On the Entropy Rate of a Random Walk on t-Designs

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Abstract

In this paper, a random walk on t-designs are considered. We assign a weight to each block and walk randomly on the vertices with a probability proportional to the weight of blocks. This stochastic process is a Markov chain. We obtain a stationary distribution for this process and compute its entropy rate. It is seen that, when the blocks have the same weight, the uniform distribution on the vertices is a stationary distribution and the entropy rate depends only on the number of vertices.

Keywords: random walk, Markov chain, design, entropy rate, stationary distribution.

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1. Introduction

Let X be a discrete random variable with alphabet $\mathcal{X}$ and probability mass function $p(x) = \Pr\{X = x\}$, $x \in \mathcal{X}$. The entropy $H(X)$ of X is defined as

$$H(X) = -\sum_{x\in\mathcal{X}} p(x) \log p(x),$$

where logarithm is to the base 2 and entropy is expressed in bits. Here, the convention $0 \log 0 = 0$ will be used. The entropy $H(X)$ is a measure of the uncertainty of X and moreover, it is a measure of the amount of information required on the

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average to describe X. Let (X, Y) be a pair of discrete random variables with a joint distribution $p(x, y)$, $(x, y) \in \mathcal{X} \times \mathcal{Y}$. The joint entropy $H(X, Y)$ is defined by

$$H(X,Y) = -\sum_{x\in\mathcal{X}}\sum_{y\in\mathcal{Y}} p(x,y)\log p(x,y).$$

Similarly, the entropy of a collection of random variables, such as $H(X_1, X_2, \ldots, X_n)$, is defined.

A stochastic process $\{X_i\}_{i\in\mathbb{N}}$ can be defined as an indexed sequence of random variables. This process is characterizied by the probability mass functions

$$\Pr\{(X_1, X_2, \ldots, X_n) = (x_1, x_2, \ldots, x_n)\} = p(x_1, x_2, \ldots, x_n),$$

where $(x_1, x_2, \ldots, x_n) \in \mathcal{X}^n$ and $n \in \mathbb{N}$. This process is called to be stationary if $\Pr\{(X_1, X_2, \ldots, X_n) = (x_1, x_2, \ldots, x_n)\}$ is equal to $\Pr\{(X_{l+1}, X_{l+2}, \ldots, X_{l+n}) = (x_1, x_2, \ldots, x_n)\}$, for all $x_1, x_2, \ldots, x_n \in \mathcal{X}$ and every shift l. A Markov chain is a stochastic process $\{X_i\}_{i\in\mathbb{N}}$ such that $\Pr\{X_{n+1} = x_{n+1}|X_n = x_n, X_{n-1} = x_{n-1}, \ldots, X_1 = x_1\}$ is equal to $\Pr\{X_{n+1} = x_{n+1}|X_n = x_n\}$, for all $x_1, x_2, \ldots, x_{n+1}$ in $\mathcal{X}$. A Markov chain $\{X_i\}_{i\in\mathbb{N}}$ is called to be time invariant if $\Pr\{X_{n+1} = b|X_n = a\} = \Pr\{X_2 = b|X_1 = a\}$, for all $n \in \mathbb{N}$ and $a, b \in \mathcal{X}$. It is easy to see that a time invariant Markov chain with alphabet $\mathcal{X} = \{1, 2, \ldots, m\}$ can be characterized by an initial state and a probability transition matrix $P = (p_{ij})$, where $p_{ij} = \Pr\{X_{n+1} = j|X_n = i\}$. A distribution μ on $\mathcal{X}$ is said to be stationary if $\mu P = P$. In other words, μ is a distribution on the states such that the distributions at the successive times are the same. The entropy rate of a stochastic process $\{X_i\}_{i\in\mathbb{N}}$ is

$$H(\mathcal{X}) = \lim_{n\to\infty} \frac{1}{n} H(X_1, X_2, \ldots, X_n),$$

when the limit exists. Also, a related quantity for entropy rate is defined by

$$H'(\mathcal{X}) = \lim_{n\to\infty} H(X_n|X_{n-1}, X_{n-2}, \ldots, X_1),$$

when the limit exists. These two quantities correspond to different notions. It can be shown that if $\{X_i\}_{i\in\mathbb{N}}$ is a stationary Markov chain then $H(\mathcal{X}) = H'(\mathcal{X}) = H(X_2|X_1)$. See [2, 6, 7] for more details and examples.

In this paper, motivated by a random walk on a weighted graph [2], a random walk on t-designs are considered. We assign a weight to each block and walk randomly on the vertices with a probability proportional to the weight of blocks. This stochastic process is a Markov chain. We obtain a stationary distribution for this process and compute its entropy rate. It is seen that, when the blocks have the same weight, the uniform distribution on the vertices is a stationary distribution and the entropy rate depends only on the number of vertices. For more information and some new results on random walks, entropy rates and their applications, please see [3, 5, 8].

2. t-Designs

Let $\mathcal{S} = (\mathcal{P}, \mathcal{B}, \mathcal{I})$ be an incidence structure which consists of point set $\mathcal{P}$, block set $\mathcal{B}$ and an incidence relation $\mathcal{I} \subseteq \mathcal{P} \times \mathcal{B}$. The elements of $\mathcal{I}$ are called flags and the notation $p\mathcal{I}B$ means that $(p, B) \in \mathcal{I}$. A block $B \in \mathcal{B}$ is sometimes identified with the set of points p incident with it. Here, $\mathcal{I}$ is in fact the membership relation $\in$. If we replace each block of $\mathcal{S}$ by its complement then we obtain the complement of the structure, denoted by $\overline{\mathcal{S}}$. The dual of $\mathcal{S} = (\mathcal{P}, \mathcal{B}, \mathcal{I})$ is the incidence structure $\mathcal{S}^\top = (\mathcal{B}, \mathcal{P}, \mathcal{I}^\top)$, where $B\mathcal{I}^\top p$ if and only if $p\mathcal{I}B$. The incidence matrix of $\mathcal{S}$ is a matrix M of size $|\mathcal{P}| \times |\mathcal{B}|$ whose rows and columns are labled by points and blocks, respectively, such that the entry (p, B) is 1 if and only if p is incident with B, and 0 otherwise. The incidence structure $\mathcal{D} = (\mathcal{P}, \mathcal{B}, \mathcal{I})$ is called a t-(v, k, λ) design if $|\mathcal{P}| = v$, $|B| = k$ for any $B \in \mathcal{B}$, and every t distinct points are incident with precisely λ blocks. It is known that the number of blocks, denoted by b, is equal to $\lambda\binom{v}{t}/\binom{k}{t}$. The design $\mathcal{D}$ is called trivial if $\mathcal{B}$ consists of all the k-subsets of $\mathcal{P}$. If $v = b$ then $\mathcal{D}$ is called symmetric. It is well-known that the number of blocks incident with s points ($s \leq t$), denoted by λ_s, is independent of the set and $\lambda_s = \lambda\binom{v-s}{t-s}/\binom{k-s}{t-s}$. Therefore, every t-(v, k, λ) design is also an s-(v, k, λ_s) design, where $s \leq t$. The complement of a t-(v, k, λ) design $\mathcal{D}$ is also a design $\overline{\mathcal{D}}$ with parameters t-$(v, v-k, \overline{\lambda})$, where $\overline{\lambda} = \sum_{s=0}^{t}(-1)^s\binom{t}{s}\lambda_s$. The number of blocks incident with any point, λ_1, is also denoted by r and called the replication number. If $\mathcal{D}$ is a t-(v, k, λ) design then $\mathcal{D}^\top$ is a design with b points such that its block size is r. If M is the incidence matrix of $\mathcal{D}$ then the incidence matrix of $\mathcal{D}^\top$ is $M^\top$. It can be shown that if $\mathcal{D}$ is a 2-(v, k, λ) design then $bk = vr$ and $\lambda(v-1) = r(k-1)$. For more details, see [1, 4].

3. Results

Let the incidence structure $\mathcal{D} = (\mathcal{P}, \mathcal{B}, \mathcal{I})$ be a t-(v, k, λ) design with the vertex set $\{1, 2, \ldots, v\}$. To each block $B \in \mathcal{B}$, we assign a weight $\omega(B) \geq 0$ in $\mathbb{R}$ and set

$$\omega = \sum_{B \in \mathcal{B}} \omega(B),$$
$$\omega_i = \sum_{i \in B \in \mathcal{B}} \omega(B),$$
$$\omega_{ij} = \sum_{i,j \in B \in \mathcal{B}} \omega(B),$$

where $i, j \in \mathcal{P}$ and $i \neq j$. In other words, ω_i is the sum of the weights of all blocks containing the vertex i and ω_{ij} is also the sum of the weights of all blocks containing the points i and j. Note that for any vertex i, we have

$$\begin{aligned}
\sum_{\substack{j\in\mathcal{P}\\ j\neq i}} \omega_{ij} &= \sum_{\substack{j\in\mathcal{P}\\ j\neq i}} \sum_{\substack{B\in\mathcal{B}\\ i,j\in B}} \omega(B)\\
&= \sum_{\substack{B\in\mathcal{B}\\ i\in B}} \sum_{\substack{j\in\mathcal{P}\\ i\neq j\in B}} \omega(B)\\
&= \sum_{\substack{B\in\mathcal{B}\\ i\in B}} (k-1)\omega(B)\\
&= (k-1)\omega_i.
\end{aligned}$$

A random walk $\{X_n\}_{n=1}^{\infty}$ in $\mathcal{D}$ is a sequence of points of $\mathcal{D}$ in such a way that $X_n = i$ and $X_{n+1} = j$ if there exists a block B containing the points i and j. Moreover, we walk from i to j with the probability $p_{ij} = \omega_{ij}/\left((k-1)\omega_i\right)$. As it is seen, we walk randomly from the vertex i to the vertex j with a probability proportional to the weight of the blocks containing i and j, and the values $\{p_{ij}\}_{1\leq j\leq v}$ form a mass probability function. By definition, this stochastic process is a Markov chain with the probability transition matrix $P = \left(p_{ij}\right)_{v\times v}$. Set $\mu = (\mu_1, \mu_2, \ldots, \mu_v)$, where $\mu_i = \omega_i/(k\omega)$ for any $1 \leq i \leq v$. Since

$$\begin{aligned}
\sum_{i=1}^{v} \mu_i &= \sum_{i=1}^{v} \frac{\omega_i}{k\omega}\\
&= \frac{1}{k\omega} \sum_{i=1}^{v} \sum_{i\in B\in\mathcal{B}} \omega(B)\\
&= \frac{1}{k\omega} \sum_{B\in\mathcal{B}} \sum_{\substack{i\in\mathcal{P}\\ i\in B\in\mathcal{B}}} \omega(B)\\
&= \frac{1}{k\omega} \sum_{B\in\mathcal{B}} k\omega(B)\\
&= 1,
\end{aligned}$$

μ is a probability distribution on the points $\mathcal{P}$. Moreover, for any $1 \leq j \leq v$,

$$\begin{aligned}
\sum_{l=1}^{v} \mu_l p_{lj} &= \sum_{l=1}^{v} \frac{\omega_l}{k\omega} \frac{\omega_{lj}}{(k-1)\omega_l}\\
&= \frac{1}{k(k-1)\omega} \sum_{l=1}^{v} \omega_{lj}\\
&= \frac{\omega_j}{k\omega}\\
&= \mu_j.
\end{aligned}$$

Therefore, μ is also a stationary distribution. Now, the entropy rate of this process is

$$\begin{aligned}
H(\mathcal{X}) &= H(X_2|X_1) \\
&= -\sum_{i=1}^{v} \mu_i \sum_{j=1}^{v} p_{ij} \log p_{ij} \\
&= -\sum_{i=1}^{v} \frac{\omega_i}{k\omega} \sum_{j=1}^{v} \frac{\omega_{ij}}{(k-1)\omega_i} \log \frac{\omega_{ij}}{(k-1)\omega_i} \\
&= -\sum_{i=1}^{v}\sum_{j=1}^{v} \frac{\omega_{ij}}{k(k-1)\omega} \log \frac{\omega_{ij}}{(k-1)\omega_i} \\
&= -\sum_{i=1}^{v}\sum_{j=1}^{v} \frac{\omega_{ij}}{k(k-1)\omega} \log \frac{\omega_{ij}}{k(k-1)\omega} + \sum_{i=1}^{v}\sum_{j=1}^{v} \frac{\omega_{ij}}{k(k-1)\omega} \log \frac{\omega_i}{k\omega} \\
&= -\sum_{i=1}^{v}\sum_{j=1}^{v} \frac{\omega_{ij}}{k(k-1)\omega} \log \frac{\omega_{ij}}{k(k-1)\omega} + \sum_{i=1}^{v} \frac{\omega_i}{k\omega} \log \frac{\omega_i}{k\omega} \\
&= H\left(\cdots, \frac{\omega_{ij}}{k(k-1)\omega}, \cdots\right) - H\left(\cdots, \frac{\omega_i}{k\omega}, \cdots\right).
\end{aligned}$$

So, the following theorem is implied:

Theorem 3.1. Let $\mathcal{D} = (\mathcal{P}, \mathcal{B}, \mathcal{I})$ be a t-(v,k,λ) design. Assign a non-negative real number $\omega(B)$ to each block $B \in \mathcal{B}$ and set

$$\begin{aligned}
\omega &= \sum_{B\in\mathcal{B}} \omega(B), \\
\omega_i &= \sum_{i\in B\in\mathcal{B}} \omega(B), \\
\omega_{ij} &= \sum_{i,j\in B\in\mathcal{B}} \omega(B),
\end{aligned}$$

for any $i \neq j \in \mathcal{P}$. Let $\{X_n\}_{n=1}^{\infty}$ be a random walk on the points of $\mathcal{D}$ with the probabiity transition matrix $P = \left(p_{ij}\right)_{v\times v}$, where $p_{ij} = \omega_{ij}/\left((k-1)\omega_i\right)$. Set $\mu_i = \omega_i/(k\omega)$, where $1 \leq i \leq v$. Then, $\{X_n\}_{n=1}^{\infty}$ is a Markov chain with the stationary distribution $\mu = (\mu_1, \mu_2, \ldots, \mu_v)$ and the entropy rate

$$H(\mathcal{X}) = H\left(\cdots, \frac{\omega_{ij}}{k(k-1)\omega}, \cdots\right) - H\left(\cdots, \frac{\omega_i}{k\omega}, \cdots\right).$$

Note that if all the blocks have equal weight then $p_{ij} = \lambda_2/(r(k-1))$ and $\mu_i = r/(kb) = 1/v$. Also,

$$\frac{\omega_i}{k\omega} = \frac{r}{kb} = \frac{1}{v},$$

and

$$\frac{\omega_{ij}}{k(k-1)\omega} = \frac{\lambda_2}{k(k-1)b} = \frac{1}{v(v-1)}.$$

Hence, in this case, the uniform distribution on $\mathcal{P}$ is a stationary distribution and the entropy rate is

$$\begin{aligned} H(\mathcal{X}) &= H(\cdots, \frac{1}{v(v-1)}, \cdots) - H(\cdots, \frac{1}{v}, \cdots) \\ &= \log(v-1). \end{aligned}$$

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