Optimal Bit Allocation Adaptive Modulation Algorithm for MIMO System

Lingyan Fan, Chen He, and Guorui Feng

Abstract: **In this paper, an adaptive minimum transmit power modulation scheme under constant data rate and fixed bit error rate (BER) for the multiple-input multiple-output (MIMO) system is proposed. It adjusts the modulation order and allocates the transmit power to each spatial sub-channel when meeting the user's requirements at the cost of minimum transmission power. Compared to the other algorithm, it can obtain good performance with lower computational complexity and can be applied to the wireless communication system. Computer simulation results present the efficiency of the proposed scheme. And its performance under different channel condition has been compared with the other algorithm.**

Index Terms: **Adaptive bit allocation, multiple-input multiple-output (MIMO).**

I. INTRODUCTION

The multiple-input multiple-output (MIMO) has gathered considerable research in recent years. Due to its promised enormous channel capacity, it has been considered to be a critical technique in the next generation high data rate wireless communication [1], [2]. It is well known that the channel of the wireless communication is variable; the traditional communication system is designed to work under the worst channel condition. But the channel does not always stay at the bad state. The introduction of adaptive modulation (AM) is to solve this problem. Similarly, in MIMO systems AM can increase spectral efficiency and system performance [3], [4].

The previous schemes on AM MIMO system have two allocation ideas. One is the classical water-filling algorithm and its improved version, which allocate the transmit power to maximize the data rate under the restriction of fixed total transmit power [5], [6]. Another is to minimize the transmit power under the restriction of fixed date rate and bit error rate (BER). The latter algorithm considers that transmission rate and BER are fixed in some communication systems. Under this condition, the total transmit power is decreased as much as possible. In [7], the author proposed a robust adaptive modulation for imperfect channel state information (I-CSI) based on minimizing the transmit power under fixed QoS (Quality of Service) for the MIMO systems. However, in its bit allocation process, he employed ergodic search method to get the number of allocated bits on every sub-channel. It has high computational complexity and is not fit to be applied to the wireless communication system. In this paper, an efficient optimal bit allocation adaptive modulation algorithm is proposed for MIMO system. It allocates the transmit power and bit to each spatial sub-channel in terms of minimum transmission power, which is implemented under the restriction of constant date rate and fixed BER. By the optimal iterative algorithm, the proposed modulation scheme can obtain optimal results. The theory and computer simulation results show that the proposed algorithm has good performance with low computational complexity.

The paper is organized as follows. Section II presents the adaptive modulation model in the MIMO system. In Section III, the proposed adaptive modulation scheme based on minimum transmit power under constant data rate and fixed BER is described in detail. And complexity analysis is given. Computer simulation results are shown in Section IV. Concluding remarks are given in Section V.

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II. ADAPTIVE MODULATION MODEL FOR MIMO SYSTEM

In this section, the AM model at the transceiver in MIMO system is presented. Consider a MIMO wireless communications system with N_t transmit antennas and N_r receiver antennas, and the channel can be represented by a $N_r \times N_t$ matrix $\mathbf{H}$. Assume that the channel is flat. Each element in $\mathbf{H}$ is a sample from independent complex Gaussian random processes with zero mean and unit variance. After channel, the received signal can be expressed as follows [8].

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} \tag{1}$$

where $\mathbf{s}$ is a MIMO channel input vector, $\mathbf{r}$ is a output vector, and $\mathbf{n}$ is additive white Gaussian noise with zero mean and variance σ_n^2. We also assume that $\mathbf{H}$ varies so slowly that it can be treated as constant in a modulation period. We assume that both transmitter and receiver have the channel state information (CSI). In general, with training sequence CSI has been obtained by channel estimation method, which can result in estimated and feedback error defined by $\widehat{\mathbf{H}}$. Now the estimated I-CSI is modeled [5].

$$\mathbf{H} = \widehat{\mathbf{H}} + \Xi \tag{2}$$

where $\Xi \in C^{N_r \times N_t}$ is channel estimation error matrix and its element $e_{i,j}$ is modeled as Gaussian variant with zero mean and variance σ_e^2. And when $\sigma_e^2 = 0$, the Perfect CSI (P-CSI) can be used in receiver and transmitter.

By applying an singular value decomposition (SVD) to $\widehat{\mathbf{H}}$ [5], we have

$$\widehat{\mathbf{H}} = \widehat{\mathbf{U}}\widehat{\Sigma}\widehat{\mathbf{V}}^H \tag{3}$$

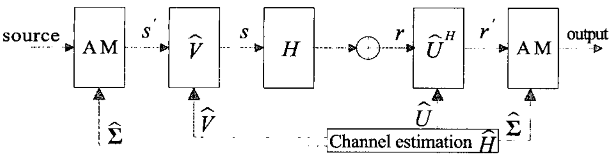

Fig. 1. AM MIMO system.

where $(\cdot)^H$ stands for conjugate transposition. $\widehat{\mathbf{\Sigma}}$ is $N_r \times N_t$ matrix with singular values of $\widehat{\mathbf{H}}$. $\{\widehat{\lambda}_1, \widehat{\lambda}_2, \cdots, \widehat{\lambda}_L\}$ as the main diagonal elements of $\widehat{\mathbf{\Sigma}}$ and $\widehat{\lambda}_1 \geq \widehat{\lambda}_2 \geq \cdots \geq \widehat{\lambda}_L$. $\widehat{\mathbf{U}}$ and $\widehat{\mathbf{V}}$ are $N_r \times N_r$ and $N_t \times N_t$ unitary matrices with left and right singular vectors of $\widehat{\mathbf{H}}$ as their columns, respectively. We define

$$\mathbf{r}' = \widehat{\mathbf{U}}^H\mathbf{r}, \;\; \mathbf{s}' = \widehat{\mathbf{V}}^H\mathbf{s}, \;\; \mathbf{n}' = \widehat{\mathbf{U}}^H\mathbf{n}. \tag{4}$$

And using (3), we can write (1) as

$$\mathbf{r}' = \widehat{\mathbf{\Sigma}}\mathbf{s}' + \widehat{\mathbf{U}}^H\mathbf{\Xi}\widehat{\mathbf{V}}\mathbf{s}' + \mathbf{n}' \tag{5}$$

Here, we set $\mathrm{T} = \widehat{\mathbf{U}}^H\mathbf{\Xi}\widehat{\mathbf{V}}\mathbf{s}' + \mathbf{n}'$, whose element $T_{i,j} \sim CN(0, \sigma_t^2)$ is still white Gaussian variant because $\widehat{\mathbf{U}}$ and $\widehat{\mathbf{V}}$ are unitary. Now a MIMO channel is decomposed into $L \leq \min(N_t, N_r)$ parallel sub-channels.

In Fig. 1, an AM MIMO system block diagram is shown [5]. The channel estimation module estimates the CSI ($\widehat{\mathbf{H}}$), and then extracts $\widehat{\mathbf{U}}$ and $\widehat{\mathbf{V}}$ as well as the square root vector of the sub-channel power gain $\{\widehat{\lambda}_1, \widehat{\lambda}_2, \cdots, \widehat{\lambda}_L\}$. $\widehat{\mathbf{U}}$ and $\widehat{\mathbf{V}}$ are used at the transmitter and receiver side, respectively, to decompose the MIMO channel into L sub-channels. $\widehat{\mathbf{\Sigma}}$ is used by the AM modules at both sides to adjust the transmit parameters.

III. THE PROPOSED ADAPTIVE MODULATION SCHEME BASED ON MINIMUM TRANSMIT POWER

A. The adaptive modulation function

Here, we propose a minimum transmit power modulation scheme under constant data rate and BER in the MIMO system. Assume that QAM modulation and ideal phase detection are employed. Then the BER of the ith sub-channel can be approximated by [9].

$$BER_i \approx 0.2\exp\left(\frac{-1.5\widehat{\lambda}_i^2 P_i}{(g2^{b_i}-1)\sigma_t^2}\right), 1 \leq i \leq L \tag{6}$$

where P_i and b_i denote the transmit power and the number of bits allocated to the ith sub-channel, respectively, and the constellation-specific constant g is defined by $g = 1$ for $b_i = 2, 4, 6 \ldots$ and 1.25 for $b_i = 1, 3, 5 \ldots$. From (5), the instantaneous transmit power can be calculated by

$$P_i = \frac{\ln(5BER_i)(1 - g2^{b_i})\sigma_t^2}{1.5\widehat{\lambda}_i^2}. \tag{7}$$

Now, the problem that minimizes the transmit power, which is subject to the data rate and BER, is formulated as a constraint optimization problem as follows

$$[b_1, \cdots, b_L]_{opt} = \arg\min_{[b_1,\cdots b_L]} \sum_{i=1}^{L} \frac{\ln(5BER_i)(1 - g2^{b_i})\sigma_t^2}{1.5\widehat{\lambda}_i^2}, \tag{8}$$

$$\text{subject to} \sum_{i=1}^{L} b_i \geq R_{tg}$$

$$\text{and } BER_i \leq B_{tg}, \;\; i = 1, \cdots, L$$

where R_{tgt} and B_{tgt} are the target data rate and the target BER respectively. To simplify to solve the problem, we assume $\sum_{i=1}^{L} b_i = R_{tg}$ and $BER_i = B_{tg}$. The optimization problem in (8) can be reformulated through the Lagrange multiplier

$$J(b_1, b_2, \cdots b_L) = \sum_{i=1}^{L} \frac{\ln(5B_{tg})(1 - g2^{b_i})\sigma_t^2}{1.5\widehat{\lambda}_i^2} + \eta(\sum_{i=1}^{L} b_i - R_{tg}) \tag{9}$$

where $J(b_1, b_2, \cdots b_L)$ is the Lagrange function and η is a constant with $\eta \geq 0$. The optimal bit allotment in terms of minimizing the transmit power can be reached when the following conditions are satisfied

$$\frac{\partial J(b_1, b_2, \cdots b_L)}{\partial b_i} = 0, \;\; i = 1, \cdots, L \tag{10}$$
$$\frac{\partial J(b_1, b_2, \cdots b_L)}{\partial \eta} = 0.$$

According to (9) and Eq. (10), we have

$$-\frac{\ln(5B_{tg})\sigma_t^2}{1.5\widehat{\lambda}_i^2} g2^{b_i}\ln 2 + \eta = 0, \tag{11}$$
$$\sum_{i=1}^{L} b_i = R_{tg}.$$

Thus,

$$\begin{aligned} b_i &= \log_2 \frac{1.5\widehat{\lambda}_i^2\eta}{\ln(5B_{tg})\ln 2g\sigma_t^2} \\ &= \frac{1}{L}(R_{tg} + 2\log_2 \frac{(\widehat{\lambda}_i)^L}{\prod_{l=1}^{L}\widehat{\lambda}_l})1 \\ &= \frac{1}{L}(R_{tg} + 2L\log_2\widehat{\lambda}_i - 2\sum_{l=1}^{L}\log_2\widehat{\lambda}_l), \;\; 1 \leq i \leq L. \end{aligned} \tag{12}$$

From (12), it can be found that b_i is only related to the singular values of $\widehat{\mathbf{H}}$ and the target data rate. We round off and make b_i become a non-negative integer for practical modulation/demodulation as follows

$$\widehat{b_i} = \text{round}(b_i), \;\; 1 \leq i \leq L \tag{13}$$

where $\widehat{b_i}$ is an approximate integer of b_i. When $i = 1, \ldots, L$, if $\widehat{b_i} \leq 0$, we set $\widehat{b_i} = 0$ and $L_{on} = L - 1$. L_{on} is the number of turned on sub-channel of the MIMO systems. That is, if $\widehat{b_i} \leq 0$, the ith sub-channel is turned off and is not used to transmit data.

Because rounding off will introduce error, $\widehat{b_i}$ is larger or smaller to b_i. So $\sum_{i=1}^{L_{on}} \widehat{b_i}$ may be not equal to R_{tgt}. Using this $\widehat{b_i}$ to allocate bit for each spatial sub-channel, the optimization condition in (8) is not satisfied. To solve the problem, $\widehat{b_i}$ needs to be optimized to meet the requirement of the system. That is to say

$$\sum_{i=1}^{L_{on}} \widehat{b_i} = R_{tg}. \tag{14}$$

We propose an adaptive iterative allocation method as follows in Subsection B to remove the impact of rounding off in the process of transmit power and bit allocation, and to guarantee optimization condition.

B. Optimal iterative algorithm

Due to (13), it is known that

$$R_{tg} - L_{on} < \sum_{i=1}^{L_{on}} \widehat{b_i} < R_{tg} + L_{on}. \tag{15}$$

Assume that the initial supremum of $\sum_{i=1}^{L_{on}} \widehat{b_i}$ is $R_{\text{sup}} = R_{tg} + L_{on}$, and its initial infimum is $R_{\text{inf}} = R_{tg} - L_{on}$. Assume that k iteration is needed to meet $\sum_{i=1}^{L_{on}} \widehat{b_i} = R_{tg}$. At first we set $k = 0$, then

$$\begin{aligned} R_{tg}(k) &= R_{tg}, \\ b_i(k) &= \frac{1}{L_{on}}(R_{tg}(k) + F(\hat{\lambda}_i)), \\ \hat{b}_i(k) &= \text{Round}(b_i(k)), \\ R_{\text{sup}}(k) &= R_{\text{sup}}, \\ R_{\text{inf}}(k) &= R_{\text{inf}} \end{aligned} \tag{16}$$

where $F(\hat{\lambda}_i) = 2L_{on}\log_2 \widehat{\lambda}_i - 2\sum_{k=1}^{L_{on}} \widehat{\lambda}_k$.

If $\sum_{i=1}^{L_{on}} \widehat{b}_i(k) > R_{tg}$, then

$$\begin{aligned} R_{tg}(k+1) &= \frac{R_{\text{inf}}(k) + R_{tg}(k)}{2} \\ R_{\text{sup}}(k+1) &= R_{tg}(k) \\ R_{\text{inf}}(k+1) &= R_{\text{inf}}(k) \end{aligned} \tag{17}$$

If $\sum_{i=1}^{L_{on}} \widehat{b}_i(k) < R_{tg}$, then

$$\begin{aligned} R_{tg}(k+1) &= \frac{R_{\text{sup}}(k) + R_{tg}(k)}{2} \\ R_{\text{sup}}(k+1) &= R_{\text{sup}}(k) \\ R_{\text{inf}}(k+1) &= R_{tg}(k) \end{aligned} \tag{18}$$

Due to the updated equations above, the following is obvious: $R_{\text{inf}}(k) < R_{tg}(k+1) < R_{\text{sup}}(k)$.

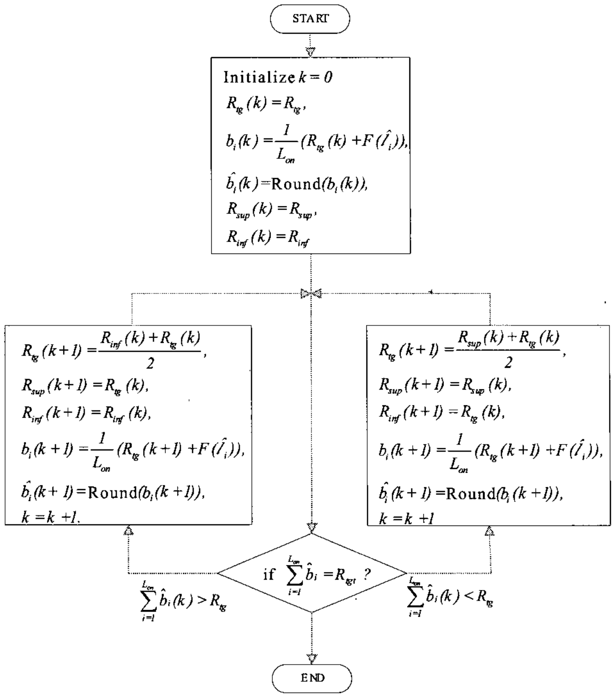

Fig. 2. Flow chart of the proposed iterative algorithm.

The following is the summary of the proposed bit allocation algorithm, and the flow chart is depicted in Fig. 2.

- (Step 1) Initialize b_i as (12), set $k = 0$, and calculate $R_{tg}(k)$, $b_i(k)$, $\hat{b}_i(k)$, $R_{\text{sup}}(k)$ and $R_{\text{inf}}(k)$ as (16).
- (Step 2) If $\sum_{i=1}^{L_{on}} \widehat{b}_i(k) = R_{tg}$, go to Step 3. If $\sum_{i=1}^{L_{on}} \widehat{b}_i(k) > R_{tg}$, update $R_{tg}(k+1)$ and $R_{\text{sup}}(k+1)$ as (17), $R_{\text{inf}}(k+1)$ keeps its old value. Using them, update $b_i(k+1)$ and $\hat{b}_i(k+1)$. And $k = k+1$. Go to step 2. If $\sum_{i=1}^{L_{on}} \widehat{b}_i(k) < R_{tg}$, update $R_{tg}(k+1)$ and $R_{\text{inf}}(k+1)$ as (17), $R_{\text{sup}}(k+1)$ keeps its old value. Using them, update $b_i(k+1)$ and $\hat{b}_i(k+1)$. And $k = k+1$. Go to step 2.
- (Step 3) Stop the iteration algorithm. Allocate the integer number of bits $\hat{b}_i(k)$, and the transmit power for each sub-channel.

Lemma 1: Having a zero measure set Z, which Lebesgue measure $m(Z) = 0$.

If $\lim_{k\to\infty} b_i(k) \in [\frac{1}{L_{on}}(R_{\text{inf}}+F(\widehat{\lambda}_i)), \frac{1}{L_{on}}(R_{\text{sup}}+F(\widehat{\lambda}_i))]\backslash Z$, $i = 1, \cdots, L_{on}$,

Then having a R^{op}, when $b_i^{op} = \frac{1}{L_{on}}(R^{op} + F(\hat{\lambda}_i))$, meets $\sum_{i=1}^{L_{on}} \widehat{b}_i^{op} = R_{tg}$.

In Appendix, we prove the lemma. By the lemma, it is proven that we always can get the optimal $\widehat{b}_1, \widehat{b}_2, \cdots, \widehat{b}_{L_{on}}$ to satisfy the requirement of system under minimum transmit power with k iteration.

C. Complexity comparisons

Based on the above algorithm, we note that the proposed algorithm does not sort and the method requires only $O(k \times L)$ operations. It shows that the proposed algorithm's computational complexity is lower than the algorithm proposed in [7]. The Table of operations for the proposed algorithm and the method

Table 1. Complexity comparisons.

Algorithm	Order of Operation
The algorithm in [7]	$O(R_{HH} \times L^3)$
The proposed algorithm	$O(k \times L)$

(R_{HH} is the total number of allocated bits, L is the number of sub-channel, and k is the required number of iterations.)

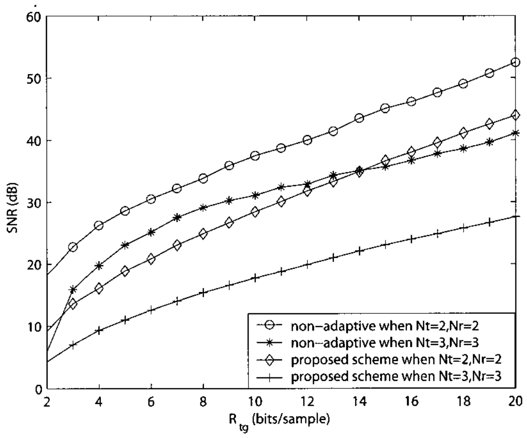

Fig. 3. SNR versus R_{tg} when $B_{tg} = 10^{-4}$.

in [7] are tabulated in Table 1. In the next section, simulation results for system performance show that the proposed has similar performance with less operation.

IV. SIMULATION RESULTS

We apply the proposed scheme to a MIMO system. The modulation scheme is uncoded quadrature amplitude modulation (QAM). In all simulations, the background noise power is kept to $\sigma_n^2 = 1$. Without loss of generality, the simulation results are obtained under the narrow band MIMO channel. The performance of power consumption versus R_{tg} of the proposed scheme is compared with non-adaptive scheme in Fig. 3 under $B_{tg} = 10^{-4}$ and $\sigma_e^2 = 0$, where the number of transmit and receive antennas are chosen as 2 and 3, respectively. As can be seen in Fig. 3, the proposed algorithm can lower transmit power to obtain the requirement of the system. And we can discover that more transmit power is required to ensure the target BER as transmission data rate increases from the figure. The higher the number of transmit and receive antennas, the lower the needed transmit power. But increasing the number of transmit and receive antenna will add to the computational complexity. So, it is necessary to reach a compromise between good performance and computational complexity according to the practical request.

Fig. 4 compares that performance of the proposed algorithm and the algorithm in [7] under different σ_e^2. That is to say, the experiment result shows the performance of standing against channel estimation error with different algorithm. These simulations are done with $B_{tg} = 10^{-4}$ and $R_{tg} = 15$ bit/sample. It is shown that they have same minimum transmit power under P-CSI. But under I-CSI, the performance of the proposed algorithm has flat

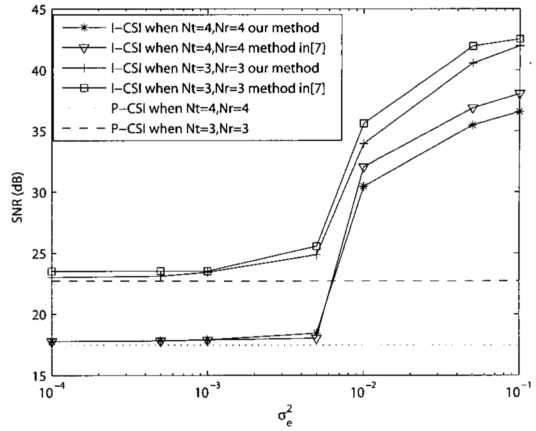

Fig. 4. Performance comparison between the proposed algorithm and algorithm in [7] under $R_{tg} = 15$ bit/sample and $B_{tg} = 10^{-4}$.

change with the variant of the error of the CSI estimation. And in the above analysis, the proposed algorithm needs low computational complexity to obtain this performance.

V. CONCLUSION

In this paper, an adaptive modulation scheme for the MIMO system, which is based on the user's requirements, is proposed. When the CSI from the receiver feedback is achieved at the transmitter, the modulation order adjustment and the power distribution to each spatial sub-channel under constant data rate and fixed BER at the cost of possible minimum transmit power can be realized by using the proposed scheme. In the proposed algorithm, we use optimal adaptive iterative algorithm to obtain allocation bit for every sub-channel. This can deliver performance with low computational complexity.

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APPENDIX

Lemma 2: Having a zero measure set Z, which Lebesgue measure $m(Z) = 0$. If $\lim_{k\to\infty} b_i(k) \in [\frac{1}{L_{on}}(R_{\inf} + F(\widehat{\lambda}_i)), \frac{1}{L_{on}}(R_{\sup} + F(\widehat{\lambda}_i))]\backslash Z$, $i = 1, \cdots, L_{on}$,
Then having a R^{op}, when $b_i^{op} = \frac{1}{L_{on}}(R^{op} + F(\hat{\lambda}_i))$, meets $\sum_{i=1}^{L_{on}} \widehat{b}_i^{op} = R_{rg}$.

Proof: Due to $b_i(R) = \frac{1}{L_{on}}(R + F(\hat{\lambda}_i))$, we know that $b_i(R)$ is a monotone increasing function about R, and $b_i(k) \in [\frac{1}{L_{on}}(R_{\inf} + F(\widehat{\lambda}_i)), \frac{1}{L_{on}}(R_{\sup} + F(\widehat{\lambda}_i))]$. Rounding off $b_i(k)$ will produce limited discontinuous points in the interval. The discontinuous point set is Z_i, which measure is $m(Z_i) = 0$. Except the zero measure set, $b_i(R) = \frac{1}{L_{on}}(R + F(\widehat{\lambda}_i))$ is a continuous function. And $\sum_{i=1}^{L_{on}} \widehat{b}_i(R)$ is also a monotone increasing continuous function about R.

Due to (16),

$$R_{\inf}(k) < R_{tg}(k) < R_{\sup}(k),$$

$$|R_{\sup}(k) - R_{\inf}(k)| = |R_{\sup} - R_{\inf}| / 2^k;$$

and

$$b_i(k) \in [\frac{1}{L_{on}}(R_{\inf}(k) + F(\widehat{\lambda}_i)), \frac{1}{L_{on}}(R_{\sup}(k) + F(\widehat{\lambda}_i))].$$

When $k \to \infty$, then

$$m(\frac{1}{L_{on}}(R_{\inf}(k) + F(\widehat{\lambda}_i)), \frac{1}{L_{on}}(R_{\sup}(k) + F(\widehat{\lambda}_i))) = \frac{|R_{\sup} - R_{\inf}|}{L_{on}2^k}$$

Because the rounding function is a continuous function based on the above explanation, therefore

$$\hat{b}_i(k) \in [\text{Round}(\frac{1}{L_{on}}(R_{\inf}(k) + F(\widehat{\lambda}_i))), \text{Round}(\frac{1}{L_{on}}(R_{\sup}(k) + F(\widehat{\lambda}_i)))].$$

That is to say $\hat{b}_i(k)$ has limit $\hat{b}_i^{op}$, which meets $\sum_{i=1}^{L_{on}} \widehat{b}_i^{op} = R_{rg}$.

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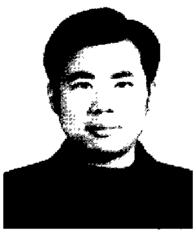

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