Rate-adaptive selective relaying using time diversity for relay-assisted FSO communications

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3rd IEEE Global Conference on Signal and Information Processing
December 16, 2015

Contents

Contents

Free-space optical (FSO) communication systems

- ❑ Applications: Metropolitan area network (MAN) extension, local area network (LAN)-to-LAN connectivity, an alternative to radio-frequency (RF) systems . . .
- ❑ Intensity Modulated and Direct Detection (IM/DD).
- ❑ Transmitter: semiconductor laser diode (LD).
- ❑ Receiver: Optical filters, lens, photodiode (PD).

✓ Advantages

- ➢ Low cost.
- ➢ Unregulated bandwidth.
- ➢ High date rates (Gbps).
- ➢ High security.

✗ Disadvantages

- ➢ Atmospheric turbulence, which produces fluctuations in the irradiance of the received optical beam.
- ➢ Misalignment between transmitter and receiver.
- ➢ Light cannot pass through walls.

Cooperative FSO systems

Cooperative communications . . .

- ✓ An alternative way of realizing spatial diversity advantages.
- ✓ The source node sends the information to the relay node and, the relay node re-sends the received information to the destination node.
- ✓ Different operation modes: Amplify-and-forward (AF) and decode-and-forward (DF).
- ✓ Different configurations: serial and parallel, or combination of serial and parallel.

- ❑ . . . are becoming essential for future wireless networks.
- ❑ . . . can significantly improve the performance by creating diversity using transceivers available at the other nodes of the network.

Error-rate performance analysis for a 3-way cooperative FSO system

- The motivation is to analyze the error-rate performance for a 3-way cooperative FSO communications system:
  - A cooperative protocol based on the optical path selection with a greater value of fading gain together with time-diversity order of 2 by using repetition coding (RC) is proposed.
  - Channel side information (CSI) is known at the transmitter as well as at the receiver.
  - The relay node is operating in DF mode.
  - Gamma-Gamma fading channels with pointing errors are considered.

Error-rate performance analysis

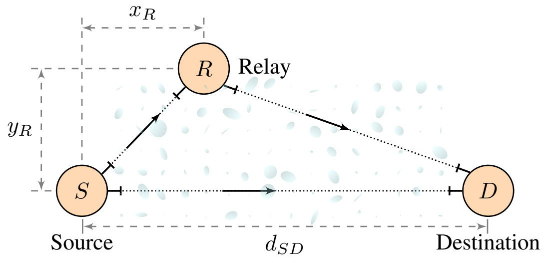
- Novel closed-form asymptotic expressions for the bit error-rate (BER).
- Diversity order gain analysis.

✓ A greater robustness to the relay location will be corroborated by using time-diversity in all links as well as a higher diversity order.

Contents

System Model I

- Block diagram under study



- ✓ A cooperative FSO system based on three separate FSO links is adopted.
- ✓ (x_R, y_R) represents the relay location.
- ✓ Equal Gain Combining (EGC) reception.
- ✓ All coefficients (irradiances) are statistically independent.

System Model II

Proposed cooperative strategy by using time-diversity in all links:

- When $I_{SD} > I_{SR}$: The FSO communication is only based on the direct transmission to the destination node, by using RC of 2.
- When $I_{SD} < I_{SR}$: The cooperation mode has been selected. The FSO communication is based on the the S-R-D path or cooperative transmission.

- ➥ The data received from the source node at the destination node as well as at the relay node are stored in a buffer for further detection. A block-fading later, the source node repeats the bit sequence transmitted, not being necessary to perform another selection when the source node is repeating the data.
- ➥ The relay node resends within the next block-fading the data sent in previous block-fading to the destination node.

The relay node detects each bit based on repetition coding and sends the bit with the new power to the destination node D regardless of these bits are detected correctly or incorrectly.

Channel Model I

The received electrical signal for each link is given by

$$Y_m = \eta X I_m + Z_m, \quad X \in \{0, d_E\}, \quad Z_m \sim N(0, N_0/2)$$

- Y_m is the received electrical signal.
- η is the detector responsivity ($\eta = 1$).
- X_m is the binary transmitted signal ($d_E = 2P_{\text{opt}}\sqrt{T_b\xi}$).
- I_m represents the irradiance between source and destination.

The irradiance (I_m) is considered to be a product of three factors $I_m = L_m \cdot I_m^{(a)} \cdot I_m^{(p)}$:

- Deterministic propagation loss (L_m).
  - Exponential Beers-Lambert law as $L_m = e^{-\Phi d}$.
  - $\Phi = (3.91/V(km))\,(\lambda(nm)/550)^{-q}$.
- Atmospheric turbulence ($I_m^{(a)}$).
  - GG turbulence model of parameters α and β, which depend on the Rytov variance.
  - Turbulence conditions from moderate to strong.
- Pointing errors ($I_m^{(p)}$).
  - Normalized beam width (ω_z/r), normalized jitter (σ_s/r) and detector size (r).
  - Ratio between equivalent beam radius at the receiver and the pointing error displacement standard deviation (jitter) at the receiver, $\varphi = \omega_{z_{eq}}/2\sigma_s$.

Channel Model II

- The probability density function (PDF) of I_m is approximated by

$$f_{I_m}(i) \approx a_m i^{b_m - 1} = \begin{cases} \frac{\varphi^2 (\alpha\beta)^\beta \Gamma(\alpha-\beta)}{(A_0 L_m)^\beta \Gamma(\alpha)\Gamma(\beta)\left(\varphi^2-\beta\right)} i^{\beta-1}, & \varphi^2 > \beta \\ \frac{\varphi^2 (\alpha\beta)^{\varphi^2} \Gamma\left(\alpha-\varphi^2\right)\Gamma\left(\beta-\varphi^2\right)}{(A_0 L_m)^{\varphi^2} \Gamma(\alpha)\Gamma(\beta)} i^{\varphi^2-1}, & \varphi^2 < \beta \end{cases}$$

  Due to the fact that the asymptotic behavior of the system performance is dominated by the behavior of the PDF near the origin.

- Parameters α and β can be directly linked to physical parameters through the following expressions:

$$\alpha = \left[\exp\left(0.49\sigma_R^2/(1+1.11\sigma_R^{12/5})^{7/6}\right) - 1\right]^{-1},$$

$$\beta = \left[\exp\left(0.51\sigma_R^2/(1+0.69\sigma_R^{12/5})^{5/6}\right) - 1\right]^{-1},$$

being $\sigma_R^2 = 1.23 C_n^2 \kappa^{7/6} d^{11/6}$ the Rytov variance.

Contents

Error-rate performance analysis I

Asymptotic BER performance analysis of cooperative FSO systems using time-diversity

The average BER behaves asymptotically as

$$P_b \doteq (G_c \gamma \xi)^{-G_d},$$

where G_d and G_c denote diversity gain and coding gain, respectively [2].

- The statistical channel model is given by

$$\begin{aligned} Y_0 &= X(I_{SD_1} + I_{SD_2}) + Z_{SD_1} + Z_{SD_2}, \qquad I_{SD_1} > I_{SR_1} \\ Y_1 &= X^*(I_{RD_1} + I_{RD_2}) + Z_{RD_1} + Z_{RD_2}, \qquad I_{SD_1} < I_{SR_1} \end{aligned}$$

- ➥ X^* represents the RV corresponding to the information detected at the relay node

$$X^* = X \qquad \text{detected correctly}$$

$$X^* = d_E - X \qquad \text{detected incorrectly}$$

The BER corresponding to the proposed cooperative protocol is given by

$$P_b = P_b^{SD} + P_b^{SRD} = P_b^{SD} + P_b^{SR_0} P_b^{RD_1} + P_b^{RD_0} P_b^{SR_1} = P_b^{SD} + P_b^{SR}(1 - P_b^{RD}) + P_b^{RD}(1 - P_b^{SR})$$

Error-rate performance analysis II

- The average BER at the node D corresponding to the S-D link is given by

$$P_b^{SD} = \int_0^\infty \int_0^\infty Q\left(\sqrt{\gamma\xi}(i_1 + i_2)\right) F_{I_{SR}}(i_1) f_{I_{SD}}(i_1) f_{I_{SD}}(i_2) di_1 di_2.$$

Since the variates I_{SD_1} and I_{SD_2} are independent, knowing that the resulting PDF of their sum I_{SD_T} can be determined by using the moment generating function of their corresponding PDFs. An approximate expression for the PDF, $f_{I_{SD_T}}(i)$, of the combined variates can easily be derived as

$$f_{I_{SD_T}}(i) \approx \frac{a_{SD}^2 \Gamma(b_{SD}) \Gamma(b_{SD} + b_{SR})}{(a_{SR})^{-1} b_{SR} \Gamma(2b_{SD} + b_{SR})} i^{2b_{SD}+b_{SR}-1}.$$

The closed-form asymptotic solution for the BER, P_b^{SD}, is obtained as

$$P_b^{SD} \doteq \frac{a_{SD}^2 a_{SR} \Gamma(b_{SD}) \Gamma\left((1 + 2b_{SD} + b_{SR})/2\right)}{b_{SR}(2b_{SD} + b_{SR}) \Gamma\left((2b_{SD} + 1)/2\right)} 2^{\frac{1}{2}(b_{SR}-2b_{SD})} (\gamma\xi)^{-\frac{1}{2}(2b_{SD}+b_{SR})}.$$

Error-rate performance analysis III

- The BER corresponding to the S-R link is given by

$$P_b^{SR} = \int_0^{\infty}\int_0^{\infty} Q\left(\sqrt{\gamma\xi}(i_1+i_2)\right) F_{I_{SD}}(i_1) f_{I_{SR}}(i_1) f_{I_{SR}}(i_2)\, di_1\, di_2 .$$

The closed-form asymptotic solution for the BER, P_b^{SR}, is obtained as

$$P_b^{SR} \doteq \frac{a_{SR}^2 a_{SD}\Gamma(b_{SR})\Gamma\left((1+2b_{SR}+b_{SD})/2\right)}{b_{SD}(2b_{SR}+b_{SD})\Gamma\left((2b_{SR}+1)/2\right)} 2^{\frac{1}{2}(b_{SD}-2b_{SR})}(\gamma\xi)^{-\frac{1}{2}(2b_{SR}+b_{SD})}.$$

- The success probability, $P_b^{SR_1}$, corresponding to the S-R link can be obtained as

$$P_b^{SR_1} = \int_0^{\infty}\int_0^{\infty}(1-P_b^{SR}(I_{SR_1}, I_{SR_2}))F_{I_{SD}}(i_1) f_{I_{SR}}(i_1) f_{I_{SR}}(i_2)\, di_1\, di_2 \doteq \int_0^{\infty} F_{I_{SD}}(i) f_{I_{SR}}(i)\, di.$$

and the corresponding closed-form asymptotic solution can be seen in

$$P_b^{SR_1} \doteq \frac{\varphi_{SR}^2\varphi_{SD}^2 G_{5,5}^{4,3}\left(\frac{\alpha_{SR}\beta_{SR}A_{SD}L_{SD}}{\alpha_{SD}\beta_{SD}A_{SR}L_{SR}}\middle|\begin{array}{c}1-\varphi_{SD}^2, 1-\alpha_{SD}, 1-\beta_{SD}, 1, \varphi_{SR}^2+1\\ \varphi_{SR}^2, \alpha_{SR}, \beta_{SR}, 0, -\varphi_{SD}^2\end{array}\right)}{\Gamma(\alpha_{SR})\Gamma(\alpha_{SD})\Gamma(\beta_{SR})\Gamma(\beta_{SD})}.$$

Error-rate performance analysis IV

The closed-form asymptotic solution for the BER, P_b^{RD}, is obtained as

$$P_b^{RD} \doteq \frac{a_{RD}^2 \Gamma(b_{RD}) (\gamma\xi)^{-\frac{1}{2}(2b_{RD})}}{2^{b_{RD}+1} b_{RD}}.$$

- The average BER expression corresponding to the PS-RC cooperative protocol can be simplified as follows

$$P_b = P_b^{SD} + P_b^{\mathrm{SRD}} \doteq \begin{cases} P_b^{SD}, & b_{\min} = 2b_{SD} + b_{SR} \\ P_b^{SR}, & b_{\min} = 2b_{SR} + b_{SD} \\ P_b^{SR_1} \cdot P_b^{RD}, & b_{\min} = 2b_{RD} \end{cases}$$

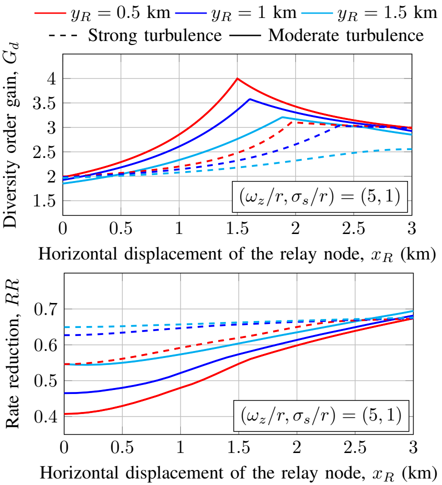
where $b_{\min} = \min\left(2b_{SD} + b_{SR}, b_{SD} + 2b_{SR}, 2b_{RD}\right)$.

Diversity order gain, G_d

$$G_d = \min\left(2b_{SD} + b_{SR}, b_{SD} + 2b_{SR}, 2b_{RD}\right) / b_{SD}.$$

Contents

Diversity order gain and average rate-reduction



✓ The condition $\varphi^2 > \beta$ is satisfied for each link.

❑ System configuration

Parameter	Symbol	Value
S-D link distance	d_{SD}	3 km
Wavelength	λ	1550 nm
Normalized beam width	ω_z/r	5
Normalized jitter	σ_s/r	1

❑ Weather parameters

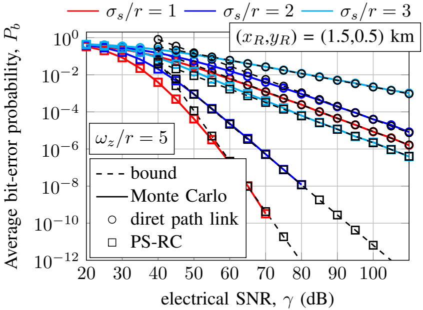
Conditions	Visibility (km)	$C_n^2 \times 10^{-14}\ m^{-2/3}$
Haze	4	2 (Moderate turb.)
Clear	16	8 (Strong turb.)

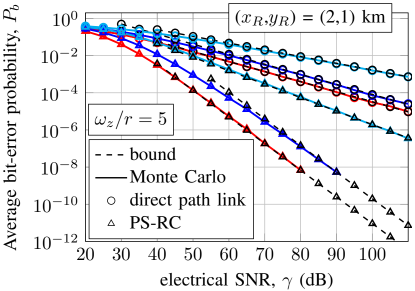
✓ The diversity order gain is always greater than 1.75, achieving a value of 4.

✓ A higher robustness is obtained when time-diversity is used in all links.

✓ The average rate-reduction decreases as source-relay link increases.

Error-rate performance





- System configuration

Parameter	Symbol	Value
S-D link distance	d_{SD}	3 km
Wavelength	λ	1550 nm
Rectangular pulse shape	ξ	1
Normalized beam width	ω_z/r	5
Normalized jitter	σ_s/r	{1, 2, 3}

- Weather parameters

Conditions	Visibility (km)	$C_n^2 \times 10^{-14}\ m^{-2/3}$
Haze	4	2 (Moderate turb.)
Clear	16	8 (Strong turb.)

✓ Direct path link is included as a benchmark and Monte Carlo simulation results are also included.

✓ These results corroborate an excellent agreement with previous figure.

✓ There is a perfect match between asymptotic results and simulation results.

Concluding remarks

- ✓ Cooperative communications can improve the error-rate performance without much increase in hardware.
- ✓ Error-rate performance depends on the relay location as well as pointing error effects.
- ✓ A relevant increase of the diversity gain is achieved when time-diversity is used in all links.
- ✓ A greater robustness is achieved regardless of the relay location and the presence of pointing errors.
- ✓ There is a perfect match between asymptotic results and simulation results.

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Cooperative strategy using time-diversity

Symbol	t_1	t_2	t_3	t_4	$\cdots$	t_n	t_{n+1}	t_{n+2}	t_{n+3}	t_{n+4}	$\cdots$	t_l	t_{l+1}
1	$S \to D$				$\ldots$	$S \to D$					$\ldots$		
2		$S \to D$			$\ldots$		$S \to D$				$\ldots$		
3			$S \to R$		$\ldots$			$S \to R$	$R \to D$		$\ldots$	$R \to D$	
4				$S \to R$	$\ldots$				$S \to R$	$R \to D$	$\ldots$		$R \to D$
$\vdots$													

- When $I_{SD} > I_{SR}$: Direct transmission to the destination node, by using RC of 2.
- When $I_{SD} < I_{SR}$: Cooperative transmission.

- ➥ The data received from the source node at the destination node as well as at the relay node are stored in a buffer for further detection. A block-fading later, the source node repeats the bit sequence transmitted, not being necessary to perform another selection when the source node is repeating the data.
- ➥ Both destination and relay node are able to detect the received information from the source node in both block-fading, establishing in this manner repetition coding.
- ➥ The relay node resends within the next block-fading the data sent in previous block-fading to the destination node.