

**FREEFORM OPTICS AND RECONFIGURABLE  
INTELLIGENT SURFACES FOR MULTI-CELL  
INDOOR VLC SYSTEM**

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# Freeform Optics and Reconfigurable Intelligent Surfaces for Multi-cell Indoor VLC System

by

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*Dedicated to **all my Mothers***

*I am profoundly grateful and indebted to your boundless  
love, sacrifices, support, and prayers,  
for shaping me into who I am today*

# Certificate

This is to certify that the thesis entitled “**FREEFORM OPTICS AND RECONFIGURABLE INTELLIGENT SURFACES FOR MULTI-CELL INDOOR VLC SYSTEM**”, submitted by **DEBLINA SABUI** to the Centre for Sensors, Instrumentation and Cyber Physical System Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**. This thesis is a bonafide record of the research carried out by her under my guidance and supervision. In my opinion the thesis has reached the standards fulfilling the requirements for the submission relating to the degree

The results contained in this thesis have not been submitted in part or in full to any other Institute or University for the award of any degree or diploma to the best of our knowledge.

**Prof. Gufran S. Khan**

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Date:

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*“Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.” -Marie Curie*

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# *Abstract*

Visible Light Communication (VLC), which uses visible light (400–800 THz) to transmit data, is considered a breakthrough technology catering to the surging demand for high-speed data connectivity. In this thesis, multi-cell indoor downlink VLC system has been studied for performance enhancement. In multi-cell framework, multiple optical atto-cells are strategically deployed to ensure uniform illumination along with efficient data transmission. However, the efficacy of such systems is hindered by a critical issue, inter-cell interference (ICI). ICI results from the overlapping channels of the adjacent atto-cells. This interference leads to poor signal-to-interference-plus-noise ratio (SINR). Additionally, the reliability of VLC depends on the presence of line-of-sight (LoS) links between the access point and the user. Any obstruction in between results in interruption of communication. Moreover, for adaptation of the VLC technology in mass market, the receiver system should be compact in size and integrable with in smart gadgets.

In this context, this thesis primarily focuses on the development of freeform based optical front-end for receiver system. Freeform surfaces have no symmetry around any axis of rotation. It offers more degrees of freedom, also has the ability to accommodate wide field as compared to the conventional symmetrical optics. Use of freeform surfaces reduces number of components and overall size of the system. The rotationally non-symmetric freeform has been proposed in this thesis to develop an off-axis quadrilateral field of view for receiver front-end, which mitigates ICI considerably by spatially separating channels from the adjacent cells.

The first part of the thesis work delved in designing freeform based receiver namely freeform diversity receiver (FDR). FDR has four freeform surface element (FSE) and each of FSE has off-axis FOV. The use of freeform optics reduces the dimension of receiver compared to the other existing multi-cell VLC receivers. The evaluation of the proposed FDR system at different operational conditions has shown it has superior SINR performance. In order to enhance the communication performance further, the receiver architecture is updated with a modified design of FDR (MFDR).

The second stage of the research work deals with the fabrication, metrology and the experimental validation of the previously proposed FSE. Single point diamond turning

(SPDT) machine and profilometry have been used for fabrication and characterization respectively. The effects of FSE form error and roughness on the SINR is evaluated and the findings are used as feedback to the machining process. One receiving unit prototype has been prepared with fabricated profile and experimentally validated on test bench. The research work is further extended to reduce optics size. A novel design of freeform-Fresnel surface has been proposed to replace FSE. The total height of freeform-Fresnel element is much smaller than FSE. The first trial freeform-Fresnel element is fabricated using SPDT and the challenges related to its development and alignment process is reported in this Section. Afterwards, a design of monolithic freeform-Fresnel has been presented with SINR performance. The idea of monolithic profile has eliminated the need of orthogonal alignment of individual element.

This thesis has also explored the utility of emerging reconfigurable intelligent surfaces (RIS) to establish alternating reflected links in the absence of LoS link. RIS is tunable passive elements made of primarily metasurface or mirrors array and has the capability to manipulate the orientation of reflected light in desired direction.

This work also explored the use of RIS in multi-cell environment to enhance communication performance. The SINR performance is studied for different FOV photodiodes (PD) with RIS, no-RIS during blocking and no blocking condition. Integration of RIS has improved SINR on a certain zone on the communication floor even in presence of blockage.

In the final phase of the thesis, the impact of FDR and MFDR, which are mainly off-axis FOV receiver system, have been evaluated during light path blockages in RIS assisted multi-cell indoor system. SINR performance, data rate, coverage probability of PD, FDR, and MFDR have been compared to identify the most suitable receiver system for the aforesaid application. Also, the relationship with RIS quantity, and RIS positions have been studied in presence of different receiver geometries. Finally, the influence of RIS on indoor illumination level has been reported.

The results obtained in this thesis confirm that the introduction of freeform optics and reconfigurable intelligent surfaces are attractive solutions for ICI mitigation and blockage management in multi-cell indoor scenarios.

## सारांश

विजिबल लाइट कम्युनिकेशन (VLC), जो डेटा संप्रेषण के लिए विजिबल लाइट (400-800 THz) का उपयोग करता है, उच्च गति डेटा कनेक्टिविटी की बढ़ती मांग को पूरा करने वाली एक क्रांतिकारी तकनीक मानी जाती है। इस थीसिस में, प्रदर्शन को बेहतर बनाने के लिए मल्टी-सेल इनडोर डाउनलिनक VLC सिस्टम का अध्ययन किया गया है। मल्टी-सेल ढांचे में, एक समान प्रकाश व्यवस्था के साथ प्रभावी डेटा संप्रेषण सुनिश्चित करने के लिए कई ऑप्टिकल एटो-सेल्स को रणनीतिक रूप से तैनात किया जाता है। हालांकि, ऐसे सिस्टम की प्रभावशीलता एक गंभीर समस्या, इंटर-सेल इंटरफेरेंस (ICI) से बाधित होती है। ICI निकटवर्ती एटो-सेल्स के ओवरलैपिंग चैनलों के कारण होता है। यह इंटरफेरेंस सिग्नल-टू-इंटरफेरेंस-प्लस-नॉइज़ अनुपात (SINR) को कम करता है। इसके अतिरिक्त, VLC की विश्वसनीयता एक्सेस पॉइंट और उपयोगकर्ता के बीच लाइन-ऑफ-साइट (LoS) लिंक की उपस्थिति पर निर्भर करती है। इनके बीच कोई भी अवरोध संचार में रुकावट पैदा करता है। इसके अलावा, व्यापक बाजार में VLC तकनीक के अनुकूलन के लिए, रिसीवर सिस्टम का आकार कॉम्पैक्ट होना चाहिए और स्मार्ट गैजेट्स में एकीकृत करने योग्य होना चाहिए।

इस संदर्भ में, यह थीसिस मुख्य रूप से रिसीवर सिस्टम के लिए फ्रीफॉर्म आधारित ऑप्टिकल फ्रंट-एंड के विकास पर केंद्रित है। फ्रीफॉर्म सतहों के चारों ओर किसी भी घूर्णन अक्ष पर कोई समरूपता नहीं होती है। यह अधिक स्वतंत्रता की डिग्री प्रदान करती है और पारंपरिक सममित प्रकाशिकी की तुलना में व्यापक क्षेत्र को समायोजित करने की क्षमता भी रखती है। फ्रीफॉर्म सतहों का उपयोग घटकों की संख्या और सिस्टम के समग्र आकार को कम कर देता है। इस थीसिस में घूर्णन-गैर-सममित फ्रीफॉर्म का प्रस्ताव किया गया है ताकि रिसीवर फ्रंट-एंड के लिए एक ऑफ-एक्सिस चतुर्भुज दृष्टि क्षेत्र विकसित किया जा सके, जो निकटवर्ती कोशिकाओं से चैनलों को स्थानिक रूप से अलग करके ICI को काफी कम कर देता है।

थीसिस के पहले भाग में फ्रीफॉर्म आधारित रिसीवर, जिसे फ्रीफॉर्म डाइवर्सिटी रिसीवर (FDR) कहा जाता है, के डिज़ाइन पर गहराई से अध्ययन किया गया है। FDR में चार फ्रीफॉर्म सतह तत्व (FSE) होते हैं और प्रत्येक FSE का ऑफ-एक्सिस FOV होता है। फ्रीफॉर्म ऑप्टिक्स का उपयोग अन्य मौजूदा मल्टी-सेल VLC रिसीवर्स की तुलना में रिसीवर के आयाम को कम करता है। विभिन्न संचालन स्थितियों में प्रस्तावित FDR सिस्टम का मूल्यांकन करने पर पाया गया कि इसका SINR प्रदर्शन उत्कृष्ट है। संचार प्रदर्शन को और बेहतर बनाने के लिए रिसीवर आर्किटेक्चर को FDR के एक संशोधित डिज़ाइन (MFDR) के साथ अद्यतन किया गया है।

शोध कार्य के दूसरे चरण में पहले प्रस्तावित FSE के निर्माण, मेट्रोलॉजी और प्रायोगिक सत्यापन पर ध्यान दिया गया है। निर्माण और लक्षण वर्णन के लिए क्रमशः सिंगल पॉइंट डायमंड टर्निंग (SPDT) मशीन और प्रोफिलोमेट्री का उपयोग किया गया है। FSE की फॉर्म एरर और रफनेस का SINR पर प्रभाव

का मूल्यांकन किया गया और निष्कर्षों का उपयोग मशीनिंग प्रक्रिया के फीडबैक के रूप में किया गया। एक रिसीविंग यूनिट प्रोटोटाइप को निर्मित प्रोफाइल के साथ तैयार किया गया और टेस्ट बेंच पर प्रायोगिक रूप से सत्यापित किया गया। शोध कार्य को ऑप्टिक्स के आकार को कम करने के लिए आगे बढ़ाया गया है। FSE को बदलने के लिए फ्रीफॉर्म-फ्रेनल सतह का एक नया डिज़ाइन प्रस्तावित किया गया है। फ्रीफॉर्म-फ्रेनल तत्व की कुल ऊंचाई FSE से बहुत छोटी होती है। पहले परीक्षण फ्रीफॉर्म-फ्रेनल तत्व को SPDT का उपयोग करके निर्मित किया गया है और इसके विकास और संरक्षण प्रक्रिया से संबंधित चुनौतियों को इस खंड में रिपोर्ट किया गया है। बाद में, SINR प्रदर्शन के साथ मोनोलिथिक फ्रीफॉर्म-फ्रेनल के एक डिज़ाइन को प्रस्तुत किया गया है। मोनोलिथिक प्रोफाइल के विचार ने व्यक्तिगत तत्व के ऑर्थोगोनल संरक्षण की आवश्यकता को समाप्त कर दिया है।

इस थीसिस ने उभरती हुई पुनः संयोज्य बुद्धिमान सतहों (RIS) की उपयोगिता का भी पता लगाया है ताकि LoS लिंक की अनुपस्थिति में वैकल्पिक परावर्तित लिंक स्थापित किए जा सकें। RIS मुख्य रूप से मेटासर्फेस या मिरर एरे से बने ट्यून करने योग्य निष्क्रिय तत्व हैं और वांछित दिशा में परावर्तित प्रकाश के अभिविन्यास को नियंत्रित करने की क्षमता रखते हैं।

इस कार्य में मल्टी-सेल वातावरण में संचार प्रदर्शन को बढ़ाने के लिए RIS के उपयोग की भी खोज की गई है। RIS, बिना RIS के, अवरोधक और बिना अवरोधक स्थिति में विभिन्न FOV फोटोडायोड्स (PD) के लिए SINR प्रदर्शन का अध्ययन किया गया है। अवरोधक की उपस्थिति में भी संचार फर्श पर एक निश्चित क्षेत्र में RIS के एकीकरण ने SINR में सुधार किया है।

थीसिस के अंतिम चरण में, RIS सहायक मल्टी-सेल इनडोर सिस्टम में प्रकाश पथ अवरोधक के दौरान मुख्य रूप से ऑफ-एक्सिस FOV रिसीवर सिस्टम, FDR और MFDR के प्रभाव का मूल्यांकन किया गया है। SINR प्रदर्शन, डेटा दर, PD, FDR, और MFDR के कवरेज संभावना की तुलना की गई है ताकि उपरोक्त अनुप्रयोग के लिए सबसे उपयुक्त रिसीवर सिस्टम की पहचान की जा सके। इसके अलावा, विभिन्न रिसीवर ज्यामितियों की उपस्थिति में RIS की मात्रा और RIS की स्थिति के साथ संबंध का अध्ययन किया गया है। अंत में, इनडोर प्रकाश स्तर पर RIS के प्रभाव की रिपोर्ट दी गई है।

इस थीसिस में प्राप्त परिणाम पुष्टि करते हैं कि फ्रीफॉर्म ऑप्टिक्स और पुनः संयोज्य बुद्धिमान सतहों का परिचय मल्टी-सेल इनडोर परिदृश्यों में ICI न्यूनीकरण और अवरोध प्रबंधन के लिए आकर्षक समाधान हैं।

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# Abbreviations

<b>ADR</b>	<b>A</b> ngular <b>D</b> iversity <b>R</b> eceiver
<b>AP</b>	<b>A</b> ccess <b>P</b> oint
<b>APD</b>	<b>A</b> valanche <b>P</b> hoto <b>D</b> iode
<b>BER</b>	<b>B</b> it <b>E</b> rror <b>R</b> ate
<b>CCD</b>	<b>C</b> harge <b>C</b> ouple <b>D</b> evice
<b>CCI</b>	<b>C</b> o- <b>C</b> hannel <b>I</b> nterference
<b>CDF</b>	<b>C</b> ummulative <b>D</b> istribution <b>F</b> unction
<b>CMM</b>	<b>C</b> ordinate <b>M</b> easureing <b>M</b> achine
<b>CMOS</b>	<b>C</b> omplementary <b>M</b> etal <b>O</b> xide <b>S</b> emiconductor
<b>CNC</b>	<b>C</b> omputer <b>N</b> umerical <b>C</b> ontrol
<b>EB</b>	<b>E</b> xa <b>B</b> ytes
<b>FDR</b>	<b>F</b> reeform <b>D</b> iversity <b>R</b> eceiver
<b>FOV</b>	<b>F</b> ield of <b>V</b> iew
<b>FSE</b>	<b>F</b> reeform <b>S</b> urface <b>E</b> lement
<b>FSO</b>	<b>F</b> ree <b>S</b> pace <b>O</b> ptical
<b>GB</b>	<b>G</b> iga <b>B</b> ytes
<b>HPBW</b>	<b>H</b> alf <b>P</b> ower <b>B</b> eam <b>W</b> idth
<b>ICI</b>	<b>I</b> nter- <b>C</b> ell <b>I</b> nterference
<b>ICI</b>	<b>I</b> nter- <b>C</b> hannel <b>I</b> nterference
<b>ISI</b>	<b>I</b> ntersymbol <b>I</b> nterference
<b>IRS</b>	<b>I</b> ntelligent <b>R</b> eflecting <b>S</b> urface
<b>LED</b>	<b>L</b> ight <b>E</b> mitting <b>D</b> iode
<b>LD</b>	<b>L</b> aser <b>D</b> iode
<b>Li-Fi</b>	<b>L</b> ight- <b>F</b> idelity
<b>LoS</b>	<b>L</b> ine-of- <b>S</b> ight
<b>MFDR</b>	<b>M</b> odified <b>F</b> reeform <b>D</b> iversity <b>R</b> eceiver

<b>NIR</b>	<b>N</b> ear- <b>I</b> nfrared
<b>OWC</b>	<b>O</b> ptical <b>W</b> ireless <b>C</b> ommunication
<b>PD</b>	<b>P</b> hoto <b>D</b> iode
<b>PMMA</b>	<b>P</b> olymethyl <b>M</b> ethacrylate
<b>RIS</b>	<b>R</b> econfigurable <b>I</b> ntelligent <b>S</b> urface
<b>RU</b>	<b>R</b> eceiving <b>U</b> nit
<b>SBC</b>	<b>S</b> elect <b>B</b> ase <b>C</b> ombination
<b>SINR</b>	<b>S</b> ignal-to- <b>I</b> nterference-plus- <b>N</b> oise <b>R</b> atio
<b>SNR</b>	<b>S</b> ignal-to- <b>N</b> oise <b>R</b> atio
<b>SPAD</b>	<b>S</b> ingle <b>P</b> hoton <b>A</b> valanche <b>D</b> iode
<b>SPDT</b>	<b>S</b> ingle <b>P</b> oint <b>D</b> iamond <b>T</b> urning
<b>TIA</b>	<b>T</b> rans-impedance <b>A</b> mplifier
<b>VLC</b>	<b>V</b> isible <b>L</b> ight <b>C</b> ommunication