Cooperative DVB-SH Satellite Broadcasting Systems with Rotated Signal Constellations

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Abstract: In this paper, we study the advantages of cooperation in broadcasting systems from a geosynchronous earth orbit (GEO) satellite to mobile terminals (MTs), achieved through a terrestrial complementary ground station (CGS) with fixed installment, which acts as a relay. Moreover and in the context of the digital video broadcasting-satellite-to-handheld (DVB-SH) standard, the performance improvements offered by the rotated constellations method are investigated, where prior transmission, a phase rotation of the transmitted symbols by a fixed angle is applied followed by a random component interleaver. Turbo codes with soft decision decoding and appropriate random channel interleavers are also considered. We present analytical expressions for the bit log-likelihood ratios (LLRs) that are needed for soft decision decoding at the MT turbo decoder, while the code combining technique is adapted to improve the end-to-end (E2E) performance. Then, we obtain through extensive computer simulations the average bit error probability (ABEP) of quadrature phase-shift keying (QPSK) signals received over pure land-mobile satellite (LMS) and pure CGS links for coding rates 1/3 and 6/7. Moreover, the optimal rotation angles are obtained for both links. E2E ABEP results are then presented assuming cooperation between GEO and CGS, while the power allocation issue is investigated under fixed total transmission power. Our performance evaluation results show that by using the constellation rotation technique, a performance gain can be achieved for high coding rates.

Keywords: broadcasting; code combining; constellation rotation; coding rate; complementary ground system (CGS); cooperation; digital video broadcasting satellite-to-hand-held (DVB-SH); decode-and-forward; log-likelihood ratio (LLR); quadrature phase-shift keying (QPSK); orthogonal frequency-division multiplexing (OFDM); relays; satellite communications; soft-decision decoding; turbo codes; random interleavers

I. INTRODUCTION

Satellite communication systems have become an important and complementary part of the 3rd and 4th generation telecommunication systems, with numerous applications such as telephony, navigation, and multimedia broadcasting [1-5]. Especially for broadcasting applications there is a worldwide deployment of digital video broadcasting (DVB) systems over satellite (DVB-S) and its later standard versions, such as DVB-S2 [6], DVB satellite-to-hand-held (DVB-SH) [7-10] and DVB next generation satellite-to-hand-held (DVB-NGH) [11, 12]. The DVB-SH standard, which was approved by the steering board of the 53rd DVB consortium in February 2007, aims to deliver video, audio, and data services to vehicles and hand-held devices, employing frequencies below 3 GHz, typically around the 2.2 GHz frequency band. Soon after, some world-wide market advances related to the DVB-SH technology are as follows. Dish Network and Alcatel-Lucent have hosted successful trials of DVB-SH systems across the United States, while ICO Global Communications has successfully launched a satellite named ICO G1 specifically for mobile television [13]. In France, SFR and Alcatel-Lucent teamed up and deployed successful DVB-SH trials. In Italy, Tre Italia, RAI and Alcatel-Lucent joined their forces for the first DVB-SH trial, while various research and development (R&D) projects related to the DVB-SH technology have been funded by the European space agency (ESA) [14-16].

Cooperation that is achieved using relays is a promising technology for contemporary communication and broadcasting systems [17]. Their architecture can be considered as distributed multiple-input multiple-output (MIMO) systems by accomplishing similar performance to conventional MIMO systems. However, an important advantage of relaying communications is that there is no need for employing multiple antennas at the transmitting and at receiving ends, since each distributed node can serve as an independent link. From the practical point of view, this is an important advantage of relaying communication systems as compared to conventional MIMO systems, due to limited-size hand-held mobile terminals (MTs). Relaying technology has been incorporated in the DVB-SH standard as optional, where a relaying type of operation (hybrid) can be established. This is achieved through a complementary ground station (CGS), which acts as a relay of the information signal received from a geosynchronous earth orbit (GEO) satellite.

Further to the hybrid type of operation, the DVB-SH standard includes sophisticated modulation techniques and powerful error-correcting codes, in order to achieve a targeted service quality. Another technique, that may be used to further enhance the reception quality over fading channels, is the constellation rotation [18-24]. This technique has been included as optional in the second version of the terrestrial DVB (DVB-T2) standard [25-27]. According to this technique, prior transmission, a phase rotation of the transmitted symbols by a fixed angle (known also at the receiver) is applied followed by a component interleaver. Such combination results in independent fading for the inphase (I-) and quadrature (Q-) components of the received complex signal, thus improving the receiver performance. However, to the best of our knowledge, this technique has not been yet applied to satellite based communication systems. For example, its application to realistic land-mobile satellite (LMS) channel has not been studied yet in the open technical literature. In addition, the application of the constellation rotation method to both hybrid (i.e. satellite and terrestrial) as well as non-hybrid (i.e. satellite only) operation of DVB-SH system is also novel. These two topics are the subject of our current paper.

In particular, and also motivated by the recent advances in digital broadcasting over satellite, we study the advantages of cooperation in broadcasting from a GEO satellite to MTs. Single- and multi-carrier transmissions are considered for the GEO-to-MT and CGS-to-MT links, respectively. For such systems, we apply the rotation constellation concept to all transmitting and receiving ends. Moreover, turbo codes with soft decision decoding and appropriate random component and channel interleavers, both being applied after constellation rotation, are considered. The relay retransmits the information signal according to the decode-and-forward (DF) protocol, while the code combining technique is adapted to efficiently utilize the received signal by the MT.

The rest of the paper is organized as follows. After this introduction, section II presents the system and channel models. In section III the required bit log-likelihood ratios (LLRs) for rotated and unrotated (fixed)

The authors present analytical expressions for the bit log-likelihood ratios (LLRs) that are needed for soft decision decoding at the MT turbo decoder, while the code combining technique is adapted to improve the end-to-end (E2E) performance.

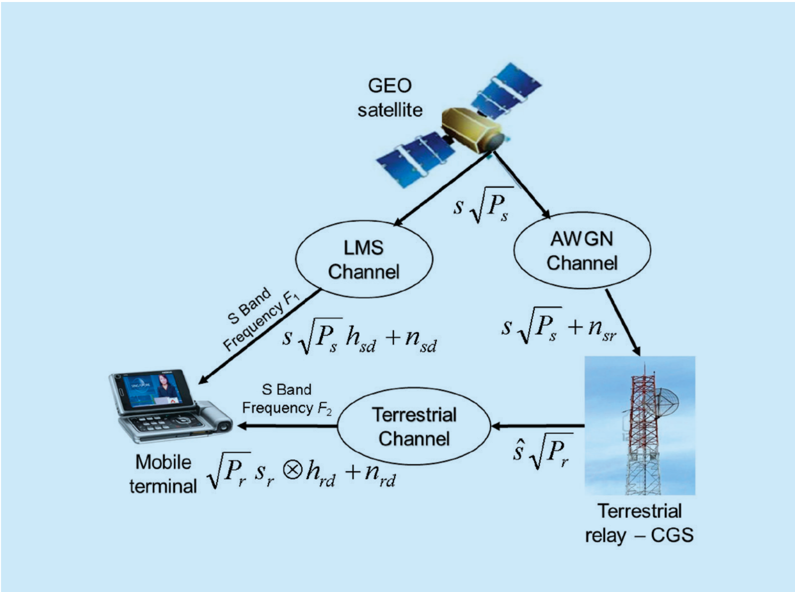

Fig.1 *The system model of the broadcasting communication system under consideration*

constellations are derived. Section IV presents various comprehensive end-to-end (E2E) performance results of the LMS-, terrestrial- and hybrid-type of operation. Finally, in section V, the most important conclusions of the paper are summarized.

II. Broadcasting Model and Channels

The broadcasting model under consideration is illustrated in Fig. 1. It consists of three separate communication subsystems, namely: A GEO satellite transmitter, a terrestrial CGS and a MT. The CGS acts as a relay that forwards the received data from the satellite to the MT. It is assumed that GEO and CGS are transmitting in different carrier frequencies in the S-band. Furthermore, the MT efficiently combines these two signals in order to improve the overall E2E performance. It is noted that the DVB-SH specifies two operational modes. On the one hand the SH-A mode specifies the use of orthogonal frequency-division multiplexing (OFDM) modulation on both satellite and terrestrial links. On the other hand, SH-B mode uses time-division multiplexing (TDM) on the satellite link and OFDM on the terrestrial link. The latter mode of operation is considered in this paper. Next the details of the channel models as well as the broadcasting communication system are investigated.

2.1 Channels models

As shown in Fig. 1, there are three distinct channels which are used to model the links between the three considered communication subsystems, as follows.

i) GEO-to-CGS: This channel models the link between the GEO and the terrestrial relay. It is assumed to be an additive white Gaussian noise (AWGN) channel, since the installation of a CGS is fixed and there will be always line-of-sight (LoS) with the GEO satellite. The AWGN for the GEO-to-CGS link is denoted as n_{sr} that is a zero-mean, i.e., $E[n_{sr}] = 0$, circular complex Gaussian RVs, with average power $E[|n_{sr}|^2] = 1$, and with E[•] being the averaging operator.

ii) GEO-to-MT: This channel models the link between the GEO and the MT. This is the so-called LMS channel and which in the S-band is usually assumed to be frequency flat. This assumption is very accurate for 1.5 MHz, accurate for 5 MHz and fairly accurate for 8 MHz channelization. In other words, the satellite propagation channel can be considered as a single complex multiplicative process between transmitted signal and fading modelled by the Loo distribution [28]. The Loo distribution is combined with a 3-state Markov process that corresponds to three different environments encountered in a typical vehicle route [29]. The Markov chain is characterized by the transition probability $P_{i,j}$ from state i to j (i, j = 1,2,3). Each state S_i of this model is described by a Loo distribution with different set of parameters. The Loo distribution is a sum of a shadowing and a multipath component, i.e., for the ith state

$$h_{sd,i} = w_i + g_i \tag{1}$$

where w_i is a lognormal random variable (RV) and g_i is a zero-mean circular complex Gaussian RV, i.e., Rayleigh envelope and uniform phase. Further to the conventional approach for the power spectral density of the multipath component, that assumes a Butterworth or Gaussian filter, in our analysis a rectangular filter has been used. Note that the shadowing process in (1) is much slower than the multipath one.

iii) CGS-to-MT: This channel models the link between the CGS and the MT in the S-band. It is a frequency selective channel characterized through a power delay profile (PDP), which gives the relative time of arrival, the relative power, and the distribution type (Ricean or Rayleigh) of each group of unresolved echoes (known as taps). Based on the PDP under consideration, a tapped delay line (TDL) model such as

$$h_{rd}(t) = \sum_{i=1}^{L} h_{rd,i}(t)\,\delta(t-\tau_i) \tag{2}$$

where τ_i is the ith tap delay and $h_{rd,i}$ is the channel impulse response (CIR) of each of the L taps ($\delta(\bullet)$ denotes the Dirac delta function) can be easily parameterized. For the purpose of this study, the 6-tap typical urban (TU6) model [30] has been adopted (L = 6). For such model, $h_{rd,i}$ is a non-zero-mean circular complex Gaussian RV, in general, with Rice envelope and a non-uniformly distributed phase. Moreover, the power spectral density of each tap is modeled according to the well-known Jake's model [31].

2.2 Broadcasting model

As presented in Fig. 1, the communication broadcasting model consists of the GEO satellite modulator, the terrestrial CGS and the MT.

The block diagram of the satellite modulator is illustrated in Fig. 2, where the source information bits are first turbo encoded, then interleaved with a random interleaver for protection from burst errors, and then mapped to quadrature phase-shift keying (QPSK) symbols. When constellation rotation is considered, two additional blocks (shown with dashed lines in Fig. 2) need to be included. The first one, namely the constellation rotation, rotates all symbols by a constant angle between 0 and π/4, while the second one, namely component interleaver, randomly interleaves the imaginary parts of the transmitted symbols. Finally, a symbol-based random channel interleaver is deployed[1]. Note that the constellation rotation angle in a practical implementation needs to be known by all parts of the communication broadcasting model prior to data transmission.

Following the DVB-SH implementation guidelines [7] with respect to the channel coding, the 3GPP2 turbo code [32-34] has been employed in the system under investigation. The main features of this code are:

- Input frame size of 12282 bits;
- 8-state recursive systematic convolutional (RSC) encoders in parallel concatenation;
- Mother turbo coding rate 1/5 having one recursive and two feed-forward generator polynomials; and
- The use of an appropriate puncturing technique to obtain different coding rates [32].

As mentioned above, a random channel interleaver, that randomly rearranges a number of transmitted symbols (and vice versa in the receiving end) is considered. The interleaving process is required to protect the link from burst errors and also to remove the time selectivity of the fading channel. The length of the interleaver for the LMS link is much higher than that of the terrestrial link, because of the shadowing component that is present in the LMS channel. Regarding the component interleaver, by rearranging only the imaginary part of the symbols a random interleaving process between symbols consisting of real and imaginary parts is performed.

In our analysis we consider waveforms proposed in the DVB-SH standard. Specifically, for the GEO transmission we consider single-carrier QPSK, with the following constellation points

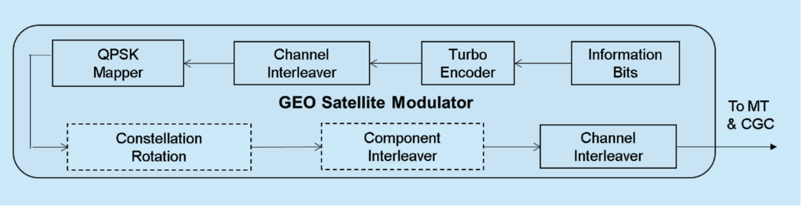

Fig.2 *Block diagram of the satellite modulator*

[1] It is noted that in the DVB-SH standard there are two interleavers: one at turbo code level (block interleaver) and on top of that a second interleaver at the symbol level (long convolutional interleaver).

$$s_q = \exp\left\{ j\frac{\pi}{4}(2q-1) \right\}, \quad (q = 1,2,3,4) \quad (3)$$

and with Gray mapping. The received sampled symbol at the MT and the CGS can be expressed as

$$r_{sd} = s\sqrt{P_s}\, h_{sd} + n_{sd} \quad (4)$$

and

$$r_{sr} = s\sqrt{P_s} + n_{sr} \quad (5)$$

respectively, where $s \in \{s_1, s_2, s_3, s_4\}$ is the information bearing signal. In the above equations P_s is the GEO transmission power, h_{sd} is the complex channel gain of the GEO-to-MT link with variance $E[|h_{sd}|^2] = \Omega_{sd}$, while n_{sd} is a zero-mean circular complex Gaussian RV, i.e., $E[n_{sd}] = 0$ with average power $E[|n_{sd}|^2] = 1$, which denotes the AWGN in the MT.

The block diagram of the terrestrial relay-CGS transceiver is illustrated in Fig. 3, where the signal received from the GEO is first channel deinterleaved and then component deinterleaved in the inverse manner as

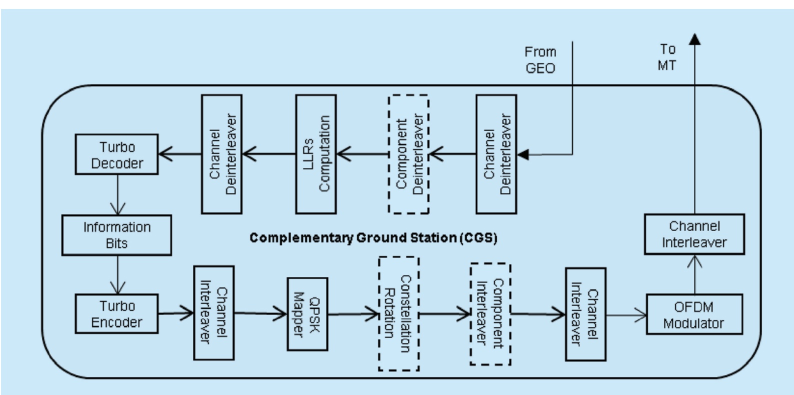

Fig.3 *Block diagram of the CGS transceiver. The constellation rotation concept is shown with dashed lines*

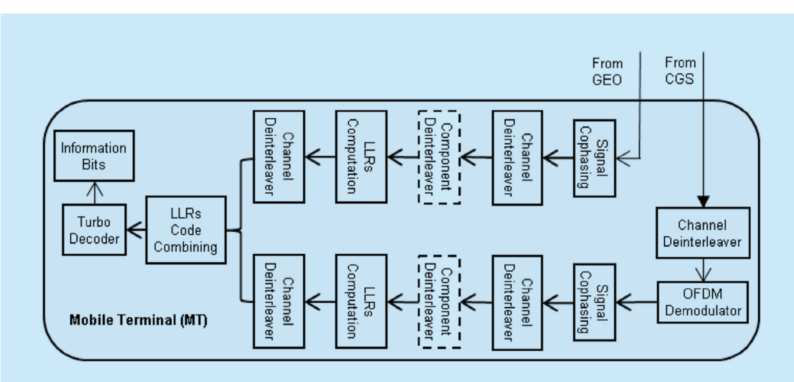

Fig.4 *Block diagram of MT receiver*

compared to the interleaving performed in GEO. Next bit LLRs computations take place and channel deinterleaving follows. Then, the received signal is turbo decoded, based on soft decision decoding, and finally, the information bit sequence is obtained. When a QPSK rotated constellation is considered, a component deinterleaver is added as a front-end (shown with dashed boxes). Note that after the component deinterleaver, the constellation is not rotated in the reverse direction for getting the original constellation, but appropriately designed extrinsic information is provided to the turbo decoder. More details on this procedure will be provided in section III. In the transmission phase, the decoded bits follow the same process such previously described for the GEO satellite (see Fig. 2), while an OFDM modulator followed by a random channel interleaver is finally deployed. Note that the OFDM waveform is a reasonable choice, since the terrestrial channel is frequency selective in the S-band.

In principle, the CGS in Fig. 3 relays the received signal using the DF protocol. In particular, the CGS demodulates the received signal and then remodulates it in an OFDM signal with N subcarriers and N_{cp} samples cyclic prefix, that is larger than the maximum tap delay of the channel. Making the usual assumption that the channel does not change during each OFDM symbol, the nth subcarrier of the received OFDM symbol can be mathematically expressed as

$$R_{rd}[n] = H_{rd}[n]\, S_r[n] \sqrt{\frac{P_r}{N}} + N_{rd}[n] \quad (6)$$

where H_{rd} is the Fourier transform of h_{rd}, i.e., $H_{rd} = \mathcal{F}\{h_{rd}\}$, $\mathbb{E}[|h_{rd}|^2] = \Omega_{rd}$, $S_r = \mathcal{F}\{s_r\}$ is the remodulated information bearing signal, P_r is the transmission power of the CGS, while $N_{rd} = \mathcal{F}\{n_{rd}\}$ stands for the AWGN of the terrestrial channel being a circular complex Gaussian RV, with $\mathbb{E}[N_{rd}] = 0$ and $\mathbb{E}[|N_{rd}|^2] = 1/N$.

The MT receiver block diagram is presented in Fig. 4. In this receiver, after performing channel deinterleaving in time domain and OFDM demodulation for the signal received from the CGS, both signals, i.e. from GEO and CGS, are aligned in phase to eliminate the impact of random channel phase rotation. The signal is symbol channel and component deinterleaved. Then, bit-level LLRs computations take place, while bit channel deinterleavers follow. The two output LLR sequences are combined and fed to the turbo decoder, which extracts the information bit sequence. The code combining block combines the LLRs of the two links to provide an improved LLR value assuming perfect channel state information (CSI) for both links. When a QPSK rotated constellation is considered, a component deinterleaver (shown as dashed boxes in Fig. 4) is added between the two (bit and symbol-based) random channel deinterleavers.

III. Bit LLRs Analysis for Rotated and Unrotated (Fixed) Constellations

In this section the rotated constellation concept is introduced for both LMS and terrestrial links. Exact and approximate LLR expressions are derived for both rotated and unrotated (fixed) constellations.

Assuming perfect CSI, i.e., h being available at the MT, the information that should be provided to the turbo decoder is $K=\log_2(M)$ bit LLRs per complex symbol, denoted as Λ_ℓ's, with M being the modulation order and $\ell=1,2,\ldots,K$. We define the bit LLR of symbol s_q as [35]

$$\Lambda_\ell = \ln\left(\frac{\Pr\{b_\ell = 1|r,h\}}{\Pr\{b_\ell = 0|r,h\}}\right) \quad (7)$$

with $\Pr\{Q|A, B\}$ being the probability of occurrence of Q, given A and B and b_l denotes bit value. Note that the above equation can be combined with any of (4)–(6)[2]. Using Bayes' rule and assuming that all symbols are transmitted with equal probability, (7) can be expressed as

$$\begin{aligned}\Lambda_\ell &= \ln\left(\frac{\Pr\{b_\ell = 1|r,h\}}{\Pr\{b_\ell = 0|r,h\}}\right) + \ln\left(\frac{\Pr\{b_\ell = 1\}}{\Pr\{b_\ell = 0\}}\right)\\ &= \ln\left(\frac{\Pr\{r,h|b_\ell = 1\}}{\Pr\{r,h|b_\ell = 0\}}\right)\end{aligned} \quad (8)$$

or

$$\Lambda_\ell = \ln\left(\frac{\sum_{k=1,a\in S_\ell^{(1)}}^{2^{K-1}} f\{r|h, s_k = a\}}{\sum_{k=1,b\in S_\ell^{(0)}}^{2^{K-1}} f\{r|h, s_k = b\}}\right) \quad (9)$$

where $S_\ell^{(0)}$ and $S_\ell^{(1)}$ are bit K-tuples of Gray encoded symbols where their ℓth bit is 1 and 0, respectively. For fixed h and s_k the probability density function (PDF) of r, $f\{r|h, s_k\}$, is Gaussian. Based on (4) for the GEO-to-MT link, and for computer simulation purposes, its mean and variance are $s\sqrt{P_s}\,h_{sd}$ and 1, respectively, while based on (6) for the per subcarrier CGS-to-MT link its mean and variance are $H[n]s_r[n]\sqrt{P_r/N}$ and $1/N$, respectively.

Next, we will limit our analysis to QPSK signaling since this modulation scheme will be most probably used in a real DVB-SH system implementation. However, the analysis which will be presented can be also easily applied to more complex constellations.

3.1 Unrotated (fixed) QPSK constellation

Based on (3) for QPSK with mapping s_1 : 11, s_2 : 10, s_3 : 00, s_4 : 01 (here constellation rotation and component interleaver are neglected), the two bit LLRs are given by

$$\Lambda_1 = \ln\left(\frac{\Pr\{s_1|r,h\} + \Pr\{s_2|r,h\}}{\Pr\{s_3|r,h\} + \Pr\{s_4|r,h\}}\right) \quad (10)$$

and

$$\Lambda_2 = \ln\left(\frac{\Pr\{s_1|r,h\} + \Pr\{s_4|r,h\}}{\Pr\{s_2|r,h\} + \Pr\{s_3|r,h\}}\right) \quad (11)$$

for the 1st and 2nd bit, respectively. It can be easily proved that the above LLRs reduce to

$$\Lambda_1 = 4\sqrt{P}\,\Im\{r\,h^*\} \quad (12)$$

and

$$\Lambda_2 = 4\sqrt{P}\,\Re\{r\,h^*\} \quad (13)$$

where R{·} and I{·} stand for the real and imaginary operators, respectively.

3.2 Rotated QPSK constellation

Further to the standard I/Q QPSK constellation, we have also considered a rotated QPSK constellation [26, sec.10.5.3]

$$s_q = \exp\left\{j\frac{\pi}{4}(2q-1) + j\theta\right\} \quad (14)$$

where $0 \le \theta < \pi/4$ is the rotation angle. The constellation rotation is followed by a com-

[2] For convenience of the presentation, for certain generic equations we will be using the notation of CIR (h), transmission power (P), and received complex signal (r) without subscripts.

ponent interleaver for the imaginary part of s_q's. The constellation diagram, after the component interleaver, consists of sixteen points which are formed by all combinations with the four real and the four imaginary values of s_q's. The advantage provided by the combination of rotation and component interleaving is that after the component deinterleaver, in the receiving end, the real and imaginary parts of the complex signal of the rotated version undergo less dependent complex channel gain between h_r and h_i.

Using (4) and (6) in (10) and (11), the new LLRs at the MT for each of the two links can be computed as

$$\Lambda_1 = \ln\left(\frac{\sum_{q=1,2}\exp\left\{-\left|r-\sqrt{P}\left(\Re\{s_q\}|h_r| + j\Im\{s_q\}|h_i|\right)\right|^2\right\}}{\sum_{q=3,4}\exp\left\{-\left|r-\sqrt{P}\left(\Re\{s_q\}|h_r| + j\Im\{s_q\}|h_i|\right)\right|^2\right\}}\right) \quad (15)$$

and

$$\Lambda_2 = \ln\left(\frac{\sum_{q=1,4}\exp\left\{-\left|r-\sqrt{P}\left(\Re\{s_q\}|h_r| + j\Im\{s_q\}|h_i|\right)\right|^2\right\}}{\sum_{q=2,3}\exp\left\{-\left|r-\sqrt{P}\left(\Re\{s_q\}|h_r| + j\Im\{s_q\}|h_i|\right)\right|^2\right\}}\right) \quad (16)$$

Note that for the unrotated QPSK constellation, R$\{s_q\}$ = I$\{s_q\}$, and hence, (15) and (16) reduce to (12) and (13), respectively.

The LLR expressions in (15) and (16) are characterized by high computation complexity, due to the required multiplication and exponential operations. Moreover, the computation of the LLRs may generate numerical evaluation errors for very high and very low values of P, given the limitation in the hardware arithmetic precision. Thus, it is useful for practical implementations to simplify the LLRs computation by applying the max-log approximation [36]

$$\ln\left(\sum_{l=1}^{q}\exp\{a_l\}\right) \cong \max_{l=1,2,\ldots,q}\{a_l\} \quad (17)$$

Using the above approximation, the above LLRs can be simplified as

$$\Lambda_1 = -\min\left\{\begin{array}{l}\left|r-\sqrt{P}\left(\Re\{s_1\}|h_r| + j\Im\{s_1\}|h_i|\right)\right|^2, \\ \left|r-\sqrt{P}\left(\Re\{s_2\}|h_r| + j\Im\{s_2\}|h_i|\right)\right|^2\end{array}\right\} + \min\left\{\begin{array}{l}\left|r-\sqrt{P}\left(\Re\{s_3\}|h_r| + j\Im\{s_3\}|h_i|\right)\right|^2, \\ \left|r-\sqrt{P}\left(\Re\{s_4\}|h_r| + j\Im\{s_4\}|h_i|\right)\right|^2\end{array}\right\} \quad (18)$$

and

$$\Lambda_2 = -\min\left\{\begin{array}{l}\left|r-\sqrt{P}\left(\Re\{s_1\}|h_r| + j\Im\{s_1\}|h_i|\right)\right|^2, \\ \left|r-\sqrt{P}\left(\Re\{s_4\}|h_r| + j\Im\{s_4\}|h_i|\right)\right|^2\end{array}\right\} + \min\left\{\begin{array}{l}\left|r-\sqrt{P}\left(\Re\{s_2\}|h_r| + j\Im\{s_2\}|h_i|\right)\right|^2, \\ \left|r-\sqrt{P}\left(\Re\{s_3\}|h_r| + j\Im\{s_3\}|h_i|\right)\right|^2\end{array}\right\} \quad (19)$$

It is noted that the use of the above approximate expressions may result in a slight performance degradation as compared to using only the metrics of (15) and (16), e.g. 0.5 dB degradation in BER performance. However, the reduction in the implementation complexity is high, while at the same time normal computations for any value of P are assured.

3.3 Code Combining

At the MT the code combining technique is used [7] where a pair of two bit LLRs per QPSK symbol and per link are first extracted based on (12)-(13), (15)-(16) or (18)-(19). Then, the two pairs corresponding to the LMS and terrestrial links, are simply added, i.e.,

$$\Lambda_1^{MT} = \Lambda_1^{LMS} + \Lambda_1^{Terr} \quad (20)$$

and

$$\Lambda_2^{MT} = \Lambda_2^{LMS} + \Lambda_2^{Terr} \quad (21)$$

with Λ_i^{LMS} is the i^{th} LLR (for the 1st and 2nd bit, $i = 1,2$) of the LMS link and Λ_i^{Terr} is the i^{th} LLR (for the 1st and 2nd bit, $i = 1,2$) of the terrestrial link. The values of Λ_1^{MT} and Λ_2^{MT} are fed into the MT turbo decoder to improve the soft decisions of the decoding process. Note that the code combining technique is a more general combining technique than the maximal-ratio combining (MRC) [37], since different coding rates for the two links may be applied.

IV. Performance Evaluation Results: Comparisons and Discussion

Using the previously presented system model as well as the bit LLR analysis, a comprehensive software platform was developed for obtaining the performance of the proposed telecommunication system. Using this platform, the proposed communication system has been extensively simulated and various performance evaluation results have been obtained under different operating conditions. Furthermore, various performance comparisons between rotated and unrotated constellations as well as for pure LMS and hybrid scenarios have been systematically carried out.

4.1 Simulation parameters

In our simulation study all parameters are aligned with the DVB-SH IGv3 technical report [7]. Specifically, we have considered MT speed V = 50 km/h, carrier frequency f_c = 2.2 GHz, perfect CSI available at the MT, exact LLRs calculation based on (15) and (16), same coding rates for all links that are R_c = 1⁄3 and 6/7, with eight (8) decoding iterations. In addition, there are other parameters which have been used and will be presented next for the various communication scenarios.

On the one hand for the GEO to MT link the following parameters have been used:

• Single carrier QPSK signaling with Gray mapping.

• The intermediate tree-shadowing (ITS) channel scenario of the 3-state Markov/Loo, with 40^o elevation angle.

• Sampling time 44.8 μs.

• Random channel and component interleavers of length 10 sec. This large length is required due to the lognormal process.

• Sample series for more than 1 h of channel realization time. Due to the Markov and lognormal nature of the channel, such a large time is required in order to archive reliable and accurate channel statistical data.

On the other hand, for the CGS to MT terrestrial link the following parameters have been used:

• The "urban" channel scenario of the TU6.

• Multicarrier OFDM/QPSK signaling with Gray mapping, N = 2048 subcarriers and N_{cp} = 64 cyclic prefix. This prefix length is larger than the TU6 channel length, guaranteeing an equivalent decomposition to N slowly-varying flat fading channels.

• Sampling time 175 nsec. This short sampling time is required in order to correctly sample the TU6 PDP.

• Random channel and component interleavers length of 200 ms.

4.2 Pure LMS and terrestrial transmission

In Fig. 5 comparison results for the E2E uncoded QPSK average symbol error probabilities (ASEPs) are presented for a pure LMS 3-state Markov/Loo channel and for a pure TU6 channel. Simulation results for both rotated by 29^o (similarly to [26] for QPSK) and unrotated constellations are included, while analytical results are also presented for the TU6 channel to verify the correctness of the corresponding simulation results. From these performance results we observe that, for both LMS and terrestrial links, the effect of the constellation rotation on the ASEP is that it doubles the slope of the corresponding curves. Essentially this means that, due to time diversity introduced by the rotation, the diversity order is doubled.

In Fig. 6 we study the effect of phase rotation on the average bit error probability (ABEP) performance of pure LMS and terrestrial links for fixed 0.25 dB and 5.0 dB signal-to-noise ratios (SNRs) per symbol, respectively, and coding rate R_c = 1⁄3. The obtained results have shown that the optimal phase rotation for the terrestrial links is around 35^o. It is important to underline that, on the one hand,

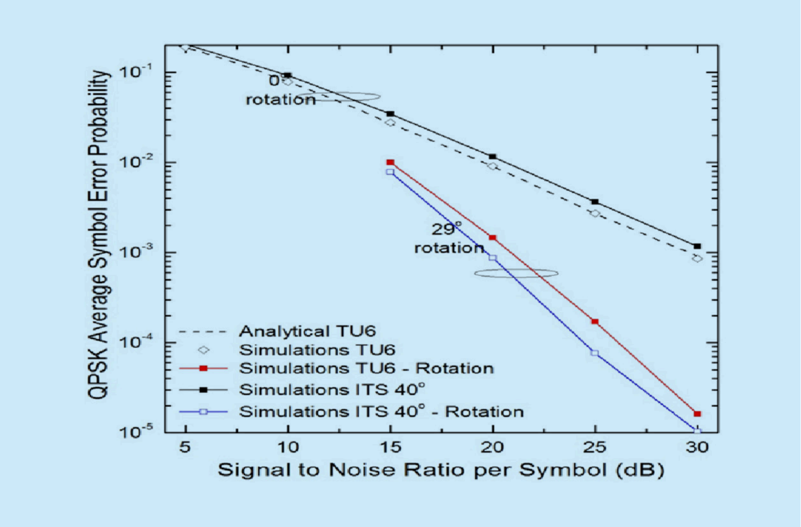

Fig.5 *ASEP of uncoded QPSK versus total average SNR per symbol for pure LMS and pure terrestrial links with and without constellation rotation*

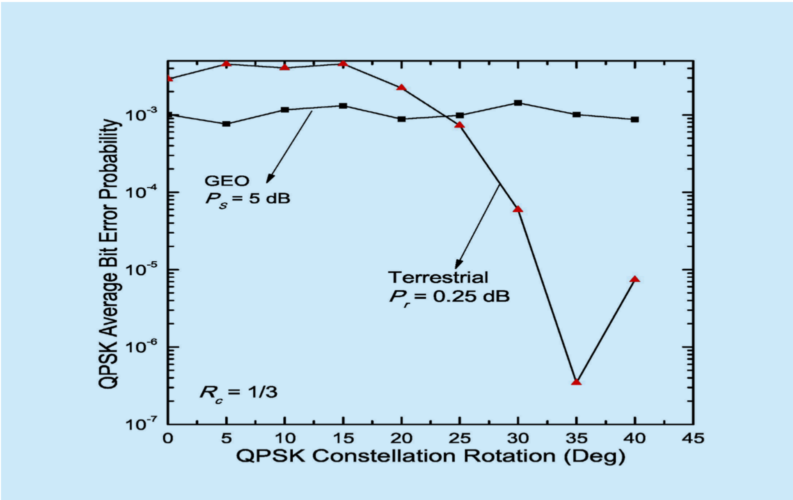

Fig.6 *ABEP of QPSK versus phase rotation for pure LMS and terrestrial channels with 5 dB and 0.25 dB SNRs per symbol, respectively, and* $R_c = 1/3$

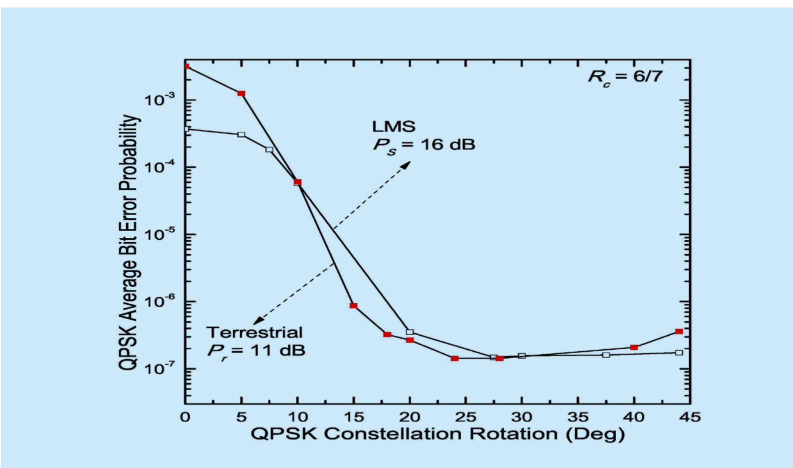

Fig.7 *ABEP of QPSK versus phase rotation for pure LMS and terrestrial channels with 16 dB and 11 dB SNRs per symbol, respectively, and* $R_c = 6/7$

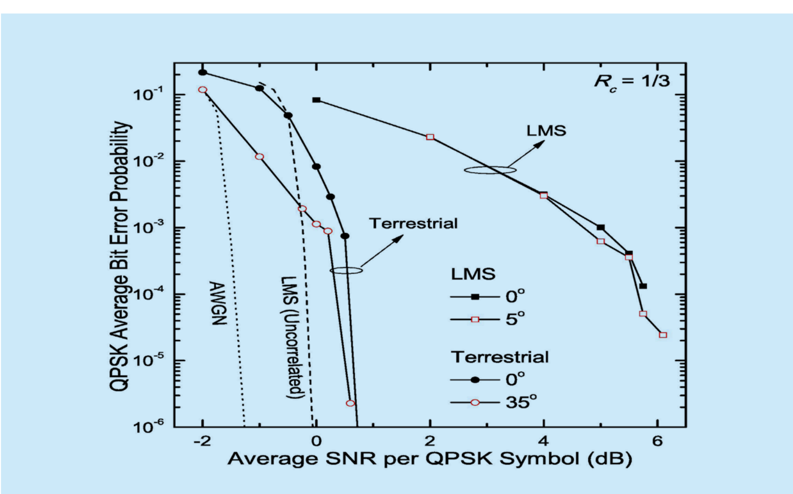

Fig.8 *ABEP of QPSK versus total average SNR per symbol for* $R_c = 1/3$*, pure LMS and terrestrial channels system with and without constellation rotation*

the performance improvement for the terrestrial link is more than three orders of magnitude.

On the other hand, the phase rotation of the QPSK signal does not allow any significant performance improvement in the LMS link. Since in Fig. 6 a 5° rotation gives the minimum ABEP, this value will be used for obtaining further results for the LMS channel with $R_c = 1/3$. It is noted that the performance improvement depends on the specific SNR values and the coding rate. Corresponding performance results for $R_c = 6/7$ can be found in Fig. 7 for fixed SNR per symbol, i.e. 11 dB and 16 dB for the terrestrial link and LMS link, respectively. From the performance evaluation results shown in this figure it is clear that also the LMS link provides some noticeable gain, due to the constellation rotation. Specifically, for a QPSK phase rotation higher than 10°, BER improvements of about 1–2 orders of magnitude are observed. Although not shown in this figure, this observation is valid independent of the SNR value, and therefore next, we use a 30° rotation for the LMS part when $R_c = 6/7$. For the terrestrial part, the same phase rotation of 30° is considered as this value also provides the minimum ABEP in Fig. 7.

In Fig. 8 the QPSK ABEPs of pure LMS (shown with square signs) and terrestrial (shown with circle signs) links with (shown with filled signs) and without (shown with blank signs) constellation rotation (using the optimal values from Fig. 6, i.e. 35° and 5° rotation for the terrestrial and the LMS links) are presented as a function of the average SNR per QPSK symbol for $R_c = 1/3$. By comparing the two LMS curves in Fig. 8 no performance improvement is obtained when rotated constellations are employed. This observation is in agreement with equivalent performance results reported in Fig. 6. On the other hand, when using constellation rotation for the terrestrial link a performance gain of about 1 dB at an ABEP 10^{-2} is observed. However, this gain decreases as SNR increases. Eventually, and for high SNRs, the two curves representing the rotated and unrotated constellation version of the terrestrial link coincide and the

ABEP falls abruptly for an SNR of about 0.75 dB. In Fig. 8 the dotted curve for an AWGN channel serves as a performance benchmark. Moreover, another reference curve is presented (shown with dashes) that corresponds to an uncorrelated version of the LMS channel. It can be concluded that the SNR loss due to the remaining time correlation when using interleavers with 10 sec time length is about 6 dB for an ABEP higher than 10^{-4}.

Similar performance evaluation results have been obtained for a higher code rate system with $R_c = 6/7$. These are illustrated in Fig. 9 where it can be observed that there is an increased SNR gain of about 2 dB, due to the phase rotation for both the LMS and terrestrial links. Additionally, the SNR loss due to 10 sec interleavers length compared to an uncorrelated version of the LMS channel is smaller than in the case of $R_c = 1/3$. From the performance evaluation results presented in Figs. 8 and 9, it is clear that as the coding rate increases, the ABEP for the rotated constellation version improves as compared to the unrotated version. Therefore, it can be concluded that the constellation rotation technique can be used either to increase the information data rate by increasing the code rate or to decrease the GEO transmission power, as it will be shown next for the hybrid scenario.

4.3 Hybrid transmission

In Figs. 10 and 11 we present the impact of power allocation on the E2E QPSK ABEP for the hybrid scenario for $R_c = 1/3$ and $R_c = 6/7$, respectively, as a function of the total SNR per symbol, i.e., $P = P_s + P_r$ assuming unity noise power for all links, i.e. SNR = P. From these performance evaluation results it is clear that the optimum power allocation (OPA) value is not constant, but depends on the total SNR per symbol, which in turns depends on the user terminal location, i.e., the geometrical distance of the user from the CGS.

Specifically, for $R_c = 1/3$ and a total SNR per symbol of 0.5 dB, the LMS/terrestrial OPA is 65%/35% for both rotated and unrotated versions, respectively. For a total SNR per

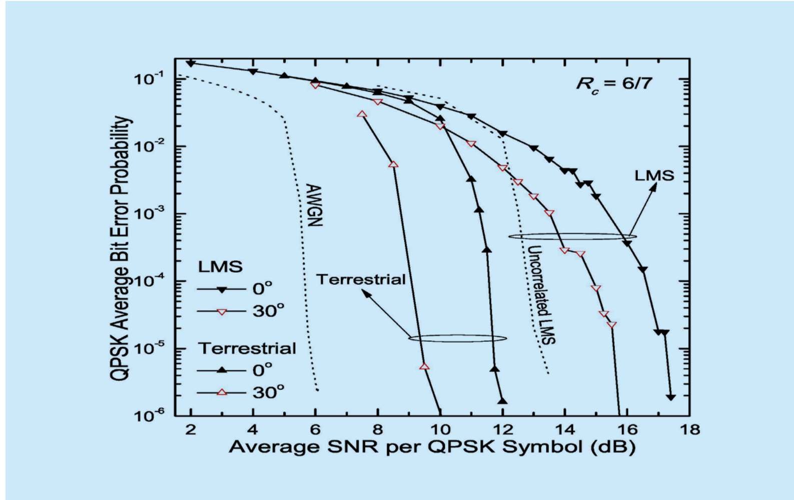

Fig.9 *ABEP of QPSK versus total average SNR per symbol for $R_c = 6/7$, pure LMS and terrestrial channels system with and without constellation rotation*

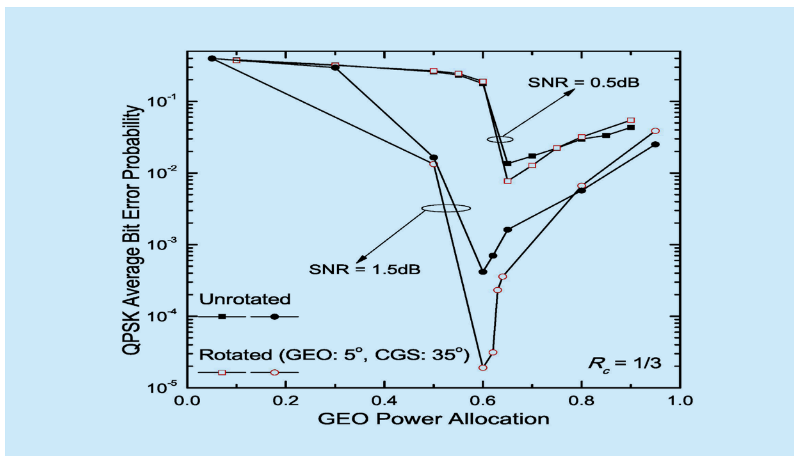

Fig.10 *E2E ABEP of QPSK versus the LMS link power allocation for $R_c = 1/3$, total average SNR per symbol 0.5, 1.5 dB, and for hybrid system with and without constellation rotation (GEO and CGS rotation angles 5° and 35°, respectively)*

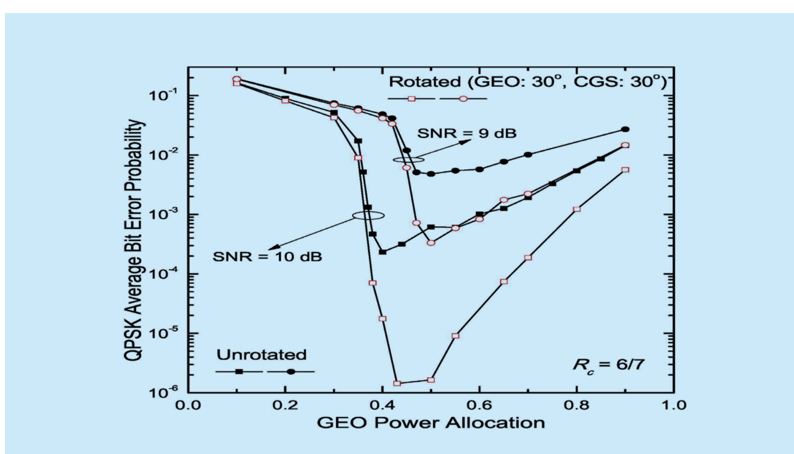

Fig.11 *E2E ABEP of QPSK versus the LMS link power allocation for $R_c = 6/7$, total average SNR per symbol 10 dB, and for hybrid system with and without constellation rotation for the LMS link (both GEO and CGS rotation angles 30°)*

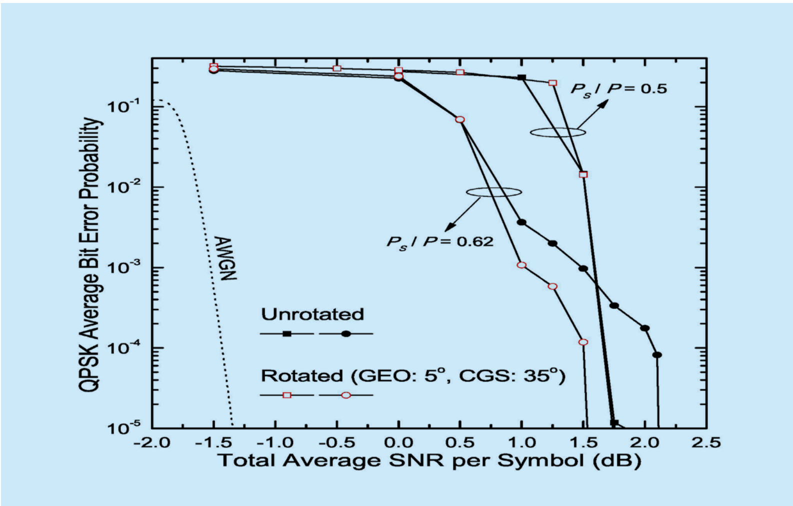

Fig.12 *E2E ABEP of QPSK versus total average SNR per symbol for hybrid system with and without constellation rotation, R_c = 1⁄3, and different power allocation (GEO and CGS rotation angles 5° and 35°, respectively)*

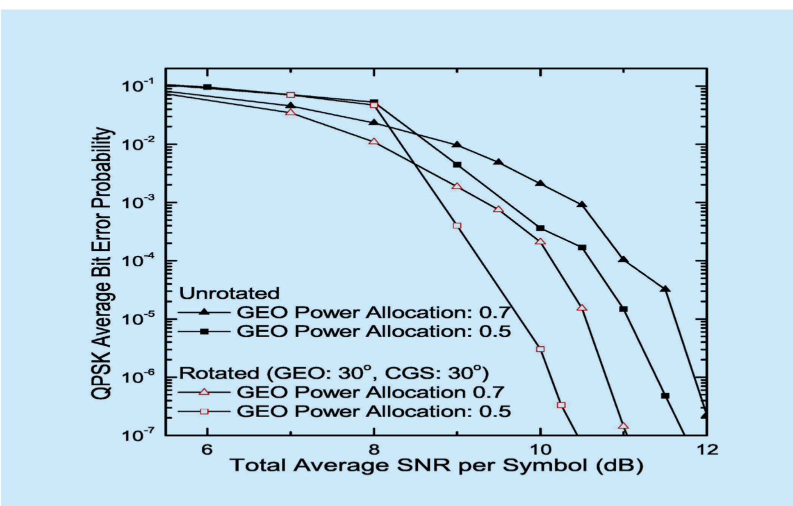

Fig.13 *E2E ABEP of QPSK versus total average SNR per symbol for hybrid system with and without constellation rotation, R_c = 6⁄7, and different power allocation (both GEO and CGS rotation angles 30°)*

symbol of 1.5 dB, the LMS/terrestrial OPA is 60%/40%, respectively. Similar findings can be observed for R_c = 6⁄7, where for total SNRs per symbol of 9 dB and 10 dB, equal and unequal (45%⁄55%) power allocation are the optimum ones for the rotated and unrotated versions, respectively.

Fig. 12 presents the E2E QPSK ABEP for the hybrid scenario as a function of the total SNR per symbol for R_c = 1⁄3. There are two groups of curves with different power allocations, where each group corresponds to the cases of with and without constellation rotation. As shown in Fig. 12, the SNR gain between the two groups of curves is about 1 dB for an E2E ABEP of 10^{-2}. The E2E performance is slightly improved when 62% of the total power is allocated to the LMS link and 38% to the terrestrial link. From the performance results of Fig. 12 it is also shown that a small performance gain, due to the constellation rotation observed in Fig. 8 mainly in the terrestrial link, is not present in the hybrid scenario. Specifically, there is no performance gain for equal power allocation, while a very small gain is observed for 62%/38% power allocation. Finally, equivalent performance evaluation results for R_c = 6⁄7 have been obtained and these are illustrated in Fig. 13. It is noted that a performance improvement of about 1 dB, due to constellation rotation is observed for both equal 50%/50% and unequal 70%/30% power allocation. Comparing the performance results presented in Figs. 12 and 13, it can be concluded that for low coding rates, where the coding gain is high, the performance improvement due to the constellation rotation is negligible. However, when the coding gain is small, due to high coding rate, there is a noticeable performance improvement, which is due to the use of constellation rotation concept. Notice that the same conclusions have reached when comparing the performance of the pure LMS and terrestrial transmission links (see Figs. 8 and 9).

V. CONCLUSIONS

In this paper the advantages of cooperation in broadcasting from a GEO satellite to MTs via a CGS terrestrial relay have been thoroughly investigated. In conjunction with this communication system, the “rotation constellation” concept has been considered with QPSK signaling and analytical expressions for the bit LLRs have been derived. Performance gains of about 2 dB have been observed using constellation rotation for a pure LMS link (GEO to MT) and a fixed ABEP 10^{-4} with R_c = 6⁄7. Similar performance gains have been also observed for the terrestrial link (CGS to MT). For R_c = 1⁄3 and the terrestrial link, about 1 dB performance gain has been observed at ABEP 10^{-2}. The impact of the power allocation on E2E performance for the hybrid scenario has been also studied and it has been shown that the OPA conditions (for minimizing ABEP) depend on the total SNR and the constellation rotation angle. The advantage of the rotation constellation concept found for the pure LMS and terrestrial links has been also observed in the hybrid scenario. A small gain of about 0.5 dB has been observed for R_c = 1⁄3 with unequal power allocation at ABEP 10^{-4}, while a noticeable performance improvement of more than 1 dB was shown for R_c = 6⁄7 and for both equal and unequal power allocation.

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Biographies

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Stylianos Papaharalabos, received his Diploma degree in Electrical and Computer Engineering from the Aristotle University of Thessaloniki, Greece (2001), his MSc by Research degree in Electrical Engineering from the University of Surrey, UK (2002) and also his PhD degree in Electrical Engineering from the same University (2006). In 2004, Fall he was a visiting researcher at the University of Bologna, Italy investigating the applicability of low-complexity LDPC decoding algorithms for DVB-S2 standard. During 2006-2014 he has been with the Institute for Space Applications and Remote Sensing (ISARS) of the National Observatory of Athens and also with the Athens Information Technology (AIT) as a post-doctoral research fellow. He is currently with the Laboratory of Wireless Communications, Institute of Informatics and Telecommunications, National Centre for Scientific Research - "Demokritos". During the past years of research he has been a Task leader in 5 European R&D IST (FP6, FP7) and ESA projects dealing with cutting edge wireless terrestrial/satellite communication systems, whereas he has established active collaborations with many academic departments worldwide (UK, Italy, Poland, Slovenia, and PR of China). His research interests are mainly advanced channel coding schemes and iterative decoding techniques and he has published 40 journal and conference papers in these fields, including co-authoring 2 book chapters and receiving more than 86 citations. He is also the co-inventor of one US patent. He has been TCP member in 22 international conferences relevant to signal processing algorithms and satellite communication systems. In SPACOMM 2010-2015 conferences he has been an Advisory Chairs Committee Member. He has been an exemplary reviewer (top 3%) for IEEE Communications Letters and an Editorial board member of the IARIA International Journal On Advances in Telecommunications.

P. Takis Mathiopoulos, has been recently elected Professor of Digital Communications in the Department of Informatics and Telecommunications, University of Athens where is has been teaching part-time since 2003. He obtained his Diploma in Electrical Engineering from the University of Patras and M.Eng. degree with specialization in Microwaves from Carleton University, and the Ph.D. degree in digital communications from the University of Ottawa, Canada, in 1989. From 1982 - 1986, he was with Raytheon Canada Ltd., working in the areas of air navigational and satellite communications. In 1989, he joined the Department of Electrical and Computer Engineering (ECE), University of British Columbia (UBC), Canada, where he was a faculty member for 13 years, and from 2000–2003 he was holding the rank of Professor. He is currently Director of Research at the Institute for Space Applications and Remote Sensing (ISARS), National Observatory of Athens (NOA), where he established and directed the Wireless Communications Research Group. As ISARS' Director, he has led the Institute to a significant expansion R&D growth, and international scientific recognition. For these achievements, ISARS has been selected as a national Centre of Excellence for the years 2005 to 2008. Since 2003 he also teaches part-time at the Department of Informatics and Telecommunications, University of Athens. In 2008 and for a period of 5 years he was appointed Guest Professor at the Southwest Jiaotong University, China. For the last 20 years he has been conducting research mainly on the physical layer of digital communication systems for terrestrial and satellite applications, including digital communications over fading and interference environments. He is also interested in channel characterization and measurements, modulation and coding techniques, network coding, cooperative communications, SIMO/MIMO, UWB, OFDM, and software/cognitive radios. In these areas, he has co-authored more than 80 journal papers, mostly published in IEEE journals, 4 book chapters and some 110 conference papers. He has supervised the thesis of 10 PhD students and more then 15 postdoctoral fellows, many of whom hold faculty positions in Canadian, USA and Greek Universities. His research has been funded by Canadian, European and Greek funding agencies as he has been the PI of more than 40 research grants. He co-authored a paper in GLOBECOM'89 establishing for the first time in the open technical literature the link between MLSE and multiple (or multi-symbol) differential detection for the AWGN and fading channels. In September 2005, this contribution has been acknowledged by the Editors of IEEE Journal of Selected Areas in Communications as a breakthrough and a seminal paper which has been selected as one of the four most influential papers of the last 40 years in the field of noncoherent detection. He has received numerous awards, including an ASI Fellowship, a Killam Research Fellowship and a best paper award from the 2008 International Conference on Communication, Control, and Signal Processing. Dr. Mathiopoulos has been or currently serves on the editorial board of several scientific journals, including the IET Communications, and the IEEE Transactions on Communications (1993-2005). He has regularly acted as a Consultant for various governmental and private organizations. Since 1993, he has served on a regular basis as a scientific advisor and a technical expert for the European Commission (EC). He has been a member of the TPC of more than 50 international conferences, as well as the Vice Chair for the Spring 2006-S IEEE VTC and the 2008-F IEEE VTC. He has delivered numerous invited presentations, including plenary lectures, and has taught many short courses all over the world.