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대수부등식들만을 이용한 갈라거 랜덤 코딩 바운드의 유도

Derivations of Gallager Random Coding Bound by Simple Manipulations of Algebraic Inequalities

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요 약

이 논문에서 우리는 이산무기억통신로 (Discrete Memoryless Channel)에 대한 갈라거 랜덤 코딩 바운드를 개념적으로 이해하기 어려운 랜덤코딩 방법론을 따르지 않고 순전히 대수부등식들만을 이용함으로써 유도해 낸다. 갈라거 랜덤코딩바운드는 결정영역(Decision Region)을 알수 없는 경우에도 적용될 뿐만아니라 채널코딩정리까지 유도할 수 있는 매우 강력한 바운드로서 정보 및 부호이론 연구에 있어서 매우 중요한 도구이다. 그동안 개념적으로 이해하기 어려웠던 갈라거 랜덤코딩바운드를 대수적으로 차근차근 유도해 봄으로써 다양한 문제에 쉽게 적용할 수 있는 이론적 바탕을 마련해 보고자 한다.

Abstract

In this letter, we derive the Gallager random coding bound for discrete memoryless channels purely by simple manipulations of algebraic inequalities rather than invoking conceptually difficult random coding arguments. Gallager random coding bound is a very useful tool in information and coding theory due to its applicability to situations in which it is difficult to determine the decision regions and due to the fact that it can be used to derive the channel coding theorem. The readers will find it relatively easy to apply to many practical problems of interest the step-by-step algebraic derivations of the Gallager random coding bound with appropriate modifications.

Key words : Gallager random comding bound, Simple manipulations of algebraic inequalities

I. Introduction

In this letter, we derive the Gallager random coding bound for discrete memoryless channels by a sequence of algebraic manipulations of simple inequalities rather than exploiting the random coding arguments [1].

Random coding bound analysis has been one of the most important analysis tools in information and coding theory [2]. First of all, it provides the cut off rate [3] which has long played the role of practical limits on

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achievable transmission rate of a given communication system design. Secondly, it has served as a primary information theoretic tool for finite packet length performance analysis. While channel capacity can be used instead of cut-off rate for the performance limit, it fails to provide useful information about the performance of a coded system with very limited packet length. However, random coding bound can still provide insightful information about the performance of finite packet length systems. This is particularly useful when we are dealing with fading channels. Thirdly, random coding bound and cut-off rate provide useful performance metric in system design [4].

However, many people find it difficult to understand the concept of random coding arguments. This is particularly true when Gallager bound rather than union bound is used. In this letter, we derive the random coding bound not by the random coding arguments but by step-by-step applications of algebraic inequalities. The procedures in this letter will lead the reader to understand the rigorous steps involved in the derivations of the random coding bound and hence will eventually make them better understand the random coding arguments itself so that they can apply the methods to practical system designs of their interest without difficulty.

Ⅱ. System Model

In this letter, we consider a q-ary (M,N) block code over a discrete memoryless channel with input alphabet $A=\{1,\cdots,q\}$ and output alphabet $B=\{1,\cdots,r\}$. Here, M denotes the number of codewords in the code and N the number of symbols in a codeword. We denote by T_{ij} the transition probability from the input alphabet i to the output alphabet j. Hence, if we denote by X and Y the input and output symbols of the channel, then

$$P[Y=j|X=i]=T_{ij} \tag{1}$$

for $i=1,\cdots,q$, and $j=1,\cdots,r$.

We assume that the M codewords are selected equally likely and the receiver is assumed to use the maximum likelihood decoding rule to minimize the codeword error probability. Since each codeword consists of N q-ary symbols, there are q^{NM} possible choices of codes. Let us denote these q^{NM} codes by $C_1,\cdots,C_{q^{NM}}$. For example, C_1 shall denote the code in which all M codewords are given by $(1,\cdots,1)$, namely, the codeword made solely by the symbol 1 and similarly $C_{q^{NM}}$ the code in which all M codewords are $(q,\cdots q)$. Obiviously, the system will perform very poorly when either C_1 or $C_{q^{NM}}$ is chosen for its channel coding scheme. Consequently, the system performance will naturally be dependant upon which code is chosen.

Let us denote by $P(C)$ the decoding error probability when a particular code C is chosen. Also, we define by $P^{(m)}(C)$ the decoding error probability when a code C is employed and its m^{th} codeword is transmitted. Then, since all the codewords are assumed to be equally likely to be transmitted, it follows that

$$P(C)=\frac{1}{M}\sum_{m=1}^{M}P^{(m)}(C) \tag{2}$$

Ⅲ. Mathematical Preliminaries

In this section, we present a series of lemmas needed to derive the random coding bound. Before proceeding, to facilitate the discussion, we define the function $P_r(\alpha_1,\cdots,\alpha_{q^{MN}})$ called the random coding bound by

$$P_r(\alpha_1,\cdots,\alpha_{q^{MN}})=\sum_{k=1}^{q^{MN}}\alpha_k P(C_k) \tag{3}$$

for non-negative real numbers $\alpha_1,\cdots,\alpha_{q^{MN}}$ satisfying $\alpha_1+\cdots+\alpha_{q^{MN}}=1$. We note that the random coding bound is a kind of weighted average of the decoding error probabilities over all possible codes. There are a number of possible ways to interpret the random coding bound. To see the most important one of them, let us consider the following lemma.

Lemma 1 : Let $\alpha_1,\cdots,\alpha_{q^{NM}}$ be arbitrary non-negative real numbers such that $\alpha_1+\cdots+\alpha_{q^{NM}}=1$. Then, there exists at least one code C_n such that

$$P(C_n) \le P_r(\alpha_1,\cdots,\alpha_{q^{MN}}). \tag{4}$$

Proof : Assume on the contrary that

$$P(C_k) > P_r(\alpha_1,\cdots,\alpha_{q^{MN}}) \tag{5}$$

holds for all code C_k. But, we note that at least one α_n must be strictly positive so that

$$\alpha_n P(C_n) > \alpha_n P_r(\alpha_1,\cdots,\alpha_{q^{MN}}) \tag{6}$$

and hence that

$$\sum_{k=1}^{q^{MN}} \alpha_k P(C_k) > \sum_{k=1}^{q^{MN}} \alpha_k P_r(\alpha_1,\cdots,\alpha_{q^{MN}}) \tag{7}$$

This is a contradiction because both the left and right hand sides of the above inequality indicates the same quantity $P_r(\alpha_1,\cdots,\alpha_{q^{MN}})$.

Lemma 1 says that there exists at least one code that has decoding error probability lower than the random coding bound. In other words, the random coding bound serves as an upper bound for performance achievable by one of the q^{MN} possible codes. But, we note that the random coding bound itself is a function of non-negative real numbers $\alpha_1,\cdots,\alpha_{q^{MN}}$ that can be chosen arbitrary as long as they satisfy the condition $\alpha_1+\cdots+\alpha_{q^{MN}}=1$. The next lemma provide a class of possible choices of $\alpha_1,\cdots,\alpha_{q^{MN}}$.

Before proceeding to Lemma 2, we define q functions $n_1,\cdots,n_q$ defined on A^N so that $n_i(\boldsymbol{c})$ denotes the number of symbol i contained in the vector $\boldsymbol{c}\in A^N$. By $n_i(\boldsymbol{c})$, we desire to indicate the number of symbol i contained in a codeword $\boldsymbol{c}\in A^N$. Next, we define another set of functions $N_1,\cdots,N_q$ defined on the set of codes $\{C_1,\cdots,C_{q^{MN}}\}$ so that $N_i(C_k)$ indicates the number of symbol i in all the codewords in C_k. Then, it follows that

$$N_i(C_k) = \sum_{\boldsymbol{c}\in C_k} n_i(\boldsymbol{c}) \tag{8}$$

Lemma 2 : Let $p_1,\cdots,p_q$ be non-negative real numbers with $p_1+\cdots+p_n=1$ and define α_k by

$$\alpha_k = p_1^{N_1(C_k)} p_2^{N_2(C_k)} \cdots p_q^{N_q(C_k)} \tag{9}$$

for $k=1,\cdots,q^{NM}$. Then, α_k's are non-negative real numbers and $\alpha_1+\cdots+\alpha_{q^{NM}}=1$.

Proof : We can regard that a code C_k can be regarded as a string of NM symbols from A with each N consecutive symbols indicating a codeword. Then, the set $\{C_1,\cdots,C_{q^{NM}}\}$ of all codes denotes the set of all strings of symbols from A of length NM. Consequently, it follows that

$$\begin{aligned}
&\sum_{k=1}^{q^{MN}} p_1^{N_1(C_k)} \cdots p_q^{N_q(C_k)} \\
&= \sum_{\boldsymbol{c}^{(1)}\in A^N} \cdots \sum_{\boldsymbol{c}^{(M)}\in A^N} p_1^{N_1(\{\boldsymbol{c}^{(1)},\cdots,\boldsymbol{c}^{(M)}\})} \cdots p_q^{N_q(\{\boldsymbol{c}^{(1)},\cdots,\boldsymbol{c}^{(M)}\})} \\
&= \sum_{\boldsymbol{c}^{(1)}\in A^N} \cdots \sum_{\boldsymbol{c}^{(M)}\in A^N} p_1^{\sum_{m=1}^{M} n_1(\boldsymbol{c}^{(m)})} \cdots p_q^{\sum_{m=1}^{M} n_q(\boldsymbol{c}^{(m)})} \\
&= \left[\sum_{\boldsymbol{c}^{(1)}\in A^N} \prod_{i=1}^{q} p_i^{n_i(\boldsymbol{c}^{(1)})}\right] \cdots \left[\sum_{\boldsymbol{c}^{(M)}\in A^N} \prod_{i=1}^{q} p_i^{n_i(\boldsymbol{c}^{(M)})}\right]
\end{aligned} \tag{10}$$

which should be equal to 1 since

$$\sum_{c\in A^N}\prod_{i=1}^{q}p_i^{n_i(c)}=\sum_{c_1\in A}\cdots\sum_{c_N\in A}\prod_{i=1}^{q}p_i^{n_i((c_1,\cdots,c_N))} \tag{11}$$
$$=\sum_{c_1=1}^{q}\cdots\sum_{c_N=1}^{q}p_{c_1}\cdots p_{c_N}$$
$$=\left(\sum_{c_1=1}^{q}p_{c_1}\right)\cdots\left(\sum_{c_N=1}^{q}p_{c_N}\right)$$
$$=1$$

We shall use the α_k's defined in Lemma 2 in deriving Gallager random coding bound. We shall first obtain a Gallager bound on $P^{(m)}(C_k)$. For that purpose, we define a notation $P(y|c)$ to denote the probability of receiving y when the codeword c is transmitted. Since we are dealing with a discrete memoryless channel with transition probability T_{ij}, it follows that

$$P(y=(j_1,\cdots,j_N)|c=(i_1,\cdots,i_N))=T_{i_1j_1}\cdots T_{i_Nj_N}. \tag{12}$$

Lemma 3 : Let $c_k^{(m)}$ denote the m^{th} codeword of the code C_k. Then, for any $\beta>0$, we have

$$P^{(m)}(C_k)\le\sum_{y\in B^N}\left[P(y|c_k^{(m)})\right]^{\frac{1}{1+\beta}} \tag{13}$$
$$\times\left\{\sum_{l\neq m}\left[P(y|c_k^{(l)})\right]^{\frac{1}{1+\beta}}\right\}^{\beta}$$

Proof : Since the decoder is assumed to use the maximum likelihood decision rule, the decision region $D^{(m)}(C_k)$ is given by
$D_k^{(m)}=\{y\in B^N: P(y|c_k^{(m)})\ge \max_l P(y|c_k^{(l)})\}$.
Now, let β be an arbitrarily chosen positive real number. Then, since for any $y\not\in D^{(m)}(C_k)$,

$$\left\{\sum_{l\neq m}\left[\frac{P(y|c_k^{(l)})}{P(y|c_k^{(m)})}\right]^{\frac{1}{1+\beta}}\right\}^{\beta}\ge 1 \tag{14}$$

and since $D^{(m)}(C_k)\subseteq B^N$, it follows

$$P^{(m)}(C_k)=\sum_{y\not\in D_k^{(m)}}P(y|c_k^{(m)}) \tag{15}$$
$$\le\sum_{y\not\in D_k^{(m)}}P(y|c_k^{(m)})\left\{\sum_{l\neq m}\left[\frac{P(y|c_k^{(l)})}{P(y|c_k^{(m)})}\right]^{\frac{1}{1+\beta}}\right\}^{\beta}$$
$$\le\sum_{y\in B^N}P(y|c_k^{(m)})\left\{\sum_{l\neq m}\left[\frac{P(y|c_k^{(l)})}{P(y|c_k^{(m)})}\right]^{\frac{1}{1+\beta}}\right\}$$
$$=\sum_{y\in B^N}\left[P(y|c_k^{(m)})\right]^{\frac{1}{1+\beta}}\left\{\sum_{l\neq m}\left[P(y|c_k^{(l)})\right]^{\frac{1}{1+\beta}}\right\}^{\beta}$$

Ⅳ. Random Coding Bound

In this section, using the lemmas presented in the previous section, we derive the random coding bound purely by algegraic manipulations of simple inequalities. The result is presented in the following theorem.

Theorem 1 (Random Coding Bound):
Let $p_1,\cdots,p_q$ be arbitrarily chosen non-negative real numbers such that $\sum_{i=1}^{q}p_i=1$. Then, for any $\beta\in(0,1)$, there exists at least one code C_n such that

$$P(C_n)\le(M-1)^{\beta}\left[\sum_{j=1}^{r}\left\{\sum_{i=1}^{q}p_iT_{ij}^{\frac{1}{1+\beta}}\right\}^{1+\beta}\right]^{N} \tag{16}$$

Proof : First, we define $\alpha_1,\cdots,\alpha_{p^{NM}}$ as in Lemma 2. Also we define $P_r^{(m)}(\alpha_1,\cdots,\alpha_{p^{NM}})$ by

$$P_r^{(m)}(\alpha_1,\cdots,\alpha_{p^{NM}})=\sum_{k=1}^{q^{NM}}\alpha_kP^{(m)}(C_k) \tag{17}$$

so that

$$P_r(\alpha_1,\cdots,\alpha_{q^{NM}})=\frac{1}{M}\sum_{m=1}^{M}P_r^{(m)}(\alpha_1,\cdots,\alpha_{q^{NM}}) \tag{18}$$

Then,

$$\begin{aligned}
&P_r^{(m)}(\alpha_1,\cdots,\alpha_{q^{NM}}) \\
&=\sum_{c^{(1)}\in A^N}\cdots\sum_{c^{(M)}\in A^N} p_1^{N_1(\{c^{(1)},\cdots,c^{(M)}\})}\cdots p_q^{N_q(\{c^{(1)},\cdots,c^{(M)}\})} \\
&\qquad\times P^{(m)}(\{c^{(1)},\cdots,c^{(M)}\}) \\
&=\sum_{c^{(1)}\in A^N}\cdots\sum_{c^{(M)}\in A^N} p_1^{\sum_{l=1}^{M} n_1(c^{(l)})}\cdots p_q^{\sum_{l=1}^{M} n_q(c^{(l)})} \\
&\qquad\times P^{(m)}(\{c^{(1)},\cdots,c^{(M)}\})
\end{aligned} \tag{19}$$

Now, let β be abitrarily chosen real number in $(0,1)$. Then, from Lemma 3, we obtain

$$\begin{aligned}
&P_r^{(m)}(\alpha_1,\cdots,\alpha_{q^{NM}}) \\
&\le \sum_{c^{(1)}\in A^N}\cdots\sum_{c^{(M)}\in A^N} p_1^{\sum_{l=1}^{M} n_1(c^{(l)})}\cdots p_q^{\sum_{l=1}^{M} n_q(c^{(l)})} \\
&\quad \sum_{y\in B^N}[P(y|c^{(m)})]^{\frac{1}{1+\beta}}\left\{\sum_{l\ne m}[P(y|c^{(l)})]^{\frac{1}{1+\beta}}\right\}^{\beta} \\
&=\sum_{y\in B^N}\left\{\sum_{c^{(m)}\in A^N}\left(\prod_{i=1}^{q}p_i^{n_i(c^{(m)})}\right)[P(y|c^{(m)})]^{\frac{1}{1+\beta}}\right\} \\
&\times\prod_{l\ne m}\left(\sum_{c^{(l)}\in A^N}\prod_{j=1}^{q}p_j^{n_j(c^{(l)})}\right)\left\{\sum_{l\ne m}[P(y|c^{(l)})]^{\frac{1}{1+\beta}}\right\}^{\beta}
\end{aligned} \tag{20}$$

Next, we apply the Jensen inequality according to which

$$t_1x_1^{\delta}+\cdots+t_rx^{\delta}\le(t_1x_1+\cdots+t_rx_r)^{\delta} \tag{21}$$

holds for any non-negative real numbers $t_1,\cdots,t_r$ and $x_1,\cdots,x_r$ such that $t_1+\cdots+t_r=1$ when $0<\delta<1$. Now, applying the above inequality,

we obtain

$$\begin{aligned}
&\left\{\prod_{l\ne m}\left(\sum_{c^{(l)}\in A^N}\prod_{j=1}^{q}p_j^{n_j(c^{(l)})}\right)\right\}\left\{\sum_{n\ne m}[P(y|c^{(n)})]^{\frac{1}{1+\beta}}\right\}^{\beta} \\
&\le\left[\prod_{l\ne m}\left(\sum_{c^{(l)}\in A^N}\prod_{j=1}^{q}p_j^{n_j(c^{(l)})}\right)\sum_{n\ne m}[P(y|c^{(n)})]^{\frac{1}{1+\beta}}\right]^{\beta} \\
&=\left[\sum_{n\ne m}\prod_{l\ne m}\left(\sum_{c^{(l)}\in A^N}\prod_{j=1}^{q}p_j^{n_j(c^{(l)})}\right)[P(y|c^{(n)})]^{\frac{1}{1+\beta}}\right]^{\beta} \\
&=\left[\sum_{n\ne m}\sum_{c^{(n)}\in A^N}\left(\prod_{j=1}^{q}p_j^{n_j(c^{(n)})}\right)[P(y|c^{(n)})]^{\frac{1}{1+\beta}}\right]^{\beta} \\
&=\left[(M-1)\sum_{c\in A^N}\left(\prod_{j=1}^{q}p_j^{n_j(c)}\right)[P(y|c)]^{\frac{1}{1+\beta}}\right]^{\beta}
\end{aligned} \tag{22}$$

Hence, it follows

$$\begin{aligned}
&P_r^{(m)}(\alpha_1,\cdots,\alpha_{q^{NM}}) \\
&\le(M-1)^{\beta}\sum_{y\in B^N}\left\{\sum_{c\in A^N}\left(\prod_{i=1}^{q}p_i^{n_i(c)}\right)[P(y|c)]^{\frac{1}{1+\beta}}\right\}^{\beta+1}
\end{aligned} \tag{23}$$

Here, if we write $c=(c_1,\cdots,c_N)$ and $y=(y_1,\cdots,y_N)$, then

$$p_1^{n_1(c)}\cdots p_q^{n_q(c)}=p_{c_1}\cdots p_{c_N} \tag{24}$$

and

$$P(y|c)=T_{c_1y_1}\cdots T_{c_Ny_N} \tag{25}$$

Consequently, by rewriting the above inequality, we obtain

$$\begin{aligned}
&P_r^{(m)}(\alpha_1,\cdots,\alpha_{q^{NM}}) \\
&\le(M-1)^{\beta}\sum_{y\in B^N}\left\{\sum_{c\in A^N}\prod_{i=1}^{N}\left(p_{c_i}[T_{c_iy_i}]^{\frac{1}{1+\beta}}\right)\right\}^{\beta+1}
\end{aligned} \tag{26}$$

Next, we note that

$$\begin{aligned}
&\sum_{y\in B^N}\left\{\sum_{c\in A^N}\prod_{i=1}^{N}\left(p_{c_i}[T_{c_iy_i}]^{\frac{1}{1+\beta}}\right)\right\}^{\beta+1} \\
&=\sum_{y\in B^N}\left\{\prod_{i=1}^{N}\left(\sum_{c_i\in A}p_{c_i}[T_{c_iy_i}]^{\frac{1}{1+\beta}}\right)\right\}^{\beta+1} \\
&=\sum_{y\in B^N}\prod_{i=1}^{N}\left\{\left(\sum_{c_i\in A}p_{c_i}[T_{c_iy_i}]^{\frac{1}{1+\beta}}\right)\right\}^{\beta+1}
\end{aligned} \tag{27}$$

$$= \prod_{i=1}^{N} \left[\sum_{y_i \in B} \left\{ \left(\sum_{c_i \in A} p_{c_i} [T_{c_i y_i}]^{\frac{1}{1+\beta}} \right) \right\}^{\beta+1} \right]$$
$$= \left[\sum_{y \in B} \left\{ \left(\sum_{c \in A} p_c [T_{cy}]^{\frac{1}{1+\beta}} \right) \right\}^{\beta+1} \right]^N$$

to conclude

$$P_r^{(m)}(\alpha_1,\cdots,\alpha_{q^{NM}}) \le (M-1)^\beta \left[\sum_{j=1}^{r} \left\{ \sum_{i=1}^{q} p_i [T_{ij}]^{\frac{1}{1+\beta}} \right\}^{1+\beta} \right]^N \quad (28)$$

This implies, in turn, that

$$P_r(\alpha_1,\cdots,\alpha_{q^{NM}}) = \frac{1}{M} \sum_{m=1}^{M} P_r^{(m)}(\alpha_1,\cdots,\alpha_{q^{NM}}) \le (M-1)^\beta \left[\sum_{j=1}^{r} \left\{ \sum_{i=1}^{q} p_i [T_{ij}]^{\frac{1}{1+\beta}} \right\}^{1+\beta} \right]^N \quad (29)$$

Finally, using Lemma 1, we conclude that there exists at least one code C_n such that

$$P(C_n) \le P_r(\alpha_1,\cdots,\alpha_{q^{NM}}) \le (M-1)^\beta \left[\sum_{j=1}^{r} \left\{ \sum_{i=1}^{q} p_i [T_{ij}]^{\frac{1}{1+\beta}} \right\}^{1+\beta} \right]^N \quad (30)$$

We note that the Gallager random coding bound in Theorem 1 depends on the choices of the probabilities $p_1,\cdots,p_q$ and the real number β. Hence, we can further attempt to obtain minimum random coding bound over all possible choices of these values. In fact, it is shown in [1] that the channel coding theorem for discrete memoryless channel can be derived from Theorem 1 by solving this minimization problem.

Ⅴ. Conclusions

In this letter, we presented an alternative derivation of the Gallager random coding bound based on simple algebraic manipulations rather than invoking the random coding argument which is conceptually harder to understand. We believe the derivation in this letter will be useful to the readers not only in obtaining various practical performance bounds but also in making themselves better understand the random coding bound arguments itself so that they can easily apply the methods to practical problems of their own interest.

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