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# A Macro and Micro MIMO Diversity Scheme for a Shadowing Environment

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**Abstract**

In this paper, we propose a 2-layer spatial diversity scheme to guarantee the reliability of indoor wireless communication/control systems. The performance in uplink is numerically evaluated with the outage probability of a required bit-error rate (BER). As a result, the superiority of the proposed system to conventional ones is clarified.

## 1. INTRODUCTION

In many conventional wireless communication systems, high data rate is the most important objective. On the contrary, for applications such as wireless control of industrial equipments or home automation, reliability of the systems is a prime requisite. For these applications, wireless communication systems are required anytime to provide a constant performance, such as constant BER or constant delay, and thus the reliability of these systems is determined by the certainty of achieving a required performance.

In indoor wireless communications, multipath fading is one of the most important factor of the degradation of the performance[2]. To combat the fading, diversity techniques, in space, time, and frequency, are effective countermeasures. Among these diversity techniques, spatial diversity has advantages in indoor wireless environment, for it can provide diversity gain in slow or static environment without additional bandwidth.

Multiple Input Multiple Output (MIMO) systems, which employ multiple antennas both at a transmitter and a receiver, are effective spatial diversity systems. Especially, MIMO with Space-Time Block Coding (STBC), which uses low-complexity linear mapping of information symbols in space and time domains, is known as a effective way to provide diversity against the fading[4][5].

In addition to the fading, if the paths between a transmitter and a receiver are interrupted, transmitted signal may encounter strong attenuation called shadowing[6]. Because of shadowing, at some spots in a room or a factory plant, the performance of wireless communication may be highly degraded. In order to ensure good performance under shadowing environment, large-scaled spatial diversity, where the distance between diversity branches is enough large, can be again an advantageous solution.

In the fading and shadowing environment, these two spatial diversity schemes should be jointly used, which is called macro / micro diversity, and have been shown to improve system performance[7]. In this paper, we focus on the bit-error outage performance of indoor wireless communication systems and introduce a new macro / micro 2-layer diversity scheme in order to realize the reliable communication system in indoor fading and shadowing environment. In the first layer, antennas in each receiver are separated by several wavelengths to provide diversity against the fading (micro diversity). In the second layer, each receiver (branch) is separated with large distance for the diversity against the shadowing (macro diversity).

## 2. SYSTEM MODEL

Figure 1 depicts the basic concept of the macro / micro diversity scheme. This paper concentrates on the performance in uplink. As shown in the figure, the transmitter (terminal) has $M$ antennas and the receiver side has $J$ macro diversity branches each with $K$ antennas.

The $K$ antennas in each branch are separated to combat the fading, and maximal-ratio combining is used to combine received signals of all $K$ antennas. The $J$ macro diversity branches are separated to each other with large distance to provide the diversity against the shadowing.

The output of each branch is passed to the base station through a certain channel, wired or wireless, and the base station makes the decision based on the branch outputs. Note that, if the channel between each branch and the base station is wireless, the proposed system can be regarded as a class of cooperative diversity[8].

### 2.1. Transmitter

Figure 2 illustrates the transmitter with $M$ antennas. The input sequence of bits $b[i] \in \{\pm 1\}$ is modulated into the sequence of QPSK symbols $x[i] \in \{\exp(j\frac{\pi}{4}), \exp(j\frac{3\pi}{4}), \exp(-j\frac{\pi}{4}), \exp(-j\frac{3\pi}{4})\}$, then each symbol is mapped to $M$ antennas using STBC mapping scheme[4][5], and transmitted from the antennas simultaneously using the same carrier frequency. The symbol transmitted from the $m$-th transmit antenna in the $i$-th symbol interval is denoted by $s_m[i]$, and all the symbols transmitted from $M$ antennas in the $i$-th symbol interval are denoted by a vector

$$\boldsymbol{s}[i] = (s_1[i], s_2[i], \cdots, s_M[i])^T \quad (1)$$

where $^T$ denotes the transpose.

For an example, if $M = 2$, the STBC mapped symbols transmitted in the $i$-th symbol interval are

$$\begin{pmatrix} s_1[i] \\ s_2[i] \end{pmatrix} = \sqrt{\frac{E_s}{2}} \sum_j \begin{pmatrix} x[2j] & -x^*[2j+1] \\ x[2j+1] & x^*[2j] \end{pmatrix} \cdot \begin{pmatrix} \delta[i-2j] \\ \delta[i-(2j+1)] \end{pmatrix} \quad (2)$$

where symbol energy of $x[i]$ is $E_s$, and $\delta[i]$ denotes a unit impulse defined by

$$\delta[i] = \begin{cases} 0, & i \neq 0 \\ 1, & i = 0 \end{cases} . \quad (3)$$

### 2.2. Channel

Transmitted signals fluctuate due to the fading and log-normal shadowing. The path loss of the path from the $m$-th transmit antenna to the $k$-th receive antenna of the $j$-th macro diversity branch in the $i$-th symbol interval is given by

$$h_{mjk}[i] = \alpha_{mjk}[i] \exp(j\phi_{mjk}[i]). \quad (4)$$

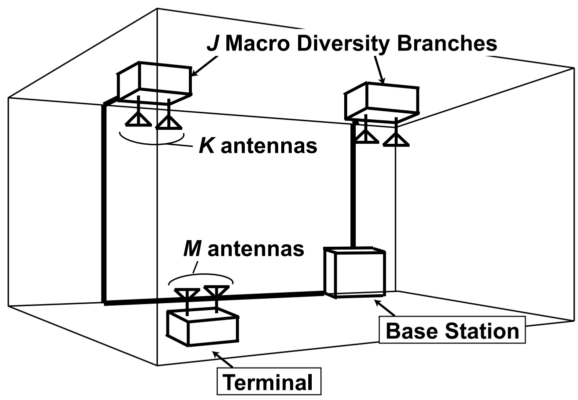


Figure 1: System model.

The phase shift $\phi_{mjk}[i]$ is uniformly distributed in $[0, 2\pi)$, while the attenuation factor $\alpha_{mjk}[i]$ is independently and identically distributed (i.i.d.) Rayleigh random variable with mean square value $E[\alpha^2_{mjk}[i]] = Z_j[i]$. The PDF of $\alpha_{mjk}[i]$ is expressed as

$$p_{\alpha_{mjk}[i]}(\alpha | Z_j[i]) = \frac{2\alpha}{Z_j[i]} \exp\left(-\frac{\alpha^2}{Z_j[i]}\right). \quad (5)$$

The value $Z_j[i]$ fluctuates due to shadowing, and it is assumed to have i.i.d. log-normal distribution with standard deviation $\sigma$. Thus, $Z_j[i]$ can be expressed in terms of a Gaussian random variable $X_\sigma$ with mean zero and variance $\sigma^2$ as

$$Z_j[i] = 10^{\frac{X_\sigma}{10}} E[Z_j[i]] \quad (6)$$

where we assume that mean path loss $E[Z_j[i]]$ is 1.

### 2.3. Receiver

Figure 3 illustrates the receiver for macro / micro diversity. There are $J$ macro diversity branches and a base station.

The received symbol at the $k$-th receive antenna of the $j$-th macro diversity branch in the $i$-th symbol interval is denoted by $r_{jk}[i]$. A set of all the received symbols at the $j$-th macro diversity branch in the $i$-th symbol interval is denoted by a vector

$$\boldsymbol{r}_j[i] = (r_{j1}[i], r_{j2}[i], \cdots, r_{jK}[i])^T \quad (7)$$

$$= \begin{pmatrix} h_{1j1}[i] & h_{2j1}[i] & \cdots & h_{Mj1}[i] \\ h_{1j2}[i] & h_{2j2}[i] & \ddots & h_{Mj2}[i] \\ \vdots & \ddots & \ddots & \vdots \\ h_{1jK}[i] & h_{2jK}[i] & \cdots & h_{MjK}[i] \end{pmatrix} \boldsymbol{s}[\boldsymbol{i}] + (n_{j1}[i], n_{j2}[i], \cdots, n_{jK}[i])^T \quad (8)$$

where noise samples $n_{jk}[i]$ are zero-mean complex Gaussian random variables with variance $N_0/2$ per dimension and independent for different $k$'s process.

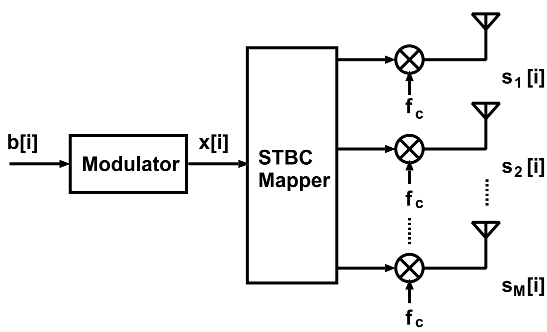


Figure 2: Transmitter.

In each macro diversity branch, the received signals are de-mapped with the STBC scheme[4][5]. For example, if $M = 2$, the de-mapped symbols at the $j$-th branch are

$$\begin{pmatrix} y_j[2i] \\ y_j[2i+1] \end{pmatrix} = \sum_{k=1}^{K} \begin{pmatrix} h^*_{1jk}[i] & h_{2jk}[i] \\ h^*_{2jk}[i] & -h_{1jk}[i] \end{pmatrix} \begin{pmatrix} r_{jk}[2i] \\ r^*_{jk}[2i+1] \end{pmatrix}. \quad (9)$$

At each branch, symbol-by-symbol maximum likelihood decision is made based on $y_j[i]$. The resulting sequence of bits $\hat{b}_j[i] \in \{\pm 1\}$, which is the estimate of $b[i]$ at the $j$-th macro diversity branch, is obtained.

The bit-error probability of the decision on symbol $y_j[i]$ at the $j$-th micro branch receiver is

$$p_j[i] \quad = \quad Q\left(\sqrt{2\gamma_j}\right) \quad (10)$$

where $Q(\cdot)$ is Q-function and

$$\gamma_j \quad = \quad \frac{E_b}{MN_0}\rho_j[i] \quad (11)$$

$$\rho_j[i] \quad = \quad \sum_{m=1}^{M}\sum_{k=1}^{K} |h_{mjk}[i]|^2 \quad (12)$$

where $E_b = E_s/2$. Thus, the micro branch receiver can obtain the estimate of the BER $\hat{p}_j[i]$ at the $j$-th macro diversity branch based on a observation of received signal energy $E_b\rho_j[i]$ and the noise density $N_0$.

In order to decrease the amount of data transmitted from $J$ branches to the base station and to improve the performance, each branch passes the estimate $\hat{b}_j[i]$ only if the estimated BER is lower than a certain threshold $\Theta$. For this, let us define the variable $\tilde{b}_j[i]$ as follows.

$$\tilde{b}_j[i] \quad = \quad \begin{cases} \hat{b}_j[i], & \text{if} \quad \hat{p}_j[i] \le \Theta \\ 0, & \text{otherwise} \end{cases} \quad (13)$$

Then the decision rule at the base station can be denoted as

$$\hat{b}[i] \quad = \quad \begin{cases} 1 & \text{if} \quad C[i] > 0 \\ -1 & \text{if} \quad C[i] \le 0 \end{cases} \quad (14)$$

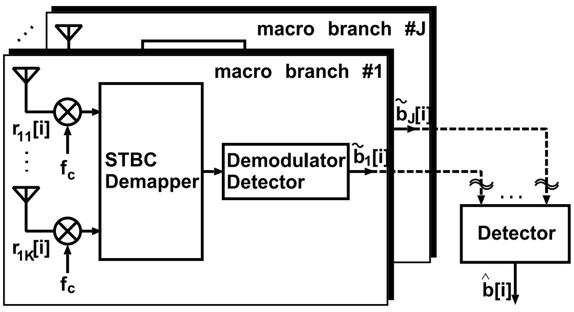


Figure 3: Receiver.

where

$$C[i] \quad = \quad \sum_{j=1}^{J} \tilde{b}_j[i]. \quad (15)$$

Equations (13)-(15) imply that the base station makes the decision with majority rule on the outputs of the branches whose expected BER are lower than $\Theta$.

## 3. OUTAGE PROBABILITY OF BIT-ERROR RATE

Let us define the number of branches with $p_j[i] < \Theta$ as $Y$. Then the bit-error probability $P[i]$ at the base station is upper-bounded as

$$P[i] \quad \le \quad \begin{cases} \displaystyle\sum_{k=\frac{Y+1}{2}}^{Y} \binom{Y}{k} \Theta^k (1-\Theta)^{Y-k} & \text{for odd } Y \\ \displaystyle\sum_{k=\frac{Y}{2}+1}^{Y} \binom{Y}{k} \Theta^k (1-\Theta)^{Y-k} & \\ \quad +\displaystyle\frac{1}{2}\binom{Y}{\frac{Y}{2}} \Theta^{\frac{Y}{2}} (1-\Theta)^{\frac{Y}{2}} & \text{for even } Y \end{cases} \quad (16)$$

In the above equation, if $\Theta << 1$ and $1 \le Y$, then $P[i] \le \Theta$. Conversely, if $Y = 0$ then $P[i] < \Theta$ cannot be ensured. Thus the probability of the event that $P[i]$ exceeds a given value $\Gamma$, which we call the outage probability, can be approximated by the probability of $Y = 0$ (or $\tilde{b}_j[i] = 0$ for all $j$) when $\Theta = \Gamma$.

The $j$-th branch output $\tilde{b}_j[i]$ becomes to be zero if $\Theta < p_j[i]$. This condition can be rewritten as $\rho_j[i] < \rho(\Theta)$, where $\rho(\Phi)$ is the value of $\rho_j[i]$ which achieves $p_j[i] = \Phi$ and denoted from Eqs. (10)-(12) as

$$\rho(\Phi) \quad = \quad \frac{MN_0}{2E_b}\left(Q^{-1}(\Phi)\right)^2. \quad (17)$$

The value $\rho_j[i]$ in Eq. (12) is an chi-square distributed random variable with mean $MKZ_j[i]$ and $2MK$ degrees of freedom with the cumulative distribution function

$$F_{\rho_j[i]}(\rho) = 1 - \exp\left(-\frac{\rho}{Z_j[i]}\right) \sum_{p=0}^{MK-1} \frac{1}{p!}\left(\frac{\rho}{Z_j[i]}\right)^p. \quad (18)$$

From this equation, we can denote the probability that $\tilde{b}_j[i] = 0$ with $\Theta = \Gamma$ as $F_{\rho_j[i]}(\rho(\Gamma))$. And since $\rho(\Gamma)/Z_j[i]$ is a finite value, this probability can be expressed by using Taylor's Formula as

$$F_{\rho_j[i]}(\rho(\Gamma)) = 1 - \exp\left(-\frac{\rho(\Gamma)}{Z_j[i]}\right)\left\{\exp\left(\frac{\rho(\Gamma)}{Z_j[i]}\right) - \frac{2}{(MK)!}\exp\left(\theta\frac{\rho(\Gamma)}{Z_j[i]}\right)\left(\frac{\rho(\Gamma)}{Z_j[i]}\right)^{MK}\right\} \quad (19)$$

Table 1: Parameters for simulations.

| | | |
|---|---|---|
| Standard deviation of log-normal shadowing | $\sigma$ | 0 and 8 [dB] |
| Number of transmit antennas | $M$ | 2 |
| Total number of receive antennas | $JK$ | 12 |
| BER threshold at branches | $\Theta$ | $1/2$ and $10^{-5}$ |

where $0 < \theta < 1$. Since $0 \leq \rho(\Gamma)/Z_j[i]$ and thus $\exp(\theta\rho(\Gamma)/Z_j[i]) \leq \exp(\rho(\Gamma)/Z_j[i])$, Eq. (19) is upper-bounded by

$$F_{\rho_j[i]}(\rho(\Gamma)) \leq \frac{1}{(MK)!}\left(\frac{\rho(\Gamma)}{Z_j[i]}\right)^{MK}. \quad (20)$$

As Eq. (20) gives the upperbound of the probability that the $j$-th branch does not give the output to the base station, the probability of $Y = 0$, which is the approximation of the outage probability $P_0(\Gamma)$ for $\Theta << 1$, can be upper-bounded as

$$P_0(\Gamma) \simeq \prod_{j=1}^{J} F_{\rho_j[i]}(\rho(\Gamma)) \quad (21)$$

$$\leq \prod_{j=1}^{J} \frac{1}{(MK)!}\left(\frac{\rho(\Gamma)}{Z_j[i]}\right)^{MK}. \quad (22)$$

## 4. NUMERICAL EXAMPLES

In this section, we evaluate the performance of the proposed macro / micro diversity based on Monte-Carlo simulations. The parameters for simulations are shown in Table 1. The value $\sigma = 0$ [dB] represents the environment without shadowing while $\sigma = 8$ [dB].

Figures 4 and 5 show the outage probability of $\Gamma = 10^{-5}$, i.e. the probability that $P[i]$ exceeds $10^{-5}$, given by Eq. (21). The horizontal axes $\overline{\gamma}$ of the figures are mean value of the ratio of single-sided noise power spectral density to the average bit energy per receive antenna, i.e. $\frac{1}{JK}\sum_{j=1}^{J}\gamma_j$. For these figures, the threshold $\Theta$ at each branch is set to be $\Theta = 10^{-5}$.

In Fig. 4, we can confirm the diversity gain for shadowing: $J$ is larger, the outage probability becomes smaller. On the contrary, if the average SNRs at all the macro diversity branches are the same, the diversity gain against the shadowing cannot be obtained. Furthermore, since the base station makes the decision based on the binary data sent from the branches, while each branch makes decision by combining the soft values of the $K$ antennas' outputs, as shown in Fig. 5, larger $J$ (smaller $K$) gives worse outage probability.

Figures 6 and 7 show the averaged BERs under the same condition as in Figs. 4 and 5. From Figs. 4-7, it can be shown that the averaged BER has the same tendency on

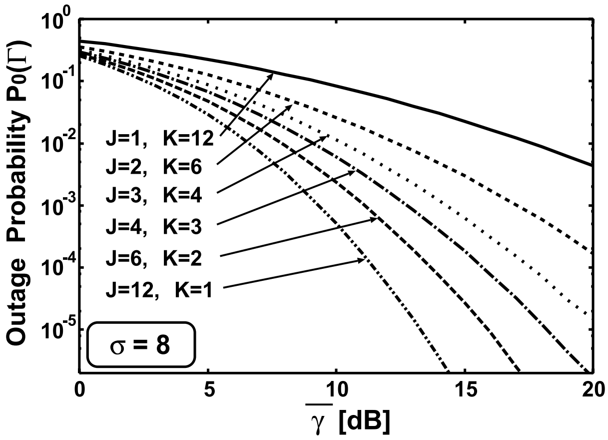


Figure 4: Outage probability at the base station corresponding to $P[i] \leq 10^{-5}$ ($\Theta = 10^{-5}$).

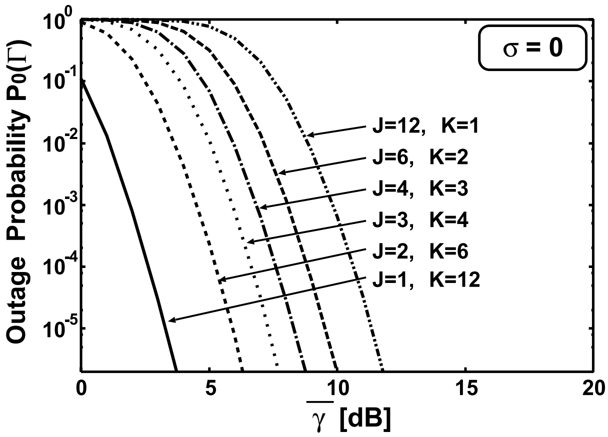


Figure 5: Outage probability at the base station corresponding to $P[i] \leq 10^{-5}$ ($\Theta = 10^{-5}$).

$J$ (and $K$): large $J$ has better performance for shadowing ($\sigma = 8$ dB) environment while smaller $J$ is suitable for non-shadowing case ($\sigma = 0$ dB).

For the purpose of comparison with the proposed macro / micro diversity scheme, the outage probability of BER and the averaged BER with $\Theta = 1/2$ are shown in Figs. 8 and 9. In comparison with the results with $\Theta = 10^{-5}$, shown in Figs. 4 and 6, it is note worthy that macro diversity with $\Theta = 1/2$ outperforms that with $\Theta = 10^{-5}$ in the sence of the averaged BER, while the sence of the outage probability of BER, $\Theta = 10^{-5}$ outperforms $\Theta = 1/2$. This fact signifies that better performance in the sence of the average BER cannot always ensure the better performance in the sence of the outage probability of BER. Also this shows that the in-

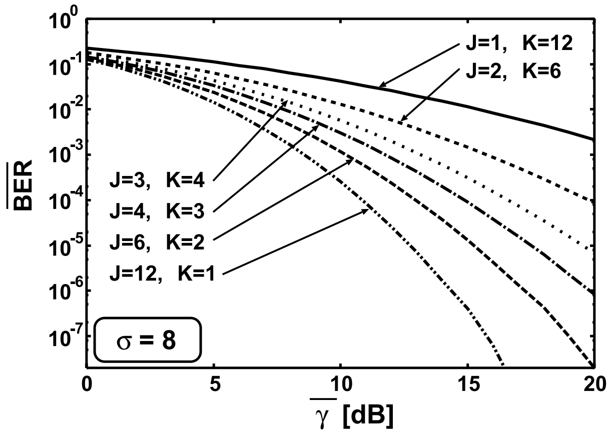


Figure 6: Average BER.

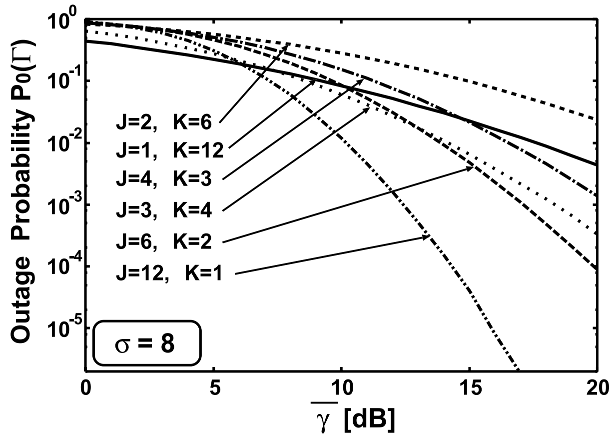


Figure 8: Outage probability at the base station corresponding to $P[i] \leq 10^{-5}$ ($\Theta = 1/2$).

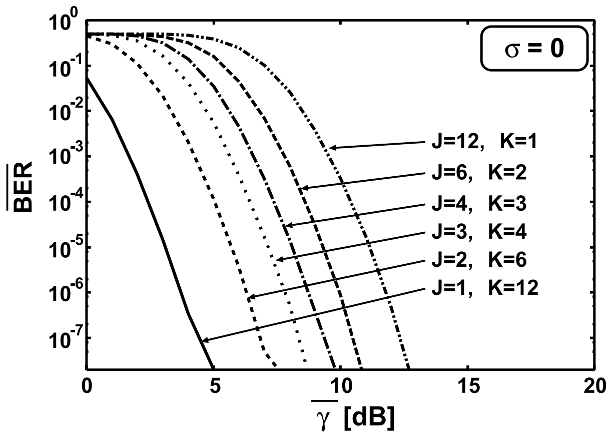


Figure 7: Average BER.

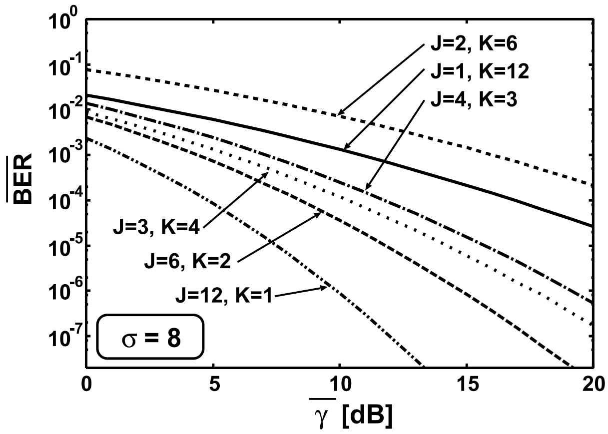


Figure 9: Average BER.

troduction of the threshold Θ is not only effective to reduce the amount of data sent from a branch to the base station, but also is important to guarantee the reliability of communication.

## 5. CONCLUSIONS

In this paper, we proposed a macro / micro diversity for aiming to improve the outage probability of required BER. From the numerical examples, we have shown that the proposed macro / micro diversity scheme improves the outage probability of required BER under the flat Rayleigh fading and log-normal shadowing environment.

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