The Marriage between Random Access and Codes on Graphs: Coded ALOHA for Massive Random Access

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PhD Summer School on Signal Processing for ICT
Bressanone, 7-11 Luglio 2014

Research supported in part by the EC under the FP7 grant agreement n. 288502

Background

- The problem of multiple access for a potentially very large population of users who wish to transmit over a shared communication medium is receiving an increasing attention.

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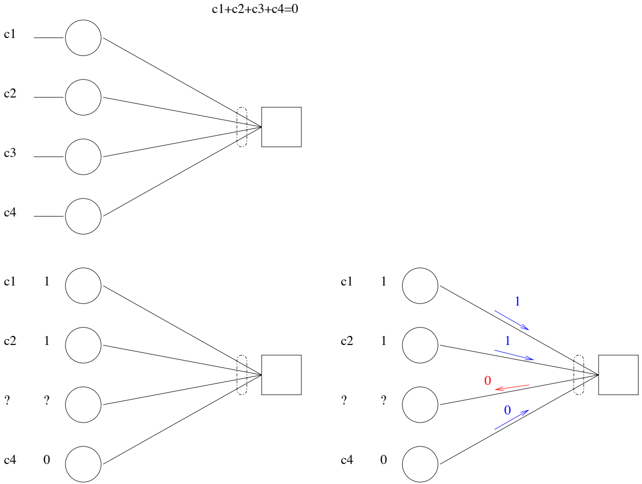
  - WSNs with a high density of sensors;
  - RF-ID systems with a high density of tags;
  - IoT applications;
  - M2M communications;
  - 5G mobile communications systems;
  - ...

Prologue

Erasure Correcting Codes



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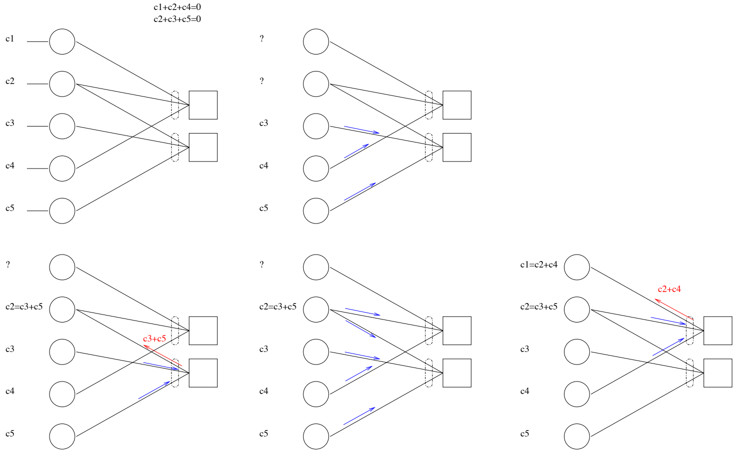
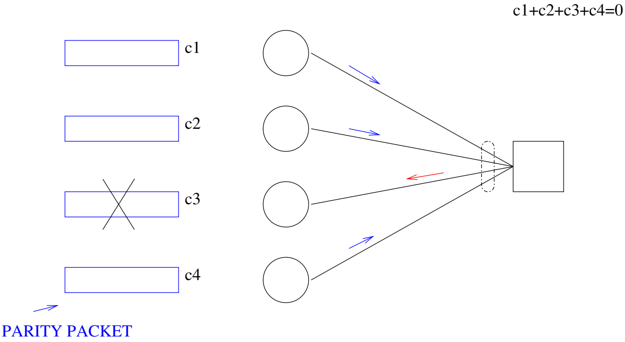


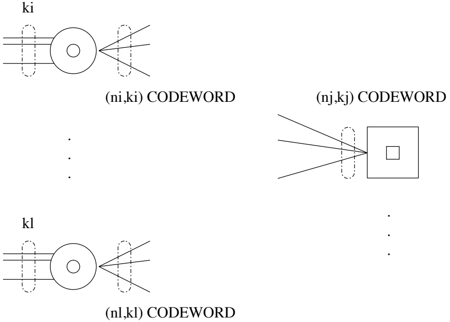
Prologue

Correcting Packets



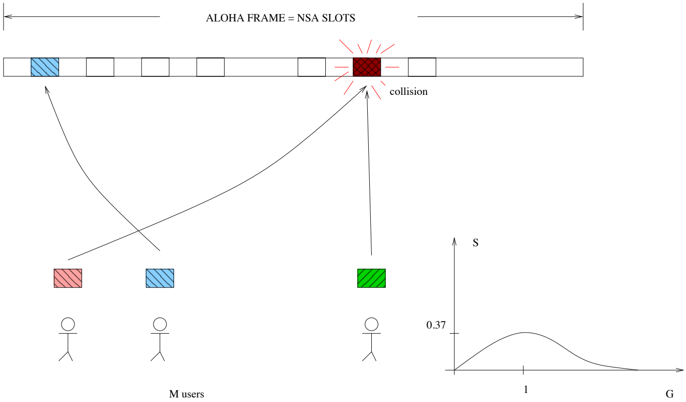
Prologue

Generalization (generalized/doubly generalized LDPC codes)



Prologue

Multiple Access: Slotted ALOHA



$$\Pr(\text{success in one slot}) = M\frac{1}{N_{SA}}\left(1-\frac{1}{N_{SA}}\right)^{M-1} \to \frac{M}{N_{SA}}e^{-\frac{M}{N_{SA}}} = Ge^{-G}$$

Summary of this talk

- Review of some modern coded random access schemes (e.g., CRDSA, IRSA, CSA) for feedback-free uncoordinated access by a large user population.
- Analytical framework to analyze the performance of coded multiple access with finite frame sizes, based on enumeration techniques.

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Background

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  - WSNs with a high density of sensors;
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  - ...
- With large number of active users, demand assignment multiple access (DAMA) protocols may become impractical.

Background

- Uncoordinated access protocols may represent an appealing solution. However ...
  - They necessarily lead to collisions among packets being transmitted by the users.
  - A collision notification mechanism may not be feasible for a large population of users and for delay-constrained applications.
  - Severe stability issues are expected with traditional random access schemes, for a large number of users wishing to access the channel.
- Recent **"modern" random access protocols** have performance close to DAMA, but supporting large number of uncoordinated users, even without retransmissions ...

Some "Classical" Random Access Schemes

- *Slotted ALOHA* (SA) [Abramson1970]: Still adopted as the initial access scheme in both cellular terrestrial and satellite communication networks.
- *Diversity slotted ALOHA* (DSA) [Choudhury1983]: Introduces a packet repetition (twin replicas) to achieve a slight throughput enhancement respect to SA at low loads.

- [Abramson1970] N. Abramson, "The ALOHA system - another alternative for computer communications," in *Proc. of 1970 Fall Joint Computer Conf.*, vol. 37, pp. 281–285, AFIPS Press, 1970.
- [Choudhury1983] G. Choudhury and S. Rappaport, "Diversity ALOHA - a random access scheme for satellite communications," *IEEE Trans. Commun.*, vol. 31, pp. 450–457, Mar. 1983.

Some “Modern” Random Access Schemes

- *Contention resolution diversity slotted ALOHA* (CRDSA) [Casini2007]: Packet repetition is combined with iterative interference cancelation.
- *Irregular repetition slotted ALOHA* (IRSA) [Liva2011]: A generalization of CRDSA that allows an irregular repetition rate.
- *Coded Slotted ALOHA (CSA)* [Paolini2011]: A generalization of IRSA in which generic linear block codes are employed by the users.
- *Constant Rate Assignment (CRA)* [Kissling2011]: An extension of CRDSA to the asynchronous (unslotted) case.
- *Frameless CSA* [Stefanovic2013]: A variant of CSA/IRSA/CRDSA in which the duration of the contention period is adaptively tuned.

- [Casini2007] E. Casini, R. D. Gaudenzi, and O. del Rio Herrero, “Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks.,” *IEEE Trans.Wireless Commun.*, vol. 6, pp. 1408–1419, Apr. 2007.
- [Liva2011] G. Liva, “Graph-based analysis and optimization of contention resolution diversity slotted ALOHA,” *IEEE Trans. Commun.*, vol. 59, pp. 477–487, Feb. 2011.
- [Paolini2011] E. Paolini, G. Liva, M. Chiani, “High throughput random access via codes on graphs: Coded slotted ALOHA,” in *Proc. IEEE ICC 2011*, Kyoto, Japan, Jun. 2011. Journal version submitted to T-IT available at http://arxiv.org/abs/1401.1626
- [Kissling2011] C. Kissling, “Performance enhancements for asynchronous random access protocols over satellite,” in *Proc. IEEE ICC 2011*, Kyoto, Japan, Jun. 2011.
- [Stefanovic2013] C. Stefanovic and P. Popovski, “ALOHA random access that operates as a rateless code,” *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4653–4662, Nov. 2013.

System Model: SA and CRDSA/IRSA

- There are M users, each attempting a packet transmission within a MAC frame of time duration T_F.
- Number of slots $N_{SA} = N_{IRSA}$, each of duration $T_{SA} = T_{IRSA} = T_F / N_{SA}$.
- Each user performs a single transmission attempt within the frame
  - either a new packet or a previously collided one if retransmissions are allowed
  - a new packet if retransmissions are not allowed - the scheme is reliable also without retransmissions.
- The normalized offered traffic (or channel traffic) is given by

$$G = \frac{M}{N_{SA}}$$

  and represents the average number of packet transmissions per slot.
- We define the normalized troughput T as the probability of successful packet transmission per time slot.

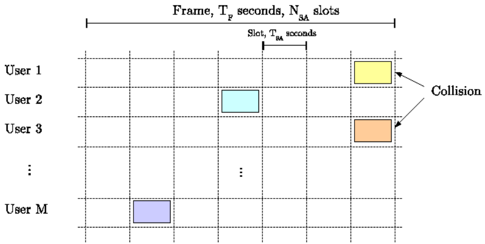
Contention Resolution Diversity Slotted ALOHA (CRDSA)

- Idea: adopt successive interference cancellation (SIC) to resolve collisions.
  - Each of the transmitted twin replicas has a pointer to the slot position where the respective copy was sent.
  - If a burst (i.e., packet) is detected and successfully decoded, the pointer is extracted and the interference contribution caused by the burst replica on the corresponding slot is removed.
  - Procedure iterated, hopefully yielding the recovery of the whole set of bursts transmitted within the same MAC frame.
- Peak normalized throughput (defined as the probability of successful packet transmission per slot):

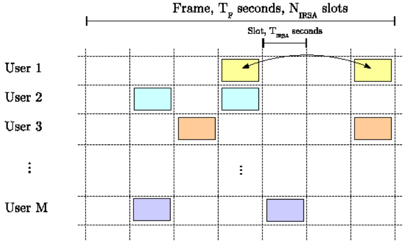
$$T \simeq 0.55$$

  versus $T = 1/e \simeq 0.37$ achieved by SA.
- Larger (by a factor of 2) average transmitted power than SA for the same peak power.

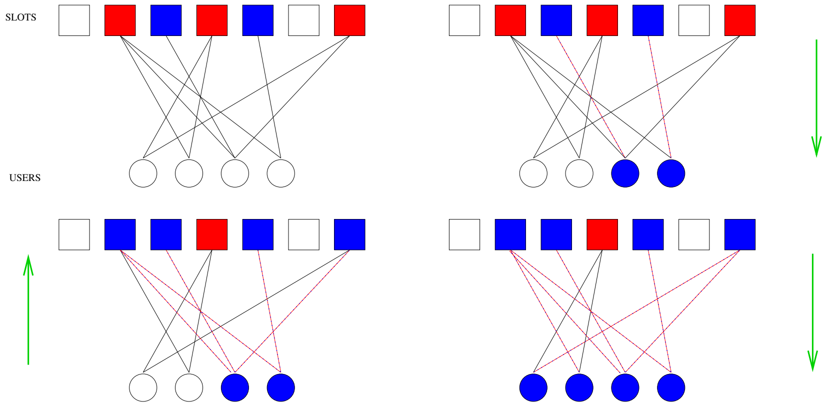
SA and CRDSA



a) Slotted ALOHA



CRDSA/IRSA and iterative decoding over graphs



IRSA

- With respect to CRDSA, a variable repetition rate for each burst is allowed.
- Letting δ_h be the fraction of time a user repeats his packet h times, the rate of the scheme is

$$R = \frac{1}{\sum_h \delta_h \, h} \leq 1/2 \, .$$

- The increment in the average transmitted power w.r.t. pure SA is $\Delta P = 10 \log_{10}(1/R) \geq 3\,\mathrm{dB}$.
- We introduce coded slotted ALOHA as a solution to obtain rates $R \geq 1/2$.

CSA: Preliminary Definitions

- We consider a framed and slotted scheme where slots are grouped in medium access control (MAC) frames, all with the same length m (in slots).
- Each slot has a time duration T_{slot}, whereas the MAC frame is of time duration T_{frame}, so $m = T_{\text{frame}}/T_{\text{slot}}$.
- We consider a large population of users, whose number is N.
- Each user is frame- and slot-synchronous.
- Neglecting guard times, the time duration of a burst is T_{slot}.
- At the beginning of a MAC frame each user generates a burst with probability $\pi \ll 1$ (activation probability).
- Users attempting the transmission within a MAC frame are referred to as active users, and users that are idle as inactive users.

CSA: Channel Load

- The number of active users is modeled by the random variable N_a, which is binomially-distributed with mean value $\mathbb{E}[N_a] = \pi N$.
- Instantaneous channel load:

$$G_a = \frac{N_a}{m} .$$

- Average channel load (expected number of burst transmissions per slot):

$$G = \frac{\mathbb{E}[N_a]}{m} = \frac{\pi N}{m} = \pi\alpha$$

where α is the population size normalized to the number of slots.

CSA: Encoding Procedure

- Each of the N_a active users divides his burst sent (duration T_{slot}) into k information (or data) segments.
- The k data segments are encoded via an (n_h, k) linear block code $\mathcal{C}_h$ generating n_h encoded segments all of the same length as the data segments.
- The (n_h, k) code is picked by the user from a set $\mathcal{C} = \{\mathcal{C}_1, \mathcal{C}_2, \ldots, \mathcal{C}_{n_c}\}$ of n_c candidate codes, all having the same dimension k. The set $\mathcal{C}$ is known to the receiver.
- Each active user draws his local code from the set $\mathcal{C}$ independently of all his previous choices and without any coordination with the other users.
- The code is picked according to a probability mass function (p.m.f.) $\boldsymbol{\delta} = \{\delta_h\}_{h=1}^{n_c}$ which is the same for all users.

CSA: Encoding Procedure

- The time duration of each transmitted segment is $T_{\text{segment}} = T_{\text{slot}}/k$. The MAC frame is composed of $M = k\,m$ slices, each of time duration T_{segment}.
- The n_h encoded segments are transmitted by the active user over n_h slices picked uniformly at random.
- Rate of the CSA scheme:

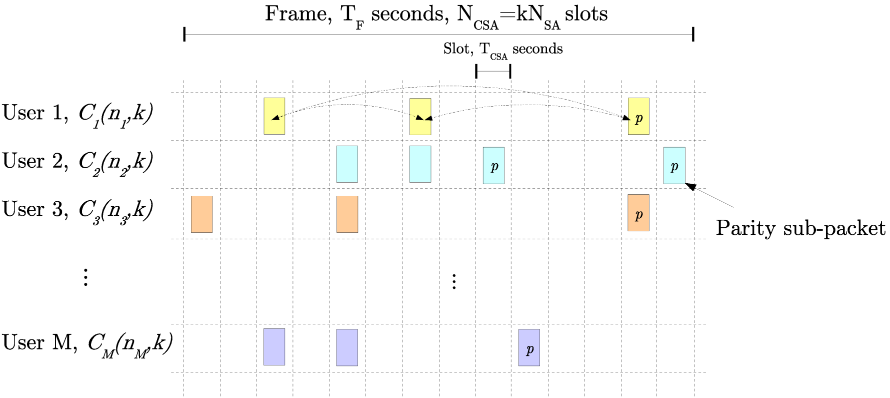
$$R = \frac{k}{\bar{n}}$$

where

$$\bar{n} = \sum_{h=1}^{n_c} \delta_h n_h \,.$$

- Increment in the average transmitted power w.r.t. pure SA is $\Delta P = 10 \log_{10}(1/R)$.
- If $\mathcal{C}$ contains only repetition codes ($k = 1$) then we obtain the IRSA scheme. Note that with CSA we can achieve $R > 1/2$.

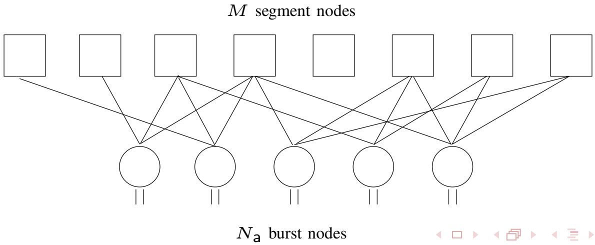
CSA: Transmission Example



c) Coded SA

CSA: Bipartite Graph Representation

- For an instantaneous population of N_a users and a frame with M slices, the frame status can be described by a bipartite graph $\mathcal{G} = (\mathcal{B}, \mathcal{S}, \mathcal{E})$.
- It consists of a set $\mathcal{B}$ of N_a burst nodes (one for each active user), a set $\mathcal{S}$ of M slice nodes (one for each slice in the frame), and a set $\mathcal{E}$ of edges.
- An edge connects a burst node $b_i \in \mathcal{B}$ to a slice node $s_j \in \mathcal{S}$ if and only if the i-th active user has transmitted an encoded segment in the j-th slice.
- Degree of a node: Number of edges connected to it.
- Example ($N_\mathrm{a} = 5$, $M = 8$, $k = 2$):



CSA: Distributions

- The component code distribution is

$$\delta(x) = \sum_{h=1}^{n_c} \delta_h x^h \,.$$

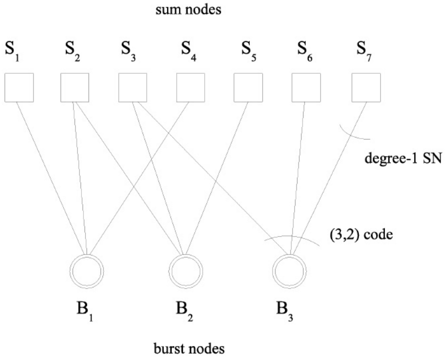
- The slice node degree distribution "from an edge perspective" is

$$\rho(x) = \sum_{i=1}^{M} \rho_i x^{i-1}$$

where ρ_i is the probability that an edge is connected to a slice node of degree i.

CSA: Decoding Example

- $N_a = 3$, $M = 7$, $k = 2$. Each user employs a $(3, 2)$ single parity-check code.



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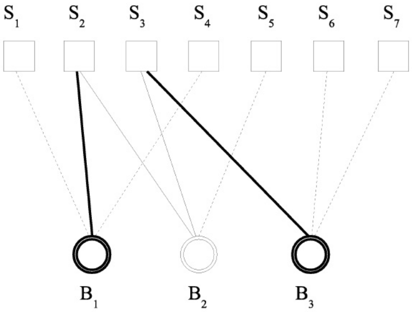

b) IC iteration 1

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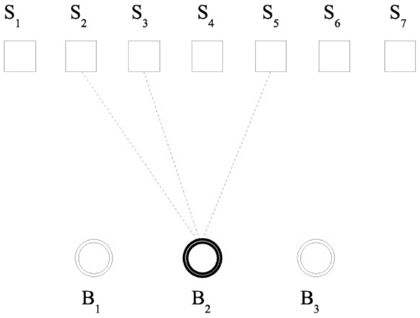
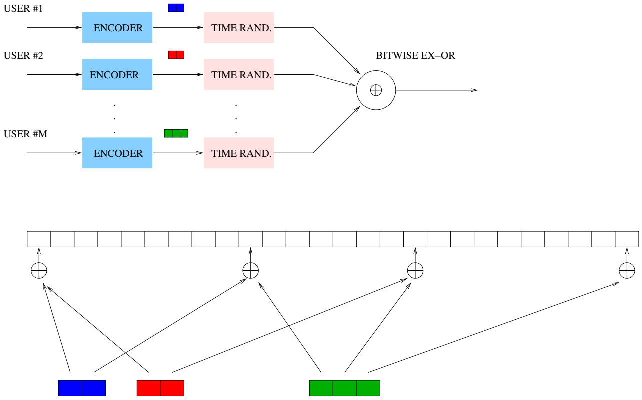


c) IC iteration 2

CSA: Simplified Channel Model

- In each slice of the MAC frame the decoder is able to discriminate between:
  - a “silence”;
  - a signal corresponding to a unique slice;
  - a “mess” being the result of a collision. (This signal provides no information to the decoder about the number and the values of colliding segments.)
- When a segment experiences no collisions, it is correctly received.
- Interference cancelation is ideal, as so is the estimation of the channel parameters necessary to perform it.
  - Cancelation of the interference contribution of a slice in a slice consists of subtracting the corresponding signal from the “mess” currently present in the slice.

CSA: The XOR Multiple Access Channel



CSA and Modern Codes on Graphs

- Under the previous assumptions, we can establish a connection with modern codes on graphs.
- SIC process represented as a message-passing decoding algorithm along the edges of a bipartite graph.
- Equivalent to iterative erasure decoding of a doubly-generalized LDPC code [Paolini2010].

- [Paolini2010] E. Paolini, M. Fossorier, and M. Chiani, “Generalized and doubly generalized LDPC codes with random component codes for the binary erasure channel,” *IEEE Trans. Inf. Theory*, vol. 56, pp. 1651–1672, Apr. 2010.

CSA: Density Evolution Equations

- Let $m \to \infty$ for a constant population size α.
- Assume MAP decoding is used at the burst nodes.
- Let ℓ be the SIC iteration index. Moreover, let:
  - $p_\ell = \Pr\{\text{an edge is connected to a SN where a collision still persists}\}$;
  - $q_\ell =$ $\Pr\left\{ \begin{array}{c} \text{an edge is connected to a BN whose contribution of interference} \\ \text{on the corresponding segment cannot yet be canceled} \end{array} \right\}$
- Then we can formulate density evolution equations as follows:

$$q_\ell = \frac{1}{\bar{n}} \sum_{h=1}^{n_c} \Lambda_h \sum_{t=0}^{n_h-1} p_{\ell-1}^t (1 - p_{\ell-1})^{n_h-1-t} [(n_h - t)\tilde{e}_{n_h-t}^{(h)} - (t+1)\tilde{e}_{n_h-1-t}^{(h)}]$$

$$p_\ell = 1 - \rho(1 - q_\ell) = 1 - \exp\left\{-\frac{\pi\alpha}{R} q_\ell\right\}$$

CSA: Density Evolution Equations

- In the previous equations, $\tilde{e}_g^{(h)}$ is the g-th un-normalized information function of code $\mathcal{C}_h$.
- This is equal to the sum of the ranks of all $k \times g$ submatrices of a generator matrix of $\mathcal{C}_h$ [Helleseth1997] [Ashikhmin2004].

- [Helleseth1997] T. Helleseth, T. Kløve, and V. I. Levenshtein, "On the information function of an error-correcting code," *IEEE Trans. Inf. Theory*, Mar. 1997.
- [Ashikhmin2004] A. Ashikhmin, G. Kramer, and S. ten Brink, "Extrinsic Information Transfer Functions: Model and Erasure Channel Properties," *IEEE Trans. Inf. Theory*, Vol. 50, Nov. 2004.

CSA: Asymptotic Threshold

- Outcome of density evolution analysis: Existence of a threshold:

$$\pi^*(\mathcal{C}, \mathbf{\Lambda}, \alpha) = \sup\{\pi \text{ s.t. } p_\ell \to 0 \text{ as } \ell \to \infty\}.$$

  Equivalently (in terms of channel load):

$$G^* = \sup\{G \text{ s.t. } p_\ell \to 0 \text{ as } \ell \to \infty\} = \alpha \times \pi^*(\mathcal{C}, \mathbf{\Lambda}, \alpha).$$

- For a given $\mathcal{C} = \{\mathcal{C}_1, \ldots, \mathcal{C}_{n_c}\}$ and a given $\mathbf{\Lambda} = \{\Lambda_h\}_{h=1,\ldots,n_c}$ there exists $G^*(\mathcal{C}, \mathbf{\Lambda})$ s.t.
  - for all $0 < G < G^*(\mathcal{C}, \mathbf{\Lambda})$, the residual packet erasure probability tends to zero as the number of IC iterations tends to infinity;
  - for all $G > G^*(\mathcal{C}, \mathbf{\Lambda})$, decoding fails with a probability that is essentially 1.
- $\boxed{\text{The access scheme is reliable even without retransmissions.}}$

CSA: Threshold Optimization

- For a given set $\mathcal{C}$ of component codes and for a given rate R, we optimize the threshold $G^*(\mathcal{C}, \mathbf{\Lambda})$ with respect to the p.m.f. $\mathbf{\Lambda}$.
- The optimization problem may be formulated as

$$\boxed{\begin{array}{l} \text{maximize } G^*(\mathcal{C}, \mathbf{\Lambda}) \\ \\ \text{subject to } \mathcal{C} = \{\mathcal{C}_1, \dots, \mathcal{C}_{n_c}\} \\ \qquad\qquad\quad R = \frac{k}{\sum_{h=1}^{n_c} \Lambda_h n_h} \end{array}}$$

- Optimization was performed via Differential Evolution algorithm [Price1997].

- [Price1997] K. Price and R. Storn, "Differential evolution – A simple and efficient heuristic for global optimization over continuous spaces," J. Global Optimization, vol. 11, 1997.

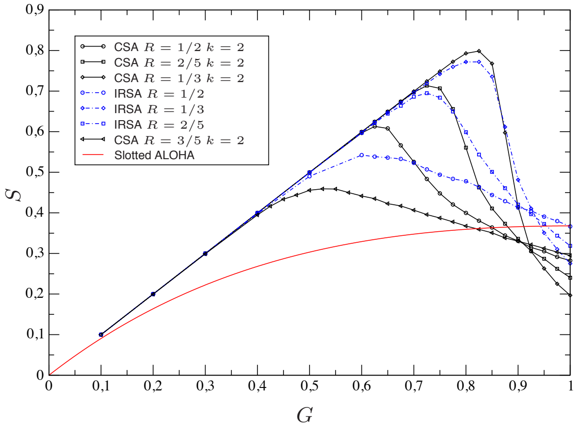
Threshold G^* Optimization

- In the table some distribution profiles $\boldsymbol{\Lambda}$ and thresholds G^* are reported for optimized IRSA and optimized CSA (with $k = 2$) schemes under the random code hypothesis.
- IRSA schemes with rates $1/3$, $2/5$ and $1/2$ and CSA schemes with rates $1/3$, $2/5$, $1/2$ and $3/5$.
- Rates higher than $R = 1/2$ are possible only in the CSA framework.
- IRSA closely approached or outperformed by CSA in all examined cases.

			IRSA				G^*
	(2, 1)	(3, 1)	(6, 1)				
$R = 1/3$	0.554016	0.261312	0.184672				0.8792
$R = 2/5$	0.622412	0.255176	0.122412				0.7825
$R = 1/2$	1.000000						0.5000
			CSA $k = 2$				G^*
	(3, 2)	(4, 2)	(5, 2)	(8, 2)	(9, 2)	(12, 2)	
$R = 1/3$	0.088459	0.544180	0.121490			0.245871	0.8678
$R = 2/5$	0.153057	0.485086	0.135499	0.114235	0.112124		0.7965
$R = 1/2$		1.000000					0.6556
$R = 3/5$	0.666667	0.333333					0.4091

Throughput Comparison

Simulation results for a finite number M of users adopting the optimized degree profiles in the previous table.



- $m = 500$, $M = k\,m = 1000$, $N_a = G \times m$ for each G.
- Linear block codes all with $k = 2$, and $n \in \{2, 4, 5, 8, 9, 12\}$).
- Remarkable performance of CSA over IRSA even for $R = 1/2$ (peak throughput about 0.6)
- All peak throughput close to the asymptotic thresholds

Information-Theoretic Upper Bound on $G^*(\mathcal{C}, \mathbf{\Lambda})$

Theorem

For rational R and $0 < R \leq 1$, let $\mathbb{G}(R)$ be the unique positive solution to the equation

$$G = 1 - e^{-G/R}$$

in $[0, 1)$. Then, the threshold $G^*(\mathcal{C}, \mathbf{\Lambda})$ fulfills

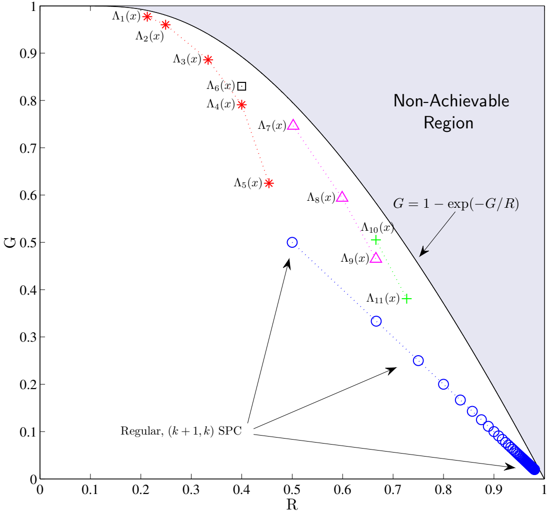
$$G^*(\mathcal{C}, \mathbf{\Lambda}) < \mathbb{G}(R)$$

for *any* choice of $\mathcal{C} = \{\mathcal{C}_1, \mathcal{C}_2, \ldots, \mathcal{C}_{n_c}\}$ and $\mathbf{\Lambda}$ associated with a rate R.

- Two proofs developed: One based on algebraic considerations, one via the Area Theorem [Ashikhmin2004].

- [Ashikhmin2004] A. Ashikhmin, G. Kramer, and S. ten Brink, “Extrinsic Information Transfer Functions: Model and Erasure Channel Properties,” *IEEE Trans. Inf. Theory*, Vol. 50, Nov. 2004.

$G^*(\mathcal{C}, \boldsymbol{\Lambda})$ for Optimized CSA Schemes with MDS Codes



- Remark: Pure SA: $R = 1$ and $G^* = 0$ (unreliable without retransmissions)

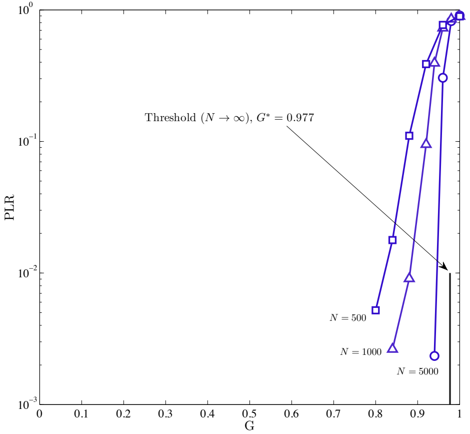
$\bar{G}^*(\mathcal{C}, \mathbf{\Lambda})$ for Optimized CSA Schemes with MDS Codes

- In the previous chart:
  - $*$ denotes a CSA scheme employing repetition codes ($k = 1$);
  - $\square$ denotes a CSA scheme employing MDS codes with $k = 2$;
  - $\triangle$ denotes a CSA scheme employing MDS codes with $k = 3$;
  - $+$ denotes a CSA scheme employing MDS codes with $k = 4$.
- Example (x^h is associated with a $(k + h, k)$ MDS code):

$$\begin{aligned}
\Lambda_7(x) &= 0.322200x^1 + 0.230500x^2 + 0.049100x^4 + 0.398300x^5 \\
R &= 0.502 \\
G^*(\mathcal{C}, \mathbf{\Lambda}_7) &= 0.7462 \\
\mathbb{G}(R) &= 0.7946\,.
\end{aligned}$$

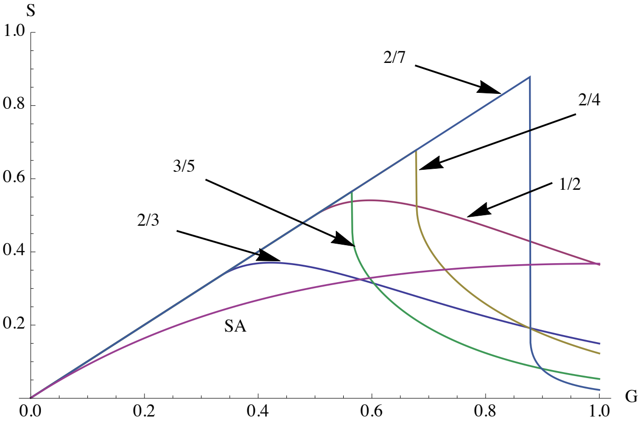
- In general, for a given R we observed an improvement in terms of threshold when increasing k.

Coded Slotted Aloha without Feedback Channel



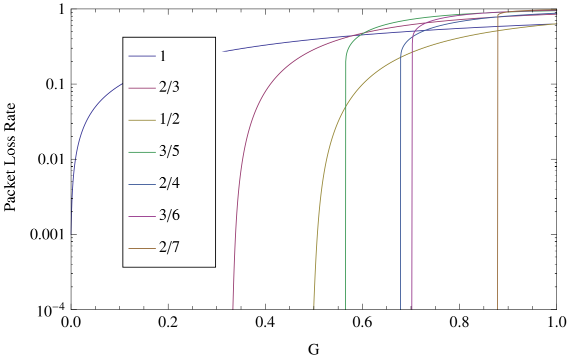
- Packet Loss Rate for Coded SA based on optimized profiles.
- $N = 5000, 1000, 500$, maximum iteration count set to 100.
- Throughput close to 1 packet/frame without feedback channel - no retransmissions!!!

Throughput Analysis for Optimized Regular Codes



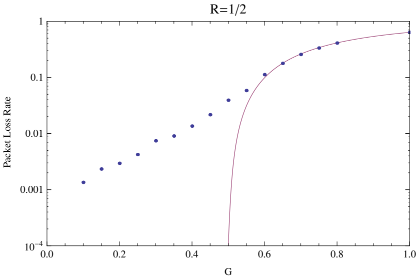
Asymptotic throughput vs. G for the CSA scheme based on: No code, i.e. Slotted Aloha ($R = 1$); repetition 2 codes ($R = 1/2$) (CRDSA); a $(3, 2)$ single parity-check code; a $(5, 3)$ code; a $(4, 2)$ code; a $(7, 2)$ code.

Packet Loss Rate Analysis for Optimized Regular Codes

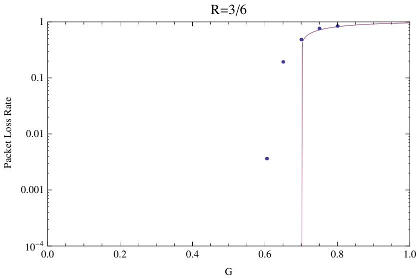


Asymptotic PLR vs. G for the CSA scheme based on: No code, i.e. Slotted Aloha ($R = 1$); repetition 2 codes ($R = 1/2$) (CRDSA); a $(3, 2)$ single parity-check code; a $(5, 3)$ code; a $(4, 2)$ code; a $(7, 2)$ code.

Packet Loss Rate Analysis for Optimized Regular Codes



PLR for the RA scheme based on the repetition-2 code (CRDSA).



PLR for the RA scheme based on a $(6, 3)$ code.

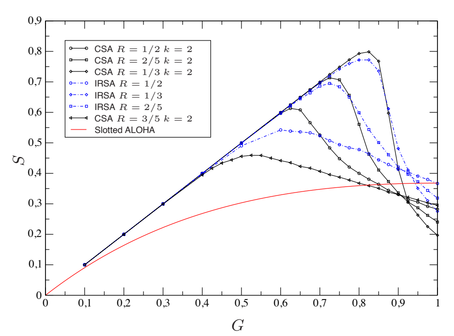
Line: asymptotic analysis. Points: simulation for $= 200$, maximum iteration count set to 200.

Some results on Coded Slotted Aloha

- Assuming infinitely long frames, we studied:
  - the codes design in CSA, based on density evolution techniques
  - the information-theoretic limits on the throughput for a given rate
  - the residual packet loss rate with a maximum number of iterations.

- Current research includes Tthe theoretical analysis for the case of finite-size frames.

Conclusions



- Analogy:

Errors:	Forward Error Correction $\Leftrightarrow$ ARQ
Collisions:	Coded Slotted Aloha $\Leftrightarrow$ Slotted Aloha

- The CSA graph-based random access scheme can approach an efficiency of 1 packet/slot without retransmissions.
- Theoretical limits and design tools are available.

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Thanks to:

- Enrico Paolini
- Gianluigi Liva
- Michael Lentmaier

Research supported in part by the EC
under the FP7 project CONCERTO, grant agreement n. 288502