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A Multi-Replica Decoding Technique for Contention Resolution Diversity Slotted Aloha

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Abstract—This paper proposes a new method for data reception over a random access channel in a satellite communication system. The method is called Multi-replica decoding using correlation based localisation (MARSALA). It uses the same transmission scheme as in Contention Resolution Diversity Slotted Aloha (CRDSA) where each user sends several replicas of the same packet over the frame. MARSALA is a new decoding technique that localises all the replicas of a packet using a correlation based method, then combines them to decode the data. With MARSALA, the system can achieve a normalized throughput higher than 1.2, resulting in a significant gain compared to CRDSA, while adding a relatively low implementation complexity at the receiver. We also highlight on the practical issues related to channel estimation and how to perform coherent signal combination in MARSALA.

I. INTRODUCTION

Recent random access (RA) methods used in satellite communications have the potential to enhance resource usage and reduce communication delays over a satellite return link. However, a main challenge of RA protocols is to deal with superimposed signals arriving simultaneously at the receiver. In fact, the information loss due to signals collision is the principal cause of throughput decrease in any wireless communication. To handle this problem, recent RA methods use Physical Layer Network Coding (PNC) [1] and Successive Interference Cancellation (SIC).

Among these methods we cite Contention Resolution Diversity Slotted Aloha (CRDSA) [2]. CRDSA has been proposed by the European Space Agency (ESA) and has been adopted by the DVB-RCS2 standard [3]. In CRDSA, each user sends two replicas of the same packet on random time slots on the frame. Each replica contains signalisation information used to localise its copy. If all the users have transmitted packets with equal power, only collision-free replicas can be decoded successfully at the receiver. Once decoded, both replicas are localised and removed from the frame. This operation is called interference cancellation. Thus, the receiver can recover other packets that have been in collision. This process is repeated iteratively each time that a replica is decoded successfully. In the case of equi-powered packets, CRDSA permits to achieve a higher normalized throughput¹ ($T_{max} \simeq 0.55$) than the Diversity Slotted Aloha (DSA) [4] protocol in which the interference cancellation is not implemented ($T_{max} \simeq 0.36$).

¹The ratio of the number of successful transmissions over the number of time slots on a frame (without including the replicas).

Another variant of CRDSA, is CRDSA++ [5], where the same concept is extended to more than two replicas per packet (from 3 to 5 replicas). With equi-powered packets, and a Forward Error Correction (FEC) code of rate 1/2, the maximum throughput is obtained with CRDSA-3 (3 replicas per packet) and it is equal to 0.7. When each user transmits an irregular number of replicas on the same frame, the method is called Irregular Repetition Slotted Aloha (IRSA) [6]. If the distribution of the number of replicas is optimal, the maximum normalized throughput obtained with IRSA can reach 0.8.

Coded Slotted Aloha (CSA) [7] has been introduced later. In this method, packet segmentation and erasure coding are used in addition to PNC and SIC, but the maximum throughput achieved is equal to 0.8 which is similar to IRSA. More recently, Multi-Slot Coded Aloha (MuSCA) [8] has been proposed to further boost the maximum achievable throughput. In MuSCA, each packet is encoded with a strong FEC code of rate R . Then the code word is divided into several fragments, and a coded localisation field is added to each fragment. The decoding entity first decodes the signalisation headers then locates all the fragments on the frame. It reassembles the fragments corresponding to one code word and attempts to decode it even if the fragments are in collision. MuSCA is able to achieve a normalized throughput greater than 1.29.

The weakness in IRSA and CSA is limited throughput. MuSCA suffers from complex implementation cost. MuSCA in particular requires significant modifications to DVB-RCS2.

In this paper, we introduce Multi-replica decoding using correlation based localisation (MARSALA) as a new method enabling to increase the throughput compared to CRDSA, IRSA and CSA. With MARSALA, we can decode a packet by combining all its replicas without any additional coding needed. MARSALA does not result in any system modifications on the CRDSA transmitter side. The only implementation complexity added is at the receiver side, and it is mainly induced by the channel estimation and the correlation based localisation. Moreover, MARSALA respects the DVB-RCS2 standard. The main contributions of our work can be summarized as follows:

- We explain precisely how packet replicas can be localised on the frame using a simple correlation based technique;
- We detail how packet replicas are combined and

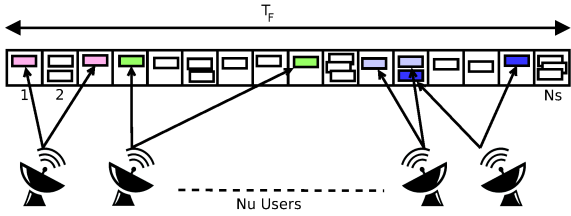


Fig. 1: System model

decoded even when they are in collision with packets sent by other users;

- We highlight on the channel estimation operations that should be done in order to ensure a good performance of MARSALA;
- We evaluate the normalized throughput achieved with MARSALA (i.e. the probability of successful packet transmission per time slot) and we compare it to CRDSA, in the case of equi-powered packets.

II. SYSTEM OVERVIEW

Fig.1 shows the system model. We consider the uplink of a wireless communication system shared between N_u users. Each user transmits N_b copies of the same packet to a destination node (a satellite or a gateway) within the duration of one frame (T_F). The frame is divided into N_s time slots. To continue to send other messages, the user must wait until the beginning of the next frame. We assume that all nodes (users and destination) operate in half duplex mode. We suppose that there is no direct link between the users. The transmission is subjected to Additive White Gaussian Noise (AWGN).

Each packet contains K bits of information. The packets are encoded with a CCSDS (Consultative Committee for Space Data Systems [9]) turbo code of rate R , which results in a code word of length K/R bits. The code word is then modulated with a modulation of order M . The payload length obtained is equal to $K/(R \cdot \log_2(M))$ symbols. Similar to CRDSA, a preamble and a postamble are added at the beginning and the end of each packet, and pilot blocks are distributed inside the packet for the purpose of channel estimation. The total packet length after modulation and coding is equal to L symbols. Before the transmission, the symbols corresponding to each packet enter a shaping filter with a square root raised cosine function, with an oversampling rate Q .

We suppose that the receiver memorizes N_s time slots, then launches the CRDSA decoding process. Once CRDSA comes to a deadlock and no packet can be decoded, the receiver proceeds with MARSALA.

III. MULTI-REPLICA DECODING USING CORRELATION BASED LOCALISATION

The proposed localisation and decoding scheme for MARSALA operates as follows:

- 1) Localisation of N_b replicas corresponding to a same packet;
- 2) For each set of N_b localised replicas:

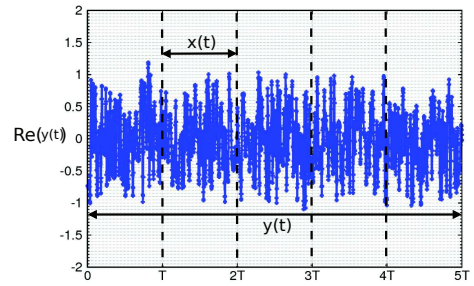


Fig. 2: Example of $x(t)$ and $y(t)$ on a frame of 5 slots

- Estimation and correction of the following parameters: timing offsets, clock drifts, frequency and phase offsets, signal amplitude;
 - Combination of the N_b replicas with corrected parameters;
 - Decoding of the packet.
- 3) Interference cancellation.
 - 4) Come back to (1).

A. Replicas Localisation

The localisation entity at the receiver allows to localise all replicas corresponding to a same packet on the received frame. This operation is based on signal correlation. First, the receiver identifies a time slot containing interfered packets and refers to it by TS_k , where k is an integer index ($k \in [1, N_s]$). It uses the signal received within this slot as a reference signal noted by $x(t)$, with $t = [(k-1)T, (k-1)T + \frac{T}{Q}, \dots, kT]$, denoting the time vector, and T being the duration of one time slot. In other words, $x(t)$ is the sum of all signals transmitted on TS_k .

Then, the receiver computes the correlation between $x(t)$ and the signal received on the rest of the frame, noted by $y(t)$. An example of $x(t)$ and $y(t)$ is given in Fig.2, where $k=2$, i.e. $x(t)$ is the signal received on the second time slot. The correlation result presents a number of correlation peaks which depends on the number of users that have transmitted a replica on TS_k . A correlation between signals on two slots is considered as a peak if the correlation amplitude is above a defined threshold. Finally, the correlation peaks are used to identify all time slots TS_m , ($m \in [1, N_s]; m \neq k$), that contain at least a packet replica of one of the packets transmitted on TS_k .

This step constitutes the main difference between MARSALA and the different versions of CRDSA. MARSALA facilitates localization of replicas without having to decode the signalling information. In other words, the correlation peaks detected are used to identify the time slots containing the replicas of the same packet.

B. Channel parameters estimation and adjustment

In real transmission conditions, the replicas sent by the same user experience different channel impairments because they are sent on different time slots of the frame. In this paper, we suppose that the varying channel parameters for one user from one time slot i to another are the clock drift $\Delta\tau_i$ and the phase offset ϕ_i . We suppose that the timing offset τ and

the frequency offset Δf remain constant for one user over the duration of a frame.

Once the receiver localises the replicas of a packet on the frame, it performs signal summation (Section III-C). But, in order to ensure a coherent signal summation, the receiver has to compensate the channel impact on the corresponding signal on each time slot.

First, the receiver estimates the channel parameters relative to the localised packet replicas, that vary from one time slot to another. The receiver computes $\Delta\tau_i$ and obtains the optimal sampling time for the localised replica on time slot i . To realize this operation, a classical algorithm for timing recovery like the algorithm of Oerder and Meyr [10] can be applied.

After the clock drift computation, the receiver estimates the phase offset ϕ_i . A phase estimator like the Viterbi estimator [11] can be used. Once the estimation is done, it corrects the phase of each replica before the summation.

At the end of these operations, we obtain N_b signals corresponding to the replicas of the same packet, which are coherent in terms of timing and phase. Thus, the receiver can proceed with signal combination as explained in the following subsection.

C. Signal Combination

At the output of the channel estimation and adjustment entity, we obtain N_b coherent signals corresponding to N_b replicas of the same user. Each signal is interfered by different users. The receiver performs the combination of these N_b signals. The power P_{eq} of the obtained signal is

$$P_{eq} = P(s_1 + s_2 + \dots + s_{N_b}) + P(I_1 + I_2 + \dots + I_{N_b}) + \sum_{i=1}^{N_b} N_0, \quad (1)$$

where s_1, s_2, \dots, s_{N_b} each denotes the signal relative to the replica of a same packet after phase and timing correction, I_1, I_2, \dots, I_{N_b} represent the interference signals on the combined time slots and N_0 is the power spectral density of AWGN. Given that the signals s_1, s_2, \dots, s_{N_b} contain the same information and are coherent in phase and timing, while interference and noise are incoherent, we can write

$$\begin{aligned} P_{eq} &= P(N_b s_1) + \sum_{i=1}^{N_b} P(I_i) + \sum_{i=1}^{N_b} N_0, \\ &= N_b^2 P(s_1) + \sum_{i=1}^{N_b} P(I_i) + N_b N_0. \end{aligned} \quad (2)$$

The goal is to obtain an equivalent Signal to Noise plus Interference Ratio (SNIR) for a localised set of N_b replicas after signal combination, higher than the SNIR for one interfered replica without signal combination. Once the signals are combined, the rest of the channel parameters are estimated (A and Δf), and the receiver attempts to demodulate and decode the useful signal. If the last step is successful, the receiver performs interference cancellation, and removes the decoded packet from the corresponding time slots on the frame.

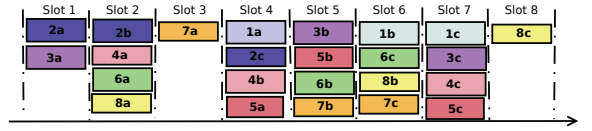


Fig. 3: A frame with 2 clean packets, $N_s = 8$ slots, $N_u = 8$ users, and $N_b = 3$ replicas per user

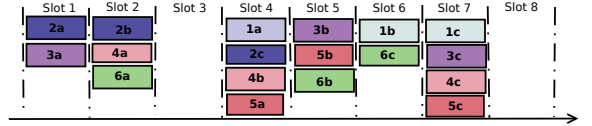


Fig. 4: The frame after cancellation of clean replicas

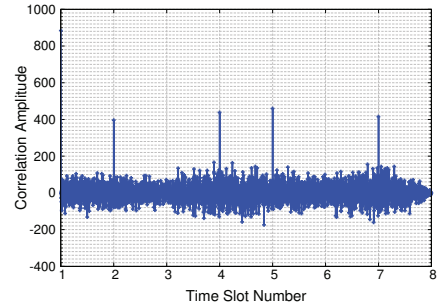


Fig. 5: Correlation of the signal received on TS_1 and the rest of the frame

IV. NUMERICAL EXAMPLE

Fig.3 illustrates an example of a received frame, where $N_s = 8$ time slots, $N_u = 8$ users and $N_b = 3$ replicas per packet. The modcod used is QPSK 1/2 and all the packets are transmitted with equal power. The received packets are affected by random phase and frequency offsets. For each user, the phase offset ϕ has a value between 0 and 2π and it is supposed to change randomly from one slot to another. The frequency offset Δf is different for each user but it is considered to remain constant on the duration of one frame. Δf can have a value between 0 to 1% of the symbol rate $1/T_s$.

At the receiver, the frame is scanned. The packets $7a$ and $8c$ transmitted by users 7 and 8, on time slots 3 and 8 respectively, are decoded successfully because they are clean packets. Then, they are removed from the frame as well as their replicas ($7b, 7c$) and ($8a, 8b$). After the interference cancellation, the new frame configuration is shown in Fig.4. All the remaining replicas are in collision. Given that all the packets are equipowered, this situation is a deadlock for CRDSA++ and IRSA. The decoder proceeds with MARSALA in order to attempt to decode the other packets.

The receiver identifies time slot 1 (TS_1) as a reference time slot. In Fig.4, TS_1 contains two packets ($2a$) and ($3a$) relative to user 2 and user 3, respectively. Their copies are received on the other time slots of the frame as follows: ($2b$) on TS_2 , ($2c$) on TS_4 , ($3b$) on TS_5 and ($3c$) on TS_7 .

The objective is to localise the replicas of the packets transmitted on TS_1 over the rest of the frame. The localisation

entity computes the correlation of the signal received on TS_1 ($x(t)$) with the signal received on the rest of the frame ($y(t)$). The signals $x(t)$ and $y(t)$ can be written as

$$x(t) = s_2(t)e^{j(\phi_2+2\pi\Delta f_2t)} + \underbrace{s_3(t)e^{j(\phi_3+2\pi\Delta f_3t)} + n_1(t)}_{w(t)} \quad (3)$$

$$y(t) = \underbrace{s_2(t-d_2)e^{j(\phi'_2+2\pi\Delta f_2t)} + s_2(t-d_4)e^{j(\phi''_2+2\pi\Delta f_2t)} + s_3(t-d_5)e^{j(\phi'_3+2\pi\Delta f_3t)} + s_3(t-d_7)e^{j(\phi''_3+2\pi\Delta f_3t)} + s(t)}_{n(t)} \quad (4)$$

where s_2 and s_3 are the signals corresponding to the packets sent by user 2 and user 3 respectively. ϕ_i , ϕ'_i and ϕ''_i denote the phase offsets of the first, second and third replica sent by user i . Δf_i refers to the frequency offset and d_i represents the position, in symbol period, on the i^{th} time slot of the frame. $n_1(t)$ is the additive white gaussian noise on TS_1 .

First, we focus on the signal sent by user 2. The same evaluation is done for user 3. In Eq. (5) and Eq. (6), we express $x(t)$ and $y(t)$ in function of the signal sent by user 2, $w(t)$ and $n(t)$.

$$x(t) = s_2(t)e^{j(\phi_2+2\pi\Delta f_2t)} + w(t) \quad (5)$$

$$y(t) = s_2(t-d_2)e^{j(\phi'_2+2\pi\Delta f_2t)} + s_2(t-d_4)e^{j(\phi''_2+2\pi\Delta f_2t)} + n(t) \quad (6)$$

The correlation $R_{Y,X}$ between $x(t)$ and $y(t)$ in the time domain can be written as follows

$$\begin{aligned} R_{Y,X}(\tau) &= \int_t y(t)x^*(t-\tau)dt \\ &= \int_t s_2(t-d_2)e^{j(\phi'_2+2\pi\Delta f_2t)} s_2^*(t-\tau)e^{-j(\phi_2+2\pi\Delta f_2(t-\tau))} \\ &+ \int_t s_2(t-d_4)e^{j(\phi''_2+2\pi\Delta f_2t)} s_2^*(t-\tau)e^{-j(\phi_2+2\pi\Delta f_2(t-\tau))} \\ &+ R_{n,s_2} + R_{n,w} + R_{s_2,w} \end{aligned} \quad (7)$$

With $R_{n,s_2} + R_{n,w} + R_{s_2,w}$ being the sum of the cross correlations between the uncorrelated terms in $x(t)$ and $y(t)$. For user 2, the peak amplitudes of $R_{Y,X}(\tau)$ are obtained for $\tau = d_2$ and $\tau = d_4$. The same evaluation is done for user 3. The correlation amplitudes obtained are illustrated in Fig. 5. The positions of the correlation peaks show that time slots 2, 4, 5 and 7 contain replicas of the packets present on TS_1 .

In order to identify which time slots correspond to the set of replicas sent by the same user, each signal received on a time slot detected by a correlation peak, is correlated with the other time slots detected.

As explained in Section III-B, once the replicas are localised, the receiver estimates the following channel parameters for user 2: the clock drifts $\Delta\tau_2$ and $\Delta\tau_4$ as well as the phase offsets ϕ_1 , ϕ_2 and ϕ_4 (see Fig.6). Then it performs parameters correction on the three replicas. Finally, it obtains three coherent signals to be combined and decoded. In the rest of the numerical example, we suppose that the parameters correction is perfect so the combined replicas are coherent in timing and phase.

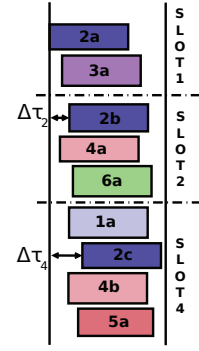


Fig. 6: Reception of packet replicas of user 2 with a timing offset $\tau = 0$ and a clock drift $\Delta\tau_i$ on each time slot i

Let us consider the following scenario for user 2. We suppose that the power of the interference term I_i is equal to the power of the signal sent by user 2 ($P(I_i) = P(s_2)$). User 2 uses a Quadrature Phase Shift Keying (QPSK) modulation and a turbocode with a coding rate $1/2$. The AWGN has the same power spectral density N_0 on the entire frame duration. The Signal to Noise Ratio for user 2 ($SNR = \frac{P(s_2)}{N_0}$) is supposed to be equal to 2 dB.

With the numerical assumptions considered, the SNIR for user 2 on each localised time slot i , can be written as

$$SNIR_{2,i} = \frac{1}{1 + \left(\frac{P(s_2)}{N_0}\right)^{-1}} (dB) = -2.12 \text{ dB}. \quad (8)$$

Given that user 2 uses a modcod QPSK $1/2$, the Packet Error Rate (PER) on each time slot i is equal to 1 when the $SNIR$ is equal to -2.12 dB. After combining the 3 replicas of user 2, the equivalent SNIR becomes

$$\begin{aligned} SNIR_{eq} &= \frac{N_b^2 P(s_2)}{\sum_{i=1}^3 iN_0 + iP(I_i)}, \\ &= \frac{3}{1 + \left(\frac{P(s_2)}{N_0}\right)^{-1}} (dB) = 2.64 \text{ dB}. \end{aligned} \quad (9)$$

The PER obtained with a modcod QPSK $1/2$ at 2.64 dB is lower than 10^{-5} . Then, after signal combination, the signal sent by user 2 can be demodulated and decoded successfully.

V. SIMULATION RESULTS

To evaluate the performance in terms of throughput of MARSALA, we realized simulations and compared the results with the throughput obtained by CRDSA. In our simulations, we supposed that all the packets are transmitted with equal power. The channel SNR is the same for all users. To take the same assumptions as in CRDSA analysis, we considered that the channel estimation and the interference cancellation are ideal. We also assumed that the combined replicas are coherent in timing and phase.

In the simulations, we still considered a frame composed of N_s time slots with N_u users attempting to transmit replicas

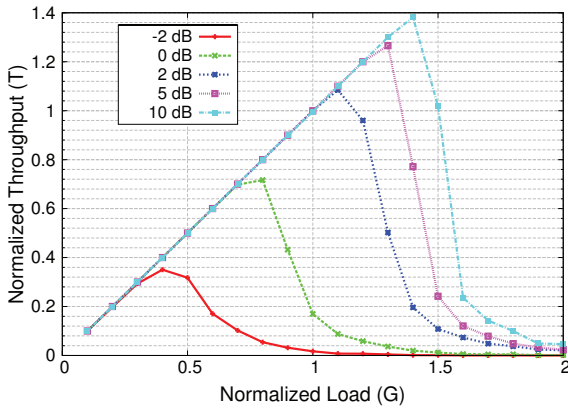


Fig. 7: T vs G with MARSALA-3 for different values of E_s/N_0 ; modcod=QPSK 1/2, $N_s = 100$ slots

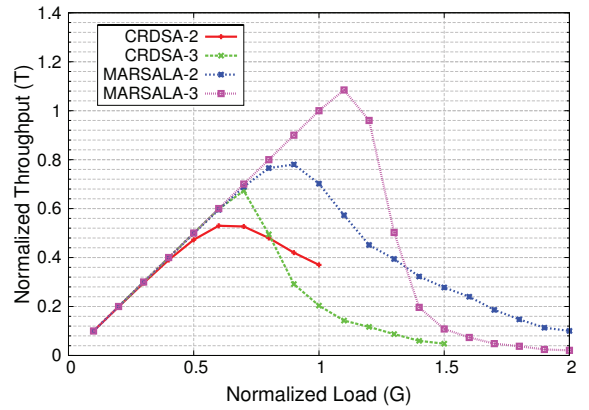


Fig. 8: T vs G with CRDSA-2,-3 and MARSALA-2,-3; modcod=QPSK 1/2, $E_s/N_0 = 2$ dB, $N_s = 100$ slots

within a frame duration. The normalized load (G) is:

$$G = \frac{N_u}{N_s}, \quad (10)$$

and the normalized throughput (T) is given by:

$$T = G * (1 - PLR(G)), \quad (11)$$

where PLR(G) is the probability that a packet is not decoded for a given G and a given SNR. To ease the recognition of several MARSALA and CRDSA versions, we denote MARSALA-2 and CRDSA-2 the MARSALA and CRDSA systems where each user transmits 2 replicas of the same packet. The same notation is taken for MARSALA-3 and CRDSA-3.

Fig.7 and Fig.8 give simulation results when the frame size is equal to 100 slots. The modcod used is QPSK 1/2. In Fig.7, the normalized throughput curves of MARSALA-3 are presented. For each studied SNR, we vary the normalized load in order to maximize the normalized throughput. We observe that, for a relatively low SNR (0 dB), MARSALA allows us to reach a throughput up to 0.7. For a higher SNR, the peak of throughput continues to increase and reaches the highest value of 1.4 at an SNR equal to 10 dB.

In Fig.8, we compare the performance in terms of normalized throughput between MARSALA and CRDSA, both with an SNR equal to 2 dB. The chosen SNR is close to the modcod ideal SNR. We can notice that the gain between the two methods is significant. The maximum normalized throughputs of MARSALA-2 and 3 are 0.8 and 1.1, respectively, while the throughput achieved by CRDSA is 1.5 times lower.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have presented MARSALA, as a new decoding technique for CRDSA. MARSALA has proposed a solution to the deadlock problem of CRDSA, by doing simple correlation operations over the received frame, and signal summation over the time slots containing packet replicas. With the simulation assumptions considered, MARSALA has proven to achieve a higher throughput than CRDSA with a modcod QPSK 1/2. In future work, we will evaluate the effect of imperfect correction of phase and timing when the replicas

of a same user are combined. Later, we will also study the gain of MARSALA with other modcods like QPSK 1/3 and higher order modulations like 8PSK and 16PSK, as well as power unbalanced packets. Furthermore, We will consider the case where MARSALA is combined to IRSA, and thus makes use of different numbers of packet replicas for each user. Then, the optimal distribution functions for the number of replicas in irregular MARSALA will be designed.

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