LOW-COMPLEXITY BEAMFORMING DESIGNS OF SUM SECRECY RATE MAXIMIZATION FOR THE GAUSSIAN MISO MULTI-RECEIVER WIRETAP CHANNEL

Yanqun Tang, Caiyao Sheng, Yunpeng Hu, Hongyi Yu, and Xiaoyi Zhang

National Digital Switching System Engineering & Technology R & D Center, Zhengzhou, China, 450000
{tangyanqun, shencaiyao, hyp1978}@126.com, maxyucn@sohu.com, xiaoyi@vip.sina.com

ABSTRACT

This paper studies the beamforming design for sum secrecy rate (SSR) maximization in the Gaussian multiple-input single-output multi-receiver wiretap channel (MISO-MRWC). The optimization problem of finding the optimal beamforming algorithm is non-convex and intractable to solve using low-complexity methods. Motivated by the thinking of zero-forcing (ZF) and signal-to-leakage-plus-noise ratio (SLNR), we propose three low-complexity beamforming algorithms for finding a local SSR optimum. The simulation results show that the SLNR-based beamforming algorithm outperforms the other two algorithms with ZF preprocessing.

Index Terms— Sum secrecy rate, beamforming design, low complexity, ZF, SLNR.

1. INTRODUCTION

In recent years, information theoretic security has gathered a renewed interest, which exploits the randomness of wireless propagation channels to enhance the security [1–3]. The studies in [2–5] on the multiple-input multiple-output (MIMO) systems provide beamforming designs for secure communication, where more and more attention has been devoted to the multi-user scenarios of the wiretap channel [5].

In [6, 7], the authors studied the secrecy capacity region (SCR) of the Gaussian MIMO multi-receiver wiretap channel (MIMO-MRWC), where a transmitter which wants to communicate with several legitimate users in the presence of an external eavesdropper. However, achieving the SCR of MIMO-MRWC for the general cases seems to be quite challenging. It is well known that the capacity region of the general broadcast channel with an arbitrary number of users is not obtained, even without the eavesdropper.

Except for the secrecy capacity region, the sum secrecy rate (SSR) of the wiretap channel to the multi-user setting is an important metric to characterize the secrecy performance. In [8], the authors studied the beamforming design for the SSR maximization problem in the multiple user-eaves pair wiretapping model and proposed an approximation algorithm based on Taylor expansion in addition to the zero-forcing (ZF) method. The extended work about the robust beamforming design for the uncertainty model was studied in [9]. In [10], the authors studied the SSR for multi-user MIMO (MU-MIMO) wiretap channel with the regularized channel inversion precoding. In [11], the SSR maximization problem in the relay network was studied.

However, unlike [8–11], the beamforming design for the SSR maximization problem in the Gaussian multiple-input single-output multi-receiver wiretap channel (MISO-MRWC) was not studied so far. Thus, we will fill up the gap in this paper. The SSR maximization problem of finding the optimal beamforming algorithm is non-convex and intractable to solve using low-complexity methods. It's natural to think of the beamforming algorithms as a reference in the MU-MIMO systems, where the algorithms based on ZF and signal-to-leakage-plus-noise ratio (SLNR) [12, 13] are widely used. These algorithms avoid the signal crossing problem induced by the inter-user interference (IUI), where the ZF preprocessing nulls out the interferences while the SLNR-based algorithm uses the leakage to measure how much signal power leaks into the other users. In the wiretap channel, it is the signal leakage to the eavesdropper that causes the information being eavesdropped. Thus, by using the thinking of ZF and SLNR, we can achieve tractable solutions to the SSR maximization with low complexity.

We first give the MISO-MRWC system model and the SSR maximization problem in Section 2. Then, we study the low-complexity beamforming design and propose three beamforming algorithms based on SLNR and ZF in Section 3. Finally, we demonstrate the SSR performance of these three algorithms through the numerical simulation.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1. System Model

We consider the Gaussian MISO-MRWC model, where a N_t-antenna transmitter (Alice) wants to have confidential communication with K single-antenna legitimate receivers (Bobs) in the presence of a passive eavesdropper (Eve) with N_e antennas. The signal transmitted at Alice can be modeled as

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$\mathbf{x} = \mathbf{F}\mathbf{s}$. Here, $\mathbf{s} = [s_1 \cdots s_K]^T \in \mathbb{C}^K$ with $\mathbb{E}\{\mathbf{s}\mathbf{s}^H\} = \mathbf{I}$, where s_k is the information-bearing symbol intended for Bob k. The matrix $\mathbf{F} = [\mathbf{f}_1 \cdots \mathbf{f}_K] \in \mathbb{C}^{N_t \times K}$, where $\mathbf{f}_k$ denotes the transmit beamforming vector for Bob k with $\text{Tr}(\mathbf{f_k}\mathbf{f_k}^H) = p_k$, where $p_k \geq 0$ is the transmit power allocated to Bob k. Besides, $\sum_{k=1}^{K} p_k \leq P_t$ with P_t denoting the total transmit power.

The signals received at Bob k and Eve, respectively, are defined as

$$y_k = \mathbf{h}_k\mathbf{x} + n_k = \mathbf{h}_k\mathbf{F}\mathbf{s} + n_k, \tag{1}$$

$$\mathbf{y}_e = \mathbf{G}\mathbf{x} + \mathbf{n}_e = \mathbf{G}\mathbf{F}\mathbf{s} + \mathbf{n}_e, \tag{2}$$

where $\mathbf{h}_k \in \mathbb{C}^{1\times N_t}$ and $\mathbf{G} \in \mathbb{C}^{N_e \times N_t}$ denote the channels from Alice to Bob k and Eve, respectively. The scalar n_k and the vector $\mathbf{n}_e \in \mathbb{C}^{N_e}$ are zero-mean white complex Gaussian noises with covariance $\sigma_{b,k}^2$ and $\sigma_e^2\mathbf{I}$, respectively.

In this paper, we assume that Alice knows the perfect channel state information of $\mathbf{H} = \left[\mathbf{h}_1^T, \ldots, \mathbf{h}_K^T\right]^T \in \mathbb{C}^{K\times N_t}$ and $\mathbf{G}$, which is reasonable when Bobs and Eve are the users in the internal network. Besides, we assume that $\mathbf{H}$ and $\mathbf{G}$ are uncorrelated to each other, the elements of which are independent and identically distributed (i.i.d) circularly symmetric complex Gaussian random variables. For ease of analysis, we also assume that $\sigma_{b,k}^2 = \sigma_e^2 = 1$.

2.2. Problem Formulation

According to (1), the signal-to-interference-plus-noise ratio (SINR) at Bob k can be expressed as

$$\text{SINR}_k = \frac{\mathbf{f}_k^H\mathbf{h}_k^H\mathbf{h}_k\mathbf{f}_k}{1 + \sum\limits_{j=1,j\neq k}^{K} \mathbf{f}_j^H\mathbf{h}_k^H\mathbf{h}_k\mathbf{f}_j}. \tag{3}$$

And also for the information-bearing symbol s_k, according to (2), we can get the SINR at Eve

$$\text{SINR}_{e,k} = \frac{\mathbf{f}_k^H\mathbf{G}^H\mathbf{G}\mathbf{f}_k}{N_e + \sum\limits_{j=1,j\neq k}^{K} \mathbf{f}_j^H\mathbf{G}^H\mathbf{G}\mathbf{f}_j}. \tag{4}$$

For the Gaussian MISO-MRWC, the SSR maximization problem can be expressed as

$$\begin{aligned} \max_{\mathbf{F}} \quad & \textstyle\sum_{k=1}^{K} \log_2(1 + \text{SINR}_k) - \log_2(1 + \text{SINR}_{e,k}) \\ \text{s.t.} \quad & \text{Tr}\left(\mathbf{F}\mathbf{F}^H\right) \leq P_t. \end{aligned} \tag{5}$$

3. LOW-COMPLEXITY BEAMFORMING ALGORITHMS

According to (3) and (4), we can easily see that the SSR maximization problem (5) is non-convex and intractable to solve. Thus, our object is to find the low-complexity beamforming algorithms for a local optimum.

3.1. SLNR-Based Beamforming Algorithm

From [12], we know that the SLNR-based algorithm uses the leakage to measure the signal power leaks into the other users, which avoid the signal crossing problem induced by the IUI. In the Gaussian MISO-MRWC, we also uses the thinking to compute the signal leakage between the legitimate users and to the eavesdropper.

Thus, we have

$$\text{SLNR}_k = \frac{\mathbf{f}_k{}^H\mathbf{h}_k^H\mathbf{h}_k\mathbf{f}_k}{1 + \sum\limits_{j=1,j\neq k}^{K} \mathbf{f}_k{}^H\mathbf{h}_j^H\mathbf{h}_j\mathbf{f}_k + \mathbf{f}_k^H\mathbf{G}^H\mathbf{G}\mathbf{f}_k}. \tag{6}$$

Let $\mathbf{f}_k = \sqrt{p_k}\mathbf{t}_k$ with $\|\mathbf{t}_k\|_2^2 = 1$, the equation (6) can be recast as

$$\text{SLNR}_k = \frac{\mathbf{t}_k{}^H\mathbf{h}_k^H\mathbf{h}_k\mathbf{t}_k}{\mathbf{t}_k{}^H\left(\mathbf{I}/p_k + \mathbf{H}_{\tilde{k}}^H\mathbf{H}_{\tilde{k}} + \mathbf{G}^H\mathbf{G}\right)\mathbf{t}_k} \tag{7}$$

with $\mathbf{H}_{\tilde{k}} = \left[\mathbf{h}_1^T, \ldots, \mathbf{h}_{k-1}^T, \mathbf{h}_k^T, \ldots, \mathbf{h}_K^T\right]^T \in \mathbb{C}^{(K-1)\times N_t}$. Then, we can transform the SSR maximization problem (5) into the SLNR maximization problem

$$\begin{aligned} \max_{\mathbf{t}_k,\forall k} \quad & \text{SLNR}_k \\ \text{s.t.} \quad & \text{Tr}\left(\mathbf{t}_k\mathbf{t}_k^H\right) \leq 1. \end{aligned} \tag{8}$$

We can easily get

$$\mathbf{t}_k \propto \mathbb{M}\left(\left(\mathbf{I}/p_k + \mathbf{H}_{\tilde{k}}^H\mathbf{H}_{\tilde{k}} + \mathbf{G}^H\mathbf{G}\right)^{-1}\mathbf{h}_k^H\mathbf{h}_k\right). \tag{9}$$

with $\mathbb{M}(\cdot)$ denoting the eigenvector corresponding to the maximum eigenvalue of a matrix. From (9), we can see that $\mathbf{t}_k$ is closely related with the value of p_k. However, the joint optimization of $\mathbf{t}_k$ and p_k is hard to resolve. Thus, the suboptimal solution can be obtained by alternating iterative optimization algorithm. First, we can obtain $\mathbf{t}_k$ based on the initial value of p_k by (9). Then, the value of p_k can be updated through resolving the following optimization problem

$$\begin{aligned} \max_{p_k} \quad & \textstyle\sum_{k=1}^{K} R_{s,k} \\ \text{s.t.} \quad & \textstyle\sum_{k=1}^{K} p_k \leq P_t \end{aligned} \tag{10}$$

with $R_{s,k} = \log_2(1 + \text{SINR}_k) - \log_2(1 + \text{SINR}_{e,k})$.

Because of the existence of signal crossing in SINR_k and $\text{SINR}_{e,k}$, the problem (10) is hard to resolve. Thus, for the sake of low complexity, we only consider the case of equal power allocation between Bobs, i.e., $p_k = P_t/K, \forall k$.

In summary, we can get

$$\mathbf{t}_k \propto \mathbb{M}\left(\left(K\mathbf{I}/P_t + \mathbf{H}_{\tilde{k}}^H\mathbf{H}_{\tilde{k}} + \mathbf{G}^H\mathbf{G}\right)^{-1}\mathbf{h}_k^H\mathbf{h}_k\right). \tag{11}$$

Correspondingly, for the SLNR-based beamforming algorithm, we can obtain the beamforming vector $\mathbf{f}_k = \sqrt{P_t/K}\mathbf{t}_k$.

3.2. ZF-based Beamforming Algorithm

As mentioned in Section 1, the signal leakage to the eavesdropper causes the information being eavesdropped in the wiretap channel. By using the thinking of ZF, we thus null out the signal received at Eve, i.e., $\mathbf{G}\mathbf{f}_k = \mathbf{0}, \forall k$, which requires that the number of transmit antenna at Alice is not less than that of receive antenna at Bobs and Eve, i.e., $N_t \geq N_e + K$.

Thus, through the ZF preprocessing, the SSR maximization problem (5) can be written as

$$\begin{array}{ll} \max\limits_{\mathbf{F}} & \sum_{k=1}^{K} \log_2 (1 + \mathrm{SINR}_k) \\ \text{s.t.} & \mathbf{G}\mathbf{F} = \mathbf{0}, \mathrm{Tr}\left(\mathbf{F}\mathbf{F}^H\right) \leq P_t. \end{array} \tag{12}$$

By defining the null space of $\mathbf{G}$ with

$$\Pi_{\mathbf{G}}^{\perp} = \mathbf{I} - \mathbf{G}^H \left(\mathbf{G}\mathbf{G}^H\right)^{-1} \mathbf{G}$$

and with the assumption of $\mathbf{f}_k = \Pi_{\mathbf{G}}^{\perp} \mathbf{w}_k$, we further get

$$\begin{array}{ll} \max\limits_{\mathbf{W}} & \sum_{k=1}^{K} \log_2 \left(1 + \frac{\mathbf{w}_k^H \Pi_{\mathbf{G}}^{\perp} \mathbf{h}_k^H \mathbf{h}_k \Pi_{\mathbf{G}}^{\perp} \mathbf{w}_k}{1 + \sum_{j=1, j\neq k}^{K} \mathbf{w}_j^H \Pi_{\mathbf{G}}^{\perp} \mathbf{h}_k^H \mathbf{h}_k \Pi_{\mathbf{G}}^{\perp} \mathbf{w}_j}\right) \\ \text{s.t.} & \mathrm{Tr}\left(\mathbf{W}\mathbf{W}^H\right) \leq P_t \end{array} \tag{13}$$

with $\mathbf{W} = [\mathbf{w}_1 \cdots \mathbf{w}_K] \in \mathbb{C}^{N_t \times K}$. Notice that the vector $\mathbf{w}_k$ is introduced for the sake of obtaining the beamforming vector $\mathbf{f}_k$ easily.

Let $\bar{\mathbf{h}}_k = \mathbf{h}_k \Pi_{\mathbf{G}}^{\perp}$, the problem (13) can be rewritten as

$$\begin{array}{ll} \max\limits_{\mathbf{W}} & \sum_{k=1}^{K} \log_2 \left(1 + \frac{\mathbf{w}_k^H \bar{\mathbf{h}}_k^H \bar{\mathbf{h}}_k \mathbf{w}_k}{1 + \sum_{j=1, j\neq k}^{K} \mathbf{w}_j^H \bar{\mathbf{h}}_k^H \bar{\mathbf{h}}_k \mathbf{w}_j}\right) \\ \text{s.t.} & \mathrm{Tr}\left(\mathbf{W}\mathbf{W}^H\right) \leq P_t. \end{array} \tag{14}$$

According to [14], the optimization problem (14) can be resolved by Algorithm 1. Due to length limitations, we don't discuss the convergence analysis of the iterative optimization process of Algorithm 1, which can refer to [14].

Algorithm 1 ZF-based beamforming algorithm

1: set $n = 0$ and the initial receive beamformers $\mathbf{w}_k^{(0)}$ randomly, the desired accuracy $\xi > 0$;

2: $n = n + 1$;

3: compute the MMSE receive filter of Bob k with the value of $\mathbf{w}_k^{(n-1)}$

$$\alpha_{k,\mathrm{MMSE}}^{(n)} = \frac{\mathbf{w}_k^H \mathbf{h}_k^H}{1 + \sum_{k=1}^{K} \mathbf{h}_k \mathbf{w}_k \mathbf{w}_k^H \mathbf{h}_k^H}; \tag{15}$$

4: assuming that MMSE receive filtering is applied, compute the MSE

$$e_k = \left(1 + \frac{\mathbf{w}_k^H \mathbf{h}_k^H \mathbf{h}_k \mathbf{w}_k}{1 + \sum_{i\neq k, i=1}^{K} \mathbf{w}_i^H \mathbf{h}_k^H \mathbf{h}_k \mathbf{w}_i}\right)^{-1}, \tag{16}$$

then compute the weighting factor of MSE as $u_k = e_k^{-1}$;

5: let $\mathbf{U} = \mathrm{diag}\left\{u_1, \ldots, u_K\right\}$,

$$\mathbf{A} = \mathrm{diag}\left\{\alpha_{1,\mathrm{MMSE}}^{(n)}, \ldots, \alpha_{K,\mathrm{MMSE}}^{(n)}\right\}$$

and compute

$$\bar{\mathbf{W}}^{(n)} = \left(\mathbf{H}^H \mathbf{A}^H \mathbf{U} \mathbf{A} \mathbf{H} + \frac{\mathrm{Tr}\left(\mathbf{U}\mathbf{A}\mathbf{A}^H\right)}{P_t} \mathbf{I}\right)^{-1} \mathbf{H}^H \mathbf{A}^H \mathbf{U}; \tag{17}$$

6: compute $\mathbf{W}^{(n)} = b\bar{\mathbf{W}}^{(n)}$ where the variable b is chosen to meet $\mathrm{Tr}\left(\mathbf{W}\mathbf{W}^H\right) \leq P_t$, i.e., $b = \sqrt{\frac{P_t}{\mathrm{Tr}\left(\bar{\mathbf{W}}\bar{\mathbf{W}}^H\right)}}$;

7: repeat steps 2-6 until $\left\|\mathbf{w}_k^{(n)} - \mathbf{w}_k^{(n-1)}\right\|_2 < \xi, \forall k$;

8: compute $\mathbf{f}_k = \Pi_{\mathbf{G}}^{\perp} \mathbf{w}_k$.

3.3. Modified ZF-based Beamforming Algorithm

In the ZF-based beamforming algorithm described in Section 3.2, the signal leakage to eavesdropper is zero. In addition, for the modified ZF-based beamforming algorithm, we also null out the interference between the legitimate users, i.e.,

$$\mathbf{H}_{\tilde{k}} \mathbf{f}_k = \mathbf{0}, \mathbf{G}\mathbf{f}_k = \mathbf{0}, \forall k$$

with $\mathbf{H}_{\tilde{k}} = \left[\mathbf{h}_1^T, \ldots, \mathbf{h}_{k-1}^T, \mathbf{h}_k^T, \ldots, \mathbf{h}_K^T\right]^T$. Similar to the ZF-based beamforming algorithm, this algorithm also requires that $N_t \geq N_e + K$.

Let $\mathbf{f}_k = \sqrt{p_k}\mathbf{t}_k$ and $\|\mathbf{t}_k\|_2^2 = 1$, the SSR maximization problem (5) can be rewritten as

$$\begin{array}{ll} \max\limits_{\mathbf{t}_k, p_k, \forall k} & \sum_{k=1}^{K} \log_2 \left(1 + p_k {\mathbf{t}_k}^H \mathbf{h}_k^H \mathbf{h}_k \mathbf{t}_k\right) \\ \text{s.t.} & \left\{ \begin{array}{l} \mathbf{H}_{\tilde{k}} \mathbf{t}_k = \mathbf{0}, \mathbf{G}\mathbf{t}_k = \mathbf{0}, \forall k, \\ \sum_{k=1}^{K} p_k \leq P_t. \end{array} \right. \end{array} \tag{18}$$

By defining the null space of $\left[\mathbf{H}_{\tilde{k}}^T, \mathbf{G}^T\right]^T \in \mathbb{C}^{(N_e+K-1)\times N_t}$ as $\mathbf{V}_k \in \mathbb{C}^{N_t \times (N_t - N_e - K + 1)}$, and applying the eigenvalue decomposition of $\mathbf{V}_k \mathbf{V}_k^H \mathbf{h}_k^H \mathbf{h}_k \mathbf{V}_k \mathbf{V}_k^H$, we can get

$$\mathbf{V}_k \mathbf{V}_k^H \mathbf{h}_k^H \mathbf{h}_k \mathbf{V}_k \mathbf{V}_k^H = \mathbf{U}_k \mathbf{\Lambda}_k \mathbf{U}_k^H, \tag{19}$$

where,

$$\mathbf{\Lambda}_k = \mathrm{diag}\left\{\lambda_{k,1}, \lambda_{k,2}, \cdots, \lambda_{k,N_t}\right\}, \lambda_{k,1} \geq \lambda_{k,2} \cdots \geq \lambda_{k,N_t}$$

and the unitary matrix $\mathbf{U}_k$ contains all the eigenvectors corresponding to the eigenvalues. Besides, we have

$$\lambda_{k,1} > 0, \lambda_{k,2} = \cdots = \lambda_{k,N_t} = 0$$

because the rank of $\mathbf{V}_k \mathbf{V}_k^H \mathbf{h}_k^H \mathbf{h}_k \mathbf{V}_k \mathbf{V}_k^H$ is one.

Let $\mathbf{t}_k = \mathbf{U}_{k,[1:N_t,1]}$, the problem (18) can be recast as

$$\begin{array}{ll} \max\limits_{p_k, \forall k} & \sum_{k=1}^{K} \log_2 (1 + p_k \lambda_{k,1}) \\ \text{s.t.} & \sum_{k=1}^{K} p_k \leq P_t. \end{array} \tag{20}$$

According to [15], the problem (20) can be resolved by the standard water filling algorithm, i.e.,

$$p_k = [u - 1/\lambda_{k,1}]^+, u \geq 0, \forall k$$

The constant u denotes "water level", which needs to guarantee $\sum_{k=1}^{K} p_k \leq P_t$. Thus, we can get the modified ZF-based beamforming vector of Bob k as $\mathbf{f}_k = \sqrt{p_k}\mathbf{U}_{k,[1:N_t,1]}$.

4. SIMULATION RESULTS

Numerical simulations have been performed to evaluate the performance of the proposed beamforming algorithms in the Gaussian MISO-MRWC. For the beamforming algorithms with ZF preprocessing, due to the requirement of $N_t \geq K + N_e$, we assume that $N_t = K + N_e$. For simplicity, we set $K = N_e$. Besides, the elements of $\mathbf{h}_k$ and $\mathbf{G}$ are zero-mean unit-covariance random variables. In the iteration process, the accuracy of error ξ is set as 10^{-3}. All the simulations are run by using MATLAB on Windows 7 with 2.81GHz CPU and 1.75GB memory.

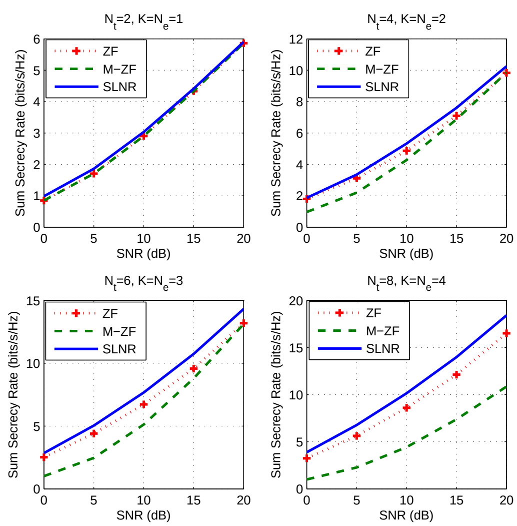

Fig. 1. Achievable SSRs of the proposed beamforming algorithms.

For ease of description, the ZF-based beamforming algorithm, the modified ZF-based beamforming algorithm and the SLNR-based beamforming algorithm are referred to as "ZF", "M-ZF" and "SLNR", respectively.

Fig. 1 shows the achieved sum secrecy rates (SSRs) of the Gaussian MISO-MRWC for three different beamforming algorithms with four cases of $K = 1, 2, 3, 4$.

Firstly, it is clear to see that "SLNR" has the best SSR performance compared with the other beamforming algorithms, "ZF" is the second, while "M-ZF" is the worst. This is mainly due to the fact that not only "SLNR" doesn't require that the IUI between Bobs or the signal leakage to Eve being restricted to be zero, but also put them into the unified leakage. Thus, although without the optimal power allocation, "SLNR" can achieve good performance. In addition to the constraint in "ZF", "M-ZF" requires that the signal leakages between the legitimate receivers are zero. Thus, although the computational complexity is brought down, the SSR performance worsen.

Secondly, we can see that the SSR performance gaps of these three algorithms increase with the number of the legitimate receivers. For the case of $K = 1$, due to the fact that the IUI doesn't exist, the SSR performance of "ZF" and "M-ZF" is similar. And also, the performance advantage of "SLNR" is not obvious. While with the increment of K, the performance gap between "ZF" and "M-ZF" is evident, especially for the case of low SNR. This is because the influence of IUI is greater in low SNR regime than the high SNR regime. On the contrary, the performance gap between "SLNR" and "ZF" increases with the SNR. The reason for this behavior is that, the impact on the SSR performance, due to the constraint of the signal leakage to Eve being zero, increases with the SNR, which is consistent with the discussion mentioned above.

Table 1. Computing time(ms) of various SNR when $N_t = 6$ and $K = N_e = 3$

SNR(dB)	0	5	10	15	20
"ZF"	6.5	6.8	6.9	8.1	10.5
"M-ZF"	6.3	6.4	6.4	6.4	6.4
"SLNR"	5.4	5.4	5.5	5.5	5.5

Table 1 compares the computing time of the proposed beamforming algorithms for various SNR with $N_t = 6$ and $K = N_e = 3$. Note that "ZF" takes more computing time than both "SLNR" and "M-ZF". This is because "ZF" requires the iterative optimization process. In summary, all of the proposed beamforming algorithms have low complexity, which are therefore potential candidates for practical beamforming designs.

5. CONCLUSION

This paper studied the low-complexity beamforming design for the Gaussian MISO-MRWC to maximize the SSR. We found the consistency between information being eavesdropped and signal leakage. As a result, based on the thinking of ZF and SLNR, we proposed three beamforming algorithms for finding a local SSR optimum. Through the numerical simulation, we demonstrate the secrecy performance of these three algorithms. The results show that the SLNR-based beamforming algorithm outperforms the other two algorithms with ZF preprocessing.

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