Supplementary Material

A. Definitions of auxiliary parameters of problem (21)

$$[\mathbf{T}_{\Psi,k}]_{1:M,1:M}=\frac{\widehat{\mathbf{T}}_a^{*}(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}})^{*}\widehat{\mathbf{T}}_a^{\mathrm{T}}}{Q},[\mathbf{T}_{\Psi,k}]_{M+1:2M,M+1:2M}=\widehat{\mathbf{T}}_p^{\mathrm{T}}\Big(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}\Big)^{*}\widehat{\mathbf{T}}_p^{*},$$

$$[\mathbf{T}_{\Psi,k}]_{1:M,M+1:2M}=[\mathbf{T}_{\Psi,k}]_{M+1:2M,1:M}^{\mathrm{H}}=\frac{\widehat{\mathbf{T}}_a^{*}(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}})^{*}\widehat{\mathbf{T}}_p^{*}}{\sqrt{Q}},\widehat{\mathbf{T}}_a=\mathrm{Diag}(\mathbf{h}_{\mathrm{RU},k}^{\mathrm{H}}\boldsymbol{\Theta}_a^{\mathrm{T}}\mathbf{E}^{\mathrm{T}})\mathbf{E}\boldsymbol{\Theta}_a\mathbf{H}_{\mathrm{BR}},$$

$$\widehat{\mathbf{T}}_p=\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\boldsymbol{\Lambda}_{\mathbf{h}_{\mathrm{RU},k}}\boldsymbol{\Theta}_p^{\mathrm{H}},\boldsymbol{\Lambda}_{\mathbf{h}_{\mathrm{RU,k}}}=\mathrm{BlkDiag}([\mathbf{h}_{\mathrm{RU},k}]_{\mathcal{S}_1,1},...,[\mathbf{h}_{\mathrm{RU},k}]_{\mathcal{S}_M,1}),\mathcal{S}_m\triangleq\{(m-1)Q+1,...,mQ\},$$

$$[\mathbf{t}_{\Psi,k}]_{1:M}=\frac{w_k}{\sqrt{Q}}\mathrm{Diag}\Bigg(\Big(|g_k|^2\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\Big(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}\Big)-g_k^{*}\mathbf{f}_k^{\mathrm{H}}\Big)\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\boldsymbol{\Theta}_a^{\mathrm{H}}\mathbf{E}^{\mathrm{H}}\Bigg)\mathbf{E}^{*}\boldsymbol{\Theta}_a^{*}\mathbf{h}_{\mathrm{RU},k},$$

$$[\mathbf{t}_{\Psi,k}]_{M+1:2M}=w_kg_k^{*}\boldsymbol{\Theta}_p^{\mathrm{H}}\big(g_k\boldsymbol{\Lambda}_{\mathrm{URB},k}-\boldsymbol{\Lambda}_{\mathbf{H}_{\mathrm{BR}}\mathbf{f}_k}^{\mathrm{H}}\big)\mathbf{h}_{\mathrm{RU},k},$$

$$\boldsymbol{\Lambda}_{\mathrm{URB},k}=\mathrm{BlkDiag}\Bigg(\Big[\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\Big(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}\Big)\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\Big]_{1,\mathcal{S}_1},...,\Big[\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\Big(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}\Big)\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\Big]_{1,\mathcal{S}_M}\Bigg),$$

$$\boldsymbol{\Lambda}_{\mathbf{H}_{\mathrm{BR}}\mathbf{f}_k}=\mathrm{BlkDiag}\Big(\big[\mathbf{H}_{\mathrm{BR}}\mathbf{f}_k\big]_{\mathcal{S}_1,1},...,\big[\mathbf{H}_{\mathrm{BR}}\mathbf{f}_k\big]_{\mathcal{S}_M,1}\Big),$$

$$\mathbf{T}_{\mathrm{V}}=\sigma_r^2\sum_{k\in\mathcal{K}}w_k|g_k|^2\mathrm{Diag}\big(\mathbf{h}_{\mathrm{RU},k}^{\mathrm{H}}\boldsymbol{\Theta}_a^{\mathrm{T}}\mathbf{E}^{\mathrm{T}}\big)\mathrm{Diag}\big(\mathbf{E}^{*}\boldsymbol{\Theta}_a^{*}\mathbf{h}_{\mathrm{RU},k}\big)+\xi\epsilon_r\mathbf{E}\boldsymbol{\Theta}_a\Bigg(\mathbf{H}_{\mathrm{BR}}\Big(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}\Big)\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}+\sigma_r^2\mathbf{I}\Bigg)\boldsymbol{\Theta}_a^{\mathrm{H}}\mathbf{E}^{\mathrm{H}},$$

$$[\overline{\mathbf{T}}_{\Psi,k}]_{1:M,1:M}=\frac{(\widehat{\mathbf{T}}_a\mathbf{f}_k\mathbf{f}_k^{\mathrm{H}}\widehat{\mathbf{T}}_a^{\mathrm{H}})^{*}}{Q},[\overline{\mathbf{T}}_{\Psi,k}]_{1:M,M+1:2M}=[\overline{\mathbf{T}}_{\Psi,k}]_{M+1:2M,1:M}^{\mathrm{H}}=\frac{(\widehat{\mathbf{T}}_a\mathbf{f}_k\mathbf{f}_k^{\mathrm{H}}\widehat{\mathbf{T}}_p)^{*}}{\sqrt{Q}},$$

$$[\overline{\mathbf{T}}_{\Psi,k}]_{M+1:2M,M+1:2M}=(\widehat{\mathbf{T}}_p^{\mathrm{H}}\mathbf{f}_k\mathbf{f}_k^{\mathrm{H}}\widehat{\mathbf{T}}_p^{\mathrm{H}})^{*},$$

$$[\overline{\mathbf{t}}_{\Psi,k}]_{1:M}=\frac{1}{\sqrt{Q}}\mathrm{Diag}(\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\mathbf{F}_{\tau,-k}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\boldsymbol{\Theta}_a^{\mathrm{H}}\mathbf{E}^{\mathrm{H}})\mathbf{E}^{*}\boldsymbol{\Theta}_a^{*}\mathbf{h}_{\mathrm{RU},k},$$

$$[\overline{\mathbf{t}}_{\Psi,k}]_{M+1:2M}=\boldsymbol{\Theta}_p^{\mathrm{H}}\mathrm{BlkDiag}\Big(\big[\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\mathbf{F}_{\tau,-k}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\big]_{1,\mathcal{S}_1},...,\big[\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\mathbf{F}_{\tau,-k}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\big]_{1,\mathcal{S}_M}\Big)\mathbf{h}_{\mathrm{RU},k},$$

$$\overline{\mathbf{T}}_{\Psi,-k}=\frac{\widehat{\mathbf{T}}_a^{*}(\sum_{i\neq k}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}})^{*}\widehat{\mathbf{T}}_a^{\mathrm{T}}}{Q},\overline{\mathbf{T}}_{\mathrm{V},k}=\sigma_r^2\mathrm{Diag}\big(\mathbf{h}_{\mathrm{RU},k}^{\mathrm{H}}\boldsymbol{\Theta}_a^{\mathrm{T}}\mathbf{E}^{\mathrm{T}}\big)\mathrm{Diag}\big(\mathbf{E}^{*}\boldsymbol{\Theta}_a^{*}\mathbf{h}_{\mathrm{RU},k}\big),$$

$$\mathbf{F}_{\tau,-k}=\mathbf{f}_k\mathbf{f}_k^{\mathrm{H}}-\tau^{\min}\sum_{i\neq k}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}.\tag{22}$$

B. Definitions of auxiliary parameters of problem (33)

$$\mathbf{P}_{\vartheta}=\sum_{k,i}\frac{w_k|g_k|^2}{\sqrt{Q}}\begin{bmatrix}\frac{\mathrm{vec}(\mathbf{S}_{k,i})\mathrm{vec}(\mathbf{S}_{k,i})^{\mathrm{H}}}{\sqrt{Q}} & \mathrm{vec}(\mathbf{S}_{k,i})\mathbf{s}_{k,i}^{\mathrm{H}}\\ \mathbf{s}_{k,i}\mathrm{vec}(\mathbf{S}_{k,i})^{\mathrm{H}} & \mathbf{0}\end{bmatrix},$$

$$\mathbf{P}_{a}=\sigma_r^2\sum_{k\in\mathcal{K}}w_k|g_k|^2\mathrm{Diag}(\mathbf{h}_{\mathrm{RU},k}^{\mathrm{T}})\mathbf{E}^{\mathrm{H}}\mathbf{V}\mathbf{E}\mathrm{Diag}(\mathbf{h}_{\mathrm{RU},k}^{*})+\xi\mathbf{C}_V,$$

$$\mathbf{S}_{k,i}=\Big(\mathrm{Diag}(\mathbf{h}_{\mathrm{RU,k}}^{\mathrm{H}})\mathbf{E}^{\mathrm{T}}\mathbf{\Lambda}_{A_S}\mathbf{E}\mathrm{Diag}(\mathbf{H}_{\mathrm{BR}}\mathbf{f}_i)\Big)^{*},\mathbf{s}_{k,i}^{\mathrm{H}}=\big(\mathbf{f}_i^{\mathrm{H}}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\mathbf{\Lambda}_{\mathbf{h}_{\mathrm{RU,k}}}(\mathbf{I}_M-\mathbf{A}_S)\big)^{*},$$

$$\mathbf{C}_V=\epsilon_r\sum_{k\in\mathcal{K}}\mathrm{Diag}(\mathbf{H}_{\mathrm{BR}}\mathbf{f}_k)^{\mathrm{H}}\mathbf{E}^{\mathrm{H}}\mathbf{V}\mathbf{E}\mathrm{Diag}(\mathbf{H}_{\mathrm{BR}}\mathbf{f}_k),$$

$$\overline{\mathbf{P}}_{a}=\sum_{k\in\mathcal{K}}\mathrm{Diag}\bigg(w_k\Big(|g_k|^2\mathbf{h}_{\mathrm{BU,k}}^{\mathrm{H}}\Big(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}\Big)\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}-g_k^{*}\mathbf{f}_k^{\mathrm{H}}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\Big)\bigg)\mathbf{E}^{\mathrm{H}}\frac{\mathbf{\Lambda}_{A_S}}{\sqrt{Q}}\mathbf{E}^{*}\mathrm{Diag}(\mathbf{h}_{\mathrm{RU,k}}),$$

$$\mathbf{P}_{p}=\sum_{k,i}w_k|g_k|^2\mathbf{s}_{k,i}\mathbf{s}_{k,i}^{\mathrm{H}},\mathbf{p}_p^{\mathrm{H}}=\sum_{k\in\mathcal{K}}w_k\Big(|g_k|^2\mathbf{h}_{\mathrm{BU,k}}^{\mathrm{H}}\Big(\sum_{i\in\mathcal{K}}\mathbf{f}_i\mathbf{f}_i^{\mathrm{H}}\Big)\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}-g_k^{*}\mathbf{f}_k^{\mathrm{H}}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\Big)^{*}\mathbf{\Lambda}_{\mathbf{h}_{\mathrm{RU,k}}}^{*}(\mathbf{I}_N-\mathbf{A}_S)^{*},$$

$$\mathbf{L}_{\vartheta,k}=\begin{bmatrix}\frac{\mathrm{vec}(\mathbf{S}_{k,k})\mathrm{vec}(\mathbf{S}_{k,k})^{\mathrm{H}}}{Q} & \frac{\mathrm{vec}(\mathbf{S}_{k,k})\mathbf{s}_{k,k}^{\mathrm{H}}}{\sqrt{Q}}\\ \frac{\mathbf{s}_{k,k}\mathrm{vec}(\mathbf{S}_{k,k})^{\mathrm{H}}}{\sqrt{Q}} & \mathbf{s}_{k,k}\mathbf{s}_{k,k}^{\mathrm{H}}\end{bmatrix},\mathbf{R}_{\vartheta,k}=\frac{\tau^{\min}}{\sqrt{Q}}\sum_{i\neq k}\begin{bmatrix}\frac{\mathrm{vec}(\mathbf{S}_{k,i})\mathrm{vec}(\mathbf{S}_{k,i})^{\mathrm{H}}}{\sqrt{Q}} & \mathrm{vec}(\mathbf{S}_{k,i})\mathbf{s}_{k,i}^{\mathrm{H}}\\ \mathbf{s}_{k,i}\mathrm{vec}(\mathbf{S}_{k,i})^{\mathrm{H}} & \mathbf{0}\end{bmatrix},$$

$$\mathbf{R}_{a,k}=\tau^{\min}\sigma_r^2\mathrm{Diag}(\mathbf{h}_{\mathrm{RU},k}^{\mathrm{T}})\mathbf{E}^{\mathrm{H}}\mathbf{V}\mathbf{E}\mathrm{Diag}(\mathbf{h}_{\mathrm{RU},k}^{*}),$$

$$\overline{\mathbf{R}}_{a,k}=-\mathrm{Diag}\big(\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\mathbf{F}_{\tau,-k}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\big)\mathbf{E}^{\mathrm{H}}\frac{\mathbf{\Lambda}_{A_S}}{\sqrt{Q}}\mathbf{E}^{*}\mathrm{Diag}(\mathbf{h}_{\mathrm{RU,k}}),$$

$$\mathbf{R}_{p,k}=\tau^{\min}\sum_{i\neq k}\mathbf{s}_{k,i}\mathbf{s}_{k,i}^{\mathrm{H}},\mathbf{r}_{p,k}^{\mathrm{H}}=\big(\mathbf{h}_{\mathrm{BU},k}^{\mathrm{H}}\mathbf{F}_{\tau,-k}\mathbf{H}_{\mathrm{BR}}^{\mathrm{H}}\mathbf{\Lambda}_{\mathbf{h}_{\mathrm{RU,k}}}(\mathbf{I}_M-\mathbf{A}_S)\big)^{*}.\tag{34}$$

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

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

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

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

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

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

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

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

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