Secure Energy Efficiency Maximization in MISO Heterogeneous Cellular Networks

Jun-Ting Liu[⋆⋆], Chien-Ming Chen and Che Lin[†], *Senior Member, IEEE*

Abstract

In this paper,

I. Introduction

With

II. System Model and Problem Formulation

For the l-th femto cell, the transmitted signal for the FU can be expressed as

$$\mathbf{x}_l = \mathbf{w}_l \cdot s_l + \mathbf{v}_l, \tag{1}$$

where $\mathbf{w}_l \in \mathbb{C}^{N_t \times 1}$ denotes the beamforming vector for the FBS l, s_i denotes the information signal sent from FBS l, and $\mathbf{v}_l \in \mathbb{C}^{N_t \times 1}$ denotes the artificial noise (AN) to interfere EVEs.

For the l-th femto cell, the received signal for the FU is expressed as

$$y_l^{FU} = \mathbf{h}_{l,l}^H \mathbf{x}_l + \sum_{m \neq l} \mathbf{h}_{m,l}^H \mathbf{x}_m + I_l^{FU} + n_l^{FU}, \tag{2}$$

where $\mathbf{h}_{m,l} \in \mathbb{C}^{N_t \times 1}$ denotes the channel from the FBS in the m-th femto cell to the FU in the l-th femto cell, I_l^{FU} is the cross-link interference from the MBS, and $n_l^{FU} \sim CN(0, \sigma^2_{FU,l})$ is the additive white Gaussian noise (AWGN) at the FU in femto cell l.

After the signal is received by the FU, it is split into two parts for information decoding (ID) and energy harvesting (EH) with parameter ρ_l and $1 - \rho_l$, respectively.

The signal received by the PE j in the l-th femto cell is

$$y_{l,j}^{PE} = \mathbf{f}_{l,l,j}^H \mathbf{x}_l + \sum_{m \neq l} \mathbf{f}_{m,l,j}^H \mathbf{x}_m + I_{l,j}^{PE} + n_{l,j}^{PE}, \tag{3}$$

where $\mathbf{f}_{m,l,j} \in \mathbb{C}^{N_t \times 1}$ denotes the channel from the FBS in the m-th femto cell to the PE j in the l-th femto cell, $I_{l,j}^{PE}$ is the cross-link interference from the MBS, and $n_{l,j}^{PE} \sim CN(0, \sigma^2_{PE,l,j})$ is the AWGN at the PE j in the l-th femto cell.

The signal received by the EVE k in the l-th femto cell is expressed as

$$y_{l,k}^{EVE} = \mathbf{g}_{l,l,k}^H \mathbf{x}_l + \sum_{m \neq l} \mathbf{g}_{m,l,k}^H \mathbf{x}_m + I_{l,k}^{EVE} + n_{l,k}^{EVE} \tag{4}$$

where $\mathbf{g}_{m,l,k} \in \mathbb{C}^{N_t \times 1}$ denotes the channel from the FBS in the m-th femto cell to the EVE k in the l-th femto cell, $I_{l,k}^{EVE}$ denotes the cross-link interference from the MBS, and $n_{l,k}^{PE} \sim CN(0, \sigma^2_{EVE,l,k})$ is the AWGN at the EVE k in the l-th femto cell.

[⋆] Jun-Ting Liu is with Department of Electrical Engineering, National Tsing Hua University, Hsinchu, Taiwan 30013, R.O.C. E-mail: —–@gmail.com

[†] Che Lin is the corresponding author. Address: Institute of Communications Engineering, National Tsing Hua University, Hsinchu, Taiwan 30013, R.O.C. E-mail: clin@ee.nthu.edu.tw.

From (1) and (2), after the signal is divided into ID and EH, we can express the signal-to-interference-plus-noise ratio (SINR) of the ID signal in the l-th femto cell as

$$\gamma_l^{FU}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\},\{\rho_l\}\right)= \frac{\rho_l|\mathbf{w}_l^H\mathbf{h}_{l,l}|^2}{\rho_l\left(\sum_{m\neq l}|\mathbf{w}_m^H\mathbf{h}_{m,l}|^2+\sum_{m=1}^{L}|\mathbf{v}_m^H\mathbf{h}_{m,l}|^2+P_l^{FU}+\sigma_{FU,l}^2\right)+\sigma_s^2} \tag{5}$$

Similarly, the SINR for the PE j receiver is expressed as

$$\gamma_{l,j}^{PE}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\}\right)= \frac{|\mathbf{w}_l^H\mathbf{f}_{l,l,j}|^2}{\sum_{m\neq l}|\mathbf{w}_m^H\mathbf{f}_{m,l,j}|^2+\sum_{m=1}^{L}|\mathbf{v}_m^H\mathbf{f}_{m,l,j}|^2+P_{l,j}^{PE}+\sigma_{PE,l,j}^2+\sigma_s^2} \tag{6}$$

The SINR for the eavesdropper k in the l-th cell is expressed as

$$\gamma_{l,k}^{EVE}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\}\right)= \frac{|\mathbf{w}_l^H\mathbf{g}_{l,l,k}|^2}{\sum_{m\neq l}|\mathbf{w}_m^H\mathbf{g}_{m,l,k}|^2+\sum_{m=1}^{L}|\mathbf{v}_m^H\mathbf{g}_{m,l,k}|^2+P_{l,k}^{EVE}+\sigma_{EVE,l,k}^2} \tag{7}$$

The harvested power by the FU in the l-th cell is expressed as

$$Q_l^{FU}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\},\{\rho_l\}\right)= \xi_1(1-\rho_l)\left(\sum_{m=1}^{L}|\mathbf{w}_m^H\mathbf{h}_{m,l}|^2+\sum_{m=1}^{L}|\mathbf{v}_m^H\mathbf{h}_{m,l}|^2+P_l^{FU}+\sigma_{FU,l}^2\right) \tag{8}$$

where ξ_1 is the efficiency.

The harvested power by the PE j in the l-th cell is

$$Q_{l,j}^{PE}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\}\right)= \xi_2\left(\sum_{m=1}^{L}|\mathbf{w}_m^H\mathbf{f}_{m,l,j}|^2+\sum_{m=1}^{L}|\mathbf{v}_m^H\mathbf{f}_{m,l,j}|^2+P_{l,j}^{PE}+\sigma_{PE,l,j}^2\right) \tag{9}$$

where ξ_2 is the efficiency.

Total power consumption is

$$P_{RF}+\zeta\left(\sum_{l=1}^{L}||\mathbf{w}_l||^2+\sum_{l=1}^{L}||\mathbf{v}_l||^2\right) \tag{10}$$

where ζ is amplifier coefficient

The following equations are zero-forcing constraints: We set the signal part from PEs and EVE's SINR as 0, as the following euations.

$$|\mathbf{w}_l^H\ \mathbf{g}_{l,l,k}|=0 \tag{11}$$

$$|\mathbf{w}_l^H\ \mathbf{f}_{l,l,j}|=0 \tag{12}$$

III. Problem Formulation

The secure energy efficiency problem can be formulated as

$$\max_{\mathbf{w}_l,\mathbf{v}_l,\rho_l} \quad \frac{\sum_{l=1}^{L} a_l \left\{\log_2\left(1+\gamma_l^{FU}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\},\{\rho_l\}\right)\right)\right\}}{P_{RF}+\zeta\left(\sum_{l=1}^{L}||\mathbf{w}_l||^2+\sum_{l=1}^{L}||\mathbf{v}_l||^2\right)} \tag{13a}$$

$$\text{s.t.} \quad Q_l^{FU}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\},\{\rho_l\}\right) \geq \Gamma_1,\ \forall l, \tag{13b}$$

$$Q_{l,j}^{PE}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\}\right) \geq \Gamma_2,\ \forall l,\ j, \tag{13c}$$

$$||\mathbf{w}_l||^2+||\mathbf{v}_l||^2 \leq P_l,\ \forall l, \tag{13d}$$

$$\sum_{l=1}^{L}||\mathbf{q}_{l,p}^H\mathbf{w}_l||^2+||\mathbf{q}_{l,p}^H\mathbf{v}_l||^2 \leq \Gamma_3,\ \forall p, \tag{13e}$$

$$|\mathbf{w}_l^H\ \mathbf{g}_{l,l,k}| = 0 \tag{13f}$$

$$|\mathbf{w}_l^H\ \mathbf{f}_{l,l,j}| = 0 \tag{13g}$$

We first define the lower bound of FU's rate and the upper bound of eavesdropper's rate as R_l^{FU} and R_l^e, respectively.

$$R_l^{FU} \triangleq \log_2\left(1+\gamma_l^{FU}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\},\{\rho_l\}\right)\right),\ \forall l \tag{14}$$

$$\tag{15}$$

Then we can reformulate the problem as

$$\max_{\mathbf{w}_l,\mathbf{v}_l,\rho_l,R_l^{FU},R_l^e} \quad \frac{\sum_{l=1}^{L}\tilde{a}_l R_l^{FU}}{P_{RF}+\zeta\left(\sum_{l=1}^{L}||\mathbf{w}_l||^2+\sum_{l=1}^{L}||\mathbf{v}_l||^2\right)} \tag{16a}$$

$$\text{s.t.} \quad R_l^{FU} \leq \log_2\left(1+\gamma_l^{FU}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\},\{\rho_l\}\right)\right),\ \forall l, \tag{16b}$$

$$Q_l^{FU}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\},\{\rho_l\}\right) \geq \Gamma_1,\ \forall l, \tag{16c}$$

$$Q_{l,j}^{PE}\left(\{\mathbf{w}_l\},\{\mathbf{v}_l\}\right) \geq \Gamma_2,\ \forall l,\ j, \tag{16d}$$

$$||\mathbf{w}_l||^2+||\mathbf{v}_l||^2 \leq P_l,\ \forall l, \tag{16e}$$

$$\sum_{l=1}^{L}||\mathbf{q}_{l,p}^H\mathbf{w}_l||^2+||\mathbf{q}_{l,p}^H\mathbf{v}_l||^2 \leq \Gamma_3,\ \forall p, \tag{16f}$$

$$|\mathbf{w}_l^H\ \mathbf{g}_{l,l,k}| = 0 \tag{16g}$$

$$|\mathbf{w}_l^H\ \mathbf{f}_{l,l,j}| = 0 \tag{16h}$$

We apply SDR, so the problem can be reformulated as

$$\max_{\mathbf{w}_l,\mathbf{v}_l,\rho_l,R_l^{FU},R_l^e} \quad \frac{\sum_{l=1}^{L}\tilde{a}_l R_l^{FU}}{P_{RF}+\zeta\left(\sum_{l=1}^{L}\mathsf{Tr}(\mathbf{W}_l)+\mathsf{Tr}(\mathbf{V}_l)\right)} \tag{17a}$$

$$\text{s.t.} \quad R_l^{FU} \leq \log_2\left(1+\gamma_l^{FU}\left(\{\mathbf{W}_l\},\{\mathbf{V}_l\},\{\rho_l\}\right)\right),\ \forall l, \tag{17b}$$

$$Q_l^{FU}\left(\{\mathbf{W}_l\},\{\mathbf{V}_l\},\{\rho_l\}\right) \geq \Gamma_1,\ \forall l, \tag{17c}$$

$$Q_{l,j}^{PE}\left(\{\mathbf{W}_l\},\{\mathbf{V}_l\}\right) \geq \Gamma_2,\ \forall l,\ j, \tag{17d}$$

$$\mathsf{Tr}(\mathbf{W}_l)+\mathsf{Tr}(\mathbf{V}_l) \leq P_l,\ \forall l, \tag{17e}$$

$$\sum_{l=1}^{L}\mathsf{Tr}(\mathbf{W}_l\mathbf{Q}_{l,p})+\mathsf{Tr}(\mathbf{V}_l\mathbf{Q}_{l,p}) \leq \Gamma_3,\ \forall p, \tag{17f}$$

$$\mathsf{Tr}\left(\mathbf{W}_l\ \mathbf{G}_{l,l,k}\right) = 0 \tag{17g}$$

$$\mathsf{Tr}\left(\mathbf{W}_l\ \mathbf{F}_{l,l,j}\right) = 0 \tag{17h}$$

FOR 15b

We define e^{ϕ_l} as the SINR of the FU in l^{th} femto cell

$$e^{\phi_l} \leq \frac{\mathsf{Tr}(\mathbf{W}_l\mathbf{H}_{l,l})}{\sum_{m\neq l}\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l}) + \sum_{m=1}^{L}\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l}) + P_l^{FU} + \sigma_{FU,l}^2 + \frac{\sigma_s^2}{\rho_l}} \tag{18}$$

and we define

$$e^{a_l} = \mathsf{Tr}(\mathbf{W}_l\mathbf{H}_{l,l}) \tag{19a}$$

$$e^{b_l} = \sum_{m\neq l}\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l}) + \sum_{m=1}^{L}\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l}) \tag{19b}$$

$$e^{c_l} = \rho_l \tag{19c}$$

Then 15b can be transformated as

$$R_l^{FU} \leq \log_2\left(1 + e^{\phi_l}\right) \tag{20a}$$

$$e^{\phi_l}\left(e^{b_l} + P_l^{FU} + \sigma_{FU,l}^2 + \sigma_s^2 e^{-c_l}\right)e^{-a_l} \leq 1 \tag{20b}$$

$$e^{a_l} \leq \mathsf{Tr}(\mathbf{W}_l\mathbf{H}_{l,l}) \tag{20c}$$

$$e^{b_l} \geq \sum_{m\neq l}\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l}) + \sum_{m=1}^{L}\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l}) \tag{20d}$$

$$e^{c_l} \leq \rho_l \tag{20e}$$

We apply first-order approximation

$$R_l^{FU} \leq \log_2\left(1 + e^{\bar{\phi}_l}\right) + \frac{e^{\bar{\phi}_l}}{\ln 2\left(1 + e^{\bar{\phi}_l}\right)}\left(\phi_l - \bar{\phi}_l\right) \tag{21a}$$

$$e^{\phi_l - a_l}\left(e^{b_l} + P_l^{FU} + \sigma_{FU,l}^2 + \sigma_s^2 e^{-c_l}\right) \leq 1 \tag{21b}$$

$$e^{a_l} \leq \mathsf{Tr}(\mathbf{W}_l\mathbf{H}_{l,l}) \tag{21c}$$

$$e^{\bar{b}_l} + e^{\bar{b}_l}\left(b_l - \bar{b}_l\right) \geq \sum_{m\neq l}\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l}) + \sum_{m=1}^{L}\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l}) \tag{21d}$$

$$e^{c_l} \leq \rho_l \tag{21e}$$

The constraints 15e and 15f, the EH constraints, are non-convex constraint.

$$\xi_1(1-\rho_l)\left(\sum_{m=1}^{L}\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l})+\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l})+P_l^{FU}+\sigma_{FU,l}^2\right)\geq\Gamma_1 \tag{22a}$$

$$\xi_2\left(\sum_{m=1}^{L}\mathsf{Tr}(\mathbf{W}_m\mathbf{F}_{m,l,j})+\mathsf{Tr}(\mathbf{V}_m\mathbf{F}_{m,l,j})+P_{l,j}^{PE}+\sigma_{PE,l,j}^2\right)\geq\Gamma_2 \tag{22b}$$

These constraints can be reformulated as

$$\sum_{m=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l})+\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l})\right\}\geq\frac{\Gamma_1}{\xi_1(1-\rho_l)}-P_l^{FU}-\sigma_{FU,l}^2 \tag{23a}$$

$$\sum_{m=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_m\mathbf{F}_{m,l,j})+\mathsf{Tr}(\mathbf{V}_m\mathbf{F}_{m,l,j}))\right\}\geq\frac{\Gamma_2}{\xi_2}-P_{l,j}^{PE}-\sigma_{PE,l,j}^2 \tag{23b}$$

$$\max_{\mathbf{w}_l,\mathbf{v}_l,\rho_l,R_l^{FU},R_l^{e}} \quad \frac{\sum_{l=1}^{L}\tilde{a}_l R_l^{FU}}{P_{RF}+\zeta\left(\sum_{l=1}^{L}\mathsf{Tr}(\mathbf{W}_l)+\mathsf{Tr}(\mathbf{V}_l)\right)} \tag{24a}$$

$$\text{s.t.} \quad R_l^{FU} \le \log_2\left(1+e^{\overline{\phi}_l}\right)+\frac{e^{\overline{\phi}_l}}{\ln 2\left(1+e^{\overline{\phi}_l}\right)}\left(\phi_l-\overline{\phi}_l\right) \tag{24b}$$

$$e^{\phi_l-a_l}\left(e^{b_l}+P_l^{FU}+\sigma_{FU,l}^2+\sigma_s^2 e^{-c_l}\right)\le 1 \tag{24c}$$

$$e^{a_l}\le \mathsf{Tr}(\mathbf{W}_l\mathbf{H}_{l,l}) \tag{24d}$$

$$e^{\bar{b}_l}+e^{\bar{b}_l}\left(b_l-\bar{b}_l\right)\ge \sum_{m\neq l}\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l})+\sum_{m=1}^{L}\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l}) \tag{24e}$$

$$e^{c_l}\le \rho_l \tag{24f}$$

$$\sum_{m=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l})+\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l})\right\}\ge \frac{\Gamma_1}{\xi_1(1-\rho_l)}-P_l^{FU}-\sigma_{FU,l}^2 \tag{24g}$$

$$\sum_{m=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_m\mathbf{F}_{m,l,j})+\mathsf{Tr}(\mathbf{V}_m\mathbf{F}_{m,l,j}))\right\}\ge \frac{\Gamma_2}{\xi_2}-P_{l,j}^{PE}-\sigma_{PE,l,j}^2 \tag{24h}$$

$$\mathsf{Tr}(\mathbf{W}_l)+\mathsf{Tr}(\mathbf{V}_l)\le P_l,\ \forall l, \tag{24i}$$

$$\sum_{l=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_l\mathbf{Q}_{l,p})+\mathsf{Tr}(\mathbf{V}_l\mathbf{Q}_{l,p})\right\}\le \Gamma_3,\ \forall p, \tag{24j}$$

$$\mathsf{Tr}\left(\mathbf{W}_l\ \mathbf{G}_{l,l,k}\right)=0 \tag{24k}$$

$$\mathsf{Tr}\left(\mathbf{W}_l\ \mathbf{F}_{l,l,j}\right)=0 \tag{24l}$$

For the objective function, we define

$$\eta = \frac{\sum_{l=1}^{L} \tilde{a}_l R_l^{FU}}{P_{RF} + \zeta \left(\sum_{l=1}^{L} \mathsf{Tr}(\mathbf{W}_l) + \mathsf{Tr}(\mathbf{V}_l) \right)} \tag{25a}$$

$$e^{\lambda} = \sum_{l=1}^{L} \tilde{a}_l R_l^{FU} \tag{25b}$$

$$e^{\theta} = P_{RF} + \zeta \left(\sum_{l=1}^{L} \mathsf{Tr}(\mathbf{W}_l) + \mathsf{Tr}(\mathbf{V}_l) \right) \tag{25c}$$

then we obtain the following constraints

$$\eta \leq e^{\lambda - \theta} \tag{26a}$$

$$e^{\lambda} \leq \sum_{l=1}^{L} \tilde{a}_l R_l^{FU} \tag{26b}$$

$$e^{\theta} \geq P_{RF} + \zeta \left(\sum_{l=1}^{L} \mathsf{Tr}(\mathbf{W}_l) + \mathsf{Tr}(\mathbf{V}_l) \right) \tag{26c}$$

We can apply first order approximation to deal with these non-convex constraints

$$\eta \leq e^{\overline{\lambda} - \overline{\theta}} \left(1 + \lambda - \overline{\lambda} - \theta + \overline{\theta} \right) \tag{27a}$$

$$e^{\lambda} \leq \sum_{l=1}^{L} \tilde{a}_l R_l^{FU} \tag{27b}$$

$$e^{\overline{\theta}} (1 + \theta - \overline{\theta}) \geq P_{RF} + \zeta \left(\sum_{l=1}^{L} \mathsf{Tr}(\mathbf{W}_l) + \mathsf{Tr}(\mathbf{V}_l) \right) \tag{27c}$$

$$
\begin{aligned}
\max_{\mathbf{w}_l,\mathbf{v}_l,\rho_l,R_l^{FU},R_l^{e}} \quad & \eta && \text{(28a)}\\
\text{s.t.} \quad & \eta \le e^{\overline{\lambda}-\overline{\theta}}\left(1+\lambda-\overline{\lambda}-\theta+\overline{\theta}\right) && \text{(28b)}\\
& e^{\lambda} \le \sum_{l=1}^{L}\tilde{a}_l R_l^{FU} && \text{(28c)}\\
& e^{\overline{\theta}}(1+\theta-\overline{\theta}) \ge P_{RF}+\zeta\left(\sum_{l=1}^{L}\mathsf{Tr}(\mathbf{W}_l)+\mathsf{Tr}(\mathbf{V}_l)\right) && \text{(28d)}\\
& R_l^{FU} \le \log_2\left(1+e^{\overline{\phi}_l}\right)+\frac{e^{\overline{\phi}_l}}{\ln 2\left(1+e^{\overline{\phi}_l}\right)}\left(\phi_l-\overline{\phi}_l\right) && \text{(28e)}\\
& e^{\phi_l-a_l}\left(e^{b_l}+P_l^{FU}+\sigma_{FU,l}^2+\sigma_s^2 e^{-c_l}\right) \le 1 && \text{(28f)}\\
& e^{a_l} \le \mathsf{Tr}(\mathbf{W}_l\mathbf{H}_{l,l}) && \text{(28g)}\\
& e^{\bar{b}_l}+e^{\bar{b}_l}\left(b_l-\bar{b}_l\right) \ge \sum_{m\neq l}\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l})+\sum_{m=1}^{L}\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l}) && \text{(28h)}\\
& e^{c_l} \le \rho_l && \text{(28i)}\\
& \sum_{m=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_m\mathbf{H}_{m,l})+\mathsf{Tr}(\mathbf{V}_m\mathbf{H}_{m,l})\right\} \ge \frac{\Gamma_1}{\xi_1(1-\rho_l)}-P_l^{FU}-\sigma_{FU,l}^2 && \text{(28j)}\\
& \sum_{m=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_m\mathbf{F}_{m,l,j})+\mathsf{Tr}(\mathbf{V}_m\mathbf{F}_{m,l,j}))\right\} \ge \frac{\Gamma_2}{\xi_2}-P_{l,j}^{PE}-\sigma_{PE,l,j}^2 && \text{(28k)}\\
& \mathsf{Tr}(\mathbf{W}_l)+\mathsf{Tr}(\mathbf{V}_l) \le P_l,\ \forall l, && \text{(28l)}\\
& \sum_{l=1}^{L}\left\{\mathsf{Tr}(\mathbf{W}_l\mathbf{Q}_{l,p})+\mathsf{Tr}(\mathbf{V}_l\mathbf{Q}_{l,p})\right\} \le \Gamma_3,\ \forall p, && \text{(28m)}\\
& \mathsf{Tr}\left(\mathbf{W}_l\ \mathbf{G}_{l,l,k}\right)=0 && \text{(28n)}\\
& \mathsf{Tr}\left(\mathbf{W}_l\ \mathbf{F}_{l,l,j}\right)=0 && \text{(28o)}
\end{aligned}
$$