# Hierarchical Modulations for Two-Level Transmission against Rain Fades in Satellite Broadcasting

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**A new family of 64ary hierarchical constellations for two level transmission is investigated in this paper. Constellation design is targeted to offer protection against rain fades for satellite broadcasting applications. This new family of constellations, derived from Amplitude Phase Shift Keying (APSK) designs, has low envelope fluctuations compared to other state of the art hierarchical constellations. It is also proven that it has superior performance compared to other types of two level transmissions such as time sharing.**

## I. Introduction

RECENTLY the demands of high data rate traffic over mobile and satellite communication systems have tremendously increased. Such demands are triggered by an ever increasing consumption of multimedia services, such as text, voice, video, or broadcasted television.

In the business of satellite communications, direct to the home (DTH) TV has one of the most important market shares. The market growth has mainly been driven by the introduction of HDTV (High Definition TV), requiring up to 1920 lines x 1080 pixels/line, which is more than twice the resolution of standard definition TV. New developments such as 3DTV may evolve towards multi-view 3DTV, requiring even more throughput. In the future, UHDTV (Ultra High Definition TV) will follow. UHDTV, also called Super Hi Vision [1], will offer 4320 lines x 7680 pixels/line TV system which roughly offers a picture resolution which is sixteen times that of what we presently call HDTV. Experimental UHDTV transmissions have already been set up for main events [2] such as the International Broadcasting Convention (IBC) 2008, or the 2012 London Olympics.

In order to accommodate high quality transmission, which requires high native bitrates (in the order of 24 Gbit/s for UHDTV for example), large transmission bandwidths are necessary. So far, satellite communications primarily use the Ku frequency band in order to accommodate different types of services: fixed and broadcast services, specific applications, backhauls, and satellite transmission from remote locations back to a television network's studio for editing and broadcasting. As the Ku band (12-18GHz) is already highly used, other frequency resources, such as the Ka band (21.4-22GHz), will be used in order to deliver satellite services in the future.

Ka market knows a great development lately, and even more is expected in the next years. Ka-band services are already offered by several operators, mostly in Europe, North America and middle-east. New Ka-band satellites are already in orbit and commercial services are to be launched current 2013. At the horizon 2014, a whole new fleet of

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Ka band satellites will be deployed, targeting global coverage for all sorts of services including broadband consumer access, military applications, backhaul for mobile networks/small cell networks, etc.

Atmospheric effects play a major role in the design of satellite-to-earth links operating at frequencies above 10GHz. Raindrops absorb and scatter radio waves, leading to signal attenuation and reduction of the system availability and reliability. The severity of rain impairment increases with frequency and varies with regional locations. The Ku band's higher frequency spectrum is particularly susceptible to signal degradation, considerably more than C band satellite frequency spectrum. But the Ku band is less vulnerable to rain fade than the Ka band frequency spectrum, which suffers from large rain attenuations [3], up to 20dB in some parts of Asia. Existing Ka-band systems have targeted low rain-fade markets with some rain fade countermeasures. In high rain-fade areas such as India, even Ku-band services can have availabilities as low as 90% today (mostly caused by monsoon season).

Under these circumstances, rain fade countermeasures need to be implemented. Mitigation techniques spread from appropriate link budget strategies, beam shaping, to site diversity and super-hydrophobic coatings. These solutions may be expensive and difficult to apply. More appropriate solutions, based on signal processing techniques, are adaptive coding and modulation (ACM) and variable coding and modulation (VCM).

ACM, usually combined with multi-spot coverage [2], [4], assumes a bi-directional link. It is assumed that within the service area there is a widespread network of rain-attenuation sensors, which could be implemented by connecting all user receivers with a feedback channel carrying real-time information on the reception margin. ACM is dynamically controlled by reception conditions at the receiver. It is not appropriate for network deployments using large beams.

VCM is a static method not requiring any feedback from the receiver. VCM splits the information into at least two streams with unequal error protection (UEP). The most straightforward way of implementing VCM is by multiplexing in the time domain several data streams with UEP. This technique is often referred to as "time sharing" (TS). But since the theoretical basis of unequal error protection was initiated in [5], it was shown that one effective method of achieving UEP is based on a constellation with signal points sometimes spaced in a non-uniform manner, called hierarchical constellation. The use of hierarchical constellations is a particular case of superposition coding based on the inherent different protection levels of the bits selecting a certain constellation point. This effect can be increased by modifying the constellation alphabet, with signal points spaced in a non-uniform manner.

The structure of this paper is as following: Section II describes the principles of hierarchical modulation and reviews some hierarchical constellations currently employed in broadcasting standards. Section III introduces some new hierarchical constellations, which will be evaluated in Section IV. Finally, Section V gives some conclusions and perspectives.

## II. Hierarchical Modulations in Current Broadcasting Standards

As discussed in Section I, in order to cope with rain fades, one solution is multi-layered transmission with different levels of protection. In this paper, we focus on the two-level case. In television broadcasting for example, one level can be used to convey a high priority (HP) data stream corresponding to an image with reduced quality, and another level can be used for a low priority (LP) stream corresponding to the information that must be received in order to get a full quality image. Typically, the LP stream is of higher bit rate, but lower robustness than the HP one. In normal conditions, both HP and LP streams can be decoded at the receiver and the user can experience a full quality image. However, in deep fade conditions, the receiver is capable of correctly decoding only the better protected HP stream. The user can only experience a standard image of lower quality than in clear sky conditions, but there is no service interruption.

Multi-layered two-level transmission can be achieved either by TS or by employing hierarchical modulations (sometimes also called layered modulation). In time sharing, the two streams are transmitted in different time slots and each stream has its own constellation and code rate.

In hierarchical modulation, the two data streams are mapped onto the points of a constellation with adapted geometry (often non-uniform), which is further processed as single data stream. An adapted bit-to-constellation mapping, sometimes combined with some changes in the geometry of the constellation, allows the HP stream to be embedded within the LP stream. The different points of the hierarchical constellation can be grouped into clusters of constellation points, where each cluster encodes the essential information of the HP stream, and the constellation points in each cluster encode the supplementary information carried by the LP stream, as presented in Fig. 1.

At the receiver side, a possibility is to decode both the HP and LP streams. Simultaneous decoding of both streams is possible, especially when the information on the cluster brings about little improvement on the decoding of the LP stream. Other decoder configurations can be imagined (feedback from the HP decoder to the LP decoder, or iterative decoding).

HP and LP streams are unequally protected to the errors, both due to different coding rates of the two streams and to the geometry of the hierarchical constellation. HP and LP streams have different performance and they ensure transmission of different quality at different signal to noise ratios (SNR). Broadcasters can also target two different types of receivers with two completely different services, some being only able to decode the LP stream and others being able to decode both streams. Backwards compatibility can be kept with the class of less capable receivers when designing the hierarchical constellation.

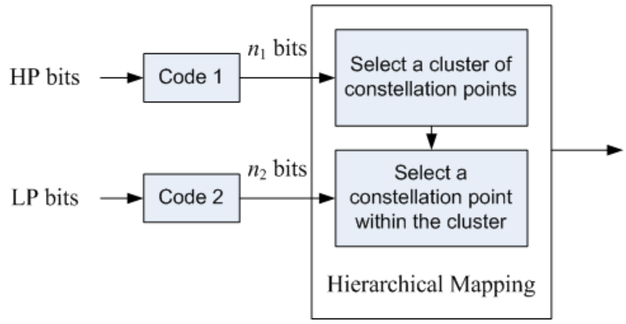
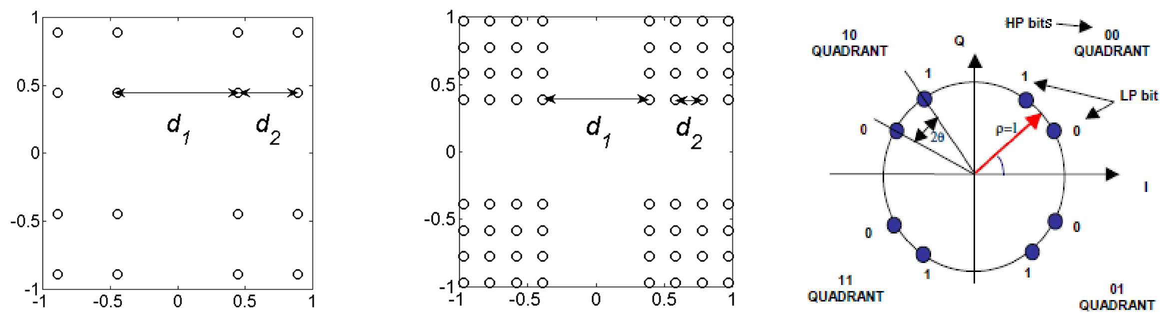



**Figure 1. Mapping two data streams onto the points of a hierarchical constellation.**

The total data rate of the two streams is identical to that of a non-hierarchical scheme. The net data rate may however be slightly lower because twice the compression overhead is incurred in the case of hierarchical modulation, on account of the two multiplexes. A possibility to overcome this last issue is to associate a hierarchical source coding to the hierarchical modulation scheme. In this case, the HP stream corresponds to a standard quality TV program, and the LP stream corresponds to the additional information needed to get a UHDTV program, for example.

Hierarchical modulations are very popular in the broadcast world and have been included in many digital broadcasting standards. Different standards of the Digital Video Broadcasting (DVB) family use hierarchical constellations. DVB-T for terrestrial transmission and DVB-H for handheld terminals implement H16QAM (Quadrature Amplitude Modulation) and H64QAM, in conjunction with OFDM (Orthogonal Frequency Division Multiplexing). The exact proportions of the constellations depend on a parameter $\alpha$ defining the geometry of the constellation [6]. The parameter $\alpha=d_1/d_2$ is the ratio minimum distance $d_1$ separating two constellation points carrying different HP-bit values (and thus belonging to different clusters of points) divided by the minimum distance $d_2$ separating any two constellation points within a cluster. Three values are employed for parameter $\alpha$, 1, 2 and 4. $\alpha=1$ corresponds to a uniform constellation (same geometry as classical 16QAM/64QAM), and $\alpha=2,4$ correspond to non-uniform constellations. High $\alpha$ values are in advantage of the HP stream and in disadvantage of the LP stream (higher distance between clusters, but low distance between constellation points within each cluster). DVB-SH (satellite transmission for handheld terminals) reuses the H16QAM hierarchical modulations of DVB-T/DVB-H. Examples of H16QAM and H64QAM are depicted in Fig.2 a) and Fig.2b), respectively.

DVB-S for satellite transmission includes a functioning mode relying on H8PSK (Phase Shift Keying) hierarchical modulation, consisting in 4 clusters of 2 modulation symbols each [7], in conjunction with Time Division Multiplexing (TDM) (single carrier) transmission. The HP stream is encoded under QPSK (Quaternary Phase Shift Keying) form, where each quadrant represents a cluster. Parameter $\theta$ sets the balance between HP and LP streams. DVB-S2 offers optional backwards compatible modes that use hierarchical constellations to allow legacy DVB-S receivers to continue to operate. Other standards like MediaFLO (Forward Link Only) or UMB (Ultra Mobile Broadband) also included hierarchical modulations. Some other hierarchical modulation schemes such




a) H16QAM, $\alpha$=2    b) H64QAM, $\alpha$=4    c) H8PSK, $\theta=\pi/12$

**Figure 2. Hierarchical modulations in current broadcasting standards**

as H8APSK (Amplitude Phase Shift Keying) [8], H16APSK [9] or enhanced QPSK/QPSK and enhanced 16QAM/QPSK [10] were also described in the literature.

## III. New Hierarchical Modulation Schemes for Satellite Broadcasting

Satellite transmissions must meet system-specific challenges, and use technology adapted to the specificities of these transmissions, such as the particular nature of the propagation channel, diffusion over large areas, long life cycles, and many other technological constraints of the satellites themselves. On top of these constraints lies the high power amplifier (HPA) that is due to bring the signal to be transmitted at a level compatible with the receiver sensibility over large areas. In order to guarantee the durability of the satellite, it is critical to keep a low power consumption of the system, and thus to optimize the amplifier power efficiency, i.e. to drive the amplifier close to saturation. This is the reason why Single Carrier (SC) transmission (also sometimes called TDM transmission, where the multiplexing aspect should be seen as multiplexing between services and not between users) has been the reference scheme for satellite transmissions for a long time.

In order to cope with the demands of high data rate traffic, high order constellations need to be employed in order to maximize the spectral efficiency. But, for the same transmission scheme, different constellations display different levels of envelope fluctuations. This is why in satellite standards APSK constellations, known to display a lower Peak to Average Power Ratio (PAPR), have been so far preferred to QAM constellations.

In the present paper we investigate the use of hierarchical high order constellations for satellite transmissions. So far non-hierarchical uniform 64APSK have already been investigated in [12], where it is considered that APSK has merits for digital transmission over nonlinear satellite channels due to its power and spectral efficiency combined with its inherent robustness against nonlinear distortion. More specifically, 4-12-20-28-APSK and 4-12-16-32-APSK were considered as relevant. Bit-to-constellation mapping and constellation dimensioning recommendations are given in [13]. Other designs such as for example 8-12-20-24APSK also exist in the literature.

Starting from an already defined uniform $X$-APSK constellation having $M\geq 2$ rings of radii $R_k$ containing $N_k$ constellation points each (with at least 2 different values for $N_k$), we propose to build a hierarchical $X$-APSK constellation. The following procedure is proposed:

1) Separate the uniform $X$-APSK constellation into $C=2^{n_1}$ angular regions, each region corresponding to a cluster of constellation points representing $n_1$ bits from the HP stream, each cluster having $2^{n_2}$ constellation points representing $n_2$ bits from the LP stream, and $2^{n_1+n_2}=X$.
2) Push each cluster away from the region borders by a distance $\beta$. Parameter $\beta$ will balance the relative performance of the HP and LP streams.
3) Compute a normalization factor $\gamma$ and re-scale the constellation to unitary mean power, to obtain an $X$-ary non-APSK hierarchical non-uniform constellation.
4) Optionally re-arrange the constellation points in order to transform this constellation into a hierarchical $X$-APSK constellation with $M$ rings of radii $R'_k$, in order to reduce the PAPR of the $X$-ary non-APSK constellation obtained at point 3.

Let us illustrate here the case $X$=64, $M$=4 and take as predefined constellation the constellation proposed in [12], [13] for example. We apply the procedure here-below in order to split the constellation into $C=2^{n_1=2}=4$ clusters of $2^{n_2=4}=16$ points each. At the first step, the constellation point on ring $k$ having index $n$ (index counting starts at 0, counting counter clockwise) is:

$$y(k,n)=R_k \exp\left(j\left(\frac{2\pi n}{N_k}+\phi_k\right)\right), \tag{1}$$

where $\phi_k$ is the phase of $y(k,0)$.

In the particular case of Fig.3a) where the constellation is symmetric with respect to the real axis and thus $\phi_k=\pi/N_k$:

$$y(k,n)=R_k \exp\left(\frac{2\pi}{N_k}\left(n+\frac{1}{2}\right)\right)=R_k \exp\left(\frac{\pi(2n+1)}{N_k}\right). \tag{2}$$

For a separation as in Fig.3a) there are no constellation points onto region borders (for constellation splitting scenarios where constellation points fall onto region borders, a decision needs to be taken for each constellation point in such a manner that all clusters have the same number of points). All points in a region are depicted with the same color, and we attributed a different color to each region. Each constellation point $y(k,n)$ has now been attributed to a cluster $c$, $c$=0...$C$-1. Cluster number $c$ depends on ($k$, $n$) for each constellation point. For each couple ($k$,$n$) there is an unique associated $c$. For each cluster $c$, there is a group of associated couples ($k$, $n$) corresponding to the group of constellation points belonging to the cluster.

At the second step, we push each cluster away from the region borders by a determined distance $\beta$, which is equivalent to pushing each region away from the constellation center and along the bisector of each angular region by a distance $\Delta = \beta / \sin(\pi / C)$.

Each constellation point $y(k,n)$ belonging to cluster $c$ is transformed into a point $y_c'(k,n)$ belonging to cluster $c$:

$$y_c'(k,n) = \Delta \exp\left(j\left(\frac{2\pi}{C}\left(c+\frac{1}{2}\right)+\phi\right)\right) + y(k,n) = \frac{\beta}{\sin\frac{\pi}{C}} \exp\left(j\left(\frac{2\pi}{C}\left(c+\frac{1}{2}\right)+\phi\right)\right) + R_k \exp\left(j\left(\frac{2\pi n}{N_k}+\phi_k\right)\right). \quad (4)$$

In the present case, $\phi = 0$ and the specific cluster separation allows to simplify (4) to:

$$y_c'(k,n) = y(k,n) + \beta\left(\operatorname{sign}\left(\operatorname{Re}\left(y(k,n)\right)\right) + j\cdot\operatorname{sign}\left(\operatorname{Im}\left(y(k,n)\right)\right)\right). \quad (5)$$

At the third step, a rescaling factor $\gamma$ can be computed in order to reduce the constellation to unitary mean power. In this particular case of the constellation in Fig.3, $\gamma$ can be analytically computed as:

$$\begin{aligned}\gamma = \operatorname{sqrt}\Bigg(\frac{1}{X}\Bigg(\sum_{k=1}^{M}\sum_{n=0}^{N_k-1}\Big(\left|y(k,n)\right|^2 + 2\beta\operatorname{Re}\Big(y(k,n)\Big(\operatorname{sign}\left(\operatorname{Re}\left(y(k,n)\right)\right) - j\cdot\operatorname{sign}\left(\operatorname{Im}\left(y(k,n)\right)\right)\Big)\Big) + \dots \\ + \beta^2\left(\left|\operatorname{sign}\left(\operatorname{Re}\left(y(k,n)\right)\right)\right|^2 + \left|\operatorname{sign}\left(\operatorname{Im}\left(y(k,n)\right)\right)\right|^2\right)^2\Big)\Bigg)\Bigg) = \quad (6) \\ = \sqrt{\frac{1}{X}\left(\underbrace{\sum_{k=1}^{M}\sum_{n=0}^{N_k-1}\left|y(k,n)\right|^2}_{=X} + 2\beta\sum_{k=1}^{M}\sum_{n=0}^{N_k-1}\left(\left|\operatorname{Re}\left(y(k,n)\right)\right| + \left|\operatorname{Im}\left(y(k,n)\right)\right|\right) + 2\beta^2\right)}.\end{aligned}$$

The normalized constellation $y_c''(k,n) = y_c'(k,n)/\gamma$ is depicted in Fig. 3b). This is a non-APSK constellation with $X$ points: after region displacement the constellation points are no longer on rings with a common center (axes origin) as it was the case before region displacement. Dotted circles represent the rings of the original constellation.

In order to further decrease the PAPR of this non-APSK constellation, a further 4th step of rearranging the constellation points onto concentric rings of radii $R'_k$ is possible, resulting in the hierarchical APSK constellation depicted in Fig.3c). Each $R'_k$ is computed by imposing that the mean power of the constellation points $y_c'''(k,n)$ on the $k$-th ring for the new hierarchical $X$-APSK constellation be the same as the mean power of the constellation points for the $X$-ary non-APSK constellation that were obtained at step 3 from constellation points belonging to ring $k$ in the original uniform constellation:

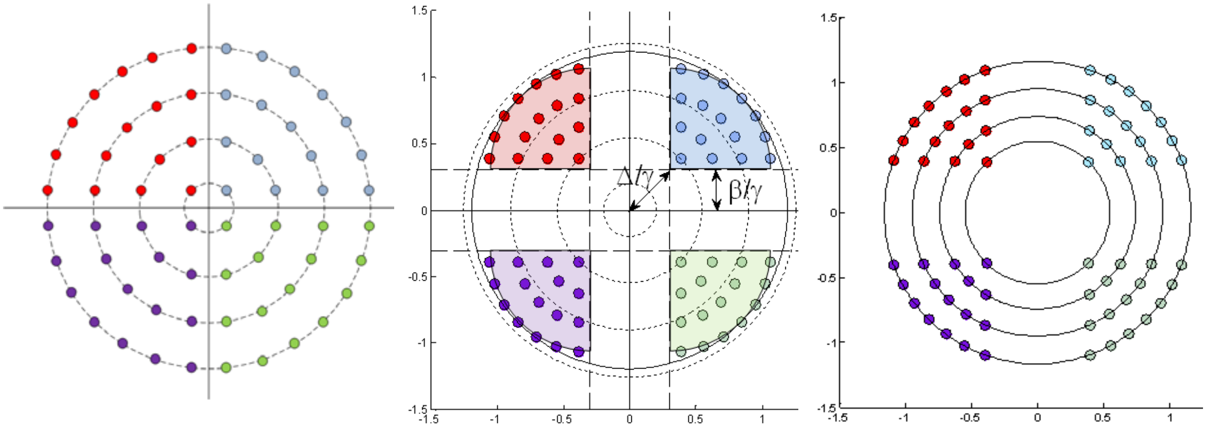
$$\sum_{c=0}^{C}\left(\sum_{\substack{\text{all } n \text{ such that} \\ y_c'''(k,n) \text{ is in } c}} \left|y_c'''(k,n)\right|^2\right) = \sum_{c=0}^{C}\left(\sum_{\substack{\text{all } n \text{ such that} \\ y_c'''(k,n) \text{ is in } c}} \left|y_c''(k,n)\right|^2\right). \quad (7)$$

After some simple computations, new radii $R'_k$ are computed as:

$$R'_k = \sqrt{\frac{\sum_{c=0}^{C} \left( \sum_{\substack{\text{all } n \text{ such that} \\ y'''_c(k,n) \text{ is in } c}} \left| y''_c(k,n) \right|^2 \right)}{N_k}} \tag{8}$$

Obviously, $y'''_c(k,n) = R'_k y''_c(k,n) / \left| y''_c(k,n) \right|$.

We have thus obtained a constellation design for hierarchical *X*-ary and hierarchical X-APSK constellations depending on a parameter $\beta$ that modulates the PAPR of the new family of constellations and operates a tradeoff between the performance of the HP and LP streams, as it will be discussed in the following section. Constellation parameter $\beta$ needs to be adapted in function of transmission conditions like for example weather conditions in the transmission regions. Parameter $\beta$ needs to be known by the receiver in order to be able to perform correct decoding.



a) 64APSK with cluster splitting    b) Hierarchical 64-ary, $\beta/\gamma$=0.3    c) H64APSK, $\beta/\gamma$=0.3

**Figure 3. Proposed Hierarchical 64-ary and H64APSK non-uniform constellations.**

## IV. Simulation Results

### A. System model

Let us assume a system model like in Fig.4. The transmitter is a classical TDM transmitter. Information bitstream is LDPC encoded (64800 bits codewords length), interleaved and mapped onto the points of an APSK constellation, before pulse shaping with a root raised cosine filter (20% rolloff) and transmission. Used modcods are QPSK (1/4, 1/3, 2/5, 1/2 , 3/5, 2/3, 3/4, 4/5; 5/6), 8PSK (3/5, 2/3, 3/4, 4/5; 5/6), 16APSK (2/3, 3/4, 4/5; 5/6) and 32APSK (3/4, 4/5, 5/6) defined in DVB-S2, plus the higher order 64APSK (3/4, 4/5, 5/6) and 256APSK (2/3, 25/36; 13/18). Input/output multiplexing (I/OMUX) and the ripple/slope filter at the receiver input are the ones defined in [16]. We used a linearized travelling wave tube amplifier TWTA from [16]. We consider an additive white Gaussian channel (AWGN). We consider perfect channel estimation and implement a frequency-domain linear minimum mean sqare error (MMSE) equalization to correct the equivalent nonlinear channel mainly affected by the phase distortion generated by the I/OMUX. In some simulations HPA will be missing.

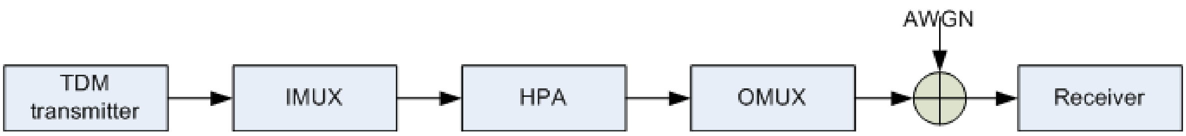



**Figure 4. System model**

## B. Envelope variations

Passing through a HPA results in signal distortion. Severely clipping one single peak in a large block has a negligible effect but distortion (even mild) of a large number of samples might have unacceptable consequences. For this reason, the CCDF of the instantaneous normalized power (INP) [14], [15], is lately more and more often considered instead of the CCDF of PAPR. The CCDF of INP, indicating the probability that the INP at a sample level exceeds a certain threshold, is plotted in Fig. 5. In order to have a good approximation of the signal after digital to analog conversion, the signal is oversampled eight times. To compare hierarchical constellations coming from different families, and thus characterized by different geometry parameters ($\alpha$, $\beta$, etc) we define a constellation-independent non-uniformity factor (NUF) as:

$$\mathrm{NUF} = -10\lg\left(\frac{\frac{X}{C}\sum_{y_k\in c}|y_k|^2 - \left|\sum_{y_k\in c} y_k\right|^2}{\left|\sum_{y_k\in c} y_k\right|^2}\right), \quad (9)$$

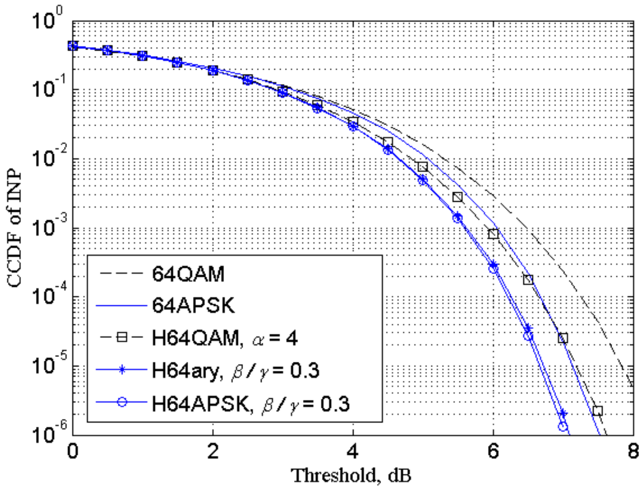



**Figure 5. CCDF of INP of H64QAM, H64-ary and H64APSK constellations with respect to 64QAM and 64APSK.**

where $y_k$ are the points of the hierarchical constellation and $c$ is an arbitrary cluster. H64QAM with $\alpha = 4$ corresponds to NUF=9.81dB and is thus equivalent to H64ary and H64APSK constellations with $\beta/\gamma = 0.3$. Non-uniform hierarchical modulations have lower envelope fluctuations than their uniform equivalents (0.5dB and 0.6dB at a target CCDF of INP of $10^{-4}$ for APSK and QAM constellations respectively). The envelope fluctuations can further be decreased by increasing NUF, but highly non-linear constellations display low Euclidean distances between the constellation points within a cluster, which results in performance loss for the LP stream. H64APSK outperforms H64QAM by 0.4dB. This difference can also be modulated by the NUF. Low NUF increases the H64APSK gain over the H64QAM (up to 0.6dB of difference for the uniform constellations), while very high values of NUF bring together the two curves, tending towards the PAPR of a QPSK constellation. Rearranging the points of H64ary constellations to form H64APSK constellations can slightly improve the PAPR performance.

Since H64-ary/H64APSK display better results than H64QAM, let us further investigate the performance of this new family of hierarchical constellations.

## C. Performance evaluation

Let us compare the performance of the hierarchical modulation constellations with a TS configuration Time sharing allocates to each receiver a fraction of time where it can use the full channel with any modulation and error protection level. This solution is the most used in practice in standards today. In superposition coding, the available energy is shared among several data streams which are sent simultaneously in the same band. This scheme was introduced by Cover in [5] in order to improve the transmission rate from a single source to multiple receivers.

Let us define the total degradation TD (in dB) as the required $E_s/N_0$ in order to attain a target packet error rate (PER), plus the loss due to the HPA non-linearity and to the IMUX/OMUX filtering. The loss due to the HPA is represented by the output backoff (OBO), and is ignored when on a linear (AWGN) channel.

Figure 6 plots the TD of the HP stream against the TD of the LP stream for the family of H64ary constellations described in section III and for TS using the modcods described in subsection IV.A, for a target PER=$10^{-2}$ and target data rates of ($D_{HP}$, $D_{LP}$) = (1.33, 2.67)bits/symbol for HP and LP streams respectively. In the case of H64ary constellations, this means that both streams were encoded with a code rate of 2/3. The theoretical lower bounds for TS and for superposition coding given in [5] for a linear channel, as well as the bounds for one stream transmission are also plotted as reference.

In the case of H64ary constellations, each curve in Fig.6 gives the global performance of the whole family of constellations at a target couple ($D_{HP}$,$D_{LP}$) and a target PER. Indeed, the balance LP/HP is performed by varying the degree of non-uniformity of the constellation as previously discussed. High NUF favor the HP transmission and thus correspond to the range of high LP TD (rightmost part of the curves). Low NUF tending towards uniform constellations correspond to the leftmost part of the curves. In the presence of a HPA, the optimum functioning point (minimizing the OBO) was chosen for each point on the curve. These curves can serve for calibrating the necessary NUF in order to get a desired system performance. For example, if we want to use H64ary constellations in the presence of a TWTA in order to cope with a 20dB rain fade, we should operate the system in the point corresponding to the crossing between the H64ary curve (in red in Fig.6) and the $\Delta_{TD}$=20dB line. This corresponds to NUF=10dB ($\beta/\gamma$=0.31).

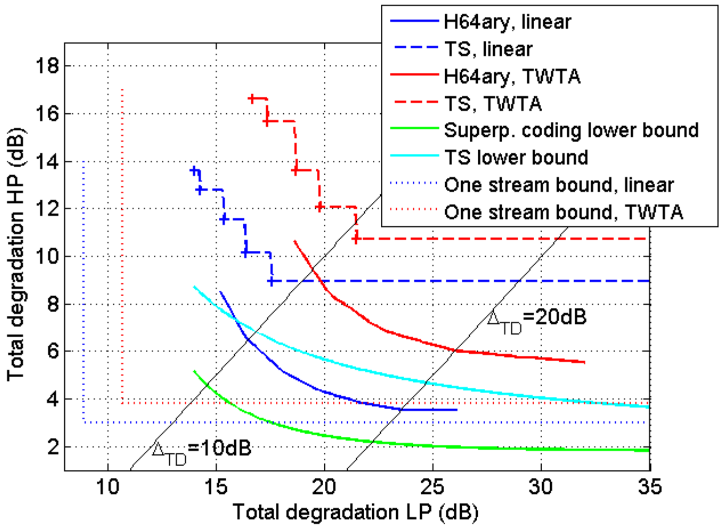



**Figure 6. Comparative performance of hierarchical modulation and time sharing in linear and non-linear channels, ($D_{HP}$,$D_{LP}$) = (1.33, 2.67)bits/symbol.**

Hierarchical modulations always outperform TS, both on linear channels and in the presence of a TWTA HPA. On a linear channel, H64ary constellations attain better performance than the TS theoretical lower bound. Introducing a HPA is more penalizing for the LP stream, using less robust constellation points.

To get some further insight on this performance comparison, let us analyze Table 1, presenting a comparative performance in terms of LP data rate $D_{LP}$ for a target PER=$10^{-2}$ and at a fixed HP data rate $D_{HP}$=1.33 bits/symbol. Please note that the data rate for TS is averaged over time for each stream (total data rate transmission can be obtained by summing the $D_{LP}$ values in the table with $D_{HP}$=1.33 bits/symbol for both hierarchical and TS transmissions). Performance of one stream transmission is given as reference in two cases. The first scenario (reference 1) assumes a high quality transmission, which is possible only in good propagation conditions; service is interrupted when the available signal to noise ratio drops below a certain level. The second scenario (reference 2)

**Table 1. LP data rate $D_{LP}$ for a target PER=$10^{-2}$ and a fixed HP data rate $D_{HP}$=1.33 bits/symbol**

| $D_{LP}$ (bits/symbol) | | $\Delta_{TD}$ = 10dB | | $\Delta_{TD}$ = 20dB | |
|---|---|---|---|---|---|
| Channel | Type | Linear | TWTA | Linear | TWTA |
| | Bad propagation conditions | 6.5dB | 9.4dB | 3.5dB | 6dB |
| | Good propagation conditions | 16.5dB | 19.4dB | 23.5dB | 26dB |
| One stream reference 1: high quality, transmission only in good conditions | | 4.8<br>64APSK 4/5 | 4.8<br>64APSK 4/5 | 5.8<br>256APSK 13/18 | 5.8<br>256APSK 13/18 |
| One stream reference 2: basic quality transmission in all conditions | | 2<br>(8PSK 2/3) | 2.4<br>(8PSK 4/5) | 1.5<br>(QPSK 3/4) | 1.8<br>(8PSK 3/5) |
| $D_{LP}$ Time sharing (HP/LP modcods) | | 1.25<br>8PSK 3/5, 74 %<br>64APSK 4/5, 26% | 1.84<br>8PSK ¾, 59 %<br>64APSK ¾, 41% | -<br>QPSK 2/3, 100%<br>- | 1.56<br>8PSK 3/5, 73%<br>256APSK 13/18 27% |
| $D_{LP}$ H64ary | | 2.67<br>NUF = 6.1 dB | 2.67<br>NUF = 5.3 dB | 2.67<br>NUF = 13.9 dB | 2.67<br>NUF = 10 dB |

assumes service continuity, but having one single stream available means that low data rate basic quality transmission is performed at all times, even in good propagation conditions.

For all evaluations, the modcod used in order to obtain the announced data rate is given. Additionally, we also give the relative time allocated for each stream in TS, and the NUF for hierarchical constellation transmission, respectively.

Both TS and hierarchical modulations are to be preferred to one stream transmission. With respect with reference scenario 1, they ensure service continuity in bad propagation conditions at the cost of a lower overall data rate when good propagation conditions are available. They acquire better overall data rate than reference scenario 2. H64ary constellation displays a higher LP data rate than TS, at the same PER target, same propagation conditions and same HP data rate, both on linear channels and in the presence of a TWTA. The improvement can go up to 167%. Moreover, hierarchical modulations are more flexible than TS, who cannot cope with deep rain fades in the order of 20dB for the desired data rates in this simulation scenario.

## V. Conclusions

A new family of 64ary hierarchical constellations for two level transmission was investigated in this paper. It has been proven that this new family of constellations outperforms H64QAM by 0.4dB in terms of envelope fluctuations and that it can ensure a data rate per stream up to 167% higher with respect to time sharing. Constellation design is targeted to offer protection against rain fades for satellite broadcasting applications. Perspectives include a more detailed performance evaluation across different signal to noise ratio ranges, and further improvements such as bit reporting from one stream to another.

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