The Capacity of Count-Constrained ICI-Free Systems

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***Abstract*—A Markov chain approach is applied to determine the capacity of a general class of q-ary ICI-free constrained systems that satisfy an arbitrary count constraint.**

I. Introduction

Let Σ be an alphabet of a finite size $q \geq 2$. A *word* over Σ is any finite string $\boldsymbol{w} = w_1 w_2 \ldots w_n$ where $w_i \in \Sigma$. Let $\mathcal{F}$ be a finite set of words over Σ. The *(finite-type) constrained system* $\mathsf{S}_{\mathcal{F}}$ consists of all words $\boldsymbol{w} = w_1 w_2 \ldots w_n$ over Σ such that $\mathcal{F}$ contains none of their substrings $w_i w_{i+1} \ldots w_j$, for any $1 \leq i \leq j \leq n$. We refer to the set $\mathcal{F}$ as the set of *forbidden words* defining the constrained system $\mathsf{S}_{\mathcal{F}}$. The constrained system $\mathsf{S}_{\mathcal{F}}$ can be presented by a (finite) directed edge-labeled graph G, with edges labeled with symbols from Σ, such that $\mathsf{S}_{\mathcal{F}}$ is the set of all words obtained by reading off the labels along paths of G. For a proof of this fact, we refer the reader to [5], which provides a comprehensive introduction to the subject of constrained systems.

Our specific interest is in a general class of "inter-cell interference free" (in short, "ICI-free") constrained systems, which we now define. For prescribed positive integers a, b, and q such that $a+b \leq q$, let Σ be an alphabet of size q which is assumed to be partitioned into three (disjoint) subsets L, H, and I, of sizes a, b, and $q-a-b$, respectively. The elements in L (respectively, H) represent the "low" (respectively, "high") symbols of Σ, while those in I are the "intermediate" symbols. The ICI-free constrained system that we consider is the constrained system[1] $\mathsf{S}_{q;a,b} := \mathsf{S}_{\mathcal{F}_{q;a,b}}$ defined by the set of forbidden words $\mathcal{F}_{q;a,b} := \{w_1 w_2 w_3 : w_1, w_3 \in H, w_2 \in L\}$. A graph $G_{q;a,b}$ presenting the constrained system $\mathsf{S}_{q;a,b}$ is shown in Fig. 1.

We additionally impose a count constraint defined by a given probability vector $\boldsymbol{p} = (p_s)_{s \in \Sigma}$ (with nonzero entries that sum to 1), which specifies the frequencies of occurrence of each $s \in \Sigma$ within words belonging to $\mathsf{S}_{q;a,b}$. To avoid trivialities, we will assume $\rho_L := \sum_{s \in L} p_s$ and $\rho_H := \sum_{s \in H} p_s$ to be strictly positive. The probability $\rho_I := \sum_{s \in I} p_s$ is allowed to be 0.

For $\varepsilon > 0$, let $\mathsf{S}_{q;a,b}(\boldsymbol{p}, \varepsilon)$ denote the subset of $\mathsf{S}_{q;a,b}$ consisting of all words $\boldsymbol{w} \in \mathsf{S}_{q;a,b}$ in which the number of occurrences of each symbol $s \in \Sigma$ lies in the interval $\big((p_s - \varepsilon)|\boldsymbol{w}|, (p_s + \varepsilon)|\boldsymbol{w}|\big)$, where $|\boldsymbol{w}|$ denotes the length of $\boldsymbol{w}$. The *capacity* (or the *asymptotic information rate*) of $\mathsf{S}_{q;a,b}$ under the count constraint specified by $\boldsymbol{p}$ is defined as[2]

$$\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p}) := \lim_{\varepsilon \to 0^+} \limsup_{n \to \infty} \frac{1}{n} \log \left| \mathsf{S}_{q;a,b}(\boldsymbol{p}, \varepsilon) \cap \Sigma^n \right| . \quad (1)$$

This quantifies, for large n, the exponential rate of growth of the number of length-n words in $\mathsf{S}_{q;a,b}$ in which the relative frequency of occurrence of each symbol $s \in \Sigma$ is approximately p_s. Dropping the count constraint, we also define the (ordinary) capacity of the constrained system $\mathsf{S}_{q;a,b}$ to be[3]

$$\mathsf{cap}(\mathsf{S}_{q;a,b}) := \lim_{n \to \infty} \frac{1}{n} \log \left| \mathsf{S}_{q;a,b} \cap \Sigma^n \right| . \quad (2)$$

The quantities $\mathsf{cap}(\mathsf{S}_{q;a,b})$ and $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ were studied in [1], [6], [7], motivated by proposed coding schemes to mitigate inter-cell interference in flash memory devices.[4] Using standard techniques from the theory of constrained systems (see e.g., [5]) the (ordinary) capacity $\mathsf{cap}(\mathsf{S}_{q;a,b})$ was shown in [1] to be the largest real root of the cubic polynomial $x^3 - qx^2 + abx - ab(q-b)$. The analysis of $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ in [1] is based on combinatorial arguments, and a Stirling approximation of the resulting expressions then yields a bivariate function which needs to be maximized (numerically) in order to obtain the values of $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$.

In this work, we make use of a result from [4] to formulate the problem of determining the capacity $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ as an

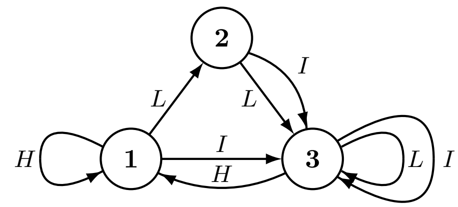

Fig. 1. The graph $G_{q;a,b}$ presenting the q-ary ICI-free constraint $\mathsf{S}_{q;a,b}$. Each arrowed line labeled by $X \in \{L, I, H\}$ represents $|X|$ parallel edges labeled by distinct symbols from X.

[1] Since only the sizes of Σ, L, and H will matter, we identify the constrained system by the sizes of these sets.

[2] All logarithms in this work are to the base 2.

[3] By a standard sub-additivity argument, the limit in this definition exists.

[4] These references used a different definition of $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$, which is shown in Appendix A in [2] to be equivalent to our definition in (1).

optimization problem over Markov chains defined on the graph $G_{q;a,b}$ shown in Fig. 1. By shifting to the dual optimization problem, we then derive an analytical solution to this optimization problem, which results in an exact expression for $\mathsf{cap}(\mathsf{S}_{q;a,b},\boldsymbol{p})$ given in Theorems 3 and 4 in Section III. While our analysis is tailored to count-constrained ICI-free systems, some of the tools that we use may be applicable to other constrained systems as well (see [3]).

II. Markov Chains and Optimization

Let $G=(V,E)$ be a directed graph with vertex set V and (directed) edge set E. For a vertex $v\in V$, we let $E_{\rm in}(v)$ and $E_{\rm out}(v)$ denote the set of incoming and outgoing edges, respectively, incident with v.

A stationary Markov chain on G is a probability distribution $P=\big(P(e)\big)_{e\in E}$ on E, with the property that for each $v\in V$, the sum of the probabilities on the incoming edges of v is equal to that on the outgoing edges of v:

$$\sum_{e\in E_{\rm in}(v)} P(e) = \sum_{e\in E_{\rm out}(v)} P(e)\ . \tag{3}$$

The induced stationary distribution on the vertex set V is given by $\pi(v)=\sum_{e\in E_{\rm out}(v)} P(e)$, for all $v\in V$. The set of all stationary Markov chains on G is denoted by $\Delta(G)$.

The *entropy rate* of a stationary Markov chain P on G is defined as

$$\mathsf{H}(P) := -\sum_{e\in E} P(e)\log P(e) - \left(-\sum_{v\in V}\pi(v)\log\pi(v)\right)\ .$$

Since $\mathsf{H}(P)=-\sum_{v\in V}\sum_{e\in E_{\rm out}(v)} P(e)\log(P(e)/\pi(v))$, the convexity properties of relative entropy imply that $P\mapsto \mathsf{H}(P)$ is a concave function.

Given a Markov chain $P\in\Delta(G)$, along with a vector of real-valued functions $\boldsymbol{f}=(f_1\ f_2\ \ldots\ f_t): E\to\mathbb{R}^t$, we denote by $\mathbb{E}_P(\boldsymbol{f})$ the expected value of $\boldsymbol{f}$ with respect to P:

$$\mathbb{E}_P(\boldsymbol{f}) = \sum_{e\in E} P(e)\boldsymbol{f}(e)\ .$$

We will only need the following special case of the function $\boldsymbol{f}$. Let $\mathsf{L}: E\to\Sigma$ be a labeling of the edges of the graph G with symbols from Σ. For a subset W of Σ of size t, we define the vector indicator function $\mathcal{I}_W: E\to\mathbb{R}^t$ by $\mathcal{I}_W=(\mathcal{I}_s)_{s\in W}$, where $\mathcal{I}_s: E\to\mathbb{R}$ is the indicator function for a symbol $s\in\Sigma$:

$$\mathcal{I}_s(e) = \begin{cases} 1 & \text{if } \mathsf{L}(e)=s \\ 0 & \text{otherwise} \end{cases}\ .$$

Then, $\mathbb{E}_P(\mathcal{I}_W)$ is a vector in $\mathbb{R}^t$ whose entry that is indexed by $s\in W$ is the probability that an edge chosen according to the distribution P is labeled with the symbol s.

These definitions allow us to state the following result, which expresses $\mathsf{cap}(\mathsf{S}_{q;a,b},\boldsymbol{p})$ as the solution to a convex optimization problem.

Proposition 1. *We have*

$$\mathsf{cap}(\mathsf{S}_{q;a,b},\boldsymbol{p}) = \sup_{\substack{P\in\Delta(G_{q;a,b}):\\ \mathbb{E}_P(\mathcal{I}_W)=\boldsymbol{p}'}} \mathsf{H}(P)\ ,$$

for any $W\subset\Sigma$ of size $q-1$ and $\boldsymbol{p}'=(p_s)_{s\in W}$.

Proof. As a consequence of [4, Lemma 2], for any $\varepsilon>0$, $\limsup_{n\to\infty}(1/n)\log|\mathsf{S}_{q;a,b}(\boldsymbol{p},\varepsilon)\cap\Sigma^n|$ is equal to $\sup\mathsf{H}(P)$, the supremum being over stationary Markov chains $P\in\Delta(G_{q;a,b})$ such that $\mathbb{E}_P(\mathcal{I}_\Sigma)\in(\boldsymbol{p}-\varepsilon\cdot\mathbf{1},\boldsymbol{p}+\varepsilon\cdot\mathbf{1})$ (where $\mathbf{1}$ denotes the all-one vector in $\mathbb{R}^q$). We claim that as $\varepsilon\to 0$, these suprema converge to $\sup\mathsf{H}(P)$, the supremum now being over stationary Markov chains $P\in\Delta(G_{q;a,b})$ such that $\mathbb{E}_P(\mathcal{I}_\Sigma)=\boldsymbol{p}$. With this, we would have

$$\mathsf{cap}(\mathsf{S}_{q;a,b},\boldsymbol{p}) = \sup_{\substack{P\in\Delta(G_{q;a,b}):\\ \mathbb{E}_P(\mathcal{I}_\Sigma)=\boldsymbol{p}}} \mathsf{H}(P)\ . \tag{4}$$

The constraint $\mathbb{E}_P(\mathcal{I}_\Sigma)=\boldsymbol{p}$ in the supremum on the right-hand side (RHS) above can be replaced by $\mathbb{E}_P(\mathcal{I}_W)=(p_s)_{s\in W}$, since the latter implies $\mathbb{E}_P(\mathcal{I}_{\{s\}})=p_s$ for the remaining symbol $s\in\Sigma\setminus W$. This would prove the proposition.

We now prove the claim above. To this end, for $\varepsilon>0$, define $\Delta_{\boldsymbol{p},\varepsilon}$ to be the set of all stationary Markov chains $P\in\Delta(G_{q;a,b})$ such that $\mathbb{E}_P(\mathcal{I}_\Sigma)\in(\boldsymbol{p}-\varepsilon\cdot\mathbf{1},\boldsymbol{p}+\varepsilon\cdot\mathbf{1})$. Its closure $\overline{\Delta_{\boldsymbol{p},\varepsilon}}$ is the set of all $P\in\Delta(G_{q;a,b})$ such that $\mathbb{E}_P(\mathcal{I}_\Sigma)\in[\boldsymbol{p}-\varepsilon\cdot\mathbf{1},\boldsymbol{p}+\varepsilon\cdot\mathbf{1}]$. By continuity of the mapping $P\mapsto\mathsf{H}(P)$, we have

$$\sup_{P\in\Delta_{\boldsymbol{p},\varepsilon}}\mathsf{H}(P) = \sup_{P\in\overline{\Delta_{\boldsymbol{p},\varepsilon}}}\mathsf{H}(P),$$

and the latter supremum is in fact a maximum. Finally, let $\Delta_{\boldsymbol{p},0}$ denote the set of all $P\in\Delta(G_{q;a,b})$ such that $\mathbb{E}_P(\mathcal{I}_\Sigma)=\boldsymbol{p}$. We wish to show that

$$\lim_{\varepsilon\to 0^+}\sup_{P\in\overline{\Delta_{\boldsymbol{p},\varepsilon}}}\mathsf{H}(P) = \sup_{P\in\Delta_{\boldsymbol{p},0}}\mathsf{H}(P). \tag{5}$$

The limit on the left-hand side (LHS) of (5) exists since $\sup_{P\in\overline{\Delta_{\boldsymbol{p},\varepsilon}}}\mathsf{H}(P)$ is a monotone function of ε.

Since $\Delta_{\boldsymbol{p},0}\subseteq\overline{\Delta_{\boldsymbol{p},\varepsilon}}$ for all $\varepsilon>0$, the RHS above cannot exceed the LHS. To prove the reverse inequality, suppose that P_ε achieves the supremum over $P\in\overline{\Delta_{\boldsymbol{p},\varepsilon}}$. Passing to a subsequence if necessary, P_ε converges (as $\varepsilon\to 0^+$) to some $P_0\in\Delta(G_{q;a,b})$. From the fact that $\mathbb{E}_P(\mathcal{I}_\Sigma)$ is continuous in P, it follows that $P_0\in\Delta_{\boldsymbol{p},0}$. Hence, again via the continuity of the mapping $P\mapsto\mathsf{H}(P)$, we obtain

$$\lim_{\varepsilon\to 0^+}\sup_{P\in\overline{\Delta_{\boldsymbol{p},\varepsilon}}}\mathsf{H}(P) = \lim_{\varepsilon\to 0^+}\mathsf{H}(P_\varepsilon) = \mathsf{H}(P_0) \le \sup_{P\in\Delta_{\boldsymbol{p},0}}\mathsf{H}(P),$$

which proves our claim. □

Thus, computation of the quantity $\mathsf{cap}(\mathsf{S}_{q;a,b},\boldsymbol{p})$ requires the solution of a constrained optimization problem in which the objective function $P\mapsto\mathsf{H}(P)$ is concave, and the constraints are linear. The theory of convex duality based upon Lagrange multipliers provides a method to translate the problem into an unconstrained optimization with a convex objective function [4].

In order to reformulate the problem, we need to introduce a vector-valued matrix function that generalizes the adjacency matrix of a directed graph $G = (V, E)$. For a function $\boldsymbol{f}$: $E \to \mathbb{R}^t$ and $\boldsymbol{\xi} \in \mathbb{R}^t$, let $A_{G;\boldsymbol{f}}(\boldsymbol{\xi})$ be the matrix defined by

$$\Big(A_{G;\boldsymbol{f}}(\boldsymbol{\xi}) \Big)_{u,v} = \sum_{e \in E_{\text{out}}(u) \cap E_{\text{in}}(v)} 2^{-\boldsymbol{\xi} \cdot \boldsymbol{f}(e)} \ .$$

We remark that for any function $\boldsymbol{f}$, the matrix $A_{G;\boldsymbol{f}}(\boldsymbol{0})$ is precisely the adjacency matrix of G. Moreover, for any choice of $\boldsymbol{\xi} \in \mathbb{R}^t$, the matrix $A_{G;\boldsymbol{f}}(\boldsymbol{\xi})$ is (entry-wise) non-negative, so that it has a unique largest positive eigenvalue, called the Perron eigenvalue, which we denote by $\lambda(A_{G;\boldsymbol{f}}(\boldsymbol{\xi}))$.

The following lemma is the main tool in translating the constrained optimization problem to a more tractable form. It is a consequence of standard results in the theory of convex duality.

Lemma 2. *Let G and $\boldsymbol{f}$ be as above. Then, for any $\boldsymbol{r} \in \mathbb{R}^t$,*

$$\sup_{\substack{P \in \Delta(G): \\ \mathbb{E}_P(\boldsymbol{f}) = \boldsymbol{r}}} \mathsf{H}(P) = \inf_{\boldsymbol{\xi} \in \mathbb{R}^t} \left\{ \boldsymbol{\xi} \cdot \boldsymbol{r} + \log \lambda(A_{G;\boldsymbol{f}}(\boldsymbol{\xi})) \right\} \ .$$

Note that since $P \mapsto \mathsf{H}(P)$ is a concave function, by convex duality, the objective function on the RHS of the lemma is a convex function of $\boldsymbol{\xi}$. Moreover, it is a differentiable function of ξ whenever the graph G is strongly-connected (as is the case when $G = G_{q;a,b}$): the matrix $A_{G;\boldsymbol{f}}(\boldsymbol{\xi})$ is then irreducible for all $\boldsymbol{\xi} \in \mathbb{R}^t$, so that its Perron eigenvalue is simple, and hence differentiable as a function of $\boldsymbol{\xi}$. Consequently, the objective function can be minimized by identifying the point at which its gradient with respect to $\boldsymbol{\xi}$ vanishes.

We illustrate the use of Proposition 1 and Lemma 2 to determine $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ in the case of $q = 3$ in Section III-A. We will later show in Section III-B that the general $q \geq 3$ case can be reduced to $q = 3$.

III. Computation of $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$

The simplest case is that of $q = 2$, i.e., the $\mathsf{S}_{2;1,1}$ constrained system. This is the "no-101" constrained system, which forbids the occurrence of the string 101. The value of $\mathsf{cap}(\mathsf{S}_{2;1,1}, (1-p, p))$, for $p \in (0, 1)$, can be computed via Proposition 1 and Lemma 2, using an analysis similar to (but simpler than) that in Section III-A. However, we do not provide the details of this analysis, as it is not difficult to convince oneself that $\mathsf{cap}(\mathsf{S}_{2;1,1}, (1-p, p)) = \mathsf{cap}(\mathsf{S}_{3;1,1}, (1-p, 0, p))$. Thus, we start with the $q = 3$ case.

A. The Case $q = 3$ and $a = b = 1$

The key to our analysis of the capacity $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ is the case $(q; a, b) = (3; 1, 1)$. As noted above, this case subsumes the case $(q; a, b) = (2; 1, 1)$. Moreover, as we will show in the next subsection, the computation of $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ for any $q \geq 3$, $a \geq 1$, and $b \geq 1$ can be reduced to the problem of computing $\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho})$, where the entries of $\boldsymbol{\rho}$ are $\rho_X = \sum_{s \in X} p_s$, for $X \in \{L, I, H\}$.

So, consider a ternary alphabet Σ partitioned into singleton subsets L, I, and H. By abuse of notation, we will assume that L, I, and H are the actual elements of the alphabet Σ. The graph presentation of $\mathsf{S}_{3;1,1}$ is given by Fig. 1, regarding each arrowed line in the figure as a single edge.

Let the count constraint vector be $\boldsymbol{\rho} = (\rho_L, \rho_I, \rho_H)$, with $\rho_L, \rho_H \in (0, 1)$ and $\rho_I \in [0, 1)$. From Proposition 1 and Lemma 2 (applied with $\boldsymbol{f} = (\mathcal{I}_I, \mathcal{I}_H)$), we obtain

$$\begin{aligned} &\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho}) \\ &\quad = \inf_{(\xi_I, \xi_H) \in \mathbb{R}^2} \left\{ \rho_I \xi_I + \rho_H \xi_H + \log \lambda(A_{G;(\mathcal{I}_I, \mathcal{I}_H)}(\xi_I, \xi_H)) \right\} \ , \end{aligned} \tag{6}$$

where

$$A_{G;(\mathcal{I}_I, \mathcal{I}_H)}(\xi_I, \xi_H) = \left(\begin{array}{ccc} 2^{-\xi_H} & 1 & 2^{-\xi_I} \\ 0 & 0 & 1 + 2^{-\xi_I} \\ 2^{-\xi_H} & 0 & 1 + 2^{-\xi_I} \end{array} \right) \ . \tag{7}$$

As noted after Lemma 2, the objective function on the RHS of (6) can be minimized by identifying the point at which its gradient with respect to (ξ_I, ξ_H) equals 0.

The case $\rho_I = 0$ needs a little extra care, as in this case the infimum in (6) is achieved by letting $\xi_I \to \infty$. This follows from the fact that for any fixed ξ_H, the Perron eigenvalue $\lambda(A_{G;(\mathcal{I}_I, \mathcal{I}_H)}(\xi_I, \xi_H))$ is strictly decreasing in ξ_I (see Problem 3.12 in [5]). Thus, the RHS of (6) reduces to the single-variable optimization problem $\inf_{\xi_H} \{\rho_H \xi_H + \log \lambda(A_{G;\mathcal{I}_H}(\xi_H))\}$, where $A_{G;\mathcal{I}_H}(\xi_H)$ is the matrix obtained by setting $2^{-\xi_I} = 0$ in (7).

We first assume that $\rho_I > 0$ (describing later the minor modifications to be made to handle the case $\rho_I = 0$). We make the change of variables $y = 2^{-\xi_I}$ and $z = 2^{-\xi_H}$ to get

$$\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho}) = \log \left(\inf_{y,z \in (0,\infty)^2} \frac{\lambda(A(y,z))}{y^{\rho_I} z^{\rho_H}} \right) \ , \tag{8}$$

where $\lambda(A(y,z))$ is the Perron eigenvalue of the matrix

$$A(y,z) := \left(\begin{array}{ccc} z & 1 & y \\ 0 & 0 & 1+y \\ z & 0 & 1+y \end{array} \right) \ .$$

It is easily checked that the determinant of the Jacobian of the transformation $(\xi_I, \xi_H) \mapsto (y, z)$ is nonzero for all $(\xi_I, \xi_H) \in \mathbb{R}^2$. It follows from this that for any $(\xi_I, \xi_H) \in \mathbb{R}^2$, the gradient of the objective function in (6) is 0 at (ξ_I, ξ_H) if and only if the gradient of the objective function in (8) is 0 at $(y, z) = (2^{-\xi_I}, 2^{-\xi_H})$. Thus, the minimization in (8) can be carried out by identifying the positive values of y, z at which the gradient of $\lambda(A(y,z))/(y^{\rho_I} z^{\rho_H})$ vanishes.

To do this, we make another convenient change of variables: $(y, z) \mapsto (y, \lambda)$ with $\lambda = \lambda(A(y,z))$. This mapping is invertible: since $A(y, z)$ is irreducible for $y, z > 0$, it follows from Problem 3.12 in [5] that $\lambda(A(y,z))$ is strictly increasing in z for every fixed $y > 0$. Also, for each fixed $y > 0$, the mapping $z \mapsto \lambda(A(y,z))$ is a continuous function from $(0, \infty)$ onto $(y+1, \infty)$ (as it is easy to see that $\lambda(A(y, 0)) = y+1$). For every fixed $y > 0$, the inverse mapping $(y, \lambda) \mapsto (y, z)$ is determined by setting the characteristic polynomial of $A(y, z)$ equal to 0, and is given by

$$z = z(y, \lambda) = \frac{\lambda^2(\lambda - y - 1)}{\lambda^2 - \lambda + y + 1} \ . \tag{9}$$

It can be verified by direct computation[5] that $\partial z/\partial\lambda > 0$ whenever $\lambda > y+1 > 1$, and hence, the Jacobian determinant of the transformation $(y,z) \mapsto (y,\lambda)$ is nonzero for all $y, z > 0$. From this, arguing as above for the mapping $(\xi_I, \xi_H) \mapsto (y,z)$, we obtain via (8) and (9) that

$$\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho}) = \log\left(\inf_{(y,\lambda)\in\mathcal{U}} g(y,\lambda)\right), \tag{10}$$

where

$$g(y,\lambda) = \frac{\lambda}{y^{\rho_I}}\left(\frac{\lambda^2-\lambda+y+1}{\lambda^2(\lambda-y-1)}\right)^{\rho_H}$$

and

$$\mathcal{U} = \{(y,\lambda)\in\mathbb{R}^2 : \lambda > y+1 > 1\} .$$

Moreover, the infimum in (10) is obtained at any point $(y,\lambda) \in \mathcal{U}$ where the partial derivatives of $g(y,\lambda)$ vanish.

Turning now to the case $\rho_I = 0$, it can be handled by setting $y = 0$ in the discussion above, assuming the convention that $0^0 = 1$. Thus, the RHS of (8) reduces to $\log\left(\inf_{z>0} \lambda(A(0,z))/z^{\rho_H}\right)$, and the RHS of (10) becomes $\log\left(\inf_{\lambda>1} g_0(\lambda)\right)$, where $g_0(\lambda) := g(0,\lambda)$. This latter infimum is achieved at any point $\lambda > 1$ where the derivative $g_0'(\lambda)$ equals 0.

In Appendix C in the full version of this paper [2], we compute the partial derivatives $\partial g/\partial y$ and $\partial g/\partial\lambda$, each being a cubic multinomial in y and λ. We then find explicitly their common root, thereby yielding the following result.

Theorem 3. *For $\boldsymbol{\rho} = (\rho_L, \rho_I, \rho_H) \in (0,1)\times[0,1)\times(0,1)$:*

$$\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho}) = \log\left[\frac{\lambda}{y^{\rho_I}}\left(\frac{\lambda^2-\lambda+y+1}{\lambda^2(\lambda-y-1)}\right)^{\rho_H}\right],$$

where (y,λ) is given as follows.

- *If $\rho_L = \frac{1}{2}$ and $\rho_I = 0$, then $y = 0$ and $\lambda = 2$.*
- *If $\rho_L = \frac{1}{2}$ and $\rho_I > 0$, then*

$$y = -1 - 2\tau + 2\sqrt{1+\tau+\tau^2} \quad \text{and} \quad \lambda = 2 ,$$

  where $\tau := \rho_H/\rho_I$.
- *If $\rho_L \neq \frac{1}{2}$, then*

$$y = \frac{\rho_I(\lambda-2)}{1-2\rho_L}$$

  and λ is a root of the cubic polynomial

$$Z(x) := (1-2\rho_L)\rho_L x^3 + \big((\rho_L-\rho_H)^2 - (1-2\rho_L)\big)x^2 - 2(\rho_L-\rho_H)(1-2\rho_H)x + (1-2\rho_H)^2$$

  chosen as follows: if $\rho_L < \frac{1}{2}$, then λ is the largest real (positive) root of $Z(x)$; and if $\rho_L > \frac{1}{2}$, then λ is the smallest real (positive) root of $Z(x)$.

It is worth noting that for $\boldsymbol{\rho} = (\frac{1}{2}, 0, \frac{1}{2})$ we obtain $\mathsf{cap}(\mathsf{S}_{3;1,1}, (\frac{1}{2}, 0, \frac{1}{2})) = \frac{1}{2}\log 3$. Thus, $\mathsf{cap}(\mathsf{S}_{2;1,1}, (\frac{1}{2}, \frac{1}{2})) = \frac{1}{2}\log 3$, which agrees with the rate derived (using two different approaches) in [6].

[5] Also see Appendix B in [2] for an argument using Perron–Frobenius theory.

B. The General Case of $q \geq 3$

Consider now a constrained system $\mathsf{S}_{q;a,b}$ over a q-ary alphabet Σ for some $q \geq 3$, where Σ is partitioned into the subsets L, H, and I of sizes $a \geq 1$, $b \geq 1$, and $q-a-b \geq 0$, respectively. Let $\boldsymbol{p} = (p_s)_{s\in\Sigma}$ be a given count constraint vector, and define $\rho_X = \sum_{s\in X} p_s$ for $X \in \{L, I, H\}$. If $I = \emptyset$, we set $\rho_I = 0$. The probabilities ρ_L and ρ_H are assumed to be strictly positive.

The aim of this subsection is to prove the result stated next. The statement requires the following standard definition: the *entropy* of a probability vector $\boldsymbol{u} = (u_i)_i$ is defined as $\mathsf{h}(\boldsymbol{u}) = -\sum_i u_i \log u_i$.

Theorem 4. *For $\mathsf{S}_{q;a,b}$ and $\boldsymbol{p}$ as above:*

$$\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p}) = \mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho}) + \mathsf{h}(\boldsymbol{p}) - \mathsf{h}(\boldsymbol{\rho}) ,$$

where the entries of $\boldsymbol{\rho}$ are $\rho_X = \sum_{s\in X} p_s$, for $X \in \{L, I, H\}$.

Thus, the computation of $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ reduces to the problem of computing $\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho})$, which was solved explicitly in Theorem 3. The rest of this subsection is devoted to a proof of Theorem 4.

Let $\mathsf{P} = (\mathsf{P}(u,s))_{u,s}$ be a stationary Markov chain on the labeled graph $G_{q;a,b}$ on the vertex set $V = \{1,2,3\}$ in Fig. 1, where $\mathsf{P}(u,s)$ is the probability of the edge labeled s leaving vertex u (and $\mathsf{P}(u,s) \equiv 0$ if there is no such edge). Note that for any $s \in \Sigma$, we have $\mathbb{E}_{\mathsf{P}}(\mathcal{I}_s) = \sum_{u\in V} \mathsf{P}(u,s)$. Thus, the constraint $\mathbb{E}_{\mathsf{P}}(\mathcal{I}_\Sigma) = \boldsymbol{p}$ on the RHS of (4) is equivalently expressed as

$$\sum_{u\in V} \mathsf{P}(u,s) = p_s , \quad \text{for all } s \in \Sigma . \tag{11}$$

Now, for $u \in V$ and $X \in \{L, I, H\}$, define

$$\mathsf{Q}(u,X) = \sum_{s\in X} \mathsf{P}(u,s) .$$

Note that $\mathsf{Q} = (\mathsf{Q}(u,X))_{u,X}$ is a stationary Markov chain on the graph in Fig. 1, where each arrowed line in the figure is regarded as a single edge (this graph is $G_{3;1,1}$). Moreover, we have for $X \in \{L, I, H\}$,

$$\mathbb{E}_{\mathsf{Q}}(\mathcal{I}_X) = \sum_{u\in V} \mathsf{Q}(u,X) = \sum_{s\in X}\sum_{u\in V} \mathsf{P}(u,s) .$$

Thus, if we impose the constraint (11) on the Markov chain P, we obtain

$$\mathbb{E}_{\mathsf{Q}}(\mathcal{I}_X) = \sum_{s\in X} p_s = \rho_X \text{ , for all } X \in \{L, I, H\} .$$

In other words, the constraint $\mathbb{E}_{\mathsf{P}}(\mathcal{I}_\Sigma) = \boldsymbol{p}$ on the Markov chain P induces the constraint $\mathbb{E}_{\mathsf{Q}}(\mathcal{I}_{\{L,I,H\}}) = \boldsymbol{\rho}$ on the Markov chain Q. Finally, observe that P and Q induce the same stationary distribution on V:

$$\begin{aligned}\pi_{\mathsf{P}}(u) = \sum_{s\in\Sigma} \mathsf{P}(u,s) &= \sum_X \sum_{s\in X} \mathsf{P}(u,s) \\ &= \sum_X \mathsf{Q}(u,X) = \pi_{\mathsf{Q}}(u) .\end{aligned}$$

The following lemma is the key to proving Theorem 4.

Lemma 5. *For a Markov chain* $\mathsf{P} \in \Delta(G_{q;a,b})$ *with* $\mathbb{E}_{\mathsf{P}}(\mathcal{I}_\Sigma) = \boldsymbol{p}$, *and* $\mathsf{Q} \in \Delta(G_{3;1,1})$ *as above, we have*

$$\mathsf{H}(\mathsf{P}) \le \mathsf{H}(\mathsf{Q}) + \mathsf{h}(\boldsymbol{p}) - \mathsf{h}(\boldsymbol{\rho}) , \qquad (12)$$

with equality holding if and only if $\mathsf{P}(u,s) = (p_s/\rho_X)\mathsf{Q}(u,X)$ *for every* $s \in X$ *(where* $\mathsf{P}(u,s) = 0$ *when* $p_s = \rho_X = 0$*).*

Proof. Let (U,S) be a pair of random variables taking values $(u,s) \in V \times \Sigma$ with probability $\mathsf{P}(u,s)$. Let $\varphi : \Sigma \to \{L, I, H\}$ be the function that maps s to X if $s \in X$. Now, U—S—$\varphi(S)$ is a Markov chain, so that by the data processing inequality, $\mathrm{I}(U;S) \ge \mathrm{I}(U;\varphi(S))$. It is easily verified that $\mathrm{I}(U;S) = \mathsf{h}(\boldsymbol{p}) - \mathsf{H}(\mathsf{P})$ and $\mathrm{I}(U;\varphi(S)) = \mathsf{h}(\boldsymbol{\rho}) - \mathsf{H}(\mathsf{Q})$. Thus,

$$\mathsf{h}(\boldsymbol{p}) - \mathsf{H}(\mathsf{P}) \ge \mathsf{h}(\boldsymbol{\rho}) - \mathsf{H}(\mathsf{Q}) ,$$

re-arranging which we obtain (12).

Equality holds in the data processing inequality above if and only if U—$\varphi(S)$—S is also a Markov chain, i.e., U and S are conditionally independent given $\varphi(S)$. Now, check that $\Pr\{U = u, S = s \mid \varphi(S) = X\}$ equals $\mathsf{P}(u,s)/\rho_X$ if $s \in X$, and equals 0 otherwise. Hence, $\Pr\{U = u, S = s \mid \varphi(S) = X\} = \sum_{s \in X} \mathsf{P}(u,s)/\rho_X = \mathsf{Q}(u,X)/\rho_X$. Finally, $\Pr\{S = s \mid \varphi(S) = X\}$ equals p_s/ρ_X if $s \in X$, and equals 0 otherwise. Thus, the required conditional independence holds if and only if $\mathsf{P}(u,s) = \mathsf{Q}(u,X)\,(p_s/\rho_X)$ for all $s \in X$. □

We can now complete the proof of Theorem 4. Taking the supremum over P in (12), we obtain (by virtue of (4)) that

$$\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p}) \le \mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho}) + \mathsf{h}(\boldsymbol{p}) - \mathsf{h}(\boldsymbol{\rho}) . \qquad (13)$$

We now argue that this is in fact an equality. Consider a $\mathsf{Q}^* = \big(\mathsf{Q}^*(u,X)\big)_{u,X}$ that achieves $\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho}) = \sup \mathsf{H}(\mathsf{Q})$, the supremum being over Markov chains $\mathsf{Q} \in \Delta(G_{3;1,1})$ such that $\mathbb{E}_{\mathsf{Q}}(\mathcal{I}_{\{L,I,H\}}) = \boldsymbol{\rho}$. Such a Q^* exists as $\mathsf{Q} \mapsto \mathsf{H}(\mathsf{Q})$ is a continuous function being maximized over a compact set. Recall that any outgoing edge from u labeled by X in $G_{3;1,1}$ is replaced in $G_{q;a,b}$ by $|X|$ parallel edges labeled by the distinct symbols $s \in X$. For each such edge (u,s), set $\mathsf{P}(u,s) = (p_s/\rho_X)\mathsf{Q}^*(u,X)$. The resulting Markov chain $\mathsf{P} \in \Delta(G_{q;a,b})$ satisfies the conditions for equality in (12), from which it follows that equality holds in (13).

IV. Discussion

Our computation of $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ consists of the following steps.

1) Applying Theorem 4 to reduce the problem to that of computing $\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho})$.
2) Expressing the computation of $\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho})$ as the bivariate minimization problem (8) in the variables (y,z).
3) Eliminating the implicit expression $\lambda(A(y,z))$ in (8) through a change of variables, resulting in the bivariate minimization problem (10) in the variables (y,λ).
4) Taking partial derivatives with respect to y and λ, resulting in two cubic bivariate polynomials in y and λ.
5) Finding the common root of these polynomials.

While Step 1 is specific to the constrained system $\mathsf{S}_{q;a,b}$, the other steps might be applicable to other count-constrained systems (albeit with varying degrees of difficulty). For any constrained system S over an alphabet Σ, the number of variables in Step 2 will be $|\Sigma| - 1$. As for Step 3, the explicit rational expression (9) for $z = z(y,\lambda)$ is attributed to the fact that the coefficients of the characteristic polynomial of $A(y,z)$ are linear terms in z. In general, this happens whenever there is a symbol $s \in \Sigma$ that has a "home state" in the graph presentation of S, namely, all edges labeled by s lead to the same vertex.

We mention that one could also compute $\mathsf{cap}(\mathsf{S}_{q;a,b}, \boldsymbol{p})$ based on Proposition 1 directly. Referring to the case $\mathsf{cap}(\mathsf{S}_{3;1,1}, \boldsymbol{\rho})$ and using the notation towards the end of Section III-B, such a computation would entail finding the nine edge probabilities of a Markov chain $\mathsf{Q} = \big(\mathsf{Q}(u,X)\big)_{u,X}$ (where $u \in V = \{1,2,3\}$ and $X \in \Sigma = \{L,I,H\}$) that maximizes $\mathsf{H}(\mathsf{Q})$, subject to the following six linear constraints:

- $\mathsf{Q}(2,H) = 0$,
- the constraints (3) for any two vertices in V (the third is dependent on these two), and—
- the three constraints obtained from $\mathbb{E}(\mathcal{I}_\Sigma) = \boldsymbol{\rho}$ (these constraints imply that $\sum_{u,X} \mathsf{Q}(u,X) = 1$).

We would then end up with three linearly independent variables to optimize over.

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