.3 Mixed partitioning

Clearly, the two partitioning approaches mentioned above can be interchanged with each other, to adapt the number of hierarchically decodable levels to the system requirements. This results in what we want to call mixed partitioning (MP). Within this contribution we will focus on the following partitioning sequence : BP-UP-UP, meaning that the first partitioning step is done according to the BP-rule whereas the remaining steps are done by UP. As will be shown shortly this results in a system having two possible degrees of received signal strength under which decoding of a part or the entire signal is possible.

2.3 Rate-Design

The three partitioning strategies result in very different degrees of freedom for the design of the coding rates of the individual levels.

Starting with UP for 8-ASK, figure 4 shows the symbol energy over noise ratio (Es/No) versus the capacities of the individual levels and the overall system capacity. The capacity function of the level to be decoded first, named C_0, is the furthest to the right of all three levels with the others successively being shifted to lower Es/No in the order they can be decoded. Since it is not efficient to operate a level at an Es/No lower than that of a level which has to be decoded at an earlier stage in the multi-stage decoder, set partitioning using the UP approach can not achieve a hierarchical decodable signal constellation. For a non hierarchical system, one will chose the necessary overall spectral efficiency (2.5

bit/symbol e.g.) and subsequently choose the code rates according to the capacities of the three level at the single Es/No corresponding (here ???dB) to the desired overall capacity.

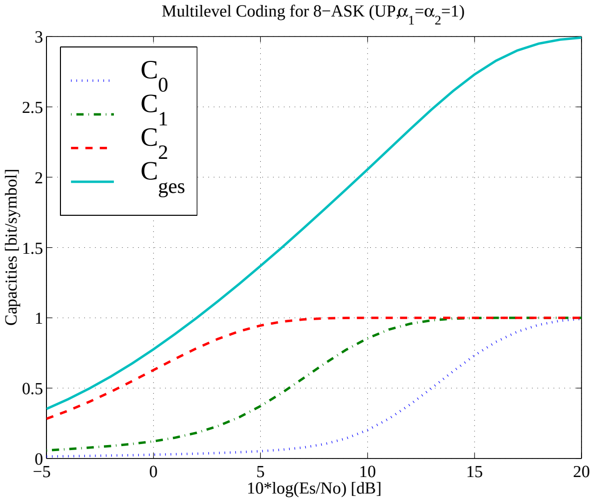

Figure 4. Capacities for 8-ASK with Ungerböck partitioning

The choice of BP instead of UP inverts the position of the capacity functions of individual levels with respect to each other. As it can be seen from figure 5, the level to be decoded first is the furthest to the left in the capacity vs. Es/No plot.

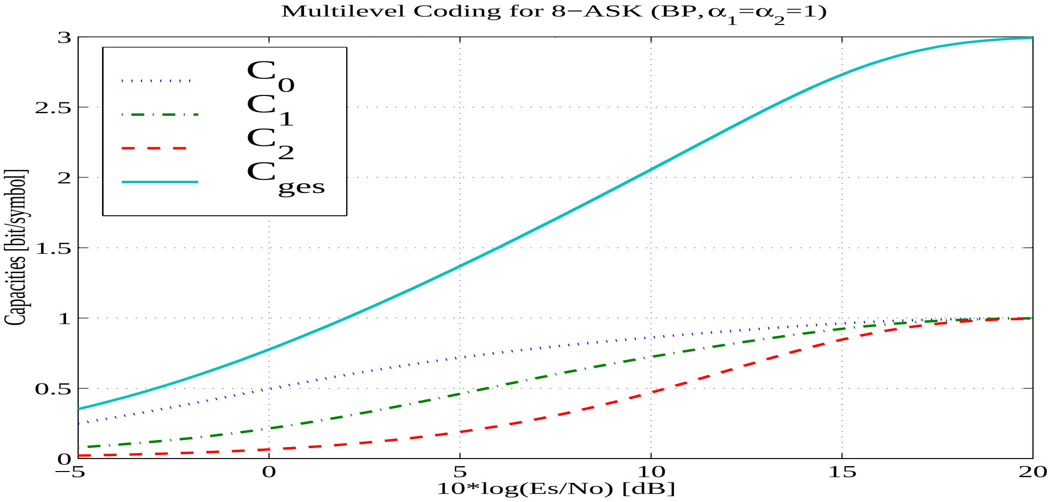

Figure 5. Capacities for 8-ASK with block partitioning

As a result, one has a wide choice for the Es/No at which to operate the individual levels. Thus we can achieve a signal with multiple qualities, in terms of required Es/No for decoding, with on single constellation. One could for example set the coding rates on all levels to ½ and obtain three quality levels with a separation of approximately 5dB at each step. Hence we can say that every block partitioning step results in the possibility for an additional quality step. Keeping in mind, what we said about finite block lengths with respect to a choice between BP and UP, we conclude that a system should incorporate exactly number of BP-step in the partitioning tree that corresponds to the number of desired quality levels that are to be transmitted. This leads us to figure 6, giving an example of what we above called mixed partitioning. The example chosen has two quality steps and the chosen partitioning scheme is BP-UP-UP. The curve for C0 is identical to the one in figure 5. Additionally figure 6 contains the summed capacity of levels 1 and 2 denoted with C_{12}. For the rest of the paper we will choose this example with the capacities set as follows : C_0=1/2, C_{12}=3/2.
Please note that the curve for the overall capacity C is independent of the partitioning and that the points of the signal constellation are equally spaced for the three figures 4,5 and 6. The spacing of the signal points is the degree of freedom in the design process we want to address next.

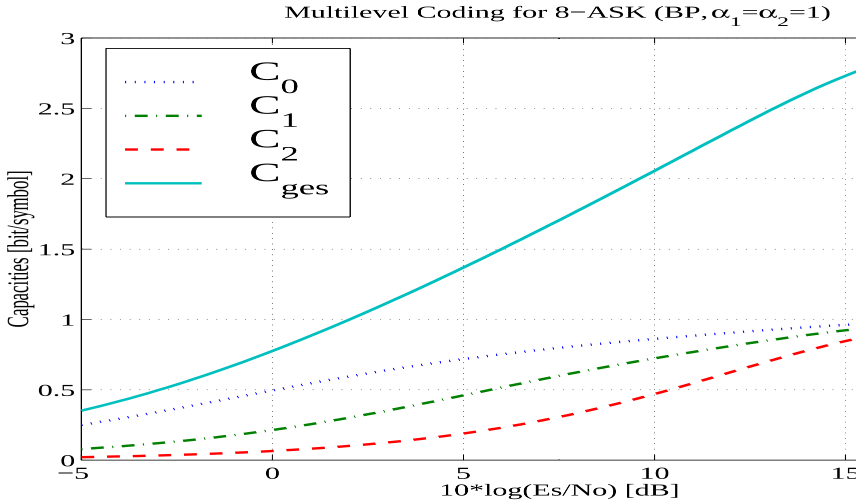

Figure 6. Capacities for 8-ASK with mixed partitioning

3 Non-uniform signal constellations

The third degree of freedom in the system design for MLC is the placement of the signal points themselves. Figures 2 and 3 showed constellations with equally spaced signal points. By allowing the points to be placed at arbitrary locations on the axes one obtains additional degrees of freedom. Below we will limit ourselves to constellations maintaining a maximum degree of symmetry in order to keep decoding as simple as possible. Following the classification of signal constellations as given by [5,6,11???], this results for level i of a MLC to be represented by a set of 2^i identical sub-constellations each of which is symmetrical with respect to a single decision threshold at its centre but the minimum distance of the nearest points to the threshold being a free system parameter.

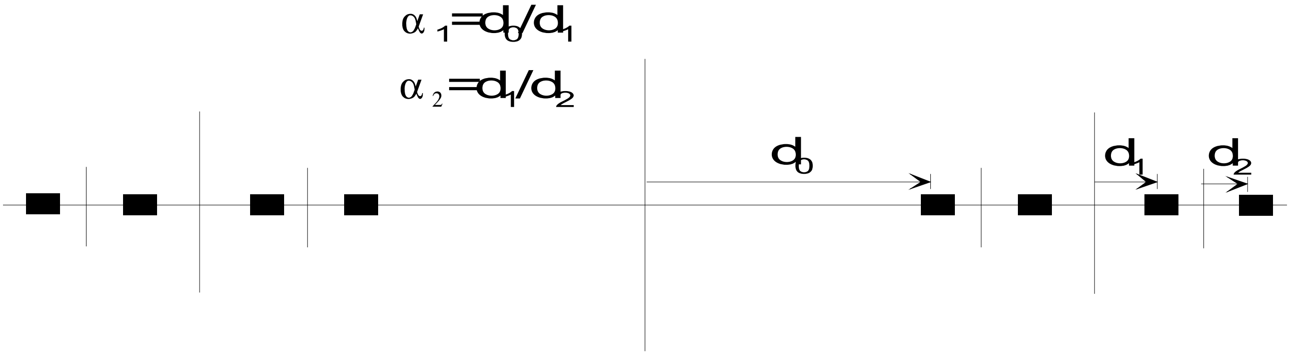

Figure 7 : Unequal distribution of signal points

Taking again 8-ASK as an example, figure 7 defines the parameters α_1 and α_2 to be the degrees of deviation from a constellation with equally spaced signal points ($\alpha_1 = \alpha_2 = 1$). α_{i+1} is defined as the ratio of the Euclidean distances of the closest signal point to the decision threshold of level i over the closest signal point to threshold i+1. To make any comparison possible, all constellations are normalised to the same average energy for one symbol and all N signal points I_k are assumed to be equally probable ($p_k = 1/N$):

$$\sum_k p_k I_k^2 = \frac{1}{N} \sum_k I_k^2 \overset{!}{=} 1 \qquad (1)$$

Figure 8 gives examples for the influences of the parameters α_i to the signal constellation. Any change for an α_i results in a variation of the capacity levels, thus increasing the choice for capacity versus signal to noise ratio. Figure 9 gives an example for α_1=2 and α_2=1 together with MP. Comparison with figure 6 shows the lowest levels to have become more robust, whereas the upper levels need higher signal to noise ratios to obtain the same capacities as for the equal distribution of signal points.

More detail on these effects can be found at (Schill ???).

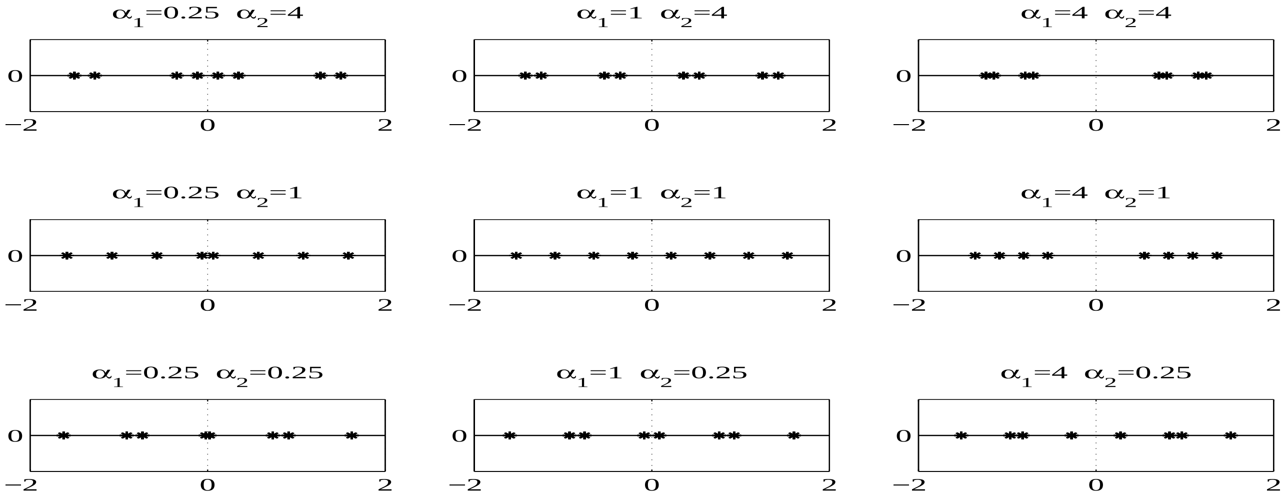

Figure 8. Influence of $\alpha_{1;2}$ to the 8-ASK signal constellation

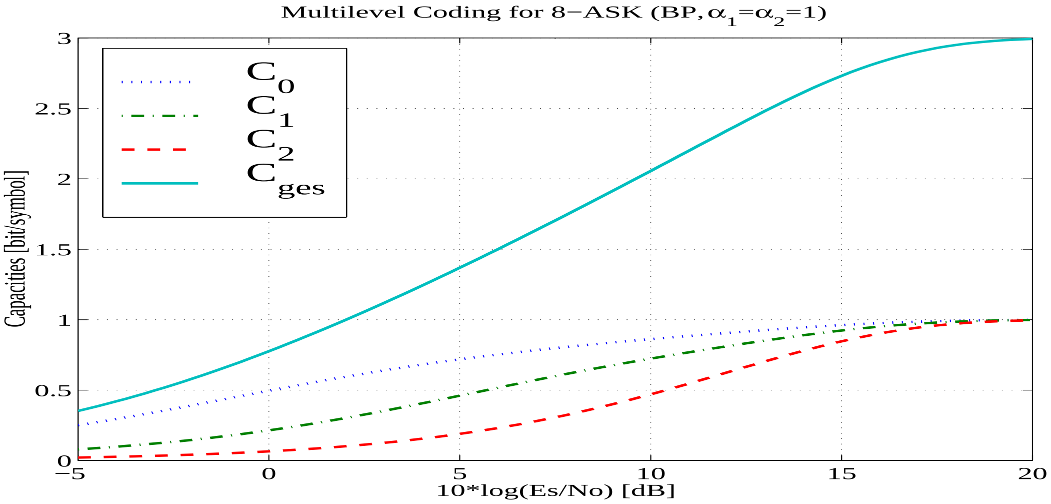

Figure 9. Capacities for 8-ASK with mixed partitioning, $\alpha_{1=}2$ and α_2=1

4 Multi-Level-Coding versus Time-Sharing

The simplest approach to transmit to signal qualities over the same channel is time sharing (TS). The transmit site generates two qualities by changing the modulation scheme, coding or both (16 and 64 QAM e.g.). Having obtained two classes of signals they are multiplexed onto the transmission channel by time division multiplexing e.g.. We call the robust signal S_{base} and the more susceptible but higher service quality signal S_{enh}. S_{base} uses ρ*100% of the transmission resources whereas S_{enh} utilises the remaining (1-ρ)*100%. Hence the total capacity C_{tot} of a time sharing system is given by equation 2:

$$C_{tot} = \rho \cdot C_{base} + (1-\rho) \cdot C_{enh} \tag{2}$$

Comparing the MLC schemes introduced above with a classical time sharing approach for achieving variable signal qualities we have to either fix the target capacities we want to transmit and compared the necessary SNRs or to fix the available SNRs and compare the achievable transmission capacities.

4.1 Fixed SNRs and variable capacities

Figure 10 gives an example for a base layer that is decodable at an Es/No of 0dB whereas the enhancement layer requires 10dB Es/No. TS allows for a linear exchange in transmission capacity between the base and the enhancement layer. The two extreme points that can be realised one transmit in one of the two qualities (ρ=0 and ρ=1). For comparison, MLC is used with the value for α_2 fixed to its optimal of 0.9 and α_1 varying between $0 < \alpha_1 < \infty$.

Additionally some point for α_2=1 are included as the values of $\alpha_2 = 1$ and $\alpha_1 = 1,2$ and 4 are defined within the DVB-T standard (????). Clearly the MP-scheme outperforms TS by an important amount.

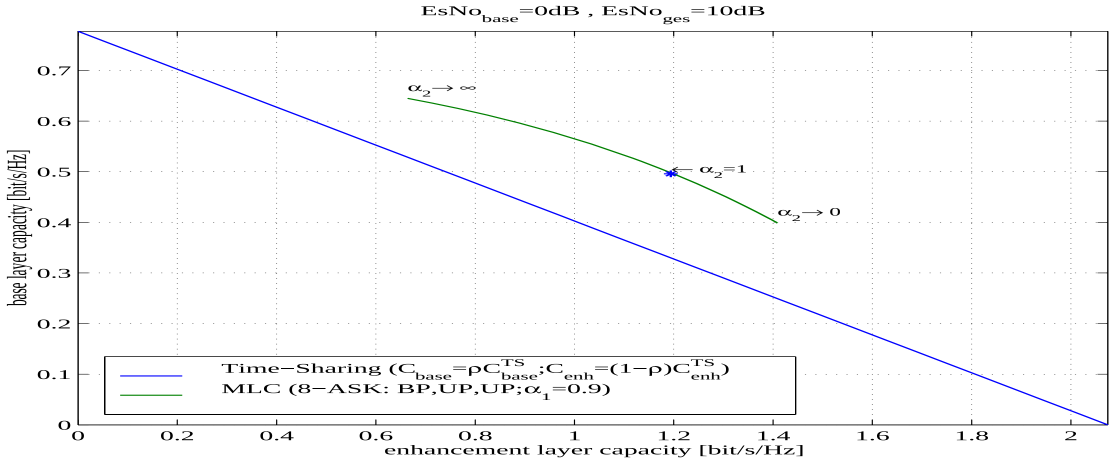

Figure 10. Comparison MLC vs. time sharing (fixed SNRs)

4.2 Fixed Capacities and variable SNRs

For the alternative way of comparison one fixes the transmission capacities that have to be achieved on the various levels and compares the minimum SNRs required at the receivers. Figure 11 gives an example for C_{base} = 0.5 bit/symbol and C_{enh} =1.5 bit/symbol. The shaded areas can not be realised by any system due to information theory. The vertical line at -3.6dB Es/No ??? sets the minimum for a 8-ASK constellation transmitting only 0.5 bit/symbol containing any enhancement information. The same applies to the horizontal line at 9.6dB, which corresponds to a non-hierarchical 8-ASK system transmitting 2 bit/symbol. The shaded area below the ???erste WH is not useful because it corresponds to an base layer requiring a higher SNR to be decodable than the enhancement layer.

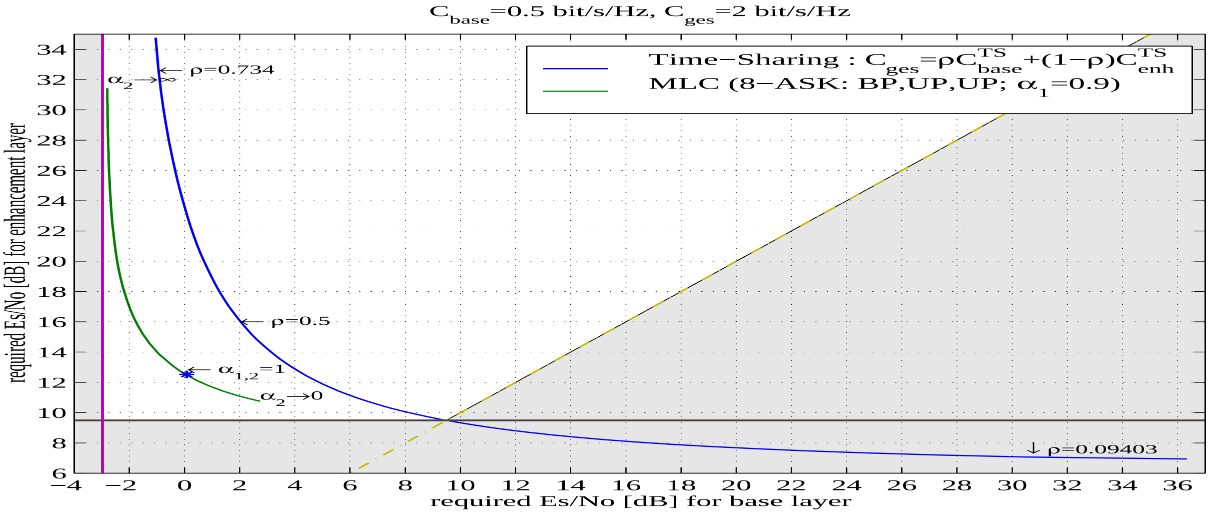

Figure 11. Comparison MLC vs. time sharing (fixed capacities)

The dotted line shows performance achievable with ASK and TS as compared to MLC with MP represented by the solid line. As in figure 10 some points from the DVB-T standard are additionally included. Again, MLC clearly outperforms TS by an important amount in necessary SNR. Although all the points on the MLC curve are efficient in a sense that no points exist that realise the same capacity combination with a lower SNR on one quality level and equal SNR on the other, they are not all equally suited for practice. This becomes clear by moving from the point of the uniform signal constellation ($\alpha_1 = \alpha_2 = 1$) to the extreme values of α_1. Any reduction in necessary Es/No on one level has to be compensated for by an increasing amount of necessary Es/No on the other level. This relationship is visualised by figure 12 that defines a figure of merit $Loss_{total}$ by summing the losses (gains) in decibel that an exchange in SNR at constant capacities between the two transmitted qualities results in. The two levels are compared against their performance for the uniform signal constellation and the individual losses L_i summed up at equal weight as given by equation 3 :

$$\text{Loss}_{total}\ [\text{dB}] = \sum_{i=0}^{l-1} \text{Loss}_i\ [\text{dB}] \tag{3}$$

We can thus characterise for every combination of capacities, a region of combinations for the values of α_1 and α_2 that allows for an efficient transmission. It has to be noted, that this region depends strongly on the choice for the capacities on the individual quality levels and that no global optimum exists. On the other hand, having made a choice for the required capacities the efficiency region provides us with a degree of freedom, in the order of several decibels, for defining the combination of necessary SNRs

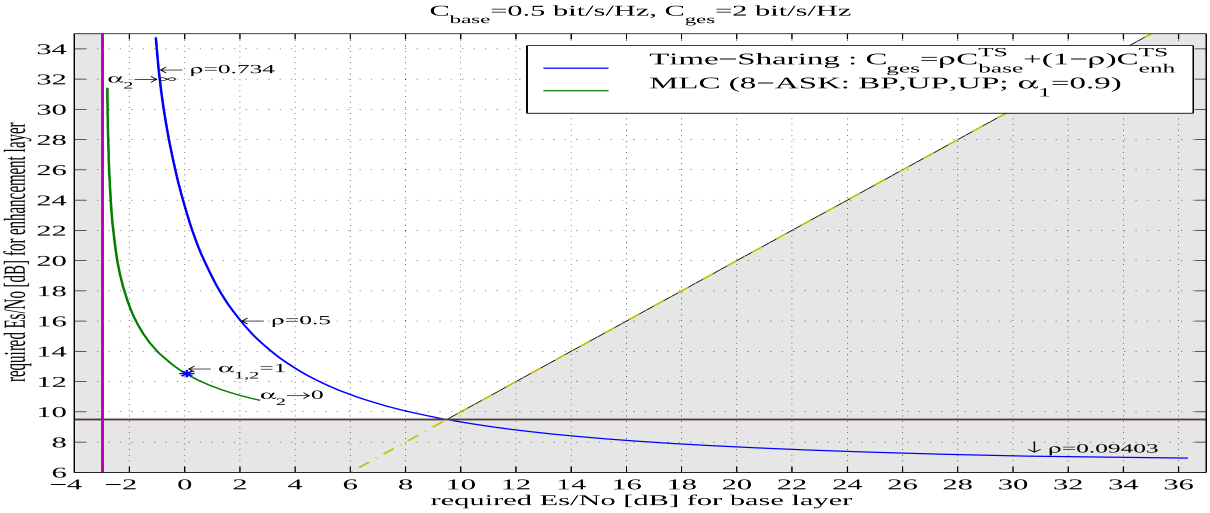

Figure 12. Efficient signal constellations

5 Conclusion

In this paper we have evaluated the degrees of freedom in designing a multilevel coding scheme, namely the partitioning strategy, the choice of coding rates and the distribution of points within the signal constellations. The required steps in order to obtain a modulation scheme suited for hierarchical transmission of signal have been identified and the necessary trade offs explained. Finally MLC was compared against time sharing, with TS proving to be strongly suboptimal. Although all investigations were made for the additive white gaussian noise channel, the same methodology can be applied to other types of channel conditions such as fading channel e.g.

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