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Legitimate Monitoring via Cooperative Relay and Proactive Jamming

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ABSTRACT With the development of communication technologies, many suspicious communication technologies have also been greatly improved. Therefore, one single monitor may not be able to afford in a monitoring process. In this paper, we propose a wireless communication system using two legitimate monitors for cooperative monitoring program, in which the signals sent by two monitors are respectively designed. One monitor is used as the cooperative relay, which is mainly used to improve the overall information transmission rate. The other monitor, which simultaneously receiving suspicious information and sending jamming signals, is used to ensure the successful eavesdropping process. Our purpose is to obtain the maximum eavesdropping rate by jointly design the transmit beamforming of two monitors. Two cases that the channel state information (CSI) is perfectly and imperfectly known by the monitors are considered. For the perfect CSI, several cases corresponding to the different conditions about the CSI from the suspicious transmitter to two monitors are discussed. In each case, a closed-form solution of the appropriate sending strategy is obtained, in which the physical meaning is also proposed. Then, for the imperfect CSI case, by employing the S-procedure method, we reformulate the robust beamforming design problem and solve it optimally. Finally, in the simulation results, the comparison between the cooperative monitoring scheme and the single monitoring scheme demonstrates that the proposed scheme is better in terms of eavesdropping rate.

INDEX TERMS Cooperative monitoring, relay, jamming, robust beamforming.

I. INTRODUCTION

With the rapid advancement of wireless communication technology, point-to-point communication becomes more convenient. Wireless communication technology can enable information exchange between two miles anywhere, anytime [1]–[10]. At the same time, security issues in the wireless communication process have become more and more important [11]–[14]. In the traditional wireless security problem, it is generally considered that the communication process is legitimate, and there may be illegal eavesdroppers or malicious attackers. The main research content of the traditional wireless security is how to obtain the maximum security rate [15]–[20], where the security rate is defined as the transmitting rate corresponding to the information that cannot be decoded by the monitor. In general, the security rate can be maximized by designing the covariance matrix at the source or adding artificial noise into the transmitted signal. On the other hand, criminals may also use existing wireless communication systems to commit crimes, endanger public security, and threaten people's property safety [21]–[32]. Therefore, for such illegal communications, government departments should not protect them [33]. Furthermore, these communication processes should be eavesdropped in order to solve the security risk. In this article, the communication process that needs to be intercepted is defined as suspicious communication, the monitors that serve the government department are called legitimate monitors.

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In the legitimate monitoring process, the success criterion of the eavesdropping is that the monitor can decode the information transmitted by the suspicious communication with any small error. In the traditional research of wireless security [28], the monitor only acts as a receiver, it receives the signal sent by the suspicious transmitter and trying to decode it. If the eavesdropping channel is better than the suspicious transmitting channel, successful monitoring can be achieved; otherwise it will result in failure. Herein, the proactive eavesdropping rate is proposed [33], If the monitor cannot eavesdrop the suspicious link successfully because of the poor channel state, the transmission rate of the suspicious communication may be reduced by sending the jamming signals, so that it achieves the successful eavesdropping [34]. In [35], A power splitting structure is adopted at the monitor, a part of the power is separated for decoding the suspicious information, another part of the power is used as a relay for suspicious communication, and the eavesdropping rate is thus increased.

It is worth noting that most of the literature is devoted to studying the monitoring performance achieved by a single monitor. However, in practical applications, when a single monitor cannot successfully monitor or monitor performance is poor, it is possible to achieve better eavesdropping performance through cooperation of multiple monitors. In this paper, we focus on a cooperative monitoring system. In order to reduce the complexity of the equipment, we use a cooperative monitoring mode in which relay and active interference coexist.

On the other hand, the channels between the monitor and the suspicious users are different assumptions according to other literature. In [35], the channels are assumed to be perfectly known; In [18] and [34], the channels are assumed to be Rayleigh fading channels. In this paper, we consider two different cases: one is that the channels are perfectly known, some insights are obtained; the other one is that imperfect channel state information is known, S-procedure is used in this case.

The main contributions of this paper are summarized as follows.

1) We propose an efficient surveillance scheme for two cooperative legitimate monitors to maximize the eavesdropping rate. The first monitor serves as a relay, which not only works for the suspicious communication, but also helps to transmit the signal from the suspicious transmitter to the second monitor. Meanwhile, the second monitor acts as a traditional monitor via jamming, which may send jamming signals to ensure successful eavesdropping. Hence, the design of the beamforming in both monitors is considered.
2) We formulate two optimization problem to maximize the eavesdropping rate corresponding to two cases that the channel state information (CSI) are perfectly and imperfectly known by the monitors. For the perfect CSI, we first analysis the feasibility of the original problem and then obtain the corresponding conditions. Then, the original problem is decomposed according to the CSI from the suspicious transmitter to the legitimate monitors and closed-form results are finally proposed. In the case of the imperfect CSI, S-procedure is introduced and the original problem with high-complex is transformed into a linear matrix inequality (LMI) that can be solved by using existing mathematical methods.
3) Numerical results are proposed to reveal the relationship between the eavesdropping rate and the chosen scheme at the legitimate monitor corresponding to the channel state information from the secondary transmitter to the legitimate monitor. Then, the optimal solution is presented to verify our theoretical analysis.

The rest of this paper is organized as follows. Section II introduces the system model of legitimate surveillance system with two cooperative monitors, then formulates the eavesdropping beamforming design problem. Section III analysis the feasibility of the problem for perfect CSI and then divides it into several cases. The optimal solution to the problem in a closed-form is proposed. Section IV solve the problem for imperfect CSI. Section V provides the simulation results. Finally, Section VI concludes the paper.

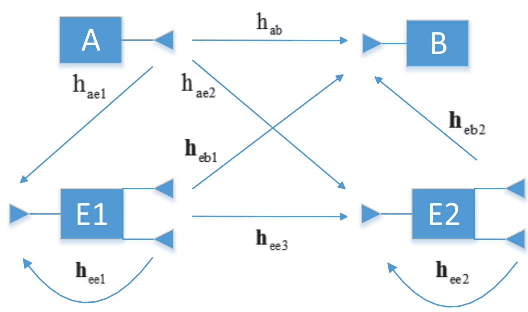

FIGURE 1. System model of legitimate surveillance system with two cooperative monitors.

II. SYSTEM MODEL AND PROBLEM FORMULATION

As shown in Fig.1, we consider an information surveillance system, where the legitimate monitors E1 and E2 are intended to eavesdrop on a suspicious communication link consists of a suspicious transmitter A and a suspicious receiver B. Both A and B are equipped with single-antenna for transmitting and receiving, E1 and E2 are equipped with one antenna for receiving, and Nt antennas for transmitting. Both E1 and E2 operate in full-duplex mode.

The monitor E2 receives signals from A to decode it, and simultaneously sends jamming signals to ensure the success of eavesdropping. E1 acts as a relay to forward signals to both E2 and B. When eavesdropping channel is better, E1 can improve the transmission capability of suspicious communication link to obtain better eavesdropping rate. When eavesdropping channel is weak, E1 can improve the eavesdropping capability. The identity of those two monitors is not fixed, it is set by the rule that E1 is closer to A while E2 is closer to B.

The signal received at E1 could be expressed as:

$$y_{E1} = \sqrt{P_A} h_{ae1} s + \bar{\mathbf{h}}_{ee1} \widehat{\mathbf{w}}_1 + n, \tag{1}$$

where s is the signal sent by A with the power P_A, h_{ae1} means the channel from A to E1, $\bar{\mathbf{h}}_{ee1}$ is the loop channel at E1 due to the full duplex mode. $n \sim \mathcal{CN}\left(0, \sigma^2\right)$ denotes the additive Gaussian noise vector. For ease of exposition, we assume that the ideal input-output isolation is achieved at E1 by designing $\bar{\mathbf{w}}_1$ that completely nulls the output of the loop-channel, i.e., $\bar{\mathbf{h}}_{ee1}\bar{\mathbf{w}}_1 = 0$. It can be obtained that the maximum power used to forward signals is denoted as the following:

$$P_{E1} = \min\left(P_A\|h_{ae1}\|^2, P_{E1}^m\right), \tag{2}$$

where P_{E1}^m is the maximum power constraint at E1.

Then, the signal received at E2 can be formulated as the following similarly

$$y_{E2} = \sqrt{P_A}h_{ae2}s + \bar{\mathbf{h}}_{ee2}\widehat{\mathbf{w}}_2 + \bar{\mathbf{h}}_{ee3}\widehat{\mathbf{w}}_1 + n, \tag{3}$$

where h_{ae2} means the channel from A to E2, $\bar{\mathbf{h}}_{ee3}$ is the channel from E1 to E2 and $\bar{\mathbf{h}}_{ee2}$ is the loop channel at E2. $\widehat{\mathbf{w}}_1$ and $\widehat{\mathbf{w}}_2$ denote the beamforming at E1 and E2, respectively. Similar to E1, $\widehat{\mathbf{w}}_2$ is also in the nulls of the loop-channel at E2. The signal received at B is

$$y_B = \sqrt{P_A}h_{ab}s + \bar{\mathbf{h}}_{eb1}\widehat{\mathbf{w}}_1 + \bar{\mathbf{h}}_{eb2}\widehat{\mathbf{w}}_2 + n, \tag{4}$$

where h_{ab} denotes the channel from A to B, $\bar{\mathbf{h}}_{eb1}$ and $\bar{\mathbf{h}}_{eb2}$ are the channel from E1 and E2 to B, respectively.

A. PROBLEM FORMULATION

In this section, we design the beamforming sent by E1 and E2 to maximize the eavesdropping rate. First, the receiving rate at E2 can be formulated as the following:

$$\begin{aligned} R_E &= \log_2\left(1 + \frac{P_A\|h_{ae2}\|^2 + \|\bar{\mathbf{h}}_{ee3}\widehat{\mathbf{w}}_1\|^2}{\sigma^2}\right), \\ R_B &= \log_2\left(1 + \frac{P_A\|h_{ab}\|^2 + \|\bar{\mathbf{h}}_{eb1}\widehat{\mathbf{w}}_1\|^2}{\|\bar{\mathbf{h}}_{eb2}\widehat{\mathbf{w}}_2\|^2 + \sigma^2}\right). \end{aligned} \tag{5}$$

The eavesdropping rate is denoted by:

$$R_{ev} = \begin{cases} R_B & \text{if } R_E \geq R_B \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

It can be observed from (6) that the eavesdropping rate is equal to the suspicious transmitting rate when E2 can monitor the suspicious transmission successfully. Thus, the optimal problem can be written as the following:

$$\max_{\mathbf{w}_1,\mathbf{w}_2} \frac{P_A\|h_{ab}\|^2 + \|\bar{\mathbf{h}}_{eb1}\widehat{\mathbf{w}}_1\|^2}{\|\bar{\mathbf{h}}_{eb2}\widehat{\mathbf{w}}_2\|^2 + \sigma^2} \tag{7}$$

$$s.t. \ \frac{P_A\|h_{ae2}\|^2 + \|\bar{\mathbf{h}}_{ee3}\widehat{\mathbf{w}}_1\|^2}{\sigma^2} \geq \frac{P_A\|h_{ab}\|^2 + \|\bar{\mathbf{h}}_{eb1}\widehat{\mathbf{w}}_1\|^2}{\|\bar{\mathbf{h}}_{eb2}\widehat{\mathbf{w}}_2\|^2 + \sigma^2}, \tag{7a}$$

$$\|\widehat{\mathbf{w}}_1\|^2 \leq P_{E1}, \quad \|\widehat{\mathbf{w}}_2\|^2 \leq P_{E2}, \tag{7b}$$

$$\bar{\mathbf{h}}_{ee1}\widehat{\mathbf{w}}_1 = 0, \quad \bar{\mathbf{h}}_{ee2}\widehat{\mathbf{w}}_2 = 0. \tag{7c}$$

Since the transmitting rate is the monotonically increasing function of the signal-to-noise-ratio (SINR), the objective function is rewritten as the SINR of the suspicious communication. The constraints (7a) means that the receiving rate at E2 should be greater than the receiving rate at B to ensure successful monitoring. The constraint (7b) represents the power constraints for the two monitors. The constraint (7c) is the interference zero-setting constraint, which means that the two monitors' sending signals are sent in the null spaces of the corresponding loop-channel vectors, respectively.

III. THE PROPOSED BEAMFORMING DESIGN WITH PERFECT CSI

To solve problem(7), we first consider the zero-forcing (ZF) constraint (7c). Two matrixs are defined as $\mathbf{H}_1 = [\bar{\mathbf{h}}_{ee1}\ \mathbf{H}_{E1}]$, $\mathbf{H}_2 = [\bar{\mathbf{h}}_{ee2}\ \mathbf{H}_{E2}]$, where $\mathbf{H}_{E1}$ and $\mathbf{H}_{E2}$ are consists of the orthogonal complement of $\bar{\mathbf{h}}_{ee1}$ and $\widehat{\mathbf{h}}_{ee2}$, respectively. The new vectors satisfy the ZF constraint in the problem(7). It can then be expressed as: $\widehat{\mathbf{w}}_1 = \mathbf{H}_{E1}\mathbf{w}_1$, $\widehat{\mathbf{w}}_2 = \mathbf{H}_{E2}\mathbf{w}_2$.

At the same time, the channel vector should be expressed by the corresponding matrix that $\bar{\mathbf{h}}_{eb1} = \mathbf{H}_{E1}\mathbf{h}_{eb1}$, $\bar{\mathbf{h}}_{eb2} = \mathbf{H}_{E2}\mathbf{h}_{eb2}$.

The problem can be transformed into the following:

$$\begin{aligned} \max_{\mathbf{w}_1,P_2} \ & \frac{P_A\|h_{ab}\|^2 + \|\mathbf{h}_{eb1}\mathbf{w}_1\|^2}{P_2\|\mathbf{h}_{eb2}\|^2 + \sigma^2} \\ s.t. \ & \frac{P_A\|h_{ae2}\|^2 + \|\mathbf{h}_{ee3}\mathbf{w}_1\|^2}{\sigma^2} \geq \frac{P_A\|h_{ab}\|^2 + \|\mathbf{h}_{eb1}\mathbf{w}_1\|^2}{P_2\|\mathbf{h}_{eb2}\|^2 + \sigma^2}, \\ & \|\widehat{\mathbf{w}}_1\|^2 \leq P_{E1}, \\ & P_2 \leq P_{E2}, \end{aligned} \tag{8}$$

in which the vector $\mathbf{w}_2$ should be maximum-ratio-transmission (MRT) with the channel $\mathbf{h}_{eb2}$ since the vector $\mathbf{w}_2$ is designed to decrease the suspicious transmitting rate.

A. ANALYSIS OF THE FEASIBILITY

In an actual system, in order to ensure the successful monitoring, the monitor's maximum transmit power or channel conditions should be required. Therefore, before solving the problem, we firstly discuss the feasibility of the problem (8) and find the region of feasible conditions.

We consider the boundaries of the power constraints at those two monitors, the problem can be formulated as the following:

$$\begin{aligned} \max_{\mathbf{w}_1} \ & \frac{P_A\|h_{ae2}\|^2 + \|\mathbf{h}_{ee3}\mathbf{w}_1\|^2}{\sigma^2} - \frac{P_A\|h_{ab}\|^2 + \|\mathbf{h}_{eb1}\mathbf{w}_1\|^2}{P_{E2}\|\mathbf{h}_{eb2}\|^2 + \sigma^2} \\ s.t. \ & \|\mathbf{w}_1\|^2 = P_{E1}. \end{aligned} \tag{9}$$

It can be obtained that if the optimal objective function of problem (9), denoted as γ, satisfies that $\gamma \geq 0$, problem (8) is feasible, otherwise, problem (8) is not feasible.

Lemma 1 [36]: the optimal solution to problem (9) is in the form of $\mathbf{w}_1^* = \alpha_w\widetilde{\mathbf{h}}_{eb1} + \beta_w\widetilde{\mathbf{h}}_{ee3\perp}$, where $\widetilde{\mathbf{h}}_{eb1} = \frac{\mathbf{h}_{eb1}^+}{\|\mathbf{h}_{eb1}\|}$, $\widetilde{\mathbf{h}}_{ee3\perp} = \frac{\mathbf{h}_{ee3\perp}}{\|\mathbf{h}_{ee3\perp}\|}$, $\mathbf{h}_{ee3\perp} = \mathbf{h}_{ee3}^H - \left(\widetilde{\mathbf{h}}_{eb1}\mathbf{h}_{ee3}^H\right)\widetilde{\mathbf{h}}_{eb1}$.

Proof: The proof of theorem 1 can be proposed by contradiction. First, we suppose $\mathbf{w}_x$ is the optimal solution of problem (9), where w_x is in the form of $\mathbf{w}_x = \alpha_{w0}\widetilde{\mathbf{h}}_{eb1} + \beta_{w0}\mathbf{b}$,

$$\max_{\theta} \frac{\|\alpha_h\|^2 P_{E1}\cos^2\theta + \|\beta_h\|^2 P_{E1}\sin^2\theta + 2\|\alpha_h\|\|\beta_h\|\sin\theta\cos\theta}{\sigma^2} - \frac{\|\mathbf{h}_{eb1}\|^2 P_{E1}\cos^2\theta}{\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2}$$
$$s.t.\ 0 \leq \theta \leq 2\pi. \tag{12}$$

$\mathbf{b}^+\widetilde{\mathbf{h}}_{eb1} = 0$, $\|\mathbf{b}\| = 1$. There is another vector $\mathbf{w}_y = \alpha_{w0}\widetilde{\mathbf{h}}_{eb1} + \beta_{w0}\widetilde{\mathbf{h}}_{ee3\perp}$, which is also feasible for the problem(9). Meanwhile, The objective function for the vector w_y is better than that of w_x since $\|\mathbf{h}_{ee3}\widetilde{\mathbf{h}}_{ee3\perp}\| \geq \|\mathbf{h}_{ee3}\mathbf{b}\|$. The proof is thus completed. ■

To obtain the complex weights, the following problem is considered:

$$\max_{\alpha_w,\beta_w} \frac{P_A\|h_{ae2}\|^2 + \|\alpha_h^+\alpha_w + \beta_h^+\beta_w\|^2}{\sigma^2} - \frac{P_A\|h_{ab}\|^2 + \|\mathbf{h}_{eb1}\|^2\|\alpha_w\|^2}{\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2}$$
$$s.t.\ \|\alpha_w\|^2 + \|\beta_w\|^2 = P_{E1}. \tag{10}$$

It can be observed that the constraint of problem (10) is proposed for the values of the weights. On the other hand, the direction of the weight is not limited. Moreover, the second part in the objective function is not related to the direction of the weights, the optimal weight should in the form of $\alpha_w = \frac{x\alpha_h}{\|\alpha_h\|}$, $\beta_w = \frac{y\beta_h}{\|\beta_h\|}$ since the objective function will increase with the increasing of the first part.

Hence, the problem (10) can be transformed into the following problem with the variable being a scalar.

$$\max_{x,y} \frac{f(x,y)}{\left(\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2\right)\sigma^2}$$
$$s.t.\ x^2+y^2 = P_{E1}, \tag{11}$$

where

$$f(x,y) = -\sigma^2\left(P_A\|h_{ab}\|^2 + \|\mathbf{h}_{eb1}\|^2 x^2\right) + \left(\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2\right)\left(P_A\|h_{ae2}\|^2 + (\|\alpha_h\|x + \|\beta_h\|y)^2\right).$$

To simplify the above problem, it is assumed that $x = \sqrt{P_{E1}}\cos\theta\, y = \sqrt{P_{E1}}\sin\theta$, the following problem is further considered as (12), as shown at the top of this page.

Combining constant items in (12), it further translates into:

$$\max_{0\leq\theta\leq 2\pi} a\cos^2\theta + b\sin^2\theta + c\sin(2\theta), \tag{13}$$

where $a = \frac{\|\alpha_h\|^2 P_{E1}}{\sigma^2} - \frac{\|\mathbf{h}_{eb1}\|^2 P_{E1}}{\|\mathbf{h}_{eb1}\|^2 P_{E1}+\sigma^2}$, $b = \frac{\|\beta_h\|^2 P_{E1}}{\sigma^2}$ and $c = \frac{\|\alpha_h\|\|\beta_h\|}{\sigma^2}$.

By using triangle transformation, problem (13) is the same as:

$$\max_{0\leq\theta\leq 2\pi} \frac{a-b}{2}\cos(2\theta) + c\sin(2\theta) + \frac{a+b}{2}. \tag{14}$$

According to the first-order derivative of (14), two important nodes are proposed: $\theta_1^* = arctan\frac{2c}{a-b}$, $\theta_2^* = arctan\frac{2c}{a-b} + \frac{\pi}{2}$. By substituting it into the objective function, it is obtained that the function should satisfies that:

$$\frac{P_A\|h_{ae2}\|^2 + \left(\|\alpha_h\|\sqrt{P_{E1}}\cos\theta + \|\beta_h\|\sqrt{P_{E1}}\sin\theta\right)^2}{\sigma^2} - \frac{P_A\|h_{ab}\|^2 + \|\mathbf{h}_{eb1}\|^2 P_{E1}\cos^2\theta}{\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2} \geq 0.$$

It could be expressed as: $mP_{E1} \geq n$, where

$$m = \frac{(\|\alpha_h\|\cos\theta + \|\beta_h\|\sin\theta)^2}{\sigma^2} - \frac{\|\mathbf{h}_{eb1}\|^2\cos^2\theta}{\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2} = \frac{\|\mathbf{h}_{ee3}\mathbf{w}_1^*\|^2}{\sigma^2} - \frac{\|\mathbf{h}_{eb1}\mathbf{w}_1^*\|^2}{\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2},$$
$$n = \frac{P_A\|h_{ab}\|^2}{\|\mathbf{h}_{eb2}\|^2 P_{E2}+\sigma^2} - \frac{P_A\|h_{ae2}\|^2}{\sigma^2}.$$

By observing the structure of m and n, we can observe that m consists of two different parts and n is a constant. The meaning of the first prat in m is the SNR gain at E2 brought by E1 when the optimal solution of (9) is applied; the meaning of the second one is the SNR gain at B brought by E1 at the same time.

If the optimal solution of (9) satisfies $m \leq 0$, it causes that the gain due to the transmission of E2 is negative. i.e., if E2 works alone, it can achieve successful monitoring, too. Therefore, the feasibility condition in this case is: For any power at E1, problem (9) is always feasible.

On the other hand, if the optimal solution of (9) satisfies that $m > 0$, it indicates that the gain at E2 brought by $\mathbf{w}_1^*$ is positive, i.e., E2 could monitor successfully without E1. Then, we analyze those two terms in n. The former one is the SINR at B, while the latter one is the SINR at E2. In this case, $n > 0$ is observed. Hence, the feasibility condition in this case is that the power at E1 satisfies $P_{E1} \geq \frac{n}{m}$.

In summary, the feasible conditions for the problem are: $m \leq 0$ or $P_{E1} \geq \frac{n}{m}$.

B. OPTIMAL SOLUTION

To obtain the optimal solution of problem (8), several special cases are discussed: If the following constraint is proposed, E2 can work in the passive eavesdropping mode while E1 tries its best to increase the suspicious transmitting rate.

$$\frac{P_A\|h_{ae2}\|^2 + \|\widehat{\mathbf{h}}_{ee3}\|^2 P_{E1}}{\sigma^2} \geq \frac{P_A\|h_{ab}\|^2 + \|\mathbf{h}_{eb1}\|^2 P_{E1}}{\sigma^2}, \tag{15}$$

where $\|\widehat{\mathbf{h}}_{ee3}\| = \frac{\|\mathbf{h}_{eb1}\mathbf{h}_{ee3}^H\|}{\|\mathbf{h}_{eb1}\|}$. In this case, the optimal solution of the problem (8) is $\mathbf{w}_1^* = \frac{\sqrt{P_{E1}}}{\|\mathbf{h}_{eb1}\|}\mathbf{h}_{eb1}^H$, $\mathbf{w}_2^* = 0$.

Remark 1: the constraint proposed in (15) would be achieved in the following two conditions:

1) The channel from A to E2 is much better than the channel from A to B. At this time, although E1 has increased the SNR at the B side as much as possible, the SNR at B is still less than or equal to the SNR at E2, which causes that E2 can eavesdropping on the suspicious link without jamming signals.

2) The E1 to E2 channels are much better than the E1 to B channels. No matter what the E2 monitoring channel is, the gain that E1 brings to E2 is much greater than the gain that it brings to B. In this case, although E1 is transmitted according to the B-side maximum ratio reception, the channel gains of E1 to E2 enable E2 to achieve positive eavesdropping.

Remark 2: The constraint (15) is determined by the channel information of E1 and E2, and merely increasing the power at the E1 side cannot achieve this effect.

If the constraint (15) is not satisfied, i.e., passive eavesdropping at E2 cannot be achieved when the direction of $\mathbf{w}_1$ is the maximum ratio transmission with $\mathbf{h}_{eb1}$. In this case, in order to ensure the successful eavesdropping, two methods are proposed to select, one is to change the direction of $\mathbf{w}_1$, another one is to impose the power of the jamming signal sent by E2. The difference between these two methods is that the sending of the jamming signal can cause the lower receiving rate at B so that E2 can successfully decode the suspicious information based on the lower suspicious communication rate; the adjustment about the direction of $\mathbf{w}_1$ can increase the receiving rate at E2 while reducing the receiving rate at B. Therefore, in order to maximize the eavesdropping rate, it should be implemented by adjusting the direction of $\mathbf{w}_1$ to make it closer to the direction of $\mathbf{h}_{eb1}^H$ until they are in the same direction.

If passive eavesdropping at E2 can be achieved when a certain direction (not yet reached the same direction with $\mathbf{h}_{eb1}^H$) is adjusted, it can be known from the above that the passive eavesdropping in this case is optimal. This condition is proposed as follows:

$$\frac{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\|^2P_{E1}}{\sigma^2} \geq \frac{P_A\|h_{ab}\|^2+\|\widehat{\mathbf{h}}_{eb1}\|^2P_{E1}}{\sigma^2}, \tag{16}$$

where $\|\widehat{\mathbf{h}}_{eb1}\| = \frac{\|\mathbf{h}_{eb1}\mathbf{h}_{ee3}^+\|}{\|\mathbf{h}_{ee3}\|}$.

According to the constraint (16), when $\mathbf{w}_1$ is in the same direction with $\mathbf{h}_{eb1}^+$, E2 can achieve passive eavesdropping. It is easy to obtain that the capacity of the eavesdropping channel at E2 is greater than the suspicious communication rate in this time. Therefore, when condition (16) is established, there must be a critical point in the adjustment process so that the received SNRs at E2 and B are exactly equal, and $\mathbf{w}_1$ corresponds to this critical point is the optimal solution that satisfies the constraints in (8).

To find the optimal $\mathbf{w}_1$ that satisfies the constraint (16), the following question is considered:

$$\begin{aligned} \max_{\mathbf{w}_1}\ & \frac{P_A\|h_{ab}\|^2+\|\mathbf{h}_{eb1}\mathbf{w}_1\|^2}{\sigma^2} \\ s.t.\ & \frac{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\mathbf{w}_1\|^2}{\sigma^2} = \frac{P_A\|h_{ab}\|^2+\|\widetilde{\mathbf{h}}_{eb1}\mathbf{w}_1\|^2}{\sigma^2}, \\ & |\mathbf{w}_1\|^2 \leq P_{E1}. \end{aligned} \tag{17}$$

For the optimal solution of problem (17), the power constraint for E1 is established as an equation, i.e., the signal sent by E1 needs to be transmitted with the maximum power. If E1 does not transmit at maximum power when the optimal solution is achieved, it can raise its power to the maximum and the receiving rate at B and E2 can both be greater than before changing the direction of $\mathbf{w}_1$. The eavesdropping rate is thus improved. Therefore, the signal at E1 must be sent at the maximum power.

Referring to the proof process of Lemma 1, we can observe that the optimal solution of the hypothetical problem (17) is: $\mathbf{w}_1^* = \alpha_{w0}\widetilde{\mathbf{h}}_{eb1} + \beta_{w0}\mathbf{b}$, where $\mathbf{b}^H\widetilde{\mathbf{h}}_{eb1} = 0$ and $\|\mathbf{b}\| = 1$. If we replace $\mathbf{b}$ with $\widetilde{\mathbf{h}}_{ee3\perp}$, we can get that the second constraint is also true. And because of $\|\mathbf{h}_{ee3}\widetilde{\mathbf{h}}_{ee3\perp}\| \geq \|\mathbf{h}_{ee3}\mathbf{b}\|$, in the first constraint, the left side of the equation will increase with the substitution about $\widetilde{\mathbf{h}}_{ee3\perp}$, while the right side will remain unchanged. At this time, in order to maintain the equation in the first constraint, the coefficients $\|\alpha_w\|$ in the equation need to be increased. At the same time, the objective function will increase. The available solution $\mathbf{w}_1^* = \alpha_{w0}\widetilde{\mathbf{h}}_{eb1} + \beta_{w0}\mathbf{b}$ is not the optimal form of the problem (17). Correspondingly, the optimal solution for problem (17) is $\mathbf{w}_1^* = \alpha_w\widetilde{\mathbf{h}}_{eb1} + \beta_w\widetilde{\mathbf{h}}_{ee3\perp}$, $\mathbf{w}_2^* = 0$, where $\widetilde{\mathbf{h}}_{ee3\perp} = \frac{\mathbf{h}_{ee3\perp}}{\|\mathbf{h}_{ee3\perp}\|}$, $\mathbf{h}_{ee3\perp} = \mathbf{h}_{ee3}^H - \left(\widetilde{\mathbf{h}}_{eb1}\mathbf{h}_{ee3}^H\right)\widetilde{\mathbf{h}}_{eb1}$.

The optimal solution to the problem (17) is composed of two directional components, one of which is the direction of the maximal channel ratio with $\mathbf{h}_{eb1}$, i.e., the same direction as $\mathbf{h}_{eb1}^H$, and the other direction is the projection from $\mathbf{h}_{ee3}^H$ into the null space of $\mathbf{h}_{eb1}^H$.

In order to get the optimal solution coefficient, we assume $\mathbf{h}_{ee3}^H = \alpha_h\widetilde{\mathbf{h}}_{eb1} + \beta_h\widetilde{\mathbf{h}}_{ee3\perp}$, the following problem is proposed:

$$\begin{aligned} \max_{\mathbf{w}_2}\ & \|\mathbf{h}_{eb1}\|^2\|\alpha_w\|^2 \\ s.t.\ & \|\alpha_h^+\alpha_w + \beta_h^+\beta_w\|^2 = P_A\left(\|h_{ab}\|^2 - \|h_{ae2}\|^2\right) \\ & \quad + \|\mathbf{h}_{eb1}\|^2\|\alpha_w\|^2, \\ & \|\alpha_w\|^2 + \|\beta_w\|^2 = P_{E1}. \end{aligned} \tag{18}$$

In the problem (18), for any fixed $\|\alpha_{w0}\|^2$, it can be observed that $\|\alpha_h^+\alpha_{w0} + \beta_h^+\beta_{w0}\|^2 \leq \|\alpha_h^+\alpha_{w1} + \beta_h^+\beta_{w1}\|^2$. By observing the first constraint in question (18), the increasing of $||\alpha_{w0}||^2$ will increase $\|\alpha_h^+\alpha_w + \beta_h^+\beta_w\|^2$. Therefore, the optimal solution is $\alpha_{w1} = \frac{x\alpha_h}{\|\alpha_h\|}$, $\beta_{w1} = \frac{y\beta_h}{\|\beta_h\|}$, where x, y are real numbers.

Substituting the optimal solution form into problem (18), it can be transformed into:

$$\begin{aligned}
&\max_{x,y}\ \|\mathbf{h}_{eb1}\|^2x^2\\
&s.t.\ \left(\|\alpha_h\|^2x+\|\beta_h\|^2y\right)^2=P_A\left(||h_{ab}\|^2-\|h_{ae2}\|^2\right)\\
&\quad+\|\mathbf{h}_{eb1}\|^2x^2\\
&\quad x^2+y^2=P_{E1}
\end{aligned}\tag{19}$$

The above problem can be solved by solving an binary equations.

If the condition (16) cannot be satisfied, i.e., the direction of $\mathbf{w}_1$ sent by E1 has been adjusted to be in the same direction with $\mathbf{h}_{eb1}^H$, the received signal to noise ratio at the E2 side is already the maximum, but silent monitoring cannot be achieved.

The corresponding conditions is in the following:

$$\frac{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\|^2P_{E1}}{\sigma^2}<\frac{P_A\|h_{ab}\|^2+\|\widehat{\mathbf{h}}_{eb1}\|^2P_{E1}}{\sigma^2},\tag{20}$$

where $\|\widehat{\mathbf{h}}_{eb1}\|=\frac{\|\mathbf{h}_{eb1}\mathbf{h}_{ee3}^H\|}{\|\mathbf{h}_{ee3}\|}$. In this case, E1 has increased the gain of the eavesdropping link as much as possible, but it still cannot achieve the passive eavesdropping. Furthermore, it is better to send the interference signal from E2 rather than to adjust direction sent by E1. Because sending the jamming signal reduces the reception SNR at the B side, there is no effect on the reception rate of the E2 side itself. If the direction is adjusted, since the maximum reception is achieved at this moment, the signal-to-noise ratio at E2 will inevitably decrease after adjustment, thereby reducing the eavesdropping rate. Therefore, in the condition (20), the selection of the transmission interference signal is adopted to ensure the successful eavesdropping.

If the successful eavesdropping can be achieved by the interference signal, the power requirement for E2 is:

$$\frac{\left(P_A\|h_{ab}\|^2+\|\widehat{\mathbf{h}}_{eb1}\|^2P_{E1}\right)\sigma^2}{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\|^2P_{E1}}-\sigma^2\le P_{E2}\tag{21}$$

The optimal solution can be expressed as the following:

$$\mathbf{w}_1^*=\frac{\sqrt{P_{E1}}}{\|\mathbf{h}_{ee3}\|}\mathbf{h}_{ee3}^H,$$

$$\mathbf{w}_2^*=\sqrt{\frac{\left(P_A\|h_{ab}\|^2+\|\widehat{\mathbf{h}}_{eb1}\|^2P_{E1}\right)\sigma^2}{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\|^2P_{E1}}-\sigma^2}\,\frac{\mathbf{h}_{eb2}^H}{\|\mathbf{h}_{eb2}\|}$$

If P_{E2} is too poor to satisfy the condition (21), we can adjust the direction of the interference signal to make it biased towards the null space direction while maintaining E2 at the maximum power. The following problem is considered:

$$\begin{aligned}
&\max_{\mathbf{w}_2}\ \frac{P_A||h_{ab}\|^2+\|\mathbf{h}_{eb1}\mathbf{w}_1\|^2}{\|\mathbf{h}_{eb2}\|^2P_{E2}+\sigma^2}\\
&s.t.\ \frac{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\mathbf{w}_1\|^2}{\sigma^2}=\frac{P_A||h_{ab}\|^2+\|\mathbf{h}_{eb1}\mathbf{w}_1\|^2}{\|\mathbf{h}_{eb2}\|^2P_{E2}+\sigma^2},\\
&\quad\|\mathbf{w}_1\|^2\le P_{E1}.
\end{aligned}\tag{22}$$

Considering the similarity between the problem and the problem (17), an effective solution to the problem (22) can be achieved by using the method in the solution problem (17).

C. SUMMARY OF DESIGN

In the above section, we analyzed the feasibility of the proposed cooperation surveillance solution and obtained the feasible area of problem (7). Then we further analyzed all available channel state information, which can be roughly summarized as follows: when the condition (15) is satisfied, the direction of $\mathbf{w}_1$ is the same as $\mathbf{h}_{eb1}^H$, and $\mathbf{w}_2=0$ at the same time; when the condition (15) cannot be satisfied, but the constraint is satisfied in (16), the direction of $\mathbf{w}_1$ is composed of two components, one of which is the same as $\mathbf{h}_{eb1}^H$, and the other component is the projection from $\mathbf{h}_{ee3}^H$ to null space of $\mathbf{h}_{eb1}^H$; $\mathbf{w}_2=0$ at the same time; when the condition (16) cannot be satisfied and the condition (21) is satisfied, the direction of $\mathbf{w}_1$ is the same as $\mathbf{h}_{eb2}^H$. At the same time, the direction of $\mathbf{w}_2$ is the same with $\mathbf{h}_{eb2}^H$; when the condition (21) cannot be satisfied, the direction of $\mathbf{w}_1$ consists of two components, one of which is in phase with $\mathbf{h}_{eb1}^H$, and the other component is a projection of $\mathbf{h}_{ee3}^H$ to the null space of $\mathbf{h}_{eb1}^H$, and the direction of $\mathbf{w}_2$ is the same with $\mathbf{h}_{eb2}^+$ at the same time. The above design is summarized as the following algorithm:

Algorithm 1 Optimal Solution for Problem (7)

If case 1 is satisfied,
  $\mathbf{w}_1^*=\frac{\sqrt{P_{E1}}}{\|\mathbf{h}_{eb1}\|}\mathbf{h}_{eb1}^H$,
  $\mathbf{w}_2^*=0$;
Else If case 2 is satisfied,
  $\mathbf{w}_1^*=\alpha_{w1}\widetilde{\mathbf{h}}_{eb1}+\beta_{w2}\widetilde{\mathbf{h}}_{ee3\perp}$,
  $\mathbf{w}_2^*=0$;
Else If case 3 is satisfied,
  $\mathbf{w}_1^*=\frac{\sqrt{P_{E1}}}{\|\mathbf{h}_{ee3}\|}\mathbf{h}_{ee3}^H$,
  $\mathbf{w}_2^*=\sqrt{\frac{(P_A\|h_{ab}\|^2+\|\widehat{\mathbf{h}}_{eb1}\|^2P_{E1})\sigma^2}{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\|^2P_{E1}}-\sigma^2}\,\frac{\mathbf{h}_{eb2}^H}{\|\mathbf{h}_{eb2}\|}$;
Otherwise
  $\mathbf{w}_1^*=\alpha_{w1}\widetilde{\mathbf{h}}_{eb1}+\beta_{w2}\widetilde{\mathbf{h}}_{ee3\perp}$,
  $\mathbf{w}_2^*=\frac{\sqrt{P_{E2}}\mathbf{h}_{eb2}^H}{\|\mathbf{h}_{eb2}\|}$.
output: $\mathbf{w}_1^*$, $\mathbf{w}_2^*$.

Case1 refers to

$$\frac{P_A\|h_{ae2}\|^2+\|\widehat{\mathbf{h}}_{ee3}\|^2\|\mathbf{w}_1\|^2}{\sigma^2}\ge\frac{P_A\|h_{ab}\|^2+\|\mathbf{h}_{eb1}\|^2\|\mathbf{w}_1\|^2}{\sigma^2},$$

where $\|\widehat{\mathbf{h}}_{ee3}\|=\frac{\|\mathbf{h}_{eb1}\mathbf{h}_{ee3}^H\|}{\|\mathbf{h}_{eb1}\|}$.

Case2 refers to

$$\frac{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\|^2P_{E1}}{\sigma^2}\ge\frac{P_A\|h_{ab}\|^2+\|\widehat{\mathbf{h}}_{eb1}\|^2P_{E1}}{\sigma^2},$$

where $\|\widehat{\mathbf{h}}_{eb1}\|=\frac{\|\mathbf{h}_{eb1}\mathbf{h}_{ee3}^H\|}{\|\mathbf{h}_{ee3}\|}$.

Case3 refers to

$$\frac{P_A\|h_{ae2}\|^2+\|\mathbf{h}_{ee3}\|^2P_{E1}}{\sigma^2}<\frac{P_A\|h_{ab}\|^2+\|\widehat{\mathbf{h}}_{eb1}\|^2P_{E1}}{\sigma^2},$$

where $\|\widehat{\mathbf{h}}_{eb1}\| = \frac{\|\mathbf{h}_{eb1}\mathbf{h}_{ee3}^H\|}{\|\mathbf{h}_{ee3}\|}$ and

$$\frac{\left(P_A\|h_{ab}\|^2 + \|\widehat{\mathbf{h}}_{eb1}\|^2 P_{E1}\right)\sigma^2}{P_A\|h_{ae2}\|^2 + \|\mathbf{h}_{ee3}\|^2 P_{E1}} - \sigma^2 \le P_{E2}.$$

$(\alpha_{w1}, \beta_{w1})$ and $(\alpha_{w2}, \beta_{w2})$ can be obtained by solving (17) and (22).

IV. ROBUST BEAMFORMING WITH IMPERFECT CSI

In the above section, we discussed the optimal design of transmit beamforming vectors when CSI is completely known. However, in actual situations, perfect CSI is difficult to obtain due to the channel estimation errors. In this paper, the suspicious channel h_{ab} and the channels from both legitimate monitors to the suspicious receiver $\mathbf{h}_{eb1}$, $\mathbf{h}_{eb2}$ are assumed to be imperfectly known since that the suspicious users do not know the existence of the monitor and the monitor cannot obtain the perfect CSI. Moreover, the channel from the suspicious transmitter to the legitimate monitors h_{ae1} and h_{ae2} are perfectly known since the monitor acts as receivers for these channels. Meanwhile, the channel $\mathbf{h}_{ee3}$ between two monitors is obviously known.

Combined with the system model we considered, the definition of the imperfect CSI is given as follows [14], [15]:

$$\begin{aligned}
\eta_{eb1} &= \left\{\mathbf{h}_{eb1}|\mathbf{h}_{eb1} = \widehat{\mathbf{h}}_{eb1} + \Delta\mathbf{h}_{eb1},\ \Delta\mathbf{h}_{eb1}\mathbf{W}_{eb1}\Delta\mathbf{h}_{eb1}^H \le 1\right\},\\
\eta_{eb2} &= \left\{\mathbf{h}_{eb2}|\mathbf{h}_{eb2} = \widehat{\mathbf{h}}_{eb2} + \Delta\mathbf{h}_{eb2},\ \Delta\mathbf{h}_{eb2}\mathbf{W}_{eb2}\Delta\mathbf{h}_{eb2}^H \le 1\right\},\\
\eta_{ab} &= \left\{h_{ab}|h_{ab} = \widehat{h}_{ab} + \Delta h_{ab},\ \Delta h_{ab}\Delta h_{ab}^H \le \varepsilon_0\right\}. \qquad (23)
\end{aligned}$$

The optimization problem is formulated as following:

$$\begin{aligned}
&\max_{\mathbf{W}_1,\mathbf{W}_2}\ \min_{\mathbf{h}_{eb1}\in\eta_{eb1},\mathbf{h}_{eb2}\in\eta_{eb2}h_{ab}\in\eta_{ab}} \frac{P_A\|h_{ab}\|^2 + \mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^H}{\mathbf{h}_{eb2}\mathbf{W}_2\mathbf{h}_{eb2}^H + \sigma^2}\\
&s.t.\ \frac{P_A\|h_{ae2}\|^2 + \mathbf{h}_{ee3}\mathbf{W}_1\mathbf{h}_{ee3}^H}{\sigma^2} \ge\\
&\qquad \max_{\mathbf{h}_{eb1}\in\eta_{eb1},\mathbf{h}_{eb2}\in\eta_{eb2}h_{ab}\in\eta_{ab}} \frac{P_A\|h_{ab}\|^2 + \mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^H}{\mathbf{h}_{eb2}\mathbf{W}_2\mathbf{h}_{eb2}^H + \sigma^2},\\
&\qquad Tr\left(\mathbf{W}_1\right) \le P_{E1},\\
&\qquad Tr\left(\mathbf{W}_2\right) \le P_{E2}. \qquad (24)
\end{aligned}$$

When the channel state information is partly known, we study the robust design that how to maximize the achievable eavesdropping rate. The objective function of problem (23) is available as a quasiconvex function. By converting the objective function into its epigraph, the optimal solution to problem (23) can be obtained. Therefore, a new auxiliary variable is proposed to replace the original objective function. At the same time, in order to eliminate the quasi-convex terms in the constraint conditions, another auxiliary variable μ is introduced in the constraints. Meanwhile, it is worth noting that the error about h_{ab} is conducted as $\|h_{ab}\|$ at all. Hence, $\max_{h_{ab}\in\eta_{ab}} \|h_{ab}\|^2 = \|\hat{h}_{ab}\|^2 + \varepsilon_0$, which is denoted as $\|\hat{h}_{ab1}\|^2$ while the minimum case is denoted as $\|\hat{h}_{ab0}\|^2 = \|\hat{h}_{ab}\|^2 - \varepsilon_0$. Finally, problem (23) can be transformed into:

$$\begin{aligned}
&\max_{\mathbf{W}_1,\mathbf{W}_2,\tau}\ \tau\\
&s.t.\ \frac{P_A\|h_{ae2}\|^2 + \mathbf{h}_{ee3}\mathbf{W}_1\mathbf{h}_{ee3}^H}{\sigma^2} \ge \mu,\\
&\qquad \frac{P_A\|h_{ab1}\|^2 + \mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^H}{\mathbf{h}_{eb2}\mathbf{W}_2\mathbf{h}_{eb2}^H + \sigma^2} \le \mu,\\
&\qquad \forall\mathbf{h}_{eb1} \in \eta_{eb1}, \forall\mathbf{h}_{eb2} \in \eta_{eb2},\\
&\qquad \frac{P_A\|h_{ab0}\|^2 + \mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^H}{\mathbf{h}_{eb2}\mathbf{W}_2\mathbf{h}_{eb2}^H + \sigma^2} \ge \tau,\\
&\qquad \forall\mathbf{h}_{eb1} \in \eta_{eb1}, \forall\mathbf{h}_{eb2} \in \eta_{eb2},\\
&\qquad Tr\left(\mathbf{W}_1\right) \le P_{E1}, \qquad (25)
\end{aligned}$$

Intuitively, the range of μ in problem (5.24) can be defined by $[0, \mu_{\max}]$, where $\mu_{\max}$ is the optimal objective function with known perfect CSI. For any fixed μ, Algorithm 2 is applied to search for the global optimal solution.

However, Algorithm 2 has the following two major disadvantages:

1) High-complexity is required due to a large number of iterations in τ and μ.

2) It is difficult to determine the feasibility for any fixed τ during infinite constraints, which is caused by the imperfect CSI.

Based on the above disadvantages, we consider the following lemmas to solve it [37].

Lemma 2: For a fixed function form: $f_m(x), m \in \{1, 2\}$ and $f_m(x) = \mathbf{x}^H A_m \mathbf{x} + 2Re\left\{\mathbf{b}_m^H\mathbf{x}\right\} + c_m$, where $A_m \in C^{N\times N}$, $\mathbf{b}_m \in C^{N\times 1}$, $c_m \in C$. $f_1(x) \le 0 \Rightarrow f_2(x) \le 0$ If and only if there exists $\omega \ge 0$ satisfying

$$\omega\begin{bmatrix} A_1 & b_1\\ b_1^H & c_1\end{bmatrix} - \begin{bmatrix} A_2 & b_2\\ b_2^H & c_2\end{bmatrix} \succeq \mathbf{0}. \qquad (26)$$

Lemma 3: For constraint $\mathbf{I} - \mathbf{X}^H\mathbf{D}\mathbf{X} \succeq \mathbf{0}$, the following inequality can be obtained:

$$\begin{bmatrix} \mathbf{H} & \mathbf{F}+\mathbf{G}\mathbf{X}\\ (\mathbf{F}+\mathbf{G}\mathbf{X})^H & \mathbf{C}+\mathbf{X}^H\mathbf{B}+\mathbf{B}^H\mathbf{X}+\mathbf{X}^H\mathbf{A}\mathbf{X}\end{bmatrix} \succeq \mathbf{0} \qquad (27)$$

if and only if there exists $t \ge 0$, which satisfies the following generalized inequality:

$$\begin{bmatrix} \mathbf{H} & \mathbf{F} & \mathbf{G}\\ \mathbf{F}^H & \mathbf{C} & \mathbf{B}^H\\ \mathbf{G}^H & \mathbf{B} & \mathbf{A}\end{bmatrix} - t\begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & -\mathbf{D}\end{bmatrix} \succeq \mathbf{0}. \qquad (28)$$

Algorithm 2 Loop Search Algorithm for Problem (24)

1: **Initialize:** $\tau \in [0, \tau_m]$, where $\tau_m = \mu_{\max}$. $\tau_{\min} \leftarrow 0$, $\tau_{\max} \leftarrow \tau_m$;
2: **Repeat**
3: **If** τ is feasible for (24),
4: $\tau_{\min} \leftarrow \tau$, $\tau \leftarrow \frac{\tau_{\min}+\tau_{\min}}{2}$;
5: **Else**
6: $\tau_{\max} \leftarrow \tau$, $\tau \leftarrow \frac{\tau_{\min}+\tau_{\min}}{2}$.
7: **Until** $\tau_{\max} - \tau_{\min} \le \delta$.
8: **Output:** $\tau^* = \tau_{\min}$.

By applying Lemma 1 to simplify the condition in question (21), for the second constraint of problem (24), it can be transformed into $\mu \mathbf{h}_{eb2}\mathbf{W}_2\mathbf{h}_{eb2}^H + \mu\sigma^2 \geq P_A\|h_{ab1}\|^2 + \mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^H$. By substituting $\mathbf{h}_{eb2} \in \eta_{eb2}$, it can be observed that

$$\begin{aligned}\Delta\mathbf{h}_{eb2}\mathbf{W}_{eb2}\Delta\mathbf{h}_{eb2}^H - 1 \leq 0 \Rightarrow \Delta\mathbf{h}_{eb2}\left(-\mu\mathbf{W}_2\right)\Delta\mathbf{h}_{eb2}^+ + 2Re\\ \times\left(-\Delta\mathbf{h}_{eb2}\mu\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H\right)\\ -\widehat{\mathbf{h}}_{eb2}\mu\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H - \mu\sigma^2\\ + P_A\|h_{ab1}\|^2 H\mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^H \leq 0\end{aligned}$$

if and only if

$$\begin{bmatrix}\mu\mathbf{W}_2 + s\mathbf{W}_{eb2} & \mu\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H\\ \mu\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2 & w_3\end{bmatrix}\succeq\mathbf{0}, \quad \forall\mathbf{h}_{eb1}\in\eta_{eb1},\ \exists s\geq 0 \tag{29}$$

is satisfied, where

$$w_3 = \mu\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H + \mu\sigma^2 - P_A\|h_{ab1}\|^2 - \mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^H - s. \tag{30}$$

By applying lemm2, it can further obtained that

$$\begin{bmatrix}\mu\mathbf{W}_2 + s\mathbf{W}_{eb2} & \mu\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^+ & \mathbf{0}_{N\times N}\\ \mu\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2 & w_4 & -\widehat{\mathbf{h}}_{eb1}\mathbf{W}_1\\ \mathbf{0}_{N\times N} & -\mathbf{W}_1\widehat{\mathbf{h}}_{eb1}^H & -\mathbf{W}_1 + e\mathbf{W}_{eb1}\end{bmatrix}\succeq\mathbf{0},\ \exists s, e\geq 0, \tag{31}$$

where $w_4 = \mu\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H + \mu\sigma^2 - P_A\|h_{ab1}\|^2 - \widehat{\mathbf{h}}_{eb1}\mathbf{W}_1\widehat{\mathbf{h}}_{eb1}^H - s - e$.

Similarly, the third constraint can be expressed as:

$$\begin{aligned}\Delta\mathbf{h}_{eb2}\mathbf{W}_{eb2}\Delta\mathbf{h}_{eb2}^H - 1 \leq 0 \Rightarrow \Delta\mathbf{h}_{eb2}\left(\tau\mathbf{W}_2\right)\Delta\mathbf{h}_{eb2}^+ + 2Re\\ \times\left(\tau\widehat{\mathbf{h}}_{eb2}^+ W_2\Delta\mathbf{h}_{eb2}\right)\\ +\widehat{\mathbf{h}}_{eb2}\left(\tau\mathbf{W}_2\right)\widehat{\mathbf{h}}_{eb2}^+ + \tau\sigma^2\\ - P_A||h_{ab0}||^2 - \mathbf{h}_{eb1}\mathbf{W}_1\mathbf{h}_{eb1}^+ \leq 0\end{aligned}$$

if and only if

$$\begin{bmatrix}-\tau\mathbf{W}_2 + m\mathbf{W}_{eb2} & -\tau\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H\\ -\tau\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2 & w_5\end{bmatrix}\succeq 0,\quad \forall\mathbf{h}_{eb1}\in\eta_{eb1}, \exists m\geq 0, \tag{32}$$

where $w_5 = -\tau\widehat{\mathbf{h}}_{eb2}W_2\widehat{\mathbf{h}}_{eb2}^H - \tau\sigma^2 + P_A\|h_{ab0}\|^2 + \mathbf{h}_{eb1}W_1\mathbf{h}_{eb1}^H - m$.

By using lemm2, the following inequality is obtained:

$$\begin{bmatrix}-\tau\mathbf{W}_2 + mW_{eb2} & -\tau\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H & \mathbf{0}_{N\times N}\\ -\tau\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2 & w_6 & \widehat{\mathbf{h}}_{eb1}\mathbf{W}_1\\ \mathbf{0}_{N\times N} & \mathbf{W}_1\widehat{\mathbf{h}}_{eb1}^H & \mathbf{W}_1 + n\mathbf{W}_{eb1}\end{bmatrix}\succeq\mathbf{0},\quad \exists m, n\geq 0,$$

where $w_6 = -\tau\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H - \tau\sigma^2 + P_A\|h_{ab0}\|^2 + \widehat{\mathbf{h}}_{eb1}\mathbf{W}_1\widehat{\mathbf{h}}_{eb1}^H - m - n$.

In summary, the constraints in (24) are all linear matrix inequalities (LMI). Hence, the original problem is actually a semi-definite problem (SDP) as follows.

$$\begin{aligned}&\max_{\mathbf{W}_1,\mathbf{W}_2,r,s,e,m,n,\mu,\tau\geq 0} \tau\\ &s.t. \frac{P_A\|h_{ae2}\|^2 + \mathbf{h}_{ee3}\mathbf{W}_1\mathbf{h}_{ee3}^H}{\sigma^2} \geq \mu,\\ &\begin{bmatrix}\mu\mathbf{W}_2 + s\mathbf{W}_{eb2} & \mu\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^H & 0_{N\times N}\\ \mu\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2 & w_4 & -\widehat{\mathbf{h}}_{eb1}\mathbf{W}_1\\ 0_{N\times N} & -\mathbf{W}_1\widehat{\mathbf{h}}_{eb1}^+ & -\mathbf{W}_1 + e\mathbf{W}_{eb1}\end{bmatrix}\succeq\mathbf{0},\\ &\begin{bmatrix}-\tau\mathbf{W}_2 + m\mathbf{W}_{eb2} & -\tau\mathbf{W}_2\widehat{\mathbf{h}}_{eb2}^+ & 0_{N\times N}\\ -\tau\widehat{\mathbf{h}}_{eb2}\mathbf{W}_2 & w_6 & \widehat{\mathbf{h}}_{eb1}\mathbf{W}_1\\ 0_{N\times N} & \mathbf{W}_1\widehat{\mathbf{h}}_{eb1}^H & \mathbf{W}_1 + n\mathbf{W}_{eb1}\end{bmatrix}\succeq\mathbf{0},\\ &Tr\left(\mathbf{W}_1\right)\leq P_{E1},\\ &Tr\left(\mathbf{W}_2\right)\leq P_{E2}.\end{aligned} \tag{33}$$

In the process of the problem, we transform the original problem with optimal beamforming design into a SDP. For the solution which is in the form of matrix, it is required to be rank-one. However, in the process of problem transformation, it is difficult to ensure that the rank of the optimal solution is one. If the rank of the optimal solution matrix is not one, an approximate algorithm may be used, and the required beamforming vectors are further obtained by decomposing the approximation matrix. Specifically, two matrix, $\mathbf{W}_1^*$ and $\mathbf{W}_2^*$ is obtained by solving (33). L sets of vectors is defined as $\mathbf{w}_{11}, \mathbf{w}_{12}, \ldots, \mathbf{w}_{1L}$ and $\mathbf{w}_{21}, \mathbf{w}_{22}, \cdots, \mathbf{w}_{2L}$, where $\mathbf{w}_{ij} \sim CN\left(\mathbf{0}, \mathbf{W}_i^*\right), i = 1, 2, j = 1, 2, \ldots L$. By substituting each set of vector into the problem (7) to verify its feasibility, an approximate solution satisfying rank-one is obtained by choosing the vector whose objective function is largest.

Algorithm 3 is proposed to obtain the optimal beamforming for the robust case.

Algorithm 3 Optimal Solution for Problem (24)

1: Compute the optimal solution $\mathbf{W}_1^*$, $\mathbf{W}_2^*$ for problem (25);
2: **If** $\mathbf{W}_1^*$ and $\mathbf{W}_2^*$ are both rank-one,
3: $\mathbf{W}_1 = \mathbf{W}_1{}^*, \mathbf{W}_2 = \mathbf{W}_2{}^*$;
4: **Else**
5: $\mathbf{W}_1 = \mathbf{w}_1{}^H\mathbf{w}_1$, $\mathbf{W}_2 = \mathbf{w}_2{}^H\mathbf{w}_2$, where $\mathbf{w}_1$ and $\mathbf{w}_2$ are estimated by choosing the vector satisfying the largest objective.
6: **output:** $\mathbf{W}_1$ and $\mathbf{W}_2$.

V. PERFORMANCE ANALYSIS

In this section, simulation results are proposed to evaluate the performance of the design we proposed. For the case of perfect CSI, each legitimate monitor is configured with one antenna for receiving and 4 antennas for transmitting. The entries of the channel vectors are generated by independent CSCG random variables distributed as $\mathbf{h}_{eb2} \sim \mathcal{CN}(0, \mathbf{I})$, $\mathbf{h}_{eb1} \sim \mathcal{CN}(0, 0.5\mathbf{I})$, $\mathbf{h}_{ee3} \sim \mathcal{CN}(0, \mathbf{I})$, $h_{ae1} \sim \mathcal{CN}(0, 1)$,

$h_{ae2} \sim \mathcal{CN}(0, 0.5)$, $h_{ab} \sim \mathcal{CN}(0, 1)$ due to the fact that the channel gain from A to E1 is greater than that to E2, and the channel gain from E1 to A is smaller than the channel gain from E2 to B.

To illustrate the superiority of the system scheme we proposed, the contrast scheme used in the simulation process is a cooperative eavesdropping scheme based on proactive eavesdropping via jamming. In the cooperative scheme via jamming, two monitors both send jamming signals. The antennas and power are same as the proposed scheme.

For the case of imperfect CSI, the channel vectors consist of two parts, namely the channel estimation sets and the uncertainty sets. The channel estimation sets are the same as that of the perfect CSI. For simplicity, it is assumed that the uncertainty sets are norm-bounded. i.e, $\mathbf{W}_{eb1} = \mathbf{W}_{eb2} = \varepsilon \mathbf{I}$, $\varepsilon_0 = \varepsilon$, in which ε can characterize the estimation error of the channel. Smaller values of ε implies better CSI knowledge at the legitimate monitors.

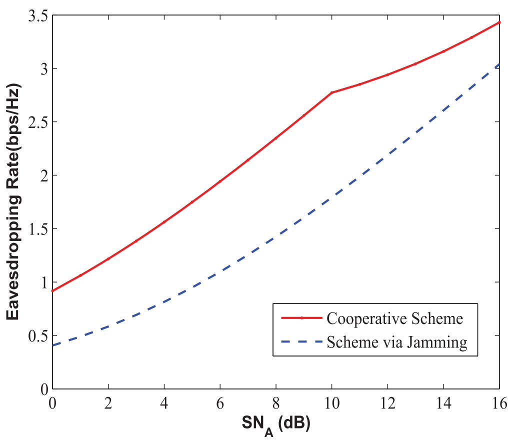

FIGURE 2. Eavesdropping rate versus the maximum power at A with perfect CSI.

Fig. 2 illustrates eavesdropping rate versus the maximum power at A for perfect CSI. It is defined that $SN_A = P_A||h_{ab}||^2/\sigma^2$, which represents the signal-to-noise ratio of the suspicious transmission when it is only affected by background noise. First, we observe the effect on the eavesdropping rate versus SN_A and assume the range of SN_A is [0, 20] dB. A new variable is defined as P_A^1, which satisfies $P_A^1 \|h_{ab}\|^2/\sigma^2 = 10$ dB. We assume that the maximum transmit power at E1 and E2 satisfy $P_{E1} = P_{E2} = P_A^1$. It can be observed from Fig. 2 when SN_A is relatively small, corresponding to case 1 in the design summary, the increase in the eavesdropping rate in the cooperative surveillance scheme comes from the increase of SN_A and the gain of E1 versus B, and the improvement is significant. At the same time, the increase in the monitoring rate in the interference monitoring scheme is entirely due to the increase in performance of SN_A, which is inferior to the cooperative monitoring scheme. When the growth of SN_A no longer satisfies the condition of case1, corresponding to case2-case3 in the design scenario, E1 reduces the reception gain at B. Therefore, the eavesdropping rate of the cooperative monitoring solution increases accordingly. At the same time, the growth trend of the interference monitoring solution is not affected, but its performance is still inferior to the cooperative monitoring solution.

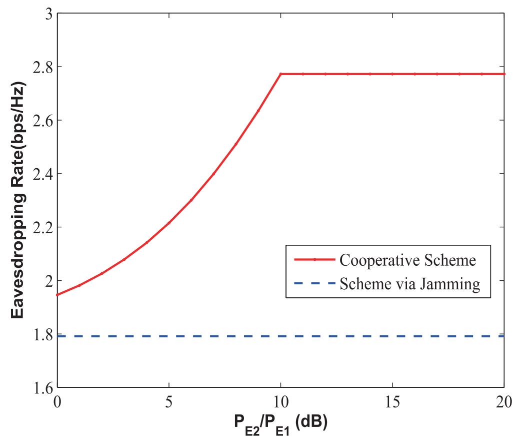

FIGURE 3. Eavesdropping rate versus the maximum power at E1 with perfect CSI.

Fig. 3 depict the eavesdropping rate versus the power ratio of E1 and E2 with perfect CSI. In Fig. 3, SN_A is 10 dB, the transmit power at E2 satisfies $P_{E2} = P_A^1$, and the transmit power at E1 satisfies that P_{E2}/P_{E1} is in the range of [-10 dB, 10 dB]. For the cooperative eavesdropping scheme, when P_{E2}/P_{E1} is in a low value, the eavesdropping rate increases as the E1 power increases. When the E1 power exceeds a certain value, the monitoring rate would not be affected by the power at the E1 since the information transmitted in E1 cannot be more than that received from A. For the scheme of proactive eavesdropping via jamming, the eavesdropping rate is equal to the suspicious communication rate; otherwise, it is 0. Therefore, the increase in the monitor power does not improve the eavesdropping rate.

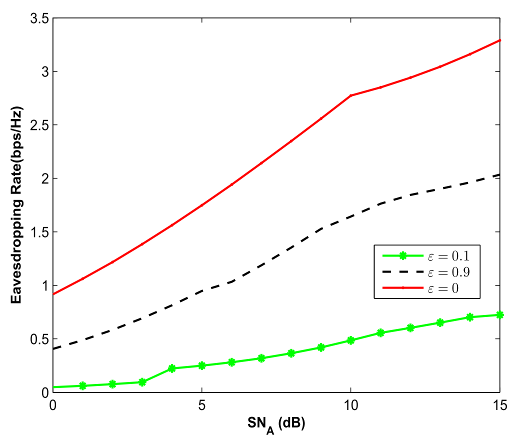

FIGURE 4. Eavesdropping rate versus the maximum power at A with imperfect CSI.

Fig.4 illustrates eavesdropping rate versus SN_A with imperfect CSI. Similarly, we suppose that the transmission power of E1 and E2 satisfy that $P_{E1} = P_{E2} = P_A^1$, and γ is in the range of $[0dB, 15\, dB]$. The above figure compares the performance under three conditions of ε as 0, 0.1, and 0.9, respectively. When ε=0, perfect CSI is known, the curve is basically consistent with the performance curve in Figure.2; When ε=0.1, small deviations in CSI estimation is assumed, the reception gain at B caused by E1 and the interference capability of E2 will both decrease. In this case, the uncertainty of the suspicious channel also increases the difficulty of eavesdropping, the performance curve of the monitoring rate has greatly declined compared with the known perfect CSI; When ε=0.9, large deviation in CSI estimation is assumed, the receiving rate of E2 is not affected, but the eavesdropping rate mainly depends on the suspicious channel status information difficult to obtain in this case, the robust eavesdropping rate is always low.

VI. CONCLUSION AND FUTURE WORK

In this paper, we study the problem of two monitors working in a cooperative mode to monitor suspicious communication processes in wireless communication systems. By optimizing the design of the transmit signal beamforming, on the basis of ensuring successful monitoring, the monitoring rate is effectively improved. Without loss of generality, this chapter considers two cases of known perfect channel state information and known partial channel state information. When the perfect channel state information is known, we apply the nature of the monitoring rate and the analysis of the known channel state information, and decompose the non-convex original problem that is difficult to directly solve, and obtain several subproblems that can obtain closed analytic expressions. When the partial channel state information is known, by introducing the S-procedure lemma, the original problem containing an infinite number of constraints is transformed into a problem that can solve the linear matrix inequality problem using the existing mathematical methods. In the end, the simulation results verify the superiority of our proposed solution.

At present, the surveillance system considers the monitor to be concealed. However, the device for suspicious communication may also have anti-eavesdropping means, such as adding artificial noise to the signal, et al. How to monitor such suspicious communication with anti-eavesdropping is one of the problems that need to be studied in the future. Due to the adaptability and intelligence of the communication nodes, an ever-changing strategy will be adopted for different situations, some knowledge such as game theory will have more applications in monitoring and confrontation monitoring.

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