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Covert Electromagnetic Nanoscale Communication System in the Terahertz Channel*

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In this paper, an electromagnetic nano random communication system (EM-nRCS) has been proposed which ensures covert communication in the terahertz (THz) band. In the proposed system, the skewed alpha-stable noise shift keying method has been used to transmit random noise signals (RNSs) from the nano-transmitter (NT) by utilizing single-walled/carbon nanotubes-based true random number generator (SWCNTs-TRNG) and a graphene-based nanoantenna. A line-of-sight THz transparency window between 0.1 THz and 0.5 THz in the THz channel with spreading loss, molecular absorption loss and molecular absorption noise has been considered. Due to the broadband nature of the RNSs, the proposed EM-nRCS provides efficient transmission by overcoming the high path loss and intense channel noise arising from random fluctuations in the THz band. Non-coherent nano-receiver (NR) consisting of the modified extreme value method (MEVM) estimator has been proposed to extract the hidden binary information in the received RNSs. The bit error rate performance shows that the proposed EM-nRCS ensures high performance and covertness for future EM nanoscale communication devices.

Keywords: Random communication systems; alpha-stable noise; terahertz band; transparency window.

1. Introduction

Nano-communications have been emerging as a field which can revolutionize the traditional vision of current wireless communication systems. Due to recent progress

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in the development of carbon nanotubes and graphene, the nano-communications have wide application area in biomedical, intra-body communications, military, vehicular networks and nano-satellite applications.[1–4] The nano-communications field has been separated into two sub-areas[5] as:

I. Electromagnetic nano-communications,
II. Molecular communications.

Electromagnetic nano-communications, defined in Ref. 6, as the transmission and reception of the electromagnetic signals from the components based on nano materials, is now emerging due to the progression in carbon and molecular electronics. One of the prime applications of electromagnetic nano-communication are the nanomachines which consist of nanoscale components such as sensing, power, processing and data storage.[7] Nano-machines can form a nanonetwork of electromagnetic nanocommunication systems (EM-nCSs) to perform cooperative operation in nanoscale environments.[7] Due to the advent of graphene-based nano-antennas and compact terahertz (THz) band plasmonic signal generators as potential nano-transmitters in Refs. 8–11 and graphene field effect detectors as potential nano-receivers in Refs. 12 and 13, it has become possible to operate in the frequency band of 0.1–10.0 THz (targeted THz band) for nanoscale communications (NCs). By utilizing the introduced nanocomponents, discussed above in Refs. 8–13, recent studies have shown that efficient EM-nCSs can be built even in the presence of the high path loss and intense molecular absorption noise of the THz channel.[14–20] However, despite the mentioned versatile future applications of EM-nCSs in Refs. 1–4, 21 and 22, no investigation has been conducted yet to ensure the security of communication devices at the nanoscale.

Therefore, in this paper, the first covert electromagnetic nano random communication system (EM-nRCS) in the THz band has been proposed to ensure the security of the future nano communication devices. Single-walled carbon nanotubes-based true random number generator (SWCNTs-TRNG), introduced in Ref. 23, is claimed to be the smallest true random number generator which has been used in this study to design the nano-transmitter (NT) for the proposed EM-nRCS. The randomness of SWCNTs-TRNG has been exploited to change the skewness parameter of skewed alpha-stable noise keying-based random communication system (SkαSNSK-RCS), hence generating secure random noise signals (RNSs) from the proposed NT. The molecular absorption in THz channel, which results in high path loss and random noise, has been considered according to the model given in Refs. 24 and 25. Modified extreme value method (MEVM) estimator-based receiver is used to extract the hidden binary information from the received signal by exploiting the pre-known parameters of the transmitted signal. The bit error rate (BER) of the introduced EM-nRCS by exploiting the transparency window in the THz band has also been evaluated.

After analyzing the results in this study, EM-nRCS has been observed as a promising approach to overcome the security limitations of EM-nCSs. The secrecy of information in the proposed system is perfect in a sense that currently there is no method, algorithm or attack available to crack any parameter involved in the transmission which is the motivation of the proposed system. The proposed EM-nRCS would benefit the field of EM-nCSs as it would persuade researchers to also focus on the security of nano communication devices and conduct future investigations concerning the establishment of secure nano-communications in the THz band. The proposed system would benefit different branches of nanonetworks, as given in Ref. 7, by providing security in (i) biomedical applications, e.g., intra-body health monitoring and drug delivery systems, immune system support mechanisms and artificial bio-hybrid implants; (ii) military applications, e.g., nuclear, biological and chemical defenses and nano-functionalized equipment; (iii) industrial and consumer goods applications, e.g., development of intelligent functionalized materials and fabrics, new manufacturing processes and distributed quality control procedures, food and water quality control systems; (iv) environmental applications, e.g., biological and chemical nano sensor networks for pollution control, biodegradation assistance and animal and biodiversity control.

Therefore, this study investigates the first possible configuration for a covert NC scheme in the THz channel. The paper comprises of six sections. Section 2 gives a brief review of the related work in the field of nano communications and highlights the absence of covert communication techniques at the nanoscale. Similarly, before proposing EM-nRCS as a solution to establish secure nano communications, a brief introduction of random communication systems and alpha-stable distributions along with the associated parameters and required properties needed to generate SαS and SkαS noise has been briefly given in Sec. 3. In Sec. 4, the proposed system model of the EM-nRCS consisting of SWCNTs-TRNG and SkαSNSK-based nano-transmitter and MEVM-based nano-receiver has been explained. The results are shown in Sec. 5, which is followed by conclusive remarks in Sec. 6.

The main contributions of the paper and the proposed system can be summarized as given below:

- Since the idea to use any conventional or unconventional communication system to achieve security in the terahertz channel has not been propagated before, therefore, this paper is the first attempt to highlight the existing vulnerabilities, i.e., absence of security and covertness, in communication devices at the nanoscale.
- As a result, this paper has introduced the first possible configuration of a covert electromagnetic nano random communication system (EM-nRCS) to ensure security of wireless nanoscale communication systems, which is a potential topic due to versatile applications of nanotechnology in communication devices.

- This study has enhanced the boundary of random communication systems from GHz to THz band for the first time by taking advantage of the recently developed carbon-nanotube-based random number generator.
- The covertness of the RNSs in the proposed EM-nRCS is perfect as up till now no method has been able to decode any parameter involved in the communication.
- The security of the proposed EM-nRCS has been further enhanced by taking real time fluctuating skewness parameter as given in (2), which has not been done in any RCS before.
- The obtained BER performances of the proposed EM-nRCS indicate that alpha-stable noise-based communication systems are not much affected by the high path loss and intense molecular absorption noise of the THz channel.
- Finally, this study will surely persuade researchers to conduct future investigations concerning the security of nano communication systems as this investigation would help in prevailing the required sense of security in nano-networks and future nano-machines.

2. Summary of the Related Work

Researchers investigating the graphene-based nano-transceivers and nano-antennas have declared the terahertz (THz) band in the range of 0.1–10 THz as the possible communication frequency range for nano-devices in the future.[8–13] Therefore, the problem of establishing communication at the nanoscale has grabbed the attention of the researchers working in the field of communications. The initial studies were focused on establishing limited communication in the THz band by examining frequency domain differential phase shift keying (FD-DPSK) modulation schemes which showed that high absorption loss due to water vapors in the THz channel leads to a high BER. Therefore in Ref. 14, an adaptive modulation scheme was proposed for the indoor pulsed terahertz (THz) channel in the range of 0–2 THz. The scheme depended on the humidity level of the channel and the distance between transmitter and the receiver which significantly enhanced the BER to achieve comparatively better data rates. Subsequently in Ref. 15, the problem of establishing synchronization in femtosecond-long pulse-based modulation schemes was addressed to enable ultra-broadband communication among nano-devices which further improved the BER for the THz channel.

With the advent of nanonetworks, which were declared as the enabling technology of long-awaited applications in Refs. 6 and 7, investigations were initiated to develop tailored communication schemes for nanonetworks, hence, an effective modulation and channel access scheme for nanonetworks in the terahertz band was proposed.[16] It was capable to support a very large number of nano-devices communicating simultaneously. Later, the BER performance of the communication schemes in the THz band was further improved by adopting a relay-assisted transmission approach in which both amplify-and-forward (AF) and decode-and-forward (DF) relaying modes were studied for nano communications.[17]

Later, major progress in the field of wireless communication, nano photonics and nanoelectronics enabled the concept of in vivo wireless nano sensor networks (iWNSNs), i.e., the interconnection of miniature devices was able to operate inside the human body with unprecedented sensing and actuation capabilities.[2] The iWNSNs were declared as the basis of emerging healthcare applications such as intra-body health-monitoring and control of biological processes at sub-cellular level. Therefore in Ref. 18, the initial investigation was conducted to assess the effect of single biological cells and cell assemblies on the propagation of optical wave for intra-body communications of nano sensors, which led to the development of new communication solutions for intra-body nanoscale optical communication networks. Similarly, the work in Ref. 20 initiated the efforts to design an intelligent/cognitive nano receiver operating in terahertz (THz) band which could differentiate between pulse-based modulation and carrier-based modulation. The investigation done in Ref. 20 triggered the interest of the community in the design of intelligent/cognitive nano receivers which were not the topics of concern previously in the field of EM-nCSs.

The proposed concept in this paper would also trigger another important factor which should be considered while designing nanonetworks, iWNSNs and EM-nCSs. This factor is the covertness and security of nano-communication devices which has been observed to be the lowest level or a matter of no concern in previous studies.[14–20] To address this issue, random communication systems have been utilized to provide covertness and security at the nanoscale.

3. Random Communication Systems

Random communication system (RCS) is a new branch of spread spectrum-based covert communication. Starting from the stochastic process shift keying in Ref. 26, then the symmetric alpha-stable (SαS) and skewed alpha stable (SkαS) stochastic processes-based RCSs were proposed and proved to be efficient and secure in both additive white Gaussian noise (AWGN) and fading channels.[27–29] Recently in Ref. 30, the optimized model of the skewed alpha-stable noise keying-based random communication system (SkαSNSK-RCS) has been proposed along with the security performance trade-off characteristics to measure the performance of RCSs on the security scale which is the first study considering the security performance; this study has shown that RCSs provide the privilege of secure transmission of binary information with lesser BER. In Ref. 31, the criterion for quantifying covertness of the RCSs in the presence of an eavesdropper has also been introduced. The applicability of RCSs has been established further by the synchronization method introduced in Ref. 32. Due to the broadband nature of random noise signals (RNSs) used in RCSs and low transmitting power required to generate them, this approach can be effective to produce covert electromagnetic RCSs at the nanoscale as well.

The key factor, in establishing covert transmission by RCS, is the α-stable noise which has a random variable X, i.e., $X \sim S_\alpha(\beta, \mu)$ has a characteristic function defined in Ref. [33, Eq. (1.1.6)] as:

$$\phi(\theta) = \begin{cases} \exp\left\{j\mu\theta - \gamma^\alpha|\theta|^\alpha\left[1 - j\beta\operatorname{sign}(\theta)\tan\frac{\alpha\pi}{2}\right]\right\}, & \text{if } \alpha \neq 1 \\ \exp\left\{j\mu\theta - \gamma|\theta|\left[1 + j\beta\frac{2}{\pi}\operatorname{sign}(\theta)\ln\frac{\alpha\pi}{2}\right]\right\}, & \text{if } \alpha = 1 \end{cases}, \tag{1}$$

where the parameters are the characteristic exponent α $(0 < \alpha \leq 2)$ the skewness/slant parameter $\beta(-1 \leq \beta \leq 1)$, the dispersion parameter $\gamma(\gamma \geq 0)$ and the location parameter $\mu \in R$ and α-stable distributions have been produced by the method given.[34]

Remark: Gaussian distribution is a special α-stable distribution defined as $X \sim S_{\alpha=2}(\beta = 0, \gamma, \mu)$.

Property: [33, Eq. (1.2.1)] Let $X \sim S_\alpha(\beta, \gamma, \mu)$ and $v \in R$. In that case, $vX \sim S_\alpha(\operatorname{sign}\{v\}\beta, |v|\gamma, h\mu)$.

4. System Model

The EM-nRCS, as shown in Fig. 1, is a single input single output (SISO) system which consists of the proposed NT and nano-receiver (NR) in the THz channel. The randomness of the SWCNTs-TRNG has been integrated with the SkαSNSK-RCS to increase the complexity of the generated RNS at the NT's side to provide covertness during transmission and to overcome the high path loss and noises as well while propagating along the THz channel. Graphene-based nano antenna is used for signal propagation, and perfect synchronization between NT and NR is assumed in our proposed system. Individual components of the proposed EM-nRCS have been explained in the sections below.

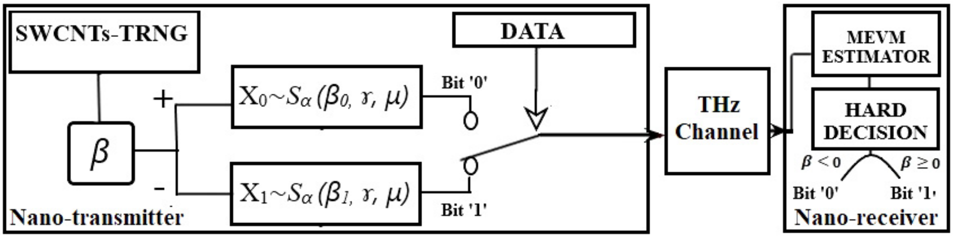

Fig. 1. System model of SWCNTs-TRNG, SkαSNSK and MEVM estimator-based EM-nRCS in the THz band.

4.1. *Nano-transmitter*

Random noise X_0, i.e., $X_0 \sim S_\alpha(\beta_{0,}\gamma, \mu)$ and X_1, i.e., $X_1 \sim S_\alpha(\beta_{1,}\gamma, \mu)$, is transmitted by the NT for the corresponding binary information bits "0" and "1", respectively by using the antipodal characteristics of the slant parameter β to slant the distributions to the right (i.e., $\beta_1 = \beta \in R^+$) or to the left (i.e., $\beta_0 = -\beta$). The complexity of the generated RNS is further increased by varying β for each transmitted binary information bit "0" or "1" by maneuvering the corresponding slant parameter β_1 (i.e., $0 \leq \beta_1 \leq 1$) or β_0 (i.e., $-1 \leq \beta_0 < 0$) w.r.t. the output of SWCNTs-TRNG by the relation given below as:

$$\beta = \frac{N_1}{N_{1,0}}, \tag{2}$$

where N_1 is the quantity of bit "1" among the total output bits comprising of "0" and "1" known as $N_{1,0}$ from SWCNTs-TRNG. The $N_{1,0}$ is selected by the user and is arbitrary taken as 10 in our system. However, increasing $N_{1,0}$ will increase the randomness in the generation of the β parameter but decrease the speed of the transmission and vice versa. The impact of randomly choosing the β parameter every time to generate RNS holding single binary information bit is that the corresponding α-stable distribution emerge to be more similar (less similar) when N_1 is small (when N_1 is large) which makes it difficult for an eavesdropper to predict the exact skewness parameter involved in conveying the binary information.

The transmitted duration of a single binary information bit is denoted by "T_s" (i.e., $T_s = T_b N$), where "T_b" is the length of a single noise sample (i.e., $x_i (1 \leq i \leq N)$ and transmitted number of noise samples per binary information bit is denoted by "N"; which are all pre-decided between the NT and NR. The transmitted RNS for the single binary information bit is represented as $\mathbf{X} = \{x_1, x_2, \ldots, x_N\}$.

4.2. *THz propagation channel*

The power of the received signal gradually reduces as it traverses through the THz channel and suffers molecular absorption, thus producing high path loss and intense noise. The THz band has been simulated by the propagation model given in Ref. 24. The impulse response of the THz channel, i.e., $h(f, d)$, is the inverse Fourier transform of the channel's frequency response, i.e., $h(t, d)$, given below as:

$$h(t, d) = \left| \left(\frac{4\pi f d}{c}\right)^2 e^{k(f)d} \right| \cdot \delta(t - t_p)\,, \tag{3}$$

$$h(t, d) = F^{-1}\{H(f, d)\}\,, \tag{4}$$

where $t_p = \frac{d}{c}$ is the arrival time of the EM wave and the transmission distance between NT and NR is denoted by "d", speed of light in vacuum is denoted by "c" and the frequency is denoted by "f". Moreover, the THz channel frequency response is given below as:

$$H(f,d) = \mathrm{PL}_{\mathrm{S}}(f,d)\,\mathrm{PL}_{\mathrm{A}}(f,d)\,, \tag{5}$$

where PL_{S} and PL_{A} are defined as the free space spreading loss and molecular absorption loss, respectively. Friis equation is used to compute PL_{S} as

$$\mathrm{PL}_{\mathrm{S}}(f,d) = \left(\frac{4\pi f d}{c}\right)^2. \tag{6}$$

PL_{A} can be computed by the transmittance of the medium, i.e., τ, and can be obtained from Beer–Lambert law as

$$\mathrm{PL}_{\mathrm{A}}(f,d) = \frac{1}{\tau} = e^{k(f)d}\,, \tag{7}$$

where the transmission medium has coefficient of absorption denoted by "$k(f)$" and given in [24, Eqs. (2) and (3)] as:

$$k(f) = \sum_g \frac{p}{p_\circ}\frac{T_{STP}}{T} Q^g \sigma^g(f)\,, \tag{8}$$

where the system pressure is denoted as "p", the reference pressure is denoted as "$p_\circ$", the standard temperature is denoted as "T_{STP}", the number of molecules per unit volume of gas g and the absorption cross-sectional area of gas "g" of the medium are denoted as "Q^g" and "σ^g", respectively. In this study, air has been considered as the transmission medium with transmission distance "d" equal to 10 mm, in a standard medium with 1% of water vapor molecules.

4.3. *Nano-receiver*

Consider that the NT is in line-of-sight (LOS) with the NR and operating at a specific frequency "f" and a distance "d" so the fading coefficient "v" is same for the single binary information bit interval T_S and the value of v can be obtained by the method in Ref. 24. Moreover, the fading coefficient has been included to consider the worst-case scenario for communication. Therefore, the fading coefficient u can be considered as $v \in R$ for each T_S, hence, by utilizing the given property 1, i.e., $vX \sim S_\alpha(\mathrm{sign}\,\{v\}\beta, |v|\gamma, h\mu)$, of alpha-stable distribution, the received signal at the NR for the single binary information bit is given below as:

$$Y = vX + N_T\,, \tag{9}$$

where N_T is the total noise present within the LOS path between NT and NR and it is given below as

$$N_T = N_I + N_A\,, \tag{10}$$

where N_I is known as the interference noise due to overlapping of symbols transmitted from different NTs simultaneously and N_A is the molecular absorption noise.

Table 1. Transparency windows for frequency ranges below 1 THz.

Window	Window's range (THz)	Window's size (GHz)
1	0.10–0.54	440
2	0.63–0.72	95
3	0.76–0.98	126

Since the proposed EM-nRCS is based on single NT and NR, therefore an interference free scenario has been modeled by assuming that there is no interference noise (i.e., $N_T = N_A$). N_A is anticipated as the key factor for noise generation in the THz band as it strictly limits the coverage of a single NT. To eliminate this coverage problem, the transparency window, known as a successive range of frequencies on which the transmittance of the medium "i.e., $\tau(f, d)$" should not be less than 95%, was suggested in Ref. 35. The available windows for frequencies less than 1 THz at distance "d" equals to 1 m can be seen in Table 1.

Window-1 has been adopted throughout for transmission where N_A is modeled as the additive colored noise which has peaks at certain frequencies in adopted window-1 and therefore, it has been modeled by a stochastic process for window-1 in Ref. [25, Eq. (5)] as:

$$N_A(t) = \sum_{i=1}^{M} A_i \cos(\omega_{oi} t + \gamma_i B_i(t) + U_i)\,, \tag{11}$$

where A_i, γ_i and ω_{oi} for $i = 1, 2, \ldots, M$ can be referred as spectrum density, spectrum impulsiveness/flattening and center frequency parameters, respectively, of the ith peak in a transparency window. $B_i(t)$ are Wiener processes considered mutually independent, and U_i are uniformly distributed random variables in a range from 0 to 2π. The mean (i.e., μ_{N_A}) and variance (i.e., $\sigma^2_{N_A}$) of $N_A(t)$ are given in Ref. [25, Eq. (6)] as:

$$\mu_{N_A} = 0; \quad \sigma^2_{N_A} = \sum_{i=1}^{M} \frac{A_i}{2}\,. \tag{12}$$

4.3.1. *MEVM estimator*

The MEVM estimator given in Ref. 36 estimates the skewness parameter for each binary information bit of the received signal Y through the AWGN channel. The method proceeds by subdividing the received data $\{x_1, x_2, \ldots, x_N\}$ in duration $T_b N$ consisting of N samples into L non-overlapping segments of length K, i.e., $K = N/L$. Each segment l (where $1 \le l \in Z^+ \le L$) from total L segments has a maximum and minimum sample. The logarithms of maximum and minimum samples are denoted by $Y_{l-\max}$ and $Y_{l-\min}$, respectively:

$$Y_{l-\max} = \log\{\max(x_{lk-k+i} | 1 \le i \in Z^+ \le K)\}\,, \tag{13}$$

$$Y_{l-\min} = \log\{-\min(x_{lk-k+i} | 1 \leq i \in Z^{+} \leq K)\}\,. \tag{14}$$

The means and the corresponding variances of $Y_{l-\max}$ and $Y_{l-\min;}$ and estimates for β are then obtained as:

$$Y_{\max} = \frac{1}{L}\sum_{l=1}^{L} Y_{l-\max;} s_{\max}^{2} = \frac{1}{L-1}\sum_{l=1}^{L}(Y_{l-\max} - Y_{\max})^{2}\,, \tag{15}$$

$$Y_{\min} = \frac{1}{L}\sum_{l=1}^{L} Y_{l-\min;} s_{\min}^{2} = \frac{1}{L-1}\sum_{l=1}^{L}(Y_{l-\min} - Y_{\min})^{2}\,, \tag{16}$$

$$\hat{\beta} = 1 - \frac{2}{\exp(\hat{\alpha}(S_{\max} - S_{\min}))}\,, \tag{17}$$

where $\hat{\alpha} = \frac{\pi}{2\sqrt{6}}(\frac{1}{Y_{\max}} + \frac{1}{Y_{\min}})$ and the binary message is estimated using the hard decision. Due to the absence of finite second order moments, the variance of the α-stable distributions does not exist; hence, the signal-to-noise-ratio is not an applicable criterion to determine the performance of RCSs. To overcome this issue, the mixed-signal-to-noise-ratio (MSNR), in Ref. 27, has been used to measure the performance of the proposed EM-nRCS as:

$$\mathrm{MSNR(dB)} \doteq 10\log\frac{\gamma}{\sigma_{N_A}^{2}}\,, \tag{18}$$

where γ denotes the dispersion of the transmitted α-stable RNS and $\sigma_{N_A}^{2}$ denotes the variance of the stochastic process modeled as the molecular absorption noise in the used transparency window-1.

5. Performance Evaluation

In this section, Monte-Carlo simulations were conducted to analyze the performance of the introduced EM-nRCS in the LOS THz channel for the desired BER of 10^{-3} where one thousand bits have been transmitted by the nano-transmitter and checked for errors at the nano-receiver. The BER performance versus MSNR (dB) has been evaluated for maneuvering various values of associated parameters "L and K" of the MEVM estimator at the NR, keeping in mind the perspective of the intended receiver where the impulsiveness parameter "α" and the number of noise samples per binary information bit "N" have been changed at the NT.

The previously introduced SkαSNSK-RCS in Refs. 27–32 has proved to be robust in the AWGN and fading channel and has shown efficient BER performances. Similarly, it has been observed that despite incorporating single NT and NR in the proposed EM-nRCS, an efficient performance has been observed even in the high path loss and intense noise of the THz band, as shown in Figs. 2–4.

In Fig. 2, by maneuvering the "L and K" at the NR, it has been observed that the BER performance of the proposed EM-nRCS is at the optimum level,

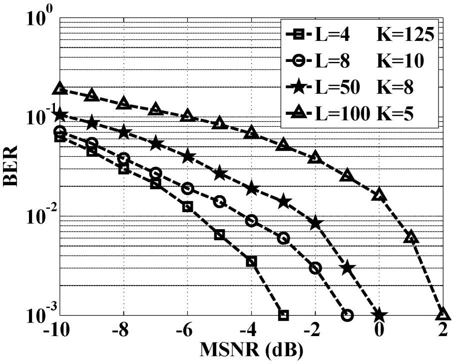

Fig. 2. BER versus MSNR (dB) in THz channel with transmitted bits $= 10^3$ with different "L and K" where $\alpha = 0.5$ and $N = 500$.

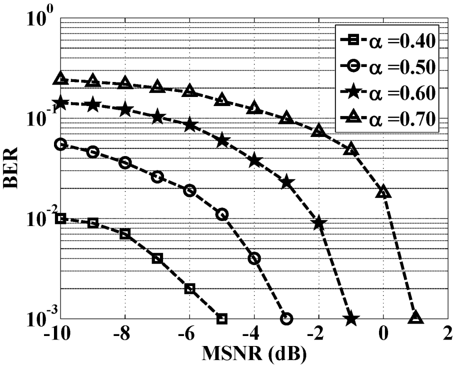

Fig. 3. BER versus MSNR (dB) in THz channel with transmitted bits $= 10^3$ with different α where $L = 4$ and $N = 500$.

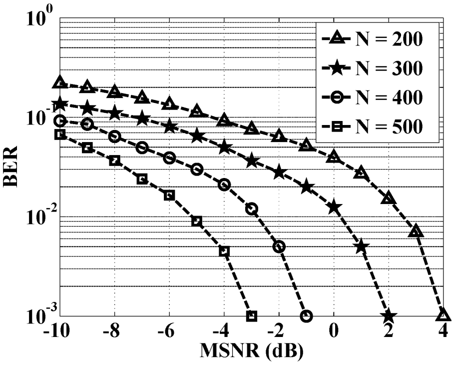

Fig. 4. BER versus MSNR (dB) in THz channel with transmitted bits $= 10^3$ with different N where $\alpha = 0.5$ and $L = 4$.

i.e., $\text{BER} = 10^{-3}$, which has been achieved by exploiting the smallest possible value of "L" and maximum possible value of "K". On the contrary, it has been observed that the BER performance starts to decrease when larger values of "L" and smaller values of "K" are utilized. In Fig. 3, by decreasing the utilized impulsiveness parameter to generate the α-stable noise carrier signals, it has been observed that the BER performance of the proposed EM-nRCS is at the optimum level, i.e., $\text{BER} = 10^{-3}$, which has been achieved by exploiting the smallest "α", i.e., $\alpha = 0.40$, possible value of "L". On the contrary, the BER performance starts to decrease when larger values of α are utilized. In Fig. 4, by changing the pre-known N at NT and NR, it has been observed that the BER performance of the proposed EM-nRCS is at the optimum level, i.e., $\text{BER} = 10^{-3}$, which has been achieved when larger values of N are utilized and vice versa. The performance starts to degrade as N starts to decrease.

It can be concluded that utilizing smaller L and α and larger N and K has enhanced the BER performance which is the general trend of SkαSNSK-RCSs introduced in Refs. 27–32. However, utilizing larger N increases the amount of computation and the overall complexity of the system which can be reduced if multiple NTs and NRs are deployed.

6. Conclusion

The concept of RCSs has been realized at the nanoscale by utilizing the transparency window in the THz band to produce EM-nRCS for secure NCs. The simulations have shown that the proposed EM-nRCS provides significant BER performance and we expect that the need of having covert EM communications at the nanoscale, for building secure EM-nCSs network or future nano-machines, can be fulfilled by the introduced EM-nRCS.

Since the proposed method utilizes RNSs to convey information, it has a potential to become an alternate way of communication for the nano devices in the future where security would be the main concern and the vulnerability of these devices could become an obstacle in the advancement of NCs. Furthermore, due to the complexity of the communication systems at the nanoscale, the authors have utilized single input single output (SISO) concept in this paper; however, multiple inputs multiple outputs systems and the application of the proposed SISO EM-nRCS in transparency windows above 1 THz are the concerns of an ongoing study.

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