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子計畫二：適用於高速移動擷取網路的等化碼技術與高階調變位元軟性決策解碼技術之研究(2/3)

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1. 中、英文摘要及關鍵詞(keywords)

在今年度的計畫中，我們嘗試並實驗一個新的想法：亦即在兩個連續的傳送區塊間，穿插傳送一串長度不短於通道記憶長度 (channel memory) 或記憶延展 (channel spread)的隨機位元 (random bits)，則通道原本的長程記憶特性可被削弱為近似區塊獨立特性 (blockwise independent)。我們同時推想，或許可以使用經由交錯器 (interleaver) 打亂序列順序的訊息序列 (information bit sequence) 的同位檢查位元 (parity check bits)， 來作為上述的 "隨機位元"，以使接收端可經由解交錯器 (de-interleaver) 得到額外的同位檢查訊息，來進一步提升系統效能。而一個最直接符合以上想法的範例架構，就是平行串接旋積碼 (parallel concatenated convolutional code)。為了驗證這個想法，我們採用隨時間改變衰減的一階高斯-馬可夫通道為實驗平台。我們推導出疊代最大事後機率演算法 (iterative MAP algorithm) 在直接假設接收向量「因為以兩位元為單位，穿插一位元的交錯訊息序列的同位檢查碼」而具有 2 位元區塊為單位的區塊統計獨立的對應量度公式。此外，我們亦針對隨時間改變衰減的高斯-馬可夫傳輸通道，作通道傳輸極限 (channel capacity) 的探討。根據實際通訊系統的傳送端與接收端是否分別具有「通道狀態資訊」 (channel state information)，定義出四種不同的通道傳輸極限公式。接著，我們推導高斯-馬可夫傳輸通道下的通道輸出與輸入信號間的通道轉換機率公式。由於，在傳送端與接收端均無「通道狀態資訊」的情況下，通道傳輸極限的計算相當困難，因此我們轉而探討其「獨立上界」 (independent bound)。我們導出在不同的通道記憶級數下的一般獨立上界公式。

關鍵詞：時變多路徑衰減通道、通道估量、通道等化、錯誤更正碼

In this year of the project, the idea that the *channel-with-memory* nature can be nearly weakened to *blockwise independence* by the insertive transmission of "random bits" between two consecutive blocks is experimented. We further conjecture that these ``random bits'' can be another parity check bits generated due to interleaved information bits such that additional coding information can be provided to improve the system performance. A simplest exemplified structure that follows this idea is perhaps the parallel concatenated convolutional code (PCCC). We thus derived its respective iterative MAP algorithm for time-varying channel with *first-order* Gauss-Markov fading, and tested whether or not the receiver can treat the received vector as blockwise independence with 2-bit blocks periodically separated by *single* parity-check bit from the second component recursive systematic convolutional (RSC) code encoder. In addition, we research on the capacity of the time-varying Gauss-Markov fading channels for comparison with the proposed system-under-test. We first remark on four different definitions of channel capacities according to whether the transmitter and the receiver have or have not the channel state information (CSI). We then provide detailed derivations for the channel transition probability of the Gauss-Markov channels. As the true capacity formula for blind-CSI in both transmitter and receiver is hard to obtain, we derive its independent upper bound instead, and establish a close-form expression of the independent bound for any memory order *M*. Discussions are finally given by numerical evaluation of the independent bounds.

Keywords: Time-varying multipath fading channel, Channel estimation, Channel equalization, Error correcting coding

2.報告內容

2.1 Introduction and motivations:

The main technology obstacle for high-bit-rate transmission under high mobility is the seemingly highly time-varying channel characteristic due to movement; such a characteristic enforces the dependence between consecutive symbols, and further effects the difficulty in compensating the intersymbol interference. In principle, the temporal channel memory can be eliminated by an intersymbol space longer than the channel memory spread. An example is the IEEE 802.11a standard, in which 0.8-μs "intersymbol space" is added between two consecutive 3.2-μs OFDM symbols to combat any delay spread less than 800 nano seconds. In order to take advantage of the circular convolution technique, the 0.8-μs "intersymbol space" is designed to be the leading 0.8-μ portion of the 3.2-μs OFDM symbol, which is often named the *cyclic prefix* [5]. Motivated by this, we experiment on a different view in the neutralization of channel memory, where the "intersymbol space" may be of use to enhance the system performance. Details will be introduced in subsequent sections.

In order to examine the performance of our proposed system, we tempted to establish the capacity of the time-varying fading channel experimented. There have been several publications investigating the capacity of fading channels in the literatures. The capacity of the flat Rayleigh fading channel has been studied in [6] under the assumption that the state of channel fading is perfectly known to both the transmitter and the receiver. While neither the transmitter nor the receiver knows the channel state information (CSI), investigation of the capacity of memoryless Rayleigh fading channels can be found in [1].

2.2 The research procedures in this project:

In this year, there are two questions on which we concentrate. The first is to experiment on a different view in the neutralization of channel memory, where the "intersymbol space" may be of use to enhance the system performance. The second question that the research aims at is that what the *capacity* of a time-varying channel, like Gauss-Markov [2][3], is. Seldom publications have been emerged in the capacity study of Gauss-Markov channels. The understanding of this quantity helps the researchers to be fully understood of the gap between a transmission scheme and the underlying limit.

2.2.1 Gauss-Markov channel

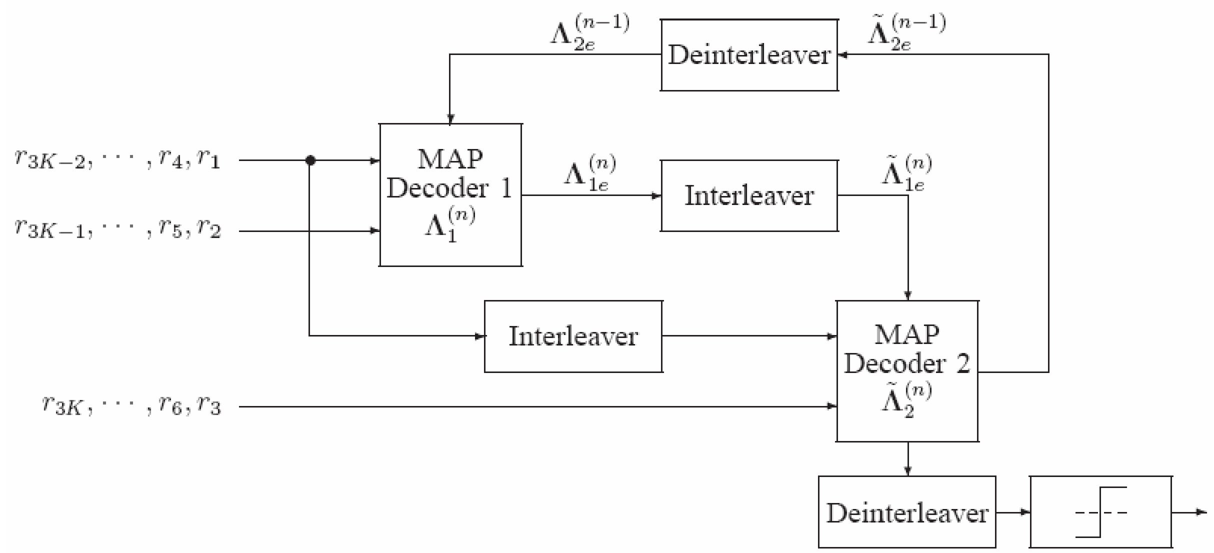
The channel model considered in this work is a complex-valued time-varying channel with Gauss-Markov fading; therefore, the received signal at time j is given by $r_j = \boldsymbol{x}_j\,\boldsymbol{h}_j + z_j$, where $\mathrm{x}_j = [x_j, x_{j-1}, \ldots, x_{j-M+1}]^T$ is the channel input vector consisting of the current input and the previous $(M-1)$ inputs, $h_j = [h_{j,1}, h_{j,2}, \ldots, h_{j,M}]^T$ is a complex column vector containing the channel impulse response coefficients at time j , $[z_1, z_2, \ldots, z_N]$ is an i.i.d. complex-valued Gaussian-distributed noise sequence with zero marginal mean and marginal variance $E[z_j z_j^*] = \sigma^2$, and M is the time spread or temporal channel memory. The channel coefficient $\boldsymbol{h}_j$ is Gauss-Markov distributed, satisfying that $\boldsymbol{h}_j = \alpha\, \boldsymbol{h}_{j-1} + \boldsymbol{v}_j$ for complex-valued scaling constant α, complex-valued initial value $\boldsymbol{h}_0$, and i.i.d. complex-valued Gaussian-distributed process $[\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_N]$ with mean $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{C}$. The complex-valued constant α is a first-order Markov factor usually chosen according to $|\alpha| = e^{-\omega T}$, where T is the system sampling period and ω/π is the Doppler spread [9]. Notably, although x_j in our system is discrete real-valued (in fact, is either +1 or −1), the resultant r_j is in general complex-valued due to its multiplication with complex $\boldsymbol{h}_j$ and addition with complex z_j. Such a complex-valued system setting can mirror the practical effect of possible unsynchronization between the transmitter and the receiver, in addition to the phase delay due to channel fading.

2.2.2 Iterative MAP algorithm for Gauss-Markov channel of memory order one

In this subsection, we will denote the mean and variance of h_k by $\bar{h}_k$ and $\bar{\sigma}_k^2$, respectively, and denote the 1-by-1 covariance matrix C of $[\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_N]$ by σ_v^2.

We had established a framework of a systematic equalizer code in the time-varying environment in the last year. The mathematical expression of the considered fading channels also had been well-defined. In addition, based on the chosen channel model, we derived the maximum-likelihood (ML) criterion which is useful for finding the subsequent decoding metric.

In this year, we experiment on the idea that whether the channel-with-memory nature can be nearly weakened to blockwise independence by the insertive transmission of informationless “random bits” (of length no less than the channel memory or channel spread) between two consecutive blocks. We then begin the experiment from the simplest case along this idea, i.e., PCCC code and its respective iterative MAP decoder over a time-varying channel with first-order Gauss-Markov fading. The structure of the iterative MAP decoder is as follows.



We first derive the metric functions used for the first component MAP decoder. By assuming that the $[r_{3i+1}, r_{3i+2}]$ is block-wisely independent in i, the *a posteriori probability* (APP) of i-th information bit u_i upon the reception of $\boldsymbol{d} = [r_1, r_2, r_4, r_5, \ldots, r_{3K-2}, r_{3K-1}]$ can be represented as

$$\Pr\{u_i = u|\boldsymbol{d}\} = \sum_{(T_s^{i-1}, T_{\bar{s}}^i) \in B_i^{(u)}} \frac{f(T_s^{i-1}, T_{\bar{s}}^i, \boldsymbol{d})}{f(\boldsymbol{d})}$$

where "*f*" is used to represent the respective pdf function, T_s^i represents the node at level *i* with state *s* over a convolutional code trellis, $B_i^{(u)}$ is the set of trellis edges such that the edge transition from node T_s^{i-1} to node $T_{\bar{s}}^i$ is due to information bit $u_i = u$. The pdf $f\{T_s^{i-1}, T_{\bar{s}}^i, \mathbf{d}\}$ can be obtained in recursive form through $f\{T_s^{i-1}, T_{\bar{s}}^i, \mathbf{d}\} = \beta(T_{\bar{s}}^{i-1})\alpha(T_s^{i-1})\gamma(T_s^{i-1}, T_{\bar{s}}^i)$, where $\alpha(T_s^{i-1}) = f\{T_s^{i-1}, d_1^{2(i-1)}\}$, $\beta(T_{\ddot{s}}^i) = f\{d_{2i+1}^{2K} \mid T_{\ddot{s}}^i\}$,

$$\gamma(T_s^{i-1}, T_{\ddot{s}}^i) = \begin{cases} \Pr\{u_i = 0\} \prod_{k=1}^2 e^{G_{3(i-1)+k}|q_{3(i-1)+k}|^2} & ,\text{if } (T_s^{i\text{-}1}, T_{\ddot{s}}^i) \in \mathrm{B}_\mathrm{i}^{(0)} \\ \Pr\{u_i = 1\} \prod_{k=1}^2 e^{G_{3(i-1)+k}|q_{3(i-1)+k}|^2} & ,\text{if } (T_s^{i\text{-}1}, T_{\ddot{s}}^i) \in \mathrm{B}_\mathrm{i}^{(1)} \\ 0 & ,\text{if } (T_s^{i\text{-}1}, T_{\ddot{s}}^i) \notin \mathrm{B}_\mathrm{i}^{(0)} \cup \mathrm{B}_\mathrm{i}^{(1)} \end{cases}$$

and

$$G_k^{-1} = \begin{cases} \dfrac{1}{\sigma^2} + \dfrac{|\alpha|^2}{\sigma_v^2} + \dfrac{1}{\bar{\sigma}_k^2}, \text{if } \ k = 3(i-1)+1; \\ \dfrac{1}{\sigma^2} + \dfrac{1}{\sigma_v^2} - \dfrac{|\alpha|^2 G_{k-1}}{\bar{\sigma}_k^4}, \text{if } \ k = 3(i-1)+2 \end{cases}, \quad q_k = \begin{cases} \dfrac{r_k x_k}{\sigma^2} + \dfrac{\bar{h}_k}{\bar{\sigma}_k^2}, \text{if } \ k = 3(i-1)+1; \\ \dfrac{r_k x_k}{\sigma^2} + \dfrac{\alpha G_{k-1} q_{k-1}}{\sigma_v^2}, \text{if } \ k = 3(i-1)+2 \end{cases}.$$

The metric functions of the second component MAP decoder can be obtained by the same recursive form, but different γ() function:

$$\gamma(T_s^{i-1}, T_{\ddot{s}}^i) = \begin{cases} \Pr\{u_i = 0\} e^{\bar{G}_{3(I(i)-1)+1}|\bar{q}_{3(I(i)-1)+1}|^2} e^{\bar{G}_{3i}|\bar{q}_{3i}|^2} & ,\text{if } (T_s^{i\text{-}1}, T_{\ddot{s}}^i) \in \mathrm{B}_\mathrm{i}^{(0)} \\ \Pr\{u_i = 1\} e^{\bar{G}_{3(I(i)-1)+1}|\bar{q}_{3(I(i)-1)+1}|^2} e^{\bar{G}_{3i}|\bar{q}_{3i}|^2} & ,\text{if } (T_s^{i\text{-}1}, T_{\ddot{s}}^i) \in \mathrm{B}_\mathrm{i}^{(1)} \\ 0 & ,\text{if } (T_s^{i\text{-}1}, T_{\ddot{s}}^i) \notin \mathrm{B}_\mathrm{i}^{(0)} \cup \mathrm{B}_\mathrm{i}^{(1)} \end{cases}$$

where

$$\bar{G}_k^{-1} = \frac{1}{\sigma^2} + \frac{1}{\bar{\sigma}_k^2} \ \text{ and } \ \bar{q}_k = \frac{r_k x_k}{\sigma^2} + \frac{\bar{h}_k}{\bar{\sigma}_k^2}.$$

Simulation results hint that the iterative MAP decoder that is derived based on *blockwise independence* assumption not only performs close to the CSI-aided decoding scheme (cf. Fig. 1(b)) but is at most 0.9 dB away from the Shannon limit (cf. Fig. 1(a)), thereby confirms the feasibility of our proposal.

2.2.3 A lower bound of the Shannon limit:

There are four kinds of capacities according to different assumptions on the knowledge that the transmitter and the receiver have. In notations, $C(S)$ corresponds to that both the transmitter and the receiver are unaware of the channel state, while $C'(S)$ is the capacity under the assumption of perfect CSI knowledge to both the transmitter and the receiver. If only the receiver knows the channel state, the capacity is denoted by $C^{(R)}(S)$. If only the transmitter is aware of the CSI, the capacity is denoted by $C^{(T)}(S)$. Their formulas are listed below.

$$C(S) = \max_{P_X \in Pb(S)} \int_H p_H(h) \sum_{x \in X} P_X(x) \int_y p_{Y|X,H}(y \mid x,h) \log\left(\frac{p_{Y|X}(y \mid x)}{p_Y(y)}\right) dydh$$

$$C^{(T)}(S) = \int_H p_H(h) \max_{P_X \in Pb(S)} \sum_{x \in X} P_X(x) \int_y p_{Y|X,H}(y \mid x,h) \log\left(\frac{p_{Y|X}(y \mid x)}{p_Y(y)}\right) dydh$$

$$C^{(R)}(S) = \max_{P_X \in Pb(S)} \int_H p_H(h) \sum_{x \in X} P_X(x) \int_y p_{Y|X,H}(y \mid x,h) \log\left(\frac{p_{Y|X,H}(y \mid x,h)}{p_{Y|H}(y \mid h)}\right) dydh$$

$$C'(S) = \int_H p_H(h) \max_{P_X \in Pb(S)} \sum_{x \in X} P_X(x) \int_y p_{Y|X,H}(y \mid x,h) \log\left(\frac{p_{Y|X}(y \mid x)}{p_Y(y)}\right) dydh$$

After defining four definitions of channel capacity, we wish to evaluate the last one based on the Gauss-Markov fading channel model. Unfortunately, the problem of finding the channel input statistics that maximizes the channel input-output mutual information is beyond our management at this stage. Thus, we turn to the determination of good upper bounds for capacities.

Theorem. Assume that there exists a complex number μ_k such that $\mu_{k,i} = \rho_i\, \mu_k$ for some real number ρ_i for every $1 \le i \le M$, where $\mu_k = [\mu_{k,1}, \mu_{k,2}, \ldots, \mu_{k,M}]$. Also, $\boldsymbol{C}$ is diagonal. Then, the capacity-cost function for blind-CSI system is upper-bounded by:

$$C(S) \le C_\infty(S) = \frac{2S}{\delta^2} - \int_R \frac{1}{\sqrt{2\pi}} e^{-t^2/2} \left[\log\left(\cosh\left(\frac{\sqrt{2S}}{|\delta|} t + \frac{2S}{\delta^2} \right)\right)\right] dt$$

where

$$\delta^2 = \frac{\sigma^2 + \frac{S}{1-|\alpha|^2} \sum_{i=1}^{M} C_{i,i}}{\left(\frac{1}{1-|\alpha|} \sum_{i=1}^{M} |\mu_i| \right)^2}.$$

With the availability of capacity upper bounds, performance lower bounds for bit error rates (BERs) can be obtained by means of the rate-distortion theorem and the joint source-channel coding theorem [7]. One can then evaluates the performance lower bound numerically in comparison with the simulations of his developed coding scheme.

2.3 Achievement:

2.3.1 Iterative MAP algorithm for Gauss-Markov channel:

Figure 1 reveals the performance of our iterative MAP algorithm. The left one depicts the difference between the performance of the iterative MAP algorithm and a lower bound of the Shannon limit. The figure shows that when $\sigma_v^2 = 0.001$ and $h_0 = 1$, the resultant performance curve of the iterative MAP algorithm is only 0.9 dB away from the lower bound of the Shannon limit at $BER = 2\times10^{-4}$. Therefore, the iterative MAP algorithm is at most 0.9 dB away from the true Shannon limit at $BER = 2\times10^{-4}$.

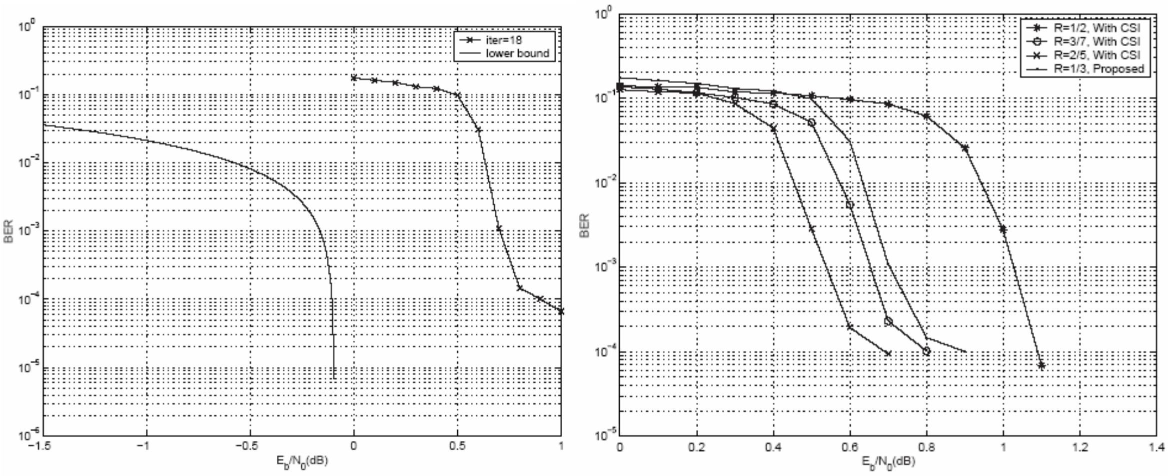


Figure 1: Parameters of Gauss-Markov channel are α = 0.995, σ_v^2 = 0.001 and h_0 = 1. (a) (left) Performance comparison between the iterative MAP decoder with 18 iterations and a lower bound of the Shannon limit. (b) (right) Performances of punctured PCCC codes with code rates 1/2, 3/7 and 2/5. The CSIs are assumed known for the iterative MAP decoder of these punctured codes. For comparison, the performance of the proposed blind-CSI iterative MAP algorithm is also depicted. All of them are decoded with 18 iterations.

It is worth mentioning that the proposed iterative MAP algorithm only requires the knowledge of channel statistics, and does not presume the existence of the channel estimation circuitry at the receiver. Thus, the system we considered does not need to transmit, e.g., training sequence for the estimation of channel states [4]. In Fig. 1(b), we simulated three kinds of punctured PCCC codes with code rates 1/2, 3/7 and 2/5 under channel parameters h_0 = 1 and σ_v^2 = 0.001. Since these code rates are all higher than 1/3, we assume that the remaining transmitted bits (i.e., N/3, 2N/9 and N/6 bits respectively for 1/2, 3/7 and 2/5 punctured codes) can be used as training bits to establish *perfect* channel estimation of $\boldsymbol{h} = [h_1, h_2, \ldots, h_N]$. The iterative MAP decoder, in such case, reduces to the conventional one derived for AWGN channels. The simulation results show that only rate-2/5 and rate-3/7 punctured systems with perfect channel state information (CSI) perform better than the proposed blind-CSI iterative MAP algorithm, but the performance deviations are limited respectively within 0.2 and 0.1 dB at $BER = 10^{-4}$. Since it is in general hard to achieve accurate channel estimation for a time-varying channel even with a large number of training bits, the small performance derivation merits the usage of the proposed blind-CSI iterative MAP algorithm.

2.3.2 A lower bound of the Shannon limit:

Figure 2 shows the independent bounds for Gauss-Markov channels of different memory orders. By intuition, for fixed $C_{i,i}$ and μ_i, the higher the channel memory order, the more involved in received vector $\boldsymbol{y}$ at the receiver end. Thus, it is reasonable to expect a lower capacity for larger M. However, the independent bound shows that $C_\infty(S)$ grows as M increases. This indicates that in the case we considered, the independent bound could be looser for higher M.

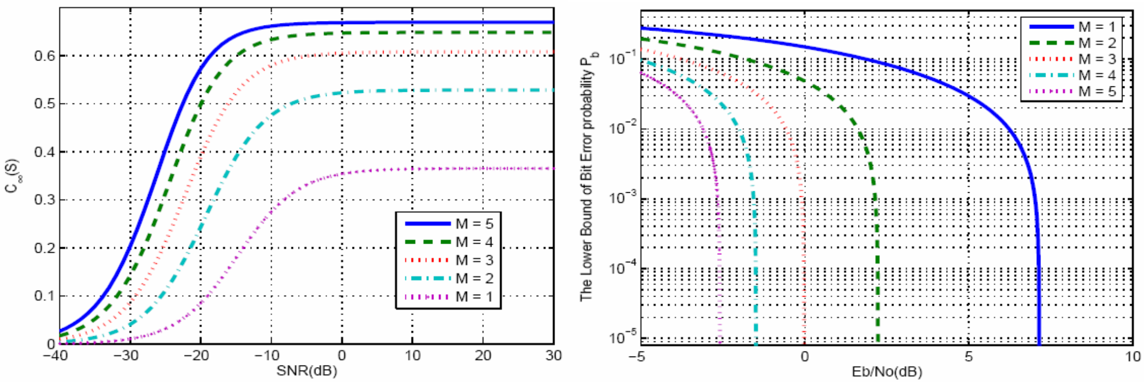


Figure 2: Illustration of $C_{\infty}(S)$. Parameters for Gauss-Markov channels are: (a) (left.) $C_{1,1} = C_{2,2} = C_{3,3} = C_{4,4} = C_{5,5} = 10$, $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = 1$, $\alpha = 0.7$ and $\sigma^2 = 1$. (b) (right.) $C_{1,1} = 10^{0.7}$, $C_{2,2} = 10^{1.5}$, $C_{3,3} = 10^2$, $C_{4,4} = 10^{2.5}$, $C_{5,5} = 10^3$, $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = 1$, $\alpha = 0.7$ and $\sigma^2 = 1$.

3. References

[1] I. C. Abou-Faycal, M. D. Trottand and S. Shamai, “The capacity of discrete-time memoryless Rayleigh-fading channels,” *IEEE Trans. Inform. Theory*, vol. 47, no. 4, pp. 1290-1301, May 2001.

[2] H. Chen, K. Buckley and R. Perry, “Time-recursive maximum likelihood base sequence estimation for unknown ISI channels,” in Proc. of *34th Asilomar Conf. Circuits, Systems, Computers,* pp. TA8a14: 1-5, Nov. 2000.

[3] H. Chen, R. Perry and K. Buckley, “On MLSE algorithm for unknown fast time-varying channels,” *IEEE Trans. Commun..*, vol. 51, pp730-734, May. 2003.

[4] T. M. Cover and Joy A. Thomas, *Elements of Information Theory* John Wiley & Sons, 1991.

[5] IEEE Std 802.11a-1999, *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHz band*, Sept. 1999.

[6] W. C. Y. Lee, “Estimate of channel capacity in Rayleigh fading environment,” *IEEE Trans. Veh. Technol.*, vol. 39, no. 3, pp. 187-189, Aug. 1990.

[7] M. Skoglund, J. Giese and S. Parkvall, “Code design for combined channel estimation and error protection,” *IEEE Trans. Inform. Theory*, vol. 48, pp. 1162-1171, May. 2002.

[8] Chia-Lung Wu, Ya-Ting Cho, Po-Ning Chen and Yunghsiang S. Han, ”Iterative MAP algorithm for Gauss-Markov channel, ” in preparation for submission.

[9] M. Stojanovic and Z. Zvonar, ``Performance of multiuser diversity reception in Rayleigh fading CDMA channels," *IEEE Trans. Commun.*, vol. 47, no. 3, pp. 356-359, March 1999.

4. 計畫成果自評

Based on the result of last year, the aims of this year are to design channel codes which have been considered the statistics properties of fading channels. In this work, we take the PCCC code and its respective iterative MAP decoder as a test vehicle to experiment on the idea that the *temporal channel memory* can be weakened to *nearly blockwise time-independence* by the insertive transmission of "random bits" of sufficient length between two consecutive blocks, for which these "random bits" are actually another parity check bits generated due to interleaved information bits. The simulation results show that the metrics derived based on blockwise independence with 2-bit blocks periodically separated by a *single* parity-check bit from the second component RSC encoder perform close to the CSI-aided decoding scheme, and is at most 0.9 dB away from the Shannon limit at $BER = 2 \times 10^{-4}$ when $h_0 = 1$ and $\sigma_v^2 = 0.001$. The result of the first part has been prepared for submission to IEEE communication letters. A natural future work is to extend the channel memory to higher order, and further examine whether the same idea can be applied to obtain well-acceptable system performance.

In the second part, we have remarked on four different definitions of channel capacities according to the transmitter/receiver with/without channel state information. We then turn to the derivation of the independent bounds for the channel capacity without CSI in both transmitter and receiver. We then found that if there is no LOS signal existing, the capacity of the blind-CSI system will be reduced to zero.