

SUPPLEMENTARY MATERIAL

*A. Definitions of auxiliary parameters of problem (21)*

$$\begin{aligned}
[\mathbf{T}_{\Psi,k}]_{1:M,1:M} &= \frac{\hat{\mathbf{T}}_a^* (\sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H)^* \hat{\mathbf{T}}_a^T}{Q}, [\mathbf{T}_{\Psi,k}]_{M+1:2M,M+1:2M} = \hat{\mathbf{T}}_p^T \left( \sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H \right)^* \hat{\mathbf{T}}_p^*, \\
[\mathbf{T}_{\Psi,k}]_{1:M,M+1:2M} &= [\mathbf{T}_{\Psi,k}]_{M+1:2M,1:M}^H = \frac{\hat{\mathbf{T}}_a^* (\sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H)^* \hat{\mathbf{T}}_p^*}{\sqrt{Q}}, \hat{\mathbf{T}}_a = \text{Diag}(\mathbf{h}_{\text{RU},k}^H \boldsymbol{\Theta}_a^T \mathbf{E}^T) \mathbf{E} \boldsymbol{\Theta}_a \mathbf{H}_{\text{BR}}, \\
\hat{\mathbf{T}}_p &= \mathbf{H}_{\text{BR}}^H \boldsymbol{\Lambda}_{\mathbf{h}_{\text{RU},k}} \boldsymbol{\Theta}_p^H, \boldsymbol{\Lambda}_{\mathbf{h}_{\text{RU},k}} = \text{BlkDiag}([\mathbf{h}_{\text{RU},k}]_{S_1,1}, \dots, [\mathbf{h}_{\text{RU},k}]_{S_M,1}), \mathcal{S}_m \triangleq \{(m-1)Q+1, \dots, mQ\}, \\
[\mathbf{t}_{\Psi,k}]_{1:M} &= \frac{w_k}{\sqrt{Q}} \text{Diag} \left( \left( |g_k|^2 \mathbf{h}_{\text{BU},k}^H \left( \sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H \right) - g_k^* \mathbf{f}_k^H \right) \mathbf{H}_{\text{BR}}^H \boldsymbol{\Theta}_a^H \mathbf{E}^H \right) \mathbf{E}^* \boldsymbol{\Theta}_a^* \mathbf{h}_{\text{RU},k}, \\
[\mathbf{t}_{\Psi,k}]_{M+1:2M} &= w_k g_k^* \boldsymbol{\Theta}_p^H (g_k \boldsymbol{\Lambda}_{\text{URB},k} - \boldsymbol{\Lambda}_{\mathbf{H}_{\text{BR}} \mathbf{f}_k}^H) \mathbf{h}_{\text{RU},k}, \\
\boldsymbol{\Lambda}_{\text{URB},k} &= \text{BlkDiag} \left( \left[ \mathbf{h}_{\text{BU},k}^H \left( \sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H \right) \mathbf{H}_{\text{BR}}^H \right]_{1,S_1}, \dots, \left[ \mathbf{h}_{\text{BU},k}^H \left( \sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H \right) \mathbf{H}_{\text{BR}}^H \right]_{1,S_M} \right), \\
\boldsymbol{\Lambda}_{\mathbf{H}_{\text{BR}} \mathbf{f}_k} &= \text{BlkDiag} \left( [\mathbf{H}_{\text{BR}} \mathbf{f}_k]_{S_1,1}, \dots, [\mathbf{H}_{\text{BR}} \mathbf{f}_k]_{S_M,1} \right), \\
\mathbf{T}_V &= \sigma_r^2 \sum_{k \in \mathcal{K}} w_k |g_k|^2 \text{Diag}(\mathbf{h}_{\text{RU},k}^H \boldsymbol{\Theta}_a^T \mathbf{E}^T) \text{Diag}(\mathbf{E}^* \boldsymbol{\Theta}_a^* \mathbf{h}_{\text{RU},k}) + \xi \epsilon_r \mathbf{E} \boldsymbol{\Theta}_a \left( \mathbf{H}_{\text{BR}} \left( \sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H \right) \mathbf{H}_{\text{BR}}^H + \sigma_r^2 \mathbf{I} \right) \boldsymbol{\Theta}_a^H \mathbf{E}^H, \\
[\bar{\mathbf{T}}_{\Psi,k}]_{1:M,1:M} &= \frac{(\hat{\mathbf{T}}_a \mathbf{f}_k \mathbf{f}_k^H \hat{\mathbf{T}}_a^H)^*}{Q}, [\bar{\mathbf{T}}_{\Psi,k}]_{1:M,M+1:2M} = [\bar{\mathbf{T}}_{\Psi,k}]_{M+1:2M,1:M}^H = \frac{(\hat{\mathbf{T}}_a \mathbf{f}_k \mathbf{f}_k^H \hat{\mathbf{T}}_p)^*}{\sqrt{Q}}, \\
[\bar{\mathbf{T}}_{\Psi,k}]_{M+1:2M,M+1:2M} &= (\hat{\mathbf{T}}_p^H \mathbf{f}_k \mathbf{f}_k^H \hat{\mathbf{T}}_p^H)^*, \\
[\bar{\mathbf{t}}_{\Psi,k}]_{1:M} &= \frac{1}{\sqrt{Q}} \text{Diag}(\mathbf{h}_{\text{BU},k}^H \mathbf{F}_{\tau,-k} \mathbf{H}_{\text{BR}}^H \boldsymbol{\Theta}_a^H \mathbf{E}^H) \mathbf{E}^* \boldsymbol{\Theta}_a^* \mathbf{h}_{\text{RU},k}, \\
[\bar{\mathbf{t}}_{\Psi,k}]_{M+1:2M} &= \boldsymbol{\Theta}_p^H \text{BlkDiag} \left( [\mathbf{h}_{\text{BU},k}^H \mathbf{F}_{\tau,-k} \mathbf{H}_{\text{BR}}^H]_{1,S_1}, \dots, [\mathbf{h}_{\text{BU},k}^H \mathbf{F}_{\tau,-k} \mathbf{H}_{\text{BR}}^H]_{1,S_M} \right) \mathbf{h}_{\text{RU},k}, \\
\bar{\mathbf{T}}_{\Psi,-k} &= \frac{\hat{\mathbf{T}}_a^* (\sum_{i \neq k} \mathbf{f}_i \mathbf{f}_i^H)^* \hat{\mathbf{T}}_a^T}{Q}, \bar{\mathbf{T}}_{V,k} = \sigma_r^2 \text{Diag}(\mathbf{h}_{\text{RU},k}^H \boldsymbol{\Theta}_a^T \mathbf{E}^T) \text{Diag}(\mathbf{E}^* \boldsymbol{\Theta}_a^* \mathbf{h}_{\text{RU},k}), \\
\mathbf{F}_{\tau,-k} &= \mathbf{f}_k \mathbf{f}_k^H - \tau^{\min} \sum_{i \neq k} \mathbf{f}_i \mathbf{f}_i^H.
\end{aligned} \tag{22}$$

*B. Definitions of auxiliary parameters of problem (33)*

$$\begin{aligned}
\mathbf{P}_\vartheta &= \sum_{k,i} \frac{w_k |g_k|^2}{\sqrt{Q}} \begin{bmatrix} \frac{\text{vec}(\mathbf{S}_{k,i}) \text{vec}(\mathbf{S}_{k,i})^H}{\sqrt{Q}} & \text{vec}(\mathbf{S}_{k,i}) \mathbf{s}_{k,i}^H \\ \mathbf{s}_{k,i} \text{vec}(\mathbf{S}_{k,i})^H & \mathbf{0} \end{bmatrix}, \\
\mathbf{P}_a &= \sigma_r^2 \sum_{k \in \mathcal{K}} w_k |g_k|^2 \text{Diag}(\mathbf{h}_{\text{RU},k}^T) \mathbf{E}^H \mathbf{V} \text{E} \text{Diag}(\mathbf{h}_{\text{RU},k}^*) + \xi \mathbf{C}_V, \\
\mathbf{S}_{k,i} &= \left( \text{Diag}(\mathbf{h}_{\text{RU},k}^H) \mathbf{E}^T \mathbf{\Lambda}_{A_S} \mathbf{E} \text{Diag}(\mathbf{H}_{\text{BR}} \mathbf{f}_i) \right)^*, \mathbf{s}_{k,i}^H = \left( \mathbf{f}_i^H \mathbf{H}_{\text{BR}}^H \mathbf{\Lambda}_{\mathbf{h}_{\text{RU},k}} (\mathbf{I}_M - \mathbf{A}_S) \right)^*, \\
\mathbf{C}_V &= \epsilon_r \sum_{k \in \mathcal{K}} \text{Diag}(\mathbf{H}_{\text{BR}} \mathbf{f}_k)^H \mathbf{E}^H \mathbf{V} \text{E} \text{Diag}(\mathbf{H}_{\text{BR}} \mathbf{f}_k), \\
\hline
\bar{\mathbf{P}}_a &= \sum_{k \in \mathcal{K}} \text{Diag} \left( w_k \left( |g_k|^2 \mathbf{h}_{\text{BU},k}^H \left( \sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H \right) \mathbf{H}_{\text{BR}}^H - g_k^* \mathbf{f}_k^H \mathbf{H}_{\text{BR}}^H \right) \right) \mathbf{E}^H \frac{\mathbf{\Lambda}_{A_S}}{\sqrt{Q}} \mathbf{E}^* \text{Diag}(\mathbf{h}_{\text{RU},k}), \\
\mathbf{P}_p &= \sum_{k,i} w_k |g_k|^2 \mathbf{s}_{k,i} \mathbf{s}_{k,i}^H, \mathbf{p}_p^H = \sum_{k \in \mathcal{K}} w_k \left( |g_k|^2 \mathbf{h}_{\text{BU},k}^H \left( \sum_{i \in \mathcal{K}} \mathbf{f}_i \mathbf{f}_i^H \right) \mathbf{H}_{\text{BR}}^H - g_k^* \mathbf{f}_k^H \mathbf{H}_{\text{BR}}^H \right)^* \mathbf{\Lambda}_{\mathbf{h}_{\text{RU},k}}^* (\mathbf{I}_N - \mathbf{A}_S)^*, \\
\mathbf{L}_{\vartheta,k} &= \begin{bmatrix} \frac{\text{vec}(\mathbf{S}_{k,k}) \text{vec}(\mathbf{S}_{k,k})^H}{Q} & \frac{\text{vec}(\mathbf{S}_{k,k}) \mathbf{s}_{k,k}^H}{\sqrt{Q}} \\ \frac{\mathbf{s}_{k,k} \text{vec}(\mathbf{S}_{k,k})^H}{\sqrt{Q}} & \mathbf{s}_{k,k} \mathbf{s}_{k,k}^H \end{bmatrix}, \mathbf{R}_{\vartheta,k} = \frac{\tau_{\min}}{\sqrt{Q}} \sum_{i \neq k} \begin{bmatrix} \frac{\text{vec}(\mathbf{S}_{k,i}) \text{vec}(\mathbf{S}_{k,i})^H}{\sqrt{Q}} & \text{vec}(\mathbf{S}_{k,i}) \mathbf{s}_{k,i}^H \\ \mathbf{s}_{k,i} \text{vec}(\mathbf{S}_{k,i})^H & \mathbf{0} \end{bmatrix}, \\
\mathbf{R}_{a,k} &= \tau_{\min} \sigma_r^2 \text{Diag}(\mathbf{h}_{\text{RU},k}^T) \mathbf{E}^H \mathbf{V} \text{E} \text{Diag}(\mathbf{h}_{\text{RU},k}^*), \\
\bar{\mathbf{R}}_{a,k} &= -\text{Diag}(\mathbf{h}_{\text{BU},k}^H \mathbf{F}_{\tau,-k} \mathbf{H}_{\text{BR}}^H) \mathbf{E}^H \frac{\mathbf{\Lambda}_{A_S}}{\sqrt{Q}} \mathbf{E}^* \text{Diag}(\mathbf{h}_{\text{RU},k}), \\
\mathbf{R}_{p,k} &= \tau_{\min} \sum_{i \neq k} \mathbf{s}_{k,i} \mathbf{s}_{k,i}^H, \mathbf{r}_{p,k}^H = \left( \mathbf{h}_{\text{BU},k}^H \mathbf{F}_{\tau,-k} \mathbf{H}_{\text{BR}}^H \mathbf{\Lambda}_{\mathbf{h}_{\text{RU},k}} (\mathbf{I}_M - \mathbf{A}_S) \right)^*. \tag{34}
\end{aligned}$$

C. Definitions of auxiliary parameters in (35)-(37)

$$\mathbf{x}_{a,t} = (\mathbf{P}_a - \lambda_{\max}(\mathbf{P}_a)\mathbf{I})\boldsymbol{\theta}_{a,t} + \mathbf{U}(\mathbf{F}_r(\mathbf{S}_{\mathbf{P}_{\vartheta,t}} + \bar{\mathbf{P}}_a) - \lambda_{\max}(\mathbf{F}_r(\mathbf{S}_{\mathbf{P}_{\vartheta,t}} + \bar{\mathbf{P}}_a))\mathbf{I})\bar{\boldsymbol{\theta}}_{a,t}^*,$$

$$\mathbf{x}_{p,t} = (\mathbf{P}_p - \lambda_{\max}(\mathbf{P}_p)\mathbf{I})\boldsymbol{\theta}_{p,t} + \mathbf{p}_p^H + \sum_{k,i} \frac{w_k |g_k|^2 \boldsymbol{\theta}_{a,t}^H \mathbf{S}_{k,i} \boldsymbol{\theta}_{a,t}^* \mathbf{s}_{k,i}^H}{\sqrt{Q}} - \lambda_{\max}(\mathbf{P}_{\vartheta})\boldsymbol{\theta}_{p,t}^H,$$

$$\mathbf{S}_{\mathbf{P}_{\vartheta,t}} = \sum_{k,i} \frac{w_k |g_k|^2}{\sqrt{Q}} \left( \frac{\boldsymbol{\theta}_{a,t}^T \mathbf{S}_{k,i}^H \boldsymbol{\theta}_{a,t} \mathbf{S}_{k,i}}{\sqrt{Q}} + \mathbf{s}_{k,i}^H \boldsymbol{\theta}_{p,t} \mathbf{S}_{k,i} \right) - \lambda_{\max}(\mathbf{P}_{\vartheta})\boldsymbol{\theta}_{a,t} \boldsymbol{\theta}_{a,t}^T,$$

$$\mathbf{U} = [\mathbf{I}, i\mathbf{I}], \bar{\boldsymbol{\theta}}_{a,t} \triangleq [\Re(\boldsymbol{\theta}_{a,t})^T, \Im(\boldsymbol{\theta}_{a,t})^T]^T, \mathbf{F}_r(\mathbf{X}) \triangleq \begin{bmatrix} \Re(\mathbf{X} + \mathbf{X}^T) & \Im(\mathbf{X} + \mathbf{X}^T) \\ \Im(\mathbf{X} + \mathbf{X}^T) & -\Re(\mathbf{X} + \mathbf{X}^T) \end{bmatrix},$$

$$\mathbf{q}_{a,k,t}^H = ((\mathbf{R}_{a,k} - \lambda_{\max}(\mathbf{R}_{a,k})\mathbf{I})\boldsymbol{\theta}_{a,t})^H + \bar{\boldsymbol{\theta}}_{a,t}^T (\mathbf{F}_r(\bar{\mathbf{S}}_{\mathbf{R}_{\vartheta,k,t}}) - \lambda_{\max}(\mathbf{F}_r(\bar{\mathbf{S}}_{\mathbf{R}_{\vartheta,k,t}}))\mathbf{I})\mathbf{U}^H,$$

$$\mathbf{q}_{p,k,t}^H = \sum_{i \neq k} \frac{\tau^{\min} \boldsymbol{\theta}_{a,t}^H \mathbf{S}_{k,i} \boldsymbol{\theta}_{a,t}^* \mathbf{s}_{k,i}^H}{\sqrt{Q}} - \lambda_{\max}(\mathbf{R}_{\vartheta,k})\boldsymbol{\theta}_{p,t}^H - \mathbf{r}_{p,k}^H - \frac{\boldsymbol{\theta}_{a,t}^H \mathbf{S}_{k,k} \boldsymbol{\theta}_{a,t}^* \mathbf{s}_{k,k}^H}{\sqrt{Q}}$$

$$- \boldsymbol{\theta}_{p,t}^H \mathbf{s}_{k,k} \mathbf{s}_{k,k}^H + ((\mathbf{R}_{p,k} - \lambda_{\max}(\mathbf{R}_{p,k})\mathbf{I})\boldsymbol{\theta}_{p,t})^H,$$

$$c_{q,k,t} = \boldsymbol{\vartheta}_t^H \mathbf{L}_{\vartheta,k} \boldsymbol{\vartheta}_t + 2\lambda_{\max}(\mathbf{F}_r(\bar{\mathbf{S}}_{\mathbf{R}_{\vartheta,k,t}}))N - \bar{\boldsymbol{\theta}}_{a,t}^T (\mathbf{F}_r(\bar{\mathbf{S}}_{\mathbf{R}_{\vartheta,k,t}}))\bar{\boldsymbol{\theta}}_{a,t} + 2\lambda_{\max}(\mathbf{R}_{\vartheta,k})(N^2 + M)$$

$$- \boldsymbol{\vartheta}_t^H \mathbf{R}_{\vartheta,k} \boldsymbol{\vartheta}_t + 2\lambda_{\max}(\mathbf{R}_{p,k})M - \boldsymbol{\theta}_{p,t}^H \mathbf{R}_{p,k} \boldsymbol{\theta}_{p,t} + 2\lambda_{\max}(\mathbf{R}_{a,k})N - \boldsymbol{\theta}_{a,t}^H \mathbf{R}_{a,k} \boldsymbol{\theta}_{a,t},$$

$$\begin{aligned} \bar{\mathbf{S}}_{\mathbf{R}_{\vartheta,k,t}} = \bar{\mathbf{R}}_{a,k} - \frac{\boldsymbol{\theta}_{a,t}^T \mathbf{S}_{k,k}^H \boldsymbol{\theta}_{a,t} \mathbf{S}_{k,k} + \sqrt{Q} \mathbf{s}_{k,k}^H \boldsymbol{\theta}_{p,t} \mathbf{S}_{k,k}}{Q} \\ + \tau^{\min} \sum_{i \neq k} \frac{\boldsymbol{\theta}_{a,t}^T \mathbf{S}_{k,i}^H \boldsymbol{\theta}_{a,t} \mathbf{S}_{k,i} + \sqrt{Q} \mathbf{s}_{k,i}^H \boldsymbol{\theta}_{p,t} \mathbf{S}_{k,i}}{Q} - \lambda_{\max}(\mathbf{R}_{\vartheta,k})\boldsymbol{\theta}_{a,t} \boldsymbol{\theta}_{a,t}^T. \end{aligned} \quad (38)$$