

Residual Hardware Impairments on Secure NOMA-Based Relay Systems

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Abstract—Non-orthogonal multiple access (NOMA) has been proposed as a promising technology that is capable of improving the spectral efficiency of fifth-generation wireless networks and beyond. However, in practical communication scenarios, transceiver architectures inevitably suffer from radio frequency (RF) front-end related impairments that cause non-negligible performance degradation. This issue can be addressed by analog and digital signal processing algorithms, but factors such as time-varying hardware characteristics and imperfect compensation schemes result to detrimental residual distortions. In the present contribution we investigate the physical layer security of NOMA-based amplify-and-forward relay systems under such realistically incurred residual hardware impairment (RHI) effects. Exact and asymptotic analytic expressions for the corresponding outage probability (OP) and intercept probability (IP) of the considered set up over multipath fading channels are derived and corroborated by respective simulation results. Based on this, it is shown that RHI affects both the legitimate users and eavesdroppers by increasing the OP and decreasing the IP. For a fixed OP, RHI generally increases the corresponding IP, thereby reducing the secure performance of the system. Further interesting insights are also provided, verifying the importance of the offered results for the effective design and deployment of secure cooperative communication systems.

I. INTRODUCTION

Non-orthogonal multiple access (NOMA) was recently introduced as a promising candidate for 5G systems. The key concept underlying NOMA is to utilize the non-orthogonal resources such as power or code domains for multiple access instead of the time or frequency domains used in orthogonal multiple access (OMA) schemes [1]. It is also known that the uncertainty and time-varying nature of wireless channels can theoretically create a secure communication link without the need for encryption algorithms [2]–[4]. In this regard, physical layer security has recently attracted considerable attention, particularly in the context of multiple access systems [5].

However, in NOMA based communication systems, physical layer security is associated with challenges that have been only recently considered [6]–[10]. Nevertheless, all related contributions assume an ideal RF front-end, which is not typically the case in realistic communication systems [11], [12], [14], [20] and the references therein. In this context, several reported analyses have investigated the impact of residual hardware impairment (RHI) on relay networks. For instance, the impact of hardware impairments has been investigated in a massive MIMO full-duplex relaying system. Meanwhile, in the context of NOMA, recently a few works considering the impact of hardware impairments on NOMA systems have emerged such as [15] where the effects of common RF impairments on NOMA are highlighted. Likewise, the outage probability of both single-carrier and multi-carrier NOMA systems under the effects of in-phase/quadrature-phase imbalance was derived [16]–[18]. More recently, the effects of RHI in the simultaneous wireless information and power transfer NOMA network was investigated in the concept of outage probability in [19].

In spite of the detrimental effects of RHI on wireless communication systems, such effects are often neglected in the analysis of conventional and emerging communication systems, leading to idealistic results that deviate from those encountered in realistic communication scenarios [20], [21]. This is also the case for the secrecy performance of cooperative multi-user NOMA systems. Motivated by this, the present contribution quantifies the effects of imperfect hardware impairment compensation on the performance of secure cooperative NOMA. To this end, useful theoretical and practical results on the corresponding OP and IP are developed which can be ultimately useful in the design and deployment of secure emerging wireless communication technologies and systems.

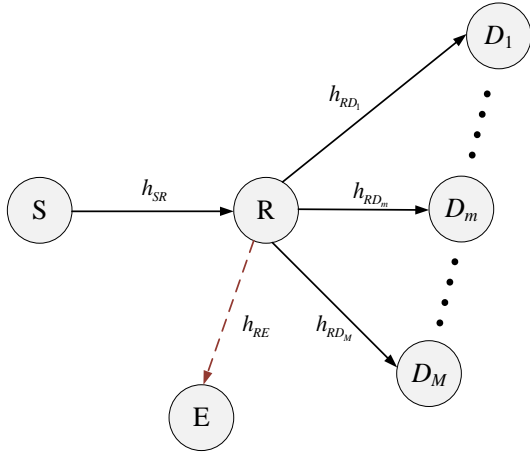


Fig. 1. C-NOMA system model with eavesdropper.

The remainder of this paper is organized as follows: Section II describes the considered system and channel models, whereas Section III is devoted to the exact and asymptotic analysis of the OP and IP of the considered setup. Section IV provides the respective numerical results and discussions, while closing remarks are given in Section V.

II. SYSTEM MODEL

In this section, we consider a downlink cooperative NOMA (C-NOMA) system with an eavesdropper (E), shown in Fig. 1, where M users ($D_m, m = 1, \dots, M$) are served by a base station (S) via an AF relay (R) using the same time and frequency, but with different power levels. Without loss of generality, we assume that there is no direct link between S and D_m , which can be justified by the presence of large objects and heavy shadowing conditions encountered between the source and destinations nodes [22]. Furthermore, we assume that E is in the range of the relay (R) only, which can wiretap the signals from R. Here, we model h_{SR} , h_{RD_m} , and h_{RE} , which, respectively, represent the fading gains of the $S \rightarrow R$, $R \rightarrow D_m$, and $R \rightarrow E$ links, as complex Gaussian random variables with zero mean and variance λ_{SR} , λ_{RD} and λ_{RE} , respectively.

The base station divides its transmission power among the users, whereas at D_m multi-user detection is realized by performing SIC. We also assume an ideal RF front end, for $|h_{RD_1}|^2 \leq |h_{RD_2}|^2 \leq \dots \leq |h_{RD_M}|^2$, so the transmitted signal at S is given by

$$x_S = \sum_{i=1}^M \sqrt{P_i} s_i \quad (1)$$

where $P_i = a_i E_s$ and s_i denote the power and information symbol of the i^{th} sorted user, respectively. Also, E_s is the transmitted power at S, a_i is the i^{th} user's power allocation factor satisfying $a_1 > \dots > a_M$ and $\sum_{i=1}^M a_i = 1$ [23]. Based on this, the transmission is carried out in two phases: during

phase 1, S sends the downlink NOMA signal in (1) to the relay R, and during phase 2, R broadcasts the received signal to the destination nodes, which are also wiretapped by E. To this effect, the received signal at the m^{th} sorted user D_m can be represented as

$$y_{D_m} = h_{RD_m} G \left(h_{SR} \sum_{i=1}^M \sqrt{P_i} s_i + n_R \right) + n_{D_m} \quad (2)$$

where G is the amplifying coefficient, whereas n_R and n_{D_m} denote the zero mean and variance, σ_R^2 and σ_m^2 , circularly symmetric complex additive white Gaussian noise (AWGN) at the relay and the m^{th} user, respectively.

Taking into account the RHI present at the nodes, the received signal at R is represented as [24]

$$y_R = h_{SR} \left(\sum_{i=1}^M \sqrt{a_i E_s} s_i + \mu_S \right) + \mu_R + n_R \quad (3)$$

where μ denotes the distortion noise from RHI and the subscripts S and R denote the source and relay nodes, respectively. Moreover, $\mu_S \sim \mathcal{CN}(0, \rho_S^2 E_s)$, where ρ_S^2 specifies the severity of TX RHI at the source, whereas $\mu_R \sim \mathcal{CN}(0, \rho_R^2 E_s |h_{SR}|^2)$ represents the distortion noise from RX RHI at R. As a result, the distortions from transceiver RHI can be regarded as an additional noise source, yielding

$$y_R = h_{SR} \left(\sum_{i=1}^M \sqrt{a_i E_s} s_i + \mu_{SR} \right) + n_R \quad (4)$$

where $\mu_{SR} \sim \mathcal{CN}(0, \rho_{SR}^2 E_s)$ is the aggregate level of RHI in the link between S and R, and $\rho_{SR}^2 = \rho_S^2 + \rho_R^2$.

Likewise, during phase 2, R amplifies and broadcasts the received signal to the users D_m , where the amplifying coefficient G is given by

$$G = \sqrt{\frac{E_R}{(1 + \rho_{SR}^2 E_s |h_{SR}|^2) + \sigma_R^2}} \quad (5)$$

where E_R denotes the transmitted power. Hence, taking into account the RHI at R and D_m , the received signal at D_m can be expressed as

$$y_{D_m} = h_{RD_m} G h_{SR} \left(\sum_{i=1}^M \sqrt{a_i E_s} x_i + \mu_{SR} \right) + h_{RD_m} G (n_R + \mu_{RD_m}) + n_{D_m} \quad (6)$$

where, $\mu_{RD_m} \sim \mathcal{CN}(0, \rho_{RD_m}^2 E_R)$ is the aggregate level of RHI in the links between R and D_m , and $\rho_{RD_m}^2 = (\rho_R^t)^2 + (\rho_{D_m}^r)^2$. The received signal at E in phase 2 is written as:

$$y_E = h_{RE} G \left[h_{SR} \left(\sum_{i=1}^M \sqrt{a_i E_s} x_i + \mu_{SR} \right) + n_R + \mu_{RE} \right] \quad (7)$$

where n_E is the AWGN at E, $\mu_{RE} \sim \mathcal{CN}(0, \rho_{RE}^2 E_R)$ and $\rho_{RE}^2 = \rho_R^2 + \rho_E^2$ is the aggregate level of RHI between R and E. Moreover, ρ_R^2 and ρ_E^2 denote the residual impairment factors at R and E, respectively.¹

At the users' receivers, SIC is used to realize multi-user detection (MUD) and mitigate interference [25]. Effectively, SIC first decodes users with the higher transmission power and then subtracts them from its received signal while treating all the signals of all other users as noise. In particular, user D_k ($k = 1, 2, \dots, M$) first detects the stronger users' signals D_j ($j < k$) and then subtracts them from the received signal. Next, it detects its own signal by treating the weaker users' signals D_l ($l > k$) as noise. Likewise, at the eavesdropper's side, considering the availability of the CSI, the SIC process is also carried out at E. Therefore, assuming perfect interference cancellation, the effective signal for user D_k to decode its own message can be obtained by substituting script m with k in (6).

III. PERFORMANCE ANALYSIS

It is recalled that the outage probability can be defined as the probability that the symbol error rate is greater than a certain required quality of service and it can be computed as the probability that the SNR falls below a corresponding threshold which depends on the detection technique, the modulation order and the encountered fading conditions [26]. According to the principle of NOMA, D_m decodes and cancels the interference from the users allocated more power than itself before decoding its own message. Therefore, D_m should first detect the signals from D_j ($j < m$) before decoding its own signal. Hence, the SIDNR for D_m when decoding D_k 's message ($k \leq m$) is given in (8) and the corresponding achievable data rate is evaluated as

$$R_{k \rightarrow m} = \frac{1}{2} \log_2(1 + \gamma_{k \rightarrow m}). \quad (9)$$

Based on the principle of NOMA, an outage event occurs at the m^{th} user if it fails to decode its own signal or the signal of any user in the SIC. Therefore, the m^{th} user's OP is evaluated as

$$P_{out}^m = 1 - P_r(A_{m,1} \cap \dots \cap A_{m,m}) \quad (10)$$

where $A_{m,k}$ denotes an event in which D_m can correctly decode the k^{th} user's signal by

¹For mathematical tractability and without loss of generality, hereafter, we assume that the main link noise variance is $\sigma_R^2 = \sigma_m^2 = \sigma^2$, whereas in the wiretap link, the noise variance is σ_e^2 .

$$A_{m,k} \triangleq \left\{ R_{k \rightarrow m} > R_k \right\} = \left\{ \frac{1}{2} \log_2 \left(1 + \frac{a_k \Upsilon_{D_m}}{\left(\sum_{j=k+1}^M a_j + \rho_0 \right) \Upsilon_{D_m} + 1} \right) > R_k \right\} \quad (11)$$

where

$$\rho_0 = \rho_{SR}^2 + \rho_{RD_m}^2 + \rho_{SR}^2 \rho_{RD_m}^2, \quad (12)$$

$$\Upsilon_{D_m} = \frac{E_s E_R |h_{SR}|^2 |h_{RD_m}|^2}{\rho_1 E_s |h_{SR}|^2 + \rho_2 E_R |h_{RD_m}|^2 + \sigma^4}, \quad (13)$$

$$\rho_1 = (1 + \rho_{SR}^2) \sigma^2, \quad (14)$$

and

$$\rho_2 = (1 + \rho_{RD_m}^2) \sigma^2. \quad (15)$$

Furthermore, taking

$$\omega_k = \left(\frac{a_k}{2^{2R_k} - 1} - \left(\sum_{j=k+1}^M a_j + \rho_0 \right) \right)^{-1}, \quad 1 \leq m \leq M-1 \quad (16)$$

$$\omega_M = \left(\frac{a_M}{2^{2R_k} - 1} - \rho_0 \right)^{-1}, \quad (17)$$

and

$$\omega_m^* = \max(\omega_1, \dots, \omega_m), \quad 1 \leq m \leq M \quad (18)$$

and assuming independent and identically distributed (i.i.d.) channels h_{RD_m} , while omitting the subscript m for notational convenience, we can obtain the OP P_{out}^m expression in (19). In addition, $|h_{RD}|^2$ also follows a Rayleigh distribution with variance λ_{RD} , while the PDF and cumulative distribution function (CDF) of the m^{th} ordered variable $|h_{RD}|^2$ are given by [22]. After some algebraic manipulations and with the aid of [27, eq. (3.471.9)], we can obtain the OP expression in (20).

The eavesdropper successfully intercepts the k^{th} legitimate user's signal only if D_k 's signal is correctly decoded. It is recalled here that according to the principle of NOMA, users with poor channel quality are allocated more transmission

$$\gamma_{k \rightarrow m} = \frac{a_k G^2 E_s |h_{SR}|^2 |h_{RD}|^2}{G^2 |h_{RD}|^2 \left(E_s |h_{SR}|^2 \left(\sum_{j=k+1}^M a_j + \rho_{SR}^2 \right) + \sigma^2 \right) + E_R \rho_{RD}^2 |h_{RD}|^2 + \sigma^2} \quad (8)$$

power. Also, we assume perfect cancellation, thus when D_k 's signal is wiretapped, E is able to successfully eliminate the high power users' signals D_j using SIC ($j < k$), whereas the signals of the low power users D_l ($M \geq l > k$) are treated as noise. Based on this and with the aid of (7), the corresponding IP achieved at E, when D_k 's message is wiretapped, is obtained in (21).

IV. NUMERICAL AND SIMULATION RESULTS

Considering the C-NOMA approach described above and utilizing the derived analytic expressions and their respective computer simulations, this section quantifies the effect of TX and/or RX RHI on the performance of communication systems based on C-NOMA with a present active eavesdropper (C-NOMA-E). Assuming Rayleigh fading conditions, we carried out extensive Monte Carlo simulations to investigate the IP and OP performance of C-NOMA-E under RHI effects. Unless otherwise stated, the number of users considered is taken as $M = 3$, and the NOMA power allocation coefficients are $a_1 = 1/2$, $a_2 = 1/3$ and $a_3 = 1/6$. The associated target data rates are $R_1 = 0.4$ bps/Hz, $R_2 = 0.6$ bps/Hz, $R_3 = 0.7$ bps/Hz, respectively. Also, we assume that all the nodes are impaired by RHI, where $\rho_t = \rho_S^t = \rho_R^t$, $\rho_r = \rho_R^r = \rho_{D_m}^r = \rho_E^r$ and we set $\sigma^2 = \sigma_e^2 = 1$, $\lambda = \lambda_{SR} = \lambda_{RD_m} = 1$, and $\lambda_e = \lambda_{SE} = \lambda_{RE}$. Throughout this section, the numerical results are shown with solid lines, whereas markers are used to illustrate the corresponding computer simulation results. Thus, it is clearly observed that the derived expressions accurately characterize the simulated IP and OP performance in the presence of RHI.

Fig. 2 illustrates the effects of joint TX/RX RHI on the IP performance of the considered C-NOMA-E system under SIC with three users and one eavesdropper, as a function of the MER. For a transmitted SNR of 35 dB, we evaluated the intercept probability of each NOMA user at E. In this case, RHI may come from the TX and/or RX, where the value of $\rho_{RE} = 0.15$ represents the aggregate level of RHI between R and E. The selected RHI values represent practical values that have been widely used in other relevant analyses. It is evident that the derived asymptotic expressions provide tight approximations to the exact IP and that the RHI effects reduce the IP probability of the NOMA users. In addition, it is shown that this impairment affects the NOMA users in different ways. For example, in the three-user scenario, RHI has little impact on D_1 's IP, whereas the IP of D_2 and D_3 exhibit more significant shifts. Moreover, if we assume that E performs SIC and can therefore eliminate the signals of D_2 and D_3 when D_1 is intercepted, joint TX/RX RHI reduces the

highest MER required for E to intercept users D_1 , D_2 and D_3 . For the three users, the MER declined from 37 dB, 34.1dB and 33.9 dB to 35.9 dB, 31 dB and 30 dB, respectively.

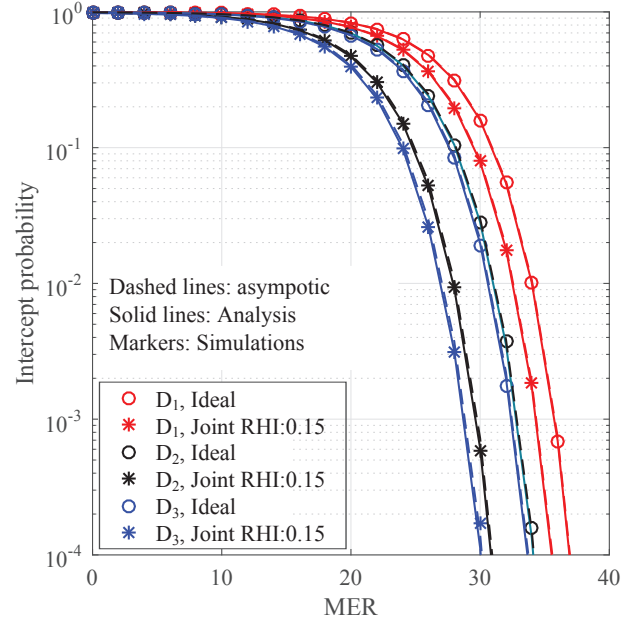


Fig. 2. IP as a function of MER for a 3 user NOMA system under SIC, SNR=35dB.

Figs. 3-4 show the effects of RHI on the OP performance of a three-user C-NOMA-E system as a function of the transmitted SNR. We consider joint TX/RX RHI, and set $\rho_r = \rho_t = 0.14$. The derived asymptotic expressions accurately characterized the exact OP, and it is shown that RHI causes significant degradation of the OP performance for all NOMA users. Moreover, the level of performance degradation depends on the user order. Precisely, from Fig. 3, it is observed that the detrimental effects of RHI appear to affect D_1 less than the other users. Interestingly, under the effects of this impairment, the performance of D_2 and D_3 are degraded to the point where their OP becomes higher than that of D_1 . In fact, RHI is an additive impairment, so the severity of the detrimental effects of this impairment depends on several factors, including the power splitting ratio and the user order.

The effect of RHI at the different nodes is shown in Fig. 4. Interestingly, RHI at the source node or the destination node only achieves a relatively small increase in the average OP value. In a scenario where RHI occurs solely at the relay

$$\begin{aligned}
P_{out}^m &= 1 - \Pr(\Upsilon_{D_m} > \omega_m^*) \\
&= \Pr(\Upsilon_{D_m} \leq \omega_m^*) \\
&= \Pr \left\{ E_s \left(E_R |h_{RD}|^2 - \rho_1 \omega_m^* \right) |h_{SR}|^2 \leq \left(\rho_2 E_R |h_{RD}|^2 + \sigma^4 \right) \omega_m^* \right\} \\
&= \int_0^{\frac{\rho_1 \omega_m^*}{E_R}} f_{|h_{RD}|^2}(y) dy + \int_{\frac{\rho_1 \omega_m^*}{E_R}}^{\infty} f_{|h_{RD}|^2}(y) \int_0^{\frac{(\sigma^4 + \rho_2 E_R y) \omega_m^*}{E_s (E_R y - \rho_1 \omega_m^*)}} f_{|h_{SR}|^2}(x) dx dy
\end{aligned} \tag{19}$$

$$P_{out}^m = 1 - 2 \frac{Q_m}{\lambda_{RD}} e^{-\frac{\rho_2 \omega_m^*}{\lambda_{SR} E_s}} \sum_{i=0}^{M-m} (-1)^i \binom{M-m}{i} \sum_{j=0}^{m+i-1} \binom{m+i-1}{j} (-1)^j \left(\frac{(\sigma^4 + \rho_1 \rho_2 \omega_m^*) \omega_m^* \lambda_{RD}}{\lambda_{SR} E_s E_R (j+1)} \right)^{\frac{1}{2}} \times e^{-\frac{(j+1) \rho_1 \omega_m^*}{E_R \lambda_{RD}}} K_1 \left(2 \sqrt{\frac{\omega_m^* (\sigma^4 + \rho_1 \rho_2 \omega_m^*) (j+1)}{\lambda_{RD} \lambda_{SR} E_s E_R}} \right) \quad (20)$$

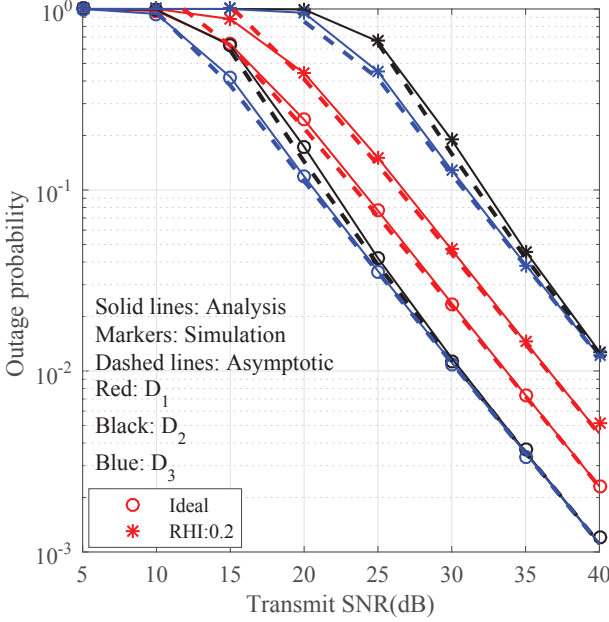


Fig. 3. OP as a function of transmit SNR for a 3 user NOMA system under joint TX/RX RHI.

node, the performance penalty is of ~ 1.5 dB only. However, joint RHI at all the nodes causes a significant penalty of ~ 4 dB.

V. CONCLUSION

We investigated the effects of RHI on secure NOMA-based amplify-and-forward cooperative systems under Rayleigh fading conditions. All derived analytic results were extensively corroborated by respective computer simulations. Capitalizing on these results, it was shown that RHI degrades both the legitimate users' and the eavesdropper's performance. Useful theoretical and practical insights were provided on the detrimental effects of hardware impairments on conventional and

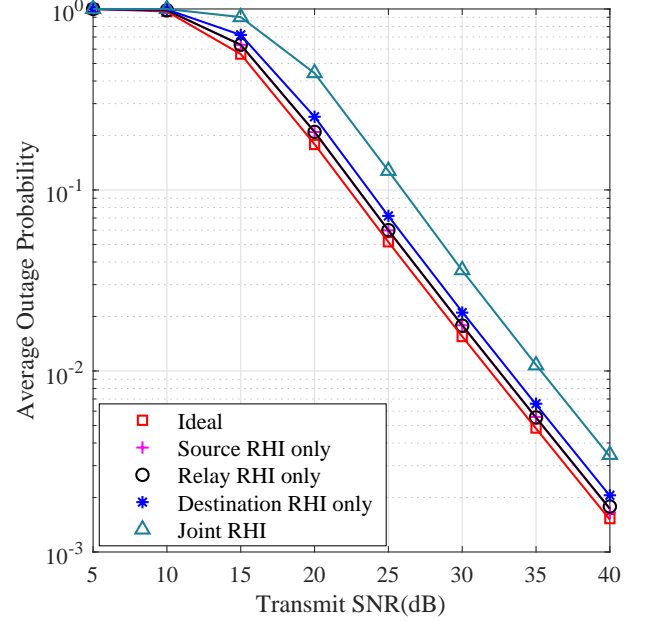


Fig. 4. Average OP as a function of transmit SNR for RHI of 0.12 at the different nodes

emerging communication systems and their potential need for compensation.

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$$P_{int}^k = \frac{1}{\lambda_{RE}} e^{-\left(\frac{e_1}{E_R \lambda_{RE}} + \frac{e_2}{E_s \lambda_{SR}}\right) \delta_k} \int_0^\infty e^{-\frac{\xi}{\lambda_{RE}} - \frac{(\sigma^2 \sigma_e^2 + e_1 e_2 \delta_k) \delta_k}{E_s E_R \lambda_{SE} \xi}} d\xi = \frac{2}{\lambda_{RE}} e^{-\left(\frac{e_1}{E_R \lambda_{RE}} + \frac{e_2}{E_s \lambda_{SR}}\right) \delta_k} \left(\frac{\lambda_{RE} (\sigma^2 \sigma_e^2 + e_1 e_2 \delta_k) \delta_k}{\lambda_{SR} E_R E_s} \right)^{\frac{1}{2}} K_1 \left(2 \sqrt{\frac{(\sigma^2 \sigma_e^2 + e_1 e_2 \delta_k) \delta_k}{\lambda_{RE} \lambda_{SR} E_R E_s}} \right) \quad (21)$$

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