On the Development of Modular Optical Wireless Elements (MOWE)

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***Abstract*—We report on the development of optical wireless arrays composed of multiple electrically interconnected optical modules (i.e., elements) forming a flat or curved terminal that is inexpensive, lightweight, and easy-to-assemble. The technology enables economic access to wide field-of-view optical communication for last-mile broadband connectivity. The smart modules provide reconfigurability, as well as local and central processing capabilities, to enable innovative short- and medium-range applications for free-space optics (FSO) beyond traditional fixed, high data rate, point-to-point links. We demonstrate several proof-of-concept optical arrays, including flat, dome, and spherical shapes. An omnidirectional spherical optical terminal weighs approximately 150*g* and costs less than $200. This technology can facilitate multiple simultaneous communication links at data rates up to 1*Mbps*. The MOWE concept is flexible and scalable to various applications like user tracking, mobile FSO, multi-hop mesh networks, noise measurements, indoor communications, and MIMO FSO, among others.**

Keywords*—*Optical Array, Optical Antenna, Modules, FSO, MIMO, Multi-element.

I. Introduction

Free-space optical (FSO) communications have primarily been considered for long-range and fixed point-to-point terrestrial or satellite applications. Vast opportunities, however, lie in the short-range, last-mile market where mobile users seek broadband connectivity at the lowest cost, smallest size, lightest weight, and minimum power consumption. Regarding mobility, FSO is clearly not competitive when compared with RF and microwave. Nonetheless, directional technologies (e.g., FSO and microwave) have many clear advantages relative to security, interference, spectrum availability, power consumption, and antenna size.

One method for overcoming light directionality in FSO is to exploit spatial diversity of multiple optical antennas [1]. Advantages of spatially distributed optical arrays were first recognized with the introduction of semiconductor laser arrays [2]–[4]. Currently, different wavelength lasers can be assembled on the same monolithic integrated circuit [5] (i.e., large-scale photonics integrated circuits (PIC), which enable wavelength and spatial diversity. Monolithic integration of semiconductor-based optical transceivers is a costly process requiring significant initial investments. Because the process is not scalable beyond standard chip dimensions, its use is inappropriate for large optical apertures.

Fiber bundle technology is a strong candidate for mobile FSO communication, and several research groups have been actively working in this area. An all-optical receiver fiber bundle with optical combining and a related lens system was developed in [6], [7]. Transmitter fiber bundles with various optical switching schemes were developed in [8]. Direct optical coupling of fiber bundles is discussed in [9]. Sets of MEMS-based switches and microlens arrays are used to control beam splitting and propagation through multiple fibers [10]. Johns Hopkins University Applied Physics Laboratory has developed a receiver fiber- bundle system with piezoelectric-controlled microlenses to optimize power coupling into a given fiber core as the source moves relative to motion between transmitter and receiver [11], [12]. Even though fiber bundle-based transceiver technology is much faster than semiconductor-based, the technology is still in its infancy with many barriers to commercialization (e.g., high cost of fibers and lenses, precision assembly requirements, and limited coverage, as well as scalability and manufacturability challenges).

LEDs, VCSELs (vertical cavity surface emitting lasers), and PDs (photo diodes) can be assembled on separate printed circuit boards (PCBs), and these can be spatially positioned in different geometries. This solution, although slower than fiber bundles, is inexpensive, scalable, and within reach of current technology. Transceiver modules were assembled in a spherical configuration in [13], [14] and in a cylindrical configuration in [15]. The latter work did not provide implementation details to prove feasibility beyond theoretical design. The former work by the University of Nevada is, to our knowledge, the most extensive in this domain. They developed line-of-sight (LoS) alignment and tracking algorithms for their spherical terminals and analyzed crosstalk among neighboring transceivers in [16]. They also performed theoretical analysis and simulation of coverage, node density and network end-to-end performance in [13], [17], and proposed 3D optical localization in [18]. Although the group provided prototypes and implementation details in [19], their concept is not scalable to different configurations. Weight and size of the supporting structure puts more constraints on possible applications and no clear path to mass production is provided, which is essential to reduce technology costs and remove barriers to market.

We propose a scalable and modular architecture that utilizes small and smart optical modules (transmitters and receivers) to build a variety of larger structures. These shell-like structures could be flat, spherical, or other curved geometric shapes that can be created from smaller elements (modules). This paper will further introduce this concept of modular optical wireless arrays in Section II. Implementation details and system features are given in Section III. Proof- of-concept prototypes are presented in Section IV, along with possible test setups. Finally, the paper concludes with future directions and suggested implementations.

II. The Modular Optical Wireless Elements

A single *array* is composed of multiple *modules* soldered side-by-side to form a single, continuous flat or curved surface that could be structurally supported by a 3D-printed plastic *frame*. The array, frame and a *central controller* with wired or wireless interface constitute a complete optical *terminal*. The MOWE concept is depicted in Fig. 1.

A. The Optical Module

Modules come in specific, standard polygonal shapes (e.g., hexagons, pentagons, and triangles) to form continuous surfaces. Each module serves as a single optical point-either transmitter, receiver, or transceiver. Transmitters can be either LEDs for short-range communication or VCSELs for longer range and higher output power. The receivers are photo diodes (or photo transistors) with high responsivity at visible or infrared light. Both transmitters and receivers are surface mounted devices with small form factor to free the bottom side of the module for other electronics. Although a single module might have multiple VCSELs/LEDs/PDs to increase transmission power or receiver sensitivity, it remains a single optical point from the spatial point-of-view.

Fig. 2 shows top-bottom illustrations of several modules fashioned from a variety of shapes and sizes. Hexagon modules shown in (a) and (d) have a side-to-side width of 20*mm*; hexagons in (b) and (e) have a width of 30*mm*. Pentagons in (c) and (f) are compatible with 30*mm* hexagons. The module top-side holds the optical component (e.g., LED, VCSEL or PD) precisely at the center of the board, while a microcontroller (MCU) and other electronic components are positioned on the bottom. Optical modules are free from connectors, wires, cables, and any other assemblies, rendering them as small and lightweight as possible. *Edge pcb connectors* are small areas of exposed copper positioned at module edges and sides for physically and electrically connecting adjacent modules. Larger edge connectors are used for power connection, while smaller ones are used for signal connection and networking.

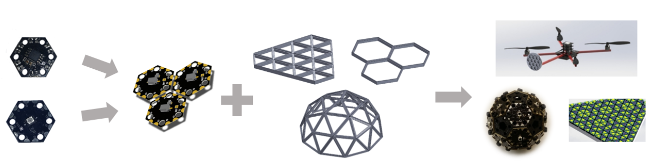
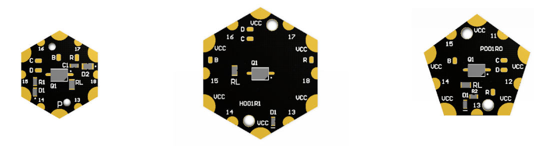
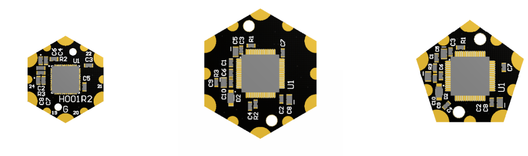


Fig. 1: Modular Optical Wireless Elements Concept.

From left to right: Individual modules are assembled into array. Arrays are fitted with structural 3D-printed frames. Arrays and frames make a complete terminal that can be used in various applications, e.g., on board a multirotor UAV.



(a) Top. (b) Top. (c) Top.



(d) Bottom. (e) Bottom. (f) Bottom.

Fig. 2: 3D Illustration of Optical Modules (Scale 1:2).

Hardware and firmware are designed so that the optical module connect with other modules using any of its side ports regardless of its orientation. The only constraint is to solder all modules facing the same orientation.

Modules communicate with each other using an asynchronous half duplex or full duplex serial protocol. Given a hexagon shape, each MCU overseas six serial ports to communicate with neighboring modules. A direct memory access (DMA) controller manages data transfer between these ports with minimal CPU intervention, making the modules invisible for transit traffic and enabling non-adjacent modules to connect seamlessly with one another. The MCU within each module renders it as a smart module, not merely an I/O point. Basic calculations can be run locally (e.g., noise cancellation, channel coding, and signal modulation/demodulation, among others.) A complete distributed sensing and control architecture is also possible, where all algorithms run locally and the central controller is merely used as an interface with the outside world.

B. The Optical Array

Hexagons can be used for flat arrays (i.e., beehive-like structures). Hexagons and pentagons are used to create spherical arrays. A full spherical array (e.g., soccer ball or truncated icosahedron) is composed of 20 hexagons and 12 pentagons. Triangles are also used to create spherical arrays called geodesic spheres or geodesic domes.

Modules can be soldered horizontally to create flat arrays or at a specific angle to form curved arrays. The array is usually homogeneous, meaning that any module can be used as an I/O module to interface the array with the central controller. Although the configuration of some arrays could be self-supporting with merely solder joints, additional structural support could be provided via special 3D-printed plastic frames that take on the shape of the surface for added protection. These hollow structures add minimal overhead weight to the terminal. Fig. 3 shows a variety of flat and curved structural frames fitted with modules.

C. The Optical Terminal

In most scenarios, the array cannot solely communicate with the outside world. Instead, a central controller is needed to configure the array, send transmitted data, and forward

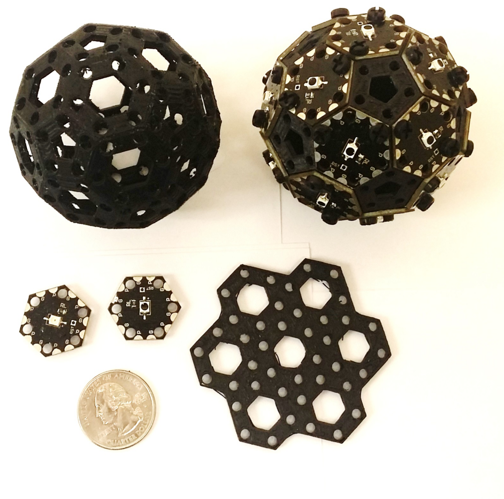


Fig. 3: Frames, Arrays and Modules.

Upper left: A spherical 3D-printed structural frame.
Upper right: Same frame fitted with hexagonal modules.
Lower right: A flat 3D-printed structural frame.
Lower left: Two hexagonal modules with a US quarter Dollar for size comparison.

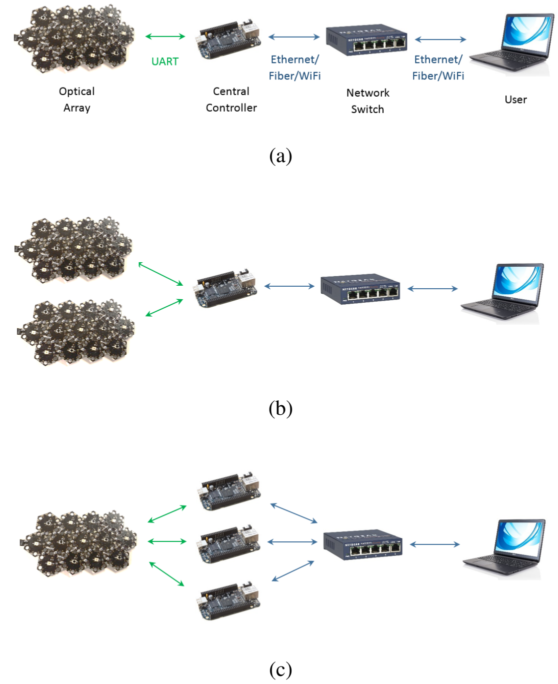


Fig. 4: Possible Configurations for an Optical Terminal.

received data to the user via a wired (e.g., Ethernet/fiber optics) or a wireless (e.g., cellular/WiFi) interface. The MOWE operating system running on all modules provides the user with intuitive control commands and simple descriptive language that can be accessed with terminal software via a virtual USB-serial port. Such commands allow users the flexibility to reprogram the array firmware, adjust array parameters, control and target specific modules or a group of modules, and stream data to or from any module or a group of modules. Fig. 3 illustrates three possible configurations for a terminal: (a) Entire array connected to a single controller; (b) More than one array connected to the same controller; or (c) Single array connected to multiple controllers. A fourth option not using a central controller is viable when running distributed control and sensing applications.

The assembled terminal can either be utilized as a fixed node or carried aboard a mobile ground vehicle (GV) or an unmanned aerial vehicle (UAV) [1], [20]. Battery and data storage capabilities can be added to the system, depending on operating scenarios.

III. MOWE Features & Implementation

A. Module Specifications

MOWE hardware design consists of six different modules: two small (20*mm*-optical resolution) transmitter and receiver hexagons for dense flat arrays plus two larger hexagons (30*mm*), and two pentagons (30*mm*) for flat and spherical arrays. Current module specifications are listed in Table I. Debug and programming ports are provided on the topside along with small LED indicator for easy module identification. Only 12 solder points are required, which makes assembly time less than one minute per module. Communication range basically depends on receiver sensitivity, which is related to load resistor R_L value. Default value is chosen to enable indoor communications with 4-5*m* range. It can be, however, adjusted according to the application requirements. Experiments showed maximum speed of 3*Mbps* for raw inter-array streams, which drops down a little bit in practical scenarios. Future generations will most likely boost higher communication speeds and use hardware accelerators. Fig. 5 presents an anticipated roadmap toward 1-*Gbps* raw datarate that can be boosted to support multi-*Gbps* communication with advanced modulation and coding schemes.

TABLE I: MOWE Hardware Specifications

Architecture	Peer-to-peer
Streaming speed	up to 1*Mbps*
MCU	32-bit ARM Cortex-M0, 48*MHz* with DMAs, 256*Kb* Flash memory
Module height	3.2*mm*
Optical resolution (Module center to center)	20*mm*, 30*mm*
Module weight	$< 2g$
Module cost	Approx. $6
Module power consumption (without sleep mode)	40-66*mW*
LED wavelength	850*nm*
LED angle of half sensitivity	$\pm 10^o$
LED radiant intensity	100*mW/sr*
PD wavelength	850*nm*, 940*nm*
PD angle of half sensitivity	$\pm 60^o$
Receiver optical sensitivity	$\approx 5\mu W/cm^2$ for R_L = 620 Ω

B. Command Line Parser

All modules run a custom-designed operating system called *Array Operating System* (AOS) that handles user interactions, inter-array communications, and array housekeeping functionality (e.g., cross-array routing, module labeling and identification, broadcast commands, firmware update, and others).

A *regular* user can interact with the array via the *command line parser* (CLP) utility within the AOS. The CLP can be accessed via any port in any module and features various intuitive control commands in a plain English language. Some commands are used to setup the array, ping the modules, rename them, and group them; other commands read samples from receiver modules and stream data in/out the modules at various speeds. More advanced commands are also available to update modules firmware on the fly, setup inter-array DMA streams, link two modules, and send a predefined signal out a transmitter module among others. These intuitive commands make the MOWE system easily accessible by any student/researcher regardless if he or she has hardware or Embedded Systems development expertise. *Experienced* users, on the other hand, can further leverage the system by writing their own firmware in C language or modifying the AOS and other available firmware implementations to suit their exact application.

C. Data Streaming

The AOS supports two modes of inter-module communication: routing and streaming. *Routing* protocol transfers messages between modules in single-cast, multi-cast, or broadcast fashion. The process utilizes short packets and keeps the port open for others. The speed, however, is slow (i.e., in the range of kbps) and the connection is not reliable. In *streaming* mode, dedicated DMA channels are configured, which supports reliable connections at speeds up to 1-2*Mbps*. Never the less, once configured as DMA streams, ports will be blocked and cannot be accessed for messaging. DMA streams are very reliable but difficult to control. They can be configured for single-input-single-output (SISO) and single-input-multiple-output (SIMO) fashion. Multiple DMA streams can be configured for port-to-port, port-to-front-end (and vice versa), and memory-to-front-end (and vice versa) channels. Fig. 6 depicts array-level DMA streams example.

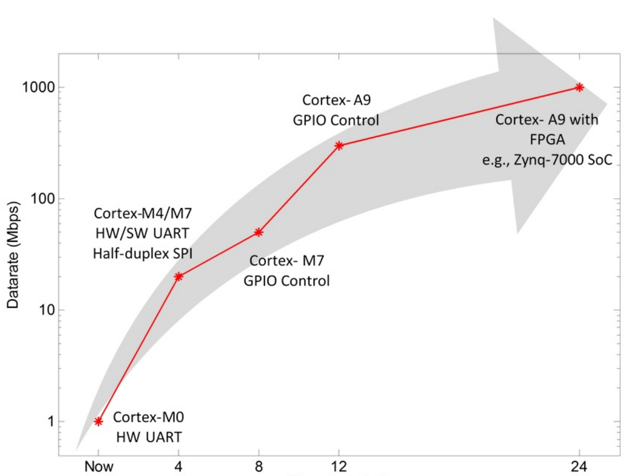


Fig. 5: Anticipated Roadmap Toward *Gbps*-speed MOWE System Using Present-day Technologies.

D. MOWE Tools

The MOWE development framework includes free software tools that aid in designing and debugging MOWE arrays, especially for large, complex designs.

1) MOWE-Tandy Simulator: Although MOWE arrays are inexpensive and easy to assemble, massive MIMO arrays composed of hundreds or thousands of modules are difficult to build and debug. We collaborated with the Tandy Supercomputing Center (TSC) [21] to create a simulator for MOWE arrays. The Tandy Simulator is a C/C++ multi-agent simulator based on Message Passing Interface (MPI) protocol and allows users to develop and test high-level MOWE applications or low-level AOS algorithms that can scale up to thousands of modules. Each module is simulated as a separate process that could run independently on a separate core or share resources with other processes.

2) MOWE Automatic Topology Generator: The automatic topology generator is a MATLAB program enabling users to design the array graphically, and then to generate the appropriate topology header file for inclusion with the modules firmware. The program will automatically generate all required parameters and configurations. The same generated topology header file is used to configure the MOWE-Tandy Simulator, as well. Fig. 7 shows a design of a flat 7-module array.

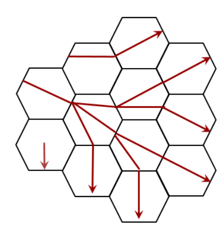


Fig. 6: Example of Array-level DMA Streams.

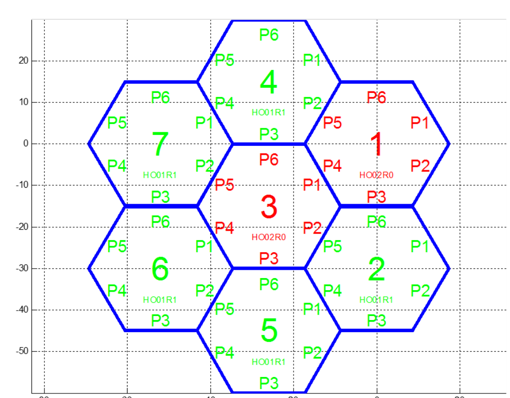


Fig. 7: An Example Using the Automatic Topology Generator.

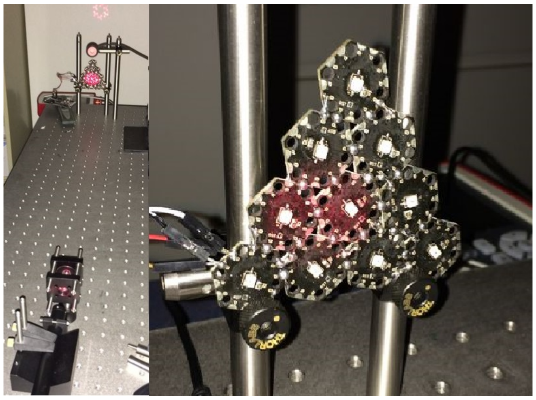


Fig. 8: Triangular 10-module Flat Receiver Array Under Test.

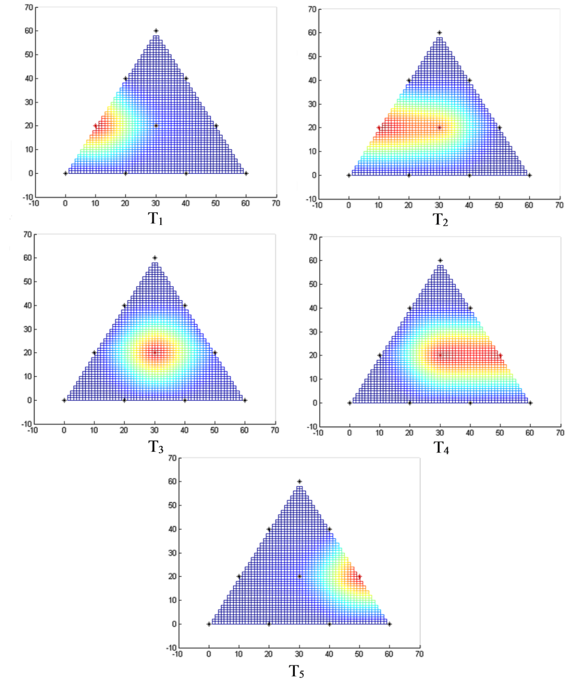


Fig. 9: Data Reconstruction of a Mobile User Crossing the 10-module Flat Array.

IV. Prototypes & Applications

We present in the following sections three proof-of-concept prototypes to illustrate some MOWE characteristics and applications. Our intent is not to provide detailed design and analysis, but rather to demonstrate MOWE capabilities and possibilities, stimulating readers to develop novel applications for MOWE in their respective research fields.

A. Flat Receiver Arrays

We constructed a flat array of 10 receiver modules, forming an equilateral triangle. (Fig. 8.) The array weighs less than $15g$ and does not require a supporting frame. The modules have an optical resolution of $20mm$, which yields $0.5 \times 20 \times 17.32 = 173.2mm^2$ total optical aperture size. The aperture is sampled at 10 discrete points, as shown in Fig. 9. The figure also shows a mobile user moving across the array from side to side. The sampled data are interpolated with a Gaussian interpolation function to accurately capture Gaussian beam movement. Such an array could aid in various applications (e.g., tracking mobile users, 3D localization, spatial diversity receivers, and detection of beam irregularities due to disturbance among others).

B. Spherical Arrays

In this prototype, we constructed an omnidirectional spherical terminal using hexagons and pentagons. (See Fig. 10.) Many variations of this terminal are possible. For example, it could be all-receivers, which is useful for tracking, detection, background noise measurements, and other functions. Alternatively, hexagons could be used as receivers, and pentagons could be left empty, yielding a lower-resolution terminal with 20 sampling points instead of 32, while reducing complexity, cost, and assembly time.

The optimal transceiver terminal design would utilize all 20 hexagonal faces as receivers and all 12 pentagonal faces as transmitters. We designed the terminal frame for use in various configurations, whether anchored on an optical table, attached to a UAV frame, or mounted from the ceiling, depending on intended application. (See Fig. 11.) Table II lists approximate SWAP (size, weight, and power) numbers, as well as prototype cost estimates for the three designs.

Fig. 10: Components of an Omni-directional Optical Wireless Terminal.

Upper left: A 3D-printed truncated icosahedron structural frame with $30mm$ optical resolution. The frame features a screw-like attachment for easy integration with other systems.
Upper right: A 3D-printed $100mm$-long terminal holder. The holder is compatible with standard optical table dimensions and thus can be easily integrated with existing optical setups.
Lower right: A 3D-printed hook attachment that enables the terminal to be mounted from the ceiling or from a UAV.
Lower left: Multiple modules with various shapes and sizes and a US quarter Dollar for size comparison.

TABLE II: Rough Estimates of Spherical Omnidirectional Terminal Specifications

Model	All-receivers	Hexagon-only-receivers	Transceiver
Modules weight (*g*)	58	40	58
Extra weight for solder, cables, etc. (*g*)	32	20	32
Frame weight (*g*)	55	55	55
Optical table holder weight (*g*)	25	25	25
Hook attachment weight (*g*)	5	5	5
Total weight using the holder (*g*)	170	140	170
Total weight using the hook (*g*)	150	120	150
Terminal cost without an external controller ($)	200	150	200
Assembly time (min)	180	120	180
Terminal power consumption without sleep mode and an external controller (*mW*)	1267-2112	792-1320	1267-2112

C. Dome-shaped Transmitter Arrays

Six transmitter modules (five hexagons and one pentagon) are assembled in a spherical dome shape, as shown in Fig. 12. This experiment demonstrates the use of multiple DMA streams for streaming data in a SIMO configuration. The signal is streamed into the array by module A at an average data rate of 100*kbps*. Next, it is transferred to module B, which transfers two exact copies of the same signal to modules C and D, rendering module B as a *switch*. All four modules transmit the same signal using their LEDs at 850*nm*. This design leverages MOWE spatial diversity to increase terminal field-of-regard, increase transmission power, and steer the signal at predefined angles to track a mobile user.

The shift delay for these data streams is approximately $11\mu sec$ per hop (Fig. 13), which can be compensated in firmware given that two different transmitters are required to be in precise synchronization. Timing error between duplicate streams inside a *switch* module is approximately $0.5\mu sec$.

Fig. 11: Assembled MOWE Omnidirectional Terminal. The terminal is anchored on an optical table (right) or mounted from the ceiling (left).

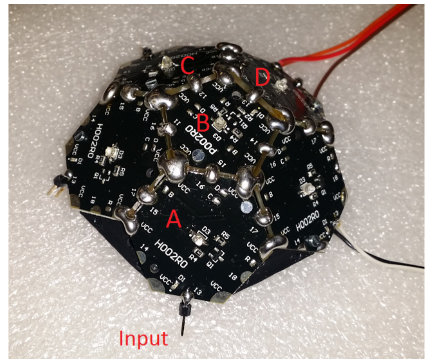


Fig. 12: Dome-shaped Transmitter Array.

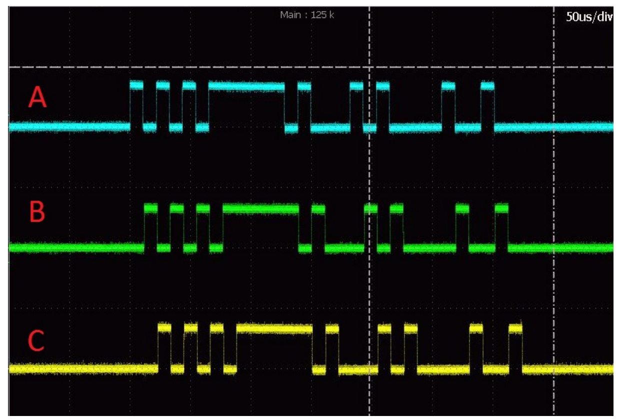


Fig. 13: Data Transmission using Three Transmitter Modules (A, B & C) with Two Hops.

Fig. 14 shows beam steering behavior using switch module B. In this example, module B is streaming incoming data from module A to either module C or D. Dome shape based on a truncated icosahedron results in $\pm 37.38^o$ steering angles, which means the terminal could cover a large field-of-regard by dynamically steering its beam. The beam can be steered between two different modules in as short as $25\mu sec$ (i.e., a steering speed of 40*kHz*).

V. Conclusion

We introduced in this paper our ongoing development of modular elements and architecture for optical wireless communication. The Modular Optical Wireless Elements (MOWE) consists of smart, electrically interconnected modules that can be combined together to build flat and curved optical wireless arrays. This novel design offers lightweight, inexpensive, and wide field-of-view terminals for various applications ranging from user tracking to broadband connectivity and MIMO FSO. We presented MOWE concept, hardware specifications, and firmware features, as well as some useful software development tools. Results from three proof-of-concept prototypes demonstrated feasibility of various implementations, such as omnidirectional optical antennas, beam steering, and mobility support. The complete MOWE development platform, including hardware schematics, firmware code, and software tools will be available to the scientific community as open-source

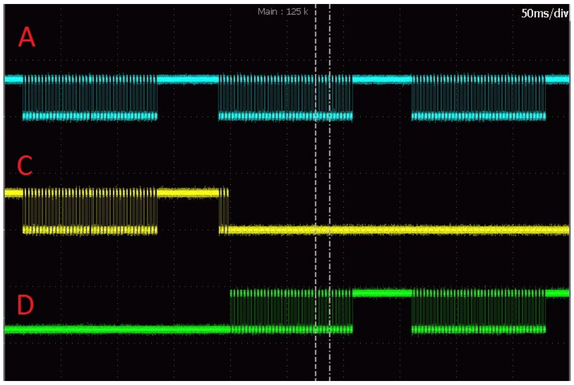


Fig. 14: Beam Steering using a Switch Module.

materials on our website: http://ouwecad.github.io/MOWE/. We hope researchers, professors and students will find innovative applications for MOWE, whether as a research and prototyping tool, or as an educational platform for various concepts in optical wireless communications as well as in other domains (e.g., digital signal processing, distributed sensing, and estimation, among others).

Acknowledgment

The authors would like to thank Brady Deetz and the Tandy Supercomputing Center (TSC) in Tulsa, Oklahoma for the development of the MOWE-Tandy Simulator. Special thanks also go to Fahed Babelli and Walid Balid from the University of Oklahoma for their assistance in hardware testing.

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