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An Enhanced Multiple Random Access Scheme for Satellite Communications

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Abstract—In this paper, we introduce Multi-Slots Coded ALOHA (MuSCA) as a multiple random access method for satellite communications. This scheme can be considered as a generalization of the Contention Resolution Diversity Slotted Aloha (CRDSA) mechanism. Instead of transmitting replicas, this system replaces them by several parts of a single word of an error correcting code. It is also different from Coded Slotted ALOHA (CSA) because collided data are used in the iterative decoding of the frame. In MuSCA, the entity in charge of the decoding mechanism collects all bursts of the same user (including the interfered slots) before decoding and implements a successive interference cancellation process to remove successfully decoded signals. Simulations show that the achievable total normalized throughput is greater than 1.25 and 1.4 for a frame of 100 and 500 slots, resulting in a gain of 85% and 75% with respect to CRDSA and CSA respectively. This gain comes from the combination between diversity introduced by the random distribution of the data on the frames and MuSCA decoding algorithm, allows the system to transmit on average more than one packet per slot. This paper is a first analysis of the proposed scheme and opens several perspectives.

I. INTRODUCTION AND RELATED WORK

Since its apparition 40 years ago, the ALOHA protocol [1] developed at the University of Hawaii and its variants, have motivated an extremely large number of studies. The pure ALOHA is a protocol for sharing channel access among a number of users wishing to send at anytime short data packets with relatively low throughput demand. The optimal normalized throughput T of this scheme is equal to 0.18. The next versions of ALOHA, the Slotted ALOHA (SA) [2] or its enhanced version named Diversity Slotted ALOHA (DSA) [3] where time is split into slots, are used in satellite networks for transmission of short bursts. In SA, the users send packets at fixed time slots of one packet length, and the maximum normalized throughput is doubled compared to the pure Aloha protocol (0.37 vs. 0.18). In DSA, the same packet is transmitted twice to improve the throughput and delay but at low normalized load. This scheme does not provide a great enhancement with respect to SA.

After DSA, improved versions (CRDSA*) named Contention Resolution Diversity Slotted ALOHA (CRDSA) [4] and CRDSA++ [5] have been developed and included into the second generation of Digital Video Broadcasting - Return Channel via Satellite (DVB-RCS2) standard [6]. Similarly to DSA, 2 replicas (3 to 5 replicas in the case of CRDSA++) of

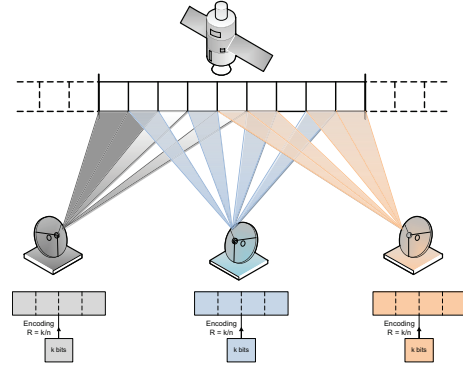


Fig. 1. Multiple access on a slotted channel

the same packet are generated and sent randomly onto a frame of N_s slots. The improvement is that each packet contains a signalling information which points to its replicas location. Whenever one packet is successfully decoded, the replicas are also located and cancelled. This procedure is iterative until no decoding is possible.

Recently, a generalized scheme of CRDSA was introduced: Irregular Repetition Slotted ALOHA (IRSA) [7] which allows a variable repetition rate for each burst to provide a higher throughput gain over CRDSA. Using this protocol in a system where N_s is equal to 200, we can achieve a normalized throughput close to 0.8.

Afterwards, a new generalization of IRSA named Coded Slotted ALOHA (CSA) [8] was also introduced. CSA encodes bursts using local codes before the transmission. The maximum achievable throughput is 0.8 when the following assumptions are satisfied: sufficiently high signal-to-noise ratio (SNR); ideal channel estimation and erasure of bursts in collision.

Lately, a new multi-user physical layer network coding method was presented in [9]. Several copies of a message are transmitted by each user. In the case of collision, the receiver decodes the exclusive or (XOR) of the transmitted messages. The set of original messages could be then decoded.

In this paper, we introduce a further generalization of CRDSA named Multi-Slots Coded ALOHA (MuSCA). We consider a system where several users share a channel to send data to a given access point or relay such as a satellite, a base station (see Figure 1 for an example where a satellite

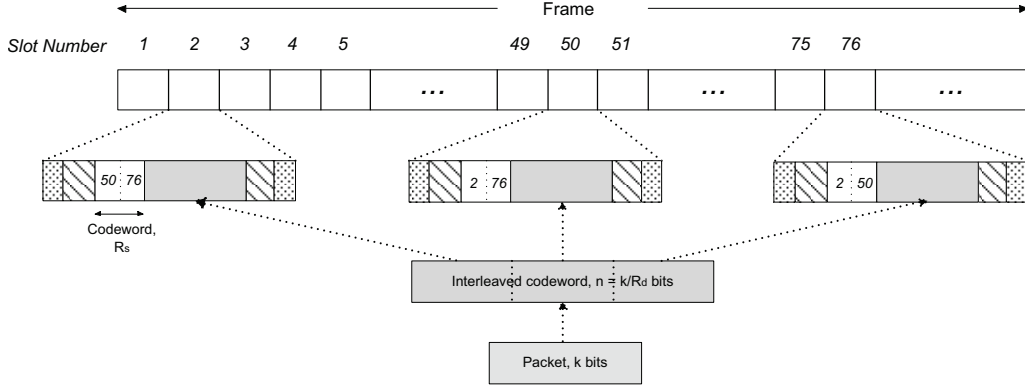


Fig. 2. Sending scheme, time-hopping case, $N_b = 3$

acts as a relay). All users encode their data with an error correcting code to generate one codeword which is equitably shared among N_b physical layer packets (N_b varies from one user to other) of same length called bursts. The bursts are transmitted on a multiple access frame which is split into logical slots. Each user randomly sends its N_b bursts in N_b different time or frequency slots, so bursts may collide. The received signal (which can be either at the level of the relay, the gateway or the terminal) is composed by the noisy sum of the signals relative to the different users. The codeword of each user is rebuilt from the N_b bursts including collided ones by the receiver. Bursts collisions are almost cleaned up by successive decoding and interference cancellation operations. The objective of our paper is to generalize the CRDSA* mechanism, to point out the proposed enhancements and to present the significant gain in terms of throughput and packet loss ratio (*PLR*) over different schemes. Subsequently, we show (under our hypothesis) how a peak throughput of 1.4 can be reached by MuSCA.

The paper is organized as follows: the proposed multiple access scheme is presented in the next section. The implementations of our mechanism are detailed in section III. Then, an analysis in terms of throughput and packet loss ratio according to different system parameters is provided in section IV, allowing performance comparisons between MuSCA and existing schemes presented in section I. Future work and conclusion are given in the last.

II. SYSTEM OVERVIEW

In this section, we first present the assumptions taken on the communication system. Then, we detail the decoding mechanism used in the receiver which combines classical error decoding and successive interference cancellation (SIC).

A. Hypotheses

We consider the uplink of a wireless communication system (see Figure 1 for an example of satellite communication) shared among N_u users. The access method is based on slotted ALOHA where the communication medium is divided into time and/or frequency slots of one burst size. The burst size is the same for all users. We consider that a set of N_s consecutive

slots forms a frame. In this paper, the channel is considered linear and the transmission is subject to an Additive White Gaussian Noise (AWGN).

In our system, a user can only send one data packet of k bits per frame. To send more messages, the user must wait until the next frame. We assume that synchronization mechanisms allow the users to be synchronized at slot and frame levels.

If several users attempt a transmission during the same slot, there is collision. Signals of all users can be either decoded at the level of the relay, embedded in the satellite, at the gateway or the terminal. Contrarily to CRDSA, IRSA and CSA, in this work, collided bursts are not considered as erased, and they are integrated into the decoding process.

B. Principle of the Mechanism



Fig. 3. Burst structure

1) *Transmitter*: In this system, each user seeks to transmit a data packet of k bits on each frame. First, an error-correcting code of rate R_d is used. A codeword of k/R_d bits is generated. This one is then split into N_b parts. Similarly to CRDSA*, signalling information bits and a preamble are added to each part to form a burst. The structure of each burst is represented in Figure 3. Modulated bursts are sent on several slots of a slotted-ALOHA-like channel (see Figure 2). The signalling bits contain information identifying the positions of the other bursts of the same user within the frame. These bits are encoded with a short code of rate R_s . We assume that both codes (to encode data and signalling bits) can be different from a user to other and are known by the receiver. Each user chooses randomly N_b slots and sends its bursts on these slots.

2) *Receiver*: The received signal on a frame is the sum of signals of N_u users after passing through the channel. The SIC process is applied twice to this signal: first to decode signalling fields and then to decode data fields of each located users' set of N_b bursts.

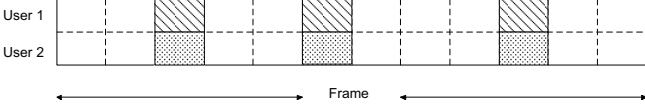


Fig. 4. Decodable by MuSCA but not by CRDSA*, IRSA and CSA

First, the receiver attempts to locate bursts of a maximum number of users by decoding the signalling fields with the SIC algorithm. It runs through each slot, tries to decode the signalling fields protected by the code of rate R_s . Note that if R_s is correctly chosen, a decoding can be successfully done even for bursts collided by other bursts (see Section III-A). If the decoding is successful, the positions of the $N_b - 1$ other bursts of the same user are discovered. This allows the receiver to generate the $N_b - 1$ signalling fields and subtract them from the received signal. After this operation, $N_u - 1$ users remain to be located. The process is iterative until bursts of all users are located or no other signalling field can be decoded.

Afterwards, data decoding is started for the located user who has the most non collided (clean) bursts. The receiver collects all bursts of the same user, rebuilds a codeword of length k/R_d and starts the decoding process. In CSA, collided bursts are treated as erasure. In MuSCA, when a burst is located, even if it is interfered by bursts of other users, it can still participate in the decoding process. A burst is considered as lost only when it is highly interfered and brings no more useful information for the decoding. The threshold for high interference is defined according to the error correcting code and the channel noise level. If the decoding is successful, the receiver creates the codeword, splits it into N_b parts to create the N_b bursts. Then the signals corresponding to the N_b recovered bursts are regenerated and subtracted with SIC processing from the received signal. The interference contribution caused by these bursts is then removed. After the subtraction, the resulting signal is the combination of channel noise and signals of the $N_u - 1$ remaining users. The decoding algorithm is iterative until data of all users are decoded or until the occurrence of a deadlock situation where no user is still decodable.

Figure 4 shows a case of deadlock situation for CSA and its previous versions (CRDSA, IRSA). In this case, with a threshold set to 2, MuSCA is able to implement the decoding even if there is no more clean burst on the frame.

III. IMPLEMENTATION

We have shown in the last section that the proposed algorithm allows us to decode configurations which cannot be recovered by other Slotted-Aloha-based system. However, the choice of codes for the signalling field, data packet and parameters N_b , N_s play an important role that may deeply influence the system performance.

Although the conception of the algorithm allows the use of a different code for each user (which could be beneficial for the system performance), we only detail the case where users encode their data with the same error correcting code of rate R_d and then the same N_b . Several studies on CRDSA and CSA

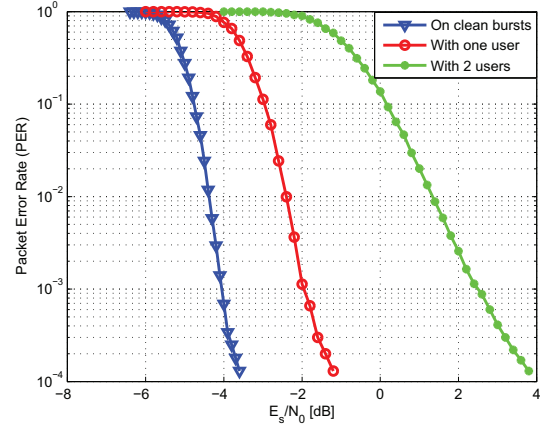


Fig. 5. Turbo code of $R = 1/6$, $k = 456$ bits, modulation QPSK, AWGN channel

[5] [8] show that these systems achieve their best performance in terms of throughput for $N_b = 3$ (normalized throughput $T = 0.7$ for CRDSA++ and $T = 0.8$ for CSA). Therefore in the following sections, only results with the parameter N_b equal to 3 are presented.

A. Signalling fields

As in CRDSA, the signalling field of each burst contains pointers to the positions where the other bursts of the same user are located. The field size depends on the size N_s of the frame but remains relatively small. Signalling data are encoded, modulated (e.g., using BPSK modulation) and added to the useful data field to form a burst. Reed-Muller codes are short codes which achieve a fair performance/complexity trade-off for soft-decision decoding [10]. Therefore, they can be used to encode these signalling fields. The signalization decoding is launched in the case that the burst is on a collision-free slot or it is interfered by only one other user.

B. Data field

Codes used to encode data by each user have to simultaneously manage errors and collisions. A good example of such code is the 3GPP2 turbo code, also used in Digital Video Broadcasting - Satellite Handheld (DVB-SH) [11]. The algorithm proposed by MuSCA does not require any constraint on the choice of codes to encode the data packets. However, in order to compare it with existing methods, we have first conducted studies with a code allowing to send an amount of information bits per slot equivalent to CRDSA. In the CRDSA* scheme, a terminal sends N_b copies of the same MAC packets in N_b randomly selected slots, the data in each burst is encoded by a convolutional [4] or turbo code [5] of rate $r = \frac{1}{2}$. In MuSCA, this is equivalent to a general code of rate $R_d = \frac{1}{2N_b}$. A CCSDS turbo encoder [12] of rate $R_d = 1/6$, associating with QPSK modulation can be applied to information bit sequences of length $k = 456$, producing codewords of 1380 QPSK symbols, equivalent to 2760 bits. Note that the turbo codes do not reach their highest performance when there are

long damaged sequences in the received codeword. Therefore, similarly to DVB-SH, we implement a bit-interleaver to each codeword. These interleaved codewords are then split into three parts of length about 460 QPSK symbols to form three bursts and these bursts are sent on slots. Figure 5 depicts the performance curves in terms of packet error rate (PER) of this turbo code in the 3 cases: a) the 3 bursts are on clean slots, b) the 3 bursts are in collision with signal of one user of the same power and c) the 3 bursts are in collision with two other users. Other analysis using a different code will be carried out in order to increase the throughput reached by the system (for example, a turbo code with $R_d = 1/4$ and length $k = 680$ bits). Note that in our work, the system performance are shown with classical CCSDS codes. Using codes specially designed for this context should improve this performance.

IV. PERFORMANCE EVALUATION

Our analysis relies on the assumptions that users arrive on the communication medium in a perfectly synchronized manner (both in time and phase) and under the constraint of equal average received power. The MuSCA decoding algorithm using SIC attempts to remove the interference of the most recently decoded user, by re-encoding the decoded bits sequence, modulating it with the appropriate amplitude and phase adjustment, and subtracting it out from the current composite received signal. To realize this operation, we assume that the channel estimation is perfect.

We still consider a frame composed of N_s slots, in which N_u users attempt a transmission. The normalized load representing the average number of packets transmissions per slot is computed as:

$$G = \frac{N_u}{N_s}. \quad (1)$$

The probability of non decoding a packet is denoted PLR and is given for each E_s/N_0 and G . For a fixed E_s/N_0 , the relation between normalized throughput (defined as the number of successful packets transmissions per slot) and PLR is given by:

$$T = G \times (1 - PLR(G)). \quad (2)$$

T can be greater than 1. In this case, on average, more than one user can transmit their packets per slot. The value of G that maximizes T must be carefully chosen. Indeed, T is bounded by G so with a greater G , the expected normalized throughput can be higher. But if G exceeds a certain value, the frame is full, the collision rate is high, which causes a large packet loss ratio and reduces T .

In the first set of simulations, a turbo code of rate $R_d = 1/6$ is used. Simulation results show that bursts interfered by 3 or more other users do not improve the turbo decoding performance. So, they are considered as erased (the threshold is set to 2). However, taking into account the bursts interfered by only one or two other users significantly ease the decoding.

In Figure 6, the throughput is evaluated for different frame sizes $N_s = 100, 200$ and 500 when $E_s/N_0 = 10dB$.

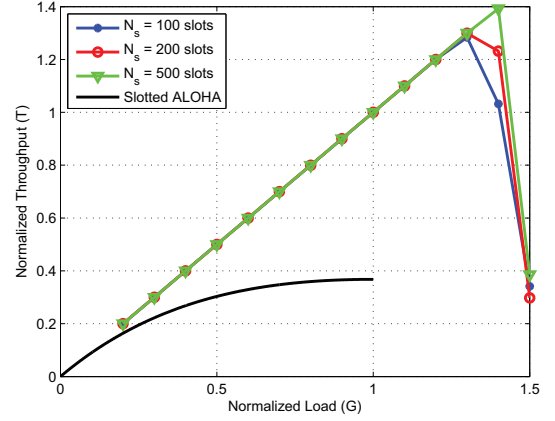
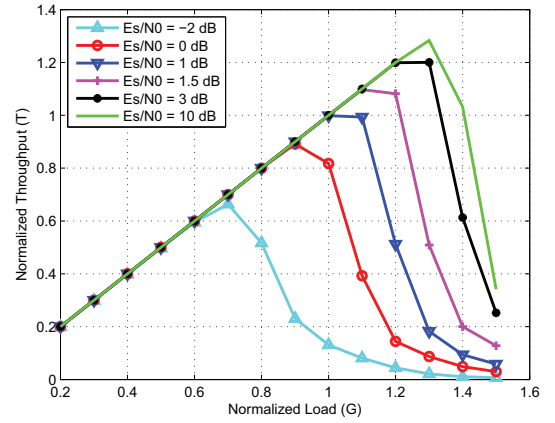
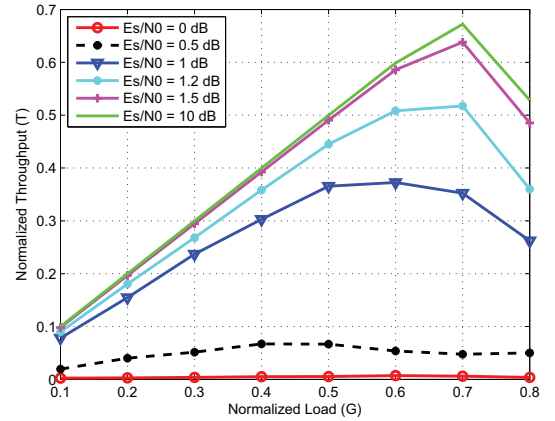


Fig. 6. Normalized throughput for MuSCA using turbo code $R=1/6$; various frame sizes



(a) MuSCA



(b) CRDSA, 3 replicas

Fig. 7. Throughput T versus the normalized load G for MuSCA and CRDSA. $N_s = 100$ slots

The curve reached by Slotted ALOHA $T = G \times e^{-G}$ is also presented for reference. The gain between MuSCA and other methods is significant. The upper bound of normalized

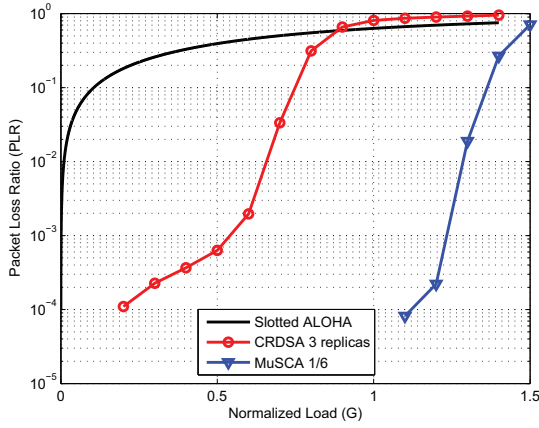


Fig. 8. Packet Loss Ratio for SA, CRDSA with 3 repetitions and for MuSCA. $E_s/N_0 = 8dB$

throughput of IRSA is 0.97 for a very large frame size ($N_s \rightarrow \infty$). With a frame of $N_s = 200$ slots, under assumption of sufficiently-high SNR , IRSA offers a throughput of 0.8 vs. 1.3 obtained by MuSCA in the same condition. For the frame length $N_s = 500$, CSA approaches $T \approx 0.8$ with the noiseless assumption [8], while MuSCA achieves a peak throughput of about 1.4 for $E_s/N_0 = 10dB$.

We can observe that the frame size does not have a significant impact on the performance of MuSCA: 1.4 for $N_s = 500$ vs. 1.28 for $N_s = 100$. In the same time, a large augmentation of N_s would increase significantly the transmission delay because the decoding process cannot be started before the entire frame is received. For example, the utilization of frame formed by 500 slots would introduce a delay 5 times longer. For this reason, a frame size of 100 slots has been assumed for all following simulations.

The system performance in terms of throughput is then studied by varying the signal-to-noise ratio and finding the normalized load G that maximizes the normalized throughput T for each SNR . A frame is split into 100 slots. From Figure 7, we see that MuSCA is able to achieve significant better thresholds than CRDSA for every E_s/N_0 . On a frame of this length, the system can transmit packets of up to 128 users ($T = 1.28$) for a high SNR ($E_s/N_0 = 8dB$) while CRDSA is limited to less than 70 users. MuSCA with turbo code $R = 1/6$ provides a peak of throughput close to 1.3 and the relation between T and G is almost linear up to G close to 1.2. That means, even if the communication medium is 120% loaded, the probability of successful transmission is almost 100%. When the power of noise is equal to the useful signal ($E_s/N_0 = 0dB$), MuSCA still allows up to 90 users to transmit, whereas the CRDSA system is completely overridden.

Figure 8 shows the PLR as a function of G for SA, CRDSA and MuSCA. MuSCA can achieve a remarkable low PLR (less than 0.1%) at a high normalized load $G = 1.2$. Consequently, most of bursts are successfully transmitted at the first

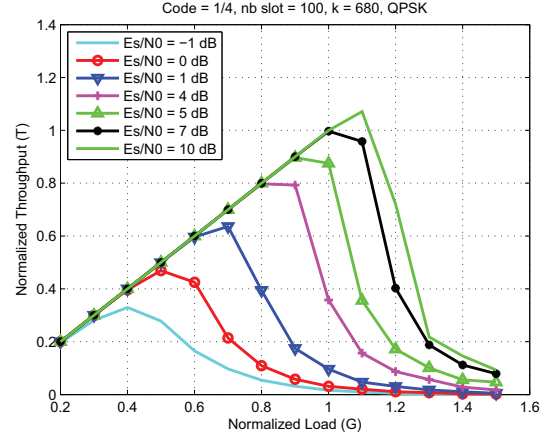


Fig. 9. Throughput T versus the normalized load G for MuSCA using turbo code 1/4, $N_b = 3$ and $N_s = 100$ slots

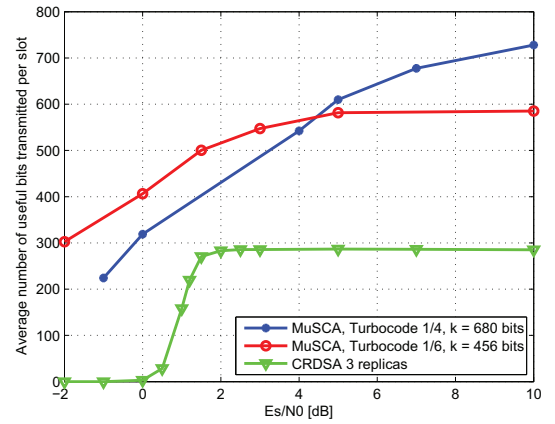


Fig. 10. Quantity of useful bits transmitted per slot for MuSCA, CRDSA 3 replicas vs. turbo code 1/6 and turbo code 1/4, $N_s = 100$ slots

attempts, resulting in low latencies. In this figure, we observe that MuSCA has much lower PLR for all loads in the case of no re-transmission. For a PLR equal to 10^{-3} , the MuSCA channel can be loaded 2.3 times more than the CRDSA channel ($G_{MuSCA} \approx 1.22$ vs. $G_{CRDSA3replicas} \approx 0.54$) and much more than the SA channel ($G_{SA} \approx 0.001$). Targeting a PLR equal to 10^{-2} , two and three replicas CRDSA can offer a traffic close to 0.35 [5] and 0.66 respectively. SA only operates at extremely low load $G_{SA} \approx 0.01$ while for MuSCA, this PLR can be achieved with a channel traffic $G \approx 1.27$.

The same simulations are executed with the second turbo code. We consider a code of rate $R_d = 1/4$ to encode sequences of 680 bits, combined with QPSK modulation. Then 1380 QPSK symbols codewords are obtained. As previously, N_b is set to 3. That means each user tries to transmit about 1.5 times more useful information on each frame and on each slot. The throughput of the MuSCA protocol has been simulated versus the normalized load G for variable values of E_s/N_0 . Performance results are given in Figure 9.

By combining numerical results from both simulations sets,

we quantify the number of maximum payload bits for each code. Focusing on the relationship between the number of useful bits transmitted per slot and the SNR , we observe that even if the normalized throughput of turbo code of rate $R_d = 1/4$ is lower than the one of turbo code $R_d = 1/6$ (peak throughput of 1.14 vs. 1.28), the system still achieves more benefits in terms of useful information sent for high values of E_s/N_0 . This is due to the low amount of redundancy. In Figure 10, curves of MuSCA using turbo code $R_d = 1/6$ and $1/4$ are compared with the curve of CRDSA. All systems operate on frames composed of 100 slots of similar sizes. We note that for any E_s/N_0 , MuSCA achieves a gain of at least 50% compared to CRDSA.

V. CONCLUSION AND FUTURE WORK

In this paper, the enhancement so-called Multi-Slots Coded ALOHA (MuSCA) scheme has been introduced and analyzed. The proposed approach represents an improvement of CRDSA, IRSA and CSA protocols. Simulation results show that MuSCA provides a large gain in terms of throughput and packet loss ratio compared to existing random access techniques currently introduced in [4], [5], [7] and [8]. It has been shown that MuSCA can achieve a normalized throughput close to 1.28 for system with frames of 100 slots and 1.4 while the frame size is up to 500 slots for E_s/N_0 equals to 10dB. This results in a 1.85 and 1.75 fold throughput increase compared to CRDSA and CSA. A low PLR (10^{-2}) is also maintained even when the transmission medium is highly loaded (G up to 1.3). In a future work, the usage of different parameters (value of N_b , error correcting codes, transmission power for each user) is scheduled. We also expect to further study asynchronous conditions, channel estimation and impacts of estimation errors on the system. Study on interactions between the access method and higher layer protocols are also envisaged.

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