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Kyoto University
Review on Capacity of Gaussian Channel with or without Feedback

Kenjiro Yanagi (Yamaguchi University)

1 Probability Measure on Banach Space

Let $X$ be a real separable Banach space and $X^*$ be its dual space. Let $\mathcal{B}(X)$ be Borel $\sigma$-field of $X$. For finite dimensional subspace $F$ of $X^*$ we define the cylinder set $C$ based on $F$ as follows

$$C = \{x \in X; (\langle x, f_1 \rangle, \langle x, f_2 \rangle, \ldots, \langle x, f_n \rangle) \in D\}.$$  

where $n \geq 1$, $\{f_1, f_2, \ldots, f_n\} \subset F, D \in \mathcal{B}(\mathbb{R}^n)$. We denote all of cylinder sets based on $F$ by $\mathcal{C}_F$. Then we put

$$\mathcal{C}(X, X^*) = \bigcup \{\mathcal{C}_F; F \text{ is finite dimensional subspaces of } X^*\}.$$  

It is easy to show that $\mathcal{C}(X, X^*)$ is a field. Let $\mathcal{C}(X, X^*)$ be the $\sigma$-field generated by $\mathcal{C}(X, X^*)$. Then $\mathcal{C}(X, X^*) = \mathcal{B}(X)$. If $\mu$ is a probability measure on $(X, \mathcal{B}(X))$ satisfying $\int_{X} \|x\|^2 d\mu(x) < \infty$, then there exist a vector $m \in X$ and an operator $R : X^* \rightarrow X$ such that

$$\langle m, x^* \rangle = \int_{X} \langle x, x^* \rangle d\mu(x),$$  

$$\langle Rx^*, y^* \rangle = \int_{X} \langle x - m, x^* \rangle \langle x - m, y^* \rangle d\mu(x),$$  

for any $x^* \in X^*, y^* \in Y^*$. $m$ is a mean vector of $\mu$ and $R$ is a covariance operator of $\mu$ which is a bounded linear operator. We remark that $R$ is symmetric in the following sense.

$$\langle Rx^*, y^* \rangle = \langle Ry^*, x^* \rangle, \text{ for any } x^*, y^* \in X^*.$$  

And also $R$ is positive in the following sense.

$$\langle Rx^*, x^* \rangle \geq 0, \text{ for any } x^* \in X^*.$$
When $\mu_f = \mu \circ f^{-1}$ is a Gaussian measure on $\mathbb{R}$ for any $f \in X^*$, we call $\mu$ a Gaussian measure on $(X, \mathcal{B}(X))$. For any $f \in X^*$, the characteristic function $\overline{\mu}(f)$ is represented by

$$\overline{\mu}(f) = \exp\{i\langle m, f \rangle - \frac{1}{2}\langle Rf, f \rangle\},$$

(1.1)

where $m \in X$ is mean vector of $\mu$ and $R : X^* \to X$ is covariance operator of $\mu$. Conversely when the characteristic function of a probability measure $\mu$ on $(X, \mathcal{B}(X))$ is given by (1.1), $\mu$ is Gaussian measure whose mean vector is $m \in X$ and covariance operator is $R : X^* \to X$. Then we can represent $\mu = [m, R]$ as Gaussian measure with mean vector $\mu$ and covariance operator $R$.

### 2 Reproducing Kernel Hilbert Space and Mutual Information

For any symmetric positive operator $R : X^* \to X$, there exists a Hilbertian subspace $H (\subset X)$ and a continuous embedding $j : H \to X$ such that $R = jj^*$. $H$ is isomorphic to the reproducing kernel Hilbert space (RKHS) $\mathcal{H}(k_{R})$ which is defined by positive definite kernel $k_{R}$ satisfying $k_{R}(x^*, y^*) = \langle Rx^*, y^* \rangle$. Then we call $H$ itself a reproducing kernel Hilbert space. Now we can define mutual information as follows. Let $X, Y$ be real Banach spaces. Let $\mu_X, \mu_Y$ be probability measures on $(X, \mathcal{B}(X)), (Y, \mathcal{B}(Y))$, respectively, and let $\mu_{XY}$ be joint probability measure on $(X \times Y, \mathcal{B}(X) \times \mathcal{B}(Y))$ with marginal distributions $\mu_X, \mu_Y$, respectively. That is

$$\mu_X(A) = \mu_{XY}(A \times Y), \quad A \in \mathcal{B}(X),$$

$$\mu_Y(B) = \mu_{XY}(X \times B), \quad B \in \mathcal{B}(Y),$$

If we assume

$$\int_X \|x\|^2 d\mu_X(x) < \infty, \quad \int_Y \|y\|^2 d\mu_Y(y) < \infty,$

then there exists $m = (m_1, m_2) \in X \times Y$ such that for any $(x^*, y^*) \in X^* \times Y^*$

$$\langle (m_1, m_2), (x^*, y^*) \rangle = \int_{X \times Y} \langle (x, y), (x^*, y^*) \rangle d\mu_{XY}(x, y),$$

where $m_1, m_2$ are mean vectors of $\mu_X, \mu_Y$, respectively, and there exists $\mathcal{R}$ such that

$$\mathcal{R} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} : X^* \times Y^* \to X \times Y$$

satisfies the following relation: for any $(x^*, y^*), (z^*, w^*) \in X^* \times Y^*$

$$\int_{X \times Y} \langle (x, y) - (m_1, m_2), (x^*, y^*) \rangle \langle (x, y) - (m_1, m_2), (z^*, w^*) \rangle d\mu_{XY}(x, y),$$

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where $R_{11}: X^* \to X$ is covariance operator of $\mu_X$, $R_{22}: Y^* \to Y$ is covariance operator of $\mu_Y$, and $R_{12} = R_{21}^*: Y^* \to X$ is cross covariance operator defined by

$$\langle R_{12} y^*, x^* \rangle = \int_{X \times Y} \langle x - m_1, x^* \rangle \langle y - m_2, y^* \rangle d\mu_{XY}(x, y)$$

for any $(x^*, y^*) \in Y^* \times X^*$.

When we put $\mu_{XY} = \{(0,0), (R_{11} \ R_{12} \ R_{21} \ R_{22})\}$, we obtain $\mu_X = [0, R_X], \mu_Y = [0, R_Y]$. And there exist RKHSs $H_X \subset X$ of $R_X$, $H_Y \subset Y$ of $R_Y$ with continuous embeddings $j_X : H_X \to X$, $j_Y : H_Y \to Y$ satisfying $R_X = j_X j_X^*$, $R_Y = j_Y j_Y^*$, respectively. Furthermore if we assume RKHS $H_X$ is dense in $X$ and RKHS $H_Y$ is dense in $Y$, then there exist $V_{XY} : H_Y \to H_X$ such that

$$R_{XY} = j_X V_{XY} j_Y^*, \|V_{XY}\| \leq 1.$$

Then the following theorem holds.

**Theorem 2.1** $\mu_{XY} \sim \mu_X \otimes \mu_Y$ if and only if $V_{XY}$ is Hilbert-Schmidt operatorsatisfying $\|V_{XY}\| < 1$.

Next we define mutual information of $\mu_{XY}$ in the following. We put

$$\mathcal{F} = \{(\{A_j\}, \{B_j\}); \{A_j\} \text{ is finite measurable partitions of } X \text{ with } \mu_X(A_j) > 0 \text{ and } \{B_j\} \text{ is finite measurable partitions of } Y \text{ with } \mu_Y(B_j) > 0\}.$$

Then

$$I(\mu_{XY}) = \sup \sum_{i,j} \mu_{XY}(A_i \times B_j) \log \frac{\mu_{XY}(A_i \times B_j)}{\mu_X(A_i) \mu_Y(B_j)}.$$

where the supremum is taken by all $(\{A_j\}, \{B_j\}) \in \mathcal{F}$. It is easy to show that if $\mu_{XY} \ll \mu_X \otimes \mu_Y$, then

$$I(\mu_{XY}) = \int_{X \times Y} \log \frac{d\mu_{XY}}{d\mu_X \otimes \mu_Y}(x, y) d\mu_{XY}(x, y)$$

and if otherwise, we put $I(\mu_{XY}) = \infty$.

We introduce several properties without proofs in order to state the exact representation of mutual information. Let $X$ be real separable Banach space and $\mu_X = [0, R_X]$, $H_X$ be RKHS of $R_X$. Let $L_X \equiv X_{\|\cdot\|_{L^2(X)}}$ be the completion by norm of $L_2(X, B(X), \mu_X)$. Then $L_X$ is a Hilbert space with the inner product

$$\langle f, g \rangle_{L_X} = \int_X \langle x, f \rangle \langle x, g \rangle d\mu_X(x)$$

For any embedding $j_X : H_X \to H_X$, there exists an unitary operator $U_X : L_X \to H_X$ such that $U_X f = j_X^* f, f \in X^*$. We give the following important properties of Radon-Nykodym derivatives.
Lemma 2.1 (Pan [17]) Let $X$ be a real separable Banach space and let $\mu_X = [0, R_X]$, $\mu_Y = [m, R_Y]$. Then $\mu_X \sim \mu_Y$ if and only if the following (1), (2), (3) are satisfied.

1. $H_X = H_Y$,
2. $m \in H_X$,
3. $JJ^* - I_X$: Hilbert Schmidt operator,

where $H_X, H_Y$ are RKHS of $R_X, R_Y$, respectively, $J : H_Y \to H_X$ is continuous injection and $I_X : H_X \to H_X$ is an identity operator.

And when (1), (2), (3) hold, we assume $\{\lambda_n\}$ is eigenvalues (≠ 1) of $JJ^*$, $\{v_n\}$ is normalized eigenvectors with respect to $\{\lambda_n\}$. Then

$$\frac{d\mu_Y}{d\mu_X}(x) = \exp\{U_X^{-1}[ JJ^* (JJ^*)^{-1/2} m](x) - \frac{1}{2} < m, (JJ^*)^{-1} m >_{H_X}$$

$$- \frac{1}{2} \sum_{n=1}^{\infty} [(U_X^{-1}v_n)^2(x)(\frac{1}{\lambda_n} - 1) + \log \lambda_n]\},$$

where $U_X : L_X \to H_X$ is an unitary operator.

And when at least one of (1), (2), (3) does not hold, $\mu_X \perp \mu_Y$.

Lemma 2.2 Let $R_X : X^* \to X$, $R_Y : Y^* \to Y$ and

$$\mathcal{R}_{X \otimes Y} \equiv \begin{pmatrix} R_X & 0 \\ 0 & R_Y \end{pmatrix}.$$

Then $\mathcal{R}_{X \otimes Y} : X^* \times Y^* \to X \times Y$ is symmetric, positive. And let $H_X, H_Y, H_{X \otimes Y}$ be RKHS of $R_X, R_Y, \mathcal{R}_{X \otimes Y}$, respectively. Then $H_{X \otimes Y} \cong H_X \times H_Y$.

We obtain the exact representation of mutual information.

Theorem 2.2 If $\mu_{XY} \sim \mu_X \otimes \mu_Y$, then $I(\mu_{XY}) < \infty$ and

$$I(\mu_{XY}) = -\frac{1}{2} \sum_{n=1}^{\infty} \log(1 - \gamma_n),$$

where $\{\gamma_n\}$ are eigenvalues of $V_{XY}^* V_{XY}$.
3 Gaussian Channel

We define Gaussian channel without feedback as follows. Let $X$ be a real separable Banach space representing input space, $Y$ be a real separable Banach space representing output space, respectively. We assume that $\lambda : X \times \mathcal{B}(Y) \to [0, 1]$ satisfies the following (1), (2).

1. For any $x \in X$, $\lambda(x, \cdot) = \lambda_x$ is Gaussian measure on $(Y, \mathcal{B}(Y))$.

2. For any $B \in \mathcal{B}(Y)$, $\lambda(\cdot, B)$ is Borel measurable function on $(X, \mathcal{B}(X))$.

We call a triple $[X, \lambda, Y]$ Gaussian channel. When an input source $\mu_X$ is given, we can define corresponding output source $\mu_Y$ and compound source $\mu_{XY}$ as follows. For any $B \in \mathcal{B}(Y)$

$$\mu_Y(B) = \int_X \lambda(x, B) d\mu_X(x),$$

For any $C \in \mathcal{B}(X) \times \mathcal{B}(Y)$

$$\mu_{XY}(C) = \int_X \lambda(x, C_x) d\mu_X(x),$$

where $C_x = \{y \in Y; (x, y) \in X \times Y\}$.

Capacity of Gaussian channel is defined as the supremum of mutual information $I(\mu_{XY})$ under appropriate constraint on input sources. We put $X = Y$ and $\lambda(x, B) = \mu_Z(B - x)$, $\mu_Z = [0, R_Z]$ for the simplicity. When the constraint is given by

$$\int_X \|x\|_2^2 d\mu_X(x) \leq P,$$

it is called matched Gaussian channel. The capacity is well known to be $P/2$. On the other hand when the constraint is given by

$$\int_X \|x\|_W^2 d\mu_X(x) \leq P,$$

where $\mu_W$ is different from $\mu_Z$, it is called mismatched Gaussian channel. The capacity is given by Baker [4] in the case of $X$ and $Y$ are the same real separable Hilbert space $H$. Yanagi [21] considered the case of channel distribution $\lambda_x = [0, R_x]$ and showed this channel corresponds to the change of density operator $\rho$ after the measurement.

4 Discere Time Gaussian Chennal with Feedback

The model of discrete time Gaussian channel with feedback is defined as follows.

$$Y_n = S_n + Z_n, \ n = 1, 2, \ldots,$$
where $Z = \{Z_n; n = 1, 2, \ldots\}$ is nondegenerate zeno mean Gaussian process representing noise, $S = \{S_n; n = 1, 2, \ldots\}$ is stochastic process representing input signal and $Y = \{Y_n; n = 1, 2, \ldots\}$ is stochastic process representing output signal. The input signal $S_n$ at time $n$ can be represented by some function of message $W$ and output signal $Y_1, Y_2, \ldots, Y_{n-1}$ The error probability for code word $x^n(W, Y^{n-1}), W \in \{1, 2, \ldots, 2^{nR}\}$ with rate $R$ and length $n$ and the decoding function $g_n : \mathbb{R}^n \to \{1, 2, \ldots, 2^{nR}\}$ is defined by

$$P_{e}^{(n)} = Pr\{g_n(Y^n) \neq W; Y^n = x^n(W, Y^{n-1}) + Z^n\},$$

where $W$ is uniform distribution which is independent with the noise $Z^n = (Z_1, Z_2, \ldots, Z_n)$. The input signals is assumed average power constraint. That is

$$\frac{1}{n} \sum_{i=1}^{n} E[S_i^2] \leq P.$$  

The feedback is causal. That is $S_i(i = 1, 2, \ldots, n)$ is dependent with $Z_1, Z_2, \ldots, Z_{i-1}$. In the nonfeedback case $S_i(i = 1, 2, \ldots, n)$ is independent with $Z^n = (Z_1, Z_2, \ldots, Z_n)$. Since the input signals can be assumed Gaussian, we can represent as follows.

$$C_{n,FB}(P) = \max \frac{1}{2n} \log \frac{|R_X^{(n)} + R_Z^{(n)}|}{|R_Z^{(n)}|},$$

where $|\cdot|$ is determinant and the maximum is taken under strictly lower triangle matrix $B$ and nonnegative symmetric matrix $R_X^{(n)}$ satisfying

$$\text{Tr}[(I+B)R_X^{(n)}(I+B)^t + BR_Z^{(n)}B^t] \leq nP.$$  

The nonfeedback capacity is given by the condition $B = 0$. The feedback capacity can be represented by the different form.

$$C_{n,FB}(P) = \max \frac{1}{2n} \log \frac{|R_{S+Z}^{(n)}|}{|R_Z^{(n)}|},$$

where the maximum is taken under nonnegative symmetric matrix $R_S^{(n)}$. Cover and Pombra [9] obtained the following.

**Proposition 4.1 (Cover and Pombra [9])** For any $\epsilon > 0$ there exists $2^{n(C_{n,FB}(P) - \epsilon)}$ cord words with block length $n$ such that $P_{e}^{(n)} \to 0$ for $n \to \infty$. Conversely For any $\epsilon > 0$ and any $2^{n(C_{n,FB}(P) + \epsilon)}$ code words with block length $n$, $P_{e}^{(n)} \to 0 (n \to \infty)$ does not hold.

$C_n(P)$ is given exactly.
Proposition 4.2 (Gallager [10])

\[ C_n(P) = \frac{1}{2n} \sum_{i=1}^{k} \log \frac{nP + r_1 + \cdots + r_k}{kr_i}, \]

where \( 0 < r_1 \leq r_2 \leq \cdots \leq r_n \) are eigenvalues of \( R_Z^{(n)} \), \( k(\leq n) \) is the largest integer satisfying \( nP + r_1 + r_2 + \cdots + r_k > kr_k \).

4.1 Necessary and sufficient condition for increase of feedback capacity

We give the following definition for \( R_Z^{(n)} \).

Definition 4.1 (Yanagi [23]) Let \( R_Z^{(n)} = \{z_{ij}\} \) and \( L_k = \{\ell(\neq k); z_{k\ell} \neq 0\} \). Then

(a) \( R_Z^{(n)} \) is called white if \( L_k = \emptyset \) for any \( k \).

(b) \( R_Z^{(n)} \) is called completely non-white if \( L_k \neq \emptyset \) for any \( k \).

(c) \( R_Z^{(n)} \) is blockwise white if there exists \( k, \ell \) such that \( L_k = \emptyset \) and \( L_\ell \neq \emptyset \).

We denote by \( \tilde{R}_Z \) the submatrix of \( R_Z^{(n)} \) generated by \( k \) with \( L_k \neq \emptyset \).

Theorem 4.1 (Ihara and Yanagi [12], Yanagi [23]) The following (1), (2) and (3) hold.

(1) If \( R_Z^{(n)} \) is white, then \( C_n(P) = C_{n,FB}(P) \) for any \( P > 0 \).

(2) If \( R_Z^{(n)} \) is completely non-white, then \( C_n(P) < C_{n,FB}(P) \) for any \( P > 0 \).

(3) If \( R_Z^{(n)} \) is blockwise white, then we have two cases in the following.

Let \( r_m \) is the minimum eigenvalue of \( \tilde{R}_Z \) and \( nP_0 = mr_m - (r_1 + r_2 + \cdots + r_m) \).

(a) If \( P > P_0 \), then \( C_n(P) < C_{n,FB}(P) \).

(b) If \( P \leq P_0 \), then \( C_n(P) = C_{n,FB}(P) \).

4.2 Upper bound of \( C_{n,FB}(P) \)

Since we can’t obtain the exact value of \( C_{n,FB}(P) \) generally, the upper bound of \( C_{n,FB}(P) \) is important. The following theorem has a kind of beautiful expression.
Theorem 4.2 (Cover and Pombra [9])

\[ C_{n,FB}(P) \leq \min\{2C_n(P), C_n(P) + \frac{1}{2} \log 2\}. \]

**Proof.** We use \( R_S, R_Z, \cdots \) for a simplification of \( R_S^{(n)}, R_Z^{(n)}, \cdots \). We obtain the following relation by using properties of covariance matrices.

\[ \frac{1}{2} R_{S+Z} + \frac{1}{2} R_{S-Z} = R_S + R_Z. \] (4.1)

By operator concavity of \( \log x \)

\[ \frac{1}{2} \log R_{S+Z} + \frac{1}{2} \log R_{S-Z} \leq \log \left\{ \frac{1}{2} R_{S+Z} + \frac{1}{2} R_{S-Z} \right\} = \log \{ R_S + R_Z \}. \]

We take \( Tr \) and get

\[ \frac{1}{2} \log |R_{S+Z}| + \frac{1}{2} \log |R_{S-Z}| \leq \log |R_S + R_Z|. \]

Then

\[ \frac{1}{2n} \log \frac{|R_{S+Z}|}{|R_Z|} + \frac{1}{2n} \log \frac{|R_{S-Z}|}{|R_Z|} \leq \frac{1}{2n} \log \frac{|R_S + R_Z|}{|R_Z|}. \]

Now since

\[ \frac{1}{2n} \log \frac{|R_{S-Z}|}{|R_Z|} \geq 0, \]

we have

\[ \frac{1}{2n} \log \frac{|R_{S+Z}|}{|R_Z|} \leq \frac{1}{2n} \log \frac{|R_S + R_Z|}{|R_Z|}. \]

By maximizing under the condition \( Tr[R_S] \leq nP \)

\[ C_{n,FB}(P) \leq 2C_n(P). \]

By (4.1)

\[ R_{S+Z} \leq 2(R_S + R_Z). \]

Then

\[ \frac{1}{2n} \log \frac{|R_{S+Z}|}{|R_Z|} \leq \frac{1}{2n} \log \frac{|R_S + R_Z|}{|R_Z|} + \frac{1}{2} \log 2. \]

By maximizing under the condition \( Tr[R_S] \leq nP \)

\[ C_{n,FB}(P) \leq C_n(P) + \frac{1}{2} \log 2. \]

\( \Box \)
4.3 Cover’s conjecture
Cover gave the following conjecture.

Conjecture 4.1 (Cover [8])

\[ C_n(P) \leq C_{n,FB}(P) \leq C_n(2P). \]

We remark the following.

Proposition 4.3 (Chen and Yanagi [5])

\[ C_n(2P) \leq \min\{2C_n(P), C_n(P) + \frac{1}{2}\log 2\}. \]

Then if we can prove Conjecture 4.1, we obtain Theorem 4.2 as its corollary.
On the other hand we proved conjecture for \( n = 2 \). But conjecture is not solved in
the case of \( n \geq 3 \) still now.

Theorem 4.3 (Chen and Yanagi [5])

\[ C_2(P) \leq C_{2,FB}(P) \leq C_2(2P). \]

4.4 Concavity of \( C_{n,FB}(\cdot) \)

Concavity of non-feedback capacity \( C_n(\cdot) \) is clear, but concavity of feedback capacity
\( C_{n,FB}(\cdot) \) is also given.

Theorem 4.4 (Chen and Yanagi [7], Yanagi, Chen and Yu [26]) For any \( P, Q \geq 0 \) and any for \( \alpha, \beta \geq 0 (\alpha + \beta = 1) \)

\[ C_{n,FB}(\alpha P + \beta Q) \geq \alpha C_{n,FB}(P) + \beta C_{n,FB}(Q). \]
5 Mixed Gaussian channel with feedback

Let $Z_1, Z_2$ be Gaussian processes with mean 0 and covariance operator $R_{Z_1}^{(n)}, R_{Z_2}^{(n)}$, respectively. Let $\tilde{Z}$ be Gaussian process with mean 0 and covariance operator

$$R_{\tilde{Z}}^{(n)} = \alpha R_{Z_1}^{(n)} + \beta R_{Z_2}^{(n)},$$

where $\alpha, \beta \geq 0(\alpha + \beta = 1)$. We define the mixed Gaussian channel by additive Gaussian channel with $\tilde{Z}$ as noise. $C_{n,\tilde{Z}}(P)$ is called capacity of mixed Gaussian channel without feedback. And $C_{n,FB,\tilde{Z}}(P)$ is called capacity of mixed Gaussian channel with feedback. Now we gave concavity of $C_{n,\tilde{Z}}(P)$ in the following sense.

Theorem 5.1 (Yanagi, Chen and Yu [26], Yanagi, Yu and Chao [27]) For any $P > 0$

$$C_{n,\tilde{Z}}(P) \leq \alpha C_{n,Z_1}(P) + \beta C_{n,Z_2}(P).$$

Theorem 5.2 (Yanagi, Chen and Yu [26], Yanagi, Yu and Chao [27]) For any $P > 0$ there exit $P_1, P_2 \geq 0(P = \alpha P_1 + \beta P_2)$ such that

$$C_{n,FB,\tilde{Z}}(P) \leq \alpha C_{n,FB,Z_1}(P_1) + \beta C_{n,FB,Z_2}(P_2).$$

The proof is given by the operator convexity of $\log(1 + t^{-1})$ essencially. But the following conjecture is not solved still now.

Conjecture 5.1 For $P > 0$

$$C_{n,FB,\tilde{Z}}(P) \leq \alpha C_{n,FB,Z_1}(P) + \beta C_{n,FB,Z_2}(P).$$

Conjecture is partially solved under some condition.

Theorem 5.3 (Yanagi, Yu and Chao [27]) If one of the following conditions is satisfied, the corollay holds.

(a) $R_{Z_1}^{(n-1)} = R_{Z_2}^{(n-1)}$.
(b) $R_{\tilde{Z}}$ is white.

We also give the following conjecture.

Conjecture 5.2 For any $Z_1, Z_2, P_1, P_2 \geq 0, \alpha, \beta \geq 0(\alpha + \beta = 1),$

$$\alpha C_{n,FB,Z_1}(P_1) + \beta C_{n,FB,Z_2}(P_2) \leq C_{n,FB,\tilde{Z}}(\alpha P_1 + \beta P_2) + \frac{1}{2n} \log \frac{|R_{\tilde{Z}}|}{|R_{Z_1}|^\alpha |R_{Z_2}|^\beta}.$$
6 Kim’s result

Definition 6.1 $Z = \{Z_i; i = 1, 2, \ldots\}$ is first order moving average Gaussian process if the following equivalent three conditions.

(1) $Z_i = \alpha U_{i-1} + U_i$, $i = 1, 2, \ldots$, where $U_i \sim N(0, 1)$ is i.i.d.

(2) Spectral density function (SDF) $f(\lambda)$ is given by

$$f(\lambda) = \frac{1}{2\pi} |1 + \alpha e^{-i\lambda}|^2 = \frac{1}{2\pi} (1 + \alpha^2 + 2\alpha \cos \lambda).$$

(3) $Z_n = (Z_1, \ldots, Z_n) \sim N_n(0, K_Z)$, $n \in \mathbb{N}$, where covariance matrix $K_Z$ is given by

$$K_Z = \begin{pmatrix}
1 + \alpha^2 & \alpha & 0 & \cdots & 0 \\
\alpha & 1 + \alpha^2 & \alpha & \cdots & 0 \\
0 & \alpha & 1 + \alpha^2 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 1 + \alpha^2
\end{pmatrix}.$$

Then entropy rate of $Z$ is given by

$$h(Z) = \frac{1}{4\pi} \int_{-\pi}^{\pi} \log \{4\pi e f(\lambda)\} d\lambda = \frac{1}{4\pi} \int_{-\pi}^{\pi} \log \{2\pi e |1 + \alpha e^{-i\lambda}|^2\} d\lambda = \frac{1}{2} \log(2\pi e) \quad \text{if } |\alpha| \leq 1$$

$$= \frac{1}{2} \log(2\pi e\alpha^2) \quad \text{if } |\alpha| > 1,$$

where the last term is used by the following Poisson’s integral formula.

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} \log |e^{i\lambda} - \alpha| d\lambda = 0 \quad \text{if } |\alpha| \leq 1,$$

$$= \log |\alpha| \quad \text{if } |\alpha| > 1.$$ 

Capacity of Gaussian channel with MA(1) Gaussian noise is given by

$$C_{Z,FB}(P) = \lim_{n \to \infty} C_{n, Z, FB}(P).$$

Recently Kim obtained capacity of Gaussian channel with feedback for the first time.

**Theorem 6.1 (Kim [15])**

$$C_{Z,FB}(P) = -\log x_0,$$

where $x_0$ is only one positive solution of the following equation;

$$Px^2 = (1 - x^2)(1 - |\alpha| x)^2.$$
7 Counter example of Conjecture 4.1

Kim [16] gave the counter example of Conjecture 4.1. When

\[ f_Z(\lambda) = \frac{1}{4\pi} |1 + e^{i\lambda}|^2 = \frac{1 + \cos \lambda}{2\pi}, \]

input is known to be taken by

\[ f_X(\lambda) = \frac{1 - \cos \lambda}{2\pi}. \]

Then output is given by

\[ f_Y(\lambda) = f_X(\lambda) + f_Z(\lambda) = \frac{1}{\pi}. \]

Then nonfeedback capacity is given by

\[
C_Z(2) = \frac{1}{4\pi} \int_{-\pi}^{\pi} \log \frac{f_Y(\lambda)}{f_Z(\lambda)} d\lambda \\
= \frac{1}{4\pi} \int_{-\pi}^{\pi} \log \frac{4}{|1 + e^{i\lambda}|^2} d\lambda \\
= \frac{1}{2\pi} \int_{-\pi}^{\pi} \log \frac{2}{|1 + e^{i\lambda}|} d\lambda \\
= \frac{1}{2\pi} \int_{-\pi}^{\pi} \log 2 d\lambda - \frac{1}{2\pi} \int_{-\pi}^{\pi} \log |1 + e^{i\lambda}| d\lambda \\
= \frac{1}{2\pi} 2\pi \log 2 - 0 \\
= \log 2.
\]

On the other hand feedback capacity is given by

\[ C_{Z,FB}(1) = -\log x_0, \]

where \( x_0 \) is only one positive solution of equation

\[ x^2 = (1 + x)(1 - x)^3. \]

Since \( x_0 < \frac{1}{2} \) is assumed, we have the following

\[ C_{Z,FB}(1) = -\log x_0 > \log 2 = C_Z(2). \]

This is a counter example of Conjecture 4.1. And we can show that there exists \( n_0 \in \mathbb{N} \) such that

\[ C_{n_0,Z,FB}(1) > C_{n_0,Z}(2). \]
References


