A new secure multi-hop untrusted relaying scheme

Ali Kuhestani, Member, IEEE, Milad Tatar Mamaghani, and Hamid Behroozi, Senior, Member, IEEE

Abstract—Cooperative relaying is utilized as an efficient method for data communication in wireless sensor networks and Internet of Things (IoT). However, sometimes due to the necessity of multi-hop relaying in such communication networks, it is challenging to guarantee the secrecy of cooperative transmissions when the relays may themselves be eavesdroppers, i.e., we may face with the untrusted relaying scenario where the relays are both necessary helpers and potential eavesdroppers. To obviate this issue, a new cooperative jamming scheme is proposed in this paper, in which the data can be confidentially communicated from the source to the destination through multi-hop untrusted relays. Toward this end, we first consider a two successive untrusted relaying network, i.e., a three-hop communication network. In our proposed secure transmission scheme, all the legitimate nodes contribute to provide secure communication by smartly injecting artificial noises to the network in different communication phases. Given this system model, a novel closed-form expression is presented in the high signal-to-noise ratio (SNR) regime for the ergodic secrecy rate (ESR). Furthermore, we evaluate the high SNR slope and power offset of the ESR to gain a basic comparison of the proposed secure transmission scheme and the state-of-arts. Our numerical results highlight that the proposed secure transmission scheme provides better secrecy rate compared with the two-hop untrusted relaying scheme as well as the direct transmission scheme.

Index Terms—Physical layer security, Untrusted relay, Multi-hop communication, Artificial noise injection.

I. INTRODUCTION

SECURITY in wireless communication networks is conventionally implemented above the physical layer using key based cryptography methods [1]. However, these methods may not be applicable to emerging Internet of Things (IoT) and ad-hoc networks. For instance, the time-varying network topologies require complicated key management which is difficult to implement in distributed networks. Additionally, the computing and processing abilities of the nodes may be limited and the complicated encryption calculations may not be supported. To complement these complex schemes, wireless transmitters can also be validated at the physical layer by exploiting the dynamic characteristics of the associated communication links [2]. To accomplish this idea, physical layer security (PLS) has been emerged as a promising paradigm for safeguarding 5G wireless communication networks without incurring additional security overhead [2].

In the context of PLS, cooperative jamming which involves the transmission of additional jamming signals to degrade the received signal-to-noise ratio (SNR) at the potential eavesdropper can be applied by any legitimate node of the network [1]. Recently, several works have considered the interesting scenario of untrusted relaying [3]–[7] where the cooperative jamming is performed by the intended receiver, which is named as destination-based jamming technique.

In real world, an untrusted relay may be assisted to provide a reliable communication. Several practical scenarios may include untrusted relay nodes, e.g., wireless sensor networks and IoT where low-cost intermediate nodes may be exploited to assist the source-to-destination transmission. In these networks, it is important to protect the confidentiality of information from the untrustworthy relay, while simultaneously exploiting its relaying capability to improve the data transmission rate. Thanks to the destination-based jamming strategy [3], positive secrecy rate can still be attained in untrusted relay networks.

While the recent works [4]–[7] have focused on the simple scenario of two-hop untrusted relaying, it is of great interest to go beyond these investigations by considering secure communication in larger networks such as ad-hoc networks and IoT where more than two hops may be required to provide the source to destination communication [8], [9]. Extending the analysis from two-hop networks to multi-hop untrusted relaying networks is non-trivial, because using more hops means that more nodes are involved in the transmission as well as more chances for eavesdropping. In addition, the number of hops becomes a design parameter which affects on the end-to-end delay and throughput.

In this paper, we take into account secure transmission in a multi-hop amplify-and-forward untrusted relaying network where all nodes have a single antenna. Each relay is considered to be a mandatory helper and a potential eavesdropper. A new artificial noise injection protocol is proposed to keep the communication confidential from the internal eavesdroppers for any number of hops. For the special case of three-hop communication network, i.e., two successive untrusted relaying, the proposed secure transmission scheme is as follows: in the first phase, while the source transmits its confidential message to the first relay, the second relay injects artificial noise to confuse the first relay. In the second phase, when the first relay forwards the received signal to the second relay, the destination injects an artificial noise to disturb the signal at the second relay. Finally, in the third phase, when the second relay broadcasts its signal to the destination, the source sends an artificial noise to confuse the first relay. For this system model, we first derive a novel closed-form expression for the ergodic secrecy rate (ESR) of three-hop untrusted relaying at the high SNR regime. Furthermore, we characterize the high SNR slope and power offset of the ESR to provide a fundamental comparison of the proposed scheme. We then extend our scheme by proposing a general multi-hop untrusted relaying transmission scheme. Our numerical examples highlight that the proposed three-hop relaying scheme outperforms the traditional two-hop relaying and direct transmission schemes where low power IoT devices are exploited.
II. SYSTEM MODEL AND TRANSMISSION SCHEME

As illustrated in Fig. 1, a three-hop communication system is studied where the source node, denoted by (S), sends the information signal to the destination (D) with the help of two consecutive relays, namely R_1 and R_2. The amplify-and-forward relay nodes are assumed to be untrusted and hence, they can overhear the transmitted information signal while relaying. Besides, all the involving nodes are equipped with a single antenna operating in half-duplex mode. We also assume that the consecutive relays are necessary helpers to deliver the information signal to the destination. This assumption is valid when the network nodes experience a heavy shadowing, or when the distance between the nodes is large, or when the nodes suffer from limited power resources. We consider a time division duplex (TDD) system with channel reciprocity. The complex Gaussian channel gains from a time division duplex (TDD) system with channel reciprocity. The complex Gaussian channel gains from the nodes suffer from limited power resources. We consider a time division duplex (TDD) system with channel reciprocity. The complex Gaussian channel gains from the nodes suffer from limited power resources. We consider a time division duplex (TDD) system with channel reciprocity. The complex Gaussian channel gains from the nodes suffer from limited power resources. We consider a time division duplex (TDD) system with channel reciprocity. The complex Gaussian channel gains from the nodes suffer from limited power resources. We consider a time division duplex (TDD) system with channel reciprocity. The complex Gaussian channel gains from the nodes suffer from limited power resources. 

We consider block fading such that the channel coefficients vary independently from one frame to another frame, but do not change within one frame. To make the analysis tractable, we consider the equal transmit power $P$ by the nodes. We also define $\gamma_g = \rho |g|^2$, $\gamma_h = \rho |h|^2$, and $\gamma_f = \rho |f|^2$, where $\rho = \frac{P}{N_0}$ describes the transmit SNR per each node. Remarkably $\gamma_g$, $\gamma_h$ and $\gamma_f$ have exponential distributions with means $\bar{\gamma}_g = \rho m_g$, $\bar{\gamma}_h = \rho m_h$, and $\bar{\gamma}_f = \rho m_f$, respectively.

Without loss of generality, the power of additive white noise at each receiver is considered to be $N_0$. We also suppose that the nodes are aware of the necessary channel state informations (CSIs), by which the relays as well as the destination can thoroughly cancel the self-interference term from the received signal. Note that since this assumption leads to the maximum probability of eavesdropping at the relays, we are forced to design a more robust network against eavesdropping attack.

The proposed scheme for source-destination secure communication takes place in three phases as shown in Fig. 1. By considering equal time duration for each phase, the proposed protocol is as follows. In the first phase of communication, by using superposition coding $S$ transmits the information signal to $R_1$ and simultaneously, $R_2$ jams the first untrusted relay by transmitting the artificial noise, as demonstrated with solid lines in the figure. During the next phase, as depicted by dashed lines, $R_1$ forwards a scaled version of the received signal towards $R_2$. Concurrently, $D$ jams $R_2$ via transmitting a jamming signal to guarantee secrecy. Finally, in the third phase, plotted by dotted lines, $R_2$ amplifies and broadcasts the received signal which can be further received by $D$ and $R_1$. After self-interference cancellation at $D$, the information signal can be extracted at $D$. Notably during the last time slot, due to the fact that $R_1$ can overhear the broadcasted signal by $R_2$, the node $S$ is forced to emit a jamming to enhance the confidentiality of communication. As such, $R_1$ may fail to successfully eavesdrop.

Based on the above descriptions and after some manipulations, the exact signal-to-interference-plus-noise-ratios (SINRs) at $R_1$ in the first phase, at $R_2$, at $R_1$ in the third phase and at $D$ are respectively, obtained as

$$\gamma_{R_1}^{(1)} = \frac{\gamma_g}{\gamma_h + 1}, \quad \gamma_{R_2}^{(1)} = \frac{\gamma_g \gamma_h}{\gamma_g \gamma_f + \gamma_h \gamma_f + \gamma_g + \gamma_f + 1}, \quad (1)$$

$$\gamma_{R_1}^{(2)} = \frac{\gamma_g \gamma_h^2}{\gamma_h^2 + \gamma_h (\gamma_g + 1)^2 + (\gamma_g + \gamma_h + 1)^2 (\gamma_f + 1)} \quad (2)$$

$$\gamma_D = \frac{\gamma_g \gamma_h \gamma_f}{3\gamma_h \gamma_f + 2\gamma_f \gamma_g + 2\gamma_g + 2\gamma_h + \gamma_g + 1} \quad (3)$$

Under the high SNR assumption with $\gamma_k \gg 1$ for $k \in \{g, h, f\}$, the above SINRs are respectively, simplified as

$$\gamma_{R_1}^{(1)} \approx \frac{\gamma_g}{\gamma_h}, \quad \gamma_{R_2}^{(2)} \approx \frac{\gamma_g \gamma_h}{\gamma_f (\gamma_g + \gamma_h)}, \quad (4)$$

$$\gamma_{R_1}^{(3)} \approx \frac{\gamma_g \gamma_h^2}{(\gamma_g + \gamma_h)^2 \gamma_f^2 + 2\gamma_h \gamma_f} \quad (5)$$

$$\gamma_D \approx \frac{\gamma_g \gamma_h \gamma_f}{3\gamma_h \gamma_f + 2\gamma_f \gamma_g + \gamma_g \gamma_h}. \quad (6)$$

Expressions in (4) and (5) reveal that the amount of information leakage is saturated when the transmit SNR goes to infinity. However, the received SINR at the legitimate receiver is a monotonically increasing function on the transmit SNR. As a result, the achievable ESR is increased as the transmit SNR grows which is fundamentally different from the direct transmission scheme [5].

**Remark 1**: As can be understood, in the proposed scheme, when a node transmits the information signal in the line of destination, the node which is near to the receiving untrusted relay is forced to propagate artificial noise to confuse the eavesdropping node. As a consequence, this proposed scheme can be routinely extended to multi-hop untrusted relaying where more than two untrusted relays cooperate to forward a confidential message to the destination.

III. SECRECY PERFORMANCE ANALYSIS

The ergodic secrecy rate (ESR), as a widely used secrecy criteria in the literature, characterizes the rate below which any average secure transmission rate can be obtained. In this section, we proceed to derive a new closed-form expression for the ESR of three-hop untrusted relaying.

Based on the definition, the instantaneous secrecy rate is achieved by subtracting the eavesdropping channel capacity.
from the legitimate channel capacity $R_s$. As such, the instantaneous secrecy rate, $R_s$, for a three-hop relaying is given by

$$R_s = \left[ I_D - \max\{ I_{R_1}^{(1)}, I_{R_2}^{(1)}, I_{R_1}^{(3)} \} \right]^+, \quad (7)$$

where $I_K = \frac{1}{3} \log_2(1 + \gamma_K)$ with $K \in \{ R_1, R_2, D \}$ and $\lfloor x \rfloor = \max(x, 0)$. Notably the pre-log factor $\frac{1}{3}$ is due to the fact that one round of transmission is done during three phases.

**Remark 2:** It is worth noting that $\gamma_{R_2} \gg \gamma_{R_1}^{(3)}$, which can be readily concluded by comparing (4) and (5). Therefore, the maximum information leakage of three-hop untrusted relaying is simplified to $\gamma E \equiv \max\{ \gamma_{R_1}, \gamma_{R_2} \}$.

The exact ESR expression of the proposed three-hop untrusted relaying is obtained by forming a multiple integral expression which can be calculated numerically. To present a new compact expression for the ESR, we first derive closed-form expressions for the ergodic legitimate rate and the ergodic eavesdropping rate and then, a tight lower-bound expression is presented for the ESR performance.

**Lemma 1.** The lower-bound closed-form expression for the ergodic rate of the legitimate channel is given by

$$\bar{R}_L = \frac{1}{3 \ln 2} \mathbb{E}\{ \ln(1 + \gamma L) \} \geq \frac{1}{3 \ln 2} \left[ \ln \left( 1 + \exp \left[ -3 \Phi + \ln \left( \gamma_{rh} \gamma_{hf} \right) \right] \right) \right] \Delta \bar{R}_L^B, \quad (8)$$

where $\Phi \approx 0.577215$ is the Euler constant.

**Proof:** The proof can be done straightforwardly by considering the facts that: 1) the Jensen’s inequality can apply on the concave function $\ln(1 + \exp(x))$ with respect to $x$ and, 2) for the exponential r.v. $X$ with the mean of $m_X$, we have $\mathbb{E}(\ln(X)) = -\Phi + \ln(m_X)$ [10 Eq. (4.3.31.1)].

**Lemma 2.** The approximate closed-form expression for the ergodic rate of the eavesdropping channel is formulated as

$$\bar{R}_E = \frac{1}{3 \ln 2} \mathbb{E}\{ \ln(1 + \gamma E) \} = \frac{1}{3 \ln 2} (\mathcal{P} T_1 + (1 - \mathcal{P}) T_2), \quad (9)$$

where $\mathcal{P} = \text{Pr}\{\gamma_{R_1}^{(1)} > \gamma_{R_2}\}$, $T_1 = \mathbb{E}\{ \ln(1 + \gamma_{R_1}^{(1)}) \}$ and $T_2 = \mathbb{E}\{ \ln(1 + \gamma_{R_2}) \}$ are formulated as closed-form expressions in Appendix A.

**Proposition 1.** The tight closed-form lower-bound expression for the ESR performance of the proposed three-hop untrusted relaying is given by

$$\bar{R}_s^{LB} = \frac{1}{3 \ln 2} \left[ \bar{R}_L^B - \bar{R}_E \right]^+. \quad (10)$$

**V. NUMERICAL EXAMPLES AND DISCUSSION**

In this part, we prepare some numerical curves to reveal the accuracy of the presented closed-form expressions. Additionally, we compare the secrecy performance of the proposed multi-hop relaying scheme with two competitive counterparts: 1) the two-hop communication scheme where only one relay is selected for data transmission and the other relay is considered as pure eavesdropper, and 2) the direct transmission where the confidential information is forwarded to the destination directly without assisting the relays. In this case, both the relays are considered as pure eavesdroppers. The following simulation parameters are adopted in Figs. 2 and 3. For simplicity and without loss of generality, we assume that the nodes $S, D, R_1$ and $R_2$ are placed on one-dimensional space at positions $-3, +3, -1$ and $+1$, respectively. Additionally, the distance-dependent path loss factor is $n = 2.7$.

Fig. 2 depicts the ESR performance versus the transmit SNR $\rho$ in dB for different secure transmission schemes. As can be seen in this figure, our proposed lower expression for the ESR in Proposition 1 agrees well with the exact ESR which is evaluated numerically by substituting (10)–(12) into (16). Furthermore, our asymptotic ESR performance in Section IV well-approximates the exact ESR in the high SNR regime. As observed from Fig. 2, the ESR curve corresponding to the case when considering only the first term of the infinite series (associated to the equivalent modified Bessel function of the second kind and first order) is so close to the exact ESR curve.

To reveal the advantage of the proposed three-hop untrusted relaying scheme, we compare the ESR performance of our new scheme with two well-known transmission schemes, i.e., two-hop untrusted relaying and direct transmission, in Fig.
3. Additionally, two network topologies is considered. In Topology 1, we have the same network structure as considered for Fig. 2, and for Topology 2, we have the scaled version of Topology 1 with factor of 1/4. i.e., the nodes $S$, $D$, $R_1$ and $R_2$ are located at -1, +1, $-\frac{1}{2}$ and $\frac{1}{2}$, respectively. Note that under two-hop relaying scheme, we face with two cases. In Case I, the relay $R_1$ is employed for data retransmission and the relay $R_2$ is considered as pure eavesdropper. Whereas in Case II, the converse scenario is considered. i.e., the relay $R_2$ is the helper node and $R_1$ is considered as an idle eavesdropper. As observed in Fig. 3, the secrecy performance of the proposed three-hop relaying scheme always outperforms the two mentioned benchmarks for the transmit SNRs fewer than 25 dB (i.e., $\rho < 25$ dB). This result highlights the priority of our scheme compared with the state-of-arts in untrusted relaying networks. One can easily predict that the proposed scheme under Topology 1 outperforms the two-hop relaying schemes for $\rho > 25$ dB. Interestingly, under Topology 2 and for $\rho > 25$ dB, the two-hop relaying scheme with Case I provides better ESR compared with our scheme. The reason is that when the communication nodes are close together with much power budget, naturally, the two-hop relaying is sufficient to data transmission and hence, it is not necessary to implement multi-hop relaying scheme. Additionally, as proved in [7], the high SNR slope for two-hop relaying is $S_{\infty} = \frac{1}{2}$ which is more than the high SNR slope of tree-hop relaying scheme, $S_{\infty} = \frac{1}{3}$, as we derived in (12). It is worth noting that in IoT and wireless sensor networks, the devices are power limited and thus, they cannot consume much power for data transmission/retransmission. As a result, the proposed secure three-hop relaying scheme in this paper is applicable for IoT where low or medium transmit SNRs can be supported by the devices. Finally, this figure depicts that the direct transmission scheme presents a near to zero, but non-zero, secrecy rate. As discussed in [7], even when the destination is very far from the source while the eavesdroppers locate between them, a positive secrecy rate is achievable.

VI. CONCLUSIONS

In this contribution, we designed a new secure transmission scheme over multi-hop untrusted relaying networks. To this end, we first studied a three-hop communication network with two successive untrusted relays. Given this system model, a novel closed-form expression was derived in the high SNR regime for the ESR performance. We next evaluated the high SNR slope and power offset of the ESR. We finally generalized our system model to multi-hop untrusted relaying. Our numerical results presented that the proposed secure transmission scheme improves the secrecy performance compared with two-hop relaying and direct transmission schemes.

APPENDIX A

PROOF OF LEMMA 2

Before proving Lemma 2, we present the following necessary Lemma.

Lemma 3. Let $X$ and $Y$ be exponential RVs with means $m_x$ and $m_y$, respectively. Then the new RVs $Z = \frac{X}{W}$ and $W = \frac{Y}{\sqrt{m_x m_y}}$ have the following cumulative distribution functions (CDFs), respectively

$$F_Z(z) = \frac{m_y z}{m_y z + m_x},$$

$$F_W(w) = 1 - \frac{2\omega}{\sqrt{m_x m_y}} \exp\left(-\frac{\omega}{m_x} - \frac{\omega}{m_y}\right) K_1\left(\frac{2\omega}{\sqrt{m_x m_y}}\right),$$

where $K_1(\cdot)$ is the modified Bessel function of the second kind and $\nu$-th order.

Proof: The proof is given in Appendix B.

In the following, we proceed to prove the different parts of Lemma 2.
A. Calculating $P$: Plugging (4) into $P = \Pr\{\gamma_R^1 > \gamma_R^2\}$, and then defining $X = \gamma_f$, $Y = \gamma_h$ and $Z = \gamma_g$, we get

$$P = \Pr\{\gamma_f > \frac{\gamma_f^2}{\gamma_g + \gamma_h}\} = 1 - \Pr\{X < \frac{Y^2}{Y + Z}\}$$

$$= 1 - \mathbb{E}\{\mathbb{E}\{F_X(\frac{y^2}{y + z})\}\}$$

$$= \frac{1}{m_y m_z} \int_0^\infty \int_0^\infty \exp(-\frac{y^2}{m_y} - \frac{y}{m_y} - \frac{z}{m_z}) dy dz$$

$$(a) = \frac{1}{m_y m_z} \int_0^\infty \int_0^\infty \exp(-\frac{v^2}{m_x} - \frac{v}{m_x} - \frac{u - v}{m_z}) du dv$$

$$(b) = \frac{4}{m_x m_y m_z} \int_0^\infty \int_0^\infty \exp(-\frac{m_y - m_z}{m_y m_z} v K_1\left(\sqrt{\frac{2}{m_x m_z}} v\right)) dv$$

$$(c) \int_0^\infty \int_0^\infty \exp(-\frac{m_y - m_z}{m_y m_z} v K_1\left(\sqrt{\frac{2}{m_x m_z}} v\right)) dv$$

$$(d) = \frac{1}{m_y m_z} \int_0^\infty \int_0^\infty \exp(-\frac{m_y - m_z}{m_y m_z} v K_1\left(\sqrt{\frac{2}{m_x m_z}} v\right)) dv$$

Finally, after calculating the integral term using (10, Eq. (3.324.1)), one can obtain the expression given in (14).

APPENDIX B

PROOF OF LEMMA 3

The CDF of $Z = \frac{X}{Y}$ has been derived in (5). To obtain the CDF of $W = \frac{XY}{X + Y}$, we start from the definition of CDF as

$$F_W(\omega) = \Pr\{\frac{XY}{X + Y} < \omega\} = \Pr\{XY - \omega(X + Y) < 0\}$$

$$= \Pr\{X < \frac{\omega Y}{Y - \omega} Y < \omega Y - 0\} \Pr\{Y - \omega Y < 0\}$$

$$= \int_0^\infty F_X\left(\frac{\omega y}{y - \omega}\right) f_Y(y) dy + \int_0^\infty f_Y(y) dy$$

$$= \int_0^\infty \left[1 - \exp\left(-\frac{\omega y}{m_x(y - \omega)}\right)\right] f_Y(y) dy + \int_0^\infty f_Y(y) dy$$

$$= \int_0^\infty \left[1 - \exp\left(-\frac{\omega y}{m_y}\right)\right] f_Y(y) dy + \int_0^\infty f_Y(y) dy$$

$$= \int_0^\infty \left[1 - \exp\left(-\frac{\omega y}{m_y}\right)\right] f_Y(y) dy + \int_0^\infty f_Y(y) dy$$

$$= \int_0^\infty \left[1 - \exp\left(-\frac{\omega y}{m_y}\right)\right] f_Y(y) dy + \int_0^\infty f_Y(y) dy$$

Finally, after calculating the integral term using (10, Eq. (3.324.1)), one can obtain the expression given in (14).

REFERENCES

[1] A. Mukherjee, S. A. A. Fakoorian, J. Huang, and A. L. Swindlehurst, “Principles of physical-layer security in multiuser wireless networks: A survey,” IEEE Commun. Surveys and Tutorials, vol. 16, no. 3, pp. 3062-3080, Feb. 2014.

[2] N. Yang, L. Wang, G. Geraci, M. Elkashlan, J. Yuan, and M. D. Renzo, “Safeguarding 5G wireless communication networks using PLS,” IEEE Commun. Mag., vol. 53, no. 4, pp. 20-27, Apr. 2015.

[3] X. He and A. Yener, “Two-hop secure communication using an untrusted relay: A case for cooperative jamming,” in Proc. IEEE Globecom, New Orleans, LA, Dec. 2008, pp. 1-5.

[4] L. Sun, P. Ren, Q. Du, Y. Wang, and Z. Gao, “Security-aware relaying scheme for cooperative networks with untrusted relay nodes,” IEEE Commun. Lett., vol. 19, no. 3, pp. 463-466, Sep. 2014.

[5] A. Kuhestani, A. Mohammad and P. L. Yeoh, “Security-aware relay selection in cyber-physical cooperative systems with non-ideal untrusted relaying,” 2018 IEEE 4th World Forum on Internet of Things (WF-IoT), Singapore, pp. 552 - 557.

[6] A. Kuhestani, et al., “Optimal power allocation by imperfect hardware analysis in untrusted relaying networks,” IEEE Trans. Wireless Commun., vol. 17, no. 7, pp. 4302-4314, July 2018.

[7] A. Kuhestani, A. Mohammad and P. L. Yeoh, “Joint relay selection and power allocation in large-scale MIMO systems with untrusted relays and passive eavesdroppers,” IEEE Trans. Inf. Forens. Sec., vol. 13, no. 2, pp. 341355, Feb. 2018.

[8] H. Wang, Y. Zhang, D. W. K. Ng and M. H. Lee, “Secure routing with power optimization for ad-hoc networks,” IEEE Trans. Commun., vol. 66, no. 10, pp. 4666-4679, Oct. 2018.

[9] J. Yao, X. Zhou, Y. Liu and S. Feng, “Secure transmission in linear multihop relaying networks,” IEEE Trans. Wireless Commun., vol. 17, no. 2, pp. 822-834, Feb. 2018.

[10] I. S. Gradshyen and I. M. Ryzik, Table of Integrals, Series, and Products, 7th ed. New York: Academic, 2007.

[11] M. Molu, et al., “A novel equivalent definition of modified Bessel functions for performance analysis of multi-hop wireless communication systems”, IEEE Access, vol. 5, pp. 7594-7605, May 2017.

[12] E. Björnson, M. Matthaiou and M. Debbah, “A new look at dual-hop relaying: Performance limits with hardware impairments,” IEEE Trans. Commun., vol. 61, no. 11, pp. 4512-4525, Nov. 2013.