PERFORMANCE ANALYSIS OF CCR BASED DISTRIBUTED SENSOR NETWORK BASED ON OPTICAL WIRELESS COMMUNICATION

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The following faculty members have examined the final copy of this thesis for form and content, and recommended that it can be accepted in partial fulfillment of the requirement for the degree of Master of Science with a Major in Electrical Engineering

Kamesh Namuduri, Committee Chair

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DEDICATION

To my parents

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor Dr. Kamesh Namuduri for his constant encouragement and supports during this thesis work. I always remember one of his valuable speeches- "It is always easy to find reasons not to do something great, but it is always hard to find reasons to do that great thing", which I think actually motivated me to do this thesis research work.

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ABSTRACT

In this thesis, we present the impact of backscattering induced crosstalk on the bit-error-rate (BER) performance of a corner cube retro-reflector (CCR) based distributed sensor network system which is based on optical wireless communication. A CCR, which consists of three flat glass plates, can send information back to the base transceiver. We study the BER for different transmitted optical powers. The photodiode at the global transceiver combines all the received signals and following that a decision circuitry makes a hard decision based on an adaptive decision threshold. It is observed that the BER decreases with the increment of the number of CCRs. This thesis also reveals that there is a power penalty suffered by the system due to the type of transceiver used in this system. The limiting values of the link range (horizontal distance between the global transceiver and the CCRs) and the imaging receiver pixel sensitivity factor are determined at a BER of 10^{-9}. Mathematical results show that the power penalty increases for about 2 watts for a decrement in the pixel sensitivity factor of about 0.5. It is also found that the system will get an improved BER by increasing the number of CCR.

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LIST OF SYMBOLS

d_c	Effective diameter of CCR (not tilted) in meter
d_l	Effective diameter of lens (not tilted) in meter
d_0	Vertical distance between the axis of laser and receiver lens in meter
d_c	Effective diameter of CCR (not tilted) in meter
D_T	Laser effective diameter in meter
D_R	Receiver aperture diameter in meter
$erfc(x)$	Complementary error function of variable x
fact	Fraction of camera pixel area that is active
G	Gain of the preamplifier at the receiver
R	Load resistance in ohms
Rc	Effective reflectivity of the CCR
T	Absolute temperature in Kelvin
T_l	Effective transmission of camera lens
T_f	Optical filter transmission
v	Optical frequency of the received signal
β_A	Backscattering cross-section for aerosol
β_M	Backscattering cross-section for molecules
θ_f	Semi-angle of illuminated field
θ_c	Angle between laser and axis of the link
θ_l	Angle between axis of the link and direction of camera lens
Z	Link range

LIST OF ABBREVIATIONS

BER	Bit Error Rate
CCR	Corner Cube Retro-reflector
CDSN	CCR Based Distributed Sensor Network
FSO	Free Space Optical Communication
LDPC	Low Density Parity Check
LOS	Line of Sight
VFC	Virtual Fusion Center
WSN	Wireless Sensor Network

CHAPTER 1

Introduction

Wireless sensor networks (WSN) and free space optical (FSO) communication [1] both have gained significant attraction in 21'st century's communication era because of their cost-effective nature and high bandwidth access technique. Despite the major advantages of wireless sensor networks like distributed control, network scalability, simple setup, its widespread use is being hampered by several challenges like limitations in power, memory, throughput, fading problem, wireless channel noise etc. Specially power efficiency has become an important challenge while deploying this type of sensor network in some places like battle field, remote areas. The sizes of wireless sensors are also a major drawback. In order to overcome these issues Teramoto *et al.* [2] first proposed corner cube retro-reflector (CCR) based distributed sensor network system which employs passive free space optical wireless communication. In this type of system, the transmitting optical laser is housed only in the global decision node/ global transceiver station. The sensor nodes are equipped with very tiny CCRs, first introduced by a group of researchers at the University of California, Barkley [3],[4]. This type of passive optical communication seems to be more attractive than the active optical communication not only for negligible power consumption but also for the reason that they do not need any physical layer beam-steering protocol.

1.1 Objectives of the Thesis

In this thesis, we study a CCR based distributed sensor network (CDSN) employing passive optical wireless transmission medium. In this type of system, the global decision center/global transceiver station contains an active optical laser which actually acts as an interrogating laser beam source to the system.

The transceiver station also has a receiving lens followed by the image sensor array which is used to receive the reflected beams from the CCRs. At the global transceiver the transmitted laser beam from the active laser can become a crosstalk factor to the received signal at the imaging receiver, being backscattered by the aerosol or molecules in the atmosphere. In the presence of fog and haze the received signal power decreases and the backscattered crosstalk factor becomes more dominant [8]. This has driven us to derive the analytical model of bit-error-rate (BER) of this type of sensor system accounting the backscattered crosstalk. The limiting parameters of the link range and the pixel sensitivity factor of the imaging receiver, to achieve a tolerable BER, have also been investigated. Another important objective of this thesis is find out how multiple CCRs help the receiver to have a low bit-error-rate.

1.2 Thesis Overview

The remaining chapters of this thesis are organized as follows:

In chapter 2, the literature review for this thesis is presented.

In chapter 3, the concepts of corner cube retro-reflector (CCR) and the architecture of the CCR based distributed optical wireless sensor network are described. The mathematical model of the bit-error-rate (BER) of a particular CCR based distributed sensor network system is also analyzed in this chapter. The typical parameters used in the simulation are also presented in this chapter.

In chapter 4, simulation results are presented with detail discussion. Performance results are compared for different link ranges and pixel sensitivity factors.

Chapter 5, summarizes the results of the research works and gives further research directions.

In Appendix A, the mathematical model for the average received optical power and backscattered optical power is presented.

CHAPTER 2

Literature Review

In [5], Karakehayov presented a low power design technique for CCR based dust motes which was mentioned as "Zero power technique". In [6], Deng *et al.* showed a free space optical communication system with a transmitter and receiver array. It was shown in that research that as the number of laser transmitter increases, the BER decreases. The major disadvantage of this approach is that in this model the receiving end will also have to have transmitting laser array to transmit signals. Navidpour *et al.* [7] investigated the bit-error-rate performance of a conventional FSO link with spatial diversity over log-normal atmospheric turbulence fading channels. Arnon *et al.* [8][9] first showed the bit-error-rate of a FSO link considering the backscattering induced crosstalk. The conventional active optical transmission system was used in their study to find out the detail BER nature. Mutaz *et al.* [10] first proposed an LDPC like wireless sensor network where a sum-product like algorithm is designed to exchange information between sensor nodes and to reach a global decision in binary hypothesis testing. Tanner graph is utilized in their model to implement message passing between sensor nodes. An irregular structure of the parity check matrix is used to model the network structure in their work. However, though this type of network is efficient in achieving a credible global decision , still it has the impairments of typical wireless sensor networks. Moreover, as in this type of network, some sensor nodes are supposed to send the sensed signal to multiple decision centers/ fusion centers, power budget might be a major constraint to deploy this type of topology.

CHAPTER 3

Architecture and BER performance of the system

In this chapter, the architecture of a CCR based distributed sensor network (CDSN) is presented. A mathematical model, to evaluate the bit-error-rate (BER) performance of this system, is also developed in this chapter by considering the backscattered noise sources.

3.1 CCR based distributed sensor network

The network structure which has been studied in this work is a CCR based distributed wireless sensor network (CDSN). In a typical CDSN, the sensor nodes contain CCRs and the transceiver station contains both the active laser and the imaging receiver. The communication medium between the sensor node and the transceiver is optical wireless.

The CCRs normally occupy cubic-millimeter area and consume power in the μ *watt* range. In this model, each transceiver is equipped with one active optical laser which is used to transmit an on-off-keyed (OOK) signal and also with an optical receiver. The receiver at the transceiver contains one optical lens which is chosen to have a large entrance aperture to increase the captured power from all the CCRs. This lens is followed by a CMOS image sensor array. The transmitting laser is pulsed periodically in synchronization with the image sensor frame clock. The laser is situated at a vertical distance of d_0 above the imaging receiver axis of the global transceiver as shown in Fig. [3.1]. In this work, the imperfection in the CCR has been neglected, also the atmospheric attenuation and ambient light from the atmosphere have not been considered . The transmitting laser which is housed at the virtual fusion center continuously emits an interrogating laser beam which has a power P_t and uniformly illuminates at a semi-angle of θ_f. The horizontal distance between the interrogating transmitting laser and the sensor nodes is denoted as Z. The transmitting laser illuminates a field with a diameter d_f. The CCR has effective diameter d_c when it is aligned with respect to the link axis. In the case where the capture area is not aligned with respect to link axis, the corresponding irradiance becomes proportional to the cosine of θ_c which is the angle between the incident axis and plane of sensor node. The lens of the imaging receiver has an effective diameter d_L and a transmission T_L. The imaging receiver has a total of 10^5 image pixels but not all of them are light sensitive. The fraction of light sensitive region to light insensitive region is denoted as f_{act}, which is actually an indicator of the sensitivity of the camera pixel to the light intensity. The imaging receiver is followed by an optical bandpass filter, which has a bandwidth of $\Delta\lambda$ and a transmission T_f, to filter out the required bandwidth from the noise. The responsivity, R of the photodetector can be defined as the ratio between the photocurrent and the incident optical power. It is assumed that the optical axis of the transmitted laser beam and the axis of the receiver field of view are in parallel to each other and $\phi_T > \phi_R$. The receiver field of view (FOV) and the transmitter's transmitting cone intersect each other at a distance z_0 from the global transceiver. The intersection is totally overlapped from a distance z_f to infinity. The receiver telescope aperture diameter and field of view are expressed as D_R ($D_R = d_l$) and ϕ_R respectively. For the distance $z_0 < z < z_f$, there is some region where the receiver can receive some portion of the transmitted beam.

A large number of sensor nodes can be reached by the transmitting laser beam by making the FOV of the transmitting laser fairly large enough. The sensor nodes consists of dust motes which are nothing but CCRs. CCRs do not have any active optical laser power. CCRs, consisting of three orthogonally placed mirrors as shown in Fig. [3.2], mainly operate in two manners. When the CCRs have a signal bit "1" to send to the global transceiver the mirrors are kept as they are, so that the entering light bounces off each surface and eventually reflects back to the global transceiver parallel to the direction it entered the CCR. In case of a "0" bit to send to the global transceiver, the mirrors are turned slightly (consuming a power lower than 1nJ/bit) so that no light is reflected back to the global transceiver [5]. This is the the reason for which in this type of system

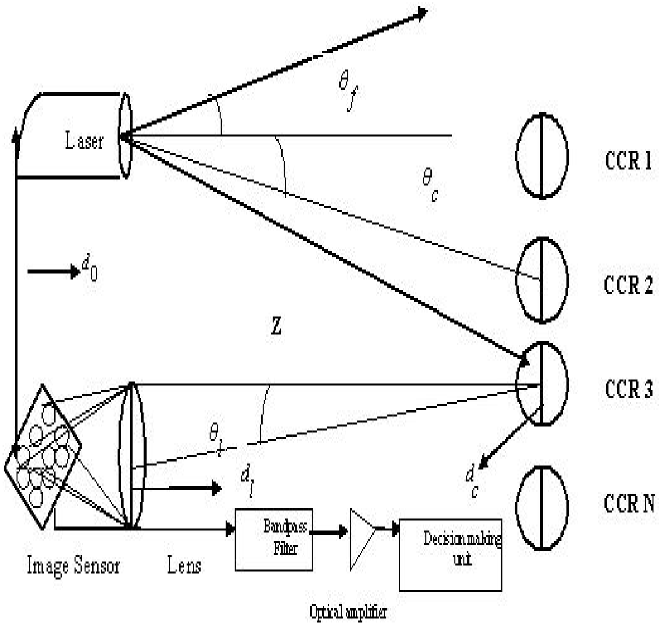

Fig. 3.1: Typical structure of CCR based sensor network system.

the laser is only situated in the transmitting system which continually emits the interrogating laser. The CCR reflectivity can be modulated by actuating one of the mirrors. The reflected laser beam is received by an optical telescope and after receiving it is pre-amplified by an amplifier and converted to the electrical signal by a photodiode. The central transceiver can transmit data to the CCRs at a bit rate of several kbps. One important specification for this type of system is the line of sight (LOS), a non-line-of-sight can make the transmitted and reflected beam to be scattered over a wide range of area.

3.2 Bit-error-rate (BER) performance

In this section, the major noise sources that impact the received signal at the receiver are discussed. The optical preamplifier amplifies the received signal with gain, G. After amplification, the optical signal is converted into electronic current by a photodiode with responsivity R which is expressed as, $R = \frac{e\eta}{hv}$, where η denotes the quantum efficiency of the photodiode, e defines the electron charge, h defines the Plank's constant and v is the optical frequency of the received power. The expected received signal power is defined as P_R, which might be degraded

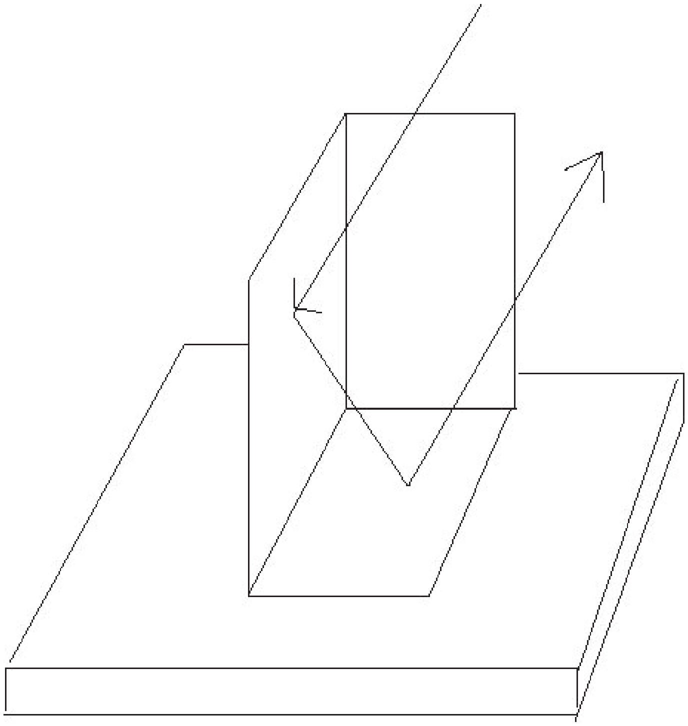

Fig. 3.2: Typical structure of corner cube retroreflector (CCR).

due to additive noise components. An optical bandpass filter with a width of Δv is applied between the optical image receiver and the preamplifier to narrow down the bandwidth of the received optical power.

At the optical receiver, which is located at the global transceiver, the received signal power from the dust mote CCR is degraded by the backscattering-induced crosstalk which is coming from the transmitting laser located also at the global transceiver. The optical preamplifier also adds some other noise factors like signal shot noise, dark current noise, background noise, thermal noise and amplified spontaneous emission (ASE) noise etc to the received signal. It is assumed that, these noise sources are not correlated and they are independent of each other. The expected received signal as well as the backscattered signal can be either a "0" or a "1". The noise associated with the two possibilities is different in the presence of the backscattered signal. For simplicity, the backscatter channel is assumed to have a memory of one symbol. The backscattered symbol, scattered from the transmitter, is actually scattered from the previous symbols and could be significantly attenuated while propagating through the intersection cone. The combination of desired received symbol and the backscattered symbol can be described as four different choices: 1)signal="1" and backscatter="0" 2)the reverse

3)both "1" and 4)both "0". The noise variances which correspond to these four combinations can be defined as $\sigma^2_{m\_n}$, where m can take either a bit "0" or "1" and n can also take either a bit "0" or "1". The noise variance $\sigma^2_{m\_n}$ actually represents the variance when a bit m or bit n gets interfered with each other.

Substitution of practical values for all noise terms shows that optical amplifier noise dominates all other sources.

In clear weather, the radiated signal power should be significant and as a result the interference of amplified spontaneous emission (ASE) and background noise is significant. In this case, the interference of ASE and backscattered noise is negligible. During fog and haze, the backscattered signal power should be dominant making the interference of ASE and backscattered power to be dominant. In this case, the interference of ASE and background noise becomes negligible.

After receiving the optical power by the imaging receiver lens, it is converted to an electronic signal $s(t)$ by the photodiode. At this point, the decision circuitry decides whether the transmitted was either "1" or "0" with a decision threshold. It is assumed that the apriori probabilities of bit "1" and "0" are to be equiprobable that is, $P(1) = P(0) = \frac{1}{2}$.

The received optical signals, which are reflected from all the CCRs and which are in the field of view of the active laser, are received by a single photo-detector at the transceiver. After receiving the combined reflected beam, the photo-detector takes a hard decision based on an adaptive decision threshold, i_{D_total}. The principle behind this hard decision is, if the total received power (reflected laser power along with the backscatterd optical power from the transmitting laser) at the photo-detector is lower than the adaptive decision threshold then the received bit is assumed as "0", otherwise it is assumed as "1".

Then the bit-error-rate (BER) of a CCR based optical wireless communication link can be expressed as:

$$\begin{aligned} BER = P(0)P(s|0)P(P_{R\_total} \geq i_{D\_total}|0, N) + \\ P(1)P(s|1)P(P_{R\_total} \leq i_{D\_total}|1, N) \end{aligned} \tag{3.1}$$

Here P_{R_total} is the total received power at the imaging receiver. The conditional probability of bit "0" and "1" are expressed as, $P(s|"0")$ and $P(s|"1")$ respectively. The adaptive decision threshold for the total received power is expressed as, i_{D_total}. Eq.[3.1] can further be expanded as,

$$BER = P(0)\{P(s=0|bs=0)+(s=0|bs=1)\}P(P_{R\_total} \geq i_{D\_total}|0,N) \quad (3.2)$$
$$+P(1)\{P(s=1|bs=0)+(s=1|bs=1)\}P(P_{R\_total} \leq i_{D\_total}|1,N)$$

Here $P(s=0|bs=0)$ represents the conditional probability when the received signal is "0" and the backscattered bit is "0", $P(s=0|bs=1)$ represents the conditional probability when the received signal is "0" and the backscattered bit is "1", $P(s=1|bs=0)$ represents the conditional probability when the received signal is "1" and the backscattered bit is "0" and $P(s=1|bs=1)$ represents the conditional probability when the received signal is "1" and the backscattered bit is "1".

After simplifying the BER can be expressed as,

$$\begin{aligned} BER_{worstcase} = \frac{1}{8}[&\{Q(\frac{1}{\sqrt{2}}\frac{i_{sig1}+i_{bs0}-i_D}{\sigma_{1\_0}}) * Q(\frac{1}{\sqrt{2}}\frac{N-i_{D\_total}}{\sigma_{1\_0\_total}})\} \\ &+\{Q(\frac{1}{\sqrt{2}}\frac{i_D-i_{bs0}-i_{sig0}}{\sigma_{0\_0}}) * Q(\frac{1}{\sqrt{2}}\frac{i_{D\_total}}{\sigma_{0\_0\_total}})\} \\ &+\{Q(\frac{1}{\sqrt{2}}\frac{i_{sig1}+i_{bs1}-i_D}{\sigma_{1\_1}}) * Q(\frac{1}{\sqrt{2}}\frac{N-i_{D\_total}}{\sigma_{1\_1\_total}})\} \\ &+\{Q(\frac{1}{\sqrt{2}}\frac{i_D-i_{bs1}-i_{sig0}}{\sigma_{0\_1}}) * Q(\frac{1}{\sqrt{2}}\frac{i_{D\_total}}{\sigma_{0\_1\_total}})\}] \end{aligned} \quad (3.3)$$

Where $Q(x)$ is a complementary error function expressed as, $Q(x) = \{1/\sqrt{2\pi} \int_x^\infty e^{-(u^2/2)}du\}$, i_{bs1} is backscattering crosstalk current for bit "1" given by, $i_{bs1} = \{R\ P_{bs}\}$, i_{sig1} is the photocurrent for received bit "1" where i_{sig0} is the photocurrent for received bit "0". The total adaptive decision making threshold current i_{D_total} can be expressed as:

$$i_{D\_total} = \frac{\sigma_{0\_1\_total}(N * i_{sig1}) + \sigma_{1\_1\_total}(N * i_{sig0})}{\sigma_{0\_1\_total} + \sigma_{1\_1\_total}} \quad (3.4)$$

The total four noise variances received at the receiver can be expressed as :

$$\sigma^2_{1\_0\_total} = \sigma^2_{th} + 2eR\{N * (P_R + P_{bs0})\}B \quad (3.5)$$

$$\sigma^2_{0\_0\_total} = \sigma^2_{th} + 2eR(N * P_{bs0})B \quad (3.6)$$

$$\sigma^2_{1\_1\_total} = \sigma^2_{th} + 2eR\{N * (P_R + P_{bs1})\}B \quad (3.7)$$

$$\sigma^2_{0\_1\_total} = \sigma^2_{th} + 2eR(N * P_{bs1})B \quad (3.8)$$

Here e represents the electronic charge and σ_{th}^2 is the variance of the thermal noise in the detector which can be expressed as [15]:

$$\sigma_{th}^2 = \frac{4kTB}{R_L} \tag{3.9}$$

In (3.9), T denotes the receiver temperature, B denotes the electrical bandwidth of the receiver and R_L denotes the receiver front end load.

CHAPTER 4

Experiments, results and discussion

Following the mathematical model presented in section 3.2, the BER of a CCR based optical wireless communication system is presented in this section taking into account the effect of backscattering induced crosstalk. We analyze the BER of the global transceiver for several values of input power. For simplicity, it is assumed that all the CCRs experience the same environment and there is no roughness in the glass planes of the CCRs. The parameters used in the numerical evaluation are listed in Table. 4.1.

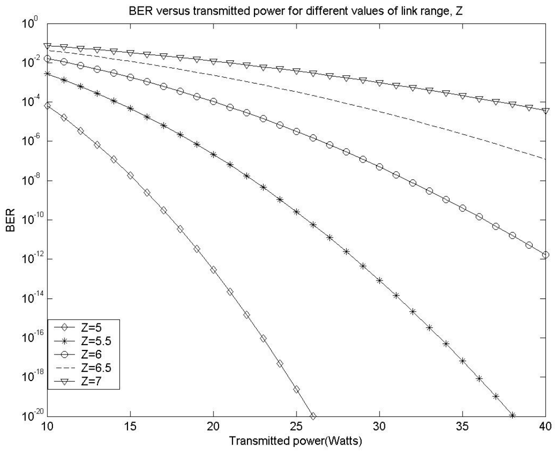

Fig. 4.1: BER versus transmitted powers in watts for different values of link range, Z (m)

The plots of BER versus transmitted power for different values of link range, Z are shown in Fig.4.1 where the number of CCR is three. The transmitting power was varied from 10 to 43 watts. It is observed from the plots that the system suffers significant power penalty due to the increment in the link range.

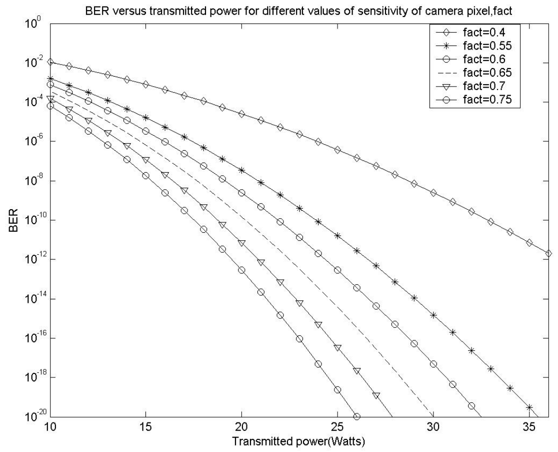

Fig. 4.2: BER versus transmitted power in watts for different values of sensitivity of the camera pixel to the light intensity, f_{act}

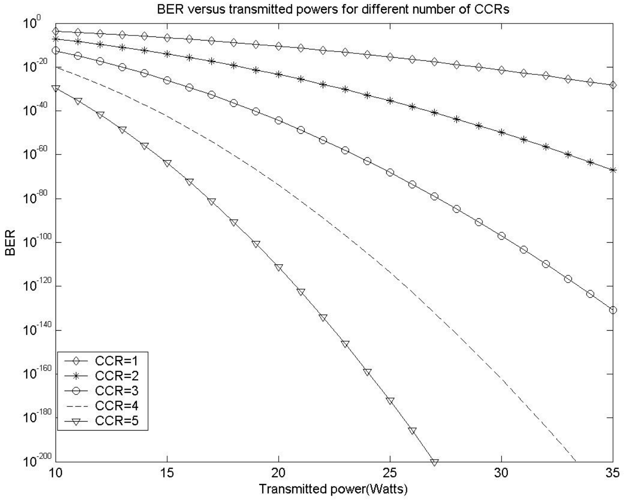

Fig. 4.3: BER versus transmitting powers in watts for different number of CCRs

It is noticeable from the plots that due to an increment in the link range of about 0.5 m the transmitting laser will require an extra power of $\sim$ 10 *watts*. It is also seen from the plots that to keep an bit-error-rate always below 10^{-9}, the link range should not be chosen beyond 6 m. In Fig. [4.2], the BERs are plotted as a function of the light sensitive fraction of each pixel, f_{act} for different transmitted powers with a link range of 5 m and for three CCRs. It is observed from the plots that the system faces a power penalty of $\sim$ 2 watts when the pixel sensitivity factor decreases by 0.5. These plots also demonstrate that the BER decreases as the pixel sensitivity factor increases and becomes abruptly high for $f_{act} \approx 0.4$. We can also see the transmitting power increases, as the pixel sensitivity factor decreases, to achieve a specific bit-error-rate. Fig. 4.3 shows BER versus transmitted power for different number of CCRs for a link range of 5 m and for a pixel sensitivity factor of 0.75. The plots demonstrate that the BER improves as the number of CCR increases. From the plots it is also evident that the transmitter can get a power gain of ~ 10 $watts$ by increasing the number of CCR as one to obtain a specific bit-error-rate. It is also observed that to get a bit-error-rate always lower than 10^{-9} the system should be chosen with more than one CCR.

4.1 Numerical values used in the simulation

Table 4.1: Values used for variables used in the numerical example

Variables	Typical Value
d_c	5×10^{-4} m
d_l	0.1 m
R_c	0.85
T_l	0.8
T_f	0.8
f_{act}	0.75
R	0.995 A/W
ϕ_R	7 $degree$
ϕ_T	1 $degree$
λ	1550 nm
Z	1000 m
p_{bg}	0.8 $w/m^2.\ nm$
R_{bg}	0.3
Δv	1 nm
e	1.602×10^{-19} coulombs
h	6.6261×10^{-34} J.s
η	0.8
v	1.9355×10^{14} Hz
F_n	4 dB
G	30 dB
d_0	0.52 m
D_T	0.008 m
α	7×10^{-3} m^{-1}
D_R	0.762 m
$\widehat{\beta}_A$	$\approx 6 \times 10^{-4} m^{-1} sr^{-1}$
K	1.380658×10^{-23} $m^2 kg s^{-2} k^{-1}$
T	300^0 K
R_L	60 Ω

CHAPTER 5

Conclusions and Future Work

This chapter summarizes the thesis works and gives future research directions in CCR based opto-wireless sensor network systems .

5.1 Conclusions

In this thesis, we present the architecture of a corner cuber retro-reflector (CCR) based distributed sensor network system and then we present a theoretical analysis to evaluate the bit-error rate (BER) performance considering the backscattering induced crosstalk. The impact of some parameters like link range and pixel sensitivity factor, considering the backscattered induced crosstalk, on the BER performance are evaluated. Some limiting values of link range and pixel sensitivity factor have been investigated to acquire a BER always lower than 10^{-9} for multiple CCRs. Results indicate that the system can have an improved BER by employing multiple CCRs as the sensor nodes. The results presented in this thesis will find applications in designing an optical-wireless distributed sensor network employing CCR based passive optical wireless communication link.

5.2 Future Work

Some possible future research works related to the performance analysis of a CCR based distributed sensor network system are as follows.

1. In remote and hazardous locations, where the CCRs might be deployed in a networked fashion, line of sight might not be guaranteed. A non-line-of-sight can severely degrade the BER performance a CCR based sensor network system. Research can be carried out to find out the detail impact

of non-line-of-sight on the BER performance of this type sensor network system.

2. In this thesis we have considered the atmospheric molecules and gases to be the only possible source of backscattered power. This backscattered power might be increased in the presence of dense fog and heavy rainfall. Extensive research need to be done to find the impact of heavy rainfall and dense fog on the backscattered power which might eventually degrade the BER performance.

BIBLIOGRAPHY

BIBLIOGRAPHY

[1] Vincent W.S. Chan *Free space optical communication*, IEEE Journal of Lightwave Technology, vol. 24, No. 12, , pp. 4750-4762,Dec. 2006.

[2] S. Teramoto and T. Ohtsuki, *Optical wireless sensor network system using corner cube retroreflectors*, EURASIP Journal on Applied Signal Processing, pp. 39-44, 2005.

[3] V. S. Hsu, J. M. Kahn and K. S. J. Pister*Wireless communication for smmart dust*, Electronic Research Laboratory Technical Memorandum, The University of California at Barkley, no. M 98/2, Feb. 1998.

[4] L. Z. Zhou, J. M. Kahn and K. S. J. Pister*Cornet-cube retroreflectors based on structure-assisted assembly for free-space optical communication*, IEEE Journal of Minroelectromechanical systems, no. 3, vol. 12, pp. 233-242, June 2003. 1998.

[5] Z. Karakehayov , *Zero-power design for smart dust networks*, First International Symposium on Intelligent Systems, pp. 302-305, Sep. 2002.

[6] Tianping Deng, Yimin Lu and Xiaoxio *Performance evaluation of free space optical commincation system*, IEEE 2005 International Conference on Wireless Communications, Networking and Mobile Computing, vol. 1, , pp. 587-590,Sep. 2005.

[7] S. M. Navidpour, Murat Uysal and M. Kavehrad *BER performance of free-space optical transmission with spatial diversity*, IEEE transactions on Wireless Communications, vol. 8, , pp. 2813-2819,Aug. 2007.

[8] Debbie Kedar and Shlomi Arnon *Backscattering-Induced crosstalk in WDM optical wireless communication*, IEEE Journal of Lightwave Technology, vol. 23, pp. 2023-2030, June. 2005.

[9] Debbie Kedar and Shlomi Arnon *Non-line-of-sight optical wireless sensor network operating in multiscattering channel*, Journal of Applied Optics, vol. 45, pp. 8454-8461, 20 Nov. 2006.

[10] M. Shukair and K. Namuduri, *LDPC like approach for distributed detection in wireless sensor networks*, MS Thesis, Wichita State University, Oct 2007.

[11] J. L. Bufton and R. S. Iyer *Continuous wave lidar measurement of atmospheric visibilty*, IEEE Transactions on Applied Optics, vol. 17, No. 2, , pp. 265-271, Jan. 1978.

[12] Yunbin Song *Optical communication system for smart dust*, MS Thesis, Virginia Polytechnic Institute and State University , Aug 2002.

[13] M. Born and E. Wolf, *Principles of Optics*, Pergamon Press, New York, NY, USA, 6th Edition, 1980.

[14] Sanjoy Dey and Satya Prasad Majumder *Impact of Component Crosstalk on the BER Performance of a WDM Cross-connect Switch based on FBG-OC*, IEEE PacRim 2005, pp.189-192.

[15] Govind P. Agrawal *Fiber-optic communication systems*, 3rd edition.

APPENDIX

APPENDIX A

Mathematical expression for received photocurrent and backscattered optical power

A.1 Average received photocurrent

The irradiance I_r at a distance Z from the interrogating laser can be expressed as [12],

$$I_r = \frac{Power\ of\ the\ CW\ beam}{Area} = \frac{P_t}{\pi(\frac{d_f}{2})^2} = \frac{P_t}{\pi Z^2 tan\theta_f{}^2} \tag{A.1}$$

Then the captured power on the CCR can be expressed as [12],

$$\begin{aligned} P_{cap} &= Irradiance \times effective\ capture\ area \\ &= I_r \times \pi(\frac{d_c}{2})^2 \times cos\theta_c \\ &= \frac{P_t d_c{}^2 cos\theta_c}{4Z^2 tan\theta_f{}^2} \\ &= \frac{P_t d_c{}^2 f_{cap}}{4Z^2 tan\theta_f{}^2} \end{aligned} \tag{A.2}$$

The CCR reflects an average power P_c (by assuming that the probabilities of ones and zeros to be equal) which can be expressed as [12],

$$\begin{aligned} P_c &= P_{cap} \times \frac{1}{2} R_c \\ &= \frac{P_{cap} R_c}{2} \\ &= \frac{P_t {d_c}^2 cos\theta_c}{4Z^2 tan{\theta_f}^2} \frac{R_c}{2} \\ &= \frac{P_t R_c {d_c}^2 cos\theta_c}{8Z^2 tan{\theta_f}^2} \\ &= \frac{P_t R_c {d_c}^2 f_{cap}}{8Z^2 tan{\theta_f}^2} \end{aligned} \tag{A.3}$$

Considering Fraunhofer's diffraction theory, the average intensity at the lens of the imaging receiver can be expressed as [12],

$$\begin{aligned} I_L &= \frac{P_c \pi (\frac{d_c}{2})^2}{Z^2 \lambda^2} \times f_{dif} \\ &= \frac{P_c \pi d_c^2}{4Z^2 \lambda^2} f_{dif} \\ &= \frac{\pi P_t R_c d_c^4}{32 Z^4 \lambda^2 tan^2 \theta_f} f_{cap} f_{dif} \end{aligned} \tag{A.4}$$

Thus the average received photocurrent at the imaging receiver can be expressed as,

$$\begin{aligned} I_{sig} &= I_L T_L \pi (\frac{d_L}{2})^2 f_{act} T_f R \\ &= \frac{\pi^2 P_t d_c^4 d_L^2 T_L T_f R_c R f_{cap} d_{dif} f_{act}}{128 Z^4 \lambda^2 tan^2 \theta_f} \end{aligned} \tag{A.5}$$

A.2 Backscattered optical power

The backscattered optical power can be expressed as [11],

$$P_{bs}(z) = A\zeta(\lambda)[\widehat{\beta}_M(H) + \widehat{\beta}_A(H)].P_t \int_{z_0}^{\infty} exp(-2\alpha(H)z) \frac{\xi(z)}{z^2} dz \tag{A.6}$$

Here $\xi(z)$ is the transmitter/receiver overlap function which takes a value between 0.00 to 1.0. This overlap starts from z_0. This overlap function can be described as [11],

$$\xi(z) = \frac{1}{\pi}\{cosh(\frac{x_T}{d_T}) - (\frac{x_T}{d_T})[1-(\frac{x_T}{d_T})^2]^{0.5} + (\frac{d_R}{d_T})^2 cosh(\frac{x_R}{d_R}) - \frac{x_R d_R}{d_T^2}[1-(\frac{x_R}{d_R})^2]^{0.5} \tag{A.7}$$

where d_T and d_R are the laser beam diameter and field of view diameter respectively which can be expressed as [11],

$$d_T = D_T + ztan(\phi_T) \tag{A.8}$$

$$d_R = D_T + ztan(\phi_R) \tag{A.9}$$

and,

$$\begin{aligned} x_T &= \frac{[(\frac{d_T}{2})^2 - (\frac{d_R}{2})^2 + d_0^2]}{d_0} \\ x_R &= \frac{[(\frac{d_R}{2})^2 - (\frac{d_T}{2})^2 + d_0^2]}{d_0} \end{aligned} \tag{A.10}$$