Shared Position Technique for Interfered Random Transmissions in Satellite Communications

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***Abstract*—In this paper we propose a new random access (RA) channel technique for the return link of satellite communications. It concerns slotted transmissions. This proposed method called Shared POsition Technique for Interfered random Transmissions (SPOTiT), is based on a shared knowledge between the receiver and each of the terminals. The shared information is about the time slot locations on which the terminal transmits its replicas as well as the preamble to use. The presented random version of SPOTiT aims to reduce the complexity of replicas localization process of the legacy technique Multireplica Decoding using Correlation based Localisation (MARSALA). It presents a less complex system without degrading performance and with no extra signaling information. Thus, SPOTiT is applied at the same level as MARSALA, i.e. when Contention Resolution Diversity Slotted Aloha (CRDSA) fails in retrieving more packets. This technique combined with CRDSA significantly reduces the number of data localization correlations, while maintaining the same performance as in CRDSA/MARSALA in terms of packet loss ratio and throughput.**

***Index Terms*—Satellite communications, Time slot position , Pseudo-orthogonal preambles, Multiuser channel, Random access**

I. INTRODUCTION

The vision of living in a connected and a smart world has led to define new access technologies. These would better meet the desired criteria of sporadic transmissions and the huge number of connected objects. As a matter of fact, the reservation resources of Demand assigned multiple access (DAMA) techniques are not sufficient and can be under-used, especially for applications such as Internet of Things (IoT) and Machine to Machine (M2M) communications. Random Access (RA) protocols based on Aloha have hence evolved considerably since the Abramson initial version 1970 [1]. Among the synchronous methods, on which we will focus in this paper: Slotted ALOHA [2] introduced first a synchronous transmission of packets on well-defined time slots within a frame; Diversity Slotted ALOHA [3] proposes a multi-replicas transmission of the same packet so that at least one of the replicas without interference can be retrieved. However, these methods have a reduced throughput compared to DAMA access. As a result, newer RA techniques have emerged. Contention Resolution Diversity Slotted Aloha (CRDSA) [4] combines the use of two or more replicas with Successive Interference Cancellation (SIC) at reception. As a result, system performance is significantly improved in terms of throughput and Packet Loss Ratio (PLR). CRDSA has thus been incorporated in the Digital Video Broadcasting - Return Chanel via Satellite (DVB-RCS2) specifications. Later, several variants have derived from it: R-CRDSA [5] proposes a Reservation scheme, SW-CRDSA [6] on the other hand is based on a no-frame scheme using a Sliding Window which characterizes especially asynchronous transmissions, Irregular Repetition Slotted Aloha (IRSA) [7] introduces an irregular number of replicas that varies from one transmitter to another, and the coding aspect has been studied in [8] [9].

Despite the great diversity of the deployed techniques in existing RA solutions, there is always a need for performance enhancement and complexity reduction at the reception level. A complementary method to CRDSA, MultireplicA decoding using corRelation baSed locAlisation (MARSALA) has then emerged [10]. It is meant to, first, locate undecoded packets through correlations between a reference time slot and the remaining signal on the rest of the frame. Then, it coherently combines the localized replicas of the same packet before demodulation and decoding. The whole MARSALA process enables to resolve CRDSA's deadlock when no more packets can be retrieved. It consequently offers better PLR and throughput, but in return, it adds a processing complexity related to the correlation computation. Signal processing aspects of MARSALA regarding channel estimation and compensation have been investigated in [11] [12].

Taking into account the performance enhancement of MARSALA and the related complexity, the proposed method SPOTiT aims to reduce the localization correlation operations. It exploits identification information of the terminal in order to randomly select a preamble and time slot positions using a pseudorandom generator. The latter allows the receiver to be aware of all potential positions and the associated preambles. We call this contribution Random SPOTiT in the rest of the paper. Another version where positions are assigned rather than randomly chosen will be developed in future work.

Random SPOTiT is further described in Section III after presenting the system overview in Section II. Complexity is

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analyzed afterwards in Section IV and simulation results are presented in Section VI.

II. SYSTEM MODEL AND ASSUMPTIONS

We focus in this paper on packets reception from a multi-access random transmission channel on the satellite return link of the DVB-RCS2. N_{U} terminals attached to a gateway transmit in a synchronous way, over the same frequency, N_{R} replicas, each on a time slot within a frame having a total of N_{S} slots. We suppose each user waits for the next frame to send another packet. Thus, no more than one packet from a user can be found on the same frame. The payload is a fixed-length set of symbols generated from N_{b} information bits which are transformed into a MODCOD through coding and modulation. Packets are then formed by adding, at the beginning and at the end of the resulted payload symbols a preamble and a postamble respectively. We consider N_{P} pseudo-orthogonal preambles, for example Gold or Zadoff-Chu sequences. In addition, pilot fragments are randomly distributed in the packet for estimation matter. Guard intervals at the end of each slot are used to avoid interpacket interference due to potential synchronization errors.

At the receiver side, which can be the gateway or the satellite, CRDSA is applied first. It analyzes the frame and proceeds to packet detection and decoding on each time slot. Replicas of the same demodulated and decoded packet are suppressed from their respective positions. The frame is then analyzed again, thus applying SIC until no more packets can be retrieved. A complementary treatment is triggered to resolve CRDSA's deadlock, which can be legacy MARSALA or the new proposed technique Random SPOTiT (see Fig. 1).

Both methods rely on replicas localization on the frame, and the combination of signals belonging to the same packet prior to decoding. The difference between MARSALA and SPOTiT is that the latter requires less complexity in the localization process thanks to the prior knowledge on replicas positions and the used preambles. The whole Random SPOTiT process at transmission and reception is detailed in the next section.

III. SHARED POSITION TECHNIQUE FOR INTERFERED RANDOM TRANSMISSIONS

The proposed multiple access solution SPOTiT describes a way of arranging packets on the frame and associating them with preambles. The goal is to make sure packets localization requires a reduced complexity. Transmission and reception aspects are detailed below.

A. Transmission

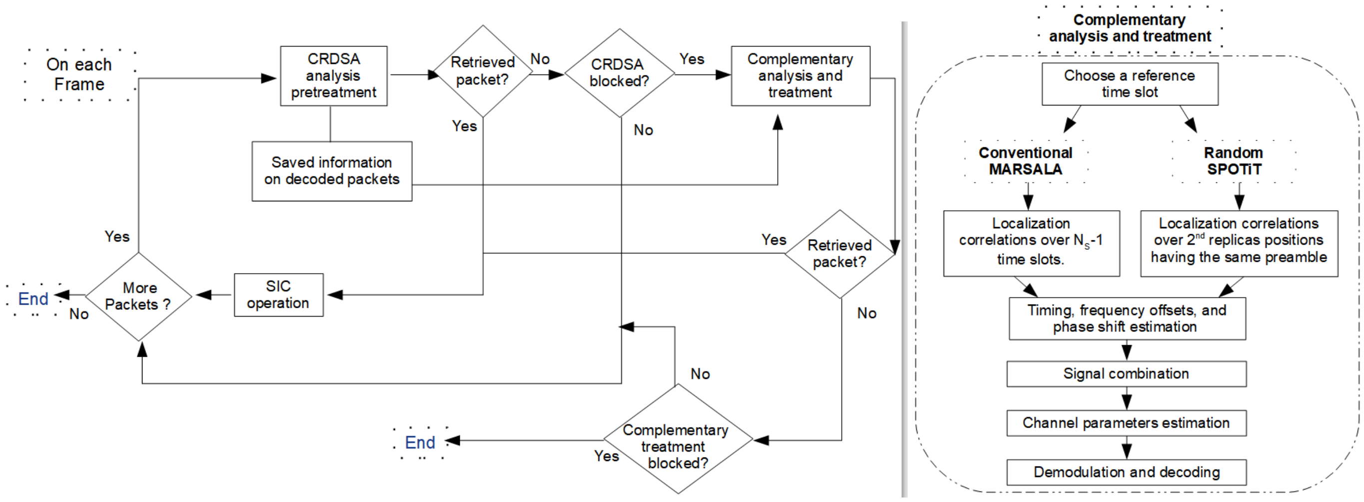
This part aims to explain how the transmitter selects its replicas positions on the frame and the preamble to use in a way that makes the receiver be aware of it. One of the characteristics of Random SPOTiT is to provide a shared knowledge between the receiver and each terminal without any additional signaling information. One solution is to use a PseudoRandom Number Generator (PRNG). It has been employed in [13] and inspired from [4] as signaling information that points to the position of a packet replicas. However, it still needs in this case to be retrieved after demodulation and decoding of one of the replicas. Although, in Random SPOTiT, the PRNG uses the Identification Information (ID) known by both the transmitter and the receiver as a seed that generates replicas positions and preamble. It is processed according to two modes:

1) Fixed seed for each user: the Hardware IDentifier (HID) of the user is known by the receiver due to the logon phase. Indeed, each subscriber uses its identifier to login to the system. In other words, users send their identification information to the gateway to which they are attached during the logon phase. Thus, this HID seed mode makes sure that the receiver and each of the users are able to determine the same time slots on the frame and the preamble to be used at each transmission. However, in some applications where several users generate the same positions, and they transmit successively on the same frames, they create an unsolvable loop. As a result, continuous failure of retrieve will occur. To remedy this, a dynamic choice of positions and preambles is introduced.

2) Dynamic seed for each user: in order to have new time slots and preamble choices at each frame for each terminal, a dynamic combination can be used. This would involve an incremental identifier as a seed. For example, it can be obtained by adding U_{ID} the terminal HID to F_{ID} the frame ID, i.e. $F_{\mathrm{ID}} + U_{\mathrm{ID}}$ that is received or calculated using the synchronization information (synchronization tables in DVB-RCS2). Indeed, the dynamic combination between the HID and the frame ID avoids a continuous loop in case of successive transmissions.

B. Reception

The receiver computes all replicas positions and preamble choices of each subscriber using the predetermined seeds in the fixed or dynamic case and creates an information table. In table I with two replicas per packet, $\mathrm{Slot}(u, r)$ refers to the time slot position of replica r belonging to user u, and P_u is the selected preamble for the same user u. This means the receiver knows all the potential users and their preambles that can transmit packets on each time slot of the frame. Thereafter, the pseudo-orthogonal characteristic of preambles is used to reduce the potential number of users on each time slot. A good preamble detection depends on the auto and cross-correlation properties of the sequences in addition to their length. As a matter of fact, a detected preamble on a time slot will point to a certain number of users having that same preamble, from the receiver's information table. These users are the ones that could transmit data on that analyzed time slot. During the preamble detection phase, when a detected preamble points to a unique potential user (according to the information table), it indicates the presence of its packet. Especially when its other replicas slots exhibit as well a correlation peak of the same preamble. However if a correlation peak of a certain preamble on a specific time slot indicates, according to the information table, that it is associated to more than one user, the following localization strategies should then be applied.



(a) CRDSA with complementary treatment process

(b) Complementary Analysis explicitness

Fig. 1. Random SPOTiT positionning at reception

1) Only preamble detection based method:
The result of preamble detection made during CRDSA is stored and utilized by Random SPOTiT. As a matter of fact, the latter will first compare it with its information table. Then, it will check all replicas positions of packets whose preamble is detected on the analyzed time slot. Positions that do not indicate the presence of the preamble of interest are eliminated from the potential transmitters. On the contrary, when one of the positions or more show a correlation peak of the same preamble, and one of them points to a one potential user, this one is confirmed to have a packet on the current frame. However, when all replicas positions of a user whose preamble is detected point to multiple possible packets, localization must resort to data correlations between slots.

2) Data localization correlations:
The only preamble detection based method becomes difficult with the increase of the number of transmitters. Therefore data localization correlations over the whole slot are to be used. Yet, in contrary to MARSALA which has $N_{\mathrm{S}} - 1$ data localization correlations, only a small number is performed in Random SPOTiT. It is equal to the number of potential users having the same detected preamble on the slot when $N_R = 2$. Otherwise, data correlations are performed over the time slots containing the other replicas of potentially collided packets. This number of potential users is the one resulting from the only preamble detection based method.

Once localization is successful, signal combination is performed between time slots containing replicas of the same packet before demodulation and decoding.

Example: $N_{\mathrm{R}} = 2$, assuming all preambles are correctly detected

Let us take the first slot slot 0 in the frame composition example of Fig. 2, with each color representing a distinct preamble. U_u is the user u which belongs to the set of N_{U} subscribers. It should be noted that the time slot positions and preambles are selected through the PRNG. According to the information table look up (Fig. 3) that concerns the slot 0, there are four potential users that can transmit one of their replicas in slot 0: U_1 and U_{11} with the blue preamble we call P_1, U_{19} using the red preamble we call P_2 and U_{22} with the purple one we call P_3. The preamble detection of pseudo-orthogonal sequences on slot 0 gives correlation peaks for P_1 and for P_2. This means the user U_{22} has not transmitted on this frame, thus only three candidates are to be investigated. Since U_{19} is the only potential user with the preamble P_2 that can send a packet on slot 0, the red peak indicates its presence. As the receiver knows the location of its replica, from the information table, no data localization correlations are necessary. However,

TABLE I
RECEIVER'S INFORMATION TABLE

Users	Position 1	Position 2	Preambles
$\mathbf{U_1}$	Slot(1,1)	Slot(1,2)	P_{U_1}
$\mathbf{U_2}$	Slot(2,1)	Slot(2,2)	P_{U_2}
$\mathbf{U_3}$	Slot(3,1)	Slot(3,2)	P_{U_3}
$\mathbf{U_4}$	Slot(4,1)	Slot(4,2)	P_{U_4}
$\mathbf{U_5}$	Slot(5,1)	Slot(5,2)	P_{U_5}
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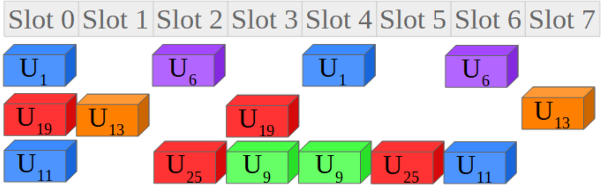

Fig. 2. Example of a frame composition

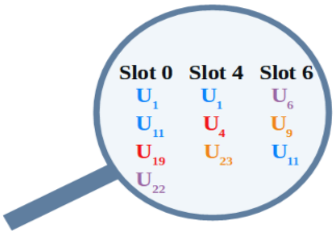

Fig. 3. Time slots look up example

the blue correlation peak can even indicate the presence of one of the packets U_1 and U_{11} or both of them. In order to determine which one has transmitted a packet, the result of preamble detection on both slots (slot 4 and slot 6) where the second replicas of U_1 and U_{11} is used. Slot 4 and slot 6 having both two correlation peaks a blue/green and blue/purple respectively will confirm the presence of U_1 and U_{11}. This is true because there is a unique potential transmitter with a blue preamble. In this example, only preamble detection was necessary. However, data localization correlations can be required in the case where more than one potential transmitter over all replicas positions occurs.

IV. COMPLEXITY ANALYSIS

This section will investigate the number of data localization correlations in the case of MARSALA and Random SPOTiT. It concerns the correlations that are necessary to decode all the packets on an analyzed time slot and those needed to decode only one packet. We consider the worst case for Random SPOTiT when the only preamble detection based method has failed to locate more packets. We start the complexity analysis for any number of replicas before putting forward the case of two replicas. As a matter of fact, when CRDSA is blocked and no more packets can be retrieved, MARSALA will randomly choose a reference time slot in order to perform necessary data correlations to locate the colliding packets replicas. The number of localization correlations depends on the number of slots, the number of replicas and the number of the collided packets on this slot. MARSALA makes a two steps processing. At first, it locates all colliding packets replicas on the frame using data correlations between the reference slot and the other remaining slots (first term of (1)). Then, it performs more correlations in order to associate the localized replicas to a given packet on the reference time slot (second term of (1)) before decoding and SIC. Therefore, one way to describe the whole process complexity is to calculate the total number of correlations $N^{\mathrm{Corr}}_{\mathrm{MARSALA}}$ taking into account localization and association on a reference time slot. We assume there are no loops or partial loops.

$$N^{\mathrm{Corr}}_{\mathrm{MARSALA}} = (N_{\mathrm{S}} - 1) + \sum_{c=1}^{N^{\mathrm{Ref}}_{\mathrm{Coll}}} \sum_{i=1}^{N_{\mathrm{R}}-2} (N_{\mathrm{R}} - 1) \times N^{\mathrm{Ref}}_{\mathrm{Coll}}(c) - i \tag{1}$$

where $N^{\mathrm{Ref}}_{\mathrm{Coll}}$ is the total number of collided packets over the reference time slot before MARSALA's decoding, $(N_{\mathrm{R}} - 1) \times N^{\mathrm{Ref}}_{\mathrm{Coll}}$ is the total number of correlation peaks, of replicas associated to $N^{\mathrm{Ref}}_{\mathrm{Coll}}$. Thus $(N_{\mathrm{R}} - 1) \times N^{\mathrm{Ref}}_{\mathrm{Coll}}(c)$ is the number of the remaining correlation peaks after $c - 1$ SIC operations.

The association process is done by combining the signal of the reference time slot with the slot whose correlation peak is the highest. Afterwards, new data correlations with the rest of the peak slots are performed until the N_{R} replicas are associated.

On the other hand, Random SPOTiT depends on the number of replicas, the number of collided packets, the number of detected preambles and the number of potential transmitters. We consider the worst scenario when all collided packets having used the same preamble have the same timing offset. This means that when that preamble is detected, the receiver has no knowledge on which among all packets candidates have transmitted. As the receiver knows about potential transmitters on a time slot and detected preambles, it will no longer be necessary to have $N_{\mathrm{S}} - 1$ localization correlations as in MARSALA. Fewer data correlations $N^{\mathrm{Corr}}_{\mathrm{SPOTiT}}$ are needed to determine which users having the same detected preamble have transmitted on the analyzed time slot.

$$N^{\mathrm{Corr}}_{\mathrm{SPOTiT}} = (N_{\mathrm{R}} - 1) \times N^{\mathrm{Ref}}_{\mathrm{PColl}} \tag{2}$$

with $N^{\mathrm{Ref}}_{\mathrm{PColl}} = \sum_{p=1}^{N^{\mathrm{P}}_{\mathrm{Det}}} N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$

- $N^{\mathrm{Ref}}_{\mathrm{PColl}}$ is the number of potential packets in collision on the reference time slot.
- $N^{\mathrm{P}}_{\mathrm{Det}}$ is the number of detected preambles.
- $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$ is the number of potential users with the detected preamble p that can transmit on the reference time slot.

Thus, for each detected preamble, Random SPOTiT performs data localization correlations only over the time slots containing the other replicas of potentially collided packets. These latter are the potentially collided over the analyzed reference time slot. No association is necessary because it is enough to confirm replicas presence by correlations on the well known time slots.

We have put our focus, in our complexity analysis, on the number of data correlations which are necessary to decode only one of the collided packets c over a time slot. This number $N^{\mathrm{Corr}(1),c}_{\mathrm{MARSALA}}$ for MARSALA is given in (3).

$$N^{\mathrm{Corr}(1),c}_{\mathrm{MARSALA}} = ((N_{\mathrm{S}})^k - 1) + \sum_{i=1}^{N_{\mathrm{R}}-2} (N_{\mathrm{R}} - 1) \times N^{\mathrm{Ref}}_{\mathrm{Coll}}(c) - i \tag{3}$$

The first and the second term are respectively, associated to the localization process for all collided packets and the association process to locate the replicas of the packet of interest. k is equal to 1 when $c = 1$ and $k = 0$ for any other value of c. This means that the global localization process is made only once.

As for Random SPOTiT, the number of data localization correlations for one packet decoding $N^{\mathrm{Corr}(1),p}_{\mathrm{SPOTiT}}$ is related to a specific detected preamble p:

$$N^{\mathrm{Corr}(1),p}_{\mathrm{SPOTiT}} = (N_{\mathrm{R}} - 1) \times N^{\mathrm{Ref}}_{\mathrm{pot}}(p) \tag{4}$$

In this case, data localization correlations are only performed over the slots that contain all replicas of packets with the same preamble p as for the packet of interest, that can be potentially collided on same time slot.

The next step consists of analyzing the number of data localization correlations, for one packet decoding, in the case of two replicas. We will consider two replicas in the rest of the paper. This case of having the minimum number of replicas is even simpler and can be a good solution for a less complex system than MARSALA-2.

- In MARSALA-2, the number of data correlations required to locate a packet before SIC does not depend on the association process:
$$N^{\mathrm{Corr}(1)}_{\mathrm{MARSALA2}} = (N_{\mathrm{S}} - 1) \tag{5}$$
- In SPOTiT, the number of correlations required to locate a packet with a preamble p becomes:
$$N^{\mathrm{Corr}(1),p}_{\mathrm{SPOTiT},2} = N^{\mathrm{Ref}}_{\mathrm{pot}}(p) \tag{6}$$

Let us take for instance the complexity related to the localization of one packet in terms of data correlations. MARSALA-2 and Random SPOTiT with two replicas have respectively $N_{\mathrm{S}} - 1$ and $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$ data correlations. This means that as long as the number of potential users having the same detected preamble is smaller than $N^{\mathrm{Corr}(1)}_{\mathrm{MARSALA2}}$, Random SPOTiT is less complex. As mentioned before, $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$ depends on the total number of subscribers, over the same frequency, attached to a gateway. Therefore, there is a maximum number of subscribers beyond which the complexity between MARSALA and Random SPOTiT remains the same. A way to further minimize localization correlations complexity in Random SPOTiT is to start localization with the time slot that has the minimum $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$ for a preamble p. $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$ is retrieved from the information table at the receiver's side. This can be applied from the beginning when the only preamble detection based method is to be proceeded. Nevertheless, the worst case can be described as when, with a certain number of subscribers, the minimum $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$ for a preamble p is equal to $N_{\mathrm{S}} - 1$, i.e. $\min N^{\mathrm{Corr}(1),p}_{\mathrm{SPOTiT},2} = N^{\mathrm{Corr}(1)}_{\mathrm{MARSALA2}}$, and all these potential collided packets have their replicas on different time slots. This means that Random SPOTiT should correlate the reference time slot with the $N_{\mathrm{S}} - 1$ different slots. In other words, Random SPOTiT will have exactly the same behavior as MARSALA. However this case is extreme and depends also on the number of preambles which can increase or decrease the value of $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$. In addition, the only preamble detection based method from part III-B-1 is not considered here. This means that $N^{\mathrm{Ref}}_{\mathrm{pot}}(p)$ would represent the potential transmitters on the reference time slot after CRDSA SIC and part III-B-1 process.

V. PREAMBLE DETECTION AND PACKET DECODING

Let us consider a time slot on which multiple users have transmitted a replica r, with a phase error $\phi_{i,r} \in [0; 2\pi]$ and shifted in time with $\tau_i \in [-2T_{\mathrm{S}}; 2T_{\mathrm{S}}]$ where T_{S} is the symbol duration, through an Additive White Gaussian Noise (AWGN) channel with an $E_{\mathrm{S}}/N_0 = 10$ dB. Each has a gold code preamble of length 31 which is generated using the preferred polynomial pair $\left\{x^5 + x^2 + 1\ ,\ x^5 + x^4 + x^3 + x^2 + 1\right\}$. It corresponds to the pair of the maximum length pseudo noise sequences (m-sequences) for the shift registers that generate the gold codes. Thus, we describe the preamble region signal P_{T} including the guard interval at time instant t as follows:

$$P_{\mathrm{T}}(t) = \sum_{i=1}^{L} p_i(t + \tau_i)\, e^{j\phi_{i,r}} + G_{\mathrm{data}}(t)\, e^{j\phi_d} + n(t) \tag{7}$$

where p_i is the i^{th} gold code among the L collided preambles on the analyzed time slot, G_{data} is the extra guard data symbols from the region around the preamble location due to potential synchronization errors, and n is the AWGN noise term with a power of σ^2.

The receiver proceeds to preamble detection by correlating the received preamble region signal with the complex conjugates of the 31 gold codes.

$$R^l_{\mathrm{P}}(\tau) = \int_0^{T_{\mathrm{search}}} P_{\mathrm{T}}(t) \times p^*_l(t - \tau)\, dt \tag{8}$$

where T_{search} is the preamble time search region.

R_{P} will have a peak for each transmitted preamble l at time instant τ_l referring to the autocorrelation function of each collided preamble. The packet decodability and the decision of preamble detection is affected by the number of collided packets. In order to provide with a first approximation, we have made a preliminary study. On the one hand, preamble detection probability is assessed with respect to the number of collided packets. On the other hand, the decoding probability is analyzed with respect to the number of interfering packets. Considering preambles as Gaussian random variables, the square modulus of correlation $|R^l_{\mathrm{P}}|^2$ can be represented as a Chi-square random variable with two degrees of freedom. A preamble l is decided to be detected if $|R^l_{\mathrm{P}}|^2$ is above a predetermined threshold. The detection threshold T_{h} can then be derived using the false alarm probability P_{FA}.

$$\begin{aligned} P_{\mathrm{FA}}(T_{\mathrm{h}}) &= P(|R^l_{\mathrm{P}}|^2 > T_{\mathrm{h}} \mid H_0) \\ &= 1 - P(R_\sigma < \frac{T_{\mathrm{h}}}{\sigma^2} \mid R_\sigma \sim \chi^2_2) = \exp\left(-\frac{T_{\mathrm{h}}}{2\sigma}\right) \end{aligned} \tag{9}$$

where H_0 is the hypothesis of having $|R^l_{\mathrm{P}}|^2$ above the threshold when the preamble l is not present, and $R_\sigma = \frac{|R^l_{\mathrm{P}}|^2}{\sigma^2}$.

$$T_{\mathrm{h}} = -2\sigma^2 \ln P_{\mathrm{FA}} \tag{10}$$

A preamble is correctly detected when the correlation of P_{T} with the right complex conjugate of the transmitted gold code reaches a maximum that is above the detection threshold T_{h}. We start with highest correlation peak. Once detected, the gold code is suppressed and the preamble region signal is analyzed again to look for the next highest correlation peak. The detection threshold at the next iteration depends then on the new level of noise.

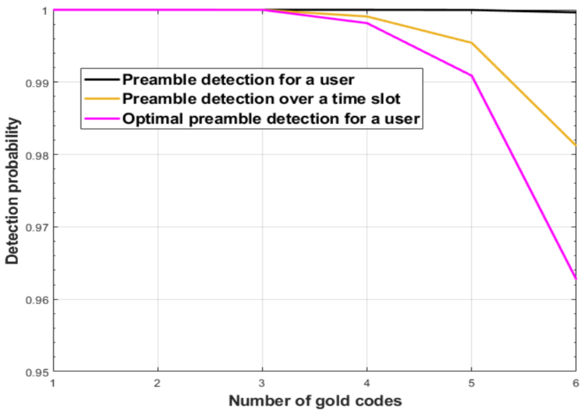

Fig. 4. Users detection probability of gold code preambles of length 31, over an AWGN channel.

In Fig. 4, with a false alarm probability set to 10^{-3} and $N_{\mathrm{R}} = 2$, the detection probability describes two cases. The first one is over one time slot; it concerns only one of the replicas of the packet of interest. The second one takes into consideration both replicas of a user when at least one of them is detected (preamble detection for a user) on its position or when both of them should imperatively be detected (optimal preamble detection for a user). The latter case is computed when both replicas are interfered by the same number of packets. Any other scenario regarding the number of interfering packets each replica incurs can be derived from the first case. As a matter of fact this would be equal to $P_1^{int} + P_2^{int} - P_1^{int} \times P_2^{int}$, where P_1^{int} is the probability that the first replica is detected on its time slot position, P_2^{int} is the probability that the second replica is detected on its time slot position, and int represents the number of interfering packets which can be different from one slot to another.

From Random SPOTiT and MARSALA perspective, signal combination enhances the SNIR value due to the higher power of the signal of interest. With the assumptions that interference is approximated to AWGN (investigation and justification is provided in [14] appendix), we can consider that the Packet Error Rate (PER) curve is associated to different values of SNIR defined in (11). The polynomial interpolation is proper to the chosen MODCOD. In our case we use QPSK modulation with Turbo coding of rate $1/3$; this means the MODCODs are of 150 symbols. Thus, the decoding probability can be calculated for different numbers of interfering packets.

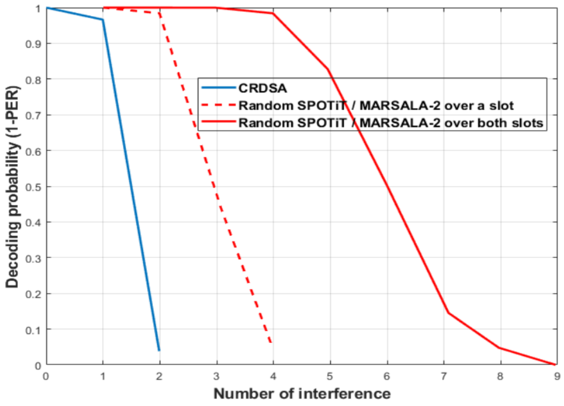

Fig. 5. Decoding probability w.r.t. the number of interfering packets of 100 bits, QPSK modulation, Turbo coding of rate $1/3$, $E_{\mathrm{S}}/N_0 = 10$ dB.

$$\mathrm{SNIR}(u,r) = \frac{E_{\mathrm{S}}/N_0}{E_{\mathrm{S}}/N_0 \times I_{u,r} + 1} \tag{11}$$

where $I_{u,r}$ is the number of interfering packets on the analyzed slot with replica r and user u.

From (11), we have the different interference rates that a replica r of a user u can incur in CRDSA case:

$$I(u,r) = \frac{E_{\mathrm{S}}/N_0 - \mathrm{SNIR}(u,r)}{\mathrm{SNIR}(u,r) \times E_{\mathrm{S}}/N_0} \tag{12}$$

If Random SPOTiT or MARSALA is applied, considering two replicas per packet, signal combination, based on summation between the first and second replica, will quadruple the packet power.

$$I_{\mathrm{SPOTiT}}(u) = \frac{4 \times E_{\mathrm{S}}/N_0 - 2 \times \mathrm{SNIR}(u)}{\mathrm{SNIR}(u) \times E_{\mathrm{S}}/N_0} \tag{13}$$

The generic expression that is applicable to all N_R is then:

$$I_{\mathrm{SPOTiT}}(u) = \frac{2^{N_R} \times E_{\mathrm{S}}/N_0 - N_R \times \mathrm{SNIR}(u)}{\mathrm{SNIR}(u) \times E_{\mathrm{S}}/N_0} \tag{14}$$

This interference rate is calculated over all slots where replicas of the same packet are present. We can derive a mean interference rate per time slot $I_{\mathrm{s}}(u)$ by dividing this number by N_R:

$$I_{\mathrm{s}}(u) = \frac{I_{\mathrm{SPOTiT}}(u)}{N_R} \tag{15}$$

Now we can associate the PER value of each SNIR to $I_{\mathrm{SPOTiT}}(u)$ or to $I_{\mathrm{s}}(u)$ and derive the decoding probability $P_{\mathrm{D}}(u) = 1 - \mathrm{PER}$.

Fig. 5 displays, for Random SPOTiT and MARSALA with two replicas, the decoding probability P_{D} with respect to the number of interfering packets. We consider no loops are created. If we take 0.98 as an acceptable value of decoding probability, we can see that with CRDSA only, an equivalent interference length of one packet has a chance to be decoded. Meanwhile, Random SPOTiT and MARSALA with two replicas have an equivalent interference length of $I_{\mathrm{SPOTiT}}(u) \approx 4$ packets over the two replicas slots; or a mean of $I_{\mathrm{s}}(u) \approx 2$ packets per time slot. This means there are six total replicas over both slots including the replicas of the packet of interest. These six replicas would refer to one scenario: two interfering packets with the packet of interest on each time slot. The possibility of having one interference on a time slot and three on the other one is dismissed because CRDSA can resolve a 'one-interference' scenario. We can see, according to Fig. 4, that when both replicas are collided with two other packets

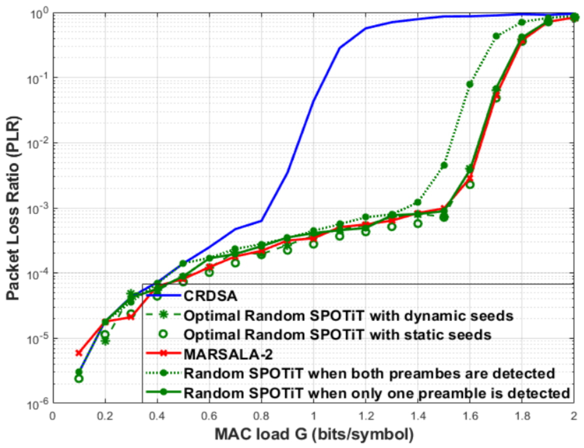

Fig. 6. Packet Loss Ratio comparison between Random SPOTiT, MARSALA-2 and CRDSA, $E_S/N_0 = 10$ dB, 100 slots per frame, QPSK modulation, Turbo coding of rate $1/3$ and equipowered packets of 100 bits.

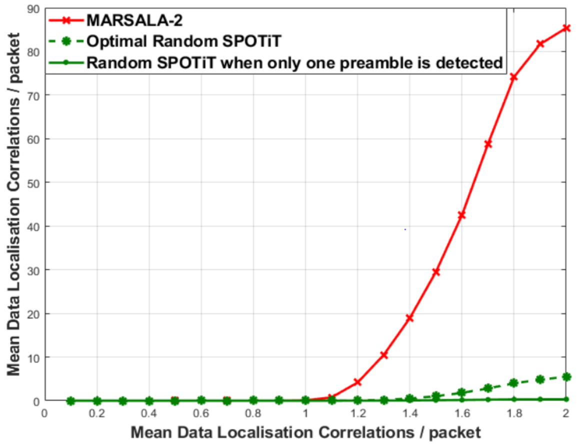

Fig. 7. Complexity of MARSALA-2 vs Random SPOTiT in terms of localization correlations, $E_S/N_0 = 10$ dB, 100 slots per frame, QPSK modulation, Turbo coding of rate $1/3$ and equipowered packets of 100 bits.

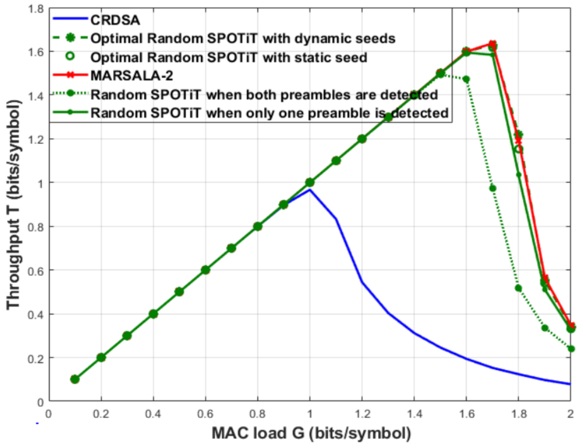

Fig. 8. Throughput comparison between Random SPOTiT, MARSALA-2 and CRDSA, $E_S/N_0 = 10$ dB, 100 slots per frame, QPSK modulation, Turbo coding of rate $1/3$ and equipowered packets of 100 bits.

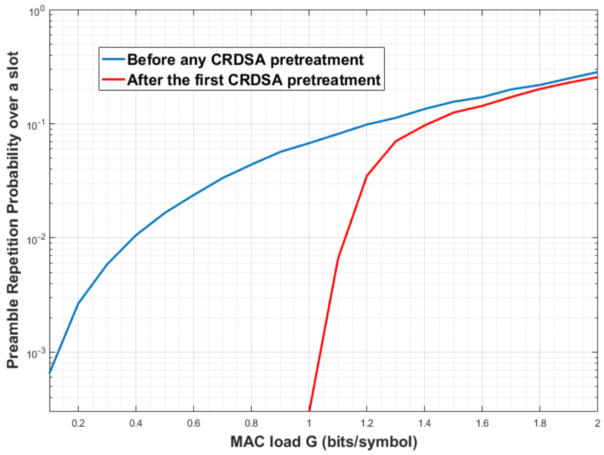

Fig. 9. Probability of having at least more than one packet with the same preamble on the same time slot before and after CRDSA preprocessing, 100 slots per frame.

(three gold codes on each slot), the user preamble detection probability is equal to 1. This is valid in both scenarios when only one of the replicas preamble peaks is necessary for detection or when both of them should be detected. It means that the preamble detection probability in this case matches the packet decoding probability we fixed at 0.98.

VI. SIMULATION AND RESULTS

We have considered that packets payloads are built from 100 information bits with QPSK modulation and rate-1/3 Turbo coding. The packet is shaped with a square root raised cosine (SRRC) filter and we assume the channel model is an AWGN with an E_S/N_0 of 10 dB. Gold pseudo-orthogonal sequences of length 31 are used as preambles. 2000 users are considered to potentially transmit over the same frequency.

Random SPOTiT is best applied, as for MARSALA, accompanied by CRDSA. Assuming we have perfect channel estimation, Fig. 6 and Fig. 8 display the performance of Random SPOTiT with two replicas per packet in terms of PLR and throughput in comparison to CRDSA and MARSALA-2. When the only preamble detection based method is used to decode a packet, both preambles shall be detected. As a result, a throughput of 1.5 bits/symbol is reached while MARSALA attains 1.63 bits/symbol. In this case no data localization correlations are necessary for Random SPOTiT. Nevertheless, performance can be enhanced when the shared information characteristic and the detected preambles are considered to perform data localization correlations. Indeed, only one detection of the two preambles of the same packet is required to perform data correlations over the second replicas positions of potentially collided packets having the same detected preamble. Considering the decoding result from previous CRDSA and Random SPOTiT iterations, potential collided packets that have been decoded will be removed from the correlations to perform.

Fig. 7 describes the average number of localization correlations needed to decode a packet in MARSALA-2 and Random SPOTiT. Data localization correlations for a packet decoding are performed only once at the first analysis by Random SPOTiT or MARSALA-2; assuming all positions are visible from the first analysis. This can be justified by the fact that a correlation over a whole slot is long enough, hence false alarms can be dismissed. Thus, when at least one of the replicas preamble is detected in its respective position, Random SPOTiT reaches a throughput of about 1.6 bits/symbol with a negligible data localization correlation that goes up to about 0.3 with a MAC load of 2 bits/symbol (see Fig. 7). As mentioned before, the number of localization correlations depends on the MAC load and thus on the potential collided packets with the same preamble on the same slot. However, CRDSA preprocessing, allowing to decode a certain number of packets, reduces this number. Especially since once a packet is decoded in SPOTiT, CRDSA is unblocked and can therefore attempt to decode other packets. The probability of having at least more than one packet with the same preamble on the same slot, before and after the first CRDSA preprocessing is illustrated in Fig. 9 with frames of 100 slots. In low MAC loads, and after one preprocessing, CRDSA decoding considerably reduces $N_{pot}^{Ref}(p)$. It joins progressively the probability of occurrence of $N_{pot}^{Ref}(p)$ in high loads until throughput collapses around 1.7 bits/symbol. As a result the number of data correlations when at least one preamble is detected is insignificant compared to MARSALA that has a mean of 85 data correlations at a load of 2 bits/symbol. In other words, localization complexity is reduced by a factor of 283.

Random SPOTiT can reach the same performance as MARSALA with extra data correlation localization in the case where none of the replicas preambles are detected. As a matter of fact, on each slot, potential undetected preambles and all possible packets using these preambles are exploited along with the previous decoding result. Data localization correlations are then performed over the second replicas positions of the potentially collided packets having the same preamble on the reference time slot. In this case, performance of Random SPOTiT remains the same in terms of PLR and throughput as in MARSALA-2. This is true regardless of the number of subscribers and how replicas are placed on the frame. Indeed, a static arrangement based on fixed seeds or a dynamic one is the same. This means that the probability of having repetitive loops on successive frames remains very low. Data correlations in this case attain a value of 5.5 while MARSALA reaches a value of 85. This means that localization complexity is reduced by a factor of 15.5 approximatively.

VII. CONCLUSION AND FUTURE WORK

This paper proposes Random SPOTiT as an alternative solution to MARSALA, which is less complex in terms of data correlations required to localize replicas. We have seen that with a complete random processing using PRNG static or dynamic seeds to choose time slot positions and preamble, it is possible to the receiver to have a prior knowledge on the potential frame composition. This includes replicas positions and the preamble used by each user. However, the receiver is not aware of whom among all the potential users have their data transmitted on the analyzed frame. Therefore, the pseudo-orthogonal property of preambles is used to reduce the number of potential users. Random SPOTiT can either rely on the only preamble detection based method to locate packets replicas or apply data correlations. The latter would be applied over the time slots that have potentially one of the packets replicas with the same detected preambles. We resort to data correlations only when the first alternative fails. Random SPOTiT offers the same performance in terms of PLR and throughput as MARSALA-2 with less complexity.

Nevertheless, the PLR floor in low network loads still persists because of the high probability of loops occurrence in comparison to a higher number of replicas system. In future work, we will analyze a smart version of SPOTiT with a no-loop packets positioning on the frame. Another aspect to be addressed is the use of the shared information to enhance preamble detection and the related complexity.

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