Power Efficient MISO Beamforming for Secure Layered Transmission

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Abstract—This paper studies secure layered video transmission in a multiuser multiple-input single-output (MISO) beamforming downlink communication system. The power allocation algorithm design is formulated as a non-convex optimization problem for minimizing the total transmit power while guaranteeing a minimum received signal-to-interference-plus-noise ratio (SINR) at the desired receiver. In particular, the proposed problem formulation takes into account the self-protecting architecture of layered transmission and artificial noise generation to prevent potential information eavesdropping. A semi-definite programming (SDP) relaxation based power allocation algorithm is proposed to obtain an upper bound solution. A sufficient condition for the global optimal solution is examined to reveal the tightness of the upper bound solution. Subsequently, two suboptimal power allocation schemes with low computational complexity are proposed for enabling secure layered video transmission. Simulation results demonstrate significant transmit power savings achieved by the proposed algorithms and layered transmission compared to the baseline schemes.

I. INTRODUCTION

The explosive growth in high data rate real time multimedia services in wireless communication networks has led to a heavy demand for energy and bandwidth. Multiple-input multiple-output (MIMO) technology has emerged as one of the most prominent solutions in fulfilling this challenging demand, due to its inherent extra degrees of freedom for resource allocation [1]–[5]. However, the hardware complexity of multiple antenna receivers limits the deployment of such technology in practice, especially for portable devices. As an alternative, multiuser MIMO has been proposed where a transmitter equipped with multiple antennas services multiple single-antenna users.

Furthermore, for video streaming, layered transmission has been implemented in some existing video standards such as H.264/Moving Picture Experts Group (MPEG)-4 scalable video coding (SVC) [6]–[7]. Specifically, a video signal is encoded into a hierarchy of multiple layers with unequal importance, namely one base layer and several enhancement layers. The base layer contains the essential information of the video with minimum video quality. The information embedded in each enhancement layer is used to successively refine the description of the pervious layers. The structure of layered transmission facilitates the implementation of unequal error protection. In fact, the transmitter can achieve a better resource utilization by allocating different amount of powers to different information layers according to their importance to the video quality.

Also, since the broadcast nature of wireless communication channels makes them vulnerable to eavesdropping, there is an emerging need for guaranteeing secure wireless video communication. For instance, misbehaving legitimate users of a communication system may attempt to use the high definition video service without paying by overhearing the video signal. Although cryptographic encryption algorithms are commonly implemented in the application layer for providing secure communication, the associated security key distribution and management can be problematic or infeasible in wireless networks. As a result, physical (PHY) layer security [8]–[12] has been proposed as a complement to the traditional methods for improving wireless transmission security. The merit of PHY layer security lies in the guaranteed perfect secrecy of communication by exploiting the physical characteristics of the wireless communication channel. In his seminal work on PHY layer security [8], Wyner showed that a non-zero secrecy capacity, defined as the maximum transmission rate at which an eavesdropper is unable to extract any information from the received signal, can be achieved if the desired receiver enjoys better channel conditions than the eavesdropper. A considerable amount of research [9]–[11] has been devoted to exploiting multiple antennas for providing communication secrecy. In [9], transmit beamforming was proposed to maximize the secrecy capacity in a multiple-input single-output (MISO) communication system. In [10] and [11], artificial noise generation was proposed for multiple antenna communication systems to cripple the interception capabilities of eavesdroppers. In particular, [10] and [11] focused on the maximization of the ergodic secrecy capacity and the outage secrecy capacity for different system settings, respectively. In [12], a power allocation algorithm was proposed to maximize the system energy efficiency while providing delay-constrained secure communication service. However, the results of [9]–[12] are based on the assumption of single layer transmission and may not be applicable to multimedia video transmission. Besides, the layered information architecture of video signals has a self-protecting structure which provides a certain robustness against eavesdropping. However, exploiting the layered transmission for facilitating PHY layer security in video communication has not been considered in the literature [3]–[7].

Motivated by the aforementioned observations, we formulate the power allocation algorithm design for secure layered video transmission in multiuser MISO beamforming systems as a non-convex optimization problem. We propose a semi-definite programming (SDP) approach for designing a power allocation algorithm which obtains an upper bound solution for the considered problem. Besides, we use the upper bound solution as a building block for the design of two suboptimal beamforming schemes with low computational complexity and near optimal performance.

II. SYSTEM MODEL

In this section, we present the adopted models for multiuser downlink communication and layered video encoding.
A. Channel Model

A downlink communication system is considered which consists of a transmitter and $K$ receivers. The transmitter is equipped with $N_T$ transmit antennas while the receivers are single antenna devices, cf. Figure 1. The transmitter conveys video information to a given video service subscriber (receiver) while the remaining $K-1$ receivers are idle. However, the transmitted video signals may be overheard by the idle receivers. In practice, it is possible that the idle receivers are malicious and eavesdrop the video information of the other subscribers, e.g., a paid multimedia video service, by overhearing the video signal transmitted by the transmitter. In other words, the idle receivers are potential eavesdroppers which should be taken into account when delivering secure video information to the desired user. We focus on a frequency flat slow time varying fading channel when delivering secure video information to the desired user. The remaining $K-1$ idle receivers are given power allocation algorithm design as an optimization problem. We assume without loss of generality that $E\{|s_i|^2\} = 1, \forall i$, and superposition coding is used to superimpose the $L$ layers of video information, where $E\{|\cdot|\}$ represents statistical expectation. $\mathbf{v} \in \mathbb{C}^{N_T \times 1}$ is the artificial noise vector generated by the transmitter to combat the potential eavesdroppers. In particular, $\mathbf{v}$ is modeled as a circularly symmetric complex Gaussian random vector represented as

$$\mathbf{v} \sim \mathcal{CN}(0, \mathbf{V}),$$

where $\mathbf{V} \in \mathbb{H}^{N_T \times N_T}, \mathbf{V} \succeq 0$ denotes the covariance matrix of the artificial noise. Here, $\mathbb{H}^N$ represents the set of all $N$-by-$N$ complex Hermitian matrices and $\mathbf{V} \succeq 0$ indicates that $\mathbf{V}$ is a positive semi-definite Hermitian matrix.

B. Video Encoding and Artificial Noise Generation

We assume that the video source is encoded into $L$ layers via scalable video coding. Without loss of generality, the video information can be represented as $\mathbf{S} = [s_1, s_2, \ldots, s_L], s_i \in \mathbb{C}, i \in \{1, \ldots, L\}$, where $s_i$ denotes the video information of layer $i$. These $L$ layers consists of one base layer, i.e., $s_1$, which can be decoded independently without utilizing the information from other layers. Specifically, the base layer data includes the most essential information of the video and can guarantee a minimum quality of service (QoS). The remaining $L-1$ layers, i.e., $s_2, \ldots, s_L$, are enhancement layers which can be used to successively refine the previous layers. In other words, the enhancement layers cannot be decoded independently; if the decoding of a layer fails, the information embedded in the following enhancement layers is lost since they are no longer decodable. In this paper, we consider a fixed rate video source encoder and the data rate of each layer is fixed. This implementation has been supported by some standards such as H.264/MPEG-4 SVC [6], [7].

On the other hand, for guaranteeing secure video transmission to the desired receiver, an artificial noise signal is transmitted along with the information signal to degrade the channels between the transmitter and the idle receivers (potential eavesdroppers). The transmitter constructs a transmit symbol vector $\mathbf{x}$ as

$$\mathbf{x} = \sum_{i=1}^{L} \mathbf{w}_i s_i + \mathbf{v}, \quad \text{desired L-layer video signals}$$

where $\mathbf{w}_i \in \mathbb{C}^{N_T \times 1}$ is the beamforming vector for the video information signal in layer $i$ dedicated to the desired receiver. We define the following variables for the sake of notational simplicity: $\mathbf{H} = \mathbf{h}^H$ and $\mathbf{G}_k = \mathbf{g}_k \mathbf{g}_k^H, k \in \{1, \ldots, K-1\}$.

A. Channel Capacity

With successive interference cancellation$^4$ the receivers first decode and cancel the lower layers before decoding the higher layers. Besides, the yet to be decoded higher layers are treated as Gaussian noise$^3$. Assuming perfect channel state information (CSI) at the receiver, the capacity (bit/s/Hz) between

$^1$We assume that the signal processing and thermal noise characteristics of all receivers are identical due to a similar hardware architecture.

$^2$The corner points of the dominant face of the multiple-access capacity region can be achieved by superposition coding and a successive interference cancellation receiver with low computational complexity [4].

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**Fig. 1.** Layered transmission system model for $K = 3$ mobile video receivers.
the transmitter and the desired mobile video receiver of layer \( i \) is given by
\[
C_i = \log_2 \left( 1 + \Gamma_i \right) \quad \text{and} \quad \Gamma_i = \frac{|h^Hw_i|^2}{\sum_{j=i+1}^{L}|h^Hw_j|^2 + \text{Tr}(HV) + \sigma_n^2},
\]
(5)
where \( \Gamma_i \) is the received signal-to-interference-plus-noise ratio (SINR) of layer \( i \) at the desired receiver. \( \text{Tr}(\cdot) \) and \(|\cdot|\) denote the trace of a matrix and the absolute value of a complex scalar, respectively. On the other hand, the channel capacity between the transmitter and idle receiver (potential eavesdropper) \( k \) of layer \( i \) is given by
\[
C_{E_i,k} = \log_2 \left( 1 + \Gamma_{E_i,k} \right) \quad \text{and} \quad \Gamma_{E_i,k} = \frac{|g^Hw_i|^2}{\sum_{j=i+1}^{L}|g^Hw_j|^2 + \text{Tr}(GkV) + \sigma_n^2},
\]
(6)
where \( \Gamma_{E_i,k} \) is the received SINR at idle receiver \( k \). It can be observed from (6) that layered transmission has a self-protecting structure. Specifically, the higher layer information via the first term in the denominator of (6) has the same effect as the artificial noise signal \( v \) in protecting the important information encoded in the lower layers of the video signal. It is expected that by carefully optimizing the beamforming vectors of the higher information layers, a certain level of communication security can be achieved in the low layers. In the literature, one of the performance metrics for quantifying the notion of communication security in the PHY layer is the secrecy capacity. Specifically, the maximum secrecy capacity between the transmitter and the desired receiver on layer \( i \) is given by
\[
C_{\text{sec}_i} = \left[ C_i - \max_{k \in \{1,...,K-1\}} C_{E_i,k} \right]^+, \quad \text{(7)}
\]
where \([a]^+ = \max\{0,a\}\). \( C_{\text{sec}_i} \) quantifies the maximum achievable data rate at which a transmitter can reliably send a secret information on layer \( i \) to the desired receiver such that the eavesdropper is unable to decode the received signal [8].

**B. Optimization Problem Formulation**

The optimal beamforming vector of video information layer \( i \), \( w_i^* \), and the optimal artificial noise covariance matrix, \( V^* \), for minimizing the total radiated power can be obtained by solving

minimize \( \sum_{i=1}^{L} ||w_i||^2 + \text{Tr}(V) \)

s.t. C1: \( \sum_{j=i+1}^{L} |h^Hw_j|^2 + \text{Tr}(HV) + \sigma_n^2 \geq \Gamma_{\text{req}_i}, \forall i \),
C2: \( \sum_{j=1}^{L} |g^Hw_j|^2 + \text{Tr}(GkV) + \sigma_n^2 \leq \Gamma_{\text{tol}_k}, \forall k \),
C3: \( \text{Tr} \left( \left( \Psi \left| V \right| + \sum_{i=1}^{L} w_i \right) \right) \leq P_{\text{max}_n}, \forall n \),
C4: \( V \succeq 0 \), C5: \( w_i \succeq 0, \forall i \), C6: \( \text{Rank}(W_i) = 1, \forall i \),

(8)
where \( ||\cdot|| \) in the objective function denotes the Euclidean vector norm. \( \Gamma_{\text{req}_i} \) in C1 is the minimum required SINR for decoding layer \( i \) at the desired receiver. \( \Gamma_{\text{tol}_k} \) in C2 denotes the maximum tolerable SINR at idle receiver (potential eavesdropper) \( k \) for decoding the first layer. We note that since layered coding is employed for encoding the video information, it is sufficient to protect the first layer of the video for ensuring secure video delivery. In practice, the transmitter sets a sufficiently small value of \( \Gamma_{\text{tol}_k} \) such that \( \Gamma_{\text{req}_i} \gg \Gamma_{\text{tol}_k} \) holds which provides an adequate protection for the first layer. We note that in this paper, we do not directly maximize the secrecy capacity of video delivery. Nevertheless, the proposed problem formulation in (8) is able to guarantee a minimum secrecy capacity for layer 1, i.e., \( C_{\text{sec}_1} \geq \log_2(1 + \Gamma_{\text{req}_1}) - \log_2(1 + \max_{k \in \{1,...,K-1\}} \Gamma_{\text{tol}_k}) \). In C3, \( {}_{(a,b)} \in V \) extracts the \((a,b)\)-th element of the input matrix. Specifically, C3 limits the maximum transmit power of antenna \( n \) to \( P_{\text{max}_n} \). C4 and \( V \in \mathbb{H}^{N_T} \) are imposed such that \( V \) is a positive semi-definite matrix to satisfy the physical requirements on covariance matrices.

**IV. SOLUTION OF THE OPTIMIZATION PROBLEM**

The optimization problem in (8) is non-convex due to constraints C1 and C2. In some cases, an exhaustive search is required to obtain the solution of non-convex problems. In order to strike a balance between the optimality of the solution and the computational complexity of the considered problem, we first recast the problem as a convex optimization problem by SDP relaxation and obtain a performance upper bound. Then, we propose two computational efficient suboptimal power allocation schemes.

**A. Semi-definite Programming Relaxation**

For facilitating the SDP relaxation, we define \( W_i = w_i w_i^H \) and rewrite problem (8) in terms of \( W_i \) as

minimize \( \sum_{i=1}^{L} \text{Tr}(W_i) + \text{Tr}(V) \)

s.t. C1: \( \sum_{j=i+1}^{L} \text{Tr}(H W_j) + \text{Tr}(HV) + \sigma_n^2 \geq \Gamma_{\text{req}_i}, \forall i \),
C2: \( \sum_{j=1}^{L} \text{Tr}(G_k W_j) + \text{Tr}(G_k V) + \sigma_n^2 \leq \Gamma_{\text{tol}_k}, \forall k \),
C3: \( \text{Tr} \left( \left( \Psi \left| V \right| + \sum_{i=1}^{L} W_i \right) \right) \leq P_{\text{max}_n}, \forall n \),
C4: \( V \succeq 0 \), C5: \( W_i \succeq 0, \forall i \), C6: \( \text{Rank}(W_i) = 1, \forall i \),

(9)
where \( \text{Rank}(-) \) in C6 denotes the rank of the input matrix. \( W_i \succeq 0, \forall i \in \{1,...,L\} \), \( W_i \in \mathbb{H}^{N_T} \), \( \forall i \), and \( \text{Rank}(W_i) = 1, \forall i \), in (9) are imposed to guarantee that \( W_i = w_i w_i^H \). We note that in constraint C3, \( \Psi_n = e_n e_n^H \) and \( e_n \) is the \( n \)-th unit vector of length \( N_T \) and \( [e_n]_{i+1} = 0, \forall i \neq n \). The transformed problem above is still non-convex due to the rank constraint in C6. However, if we relax this constraint (remove it from the problem formulation), the transformed problem becomes a convex SDP and can be solved efficiently by off-the-shelf numerical solvers such as SeDuMi [14]. It is known that if the obtained solution \( W_i \) for the relaxed problem admits a rank-one matrix \( V_i \), then it is the optimal solution of the original problem in (9). Yet, the proposed constraint relaxation may not be tight, i.e., a rank-one solution may not exist, and, in this case, the result of the relaxed problem serves as a performance upper bound for the original problem, since a larger feasible solution set is considered in the relaxed problem. In the following, we provide a sufficient condition for \( \text{Rank}(W_i) = 1, \forall i \), of the relaxed problem and exploit it for the design of two suboptimal power allocation schemes.
In this subsection, the tightness of the proposed SDP relaxation is investigated by studying the Karush-Kuhn-Tucker (KKT) conditions and the dual problem of the relaxed version of problem (9). To this end, we first need the Lagrangian function of (9) which is given by

\[
\mathcal{L}(\mathbf{W}_i, \mathbf{V}, \lambda, \beta, \delta, \mathbf{Y}_i, \mathbf{Z}) = \sum_{i=1}^{L} \text{Tr}(\mathbf{W}_i) + \text{Tr}(\mathbf{V}) - \sum_{i=1}^{L} \text{Tr}(\mathbf{Y}_i^\top \mathbf{W}_i) - \text{Tr}(\mathbf{Z}\mathbf{V}) + \sum_{i=1}^{L} \lambda_i \left( \text{Tr}(\mathbf{H}\mathbf{W}_i) - \frac{1}{\Gamma_{\text{eq}_i}} + \frac{1}{\Gamma_{\text{tol}_i}} \sum_{j=2}^{L} \text{Tr}(\mathbf{G}_k \mathbf{W}_j) - \text{Tr}(\mathbf{G}_k \mathbf{V}) - \sigma_n^2 \right) + \sum_{k=1}^{K-1} \beta_k \left( \frac{\text{Tr}(\mathbf{G}_k \mathbf{W}_1)}{\Gamma_{\text{tol}_k}} - \sum_{j=2}^{L} \text{Tr}(\mathbf{G}_k \mathbf{W}_j) - \text{Tr}(\mathbf{G}_k \mathbf{V}) - \sigma_n^2 \right) + \sum_{n=1}^{N_T} \delta_n \left( \text{Tr}(\Psi_n (\mathbf{V} + \sum_{i=1}^{L} \mathbf{W}_i)) - P_{\text{max}_n} \right).
\]

(10)

Here, \( \lambda_i \geq 0, \forall i \in \{1, \ldots, L\} \), is the Lagrange multiplier vector associated with the minimum required SINR for decoding layer \( i \) for the desired receiver in C1, \( \beta_k \geq 0, \forall k \in \{1, \ldots, K-1\} \), is the vector of Lagrange multipliers for the maximum tolerable SINRs of the potential eavesdroppers in C2, \( \delta_n \geq 0, \forall n \in \{1, \ldots, N_T\} \), is the Lagrange multiplier vector for the per-antenna maximum transmit power in C3. Matrices \( \mathbf{Z}, \mathbf{Y}_i \geq 0 \) are the Lagrange multipliers for the positive semi-definite constraints on matrices \( \mathbf{V} \) and \( \mathbf{W}_i \) in C4 and C5, respectively. The dual problem for the SDP relaxed problem is given by

\[
\begin{align*}
\text{maximize} & \quad \minimize_{\mathbf{W}_i, \mathbf{V} \in \mathbb{H}^{N_T}} \mathcal{L}(\mathbf{W}_i, \mathbf{V}, \lambda, \beta, \delta, \mathbf{Y}_i, \mathbf{Z}) \\
\text{subject to} & \quad \lambda_i, \beta_k, \delta_n 
\end{align*}
\]

(11)

For facilitating the presentation in the sequel, we define \( \mathbf{W}_i^\star, \mathbf{V}^\star \) as the optimal solution of the relaxed version of problem (9). In the following proposition, we provide a sufficient condition\(^3\) for a rank-one matrix solution for the relaxed version of problem (9).

**Proposition 1:** For \( \Gamma_{\text{eq}_i} > 0, \forall i \), in the relaxed version of problem (9), \( \text{Rank}(\mathbf{W}_i^\star) = 1 \) always holds. On the other hand, \( \text{Rank}(\mathbf{W}_i^\star) = 1, \forall j \in \{2, \ldots, L\} \), holds when \( \beta_k = 0, \forall k \in \{1, \ldots, K-1\} \).

**Proof:** Please refer to the Appendix.

In the following, two suboptimal power allocation schemes are proposed based on Proposition 1.

1) **Suboptimal Power Allocation Scheme 1:** It can be concluded from Proposition 1 that when constraint C2 is independent of optimization variable \( \mathbf{W}_i \), the solution of the relaxed problem has a rank-one structure for \( \mathbf{W}_i, \forall i \). Thus, for facilitating an efficient power allocation algorithm design, we replace constraint C2 in (9) by C2 and the new optimization problem is as follows:

\[
\begin{align*}
\text{minimize} & \quad \sum_{i=1}^{L} \text{Tr}(\mathbf{W}_i) + \text{Tr}(\mathbf{V}) \\
\text{s.t.} & \quad \sum_{j=2}^{L} \text{Tr}(\mathbf{G}_k \mathbf{W}_j) - \text{Tr}(\mathbf{G}_k \mathbf{V}) - \sigma_n^2 \leq \frac{\text{Tr}(\mathbf{G}_k \mathbf{W}_1)}{\Gamma_{\text{tol}_k}}, \forall k.
\end{align*}
\]

(12)

We note that the new constraint \( C2 \) does not take into account the contribution of video signal layer \( 2, \ldots, L \) at the potential eavesdroppers. In particular,

\[
\begin{align*}
\sum_{j=2}^{L} \text{Tr}(\mathbf{G}_k \mathbf{W}_j) - \text{Tr}(\mathbf{G}_k \mathbf{V}) - \sigma_n^2 & \leq \frac{\text{Tr}(\mathbf{G}_k \mathbf{W}_1)}{\Gamma_{\text{tol}_k}}, \forall k.
\end{align*}
\]

(13)

holds and replacing constraint \( C2 \) by \( \tilde{C}2 \) results in a smaller feasible solution set for the original problem. Thus, the obtained solution of problem (12) serves as a performance lower bound for the original optimization problem (9). Besides, it is expected that the problem formulation in (12) requires a higher artificial noise power compared to (9), in order to fulfill constraint \( \tilde{C}2 \).

We note that (12) is a convex optimization problem which can be solved by numerical solvers. On the other hand, we can follow a similar approach as in the Appendix to verify that the sufficient condition in Proposition 1 is always satisfied for problem formulation (12) and thus a rank-one solution always results.

2) **Suboptimal Power Allocation Scheme 2:** A hybrid scheme is proposed as suboptimal power allocation scheme 2. It computes the solutions for suboptimal scheme 1 and the SDP relaxation in (9) in parallel and selects one of the solutions, cf. Table II. Specifically, when the upper bound solution of SDP relaxation in (9) in parallel and selects one of the solutions, then we adopt the solution given by the proposed suboptimal scheme 1. Otherwise, the proposed scheme 2 will select the solution given by SDP relaxation since the global optimal is achieved when \( \text{Rank}(\mathbf{W}_i^\star) = 1, \forall i \).

**Remark 1:** We note that suboptimal power allocation scheme 2 is based on the solution of two convex optimization problems with polynomial time computational complexity.

V. Results

In this section, we evaluate the system performance for the proposed resource allocation schemes using simulations. We consider a single cell communication system with \( K \) receivers and the corresponding simulation parameters are provided in Table III. The system performance is obtained by averaging over 10000 multipath fading realizations. Given the system parameters in Table III in all considered scenarios, the minimum
secrecy capacity of layer 1 video information is bounded below by $C_{\text{sec}} = \log_2 (1 + \Gamma_{\text{req}}) - \log_2 (1 + \Gamma_{\text{tol}}) \geq 2.179 \text{ bit/s/Hz}$. 

A. Average Total Transmit Power versus Number of Potential Eavesdroppers

Figure 2 depicts the average total transmit power versus the number of idle receivers (potential eavesdroppers), $K - 1$, for $N_T = 4$ transmit antennas and different power allocation schemes. It can be observed that the average total transmit power for the proposed schemes increases with the number of potential eavesdroppers. In fact, the transmitter has to generate a higher amount of artificial noise for providing secure communication when there are more potential eavesdroppers in the system. Besides, the two proposed suboptimal power allocation schemes perform close to the performance upper bound achieved by SDP relaxation. In particular, the performance of proposed scheme 1 serves as a lower bound (i.e., a higher average transmit power) for the two proposed schemes since a smaller feasible solution set is considered in (12). On the other hand, the performance of proposed scheme 2 coincides with the SDP relaxation upper bound. This is due to the fact that proposed scheme 2 is a hybrid scheme which exploits the possibility of achieving the global optimal solution via SDP relaxation.

For comparison, Figure 2 also contains the average total transmit power of two baseline power allocation schemes. For baseline scheme 1, we adopt single layer transmission for delivering the video signal. In particular, we solve the corresponding optimization problem with respect to $\{W_1, V\}$ subject to constraints C1–C5 via semi-definite relaxation. The minimum required SINR for decoding the single layer video information at the desired receiver for baseline scheme 1 is set to $\Gamma_{\text{req}} = 2 \sum_{i=1}^{K-1} \log_2 (1 + \Gamma_{\text{tol}}) - 1$. It is expected that the minimum required secrecy capacity in baseline scheme 1 is higher than that in multilayer transmission. In baseline scheme 2, layered video transmission is considered. Specifically, we adopt maximum ratio transmission (MRT) for delivering the video information of each layer, i.e., we apply a fixed direction for beamforming vector $w_{\text{sub}}$, where $w_{\text{sub}}$ is the eigenvector corresponding to the maximum eigenvalue of $H$. Then, we set the beamforming matrix as $u_i W = u_i w_{\text{sub}} (w_{\text{sub}})^H$, where $u_i$ is a new non-negative scalar optimization variable for adjusting the power of $u_i W$. Subsequently, we adopt the same setup as in (9) for optimizing $\{u_i, V\}$ and obtain a suboptimal rank-one solution $u_i W_i$. It can be observed that baseline 1 requires a higher total average power compared to the proposed power allocation schemes. This is attributed to the fact that single layer transmission for providing secure communication in baseline 1 does not possess the self-protecting structure that layered transmission has. As a result, a higher transmit power for artificial noise generation is required in baseline 1 to ensure secure video delivery. On the other hand, although layered transmission is adopted in baseline 2, the performance of baseline 2 is the worst among all the schemes. The reason for this is that the transmitter loses degrees of freedom in power allocation when the structure of video information beamforming matrix, $W_i, V_i$, is fixed to $w_{\text{sub}} (w_{\text{sub}})^H$ which causes a serious performance degradation.

B. Average Total Transmit Power versus Number of Antennas

Figure 3 shows the average total transmit power versus the number of transmit antennas for $K - 1 = 3$ potential eavesdroppers and different power allocation schemes. It is expected that the average total transmit power decreases with increasing number of antennas for all power allocation schemes. This is because extras degrees of freedom can be exploited for power allocation when more antennas are available at the transmitter. On the other hand, the proposed schemes provide substantial power savings compared to both baseline schemes for all considered scenarios due to the adopted layered transmission and the optimization of $\{W_i, V\}$.
VI. CONCLUSIONS

In this paper, we focused on the power allocation algorithm design for secure layered video transmission. The algorithm design was formulated as a non-convex optimization problem taking into account artificial noise generation to weaken the channel of potential eavesdroppers. Exploiting SDP, a power allocation algorithm was developed to solve the relaxed version of the non-convex optimization problem which resulted in an upper bound solution for minimization of the total transmit power. Subsequently, two suboptimal power allocation schemes were designed by exploiting the structure of the upper bound solution. Simulation results unveiled the power savings enabled by layered transmission and the optimization of beamforming and artificial noise generation for facilitating secure video transmission. In our future work, we will consider the impact of imperfect channel state information on secure layered transmission systems.

APPENDIX - PROOF OF PROPOSITION 1

It can be verified that the relaxed version of problem (9) is jointly convex with respect to the optimization variables and satisfies Slater’s constraint qualification. Thus, the KKT conditions provide the necessary and sufficient conditions for the optimal solution of the relaxed problem. In the following, we study the rank of $W_i$ by focusing on the corresponding KKT conditions:

$$
Y_i^* \succeq 0, \quad \beta_i^*, \delta_n^*, \lambda_i^* \geq 0, \forall i, n, k,
$$

$$
Y_i^* W_i^* = 0, \forall i,
$$

$$
Y_i^* = Y + \sum_{k=1}^{K-1} \frac{G_k}{\Gamma_{tol_k}} \beta_k^* - \frac{\lambda_i^*}{\Gamma_{req_i}} H_i,
$$

$$
Y_i^* = Y - \sum_{k=1}^{K} G_k \beta_k^* + \left( \sum_{j<i} \lambda_j^* - \frac{\lambda_i^*}{\Gamma_{req_i}} \right) H_i, \quad i > 1,
$$

where $Y = I_{N_t} + \sum_{n=1}^{N_T} \delta_n^* \Psi_n$ and $Y_i^*, \beta_k^*, \delta_n^*, \lambda_i^*$ are the optimal Lagrange multipliers for (11). Equation (15) is the complementary slackness condition.

The proof is divided into two parts. In the first part, we prove that $\text{Rank}(W_i^*) = 1$. To this end, we post-multiply both sides of (16) by $W_i^*$ and after some manipulations we obtain for

$$
\left( Y + \sum_{k=1}^{K-1} \frac{G_k}{\Gamma_{tol_k}} \beta_k^* \right) W_i^* = \frac{\lambda_i^*}{\Gamma_{req_i}} H W_i^*.
$$

Since $I_{N_T} + \sum_{k=1}^{K-1} \frac{G_k}{\Gamma_{tol_k}} \beta_k^*$ is a positive definite matrix, the following equality holds:

$$
\text{Rank}(W_i^*) = \text{Rank}\left( \left( Y + \sum_{k=1}^{K-1} \frac{G_k}{\Gamma_{tol_k}} \beta_k^* \right) W_i^* \right)
$$

$$
= \text{Rank}\left( \frac{\lambda_i^*}{\Gamma_{req_i}} H W_i^* \right)
$$

$$
= \min \{ \text{Rank} \left( \frac{\lambda_i^*}{\Gamma_{req_i}} H, \text{Rank} \left( W_i^* \right) \right) \}.
$$

We note that $\text{Rank}(H) = 1$ and $\text{Rank}(\frac{\lambda_i^*}{\Gamma_{req_i}} H)$ is either zero or one. On the other hand, $W_i^* \neq 0$ is required to satisfy the minimum SINR requirement of the desired receiver in C1 of (9) when $\Gamma_{req} > 0$. As a result, we need to prove $\lambda_i^* > 0$ in order to show $\text{Rank}(W_i^*) = 1$. In other words, constraint C1 has to be satisfied with equality for $i = 1$. In the following, we prove by contradiction that constraint C1 is indeed satisfied with equality, i.e.,

$$
\begin{aligned}
\text{tr}(H W_i^*) &\quad \sum_{j=i+1}^{L} \text{tr}(H W_j^*) + \text{tr}(H V) + \sigma^2 \\
&\quad = \Gamma_{req}, \forall i.
\end{aligned}
$$

Without loss of generality, we denote $(W_i^*, V^*)$ as the optimal solution. Suppose that for layer $a \in \{1, \ldots, L\}$, C1 is satisfied with strict inequality, i.e., “>”, at the optimal solution. Then, we construct a new feasible solution $W_i^* = V_i^*$ except in layer $a$: $W_a = \alpha W_i^*$, $0 < \alpha < 1$ is imposed in the new solution such that the considered constraint is satisfied with equality. It can be verified that the new solution $(W_i^*, V^*)$ achieves a lower objective value in (9) than $(W_i^*, V^*)$. Thus, $(W_i^*, V^*)$ cannot be the optimal solution. As a result, $\lambda_i^* > 0, \forall i$, holds for the optimal solution. By combining (19) and $\lambda_i^* > 0, \forall i$, we obtain for $\alpha = 0, \forall k$,

$$
\left( Y - \sum_{k=1}^{K-1} G_k \beta_k^* \right) W_i^* = \lambda_i^* H W_i^*.
$$

It can be seen that (21) has a similar structure as (18). Thus, we can use a similar approach as in the first part of the proof to show that $\text{Rank}(W_j^*) = 1, j \in \{2, \ldots, L\}$ if $\beta_k^* = 0, \forall k$.

REFERENCES

[1] D. Tse and P. Viswanath, Fundamentals of Wireless Communication, 1st ed. Cambridge University Press, 2005.
[2] D. W. K. Ng, E. Lo, and R. Schober, “Energy-Efficient Resource Allocation in OFDMA Systems with Large Numbers of Base Station Antennas,” IEEE Trans. Wireless Commun., vol. 11, pp. 3292–3304, Sep. 2012.
[3] K. Bhattachad, K. Narayanan, and G. Caire, “On the Distortion SNR Exponent of Some Layered Transmission Schemes,” IEEE Trans. Inf. Theory, vol. 54, pp. 2943–2958, Jun. 2008.
[4] D. Song and C. W. Chen, “Scalable H.264/AVC Video Transmission Over MIMO Wireless Systems With Adaptive Channel Selection Based on Partial Channel Information,” IEEE Trans. Circuits Syst. Video Technol., vol. 17, pp. 1218–1226, Sep. 2007.
[5] I. Xuan, S. H. Lee, and S. Vishwanath, “Broadcast Strategies for MISO and Multiple Access Channels,” in Proc. IEEE Personal, Indoor and Mobile Radio Commun. Sympos., 2007, pp. 1–4.
[6] Y. Fallah, H. Mansour, S. Khan, P. Nasiopoulos, and H. Alnuweiri, “A Link Adaptation Scheme for Efficient Transmission of H.264 Scalable Video Over Multirate WLANs,” IEEE Trans. Circuits Syst. Video Technol., vol. 18, pp. 875–887, Jun. 2008.
[7] B. Barmada, M. Ghandi, E. Jones, and M. Ghanbari, “Prioritized Transmission of Data Partitioned H.264 Video with Hierarchical QAM,” IEEE Trans. Circuits Syst. Video Technol., vol. 17, pp. 577–580, Jul. 2005.
[8] A. D. Wyner, “The Wire-Tap Channel,” Tech. Rep., Oct 1975.
[9] Q. Li and W.-K. Ma, “Multicast Secrecy Rate Maximization for MISO Channels with Multiple Multi-Antenna Eavesdroppers,” in Proc. IEEE Intern. Conf. Wireless Commun., pp. 2662–2671, May 2009.
[10] D. W. K. Ng, E. Lo, and R. Schober, “Secure Resource Allocation and Scheduling for OFDMA Decode-and-Forward Relay Networks,” IEEE Trans. Wireless Commun., vol. 10, pp. 3528–3540, Aug. 2011.
[11] S. Goel and R. Negi, “Guaranteeing Secrecy using Artificial Noise,” IEEE Trans. Circuits Syst. Video Technol., vol. 17, pp. 3292–3304, Sep. 2012.
[12] A. Iyer, C. Rosenberg, and A. Karnik, “What is the Right Model for Security in Multi-Antenna Downlink Networks with QoS Guarantee,” IEEE Trans. Wireless Commun., vol. 11, pp. 3292–3304, Sep. 2012.
[13] J. Xuan, S. H. Lee, and S. Vishwanath, “Broadcast Strategies for MISO and Multiple Access Channels,” in Proc. IEEE Personal, Indoor and Mobile Radio Commun. Sympos., 2007, pp. 1–4.
[14] Y. Fallah, H. Mansour, S. Khan, P. Nasiopoulos, and H. Alnuweiri, “A Link Adaptation Scheme for Efficient Transmission of H.264 Scalable Video Over Multirate WLANs,” IEEE Trans. Circuits Syst. Video Technol., vol. 18, pp. 875–887, Jun. 2008.
[15] B. Barmada, M. Ghandi, E. Jones, and M. Ghanbari, “Prioritized Transmission of Data Partitioned H.264 Video with Hierarchical QAM,” IEEE Signal Process. Lett., vol. 12, pp. 577–580, Jul. 2005.
[16] A. D. Wyner, “The Wire-Tap Channel,” Tech. Rep., Oct 1975.
[17] Q. Li and W.-K. Ma, “Multicast Secrecy Rate Maximization for MISO Channels with Multiple Multi-Antenna Eavesdroppers,” in Proc. IEEE Intern. Conf. Wireless Commun., pp. 2662–2671, May 2009.
[18] D. W. K. Ng, E. Lo, and R. Schober, “Secure Resource Allocation and Scheduling for OFDMA Decode-and-Forward Relay Networks,” IEEE Trans. Wireless Commun., vol. 10, pp. 3528–3540, Aug. 2011.
[19] X. Chen and L. Lei, “Energy-Efficient Optimization for Physical Layer Interference?” IEEE Trans. Wireless Commun., vol. 8, pp. 2662–2671, May 2009.
[20] J. F. Sturm, “Using SeDuMi 1.02, A MATLAB Toolbox for Optimization over Symmetric Cones,” Optimiz. Methods and Software, vol. 11-12, pp. 625–653, Sep. 1999.
[21] S. Boyd and L. Vandenberghe, Convex Optimization. Cambridge University Press, 2004.
[22] R. A. Horn and C. R. Johnson, Matrix Analysis. Cambridge University Press, 1985.