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Power Allocation Strategies for Secure Spatial Modulation

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***Abstract*—In secure spatial modulation (SM) networks, power allocation (PA) strategies are investigated under the total power constraint. Considering that there is no closed-form expression for secrecy rate (SR), an approximate closed-form expression of SR is presented, which is used as an efficient metric to optimize PA factor and can greatly reduce the computation complexity. Based on this expression, a convex optimization (CO) method of maximizing SR (Max-SR) is proposed accordingly. Furthermore, a method of maximizing the product of signal-to-leakage and noise ratio (SLNR) and artificial noise-to-leakage-and noise ratio (ANLNR) (Max-P-SAN) is proposed to provide an analytic solution to PA with extremely low-complexity. Simulation results demonstrate that the SR performance of the proposed CO method is close to that of the optimal PA strategy of Max-SR with exhaustive search and better than that of Max-P-SAN in the high signal-to-noise ratio (SNR) region. However, in the low and medium SNR regions, the SR performance of the proposed Max-P-SAN slightly exceeds that of the proposed CO.**

***Index Terms*—Spatial modulation, power allocation, secure transmission, finite-alphabet inputs.**

I. Introduction

As a promising and green technology in of multiple-input-multiple-out (MIMO) systems, spatial modulation (SM) [1] exploits both the index of activated antenna and amplitude phase modulation (APM) symbol to transmit messages. Due to the broadcasting characteristic of wireless transmission [2]–[4] , physical layer security (PLS) becomes an extremely urgent and important problem in wireless communication [5]–[7].

How to make SM have a capability to achieve a secure transmission become an extremely important issue for SM networks. In [8], without the knowledge of Eve's location, the confidential messages are securely transmitted from the SM transmitter to the desired receiver by projecting AN onto the null-space of the desired channel. In [9], the authors proposed a full-duplex desired receiver, where the confidential messages is received and meanwhile artificial noise (AN) is emitted to corrupt the illegal receiver (Eve). This scheme can provide a high ability to combat eavesdropping. The authors in [10] proposed two new schemes of transmit antenna selection for secure SM networks: maximizing secrecy rate (SR) and leakage, where the proposed leakage-based antenna selection scheme achieve an excellent SR performance with a very low-complexity.

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As an efficient way to improve the security of SM networks, power allocation (PA) has an important impact on SR performance. However, there are only few literature of making an investigation on PA strategies for SM. In [11], the optimal PA factor was given for precoding SM by maximizing the SR performance with exhaustive search (ES). Thus, no closed-form SR expression can be developed for PA, which will result in a high computational complexity to complete ES. This motivates us to find some closed-form solutions or low-complexity iterative methods for different PA strategies. In this paper, we will focus on the investigation of PA strategies in secure SM networks. The main contributions are summarized as follows:

1) Due to the fact that SR lacks a closed-form expression in secure SM systems, its effective approximate simple expression is defined as a metric, which can dramatically reduce the evaluation complexity of SR values to optimize PA factor. Following this definition, a convex optimization (CO) method is proposed to address the optimization problem of maximizing SR (Max-SR). From simulation results, it is obvious that the SR difference between the proposed CO and the Max-SR with ES can be negligible for almost all SNR regions.
2) To reduce the computational amount of the above CO method and at the same time provide a closed-form PA strategy, a PA strategy of maximizing the product of signal-to-leakage and noise ratio (SLNR) and AN-to-leakage and noise ratio (ANLNR) (Max-P-SAN) is proposed, which can strike a good balance between maximizing SLNR and maximizing ANLNR. Its analytic expression of PA factor is also given. Simulation results show the SR performance of Max-P-SAN method, with extremely low complexity, tends to that of Max-SR with ES method and is slightly better than that of CO in the low and medium SNR regions.

The reminder is organized as follows. In Section II, a secure SM system with the aid of AN is described. In Section III, first, the approximate simple formula of average SR is given, and two PA strategies, CO and Max-P-SAN, are proposed to maximize approximate SR and the product of SLNR and ANLNR, respectively. Subsequently, numerical simulations and analysis are presented in Section IV. Finally, we make our conclusions in Section V.

II. System Model

Fig. 1 sketches a secure SM system with N_t transmit antennas (TAs) at Alice, N_r receive antennas (RAs) at Bob,

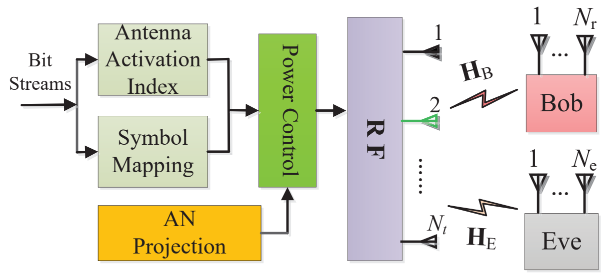

Fig. 1. A secure SM system model.

and N_e RAs at (Eve), respectively. Here, Eve intends to intercept the confidential messages. Additionally, we denote the size of signal constellation $\mathcal{M}$ by M. As a result, $\log_2 N_t M$ bits per channel use can be transmitted, where $\log_2 N_t$ bits are used to select one active antenna, and the remaining $\log_2 M$ bits are used to form a constellation symbol.

Referring to the secure SM model in [10], the transmit signal with the aid of AN is represented by

$$\mathbf{s} = \sqrt{\beta P}\mathbf{e}_i b_j + \sqrt{(1-\beta)P}\mathbf{T}\mathbf{n} \tag{1}$$

where $\beta \in [0,1]$ is the PA factor, P denotes the total transmit power. $\mathbf{e}_i$ is the ith column of identity matrix $\mathbf{I}_{N_t}$, which means the ith antenna is chosen for transmitting symbol b_j, and b_j is the input symbol equiprobably drawn from a M-ary constellation. $\mathbf{T}$ is the projection matrix of the AN vector $\mathbf{n} \in \mathbb{C}^{N_t \times 1}$ with $\mathrm{tr}(\mathbf{T}\mathbf{T}^H) = 1$, where $\mathrm{tr}(\cdot)$ denotes the matrix trace. The receive vector of symbols at the desired and eavesdropping receivers are

$$\mathbf{y}_B = \sqrt{\beta P}\mathbf{H}_B\mathbf{e}_i b_j + \sqrt{(1-\beta)P}\mathbf{H}_B\mathbf{T}\mathbf{n} + \mathbf{n}_B \tag{2}$$

$$\mathbf{y}_E = \sqrt{\beta P}\mathbf{H}_E\mathbf{e}_i b_j + \sqrt{(1-\beta)P}\mathbf{H}_E\mathbf{T}\mathbf{n} + \mathbf{n}_E \tag{3}$$

where $\mathbf{H}_B \in \mathbb{C}^{N_r \times N_t}$ and $\mathbf{H}_E \in \mathbb{C}^{N_e \times N_t}$ are the complex channel gain matrices from Alice to Bob and from Alice to Eve, with each elements of $\mathbf{H}_B$ and $\mathbf{H}_E$ obeying the Gaussian distributions with zero mean and unit variance, i.e., $\mathcal{CN}(0,1)$. Additionally, $\mathbf{n}_B \in \mathbb{C}^{N_r \times 1}$, and $\mathbf{n}_E \in \mathbb{C}^{N_e \times 1}$ are complex Gaussian noise at desired and eavesdropping receivers with $\mathbf{n}_B \sim \mathcal{CN}(0, \sigma_B^2\mathbf{I}_{N_r})$ and $\mathbf{n}_E \sim \mathcal{CN}(0, \sigma_E^2\mathbf{I}_{N_e})$, respectively. Given a specific channel realization, the mutual information between Alice and Bob, and between Alice and Eve are

$$I_B(\mathbf{s};\mathbf{y}'_B|\mathbf{H}_B) = \log_2 N_t M - \frac{1}{N_t M}\sum_{i=1}^{N_t M}\mathbb{E}_{\mathbf{n}'_B}\left\{\log_2\sum_{j=1}^{N_t M}\exp\left(-f_{b,i,j} + \|\mathbf{n}'_B\|^2\right)\right\} \tag{4}$$

$$I_E(\mathbf{s};\mathbf{y}'_E|\mathbf{H}_E) = \log_2 N_t M - \frac{1}{N_t M}\sum_{m=1}^{N_t M}\mathbb{E}_{\mathbf{n}'_E}\left\{\log_2\sum_{k=1}^{N_t M}\exp\left(-f_{e,m,k} + \|\mathbf{n}'_E\|^2\right)\right\} \tag{5}$$

where $f_{b,i,j} = \|\sqrt{\beta P}\mathbf{W}_B^{-1/2}\mathbf{H}_B\mathbf{d}_{ij} + \mathbf{n}'_B\|^2$, $f_{e,m,k} = \|\sqrt{\beta P}\mathbf{W}_E^{-1/2}\mathbf{H}_E\mathbf{d}_{mk} + \mathbf{n}'_E\|^2$, $\mathbf{d}_{ij} = \mathbf{x}_i - \mathbf{x}_j$, and $\mathbf{d}_{mk} = \mathbf{x}_m - \mathbf{x}_k$. Here, $\mathbf{x}_i$, $\mathbf{x}_j$, $\mathbf{x}_m$, or $\mathbf{x}_k$ is one possible transmit vector in the set of combining antenna and all possible symbols. $\mathbf{W}_B$ is the covariance matrix of the last two terms of $\mathbf{y}_B$ in (2), i.e. AN plus noise, and $\mathbf{W}_B = (1-\beta)P\mathbf{C}_B + \sigma_B^2\mathbf{I}_{N_r}$, where $\mathbf{C}_B = \mathbf{H}_B\mathbf{T}\mathbf{T}^H\mathbf{H}_B^H$. Similarly, $\mathbf{W}_E = (1-\beta)P\mathbf{C}_E + \sigma_E^2\mathbf{I}_{N_e}$ where $\mathbf{C}_E = \mathbf{H}_E\mathbf{T}\mathbf{T}^H\mathbf{H}_E^H$. From [8], it is known that pre-multiplying $\boldsymbol{y}_B$ in (2) by $\mathbf{W}_B^{-1/2}$ from left is to whiten the AN plus noise into a white Gaussian noise. The linear transformation does not change the mutual information, thus $I(\mathbf{x};\mathbf{y}_B) = I(\mathbf{x};\mathbf{y}'_B)$, where $\mathbf{y}'_B = \mathbf{W}_B^{-1/2}\mathbf{y}_B$, and $\mathbf{n}'_B = \mathbf{W}_B^{-1/2}(\sqrt{(1-\beta)P}\mathbf{H}_B\mathbf{T}\mathbf{n} + \mathbf{n}_B)$. Similarly, $I(\mathbf{x};\mathbf{y}_E) = I(\mathbf{x};\mathbf{y}'_E)$. The average SR is defined as

$$\bar{R}_s = \mathbb{E}_{\mathbf{H}_B,\mathbf{H}_E}\left[I(\mathbf{x};\mathbf{y}_B) - I(\mathbf{x};\mathbf{y}_E), 0\right]^+. \tag{6}$$

where $[a]^+$=max(a,0) and $R_s(\beta) = I(\mathbf{x};\mathbf{y}_B) - I(\mathbf{x};\mathbf{y}_E)$ is the instantaneous SR for a specific channel realization. Here, we suppose that the ideal channel knowledge of $\mathbf{H}_B$ and $\mathbf{H}_E$ per channel use are available at transmitter [7]. In accordance with the above equations, the optimization problem of maximizing SR over PA factor can be casted as

$$\max_{\beta}\; R_s(\beta) \quad \text{s.t.}\quad 0 \le \beta \le 1. \tag{7}$$

III. Power allocation strategy for secrecy rate maximization

In this section, two new PA methods, called CO and Max-P-SAN, are proposed. The former forms an iterative solution, and the latter produces a closed-form PA expression.

A. Proposed CO method

Due to the absence of closed-form expression of SR, it is hard for us to design an efficient method to optimize PA factor directly. Although the ES method in [11] is employed to find out the optimal PA factor for a given SNR, but its high complexity limits its applications to practical SM systems. In view of this, the cut-off rate [4] with closed-form for traditional MIMO systems can be easily extended to the secure SM systems, and may be adopted as an efficient metric to optimize the PA factor as follows

$$R_s^a(\beta) = I_0^B - I_0^E, \tag{8}$$

where I_0^B is the cut-off rate for the desired receiver given by

$$I_0^B = \zeta - \log_2\sum_{i=1}^{N_t M}\sum_{j=1}^{N_t M}\exp\left(\frac{-\beta P}{4}\mathbf{d}_{ij}^H\mathbf{H}_B^H\boldsymbol{\omega}_B\mathbf{H}_B\mathbf{d}_{ij}\right) \tag{9}$$

where $\zeta = 2\log_2 N_t M$, $\boldsymbol{\omega}_B(\beta) = \mathbf{W}_B^{-1}$. Similarly, the cut-off rate I_0^E for the eavesdropper is

$$I_0^E = \zeta - \log_2\sum_{m=1}^{N_t M}\sum_{k=1}^{N_t M}\exp\left(\frac{-\beta P}{4}\mathbf{d}_{mk}^H\mathbf{H}_E^H\boldsymbol{\omega}_E\mathbf{H}_E\mathbf{d}_{mk}\right) \tag{10}$$

where $\boldsymbol{\omega}(\beta) = \mathbf{W}_E^{-1}$. The detailed process of (8) refers to Appendix A in [4]. Replacing the objective function in (7) by (8) yields

$$\max_{\beta}\; R_s^a(\beta) \quad \text{s.t.}\quad 0 \le \beta \le 1. \tag{11}$$

However, the objective function of problem (11) is non-concave. Note that $\boldsymbol{\omega}_E(\beta) \approx \frac{1}{(1-\beta)P}\mathbf{C}_E^{-1}$ in the high SNR region (i.e, $\sigma_B^2 \to 0$) when $\mathbf{C}_E$ is nonsingular, thus we have

$$\tilde{\kappa}_E(\beta) \approx \log_2 \kappa_E = \log_2 \sum_{m=1}^{N_t M}\sum_{k=1}^{N_t M} \exp\left(\frac{-\beta \mathbf{d}_{mk}^H \mathbf{H}_E^H \mathbf{C}_E^{-1}\mathbf{H}_E \mathbf{d}_{mk}}{4(1-\beta)}\right). \quad (12)$$

It can be seen that $\tilde{\kappa}_E(\beta)$ is convex with respect to β and then the objective function becomes a difference between two convex functions. To convert this difference to a concave function, we have the linear under-estimator of $\tilde{\kappa}_E(\beta)$ at the feasible point β_{k-1} as follows

$$\tilde{\kappa}_E \geq \tilde{\kappa}_E(\beta_{k-1}) + \tilde{\kappa}'_E(\beta_{k-1})(\beta_k - \beta_{k-1}) = g_E(\beta_k) \quad (13)$$

where $\tilde{\kappa}'_E(\beta_{k-1})$ is the first derivative value of function $\tilde{\kappa}_E$ at β_{k-1}, and

$$\kappa'_E = \frac{1}{\ln 2 \cdot \kappa_E} \sum_{m=1}^{N_t M}\sum_{k=1}^{N_t M} \frac{-PQ_{mk}}{4(1-\beta)^2} \exp\left(\frac{-\beta P Q_{mk}}{4(1-\beta)}\right) \quad (14)$$

where $Q_{mk} = \mathbf{d}_{mk}^H \mathbf{H}_E^H \mathbf{C}_E^{-1} \mathbf{H}_E \mathbf{d}_{mk}$. For a given feasible solution β_0, the problem (11) can be solved by the following approximate iterative sequence of convex problems

$$\max_{\beta} \; G(\beta_k) = g_E(\beta_k) - \tilde{\kappa}_B(\beta_k) \quad \text{s.t.} \quad 0 < \beta_k < 1. \quad (15)$$

It is clear that the objective function in (15) is concave. Starting from a feasible point β_0, the optimization problem (15) is iteratively solved with different β_k, where $\{\beta_k\}$ is the generated sequence of solutions corresponding to the kth iteration. This iterative process terminates until $\mid G(\beta_k) - G(\beta_{k-1}) \mid \leq \varepsilon$, where ε is a prechosen threshold.

B. Proposed Max-P-SAN method

Utilizing the leakage idea [12], [13], the SLNR, mainly denoting the desired signal leakage to the eavesdropping direction, is given by

$$\text{SLNR}_B = \text{tr}(\mathbf{H}_B^H \mathbf{H}_B)\left(\text{tr}(\mathbf{H}_E^H \mathbf{H}_E) + \sigma_B^2 N_t N_r / \beta P\right)^{-1} \quad (16)$$

In the same manner, the AN is viewed as the useful signal of the eavesdropper, the ANLNR from the wiretap channel to the desired channels is as follows

$$\text{ANLNR}_E = \text{tr}(\mathbf{C}_E)\left(\text{tr}(\mathbf{C}_B) + \sigma_E^2 N_e / (1-\beta) P\right)^{-1} \quad (17)$$

It is hard to jointly optimize the two objective functions $\text{ANLNR}_E(\beta)$ and $\text{SLNR}_B(\beta)$. To simplify the joint optimization problem, we multiply the two functions to form a new product of $\text{SLNR}_B(\beta)$ and $\text{ANLNR}_E(\beta)$, which is used as a single objective function. This will significantly simplify our optimization manipulation. Maximizing their product means maximizing at least one of them, or both them. From simulations, we find that the proposed product method performs very well and make a good balance between performance and complexity. Then, the associated optimization problem can be written as

$$\max_{\beta} \; F(\beta) = \frac{\kappa_B \cdot \beta}{\kappa_E \cdot \beta + \sigma_B^2 N_t N_r} \cdot \frac{(1-\beta)\cdot \omega_E}{(1-\beta)\cdot\omega_B + \sigma_E^2 N_e} \quad \text{s.t.} \;\; 0 \leq \beta \leq 1. \quad (18)$$

where $\kappa_B = \frac{P}{N_t}\text{tr}(\mathbf{H}_B^H \mathbf{H}_B)$, $\kappa_E = \frac{P}{N_t}\text{tr}(\mathbf{H}_E^H \mathbf{H}_E)$, $\omega_B = P\text{tr}(\mathbf{C}_B)$, and $\omega_E = P\text{tr}(\mathbf{C}_E)$. Therefore, the promising optimal values of β in (18) should satisfy the following equation

$$F'(\beta) = \frac{\varphi_a\left(\varphi_o \beta^2 - 2\varphi_d \beta + \varphi_d\right)}{(-\varphi_b \beta^2 + \varphi_c \beta + \varphi_d)^2} = 0 \quad (19)$$

where $\varphi_a = \kappa_B \omega_E$, $\varphi_b = \kappa_E \omega_B$, $\varphi_c = \kappa_E \omega_B + \sigma_B^2 \kappa_E N_e$, $\varphi_d = \sigma_B^2 \omega_B N_r + \sigma_B^2 \sigma_E^2 N_r N_e$, and $\varphi_o = \varphi_b - \varphi_c$. Based on (19), it is seen that the denominator of the derivative and φ_a in (19) are both greater than 0, we only need to solve the roots of equation $\varphi_o \beta^2 - 2\varphi_d \beta + \varphi_d = 0$. Due to $\varphi_o < 0$ and $\triangle = \varphi_d^2 - \varphi_o \varphi_d > 0$, this equation has two real-valued roots. In summary, the set of feasible solutions to (18) is

$$S = \left\{\beta_1 = \frac{\varphi_d + \sqrt{\triangle}}{\varphi_o}, \beta_2 = \frac{\varphi_d - \sqrt{\triangle}}{\varphi_o}, \beta_3 = 0, \beta_4 = 1\right\}$$

where β_1, and β_2 are two solutions to the quadratic equation in (19) while $\beta_3 = 0$, and $\beta_4 = 1$ are two end-points of the feasible search interval $[0, 1]$. Obviously, $\beta_3 = 0$ means that there is no confidential messages to be sent. In other words, SR=0. Thus, this point can be directly removed from the solution set. $\beta_1 < 0$ falls outside the feasible set $[0, 1]$, and can be deleted directly. Considering the function $F(\beta)$ is a continuous and differentiable function over the interval $[0, 1]$, its first derivative is negative as β goes to one from the left. Thus, $F(1)$ is the local minimum point, which rules out it from the feasible solution set referring to the set of maximizing the $F(\beta)$. Finally, we have the unique solution

$$\beta_2 = (\varphi_d - \sqrt{\triangle})/\varphi_o \quad (20)$$

due to the fact that the objective function $F(\beta)$ is continuous and differentiable over the closed interveal [0, 1].

C. Complexity Analysis and Comparison

Below, we present a complexity comparison among the three methods: CO, Max-P-SAN, and ES. Firstly, the complexity of the ES method in [11] is about $\mathcal{C}_{\text{ES}} = 2N_t^2 M^2 l N_{\text{samp}} [2(N_r + N_e)N_t^2 + N_r + N_e]$ floating-point operations (FLOPs), where l denotes the number of searches depending on the required accuracy, and $N_{\text{samp}} (\geq 500)$ is the number of realizations of noise sample points for accurately estimating expectation operators. For the proposed CO, its computational complexity is approximated as $\mathcal{C}_{\text{CO}} = 3N_t^2 M^2 D_{\text{ite}}(2N_t^2 + 2N_t)$ FLOPs, where D_{ite} is the number of iterations. Finally, it is obvious that the proposed Max-P-SAN scheme has the lowest complexity among the three methods, and its complexity is $\mathcal{C}_{\text{Max-P-SAN}} = 2N_t^2(2N_r + 3N_e) + 2N_r^2 N_t + 2N_e^2 N_t + N_t + N_r + N_e$ FLOPs. From the three complexity expressions, the dominant term in $\mathcal{C}_{\text{Max-P-SAN}}$ is only quadratic. In general, $N_{\text{samp}} \gg N_t > N_r(N_e)$, their complexities have an increasing order as follows: Max-P-SAN, CO, and ES.

IV. Simulation Results

In what follows, numerical simulations are presented to evaluate the SR performance for two proposed PA strategies, with ES method as a performance benchmark. Specially, the

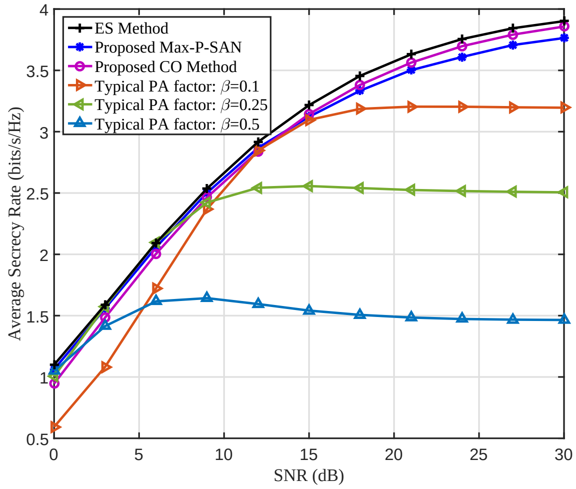

Fig. 2. Comparison of average SR for various PA methods with $N_t = 4, N_r = 2$ and $N_e = 2$.

noise variances are assumed to be identical, i.e., $\sigma_B^2 = \sigma_E^2$. Modulation type is quadrature phase shift keying (QPSK).

Fig. 2 plots the curves of SR versus SNR with $N_t = 4, N_r = 2$, and $N_e = 2$. Here, three typical PA strategies, $\beta = 0.1$, 0.25, and 0.5, are used as performance references. From Fig. 2, it is seen that the proposed CO method can achieve the optimal SR performance being close to that of the ES method for almost all SNR regions. The proposed Max-P-SAN method approaches the ES performance in the low and medium SNR regions, but slightly worse than the ES in the high SNR region in terms of SR. Because Max-P-SAN has a closed-form expression, it strikes a good balance between performance and complexity. Also, the two proposed methods perform much better than three typical fixed PA schemes. This means that they can harvest appreciable SR performance gains.

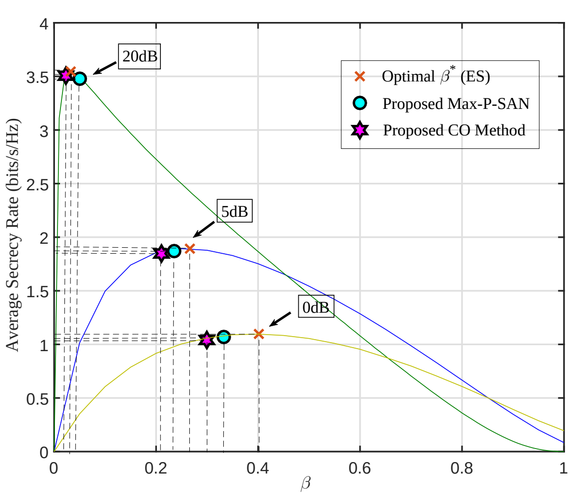

Fig. 3. Comparison of the achievable SR for SNR=0, 5, 20dB with same configuration as Fig. 2.

Fig. 3 plots the curves of maximum achievable SR versus β for three given SNRs: 0dB, 5dB, and 20dB, with ES as a performance benchmark. Observing this figure, it is obvious that all optimal values of β reduces as SNR increases from 0dB to 20dB. This can be readily explained as follows: a high SNR means a good channel quality. This implies that less power is required to transmit confidential messages, and more power is utilized to emit AN to corrupt eavesdroppers. Additionally, as SNR increases, the optimal values of β corresponding to the two proposed PA are closer to that of β for ES.

V. Conclusion

In this paper, we have made an investigation of PA strategies for secure SM system. An efficient approximated expression of SR is given to simplify the computational complexity for optimizing PA factor. Then, two PA strategies are proposed to implement power allocation between confidential messages and AN. The first one is CO and the second one is Max-P-SAN. The former is iterative while the latter is closed-form. In accordance with simulations, we find: the proposed CO provides a SR performance being close to the ES method for almost all SNR regions, and the proposed Max-P-SAN can achieve the optimal SR performance in the low and medium regions with an extremely low-complexity. The two proposed PA strategies can be applied to the future SM networks.

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