INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. 2012; **25**:1465–1478
Published online 11 October 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/dac.2450

Network-coded multiple-source cooperation aided relaying for free-space optical transmission

Xiaolin Zhou[1,*,†], Dingchen Zhang[1], Yandong Yang[1] and Mohammad S. Obaidat[2]

[1] *Department of Communication Science and Engineering, Fudan University, Shanghai, China*
[2] *Department of Computer Science and Software Engineering, Monmouth University, West Long Branch, NJ 07764, USA*

SUMMARY

A network-coded cooperative relaying aided free-space optical (FSO) transmission scheme is designed. The resultant multiple-source cooperation diversity is exploited by the relay to mitigate the strong turbulence-induced fading experienced in FSO channels. At the destination, an iterative multiple source detection algorithm is proposed in conjunction with a chip-level soft network decoding method. Our performance evaluation results using simulation analysis demonstrate that the proposed FSO multiple source detection is capable of approaching the single-user-bound for transmission over Gamma–Gamma turbulence channels. Also, the network-coded cooperative FSO scheme can achieve a significant BER improvement in comparison with conventional noncooperation schemes. Copyright © 2012 John Wiley & Sons, Ltd.

Received 6 August 2012; Accepted 16 September 2012

KEY WORDS: free-space optical; network coding; cooperation relay; multisource detection; atmospheric turbulence

1. INTRODUCTION

Free-space optical (FSO) communications have been recognized as a potential future enabler of the classic last-mile problem thanks to its combined advantages of providing a high data rate, requiring no licensed spectrum and low deployment costs [1–4]. However, FSO systems are typically vulnerable to weather-dependent attenuation and atmospheric turbulence, which reduce the achievable transmission reliability and throughput [5, 6].

The relay-aided transmission, extensively studied in radio-frequency (RF) communications [7–9], has also been introduced to circumvent the above-mentioned limitations of FSO systems. Specifically, an in-depth analysis of multihop relaying over Gamma–Gamma fading channels was presented in [10]. In addition, the outage performance of amplify-and-forward (AF) and decode-and-forward (DF) aided relaying was presented in [11]. Building on the above advances, a novel cooperative scheme, namely network-coded relaying, has drawn substantial research interest because of its capability of improving the system's reliability and hence combating link failures in an efficient manner [12–15]. As another extension, a photonic bitwise eXclusive OR (XOR) network coding technique was proposed for fault-tolerant all-optical multicast networks [12]. Furthermore, Kamal [13] investigated a novel design capable of achieving protection against single-link failure with the aid of network coding over p-cycles.

In this paper, we develop a network-coded iterative multisource cooperative FSO relaying transmission scheme communicating over Gamma–Gamma turbulence channels. Our proposed scheme exhibits several design merits:

*Correspondence to: Xiaolin Zhou, Department of Communication Science and Engineering, Fudan University, Shanghai, China.

†E-mail: zhouxiaolin@fudan.edu.cn

- Two time slots are sufficient for a round of multisource DF FSO relaying cooperation. A single relay node (RN) is sufficient for simultaneously serving several source nodes (SNs) to benefit from both a useful cooperation diversity gain and low deployment costs.
- We derive a soft MSC network-decoding method and an iterative FSO multisource detection (MSD) algorithm.

The remainder of this paper is organized as follows. Section 2 discusses related works. Section 3 describes the proposed FSO network-coded MSC scheme and an iterative MSD method and a soft MSC network decoding algorithm are also introduced. Section 4 presents our simulation results over Gamma–Gamma fading channels. Finally, we conclude in Section 5.

2. RELATED WORKS

This section introduces the major related works [12–18]. Safari and Uysal [16] introduced the concept of multihop relaying to FSO systems. The serial and parallel relaying techniques, each operating in AF or DF modes, are investigated. The work shows that the distance-dependent fading variance of FSO links constitutes the major difference between RF and FSO systems. The multihop relaying can achieve great performance improvement against turbulence fading than the direct transmission with shorter hop distance and lower scintillation index (*SI*). Moreover, the parallel relaying can be a possible alternative to serial relaying with multiple transmitter apertures directed to relay nodes, creating an artificial broadcasting.

Abou-Rjeily and Slim [17] studied the cooperative diversity for combating atmospheric turbulence-induced fading. The example of a metropolitan area FSO mesh network is considered. Simulation results prove that the cooperative diversity can achieve significant performance gains over the noncooperative direct FSO links. Besides, a full transmit diversity order can be obtained in the no-background radiation case.

A pulse-position modulation based multisource multirelay (MSMR) cooperative scheme was designed in our previous work [18]. The results confirm that the proposed MSMR scheme can obtain the obvious diversity gain with considering the effects of scintillation, thermal noise, background noise, and multiuser interference, and the rapid convergence property has been demonstrated by Extrinsic Information Transfer (EXIT) chart. Compared with the MSMR scheme requiring multiple relay nodes [18], in this paper, one single relay node is sufficient for serving the multisource, saving the equipment cost.

Currently, a new form of cooperative relay method, known as network coding, has attracted tremendous interest [12–15]. It can increase the system throughput and transmission robustness.

Menendez and Gannet [12] proposed a photonic XOR network coding technique for efficient and fault-tolerant all-optical networks. The XOR hardware element is simple, but supplies a key functionality. The analysis shows that the performance and efficiency of all-optical multicast networks can be very beneficial by utilizing this functionality and the information spreading can be achieved.

Kamal [13] proposed a novel method for protecting against the single-link failure using p-cycle network coding. Thanks to the $(1+N)$ protection, the scheme makes it possible to obtain a rapid and graceful recovery from link failures and to simplify the management and control planes. The evaluations show that the performance of the $(1+N)$ protection can be improved by increasing the graph density. Moreover, such a scheme is more efficient than the (1+1) protection under the same conditions.

Manley *et al.* [14] investigated the algorithmic problem for optical multicast protection and corresponding infrastructural designs with all-optical network coding. A heuristic scheme is proposed for solving the problem of how to set up the protected multicast connection by utilizing network coding. Compared with the existing techniques for multicast protection, the performance of heuristic can be near optimal and a significant improvement is obtained.

3. SYSTEM DESCRIPTION

The network coding aided multisource FSO relaying system considered in this paper consists of K SNs, an RN, and a destination node (DN). The transmission procedure is separated into two phases:

DOI: 10.1002/dac

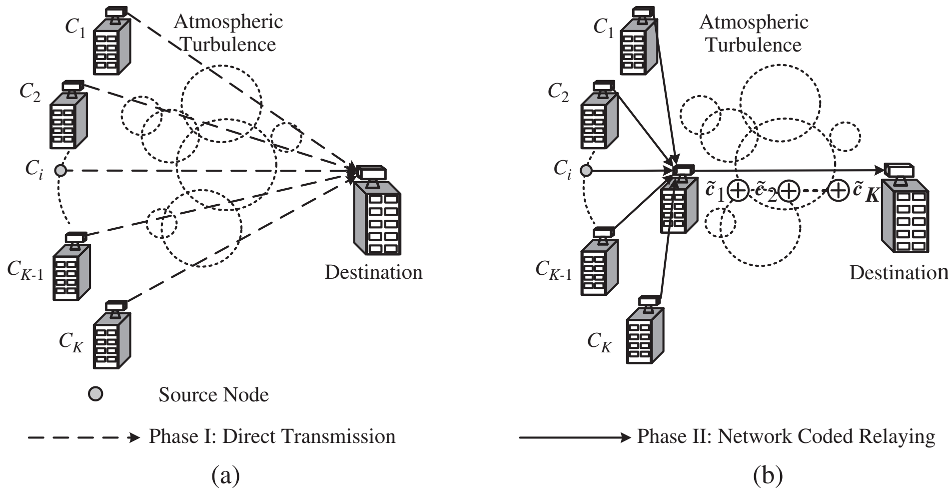

Figure 1. Illustration of network-coded MSC-aided relaying.

direct transmission and network coded relaying, as shown in Figure 1. More explicitly, in Phase I, the SNs send their data directly to the DN. In Phase II, the SNs retransmit their message to the DN through a full-duplex RN using network coding. The DN then combines the two signals to get a cooperative diversity gain. Throughout the paper, we use superscripts to distinguish the Phase I and II transmissions. Furthermore, we assume that the underlying optical transmission scheme employs the intensity modulation and direct detection technique combined with on–off keying (OOK) modulation.

3.1. *Phase I: direct transmission*

In Phase I, the bits sequence $\boldsymbol{d}_i = \{d_i[n], n = 1, \cdots, L_d\}$, $1 \leqslant i \leqslant K$, is encoded by a forward error correction (FEC) code, generating the encoded stream $\boldsymbol{c}_i = \{c_i[m], m = 1, \cdots, L_c\}$ of Figure 2(a), where L_d denotes the uncoded frame length,while L_{c} denotes the FEC encoded frame length. The FEC coded sequence is further interleaved by a unique, source-specific interleaver Π_i^{S}. Finally, the sequence is OOK modulated, producing the symbol stream $\boldsymbol{x}_i = \{x_i[l], l = 1, \cdots, L_{\mathrm{s}}\}$, where L_{s} is the symbol frame length. The symbols $\{x_i[l]\}$ may also be referred to as 'chips' [19], which drive an optical modulator for transmission over the FSO link, as shown in Figure 2.

The optical signals propagating in free space are subject to atmospheric turbulence-induced fading and these effects are usually modeled by a block fading process [20]. At the receiver, the positive-intrinsic-negative photodetector's output signal is assumed to be further contaminated by zero-mean AWGN. Thus, the received electrical signal is written as [21]

$$r^{(1)}[l] = \Re \sum_{i=1}^{K} I_i^{(1)} x_i[l] + n[l], \tag{1}$$

where $\Re$ is the optical-to-electrical conversion coefficient, while $\{n[l]\}$ represents the samples of the zero mean AWGN with variance of $\sigma_1^2 = N_0 / 2$. N_0 is the one-sided power spectral density. We let $I_i^{(1)}$ denote the real-valued fading gain between the $i$thSN and DN, which obeys a Gamma–Gamma distribution and is formulated as in [22]

$$\Pr(I) = \frac{2\,(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} \mathrm{K}_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right), \quad I > 0\,, \tag{2}$$

where $\Gamma(\cdot)$ is the standard Gamma function and $\mathrm{K}_n(\cdot)$ is the modified Bessel function of the second kind of order n. Furthermore, the scintillation parameters α and β, respectively, are defined as in (3), (4) below.

DOI: 10.1002/dac

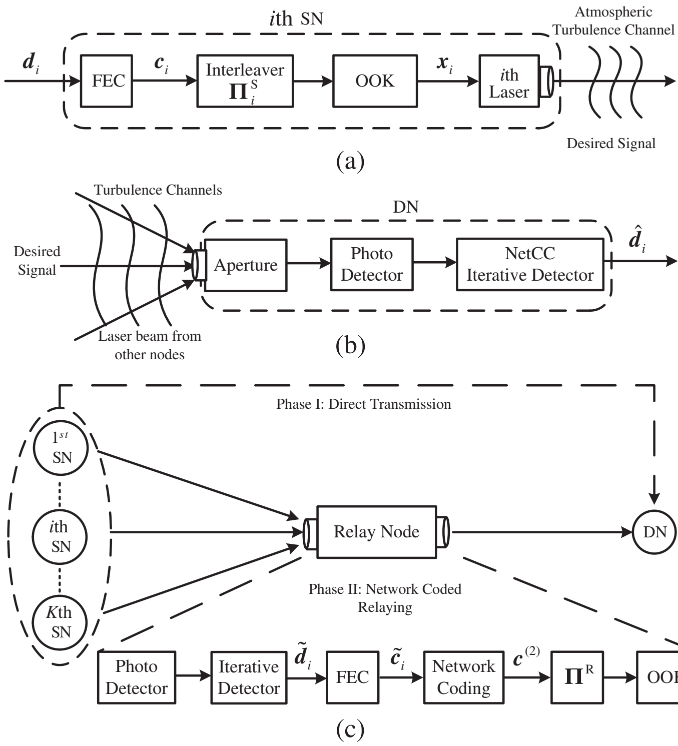

Figure 2. Model of free-space optical transmission link with multisource interference: (a) SN transmitter structure, (b) DN receiver structure, and (c) RN transceiver.

$$\alpha = \left[\exp\left(\frac{0.49\chi^2}{\left(1 + 0.18d^2 + 0.56\chi^{12/5}\right)^{7/6}} \right) - 1 \right]^{-1}, \tag{3}$$

$$\beta = \left[\exp\left(\frac{0.51\chi^2 \left(1 + 0.69\chi^{12/5}\right)^{-5/6}}{\left(1 + 0.9d^2 + 0.62d^2\chi^{12/5}\right)^{5/6}} \right) - 1 \right]^{-1}, \tag{4}$$

where the Rytov variance is given by $\chi^2 = 0.5C_n^2\kappa^{7/6}L^{11/6}$ and the geometry-related factor d is defined as $d = \left[\kappa D^2/(4L)\right]^{1/2}$, with L representing the link distance, D denoting the diameter of the receiver lens aperture, C_n^2 represents the refractive index structure parameter and $\kappa = 2\pi/\lambda$ denotes the wave number associated with a wavelength of λ. Finally, the scintillation index is defined as $SI = \alpha^{-1} + \beta^{-1} + (\alpha\beta)^{-1}$[4].

As depicted in Figure 3, the network-coded cooperative (NetCC) iterative receiver of DN consists of two processing chains involving SN-DN and RN-DN pairs. The SN-DN chain is constituted by a soft MSD module and K soft decoders (DECs). Note that the received electronic signal of Phase I is written as $r^{(1)}[l] = \Re \sum_{i=1}^{K} I_i^{(1)} x_i[l] + n[l]$. We now rewrite it as $r^{(1)}[l] = \Re I_i^{(1)} x_i[l] + \zeta_i[l]$, where $\zeta_i[l] = \Re \sum_{\tilde{i} \neq i} I_{\tilde{i}}^{(1)} x_{\tilde{i}}[l] + n[l]$ denotes the equivalent noise. To mitigate the multisource (MS) interference, a soft network coded iterative MSD algorithm is proposed for mitigating the effects of the turbulence channel and of the MS interference. Let us describe our MSD algorithm conceptually, while providing the full analytical derivation in Appendix A. In the following, the time index is omitted for notational simplicity. The extrinsic log-likelihood ratios (LLRs) about $x_i^{(1)}$ quantify the extra information gleaned at the output of the soft MSD of Figure 3, which can be written as

DOI: 10.1002/dac

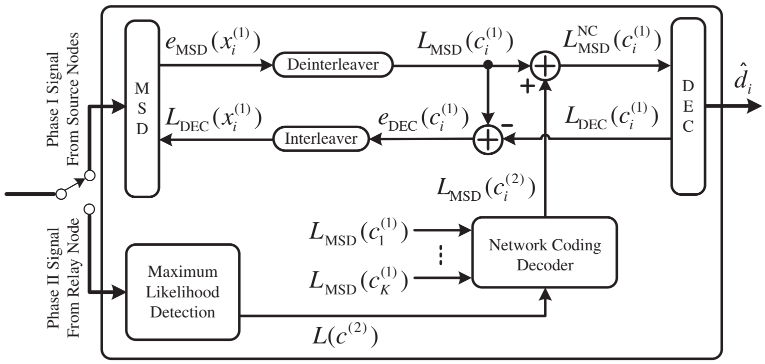

Figure 3. Structure of the iterative NetCC detector.

$$e_{\mathrm{MSD}}\left(x_i^{(1)}\right) = \frac{\Re I_i^{(1)}\left[2r^{(1)} - \Re I_i^{(1)} - 2\mathrm{E}(\zeta_i)\right]}{2\mathrm{Var}(\zeta_i)}, \quad \forall i\ , \tag{5}$$

where we have

$$\mathrm{E}\left(x_i^{(1)}\right) = \frac{\exp\left[L_{\mathrm{MSD}}^{\mathrm{a}}\left(x_i^{(1)}\right)\right]}{1+\exp\left[L_{\mathrm{MSD}}^{\mathrm{a}}\left(x_i^{(1)}\right)\right]}, \quad \forall i\ , \tag{5.1}$$

$$\mathrm{Var}\left(x_i^{(1)}\right) = \frac{\exp\left[L_{\mathrm{MSD}}^{\mathrm{a}}\left(x_i^{(1)}\right)\right]}{\left[1+\exp\left(L_{\mathrm{MSD}}^{\mathrm{a}}\left(x_i^{(1)}\right)\right)\right]^2}, \quad \forall i\ , \tag{5.2}$$

$$\mathrm{E}(\zeta_i) = \Re \sum_{\tilde{i}\neq i} I_{\tilde{i}}^{(1)} \mathrm{E}\left(x_{\tilde{i}}^{(1)}\right), \quad \forall i\ , \tag{5.3}$$

$$\mathrm{Var}(\zeta_i) = \Re^2 \sum_{\tilde{i}\neq i} \left|I_{\tilde{i}}^{(1)}\right|^2 \mathrm{Var}\left(x_{\tilde{i}}^{(1)}\right) + \sigma_1^2, \quad \forall i\ , \tag{5.4}$$

Here, $\mathrm{Var}(\cdot)$ and $\mathrm{E}(\cdot)$ stand for the variance and mean of the random variable argument, respectively. $L_{\mathrm{MSD}}^{\mathrm{a}}\left(x_i^{(1)}\right)$ is the *a priori* LLR about $x_i^{(1)}$, which is set to zero at initial iteration and is updated by the interleaved extrinsic information $e_{\mathrm{DEC}}\left(c_i^{(1)}\right)$ of the soft DEC module. As shown in Figure 3, the extrinsic information $e_{\mathrm{MSD}}\left(x_i^{(1)}\right), \forall i$ is forwarded to the deinterleaver. To achieve a cooperative diversity gain, the deinterleaved extrinsic information $L_{\mathrm{MSD}}\left(c_i^{(1)}\right), \forall i$ and the LLR outputs $L_{\mathrm{MSD}}\left(c_i^{(2)}\right), \forall i$ gleaned from the network coding decoders are combined. The related chip-level soft network decoding algorithm will be discussed in the next subsection. After the beneficial combining of the MSC signals, the resultant LLR information $L_{\mathrm{MSD}}^{\mathrm{NC}}\left(c_i^{(1)}\right), \forall i$ is then forwarded as *a priori* information to the soft DEC of Figure 3, which calculates both the *a posteriori* LLR$L_{\mathrm{DEC}}\left(c_i^{(1)}\right), \forall i$ and the extrinsic LLR $e_{\mathrm{DEC}}\left(c_i^{(1)}\right), \forall i$, yielding $e_{\mathrm{DEC}}\left(c_i^{(1)}\right) = L_{\mathrm{DEC}}\left(c_i^{(1)}\right) - L_{\mathrm{MSD}}\left(c_i^{(1)}\right), \forall i$. The extrinsic LLR $e_{\mathrm{DEC}}\left(c_i^{(1)}\right), \forall i$ is the re-interleaved and used as *a priori* information fed to the soft MSD of Figure 3 for the next iteration. Following the final iteration, the detected information bits $\hat{\boldsymbol{d}}_i, \forall i$ are output after a hard decision decoding of $L_{\mathrm{DEC}}\left(c_i^{(1)}\right), \forall i$, as seen in Figure 3.

DOI: 10.1002/dac

3.2. *Phase II: network-coded relaying*

In Phase II, the SNs retransmit their data to DN via the RN, as shown in Figure 2(c). The RN provides cooperation spatial diversity gain for each SN, hence beneficially combating the atmospheric turbulence. Again, here we briefly describe our algorithm conceptually in tangible physical terms and provide the related full mathematical derivation in Appendix A and B.

The RN detects the information bit sequence $\tilde{\boldsymbol{d}}_i = \left\{\tilde{d}_i[n], n = 1, \cdots, L_d\right\}$ for $1 \leqslant i \leqslant K$ of each SN with the aid of the proposed iterative MSD algorithm as detailed in Appendix A, because the iterative receiver architecture of RN is similar to that of the DN without the involvement of a network decoder. Hence, we will not discuss it for the sake of space economy. Employing the DF technique, the RN's recovered sequence $\tilde{\boldsymbol{d}}_i$ is re-encoded, yielding the FEC-coded stream $\tilde{\boldsymbol{c}}_i = \{\tilde{c}_i[m], m = 1, \cdots, L_c\}$. More particularly, the RN applies linear network coding to the incoming information creating the XOR function of each SN's signal. As a result, we have the combined stream $\boldsymbol{c}^{(2)} = \left\{c^{(2)}[m], m = 1, \cdots, L_c\right\}$, which is written as $c^{(2)}[m] = \tilde{c}_1[m] \oplus \cdots \oplus \tilde{c}_i[m] \cdots \oplus \tilde{c}_K[m]$, where $\oplus$ denotes the element-wise XOR operation. This is followed by further interleaving and OOK modulation. Finally, the full-duplex RN transmits the modulated chips $x^{(2)}[l]$ to the DN.

The DN's received chip stream is written as $r^{(2)}[l] = \Re I^{(2)} x^{(2)}[l] + n'[l], \quad 1 \leqslant l \leqslant L_s$, where $x^{(2)}[l]$ denotes the lth chip received from RN and $n'[l]$ represent the samples of the zero mean AWGN having a variance of σ_2^2. Furthermore, $I^{(2)}$ is the turbulence-induced fading intensity between the RN and the DN.

In the following, we discuss the RN-DN chain of the NetCC iterative receiver, which is constituted by the maximum likelihood detection and network coding decoder and we omit the time index for notational simplicity. Assuming the availability of perfect channel state information, the second phase detector first retrieves the LLRs of $c^{(2)}$ with the aid of maximum likelihood detection, which may be written as

$$L\left(c^{(2)}\right) = \log \frac{\Pr\left[r^{(2)} / c^{(2)} = 1\right]}{\Pr\left[r^{(2)} / c^{(2)} = 0\right]} = \frac{\Re^2}{2\sigma_2^2}\left[2r^{(2)} I^{(2)} - \left(I^{(2)}\right)^2\right] .$$

Then the decomposition into each individual LLR of $L_{\mathrm{MSD}}\left(c_i^{(2)}\right)$ for each SN is performed at the network coding decoder, which takes into account the observations from two phases. When using the full mathematical derivation provided in Appendix B, we have

$$\begin{aligned} L_{\mathrm{MSD}}\left(c_i^{(2)}\right) &= \log \frac{\Pr\left[c_i^{(2)} = 1 \left| r^{(1)}, r^{(2)}\right.\right]}{\Pr\left[c_i^{(2)} = 0 \left| r^{(1)}, r^{(2)}\right.\right]} \\ &= \log \frac{\omega + \exp\left[L\left(c^{(2)}\right)\right]}{1 + \omega \times \exp\left[L\left(c^{(2)}\right)\right]}, \end{aligned} \tag{6}$$

where $\omega = \frac{G_1 + G_3 + \cdots + G_k + \cdots + G_{K-1}}{1 + G_2 + \cdots + G_{k-1} + \cdots + G_{K-2}}$, when K is even, and

$$G_k = \sum_{l_1 < l_2 < \cdots < l_k \in \Theta} \exp\left[\sum_{m=1}^{k} L_{\mathrm{MSD}}\left(c_{l_m}^{(1)}\right)\right]. \tag{7}$$

In conjunction with $k = \{1, 2, \cdots, (K-1)\}$, $\Theta = \{1, 2, \cdots, (i-1), (i+1), \cdots, K\}$, and $G_0 = 0$. Then, these LLRs are beneficially combined with first phase LLRs from SN-DN chain and participate in the iterative chain as seen in Figure 3.

4. SIMULATION RESULTS

In this section, we evaluated the performance of the proposed NetCC FSO scheme for transmission over Gamma–Gamma turbulence channels using simulation analysis. The simulation scenario

DOI: 10.1002/dac

is depicted in Figure 1, where the source–destination (SD) and relay–destination (RD) channels are assumed to experience independent Gamma–Gamma fading. The SN and RN are in close proximity of each other. We also assume that the source–relay (SR) channels are perfectly error-free [9]. We first investigate the BER performance metric of the noncooperative (NonC) direct transmission as a benchmarker scheme, which will serve as the comparative basis of the proposed NetCC scheme. For the sake of a fair comparison, the total power P_{T} of both schemes is the same [9]. More explicitly, in the NonC system, the power P_{T} is equally shared among all SNs, that is, we have $P_{\mathrm{NonC}} = P_{\mathrm{T}}/K$. On the other hand, the power allocation in the NetCC system obeys $P^{\mathrm{S}}_{\mathrm{Coop}} = 2P_{\mathrm{T}}/2K+1$, $P^{\mathrm{R}}_{\mathrm{Coop}} = P_{\mathrm{T}}/2K+1$, where $P^{\mathrm{S}}_{\mathrm{Coop}}$ is the power of a single information bit at an SN, while $P^{\mathrm{R}}_{\mathrm{Coop}}$ is that at the RN. The repetition-based FEC code and OOK modulation are employed. In the following, the x-axis E_{b} / N_0 denotes the signal-to-noise ratio per bit.

4.1. *Simulation Experiment 1*

We first evaluate the BER performance and convergence behavior of the iterative MSD algorithm relying on the NonC scheme having $K = 4$ SNs and employing a repetition code of rate $R_c = 1/8$.

Figure 4 illustrates the BER performance of the proposed MSD algorithm for transmission over Gamma–Gamma fading channels. The scintillation parameters are set to $\alpha = 3.1$and $\beta = 2.0$. Observe in Figure 4 that the MSD algorithm exhibits a rapid convergence in $It = 4$ iterations to the single-user-bound.

4.2. *Simulation Experiment 2*

Here we investigate the MSD algorithm under different Gamma–Gamma fading conditions for the NonC scheme having $K = 4$SNs and employing a repetition code of rate $R_{\mathrm{c}} = 1/8$.

Figure 5 characterizes the BER performance of our proposed MSD algorithm under different turbulence conditions. The optical scintillation parameters are set to values of $\alpha = 2.1, 3.1, 4.1$ and $\beta = 2.0$. The related scintillation indexes are set to *SI* =1.2143, 0.9839, and 0.8659, respectively.

As shown in Figure 5, the higher *SI* values result in stronger Gamma–Gamma turbulence-induced fading, which degrades the BER performance. At a BER of 10^{-3}, there is a 6.5 dB performance difference between the scenarios having *SI*=1.2143 and *SI*=0.8659. These results imply that to mitigate the turbulence-induced fading and to enhance the achievable transmission reliability, both cooperation and diversity combining should be considered.

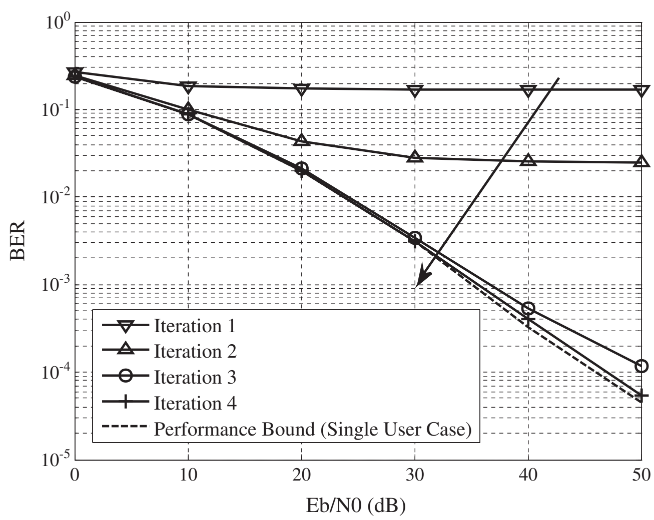

Figure 4. BER of MSD algorithm over Gamma–Gamma fading channels associated with $\alpha = 3.1$ and $\beta = 2.0$.

DOI: 10.1002/dac

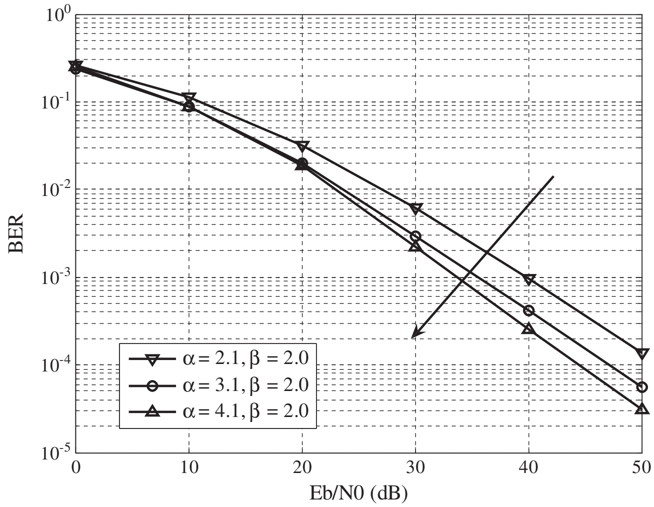

Figure 5. BER of MSD algorithm with different scintillation parameters.

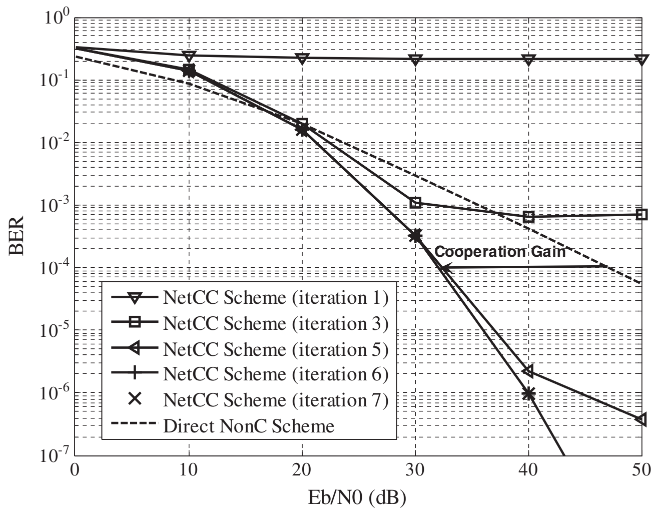

Figure 6. Comparisons between the NetCC relaying scheme to the direct NonC scheme for Gamma–Gamma fading associated with $\alpha = 3.1$ and $\beta = 2.0$.

4.3. Simulation Experiment 3

This investigation characterizes the BER performance of our proposed NetCC relaying scheme in comparison with the direct NonC scheme having $K = 4$ SNs and one RN. The repetition coding rate of the NetCC scheme is set to $R_c = 1/4$. To maintain the same effective spectral efficiency, the coding rate of the direct NonC scheme equals to $R_c = 1/8$.

Figure 6 demonstrates that the NetCC scheme is capable of providing the obvious performance gain compared with the direct NonC scheme and exhibits a rapid convergence, regarding six iterations.

4.4. Simulation Experiment 4

This experiment investigates the impact of distance on the resultant BER performance. Our comparisons are carried out between the NetCC and direct NonC scheme having $K = 4$SNs and one RN, while employing a repetition coding rate of $R_c = 1/4$ in the NetCC scheme and $R_c = 1/8$ in the direct NonC scheme. The FSO system operates at $\lambda = 1550$ nm, $C_n^2 = 1.7 \times 10^{-14}\mathrm{m}^{-2/3}$ and

DOI: 10.1002/dac

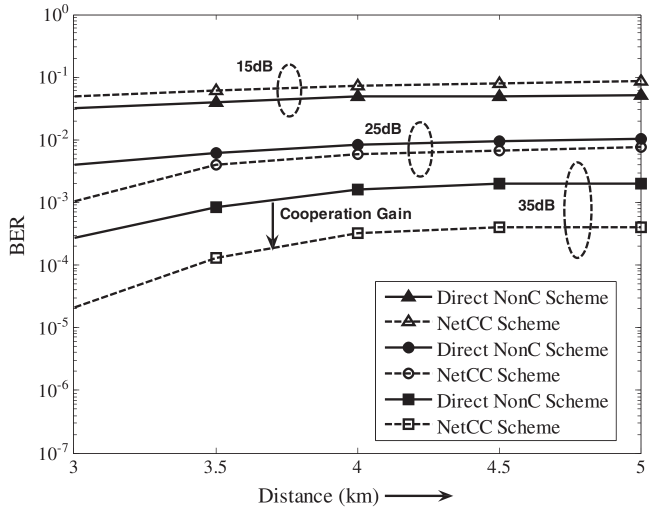

Figure 7. Impact of link distance on the BER performance.

Table I. Scintillation index versus distance.

Distance(km)	3.0	3.5	4.0	4.5	5.0
α	2.9020	2.5196	2.2965	2.1676	2.0979
β	2.5100	2.0918	1.8219	1.6383	1.5084
SI	0.8803	1.0647	1.2233	1.3533	1.4556

$D << L$. Furthermore, we set the E_{b}/N_0 equals to 15, 25, 35 dB, respectively. The impact of path loss-induced attenuation is separated from the dependence of L on $\alpha$and β [23].

Figure 7 shows that at higher E_{b}/N_0, the NetCC scheme is capable of gleaning a higher cooperation diversity gain because the confident decisions of the unimpaired network-coded streams provide valuable extrinsic information for less reliable streams. Thus, a better BER performance can be achieved in comparison with the direct NonC scheme. On the other hand, even in the absence of attenuation, the BER degrades with the increase of the distance and the scintillation index, as quantified in Table I.

5. CONCLUSIONS

In this paper, a network-coded FSO cooperative relaying scheme was developed for mitigating the atmospheric turbulence fading. At the destination, an OOK-modulated FSO iterative MSD scheme was invoked in conjunction with the chip-level multisource soft network decoding. Furthermore, we investigated the attainable system performance for transmission over Gamma–Gamma turbulence fading channels. Our numerical results confirm that the proposed NetCC FSO scheme is capable of achieving a substantial reduction in BER compared with the conventional noncooperative scheme. Additionally, our design requires less equipment cost and high flexibility in the context of multisource FSO cooperative transmissions.

APPENDIX A

In this appendix, we analytically characterize the OOK-modulated iterative MS detection algorithm of Section 3.

When OOK is employed, we have $x_i^{(1)}[l] \in \{0,1\}$, $\forall i, l$. To focus on the ith SN, given the turbulence channels' observation $\boldsymbol{I}^{(1)} = \left\{ I_i^{(1)} \right\}, \forall i$, the *a posteriori* LLR of $x_i^{(1)}$ is

$$\begin{aligned} L_{\mathrm{MSD}}\left(x_i^{(1)}\right) &= \log \frac{\Pr\left[x_i^{(1)} = 1 \middle| r^{(1)}, \boldsymbol{I}^{(1)}\right]}{\Pr\left[x_i^{(1)} = 0 \middle| r^{(1)}, \boldsymbol{I}^{(1)}\right]} \\ &= \underbrace{\log \frac{\Pr\left[r^{(1)} \middle| x_i^{(1)} = 1, \boldsymbol{I}^{(1)}\right]}{\Pr\left[r^{(1)} \middle| x_i^{(1)} = 0, \boldsymbol{I}^{(1)}\right]}}_{e_{\mathrm{MSD}}\left(x_i^{(1)}\right)} + \underbrace{\log \left[\frac{\Pr\left(x_i^{(1)} = 1\right)}{\Pr\left(x_i^{(1)} = 0\right)}\right]}_{L^{\mathrm{a}}_{\mathrm{MSD}}\left(x_i^{(1)}\right)}, \end{aligned} \tag{A.1}$$

where $e_{\mathrm{MSD}}\left(x_i^{(1)}\right)$ is the extrinsic LLR of $x_i^{(1)}$. $L^{\mathrm{a}}_{\mathrm{MSD}}\left(x_i^{(1)}\right)$ is the *a priori* information of $x_i^{(1)}$. Furthermore,

$$\begin{aligned} e_{\mathrm{MSD}}\left(x_i^{(1)}\right) &= \log \frac{\Pr\left[r^{(1)} \middle| x_i^{(1)} = 1, \boldsymbol{I}^{(1)}\right]}{\Pr\left[r^{(1)} \middle| x_i^{(1)} = 0, \boldsymbol{I}^{(1)}\right]} \\ &= \frac{\Re I_i^{(1)}\left[2r^{(1)} - \Re I_i^{(1)} - 2\mathrm{E}\left(\zeta_i\right)\right]}{2\mathrm{Var}(\zeta_i)}, \end{aligned} \tag{A.2}$$

where the estimates of the interference mean and variance are $\mathrm{E}(\zeta_i) = \Re \sum_{\tilde{i} \neq i} I_{\tilde{i}}^{(1)} \mathrm{E}\left(x_{\tilde{i}}^{(1)}\right)$, and $\mathrm{Var}\left(\zeta_i\right) = \Re^2 \sum_{\tilde{i} \neq i} \left| I_{\tilde{i}}^{(1)} \right|^2 \mathrm{Var}\left(x_{\tilde{i}}^{(1)}\right) + \sigma_1^2$, respectively. More explicitly, the estimated mean and variance of each chip is given by

$$\begin{aligned} \mathrm{E}\left(x_i^{(1)}\right) &= 0 \cdot \Pr\left(x_i^{(1)} = 0\right) + (+1) \cdot \Pr\left(x_i^{(1)} = +1\right) \\ &= \frac{\exp\left[L^{\mathrm{a}}_{\mathrm{MSD}}\left(x_i^{(1)}\right)\right]}{1 + \exp\left[L^{\mathrm{a}}_{\mathrm{MSD}}\left(x_i^{(1)}\right)\right]}, \end{aligned} \tag{A.3}$$

$$\begin{aligned} \mathrm{Var}\left(x_i^{(1)}\right) &= \mathrm{E}\left[x_i^{(1)}\right]^2 - \mathrm{E}^2\left[x_i^{(1)}\right] \\ &= \frac{\exp\left[L^{\mathrm{a}}_{\mathrm{MSD}}\left(x_i^{(1)}\right)\right]}{\left[1 + \exp\left[L^{\mathrm{a}}_{\mathrm{MSD}}\left(x_i^{(1)}\right)\right]\right]^2}. \end{aligned} \tag{A.4}$$

The *a priori* information $L^{\mathrm{a}}_{\mathrm{MSD}}\left(x_i^{(1)}\right)$ is zero during the first detection iteration, which is then updated by the interleaved extrinsic information $e_{\mathrm{DEC}}\left(c_i^{(1)}\right)$ gleaned from the soft DEC module of Figure 3.

DOI: 10.1002/dac

APPENDIX B

In this appendix, we derive the MS's soft network decoding algorithm used in Section 3. The LLRs of $c_i^{(2)}$ in Figure 3 are given by

$$
\begin{aligned}
L_{\mathrm{MSD}}\left(c_i^{(2)}\right) &= \log\frac{\Pr\left[c_i^{(2)}=1\left|r^{(1)},r^{(2)}\right.\right]}{\Pr\left[c_i^{(2)}=0\left|r^{(1)},r^{(2)}\right.\right]} = \log\frac{\Pr\left[c^{(2)}\oplus(c_1\oplus c_2\oplus\cdots\oplus c_{i-1}\oplus c_{i+1}\oplus\cdots\oplus c_K)=1\left|r^{(1)},r^{(2)}\right.\right]}{\Pr\left[c^{(2)}\oplus(c_1\oplus c_2\oplus\cdots\oplus c_{i-1}\oplus c_{i+1}\oplus\cdots\oplus c_K)=0\left|r^{(1)},r^{(2)}\right.\right]} \\
&= \log\frac{\upsilon\Pr\left[\frac{1-(-1)^{c_1+c_2+\cdots+c_{i-1}+c_{i+1}+\cdots+c_K}}{2}=1\left|r^{(1)}\right.\right]+(1-\upsilon)\Pr\left[\frac{1-(-1)^{c_1+c_2+\cdots+c_{i-1}+c_{i+1}+\cdots+c_K}}{2}=0\left|r^{(1)}\right.\right]}{\upsilon\Pr\left[\frac{1-(-1)^{c_1+c_2+\cdots+c_{i-1}+c_{i+1}+\cdots+c_K}}{2}=0\left|r^{(1)}\right.\right]+(1-\upsilon)\Pr\left[\frac{1-(-1)^{c_1+c_2+\cdots+c_{i-1}+c_{i+1}+\cdots+c_K}}{2}=1\left|r^{(1)}\right.\right]} \\
&= \log\frac{\omega+\exp\left[L\left(c^{(2)}\right)\right]}{1+\omega\times\exp\left[L\left(c^{(2)}\right)\right]},
\end{aligned}
\tag{B.1}
$$

where we let $\upsilon=\Pr\left[c^{(2)}=0\left|r^{(2)}\right.\right]$ and

$$
\begin{aligned}
\omega &= \frac{\Pr\left[\frac{1-(-1)^{c_1+c_2+\cdots+c_{i-1}+c_{i+1}+\cdots+c_K}}{2}=1\left|r^{(1)}\right.\right]}{\Pr\left[\frac{1-(-1)^{c_1+c_2+\cdots+c_{i-1}+c_{i+1}+\cdots+c_K}}{2}=0\left|r^{(1)}\right.\right]} \\
&= \begin{cases} 0, & K=1, \\ \frac{G_1+G_3+\cdots+G_k+\cdots+G_{K-1}}{1+G_2+\cdots+G_{k-1}+\cdots+G_{K-2}}, & K=2,4,6,\cdots,\ \text{even number}, \\ \frac{G_1+G_3+\cdots+G_k+\cdots+G_{K-2}}{1+G_2+\cdots+G_{k-1}+\cdots+G_{K-1}}, & K=3,5,7,\cdots,\ \text{odd number}. \end{cases}
\end{aligned}
\tag{B.2}
$$

In the expression of ω, we have

$$
\begin{aligned}
G_k &= \sum_{l_1<\cdots<l_k\in\Theta} A_{l_1}A_{l_2}\cdots A_{l_k} \\
&= \sum_{l_1<\cdots<l_k\in\Theta} \exp\left[L_{\mathrm{MSD}}(c_{l_1})\right]\exp\left[L_{\mathrm{MSD}}\left(c_{l_2}\right)\right]\cdots\exp\left[L_{\mathrm{MSD}}\left(c_{l_k}\right)\right] \\
&= \sum_{l_1<\cdots<l_k\in\Theta} \exp\left[\sum_{m=1}^{k} L_{\mathrm{MSD}}(c_{l_m})\right],
\end{aligned}
\tag{B.3}
$$

where $1\leqslant k\leqslant(K-1)$, $\Theta=\{1,2,\cdots(i-1),(i+1),\cdots K\}$, $G_0=0$.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China under Grant No. 60802011 and the National High Technology Research and Development Program of China under Grant No. 2011AA100701.

REFERENCES

1. Hanzo L, Haas H, Imre S, O'Brien D, Rupp M, Gyongyosi L. Wireless myths, realities, and futures: from 3G/4G to optical and quantum wireless. *Proceedings of the IEEE* 2012; **100**:1853–1888.
2. Chan VWS. Free-space optical communications. *IEEE/OSA Journal of Lightwave Technology* 2006; **24**(12):4750–4762.
3. Uysal M, Li J, Yu M. Error rate performance analysis of coded free-space optical links over gamma-gamma atmospheric turbulence channels. *IEEE Transactions on Wireless Communications* 2006; **5**(6):1229–1233.
4. Letzepis N, Fabregas AGi. Outage probability of the Gaussian MIMO free-space optical channel with PPM. *IEEE Transactions on Communications* 2009; **57**(12):3682–3690.
5. Sandalidis HG. Coded free-space optical links over strong turbulence and misalignment fading channels. *IEEE Transactions on Communications* 2011; **59**(3):669–674.
6. Andrews LC, Phillips RL, Hopen CY. *Laser Beam Scintillation with Applications*. SPIE: Bellingham, WA, 2001.

DOI: 10.1002/dac

7. Rui X, Hou J, Zhou L. Decode-and-forward with full-duplex relaying. *International Journal of Communication Systems* 2012; **25**(2):270–275.
8. Jia X, Fu H, Yang L, Zhao L. Superposition coding cooperative relaying communications: outage performance analysis. *International Journal of Communication Systems* 2011; **24**(3):384–397.
9. Zhang R, Hanzo L. Space-time coding for high-throughput interleave division multiplexing aided multi-source cooperation. *Electronics Letters* 2008; **44**(5):367–368.
10. Datsikas C, Peppas K, Sagias N, Tombras G. Serial free-space optical relaying communications over gamma-gamma atmospheric turbulence channels. *IEEE/OSA Journal of Optical Communications and Networking* 2010; **2**(8):576–586.
11. Karimi M, Nasiri-Kenari M. Outage analysis of relay-assisted free-space optical communications. *IET Communications* 2010; **4**(12):1423–1432.
12. Menendez RC, Gannet JW. Efficient, fault-tolerant all-optical multicast networks via network coding. *Proceedings of OFC/NFOEC*, Article ID JThA82, San Diego, CA, February 2008; 3.
13. Kamal AE. 1+N network protection for mesh networks: network coding-based protection using p-cycles. *IEEE/ACM Transactions on Networking* 2010; **18**(11):67–80.
14. Manley ED, Deogun JS, Xu L, Alexander DR. All-optical network coding. *Journal of Optical Communications and Networking* 2010; **2**(4):175–191.
15. Minkyu K, Medard M, OReilly UM. Network coding and its implications on optical networking. *Proceedings of OFC/NFOEC*, Article ID OThO3, San Diego, CA, March 2009; 3.
16. Safari M, Uysal M. Relay-assisted free-space optical communication. *IEEE Transactions on Wireless Communications* 2008; **7**(12):5441–5449.
17. Abou-Rjeily C, Slim A. Cooperative diversity for free-space optical communications: transceiver design and performance analysis. *IEEE Transactions on Communications* 2011; **59**(3):658–663.
18. Fan J, Zhou X, Liu J. Design and evaluation of an IDMA cooperative relay free-space optical system. *Proceedings of IEEE ICSOS*, Santa Monica, CA, May 2011; 358–362.
19. Ping L, Liu L, Wu K, Leung WK. Interleave division multiple access. *IEEE Transactions on Wireless Communications* 2006; **5**(4):938–947.
20. Letzepis N, Nguyen K, Guillen i Fabregas A, Cowley W. Outage analysis of the hybrid free-space optical and radio-frequency channel. *IEEE Journal on Selected Areas in Communications* 2009; **27**(9):1709–1719.
21. Zhu X, Kahn JM. Free-space optical communication through atmospheric turbulence channel. *IEEE Transactions on Communications* 2002; **50**(8):1293–1300.
22. Andrews L, Phillips R. *Laser Beam Propagation Through Random Media*, (2nd edn). SPIE Press: Bellingham, 2005.
23. Bayaki E, Schober R, Mallik RK. Performance analysis of free-space optical systems in gamma-gamma fading. *IEEE Global Communications Conference (GCC'2008)*, New Orleans, LA, USA, December 2008; 2859–2864.

AUTHORS' BIOGRAPHIES

Xiaolin Zhou received his BEng degree from the Department of Technical Physics, Xidian University, China, in 1996. He received his MEng degree from Nanjing University of Aeronautics and Astronautics, China, in 1999. And he received his PhD degree from Shanghai Jiaotong University, China, in 2003. During 2005-2006, he was a visiting researcher at Monash University, Australia. He is currently an assistant professor in the Department of Communication Science and Engineering, Fudan University, China. His research interests include free-space optical communications and signal processing technology.

Dingchen Zhang received his BEng degree in Communication Engineering from Fudan University, China, in 2010, and currently, he is studying in the Department of Communication Science and Engineering at Fudan University for a MEng degree. His research interests include iterative decoding and multiuser detection in free-space optics.

DOI: 10.1002/dac

Yandong Yang received his BEng degree from Fudan University, China, in 2009. He received the MEng degree from Fudan University, China, in 2012. His research interests include iterative detection, cooperative communications and free-space optical communications.

Mohammad S. Obaidat (Fellow of IEEE and Fellow of SCS) is an internationally well-known academic/researcher/ scientist. He received his PhD and MS degrees in Computer Engineering with a minor in Computer Science from The Ohio State University, Columbus, Ohio, USA. Dr Obaidat is currently a Full Professor of Computer Science at Monmouth University, NJ, USA. Among his previous positions are Chair of the Department of Computer Science, Director of the Graduate Program at Monmouth University and a faculty member at the City University of New York. He has received extensive research funding and has published over 10 books and over 550 refereed technical articles in scholarly international journals and proceedings of international conferences, and currently, he is working on three more books. Professor Obaidat has served as a consultant for several corporations and organizations worldwide. Mohammad is the Editor-in-Chief of the Wiley International Journal of Communication Systems, the FTRA Journal of Convergence and the KSIP Journal of Information Processing. He served as an Editor of IEEE Wireless Communications from 2007 to 2010. Between 1991 and 2006, he served as a Technical Editor and an Area Editor of Simulation: Transactions of the Society for Modeling and Simulations (SCS) International, TSCS. He also served on the Editorial Advisory Board of Simulation. He is now an Editor of the Wiley Security and Communication Networks Journal, Journal of Networks, International Journal of Information Technology, Communications and Convergence, IJITCC, and Inderscience. He served on the International Advisory Board of the International Journal of Wireless Networks and Broadband Technologies, IGI-global. Prof. Obaidat is an Associate Editor/Editorial Board Member of seven other refereed scholarly journals including two IEEE Transactions, Elsevier Computer Communications Journal, Kluwer Journal of Supercomputing, SCS Journal of Defense Modeling and Simulation, Elsevier Journal of Computers and EE, International Journal of Communication Networks and Distributed Systems, The Academy Journal of Communications, International Journal of BioSciences and Technology, and International Journal of Information Technology. He has guest edited numerous special issues of scholarly journals such as IEEE Transactions on Systems, Man and Cybernetics, SMC, IEEE Wireless Communications, IEEE Systems Journal, and SIMULATION: Transactions of SCS, Elsevier Computer Communications Journal, Journal of C & EE, Wiley Security and Communication Networks, Journal of Networks, and International Journal of Communication Systems, among others. Obaidat has served as the Steering Committee Chair, Advisory Committee Chair and Program Chair of numerous international conferences.

He is the founder of two well-known international conferences: the International Conference on Computer, Information and Telecommunication Systems (CITS), and the International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS). He is also the co-founder of the International Conference on Data Communication Networking, DCNET.

Between 1994 and 1997, Obaidat has served as a distinguished speaker/visitor of IEEE Computer Society. Since 1995, he has been serving as an ACM distinguished Lecturer. He is also an SCS distinguished Lecturer. Between 1996 and 1999, Dr Obaidat served as an IEEE/ACM program evaluator of the Computing Sciences Accreditation Board/Commission, CSAB/CSAC. Obaidat is the founder and first Chairman of SCS Technical Chapter (Committee) on PECTS (Performance Evaluation of Computer and Telecommunication Systems). He has served as the Scientific Advisor for the World Bank/UN Digital Inclusion Workshop - The Role of Information and Communication Technology in Development. Between 1995 and 2002, he has served as a member of the board of directors of the Society for Computer Simulation International. Between 2002 and 2004, he has served as Vice President of Conferences of the Society for Modeling and Simulation International SCS. Between 2004 and 2006, Prof. Obaidat has served as Vice President of Membership of the Society for Modeling and Simulation International SCS. Between 2006 and 2009, he has served as the Senior Vice President of SCS. Between 2009 and 2011, he served as the President of SCS. One of his recent co-authored papers has received the best paper award in the IEEE AICCSA 2009 international conference. He also received the best paper award for one of his papers accepted in IEEE GLOBCOM 2009 conference. Prof. Obaidat has been awarded a Nokia Research Fellowship and the distinguished Fulbright Scholar Award. He received the SCS Outstanding Service Award for his excellent leadership, services and technical contributions. Dr Obaidat received very recently the Society for Modeling and Simulation Intentional (SCS) prestigious McLeod Founder's Award in recognition of his outstanding technical and professional contributions to modeling and simulation. He received in December 2010 the IEEE ComSoc - GLOBECOM 2010 Outstanding Leadership Award for his outstanding leadership of Communication Software Services and Multimedia Applications Symposium, CSSMA 2010. He received very recently the Society

DOI: 10.1002/dac

for Modeling and Simulation International's (SCS) prestigious Presidential Service Award for his outstanding unique, long-term technical contributions and services to the profession and society.

He has been invited to lecture and give keynote speeches worldwide. His research interests are as follows: wireless communications and networks, telecommunications and networking systems, security of network, information and computer systems, security of e-based systems, performance evaluation of computer systems, algorithms and networks, green ICT, high performance and parallel computing/computers, applied neural networks and pattern recognition, adaptive learning and speech processing. During the 2004/2005, he was on sabbatical leave as Fulbright Distinguished Professor and Advisor to the President of Philadelphia University in Jordan, Dr Adnan Badran. The latter became the Prime Minister of Jordan in April 2005 and served earlier as Deputy Director General of UNESCO. Prof. Obaidat is a Fellow of the Society for Modeling and Simulation International SCS and a Fellow of the Institute of Electrical and Electronics Engineers (IEEE). For more info, see http://bluehawk.monmouth.edu/mobaidat/.