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New DVB-S2X constellations for improved performance on the satellite channel

Mustafa Eroz[1,*,†], Lin-Nan Lee[1], Nabil Loghin[2], Ulrik De Bie[3], Frederik Simoens[3] and Daniel Delaruelle[3]

[1]*Hughes Network Systems, Germantown, MD, USA*
[2]*Sony, Stuttgart, Germany*
[3]*Newtec, Sint-Niklaas, Belgium*

SUMMARY

Digital Video Broadcasting via satellite second generation has experienced worldwide adoption because of its revolutionary and yet practical physical layer technology and its flexibility. Recently, the standard has been updated with several new features without changing its fundamental structure. This paper provides a high-level discussion on several of the most important additions to the new standard with particular emphasis on some of the new signal constellations. Copyright © 2015 John Wiley & Sons, Ltd.

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KEY WORDS: DVB-S2X; higher order constellation; constrained capacity; phase noise; physical layer header; LDPC

1. INTRODUCTION

Digital Video Broadcasting via satellite (DVB-S) was initially conceived for Direct-to-Home (DTH) applications. The first generation DVB-S standard was based on quadrature phase shift keying modulation and convolutional code concatenated with Reed Solomon code. In 2003, DVB introduced a novel family of low-density parity check (LDPC) codes, which are not only within a dB of the theoretical Shannon limit but also possess intrinsic structure that enables high-speed reception in an efficient way leading to practical implementation. This set of LDPC codes along with a set of amplitude and phase-shift keying (APSK)-based modulation forms the basis of DVB-S second generation (DVB-S2) standard [1]. Because of its unprecedented performance and availability of inexpensive receiver implementation, it soon saw worldwide deployment by the very small aperture terminal network operators as well as the satellite TV broadcasters. Other terrestrial and cable standards followed the footsteps of S2 (DVB-S2) by adopting the same set of codes. After 10 years since its introduction, even though there was no new breakthrough in the forward error correction technology, a new activity started to improve DVB-S2 on a system level without fundamentally changing its original structure. Finalized in 2014, this evolution of DVB-S2 is called DVB-S2X, or DVB-S2, Part II [2].

DVB-S2X introduced additional modulation/coding pairs (modcods) to improve the granularity of S2, modified physical layer signaling (PLS) to enable these modcods, and extended the signal-to-noise ratio (SNR) range towards very low SNR (VL-SNR) to support mobile applications and ultra small-aperture terminals, as well as towards very high SNR to support professional applications. Moreover, a new frame structure has been defined for VL-SNR data, which allows these frames to coexist with 'regular' transmission without causing the regular frames additional overhead. Furthermore, sharper

*Correspondence to: M. Eroz, Hughes Network Systems, Germantown, MD, USA.
†E-mail: meroz@hns.com

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roll-off factors have been introduced to improve the system spectral efficiency in certain conditions, and five additional configurable scrambling sequences have been defined to suppress co-channel interference. Besides these physical layer improvements, DVB-S2X also introduced channel bonding, allowing operators to merge the capacity of several transponders, which helps increase the statistical multiplexing gain. Compared with single transponder schemes, channel bonding is expected to offer significant improvement especially with the introduction of ultra-high definition TV that requires very high data rate.

This paper focuses on the introduction of new constellations for S2X (DVB-S2X) to improve the signal modulation. While S2 considered APSK constellations with ring ratios optimized for the linear additive White Gaussian noise (AWGN) channel, S2X focused on a more realistic nonlinear channel model, which reflects the behavior of modern linearized travelling wave tube amplifiers. For certain operation modes, the satellite link can also be considered as an instance of the classical linear AWGN channel, for which case non-uniform constellations (NUCs) [3] have been introduced.

In this paper, we first provide an overview of improvements provided by S2X. Some of the new constellation designs are then presented along with theoretical and practical justifications. An extended PLS code is described that supports all of the new modcods of DVB-S2X without any fundamental change to the legacy PLS code and its DVB-S2 modcod codewords.

2. OVERVIEW OF IMPROVEMENTS INTRODUCED BY NEW DVB-S2X CONSTELLATIONS

2.1. Very low signal-to-noise ratio

Mobile terminals and/or terminals with small apertures typically suffer from poor signal-to-noise ratios. In order to protect these terminals in high rain fade regions, novel modcods have been introduced in DVB-S2X. These modcods are based on $\pi/2$–binary phase shift keying modulation and are protected by low-rate LDPC codes (as low as code rate 1/5). These low code rates are further supported by symbol repetition (which leads to spreading by the particular scrambling sequence selected) to further reduce the required SNR [4].

As a result, DVB-S2X provides modcods that can operate at Es/No levels as low as -10 dB. In order to accommodate these new modcods, the PLS mechanism had to be adjusted as well. The original DVB-S2 PLS header was designed to operate reliably at symbol-energy per noise levels of slightly lower than Es/No $= -2.5$ dB. A new frame structure with a more robust VL-SNR header has been introduced in DVB-S2X. This new header can be decoded up to Es/No $= -10$ dB. Considering the fact that mobile and VL-SNR terminals are likely to be only a small minority of the population in any given network, only VL-SNR modcods are equipped with this better protected header. In this manner, only the VL-SNR frames exhibit additional PLS overhead, whereby regular frames still benefit from the efficiency of the low overhead as in DVB-S2 [4].

2.2. High signal-to-noise ratio modulation schemes

Professional satellite applications often use receive stations with large antennas (compared with DTH terminals). Moreover, thanks to adaptive coding and modulation and/or uplink power control, these services operate with little fading margins. For these scenarios, DVB-S2X introduced higher modulation orders up to 256APSK, as opposed to 32APSK of DVB-S2. This significantly increases the spectral efficiency for links with a high signal-to-noise ratio (Es/No $= 16$ dB and above).

2.3. Finer modcod granularity

The new DVB-S2X standard introduces a large number of new modcods, in order to reduce the SNR spacing between individual modcods. Especially, in the Es/No range from 5 to 12 dB, which is typically used for the important DTH applications, modcod Es/No separations have been reduced from 1.5 to less than 0.5 dB. This allows to better match the modcod to the available SNR and to maximize the spectral efficiency.

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2.4. Lower rate modcods

In addition to finer granularity modcods, DVB-S2X also extends the S2 code rates to lower rates for any given constellation. From a theoretical point of view, this leads to more efficient modcods, because for a fixed constellation, the constrained capacity diverges from unconstrained capacity as SNR increases. Therefore, for any given bandwidth efficiency, it is more desirable to employ higher-order constellations and lower code rates as long as carrier synchronization is not an issue. As an example, the lowest code rate for 16APSK in DVB-S2 is 2/3. As a result, for links with less available SNR, one would have to resort to 8PSK modcods. DVB-S2X, on the other hand, provides with an extensive choice of 16APSK low code rates such as 1/2, 8/15, 5/9, 26/45, 3/5, 28/45, and 23/36, providing in most cases a more attractive solution than 8PSK. For example, rate 2/3 8PSK of DVB-S2 requires about Es/No = 6.6 dB with a throughput of about 2.0 bits/symbol, whereas rate 8/15 16APSK of DVB-S2X requires about the same SNR with a throughput of about 2.13 bits/symbol. Therefore, for this particular example, DVB-S2X provides more than 6% throughput improvement. On the other hand, it should be mentioned that the above example assumes a linear channel, or a multi-carrier transmission with sufficiently high output backoff. For nonlinear channels, the relative performance advantage of 16APSK with respect to 8PSK would diminish because of AM/AM nonlinear distortion.

2.5. Linear and nonlinear modulation schemes

DVB-S2X introduces two categories of new modcods. The bulk of new modcods have been optimized for a nonlinear channel. A hard-limiter channel was used as a reference channel model to optimize the modulation parameters. Next to these so-called nonlinear modcods, the new standard also introduced a number of modcods optimized for a linear AWGN channel. Such a channel model is representative for scenarios whereby multiple carriers are placed on a transponder, and a large output backoff is employed. In addition to optimizing performance for the AWGN channel, some linear modcods, such as 2 + 4 + 2APSK, offer vastly improved synchronization performance compared with their nonlinear counterparts (8PSK).

3. NEW CONSTELLATIONS OF DVB-S2X

3.1. Design methodologies

Digital Video Broadcasting-S second generation has often been cited as the forefront of communication systems, which can approach the ultimate limits for reliable data transfer, set by the famous Shannon limit [4]. For low constellation sizes, like quadrature phase shift keying, the S2 modcods have approached the theoretical limits by less than 1 dB, which can be contributed mostly to the powerful deployed LDPC codes. Further improving the forward error correcting codes was thus a difficult task, which resulted in only minor potential gains over the last 10 years. For the extension of DVB-S2, it was only natural to improve modcod performance by tackling the second ingredient: the constellations [5].

For linear modcods of DVB-S2X, NUCs [3] have been optimized, which aim at maximizing the Bit-Interleaved Coded Modulation (BICM) capacity [6] of the AWGN channel, including mapper and optimum demapper. In particular, certain parameters of the constellations are optimized using a constrained nonlinear optimization algorithm [7] for SNR values in the proximity of LDPC waterfall. Thereby, these constellations allow for maximized reliability values at the input to the LDPC decoder, reducing decoding error probabilities.

For example, for a 16-ary constellation, all 16 complex constellation points have been used as variables for a nonlinear optimization problem (maximizing capacity), with the constraint that the average power of all points needs to be normalized, for example, to 1. As a remarkable outcome, these NUCs usually exhibit amplitude and phase-shift keying-like structures, allowing simple implementation, high resilience to phase noise and low peak-to-average power ratio values.

As an example, a 16NUC has been optimized for LDPC code rate of 3/5. The design SNR for this NUC takes the waterfall of the bit error rate (BER) curve into account. The waterfall of an LDPC BER curve is the narrow SNR region, in which the curve dramatically drops by several orders of magnitude,

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in this case at about 7 dB. Figure 1 depicts the constellation points of this NUC, where the bit labels are attached to the points and given in integer numbers (e.g., 7 denotes bit labels 0111). It should be noted that the constellation is not exactly an 8 + 8APSK constellation, but more precisely a 4 + 4 + 4 + 4APSK with minor differences in the ring radii.

Figure 2 shows the BER and frame error rate (FER) for this new S2X constellation over the AWGN channel. Both modcods use the 64k LDPC code from S2 (even though the new S2X modcod introduced both a new constellation and a new LDPC code of rate 3/5). An outer Bose-Chaudhuri-Hocquenghem (BCH) code with $t = 12$ error correction capability is deployed, and no roll-off was applied. As can be seen, the new constellation allows reception at 0.35 dB lower SNR, which can be considered as an extraordinarily large shaping gain, considering the limited number of degrees of freedom. The potential shaping gain for 16-ary NUCs, when compared with uniform quadrature amplitude modulation constellations, as for example, deployed in terrestrial and cable standards, is in the order of only 0.1–0.2 dB [3].

As another example, Figure 3 shows a new 64-ary constellation introduced by DVB-S2X. This constellation has a symbol arrangement of 8 + 16 + 20 + 20APSK. Figure 4 depicts a constrained capacity comparison of several 64-ary constellations where the S2X constellation achieves the highest capacity. It is also worth mentioning that this constellation achieves optimum or very close to optimum results on both linear and nonlinear channels as tested through extensive computer simulations.

Figure 5 depicts the new 2 + 4 + 2APSK linear constellation. Figure 6 illustrates the improved synchronization properties of this new constellation compared with its well-known 8PSK counterpart.

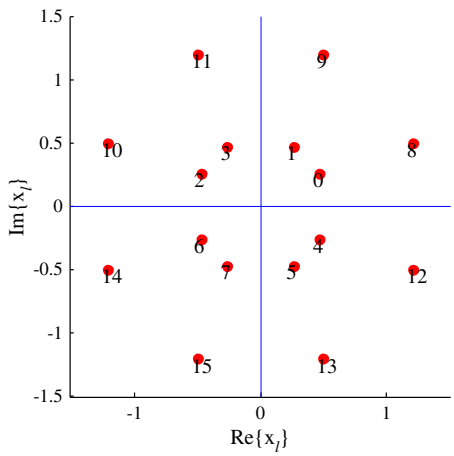

Figure 1. 16NUC for S2X for code rate of 3/5.

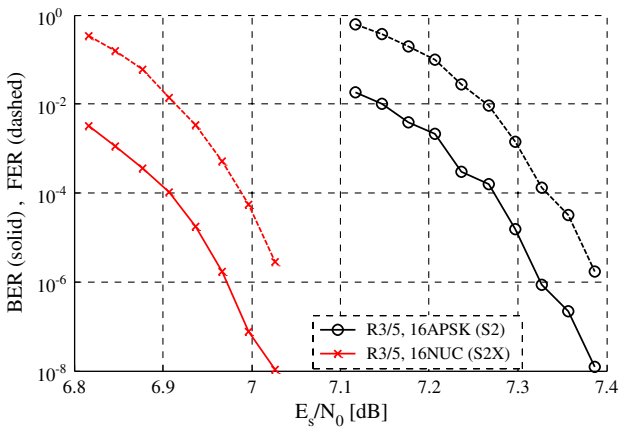

Figure 2. Performance of optimized non-uniform constellation (NUC) over additive White Gaussian noise channel compared with S2 constellation.

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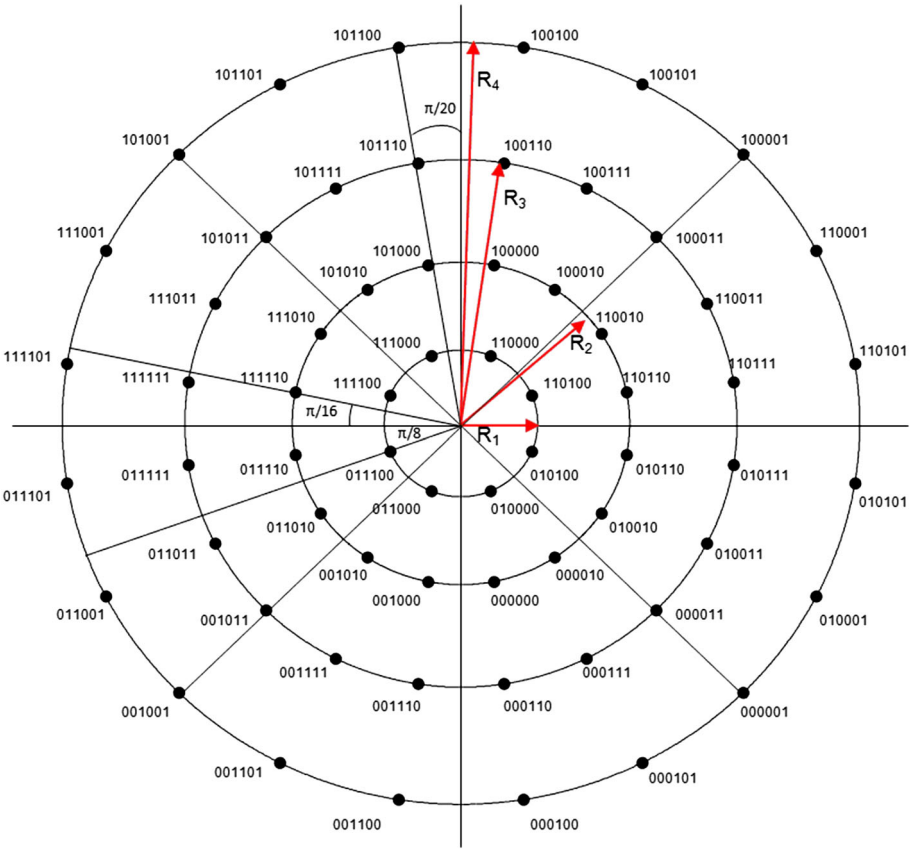

Figure 3. 64-Ary constellation of DVB-S2X.

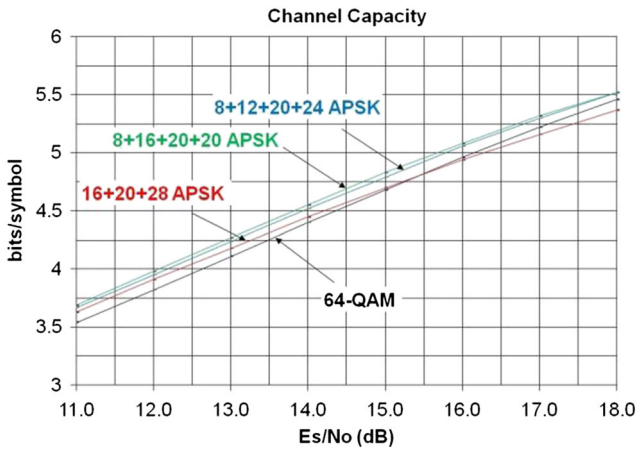

Figure 4. Constrained capacity comparison of several 64-ary constellations.

Consequently, the $2+4+2$APSK constellation can often be operated with pilots switched off, resulting in 2.5% overhead reduction. This benefit comes on top of an SNR gain of 0.2dB for standard (non-iterative) demapping and LDPC decoding.

3.2. Phase noise resilience

The DVB-S2X User Guidelines [8] detail the phase noise assumptions for the different satellite system components and for various service types, resulting in end-to-end phase noise masks denoted as P1

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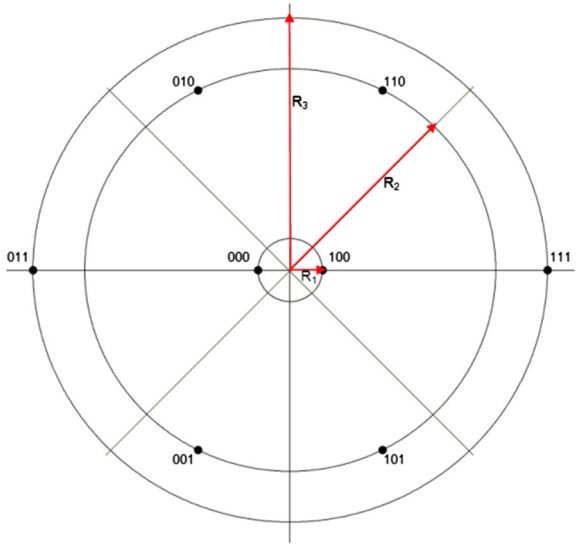

Figure 5. 2 + 4 + 2APSK constellation.

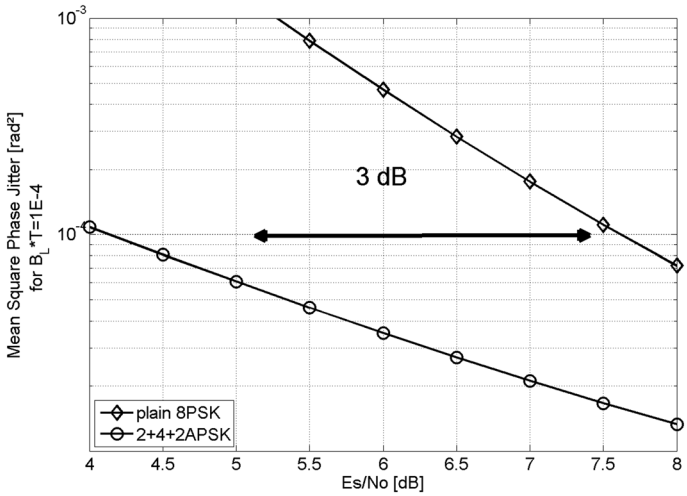

Figure 6. 2 + 4 + 2APSK improved synchronization performance for non-data-aided carrier synchronization (when pilots not used).

(first priority; legacy components) and P2 (second priority; year 2012 state-of-the-art system components). It was verified that constellations up to 64APSK operate under the P1 mask for the very small aperture terminal outbound channel at 10 MBd with degradation below 1.5dB @FER = 10^{-5}. At higher outbound channel symbol rates, this degradation dwindles. The P2 mask on the other hand permits deployment of 256-ary constellations with very low degradation down to at least 1 MBd, thereby enabling highly efficient professional services. Figure 7 illustrates the simulated phase noise resilience of a (nonlinear) 256-APSK constellation, assuming linear interpolation between estimated pilot phases.

4. EXTENDED PLS CODE OF DVB-S2X

In DVB-S2, a physical layer header is transmitted before each LDPC coded data to signal the receiver the modcod identity (5 bits), the length of the code (1 bit), and the presence/absence of pilots (1 bit). The seven bits are coded into 64-coded bits using a first order Reed–Muller code. For DVB-S2X, on the other hand, in order to signal the additional modcods, the standard extends the original DVB-S2 PLS code in a backwards compatible way. DVB-S2X defines an additional eighth bit b_0. For all

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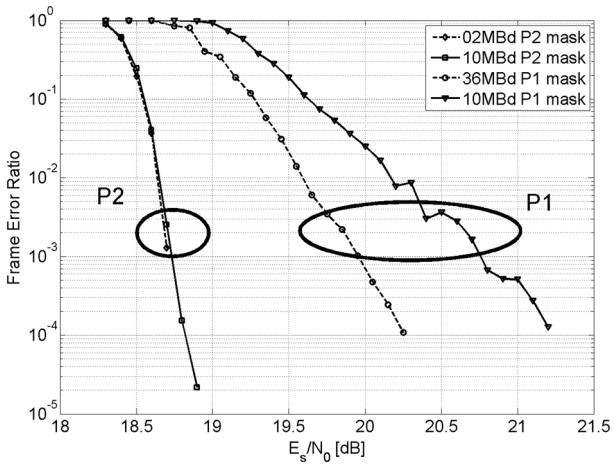

Figure 7. Performance of modcod 256APSK-32/45 for P2 and P1 phase noise profiles.

DVB-S2 modcods, this bit b_0 is set to 0, and the PLS code remains the same as DVB-S2. For the newly introduced DVB-S2X modcods, this bit b_0 is set to 1. For the case of $b_0 = 1$, the length bit is used in the signaling of additional modcods. The reason of this change is that in DVB-S2X, the majority of the modcods are already of normal length. So listing the short modcods explicitly instead of allocating an entire bit field to signal the length is more economical. In order to keep the performance of non-coherent decoding of the PLS code almost similar to DVB-S2, the bit b_0 is signaled using an updated (32, 7) generator matrix as shown in Figure 8. This generator matrix is identical to the (32, 6) generator matrix in DVB-S2 except the inclusion of a new first row. As a result, when $b_0 = 0$, the resulting codeword is identical to the DVB-S2 PLS codeword. As in DVB-S2, the particular construction in Figure 8 guarantees that each odd bit in the (64, 8) code is either always equal to the previous bit or is always opposite to the previous bit depending on the value of b_7. This fact can be exploited in case differentially coherent detection is adopted in the receiver.

It should be mentioned that the (32, 7) code does not maintain the bi-orthogonal property of the (32, 6) code. The minimum distance between the code words is somewhat reduced. To preserve the error rate performance, the set of codewords corresponding to the DVB-S2 modcods are made orthogonal to the set of codewords corresponding to new DVB-S2X modcods in the modulation space.

Similar to the DVB-S2, 64 symbol PLS code is $\pi/2$ BPSK modulated and transmitted after the 26 symbol start of frame (SOF) field. When $b_0 = 0$, the $\pi/2$ BPSK modulation regularly continues after the SOF field as for S2, while if $b_0 = 1$, a phase jump of $\pi/2$ is introduced after the SOF field. As a result, not only this one additional bit is encoded without changing the number of coded symbols in a backward compatible way but also the performance of the DVB-S2X PLS code only degrades slightly from that of the DVB-S2 PLS code. The coherent detection performance of DVB-S2X (64, 8) code is compared with that of S2 (64, 7) code in Figure 9. As shown by the simulation results, the performance penalty for sending one more data bit is about twice the error rate of the S2 case, because in the two-dimensional phase space, there are now two sets of codewords, orthogonal to each other due to the 90° phase shift, where the codewords in each set are mutually orthogonal.

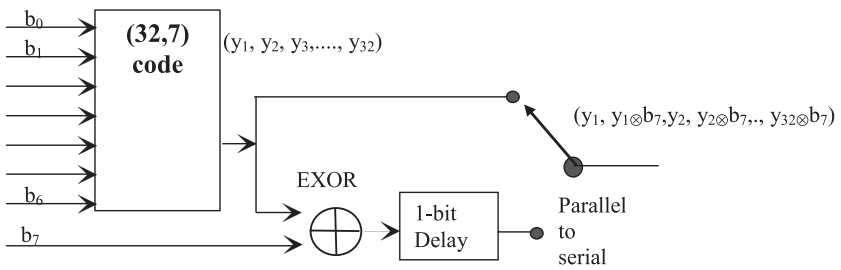

Figure 8. DVB-S2X physical layer signaling code (the symbol ⊗ stands for binary Exclusive or (EXOR)).

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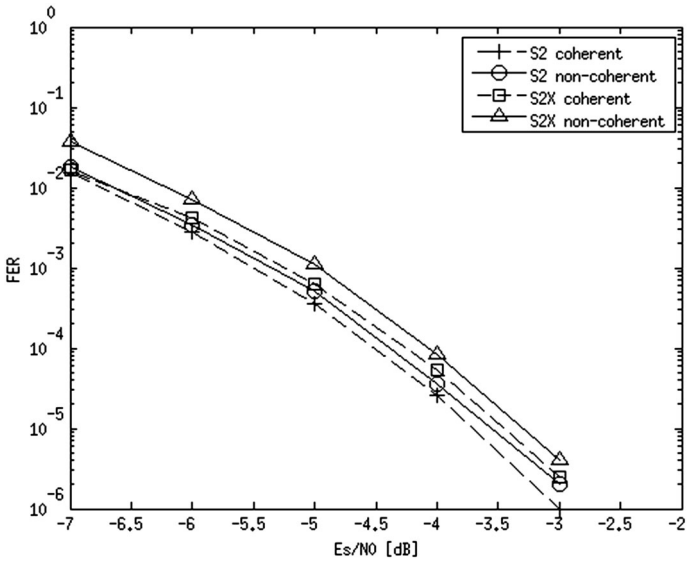

Figure 9. Performance comparison of S2 and S2X physical layer signaling codes with non-coherent detection.

For non-coherent detection, however, the phase shift is no longer distinguishable, and the first row of the generator matrix is used to differentiate the set of codewords corresponding to S2 or S2X modcods. Performance comparison of the two PLS codes with non-coherent detection is also shown in Figure 9. Due to the fact that the two sets of codewords are actually orthogonal to each other in the modulated space, the performance loss of the S2X PLS code is still less than 0.3 dB at FER = 10^{-6} from the non-coherent detection performance of the original DVB S2 PLS.

5. CONCLUSION

Digital Video Broadcasting-S second generation offers several additional improvements on DVB-S2 without modifying any aspect of the original standard and by keeping the underlying structure the same. New constellations with improved constrained capacity and better phase noise resiliency have been introduced. As a result, the updated standard covers 30 dB range of Es/No from 20 dB down to −10 dB, while maintaining a performance very close to Shannon capacity. Based on the successful history of DVB-S2, it can be expected for DVB-S2X to be also widely adopted for many years to come.

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AUTHOR'S BIOGRAPHIES

Mustafa Eroz received his PhD from the University of Maryland, College Park in 1996 where he was an Institute for Systems Research fellow. Since then, he has been with the Advanced Development Group of Hughes Network Systems. His current research interests include error control coding, multiple access schemes, coding for multiple antennas, and iterative receiver techniques. He played a leading role in the design of a new class of LDPC codes adopted by DVB-S2 and DVB-S2X and, in the specification of the turbo code, adopted in IEEE 802.11n. He received numerous awards from Hughes.

Lin-Nan Lee received his BS degree from National Taiwan University, his MS and PhD from the University of Norte Dame, all in Electrical Engineering. He is a Vice President of Engineering of Hughes leading its Advance Development Group. His research areas include data compression, channel coding, modulation, multiple access, and antenna signal processing. He actively participated in and made major contributions to DVB-S2 and DVB-S2X standardization activities. He also participated and contributed to wireless communications standards such as 3GPP, 3GPP2, and IEEE802.11.n, particularly in the area of forward error correction coding.

Nabil Sven Loghin (born Muhammad) received his diploma degree in Electrical Engineering and PhD degree from the University of Stuttgart, Germany, in 2004 and 2010, respectively. Since 2009, he has been with Sony, working on DTV standardization and localization algorithms. His research interests include channel coding, iterative decoding, QAM mapping optimization, and multiple-antenna communications.

Ulrik De Bie entered the world of satellite telecommunication when he joined Newtec Cy, Belgium as a system engineer in 2001/2002. His research interests include DVB-RCS and DVB-RCS2 satellite scheduling and encapsulation in the return link, ACM scheduling and encapsulation in DVB-S/S2/S2X forward link, control plane functions in satellite internet access systems, and user plane performance improvement. He is an active participant in the specification and engineering of satellite telecommunication standards. He participates in DVB TM and the ad hoc working groups TM-S2 (Wideband, DVB-CID, DVB-S2X), TM-GBS (GSE, SI), and TM-RCS (RCS and RCS2). He received the Licentiaat Informatica degree from the Katholieke Universiteit Leuven, Belgium, in 1998.

Frederik Simoens obtained a Masters degree in Electrical Engineering and a PhD degree in Digital Communications, both from the University of Ghent in 2003 and 2008, respectively. He also holds an MBA degree from Vlerick Business School. Since 2008, he has been working at Newtec, a satellite equipment manufacturer. His key areas of expertise include physical layer technologies and satellite communication modems and systems.

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Daniel Delaruelle has been active in satellite communications since 1985 and joined Newtec Cy, Belgium in 1988, where he took up equipment design, team lead, and staff scientist positions. His research interests include system synchronisation, waveform design, optimal resource scheduling, channel estimation, and distortion/interference countermeasures. He made key contributions to widely deployed standard-based and proprietary satellite transmission technologies and served on the DVB ad hoc workgroups evolving the DVB-DSNG, DVB-RCS, DVB-S2, DVB-S2X, and DVB-CID specifications. He received his Masters degree in Electrical Engineering from the University of Ghent, Belgium, in 1984.

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