Generalized Encoding CRDSA: Maximizing Throughput in Enhanced Random Access Schemes for Satellite

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Abstract. This work starts from the analysis of the literature about the Random Access protocols with contention resolution as Contention Resolution Diversity Slotted Aloha (CRDSA) and introduces a possible enhancement, named Generalized Contention Resolution Diversity Slotted Aloha (GE-CRDSA). The GE-CRDSA aims to improve the aggregated throughput when the system load is less than 50%, playing on the opportunity of transmitting an optimal combination of information and parity packets frame by frame.

Keywords: Satellite, Interference Cancellation, DVB-RCS2, CRDSA, Slotted Aloha.

1 Introduction

Many efforts have been made in the field of random access protocols for satellite communications, aiming to maximizing the aggregated throughput. Contention Resolution Diversity Slotted Aloha (CRDSA) [1] in the forthcoming DVB-RCS2 standard [2] and in general all the variants of Slotted Aloha (SA) protocols, which take advantage of contention resolution (CR), are clear examples of the strong interest in such results.

The advantage of this technique is represented by the increment of the performance in terms of throughput: in fact, CRDSA exhibits almost ideal performances (i.e low collision losses), up to 50-60% of the global access network load, in case of ideal power control [1]. Both CRDSA and SA assume the MAC frame duration equal to T_F, during which N_s slots are allocated. Then the time slot has duration $T_S = T_F/N_s$. Assuming that at each frame M users try to transmit data packets, each user transmits one or more replicas of the same packet in the current MAC frame. In each packet a pointer to the positions of its replicas is included. The pointer is used to locate its own other replicas into the frame and to remove the interfering ones in the collided slots. The contention resolution proceeds iteratively, by removing the decoded signals in the relative collided slots. At the end of the procedure the Packet Loss (P_L) due to the un-cancelled collisions is significantly reduced. By definition, the throughput is given by:

$$T = G(1 - P_L) \tag{1}$$

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where for given number of stations M and number of time slots N_s, the constant $G = \frac{M}{N_s}$ is the average number of packet transmission attempts per frame, i.e., the average load of the system, when a single information packet is transmitted per station per frame. In the SA is the probability that no others attempts of transmission arises during a time slot. This value can be calculated through the Poisson distribution at $k = 0$:

$$P(k) = G^k \frac{e^{-G}}{k!} \xrightarrow{k = 0} e^{-G}$$

Let G^* be the supremum of G such that, in the asymptotic setting $M \rightarrow \infty$, the throughput T fulfills $T = G$; therefore G^* is the asymptotic peak throughput. In the SA the maximum throughput $T_{SA}^{max} = G^* e^{-G^*} = \frac{1}{e}$ is achieved at $G^* = 1$. In CRDSA, reducing P_L at a given G value leads to a throughput gain with the respect to SA and its non-SIC variants[1]. This improvement is quantified in [1] as the normalized throughput $T_{CRDSA} \approx 0.55$, which is the probability of successful packet transmission per time slot, whereas the peak throughput for SA is $T_{SA} \approx \frac{1}{e}$. Further improvements can be achieved by exploiting the capture effect [4,5]. In [6] Irregular Repetition Slotted ALOHA (IRSA) was introduced to provide a further throughput gain over CRDSA. Higher throughput can be achieved by IRSA, allowing the satellite terminal (ST) to choose the number of replicas in a random way. As stated in [6], CRDSA and further improvements such as CRDSA++ can be considered as particular cases of IRSA where the repetition rate, frame by frame, is fixed. In [7] is shown that a variable repetition rate does not introduce significant improvements in terms of throughput, if N_s is limited to a few hundred of slots i.e., in the range foreseen in DVB-RCS2 standard [2]. $T_{IRSA} \leq 0.8$ is obtained in [6], when Ns is around 200. While CRDSA, CRDSA++ and IRSA are based on repetitions, Coded Slotted ALOHA (CSA) encodes the bursts of each user before transmitting [8].

All the methods presented above implicitly impose that the average load in the system is targeted around the G^* value, otherwise any improvement is appreciable. A centralised load control should reduce/increase Ns, according to the actual estimation of the average number of STs, which try to access to the channel. Since Ns in DVB-RCS2 standard is bounded between 64 and 128 slots [2], the satellite system may perform at G loads under the desired G^*, leading to the under-utilization of the available bandwidth. For example, according to (1), if P_L is negligible, it results that $T \approx G$. In CSA, the transmitted burst is made up of $k = 2$ information packets out of n transmitted packets. The others $r = n - k$ packets are generated by a packet-oriented binary linear block code.

This work aims at studying a generalized case of CSA, named Generalized Encoding CRDSA (GE-CRDSA), where each ST randomly sorts the $\{k, r\}$ pair, according to the relative probability distributions - described in the following - that generate the code (n, k). GE-CRDSA aims at optimizing CSA, by allowing each ST to transmit more than two information packets per frame, by reducing the queuing delay with the respect to those systems, which consider only a single information packet per frame.

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[1] DSA [3] with two or more replicas for each information packet transmission.

2 System Overview

Let us consider a SA system, with a MAC frame duration of T_F, composed of N_s slots. Let be m_i a Poisson distributed r.v. of mean λ, which represents the number of active STs out of M terminals at frame i. Let us define:

$$G = \frac{\lambda \, \overline{k}}{N_s}$$

being G the system load and $\overline{k}$ the average number of information packets that STs transmit in a frame. Let $p_k\{\Omega_i\}$ be the probability distributions of the number of information packets k and $p_r\{\Psi_j\}$ the probability distributions of the number of parity packets r transmitted for a given frame, respectively. At any frame, a ST randomly sorts the $\{k, r\}$ pair, according to the probability distributions defined above. Hence, the number of information k and parity r packets sent by an active ST in a frame can be represented by the polynomials:

$$\Omega_k(x) \triangleq \sum_i \Omega_i x^i \tag{2}$$

$$\Psi_r(x) \triangleq \sum_j \Psi_j x^j \tag{3}$$

where the weights Ω_i and Ψ_j are the probability of having i information packets and j parity packets, respectively. From (2) and (3) the average information length $\overline{k}$ and the average parity length $\overline{r}$ are respectively given by the following equations:

$$\overline{k} = \sum_i i\Omega_i = \Omega'(1), \qquad \overline{r} = \sum_j j\Psi_j = \Psi'(1)$$

The Satellite Master Control Station shall account for monitoring the average system load and to communicate the weight vectors $\boldsymbol{\Omega}$ =$\{\Omega_i\}$ and $\boldsymbol{\Psi}$ =$\{\Psi_i\}$ at each load variation. The optimal choice of the load vectors $\boldsymbol{\Omega}$ and $\boldsymbol{\Psi}$ is not trivial and the optimization problem is not addressed in this manuscript. However, some considerations are presented in the section 4.

3 Numerical Results

In the previous section we have introduced the mathematical framework behind the GE-CRDSA. The algorithm allows the users to choose randomly the number of information packets as well as the number of parities from the probability distributions $p_k\{\Omega_i\}$ and $p_r\{\Psi_j\}$, respectively. In this section some simulation results are presented, showing how the choice of the $\{k, r\}$ pair affects the throughput and the packet loss at different

Table 1. Simulation parameters for the case study

Parameter	Value
Bandwidth	8 Mhz
Modulation	QPSK
Phy FEC	3GPP 1/3
Frame Duration	0.0202s
N_s (slots)	100÷1000
IC iterations[2]	20

G values. Matlab [9] has been used as simulation environment. System and simulation parameters are summarized in Table 1.

According to section 2, we estimated the aggregated throughput and the relative packet loss for each load G/k by changing exhaustively the coding rate, i.e. considering all the possible combinations of the couple $\{k, r\}$ up to $n_{max} = r + k <=10$ that could be randomly extracted from the probability distributions $p_k\{\Omega_i\}$ and $p_r\{\Psi_j\}$, respectively.

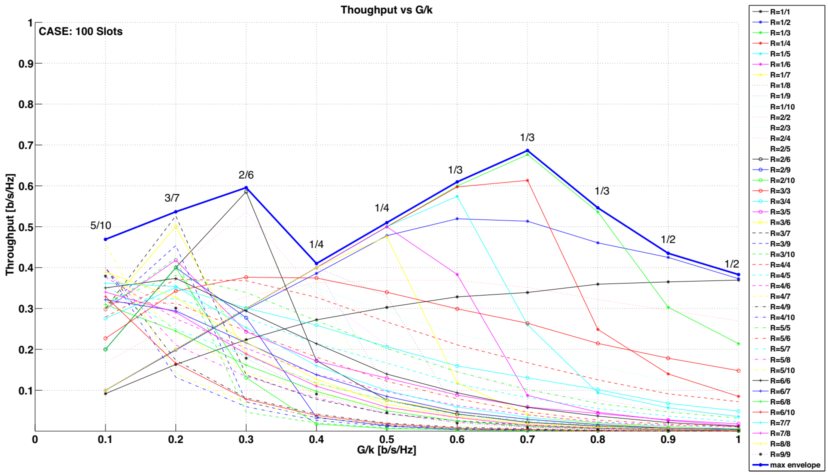

Fig. 1. Throughput vs G/k (N_s=100)

Figure 1 shows the throughput for all the different (n, k) pairs with respect to the ratio between the normalised offered load G and information length k. The most significant curve is the maximum envelope, which reports, for any G/k value, the k/n ratio

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[2] The interference cancellation (IC) process performs several iterations in order to recover the maximum number of packets in each frame. A DSA is equivalent to a CRDSA using a single iteration [6]. Trivially, SA is for $k = n = 1$.

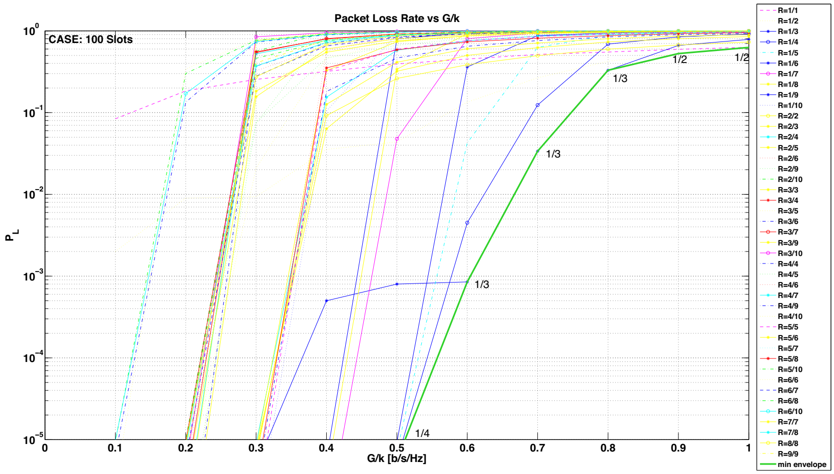

Fig. 2. Packet Loss Rate vs G/k (N_s=100)

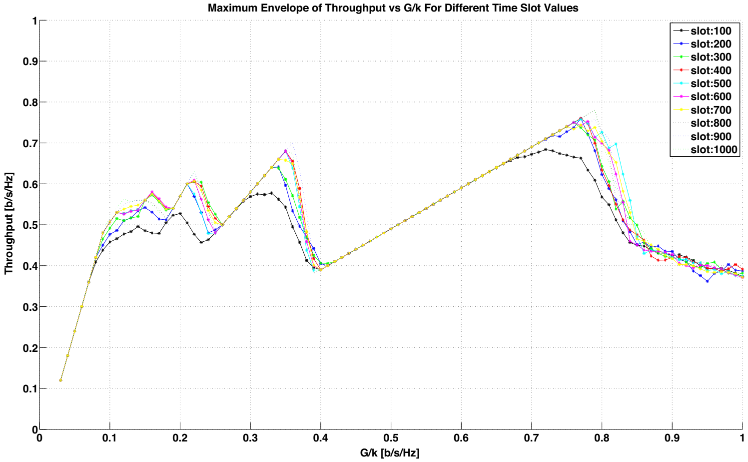

Fig. 3. Throughput vs G/k for different number of time slots

which maximises the overall system throughput. In other words, the means of distributions p_k and p_r should track the values on the maximum envelope in order to guarantee the highest throughput at every system load. In particular, GE-CRDSA reaches higher values of throughput than CRDSA *et alt.* for G/k lower than 0.4, imposing to transmit 2, 3 or more information packets per station per frame.

Figure 2 shows the packet loss rate for different (n, k) pairs used during the simulations, with respect to the ratio between the normalised offered load G and information length k. Dually, the figure also shows the minimum envelope of the packet loss rate

P_L^{min}, which corresponds to the (n, k) pair that maximises the throughput envelope in Figure 1.

According to the outcome in Figures 1 and 2, in Figure 3 we differently focus on the sole maximum envelope of the throughput, thus making N_s ranging in the interval $100 \div 1000$. The curves in Figure 3 show the expected trend, with maximum variation range that falls within 45%. Hence, changing N_s does not significantly affect the overall throughput and the k/n ratios on the max envelope remain almost the same. Therefore, the throughput can be enhanced choosing an appropriate (n, k) pair as well as the number of time slots N_s. Note that the choice of these parameters can be performed during the transmission according to a control flow policy that tracks the G^* value.

Figure 4 shows all the minimum envelopes of the packet loss rate vs. N_s.

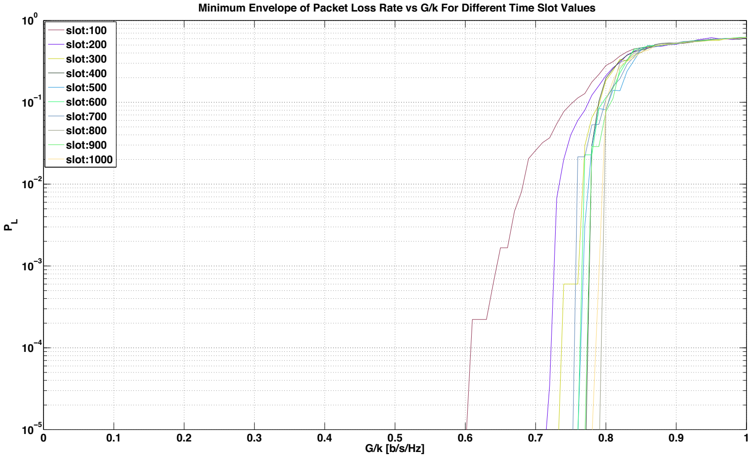

Fig. 4. Packets Loss Rate vs G/k for different number of time slots

4 Conclusions

Contention resolution algorithms have demonstrated to successfully reduce the collision probability in random access methods, renewing the application of random access for information delivery. We have shown that by increasing the mean number of information packets sent by a station at each frame, when the system load is poorly loaded, the system throughput can be significantly improved up to get the twice of that obtained with a standard CRDSA. Since this study only accounts for colliding packets with the same $SNIR$ (Signal-to-Noise plus Interference Ratio), further improvements in terms of optimal system load G^* and maximum achievable aggregated throughput can be obtained, by considering power unbalancing and capture effect. However, achieving higher loads thanks to capture effect does not impact on the rationale behind the proposed scheme and further improvements could be showed in terms of aggregated throughput. GE-CRDSA does not neglect a load control system in order to track the optimal load correspondent to the maximum achievable throughput, but it relaxes the tracking constraints over a wider range of target loads, reducing the dynamic allocation of the pool of slots dedicated to random access. In our preliminary simulations, we have provided an exhaustive evaluation of all the possible combinations of k and r in order to achieve the maximum aggregated throughput. Future work foresees the definition of an optimisation problem, in order to define a control law to extract the $\{k, r\}$ pair for a given G that maximise the aggregated throughput and to evaluate the stability of the system in a dynamic context, i.e., when G is time variant. Assuming that any station at the frame t can randomly choose the $\{k, r\}$ pair, according to the probability distributions p_k and p_r, the throughput maximisation, over all the possible values of G, can be stated as in the following.

$$\begin{aligned} &\max\{T\}_{\{\Omega_1 \cdots \Omega_k\}} \\ &\qquad\qquad \text{s.t.} \\ &\qquad\qquad r = \mathcal{G}(P_L) \\ &\qquad\qquad k + r \leq n_{max} \end{aligned} \tag{4}$$

The solution of the optimization problem (4) is the probability distribution p_k, used by the user to extract the number of information packets to transmit at the frame t. This kind of problem can be addressed through both analytical or numerical solution [10], even if the first kind of solution gives much more information about the behavior of the system. The constraints of the optimization problem are the number of parity packets chosen according to the relation between the packet loss probability and the total number of transmitted packets, and the maximum number of transmitted packets n_{max}[3] per station per frame. Note that, $r = \mathcal{G}(P_L)$ is the probability distribution p_r, which can be estimated, given set of empirical data and few features assumptions, through nonparametric density estimation techniques such as the Generalized Cross Entropy Method (GCE) [11].

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[3] Note that in case of a single terminal it would be possible at limit that $k \leq n_{max} \leq N_s$, i.e. the station occupies an entire frame.

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