Robust Layered Transmission in Secure MISO Multiuser Unicast Cognitive Radio Systems

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Abstract

This paper studies robust resource allocation algorithm design for a multiuser multiple-input single-output (MISO) cognitive radio (CR) downlink communication network. We focus on a secondary system which provides unicast secure wireless layered video information to multiple single-antenna secondary receivers. The resource allocation algorithm design is formulated as a non-convex optimization problem for minimization of the total transmit power at the secondary transmitter. The proposed framework takes into account a quality of service (QoS) requirement regarding video communication secrecy in the secondary system, the imperfection of the channel state information (CSI) of potential eavesdroppers (primary receivers) at the secondary transmitter, and a limit for the maximum tolerable received interference power at the primary receivers. Thereby, the proposed problem formulation exploits the self-protecting architecture of layered transmission and artificial noise generation to ensure communication secrecy. Semidefinite programming (SDP) relaxation is employed to derive a resource allocation algorithm which finds the global optimal solution to the formulated problem. Simulation results demonstrate significant transmit power savings and robustness against CSI imperfection for the proposed resource allocation algorithm for layered transmission compared to baseline schemes with traditional single-layer transmission.

Index Terms

Layered transmission, physical layer security, cognitive radio, non-convex optimization.

∗†‡§The authors are also with the University of British Columbia, Vancouver, Canada. This paper has been presented in part at the IEEE WCNC 2014 [1]. This research was supported by the Qatar National Research Fund (QNRF), under project NPRP 5-401-2-161.
I. INTRODUCTION

In recent years, the rapid expansion of high data rate multimedia services in wireless communication networks has led to a tremendous demand for energy and bandwidth. Consequently, multiple-input multiple-output (MIMO) technology has emerged as one of the most prominent solutions in reducing the system power consumption. In particular, MIMO provides extra spatial degrees of freedom for resource allocation [1]–[6] which facilitates a trade-off between multiplexing and diversity. Unfortunately, the hardware complexity of multiple-antenna receivers constrains the deployment of MIMO in practice, especially for small portable mobile devices. As an alternative, multiuser MIMO has been proposed as a compromise solution for realizing the potential performance gain offered by multiple antennas. Specifically, multiuser MIMO allows a multiple-antenna transmitter to serve multiple single-antenna receivers; it shifts the signal processing burden from the receivers to the transmitter while providing a promising system performance. On the other hand, fixed spectrum assignment has been implemented for resource sharing in traditional wireless communication systems. Although this design facilitates a simple implementation and interference can be avoided by assigning different wireless services to orthogonal licensed frequency bands, the fixed spectrum allocation strategy may result in spectrum underutilization and scarcity. In practice, the demand for spectrum varies highly across time, frequency, and space. For instance, the Federal Communications Commission (FCC) has reported that 70 percent of the allocated spectrum in the United States is not fully utilized, cf. [7]. As a result, cognitive radio (CR) was proposed as a possible solution for improving spectrum utilization [8]. CR enables a secondary system to dynamically access the spectrum of a primary system if the interference from the secondary system is controlled such that it does not severely degrade the quality of service (QoS) of the primary system [7]–[17]. Spectrum sensing plays an important role for facilitating the spectrum reuse in CR networks and has received considerable interest in the literature. In [9] and [10], cooperative spectrum sensing was investigated for two-user and multiuser single-antenna systems, respectively. In [11], the authors optimized the spectrum sensing duration for throughput maximization in the secondary network while protecting the primary users. In [12], an optimal linear cooperation framework was proposed to detect weak signals from primary users by combining the local statistics of individual CRs. Furthermore, different resource allocation algorithms have been studied for controlling the interference leakage from the secondary network to the primary network. By exploiting multiple antennas in a secondary transmitter, beamforming designs minimizing the transmit power of a CR secondary downlink system were studied in [13]. In [14], joint beamforming and power control for multiple access channels was studied by assuming the availability of perfect channel state information (CSI). Later, in [15] and [16], the beamforming algorithm design was improved by taking into account the imperfection of the CSI in practical single and multiple secondary users systems, respectively. In [17], multiple objective optimization
adopted for CR networks to study the trade-off between the interference leakage to the primary network and the transmit power of the secondary transmitter. However, the problem formulations in [13]–[17] did not take into account the characteristics of the underlying communication services. Besides, the results in [13]–[17] were obtained by assuming single-antenna primary receivers. Thus, the corresponding results may not be applicable to CR networks with multiple antenna primary receivers and secondary networks providing multimedia applications such as video streaming.

Scalable video coding (SVC) [18], [19] has been proposed for video information encoding. In particular, multiple description coding (MDC) and successive refinement coding (SRC) are two common multimedia SVC techniques. For MDC, the video source signal is encoded into multiple sub-streams/descriptions, each of which has equal importance. Besides, each description can be decoded independently without utilizing the information embedded in other descriptions. Also, each decoded description alone can guarantee a basic level of video quality and combining additional descriptions can further improve the quality. On the other hand, in SRC, 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 previous layers. The structure of layered transmission facilitates the implementation of unequal error protection. In fact, SRC provides a higher flexibility to the service provider compared to MDC since the transmitter can achieve a better resource utilization by allocating different powers to different information layers depending on the required video quality. Besides, layered transmission with SRC has been implemented in some existing video standards such as H.264/Moving Picture Experts Group (MPEG)-4. Thus, in this paper, we focus on layered transmission based on SRC. Recently, resource allocation algorithm design for layered transmission has been pursued for wireless communication systems. In [20], power allocation in layered transmission with successive enhancement was investigated. Subsequently, this study was extended to the joint design of rate and power allocation in [21]. Yet, the resource allocation algorithms in [20] and [21] are designed for single antenna transmitters with long-term average system design objectives. Hence, the results of [20] and [21] may not be applicable for delay-sensitive application and multiple antennas systems.

Furthermore, wireless communication channels are vulnerable to eavesdropping due to their broadcast nature. As soliciting multimedia services over the wireless medium becomes more popular, there is an emerging need for guaranteeing secure wireless video communication. For instance, illegitimate users or misbehaving legitimate users of a communication system may attempt to use high definition video services without paying by overhearing the video signal. Conventionally, secure communication is guaranteed by cryptographic encryption algorithms implemented in the application layer. However, the associated required
secrete key distribution and management can be problematic or infeasible in wireless networks. Besides, with the development of quantum computing, the commonly used encryption algorithms may become eventually crackable with brute force approach within a reasonable amount of time. As a result, physical (PHY) layer security [22]–[28] has been proposed as a complement to the traditional secrecy methods for improving wireless transmission security. The merit of PHY layer security lies in the guaranteed perfect secrecy of communication, even if the eavesdroppers have unbounded computational capability. In [22], 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. This result was subsequently generalized to the broadcast channel and the Gaussian channel in [23] and [24], respectively. Recently, a considerable amount of research [25]–[28] has been devoted to exploiting multiple antennas for providing communication secrecy. In [25], a suboptimal transmit beamforming scheme was proposed for maximization of the minimum secrecy capacity in a multiple-input single-output (MISO) multicast communication system. In [26] and [27], artificial noise generation was exploited for multiple-antenna transmitters to weaken the information interception capabilities of the eavesdroppers. In particular, artificial noise is transmitted concurrently with the information signal in [26] and [27] for maximization of the ergodic secrecy capacity and the outage secrecy capacity, respectively. In [28], a joint power and subcarrier allocation algorithm was proposed for maximization of the system energy efficiency of wide-band communication systems while providing communication secrecy. However, single-layer transmission is assumed in [25]–[28] and the corresponding results may not be applicable to the layered transmission structure used in multimedia applications. In fact, the layered information architecture of video signals has a self-protecting structure which provides a certain robustness against eavesdropping. However, exploiting the layered transmission architecture for facilitating PHY layer security for video communication has not been considered in the literature, e.g., [4]–[21]. The notion of secure communication in layered transmission systems has recently been studied in our preliminary work in [1]. Specifically, a power allocation algorithm was designed for minimization of the transmit power under a communication secrecy constraint for a single video receiver. Yet, with the design proposed in [1], a strong artificial noise/interference is generated to ensure secure video communication and this may cause a significant performance degradation for the primary receivers if the results of [1] are directly applied to CR networks.

In this paper, we address the above issues and the contributions of the paper are summarized as follows:

- We propose a non-convex optimization problem formulation for minimization of the total transmit power in layered video transmission to multiple secondary receivers. The proposed framework takes into account the imperfection of the CSI of the potential eavesdroppers (primary receivers) for
guaranteeing secure communication to the secondary receivers and controlling the interference leakage to the multiple-antenna primary receivers.

- The considered non-convex optimization problem is recast as a convex optimization problem via semidefinite programming (SDP) relaxation. We prove that the global optimal solution of the original problem can be constructed by exploiting the solutions of the primal and the dual versions of the SDP relaxed problem.

- Two suboptimal resource allocation schemes are proposed for the case when the solution of the dual problem of the SDP relaxed problem is unavailable for construction of the optimal solution.

- Our simulation results show that the inherently self-protecting structure of layered transmission enables significant transmit power savings in providing secure video communication for the secondary receivers compared to two baseline schemes employing traditional single-layer transmission.

II. SYSTEM MODEL

In this section, we present the adopted system model for secure layered video transmission.

A. Notation

We use boldface capital and lower case letters to denote matrices and vectors, respectively. $A^H$, $\text{Tr}(A)$, $A^\dagger$, $\text{Rank}(A)$, and $\det(A)$ represent the Hermitian transpose, trace, square-root, rank, and determinant of matrix $A$; $\text{vec}(A)$ denotes the vectorization of matrix $A$ by stacking its columns from left to right to form a column vector; $A \otimes B$ denotes the Kronecker product of matrices $A$ and $B$; $A \succ 0$ and $A \succeq 0$ indicate that $A$ is a positive definite and a positive semidefinite matrix, respectively; $\lambda_{\text{max}}(A)$ denotes the maximum eigenvalue of matrix $A$; $I_N$ is the $N \times N$ identity matrix; $\mathbb{C}^{N \times M}$ denotes the set of all $N \times M$ matrices with complex entries; $\mathbb{H}^N$ denotes the set of all $N \times N$ Hermitian matrices. The circularly symmetric complex Gaussian (CSCG) distribution is denoted by $CN(m, \Sigma)$ with mean vector $m$ and covariance matrix $\Sigma$; $\sim$ indicates “distributed as”; $|\cdot|$, $\|\cdot\|$, and $\|\cdot\|_F$ denote the absolute value of a complex scalar, the Euclidean norm, and the Frobenius norm of a vector/matrix, respectively.

B. Channel Model

We consider a CR secondary network. There are one secondary transmitter equipped with $N_T > 1$ transmit antennas, $K$ legitimate secondary video receivers, and $J$ primary receivers. The secondary receivers and the primary receivers share the same spectrum concurrently, cf. Figure 1. The secondary receivers are low complexity single-antenna devices for decoding the video signal. On the other hand, each primary receiver is equipped with $N_R > 1$ antennas. We assume that $N_T > N_R$ in this paper. In every time instant, the transmitter conveys $K$ video information signals to $K$ unicast secondary video receivers.
The unicast scenario is applicable for on-demand video streaming service and provides high flexibility to the end-users. However, the transmitted video signals for each secondary receiver may be overheard by primary receivers and unintended secondary receivers which share the same spectrum simultaneously. In practice, it is possible that some 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 secondary transmitter. As a result, the \( J \) primary receivers and unintended secondary receivers are potential eavesdroppers which should be taken into account in the resource allocation algorithm design for providing secure communication. We focus on frequency flat fading channels. The downlink received signals at secondary video receiver \( k \in \{1, \ldots, K\} \) and primary receiver \( j \in \{1, \ldots, J\} \) are given by

\[
\begin{align*}
y_k &= h_k^H x + n_k, \\
y_j^{PU} &= G_j^H x + z_j,
\end{align*}
\]  

where \( x \in \mathbb{C}^{N_T \times 1} \) denotes the transmitted signal vector. The channel vector between the secondary transmitter and secondary receiver \( k \) is denoted by \( h_k \in \mathbb{C}^{N_T \times 1} \). The channel matrix between the secondary transmitter and primary receiver \( j \) is denoted by \( G_j \in \mathbb{C}^{N_T \times N_R} \). \( n_k \sim \mathcal{CN}(0, \sigma^2_{n_k}) \) and \( z_j \sim \mathcal{CN}(0, \sigma^2_{PU,j} I_{N_R}) \) are additive white Gaussian noise (AWGN) at the secondary receivers and the primary receivers, respectively. Variables \( \sigma^2_{n_k} \) and \( \sigma^2_{PU,j} \) denote the noise powers at the antennas of secondary receiver.
and primary receiver \( j \), respectively. We assume that the primary network is a legacy system which does not participate in adaptive transmit power control. The received power from the primary transmitter at the secondary receivers is incorporated in the AWGN, \( n_{sk} \).

C. Video Encoding and Artificial Noise

Layered video encoding based on SRC is adopted to encode the video information. Specifically, the video source intended for secondary receiver \( k \) is encoded into \( L_k \) layers at the secondary transmitter and the data rate of each layer is fixed, cf. H.264/SVC [18], [19]. The video information for secondary receiver \( k \) can be represented as \( S_k = [s_{1,k}, s_{2,k}, \ldots, s_{l,k}, \ldots, s_{L_k,k}] \), where \( s_{l,k} \in \mathbb{C} \) denotes the video information of layer \( l \) for secondary receiver \( k \). For the video signal of receiver \( k \), the \( L_k \) layers include one base layer, i.e., \( s_{1,k} \), which can be decoded independently without utilizing the information from the upper layers. Specifically, the base layer data includes the most essential information of the video and can guarantee a basic video quality. The remaining \( L_k - 1 \) layers, i.e., \( \{s_{2,k}, \ldots, s_{L_k,k}\} \), are enhancement layers which are used to successively refine the decoded lower 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.

Furthermore, in order to provide communication security, artificial noise is transmitted along with the information signals. Hence, the transmit symbol vector \( x \) can be expressed as

\[
x = \sum_{k=1}^{K} \sum_{l=1}^{L_k} w_{l,k}s_{l,k} + v,
\]

where \( w_{l,k} \in \mathbb{C}^{N_T \times 1} \) is the beamforming vector for the video information in layer \( l \) dedicated to desired receiver \( k \). We note that superposition coding is used to superimpose the \( L_k \) video information layers. \( v \in \mathbb{C}^{N_T \times 1} \) is an artificial noise vector generated to facilitate secure communication. In particular, \( v \) is modeled as a complex Gaussian random vector, i.e., \( v \sim \mathcal{CN}(0, V) \), where \( V \) denotes the covariance matrix of the artificial noise. Hence, \( V \) is a positive semidefinite Hermitian matrix, i.e., \( V \in \mathbb{H}^{N_T}, V \succeq 0 \).

III. Resource Allocation Algorithm Design

In this section, we present the adopted performance metrics and the problem formulation.

A. Achievable Rate

We assume that perfect local CSI is available at the secondary video receivers. Besides, successive interference cancellation (SIC) [2] is performed at the receivers for decoding video information. Thereby, before decoding the information in layer \( l \), the receivers first decode and cancel the video information in
layers \{1,\ldots,l-1\} successively. Therefore, the instantaneous achievable rate between the transmitter and primary video receiver \(k\) in layer \(l \in \{1,\ldots,L_k\}\) is given by

\[
C_{l,k} = \log_2 \left( 1 + \Gamma_{l,k} \right) \quad \text{and} \quad \Gamma_{l,k} = \frac{|h_{k}^{H}w_{l,k}|^2}{\sum_{n \neq k}^{K} \sum_{r=1}^{L_{n}} |h_{r,n}^{H}w_{r,n}|^2 + \sum_{t=l+1}^{L_k} |h_{t,k}^{H}w_{t,k}|^2 + \text{Tr}(h_{k}^{H}Vh_{k}) + \sigma_{s_{k}}^2},
\]

where \(\Gamma_{l,k}\) is the received signal-to-interference-plus-noise ratio (SINR) of layer \(l\) at secondary video receiver \(k\).

On the other hand, it is possible that secondary video receiver \(t\) attempts to decode the video information intended for secondary receiver \(k\) after decoding its own video information. Hence, secondary video receiver \(t\) is also treated as a potential eavesdropper with respect to the video information of secondary video receiver \(k\). The instantaneous achievable rate between the transmitter of secondary receiver \(k\) and secondary receiver \(t\) in decoding layer \(l \in \{1,\ldots,L_k\}\) is given by

\[
C_{t,l,k} = \log_2 \left( 1 + \Gamma_{t,l,k} \right) \quad \text{and} \quad \Gamma_{t,l,k} = \frac{|h_{t}^{H}w_{l,k}|^2}{\sum_{n \neq t}^{K} \sum_{r=1}^{L_{n}} |h_{r,n}^{H}w_{r,n}|^2 + \sum_{m=l+1}^{L_k} |h_{m,k}^{H}w_{m,k}|^2 + \text{Tr}(h_{t}^{H}Vh_{t}) + \sigma_{s_{t}}^2},
\]

It can be observed from (6) that layered transmission has a self-protecting structure. Specifically, via the first term in the denominator of (7), the higher layer information 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 lower layers.

Besides, the transmitted video signals are also overheard by the primary receivers due to the broadcast nature of the wireless communication channel. Therefore, the achievable rate between the transmitter and primary receiver \(j\) for decoding the \(l\)-th layer signal of secondary receiver \(k\) can be represented as

\[
C_{l,k}^{PUj} = \log_2 \det \left( I_{N_{k}} + \Lambda_{j,k}^{-1}G_{j}^{H}w_{l,k}w_{l,k}^{H}G_{j} \right) \text{ where}
\]

\[
\Lambda_{j,k} = \Sigma_{j} + \sum_{n \neq k}^{K} \sum_{r=1}^{L_{n}} G_{j}^{H}w_{r,n}w_{r,n}^{H}G_{j} + \sum_{m=l+1}^{L_k} G_{j}^{H}w_{m,k}w_{m,k}^{H}G_{j} + \Sigma_{j} + \sigma_{PUj}^2 I_{N_{k}} > 0.
\]

\(\Sigma_{j} = G_{j}^{H}V_{j}G_{j} + \sigma_{s_{j}}^2 I_{N_{k}}\).
For ensuring communication security, the primary receivers are also treated as potential eavesdroppers who attempt to decode the messages transmitted for all $K$ desired secondary receivers. Thereby, we focus on a worst case scenario for the decoding capability of the primary receivers for providing communication security to the secondary receivers. In particular, we assume that primary receiver $j$ performs SIC to remove all multiuser interference and the multilayer interference from upper layers before decoding the message of layer $l$ of secondary receiver $k$. As a result, the achievable rate in (8) is bounded above by

$$\tilde{C}_{l,k}^{PU_j} = \log_2 \det \left( I_{N_t} + \sum_j G_j^H w_{l,k} w_{l,k}^H G_j \right).$$  

(11)

Thus, the secrecy rate [26] between the transmitter and secondary receiver $k$ on layer $l$ is given by

$$C_{\text{sec}}_{l,k} = \left[ C_{l,k} - \max_{\forall j \neq k} \{ C_{l,k}^{t}, \tilde{C}_{l,k}^{PU_j} \} \right]^+. \quad (12)$$

$C_{\text{sec}}_{l,k}$ quantifies the maximum achievable data rate at which a transmitter can reliably send secret information on layer $l$ to primary receiver $k$ such that the potential eavesdroppers are unable to decode the received signal [22].

Remark 1: We note that if secondary receiver $t$ has the same capability in eavesdropping the information as the primary receiver, i.e., it is able to cancel the multiuser interference and multilayer interference before eavesdropping the information of layer $l$ of receiver $k$, we can use equation (11) instead of equation (8) to denote the achievable rate between the transmitter and secondary receiver $t$ in decoding layer $l$ of secondary receiver $k$ without loss of generality.

B. Channel State Information

In this paper, we focus on a Time Division Duplex (TDD) communication system with slowly time-varying channels. At the beginning of each time slot, handshaking is performed between the secondary transmitter and the secondary receivers. As a result, the downlink CSI of the secondary transmitter to the secondary receivers can be obtained by measuring the uplink training sequences embedded in the handshaking signals. Thus, we assume that the secondary-transmitter-to-secondary-receivers fading gains, $h_{k}^{l}$, can be reliably estimated at the secondary transmitter with negligible estimation error.

On the other hand, the primary receivers may not directly interact with the secondary transmitter. Besides, the primary receivers may be silent for a long period of time due to bursty data communication. As a result, the CSI of the primary receivers can be obtained only occasionally at the secondary transmitter when the primary receivers communicate with the primary transmitter. Hence, the CSI for the idle primary receivers

\[1\] Although the worst case secrecy rate is assumed, the results of this work are also applicable to the case of primary receivers (potential eavesdroppers) employing single user detectors by modifying the term $\Sigma_{j,k}$ in (11) accordingly.
may be outdated when the secondary transmitter performs resource allocation. We adopt a deterministic model \cite{29}–\cite{32} to model the impact of the CSI imperfection on resource allocation design. The CSI of the link between the secondary transmitter and primary receiver \(j\) is modeled as

\[
G_j = \hat{G}_j + \Delta G_j, \quad \forall j \in \{1, \ldots, J\},
\]

and

\[
\Psi_j \triangleq \left\{ \Delta G_j \in \mathbb{C}^{N_T \times N_R} : \|\Delta G_j\|_F^2 \leq \varepsilon_j^2 \right\}, \quad \forall j,
\]

where \(\hat{G}_j \in \mathbb{C}^{N_T \times N_R}\) is the matrix CSI estimate of the channel of primary receiver \(j\) that is available at the secondary transmitter. \(\Delta G_j\) represents the unknown channel uncertainty due to the time varying nature of the channel during transmission. In particular, the continuous set \(\Psi_j\) in (14) defines a continuous space spanned by all possible channel uncertainties and \(\varepsilon_j\) represents the maximum value of the norm of the CSI estimation error matrix \(\Delta G_j\) for primary receiver \(j\).

C. Optimization Problem Formulation

The system design objective is to minimize the total transmit power of the secondary transmitter while providing QoS for both the secondary receivers and the primary receivers. The optimal resource allocation policy \(\{w_{l,k}^*, V^*\}\) can be obtained by solving

\[
\begin{aligned}
\text{minimize} & \quad \sum_{k=1}^K \sum_{l=1}^{L_k} \|w_{l,k}\|^2 + \operatorname{Tr}(V) \\
\text{subject to} & \quad |h_k^H w_{l,k}|^2 \geq \Gamma_{\text{req},l,k}, \quad \forall l, \forall k, \\
& \quad \sum_{n \neq k} \sum_{r=1}^{L_n} |h_k^H w_{r,n}|^2 + \sum_{l=1}^{L_k} |h_k^H w_{l,k}|^2 + \operatorname{Tr}(h_k^H V h_k) + \sigma_k^2 \\
& \quad \sum_{n \neq k} \sum_{r=1}^{L_n} |h_k^H w_{r,n}|^2 + \sum_{l=1}^{L_k} |h_k^H w_{l,k}|^2 + \operatorname{Tr}(h_k^H V h_k) + \sigma_k^2 \\
& \quad \max_{\|\Delta G_j\|_F \in \Psi_j} \log_2 \det \left( I_{N_t} + \sum_{j=1}^J G_j^H (V + \sum_{k=1}^K \sum_{l=1}^{L_k} w_{l,k} w_{l,k}^H) G_j \right) \leq R_{\text{Eav},j,k}, \quad \forall j \in \{1, \ldots, J\}, \forall k \in \{1, \ldots, K\}, \\
& \quad |h_k^H w_{1,k}|^2 \leq \Gamma_{\text{tol}}, \forall t \neq k, t \in \{1, \ldots, K\}, \\
& \quad \max_{\|\Delta G_j\|_F \in \Psi_j} \log_2 \det \left( I_{N_t} + \sum_{j=1}^J G_j^H w_{1,k} w_{1,k}^H G_j \right) \leq R_{\text{Eav},j,k}, \quad \forall j \in \{1, \ldots, J\}, \forall k \in \{1, \ldots, K\}, \\
& \quad V \succeq 0.
\end{aligned}
\]

Here, \(\Gamma_{\text{req},l,k}\) in C1 is the minimum required SINR for decoding layer \(l\) at receiver \(k\). In practice, the desired video receivers may be divided into different classes with different numbers of video layers and different QoS requirements. For instance, the secondary video receivers may be categorized into two categories, namely premium video receivers and regular video receivers, based on the subscribed services. Specifically, the secondary transmitter is required to guarantee the QoS (i.e., SINR) of all video layers.
for premium secondary receivers while the transmitter may guarantee only the basic QoS of videos (i.e., the SINR of the first layer) for regular receivers. In C2, $\Gamma_{\text{tol}}$ denotes the maximum tolerated received SINR of layer 1 at the unintended secondary receivers for decoding layer 1 of a video signal intended for another receiver. Since layered coding is employed for video information encoding, it is sufficient to protect the first layer of each video signal for each secondary receiver against eavesdropping. C3 is the interference temperature constraint. Specifically, the secondary transmitter is required to control the transmit power such that the maximum received interference power at primary receiver $j$ is less than a given interference temperature $P_I$, despite the imperfection of the CSI. We note that the considered problem formulation is a generalization of the cases where the primary receivers are co-existing with the secondary receivers. If the interference from the secondary transmitter to the primary receivers is not a performance concern, we can either set $P_I \rightarrow \infty$ or remove constraint C3 from the above problem formulation without loss of generality. On the other hand, since any secondary receiver could be chosen as an eavesdropping target of primary receiver $j$ and layer transmission is adopted, the upper limit $R_{Eav,j,k}$ is imposed in C4 to restrict the achievable rate of primary receiver $j$, if it attempts to decode the first video layer of secondary receiver $k$, $\forall k$. In this paper, we do not maximize the secrecy rate of video delivery as it does not necessarily lead to a power efficient resource allocation. Yet, the problem formulation in (15) guarantees a minimum secrecy rate of layer 1 for a video signal intended for secondary receiver $k$, i.e., $C_{\text{sec},1,k} \geq \left[ C_{1,k} - \max_{\forall t \neq k} \{ \log_2 (1 + \Gamma_{\text{tol}}), R_{Eav,j,k} \} \right]^+$. Besides, the communication security of layer 2 to layer $L_k$ is ensured when layer 1 in unable to be decoded by the potential eavesdroppers. C5 and $V \in \mathbb{H}^{N_T}$ are imposed such that $V$ satisfies the requirements for a covariance matrix.

Remark 2: We would like to emphasize that the layered transmission approach has two major advantages compared to single-layer transmission. First, the video quality increases with the number of decoded layers. Thus, for layered transmission, the desired users can be easily divided into different classes with different receive video quality for layered-transmission. In practice, the desired users may be charged with higher subscription fees for a higher video quality. Second, the layered structure facilitates more power efficient resource allocation under physical layer security constraints. In particular, instead of protecting the entire encoded video signal as in single-layer transmission, in layered transmission, the transmitter is required to protect only the most important part of the video, i.e., the base layer, to provide communication security.

Remark 3: In practice, the problem in (15) may be infeasible when the channels are in unfavourable conditions and/or the QoS requirements are too stringent. However, in the sequel, for designing the optimal resource allocation scheme, we assume that the problem is feasible.
IV. SOLUTION OF THE OPTIMIZATION PROBLEM

The optimization problem in (15) is a non-convex quadratically constrained quadratic program (QCQP). In particular, the non-convexity of the considered problem is due to constraints C1, C2, and C4. Besides, constraints C3 and C4 involve infinitely many inequality due to the continuity of the CSI uncertainty sets, $\Psi_j, j \in \{1, \ldots, J\}$. In order to derive an efficient resource allocation algorithm for the considered problem, we first rewrite the original problem to avoid the non-convexity associated with constraints C1 and C2. Then, we convert the infinitely many constraints in C3 and C4 into an equivalent finite number of constraints. Finally, we use semi-definite programming relaxation (SDR) to obtain the resource allocation solution for the reformulated problem.

A. Semidefinite Programming Relaxation

First, we rewrite problem (15) in an equivalent form:

$$\minimize_{W_{l,k}, V \in \mathbb{H}^{N_T}} \sum_{k=1}^{K} \sum_{l=1}^{L_k} \text{Tr}(W_{l,k}) + \text{Tr}(V)$$

subject to:

C1: \[ \frac{\text{Tr}(H_k W_{l,k})}{\text{Tr} \left( H_k \left( \sum_{n \neq k} W_{r,n} + \sum_{m=l+1}^{L_k} W_{j,k} \right) \right) + \text{Tr}(VH_k) + \sigma^2_{s_k}} \geq \Gamma_{\text{req},l,k}, \forall l, \forall k, \]

C2: \[ \frac{\text{Tr}(H_t W_{1,k})}{\text{Tr} \left( H_t \left( \sum_{n \neq t} W_{r,n} + \sum_{m=2}^{L_k} W_{m,k} \right) \right) + \text{Tr}(VH_t) + \sigma^2_{s_k}} \leq \Gamma_{\text{tol}}, \forall t \neq k, t \in \{1, \ldots, K\}, \]

C3: \[ \max_{\|G_j\|_F \in \Psi_j} \text{Tr} \left( G_j^H (V + \sum_{k=1}^{K} \sum_{l=1}^{L_k} W_{l,k}) G_j \right) \leq P_j, \forall j \in \{1, \ldots, J\}, \]

C4: \[ \max_{\|G_j\|_F \in \Psi_j} \log_2 \text{det} \left( I_N + \Sigma_j^{-1} G_j^H W_{1,k} G_j \right) \leq R_{Eav,j,k}, \forall j \in \{1, \ldots, J\}, \forall k \in \{1, \ldots, K\}, \]

C5: \[ V \succeq 0, \quad C6: W_{l,k} \succeq 0, \forall k, l, \quad C7: \text{Rank}(W_{l,k}) \leq 1, \forall k, l, \]

where $H_k = h_k^H h_k$ and $W_{l,k} = w_{l,k} w_{l,k}^H$. We note that $W_{l,k} \succeq 0, W_{l,k} \in \mathbb{H}^{N_T}$, and $\text{Rank}(W_{l,k}) \leq 1, \forall l, k, in (16)$ are imposed to guarantee that $W_{l,k} = w_{l,k} w_{l,k}^H$ holds after optimization.

Next, we introduce a Lemma which will allow us to transform constraint C3 into linear matrix inequalities (LMIs).

Lemma 1 (S-Procedure [33]): Let a function $f_m(x), m \in \{1, 2\}, x \in \mathbb{C}^{N \times 1}$, be defined as

$$f_m(x) = x^H A_m x + 2 \text{Re}\{b_m^H x\} + c_m,$$

where $A_m \in \mathbb{H}^N, b_m \in \mathbb{C}^{N \times 1}$, and $c_m \in \mathbb{R}$. Then, the implication $f_1(x) \leq 0 \Rightarrow f_2(x) \leq 0$ holds if and
only if there exists a $\omega \geq 0$ such that

$$
\omega \begin{bmatrix} A_1 & b_1 \\ b_1^H & c_1 \end{bmatrix} - \begin{bmatrix} A_2 & b_2 \\ b_2^H & c_2 \end{bmatrix} \succeq 0,
$$

(18)

provided that there exists a point $\hat{x}$ such that $f_k(\hat{x}) < 0$.

Now, we apply Lemma 1 to constraint C3. In particular, we define $\hat{g}_j = \text{vec}(\hat{G}_j)$, $\Delta g_j = \text{vec}((\Delta G)_j)$, $\bar{W}_{l,k} = I_{N_R} \otimes W_{l,k}$, and $\bar{V} = I_{N_R} \otimes V$. By exploiting the fact that $\|\hat{G}_j\|_F^2 \leq \varepsilon_j^2 \iff \Delta g_j^H \Delta g_j \leq \varepsilon_j^2$, then we have

$$
\|\hat{G}_j\|_F^2 \leq \varepsilon_j^2
$$

(19)

if and only if there exists a $\omega_j \geq 0$ such that the following LMIs constraint holds:

$$
\begin{align*}
\text{C3: } & 0 \geq \max_{\Delta g_j \in \mathcal{W}_j} \Delta g_j^H \left( \sum_{k=1}^{K} \sum_{l=1}^{L_k} \bar{W}_{l,k} + \bar{V} \right) \Delta g_j \\
& + 2\text{Re} \left\{ \hat{g}_j^H \left( \sum_{k=1}^{K} \sum_{l=1}^{L_k} \bar{W}_{l,k} + \bar{V} \right) \Delta g_j \right\} + \hat{g}_j^H \left( \sum_{k=1}^{K} \sum_{l=1}^{L_k} \bar{W}_{l,k} + \bar{V} \right) \hat{g}_j - P_j, \forall j \in \{1, \ldots, J\},
\end{align*}
$$

(20)

where $U_{g_j} = \left[ I_{N_R} \otimes \mathcal{T}_n, \hat{g}_j \right]$. The new constraint $\text{C3}$ is not only an affine function with respect to the optimization variables, but also involves only a finite number of constraints.

Next, we handle non-convex constraint C4 by introducing the following proposition for simplifying the considered optimization problem.

**Proposition 1:** For $R_{Eav, j, k} > 0$, the following implication holds for constraint C4:

$$
\text{C4} \iff \text{C4}: \max_{\|\Delta G_j\|_F \in \mathcal{W}_j} G_j^H W_{1,k} G_j \preceq \xi_{Eav, j, k} \Sigma_j, \forall j \in \{1, \ldots, J\}, \forall k \in \{1, \ldots, K\},
$$

(21)

where $\xi_{Eav, j, k} = 2^{R_{Eav, j, k}} - 1$ is an auxiliary constant with $\xi_{Eav, j, k} > 0$ for $R_{Eav, j, k} > 0$. We note that constraint $\text{C4}$ is equivalent to constraint C4 if Rank$(W_{1,k}) \leq 1, \forall k$.

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

Although constraint $\text{C4}$ is less complex compared to C4, there are still infinitely many LMI constraints to satisfy in $\text{C4}$ with respect to $\Delta G_j$. To this end, we adopt the following Lemma for further simplifying $\text{C4}$:

**Lemma 2 (Robust Quadratic Matrix Inequalities [34]):** Let a quadratic matrix function $f(X)$ be defined as

$$
f(X) = X^H AX + X^H B + B^H X + C,
$$

(22)
where $X, A, B,$ and $C$ are arbitrary matrices with appropriate dimensions. Then, the following two statements are equivalent:

$$f(X) \succeq 0, \forall X \in \{X \mid \text{Tr}(DXX^H) \leq 1\}$$  \hspace{1cm} (23)

$$\iff \begin{bmatrix} C & B^H \\ B & A \end{bmatrix} - \delta \begin{bmatrix} I & 0 \\ 0 & -D \end{bmatrix} \succeq 0, \text{ if } \exists \delta \geq 0,$$  \hspace{1cm} (24)

for matrix $D \succeq 0$ and $\delta$ is an auxiliary constant.

By applying Lemma 2 to (21) and following similar steps as in [35], i.e., setting $X = \Delta G_j$, $A = \xi_{Eav,j,k} V - W_{1,k}$, $B = (\xi_{Eav,j,k} V - W_{1,k}) \hat{G}_j$, $C = \xi_{Eav,j,k} I_{N_R} \sigma^2_{P_{U,j}} + \hat{G}_j^H (\xi_{Eav,j,k} V - W_{1,k}) \hat{G}_j^H$, and $D = \frac{I_{N_T}}{\varepsilon_j}$ in (23), we obtain

$$C_4 \iff \tilde{C}_4 \iff \begin{bmatrix} (\xi_{Eav,j,k} \sigma^2_{P_{U,j}} - \delta_{k,j}) I_{N_R} + \xi_{Eav,j,k} \hat{G}_j^H V \hat{G}_j & \xi_{Eav,j,k} \hat{G}_j^H V \\ \xi_{Eav,j,k} V \hat{G}_j & \xi_{Eav,j,k} V + \frac{\delta_{k,j}}{\varepsilon_j} I_{N_T} \end{bmatrix} - R_j^H W_{1,k} R_j \succeq 0, \forall k,j,$$  \hspace{1cm} (25)

where $R_j = [\hat{G}_j, I_{N_T}]$ and $\delta_{k,j}$ is an auxiliary optimization variable. Besides, $C_4$ is equivalent to $\tilde{C}_4$ when $\text{Rank}(W_{1,k}) \leq 1$.

Subsequently, we replace constraints $C_3$ and $C_4$ with constraints $\overline{C}_3$ and $\overline{C}_4$, respectively. The new optimization problem can be written as

$$\begin{align*}
& \text{minimize} & & \sum_{k=1}^{K} \sum_{l=1}^{L_k} \text{Tr}(W_{l,k}) + \text{Tr}(V) \\
& \text{subject to} & & \overline{C}_1, \overline{C}_2, \overline{C}_5, \overline{C}_6, \\
& & & \overline{C}_3: S_{C_{3,k,j}}(W_{l,k}, V, \omega_j) \succeq 0, \forall j, \\
& & & \overline{C}_4: S_{C_{4,k,j}}(W_{1,k}, V, \delta_{k,j}) \succeq 0, \forall j \in \{1, \ldots, J\}, \forall k \in \{1, \ldots, K\}, \\
& & & \overline{C}_7: \text{Rank}(W_{l,k}) \leq 1, \forall k,l, \overline{C}_8: \omega_j \geq 0, \forall j, \overline{C}_9: \delta_{k,j} \geq 0, \forall k,j, \\
& & & \overline{C}_6
\end{align*}$$  \hspace{1cm} (26)

where $\omega_j$ and $\delta_{k,j}$ in $\overline{C}_8$ and $\overline{C}_9$ are connected to the LMI constraints in (20) and (25), respectively. Since optimization problems (26) and (16) share the same optimal solution, we focus on the design of the optimal resource allocation policy for the problem in (26) in the sequel.

The only obstacle in solving (26) is the combinatorial rank constraint in $\overline{C}_7$. We adopt the SDP relaxation approach by relaxing constraint $\overline{C}_7$: $\text{Rank}(W_{l,k}) \leq 1$, i.e., we remove $\overline{C}_7$ from the problem formulation. Then, the considered problem becomes a convex SDP which can be solved efficiently by numerical solvers such as CVX [36]. We note that removing constraint $\overline{C}_7$ results in a larger feasible solution set. In general, the optimal objective value of the relaxed problem of (26) is expected to be no higher than the optimal
objective value of (16). However, if the obtained solution $W_{l,k}$ for the relaxed problem admits a rank-one matrix, this is also the optimal solution of the original problem in (16) and the adopted SDP relaxation is tight. Subsequently, the optimal $w_{l,k}$ can be obtained by performing eigenvalue decomposition on $W_{l,k}$ and selecting the principal eigenvector as the beamforming vector. However, it is known that in general the constraint relaxation may not be tight and $\text{Rank}(W_{l,k}) > 1$ may occur. In the following, we propose a method for constructing an optimal solution of the relaxed version of (26) with a rank-one matrix $W_{l,k}, \forall k, l$.

**B. Optimality Condition for SDP Relaxation**

In this subsection, we first reveal the tightness of the proposed SDP relaxation. The existence of a rank-one solution matrix $W_{l,k}$ for the relaxed SDP version of (26) is summarized in the following theorem which is based on [37, Proposition 4.1].

**Theorem 1:** Suppose the optimal solution of the SDP relaxed version of (26) is denoted as $\{W^*_{l,k}, V^*, \omega^*_j, \delta^*_{k,j}\}$ and $\exists k, l : \text{Rank}(W^*_{l,k}) > 1$. Then, there exists a feasible optimal solution of the SDP relaxed version of (26), denoted as $\tilde{\Lambda} \triangleq \{\tilde{W}_{l,k}, \tilde{V}, \tilde{\omega}_j, \tilde{\delta}_{k,j}\}$, with a rank-one matrix $\tilde{W}_{l,k}$, i.e., $\text{Rank}(\tilde{W}_{l,k}) = 1$. This optimal solution can be obtained by construction.

**Proof:** Please refer to Appendix B for the proof of Theorem 1 and the method for constructing the optimal solution.

Since the optimal solution of the SDP relaxed version of (26) is a rank-one beamforming matrix $\tilde{W}_{l,k}, \forall l, k$, by construction, the global optimum of (16) can be obtained despite the SDP relaxation.

**C. Suboptimal Resource Allocation Schemes**

The construction of the optimal solution $\tilde{\Lambda}$ with $\text{Rank}(\tilde{W}_{l,k}) = 1$ requires the optimal solution of the dual version of the relaxed problem of (26), cf. variable $Y^*_{l,k}$ in (36) in Appendix B. However, the solution of the dual problem may not be provided by some numerical solvers and thus the construction of a rank-one solution matrix $\tilde{W}_{l,k}$ may not be possible. In the following, we propose two suboptimal resource allocation schemes based on the solution of the primal problem of the relaxed version of (26) which do not require the solution of the dual problem.

1) **Suboptimal Resource Allocation Scheme 1**: A hybrid resource allocation scheme is proposed which is based on the solution of the relaxed version of (26). We first solve (26) by SDP relaxation. The global optimal solution of (26) is found if the obtained solution $W^*_{l,k}$ is a rank-one matrix. Otherwise, we construct a suboptimal solution set $\tilde{W}_{l,k}^{\text{sub}} = w_{l,k}^{\text{sub}}(w_{l,k}^{\text{sub}})^H$, where $w_{l,k}^{\text{sub}}$ is the eigenvector corresponding to the principal eigenvalue of matrix $W^*_{l,k}$. Then, we define a scalar optimization variable $P_{l,k}$ which controls
the power of the suboptimal beamforming matrix of layer $l$ for secondary receiver $k$. Subsequently, a new optimization problem is formulated as:

$$\begin{align*}
\text{minimize} & \sum_{k=1}^{K} \sum_{l=1}^{L_k} \text{Tr}(P_{l,k} W_{l,k}^{\text{sub}}) + \text{Tr}(V) \\
\text{s.t.} C1: & \frac{\text{Tr}(H_k P_{l,k} W_{l,k}^{\text{sub}})}{\text{Tr} \left( H_k \left( \sum_{n \neq k}^{L_n} \sum_{m=l+1}^{L_k} P_{l,m} W_{l,m}^{\text{sub}} + \sum_{m=1}^{L_k} P_{j,k} W_{j,k}^{\text{sub}} \right) \right)} \geq \Gamma_{\text{req},k}, \forall l, \forall k, \\
C2: & \frac{\text{Tr}(H_l P_{l,k} W_{l,k}^{\text{sub}})}{\text{Tr} \left( H_l \left( \sum_{n \neq l}^{L_n} \sum_{m=1}^{L_l} P_{l,m} W_{l,m}^{\text{sub}} + \sum_{m=2}^{L_l} P_{m,k} W_{m,k}^{\text{sub}} \right) \right)} \geq \Gamma_{\text{tol}}, \forall t \neq k, t \in \{1, \ldots, K\}, \\
C3: & S_{j,k}(P_{l,k} W_{l,k}^{\text{sub}}, V, \omega_j) \geq 0, \forall j, \\
C4: & S_{j,k}(P_{l,k} W_{l,k}^{\text{sub}}, V, \delta_{k,j}) \geq 0, \forall j \in \{1, \ldots, J\}, \forall k \in \{1, \ldots, K\}, \\
C5: & V \succeq 0, \ C6: P_{l,k} \succeq 0, \ C8: \omega_j \succeq 0, \forall j, \ C9: \delta_{k,j} \geq 0, \forall k, j.
\end{align*}$$

(27)

It can be shown that the above optimization problem is jointly convex with respect to the optimization variables and thus can be solved by using efficient numerical solvers. Besides, the solution of (27) also satisfies the constraints of (16). In other words, the solution of (27) serves as a suboptimal solution for (16).

2) Suboptimal Resource Allocation Scheme 2: The second proposed suboptimal resource allocation scheme adopts a similar approach to solve the problem as suboptimal resource allocation scheme 1, except for the choice of the suboptimal beamforming matrix $W_{l,k}^{\text{sub}}$ when $\text{Rank}(W_{l,k}^{\text{sub}}) > 1$. For scheme 2, the choice of beamforming matrix $W_{l,k}^{\text{sub}}$ is based on the rank-one Gaussian randomization scheme \[38\]. Specifically, we calculate the eigenvalue decomposition of $W_{l,k} = U_{l,k} \Theta_{l,k} U_{l,k}^H$, where $U_{l,k}$ and $\Theta_{l,k}$ are an $N_T \times N_T$ unitary matrix and a diagonal matrix, respectively. Then, we adopt the suboptimal beamforming vector $w_{l,k}^{\text{sub}} = U_{l,k} \Theta_{l,k}^{1/2} q_{l,k}$, where $q_{l,k} \sim \mathcal{CN}(0, I_{N_T})$. Subsequently, we follow the same approach as in (27) for optimizing $\{V, P_{l,k}, \omega_j, \delta_{k,j}\}$ and obtain a suboptimal rank-one solution $P_{l,k} W_{l,k}^{\text{sub}}$. Furthermore, we can execute scheme 2 repeatedly for different realizations of the Gaussian distributed random vector $q_{l,k}$ such that the performance of scheme 2 can be improved by selecting the best $w_{l,k}^{\text{sub}} = U_{l,k} \Theta_{l,k}^{1/2} q_{l,k}$ over different trials at the expense of higher computation complexity.

V. RESULTS

In this section, we study the system performance of the proposed resource allocation scheme via simulations. There are $K$ secondary receivers and $J$ primary receivers, which are uniformly distributed...
| Parameter                                                                 | Value                                      |
|--------------------------------------------------------------------------|--------------------------------------------|
| Carrier center frequency                                                | 2.6 GHz                                    |
| Small-scale fading distribution                                         | Rayleigh fading                            |
| Large-scale fading model                                                | Non-line-of-sight, urban micro scenario, 3GPP [39] |
| Cell radius                                                             | 500 meters                                 |
| Transceiver antenna gain                                                | 0 dBi                                      |
| Thermal noise power, $\sigma^2$, $\sigma^2_{PU}$                        | $-107.35$ dBm                              |
| Maximum tolerable received interference power at primary receiver $j$, $P_{I_j}$ | $-110.35$ dBm                              |
| Minimum requirement on the SINR of layers $[\Gamma_{req_1}, \Gamma_{req_2}]$ | $[\Gamma_{Base}, \Gamma_{Base}+3]$ dB      |
| Maximum tolerable SINR for information decoding at unintended primary receivers, $\Gamma_{tot}$ | 0 dB                                      |
| Maximum tolerable data rate at primary receiver, $R_{Bav,j,k}$          | 1 bit/s/Hz                                  |

in the range between a reference distance of 30 meters and the maximum cell radius of 500 meters. We assume that there is always one premium secondary receiver and the secondary transmitter is required to guarantee the SINR of all video layers for this receiver. On the contrary, the transmitter guarantees only the SINR of the first layer for the remaining $K - 1$ regular receivers. We assume that the video signal of each secondary receiver is encoded into two layers. For the sake of illustration, the minimum required SINR of the first layer and the second layer are denoted as $\Gamma_{Base}$ and $\Gamma_{Base} + 3$, respectively. Also, we solve the optimization problem in [15] via SDP relaxation and obtain the average system performance by averaging over different channel realizations. In the sequel, we define the normalized maximum channel estimation error of primary receiver $j$ as $\sigma^2_{PU,j} = \frac{\epsilon^2}{\|G_j\|^2_2}$ with $\sigma^2_{PU,a} = \sigma^2_{PU,b}, \forall a, b \in \{1, \ldots, J\}$. Unless specified otherwise, we assume a normalized maximum channel estimation error of $\sigma^2_{PU,j} = 0.05, \forall j$ for primary receiver $j$ and there are $N_R = 2$ receive antennas at each primary receiver. Besides, the maximum tolerable interference power at the primary receivers is set to $P_{I_j} = -110.35$ dBm, $\forall j \in \{1, \ldots, J\}$. The parameters adopted for our simulation are summarized in Table I.

A. Average Total Transmit Power versus Minimum Required SINR

Figure 2 depicts the average total transmit power versus the minimum required SINR of the base layer, $\Gamma_{Base}$, for $N_T = 8$ transmit antennas, $K = 2$ secondary receivers, $J = 2$ primary receivers, and different resource allocation schemes. It can be observed that the average total transmit power for the proposed schemes is a monotonically increasing function with respect to the minimum required SINR of the base layer. Clearly, the transmitter has to allocate more power to the information signal as the
Fig. 2. Average total transmit power (dBm) versus minimum required SINR of the base layer, $\Gamma_{\text{Base}}$, for $N_T = 8$ transmit antennas, $K = 2$ secondary receivers, $J = 2$ primary receivers, and different resource allocation schemes. The double-sided arrow indicates the performance gain achieved by the proposed schemes compared to single-layer transmission adopted in baseline scheme 1.

SINR requirement gets more stringent. Besides, the two proposed suboptimal resource allocation schemes approach the optimal performance. In fact, the proposed suboptimal schemes exploit the possibility of achieving the global optimal solution via SDP relaxation.

For comparison, Figure 2 also contains results for the average total transmit power of two baseline resource allocation schemes. For baseline scheme 1, we adopt single-layer transmission for delivering the multiuser video signals. In particular, we solve the corresponding robust optimization problem with respect to $\{W_{l,k}, V, \omega_j, \delta_{k,j}\}$ subject to constraints C1 – C9 via SDP relaxation. The minimum required SINR for decoding the single-layer video information at the secondary receivers for baseline scheme 1 is set to $\Gamma_{\text{Single req}} = 2^{\sum_{l=1}^{L_k} \log_2(1+\Gamma_{\text{req},l,k})} - 1$. In baseline scheme 2, we consider a naive layered video transmission. Specifically, the secondary transmitter treats the estimated CSI of the primary receivers as perfect CSI and exploits it for resource allocation. In other words, robustness against CSI errors is not provided by baseline scheme 2. It can be observed that baseline scheme 1 requires a higher total average power compared to the proposed power allocation schemes. This can be attributed to the fact that single-layer transmission does not possess the *self-protecting* structure for providing secure communication that layered transmission has. As a result, a higher transmit power is required in baseline scheme 1 to ensure secure video delivery. On the other hand, it is expected that for baseline scheme 2, the average transmit power is lower than that of the proposed scheme. This is due to the fact that the secondary transmitter assumes the available CSI
is perfect and transmits with insufficient power for providing secure communication. The next sections will show that baseline scheme 2 cannot meet the QoS requirements regarding communication security and interference leakage to the primary network.

**B. Average Total Transmit Power versus Number of Secondary Receivers**

Figure 3 illustrates the average total transmit power versus the number of secondary receivers for a minimum required SINR of the base layer of $\Gamma_{\text{Base}} = 5$ dB, $J = 1$ primary receiver, $N_T = 8$ transmit antennas, and different resource allocation schemes. It can be seen that the average total transmit power increases with the number of secondary receivers for all resource allocation schemes. In fact, the requirement of secure communication becomes more difficult to meet if there are more secondary receivers in the system. Besides, more degrees of freedom are utilized for reducing mutual interference between the secondary receivers which leads to a less efficient power allocation. Hence, a higher total transmit power is required to meet the target QoS.

On the other hand, the two proposed suboptimal resource allocation schemes achieve a similar performance as the optimal resource allocation. Also, the proposed schemes provide substantial power savings compared to baseline scheme 1 for $K > 1$ due to the adopted layered transmission. In particular, the performance gap between the proposed schemes and baseline scheme 1 increases with increasing numbers.
Fig. 4  Average total transmit power (dBm) versus the number of transmit antennas, $N_T$, for a minimum required SINR of the base layer of $\Gamma_{\text{Base}} = 5$ dB, $J = 2$ primary receivers, $K = 2$ secondary receivers, and different resource allocation schemes. The double-sided arrow indicates the performance gain achieved by the proposed schemes compared to single-layer transmission adopted in baseline scheme 1.

of primary receivers. In other words, layered transmission is effective for reducing the transmit power in multi-receiver environments. As for baseline scheme 2, although it consumes less transmit power compared to the optimal scheme, it cannot guarantee any QoS in communication secrecy and interference to the primary receivers, cf. Figures 5 – 7.

C. Average Total Transmit Power versus Number of Antennas

Figure 4 shows the average total transmit power versus the number of transmit antennas, $N_T$, for a minimum required SINR of the base layer of $\Gamma_{\text{Base}} = 5$ dB, $J = 2$ primary receivers, $K = 2$ secondary receivers, and different resource allocation schemes. It is expected that the average total transmit power decreases for all resource allocation schemes with increasing number of transmit antennas. This is because extra degrees of freedom can be exploited for resource allocation when more antennas are available at the transmitter. Specifically, with more antennas, the direction of beamforming matrix $W_{l,k}$ can be more accurately steered towards the secondary receivers which reduces both the power consumption at the secondary transmitter and the power leakage to the primary receivers. On the other hand, the proposed schemes provide substantial power savings compared to baseline scheme 1 for all considered scenarios because of the adopted layered transmission. Besides, baseline scheme 2 consumes less transmit power compared to the optimal scheme again. Although baseline scheme 2 can exploit the extra degrees of
freedom offered by the increasing number of antennas, it is unable to protect the primary receivers from interference and cannot guarantee communication security due to the imperfection of the CSI, cf. Figures 5 – 7.

D. Average Secrecy Rate

Figure 5 depicts the average secrecy rate of the base layer versus the minimum required SINR of the base layer, $\Gamma_{\text{Base}}$, for $N_T = 8$ transmit antennas, $K = 2$ secondary receivers, $J = 2$ primary receivers, and different resource allocation schemes. Despite the imperfection of the CSI, the proposed optimal resource allocation scheme and the two suboptimal resource allocation schemes are able to guarantee the minimum secrecy rate required by constraints C2 and C4 in every time instant, because of the adopted robust optimization framework. On the other hand, baseline scheme 1 achieves an exceedingly high average secrecy rate since the entire video information is encoded in the first layer. The superior secrecy rate performance of baseline scheme 1 comes at the expense of an exceedingly high transmit power, cf. Figure 2. In the low $\Gamma_{\text{Base}}$ regime, even though baseline scheme 2 is able to meet the minimum secrecy rate requirement on average, we emphasize that baseline scheme 2 is unable to fulfill the requirement for all channel realizations, i.e., secure communication is not ensured. Besides, in the high $\Gamma_{\text{Base}}$ regime, in contrast to the proposed schemes, baseline scheme 2 cannot even satisfy the minimum secrecy rate requirement on average.
E. Average Interference Power

Figure 6 depicts the average received interference power at each primary receiver versus the minimum required SINR of the base layer \( \Gamma_{\text{Base}} \), for \( N_T = 8 \) transmit antennas, \( K = 2 \) secondary receivers, \( J = 2 \) primary receivers, and different resource allocation schemes. As can be observed, the proposed optimal resource allocation scheme and the two suboptimal resource allocation schemes are able to control their transmit power such that the received interference powers at the primary receivers are below the maximum tolerable interference threshold. Similar results can be observed for baseline scheme 1 as robust optimization is also adopted in this case. As for baseline scheme 2, although the average interference received by each primary receiver is below the maximum tolerable threshold for \( \Gamma_{\text{Base}} \leq 6 \) dB, baseline scheme 2 cannot meet the interference requirement for all channel realizations. Besides, as the value of \( \Gamma_{\text{Base}} \) increases, the received interference power at each primary receiver increases significantly compared to the proposed schemes. For high values of \( \Gamma_{\text{Base}} \), the average received interference at each primary receiver for baseline scheme 2 exceeds the maximum tolerable interference limit.

Figure 7 shows the average received interference power at each primary receiver versus the number of secondary receivers \( K \) for a minimum required SINR of the base layer of \( \Gamma_{\text{Base}} = 5 \) dB, \( N_T = 8 \) transmit antennas, \( J = 1 \) primary receiver, and different resource allocation schemes. It can be observed that the received interference power at each primary receiver increases with the number of secondary receivers.
Fig. 7. Average received interference power (dBm) at each primary receiver versus the number of secondary receivers, $K$, for a minimum required SINR of the base layer of $\Gamma_{\text{Base}} = 5$ dB, $N_T = 8$ transmit antennas, $J = 1$ primary receiver, and different resource allocation schemes.

since the secondary transmitter is required to transmit with higher power for serving extra receivers. Besides, the proposed schemes and baseline scheme 1 are able to control the interference leakage to the primary network for any number of secondary receivers. However, baseline scheme 2 fails to properly control the transmit power and cannot satisfy the maximum tolerable received interference limit for all channel realizations, due to the non-robust resource allocation algorithm design.

VI. Conclusions

In this paper, we studied the robust resource allocation algorithm design for layered transmit power minimization for secure layered video transmission in secondary CR networks. The algorithm design was formulated as a non-convex optimization problem taking into account the communication secrecy for transmission to the secondary receivers, the imperfection of the CSI of the primary receivers, and the interference leakage to the primary network. We showed that the global optimal solution of the considered non-convex optimization problem can be constructed based on the primal and the dual solutions of the SDP relaxed problem. Furthermore, two suboptimal resource allocation schemes were proposed for the case when the dual problem solution is unavailable for construction of the optimal solution. Simulation results unveiled the power savings enabled by the self-protecting structure of layered transmission and the
robustness of our proposed optimal scheme against the imperfect knowledge of the CSI of the primary receivers.

APPENDIX

A. Proof of Proposition 1

Constraint C4 is non-convex due to the log-determinant function and the coupling between optimization variables $W_{1,k}$ and $V$. In light of the intractability of the constraint, we first establish a lower bound on the left hand side of C4. Then, we will reveal the tightness of the proposed lower bound. We now start the proof by rewriting C4 as

$$ C4: \log_2 \det \left( I_{NR} + \Sigma_j^{-\frac{1}{2}} G_j^H W_{1,k} G_j \Sigma_j^{-\frac{1}{2}} \right) \leq R_{Eav,j,k} \quad (28a) $$

$$(a) \iff \det \left( I_{NR} + \Sigma_j^{-\frac{1}{2}} G_j^H W_{1,k} G_j \Sigma_j^{-\frac{1}{2}} \right) \leq 1 + \xi_{Eav,j,k}, \quad (28b)$$

where $(a)$ is due to the fact that $\Sigma_j \succ 0$ and $\det(I + AB) = \det(I + BA)$ holds for any choice of matrices $A$ and $B$. Then, we introduce the following lemma which provides a lower bound on the left hand side of $(28b)$.

**Lemma 3**: For any square matrix $A \succeq 0$, we have the following inequality [35], [40]:

$$ \det(I + A) \geq 1 + \text{Tr}(A), \quad (29) $$

where equality holds if and only if $\text{Rank}(A) \leq 1$.

Exploiting Lemma 3 the left hand side of $(28b)$ is lower bounded by

$$ \det(I_{NR} + \Sigma_j^{-\frac{1}{2}} G_j^H W_{1,k} G_j \Sigma_j^{-\frac{1}{2}}) \geq 1 + \text{Tr}(\Sigma_j^{-\frac{1}{2}} G_j^H W_{1,k} G_j \Sigma_j^{-\frac{1}{2}}). \quad (30) $$

Subsequently, by combining equations $(28)$ and $(30)$, we have the following implications

$$(28a) \iff (28b) \implies \text{Tr}(\Sigma_j^{-\frac{1}{2}} G_j^H W_{1,k} G_j \Sigma_j^{-\frac{1}{2}}) \leq \xi_{Eav,j,k} \quad (31a)$$

$$(b) \implies \lambda_{\text{max}}(\Sigma_j^{-\frac{1}{2}} G_j^H W_{1,k} G_j \Sigma_j^{-\frac{1}{2}}) \leq \xi_{Eav,j,k} \quad (31b)$$

$$\iff \Sigma_j^{-\frac{1}{2}} G_j^H W_{1,k} G_j \Sigma_j^{-\frac{1}{2}} \preceq \xi_{Eav,j,k} I_{NR} \quad (31c)$$

$$\iff G_j^H W_{1,k} G_j \preceq \xi_{Eav,j,k} \Sigma_j \quad (31d)$$

where $(b)$ is due to $\text{Tr}(A) \geq \lambda_{\text{max}}(A)$ for a positive semidefinite square matrix $A \succeq 0$. We note that $\text{Tr}(A) \geq \lambda_{\text{max}}(A)$ holds if and only if $\text{Rank}(A) \leq 1$. Thus, in general, the set spanned by $(28a)$ is a subset of the set spanned by $(31d)$. Besides, $(28a)$ is equivalent to $(31d)$ when $\text{Rank}(W_{1,k}) \leq 1, \forall k$. 

Thursday 26th June, 2014  
DRAFT
B. Proof of Theorem 1

The proof is divided into two parts. We first study the structure of the optimal solution \( W_{l,k}^* \) of the relaxed version of problem (26). Then, if \( \exists l, k : \text{Rank}(W_{l,k}^* k) > 1 \), we propose a method to construct a solution \( \tilde{\Lambda} \triangleq \{ \tilde{W}_{l,k}, \tilde{V}, \tilde{\omega}_j, \tilde{\delta}_{k,j} \} \) that not only achieves the same objective value as \( \Lambda^* \triangleq \{ W_{l,k}^*, V^*, \omega_j^*, \delta_{k,j}^* \} \), but also admits a rank-one beamforming matrix \( \tilde{W}_{l,k} \).

The relaxed version of problem (26) is jointly convex with respect to the optimization variables and satisfies Slater’s constraint qualification. As a result, the Karush-Kuhn-Tucker (KKT) conditions are necessary and sufficient conditions [33] for the optimal solution of the relaxed version of problem (26). The Lagrangian function of the relaxed version of problem (26) is given by

\[
\mathcal{L} = \sum_{k=1}^{K} \sum_{l=1}^{L_k} \text{Tr}(W_{l,k}) + \sum_{k=1}^{K} \sum_{l=1}^{L_k} \gamma_{l,k} \left\{ \Gamma_{\text{req},l,k} \left[ \sum_{n \neq k}^{L_n} \sum_{l=1}^{L_k} \text{Tr}(H_{k}W_{l,n}) + \sum_{m=l+1}^{L_k} \text{Tr}(H_{k}W_{m,k}) - \text{Tr}(H_{k}W_{l,k}) \right] \right. \\
+ \sum_{t=1}^{K} \sum_{k \neq t}^{K} \psi_{l,k} \left\{ \text{Tr}(H_{t}W_{l,k}) - \Gamma_{\text{tol}} \left[ \sum_{n \neq k}^{L_n} \sum_{l=1}^{L_k} \text{Tr}(H_{l}W_{l,n}) + \sum_{m=l+1}^{L_k} \text{Tr}(H_{l}W_{m,k}) \right] \right\} + \Omega \\
- \sum_{j=1}^{J} \text{Tr}(S_{C_{3,j}}(W_{l,k}, V, \omega_j) D_{C_{3,j}}) - \sum_{k=1}^{K} \text{Tr}(S_{C_{4,k,j}}(W_{l,k}, V, \delta_{k,j}) D_{C_{4,k,j}}) - \sum_{k=1}^{K} \sum_{l=1}^{L_k} \text{Tr}(W_{l,k,Y_{l,k}}),
\]

where \( \Omega \) denotes the collection of the terms that only involve variables that are not relevant for the proof. \( \gamma_{l,k} \geq 0, k \in \{1, \ldots, K\}, l \in \{1, \ldots, L_k\} \), and \( \psi_{l,k} \geq 0, t \in \{1, \ldots, K\} \), are the Lagrange multipliers associated with constraints C1 and C2, respectively. Matrix \( Y_{l,k}^* \geq 0 \) is the Lagrange multiplier matrix corresponding to the semidefinite constraint on matrix \( W_{l,k} \) in C6. \( D_{C_{3,j}} \geq 0, \forall j \in \{1, \ldots, J\} \), and \( D_{C_{4,k,j}} \geq 0, \forall k \in \{1, \ldots, K\}, j \in \{1, \ldots, J\} \), are the Lagrange multiplier matrices for the interference temperature constraint and the maximum tolerable SINRs of the secondary receivers in \( C_3 \) and \( C_4 \), respectively. In the following, we focus on the KKT conditions related to the optimal \( W_{l,k}^* \):

\[
Y_{l,k}^*; D_{C_{3,j}}^*, D_{C_{4,k,j}}^* \geq 0, \gamma_{l,k}^*, \psi_{l,k}^* \geq 0, \\
Y_{l,k}^* W_{l,k}^* = 0, \\
\nabla W_{l,k}^* \mathcal{L} = 0,
\]

where \( Y_{l,k}^*; D_{C_{3,j}}^*, D_{C_{4,k,j}}^*; \gamma_{l,k}^*, \psi_{l,k}^* \), are the optimal Lagrange multipliers for the dual problem of (26). From the complementary slackness condition in (34), we observe that the columns of \( W_{l,k}^* \) are required to lie in the null space of \( Y_{l,k}^* \) for \( W_{l,k}^* \neq 0 \). Thus, we study the composition of \( Y_{l,k}^* \) to obtain the structure
express the optimal solution of (35) leads to
\[
Y_{l,k}^* = A_{l,k} \left[ \sum_{t<l} \gamma_{l,t}^* \Gamma_{req,l,k} - \gamma_{l,l}^* \right] H_k
\]  
(36)

where
\[
A_{l,k} = \left\{ \begin{array}{ll}
B_{l,k} + \sum_{t \neq k} \psi_{l,t}^* H_t + \sum_{j=1}^K \sum_{k=1}^J R_{j,D_{C\mathbf{T}_{k,j}}}^* R_{j}^H & \text{if } l = 1 \\
B_{l,k} - \sum_{t \neq k} \psi_{l,t}^* \Gamma_{tol,H} & \text{otherwise}
\end{array} \right.
\]  
(37)

and
\[
B_{l,k} = \sum_{m \neq k} \sum_{r=1}^{L_m} \gamma_{r,m}^* \Gamma_{req,m} - \Gamma_{tol} \left[ \sum_{t \neq k} \sum_{n \neq l,k} \psi_{l,n}^* H_t \right] + \sum_{j=1}^J U_{g_j} D_{C\mathbf{T}_{j}}^* U_{g_j}^H.
\]  
(38)

Without loss of generality, we define \( r_{l,k} = \text{Rank}(A_{l,k}^*) \) and the orthonormal basis of the null space of \( A_{l,k}^* \) as \( \Upsilon \in \mathbb{C}^{N_T \times (N_T - r_{l,k})} \) such that \( A_{l,k}^* \Upsilon_{l,k} = 0 \) and \( \text{Rank}(\Upsilon_{l,k}) = N_T - r_{l,k} \). Let \( \phi_{r_{l,k}} \in \mathbb{C}^{N_T \times 1} \), \( 1 \leq r_{l,k} \leq N_T - r_{l,k} \), denote the \( r_{l,k} \)-th column of \( \Upsilon_{l,k} \). By exploiting \cite{57}, Proposition 4.1, it can be shown that \[ \sum_{t<l} \gamma_{l,t}^* \Gamma_{req,t} - \gamma_{l,l}^* \] \( H_k \neq 0 \) and \( H_k \Upsilon_{l,k} = 0 \) for the optimal solution. Besides, we can express the optimal solution of \( W_{l,k}^* \) as
\[
W_{l,k}^* = \sum_{r_{l,k}=1}^{N_T-r_{l,k}} \alpha_{r_{l,k}} \phi_{r_{l,k}} \phi_{r_{l,k}}^H + \sum_{l,k} f_{l,k} u_{l,k} u_{l,k}^H
\]  
(39)

where \( \alpha_{r_{l,k}} \geq 0, \forall r_{l,k} \in \{1, \ldots, N_T - r_{l,k}\} \), and \( f_{l,k} > 0 \) are positive scalars and \( u_{l,k} \in \mathbb{C}^{N_T \times 1} \), \( \| u_{l,k} \| = 1 \), satisfies \( u_{l,k}^H \Upsilon_{l,k} = 0 \). In particular, we have the following equality:
\[
H_k W_{l,k}^* = \sum_{r_{l,k}=1}^{N_T-r_{l,k}} H_k \alpha_{r_{l,k}} \phi_{r_{l,k}} \phi_{r_{l,k}}^H + H_k f_{l,k} u_{l,k} u_{l,k}^H.
\]  
(40)

In the second part of the proof, we construct another solution \( \tilde{\Lambda} = \{ \tilde{W}_{l,k}, \tilde{V}, \tilde{\omega}_j, \tilde{\delta}_{k,j} \} \) based on (40). Suppose there exist pair of \( l \) and \( k \) such that \( \text{Rank}(W_{l,k}^*) > 1 \). Let
\[
\tilde{W}_{l,k} = f_{l,k} u_{l,k} u_{l,k}^H = W_{l,k}^* \sum_{r_{l,k}=1}^{N_T-r_{l,k}} \phi_{r_{l,k}} \phi_{r_{l,k}}^H,
\]  
(41)

\[
\tilde{V} = V^* + \sum_{r_{l,k}=1}^{N_T-r_{l,k}} \alpha_{l,k} \phi_{r_{l,k}} \phi_{r_{l,k}}^H, \quad \tilde{\omega}_j = \delta_j, \quad \tilde{\delta}_{k,j} = \delta_{k,j}.
\]

Then, we substitute the constructed solution \( \tilde{\Lambda} \) into the objective function and the constraints in (46)
yields

\[
\text{Objective value: } \sum_{k=1}^{K} \sum_{l=1}^{L_k} \text{Tr}(\tilde{W}_{l,k}) + \text{Tr}(\tilde{V}) = \sum_{k=1}^{K} \sum_{l} \text{Tr}(W_{l,k}^*) + \text{Tr}(V^*) \tag{42}
\]

C1:

\[
\frac{\text{Tr}(H_k \tilde{W}_{l,k})}{\text{Tr}(H_k (\sum_{n \neq k}^{K} W_{r,n}^* + \sum_{m = l+1}^{L_k} W_{j,k}^*) + \text{Tr}(H_k \tilde{V}) + \sigma_k^2)} = \frac{\text{Tr}(H_k W_{l,k}^*)}{\text{Tr}(H_k (\sum_{n \neq k}^{K} W_{r,n}^* + \sum_{m = l+1}^{L_k} W_{j,k}^*) + \text{Tr}(H_k V^*) + \sigma_k^2)} \geq \gamma_{\text{req}}, \forall l, k;
\]

C2:

\[
\frac{\text{Tr}(H_l \tilde{W}_{l,k})}{\text{Tr}(H_l (\sum_{m = 1}^{L_k} W_{r,n}^* + \sum_{m = 2}^{L_k} W_{m,k}^*) + \text{Tr}(\tilde{V} H_l) + \sigma_k^2)} \leq \gamma_{\text{tol}}, \forall l \neq k, t \in \{1, \ldots, K\},
\]

C3: \( S_{\tilde{W}_{l,k}}(\tilde{W}_{l,k}, \tilde{V}, \omega_j) \geq S_{\tilde{W}_{l,k}}(W_{l,k}^*, V^*, \omega_j^*) + U_{\tilde{g}_j}^{H} \left[ \sum_{\gamma_{l,k} = 1}^{N_T - r_{l,k}} \alpha_{l,k} \phi_{\gamma_{l,k}} \phi_{\gamma_{l,k}}^{H} \right] U_{\tilde{g}_j} \geq 0, \forall j \in \{1, \ldots, J\};
\]

C4: \( S_{\tilde{W}_{l,k}}(\tilde{W}_{l,k}, \tilde{V}, \omega_j) \geq S_{\tilde{W}_{l,k}}(W_{l,k}^*, V^*, \delta_{l,j}^*) + R_{\tilde{r}_j}^{H} \left[ \sum_{\gamma_{l,k} = 1}^{N_T - r_{l,k}} \alpha_{l,k} \phi_{\gamma_{l,k}} \phi_{\gamma_{l,k}}^{H} \right] R_{\tilde{r}_j} \geq 0, \forall k, j;
\]

C5: \( \tilde{W}_{l,k} \succeq 0, \quad C6: \tilde{V} \succeq 0, \quad C8: \tilde{\omega}_j = \omega_j^* \succeq 0, \quad C9: \tilde{\delta}_{l,k} = \delta_{l,j}^* \succeq 0.
\]

It can be seen from (42) that the constructed solution set achieves the same optimal value as the optimal solution while satisfying all the constraints. Thus, \( \tilde{\Lambda} \) is also an optimal solution of (26). Besides, the constructed beamforming matrix \( \tilde{W}_{l,k} \) is a rank-one matrix, i.e., \( \text{Rank}(\tilde{W}_{l,k}) = 1 \). On the other hand, we can obtain the values of \( f_{l,k} \) and \( \alpha_{l,k} \) in (41) by substituting the variables in (41) into the relaxed version of (26) and solving the resulting convex optimization problem for \( f_{l,k} \) and \( \alpha_{l,k} \).

If there is more than one pair of \( l \) and \( k \) such that \( \text{Rank}(W_{l,k}) > 1 \), then we employ (41) more than once and construct the rank-one solution by handling the non-rank-one beamforming matrices one by one. Besides, the ordering of the \( l \) and \( k \) pairs in constructing the optimal solution does not affect to the optimal objective value.
REFERENCES

[1] D. W. K. Ng, R. Schober, and H. Alnuweiri, “Power Efficient MISO Beamforming for Secure Layered Transmission,” in Proc. IEEE Wireless Commun. and Networking Conf., Apr. 2014.

[2] D. Tse and P. Viswanath, Fundamentals of Wireless Communication, 1st ed. Cambridge University Press, 2005.

[3] 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.

[4] K. Bhattad, K. Narayanan, and G. Caire, “On the Distortion SNR Exponent of Some Layered Transmission Schemes,” IEEE Trans. Inf. Theory, vol. 54, pp. 2943–2958, Jul. 2008.

[5] 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.

[6] 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., Sep. 2007, pp. 1–4.

[7] “Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies,” Federal Communications Commission, Tech. Rep., 2002, FCC 02-155.

[8] Y.-C. Liang, K.-C. Chen, G. Li, and P. Mahonen, “Cognitive Radio Networking and Communications: An Overview,” IEEE Trans. Veh. Technol., vol. 60, pp. 3386–3407, Sep. 2011.

[9] G. Ganesan and Y. Li, “Cooperative Spectrum Sensing in Cognitive Radio, Part I: Two User Networks,” IEEE Trans. Wireless Commun., vol. 6, pp. 2204–2213, Jun. 2007.

[10] J. Ma, G. Zhao, and Y. Li, “Soft Combination and Detection for Cooperative Spectrum Sensing in Cognitive Radio Networks,” IEEE Trans. Wireless Commun., vol. 7, pp. 4502–4507, Nov. 2008.

[11] Y.-C. Liang, Y. Zeng, E. Peh, and A. T. Hoang, “Sensing-Throughput Tradeoff for Cognitive Radio Networks,” IEEE Trans. Wireless Commun., vol. 7, pp. 1326–1337, Apr. 2008.

[12] Z. Quan, S. Cui, and A. Sayed, “Optimal Linear Cooperation for Spectrum Sensing in Cognitive Radio Networks,” IEEE J. Select. Areas Commun., vol. 2, pp. 28–40, Feb. 2008.

[13] H. Islam, Y.-C. Liang, and A. T. Hoang, “Joint Beamforming and Power Control in the Downlink of Cognitive Radio Networks,” in Proc. IEEE Wireless Commun. and Networking Conf., Apr. 2007, pp. 21–26.

[14] L. Zhang, Y.-C. Liang, and Y. Xin, “Joint Beamforming and Power Allocation for Multiple Access Channels in Cognitive Radio Networks,” IEEE J. Select. Areas Commun., vol. 26, pp. 38–51, Jan. 2008.

[15] L. Zhang, Y.-C. Liang, Y. Xin, and H. Poor, “Robust Cognitive Beamforming with Partial Channel State Information,” IEEE Trans. Wireless Commun., vol. 8, pp. 4143–4153, Aug. 2009.

[16] G. Zheng, K.-K. Wong, and B. Ottersten, “Robust Cognitive Beamforming With Bounded Channel Uncertainties,” IEEE Trans. Signal Process., vol. 57, pp. 4871–4881, Dec. 2009.

[17] D. W. K. Ng, E. S. Lo, and R. Schober, “Multi-Objective Resource Allocation for Secure Communication in Cognitive Radio Networks with Wireless Information and Power Transfer,” Submitted for possible journal publication, Mar. 2014. [Online]. Available: http://arxiv.org/abs/1403.0054

[18] 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.

[19] 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, Aug. 2005.

[20] W. Mesbah, M. Shaqfeh, and H. Alnuweiri, “Jointly Optimal Rate and Power Allocation for Multilayer Transmission,” IEEE Trans. Commun., vol. 13, pp. 834–845, Feb. 2014.

[21] M. Shaqfeh, W. Mesbah, and H. Alnuweiri, “Utility Maximization for Layered Transmission Using the Broadcast Approach,” IEEE Trans. Wireless Commun., vol. 11, pp. 1228–1238, Mar. 2012.

[22] A. D. Wyner, “The Wire-Tap Channel,” Tech. Rep., Oct. 1975.
[23] I. Csiszar and J. Korner, “Broadcast Channels with Confidential Messages,” *IEEE Trans. Inf. Theory*, vol. 24, pp. 339–348, May 1978.

[24] S. K. Leung-Yan-Cheong and M. E. Hellman, “The Gaussian Wire-Tap Channel,” *IEEE Trans. Inf. Theory*, vol. 24, pp. 451 – 456, Jul. 1978.

[25] Q. Li and W.-K. Ma, “Multicast Secrecy Rate Maximization for MISO Channels with Multiple Multi-Antenna Eavesdroppers,” in *Proc. IEEE Intern. Commun. Conf.*, Jun. 2011, pp. 1–5.

[26] S. Goel and R. Negi, “Guarantee Secrecy using Artificial Noise,” *IEEE Trans. Wireless Commun.*, vol. 7, pp. 2180–2189, Jun. 2008.

[27] D. W. K. Ng, E. S. 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.

[28] D. Ng, E. Lo, and R. Schober, “Energy-Efficient Resource Allocation for Secure OFDMA Systems,” *IEEE Trans. Veh. Technol.*, vol. 61, pp. 2572–2585, Jul. 2012.

[29] G. Zheng, K. K. Wong, and T. S. Ng, “Robust Linear MIMO in the Downlink: A Worst-Case Optimization with Ellipsoidal Uncertainty Regions,” *EURASIP J. Adv. Signal Process.*, vol. 2008, 2008, Article ID 609028.

[30] C. Shen, T.-H. Chang, K.-Y. Wang, Z. Qiu, and C.-Y. Chi, “Distributed Robust Multicell Coordinated Beamforming With Imperfect CSI: An ADMM Approach,” *IEEE Trans. Signal Process.*, vol. 60, pp. 2988–3003, Jun. 2012.

[31] N. Vucic and H. Boche, “Robust QoS-Constrained Optimization of Downlink Multiuser MISO Systems,” *IEEE Trans. Signal Process.*, vol. 57, pp. 714–725, Feb. 2009.

[32] D. W. K. Ng, E. S. Lo, and R. Schober, “Robust Beamforming for Secure Communication in Systems with Wireless Information and Power Transfer,” *IEEE Trans. Wireless Commun.*, vol. PP, no. 99, 2014.

[33] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[34] Z. Q. Luo, J. Sturm, and S. Zhang, “Multivariate Nonnegative Quadratic Mappings,” *SIAM J. Optim.*, vol. 14, pp. 1140–1162, Jul. 2004.

[35] Q. Li and W.-K. Ma, “Spatially Selective Artificial-Noise Aided Transmit Optimization for MISO Multi-Eves Secrecy Rate Maximization,” *IEEE Trans. Signal Process.*, vol. 61, pp. 2704–2717, May 2013.

[36] M. Grant and S. Boyd, “CVX: Matlab Software for Disciplined Convex Programming, version 2.0 Beta,” [Online] https://cvxr.com/cvx, Sep. 2012.

[37] L. Liu, R. Zhang, and K.-C. Chua, “Secrecy Wireless Information and Power Transfer with MISO Beamforming,” *IEEE Trans. Signal Process.*, vol. 62, pp. 1850–1863, Apr. 2014.

[38] N. Sidiropoulos, T. Davidson, and Z.-Q. Luo, “Transmit Beamforming for Physical-Layer Multicasting,” *IEEE Trans. Signal Process.*, vol. 54, pp. 2239–2251, Jun. 2006.

[39] “Evolved Universal Terrestrial Radio Access (E-Utra); Further Advancements for E-Utra Physical Layer Aspects,” 3GPP TR 36.814 V9.0.0 (2010-03), Tech. Rep.

[40] Q. Li and W.-K. Ma, “Optimal and Robust Transmit Designs for MISO Channel Secrecy by Semidefinite Programming,” *IEEE Trans. Signal Process.*, vol. 59, pp. 3799–3812, May 2011.