REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
15-11-2016	Final Report	1-Aug-2014 - 31-Jul-2016

4. TITLE AND SUBTITLE
Final Report: Multi-Element Free-Space-Optical Modules for Mobile Opportunistic Networking

5a. CONTRACT NUMBER
W911NF-14-1-0531

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

6. AUTHORS
Murat Yuksel

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Nevada - Reno
1664 N Virginia Street
Mail Stop 312
Reno, NV 89557 -0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
65192-NS-RIP.14

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
As the RF spectrum is getting scarcer, there is an urgent need for innovations that will allow new and complementary wireless spectrum bands in both military and civilian settings. Recent research has shown that free-space-optical (FSO), a.k.a. optical wireless, communications is a promising complementary approach to address the exploding mobile wireless traffic demand. The major impediment for using FSO in a mobile setting is the line-of-sight (LOS) alignment requirement. Our existing efforts have pointed to the possibility of employing FSO within the context of mobile ad-hoc networking by handling its mobility and range issues via multi-element and multi-hop

15. SUBJECT TERMS
free-space-optical systems, optical wireless communications, visible light communications

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Murat Yuksel
UU	UU	UU	UU		19b. TELEPHONE NUMBER 775-327-2246

Report Title

Final Report: Multi-Element Free-Space-Optical Modules for Mobile Opportunistic Networking

ABSTRACT

As the RF spectrum is getting scarcer, there is an urgent need for innovations that will allow new and complementary wireless spectrum bands in both military and civilian settings. Recent research has shown that free-space-optical (FSO), a.k.a. optical wireless, communications is a promising complementary approach to address the exploding mobile wireless traffic demand. The major impediment for using FSO in a mobile setting is the line-of-sight (LOS) alignment requirement. Our existing efforts have pointed to the possibility of employing FSO within the context of mobile ad-hoc networking by handling its mobility and range issues via multi-element and multi-hop designs. Since optical wireless spectrum allows high data bandwidth (at least Mbps) when LOS occurs, a promising approach is to opportunistically leverage it with fast acquisition of FSO links. In earlier work, we produced a proof-of-concept prototype of an LOS alignment protocol that can electronically steer data transmissions over mobile multi-transceiver spherical modules. The goal of this project was to execute an instrumentation program that will enable us to improve our existing FSO prototype modules to low power consuming, miniature devices with high data transfer rates.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
11/15/2016	2.00	. LOS Discovery in 3D for Highly Directional Transceivers, IEEE Military Communications Conference (MILCOM). 07-NOV-16, Baltimore, MD. : ,
11/15/2016	3.00	. LOS Discovery for Highly Directional Full Duplex RF/FSO Transceivers, IEEE Military Communications Conference (MILCOM). 07-NOV-16, Baltimore, MD. : ,
11/15/2016	4.00	. Optimal multi-element VLC bulb design with power and lighting quality constraints, ACM MobiCom Workshop on Visible Light Communication Systems (VLCS). 03-OCT-16, New York City, New York. : ,
11/15/2016	5.00	. In-band autonomous maintenance of mobile Free-Space-Optical links: A prototype, 2016 ICC - 2016 IEEE International Conference on Communications Workshops (ICC). 23-MAY-16, Kuala Lumpur, Malaysia. : ,
11/15/2016	6.00	. Autonomous Alignment of Free-Space-Optical Links Between UAVs, ACM MobiCom Workshop on Hop Topics in Wireless (HotWireless). 11-SEP-15, Paris, France. : ,
11/15/2016	7.00	. A Multi-Element VLC Architecture for High Spatial Reuse, ACM MobiCom Workshop on Visible Light Communication Systems (VLCS). 11-SEP-15, Paris, France. : ,
11/15/2016	8.00	. Accuracy of AOA-Based and RSS-Based 3D Localization for Visible Light Communications, 2015 IEEE 82nd Vehicular Technology Conference (VTC Fall). 06-SEP-15, Boston, MA, USA. : ,
11/15/2016	11.00	. AOA-based localization and tracking in multi-element VLC systems, 2015 IEEE 16th Annual Wireless and Microwave Technology Conference (WAMICON). 13-APR-15, Cocoa Beach, FL, USA. : ,
11/15/2016	12.00	. Maintaining a free-space-optical communication link between two autonomous mobiles, 2014 IEEE Wireless Communications and Networking Conference (WCNC). 06-APR-14, Istanbul, Turkey. : ,
TOTAL:	**9**	

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
TOTAL:	

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

1. M. R. Khan and M. Yuksel, In-Band Autonomous Line-Of-Sight Alignment for Highly Directional Link Maintenance Between Mobiles, USPTO provisional patent application 62/338,947, May 19, 2016.
2. S. Bhunia, M. R. Khan, S. Sengupta, and M. Yuksel, In-Band Line-of-Sight (LOS) Discovery for Directional Full-Duplex Transceivers, USPTO provisional patent application 62/338,953, May 19, 2016.

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Mahmudur Khan	0.50	
Sifat Ibne Mushfique	0.50	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Murat Yuksel	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Garrett Winkelmaier	0.00	Electrical Engineering
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Mahmudur Khan
Total Number: **1**

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

5 **In-Band Autonomous Line-Of-Sight Alignment for Highly Directional Link Maintenance Between Mobiles**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Mahmudur Khan

5f-1a: University of Central Florida

5f-c: 4328 Scorpius Street

Orlando FL 32816

5a: Murat Yuksel

5f-1a: University of Central Florida

5f-c: 4328 Scorpius Street

Orando FL 328162362

5 **In-Band Line-of-Sight (LOS) Discovery for Directional Full-Duplex Transceiver**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Murat Yuksel

5f-1a: University of Central Florida

5f-c: 4328 Scorpius Street

Orando FL 328162362

5a: Mahmudur Khan

5f-1a: University of Central Florida

5f-c: 4328 Scorpius Street

Orlando FL 32816

5a: Shamik Sengupta

5f-1a: University of Nevada, Reno

5f-c: 1664 N Virginia St

Reno NV 89557

5a: Suman Bhunia

5f-1a: University of Nevada, Reno

5f-c: 1664 N. Virginia St

Reno NV 89557

Scientific Progress

See Attachment

Technology Transfer

We have been talking to several DoD scientists but no particular tech transfer activity yet.

Final Report

November 14, 2016

Sponsor: DOD-USAMC-MAT
Title: Multi-Element Free Space Optical (FSO) modules for Mobile Opportunistic Networking
PoP: 08/01/2014 to 07/30/2016
Award ID: W911NF-14-1-0531

PI: Murat Yuksel
University of Central Florida
(was with University of Nevada, Reno during the project)

Program Manager: Dr. Robert Ulman, (919) 549-4330, E-mail: robert.j.ulman.civ@mail.mil
Agency to Evaluate the Proposal: Army Research Office (ARO)
Scientific Division or Directorate: Network Science

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1. Summary of the Project Activities and Timeline

As the RF spectrum is getting scarcer, there is an *urgent need for innovations that will allow new and complementary wireless spectrum bands* in both military and civilian settings. Recent research has shown that free-space-optical (FSO), a.k.a. optical wireless, communications is a promising complementary approach to address the exploding mobile wireless traffic demand. The major impediment for using FSO in a mobile setting is the line-of-sight (LOS) alignment requirement. Our existing efforts have pointed to the possibility of employing FSO within the context of mobile ad-hoc networking by handling its mobility and range issues via multi-element and multi-hop designs. Since optical wireless spectrum allows high data bandwidth (at least Mbps) when LOS occurs, a promising approach is to opportunistically leverage it with fast acquisition of FSO links. In earlier work, we produced a proof-of-concept prototype of an LOS alignment protocol that can electronically steer data transmissions over mobile multi-transceiver spherical modules.

The goal of this project was to execute an instrumentation program that will enable us to *improve our existing FSO prototype modules to low power consuming, miniature devices with high data transfer rates*. Particularly, we aim to (a) reduce the size of our prototype modules to 5cms in diameter, (b) increase their transfer rates to tens of Mbps, (c) achieve an operational range at 10s of meters, and (d) hybridize them so that opportunistic FSO link acquisition becomes complementary to an existing RF link. DURIP funding was deemed a key to establishing the set of testbeds and prototypes necessary to research such FSO systems. Most of these goals were achieved with initial prototypes and their publications.

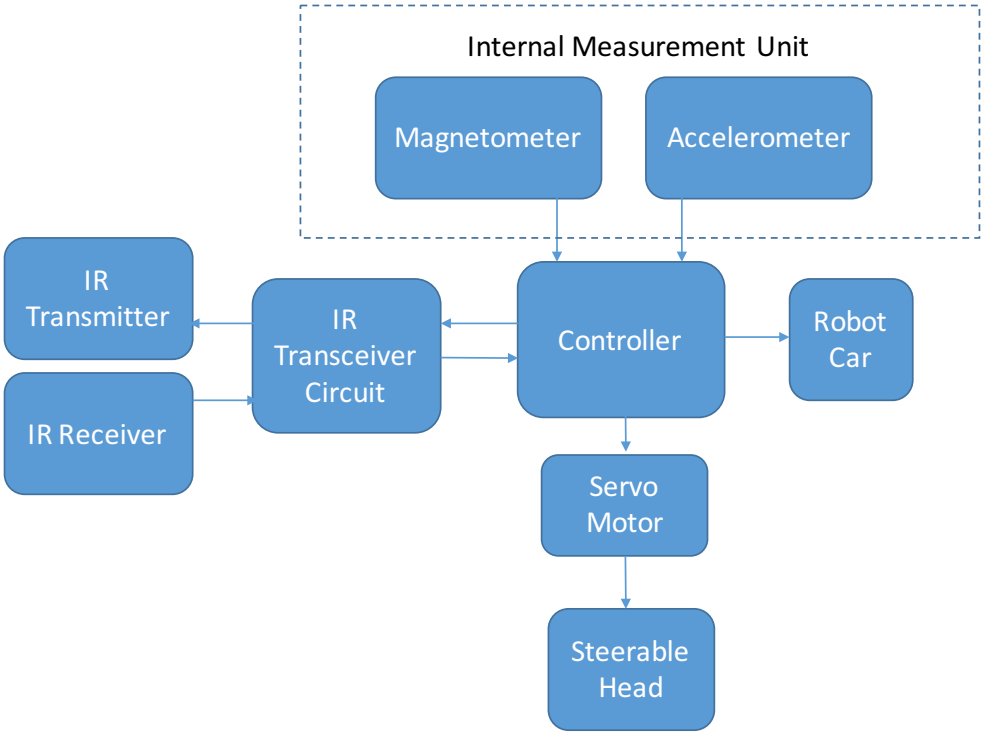
The project was leveraged to purchase equipment for needed to establish three testbeds: (1) FSO-Capable Unmanned Ground Vehicle (UGV), (2) FSO-Capable UAV Modules, and (3) Multi-Element Visible Light Communication (VLC) Testbed. Their design and specific items purchased are detailed in Section 2. The design and the acquisition of the relevant items were completed. Unfortunately, the final fabrication of them could not be completed since PI Yuksel moved to a new institution (University of Central Florida) and the purchased equipment were not allowed to be transferred to his new institution. The activities detailed in this report are based on the design and prototyping efforts during the time PI Yuksel worked at the University of Nevada, Reno.

2. Equipment Purchased and Related Testbed Designs

The project funds were used to purchase items to design three different testbeds on FSO and VLC research. The details of these testbed designs and specific items are debriefed below.

A. FSO-Capable Unmanned Ground Vehicle (UGV)

The controller, Internal Measurement Unit (IMU) consisting of magnetometer and accelerometer, the robot car, the steerable head, the IR transceiver circuit, the IR transmitter and the IR receiver will be used to make a single piece of equipment. This equipment is an unmanned ground vehicle capable of maintaining line-of-sight and perform wireless communication using free-space-optical (FSO) transceiver with another vehicle of this kind.



The figure above illustrates how the integration of the individual components will take place. The controller centrally controls all the different parts of the equipment. A raspberry pi or laptop can be used as the controller. The robot makes the equipment mobile. All the other parts will be attached to the robot car to make the main equipment. The mechanically steerable head will be attached on top of the robot car. A servo motor will be used to steer the head. The IR transmitter and IR receiver will be placed on the steerable head. The steerable head will be used to steer the IR transceiver (transmitter + receiver) as needed to maintain an optical wireless/ FSO link. The controller uses the IR transceiver circuit to make the transceiver work. The IMU will also be placed on the robot car. The magnetometer provides the controller with direction information and the accelerometer provides the velocity information. The controller uses the information received from the IMU and the IR receiver to calculate which way and how much to rotate the steerable head to maintain the desired FSO link.

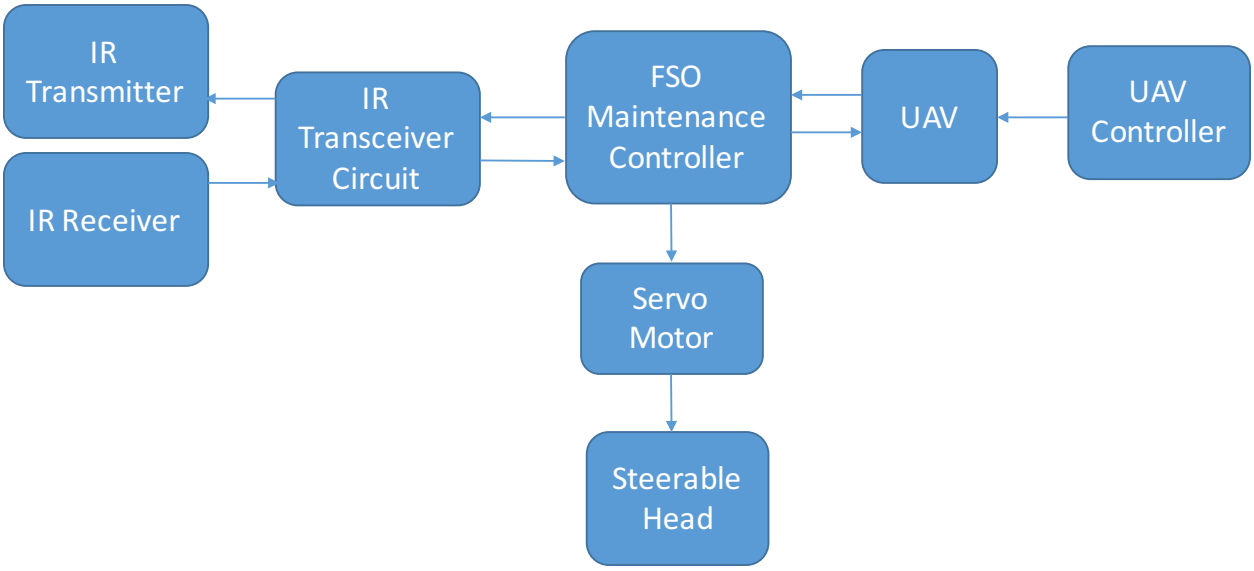
A detailed list of the items for each component of the equipment and estimates of cost of each are provided below.

Item #			Equipment Name	Cost	Quantity	Total
1	IR Transmitter	LED	High Brightness LED, BCR44 Series, White, 62 lm, 350 mA, 500 mA	$1.89	100	$189.00
2		LED	LED, WHITE, T-1 3/4 (5MM), 16CD	$1.78	100	$177.60
3		LED	LED ROUND WHITE 40DEG 5MM	$2.36	100	$236.00
4		LED	LED WHITE 5MM RND WATER	$1.13	100	$112.64
5	IR Receiver	Photo Detector	PHOTODIODE PIN HI SPEED HI SENS	$0.71	100	$70.75
6		Photo Detector	PHOTODIODE 850NM 5MM CLEAR	$0.88	100	$88.00
7		Si PIN	Hamamatsu s3883 300 MHz	$90	10	$900.00
8		Si PIN	s2506	$4.40	100	$440.00
9	Transceiver Circuit	IR transceiver board	IrDA2 click	$25.90	10	$259.00
10		Capacitor	100 Piece Radial Axial and Snap Electrolytic Capacitors	$8.95	10	$89.50
11		High Speed	TRANS NPN 15V 5GHZ SOT323	$0.22	250	$55.00
12		Prototype Boards	Prototype Board, QFP, QFN, SOIC, SOT, SOP, SSOP	$10.95	25	$273.75
13		Resistor	COMPONENT KIT, RESISTORS	$26.95	10	$269.50
14		OpAmp	IC OPAMP VFB 280MHZ SGL	$2.04	100	$203.58
15		Transistor	TRANSISTOR SET	$69.95	1	$69.95
16	FSO Maintenance Controller	Raspberry Pi	CanaKit Raspberry Pi 2 Complete Starter Kit with WiFi	$38.49	10	$384.90
17	Steerable Head		Aluminium Robot Turntable Swivel Base	$58.00	10	$580.00
18	Servo Motors			$37.89	10	$378.90
19	Robot Car	Robots	iRobot Create 2	$199.99	10	$1,999.90
20	Internal Measurement Unit	Accelerometer	Makerfire® Arduino GY-521 MPU-6050 Module 3 Axial Gyroscope	$9.95	10	$99.50
21		Magnetometer	Triple Axis Accelerometer Breakout -MMA8452Q	$7.29	10	$72.90
	Total					$6,950.37

Item #	Link
1	http://www.newark.com/optek-technology/ovspw1bcr44/led-hb-1-2w-wht-smd/dp/60R4582
2	http://www.digikey.com/product-detail/en/SSL-LX3054UWC%2FA/67-160ND/334582
3	http://www.newark.com/nte-electronics/nte30045/led-hb-white-120mw-5mmth/dp/73J8078
4	http://www.digikey.com/product-detail/en/SLA560WBD2PT2/511-1639-1-12ND/1956135
5	http://www.digikey.com/product-detail/en/VBPW34S/751-1500-1-ND/2354866
6	http://www.digikey.com/product-search/en/sensors-transducers/optical-photo-detectors-photodiodes/1967048?k=sfh213
7	http://www.hamamatsu.com/us/en/product/category/3100/4001/4103/S3883/index.html
8	http://www.hamamatsu.com/us/en/community/automotive/product/search/S2506-02/index.html
9	http://www.mikroe.com/click/irda2/
10	http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_17911_-1
11	http://www.digikey.com/product-detail/en/BFR92AW,115/568-1989-6-8ND/1857789
12	http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_2117270_-1
13	http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_81832_-1
14	http://www.digikey.com/product-detail/en/OPA820ID/296-17130-5-8SOICND/664650
15	http://www.jameco.com/1/1/25520-transistor-kit-560-piece-transistor-kit-assortments.html
16	http://www.amazon.com/CanaKit-Raspberry-Complete-Original-Preloaded/dp/B008XVAVAW/ref=sr_1_5?s=pc&ie=UTF8&qid=1447822928&sr=1-5&keywords=raspberry+pi
17	http://www.ebay.com/itm/Aluminium-Robot-Turntable-Swivel-Base-2-DOF-PTZ-2pcs-Servo-Set-for-Arduino-/271254609757
18	http://www.robotshop.com/en/hitec-hs-7966hb-high-speed-high-torque-servo-motor.html
19	http://store.irobot.com/irobot-create-2-programmable-robot/product.jsp?productId=54235736&cp=2591511
20	http://www.amazon.com/Makerfire%C2%AE-Arduino-MPU-6050-Gyroscope-Accelerometer/dp/B00NH8Z6BU/ref=sr_1_15?ie=UTF8&qid=1447822282&sr=8-15&keywords=accelerometer
21	http://www.amazon.com/Triple-Axis-Accelerometer-Breakout-MMA8452Q/dp/B006TG814Q/ref=sr_1_3?ie=UTF8&qid=1447822282&sr=8-3&keywords=accelerometer

B. FSO-Capable UAV Modules

The FSO maintenance controller, the unmanned aerial vehicle (UAV), the UAV controller, the steerable head, the servo motor, the IR transceiver circuit, the IR transmitter and the IR receiver will be used to make a single piece of equipment. This equipment is a UAV capable of maintaining line-of-sight and perform wireless communication using free-space-optical (FSO) transceiver with another vehicle of this kind.



The figure above illustrates how the integration of the individual components will take place. The controller centrally controls all the different parts of the equipment. A raspberry pi or laptop can be used as the controller. The UAV makes the equipment mobile. All the other parts will be attached to the UAV to make the main equipment. The UAV controller (smart phones) is used to fly the UAV. The mechanically steerable head will be attached on top of the UAV. A servo motor will be used to steer the head. The IR transmitter and IR receiver will be placed on the steerable head. The steerable head will be used to steer the IR transceiver (transmitter + receiver) as needed to maintain an optical wireless/ FSO link. The controller uses the IR transceiver circuit to make the transceiver work.

A detailed list of the items for each component of the equipment and estimates of cost of each are provided below.

Item #			Equipment Name	Cost	Quantity	Total
1	IR Transmitter	LED	High Brightness LED, BCR44 Series, White, 62 lm, 350 mA, 500 mA	$1.89	100	$189.00
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3		LED	LED ROUND WHITE 40DEG 5MM	$2.36	100	$236.00
4		LED	LED WHITE 5MM RND WATER	$1.13	100	$112.64
5	IR Receiver	Photo Detector	PHOTODIODE PIN HI SPEED HI SENS	$0.71	100	$70.75
6		Photo Detector	PHOTODIODE 850NM 5MM CLEAR	$0.88	100	$88.00
7		Si PIN	Hamamatsu s3883 300 MHz	$90	10	$900.00
8		Si PIN	s2506	$4.40	100	$440.00
9	Transceiver Circuit	IR transceiver board	IrDA2 click	$25.90	10	$259.00
10		Capacitor	100 Piece Radial Axial and Snap Electrolytic Capacitors	$8.95	10	$89.50
11		High Speed	TRANS NPN 15V 5GHZ SOT323	$0.22	250	$55.00
12		Prototype Boards	Prototype Board, QFP, QFN, SOIC, SOT, SOP, SSOP	$10.95	25	$273.75
13		Resistor	COMPONENT KIT, RESISTORS	$26.95	10	$269.50
14		OpAmp	IC OPAMP VFB 280MHZ SGL	$2.04	100	$203.58
15		Transistor	TRANSISTOR SET	$69.95	1	$69.95
16	FSO Maintenance Controller	Raspberry Pi	Raspberry Pi 2 Model B Project Board - 1GB RAM - 900	$38.49	10	$384.90
17	Steerable Head		Aluminium Robot Turntable Swivel Base	$58.00	10	$580.00
18	Servo Motors			$37.89	10	$378.90
19	UAV	Phantom 3		$699	2	$1,398.00
20		Advanced		$999	2	$1,998.00
21		Mini		$299	2	$598.00
22		Solo Drone		$999.95	2	$1,999.90
23		IRIS+		$599.99	2	$1,199.98
24		AR Drone		$299.00	2	$598.00
25	UAV Controller	Smart Phone				
26						
	Total					$12,569.95

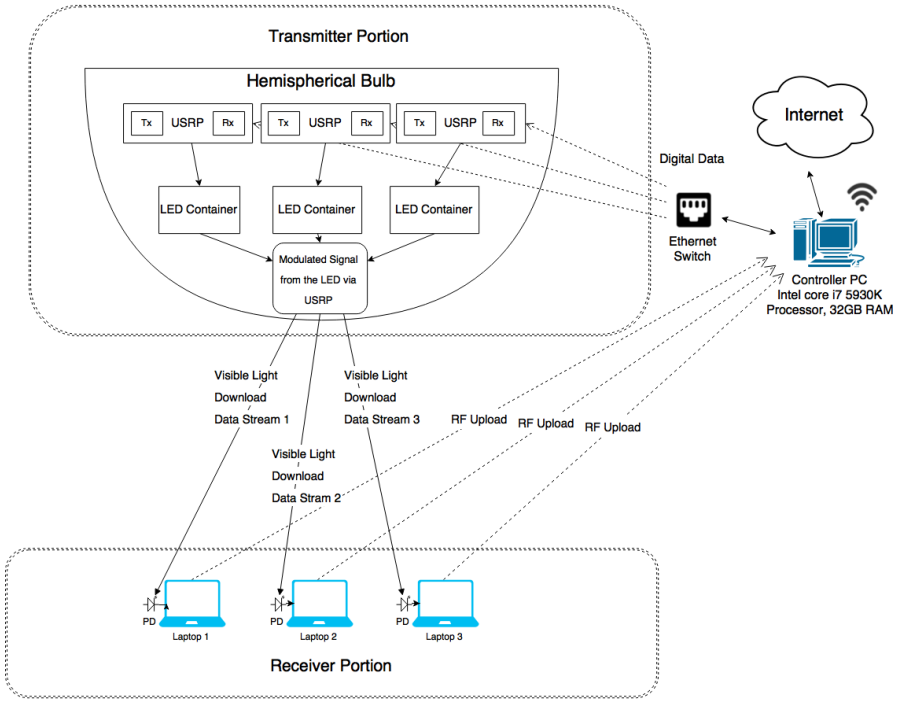
Item #	Link
1	http://www.newark.com/optek-technology/ovspw1bcr44/led-hb-1-2w-wht-smd/dp/60R4582
2	http://www.digikey.com/product-detail/en/SSL-LX3054UWC%2FA/67-160ND/334582
3	http://www.newark.com/nte-electronics/nte30045/led-hb-white-120mw-5mmth/dp/73J8078
4	http://www.digikey.com/product-detail/en/SLA560WBD2PT2/511-1639-1-12ND/1956135
5	http://www.digikey.com/product-detail/en/VBPW34S/751-1500-1-ND/2354866
6	http://www.digikey.com/product-search/en/sensors-transducers/optical-photo-detectors-photodiodes/1967048?k=sfh213
7	http://www.hamamatsu.com/us/en/product/category/3100/4001/4103/S3883/index.html
8	http://www.hamamatsu.com/us/en/community/automotive/product/search/S2506-02/index.html
9	http://www.mikroe.com/click/irda2/
10	http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_17911_-1
11	http://www.digikey.com/product-detail/en/BFR92AW,115/568-1989-6-8ND/1857789
12	http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_2117270_-1
13	http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_81832_-1
14	http://www.digikey.com/product-detail/en/OPA820ID/296-17130-5-8SOICND/664650
15	http://www.jameco.com/1/1/25520-transistor-kit-560-piece-transistor-kit-assortments.html
16	http://www.amazon.com/Raspberry-Pi-Model-Project-Board/dp/B00T2U7R7I/ref=sr_1_4?s=pc&ie=UTF8&qid=1447820850&sr=1-4&keywords=raspberry+pi
17	http://www.ebay.com/itm/Aluminium-Robot-Turntable-Swivel-Base-2-DOF-PTZ-2pcs-Servo-Set-for-Arduino-/271254609757
18	http://www.robotshop.com/en/hitec-hs-7966hb-high-speed-high-torque-servo-motor.html
19	http://store.dji.com/product/phantom-3-standard
20	http://store.dji.com/product/phantom-3-advanced
21	http://www.helipal.com/storm-drone-4-flying-platform-v2.html
22	https://www.store.3drobotics.com/products/solo?_ga=1.68583249.1514295626.1440462438
23	https://store.3drobotics.com/products/iris
24	https://us.store.parrot.com/en/ar-drone-20/296-ar-drone-20-elite-edition.html?search_query=AR+Drone&results=59#/color-
25	
26	

C. Multi-Element Visible Light Communication (VLC) Testbed

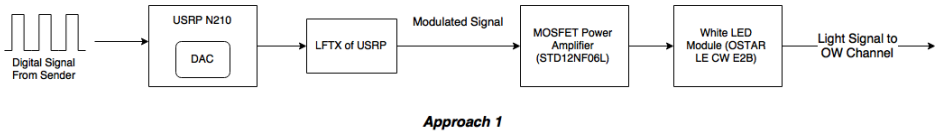
The multi-element VLC architecture consists of mainly 3 portions – transmitter, receiver and controller – which come together to serve as a single component. This prototype is intended for data communication using visible light and transferring multiple data streams simultaneously.

The architecture we will use for implementing the multi-element VLC testbed and each of the main components are shown in the figure below. Subsequent figures show specifics of individual components. Then, a high-level description of what each component does and how they interact with other components is given.

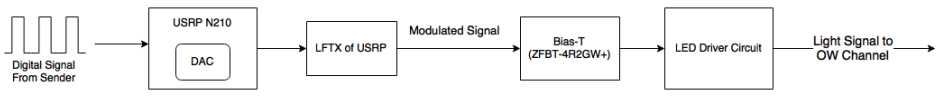
Architecture of The Multi-Element VLC Testbed



Designs for The Transmitter Component

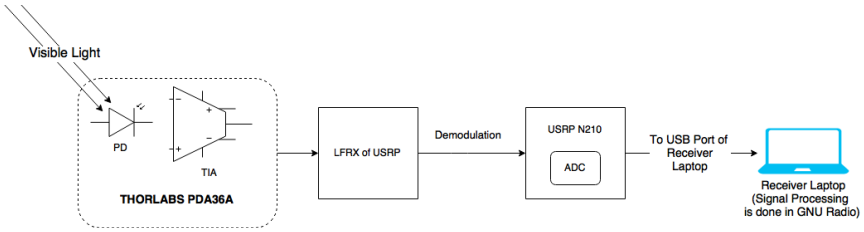


Approach 1

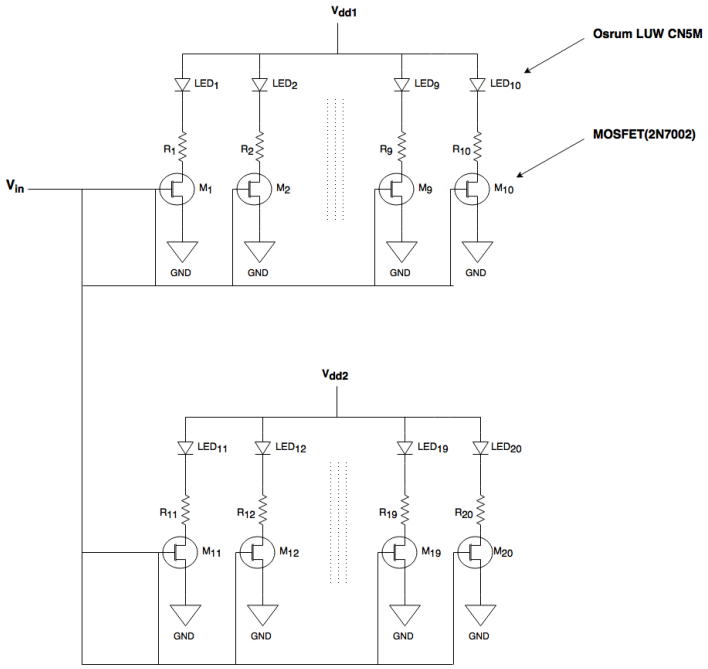


Approach 2

Design for The Receiver Component



Custom Design for LED Driver Circuits



The Transmitter portion of the architecture consists of a hemispherical bulb structure, inside of which there will be LED containers. This LEDs will be fed by the modulated digital signal from the sender devices via USRPs which also have their own transmitter and receiver known as LFTX and LFRX. The signal can be fed in 2 ways. In one approach, the signal coming from the LFTX of the USRP will be passed into a Power MOSFET Transistor, and the output of this transistor will be fed to the White LED Module, OSTAR LE CW E2B inside the LED container. In the other approach, the LED container will not contain a module, but small Osrum Semiconductor LEDs, LUW CN5M, which will be driven by a LED Driver Circuit. The modulated signal from the LFTX of USRP will be given as input of the driver circuit, and the MOSFETs 2N7002 will control the light emitted from each LED that generates a current proportional the incoming voltage from the USRP.

The Controller will control the line-of-sight alignment between the Transmitter and Receiver, i.e. which transmitter is connected to which receiver. For versatility, a Desktop PC will be used as controller, and it should be powerfully configured as well, as it will be connected with multiple high-range USRPs. For that reason, an Intel Core i7-5930K 3.50 GHz CPU, an ASUS-X99 Motherboard, and G-Skill Ripjaws 8x8 GB RAM is proposed. This controller PC will be connected to the USRPs via an Ethernet Switch.

At the Receiver portion, the visible light from the optical channel will fall into the Commercial Photodetector, Thorlabs PDA36A which generates a voltage proportional to the received optical power and sends it to the LFRX daughterboard of the USRP.

A detailed list of the items for each component of the equipment and estimates of cost of each are provided below.

Item #	Equipment Type	Equipment Name	Cost	Quantity	Total
1	**USRP**	USRP N210	$1,993.76	7	**$13,956.32**
2	**LFTX**	LFTX Daughterboard 0-30 MHz Tx	$76.00	7	**$532.00**
3	**LFRX**	LFRX Daughterboard 0-30 MHz Rx	$76.00	7	**$532.00**
4	**Photo Detector**	Thorlabs PDA36A	$314.00	3	**$942.00**
5	**Ethernet Switch**	FS116 10/100 16 port dual speed switch	$65.99	1	**$65.99**
6	**Power MOSFET Transistor**	STMicroelectronics STD12NF06L-1	$1.17	10	**$11.70**
7	**White LED Module**	OSTAR LE CW E2B	$19.70	3	**$59.10**
8	**LED**	Osrum Semiconductor LEDs (LUW CN5M)	$0.93	100	**$92.60**
9	**MOSFET**	MOSFET 2N7002	$0.09	100	**$9.39**
10	**Controller CPU**	Intel Core i7-5930K 3.50 GHz	$651.93	1	**$651.93**
11	**Controller Motherboard**	Asus X99-DELUXE ATX LGA2011-3 Motherboard	$386.98	1	**$386.98**
12	**Controller RAM**	G.SKILL Ripjaws X Series 64GB (8 x 8GB)	$299.99	1	**$299.99**
13	**Optical Spectrum Analyzer**	Thorlabs OSA202	$24,250.00	1	**$24,250.00**
14	**RF Spectrum Analyzer**	Agilent 4396B	$7,995.00	1	**$7,995.00**
15	**High Power LEDs for OpenVLC**	WHITE Bulb T5 Wedge 2.5W 360Deg LEDs	$25.99	2	**$51.98**
16	**Beaglebone Black**	Digikey BEAGLEBONE BLACK REV C	$59.06	6	**$354.36**
	TOTAL				**$50,191.34**

Item #	Link
1	http://www.ettus.com/product/details/UN210-KIT
2	http://www.ettus.com/product/details/LFTX
3	http://www.ettus.com/product/details/LFRX
4	https://www.thorlabs.com/thorProduct.cfm?partNumber=PDA36A
5	http://accessories.us.dell.com/sna/productdetail.aspx?c=us&l=en&s=&cs=04&sku=A0136899&dgc=ST&cid=293344&lid=5616479&acd=12309152537461010&ven1=sE1inYhPj&ven2=,
6	http://www.digikey.com/product-detail/en/STD12NF06L-1/497-6730-5-ND/1039352
7	http://uk.rs-online.com/web/p/visible-leds/6656025/
8	http://www.mouser.com/ProductDetail/OSRAM-Opto-Semiconductors/LUW-CN5M-GBHB-5P7R-
9	http://www.digikey.com/product-detail/en/2N7002,215/568-1369-1-ND/763366
10	http://www.amazon.com/Intel-BX80648I75930K-CORE-I7-5930K-3-50GHZ/dp/B00N5GYRSM%3FSubscriptionId%3DAKIAI2I36U2HOIVJCKMA%26tag%3Dfuturemark-20%26linkCode%3Dxm2%26camp%3D2025%26creative%3D165953%26creativeASIN%3DB00N5GYRSM
11	http://pcpartpicker.com/part/asus-motherboard-x99deluxe
12	http://www.newegg.com/Product/Product.aspx?Item=N82E1682023151
13	https://www.thorlabs.com/thorproduct.cfm?partnumber=OSA202
14	http://www.bellnw.com/manufacturer/Agilent/4396B.htm
15	http://www.amazon.com/BestW6WPACKW360DegWMalibuWLandscape/dp/B00MTRGYH0/ref=pd_sim_60_5?ie=UTF8&dpID=41NIgv4GjtL&dpSrc=sims&preST=_AC_UL160_SR160,160_&refRID=11RAYDTJZVDH68VME120
16	http://www.digikey.com/product-search/en?lang=en&site=us&keywords=BB-BBLK-000-REVC-ND

3. Prototyping and Research Activities

Our activities have focused on the three major aspects: (i) designing and investigating ways to maintain a free-space-optical (FSO) link between two mobiles, (ii) designing techniques to discover neighbor nodes using FSO link only, (iii) designing and developing high-throughput VLC systems, and (iv) designing VLC-based localization techniques. A summary of our key activities by topics follows:

A. Maintaining an FSO Link Between Two Mobiles:

In order to use optical wireless communication among mobile units like PackBots, we need the capability to establish and maintain an FSO link between two mobile units. Despite its advantages, FSO communication is prone to mobility. The highly directional FSO transceivers require establishment and maintenance of line-of-sight (LOS) between them. Facilitating continuous alignment requirements has been a major concentration of mobile FSO research to date.

We considered two autonomous mobile nodes, each with one FSO transceiver mounted on a movable head capable of rotating 360 degrees. We designed a novel scheme that deals with the problem of automatic detection, establishment and maintenance of LOS alignment between the two nodes with mechanical steering of the FSO transceivers. The proposed method shows that using such mechanically steerable transceivers and a simple auto-alignment mechanism, it is possible to maintain optical wireless links in a mobile setting with nominal disruption. For the problem of maintaining an FSO link between two mobiles, we made the assumptions that the two nodes:

- are in a GPS-free environment with no medium of communication available other than FSO;
- are mobile and completely autonomous;
- move on straight lines only, but in either direction;
- are equipped with a compass giving them the sense of direction; and
- are also equipped with a mechanically steerable head (with which they can scan complete 360 degrees) that is mounted with an FSO transceiver.

We published initial designs of the algorithm at the IEEE WCNC 2015 conference [13]. In this first publication, using the proposed algorithm to control the mechanically steered head, we showed that the FSO transceivers on the nodes can maintain a communication link successfully. We outlined all possible cases for calculating the angular velocity of the nodes' heads and the direction of the heads' rotation so as to maintain the FSO link. We showed that the number of message exchanges needed to maintain the FSO link can be kept reasonably small for walking and driving speeds.

We, then, implemented a prototype of the algorithm between two mobile toy cars and showed that it works with off-the-shelf infrared transceivers. The prototype exhibited the tradeoffs we expected in our designs. It showed that an interval of 500ms is sufficient to exchange the link maintenance signals in order to maintain an FSO link between mobiles at walking speeds. We published these results along with the prototype design details in IEEE ICC Workshop on Optical Wireless (OWC) 2016 [7]. We, recently, updated the algorithm so that the mobiles can move on curves. Under this

circumstance, we again showed that the messaging overhead could be kept small enough to maintain a highly directional FSO link. The updated work is now accepted by IEEE Transactions on Mobile Computing [1].

We extended the concept of in-band LOS alignment and maintenance to 3D and designed the algorithm for unmanned aerial vehicles (UAVs). We considered two UAVs, each with one FSO transceiver mounted on a hemispherical structure/head capable of rotating 360 degrees in the horizontal plane and 180 degrees in the vertical plane. We designed a novel scheme that deals with the problem of automatic establishment and maintenance of LOS alignment between the UAVs with mechanical steering of the FSO transceivers. The proposed method showed that using such mechanically steerable transceivers and a simple auto-alignment mechanism, it is possible to maintain an optical wireless link between two UAVs with nominal disruption. We published the results in ACM Mobicom HotWireless 2015 Workshop [8]. Finally, we filed a provisional patent on the concept of in-band FSO link alignment and maintenance [4].

B. In-Band Discovery of Neighbors Using FSO Links Only:

Full duplex directional Radio Frequency (RF) or FSO transceivers are envisioned to play a great role in future generation wireless networks. They provide benefits in terms of better throughput, enhanced spectrum utilization and lower interference from unwanted sources. However, the stringent requirement of LOS communication makes it tough for a mobile node to maintain a link without a-priori information about its neighbor's position. Hence, neighbor discovery takes a very crucial role in mobile ad hoc networks with directional transceivers. Within this context as well as to complement the FSO link maintenance efforts of the project, we worked on neighbor discovery using full duplex directional transceivers. We considered two nodes that can discover each other by steering their transceivers with a randomly chosen angular speed and performing a simple three-way handshaking protocol. We provided a theoretical analysis of the proposed neighbor discovery method. Additionally, we proposed an algorithm where each node chooses its transceiver's angular speed and renews it if the neighbor is not discovered within an optimal time interval. We evaluated the algorithm via simulations and showed its effectiveness under various scenarios in a recent paper in IEEE MILCOM'2016 [3].

We also considered two UAV nodes hovering in 3D space, each with one directional transceiver mounted on a mechanically steerable spherical structure/head, with which they can scan 360 degrees in the horizontal plane and 360 degrees in the vertical plane. We proposed a novel scheme that deals with the problem of automatic discovery and establishment of LOS alignment between these nodes. We performed extensive simulations to show the effectiveness of the proposed neighbor discovery method. The results show that, using such mechanically steerable directional transceivers, it is possible to establish communication links to similar neighboring nodes within minimal discovery times. We published these initial insights in IEEE MILCOM'2016 [2].

The concept of in-band discovery of neighbors using highly directional RF/FSO links is very promising. It has vast amount of applications in military and space communications. We recently filed a provisional patent on the concept [6].

C. High-Throughput VLC Systems:

Visible light communication (VLC) is an emerging wireless technology that offers more capacity than legacy radio frequency (RF) communications can offer. Free-space-optical (FSO) communication is VLC's general form spanning infrared bands, and it has an upper hand on traditional RF systems due to license-free spectrum, containment of beams, inherent security, energy efficient communications, and high transmission rates. We leveraged the DURIP project to make progress on the VLC systems we work on. We considered a hybrid RF/FSO mechanism [9] to transmit multiple data streams over multi-element VLC modules. We evaluated the link quality performance of a novel multi-element hemispherical design that can simultaneously provide good lighting and communication coverage across a room. We further formulated the problem of balancing lighting quality and the communication efficiency as an optimization problem [4].

D. VLC-Based Hybrid Localization Techniques:

Another key advantage of FSO/VLC communications is the possible usage of its beam directionality for indoor or GPS-free localization. We investigated hybrid utilization of angle-of-arrival (AOA) and received signal strength (RSS) information in VLC systems for 3-D localization. We showed that AOA-based localization method allows the receiver to locate itself via a least squares estimator by exploiting the directionality of LEDs [12]. We then proved that when the RSS information is taken into account, the positioning accuracy of AOA-based localization can be improved further using a weighted least squares solution [11]. On the other hand, when the radiation patterns of LEDs are explicitly considered in the estimation, RSS-based localization yields highly accurate results. In order to deal with the system of non-linear equations for RSS-based localization, we developed an analytical learning rule based on the Newton–Raphson method. The non-convex structure is addressed by initializing the learning rule based on 1) location estimates, and 2) a newly developed method, which we refer as a random report and cluster algorithm. As a benchmark, we also derived the analytical expression of the Cramer–Rao lower bound for RSS-based localization, which captures any deployment scenario positioning in 3-D geometry. Finally, we demonstrated the effectiveness of the proposed solutions for a wide range of LED characteristics and orientations through extensive computer simulations [10].

3. List of Publications Produced from the Project Activities

1. M. Khan, M. Yuksel, and G. Winkelmaier, GPS-Free Maintenance of a Free-Space-Optical Link Between Two Autonomous Mobiles, to appear *IEEE Transactions on Mobile Computing*.
2. M. R. Khan, S. Bhunia, M. Yuksel, and S. Sengupta, LOS Discovery in 3D for Highly Directional Transceivers, *Proceedings of IEEE Military Communications Conference (MILCOM)*, Baltimore, MD, November 2016.
3. S. Bhunia, M. R. Khan, S. Sengupta, and M. Yuksel, LOS Discovery for Highly Directional Full Duplex RF/FSO Transceivers, *Proceedings of IEEE Military Communications Conference (MILCOM)*, Baltimore, MD, November 2016.
4. S. Ibne Mushfique and M. Yuksel, Optimal Multi-Element VLC Bulb Design with Power and Lighting Quality Constraints, *Proceedings of ACM MobiCom Workshop on Visible Light Communication Systems (VLCS)*, New York, NY, October 2016.
5. M. R. Khan and M. Yuksel, *In-Band Autonomous Line-Of-Sight Alignment for Highly Directional Link Maintenance Between Mobiles*, USPTO provisional patent application 62/338,947, May 19, 2016.
6. S. Bhunia, M. R. Khan, S. Sengupta, and M. Yuksel, *In-Band Line-of-Sight (LOS) Discovery for Directional Full-Duplex Transceivers*, USPTO provisional patent application 62/338,953, May 19, 2016.
7. M. R. Khan, G. Winkelmaier, and M. Yuksel, In-Band Autonomous Maintenance of Mobile Free-Space-Optical Links: A Prototype, *Proceedings of IEEE ICC Workshop on Optical Wireless Communication (OWC)*, Pages 157-162, Kuala Lumpur, Malaysia, May 2016.
8. M. Khan and M. Yuksel, Autonomous Alignment of Free-Space-Optical Links Between UAVs, *Proceedings of ACM MobiCom Workshop on Hop Topics in Wireless (HotWireless)*, Pages 36-40, Paris, France, September 2015.
9. P. Palathingal, M. Yuksel, I. Guvenc, and N. Pala, A Multi-Element VLC Architecture for High Spatial Reuse, *Proceedings of ACM MobiCom Workshop on Visible Light Communication Systems (VLCS)*, Pages 21-26, Paris, France, September 2015.
10. A. Sahin, Y. S. Eroglu, I. Guvenc, N. Pala, and M. Yuksel, Accuracy of AOA-Based and RSS-Based 3D Localization for Visible Light Communications, *Proceedings of IEEE Vehicular Technology Conference (VTC)*, Pages 1-5, Boston, MA, September 2015.
11. A. Sahin, Y. S. Eroglu, I. Guvenc, N. Pala, and M. Yuksel, Hybrid 3D Localization for Visible Light Communication Systems, *IEEE/OSA Journal of Lightwave Technology*, Volume 33, Issue 22, Pages 4589-4599, September 2015.
12. Y. S. Eroglu, I. Guvenc, N. Pala, and M. Yuksel, AOA-Based Localization and Tracking in Multi-Element VLC Systems, *Proceedings of IEEE Wireless and Microwave Technology Conference (WAMICON)*, Pages 1-5, Cocoa Beach, FL, April 2015.
13. M. Khan and M. Yuksel, Maintaining A Free-Space-Optical Communication Link Between Two Autonomous Mobiles, *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, Pages 3196-3201, Istanbul, Turkey, April 2014.