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On the rate of channel polarization

Erdal Arıkan
Department of Electrical-Electronics Engineering
Bilkent University
Ankara, TR-06800, Turkey
Email: arikan@ee.bilkent.edu.tr

Emre Telatar
Information Theory Laboratory
Ecole Polytechnique Fédérale de Lausanne
CH-1015 Lausanne, Switzerland
Email: emre.telatar@epfl.ch

***Abstract*—A bound is given on the rate of channel polarization. As a corollary, an earlier bound on the probability of error for polar coding is improved. Specifically, it is shown that, for any binary-input discrete memoryless channel W with symmetric capacity $I(W)$ and any rate $R < I(W)$, the polar-coding block-error probability under successive cancellation decoding satisfies $P_e(N, R) \le 2^{-N^\beta}$ for any $\beta < \frac{1}{2}$ when the block-length N is large enough.**

I. Results

Channel polarization is a method introduced in [1] for constructing capacity-achieving codes on symmetric binary-input memoryless channels. Both the construction and the probability of error analysis of polar codes, as these codes were called, are centered around a random process $\{Z_n : n \in \mathbb{N}\}$ which keeps track of the Bhattacharyya parameters of the channels that arise in the course of channel polarization. The aim here is to give an asymptotic convergence result on $\{Z_n\}$ in as simple a setting as possible. For further background on the problem, we refer to [1].

For the purposes here, the polarization process can be modeled as follows. Suppose B_i, $i = 1, 2, \ldots$, are i.i.d., $\{0, 1\}$-valued random variables with

$$P(B_1 = 0) = P(B_1 = 1) = \frac{1}{2}$$

defined on a probability space $(\Omega, \mathcal{F}, P)$. Set $\mathcal{F}_0 = \{\emptyset, \Omega\}$ as the trivial σ-algebra and set $\mathcal{F}_n$, $n \ge 1$, to be the σ-algebra generated by $(B_1, \ldots, B_n)$. We may assume that $\mathcal{F} = \bigcup_{n\ge 0} \mathcal{F}_n$.

Suppose further that a stochastic process $\{Z_n : n \in \mathbb{N}\}$ is defined on this probability space with the following properties:

(z.1) For each $n \in \mathbb{N}$, Z_n takes values in the interval $[0, 1]$ and is measurable with respect to $\mathcal{F}_n$. That is, Z_0 is constant, and Z_n is a function of $B_1, \ldots, B_n$.

(z.2) For some constant q and for each $n \in \mathbb{N}$,

$$\begin{aligned} Z_{n+1} &= Z_n^2 && \text{when } B_{n+1} = 1, \\ Z_{n+1} &\le q Z_n && \text{when } B_{n+1} = 0. \end{aligned}$$

(z.3) $\{Z_n\}$ converges a.s. to a $\{0, 1\}$-valued random variable Z_∞ with $P(Z_\infty = 0) = I_0$ for some $I_0 \in [0, 1]$.

The main result of this note is that whenever $\{Z_n\}$ converges to zero, this converges is almost surely fast:

Theorem 1: For any $\beta < 1/2$,

$$\lim_{n\to\infty} P\big(Z_n < 2^{-2^{n\beta}}\big) = I_0. \tag{1}$$

Remark 1: The random process $\{Z_n : n \in \mathbb{N}\}$ considered in [1] satisfies the properties (z.1)–(z.3) with $q = 2$ and $I_0 = I(W)$ where $I(W)$ denotes the symmetric capacity of the underlying channel W. The framework in this note is held more general than in [1] in anticipation of the results here being applicable to more general channel polarization scenarios.

Remark 2: Clearly, the statement of the theorem remains valid if we replace $2^{-2^{n\beta}}$ with $\alpha^{-2^{n\beta}}$ for any $\alpha > 1$.

Remark 3: As a corollary to Theorem 1, the result of [1] on the probability of block-error for polar coding under successive cancellation decoding is strengthened as follows.

Theorem 2: Let W be any B-DMC with $I(W) > 0$. Let $R < I(W)$ and $\beta < \frac{1}{2}$ be fixed. Then, for $N = 2^n$, $n \ge 0$, the block error probability for polar coding under successive cancellation decoding at block length N and rate R satisfies

$$P_e(N, R) = \mathcal{O}\big(2^{-N^\beta}\big).$$

In comparison, the result in [1] was that for $R < I(W)$

$$P_e(N, R) = \mathcal{O}(N^{-\frac{1}{4}}).$$

Remark 4: The polarization process $\{Z_n\}$ considered in [1] satisfies the additional condition that $Z_{n+1} \ge Z_n$ when $B_{n+1} = 0$. Under this condition, Theorem 1 has the following converse.

Theorem 3: If the condition (z.2) in the definition of $\{Z_n : n \in \mathbb{N}\}$ is replaced with the condition that

$$\begin{aligned} Z_{n+1} &= Z_n^2 && \text{when } B_{n+1} = 1, \\ Z_{n+1} &\ge Z_n && \text{when } B_{n+1} = 0, \end{aligned}$$

and if $Z_0 > 0$, then for any $\beta > 1/2$,

$$\lim_{n\to\infty} P\big(Z_n < 2^{-2^{n\beta}}\big) = 0. \tag{2}$$

In the rest of this note, we prove Theorems 1 and 3. We leave out the proof of Theorem 2 since it follows readily from the existing results in [1].

II. Proof of Theorem 1

Lemma 1: Let $A : \mathbb{R} \to \mathbb{R}$, $A(x) = x + 1$ denote adding one, and $D : \mathbb{R} \to \mathbb{R}$, $D(x) = 2x$ denote doubling. Suppose a sequence of numbers $a_0, a_1, \ldots, a_n$ is defined by specifying a_0 and the recursion

$$a_{i+1} = f_i(a_i)$$

with $f_i \in \{A, D\}$. Suppose $\big|\{0 \le i \le n-1 : f_i = D\}\big| = k$ and $\big|\{0 \le i \le n-1 : f_i = A\}\big| = n-k$, i.e., during the first n iterations of the recursion we encounter doubling k times and adding-one $n-k$ times. Then

$$a_n \le D^{(k)}\big(A^{(n-k)}(a_0)\big) = 2^k(a_0 + n - k).$$

Proof: Observe that the upper bound on a_n corresponds to choosing

$$f_0 = \cdots f_{n-k-1} = A \quad \text{and} \quad f_{n-k} = \cdots = f_{n-1} = D.$$

We will show that any other choice of $\{f_i\}$ can be modified to yield a higher value of a_n. To that end suppose $\{f_i\}$ is not chosen as above. Then there exists $j \in \{1, \ldots, n-1\}$ for which $f_{j-1} = D$ and $f_j = A$. Define $\{f_i'\}$ by swapping f_j and f_{j-1}, i.e.,

$$f_i' = \begin{cases} A & i = j-1 \\ D & i = j \\ f_i & \text{else} \end{cases}$$

and let $\{a_i'\}$ denote the sequence that results from $\{f_i'\}$. Then

$$\begin{aligned} a_i' &= a_i \quad \text{for } i < j \\ a_j' &= a_{j-1} + 1 \\ a_{j+1}' &= 2a_j' = 2a_{j-1} + 2 \\ &> 2a_{j-1} + 1 = a_{j+1}. \end{aligned}$$

Since the recursion from $j+1$ onwards is identical for the $\{f_i\}$ and $\{f_i'\}$ sequences, and since both A and D are order preserving, $a_{j+1}' > a_{j+1}$ implies that $a_n' > a_n$. ∎

Lemma 2: For any $\epsilon > 0$ there exists an m such that

$$P\big(Z_n \le 1/q^2 \text{ for all } n \ge m\big) > I_0 - \epsilon.$$

Proof: Let $\Omega_0 = \{\omega : Z_n(\omega) \to 0\}$. Recall that by (z.3) $P(\Omega_0) = I_0$. Since for non-negative sequences, "$a_n \to 0$" is the same as "for all $k \ge 1$ there exists n_0 such that for all $n \ge n_0$, $a_n < 1/k$," we have

$$\Omega_0 = \bigcap_{k \ge 1} \bigcup_{n_0 \ge 1} A_{n_0,k}$$

where $A_{n_0,k} := \big\{\omega : \text{for all } n \ge n_0,\, Z_n(\omega) < 1/k\big\}$. Thus, for any choice of k, Ω_0 is included in $\bigcup_{n_0} A_{n_0,k}$, and for $k = q^2$,

$$I_0 = P(\Omega_0) \le P\left(\bigcup_{n_0 \ge 1} A_{n_0,q^2}\right).$$

Since A_{n_0,q^2} is increasing in n_0, for any $\epsilon > 0$ there is an m so that

$$P\big(A_{m,q^2}\big) > P\left(\bigcup_{n_0 \ge 1} A_{n_0,q^2}\right) - \epsilon \ge I_0 - \epsilon.$$ ∎

Lemma 3: For any $\epsilon > 0$ there is an n_0 such that whenever $n \ge n_0$

$$P\big(\log_q Z_n \le -n/10\big) > I_0 - \epsilon.$$

Proof: Define $S_n = \sum_{i=1}^n B_i$. Define $G_{m,n,\alpha}$ as the event

$$S_n - S_m \ge \alpha(n-m)$$

i.e., the event that the slice $\{B_i : i = m+1, \ldots, n\}$ contains more than an α fraction of ones. Note that for any $\alpha < 1/2$, whenever $n - m$ is large, this event has probability close to 1; formally, for any $\alpha < 1/2$ and $\epsilon > 0$ there is $n_0 = n_0(\epsilon, \alpha)$ such that $P(G_{m,n,\alpha}) > 1 - \epsilon$ whenever $n - m \ge n_0$. Let $A_m := \{\omega : Z_n(\omega) < 1/q^2 \text{ for all } n \ge m\}$. Given $\epsilon > 0$, find $m = m(\epsilon)$ such that $P(A_m) > I_0 - \epsilon/2$. Such an m exists by Lemma 2.

Note that for $\omega \in A_m$, and $n \ge m$, we have

$$\begin{aligned} Z_{n+1} &= Z_n^2 \le Z_n/q^2 && \text{when } B_{n+1} = 1, \\ Z_{n+1} &\le qZ_n && \text{when } B_{n+1} = 0. \end{aligned}$$

Considering $\log_q Z_n$, we get

$$\begin{aligned} \log_q Z_{n+1} &\le \log_q Z_n - 2 && \text{when } B_{n+1} = 1, \\ \log_q Z_{n+1} &\le \log_q Z_n + 1 && \text{when } B_{n+1} = 0. \end{aligned}$$

Consequently,

$$\begin{aligned} \log_q Z_n &\le \log_q Z_m - 2(S_n - S_m) + (n - m - (S_n - S_m)) \\ &\le -3(S_n - S_m) + (n - m). \end{aligned}$$

Now find $n_0 \ge 2m$ such that whenever $n \ge n_0$, $P(G_{m,n,2/5}) > 1 - \epsilon/2$. Then for any $n \ge n_0$, for $\omega \in A_m \cap G_{m,n,2/5}$ we have

$$\log_q Z_n \le -(n-m)/5 \le -n/10.$$

Noting that $P\big(A_m \cap G_{m,n,2/5}\big) > I_0 - \epsilon$, the proof is completed. ∎

Proof of Theorem 1. Given $\beta < 1/2$, fix $\beta' \ge 1/3$ and $\beta' \in (\beta, 1/2)$. Choose $n_3(\epsilon)$ such that with $n_2(\epsilon) := 3\log_2 n_3(\epsilon)$ and $n_1(\epsilon) := 20\, n_2(\epsilon)$, we have

(i) $n_1(\epsilon) \ge 40$ and $n_1(\epsilon) \ge n_0(\epsilon/3)$ where n_0 is as in Lemma 3,
(ii) $P(G_{n_1(\epsilon), n_1(\epsilon)+n_2(\epsilon), \beta'}) > 1 - \epsilon/3$,
(iii) $P(G_{n_1(\epsilon)+n_2(\epsilon), n_3(\epsilon), \beta'}) > 1 - \epsilon/3$,
(iv) $\beta'(n_3(\epsilon) - n_1(\epsilon) - n_2(\epsilon)) \ge \beta n_3(\epsilon) + \log_2(\log_q(2))$.

Given $n \ge n_3(\epsilon)$ set $n_2 = 3\log_2 n$ and $n_1 = 20\, n_2$. Observe that (i)–(iv) are satisfied with (n_1, n_2, n) in place of $(n_1(\epsilon), n_2(\epsilon), n_3(\epsilon))$. Let

$$G = \big\{\log_q Z_{n_1} \le -n_1/10\big\} \cap G_{n_1, n_1+n_2, \beta'} \cap G_{n_1+n_2, n, \beta'}.$$

Note that $P(G) > I_0 - \epsilon$. Observe that the process $\{\log_q Z_i : i \ge n_1\}$ is upper bounded by the process $\{L_i : i \ge n_1\}$ defined by $L_{n_1} = \log_q Z_{n_1}$ and for $i \ge n_1$

$$\begin{aligned} L_{i+1} &= 2L_i && \text{when } B_{i+1} = 1, \\ L_{i+1} &= L_i + 1 && \text{when } B_{i+1} = 0. \end{aligned}$$

For $\omega \in G$ we have

(a) $L_{n_1} \leq -n_1/10$,
(b) during the evolution of L_i from time n_1 to n_1+n_2 there are at least $\beta' n_2$ doublings,
(c) during the evolution of L_i from time n_1+n_2 to n there are at least $\beta'(n-n_1-n_2)$ doublings.

By Lemma 1 we obtain

$$\begin{aligned} L_{n_1+n_2} &\leq 2^{\beta' n_2}(L_{n_1}+n_2) \\ &\leq 2^{\beta' n_2}(-n_1/10+n_2) \\ &\leq -2^{\beta' n_2} n_1/20 \end{aligned}$$

and

$$\begin{aligned} L_n &\leq 2^{\beta'(n-n_1-n_2)}\big(L_{n_1+n_2}+(n-n_1-n_2)\big) \\ &\leq 2^{\beta'(n-n_1-n_2)}\big(-2^{\beta' n_2} n_1/20+n\big) \\ &\leq 2^{\beta'(n-n_1-n_2)}\big(-2^{n_2/3} n_1/20+n\big) \\ &\leq 2^{\beta'(n-n_1-n_2)}\big(-n(n_1/20-1)\big) \\ &\leq -n2^{\beta'(n-n_1-n_2)} \\ &\leq -2^{\beta'(n-n_1-n_2)} \\ &\leq -(\log_q(2))^{\beta n}. \end{aligned}$$

This implies that $Z_n \leq 2^{-2^{\beta n}}$ on a set of probability at least $I_0-\epsilon$ whenever $n \geq n_3(\epsilon)$, completing the proof.

III. Proof of Theorem 3

Let $\{Z_n : n \in \mathbb{N}\}$ be a process satisfying the hypothesis of Theorem 3. Observe that the random process $\big\{\log_2\big(-\log_2(Z_n)\big) : n \in \mathbb{N}\big\}$ is upper bounded by the process $\{K_n : n \in \mathbb{N}\}$ defined by $K_0 := \log_2(-\log_2(Z_0))$ and for $n \geq 1$

$$K_n := K_{n-1} + B_n = K_0 + \sum_{i=1}^{n} B_i.$$

So, we have

$$\begin{aligned} P\big(Z_n \leq 2^{-2^{\beta n}}\big) &= P\big(\log_2\big(-\log_2(Z_n)\big) \geq \beta n\big) \\ &\leq P(K_n \geq \beta n) \\ &= P\left(\sum_{i=1}^{n} B_i \geq n\beta - K_0\right). \end{aligned}$$

For $\beta > \frac{1}{2}$, this last probability goes to zero as n increases by the law of large numbers.

IV. Concluding remarks

In an earlier version of this note [2], Theorem 1 was proved using the following inequality due to Hajek [3] in place of Lemma 2.

Lemma 4: Suppose $\{Z_n : n \in \mathbb{N}\}$ satisfies the conditions (z.1)-z(3) with (z.2) replaced with:

(z.2) For each $n \in \mathbb{N}$,

$$\begin{aligned} Z_{n+1} &= Z_n^2 && \text{when } B_{n+1}=1, \\ Z_{n+1} &= Z_n^2 - 2Z_n && \text{when } B_{n+1}=0. \end{aligned}$$

Then $E\big[\sqrt{Z_n(1-Z_n)}\big] \leq \frac{1}{2}\big(\frac{3}{4}\big)^{n/2}$.

The present proof is more direct and simpler than the one in [2].

In recent work, Korada et al. generalized the above rate of channel polarization results as part of a study where they considered more general forms of polar code constructions [4]. There $\{B_i : i = 1, 2, \ldots\}$ were taken as i.i.d., $\{0, 1, \ldots, \ell-1\}$-valued random variables with

$$P(B_1 = i) = \frac{1}{\ell}, \qquad i = 0, \ldots, \ell-1,$$

for some $\ell \geq 2$. The random process $\{Z_n : n \in \mathbb{N}\}$ was defined with the properties (z.1) and (z.3) as in here, but with (z.2) modified as:

(z.2) For each $n \in \mathbb{N}$ and $i = 0, \ldots, \ell-1$,

$$Z_n^{D_i} \leq Z_{n+1} \leq 2^{\ell-i} Z_n^{D_i} \qquad \text{when } B_{n+1} = i$$

where $\{D_i : 0 \leq i \leq \ell-1\}$ are a set of positive constants.

The following result was proved in [4].

Theorem 4: Let $E := \frac{1}{\ell}\sum_{i=0}^{\ell-1} \log_\ell D_i$. Then,

$$\begin{aligned} &\lim_{n\to\infty} P(Z_n < 2^{-\ell^{n\beta}}) = I_0 && \text{when } \beta < E, \\ &\lim_{n\to\infty} P(Z_n < 2^{-\ell^{n\beta}}) = 0 && \text{when } \beta > E. \end{aligned}$$

An open problem that remains is to obtain a more refined bound on the rate of channel polarization. Specifically, it would be of interest to find a function $\gamma : \mathbb{N} \times [0,1] \to [0,1]$ such that for any given $R \in [0,1]$

$$\lim_{n\to\infty} P(Z_n \leq \gamma(n,R)) = R.$$

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