Asymptotically Optimal Cooperative Jamming for Physical Layer Security

Jun Yang, Soheil Salari, Il-Min Kim, Dong In Kim, Seokki Kim, and Kwangae Lim

Abstract: Design of effective cooperative jamming (CJ) algorithm is studied in this paper to maximize the achievable secrecy rate when the total transmit power of the source and multiple trusted terminals is constrained. Recently, the same problem was studied in [1] and an optimal algorithm was proposed involving a one-dimensional exhaustive searching. However, the computational complexity of such exhaustive searching could be very high, which may limit the practical use of the algorithm. We propose an asymptotically optimal algorithm, involving only a fast line searching, which is guaranteed to achieve the global optimality when the total transmit power goes to infinity. Numerical results demonstrate that the proposed asymptotically optimal algorithm essentially gives the same performance as the algorithm in [1, (44)] but with much lower computational complexity.

Index Terms: Cooperative jamming, physical layer security, secrecy rate.

I. INTRODUCTION

The fundamental idea of physical layer security is to exploit the physical characteristics of the wireless medium in order to communicate confidential messages. Secure communication from information-theoretic point of view was first studied by Wyner [2] for the classical wiretap channel and later extended for Gaussian channels in [3] and [4]. One of the effective methods for physical layer security is to transmit artificial jamming signal [5] to the eavesdropper using multiple antenna or cooperating terminals. This technique is often called artificial noise or cooperative jamming (CJ), which was studied in [5]–[11] based on information-theoretic approaches.

For the CJ networks, the use of achievable secrecy rate as the benchmark of security was considered in [12]–[15]. The works in [12]–[14] were the first few to investigate the design of CJ weight vectors under different types of power constraints. In [13], the authors assumed that each individual node (including the source node and each of the trusted terminals) had its own transmit power constraint, and derived an optimal CJ algorithm using a combination of convex optimization and a line searching. In [14], the authors assumed the source transmit power and the total transmit power of all trusted terminals were constrained separately, and proposed an optimal solution using an iterative approach. The scenario that the total transmit power of source and trusted terminals is constrained, which is referred to as the combined power constraint in this paper, was first discussed in [1] and [12]. In [12], a suboptimal CJ vector and the corresponding power allocation were obtained in closed forms by adding an extra constraint to completely null out the jamming signal at the destination. However, as shown in [15], the CJ vector proposed in [12] is not optimal in general. The optimal algorithm for the combined power constraint scenario was recently derived in [1, (44)] based on a one-dimensional exhaustive searching. However, the computational complexity of exhaustive searching can be very high, which may limit the application of the optimal algorithm in practice. Thus, computationally effective algorithms that give performance close to the optimal algorithm in [1, (44)] are desirable.

The contribution of our work is that we derive a fast asymptotically optimal algorithm for the combined power constraint that has much lower computational complexity than the optimal one in [1, (44)]. More specifically, we mathematically prove that our proposed asymptotically optimal algorithm guarantees to obtain the global maximum point when the transmit power goes to infinity, or the signal-to-noise ratio (SNR) goes to infinity. To study the performance of our proposed method in the finite SNR, we performed extensive simulation trials from various aspects. All of the simulation studies indicate that the proposed asymptotically optimal algorithm and the optimal one [1, (44)] essentially give the same performance over the entire SNR range, not necessarily high SNR values. Our extensive experiments not only show that the searching range of our proposed asymptotical algorithm is narrower than that of the exhaustive searching method derived in [1, (44)], but also confirm that, in this narrower range, the objective function is quasi-concave. This means there is at most one critical point that must be the global maximum point. Thus, any of the existing effective line searching algorithms, such as bisection method, steepest decent method, and Newton’s method [18], can be applied to compute the global maximum point, which requires much lower computational complexity than the exhaustive-searching method of [1]. It is well known that the reduction of the total power cost
assumption of a wireless network saves the energy cost. Therefore, total power consumption is an important metric to compare the performances of different wireless networks, especially in practical applications. Moreover, it is important to minimize the amount of the interference generated by the whole wireless network. This calls for minimization of the total network transmit power. Since each node in a network has its own amplifier, the individual power constraints has to be considered in practice. However, considering additional individual power constraints (one constraint for each user and trusted terminal) is extremely challenging and beyond the scope of this paper. For all these reasons, similar to most published works in this area [1], we only consider the combined power constraint scenario.

Notation: We use $A := B$ (or $B =: A$) to denote that $A$, by definition, equals to $B$. Also, $A \ll B$ means $A$ is necessary and sufficient for $B$, and $A \propto B$ means that $A = kB$ for some constant $k$. Furthermore, $(A)^+$ equals to $A$ if $A > 0$, and 0 otherwise. For two functions $f(x)$ and $g(x)$, $f(x) \asymp g(x)$ means $\lim_{x \to \infty} f(x)/g(x) = 1$: $f(x)$ asymptotically equals to $g(x)$.

II. BACKGROUND

A. System Model and Problem Formulation

We consider a wireless network in Fig. 1, where there exists one source node (Alice), $N$ trusted terminals helping the source by transmitting CJ signals, one destination node (Bob), and one passive eavesdropper (Eve). All nodes are assumed to have a single antenna and work synchronously in the half-duplex mode. In this paper, $h_D$ denotes the channel from Alice to Bob, and $h_E$ denotes the channel from Alice to Eve. The channel vectors from $N$ trusted terminals to Bob and to Eve are denoted by $h \in \mathbb{C}^{N \times 1}$ and $g \in \mathbb{C}^{N \times 1}$, respectively (see Fig. 1), where $\mathbb{C}$ denotes the set of complex numbers. All channels are assumed to undergo flat fading and are quasi-static. Also, global channel state information (CSI) is perfectly known to Alice. Note that this is a very common assumption in the area of the secrecy rate optimization, which can be justified for certain situations. For example, consider the cases where the eavesdropper is active in the network and its CSI can be monitored. Also, this assumption is applicable in multi-user networks, in which the destinations play dual roles as legitimate users for some signals and eavesdroppers for others [19]. By adopting an opportunistic transmission scheduling scheme at source, at a time, the best destination is selected among multiple users to send the desired signal. The trusted terminals helping the source by transmitting CJ signals to the other user.

Thermal noises at Bob and Eve are assumed to be zero-mean complex Gaussian with variance $\sigma_D^2$ and $\sigma_E^2$, respectively, which are positive. In CJ [5], when Alice transmits zero-mean Gaussian source message $x_s$ at power $P_s$, the $N$ trusted terminals transmit in the same time slot a weighted jamming signal $x_J$, which is independent of the source message, in order to interfere Eve. Note that the trusted terminals cannot be used for transmitting $x_s$ to form a large distributed antenna array because the overhead required to spread the data $x_s$ over to all trusted terminals is too large. If we define $w \in \mathbb{C}^{N \times 1}$ as the CJ weight vector, the power of transmitted CJ signal can be written as $\|w\|^2$ under the assumption $E[|x_J|^2] = 1$. For the combined power constraint, the total transmit power is constrained by $P_{\text{tot}}^\text{max}: P_s + \|w\|^2 \leq P_{\text{tot}}^\text{max}$. In our setting, the CJ vector $w$ is only affected by channel conditions between the trusted terminals to Bob and to Eve.

The received signal-to-interference-plus-noise ratios (SINRs) at Bob and Eve can be, respectively, written as

\[
\text{SINR}_D = \frac{P_s|h_D|^2}{\|w^H h\|^2 + \sigma_D^2},
\]

\[
\text{SINR}_E = \frac{P_s|h_E|^2}{\|w^H g\|^2 + \sigma_E^2}.
\]

Note that the jamming signal introduces artificial noise at Bob as well as Eve. For the purpose of evaluating the achievable secrecy rate, we assume that the CJ codewords as well as the source’s codeword are independent zero-mean Gaussian inputs. Thus, the jamming signals are also zero-mean Gaussian. Therefore, even for the worst case where the perfect knowledge of $g$ and $w$ are available at Eve, Eve is still not able to cancel out the jamming signal $g^H w x_J$. This is because that, given $g$ and $w$, the summation of jamming signal $g^H w x_J$ and noise $n_E$ becomes a complex Gaussian random variable with zero mean and variance $\|w^H g\|^2 + \sigma_E^2$. Then, under the memoryless channel assumption, the achievable secrecy rate is known [5] as

\[
R_s = [\log(1 + \text{SINR}_D) - \log(1 + \text{SINR}_E)]^+.
\]

Without loss of generality, in this paper we are only interested in the case that the achievable secrecy rate using the CJ is positive, i.e., $\text{SINR}_D > \text{SINR}_E$, which will be referred to as the positive secrecy rate assumption [20]-[24]. Thus, the notation $(\cdot)^+$ will be omitted in the rest of this paper.

In this paper, we study the following important CJ problem, which was also studied in [1]:

\[
\{w_{\text{opt}}, P_{s_{\text{opt}}}\} = \arg \max_{w, P_s} R_s \quad \text{s.t.} \quad P_s + \|w\|^2 \leq P_{\text{tot}}^\text{max}. \tag{4}
\]

In this problem, both the optimal CJ weight vector and the optimal power are derived jointly at the same time, and this is one of the most important problems in the area of CJ. In fact, the Problem (4) achieves the optimal power tradeoff between Alice and the trusted terminals given a total power constraint. Therefore, the secrecy rate achieved by problem (4) can be considered as the ultimate upper bound of the secrecy rate given a total power of the entire network.
B. Existing Results

In [1], by defining
\[ z := \frac{\mathbf{w}^H \mathbf{h} \mathbf{H} \mathbf{w}}{(P_{\text{tot}} - P_s) \| \mathbf{h} \|^2}, \]  
(5)
the authors first recast the problem of (4) as a two variable optimization problem as follows (also see [1, (44)]):
\[
\max_{P_s, z} \log \frac{1 + \frac{P_s}{P_{\text{tot}} - P_s} \alpha_1 + \alpha_2}{1 + \frac{P_s}{P_{\text{tot}} - P_s} \alpha_3 \alpha_1 + \alpha_4}
\]
(6)
s.t. \( z \in [0, 1], \quad P_s \in [0, P_{\text{tot}}] \)
where \( \alpha_1 := \| \mathbf{h} \|^2 / \| \mathbf{h} \|^2, \) \( \alpha_2 := \sigma_D^2 / \| \mathbf{h} \|^2, \) \( \alpha_3 := \| \mathbf{g} \|^2 / \| \mathbf{h} \|^2, \) and \( \alpha_4 := \sigma_E^2 / \| \mathbf{h} \|^2. \) The function \( G(z) \) is defined by
\[
G(z) := 1 - \left( \frac{\mathbf{h}^H \mathbf{g}}{\| \mathbf{h} \| \| \mathbf{g} \|} \sqrt{1 - z} - \sqrt{1 - \left( \frac{\mathbf{h}^H \mathbf{g}}{\| \mathbf{h} \| \| \mathbf{g} \|} \right)^2 z} \right)^2.
\]
(7)
Then the authors in [1] claimed that \( P_s \) in (6) can be explicitly denoted as a function of \( z \). Thus, by denoting \( P_s \) as \( P_s(z) \), the problem (6) is reduced to one-dimensional optimization problem as follows (also see [1, (44)]):
\[
\max_{z} \log \frac{1 + \frac{P_s(z)}{P_{\text{tot}} - P_s(z)} \alpha_1 + \alpha_2}{1 + \frac{P_s(z)}{P_{\text{tot}} - P_s(z)} \alpha_3 \alpha_1 + \alpha_4}
\]
(8)
s.t. \( z \in [0, 1] \).

However, since the objective function of (8) is non-concave, one dimensional exhaustive searching must be applied to find the optimal solution of (8).

III. ASYMPTOTICALLY OPTIMAL COOPERATIVE JAMMING

In this section, we develop an asymptotically optimal CJ algorithm for the problem of (4) when \( P_{\text{tot}} \) goes to infinity, which only involves a fast line searching so that the computational complexity is (much) lower than the existing optimal CJ of (8) in which one dimensional exhaustive searching is needed. However, directly deriving an asymptotically optimal CJ algorithm based on (8) is very difficult, since the explicit expression of \( P_s \) as a function of \( z \) is very complex. To this end, we first derive an alternative form of one dimensional searching problem that is mathematically equivalent to (8). From this new expression, we derive the optimal point when \( P_{\text{tot}} \) goes to infinity, which means an asymptotically optimal CJ algorithm could be derived.

A. Equivalent Optimal Algorithm Using One-dimensional Exhaustive Searching

Defining
\[
\beta := (P_{\text{tot}} - P_s) \alpha_3 G(z) = \| \mathbf{w}^H \mathbf{g} \|^2,
\]
(9)
\[ P_{\text{wo}} := P_{\text{tot}} - P_s, \]
(10)
one can reformulate the problem of (6) with variables \( P_s \) and \( z \) to an equivalent problem with new variables \( P_{\text{wo}} \) and \( \beta \), which can also be solved using one-dimensional exhaustive searching. The results are summarized in the following lemma:

**Lemma 1**: The problem (6) is equivalent to
\[
\{ \beta_{\text{opt}}, P_{\text{woopt}} \} = \arg \max_{0 \leq P_{\text{wo}} \leq P_{\text{max}}, \beta_L \leq \beta \leq \beta_U} \log \left( \frac{1 + \frac{P_s}{\beta (P_{\text{wo}} + \sigma_p^2)} \| \mathbf{h} \|^2}{1 + \frac{P_s}{\beta |\mathbf{h} \|^2} + \sigma_p^2} \right)
\]
(11)
in which
\[
\beta(\beta, P_{\text{wo}}) = \left[ \frac{|g^H \mathbf{h}|}{\| \mathbf{g} \|} \sqrt{\beta - \| \mathbf{h} \|^2 - \frac{|g^H \mathbf{h}|^2}{\| \mathbf{g} \|^2}} \right] + 1.
\]
(12)
The lower and upper bounds of \( \beta \) are given by
\[
\beta_L = P_{\text{wo}} \left( \| \mathbf{g} \|^2 - \frac{|g^H \mathbf{h}|^2}{\| \mathbf{h} \|^2} \right),
\]
(13)
\[
\beta_U = P_{\text{wo}} \| \mathbf{g} \|^2.
\]
(14)
The optimal \( \beta_{\text{opt}} \) and \( P_{\text{woopt}} \) in (11) can be obtained using \( t_{\text{opt}} \) by \( \beta_{\text{opt}} = f(t_{\text{opt}}) \) and \( P_{\text{woopt}} = \beta_{\text{opt}} P_{\text{wo}} \), where \( t_{\text{opt}} \) is determined by one-dimensional searching:
\[
t_{\text{opt}} = \arg \max \log \left( \frac{1 + \frac{|P_{\text{wo}} - f(t)| |\mathbf{h} \|^2}{f(t)} + \sigma_p^2}{1 + \frac{|P_{\text{wo}} - f(t)| |\mathbf{h} \|^2}{f(t)} + \sigma_p^2} \right)
\]
(15)
in which \( t_L = 1 / \| \mathbf{g} \|^2, \) \( t_U = 1 / (\| \mathbf{g} \|^2 - |g^H \mathbf{h} |^2 / |\mathbf{h} \|^2) \), \( a_1 = |g^H \mathbf{h}| / \| \mathbf{g} \|^2 \), \( a_2 = \sqrt{|\mathbf{h} \|^2 - |g^H \mathbf{h} |^2 / |\mathbf{h} \|^2} \), and the function \( f(t) \) is defined by
\[
\min \left( \frac{-B - \sqrt{B^2 - 4AC}}{2A} \right), P_{\text{wo}} \left( \frac{\| g \|^2 - \frac{|g^H \mathbf{h}|^2}{\| \mathbf{h} \|^2}}{2} \right)
\]
(16)
where \( A := \text{A1B2} - \text{A2B1}, B := 2(\text{A1C2} - \text{A2C1}), \) and \( C := B_1C_2 - B_2C_1. \) In the above equations,
\[
A_1 := (a_1 - a_2 \sqrt{t - \frac{1}{\| \mathbf{g} \|^2}})^2 - t |\mathbf{h} \|^2,
\]
(17)
\[
A_2 := (a_1 - a_2 \sqrt{t - \frac{1}{\| \mathbf{g} \|^2}})^2 (1 - |\mathbf{h} \|^2 t),
\]
(18)
\[
B_1 := (a_1 - a_2 \sqrt{t - \frac{1}{\| \mathbf{g} \|^2}})^2 \sigma_E^2 - t |\mathbf{h} \|^2 \sigma_E^2
\]
(19)
Algorithm and the optimal one proposed in [1, (44)]: Narrower searches between our proposed fast asymptotically optimal algorithm and the global maximum point must be achieved at the boundary.

\[ \Delta \text{in the range of } [\tilde{t}_L, t_U]. \]

Note that both the optimal algorithm proposed in [1, (44)] and the equivalent algorithm in (15) requires a one-dimensional exhaustive searching. To reduce the complexity, we study a fast asymptotically optimal algorithm in this subsection based on (15). To this end, we prove an asymptotic property as follows: When \( P_{\text{tot}}^{\text{max}} \to \infty \), there is at most one critical point in the range of \([\tilde{t}_L, t_U]\) where \( t_L \geq \tilde{t}_L \), and the critical point must be the global maximum point. This implies that the searching range is narrower and, in this narrower range, the objective function is monotone increasing in the range \([\tilde{t}_L, t_U]\) and monotone decreasing in the range \([t_U, t_{\text{opt}}]\). Thus, the objective function is quasi-concave in the range \([\tilde{t}_L, t_U]\). Hence, many efficient searching algorithms with much lower computational complexities than exhaustive searching [25, Chapter 9], such as the bisection method, steepest descent method and Newton’s method, can be used for searching \( t_{\text{opt}} \) when \( P_{\text{tot}}^{\text{max}} \to \infty \). The result is summarized in the following theorem:

**Theorem 1:** When \( P_{\text{tot}}^{\text{max}} \to \infty \), the problem of (15) has at most one local maximum point in the range of \([\tilde{t}_L, t_{\text{opt}}]\) and it must be the global maximum point where

\[
\tilde{t}_L = t_L + \left( \frac{a_1 - \frac{|h_D|}{\sqrt{2a_2|h_E|}}}{} \right)^2. 
\]

If there is no local maximum point in the range of \([\tilde{t}_L, t_U]\), the global maximum point must be achieved at the boundary \( t = \tilde{t}_L \) or \( t = t_U \).

**Proof:** See Appendix B.

In practice, one can, for example, use the bisection method in the range of \([\tilde{t}_L, t_U]\) or a steepest descent method with \( \Delta t < 0 \) and initial point \( t_0 = t_U \).

It is worth mentioning that there are two fundamental differences between our proposed fast asymptotically optimal algorithm and the optimal one proposed in [1, (44)]: Narrower search interval and efficient searching rather than full searching. Based on our analysis, the complexity reduction due to narrowing the uncertainly interval is not significant. The majority of the computational complexity reduction comes from the usage of efficient searching method rather than narrowing the searching interval, as will be evidenced by our numerical results. The simulation results will also demonstrate that the performance of our proposed method is the same as the optimal full searching algorithm, not only in the high SNR range but also in the small-to-medium SNR values. This result is an algorithm of a resellable complexity which is suitable for practical applications over the entire SNR range.

**C. Possible Extensions**

In this subsection, we discuss two possible extensions of the work: i) limited CSI and ii) separate power constraint.

**C.1 Limited CSI**

To the best of our knowledge, no efficient low-complexity beamforming scheme has been reported yet in the context of cooperative jamming. In this paper, we have just assumed perfect CSI as our first step to provide a practical algorithm which is able to jointly obtain the beamforming vector and transmit power. Nevertheless, in practice, it might be difficult to obtain the perfect CSI, and hence, it is of both theoretical and practical interest to study the impact of limited CSI on the secrecy rate performance.

Assuming that only the second-order statistics (SOS) of the channels are known, we rewrite equations (1) and (2) as follows:

\[
\text{SINR}_D = \frac{P_s E[h_D h_D^H]}{w^H E[|h|^2 h h^H]|w + \sigma_D^2}, \\
\text{SINR}_E = \frac{P_s E[h_E h_E^H]}{w^H E[|g|^2 g g^H]|w + \sigma_E^2}. 
\]

The assumption that the SOS of channels are available allows us to consider uncertainty through introducing the covariance matrices of the CSIs, defined as \( R = E[|h|^2 h h^H] \) and \( Q = E[|g|^2 g g^H] \).

We aim to jointly find the optimal CJ weight vector and the optimal power under the assumption that Alice only knows the SOS of channels. This problem can be formulated as

\[
\{w_{\text{opt}}, P_{s_{\text{opt}}}\} = \arg\max_{\{w, P_s\}} \log \left( 1 + \frac{P_s E[h_D h_D^H]}{w^H R w + \sigma_D^2} \right) \\
- \log \left( 1 + \frac{P_s E[h_E h_E^H]}{w^H Q w + \sigma_E^2} \right) \\
\text{s.t. } P_s + \|w\|^2 = P_{\text{tot}}^{\text{max}}.
\]

Unfortunately, solving problem (26) is extremely challenging since its objective function is non-convex. Overall, we believe that it is beyond the scope of this paper to solve such a problem. However, it is an interesting problem as further work.

**C.2 Separate Power Constraint**

Since each node in a CJ network has its own amplifier, the individual power constraint of each node has to be considered.
In general, it is very difficult and costly to obtain the CJ weight vector in the case of separate power constraint. However, we provide some preliminary results for the case of separate power constraint, which is formulated as

\[
\{ w_{\text{opt}}, P_{s_{\text{opt}}} \} = \arg \max_{(w, P_{s})} R_s
\]

s.t. \( P_s \leq P_{s_{\text{max}}}, \| w \|^2 \leq P_{w_{\text{max}}} \). (27)

Here, Alice transmits source message with power no more than \( P_{s_{\text{max}}} \) and all the \( N \) trusted terminals help Alice using CJ with total power at most \( P_{w_{\text{max}}} \). Unfortunately, directly solving this problem is difficult, since the objective function of (27) is non-convex. In order to make the analysis tractable, we first determine \( P_{s_{\text{opt}}} \), and derive a useful condition on the optimal \( w_{\text{opt}} \) in the following lemma.

**Lemma 2:** For problem (27), the optimal source’s power is \( P_{s_{\text{opt}}} = P_{s_{\text{max}}} \) and the optimal CJ vector satisfies

\[
P_{w_{\text{opt}}} (\| g \|^2 - | g^H h |^2 / \| h \|^2) \leq \| (w_{\text{opt}}) g \|^2 \leq P_{w_{\text{max}}} | g |^2.
\]

**Proof:** First, since we only consider the case that secrecy rate is positive, it can be easily seen that the secrecy rate is an increasing function of \( P_s \). Thus, the maximum secrecy rate must be achieved with \( P_s = P_{s_{\text{max}}} = P_{s_{\text{opt}}} \). Also, if we constrain \( w^H h = 0 \) (the ZF constraint used in [12]), we have \( w^H g = w^H (g - (h^H g / \| h \|^2) h) \leq P_{w_{\text{max}}} (\| g \|^2 - | g^H h |^2 / \| h \|^2) \), the secrecy rate is an increasing function of \( \beta := \| w^H g \|^2 / \)\( \| g \|^2 \):

\[
\log_2 \left( 1 + \frac{P_{w_{\text{max}}} | g |^2}{\beta + \sigma_B^2} \right) \leq \log_2 \left( 1 + \frac{P_{w_{\text{max}}} | g |^2}{\| g \|^2} \right).
\]

Thus, the maximum secrecy rate cannot be achieved when \( \beta \leq \frac{P_{w_{\text{max}}} | g |^2}{\| g \|^2} \). Finally, it is obvious that \( \beta = \| w^H g \|^2 / \| g \|^2 \leq P_{w_{\text{max}}} | g |^2 \). The maximum is achieved with \( w = \sqrt{P_{w_{\text{max}}}} g / | g | \), which corresponds to the traditional transmit beamforming (Tx-BF) technique [26]. \( \square \)

Since \( P_{s_{\text{opt}}} \) has been determined, we now only need to determine \( w_{\text{opt}} \).

**IV. NUMERICAL RESULTS**

In this section, we investigate the performance of the proposed algorithms numerically. We set the noise power \( \sigma_D^2 = \sigma_E^2 = 1 \). Note that the average SINRs in linear scale are defined in equations (1) and (2), and the average SINR in dB is given by \( 10 \log_{10}(\text{SINR}) \). The channel \( h_D \) and \( h_E \) are generated according to Rayleigh fading with average received power 3 dB. The channel vectors \( h \) and \( g \) undergo Rayleigh fading with 0 dB received power. The total transmit power is constrained by \( P_{s_{\text{max}}} = 8 \) dB. We perform the Monte Carlo experiments consisting of 1000 independent trials to obtain the average results. The tested methods include the suboptimal zero-forcing CJ algorithm in [12, Equations (48) and (49)], the optimal exhaustive-searching CJ algorithm in (8) or [1, (44)], and the proposed asymptotic algorithm in (15).

In this paper, we discuss the performance improvement of the proposed asymptotic algorithm over the suboptimal zero-forcing algorithm. In fact, the performance improvement depends on the amount of instantaneous correlation between the channel vectors \( h \) and \( g \). If \( h \) and \( g \) are orthogonal, it can be easily shown the proposed asymptotically optimal CJ algorithm as well as the optimal exhaustive-searching algorithm are equivalent to the zero-forcing algorithm. On the other hand, if the correlation between \( h \) and \( g \), which is defined by \( \| g^H h / (\| h \| \| g \|) \), becomes large, then the performance improvement of the proposed algorithm increases. This can be understood from the difference between the zero-forcing method and the proposed asymptotically optimal method. The suboptimal zero-forcing method always forces a null to Bob. Therefore, when the channel to Bob and the channel to Eve are correlated, the zero-forcing method cannot transmit jamming signals to Eve effectively, under the constraint of forming a null to Bob. On the other hand, the proposed asymptotically optimal CJ method does not force a null to Bob; instead it achieves an asymptotically optimal trade-off between the interference power to Bob and the jamming power to Eve. Therefore, when the correlation between \( h \) and \( g \) becomes high, the performance improvement of the proposed method over the zero-forcing method grows as well. Note that the case of high correlation between \( h \) and \( g \) can model the scenario where Eve is very close to Bob, which should be considered as a serious security threat. In the cases that light-of-sight paths exist from Alice to Bob and Alice to Eve, such as Rician fading channels, the correlation between \( h \) and \( g \) may also be high. Thus, the scenario that \( h \) and \( g \) are highly correlated is extremely important for physical layer security.

In Fig. 2, we present the achievable secrecy rate versus instantaneous correlation between \( h \) and \( g \). From the figure, one can see that the suboptimal zero-forcing CJ algorithm becomes worse compared to the optimal performance when the channel vectors are highly correlated. The proposed asymptotically optimal CJ algorithm gives essentially the same performance as the optimal CJ algorithm. In the next two examples, we fix the instantaneous correlation between \( h \) and \( g \) to 0.95, which should be considered as a serious security threat where the eavesdropper Eve is very close to the destination Bob. From the numerical
Table 1. Comparison of running times of the optimal and asymptotically optimal algorithms.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Number of points</th>
<th>Running time</th>
<th>Ratio II/I</th>
<th>Step size</th>
<th>Running time</th>
<th>Ratio III/I</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>10^7</td>
<td>12.18 s</td>
<td>0.79</td>
<td>10^6</td>
<td>0.0154 s</td>
<td>1.3 × 10^-5</td>
</tr>
<tr>
<td>II</td>
<td>10^7</td>
<td>9.62 s</td>
<td>1.00</td>
<td>10^6</td>
<td>0.0180 s</td>
<td>1.4 × 10^-5</td>
</tr>
<tr>
<td>III</td>
<td>10^7</td>
<td>1003.21 s</td>
<td>0.79</td>
<td>10^6</td>
<td>0.0227 s</td>
<td>1.1 × 10^-5</td>
</tr>
</tbody>
</table>

Fig. 3. Achievable secrecy rate versus number of trusted terminals.

Fig. 4. Achievable secrecy rate versus SNR.

results of Figs. 3 and 4, we can see that the proposed asymptotically optimal CJ algorithm gives essentially the same performance as the optimal CJ algorithm not only in the high SNR but also in the small-to-medium SNR.

Table 1 compares the running time of the exhaustive searching method [1, (44)] (denoted as algorithm I), exhaustive searching method over narrower searching range (denoted as algorithm II), and the proposed asymptotically optimal method over narrower searching range (denoted as algorithm III) for different number of points and step sizes. In algorithm II, \( \varphi = \frac{(t_U - \tilde{t}_L)}{(t_U - t_L)} \) accounts for the narrower searching interval. We used the steepest-descent method to implement the asymptotically optimal algorithm. To provide a fair comparison, we varied the step size of the steepest-descent algorithm in accordance with the number of points searched over the uncertain interval. It can be seen that our proposed method is much faster. The speed difference becomes much more significant as the number of points grows.

Overall, the proposed asymptotically optimal CJ algorithm always performs essentially the same as the optimal exhaustive-searching algorithm in a wide range of SNR. Considering the much lower computational complexity of the proposed asymptotic algorithm, it is very desirable for practical applications.

V. CONCLUSION

We have studied the joint design of optimal CJ and power allocation to maximize the secrecy rate with combined power constraint and we have proposed a fast asymptotically optimal algorithm involving an efficient line searching, which theoretically guarantees to achieve the global optimality when the SNR goes to infinity. The proposed algorithm is much faster than the existing full searching method, because the searching range is narrower and, within this narrower range, the objective function is quasi-concave. The numerical results showed that the proposed fast algorithm essentially gives the optimal performance over the entire range of the SNR. Similar to the numerous published works in the area of cooperative jamming, it is assumed that the CSI is perfectly available. Nevertheless, in practice, it might be difficult to obtain the perfect CSI. Therefore, in our future work, we will study the impact of limited CSI on the secrecy rate performance. Moreover, since each node in a network has its own amplifier, another goal is to consider the separated/individual power constraints.

APPENDICES

A. Proof of Lemma 1

By substituting the definitions of \( \beta \) and \( P_w \) into (6), it can be easily proven that the problem (11) is equivalent to (6). Thus, we only need to prove the problem (11) can be solved by the one-dimensional exhaustive searching described in (15).

For simplicity, we first denote \( ||w||^2 \) by \( P \) so that we have the power constraint as \( P_s + P \leq P_{\text{max}}^{\text{tot}} \). Then, using the definition of \( a_1 \) and \( a_2 \), the function \( h(\beta, P) \) can be written as

\[
h(\beta, P) = \left( a_1 \sqrt{\beta} - a_2 \sqrt{P - \frac{\beta}{||g||^2}} \right)^2.
\]
Since the relationship between $\beta$ and $P$ is
\[
\frac{\beta}{\|g\|^2} \leq P \leq \frac{\beta}{\|g\|^2 - \|g^H h\|^2},
\]
we define a new variable $t := P/\beta$ to replace $P$. Note that the
function $\log(\cdot)$ is monotonically increasing; so we only need to maximize
\[
1 + \frac{(P_{\max} - \beta t)\|h\|^2}{\beta (a - a_2 \sqrt{1/t})^2 + \sigma_D^2},
1 + \frac{(P_{\max} - \beta t)\|h\|^2}{\beta + \sigma_E^2},
\]
(30)

We can see that the first term of (31) decreases with either $b$ or $t$, whereas
the second term increases with either $b$ or $t$, for which we can fix $t$ and solve $\beta$ analytically as a function of $t$ as follows. First, the first-order derivative
\[
\left(\begin{array}{c}
A_1 \beta^2 + B_1 \beta + C_1
\end{array}\right) =
\frac{(A_1 B_2 - A_2 B_1)\beta^2 + 2(A_1 C_2 - A_2 C_1)\beta + (B_1 C_2 - B_2 C_1)}{(A_2 \beta^2 + B_2 \beta + C_2)^2}
\]
(32)

Thus, when the first derivative is zero, we have $A\beta^2 + B\beta + C = 0$.

Note that in the situations we are interested in, we have $C > 0$, which means the secrecy rate can be increased by introducing CJ. If $C < 0$, the optimal $\beta$ is zero, which means no CJ is needed. Also, in the scenario we are interested in, we have $B^2 \geq 4AC$. Because when $B^2 < 4AC$ the optimal $\beta$ is achieved at either 0 or $P_{\max}$, which are certainly not the cases we consider.

The analytical expressions of optimal $\beta$ when $t$ can be written as:

i) When $C > 0$, $A > 0$, and $B > 0$: The optimal solution is $\beta = 0$;

ii) When $C > 0$, $A > 0$, and $B^2 < 4AC$: The optimal solution is
\[
\beta = \frac{P_{\max}}{\text{tot}} \left(\|g\|^2 - \left\|\frac{g^H h}{\|h\|^2}\right\|^2\right);
\]
(33)

iii) When $C > 0$, $A > 0$, and $B^2 \geq 4AC$, or $C > 0$ and $A < 0$, the optimal solution is
\[
\beta = \min \left\{-B - \sqrt{B^2 - 4AC} \right\} / 2A ; P_{\max} \left(\|g\|^2 - \left\|\frac{g^H h}{\|h\|^2}\right\|^2\right)
\]
(34)

iv) When $C < 0$: The optimal solution is $\beta = 0$;

v) When $C < 0$ and $A > 0$: $\beta = 0$ or $\beta = \frac{P_{\max}}{\text{tot}}$;

vi) When $C < 0$ and $A < 0$: $\beta = 0$ or $\beta \left(-B - \sqrt{B^2 - 4AC}\right) / 2A$ if $B > 0$, $\beta = 0$ if $B < 0$.

Overall, the optimal $\beta$ can be expressed as
\[
f(t) = \min \left\{-B - \sqrt{B^2 - 4AC} \right\} / 2A ; P_{\max} \left(\|g\|^2 - \left\|\frac{g^H h}{\|h\|^2}\right\|^2\right)
\]
(35)
in the scenario $C > 0$ and $B^2 \geq 4AC$. Since $A$, $B$, and $C$ are all functions of $t$, the solution of $\beta$ is only a function of $t$. Thus, the optimization problem can be solved by exhaustive searching of $t$ in which $\beta$ is replaced by $f(t)$.

B. Proof of Lemma 2

The proof consists of three steps: i) we prove for given $\beta$ the secrecy rate is quasi-concave of $t$, and the optimal $t = f(\beta)$ is a decreasing function of $\beta$ where
\[
\tilde{f}(x) := \frac{P_{\max} - \beta (x^2 + \frac{1}{\|g\|^2})\|h_b\|^2}{\beta (a - a_2 x^2) + \sigma_D^2} + \frac{P_{\max} - \beta (x^2 + \frac{1}{\|g\|^2})\|h_e\|^2}{\beta + \sigma_E^2}
\]
(36)

ii) we prove for given $t$, the optimal $\beta = f(t)$ is a increasing function of $t$ if $|h_b|/|h_e| > \sqrt{2}\|g^H h_b\|/\|g\|^2$. On the other hand, if $|h_b|/|h_e| < \sqrt{2}\|g^H h_b\|/\|g\|^2$, $\beta = f(t)$ is a increasing function in the range of $t_L < t < t_U$; iii) using the results of the first two parts, we prove that if there are some local maximum points at $t < t_L$, the corresponding secrecy rate cannot be higher than 1 bits/s/Hz, so none of them can be the global maximum point. Moreover, there exists at most one point meanwhile satisfies $t = f(\beta)$ and $\beta = f(t)$ when $t_L < t < t_U$, which must be the global maximum point. If there is no local maximum point in the range $t_L < t < t_U$, the global maximum point must be achieved at the boundary $t = t_L$ or $t = t_U$.

B.1 Proof of the first step

Define
\[
x := \sqrt{t - \frac{1}{\|g\|^2}},
\]
(37)
then $x$ satisfies
\[
0 < x \leq \frac{\|g^H h_b\|}{\|g\|} \sqrt{\|g\|^2 |h_b| - \|g^H h_b\|^2} = \frac{a_1}{a_2}.
\]
(38)

Since $\log(\cdot)$ is monotonically increasing, we can only consider the objective function $f(x)$ and denote $t = f(\beta)$ as the optimal $t$ for given value $\beta$. To prove $f(x)$ is quasi-concave for $0 < x < a_1/a_2$, we assume $a_1 \neq 0$ (when $a_1 = 0$, $t = 1/\|g\|^2$ is the only feasible point in the range of $t$; so it is the optimal $t$) and prove that: i) $\tilde{f}(0) > 0$; ii) $f(a_1/a_2) < 0$; iii) there is only one solution of $f'(x) = 0$ in $(0, a_1/a_2)$; so it is the optimal point.

Note that the function $f(x)$ can be written as (39), presented at the top of the next page. For simplicity, denote
\[
q_1 := \beta + \sigma_E^2,
q_2 := \frac{P_{\max}}{\text{tot}} - \beta,
q_3 := \beta |h_b|^2,
q_4 := \frac{|h_e|^2}{|h_b|^2},
q_5 := a_1 \sqrt{\beta},
q_6 := a_2 \sqrt{\beta},
q_7 := \sigma_D^2.
\]
(40) (41) (42) (43) (44) (45) (46)
\[ f(x) = (b + \sigma_E^2) \left\{ \frac{1}{b + \sigma_E^2 + P_{\text{tot}}\max |h_D|^2 - b(x^2 + \frac{1}{|h_E|^2})|h_D|^2} \right\} \]

\[ = (b + \sigma_E^2) \frac{1}{b + \sigma_E^2 + P_{\text{tot}}\max |h_E|^2 - b(x^2 + \frac{1}{|h_E|^2})|h_E|^2} \]

\[ \frac{1}{q_1} f(x) = \frac{1}{q_1 \sigma_E + q_3 x^2} + \frac{q_4}{q_1} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

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\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]

\[ \frac{1}{q_1} f(x) = \frac{2q_3 x}{(q_1 + q_2 q_3 - q_3 x^2)^2} + \frac{2(q_5 - q_6 x) q_4 q_1}{(q_1 + q_2 q_3 - q_3 x^2)^2 + q_7^2} \]
Note that the right term is always positive, and when $P_{\text{tot}}^\text{max}(1 - 2|h_E|^2) \leq 2(1 - t|h_E|^2)/\beta t$, the left term is negative; so the above inequality holds. If $P_{\text{tot}}^\text{max}(1 - 2|h_E|^2) > 2(1 - t|h_E|^2)/\beta t$, we can prove (58) using (57) as follows:
\begin{align*}
&\frac{(a_1 - a_2)x_2q_4}{x} = \\
&\frac{\beta|x_4 - (a_1 - a_2)x_2|^2 - q_7}{P_{\text{tot}}^\text{max} - \beta t} = \frac{\beta(a_1 - a_2)x_2^2 + q_7}{\beta + |h_E|^2(P_{\text{tot}}^\text{max} - \beta t)} \\
&= \frac{(a_1 - a_2)x_2^2 + q_7}{1 - t|h_E|^2 + \frac{P_{\text{tot}}^\text{max}|h_E|^2}{\beta}} \\
&= \frac{(a_1 - a_2)x_2^2 + q_7}{1 - t|h_E|^2 - \frac{P_{\text{tot}}^\text{max}|h_E|^2}{\beta}} < \frac{(a_1 - a_2)x_2^2 + q_7}{1 - t|h_E|^2 - \frac{P_{\text{tot}}^\text{max}|h_E|^2}{\beta}} < \frac{2(a_1 - a_2)x_2^2 + \beta q_4 - (a_1 - a_2)x_2^2}{1 - 2t|h_E|^2 - \frac{P_{\text{tot}}^\text{max}|h_E|^2}{\beta}} \\
&= \frac{2(a_1 - a_2)x_2^2q_4 - (a_1 - a_2)x_2^2|\beta + q_7q_4 - (a_1 - a_2)x_2^2|}{2(1 - t|h_E|^2)/\beta t + P_{\text{tot}}^\text{max}(1 - 2t|h_E|^2)} \\
\end{align*}

Thus, for given $\beta$, the optimal $t = f(\beta)$ is a decreasing function of $\beta$.

B.2 Proof of the second step

When $P_{\text{tot}}^\text{max} \to \infty$, we have
\begin{align*}
B_1 &= P_{\text{tot}}^\text{max}|h_D|^2, \\
B_2 &\geq (a_1 - a_2)x_2^2P_{\text{tot}}^\text{max}|h_E|^2, \\
C_2 &\geq P_{\text{tot}}^\text{max}|h_E|^2|\sigma_D|^2.
\end{align*}

Thus, we have
\begin{align*}
A &= A_1B_2 - A_2B_1 \\
&\simeq P_{\text{tot}}^\text{max}|h_E|^2(a_1 - a_2)x_2^2 - |h_D|^2(a_1 - a_2)x_2^2, \\
B &= 2A_1C_2 = 2(a_1 - a_2)x_2^2 - t|h_D|^2P_{\text{tot}}^\text{max}|h_E|^2|\sigma_D|^2, \\
C &= B_1C_2 = P_{\text{tot}}^\text{max}|h_D|^2|h_E|^2|\sigma_D|^2.
\end{align*}

Note that $A < 0$; so the optimal $\beta$ for given $t$ is
\begin{align*}
f(t) &= B + \sqrt{B^2 + 4|A|C} \\
&\simeq \sqrt{P_{\text{tot}}^\text{max}|h_D|^2|h_E|^2|\sigma_D|^2} \\
&\simeq \sqrt{|h_D|^2 - (a_1 - a_2)x_2^2} (a_1 - a_2)x_2^2,
\end{align*}

which is an increasing function of $t$ when the expression $|h_D|^2/h_E|^2 - (a_1 - a_2)^2(a_1 - a_2) $ is a decreasing function of $x$. This holds when
\begin{equation}
\frac{|h_D|^2}{|h_E|^2} > 2(a_1 - a_2x)^2.
\end{equation}

Note that
\begin{equation}
2(a_1 - a_2x)^2 \leq 2a_1^2 = 2\frac{g[h_0]h_0}{|g|^2}.
\end{equation}

Thus, a sufficient condition is
\begin{equation}
\frac{|h_D|^2}{|h_E|^2} > 2\frac{g[h_0]h_0}{|g|^2}.
\end{equation}

or
\begin{equation}
\frac{|h_D|^2}{|h_E|^2} > \frac{\sqrt{2}g[h_0]h_0}{|g|^2}.
\end{equation}

When there exists $x$ satisfying $|h_D|^2/|h_E|^2 < 2(a_1 - a_2x)^2$, the function $f(t)$ is increasing with $t$ when
\begin{equation}
\frac{a_1}{a_2} - \frac{|h_D|}{\sqrt{2a_2|h_E|}} \leq x \leq \frac{a_1}{a_2}.
\end{equation}

B.3 Proof of the third step

Note that the global maximum point must be the one when $f(t)$ is increasing, i.e., when $a_1/a_2 - |h_D|/\sqrt{2a_2|h_E|} \leq x \leq a_1/a_2$. This is because when $|h_D|^2/|h_E|^2 < 2(a_1 - a_2x)^2$, the achievable secrecy rate for $P_{\text{tot}}^\text{max} \to \infty$ asymptotically equals to
\begin{equation}
1 + \frac{P_{\text{tot}}^\text{max}|h_D|^2}{1 + \frac{P_{\text{tot}}^\text{max}|h_D|^2}{\beta}} < 1 + \frac{P_{\text{tot}}^\text{max}|h_D|^2}{\beta} < 2,
\end{equation}

which means the achievable secrecy rate cannot be more than 1 bits/s/Hz. However, under the positive secrecy rate assumption, the maximum secrecy rate should approach $\infty$ when $P_{\text{tot}}^\text{max} \to \infty$. Thus, the global maximum point must be the one in
\begin{equation}
\frac{a_1}{a_2} - \frac{|h_D|}{\sqrt{2a_2|h_E|}} \leq x \leq \frac{a_1}{a_2}.
\end{equation}

For any local maximum point $(\beta', t')$, we must have both $\beta' = f(t')$ and $t' = f(\beta')$. However, according to the results above, $f(t)$ is an increasing function of $t$, whereas $f(\beta)$ is a decreasing function of $\beta$. Thus, there is at most one local maximum point, which is the global maximum point. Thus, the global maximum point of the one-dimensional searching function is the local maximum point that has the largest $t$. If there is no local maximum point in
\begin{equation}
\frac{a_1}{a_2} - \frac{|h_D|}{\sqrt{2a_2|h_E|}} \leq x \leq \frac{a_1}{a_2},
\end{equation}

...
the global maximum point must be achieved at the boundary
\[ x = \frac{a_1}{a_2} = \frac{|h_D|}{\sqrt{2a_1^2|h_E^2|}} \]  \hspace{1cm} (75)

or
\[ x = \frac{a_1}{a_2}. \]  \hspace{1cm} (76)

REFERENCES

Dong In Kim received the Ph.D. degree in Electrical Engineering from the University of Southern California, Los Angeles, CA, USA, in 1990. He was a tenured Professor with the School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada. Since 2007, he has been with Sungkyunkwan University (SKKU), Suwon, Korea, where he is currently a Professor with the College of Information and Communication Engineering. Dr. Kim has served as an Editor and a Founding Area Editor of Cross-Layer Design and Optimization for the IEEE Transactions on Wireless Communications from 2002 to 2011. From 2008 to 2011, he served as the Co-Editor-in-Chief for the IEEE/KICS Journal of Communications and Networks (JCN). He has served as the Founding Editor-in-Chief for the IEEE Wireless Communications Letters from 2012 to 2015. From 2001 to 2014, he served as an Editor of Spread Spectrum Transmission and Access for the IEEE Transactions on Communications, and then serving as an Editor-at-Large in Wireless Communication. He is a first recipient of the NRF of Korea Engineering Research Center (ERC) in Wireless Communications for Energy Harvesting Wireless Communications (2014-2021).

Seokki Kim received his B.S. and M.S. degree in Science in Electrical and Electronics Engineering, Chung-Ang University, Seoul, Korea in 2007 and 2009. He is currently a Senior Researcher at the Electronics and Telecommunications Research Institute (ETRI). His current research interests are in the areas of advanced MIMO and low-latency system.

Kwangae Lim received his B.S., M.S., and Ph.D. from the Department of Electronics Engineering at Inha University, Incheon, Rep. of Korea in 1992, 1994, and 1999, respectively. In Mar. 1999, he joined ETRI, Daejeon, Rep. of Korea. Since 1999, he has worked on the standardization of mobile and satellite communications. His research interests are in mobile and wireless communications.