Enhancement of MARSALA Random Access with Coding Schemes, Power Distributions and Maximum Ratio Combining

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***Abstract*—Several random access (RA) techniques have been proposed recently for the satellite return link. The main objective of these techniques is to resolve packets collisions in order to enhance the limited throughput of traditional RA schemes. In this context, Multi-Replica Decoding using Correlation based Localisation (MARSALA) has been introduced and has shown good performance with DVB-RCS2 coding scheme and equi-powered transmissions. However, it has been shown in the literature that alternative coding schemes and packets power distributions can have a positive impact on RA performance. Therefore, in this paper, we investigate the behaviour of MARSALA with various coding schemes and various packet power distributions, then we propose a configuration for optimal performance. This paper also introduces the enhancement of MARSALA RA scheme by adding MRC to optimize replicas combination and study the impact on the throughput. We compare two different MRC techniques and we evaluate, via simulations, the gain achieved using MRC with different coding schemes and unbalanced packets. The simulation results demonstrate that the proposed enhancements to MARSALA show substantial performance gain, i.e. throughput achieved for a target Packet Loss Ratio (PLR).**

I. Introduction

The use of Random Access (RA) techniques over the satellite return link has gained a huge research interest recently. With the large spread of low-cost satellite terminals and Machine to Machine (M2M) applications, researchers have started to investigate the performance of RA techniques on the satellite return link in order to handle larger networks with low latencies. A number of RA use cases has been presented in the recent standard DVB-RCS2 [1]. In particular, the combination of RA and dedicated access is of interest for communications with long silent periods and very short packets transmissions. However, synchronous RA methods like Slotted Aloha (SA) [2] and Diversity Slotted Aloha (DSA) [3] do not perform well on a satellite return link, due to destructive packets collisions. Although DSA is a variant of SA with multiple replicas per packet, it performs slightly better than SA but only for small channel loads.

In 2007, Contention Resolution Diversity Slotted Aloha (CRDSA) [4] has been introduced as the first synchronous RA technique to combine packets replication with Successive Interference Cancellation (SIC). In CRDSA and its variants [5], [6], each terminal transmits multiple replicas of the same packet on different timeslots of the frame. Each replica contains pointers to the locations of the other replicas of the same packet. The receiver stores the frame then reads the timeslots in a sequential order. On each timeslot, if a packet is decoded successfully (due to the absence of collisions or the capture effect), the receiver locates the other replicas then removes the packet and its replicas from the frame. This SIC process allows to cancel the interference contribution of the successfully decoded packets and their replicas, and possibly recover additional packets. CRDSA significantly enhances the throughput and the Packet Loss Ratio (PLR) compared to SA and DSA, and it has been included in the DVB-RCS2 standard.

Irregular Repetition Slotted Aloha (IRSA) [7] follows the same concept as CRDSA, except that the terminals can transmit an irregular number of packet replicas. IRSA enables to enhance the throughput by computing an optimal probability distribution of the number of replicas to be transmitted by each terminal. However, the performance of IRSA for a PLR lower than 10^{-3} is less important than CRDSA with a fixed number of 3 or 4 replicas. Other recent RA techniques have been proposed in the literature like Coded Slotted Aloha (CSA) [8] and Multi-Slot Coded Aloha (MuSCA) [9]. CSA and MuSCA also use the SIC principle, but they are both based on packets coding and fragmentation rather than packets replication. In CSA, each packet is divided into k fragments, then the fragments are encoded with an erasure code (n,k) and the resulting n coded fragments are transmitted on randomly chosen timeslots of the frame. As for MuSCA, each packet is encoded with a robust Forward Error Correction (FEC) code of rate R, then it is divided into N_b fragments. A signalling field containing the location of the other fragments is coded separately and added to each packet. A variant of MuSCA with an irregular fragmentation rate has also been proposed in [10]. MuSCA allows to significantly enhance the throughput compared to the existing synchronous RA methods, however it requires additional signalling overhead.

The challenge to compromise on low signalling overhead and enhanced throughput has motivated the proposition of a new decoding and demodulation technique for CRDSA called Multi Replica Decoding using Correlation Based Localisation

(MARSALA) [11]. MARSALA introduces a technique for replicas localisation and decoding, in order to recover non-decoded packets in CRDSA. The transmission scheme is the same as in CRDSA, the only modifications to take into account are at the receiver side. To localise the replicas of a given packet, MARSALA performs correlation of the signal received on one timeslot with the signals received on other timeslots of the frame. When correlation peaks are detected, the replicas are combined to obtain a higher Signal to Noise plus Interference Ratio (SNIR). Moreover, a method to correct the timing offsets and phase shifts between the replicas, and ensure coherent replicas combination has been presented in [12].

MARSALA has shown good performance in a scenario of equi-powered packets using the DVB-RCS2 turbo code for linear modulation. However, it has been shown in previous studies [5], [6], [13], that packets power unbalance can significantly enhance the SIC performance. In addition, it has been proven that the choice of the coding scheme has also an important impact on triggering more SIC iterations. For all these reasons, these enhancements will be studied for MARSALA in this paper. Overall, three main contributions are proposed in this paper, having the objective to enhance the performance of MARSALA RA scheme:

- Adding Maximum Ratio Combining (MRC) to MARSALA. Two techniques for applying MRC with MARSALA are proposed and evaluated via simulations.
- Evaluating MARSALA with packets power unbalance, as well as presenting an adequate packets power distribution to further enhance the performance.
- Study of MARSALA with various coding schemes.

II. System Model

We consider a frame structure over one frequency carrier for the return link RA channel. The frame of length T_f is divided into N_s timeslots. The transmission scheme for each terminal is the same as defined in CRDSA. We denote by λ the total number of users (i.e. terminals) sharing the transmission on one frame duration. Each users sends N_b replicas of the same packet on randomly chosen timeslots. We suppose that only one packet (with its replicas) per user is sent on the duration of one frame. Before transmission, each packet is encoded with a turbo code of rate R and modulated with Quadrature Phase Shift Keying (QPSK). Finally, signalling fields for the purpose of channel estimation are added.

We consider a scenario with fixed terminals communicating with a geostationary satellite. Therefore, we assume a stationary channel model with the following parameters: **(1)** carrier frequency and timing offsets randomly distributed among different users, but constant among the replicas of a same user over the duration on one frame, **(2)** constant replicas amplitude over the frame duration and **(3)** random phase shifts among the replicas of a same packet. However, the phase shift is considered constant over the duration of one timeslot and phase noise fluctuations on a timeslot duration are neglected.

The processing scheme at the receiver side is illustrated in Fig. 1. First, the frame is stored, then each timeslot is processed in order to recover the received packets. In a first

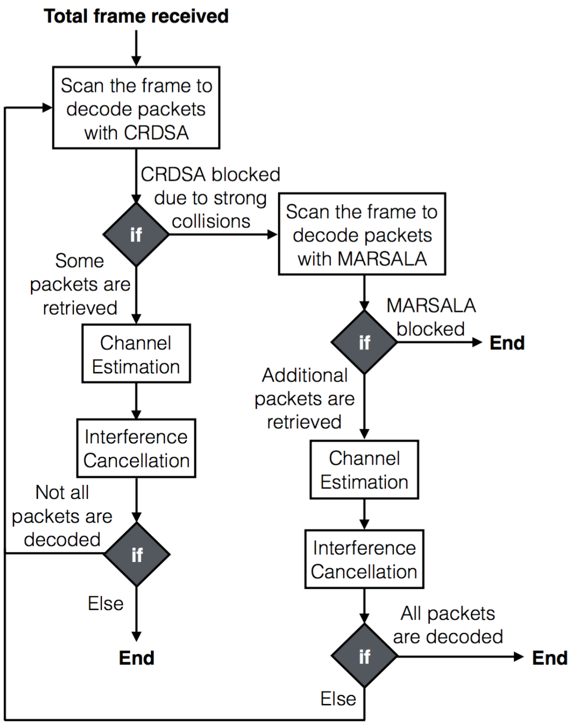


Fig. 1: Processing scheme for each frame at the receiver side, with combination of CRDSA and MARSALA.

step, the receiver attempts to recover the packets by using CRDSA. Each recovered packet is removed from the frame (after channel estimation) along with its replicas localised with the decoded pointers. The next step is to re-scan the frame and repeat the process of packets recovery with SIC until all the packets are decoded successfully. However, if CRDSA is blocked, i.e. the frame is scanned iteratively with no additional packets retrieved due to strong collisions, MARSALA is applied.

As described in [11], [12], MARSALA chooses one timeslot as a reference slot TS_{ref} and correlates its signal with the other slots of the frame. The correlation peaks are used to identify the replicas of the packets present on TS_{ref}. Then the timing offsets and phase shifts between the replicas are corrected as detailed in [12], and coherent replicas combination is performed. With the resulting SNIR and depending on the encoding scheme, the packet has a higher successful decoding probability. Thus, if the packet is decoded successfully thanks to this SNIR gain, it is removed from the frame. Then CRDSA scheme is applied again in the next iteration. It is worth clarifying that, although frequency, timing and phase shifts between replicas were taken into account in [12], the fluctuating phase noise was not. According to the DVB-RCS2 guidelines [14], the phase noise is lower than -16 dBc/Hz (with dBc/Hz denoting noise power relative to the carrier contained in a 1 Hz bandwidth centered at different offsets from the carrier). Given that those fluctuations are relatively low compared to packet collisions distortions, the results presented in this work assume a negligible impact of phase noise, and open perspectives for evaluating it in future work.

III. MARSALA SCHEME WITH MRC

In previous work, MARSALA with Equal Gain Combining (EGC) has been presented. In this section, we propose to add Maximum Ratio Combining (MRC) [15], [16] to MARSALA in order to effectively use the information from all the received packet replicas. As a matter of fact, MRC has been widely used in diversity reception communication systems such as Multiple-Input Multiple-Output (MIMO) and Single-Input Multiple-Output (SIMO). Given that MARSALA is also a diversity-based transmission/reception method, we propose two MRC techniques for MARSALA: MRC based on packet SNIR knowledge and MRC based on received power per timeslot.

At this point, it is important to note that a method involving MRC of replica packets chunks has been proposed for an asynchronous RA scheme in [17], [18]. However, the MRC technique used requires the knowledge of a symbol-by-symbol SNIR and this information is not easily retrieved especially in high channel traffic regimes.

In order to describe the MRC scheme for MARSALA, let us detail the signal received on the reference timeslot TS_{ref} as shown below

$$y_1(t) = s_1(t)e^{j2\pi\Delta f_1 t+\phi_1} + n_1(t) + i_1(t) \quad , \tag{1}$$

where s_1 is the signal corresponding to the first replica of a given packet on TS_{ref}, n_1 and i_1 denote respectively the noise and interference terms on TS_{ref}. Δf_1, ϕ_1 are respectively the frequency offset and phase shift relative to the first replica. We suppose that the frequency offset is the same for all replicas, however the phase shift varies randomly from one replica to another. Supposing that the k^{th} replicas of s_{ref} are localised using the correlation procedures, we express the signal containing the k^{th} replica as follows

$$y_k(t) = s_1(t-\Delta\tau_k)e^{j2\pi\Delta f_1 t+\phi_k} + n_k(t) + i_k(t) \quad , \tag{2}$$

with ϕ_k denoting the phase shift of the k^{th} replica and $\Delta\tau_k$ representing the timing offset between the replicas. n_k, i_k are the noise and interference terms on the timeslot containing the k^{th} replica. For sake of simplicity, we suppose that timing offsets and phase shifts between the replicas are perfectly compensated. Then, each signal is multiplied by a weighting factor α. The resulting combined signal is shown below:

$$y_{sum}(t) = \left(\sum_{k=1}^{N_b}\alpha_k\right)s_1(t)e^{j2\pi\Delta f_1 t+\phi_1} + \sum_{k=1}^{N_b}\alpha_k(n_k(t)+i_k(t)) \quad . \tag{3}$$

The equivalent SNIR obtained with MARSALA is

$$SNIR_{eq} = \frac{\left(\sum\limits_{k=1}^{N_b}\alpha_k\right)^2 P_{s_1}}{\sum\limits_{k=1}^{N_b}\alpha_k^2(N_k+I_k)} = \frac{\left(\sum\limits_{k=1}^{N_b}\alpha_k\right)^2}{\sum\limits_{k=1}^{N_b}\alpha_k^2 SNIR_k^{-1}} \quad , \tag{4}$$

where P_{s_1} is the power of s_1 and $N+I$ is the noise plus interference power term. If EGC is applied, $\alpha_k = 1$, otherwise α_k is defined according to the MRC technique used.

A. MRC based on packet SNIR knowledge

According to (4), the optimal value of $SNIR_{eq}$ can be obtained with $\alpha_k = SNIR_k$. Then $SNIR_{eq}$ would be equal to:

$$SNIR_{eq,max} = \sum_{k=1}^{N_b} SNIR_k \quad . \tag{5}$$

Therefore, obtaining the maximum gain of MRC requires the knowledge of the received $SNIR$ for each replica on each timeslot. A number of SNIR estimation techniques as well as the impact of estimation errors on MRC, can be found in the literature [15], [16]. It has been demonstrated in [16] that data-aided channel estimation only slightly degrades MRC performance. Therefore, in this paper, as a first contribution to analyse the impact of MRC on MARSALA, we will consider perfect SNIR knowledge per timeslot.

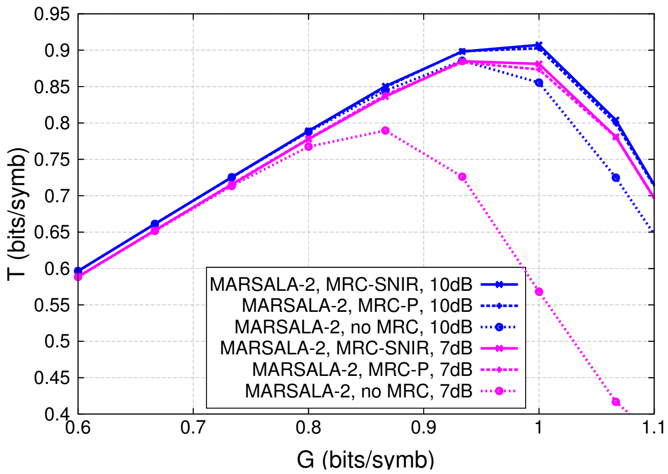
B. MRC based on received power per timeslot

In case we do not have proper SNIR estimation for each replica on each timeslot, we propose to use MRC based on received power per timeslot. This technique requires the condition that all the replicas of a given packet are equi-powered, however the interference packets can have different power levels. We also consider that in a frame duration, the attenuation is constant; so the useful signal received powers are equal for each set of packet replicas. The concept is the following: given that replicas of a same packet are equi-powered, then we can deduce the interference level on each timeslot by measuring P_k, the total received power on each timeslot. In other words, among the N_b signals on the timeslots containing replicas of a given packet, the signal having the highest received power, contains the highest interference level. Therefore, once the interference level is known for each replica with the power measuring method, we can use this criteria to choose the MRC weighting factor as $\alpha_k = (P_k)^{-1}$.

C. Evaluation of MARSALA with MRC via simulations

Following the two MRC techniques described above, we evaluate the performance gain of MARSALA with MRC compared to EGC, in terms of throughput and PLR. In the simulations, CRDSA and MARSALA are combined according to the system model described in Section II. For MARSALA, the impact of imperfect replicas combination on the performance is taken into account, following the model defined in [12]. Also, the effect of residual channel estimation errors caused by imperfect interference cancellation [19], [20] is taken into consideration. The simulations environment is provided by a satellite communications simulator developed by Thales Alenia Space and CNES. In order to only evaluate the MRC gain metric, we consider in the following that all the packets are equi-powered and QPSK modulation with DVB-RCS2 turbo code for linear modulation of rate $1/3$ are used. To facilitate the recognition of several MARSALA and CRDSA versions, we denote by MARSALA-2 and CRDSA-2, the MARSALA and CRDSA systems where each terminal transmits 2 replicas of a given packet. The same notation is taken for MARSALA-3 and CRDSA-3.

Fig.2 and Fig.3 show the normalised throughput and PLR in function of the normalised load on the frame, obtained



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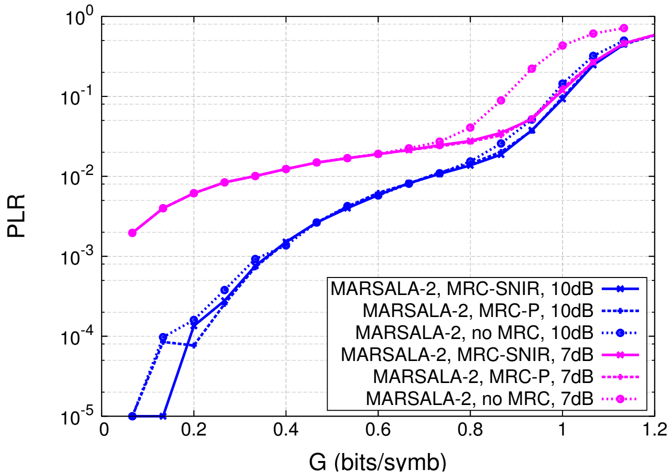

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Fig. 2: Comparison between MARSALA with EGC, with MRC based on packet SNIR (MRC-SNIR) and with MRC based on received power per timeslot (MRC-P). $N_b = 2$ replicas. QPSK modulation, DVB-RCS2 turbo code $R = 1/3$, $E_s/N_0 = 10$ dB. Equi-Powered packets. (a) Throughput. (b) PLR.

respectively with MARSALA-2 and MARSALA-3. The normalized load (G) is expressed in bits per symbol and computed as shown below:

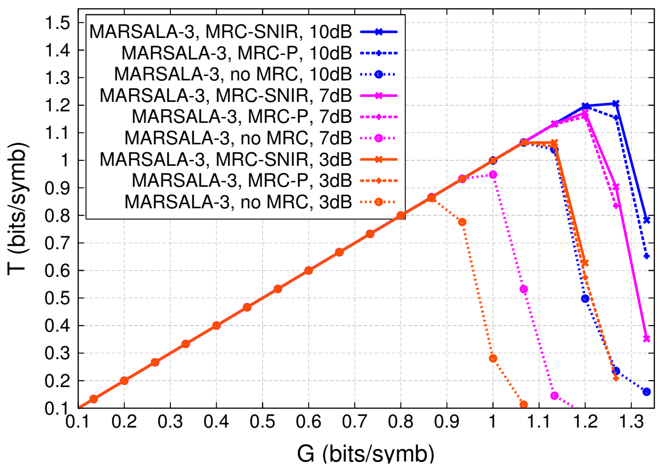
$$G = R * \log_2(M) * \frac{\lambda}{N_s} \quad , \tag{6}$$

with R being the code rate and M the modulation order. The normalized throughput (T) is given by

$$T = G\,(1 - PLR(G)) \quad , \tag{7}$$

where PLR(G) is the probability that a packet is not decoded for a given G and a given SNIR.

We can observe that the performance of MARSALA with MRC based on SNIR knowledge and MARSALA with MRC based on received power per timeslot, is nearly the same. Therefore, the complexity of SNIR estimation procedures in



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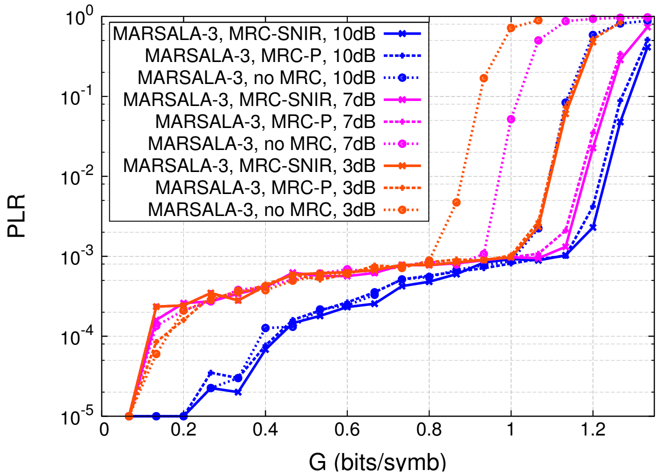


(b)

Fig. 3: Comparison between MARSALA with and without MRC techniques. $N_b = 3$ replicas. QPSK modulation, DVB-RCS2 turbo code $R = 1/3$, $E_s/N_0 = 10$ dB. Equi-Powered packets. (a) Throughput. (b) PLR.

very low SNIR regimes, can be replaced with less complex operations of received power measurement per timeslot.

Based on the results in Fig.2 and Fig.3, let us discuss the impact of MRC techniques on the performance of MARSALA. We can see that the performance enhancement is more visible for MARSALA-3 than MARSALA-2. On one hand we notice that the throughput of MARSALA-2 at 7 dB is increased by 20% but it is still nearly the same at 10 dB. Yet, the PLR plots do not show important enhancement for MARSALA-2. On the other hand, we can observe that MARSALA-3 throughput is increased by 20% at 3 dB and 7 dB. At 10 dB, the throughput of MARSALA-3 with MRC is enhanced by 12% and it has a maximum value of 1.2 bits/symbol. The PLR at 10^{-3} is also enhanced. In addition, we can notice that the throughput obtained with MARSALA-3 and MRC at 3 dB is approximately equal to the throughput obtained at 10 dB without MRC. However, the performance in terms of PLR is less significant. In the rest of the paper, MRC will be taken into account for MARSALA in the simulations scenarios.

IV. MARSALA WITH PACKETS POWER UNBALANCE

It has been shown in [5], [6] that received packets power unbalance between different users has a positive impact on the performance of CRDSA. In fact, power unbalance enables CRDSA to decode packets in collision thanks to the capture effect [21]. In other words, the strongest packets are decoded first with a higher successful decoding probability, then they are removed with SIC iterations. Thus, the weaker packets are less interfered and have a higher successful decoding probability as well.

In this section, we apply the same concept to MARSALA, given that it is also a diversity based RA method with SIC. First, in order to give a comparison with CRDSA, we study the same packets power distribution as described in [5], [6]: lognormal distribution. Then, we analyse three other probability distribution functions in order to further enhance the performance.

A. Lognormal packets power distribution

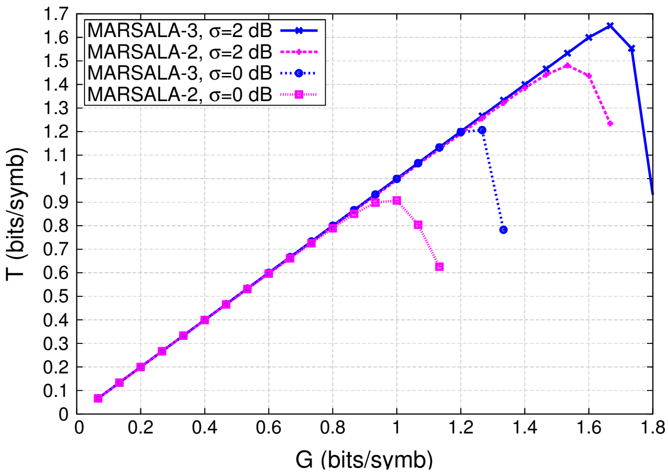
Fig.4 shows the throughput and PLR of MARSALA-2 and MARSALA-3, with lognormally distributed packets power. We suppose that all the users transmit their packets at an (E_s/N_0) ratio equal to 10 dB. Then, at the receiver side, the received packets are attenuated following a lognormal Probability Distribution Function (PDF) of parameters $\mu = 0$ dB and $\sigma = 0$ dB (equi-powered packets case) or $\sigma = 2$ dB.

As expected, we can observe that the performance enhancement with $\sigma = 2$ dB is significant compared to the equi-powered packets case. With lognormal PDF, the throughput is increased by around 50% in MARSALA-2 and MARSALA-3. The PLR enhancement at 10^{-3} is only visible for MARSALA-3 with $G = 1.6$ bits/symbol.

B. Proposed packets power distributions for MARSALA

Given the important positive impact of packets power unbalance on the performance of RA methods employing SIC, recent research has proposed to apply power control techniques on the terminals and to derive an optimal PDF for the packets transmission power. In [13], an optimal packets power distribution has been derived for spread Aloha packet detectors with iterative SIC. The authors have found that a PDF uniform in dB is the optimal solution for their scheme. Also, as stated in [5], ongoing work in the European Space Agency (ESA) is studying the optimal packets power distribution for CRDSA. As for MARSALA, an analytical study shall be done in close future. However, in this work, we consider three PDFs for packets power, as shown in Fig.5:

- **The uniform distribution (in dB)**, with E_s/N_0 varying in the interval $[0-13]$ dB.
- **The half normal distribution (in linear scale)**, with parameters $\mu = 1$ and $\sigma = 7$ (in linear scale) and E_s/N_0 varying in $[0-13]$ dB. We pick the value $\sigma = 7$ in order to have a large variance and to approach the uniform distribution, but still have lower probabilities at the rightmost edges of the PDF.



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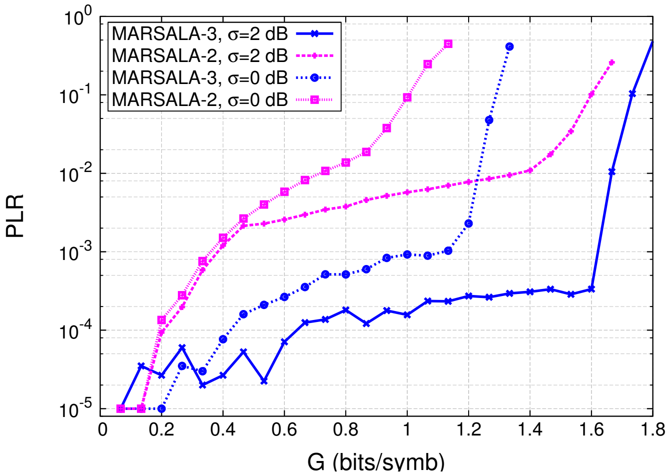


(b)

Fig. 4: Comparison between MARSALA-2 and MARSALA-3 with equi-powered packets and lognormally distributed packets power. QPSK modulation, DVB-RCS2 turbo code $R = 1/3$, $E_s/N_0 = 10$ dB. (a) Throughput. (b) PLR.

	Logn $\sigma = 0$ dB	Logn $\sigma = 2$ dB	Half Normal	Uniform	Half Normal Reversed
T	1.13	1.6	1.8	1.4	1.33
Gain	-	45.45%	63.63%	24%	18%

TABLE I: Comparison of MARSALA-3 maximum throughput (in bits/symbol) and performance gain at PLR $< 10^{-3}$, with various packets power distributions.

- **The reversed half normal distribution (in linear scale)**, with $\mu = 1$ and $\sigma = 7$ (in linear scale).

Fig.6 shows the performance of MARSALA-3 with the packets power distributions described above compared to the equi-powered packets case as well as the lognormal distribution with parameters $\mu = 0$ dB, $\sigma = 2$ dB and $E_s/N_0 = 10$ dB. Based on the results obtained, Table I summarizes the maximum

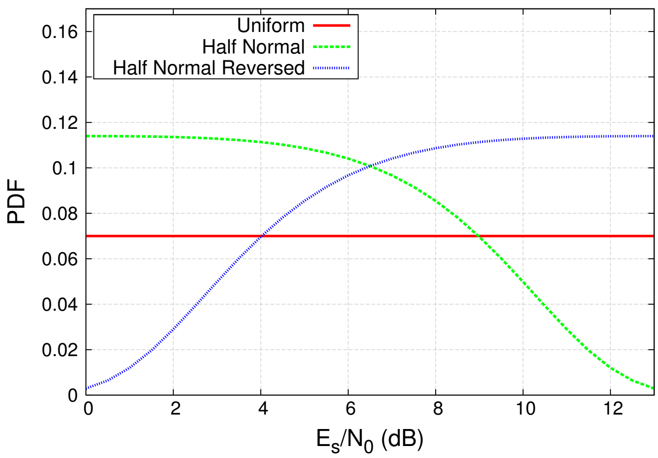


Fig. 5: PDFs proposed for packets power in MARSALA-3.

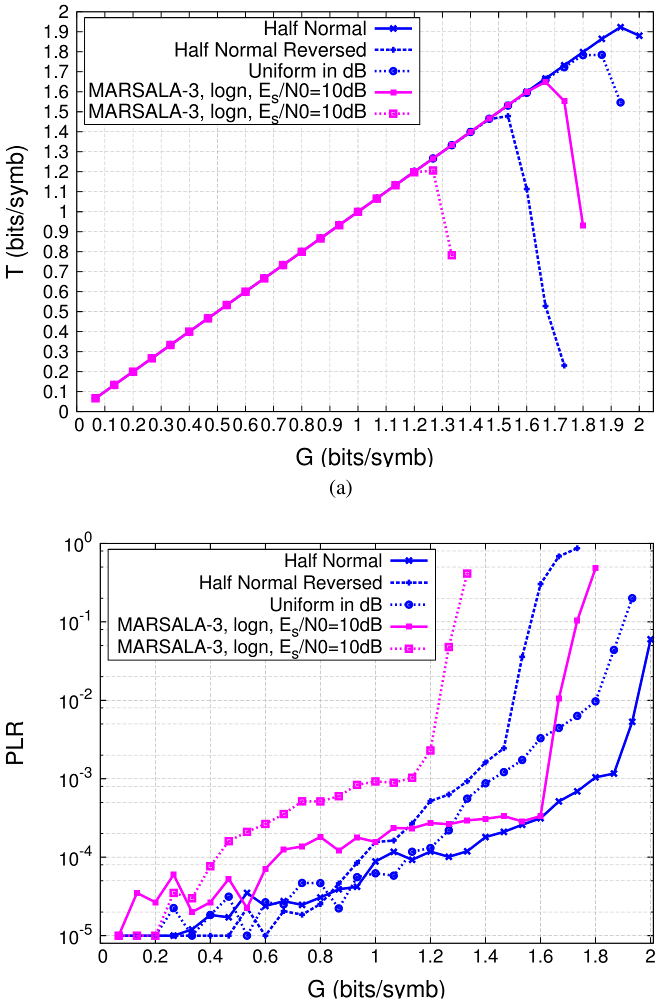
throughput values obtained for a PLR $< 10^{-3}$. We can notice that, among the three proposed PDFs, the packets power following the half normal distribution, presents a maximum gain (63.63%) compared to the equi-powered packets case. The advantage of using this distribution is that a high probability of users is given a low E_s/N_0 ratio (between 0 dB and 4 dB).

V. Performance Comparison of MARSALA with Various Coding Schemes

Lately, MARSALA performance has been evaluated only with DVB-RCS2 turbo code for linear modulation. Yet, it has been shown in previous research [5] that the coding scheme behaviour in the Packet Error Rate (PER) region between 0.1 and 1, has an impact on RA schemes using SIC. For this reason, the authors in [5] have proven that the choice of 3GPP code for CRDSA instead of DVB-RCS2, enables to trigger more SIC iterations and achieve a better performance.

Seen that MARSALA is also a RA method that uses SIC, the choice of the coding scheme will also affect its performance. Therefore, in this section we will compare the throughput and PLR of MARSALA with three encoding schemes:

- **DVB-RCS 2 turbo FEC code for linear modulation**, which is a 16-states double binary Circular Recursive Systematic Convolutional (CRSC) code. In the simulations, we consider the reference waveform id-13 as defined in the DVB-RCS2 standard (payload burst length $= 1476$ symbols, with QPSK modulation and code rate $R = 1/3$).
- **3GPP turbo code [22]**, with a burst length equal to 150 bits.
- **Consultative Committee for Space Data Systems (CCSDS) [23] turbo code**, of rate $1/3$ constructed from information block lengths of 456 bits. The CCSDS turbo code used in the simulations is provided by the Coded Modulation Library (CML) [24].



(a)

(b)

Fig. 6: MARSALA-3 performance with various proposed packets power distributions. QPSK modulation, DVB-RCS2 turbo code $R = 1/3$. (a) Throughput. (b) PLR.

Fig.7 shows the theoretical PER curve for each of the 3 coding schemes. We can remark that for the PER region $[0.1 - 1]$, the 3GPP turbo code has the best performance. The impact of the coding schemes on the throughput and PLR of MARSALA-3 with equi-powered packets is shown in Fig.8. As expected, MARSALA-3 with 3GPP and CCSDS achieves largely better performance than DVB-RCS2, and the best results are obtained with 3GPP. The throughput is enhanced by 54% compared to the DVB-RCS2 coding scheme and it is almost doubled compared to CRDSA. In addition, the PLR floor is significantly lower.

VI. Conclusion

MARSALA is a diversity based RA method employing SIC, therefore its performance is highly affected by the following design metrics: the method used for replicas combination, the packets power unbalance and the coding scheme behaviour. In this paper, we have proposed to add MRC to MARSALA. Two MRC techniques have been described and they have both shown a performance gain of around 20% in terms of

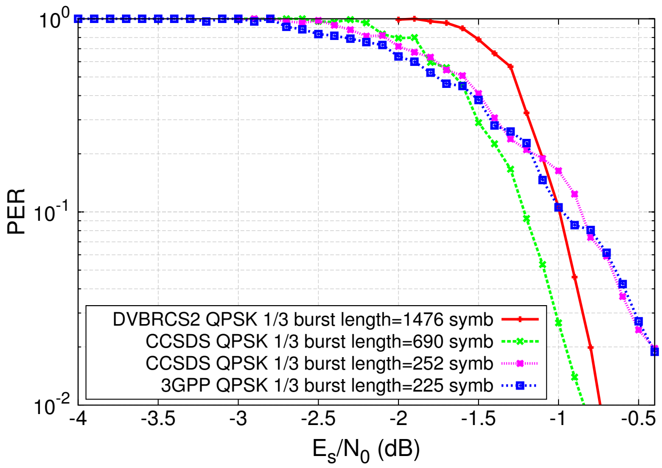
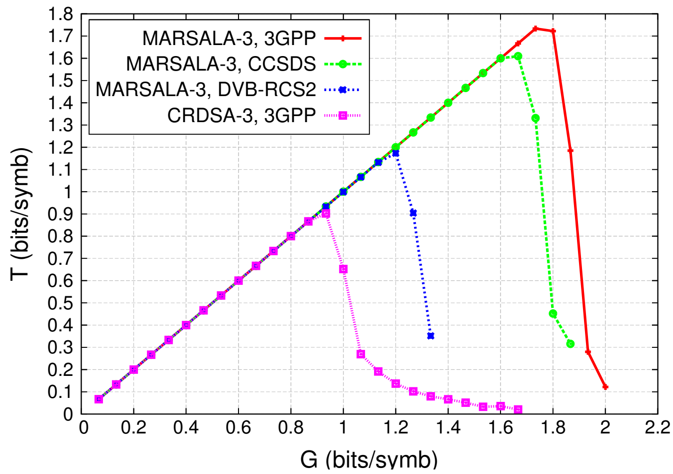


Fig. 7: PER vs. E_s/N_0 for 3GPP, DBB-RCS 2 and CCSDS turbo codes. QPSK modulation with code rate $R = 1/3$.



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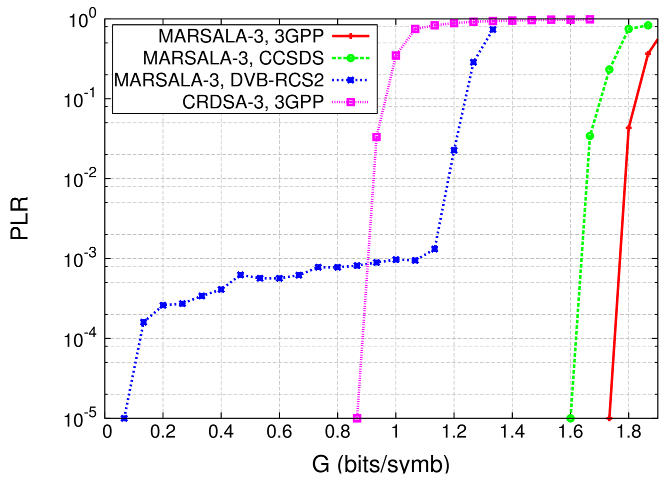

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Fig. 8: Comparison between MARSALA-3 with DVB-RCS2, 3GPP and CCSDS turbo codes. QPSK modulation, code rate $R = 1/3$. Equi-powered packets. (a) Throughput. (b) PLR.

throughput and PLR. We have also concluded that, similarly to CRDSA, packets power unbalance enables MARSALA to achieve a better performance. Thus, we have shown that the throughput can reach 1.8 bits/symbol with the half normal packets power distribution. In addition, we have evaluated MARSALA with various coding schemes, and the maximum throughput has been obtained with 3GPP turbo code. In conclusion, combining MARSALA with MRC, half normal packets power distribution and 3GPP turbo code can present an optimal design for an optimal performance, by maximizing the throughput and minimizing the PLR.

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