Proof of Proposition 2

Proposition 2: The optimal TS factor maximizing the UB/LB of the expected secrecy rate can be written as

$$(\alpha_{opt}^{UB})_i = \begin{cases} 1 - \dfrac{\eta P_s \frac{|h_{sd}|^2 |\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{sd}^m d_{si}^m d_{ie}^m}}{Q + \sqrt{Q \frac{|h_{se}|^2}{d_{se}^m}(N_0 + P_s \frac{|h_{sd}|^2}{d_{sd}^m})}}, & C_1 \ or \ C_2 \\ 0, & otherwise \end{cases} \tag{1}$$

$$(\alpha_{opt}^{LB})_i = \begin{cases} 1 - \dfrac{\eta P_s \frac{|h_{sd}|^2 |\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{sd}^m d_{si}^m d_{ie}^m} \sqrt{2N_0 + P_s \frac{|h_{sd}|^2}{d_{sd}^m}}}{Q\sqrt{2N_0 + P_s \frac{|h_{sd}|^2}{d_{sd}^m}} + \sqrt{2QN_0 \frac{|h_{se}|^2}{d_{se}^m}(N_0 + P_s \frac{|h_{sd}|^2}{d_{sd}^m})}}, & C_1 \ or \ C_2 \\ 0, & otherwise \end{cases} \tag{2}$$

where constraints $C_1 = \{h_0 < \frac{|h_{sd}|^2}{d_{sd}^m} < h_1, \forall P_i\}$, $C_2 = \{\frac{|h_{sd}|^2}{d_{sd}^m} \geq h_1, P_i \leq P_{th}\}$, and $Q = \frac{|h_{sd}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{sd}^m d_{ie}^m}(\eta P_s \frac{|\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2}{d_{si}^m} - P_i) - N_0(\frac{|h_{sd}|^2}{d_{sd}^m} - \frac{|h_{se}|^2}{d_{se}^m})$, $h_0 = (N_0 \frac{|h_{se}|^2}{d_{se}^m})/[N_0 + (P_i + \frac{\eta \alpha_i}{1-\alpha_i} P_s \cdot \frac{|\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2}{d_{si}^m}) \frac{|\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{ie}^m}]$, $h_1 = (N_0 \frac{|h_{se}|^2}{d_{se}^m})/[N_0 + P_i \frac{|\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{ie}^m} - \eta P_s \frac{|\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{si}^m d_{ie}^m}]$, $P_{th} = (\eta P_s \frac{|\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{si}^m d_{ie}^m} - N_0) / \frac{|\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{ie}^m}$.

Proof: For the upper bound of R_s, the relationship between R_s^{UB} and α_i can be simplified as the following function $f(x) = \frac{1}{1+x} \frac{a_1 x + a_2}{b_1 x + b_2}$ for $x = \frac{\alpha_i}{1-\alpha_i} \geq 0$. According to the upper bound equation, we have

$$a_1 = \eta P_s^2 \frac{|\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2 |h_{sd}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{si}^m d_{sd}^m d_{ie}^m}, \tag{R.1}$$

$$a_2 = N_0 P_s (\frac{|h_{sd}|^2}{d_{sd}^m} - \frac{|h_{se}|^2}{d_{se}^m}) + P_i P_s \frac{|h_{sd}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{sd}^m d_{ie}^m}, \tag{R.2}$$

$$b_1 = \eta N_0 P_s \frac{|\mathbf{h}_{si}^{\dagger}\mathbf{w}_{i,H}|^2 |\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{si}^m d_{ie}^m}, \tag{R.3}$$

$$b_2 = N_0 (N_0 + P_s \frac{|h_{se}|^2}{d_{se}^m} + P_i \frac{|\mathbf{h}_{ie}^{\dagger}\mathbf{w}_{i,J}|^2}{d_{ie}^m}). \tag{R.4}$$

It is obvious that $a_1 > 0$, $b_1 > 0$, $b_2 > 0$, and $a_1 b_2 - a_2 b_1 > 0$. To obtain the optimal solution maximizing $f(x)$, the following proposition is proposed.

Proposition R.1. *The optimal solution to maximize $f(x)$ is*

$$x^{opt} = \begin{cases} \frac{\sqrt{(a_1 - a_2)(a_1 b_2 - a_2 b_1)} - a_2 \sqrt{b_1}}{a_1 \sqrt{b_1}}, & a_2 \leq 0 \ or \ 0 < a_2 < a_1 \\ 0, & otherwise \end{cases} \tag{R.5}$$

Proof: Using properties of derivate function and Vieta theorem, the proposition can be proved. ■

On the basis of Proposition R.1, there are three possibilities (i.e., $a_2 \leq 0$, $0 < a_2 < a_1$, and $a_2 \geq a_1$) to be analyzed to obtain the optimal time switching factor.

- Case 1) For $a_2 \leq 0$, considering positive R_s constraint obtained in Proposition 1 and ZF beamforming approach adopted for jamming transmission, we have $C_1^{'} = \{h_0 < \frac{|h_{sd}|^2}{d_{sd}^m} \leq h_1^{'}, \forall P_i\}$, where $h_1^{'} = N_0 \frac{|h_{se}|^2}{d_{se}^m} / [N_0 + P_i \frac{|\mathbf{h}_{ie}^{\dagger} \mathbf{w}_{i,J}|^2}{d_{ie}^m}]$. Based on Vieta theorem, there is one positive root for $h(x)$ in the interval $[0, +\infty)$, and the sign of it turns from positive to negative. Hence, $f(x)$ is a concave function of x, and the non-zero solution in Proposition is obtained.

  Then the optimal time switching factor can be obtained as the first equation in Proposition 2.
- Case 2) For $0 < a_2 < a_1$, $f(x)$ is also a concave function of x, and there exists only one optimal $(\alpha_{opt}^{UB})_i$ in (11) to maximize $f(x)$. In this case, the channel conditions to satisfy $0 < a_2 < a_1$ are denoted as $\frac{|h_{sd}|^2}{d_{sd}^m} > h_1^{'}$, and

$$(N_0 + P_i \frac{|\mathbf{h}_{ie}^{\dagger} \mathbf{w}_{i,J}|^2}{d_{ie}^m} - \eta P_s \frac{|\mathbf{h}_{si}^{\dagger} \mathbf{w}_{i,H}|^2 |\mathbf{h}_{ie}^{\dagger} \mathbf{w}_{i,J}|^2}{d_{si}^m d_{ie}^m}) \frac{|h_{sd}|^2}{d_{sd}^m} < N_0 \frac{|h_{se}|^2}{d_{se}^m}. \tag{R.6}$$

  If $N_0 + P_i \frac{|\mathbf{h}_{ie}^{\dagger} \mathbf{w}_{i,J}|^2}{d_{ie}^m} \eta P_s \frac{|\mathbf{h}_{si}^{\dagger} \mathbf{w}_{i,H}|^2 |\mathbf{h}_{ie}^{\dagger} \mathbf{w}_{i,J}|^2}{d_{si}^m d_{ie}^m} \leq 0$, the above inequality always holds, i.e., condition $C_2^{'} = \{ \frac{|h_{sd}|^2}{d_{sd}^m} > h_1^{'}, P_i \leq P_{th}\}$. Otherwise, only $C_3^{'} = \{h_1^{'} < \frac{|h_{sd}|^2}{d_{sd}^m} < h_1, P_i > P_{th}\}$ satisfied, $(\alpha_{opt}^{UB})_i$ is obtained.
- Case 3) For $a_2 \geq a_1$, $f(x)$ is a monotonically decreasing function for $x \geq 0$, and when $x = 0$, the maximum value of $f(x)$ can be obtained. That is, when the constraint $C_4^{'} = \{ \frac{|h_{sd}|^2}{d_{sd}^m} \geq h_1, P_i > P_{th}\}$ is satisfied, the secrecy rate can only be maximized at $\alpha_i^{opt} = 0$.

Consequently, when $C_1^{UB} = \{h_0 < \frac{|h_{sd}|^2}{d_{sd}^m} < h_1, \forall P_i\}$ or $C_2^{UB} = \{ \frac{|h_{sd}|^2}{d_{sd}^m} \geq h_1, P_i \leq P_{th}\}$ is satisfied, the optimal $(\alpha_{opt}^{UB})_i$ in (1) can be obtained. Otherwise, if the constraint $C_3^{UB} = \{ \frac{|h_{sd}|^2}{d_{sd}^m} \geq h_1, P_i > P_{th}\}$, it does not need energy harvesting operation in secure systems , i.e., $\alpha_i^{opt} = 0$.

Similarly, the optimal solution for the LB-based method can be obtained as equation (2).