CENTER FOR INTEGRATED ACCESS NETWORKS

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In This Issue

MESSAGE FROM THE DIRECTOR

Nasser Peyghambarian

I would like to thank everyone who contributed to another very successful site visit this past May 15th and 16th. Our faculty, staff, and students put together an impressive collection of presentations, posters, and laboratory demonstrations for our NSF guests. I also want to thank our industry partners for their participation. We received notice of a recommendation for continued funding just one week after the site visit.

CIAN's many strategic planning meetings during the past year paid off as the site visit team reported that the "overall roadmap and vision is clear and the overall plan is highly coherent and consistent across the various thrusts with good linkages between the various teams." The NSF team also acknowledged CIAN's research productivity as evidenced by publications in high-profile journals such as *Nature* and *Science*. CIAN students will be happy to know that the site visit team saw them as "highly engaged" and reported that students "see how their research can contribute to other areas." The NSF team also noted that "significant progress has been made in the areas of diversity and education."

Our industry program continues to expand. Eight new companies joined CIAN in the last 12 months, and CIAN's interaction with industry is stronger than ever. The past year saw an initiation of successful collaboration between CIAN and the Optoelectronic Industry Association (OIDA).

CIAN's education and outreach program has also grown significantly. CIAN has strengthened partnerships with Native American and Hispanic-serving schools, and significantly increased the involvement of underrepresented minorities.

I look forward to working with you all during the upcoming year.

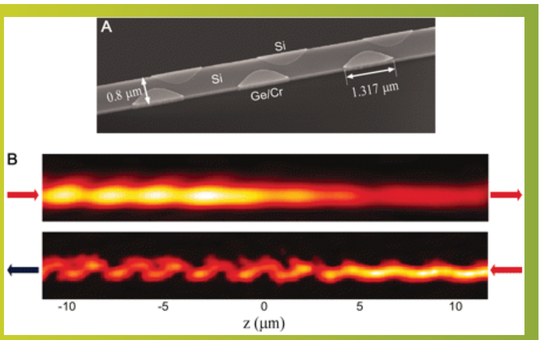
Research Highlights

Optical Diode on a Silicon Photonic Chip

A collaborative team from two CIAN partner universities, Caltech and UC San Diego, has discovered a way to establish non-symmetric mode propagation on a silicon chip. The breakthrough marks a significant achievement in the development of photonic chips that could replace electronic chips as the backbone of information technology. Their findings are published in the August 2011 edition of the journal Science*.

Although information systems now rely primarily on fiber-optic networks to connect and share data around the world using photons instead of electrons, the underlying computer technology is still based on electronic chips that are slower and more prone to data loss than photonic chips. The CIAN team developed a metallic-silicon optical waveguide system to channel light so it travels in different modes depending on its propagation direction. The mode is symmetric when traveling forward and asymmetric when reflected backwards along the same path. Similar to a diode in electronics, the backscattered light is dissipated and is not able to reach the source.

The one-way mode converter is Lorentz reciprocal and on its own cannot be used as the basis of an optical isolator. Nevertheless, the demonstrated asymmetric mode conversion, combined with the inherent optical nonlinearity of silicon, may be useful to achieve non-reciprocal transmission in a silicon waveguide on-chip without integrating other CMOS-incompatible materials. This discovery will help to realize a long-term goal of combining electronics with photonics to enable chip-scale, densely integrated circuits and systems in the future that will enable scalable, energy-efficient and cost-effective technology that will impact a wide range of computing systems, including supercomputers, data centers and the Internet.



(A) Scanning electron microscope image of the fabricated device. (B) Measured near-field amplitude distribution of light in the one-way mode converter for both forward (upper) and backward (lower) light

The work was performed by Dr. Liang Feng, who was a CIAN student before receiving his Ph.D. from UC San Diego, and then became a CIAN Postdoctoral Fellow at Caltech. Another CIAN student at UCSD, Maurice Ayache, conducted the measurements and analysis for the experiment.

***Nonreciprocal Light Propagation in a Silicon Photonic Circuit**, Liang Feng, Maurice Ayache, Jingqing Huang, Ye-Long Xu, Ming-Hui Lu, Yan-Feng Chen, Yeshaiahu Fainman and Axel Scherer, Vol. 333, pp. 729-733, Science, August 2011.

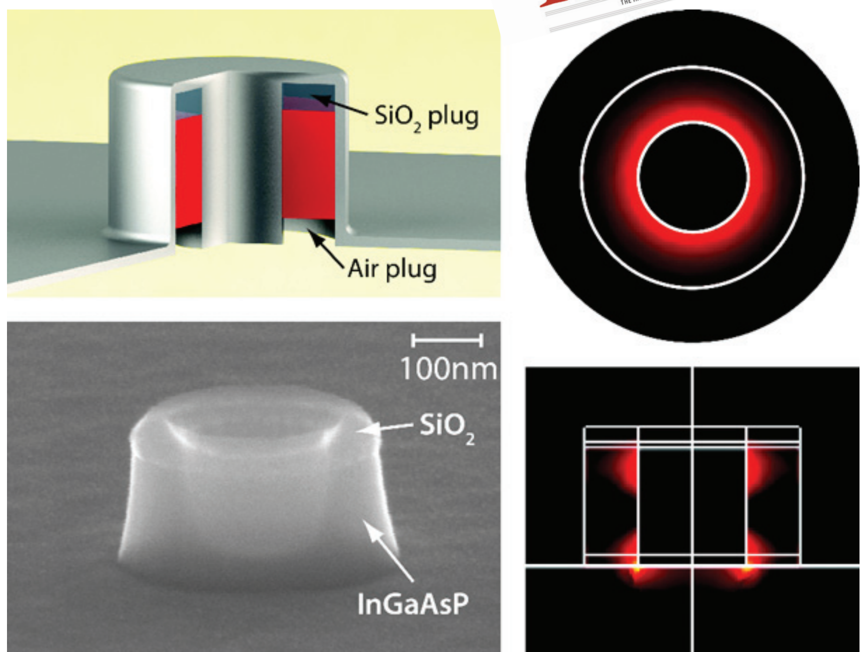
Threshholdless Nanoscale Coaxial Lasers

Researchers at UC San Diego reported in the February 9 issue of the journal Nature that they have made a thresholdless, nanoscale, continuous wave coaxial laser that operates at telecommunication wavelengths. The discovery is important for the realization of future, low-energy optical networks on computer chips, because arrays of such lasers will be able to send and receive optical signals powered only by the miniscule amounts of energy available in semiconductors.

The first commercial application of such nanolasers is expected to be in optical interconnects for on-chip communication. With their small size and lack of threshold, these devices can be modulated much quicker than existing lasers and they generate coherent emission at infinitely low energies, and can thus become a backbone for future communication devices on a chip. This work was spearheaded by CIAN Postdoctoral Fellow, Mercedeh Khajavikhan, at UC San Diego.

The team got the photons moving in the right direction by formulating their device as a coaxial waveguide. In this case, a metallic rod was surrounded by an indium-gallium-arsenic-phosphide semiconductor ring coated in metal. To form the lasing cavity, the waveguide was capped at both ends with low-index dielectric plugs. One plug, made of silicon dioxide coated in silver, forms a totally reflecting mirror; the other plug, which allows the pump beam to enter and the laser light to escape, is filled with air. This setup is sufficient to ensure that the laser cavity can emit energy only in the transmission mode, where the amount of light amplification is always high enough to overcome energy losses from the cavity itself.

The laser emitted coherent beams when excited by a pump source with an incident power of only 720 picowatts. The performance at room temperature was comparable to that achieved in the past with larger-sized resonators, with thresholdless operation occurring at 4.5 kelvin. The metallic coating around the semiconductor ring serves as a heat sink.



Design, fabrication and mode distribution of a coaxial nanolaser

***Threshholdless Nanoscale Coaxial Lasers**, M. Khajavikhan, A. Simic, M. Katz, J.H. Lee, B. Slutsky, A. Mizrahi, V. Lomakin and Y. Fainman, Vol. 482, pps. 204-207, Nature, February 9, 2012.

Hybrid EO Polymer / Sol-Gel / Silicon Modulators Drive Silicon Photonics

CIAN researchers from the University of Arizona and Intel Corp. have teamed up to develop electro-optic (EO) polymer modulators based on silicon. The modulators were enabled by the development of novel sol-gel cladding materials that feature an exceptional range of properties. An efficient, low-voltage, low-insertion-loss optical modulator is one of the key missing ingredients in the silicon photonics toolkit, since free carrier absorption modulators in silicon suffer from both high power consumption and high optical loss.

EO polymers have undergone extensive development over the last decade and are now getting close to full-scale integration into telecommunications applications. A significant development in the industry in 2011 was Telcordia's qualification of CIAN member company GigOptix's electro-optic polymer modulator – the first Telcordia-qualified EO polymer device of any kind. This established the viability of these materials for advanced applications, such as silicon photonics hybrid modulators. These devices require prior development of suitable cladding materials with an optimal set of optical and electrical properties to enable efficient poling of the EO polymers on silicon, and excellent performance. The figure shows the structure of a new index-tunable, titania-based sol-gel that was developed by CIAN graduate student Roland Himmelhuber in the UA research group of Prof. Robert Norwood and Prof. Nasser Peyghambarian. This long-shelf- life material can be deposited with low-cost, wet-film deposition techniques. It also has a composition tunable refractive index ranging from 1.7 to 2.1, and excellent dielectric and optical-loss properties. The sol-gels were used together with commercially available higher-EO-coefficient polymers to demonstrate for the first time an EO polymer/sol-gel/silicon phase modulator based on silicon nanowire geometry.

Next steps in the development of this technology involve further optimization of waveguide and electrode geometry to maximize the overall modulator figure of merit, followed by pursuit of both more advanced sol-gel materials and more sophisticated modulator designs.

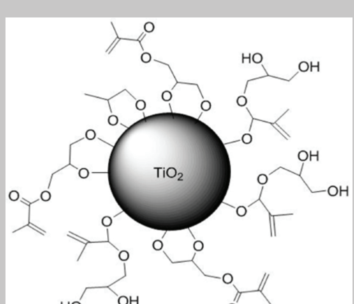
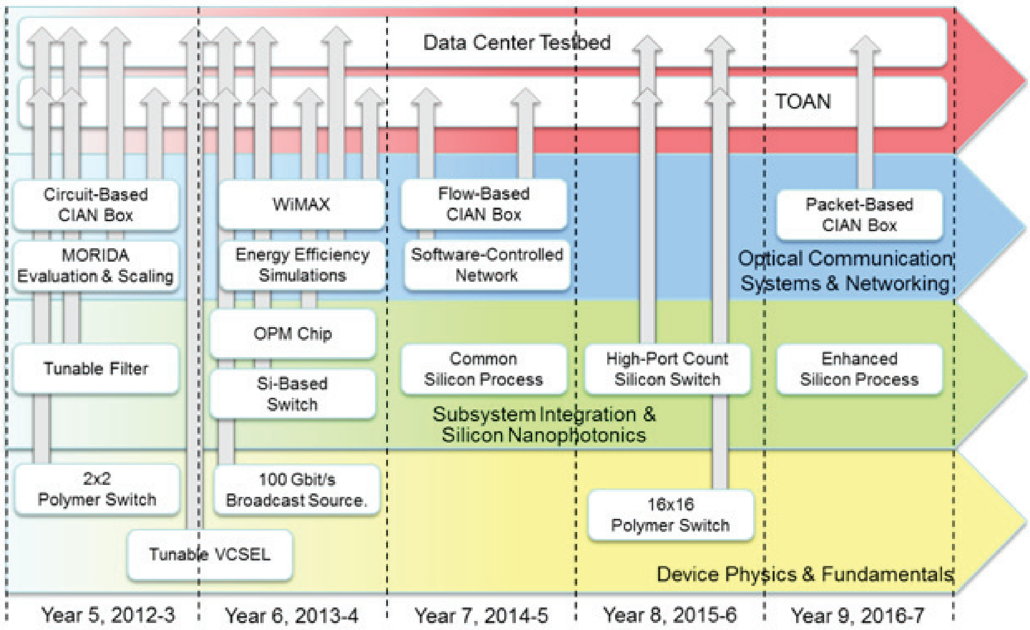


Figure above from R. Himmelhuber, P. Gangopadhyay, R. A. Norwood, D. A. Loy, and N. Peyghambarian, "Titanium oxide sol-gel films with tunable refractive index," *Optical Materials Express* 1, 252 (2011).

CIAN Timeline

The timeline for CIAN's strategic research plan is illustrated with the collection of key milestones and deliverables pictured to the right. CIAN's research on optics in Data Centers (Working Group 1) is currently driven by the MORDIA system, while CIAN's research on geographically-dispersed intelligent aggregation networks (Working Group 2) is driven by the developments of the CIAN box. Many of the deliverables from Thrusts 2 and 3 benefit both the MORDIA and CIAN box systems, and inserted into both the Data Center Testbed and Testbed for Optical Aggregation Networks (TOAN).



Five-year timeline for CIAN research

MORDIA, a demonstration of an optical mesh network with re-configurability on a microsecond time-scale, was constructed using commercial components during Year 4. MORDIA will be fully evaluated in Year 5 and modeled to identify roadblocks for scale-up to larger numbers of interconnected nodes. Projects from CIAN Thrust's 2 and 3 are developing components, with performance and functionality that are not commercially available, for use in the MORDIA system and insertion into the Data Center Testbed. An example of this technology is a fast tunable vertical-cavity surface-emitting laser (VCSEL), of potentially very-low cost that will replace multiple commercial lasers operating at different discrete wavelengths currently used in the MORDIA system.

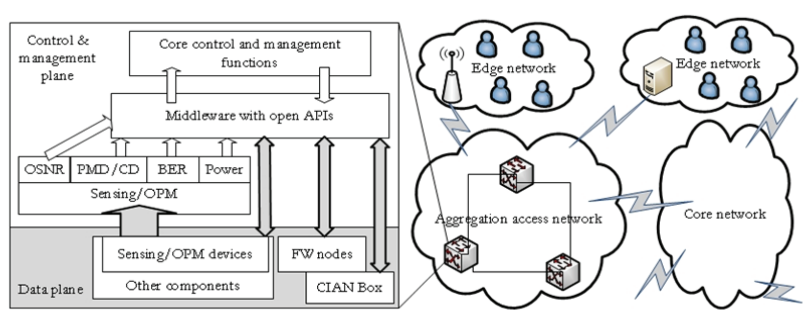
The CIAN box is a network node that can be inserted into an access network to create an adaptive aggregation that routes traffic flow according to user demand and network conditions, while minimizing power consumption, overcoming network impairments, and providing intelligence to match and optimize various applications. CIAN is developing a sequence of CIAN boxes that incorporates switching at increasingly shorter timescales. An improved version of the Stage 1 CIAN box (circuit-timescale switching), which will perform signal regeneration, only if required, based on data type and optical signal-to-noise ratio will be demonstrated in Year 5. Stage II and III CIAN boxes with packet-timescale and bit-timescale switching, respectively, are planned for later years. Technology from CIAN Thrust's 2 and 3 is essential for the development of the CIAN box. For example, an optical performance monitor fabricated on a silicon chip will be incorporated into a CIAN box and evaluated in the TOAN testbed during Year 6. A network node with the functionality of a CIAN box would be prohibitively large, energy inefficient, and costly without this enabling technology.

...Working Groups continue on page 4

Bringing Intelligence to Optical Networks

CIAN researchers from the University of Arizona and Fujitsu have demonstrated a novel intelligent network control and management software (CMS) system, which features several key new functionalities for 'smart' optical networks. The CMS utilizes dynamic decision-making, which can route messages intelligently with impairment-awareness, or put the highest-priority traffic on the best-quality fiber channels.

Demonstrated on CIAN's Testbed of Optical Aggregation Network (TOAN), the intelligent CMS is a key component in satisfying the requirements of emerging applications such as time-sensitive network applications (e.g., online real-time gaming and high-frequency stock trading on Wall Street) and high-throughput network applications such as e-health care services and high-definition video streaming. The CMS introduces cross-layer optimization and offers situation-aware network reconfiguration.



Architecture of control and management system for aggregation networks

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WG1: Scalable and Energy-Efficient Data Centers

A significant component of the next-generation aggregation networks involves accessing and interacting with increasingly larger data centers that form the backbone of the emerging search engines and cloud computing paradigm. The focus of Working Group 1 is to construct and test a hybrid electrical/optical network for use in a data center and to address issues with regard to aggregation of data transferred within data center, and between the data centers.

Our current research is focused in two interrelated areas. This first area is systems-level research to determine protocols to schedule a network that consists of a microsecond optically circuit-switched network running in parallel with a conventional packet-switched network in data centers and aggregation environments. This work is based on our Year 3 results in developing protocols for a space-switched optical network.

CIAN WG1 research is organized around increasing the bisection bandwidth, decreasing energy consumption and aggregation efficiency of modern data centers using prototype hybrid electrical/optical networks. Research using this prototype network defines the required system-level protocols as well as the required optical subsystem and component technology.

Our second area of research is determining the optimal physical architecture of the optical circuit-switched network. This research involves surveying optical switch technology and network architectures in the context of data center and aggregation environments. Several candidate systems based on this survey is being analyzed followed by a physical optical system design for the most promising candidates. These designs consist of both near-term solutions that can form the basis of a next generation prototype system as well as more speculative solutions that may be attractive in a 5- to10-year time frame. This work is highly coupled to the first area of interest because of the interplay between the optical circuit-switched architecture and the standard packet-switched architecture.

The combination of the systems-level research using our existing prototype networks along with our coordinated research into possible optical network architectures that can improve the optical switching performance, will enable us to provide quantitative answers to the following fundamental research questions:

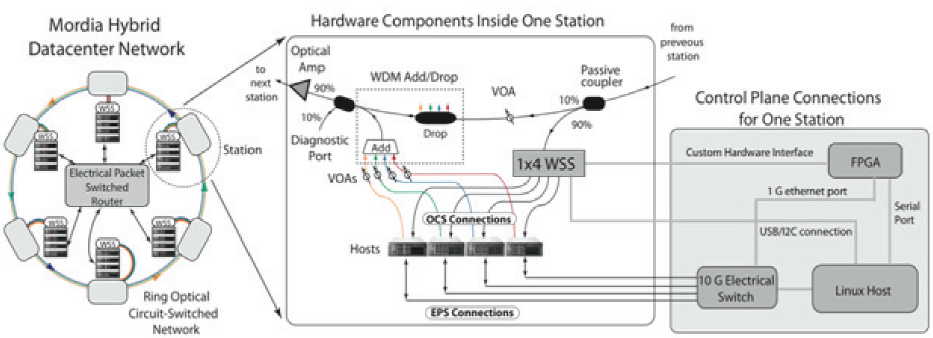
- How fast does an optical circuit switch have to be in order to be a viable candidate in data center applications?
- What are the potential near-term and long-term optical technologies that can provide the required switching functionality?
- What are the control plane issues of integrating a microsecond optical circuit switch with an electrical packet switch?
- How dependent is the optical network architecture on the workload traffic patterns and on the transmission rate per end host?
- What is the relationship between the performance in the optical network architecture and the available degrees of freedom?
- What is the interface to the rest of the system?
- To what extent does incorporating application semantics into the network scheduler improve performance?
- What other aspects of system performance (disk/bus I/O) are affected by microsecond hybrid networks?
- How additional degrees of freedom (space, wavelength and polarization) can be used to increase system performance.

This systems-level research using our existing opto-electronic prototype networks is being exploited to identify and develop novel underlying technologies that will enable dynamic and reconfigurable networks. The system-level research poses a number of questions:

- What switching fabric technologies will need to be developed to enable high-speed optical-electrical networking?
- How can we use the unique aspects of nanophotonics to achieve dense integration of required functionalities using CMOS compatible fabrication?
- Which functionalities can be achieved with monolithic integration and which with heterogeneous integration?
- How can a WDM interconnection system be dynamically reconfigured using tunable devices and circuits?
- How can CMOS compatible manufacturing be exploited to create large port count switching fabric?
- How to create a combined functionality via space-wavelength switching?
- Can control and switching functionalities be integrated into the same design and manufacturing platform?
- What are the required functionalities for tunable filters in terms of adjusting the spectral band and the tuning rate?
- What are the required functionalities for tunable lasers in terms of tuning rate, power and the ability to integrate modulators?
- What are the potential technologies that can be used to develop an optical cross-connect suitable for datacenters?

CIAN Approach

The WG1 research plan is based on developing prototype hybrid networks to conduct systems-level research as well as define the required component technologies. These prototype systems serve a dual role: first, to provide an operational research system; and second, to be an evolving, dynamic testbed for the insertion of CIAN-developed subsystems and devices. The first-generation prototype system we built and reported in year 3 was Helios and was based on a space switch. The second generation prototype system (diagram below) is the Microsecond Optical Research Datacenter Interconnect Architecture (MORDIA).



The MORDIA prototype network system consists of 24 hosts organized into six stations (or nodes) with four servers in each node (Figure 2.5). Each of the end hosts transmits on different discrete wavelengths. The four wavelengths are multiplexed into a ring. The ring currently has a total of 24 wavelengths. At each node, a passive splitter drops all 24 wavelengths onto a wavelength selective switch (WSS). The WSS selects a subset of four wavelengths from the set of 24 wavelengths and routes them to the end hosts.

The design of the MORDIA circuit switch prototype is divided into 1) a data plane, 2) a control plane, 3) connected devices that are either top-of-rack (TOR) switches or hosts, and 4) Time-division Multiple Access (TDMA)-based coordination.

WG2: Intelligent Aggregation Networks (IAN)

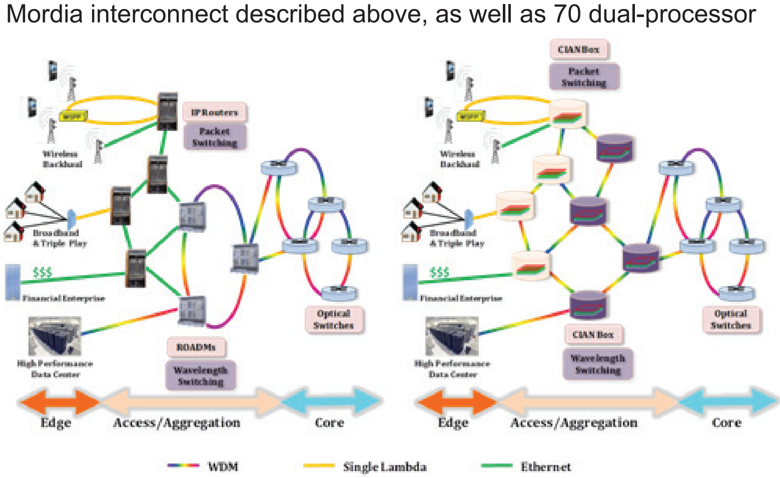
Overview

CIAN's vision for the next-generation access/aggregation network is driven by the accelerated growth in user demand for broadband access due to the vast heterogeneity of applications, services, and emerging technologies. CIAN's Working Group 2 (WG2) addresses the resulting exploding traffic demand and the increasing energy consumption faced by today's networks, thereby driving the designs of next-generation networking technologies.

The CIAN WG2 research is organized around an evolving CIAN box system, an information aggregation node that can be interconnected to create dynamic and adaptive transformative optical access network architecture. The boxes integrate real-time optical performance measurement (OPM), energy consumption monitoring, high-performance switching, signal conditioning and recovery, and the ability to extract in-band data that can be used as context to a broader systems approach. The goal is to explore the systems interactions of dynamic optical configuration for network optimization using the CIAN box as:

- A platform to showcase state-of-the-art, energy-efficient devices and subsystems,
- A demonstration of energy-aware network architectures and switching capabilities,
- Dynamic resource allocation based on dynamic, real-time access to in-band data context,
- Programmable flexibility to support application-specific quality-of-service (QoS) and optical quality-of-transmission (QoT) constraints,
- QoS support in heterogeneous traffic environments (wireless and wired),
- Delivery of efficient, low-cost high-bandwidth aggregation of traffic between multiple users and applications and the network core, and
- Support for reliability and protection schemes with some of the diagnostic equipment are shown below.

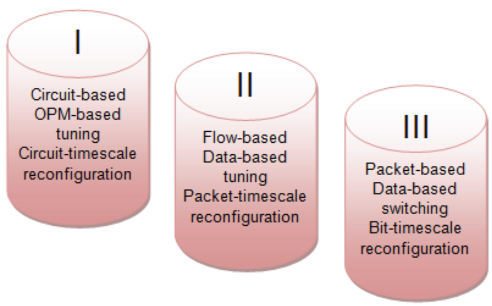
The current version of the testbed coordinates research efforts by CIAN-related academic and industry efforts by providing a vehicle for experimental validation and integration. It contains the prototype Mordia interconnect described above, as well as 70 dual-processor servers, each with 20 Gbps of network capacity for a total bandwidth of 1.4 terabits per second. In addition to Mordia, there are two Cisco data center switches capable of providing full electrical packet-switching functions.



(Left) Existing and (right) next-generation aggregation network topology

CIAN WG2 research is organized around developing and evolving the CIAN box. This box is an information exchange node that provides a venue to explore systems interactions of optical network optimization by supporting increased data rates, optimizing network performance and flexibility, and maximizing the network's energy efficiency for heterogeneous access aggregation traffic.

The CIAN WG2 research plan centers on the concurrent development of a sequence of CIAN boxes that demonstrates the evolution of dynamic optical access networking and enable the exploration of distributed systems interactions (figure below). These boxes provide a platform for integrating new real-time OPM devices and signal conditioning mechanisms with adaptive configuration



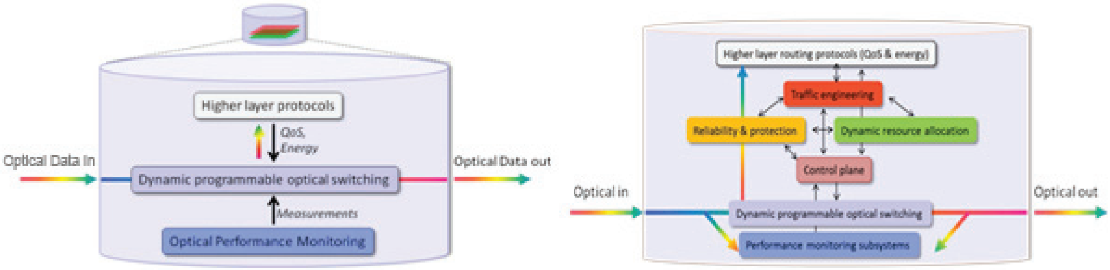
(left) CIAN box and its stages of evolution

and path management. The Stage I CIAN box integrates OPM to enable feedback-based signal adaptation and automatic circuit re-routing to stabilize performance in the presence of path and device variations. The Stage II CIAN box reconfigures on much smaller timescales, and can use in-band data plane context, such as QoS labels, to control tuning and adaptation. The Stage III CIAN box switches on packet timescales, reconfigures on bit timescales, and can direct data on a per-packet basis towards the desired path. These three stages represent the evolution of optical circuit switching into adaptive, reactive, and self-correcting optical packet switching. Their development is concurrent, such that earlier stages are prototyped sooner and provide a testbed for existing and emerging optical devices and subsystem implementations, and the design and analysis of later stages helps provide context to drive the development of new optical device and subsystem capabilities.

These CIAN boxes are deployed as a group of collaborating nodes in an aggregation network, and the interactions between these nodes – as well as the integration of capabilities within them – help explore the systems aspects of optical network optimization. The figure at far left shows the topology of today's aggregation network, which resides between the high-bandwidth core and heterogeneous edge nodes. This network gathers data from the edge nodes, groups them onto different wavelengths, and groups the wavelengths onto different DWDM fibers. We envision the next-generation aggregation network (near left) consisting of CIAN boxes that provide much higher capacity more efficiently, adaptively, and with lower power. This vision is achieved through the following stages and steps.

The CIAN Box

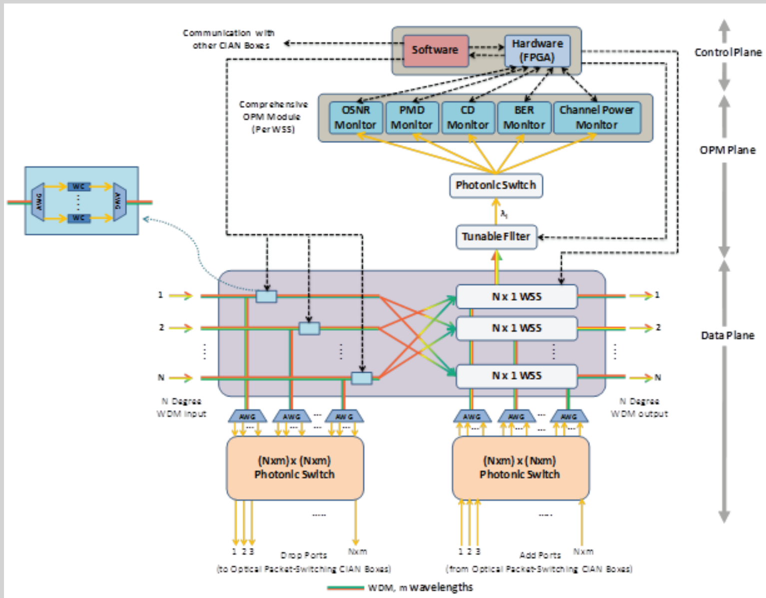
The CIAN box is an intelligent optical aggregation network node, which can support optical packet switching (OPS) or optical circuiting switching (OCS) while simultaneously delivering high optical Quality of Transmission (QoT) and maintaining application-specific QoS constraints. Optical switching can be triggered by real-time optical signal degradation measurements. Early stages of this box rely on circuit-timescale reconfiguration and adaptation, and later stages rely on packet- and bit-timescale versions of these capabilities. A prototype CIAN box is being constructed using commercially available, off-the-shelf components. This initial prototype demonstrates an optical switching fabric integrated with a performance monitoring subsystem, and a cross-layer control and management plane. Two future implementations are described below.



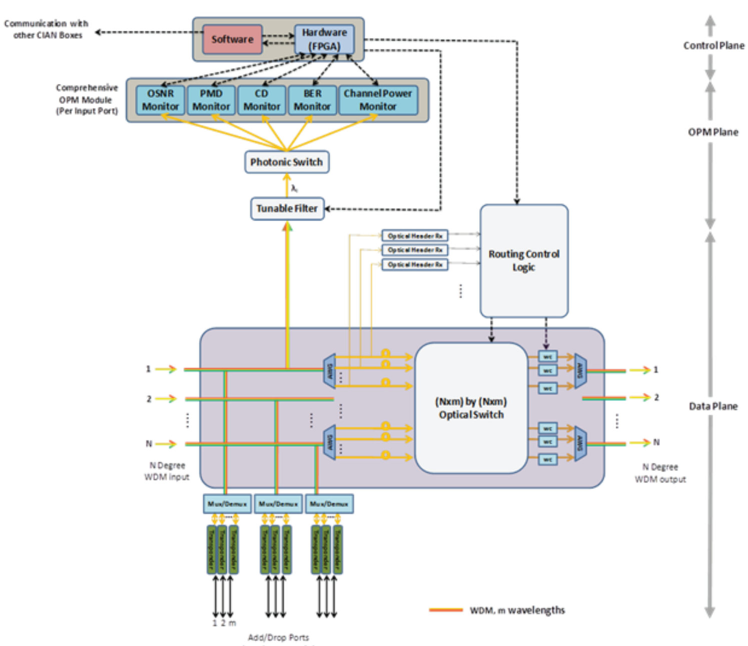
Block schematic of CIAN box (left) and detailed internal architecture (right). Higher-layer routing protocols are those that are above the physical layer in the Open Systems Interconnection stack.

Stage I: Circuit and Wavelength-Switched CIAN Box

This Stage I CIAN box dynamically reconfigures lightpaths (circuit and wavelength-switched optical connections) based real-time measurements, providing fast, adaptive automatic path correction, integrating these functions and exploring the interactions between them. The CIAN-box also incorporates adaptive coding - changing the encoding, for example, to one bit per symbol from multi-level amplitude encoding to make the signal more robust; or adding forward error correction when necessary. This type of intelligent provisioning, using the CIAN-box to allocate lightpaths where and when they are needed, significantly improves the bandwidth utilization of the network by avoiding over-provisioning. Round-robin OPM measurement of each wavelength leverages fast tunable filters to minimize the required hardware. Measurements include optical signal to noise ratio (OSNR), polarization mode dispersion (PMD), chromatic dispersion (CD), bit-error-rate (BER), and the signal channel power, using CIAN WG2-developed technologies (depicted at right).



(Right) Circuit and wavelength-switched CIAN box internal architecture



Stage II: Flow-Switched, Packet-Dependent CIAN Box

This Stage II CIAN box reconfigures on faster, packet timescales and includes the ability to use in-band data as adaptation context, further exploring additional component integration within and interaction between these boxes. This box can extract packet header information, such as QoS level or addressing that can be included in decisions for fast circuit rerouting or signal conditioning, as shown in the figure at left.

It is important to note that reconfiguring based on packet header information does not mean that decisions must occur fast enough for a given packet – they may only be fast enough to affect a stream of packets with similar headers. Packet-timescale switching means that only a packet or a few packets are either lost or fail to gain from a change. Bit-timescale decisions are needed to affect a specific packet and are equivalent to packet-switching decisions (as opposed to the flow-switching described here).

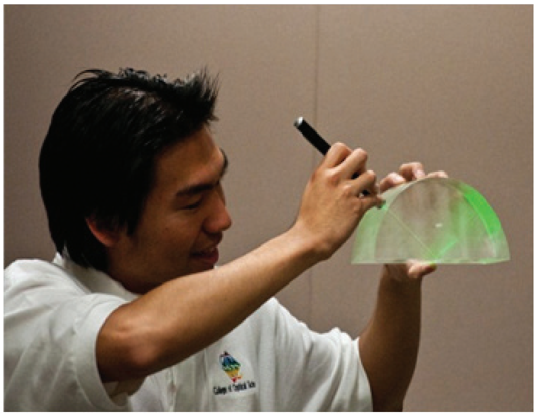
(Left) Flow-switched, packet-dependent CIAN box internal architecture

Outreach to Native American Students and Community Colleges

CIAN has been building partnerships and links to institutions with high populations of Native American students or organizations focused on outreach in Native American communities. This approach builds on CIAN's long-term partnership with the University of Arizona Office of Early Academic Outreach and its MESA program. We hosted and co-organized a MESA Saturday Academy, which allowed undergraduate and graduate students to showcase ten optics-related demonstrations during the half-day event. Some 90 middle and high school students attended from the Baboquivari Indian Oasis School District of the Tohono O'odham tribal reserve outside of Tucson, Arizona, together with some 60 Hispanic students from surrounding, underrepresented schools. CIAN also provided optics demonstrations at the Baboquivari High School Indian Day in the same school district. The technology demos show young students that optics is everywhere, especially in the not-so-obvious tech devices that they use daily, and they reinforce the science, technology, engineering and math (STEM) classes the students are already taking, and encourages them to pursue science and engineering at a higher level.

CIAN member and UA professor Galina Khitrova and her research group (including visiting scientist Antti Saynatjoki from Finland) visited science classes at Baboquivari High School to generate interest in photonics, and did optics demonstrations. CIAN also organized a UA outreach event at Johnson Primary School in Tucson, where 65 percent of the students are Native American. In addition, CIAN provided a recruitment presentation at Northern Arizona University (NAU), which has a large population of Native American students. During Year 5, CIAN is also partnering with the UCSD Early Academic Outreach Program, which has agreed to connect CIAN with its outreach programs to Native American tribes in the San Diego area.

CIAN also continues to partner with the UA Office of Early Academic Outreach to provide the Native American Science and Engineering Program (NASEP) for the third year, with a cohort of 28 students. The 52 students who have participated in NASEP over the last three years represent the tribes of Tohono O'odham, Navajo, Pascua Yaqui, Apache, and Hopi.



Undergraduate and graduate students demonstrating total internal

This summer CIAN will be interning NASEP high school students in CIAN labs. CIAN funded two NASEP students and three teachers from ROKET, CIAN's RET program at UA targeted at Native American schools, to attend the national 2011 American Indian Science and Engineering Society (AISES) conference. The three ROKET teachers presented their RET lesson plans in a panel format that allowed for audience discussion on the topic of integrating Native American culture in the science curriculum. The teachers also chaperoned four Native American students from their schools who attended.

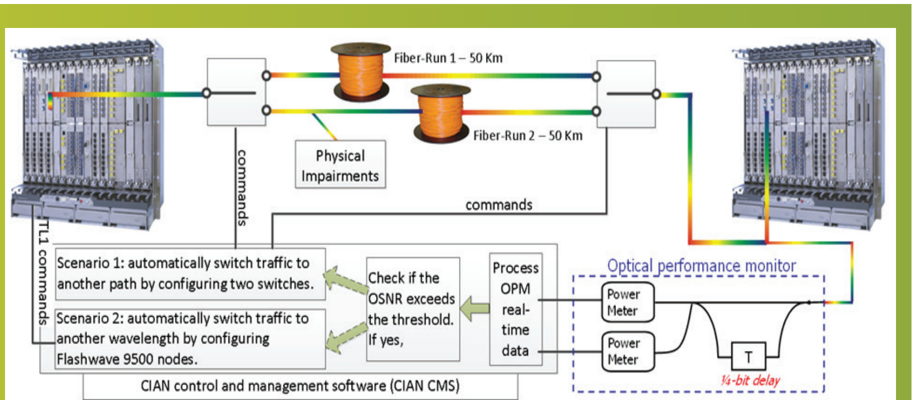
The Southwestern Indian Polytechnic Institute (SIPI), located in Albuquerque, NM, is a new CIAN outreach partner. SIPI is a National Indian Community College and Land Grant Institution. Dr. Frances Williams from NSU traveled to SIPI last fall to give a recruitment presentation and meet with faculty and the Department Chair of the Engineering and Engineering Technology Programs. They are assisting CIAN with recruitment of Native American students and in promoting other CIAN outreach programs. In summer 2012, two SIPI students have been accepted into CIAN's Research Experiences for Undergraduates (REU) program.

Each of the ten CIAN partner universities has formed links to local community college faculty in order to build a mentoring pipeline for high-achieving students. Nine of the 35 CIAN-sponsored student researchers have been recruited from community college programs. All nine of these students are now enrolled in a Bachelor's program in engineering and they are receiving counseling and support to pursue higher education.

Bringing Intelligence to Optical Networks

(continue from p. 3)

A team led by UA's June He and John Wissinger in collaboration with Craig Healy of Fujitsu Network Communications, a CIAN industry partner, developed the intelligent CMS to enable seamless integration of cross-layer information and interconnection between different devices. The experimental results show a significant reduction in delays (from hours to several seconds) in the time it takes to restore optical-network service or to detect and recover from a network failure such as a fiber disconnection.



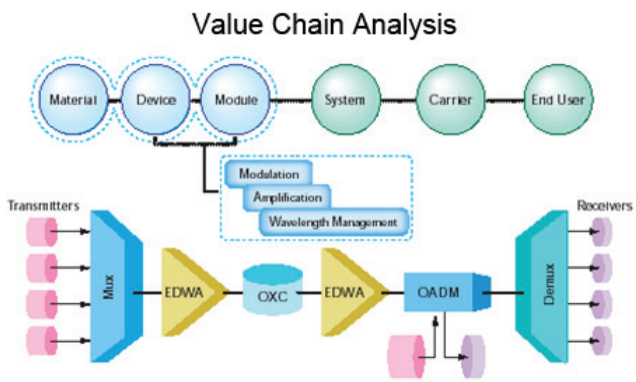
New Courses Bring CIAN to the Classroom

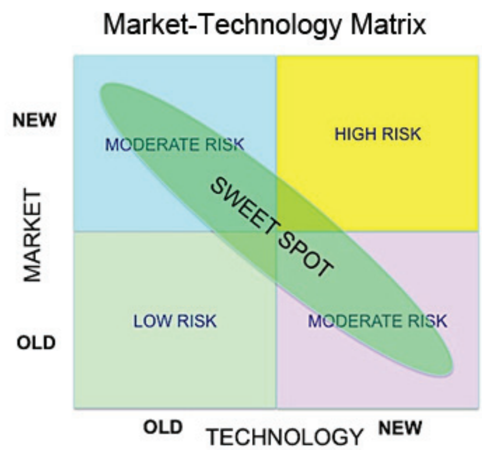
Gen 3 Course: From Photonics Innovation to the Marketplace

A key part of the Gen 3 ERC education mission is to teach CIAN students about technology commercialization and thereby provide foundational information that can assist them in the development and launch of new products and the creation of new companies. To address this need, a new graduate-level course, "From Photonics Innovation to the Marketplace," was developed for the College of Optical Sciences at the University of Arizona by Prof. Robert Norwood. The inaugural class consisted of 10 students, each of whom learned the foundations of intellectual property, new product development and team leadership. Prof. Norwood draws on his 11 years of experience with Fortune 50 companies, as well as his background as a co-founder of a venture capital-backed startup, and he incorporates specific case studies from the photonics industry in the curriculum.

The emphasis of the course is on developing skills that are critical to both entrepreneurs and corporate researchers, including the basics of intellectual property development, the use of various technology development tools and concepts (show in the figure), and elementary project leadership skills. All students draft a mock invention disclosure and participate in a team-based, business-plan development exercise culminating in a five-slide presentation of the essence of their value proposition. Student feedback on the course was positive: comments included: "*Key points to a successful business*", "*New things I never learned before*", "*Outstanding overview and insight*", "*Highly recommended*", and "*Practical knowledge and real examples*".

There was also an enthusiastic reception for a condensed version of the course material that was incorporated into the CIAN Innovation Workshop held at UC San Diego in summer 2011.





Optics Kits for Science Teachers

Building on the success of its summer Research Experiences for Teachers (RET) program, CIAN sponsored a day-long Optics Kits for Science Teachers workshop at UC San Diego in March 2012. The goals were to replicate the optics kits that CIAN RET teachers had developed during past summers, present them to the science teachers, show the teachers how to use them, and give science teachers hands-on experience so that they can make their own lenses and prisms to take back to their classrooms. Seven science teachers from elementary, middle and high schools attended the workshop. RET teacher-alumni presented their optics kits to the participants. Members of CIAN SLC, CIAN graduate students and staff led the hands-on session and showed various demos for K-12 outreach.

Serving as a pilot for potentially larger workshops for science teachers, the optics-kit workshop was a success. Presenters and participants alike felt it was a valuable experience. As one teacher replied on the feedback form: "*…lots of good ideas… I foresee myself using many of the demos and problem-based learning [modules] to teach various aspect of optics… I would recommend this workshop to my colleagues to gain a better understanding of various ways to learn and teach optics.*" Wrote another science teacher: "*After the research presentation for the group of teachers… I walked away with a wealth of information and insight… thanks to CIAN which really made the experience a pleasant one.*"

Workshop participants, CIAN graduate students, RET alumni and staff

Foreign Partners Contribute to CIAN Agenda

CIAN's international partner activity continues to benefit from strong and growing collaborations, frequent personnel exchanges, and compelling research topics. Following is a brief summary of three such efforts.

Finland: Aalto University and University of Eastern Finland

A number of significant research interactions occurred with Dr. Seppo Honkanen of the University of Eastern Finland and his collaborators at Aalto University. The ongoing research in Dr. Norwood's and Dr. Peyghambarian's group at the University of Arizona on polymer-based magneto-optic devices, in particular integrated optical isolators, has been a fruitful area for interaction with Dr. Honkanen for several years, and has featured joint publications and conference presentations. Dr. Antti Säynätjoki, a postdoctoral researcher in Prof. Honkanen's group, has spearheaded collaboration with the UA team on silicon photonics-based hybrid optical isolators, which would be a significant breakthrough in the field of integrated optics. Dr. Säynätjoki spent January through April 2012 as a visiting scientist at the UA College of Optical Sciences. In addition to collaborating with professors Norwood and Peyghambarian, the Aalto/University of Eastern Finland team has also been collaborating with Dr. Hyatt Gibbs and Dr. Galina Khitrova. In this case, the group at Aalto has been forming titanium dioxide layers on semiconductor resonator structures (provided by Gibbs/Khitrova) by atomic layer deposition (ALD). The researchers have found that ALD films actually improve the quality of these resonators, a result that continues to be tested.

Germany: Darmstadt University of Technology

During the summer of 2011, Hacene Chaouch of the UA College of Optical Sciences joined the photonic and microwave technology team led by Dr. Franko Kueppers at the Darmstadt University of Technology in Germany. They are undertaking an exhaustive study of the role that semiconductor optical amplifiers (SOA) play in the regeneration of impaired phase modulated signals. Hacene worked for three months on modeling and simulating a promising new SOA configuration known as a "colliding-pulses scheme''. In this configuration, each output arm of a demodulated DPSK signal is input to one end of a saturated SOA. The output signal is then passed through a detuned filter and analyzed with a BER tester and an optical spectrum analyzer. The results of this study demonstrated that this regime can significantly reduce fluctuations in the marks, and amplify the signal, as well as filter out the noise in the spaces where most of the accumulated nonlinear phase noise is transferred after demodulation. Thanks to CIAN support, a thorough characterization of this new scheme was made possible and the findings were presented during the SPIE Photonics West 2012 conference.

South Korea: Korea Advanced Institute of Science and Technology

CIAN students J. D. Olitzky and Sander Zandbergen from the University of Arizona's Khitrova group traveled (with CIAN assistance) to the Korea Advanced Institute of Science and Technology (KAIST) located in Daejeon, South Korea, to work with their international collaborator Prof. Yong-Hee Lee (pictured at left) and his research group. Prof. Lee's group focuses on semiconductor nano-photonics with silicon and III-V materials. They have nano-fabrication facilities and excellent optical spectroscopy capabilities both for free space and fiber-coupled measurements, allowing for fabrication of nano structures, subsequent characterization, and final experiments. In the past, the Khitrova group has collaborated with the Lee group by providing MBE samples for use in the Lee group's experiments while the Lee group fabricated structures for experiments in the Khitrova group. In the past two years, the Khitrova group published several papers and a book chapter on the use of a curved, single-mode optical micro-fiber taper spectroscopy apparatus that a visiting student from KAIST helped to implement. The Khitrova group had no previous experience making the custom fiber tapers needed to use this spectroscopy apparatus. CIAN students Zandbergen and Olitzky learned about the necessary equipment and techniques needed to fabricate micro-fiber tapers while in Korea, ultimately giving the Khitrova group the ability to set up a micro-fiber curving/ taper apparatus in the lab at the College of Optical Sciences in Arizona. Furthermore, the students learned how to nanofabricate using electron-beam lithographic techniques, reactive ion etching, and chemically assisted ion beam etching. They were involved in fabricating structures similar to those used in the Khitrova group's experiments and similar to the interesting current-injected suspended nanobeam lasers.

Enhancing Industry Impact

CIAN has a successful history of industry collaboration through our testbeds, but this success is largely limited to just a few companies. Going forward, the center will work toward broadening the base of collaboration, both in terms of the numbers of engagements, but also the depth of those engagements. Our objective is deeper and more productive research collaborations with clear prospects for technology translation and transfer to the marketplace.

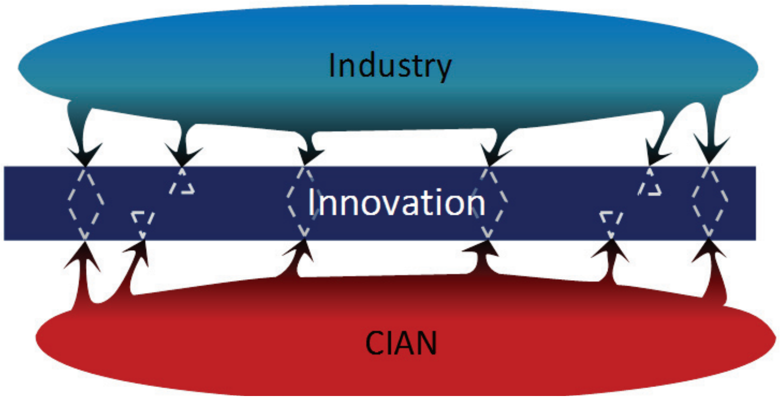
Innovation Ecosystem

CIAN's Innovation Management Team (IMT) includes Nasser Peyghambarian (Director), Shaya Fainman (Deputy Director), Alan Kost (Administrative Director), Daniel Carothers (Industry Liaison Officer), Kimberly Sierra-Cajas (Education and Outreach Director), Robert Norwood (Thrust Leader), John Wissinger (CIAN Testbed Manager), Oscar Herrera (SLC representative) and Srinivas Sukumar (Strategic Initiatives Director).

In year 4 the IMT worked to improve its coordinated efforts within the various aspects of CIAN that contribute to creating an innovative environment. This has allowed CIAN members to encourage innovation in technology and the processes that create opportunities for innovation with our industry partners. Key focus areas have been the creation of opportunities for the commercialization of CIAN technology, and charting multiple paths for this technology to reach the market. To better target these efforts, a range of strategies is being employed to enable the development of a dynamic and highly productive Innovation Ecosystem. These approaches allow the CIAN IMT to identify areas where industry interest and knowledge coincide with knowledge and capability embodied by CIAN to help focus our innovation strategy.

In addition to cultivating partnerships with individual companies, CIAN is working on creative ways to foster collaboration among multiple CIAN PIs and selected industry partners, enhancing interactions with industry and providing valuable information to CIAN researchers on industry and customer needs. These interactions are described in greater detail below.

CIAN is partnering with industry associations such as the Optoelectronic Industry Development Association (OIDA) to bring together several hundred industry participants in public forums to discuss key metrics for CIAN-related system areas (aggregation networks and future data centers). With strong support from CIAN's NSF Program Manager, Dominique Dagenais, and in cooperation with OIDA, CIAN held two very successful roadmapping workshops. The first took place Oct. 18-19, 2011, in San Jose, CA, on "Future Directions and Metrics in Aggregation Networks," with 12 graduate students and postdocs from six CIAN universities in attendance). The second industry-related workshop on "Quantitative Metrics in the Data Center" took place March 4, 2012, in Los Angeles (co-located with the Optical Fiber Conference). The 2012 workshop had more than 170 participants, including 17 grad students and postdocs from five CIAN universities.



CIAN's Value to Industry

CIAN is strengthening its outbound marketing effort to industry by clarifying specific value propositions and enhancing its collateral materials. Some specific messages we have targeted include:

Accelerate R&D
- Obtain feedback on product performance within realistic network and data center settings;
- Test prototype devices and system concepts, perform beta testing, assess interoperability;

Increase Sales
- Seed new/future users, create brand awareness, showcase new products;

Enhance Fit of New Recruits
- Training and hands-on experience with real operational systems, commercial SOA equipment;
- Proficient in member company's own product capabilities;

Gain Visibility into New-Product Needs and Markets
- Obtain input into future product requirements;
- Identify unrecognized requirements or constraints;
- Identify gaps in current industry capability that present opportunities; and

Enable Member-Member Partnering & Joint Development
- Up and down the customer / member / vendor chain.

We are enhancing testbed collateral materials in the form of videos, spec sheets, brochures, etc., to better describe these value propositions and to better promote CIAN to industry.

Industry Interns Help CIAN Knowledge Transfer

One of CIAN's Year 5 goals is to increase the number of internships for CIAN students. Six internships are underway in summer 2012. CIAN's Industry Liaison Office (ILO) set up internships for: Robert Margolies from Columbia at AT&T; Mike Zhang from the University of Arizona, who is interning with NEC Labs in Princeton, NJ.; and four graduate students from UC San Diego, Olesya Bondarenco with Oracle, Shaojing Li at Qualcomm, Ruinan Chang with Ansoft-Ansys in Pittsburgh, and Marco Escobar at Western Digital.

Seven CIAN students became industry interns in all of year four:

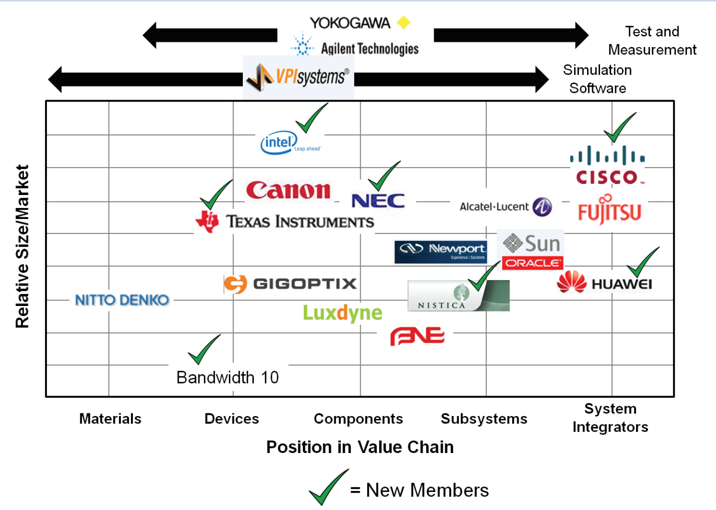
- **Oscar Herrera**, a CIAN student in the Industry Liaison Office (ILO), traveled to San Francisco for a weeklong internship with Fiber Network Engineering (FNE) to learn the details of the WDM-PON system that FNE was donating to CIAN. As a Thrust 3 member, his research in hybrid EO polymer/silicon modulators directly contributed to the device tier of CIAN.
- A CIAN student from Columbia, **Berk Birand**, participated in an internship at the IBM T.J. Watson Research Center throughout fall 2011 and worked on efficient architecture for wireless backhaul. Berand was also a recipient of an IBM Research Graduate Fellowship for 2011-2012.
- Another student from Columbia, **Daniel Brunina**, also participated in an internship with IBM Research.
- UA student **Yequn Zhang** participated in an internship at Mitsubishi Electric. The project focused on "Fiber Nonlinearity Compensation for Optical Communications", and it included evaluating techniques that could suppress fiber nonlinearities.
- UC San Diego's **Shaojing Li** interned at Advanced Micro Devices (AMD).
- University of Arizona Ph.D. Candidate **Adam Jones** held an internship at Sandia National Labs, and currently works in UA's well-known silicon photonics group (an important area to CIAN.
- Finally, from April 2011 to January 2012, UCLA Ph.D. Candidate **Brandon Buckley** held an Intel Corp. internship in the Intel Photonics Technology Lab headed by Dr. Mario Paniccia.

INDUSTRY ADVISORY BOARD

Nineteen companies are now members of the CIAN Industry Advisory Board (IAB), and discussions are underway with four other potential members. CIAN also accesses the rich industry ecosystem that supports today's communications network infrastructure, including carriers, systems providers, component providers, and tool-set providers. The traditional end-user community has also expanded to include media/content and application/service providers that are increasingly important drivers of network requirements. At the most recent IAB annual meeting in January 2012, 50 researchers, staff and students attended and 12 companies were represented.

CIAN industry partners as of July 2012 include: Agilent Technologies, Alcatel-Lucent, Bandwidth10, Canon, Cisco Systems, FNE, Fujitsu, GigOptix, Huawei, Intel, Luxdyne, NEC, Newport, Nistica, Nitto Denko, Oracle, Texas Instruments, VPI Systems, and Yokogawa.

Recent member Bandwidth10 is a startup to commercialize VCSEL technology. The firm was formed by recent CIAN graduate student Christopher Chase, CIAN Berkeley Prof. Connie Chang-Hasnain, and her grad students Yi Rao and Phillip Worland (now CEO).



Academic Partners

The University of Arizona · Columbia University in the City of New York · UCLA · Berkeley University of California · UC San Diego · California Institute of Technology · Tuskegee University · USC · NSU Norfolk State University · NSF · KAIST · TKK · Cornell University · Technische Universität Darmstadt · University of Eastern Finland / Aalto University