NI Research Framework Systems

Software-Defined Baseband for Visible Light Communication

NI Research Framework Systems

Software-Defined Baseband for Visible Light Communication

Overview

Consumer adoption of 3G and 4G LTE standards outpaced all other technologies and grew to nearly 3 billion connections in less than 15 years. It is now projected that the number of connected devices will exceed 50 billion by 2020 and mobile data traffic will approach 197,000 PB (petabytes). The combination of high bandwidth data capacity, low latency and an exponential number of connected devices lead researchers investigating networks operating above 6 GHz as the frequency spectrum. While innovative techniques will be put into operation to make more efficient use of already allocated spectrum below 6 GHz, there will be a growing need to unlock new spectrum bands such as visible light.

Visible Light Communication (VLC) can be used as a communications medium for ubiquitous computing, because light-producing devices (such as indoor/outdoor lamps, TVs, traffic signs, commercial displays and car headlights/taillights) are used everywhere.

NI is providing tools and technologies for prototyping and defining this new frontier for wireless communications. NI's hardware and software platform enables researchers to innovate faster by providing a path from theoretical research to rapid prototyping. With a simplified design flow for creating FPGA-based logic and streamlined deployment for high-performance processing, researchers in this field can meet the demands of prototyping these complex systems with a unified hardware and software design flow.

TABLE OF CONTENTS:

Introduction to Visible Light Communication

How do we transmit wireless data? Mostly through radio waves, which aren't cheap, require the use of inefficient base stations, and live in a part of the electromagnetic spectrum that's quickly running out of space. Wireless consumers' insatiable demand for bandwidth has spurred unprecedented levels of public and private sector investment to increase network capacity. This demand is also driving wireless researchers to develop new ways to address capacity challenges and even explore new network topologies. Researchers not only have to address capacity concerns, but offer new features and functions never before thought possible.

While there is a potential spectrum crisis within low GHz ISM bands (as Wi-Fi is close to full capacity); Visible Light Communications has almost no limitations on capacity. The visible light spectrum is 10,000 times larger than the entire radio frequency spectrum.

Light-fidelity (LiFi) is a continuation of the trend to move to higher frequencies in the electromagnetic spectrum. Specifically, LiFi could be classified as nm-wave communication. LiFi uses light emitting diodes (LEDs) for high speed wireless communication, and speeds of over 3Gb/s from a single micro-light emitting diode (LED) have been demonstrated using optimized direct current optical orthogonal frequency division multiplexing (DCO-OFDM) modulation.

System works by switching the current to the LEDs off and on at a very high rate, too quick to be noticed by the human eye. Although the light waves cannot penetrate walls which makes a much shorter range, direct line of sight isn't necessary for Li-Fi to transmit a signal. There are research outcomes where reflected light off the walls can achieve 70 Mbit/s. VLC has the advantage of being useful in electromagnetic sensitive areas such as in aircraft cabins, hospitals and nuclear power plants without causing electromagnetic interference. The new wireless LiFi networking paradigm offers performance enhancements that are not only aimed for by 5G initiatives, but also due to the ubiquitous use of LEDs, that will provide an infrastructure for the emerging IoT.

To transition from concept to reality, researchers must prototype with real signals and waveforms. Using optical bands for communication poses some unique challenges. Using NI's Software-Defined (SD) Baseband Solutions, researchers can build scalable channel count systems to rapidly prototype applications for communications prototyping using award-winning LabVIEW System Design software and state-of-the-art NI SDR products.

These component, processing, and data collection challenges make prototyping vital. For researchers to validate theory, this means moving from theoretical work to testbeds. Using real-world waveforms in real-world scenarios, researchers can develop prototypes to determine the feasibility and commercial viability of VLC. As with any new wireless standard or technology, the transition from concept to prototype impacts the time to actual deployment and commercialization. And the faster researchers can build prototypes, the sooner society can benefit from the innovations.

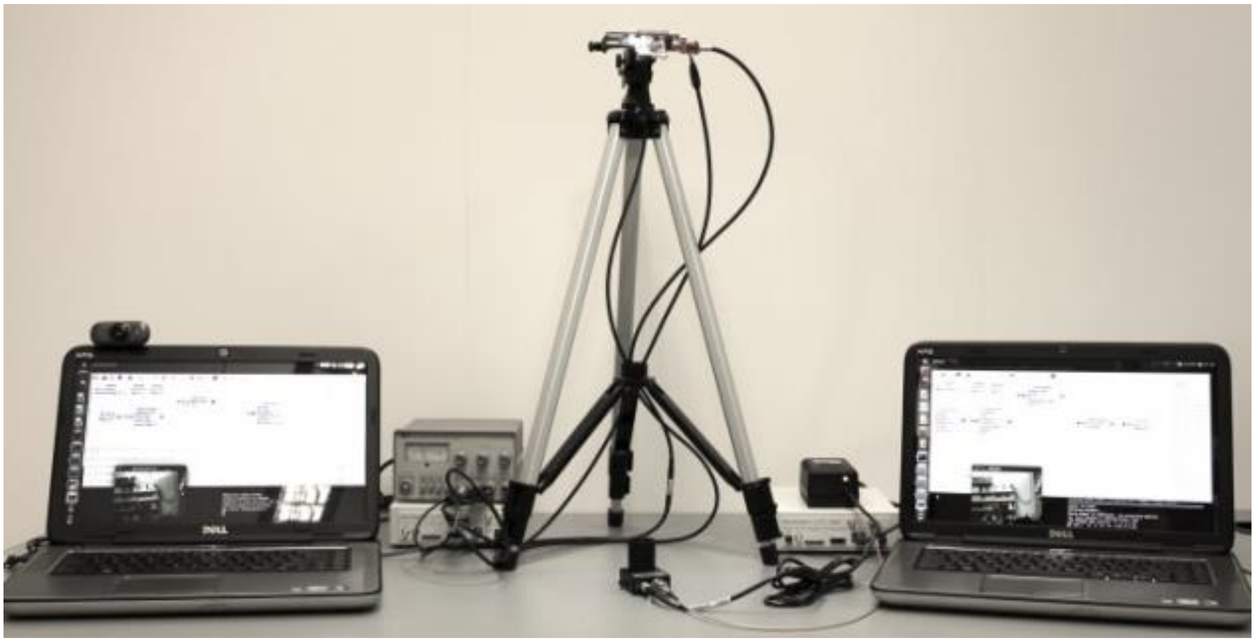


Figure 1- An Example Software Defined VLC Implementation. Courtesy of Boston University.

1. Potential Research Topics of VLC Systems

In this section; the intention is to list some research problems that may fall under the subjects of Visible Light Communication research. These lists might serve as an accessible entry-point for those who want to study these fields using the proposed framework.

VLC research topics might be divided into 4 main areas:

i. Component and subsystem development
ii. Signal processing and modulation techiques
iii. Optical MIMO
iv. Applications

All topics are open for research and further development.

For component and subsystem research area; there are various implementations of front-end systems based on LEDs and photodiodes and their electronic driving circuitries. Instead of photodiodes (PIN or APD) which are conventional receivers of optical signals, image sensors (i.e. cameras) are also being considered for use in VLC detection. Whereas the former are more suitable for high-speed applications, the latter are very attractive in applications where determination of the source location is in the focus (not so much the transmission rate). Image sensors obtain images and receive data (based on several image frames) simultaneously. In general; optimization of optical senders and receivers for high bandwidth, high linearity and achieving high signal-to-noise ratio are the main objectives for the component and subsystem research and development topic.

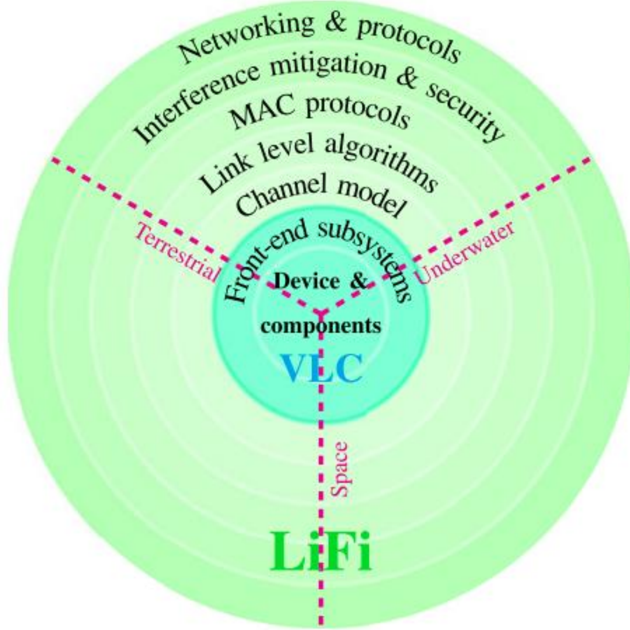


Figure 2 - Principal building blocks of Li-Fi and its applications

The second topic for innovation covers the implementation and research of existing and new modulation techniques into the optical communication. In order to reach high transmission rates over a limited system bandwidth, spectrally efficient types of modulation such as OFDM are employed. Due to fact that LEDs require real-valued non-negative time domain signals for transmission; standard techniques such as PAM has to be changed for meainingfull performance.

Another key research subject is the optical MIMO implementations. Similarly as in radio systems, possibilities to increase the throughput of an optical wireless system by transmitting data in parallel over multiple transmitter and receiver elements are being investigated. Note that a typical indoor lighting scenario requires white LED arrays in order to achieve a certain illumination level anyhow, making the use of MIMO techniques intuitively attractive. MIMO processing can compensate inter-channel cross-talk, thus allowing for parallel transmission from a number of LEDs.

Given the vast amount of currently installed channels (LEDs), applications aspect of the VLC also gives multiple potential topics such as position localization, Hybrid WiFi-VLC and IoT are few to name. Also; Underwater communication presents a very attractive field for optical wireless technology. High volume data transfer and reliable information exchange as well as remote operation of freely moving underwater units are some of important requirements for a viable underwater communication technology.

NI’s Software-Defined baseband solutions typically cover the most of the research topics, only except the optical component (LEDs and similar) research and development topics including parametric measurements.

2. SD-Baseband for VLC System Synopsis

Fundamental differences between optical and RF media also lead to challenges in adapting an SDR platform to the optical medium. VLC systems, with non-coherent sources, typically implement Intensity Modulation with Direct Detection (IM/DD); therefore limitations in the bandwidth of illumination-grade LEDs constrain modulation to low frequency or baseband techniques. Optical devices have nonlinear electro-optic conversion characteristics and require a positive drive signal; therefore device-dependent signal pre-distortion and biasing is needed. To achieve a desired illumination profile for lighting, a specific irradiance is required at the surface under consideration; therefore the modulation of the optical signal must be adaptable to meet constraints on average optical power in contrast to satisfying the maximum average electrical power requirement as is necessary in an RF link. Finally, optical receivers are inherently directional and the received signal is dependent on the angles emission and arrival; therefore the use of multi-channel optical diversity receivers (similar to antenna arrays) should be explored when considering the optimization of a VLC network.

Given the early stage of development in the area of VLC and the complexities involved in implementing signal chain components in a testbed, there is a need for tools to accelerate the development and testing of VLC prototypes, solutions and protocols. Software-defined systems offer an efficient platform with the flexibility to assist in development by (a) providing a modular separation of front-end hardware and signal processing techniques, (b) offering the agility to modify and test various signal processing techniques without any hardware updates, and (c) allowing for dynamic variations of the signal processing techniques in order to adapt to changes in the lighting requirements.

Using SDR concepts, NI system engineering teams developed system software for a starting point. The software developed is available as the baseband software component of these systems. In order to maximize the use cases; portable (low channel) configurations and scalable massive channel count options are provided with the same software architecture.

Table 1 shows the system and protocol parameters supported by the proposed Software-Defined Baseband for Visible Light Communication Systems.

System Type / **Parameters**	**Low-Channel Count Bb Units**	**Scalable-Channel Count Bb Units**
Channel Configurations	1x1 Uni- or Bi-directional 2x2 Uni- or Bi-directional	Scalable from 2x2 to 32x32 configurations (more available with multi-chassis)
Bandwidth per Channel	30 MHz.	40 MHz. for balanced transceivers >125 MHz. for wideband option
Sampling Rate	200 MS/s	100 MS/s for balanced transceivers 250 MS/s for wideband option
Modulation Schemas	On-Off Keying (OOK) Minimum Shift Keying (MSK) Phase Shift Keying (PSK) DC Biased Optical OFDM	

Table 1 – Baseband for VLC System Parameters

3. SD-Baseband for VLC System Architecture

As named; Software-Defined Baseband for VLC Systems covers the signal chain of the wireless optical communication system to the baseband stage. This consists of a central processor unit, FPGA based co-processor(s), timing and synchronization subsystems and finally the baseband signal blocks which are made of high-speed, wide-bandwidth and quality ADC and DAC blocks. High frequency optical signal chain of the communication system are out of the scope of the proposed baseband systems and varies with different applications. It should be noted that, necessary electronic interface and optical transducers are needed for the VLC system to function.

At the heart of the SD-Baseband system lies the NI's 2 popular SDR platforms; the low-cost, highly portable Universal Software-Defined Radio Peripheral (USRP) platform and highest-performance, modular PXI platform.

NI Universal Software Radio Peripheral (USRP) are computer-hosted RF transceivers used for development and exploration of software-defined radios. NI USRP transceivers can transmit and receive signals in several bands (including baseband) and can be used for applications in communications education and research. Paired with NI LabVIEW software, NI USRP transceivers provide affordable solution that offers access to real-world signals to enable interactive development.

PXI stands for PCI™ Extension for Instrumentation and it is the industry leading platform for Test, Measurement, and Control. PXI combines PCI electrical-bus features with the rugged, modular, Eurocard packaging of CompactPCI and then adds specialized synchronization buses and key software features. These systems serve applications such as manufacturing test, military and aerospace, machine monitoring, automotive, and industrial test. National Instruments is the creator and leading provider of PXI. PXI platform covers system throughput and also modularity-upscale requirements of the VLC research.

High level system architecture of the SD-Baseband System is drawn in Figure 3. The main hardware ingredients of the system are depicted in detail within the following sections.

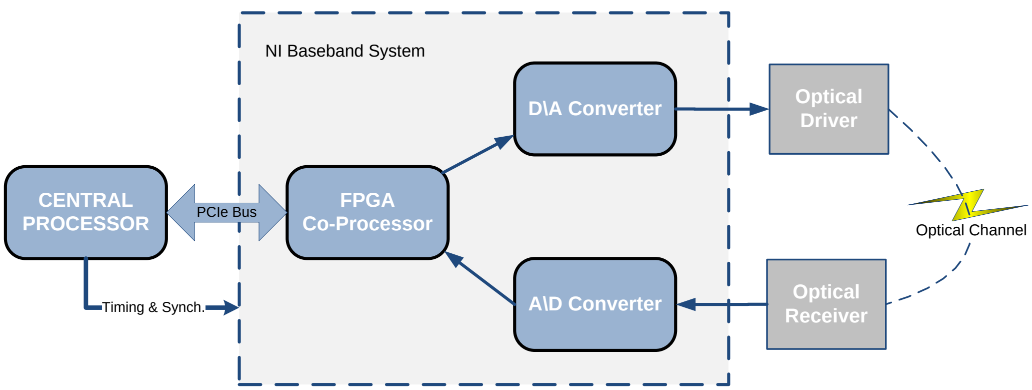


Figure 3 – High Level System Architecture

Although many configurations are possible with both architectures, the SD-Baseband for VLC Communication System is presented with 2 common configuration:

1. Low-Channel count and highly portable USRP based systems
2. Scalable-Channel count, high performance PXI based systems

The hardware and software platform elements combine to form an architecture that scales from 1x1 uni-directional link into synchronized multiple channel MIMO systems. This document outlines 1x1 and 2x2 configurations for USRP & PC based systems and 2x2 up to 32x32 channel configurations for PXI based scalable-channel count systems. In general USRP systems are better suited for mobile, lower channel count and lower bandwidth applications, where PXI systems are well suited for multi-channel, low-skew, high bandwidth research topics. Note that, massive channel counts are also possible with multi-PXI chassis combinations but not included in this document.

In Figure 4; NI USRP based 1 and 2 Channel options are shown. Although each USRP can accommodate 2x LFTX and 2x LFRX front-end daughterboards; for better spectral performance it is better to separate the 2 channel and 2-way link configurations into independent USRP systems. For that reason; only in configuration #1 is based on single USRP system and others require Qty.2 USRPs.

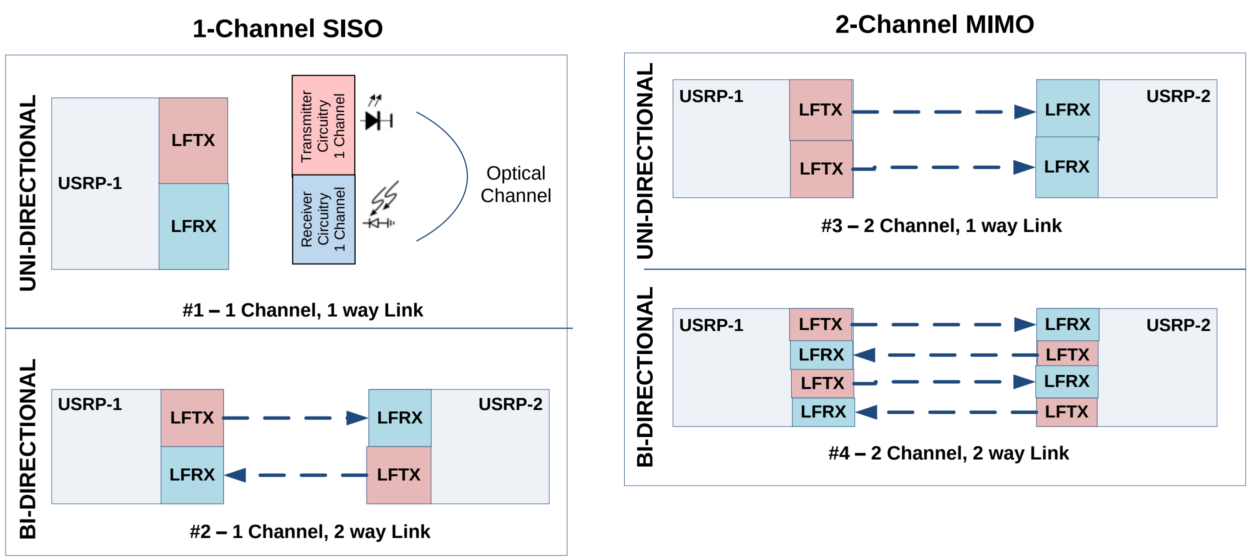
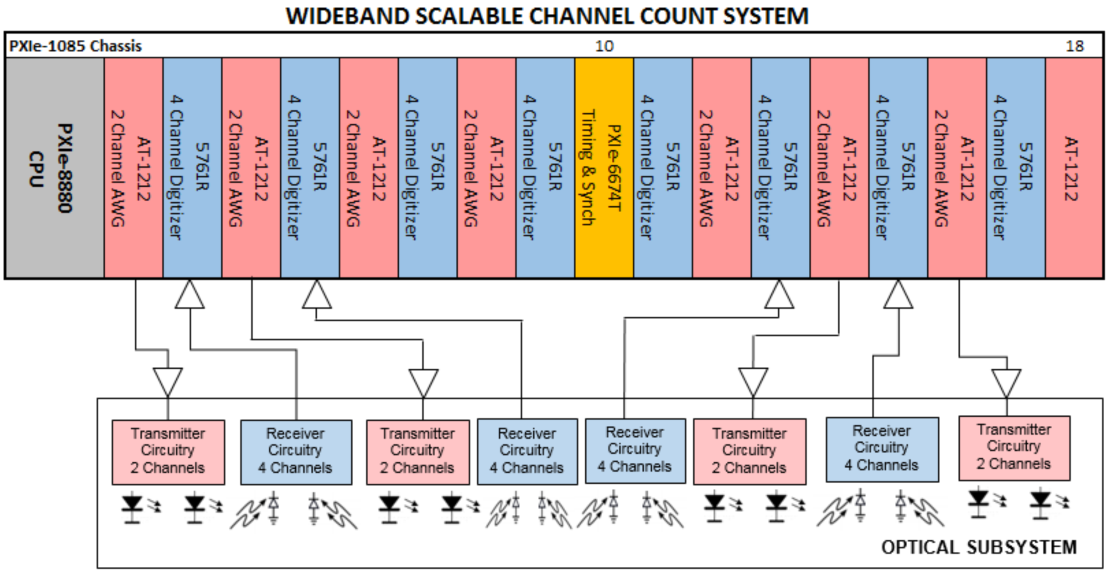


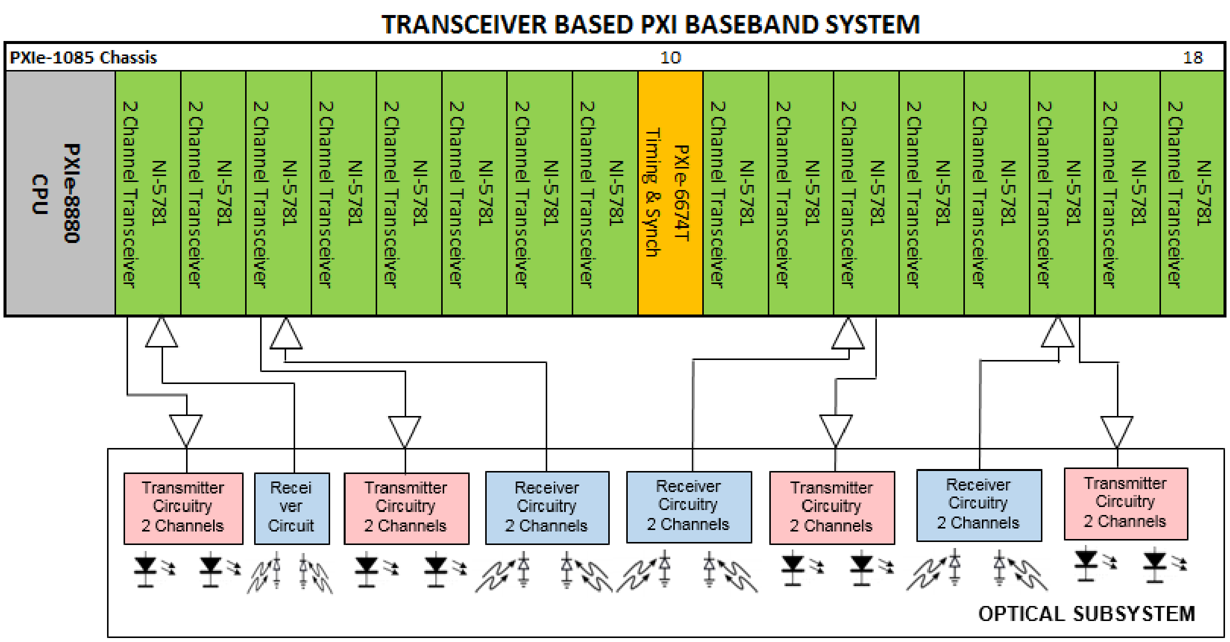
Figure 4 – Low Channel Count USRP Based Baseband Systems (optical subsystems are omitted except #1)

In Figure 5a and 5b; PXI based scalable channel count options are presented. In PXI; there is an option for channel bandwidth. First option is based on separate signal generators (AT-1212) and digitizers (NI 5762). The other option uses 2 channel baseband transceiver (NI 5781) modules which brings higher channel density into a single slot with reduced signal bandwidth and total communication throughput.

As depicted in Figure 5, each PXIe-1085 chassis aggregates the communication nodes (32 TX-32 RX and 16 TX-32 RX is shown) and runs real-time signal processing locally. The PXI chassis provides 17 slots open for input/output devices, timing and synchronization, FlexRIO FPGA boards for real-time signal processing. Depending on the type of the application 2-way optical link may require high data throughput to aggregate and process in real time; where the PXIe-1085 is well suited, supporting PCI Generation 2 x8 data paths capable of up to 3.2 GB/s throughput per slot.



(a)



(b)

Figure 5 – a) Wide-bandwidth Baseband System b) Transceiver Based PXI Baseband System for VLC (not all connections are shown)

Also Table 2 & 3 provides a quick reference of both low-channel (USRP based) and scalable-channel count (PXI based) system parts list for above predefined systems.

Product Type	Description	Part No	SISO		MIMO	
			1way	2ways	1way	2ways
USRP and Accessories	**NI USRP-2950R** *SDR With GPS Disciplined Clock*	783150-01	1	2	2	1
	LFTX USRP Daughterboard *DC - 30 MHz transmitter board*	782753-01	1	2	1	2
	LFRX USRP Daughterboard *DC - 30 MHz receiver board*	782752-01	1	2	1	2
	Power Cord for USRP-RIO	783490-01	1	2	2	2
	ExpressCard PCIe Interface Kit *PCIe connectivity to Laptops*	783347-01	1	2	2	2
	Laptop with ExpressCard Slot	User Supplied	1	2	2	2
	SMA-SMA Cable (1m)	783469-01	2	4	4	6
	LabVIEW Research Only License (1 user)	784213-3502	1	1	1	1

Table 2 – Parts List for USRP Based Baseband Systems

Product Type	Description	Part No	Wideband		Transceiver	
			2x4	16x32	2x2	32x32
PXI Chassis & Accessories	**PXIe-1085** *18 Slot 3U Chassis, 24 GB/s BW*	783588-01	1	1	1	1
	PXI Power Cord *240V, 10A, Euro, Right Angle*	763067-01	1	1	1	1
	PXIe-8880 *Xeon Eight-Core Win7 Controller*	783513-04	1	1	1	1
	24 GB RAM Upgrade PXIe-8880	783813-01	1	1	1	1
Baseband Modules	**NI 5781** *2 Channel Transceiver Adapter for NI FlexRIO*	781267-01	0	0	1	16
	MCX Plug to SMA Plug Cable (1m)	188377-01	0	0	4	64
	MCX 50 Ohm Termination Plug	778831-01	0	0	4	64
	PXIe-7966R *LabVIEW FPGA Programmable Module (Xilinx Virtex-5 SX95T)*	781805-01	0	0	1	16
	NI 5761 *4 Channel Digitizer Adapter for NI FlexRIO*	781287-02	1	8	0	0
	AT-1212 *2 Channel AWG Adapter for NI FlexRIO*	782248-02	1	8	0	0
	SMA to SMA Cable (1m) *Coax, RG-402, 50 Ohm*	781845-01	6	48	0	0

	PXIe-7976R *LabVIEW FPGA Programmable Module (Xilinx Kintex-7 410T)*	783625-01	2	16	0	0
Timing & Synch.	**PXIe-6674T** *Timing and Multichassis Synchronization Module*	781037-01	1	1	1	1
	PXI EMC Filler Panel Kit (Qty.6) *Required for empty slots*	778700-01	14	0	15	0
	SMA 100 (0.3m) *SMA Male to SMA Male Flexible Cable*	763444-01	2	8	0	0
SW	**LabVIEW Research Only License (1 user)**	784213-3502	1	1	1	1

Table 3 –Parts List for PXI Based Baseband Systems

4. SD-Baseband for VLC - Hardware and Software Elements

Designing a modular mmWave Communication system requires five key attributes:

1. Flexible SDRs with high speed & precision A/D and D/A converters that can acquire and transmit baseband signals
2. A high-throughput deterministic bus for moving and aggregating large amounts of data
3. High-performance FPGA based processing for PHY and media access control (MAC) execution to meet the real-time performance requirements
4. Clock and trigger synchronization sub-systems for multi-channel operation

Ideally, these key attributes can also be rapidly customized for a wide variety of research needs.

NI SD-Baseband for VLC System combines high-speed baseband modules, FPGA co-processor modules. and LabVIEW software to provide a programmable, robust, deterministic prototyping platform for research. For low-channel count, mobile applications; NI USRP modules are the recommended option. For multi-channel architectures; high-throughput PXI systems are used. This section details the various hardware and software elements used in both systems.

USRP Software Defined Radio

The USRP RIO software defined radio provides an integrated 2x2 MIMO transceiver and a high-performance Xilinx Kintex-7 FPGA for accelerating baseband processing, all within a half width-1U rack-mountable enclosure. It connects to a host controller through cabled PCI Express x4 to the system controller allowing up to 800 MB/s of streaming data transfer to the desktop or PXI Express host computer (or laptop at 200 MB/s over ExpressCard). Figure 6 provides a block diagram overview of the USRP RIO hardware.

USRP RIO is powered by the LabVIEW reconfigurable I/O (RIO) architecture, which combines open LabVIEW system design software with high-performance hardware to dramatically simplify development. The tight hardware and software integration alleviates system integration challenges, which are significant in a system of this scale, so researchers can focus on research. Although the NI application framework software is written entirely in the LabVIEW programming language, LabVIEW can incorporate IP from other design languages such as .m file script, ANSI C/C++, and HDL to help expedite development through code reuse.

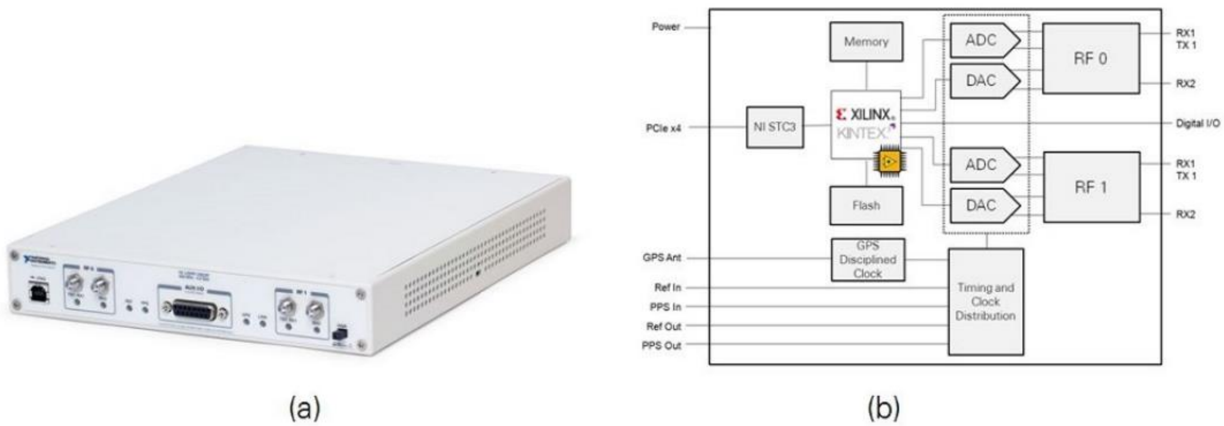


Figure 6-USRP RIO Hardware (a) and System Block Diagram (b)

High-Speed A/D and D/A Baseband Modules

The SD-Baseband for VLC System uses FlexRIO FPGA based modular instruments for baseband signal generation and acquisition. FlexRIO FPGA modules are flexible, high-performance processing modules, programmable with the LabVIEW FPGA Module, within the PXI form factor.

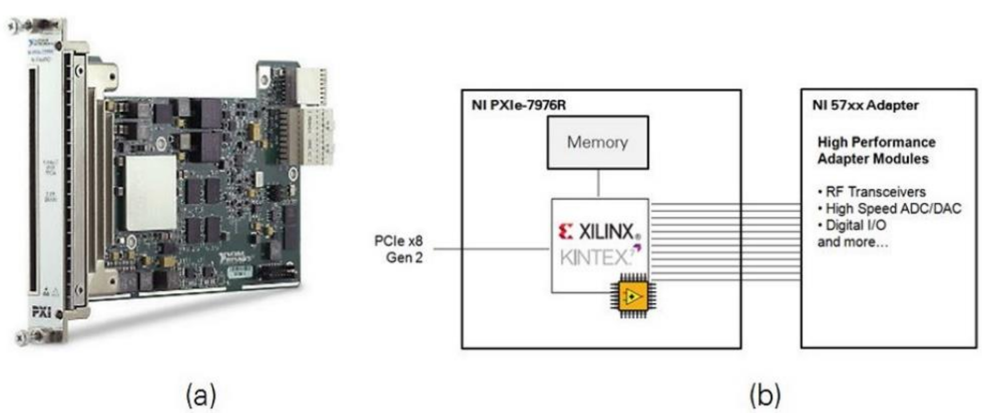


Figure 7 - PXIe-FlexRIO Module (a) and System Diagram (b)

As listed in Table 3; there are 2 different options (Wideband, Transceiver) for the baseband signals:

1. WIDEBAND: This option is based on NI 5761 wideband, high-speed digitizer and AT-1212 high-speed signal generator adapter modules for FlexRIO.
2. TRANSCEIVER: This option is based on NI 5781 baseband transceiver adapter for NI's FlexRIO modules.

For both cases; channels are accessible through the FPGA fabric using the LabVIEW FPGA module to the pin level. Adapter module details are given as follows:

Figure 8 - PXIe-FlexRIO Module and Baseband Adapters

NI 5761

For acquiring the baseband signals of the photodiode subsystems, NI 5761 provides a DC-coupled, up to 500 MHz analog bandwidth and a highly sensitive analog-to-digital conversion front end to FlexRIO FPGA modules. Quad, simultaneous sampling 250 MS/s ADCs provide the tight synchronization per module. Also; multiple 5761s are easily synchronized thanks to the timing & synchronization capabilities of the PXI backplane. In order to synchronize multiple 5761s; additional PXI-6674T timing and synchronization module is required for clock generation and sharing

AT-1212

For generating the high-speed baseband communication signals, Active Technologies AT-1212 provides a DC-coupled, up to 480 MHz analog bandwidth, digital-to-analog conversion front end to FlexRIO FPGA modules. Dual, simultaneous sampling 1.25 GS/s DACs provide crisp signals and tight synchronization between channels. Also; multiple AT-1212s are easily synchronized thanks to the timing & synchronization capabilities of the PXI backplane.

NI 5781

The NI 5781 is an analog two-input, two-output NI FlexRIO adapter module. The two 100 MS/s, 14-bit, differential, DC-coupled inputs and two 100 MS/s, 16-bit, differential, DC-coupled outputs are optimized for interfacing with baseband signals of LEDs and photodiodes. With 40 MHz bandwidth (-3 dB) on the anti-alias (input) and reconstruction (output) filters, crisp and clean signals are achieved.

On the NI FlexRIO field-programmable gate array (FPGA) module, you can implement custom RF modulation and demodulation, channel emulation, bit error rate testing, or spectral monitoring and jamming. In addition, with the appropriate 50 Ω termination on the negative (-) inputs and outputs, the module can be used as a single-ended device in ultrahigh-speed control applications.

PXI Express Chassis Backplane

The SD-Baseband for VLC System uses PXIe-1085, an advanced 18-slot PXI chassis that features PCI Express Generation 2 technologies in every slot for high-throughput, low-latency applications. The chassis is capable of 4 GB/s of per-slot bandwidth and 24 GB/s of system bandwidth, which covers the bandwidth and latency requirements of the VLC systems. Figure 3 shows the dual-switch backplane architecture. Multiple PXI chassis can be daisy chained together or put in a star configuration when building higher channel-count systems.

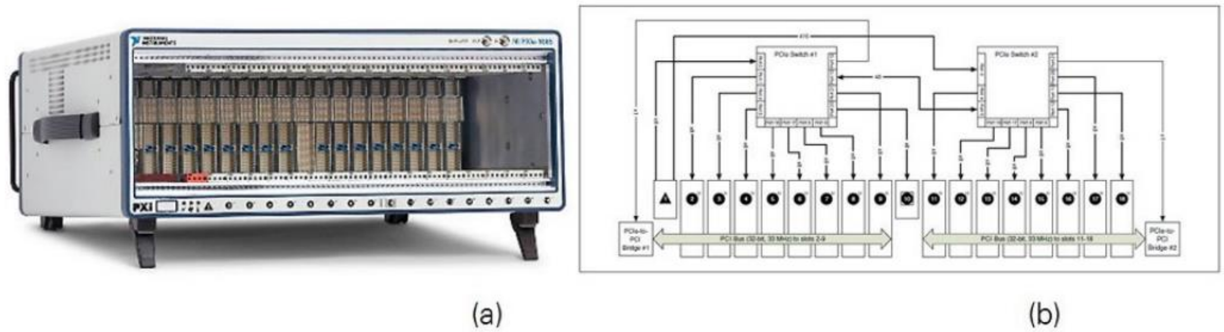


Figure 9 - 18-Slot PXIe-1085 Chassis (a) and System Diagram (b)

High-Performance Reconfigurable FPGA Processing Module

NI's Baseband for VLC System uses FlexRIO FPGA modules to add flexible, high-performance processing modules, programmable with the LabVIEW FPGA Module, within the PXI form factor. The PXIe-7966R and PXIe-7976R FlexRIO FPGA modules can be used standalone, providing a large and customizable Xilinx FPGAs with PCI Express Generation 2 x8 connectivity to the PXI Express backplane.

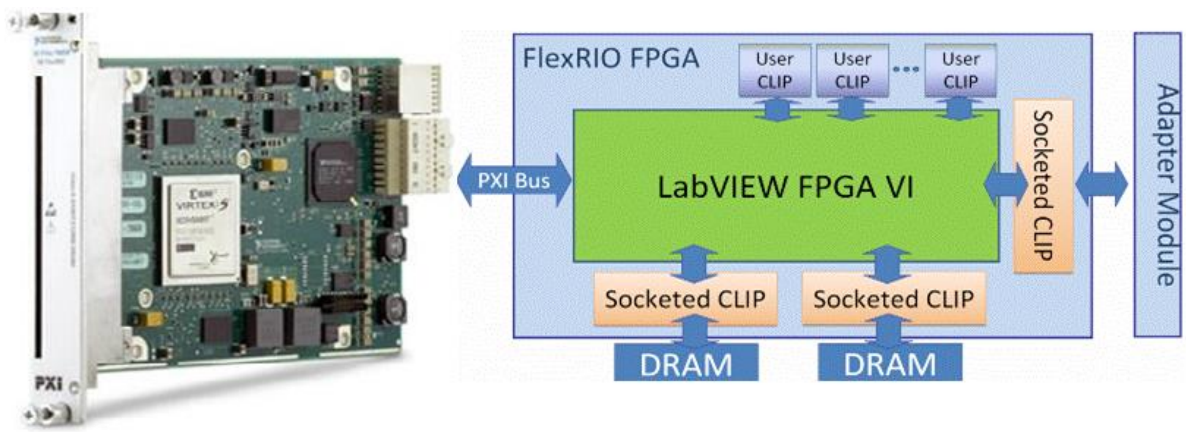


Figure 10 - PXIe-7976R FlexRIO Module (a) and System Diagram (b)

Multiple FPGA modules can share the common system clock, can transfer data among each other using DMA transfers over PCI Express bus. By utilizing the Peer-to-Peer streaming technology these operations will not overload the CPU.

Clock Synchronization Systems

Timing and synchronization are important aspects of any system that deploys large numbers of radios; thus, they are critical in a mmWave Communication System as well. The PXI system shares a common 10 MHz reference clock and a digital trigger to start acquisition or generation on each channel, ensuring system-level synchronization across the entire system (see Figure 6). The PXIe-6674T timing and synchronization module with OCXO, located in slot 10 of the master chassis, produces a very stable and accurate 10 MHz reference clock (80 ppb accuracy) and supplies this clock along with a digital trigger signal to the additional PXI chassis' hosting additional channels. For systems physically separated such as channel sounding applications, using GPS clock with the PXI-6683 GPS Modules provides another synchronization solution.

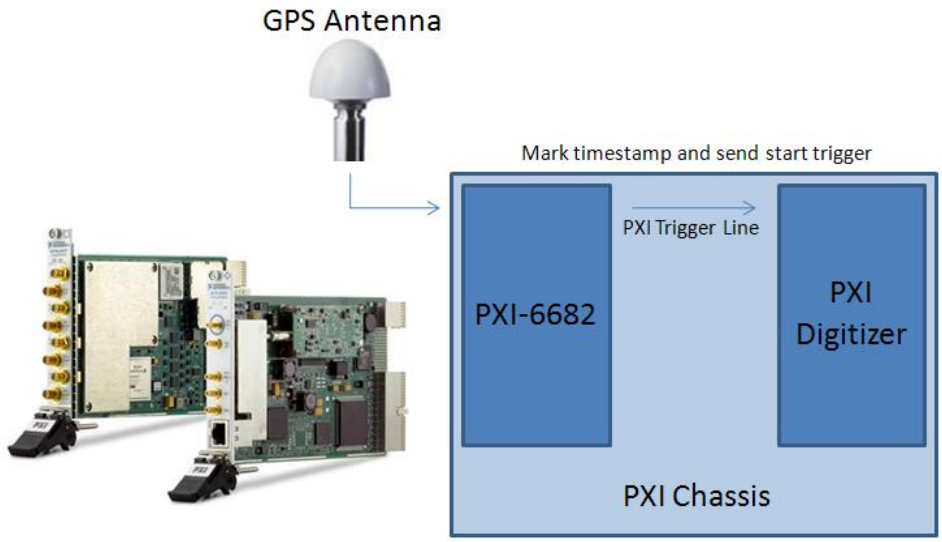


Figure 11 – SD-Baseband for VLC System Clock Distribution Diagram (for 2 separate site configuration)

LabVIEW System Design Suite

LabVIEW provides an integrated tool flow for managing system-level hardware and software details; visualizing system information in a GUI, and developing general-purpose processor (GPP), real-time, and FPGA code; and deploying code to a research testbed. With LabVIEW, users can integrate additional programming approaches such as ANSI C/C++ through call library nodes, VHDL through the IP integration node, and even .m file scripts through the LabVIEW MathScript RT Module. This makes it possible to develop high-performance implementations that are also highly readable and customizable. All hardware and software is managed in a single LabVIEW project, which gives the researcher the ability to deploy code to all processing elements and run testbed scenarios with a single environment. The SD-Baseband for VLC System uses LabVIEW for its high productivity and ability to program and control the details of such as I/O via LabVIEW FPGA.

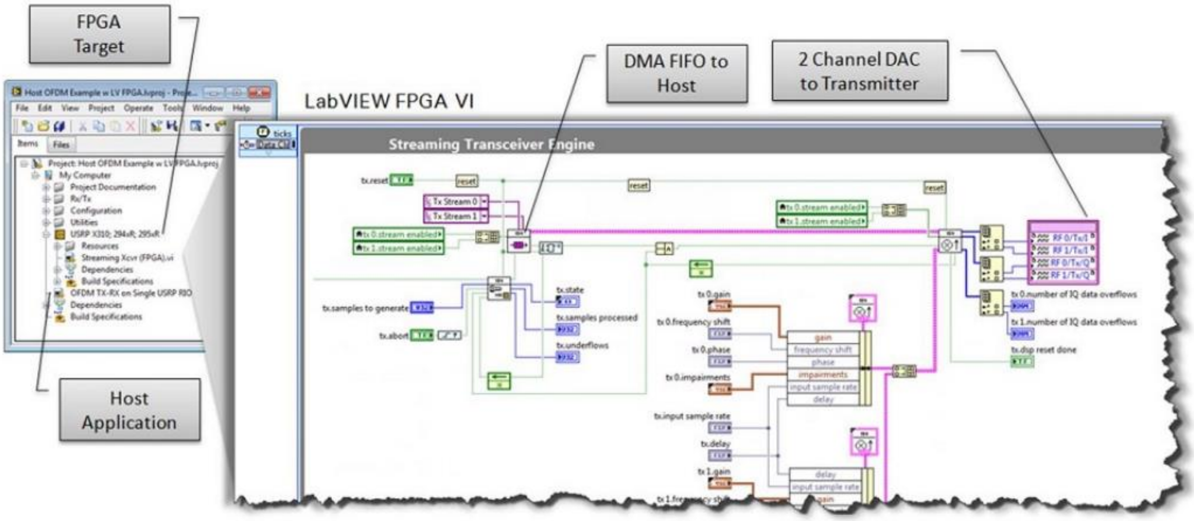


Figure 12 - LabVIEW Project and LabVIEW FPGA Application

5. Software Architecture

The SD-baseband for VLC systems software is based on open & scalable software of Over-the-Air Video Stream Using OFDM TDD Example. The example is scalable to run on a single USRP device and also in multiple FPGA boards for PXI multi-channel based systems.

Code is divided into Host and FPGA processing diagrams. Each diagram is self-documented and there are multiple places for integrating new algorithms with intuitive explanations.

Excerpts from host interface and FPGA diagrams are given in Figure 13 and Figure 14.

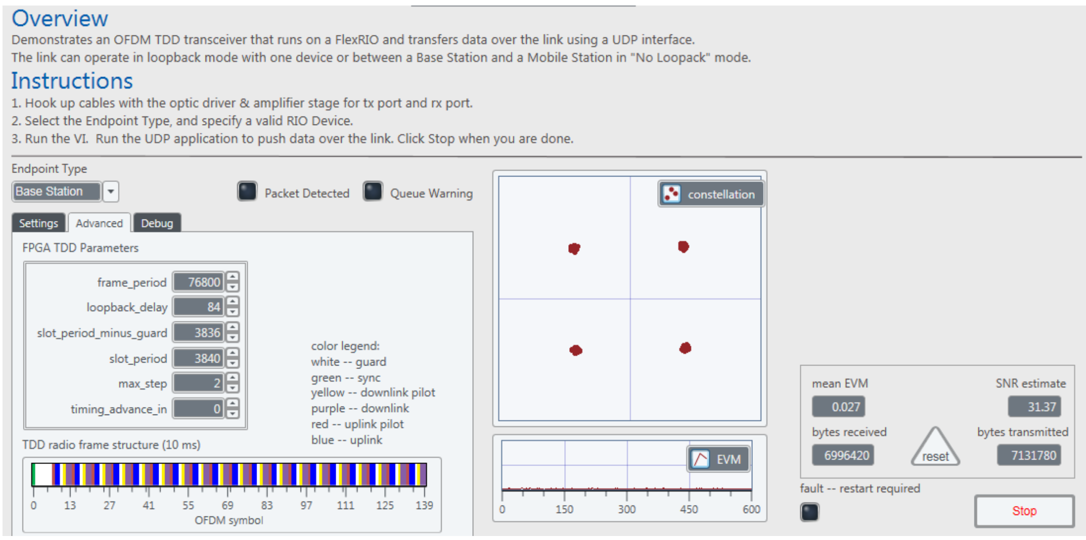


Figure 13 – User Interface Running on Host

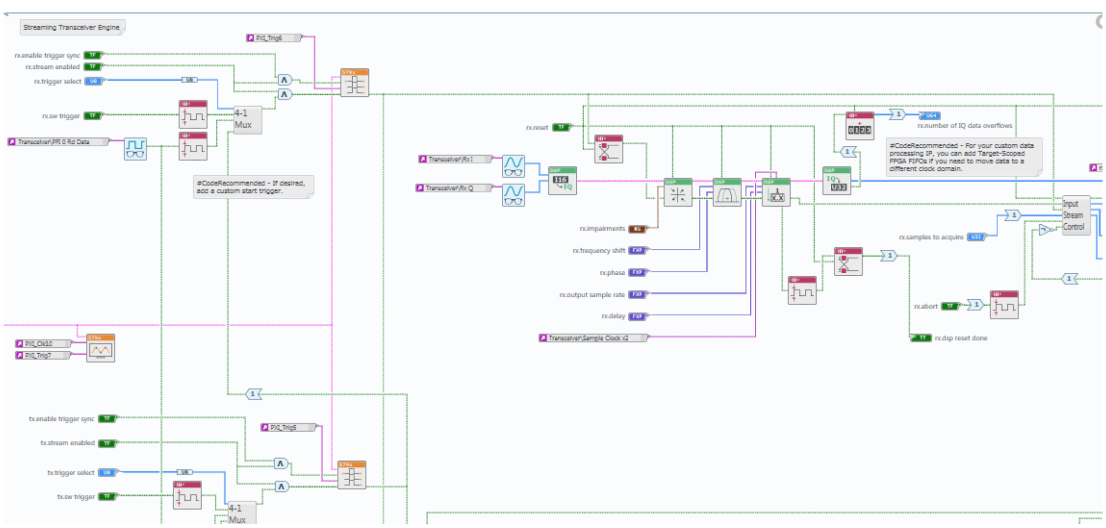


Figure 14 – Streaming FPGA Block Diagram for OFDM TDD Example

Starting at the baseband signals, the OFDM PHY processing is performed in the FPGA, which allows the most computationally intensive processing to happen near the optical transducers. Although some aspects of the MAC are implemented in the FPGA, the majority of it and other upper layer processing are implemented on the GPP. The specific algorithms being used for each stage of the system is an active area of research. The entire system is reconfigurable, implemented in LabVIEW and LabVIEW FPGA—optimized for speed without sacrificing readability.

6. Conclusion

NI technology is revolutionizing the prototyping of high-end research systems with LabVIEW system design software coupled with the USRP and PXI platforms. This document demonstrates one viable option for building a baseband system in an effort to research Visible Light Communication Systems. The unique combination of NI technology introduced throughout the document enables the synchronization of time and frequency for a large number of optical channels and the PCI Express infrastructure addresses throughput requirements necessary to transfer and aggregate data samples on the uplink and downlink. Design flows for the FPGA simplify high-performance processing on the PHY and MAC layers to meet real-time timing requirements.

To ensure that these products meet the specific needs of wireless researchers, NI is actively collaborating with leading researchers and thought leaders such as Edinburgh University. These collaborations advance exciting fields of study and facilitate the sharing of approaches, IP, and best practices among those needing and using tools like the SD-Baseband for VLC Systems.

Read more solutions at ni.com/rf (**http://www.ni.com/rf**).

7. Contact Information

For further details, price inquiries and product demonstrations; feel free to contact NI through the following channels:

ACADEMIC INQUIRIES

ENOVAS Mühendislik
Kaya Sultan Sok. No:83 Hayriye İş Merkezi
Kadıköy / İSTANBUL
Mail: info@enovas.com.tr
Call: +90-216-576 20 61

GENERAL INQUIRIES

National Instruments Asia Minor A.Ş.
Kore Şehitleri Cad. No:1/A
Şişli / İSTANBUL
Mail: ni.turkey@ni.com
Call: +90-212-279 30 31

8. References

H. Haas, L. Yin, Y. Wang, C. Chen "What is LiFi" in Journal Of Lightwave Technology, (http://www.homepages.ed.ac.uk/hxh/Li-Fi_PAPERS/what_is_LiFi_invited_jlt_ecoc15.pdf) Oct. 2015

"Visible light communication" (https://en.wikipedia.org/wiki/Visible_light_communication) Feb. 2016

M. Rahaim, T.D.C. Little, A. Mirvakili, V.J. Koomson, S. Ray and M. Hella "Software Defined Visible Light Communication," in WinnComm-SDR Wireless Innovation Forum Conference on Wireless Communicaitons Technologies and Software Defined Radio, Schaumburg, IL, March 2014.

Vucic, J.; Langer, K.-D. "High-speed visible light communications: State-of-the-art", in Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012 and the National Fiber Optic Engineers Conference.