Nonlinearity Attack against the Kirchhoff-Law-Johnson-Noise (KLJN) Secure Key Exchange Protocol

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Abstract: This paper introduces a new attack against the Kirchhoff-Law-Johnson-Noise (KLJN) secure key exchange scheme. The attack is based on the nonlinearity of the noise generators. We explore the effect of total distortion (TD) at the second order (D2), third order (D3), and a combination of the second and third orders (D2,3) on the security of the KLJN scheme. It is demonstrated that a TD as little as 1% results in a notable power flow along the information channel, which leads to a significant information leak. We also show that decreasing the effective temperature (that is, the wire voltage) and, in this way reducing nonlinearity, results in the KLJN scheme approaching perfect security.

Keywords: secure key exchange; nonlinearity; information leak; unconditional security.

1. Introduction

1.1. Secure Communications

Secure communications involve communicating parties Alice and Bob exchanging messages over a public channel. In the symmetric-key protocol, they use the same secure key and ciphers to perform encryption and decryption [1]. Thus there is a demand for a secure key exchange, or the generation and distribution of the secure key over the information channel. This is usually the most demanding process because the secure key exchange is a secure communication itself.

Note, the secure key exchange must invoke Kerckhoff’s Principle/Shannon’s Maxim [2]: Eve knows everything there is to know about the key exchange system, except for the key.

1.2. Conditional Security

A secure key exchange system can be either conditionally or unconditionally secure. The algorithmic secure key exchange systems of today rely on limited computational power and mathematically hard problems to solve. These are regarded as conditionally secure because Eve has all the data needed to crack the key and only the available computational power provides the security over a limited time interval. These systems are not future-proof as technology and algorithms can evolve in unexpected ways. This raises the demand for unconditionally (information theoretically) secure key exchange systems where, in the situation of perfect security, Eve has not useful data for cracking the secure key and computational power is irrelevant.

1.3. Unconditional Security

The security of known unconditionally secure key exchange systems is guaranteed by the laws of physics. The distinction that these systems provide is that no matter how advanced Eve’s equipment is, her information entropy does not decrease, even after an arbitrary attack or an unlimited amount of time. There are currently two types of unconditionally secure key exchange systems: quantum key distribution (QKD) [3-38] and the Kirchhoff-law-Johnson-noise (KLJN) scheme [39-96]. Important criticisms have been made about QKD in relation to its fundamental claims and the realization in practice [3-38].

Our focus topic, the KLJN scheme, which is the classical physics competitor of QKD, is a statistical physical secure key exchange scheme whose unconditional security is based on the 2nd law of thermodynamics (i.e. the impossibility to build a perpetual motion machine of the second kind) [39-43].
1.4. The KLJN Secure Key Exchange System

Figure 1 shows the core of the KLJN scheme. Alice and Bob are connected via a wire (with voltage and current $U(t)$ and $I(t)$, respectively), which serves as their information channel. They each have identical pairs of resistors $R_H$ and $R_L$ ($R_H > R_L$) with respective thermal noise voltages $U_{H,A}(t)$ and $U_{L,A}(t)$, and $U_{H,B}(t)$, $U_{L,B}(t)$.

At the beginning of the bit exchange period, Alice and Bob randomly select one of their resistors to connect to the wire. In the voltage-based protocol, they measure the mean-square voltage of the wire. Theoretically, the mean-square voltage of the wire is given by the Johnson formula,

$$U_w^2 = 4kT_{eff} R_p \Delta f_b,$$

(1)

where $k$ is the Boltzmann constant ($1.38 \times 10^{-23}$ J/K), $T_{eff}$ is the publicly-agreed effective temperature (usually $T_{eff} > 10^{12}$ K), $R_p$ is the parallel resultant of Alice’s and Bob’s chosen resistors $R_A$ and $R_B$, respectively, given by

$$R_p = \frac{R_A R_B}{R_A + R_B},$$

(2)

and $\Delta f_b$ is the noise bandwidth of the generators emulating the thermal noise.

There are four possible bit situations that can be formed by Alice’s and Bob’s choices of resistors: HH, LL, LH, and HL. From the Johnson Formula (see Equations 1 and 2), this results in three possible mean-square voltage levels, as illustrated in Figure 2. The HH and LL bit situations are insecure because they render in a distinct mean-square voltage. Alice and Bob discard these periods. The LH and HL bit situations, on the other hand, are secure because they render the same mean-square voltage. Eve cannot differentiate between the LH and HL bit situations, but Alice and Bob can because they know which resistor they have chosen.
Several attacks have been proposed against the KLJN scheme [73-96], but each known attack was either conceptually/experimentally incorrect or met with a nullifying defense scheme. In this paper, we propose an attack based on the nonlinear properties of Alice’s and Bob’s noise generators.

1.5. Nonlinearity

The noise generators of Alice and Bob have analog amplifiers as drivers. These have nonlinear characteristics [97]. We can model their output voltage by taking the Taylor Series approximation

\[
U^\prime(t) = A[U(t) + BU^2(t) + CU^3(t) + ...],
\]

where \( U^\prime(t) \) is the output voltage of the generator, \( A \) is the linear amplification, \( U(t) \) is the input noise voltage, and \( B \) and \( C \) are the second and third order nonlinearity coefficients, respectively. Nonlinearity obviously distorts the amplitude distribution function and the Gaussianity of the noise sources. Vadai, Mingesz, and Gingl mathematically proved [17] that the KLJN scheme is secure only if the distribution of the noise voltages is Gaussian. Thus nonlinearity is expected to cause information leak in these systems. It is an open question how much is this leak at practical conditions.

In this paper, we explore the effect of nonlinearity at the second order, third order, and a combination of the two orders. We also show that, as we decrease \( T_{\text{eff}} \), the KLJN scheme approaches perfect security because the nonlinear components get negligibly small due to the reduced noise voltage.

2. The Nonlinearity Attack

For illustrative purposes, we use only the second and third order nonlinearities to account for the effects of the even and odd order nonlinearities. To quantify the nonlinearity, we use the total distortion, given by the sum of the normalized mean-square components:

\[
TD = \sqrt{\frac{\left\langle \left[ BU^2(t) \right]^2 \right\rangle + \left\langle \left[ CU^3(t) \right]^2 \right\rangle}{\left\langle U(t)^2 \right\rangle}}.
\]

Eve measures the channel voltage and current, \( U_w(t) \) and \( I_w(t) \) (see Figure 1) and calculates the net power flow from Alice to Bob,

\[
\left\langle P_w(t) \right\rangle = \left\langle I_w(t)U_w(t) \right\rangle.
\]
where interpretation of voltage and current polarities are properly chosen for the direction of the power flow. Suppose the following protocol is publicly shared between Alice and Bob:

(i) If the net power flow is greater than zero, Eve surmises that HL is the secure bit situation;

(ii) If the net power flow is less than zero, Eve surmises that LH is the secure bit situation.

For example, in accordance with Equation 1 and 3 we conclude: In the case of positive nonlinear coefficients in Equation 3, the HL case means higher mean-square voltage and higher temperature at Alice’s end, thus a positive power flow from Alice to Bob. If Eve extracts a key, she can test that key or its inverse. One of them will be the true key. (For example, with proper negative coefficients, HL can imply a negative power flow, which would lead to the inverse key. If Eve, in accordance with Kerckhoffs’s principle, knows the nonlinear coefficient in Equation 3, the inverse operation with the key is not needed.)

3. Demonstration

Computer simulations with Matlab measure the information leak with practical nonlinearity parameters in Equation 3. The tests show a significant amount of information leak even with small nonlinearity.

The protocol is as follows:

- For each bit exchange, Eve measures and evaluates the average power at the information channel $\langle P_w(t) \rangle$ (see Equation 5).
- If the result is greater than zero, she guesses that HL is the secure bit situation;
- If the result is less than zero, she guesses that LH is the secure bit situation (see Section 2).
- The process above is independently repeated 1,000 times to obtain the statistics shown.

Out of the linear (Ideal) case, the investigated nonlinear situations are:

(a) Case $D_2$ with second-order nonlinearity;
(b) Case $D_3$ with third-order nonlinearity;
(c) Case $D_{2,3}$ with the combination of the $D_2$ and the $D_3$ cases.

Figure 3 illustrates the IV scatterplots between the wire voltage and current for the Ideal (a), $D_2$ (b), $D_3$ (c), and $D_{2,3}$ (d) situations. The chosen parameters are $R_\| = 100$ kΩ, $R_e = 10$ kΩ, $T_{ref} = 10^{18}$ K, and $Δf_0 = 500$ Hz. At $D_2$, $B = 6 \times 10^{-3}$ and $C = 0$. At $D_3$, $B = 0$ and $C = 5 \times 10^{-5}$. At $D_{2,3}$, $B = 1 \times 10^{-6}$ and $C = 5 \times 10^{-5}$. The blue circles represent the HL case, whereas the orange crosses represent the LH case.

The HL and LH situations are statistically indistinguishable in the Ideal (linear) situation, indicating perfect security.

In the $D_2$ case, the HL arrangement has an upward dominance, while the LH has a downward tendency. In the $D_3$ and $D_{2,3}$ cases, the HL situation has a right-diagonal footprint, while the LH situation has a left-diagonal footprint. In conclusion, the nonlinear IU scatterplots indicate lack of security at the given conditions.
Figure 3. The IU scatterplots between the wire voltage and current for the ideal (a), D_2 (b), D_3 (c), and D_{2,3} (d) situations. The parameters chosen are $R_{ii} = 100 \, \text{k}\Omega$, $R_{li} = 10 \, \text{k}\Omega$, $T_{eff} = 10^{18} \, \text{K}$, and $\Delta f_0 = 500 \, \text{Hz}$. At D_2, $B = 6 \times 10^{-3}$ and $C = 0$. At D_3, $B = 0$ and $C = 5 \times 10^{-5}$. At D_{2,3}, $B = 1 \times 10^{-6}$ and $C = 5 \times 10^{-5}$. The blue circles represent the HL case, whereas the orange crosses represent the LH case. The HL and LH situations are statistically indistinguishable in the ideal situation. In the D_2 case, the HL arrangement has an upward dominance, while the LH has a downward tendency. In the D_3 and D_{2,3} cases, the HL situation has a right-diagonal trajectory, while the LH has a left-diagonal trajectory.

Table 1 shows the statistical run for Eve’s probability $p$ of correctly guessing the bit situations, and its standard deviation $\sigma$, for four different sample sizes (time steps) $\gamma$. For each nonlinearity situation, the $p$ value increases as $\gamma$ increases, as expected, due to the increasing accuracy of Eve’s statistics.

| Nonlinearity | $\gamma$ | $p$  | $\sigma$ |
|--------------|----------|------|----------|
| D_2          | 10       | 0.5502 | 0.0135   |
|              | 20       | 0.6172 | 0.0203   |
|              | 100      | 0.7498 | 0.0149   |
|              | 1000     | 0.9869 | 0.0042   |
| D_3          | 10       | 0.5632 | 0.0159   |
|              | 20       | 0.5982 | 0.0140   |
|              | 100      | 0.7383 | 0.0126   |
|              | 1000     | 0.9831 | 0.0047   |
| D_{2,3}      | 10       | 0.5761 | 0.0114   |
|              | 20       | 0.6106 | 0.0166   |
|              | 100      | 0.7434 | 0.0137   |
|              | 1000     | 0.9855 | 0.0037   |

Table 1. The statistical sun for Eve’s correct-guessing probability $p$ and its standard deviation $\sigma$ for four different sample sizes $\gamma$. For each nonlinearity situation, the $p$ value increases as $\gamma$ increases.
Varying the effective temperature $T_{\text{eff}}$ resulted in varying the effective voltage on the wire $U_w$ (see Equation 1). The statistical protocol with results shown in Table 1 was repeated for various effective temperatures.

Figure 4 illustrates Eve’s correct-guessing probability $p$ (top) and Eve’s bit error $\varepsilon$ (bottom), given by

$$\varepsilon = 1 - p,$$  \hspace{1cm} (6)

with respect to the effective wire voltage $U_w$ for $D_2$ (a), $D_3$ (b), and $D_{23}$ (c) for all sample sizes $\gamma$. As $\gamma$ and $U_w$ (that is the effective temperature) decrease, $p$ approaches perfect security.

Figure 5 shows $p$ and $\varepsilon$ vs. $U_w$ at $\gamma = 1,000$ for all the distortions. With the given parameters, convergence toward perfect security happens at $D_2$ before $D_3$ and $D_{23}$. 
Figure 4. Eve’s correct-bit-guessing probability $p$ (top) and Eve’s bit error $\varepsilon$ (bottom) with respect to the effective voltage $U_w$ for: $D_2$ (a), $D_3$ (b), and $D_{2,3}$ at $\gamma = 10$ (blue), $\gamma = 20$ (orange), $\gamma = 100$ (yellow), and $\gamma = 1000$ (purple). As $\gamma$ and $U_w$ (driven by the effective temperature) decrease, $p$ approaches perfect security.
Figure 5. Eve’s correct-bit-guessing probability $p$ (top) and Eve’s bit error $\varepsilon$ (bottom) with respect to the effective voltage $U_w$ at $\gamma = 1,000$ for $D_2$, $D_3$, and $D_{2,3}$. $p$ increases and $\varepsilon$ decreases as $U_w$ (driven by the effective temperature) increases. Convergence to perfect security happens at $D_2$ before $D_3$ and $D_{2,3}$.

4. Conclusions

This paper introduces a new passive attack against the KLJN secure key exchange scheme when nonlinearity is present in the transfer function of the amplifier stage of noise generators. We demonstrated the effect of a 1% total distortion at the second order ($D_2$), third order ($D_3$), and a combination of the two orders ($D_{2,3}$) on the KLJN scheme.

We also demonstrated that, at a given nonlinear transfer characteristic, decreasing the effective voltage and, in this way reducing the nonlinearity, is a viable defense against the effect of nonlinearity in the KLJN scheme.

Our results showed that nonlinearity causes a notable power flow that leads to a significant information leak, so a careful design must be implemented such that the total distortion is kept at a minimum.

Alternatively, privacy amplification protocols [43,45,52,93] can also be used. For example, as an active privacy amplification, Alice and Bob can also measure and compare the power flow, and discard a proper fraction of high-risk bits [43,45].

References

1. Shannon, C.E. Communication theory of secrecy systems. Bell Systems Technical Journal 1949, 656-715.
2. Liang, Y.; Poor, H.V.; Shamai, S. Information theoretic security. Found. Trends Commun. Inform. Theory 2008, 5, 355-380.
3. Yuen, H.P. Security of quantum key distribution. IEEE Access 2016, 4, 7403842.
4. Sajeev, S.; Huang, A.; Sun, S.; Xu, F.; Makarov, V.; Curty, M. Insecurity of detector-device-independent quantum key distribution. Phys. Rev. Lett. 2016, 117, 250505.
5. Yuen, H.P. Essential elements lacking in security proofs for quantum key distribution. Proc. SPIE 2013, 8899, 88990J.
6. Yuen, H.P. Essential lack of security proof in quantum key distribution. 2013, https://arxiv.org/abs/1310.0842.
7. Hirota, O. Incompleteness and limit of quantum key distribution theory. 2012, https://arxiv.org/abs/1208.2106.
8. Jain, N.; Anisimova, E.; Khan, I.; Makarov, V.; Marquardt C.; Leuchs, G. Trojan-horse attacks threaten the security of practical quantum cryptography. New J. Phys. 2014, 16, 123030.
9. Gerhardt, I.; Liu, Q.; Lamas-Linares, A.; Skaar, J.; Kurtsiefer, C.; Makarov, V. Full-field implementation of a perfect eavesdropper on a quantum cryptography system. Nature Commun. 2012, 349.
10. Lydersen, L.; Wicbers, C.; Wittmann, C.; Elser, D.; Skaar J.; Makarov, V. Hacking commercial quantum cryptography systems by tailored bright illumination. Nature Photon. 2010, 4, 686–689.
11. Gerhardt, I.; Liu, Q.; Lamas-Linares, A.; Skaar, J.; Scarani, V.; Makarov, V.; Kurtsiefer, C. Experimentally faking the violation of Bell’s inequalities. Phys. Rev. Lett. 2011, 107, 170404.
12. Makarov, V.; Skaar, J. Fakes states attack using detector efficiency mismatch on SARG04, phase-time, DPSK, and Ekert protocols. Quant. Inform. Comput. 2008, 8, 622–635.
13. Wiechers, C.; Lydersen, L.; Wittmann, C.; Elser, D.; Skaar, J.; Marquardt, C.; Makarov, V.; Leuchs, G. After gate attack on a quantum cryptosystem. *New J. Phys.* 2011, 13, 013043.

14. Lydersen, L.; Wiechers, C.; Wittmann, C.; Elser, D.; Skaar, J.; Makarov, V. Thermal binding of gated detectors in quantum cryptography. *Opt. Express* 2010, 18, 27938–27954.

15. Jain, N.; Wittmann, C.; Lydersen, L.; Wiechers, C.; Elser, D.; Marquardt, C.; Makarov, V.; Leuchs, G. Device calibration impacts security of quantum key distribution. *Phys. Rev. Lett.* 2011, 107, 110501.

16. Lydersen, L.; Skaar, J.; Makarov, V. Tailored bright illumination attack on distributed-phase-reference protocols. *J. Mod. Opt.* 2011, 58, 680–685.

17. Lydersen, L.; Akhlaghi, M.K.; Majedi, A.H.; Skaar, J.; Makarov, V. Controlling a superconducting nanowire single-photon detector using tailored bright illumination. *New J. Phys.* 2011, 13, 113042.

18. Lydersen, L.; Makarov, V.; Skaar, J. Comment on “Resilience of gated avalanche photodiodes against bright illumination attacks in quantum cryptography”. *Appl. Phys. Lett.* 2011, 98, 231104.

19. Chaiwongkhot, P.; Kuntz, K.B.; Zhang, Y.; Huang, A.; Bourgoin, J.P.; Sajeeed, S.; Lütkenhaus, N.; Jennewein, T.; Makarov, V. Eavesdropper’s ability to attack a free-space quantum-key-distribution receiver in atmospheric turbulence. *Phys. Rev. A* 2019, 99, 062315.

20. Gras, G.; Sultana, N.; Huang, A.; Jennewein, T.; Bussieres, F.; Makarov, V.; Zbíhden, H. Optical control of single-photon negative-feedback avalanche diode detector. *J. Appl. Phys.* 2020, 127, 094502.

21. Huang, A.; Li, R.; Egorov, V.; Tchouragoulov, S.; Kumar, K.; Makarov, V. Laser-damage attack against optical attenuators in quantum key distribution. *Phys. Rev. Appl.* 2020, 13, 034017.

22. Huang, A.; Navarrete, A.; Sun, S.H.; Chaiwongkhot, P.; Curty, M.; Makarov, V. Laser-seeding attack in quantum key distribution. *Phys. Rev. Appl.* 2019, 12, 064043.

23. Chistiakov, V.; Huang, A.; Egorov, V.; Makarov, V. Controlling single-photon detector ID210 with bright light. *Opt. Express* 2019, 27, 32253.

24. Fedorov, A.; Gerhardt, I.; Huang, A.; Jogenfors, J.; Kurochkin, Y.; Lamas-Linares, A.; Larsson, J.Å.; Leuchs, G.; Lydersen, L.; Makarov, V.; Skaar, J. Comment on “Inherent security of phase coding quantum key distribution systems against detector blinding attacks”. *Laser Phys. Lett.* 2019, 16, 019401.

25. Huang, A.; Barz, S.; Andersson, E.; Makarov, V. Implementation vulnerabilities in general quantum cryptography. *New J. Phys.* 2018, 20, 103016.

26. Pinheiro, P.V.P.; Chaiwongkhot, P.; Sajeeed, S.; Horn, R.T.; Bourgoin, J.P.; Jennewein, T.; Lütkenhaus, N.; Makarov, V. Eavesdropping and countermeasures for backflash side channel in quantum cryptography. *Opt. Express* 2018, 26, 21020.

27. Huang, A.; Sun, S.H.; Liu, Z.; Makarov, V. Quantum key distribution with distinguishable decoy states. *Phys. Rev. A* 2018, 98, 012330.

28. Qin, H.; Kumar, R.; Makarov, V.; Alleaume, R. Homodyne-detector-blinding attack in continuous-variable quantum key distribution. *Phys. Rev. A* 2018, 98, 012312.

29. Sajeeed, S.; Minshull, C.; Jain, N.; Makarov, V. Invisible Trojan-horse attack. *Sci. Rep.* 2017, 7, 8403.

30. Chaiwongkhot, P.; Sajeeed, S.; Lydersen, L.; Makarov, V. Finite-key-size effect in commercial plug-and-play QKD system. *Quantum Sci. Technol.* 2017, 2, 044003.

31. Huang, A.; Sajeeed, S.; Chaiwongkhot, P.; Soucarros, M.; Legre, M.; Makarov, V. Testing random-detector-efficiency countermeasure in a commercial system reveals a breakable unrealistic assumption. *IEEE J. Quantum Electron.* 2016, 52, 8000211.

32. Makarov, V.; Bourgoin, J.P.; Chaiwongkhot, P.; Gagne, M.; Jennewein, T.; Kaiser, S.; Kashyap, R.; Legre, M.; Minshull, C.; Sajeeed, S. Creation of backdoors in quantum communications via laser damage. *Phys. Rev. A* 2016, 94, 030302.

33. Sajeeed, S.; Chaiwongkhot, P.; Bourgoin, J.P.; Jennewein, T.; Lütkenhaus, N.; Makarov, V. Security loophole in free-space quantum key distribution due to spatial-mode-detector-efficiency mismatch. *Phys. Rev. A* 2015, 91, 062301.

34. Sajeeed, S.; Radchenko, I.; Kaiser, S.; Bourgoin, J.P.; Pappa, A.; Monat, L.; Legre, M.; Makarov, V. Attacks exploiting deviation of mean photon number in quantum key distribution and coin tossing. *Phys. Rev. A* 2015, 91, 032326.

35. Jain, N.; Stiller, B.; Khan, I.; Makarov, V.; Marquardt C.; Leuchs, G. Risk analysis of Trojan-horse attacks on practical quantum key distribution systems. *IEEE J. Sel. Top. Quantum Electron.* 2015, 21, 6600710.

36. Tanner, M.G.; Makarov, V.; Hadfield, R.H. Optimised quantum hacking of superconducting nanowire single-photon detectors. *Opt. Express* 2014, 22, 6734.

37. Bugge, A.N.; Sauge, S.; Ghazali, A.M.M.; Skaar, J.; Lydersen, L.; Makarov, V. Laser Damage helps the eavesdropper in quantum cryptography. *Phys. Rev. Lett.* 2014, 112, 070503.

38. Liu, Q.; Lamas-Linares, A.; Kurtzbeier, C.; Skaar, J.; Makarov, V.; Gerhardt, I. A universal setup for active control of a single-photon detector. *Rev. Sci. Instrum.* 2014, 85, 013108.

39. Chamon, C.; Kish, L.B. Perspective - on the thermodynamics of perfect unconditional security. *Appl. Phys. Lett.* in press.

40. Kish, L.B. *The Kish Cypher: The Story of KLJN for Unconditional Security*; World Scientific: New Jersey, USA, 2017.

41. Kish, L.B. Totally secure classical communication utilizing Johnson (-like) noise and Kirchhoff’s law. *Phys. Lett. A* 2006, 352, 178–182.

42. Cho, A. Simple noise may stymie spies without quantum weirdness. *Science* 2005, 309, 2148.

43. Kish, L.B.; Granqvist, C.G. On the security of the Kirchhoff-law–Johnson-noise(KLJN) communicator. *Quant. Inform. Proc.* 2014, 13, 2213–2219.

44. Kish, L.B. Enhanced secure key exchange systems based on the Johnson-noise scheme. *Metrol. Meas. Syst.* 2013, 20, 191–204.
45. Kish, L.B.; Horvath, T. Notes on recent approaches concerning the Kirchhoff-law-Johnson-noise based secure key exchange. Phys. Lett. A 2009, 373, 2858–2868.
46. Vadai, G.; Mingesz, R.; Gingl, Z. Generalized Kirchhoff-law-Johnson-noise (KLJN) secure key exchange system using arbitrary resistors. Scientific Reports 2015, 5, 13653.
47. Ferdous, S.; Chamon, C.; Kish, L.B. Comments on the “generalized” KLJN key exchanger with arbitrary resistors: power, impedance, security. Fluct. Noise Lett. 2020, 20, 2130020.
48. Kish, L.B.; Granqvist, C.G. Random-resistor-random-temperature Kirchhoff-law-Johnson-noise(RRRT-KLJN) key exchange. Metrol. Meas. Syst. 2016, 23, 3–11.
49. Smulko, J. Performance analysis of the ’intelligent Kirchhoff-law-Johnson-noise secure key exchange”. Fluct. Noise Lett. 2014, 13, 1450024.
50. Mingesz, R.; Gingl, Z.; Kish, L.B. Johnson(-like)-noise Kirchhoff-loop based secure classical communicator characteristics for ranges of two to two thousand kilometers, viamodel-line. Phys. Lett. A 2008, 372, 978–984.
51. Mingesz, R.; Kish, L.B.; Gingl, Z.; Granqvist, C.G.; Wen, H.; Peper, F.; Eubanks T.; Schmera, G. Unconditional security by the laws of classical physics. Metrol. Meas. Syst. 2013, 20, 3–16.
52. Horvath, T.; Kish, L.B.; Scheuer, J. Effective privacy amplification for secure classical communications. EPL 94 2011, 28002.
53. Saez, Y.; Kish, L.B. Errors and their mitigation at the Kirchhoff-law-Johnson-noise secure key exchange. PLoS ONE 2013, 8, e81103.
54. Mingesz, R.; Vadai, G.; Gingl, Z. What kind of noise guarantees security for the Kirchhoff-Loop-Johnson-Node key exchange? Fluct. Noise Lett. 2014, 13, 1450021.
55. Saez, Y.; Kish, L.B.; Mingesz, R.; Gingl, Z.; Granqvist, C.G. Current and voltage based bit errors and their combined mitigation for the Kirchhoff-law-Johnson-noise secure key exchange. J. Comput. Electron. 2014, 13, 271–277.
56. Saez, Y.; Kish, L.B.; Mingesz, R.; Gingl, Z.; Granqvist, C.G. Bit errors in the Kirchhoff-law-Johnson-noise secure key exchange. Int. J. Mod. Phys.: Conference Series 2014, 33, 140367.
57. Gingl, Z.; Mingesz, R. Noise properties in the ideal Kirchhoff-Law-Johnson-Noise secure communication system. PLoS ONE 2014, 9, e96109.
58. Liu, P.L. A key agreement protocol using band-limited random signals and feedback. IEEE J. of Lightwave Tech. 2009, 27, 5230–5234.
59. Kish, L.B.; Mingesz, R. Totally secure classical networks with multipoint telecloning (teleportation) of classical bits through loops with Johnson-like noise, Fluct. Noise Lett. 2006, 6, C9–C21.
60. Kish, L.B. Method of using existing wire lines (power lines, phone lines, internet lines) for totally secure classical communication utilizing Kirchhoff’s Law and Johnson-like noise 2006, https://arXiv.org/abs/physics/0610014.
61. Kish, L.B.; Peper, F. Information networks secured by the laws of physics. IEE Trans. Fund. Commun. Electron. Inform. Syst. 2012, E35–B5, 1501–1507.
62. Gonzalez, E.; Kish, L.B.; Balog, R.S.; Enjeti, P. Information theoretically secure, enhanced Johnson noise based key distribution over the smart grid with switched filters. PLoS One 2013, 8, e70206.
63. Gonzalez, E.; Kish, L.B.; Balog, R.S. Encryption Key Distribution System and Method. U.S. Patent # US9270448B2 (granted 2/2016), https://patents.google.com/patent/US9270448B2
64. Gonzalez, E.; Balog, R.; Mingesz, R.; Kish, L.B. Unconditional Security for the Smart Power Grids and Star Networks, 23rd International Conference on Noise and Fluctuations (ICNF 2015), Xian, China, June 2–5, 2015.
65. Gonzalez, E.; Balog, R.S.; Kish, L.B. Resource requirements and speed versus geometry of unconditionally secure physical key exchanges. Entropy 2015, 17, 2010–2014.
66. Gonzalez, E.; Kish, L.B. Key exchange trust evaluation in peer-to-peer sensor networks with unconditionally secure key exchange. Fluct. Noise Lett. 2016, 15, 1650008.
67. Kish, L.B.; Saidi, O. Unconditionally secure computers, algorithms and hardware, such as memories, processors, keyboards, flash and hard drives. Fluct. Noise Lett. 2008, 8, L95–L98.
68. Kish, L.B.; Entesari, K.; Granqvist, C.G.; Kwan, C. Unconditionally secure credit/debit card chip scheme and physical unclonable function. Fluct. Noise Lett. 2017, 16, 1750002.
69. Kish, L.B.; Kwan, C. Physical unclonable function hardware keys utilizing Kirchhoff-law-Johnson noise secure key exchange and noise-based logic. Fluct. Noise Lett. 2013, 12, 1350018.
70. Saez, Y.; Cao, X.; Kish, L.B.; Pesti, G. Securing vehicle communication systems by the KLJN key exchange protocol. Fluct. Noise Lett. 2014, 13, 1450020.
71. Cao, X.; Saez, Y.; Pesti, G.; Kish, L.B. On KLJN-based secure key distribution in vehicular communication networks. Fluct. Noise Lett. 2015, 14, 1550008.
72. Kish, L.B.; Granqvist, C.G. Enhanced usage of keys obtained by physical, unconditionally secure distributions. Fluct. Noise Lett. 2015, 14, 1550007.
73. Vadai, G.; Gingl, Z.; Mingesz, R. Generalized attack protection in the Kirchhoff-law-Johnson-noise key exchanger. IEEE Access 2016, 4, 1141–1147.
74. Kish, L.B. Protection against the man-in-the-middle-attack for the Kirchhoff-loop-Johnson (-like)-Noise Cipher and Expansion by Voltage-Based Security. Fluct. Noise Lett. 2006, 6, L57–L63.
75. Chen, H.P.; Mohammad, M.; Kish, L.B. Current injection attack against the KLJN secure key exchange. Metrol. Meas. Syst. 2016, 23, 173–181.
76. Melhem, M.Y.; Kish, L.B. Generalized DC loop current attack against the KLJN secure key exchange scheme. *Metrol. Meas. Syst.* **2019**, *26*, 607–616.
77. Melhem, M.Y.; Kish, L.B. A static-loop-current attack against the Kirchhoff-law-Johnson-noise (KLJN) secure key exchange system. *Applied Sciences* **2019**, *9*, 666.
78. Melhem, M.Y.; Kish, L.B. The problem of information leak due to parasitic loop currents and voltages in the KLJN secure key exchange scheme. *Metrol. Meas. Syst.* **2019**, *26*, 37–40.
79. Liu, P.L. A complete circuit model for the key distribution system using resistors and noise sources. *Fluct. Noise Lett.* **2020**, *19*, 2050012.
80. Liu, P.L. Re-examination of the cable capacitance in the key distribution system using resistors and noise sources. *Fluct. Noise Lett.* **2017**, *16*, 1750025.
81. Hao, F. Kish’s key exchange scheme is insecure. *IEE Proceedings-Information Security* **2006**, *153*, 141–142.
82. Kish, L.B. Response to Feng Hao’s paper “Kish’s key exchange scheme is insecure”. *Fluct. Noise Lett.* **2006**, *6*, C37–C41.
83. Kish, L.B.; Scheuer, J. Noise in the wire: The real impact of wire resistance for the Johnson (-like) noise based secure communicator. *Phys. Lett. A* **2010**, *374*, 2140–2142.
84. Kish, L.B.; Granqvist, C.G. Elimination of a second-law-attack and all cable-resistance-based attacks, in the Kirchhoff-law-Johnson-noise (KLJN) secure key exchange system. *Entropy* **2014**, *16*, 5223–5231.
85. Melhem, M.Y.; Chamon, C.; Ferdous, S.; Kish, L.B. AC loop current attacks against the KLJN secure key exchange scheme. *Fluct. Noise Lett.* in press.
86. Chen, H.P.; Gonzalez, E.; Saez, Y.; Kish, L.B. Cable capacitance attack against the KLJN secure key exchange. *Information* **2015**, *6*, 719–732.
87. Melhem, M.Y.; Kish, L.B. Man in the middle and current injection attacks against the KLJN key exchanger compromised by DC sources. *Fluct. Noise Lett.* in press.
88. Chamon, C.; Ferdous, S.; Kish, L.B. Random Number Generator Attack against the Kirchhoff-Law-Johnson-Noise Secure Key Exchange Protocol **2020**, https://arxiv.org/abs/2005.10429.
89. Gunn, L.J.; Allison, A.; Abbott, D. A directional wave measurement attack against the Kish key distribution system. *Scientific Reports* **2014**, *4*, 6461.
90. Chen, H.P.; Kish, L.B.; Granqvist, C.G. On the “Cracking” Scheme in the Paper “A Directional Coupler attack against the Kish key distribution system” by Gunn, Allison and Abbott. *Metrol. and Meas. Syst.* **2014**, *21*, 389–400.
91. Chen, H.P.; Kish, L.B.; Granqvist, C.G.; Schmera, G. Do electromagnetic waves exist in a short cable at low frequencies? What does physics say? *Fluct. Noise Lett.* **2014**, *13*, 1450016.
92. Kish, L.B.; Gingl, Z.; Mingesz, R.; Vadai, G.; Smulko, J.; Granqvist, C.G. Analysis of an Attenuator artifact in an experimental attack by Gunn–Allison–Abbott against the Kirchhoff-law–Johnson-noise (KLJN) secure key exchange system. *Fluct. Noise Lett.* **2015**, *14*, 1550011.
93. Kish, L.B.; Abbott, D.; Granqvist, C.G. Critical analysis of the Bennett–Riedel attack on secure cryptographic key distributions via the Kirchhoff-law–Johnson-noise scheme. *PloS One* **2013**, *8*, e81810.
94. Gunn, L.J.; Allison, A.; Abbott, D. A new transient attack on the Kish key distribution system. *IEEE Access* **2015**, *3*, 1640–1648.
95. Kish, L.B.; Granqvist, C.G. Comments on “A new transient attack on the Kishkey distribution system”. *Metrol. Meas. Syst.* **2015**, *23*, 321–331.
96. Chamon, C.; Ferdous, S.; Kish, L.B. Deterministic Random Number Generator Attack against the Kirchhoff-Law-Johnson-Noise Secure Key Exchange Protocol. *Fluct. Noise Lett.* in press.
97. Razavi, B. *RF Microelectronics*; Prentice Hall: New Jersey, USA, 2011.