ADAPTIVE CODING AND MODULATION FOR THE DVB-S2 STANDARD INTERACTIVE APPLICATIONS: CAPACITY ASSESSMENT AND KEY SYSTEM ISSUES

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The authors show how the ACM introduction in the satellite downlink enables greatly enhanced system performance but also has a profound impact on the way the system and some of the key system components are designed.

ABSTRACT

Point-to-point multi-beam satellite systems based on the DVB-S standard [1] are currently designed for link closure in the worst-case propagation and location conditions. The DVB-S standard, conceived for broadcasting applications, considers a fixed coding rate and modulation format that are selected according to the assumed coverage and availability requirements. This approach implies the occurrence of high margins in the majority of the cases, when interference and propagation conditions allow for higher signal-to-noise-plus-interference ratio. The adaptive coding and modulation (ACM) introduction in the new DVB-S2 standard [2] for the interactive service profile opens up a number of appealing opportunities for the design and development of satellite broadband networks. In this article we show how the ACM introduction in the satellite downlink enables greatly enhanced system performance but also has a profound impact on the way the system and some of the key system components are designed.

INTRODUCTION

The recently defined Satellite Digital Video Broadcasting Standard DVB-S2 [2] represents a major step forward compared to the current DVB-S1 [1]. Among the major features outlined in detail in [3, 4], DVB-S2 provides a near-Shannon forward error correcting scheme based on low-density parity check codes (LDPC) that outperform DVB-S in power efficiency by more than 30 percent. Furthermore, the standard encompasses a wide range of coding rates (ranging from rate $r = 1/4$ to $r = 9/10$) and modulation formats spanning from quadrature phase-shift keying (QPSK) to 32 amplitude and phase-shift keying (APSK). This enables DVB-S2 to operate over a signal-to-noise range exceeding 18 dB. This exceeds by far the QPSK-based DVB-S operating range restricted to less than 5 dB. Further spectral efficiency improvement is enabled by the support of symbols shaping a square-root raised-cosine filter roll-off factor down to 0.2 instead of the 0.35 value supported by DVB-S. Of great relevance in terms of system capacity improvement is the DVB-S2 support of variable coding and modulation (VCM) and adaptive coding and modulation (ACM) modes on top of the conventional DVB-S constant coding and modulation (CCM) profile. While CCM forces the use of the same physical layer configuration for all ground stations receiving the same modulated carrier, VCM enables multiplexing in time division fashion (TDM) frames with different physical layer configurations. The VCM mode is useful to broadcast information with different error protection per multiplex. For example, VCM can be used to multiplex on the same carrier, highly-protected standard television quality (SDTV) with less protected high-definition television (HDTV). ACM enables the configuration in a fully dynamic way of each TDM carrier physical layer frame according to one of the possible coding rates and modulation formats supported by the DVB-S2 standard. The new DVB-S2 ACM mode of operations is highly recommended for unicast or point-to-point applications to adapt the physical layer configuration to the time and location dependent channel conditions. In the following, we focus on the profound impact of the new DVB-S2 ACM profile on the design paradigm and the capacity estimation for the downlink of interactive broadband satellite networks. The results obtained applying modern design techniques to the ACM interactive profile are contrasted to the more conventional CCM design methodology.

PROBLEM STATEMENT

Typical Ku-band broadcasting downlinks are designed with a clear-sky margin of four to six

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dB and a service availability target of about 99 percent of the worst month (or 99.6 percent of the average year). Since the rain attenuation curves are very steep in the region 99 to 99.9 percent of the time, many dB of the transmitted satellite power are useful, in a given receiving location, for only about ten minutes per year. Unfortunately, this waste of satellite power/capacity cannot be easily avoided for broadcasting services, where millions of users, spread over very large geographical areas, receive the same content at the same time.

The situation is different for unicast networks. In fact, the point-to-point nature of link connections enables the exploitation of spatial and temporal variability of end-user channel conditions to increase the average system throughput. This is achieved by adapting coding rate and modulation format (ACM) of the downlink time division multiplex (TDM) frame addressed to a specific user (or a subset of users experiencing the same signal-to-noise plus interference [SNIR] condition) to best match the current user link SNIR. As a consequence, the received downlink carrier bit rate is location and time dependent. Instead, the TDM carrier baud rate is constant to ease the frequency resource allocation [5]. However, the individual user bit rate at which packets are received is dependent in a complex way on the instantaneous carrier bit rate and the resource management policy implemented at the gateway [6].

If a proper ACM dynamic physical layer adaptation algorithm, capable of tracking the instantaneous SNIR variation at the user terminal is implemented, then link margins can be greatly reduced compared to a CCM system. Due to the physical layer adaptation loop latency, the physical layer threshold margin remains to be considered [7]. With reference to this, a possible approach to design the ACM physical layer configuration control loop is provided. It is shown that, by proper control loop design, ACM loop implementation losses can be kept reasonably small.

Assuming a fixed beam power allocation, there are several key parameters responsible for SNIR variability within the satellite coverage. They can be grouped into two categories.

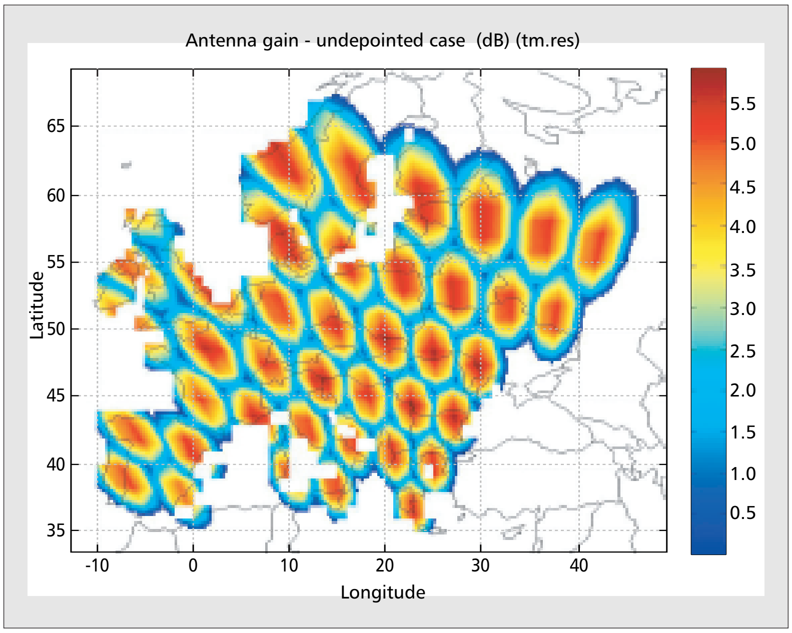
GEOGRAPHICALLY DEPENDENT PARAMETERS

Satellite antenna gain: The (multibeam) antenna gain is non-uniform over the coverage. For example, a difference of 5dB could exist between the peak antenna gain (at the center of the beam) and the edge of beam gain. This is illustrated in Fig. 1.

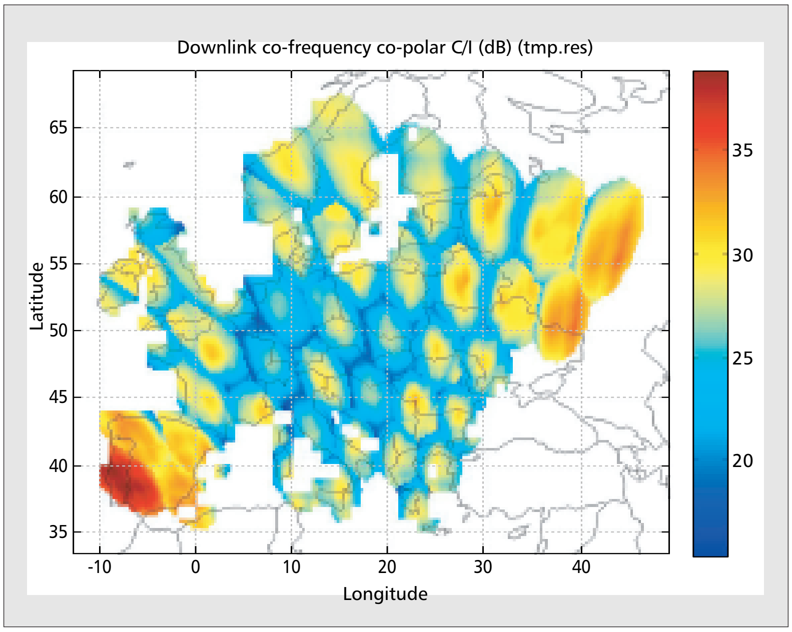
Interference level: The interference level varies over the coverage. It depends on the antenna performances (beam isolation) and the beam frequency reuse pattern. For example, a C/I range of nearly 20 dB (Fig. 2) could exist over the coverage of a multibeam system based on a four-color frequency reuse scheme and uniform power beam loading. When different powers and the number of carriers are associated to the different beams, more extreme situations can occur due to the non-uniform traffic loading over the coverage region.

Atmospheric attenuation (mainly rain attenuation): For a given availability, the intensity of the fading varies over the coverage due to different climatic zones. For example, in Ka-band over Europe, for a target availability of 99.7 percent, the range of the required attenuation margin over the coverage is nearly equal to five dB. This is illustrated in Fig. 3.

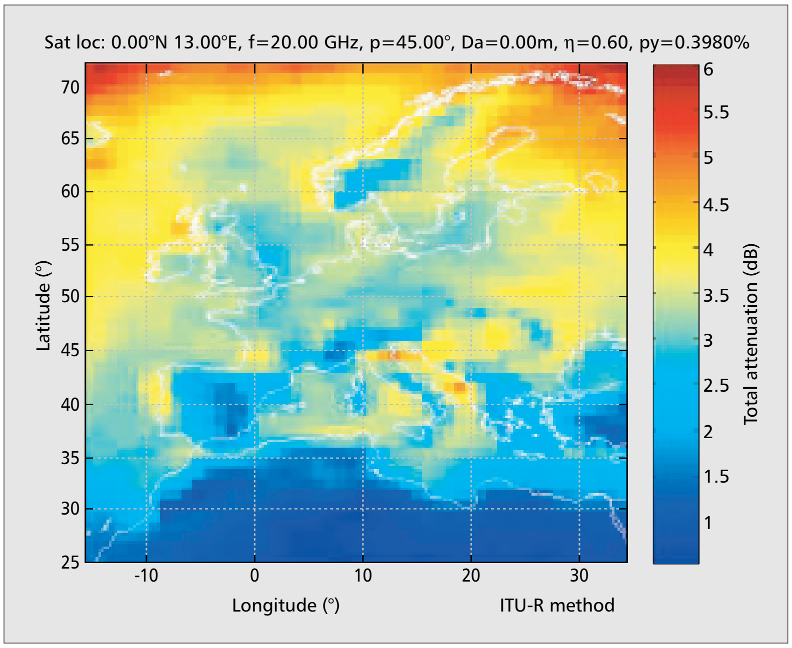
User terminal antenna gain: If several terminal antenna sizes are used in the system, then different user terminal antenna gains are implied. ACM allows automatically matching physical layer parameters to the user terminal characteristics, thus avoiding system over sizing.



■ **Figure 1.** *Example of satellite multibeam antenna gain variation over the coverage area.*



■ **Figure 2.** *Example of satellite multibeam antenna C/I ratios over the coverage area.*



■ **Figure 3.** *Fading attenuation over Europe at 20.2 GHz for 99.7 percent link availability.*

TIME-DEPENDENT PARAMETERS

The most important parameter that is time-dependent is the atmospheric attenuation (mainly rain attenuation). This corresponds to the fading difference between clear sky and rain conditions. For example, in Ka-band over Europe and for a target availability of 99.7 percent, the difference between clear sky and rain fading could be up to six dB. It is noted that the satellite terminal (ST) SNIR variation range is typically smaller than the propagation fading depth due to the co-channel interference effect. In fact, downlink co-channel interference fades with the useful signal, thus smoothing the channel fading impact on the ST SNIR. This fading mitigation effect grows with the interference over the thermal noise power spectral density ratio [5].

ACM SYSTEM ANALYSIS METHODOLOGY

From the previous discussion, it is apparent that the evaluation of the system capacity achievable when adopting the DVB-S2 ACM profile cannot be performed through conventional one-dimensional link budgets. Whereas for CCM, the notion of capacity is easily defined, this same concept requires specific assumptions and analysis in the case of ACM. In fact, the physical layer throughput in each beam is, in general, different and time-variant. The presence of geographically and timely dependent system parameters calls for a more comprehensive physical layer throughput analysis methodology that has been illustrated in detail in [5] and not repeated here. A new software tool has been developed in the frame of European Space Agency (ESA) contracts [8, 9, 10], implementing the ACM capacity analysis approach devised in [5]. In the following the tool analysis, methodology and key considerations related to the system sizing and design when DVB-S2 ACM profile is adopted are summarized. Differences in the system sizing methodology with respect to the conventional CCM-based design methodology also are properly addressed.

SYSTEM SIZING ISSUES

Before proceeding to the description of the system tool analysis methodology, we first discuss conventional (CCM) system-sizing issues and how they are affected by ACM adoption.

The traditional system design involves fixing a priori the system throughput together with the link availability requirement to be achieved and the target service area. Based on these requirements, system sizing is then performed. System sizing involves the definition of several system aspects, the most important being the:

- Number of satellite beams for covering the service area
- Onboard effective isotropic radiated power (EIRP) per beam — typically defined at the edge of coverage (EOC) as this represents the worst case
- The gain-to-noise-temperature (G/T) requirement of the ST

Moreover, sizing of the gateway (GW) feeder link also is defined. In this regard, feeder link often is sized so that it does not have too much impact on the overall link budget (e.g., less than 1 dB). This is not always easily achievable at Ka-band but for the sake of simplicity, we do not address the feeder link sizing here more specifically.

The G/T performance of ST is often not a free variable in the system-sizing exercise and is often constrained by market requirements (e.g., maximum ST antenna size acceptable by the user).

The number of satellite beams and the on-board EIRP parameters are quite interrelated, as one parameter can influence the other. However, the selection of the number of beams also depends on the degree of frequency reuse to be provided, which in turn depends on the target overall system capacity and total spectrum resource bandwidth available.

In practice, after sizing the number of beams and their bandwidth, and taking into account all system and satellite platform constraints, the last step in system sizing is to adjust the on-board provided EIRP so that the link availability constraints are satisfied.[1]

To avoid satellite EIRP over sizing, often it is acceptable not to achieve the link availability target in all locations in the service area. Hence, the link availability requirements often are formulated as achieving the link closure, for example, for 99.7 percent of the time for a subset of the service area corresponding to, for example, at least 95 percent of the coverage surface (the remaining five percent of the coverage having either a lower time availability or a higher terminal antenna size). This design approach is, however, causing a non-uniform service availability figure that may have some marketing drawbacks, for example, it requires the adoption of different ST antenna sizes depending on the ST location.

The great advantage of ACM — compared to CCM when operating at frequency bands whose

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[1] *The system sizing is obviously more complex than that depicted previously as technological constraints also must be taken into account.*

link fading attenuation becomes large in the presence of (heavy) rain — is that it enables the adaptation of the ST physical layer configuration individually (hence, the SNIR modem threshold), thus maintaining the service active even under very unfavorable fading conditions. In this way, the service provision to the "unlucky" active users has the minimum impact on the aggregate throughput, because only a very small percentage of users are affected at the same time by heavy fading over the satellite coverage region. Also, the long-term (e.g., yearly) system throughput statistics are very marginally affected by fading events, considering their limited time duration.

When defining the service availability, note that it refers to a per-user quality of service (QoS) and thus, it is also dependent on the resource management policies that are in place in the system [4]. Concerning the service availability for the most common case of best effort services (such as asymmetric digital subscriber line [ADSL] Internet access offer), due to the wide DVB-S2 operating SNIR range, it is typically equal, or very close, to 100 percent. This is because ACM allows the keeping of users connected to the satellite network even under the worst link conditions with negligible impact on the other users. For the same high availability, CCM systems must instead pay an excessively high cost, which is the cost of providing all users in the coverage area the physical configuration required by only a few users.

The minimum useful ST bit rate associated with the service availability must be related to a per-user definition. This complicates the analysis as the user bit rate also depends on current beam carrier traffic and on the policy of the resource manager and not just on the current physical layer bit rate. In ACM systems, the GW resource manager can counteract the effects of poor propagation conditions by allocating more TDM downlink carrier time resources to users in deep fading conditions. This can be achieved by removing resources from users in clear-sky conditions and thus, receiving a carrier bit rate that is much higher than in CCM systems — considering that heavy fading events are typically affecting only a limited geographical area. For further discussion about this important issue, see [4].

SYSTEM ANALYSIS TOOL DESCRIPTION

Following the methodology described in [6], the software-based tool can simultaneously simulate the link budget of thousands of ST dispersed over the target coverage area. For each ST location, fading attenuation is generated at each iteration step according to long-term statistics (one year). When the simulation is sufficiently long, during the simulation each ST experiences all the possible propagation conditions with the associated probability. This enables the derivation of precise global and local (e.g., beam) statistics about the total system throughput, as well as statistics about unavailability (both temporal and spatial) that can be used for assess if the link availability and service area targets were achieved.

The tool input parameters consist of the satellite system characteristic parameters, as well as physical layer performance figures. Some system parameters, like antenna pattern and frequency reuse plan, are spatially variant within the coverage area, thus motivating a statistical analysis.

The simulation phase is performed in the following steps:

1. Generate a sufficient number of ST distributed over the coverage area. ST density can be sized to match a realistic traffic distribution. Dense areas have a larger weight on the overall performance figures.

2. For a given time instant, randomly generate fading at each ST and each GW. For this purpose, an indoor transmit unit radio (ITU-R) communication model for rain, gas (oxygen, water vapor), and scintillation can be considered. The generated random fading must correctly reproduce the fading cumulative distribution function (CDF) at the considered location.[2] Note that for the purposes of average capacity evaluation, the fading model is not required to reproduce the correct time and spatial correlation. In case of polarization reuse, the effect of propagation on cross polarization discrimination (XPD) also should be considered.

3. For each ST, perform a link budget (both up-link from GW to satellite and down-link from satellite to ST), taking into account the intra-system interference. The co-channel intra-system interference can be computed exactly because all parameters that influence it are known. Adjacent channel interference can be evaluated approximately, assuming a nominal level for adjacent carriers and the channel isolation (to be provided as input parameters for both up- and downlink).

4. For each ST, compare the current link budget result, that is, the obtained $E_s/(N_0 + I_0)$ with the one required by each operating mode. If the obtained value is lower than the one required for the most protected operating mode, then the link is unavailable. Otherwise, the link is available. Then, the corresponding throughput can be derived, assuming you adopt the highest spectral efficient protection mode that can be supported by the obtained $E_s/(N_0 + I_0)$.

5. Repeat steps 2 to 4 for a sufficient number of iterations. The number of iterations required depends on the target system availability. As a rule of thumb, a number of iterations at least equal to 10 times the inverse of target unavailability should be considered (e.g., for an availability of 99.9 percent of the time, the number of iterations should be larger than 10/0.001, i.e., ten thousands).

The post-processing phase consists of the following steps:

1. For each ST, compute the average time link availability (obtained as the ratio of the number of times the ST is available with the total number of simulation iterations).

2. Compute the spatial availability by computing the percentage of ST fulfilling the required time-link availability target.

3. For each ST, compute the average throughput, by averaging the throughput obtained at each simulation step over all the simulation iterations.

> The tool input parameters consist of the satellite system characteristic parameters, as well as physical layer performance figures. Some system parameters, like antenna pattern and frequency reuse plan, are spatially variant within the coverage area, thus motivating a statistical analysis.

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[2] *Such fading will depend, in addition to the carrier frequency, on the station geographical location and satellite position.*

As practical systems must support a non-uniform beam loading, whose distribution changes over the satellite lifetime, the capability of ACM to self-adapt in each location to changing interference patterns (e.g., non-uniform frequency reuse patterns) is a key property.

Figure 4. *40 Ka-band spot beams –3 dB contours over typical European coverage.*

4. Compute the average system throughput by averaging the aggregated throughput of all the ST during the whole simulation.

Then, the obtained availability and throughput results can be compared with the requirements, and in the case of unsatisfying results, possibly system sizing could be changed.

FURTHER SYSTEM CONSIDERATIONS

Note that the previously described methodology to design and/or assess the capacity of an ACM system has a number of limitations, for example:

- To simplify the matter, we limit ourselves to the physical layer throughput, as the effective user throughput also is dependent on the particular radio resource management (RRM) policies implemented.
- The required margin for loop control inaccuracy was not included. However, parallel simulation work performed in another context, taking into account realistic propagation events, signaling delay, and physical layer adaptation margins, demonstrated that the throughput degradation does not exceed 15 percent, and the link availability is not affected [7].
- No encapsulation inefficiencies of the received data traffic into the DVB-S2 frames were considered.
- The system throughput was computed assuming a uniform distribution of ST over the coverage area and equal time allocation to all ST regardless of the location of the ST (e.g., beam edge or beam center) and regardless of the experienced fading. For example, it implies that more throughput is provided at beam center than at beam edge, due to the more favorable link budget. If provision of equal throughput per ST is a design goal, then the time allocation to ST should not be uniform and should consider the channel quality of each ST. However, no major impact on the system throughput, which has been derived with uniform time allocation, is expected due to low probability of extremely robust ACM modes utilization (a preliminary assessment has only shown one percent of system throughput decrease).
- As practical systems must support a non-uniform beam loading, whose distribution changes over the satellite lifetime, the capability of ACM to self-adapt in each location to changing interference patterns (e.g., non-uniform frequency reuse patterns) is a key property. In these more practical operating conditions, the ACM advantages are assessed on a case-by-case basis.
- No attempt was made to optimize the system design when exploiting ACM (including feeder uplink power control and transponder input power flux density (IPFD)). In fact, with ACM, the system parameters are optimized following a different approach than the conventional one, because they have a different impact on overall system throughput. Furthermore, satellite multi-beam antennas are designed with average performance in mind rather than worst-case figures (gain, C/I). This also can lead to a simplified payload design. ACM also may help to cope with the satellite and ST antenna mispointing

errors.

Another main benefit of ACM systems, which is impossible in CCM systems and has not been considered in the simulations, is that ACM systems can take advantage of different ST antenna sizes to increase the provided throughput. This implies that an ACM system is much more scalable than a CCM system. If a user would like to increase the received data rate of its link, a bigger antenna could be used.

STUDY CASE RESULTS

The aim of this section is to provide a realistic reference scenario where the gain of ACM compared to CCM was assessed using the described methodology. The proposed scenario, considered a representative example of a broadband system over Europe, is one possible system implementation. Other implementations may lead to different results even though the same general conclusions apply. However, to make system analysis results more generally applicable, a sensitivity analysis of some parameters also is proposed at the end of the section.

REFERENCE SYSTEM

The reference system is based on a 40 Ka-band spot beams satellite that is well within reach of technology that exists today. The antenna pattern is a 40 Ka-band spot beams system over a European coverage (Fig. 4). The computed C/I (taking into account only the antenna pattern and no intra-system interference) ranges from about 16 dB to 38 dB). The satellite antenna beam width is approximately equal to 0.6°.

The link is divided in channels of 125 MHz bandwidth supporting one carrier of 90 Msymb/s. Only one channel is allocated per user beam, according to a regular 1:4 color (frequency and polarization) reuse plan. The total user bandwidth is equal to 250 MHz (2×125 MHz in two polarizations).

Each gateway transmits four channels of 125 MHz, all in the same polarization (to have a simple gateway RF transmit section). Therefore, the feeder link bandwidth is equal to 500 MHz (4x125 MHz in one polarization). On-board, downlink channels are converted in frequency and transmitted to the right polarization according to the frequency plan.

In case a smaller carrier granularity is required, for example, due to flexibility issues, multi-carrier satellite high power amplifier (HPA) operations are required. As discussed in [3], this results in slightly increased output back-off (OBO) and link impairment.

The selected approach is to dimension the reference system for providing 99.7 percent target link availability over 95 percent of the coverage region for a DVB-S QPSK carrier with a coding rate equal to 3/4.

Classical sizing has been performed, that is, based on the worst case link budget for the target link and coverage availability. The same derived system configuration is used as a reference system study case for assessing the capacity of the DVB-S2 CCM system and DVB-S2 ACM system (both discussed later), following the methodology described in the previous section.

Physical layer parameters	
Carrier rate	90 Msamples/s
Satellite downlink frequency band	19.95–20.2 GHz
Gateway parameters	
Gateway antenna diameter	4.5 m
Gateway HPA	120 dBW
Gateway EIRP per carrier	74 dBW
Gateway NPR	21 dB
Satellite parameters	
Satellite EIRP per carrier at edge of coverage	60.5 dBW
OBO	0.5 dB
EOC gain	49.5 dBi
Satellite input losses	3 dB
Terminal parameters	
Terminal antenna diameter	0.75 m
Terminal G/T	16.5 dB/K
Intersystem interferences	
Adjacent satellite systems' PSD relative to AWGN	0.97 dB
Intrasystem interference	
Cofrequency copolarization (95 percent of coverage)	21 dB

■ **Table 1.** *List of main system parameters.*

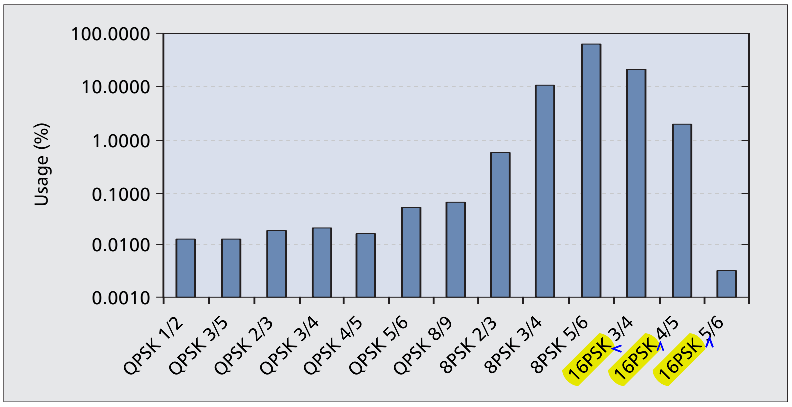
Table 1 lists the main system parameter values considered for the reference system scenario.

Note that the satellite number of beams and gain assumptions are conservative for current payload technological capabilities.

The computed total throughput for the reference system amounts to 4.97 Gb/s.

DVB-S2 PERFORMANCE ASSESSMENT

To ease system performance comparison, the same system parameters of Table 1 were adopted for the DVB-S2 performance assessment. For the DVB-S2 physical layer, a short frame configuration was assumed together with dynamic predistortion and the demodulator algorithms presented in [11]. The related SNR thresholds were then derived for each coding rate and modulation format through end-to-end physical layer simulations. They include implementation and demodulation losses. In addition, the output power back off at the optimum operating point for the different modulation schemes were considered in the link budget [11].



■ **Figure 5.** *Distribution of modulation and coding usage (percent) for enhanced DVB-S2 ACM system configuration.*

DVB-S2 CCM System — The $E_s/(N_0 + I_0)$ value, relative to the target link and space availability, leads the DVB-S2 CCM system to adopt the 8-PSK modulation format and 2/3 coding rate. This is possible by utilizing the improved DVB-S2 physical layer performance compared to DVB-S.

The total DVB_S2 CCM profile system throughput is equal to 6.92Gb/s, which implies a capacity increase of 39 percent with respect to the DVB-S system.

DVB-S2 ACM System — To ease the comparison with the reference system, the ACM performance first was computed assuming the same system parameters. Note that this approach penalizes the ACM performance as system parameter optimization may further improve ACM performance.

As explained earlier, the DVB-S2 ACM system experiences, in general, both higher availability and throughput than the DVB-S2 CCM system. The higher availability is guaranteed by the utilization of spectral efficiencies lower then 8-PSK 2/3 when in the presence of deep fade events, provided the minimum required user bit rate is met. The higher throughput results from using high-spectral efficiency modes in clear sky conditions. Using the system analysis tool previously described, the modulation and coding distribution resulted in: 6.6 percent for 16APSK $r = 5/6$, 23.5 percent for 16APSK $r = 4/5$, 30.5 percent for 8PSK $r = 5/6$, 1.1 percent for 8PSK $r = 3/4$, 1 percent for 8PSK r = 2/3.

The spectral efficiencies lower than 8PSK 2/3 are used very rarely by the ACM system, but they allow the increase of the link availability to 99.9 percent for a space availability of 98 percent. Note that in the current example, the 32-APSK modulation is never used.

A total average system throughput of 9.66 Gb/s is achieved, which means a remarkable capacity increase of 40 percent with respect to the DVB-S2 CCM system and 94 percent vs. DVB-S.

The gain of the ACM system heavily depends on system parameters. As shown in the following section, the gain greatly improves with an increase of the target link availability and the reduction of the satellite EIRP and/or terminal G/T. Indeed, in these cases, the utilization of a range of physical layer modes of the ACM system can be better exploited.

SENSITIVITY ANALYSIS TO SYSTEM PARAMETERS

This section presents results for the sensitivity of ACM system performances to system and physical layer parameters.

Sensitivity Analysis to Reference System Definition — For this sensitivity analysis exercise, the same parameters as in Table 1 were assumed, with the exception of the satellite EIRP per carrier, which was reduced to 57.8 dBW EOC (instead of 60.5 dBW). Moreover, the target link availability is now set to 99.8 percent (instead of 99.7 percent) over 95 percent of the coverage. This new availability requirement calls for the adoption in CCM systems of a higher link budget margin. Due to both the reduced EIRP and to the more stringent availability requirement, QPSK modulation and 1/2 coding rate (instead of 8-PSK 2/3) will be used in a DVB-S2 CCM system.

The total system throughput for DVB-S2 CCM mode is, in this case, equal to 2.99 Gb/s (instead of 6.92 Gb/s).

The distribution of modulation and coding usage obtained in the same system scenario for the ACM profile is described in Fig. 5.

In this simulation, it was assumed that the lowest modulation and coding scheme supported by the system is equal to the modulation and coding scheme of the CCM system, that is, QPSK $r = 1/2$. Usage of lower spectral efficiencies for ACM enables improvement of the system availability but does not have an impact on the system throughput.

With the slightly increased availability requirement and 3 dB satellite EIRP reduction, the total average system throughput of the ACM system is equal to 8.65 Gb/s, implying a capacity increase of 190 percent with respect to the DVB-S2 based CCM system.

This result shows that:

- As the reference system has been sized for a slightly higher availability (99.8 percent instead of 99.7 percent), the potential gain of ACM is greatly increased. The reason is that the higher availability target implies that the system is sized for coping with deeper fading; hence, higher link margins should be put in place for CCM to provide the improved service availability. The satellite RF power used for static margins is completely wasted, because for the majority of the time, users will experience higher SNIR than required by the demodulator. Instead, ACM can exploit the available SNIR at any time, implying a significant increase of the average throughput. Similar conclusions would apply when considering larger (> 95 percent) system spatial availability.
- While the satellite RF power is decreased by 46 percent, the average throughput of the ACM system is decreased only by 10.5 percent (the gain of the ACM system with respect to the CCM system is higher in the second system scenario than in the first one, but the absolute capacity is lower). The main reason is that the higher the spectral efficiency of the modulation and coding scheme, the lower the power effi-

ciency (due to the impact of the flattening of the capacity curve at a high value of SNIR). In addition, a reduction of the satellite RF power makes the system operate in less interference-limited conditions, thus, with a lower impact of interference on the link budget.

The PDF region typically corresponds to the rare fading events that can be covered by just one or two physical layer configurations. By doing so, you improve the ACM adaptation system robustness without affecting the overall throughput.

Sensitivity Analysis to Selected Modulation and Coding Schemes — If the system does not implement all the modulation and coding schemes of the DVB-S2 standard, then the efficiency of the system is somewhat affected.

For example, referring to the system considered previously, if only the following subset of modulation and coding schemes are implemented: QPSK 1/2, QPSK 2/3, QPSK 5/6, 8PSK 3/4, and 16APSK 4/5 — then the total average system throughput is equal to 7.53 Gb/s, which implies a decrease of 13 percent with respect to the implementation of all modulation and coding schemes. In this case, the ACM capacity increase is equal to 152 percent with respect to a CCM system. It should be noted that in the previous example, the subset of modulation and coding schemes was not optimized. Given a limit on the total number of modulation and coding schemes supported by the system, an optimum selection of the ACM modes may significantly decrease the impact on the capacity. For example, if the following modulation and coding schemes were selected: QPSK 1/2, 8-PSK 2/3, 8-PSK 3/4, 8-PSK 5/6, and 16-APSK 3/4, then the capacity decrease would be only 0.3 percent. This implies that a good ACM system performance can be achieved without requiring a large number of modulation and coding schemes, provided that those that are implemented span the range of $E_s/(N_0 + I_0)$ with the optimal granularity. In this regard, the implemented physical layer configurations can be optimized to best fit the SNIR simulated distribution and also to simplify the physical layer adaptation. In fact, it is more effective to reduce the granularity corresponding to the left part of the tails of the received SNIR probability density function (PDF). The PDF region typically corresponds to the rare fading events that can be covered by just one or two physical layer configurations. By doing so, you improve the ACM adaptation system robustness without affecting the overall throughput.

Other simulations were run to assess the impact of implementing only QPSK and 8-PSK modulation formats. In the system scenario with the reduced EIRP = 57.8 dBW EOC, the throughput is now reduced to 8.30 Gb/s (compared with 8.65 Gb/s when all the modulations are supported).[3] In the reference case, where EIRP = 60.5 dBW EOC, it is 8.41 Gb/s that must be compared with 9.66 Gb/s when the whole set of modulations are supported. Then, the loss is more significant due to the higher use of 16-APSK modes.

The previous results show that the impact of supporting only QPSK and 8-PSK modulations may be significant (up 15 percent) depending on the particular system sizing and in particular, on the available on-board power.

Satellite Multibeam Antenna Design Issues — Before discussing the impact of the satellite downlink antenna parameters on the average system throughput, a consideration of the impact of ACM on the satellite antenna design is appropriate. In CCM systems, the satellite multi-beam antenna is typically specified through its minimum performance over the coverage region (or a subset of it) in terms of gain and C/I. This is because the CCM physical layer is dimensioned on the worst-case location for the worst-case time of the year. Thus, knowing the satellite RF power limitations, the antenna design should ensure that the CCM physical layer efficiency is acceptable for the worst-case location. For ACM, the average antenna performance has more relevance than the worst-case. This is because, as for the fading attenuation, worst-case C/I or gain variations, if limited in area extension, can be accommodated by the ACM intrinsic adaptability with minimum impact on the overall throughput performance. This is an essential issue as it enables the:

- Relaxing of the multibeam antenna design in terms of minimum C/I, for example, reducing the number of feeds required/beam in a multi-feed/beam (AFR) antenna architecture. This has the advantage of simplifying the payload RF front-end and at the same time easing the introduction of digital processors with digital beam forming networks (DBFN).
- Increasing the beam overlap to one side reduces the gain ripple within the beam while reducing the antenna mispointing errors impact.
- Accept variable frequency reuse over the system coverage region to cope with uneven traffic distributions.

These features are considered key drivers for designing very efficient broadband satellite networks.

Sensitivity to the Number of Satellite Antenna Beams and Frequency/Polarization Reuse — Simulation tests were carried out for system study cases assuming constant overall satellite RF power and bandwidth with different number of beams, from 60 up to 205 beams. Results show that the ratio between the average ACM system spectral efficiency and the correspondent CCM system efficiency remains almost the same regardless of the number of beams. Therefore, the absolute capacity increase due to ACM is larger in systems with a high number of beams. Indeed, results show that the capacity gain achieved for a constant satellite RF power by ACM systems over conventional CCM systems moves from 5 Gb/s (60 beams) up to 22 Gb/s (206 beams).

Additional parameters directly affecting system throughput are frequency and polarization reuse. Simulations indicate that for ACM systems, an additional gain of about 50 percent can be obtained by the use of the two orthogonal polarizations with the same overall satellite bandwidth. That means that the useful bandwidth/beam is now doubled although the overall satellite power remains constant. This fact explains why the improvement is not close to 100 percent as one might expect. The utilization of a more pushed satellite multibeam antenna frequency reuse pattern, 1:3, with respect to a more conventional 1:4 frequency reuse pattern results

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[3] *Here we have considered all QPSK modes down to rate 1/4, while before the lowest mode was QPSK 1/2, but this should not impact the throughput in a significant way.*

in a gain of about 15 percent at the expense of an increased feeder link bandwidth requirement and a more complex satellite RF front-end.

CONCLUSIONS

In this article we showed that the adoption of the ACM profile supported by the new DVB-S2 satellite physical layer standard has a profound impact on the system sizing and optimization methodology. A computer-based semi-analytic capacity analysis approach for the forward link of a multi-beam satellite broadband access network exploiting the DVB-S2 ACM profile was described. Numerical results for a few realistic study cases showed that adaptive coding and modulation techniques could significantly increase the average system throughput and availability, thus making the system economically more attractive for interactive applications. This capacity increase is mainly dependent on the frequency band adopted, target link and service area availability requirements, and related system sizing options.

Numerical results for a few realistic study cases showed that adaptive coding and modulation techniques could significantly increase the average system throughput and availability, thus making the system economically more attractive for interactive applications.

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BIOGRAPHIES

ERIC ALBERTY graduated from École Nationale Supérieure des Télécommunications. He joined Matra Espace (now EADS Astrium) in 1989. In the Telecom Systems Department of the Telecom Satellites Business Division, he is responsible for the satellite system engineering expert group. In the past few years, he has been involved in advanced broadband projects and has been contributing for more than five years to the West Early Bird broadband project, an ESA ARTES3 program, as a system engineer and project manager.

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ALBERTO GINESI received his Dr. Ing. (cum laude) and Ph.D. degrees in electronic engineering from the University of Pisa in 1993 and 1998, respectively. In 2002 he joined ESTEC, where he is responsible for the definition and development of advanced broadband satellite communication systems. His main research interests are in the area of advanced digital communication techniques from theory to hardware implementation. In 1996–1997 he spent one year at Carleton University, Ottawa, Canada, doing research on digital transmissions for wireless applications. In 1997 he joined Nortel Networks and in 2000 Catena Networks, both in Ottawa, Canada, where he worked on DSL technologies and contributed to the definition of the second-generation ADSL standard.

RITA RINALDO obtained her Master's degree in telecommunications engineering (summa cum laude) from the University of Bologna, Italy, in March 2000; in May 2005 she received her Ph.D. for a dissertation entitled *Adaptive Coding and Modulation Techniques for Broadband Satellite Systems*. Since February 2001 she has been with the Communication System section in the Technical and Quality Management Directorate of the ESA. Her interests are mainly in the fields of communication satellite system design, physical layer algorithms, and resource optimization techniques. From June 2000 to January 2001 she was with TiLab, the technology research center of TelecomItalia.

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