The auxiliary random variable X is given by

$$X = \| (\mathbf{H}_e + \mathbf{G}_e \mathbf{\Theta} \mathbf{H}) \mathbf{b} \|^2$$
$$= \| \beta_d \mathbf{Z} \mathbf{b} + \beta_r \mathbf{C} \mathbf{\Theta} \mathbf{H} \mathbf{b} \|^2$$
$$= \| \beta_d \mathbf{a} + \beta_r \mathbf{C} \mathbf{\Theta} \mathbf{H} \mathbf{b} \|^2.$$

where  $\mathbf{a} \sim \mathcal{CN}_{N_e,1}\left(\mathbf{0},\mathbf{I}_{N_e}\right)$ , the mean of X is expressed as

$$egin{aligned} \mathbb{E}[X] &= \mathbb{E}\left[\|eta_d\mathbf{a}\|^2
ight] + \mathbb{E}\left[\|eta_r\mathbf{C}\mathbf{\Theta}\mathbf{H}\mathbf{b}\|^2
ight] \ &= \mathbb{E}\left[eta_d^2
ight] \cdot \mathbb{E}\left[\|\mathbf{a}\|^2
ight] + \mathbb{E}\left[eta_r^2
ight] \cdot \mathbb{E}\left[\|\mathbf{C}\mathbf{\Theta}\mathbf{H}\mathbf{b}\|^2
ight] \ &= \left(eta_d^2 + eta_r^2\|\mathbf{\Theta}\mathbf{H}\mathbf{b}\|^2
ight)N_e. \end{aligned}$$

The variance of X is given by

$$egin{aligned} ext{Var}[X] &= \mathbb{E}\left[|X|^2
ight] - |\mathbb{E}[X]|^2 \ &= \left(eta_d^4 + eta_r^4 \|\mathbf{\Theta}\mathbf{H}\mathbf{b}\|^4 + 2eta_d^2eta_r^2 \|\mathbf{\Theta}\mathbf{H}\mathbf{b}\|^2
ight) N_e \end{aligned}$$

Hence, the shape and scale of the Gamma distribution can be given by

$$egin{align} k &= rac{\left|\mathbb{E}[X]
ight|^2}{ ext{Var}[X]} = N_e, \ w &= rac{ ext{Var}[X]}{\mathbb{E}[X]} = eta_d^2 + eta_r^2 \|\mathbf{\Theta}\mathbf{H}\mathbf{b}\|^2. \end{split}$$

With the help of a Gamma distribution, the CDF of X can be expressed as

$$egin{align} F_X(x) &= 1 - rac{1}{\Gamma(k)} \Gamma\left(k,rac{x}{w}
ight) \ &= 1 - rac{1}{\Gamma(N_e)} \Gamma\left(N_e,rac{x}{eta_d^2 + eta_r^2 \|\mathbf{\Theta}\mathbf{Hb}\|^2}
ight). \end{split}$$

where  $\Gamma(m)=\int_0^\infty t^{m-1}e^{-t}\;\mathrm{d}t$  is the Gamma function, and  $\Gamma(m,n)=\int_n^\infty t^{m-1}e^{-t}\;\mathrm{d}t$  is the upper incomplete Gamma function. Then, we can deduce an approximate expression of secrecy outage probability as

$$egin{align} P_{ ext{out}} \; \left( R_s 
ight) &= 1 - F_X(\phi) \ &= rac{1}{\Gamma \left( N_e 
ight)} \Gamma \left( N_e, rac{\phi}{eta_d^2 + eta_r^2 \| oldsymbol{\Theta} \mathbf{H} \mathbf{b} \|^2} 
ight) \end{split}$$

where  $\phi = \sigma_e^2 \left( 2^{C_m - R_s} - 1 \right) / P_t.$