**Perspectives on Leading the CIAN ERC**

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Over the 10-year span of its life as an NSF-funded Engineering Research Center, from 2008 to 2018, the CIAN (Center for Integrated Access Networks) ERC has laid the technological foundations that will enable low-cost access to the Internet for the demanding applications and services of tomorrow. As data networks find wider use throughout society—including the educational, commercial, government, and entertainment sectors—higher network performance will be needed in more places with lower latency and greater availability. At the leading edge are high bandwidth on-demand services requiring real-time responsiveness throughout the network. These include many promising and potentially transformational applications such as immersive, interactive telepresence in multiple views, and holographic 3D imaging for tele-medicine.

While video was seen as the main driver and remains important today, it is in fact the next-generation 5G, mobile networks and applications combined with hyperscale computing that are the real drivers. 5G networks are not just about higher speeds; they will enable a new Internet that merges the physical and virtual worlds in ways that were never before possible. These include virtual and augmented reality, smart and autonomous vehicles, remote medicine, autonomous product manufacturing and delivery, and a host of applications not yet imagined that the sensors or controls in the physical world around us will bring. This “future Internet” is about enhancing the physical world around us through cloud computing at massive scale using artificial intelligence and machine learning. Mobile access networks are being re-architected into centralized edge clouds and central offices redesigned into edge data centers.

The CIAN ERC was established to put together a pathway to overcome the bottlenecks of the Internet including its cost, energy consumption, latency, and speed. The Director and Deputy Director of CIAN have been working together for over 18 years to formulate, start up, and operate CIAN. We worked closely with a super-strong team of faculty, students, and researchers from some of the best universities in the U.S. and worldwide. Our team was like our family; we not only tackled intellectually challenging issues but were also helpful to each other on personal issues. As a team, we collaborated closely, brainstormed several times a year, published together, and remained good friends. The most rewarding part was to see our team gel so well and achieve outstanding scientific and engineering results.

This cohesiveness was not always easy to achieve in the early days of the Center. We held retreats in which we carried out “gap analysis” to determine what expertise we were lacking and what projects needed to be pursued or, in some cases, phased out. At times we had to make strategic but painful decisions to restructure the team when excellent researchers were nevertheless not fitting into the increasingly clear Center research plan. Thus, over the years, as co-leaders we sometimes had to be the "bad guys" to make sure the team worked together well. Weekly meetings between the two of us were very helpful because they allowed us to discuss and resolve quickly the issues as they arose.

These efforts paid off with research results. Our team proposed a novel hybrid optical-electronic switching approach useful in numerous network system architectures to reduce latency and enhance the speed of data transmission. For example, the Data Centers application takes advantage of this hybrid optical-electronic routing approach, with large data flows (“elephant flows”) being routed optically through optical circuit switching while the small data flows (“mice flows”) are routed electronically (i.e., the way the traditional CISCO routers operate). We built a Data Center testbed and installed, tested, and validated this new architecture. This research was well-received and was cited internationally. It was rewarding to see that CIAN’s new architecture was adopted by industry and many other researchers in the field.

CIAN brought attention to the access/aggregation network bottleneck. We led the way in software- defined networking (SDN) for optical systems. We also focused on making real-time dynamic optical systems in aggregation and data center networks a reality. Our 3D holographic telepresence breakthrough made the cover of *Nature* magazine and was highly cited by news media around the globe, including *USA Today*, CNN, and the *New York Times*.

CIAN’s work has been instrumental for advancing integrated photonics and in particular silicon photonics for communications within the scientific community. We adopted silicon photonics for integrating discrete optical components on a silicon chip in order to reduce cost, energy consumption, and the physical footprint on the chip. Working closely with Sandia National Labs, we demonstrated a Data Center network-node-on-a-chip that integrated 20 variable optical attenuators (VOAs) and 52 electrically tunable micro-ring resonators. Another example is our 128x128 ports cross bar switch-on-a-chip with microsecond switching speed for Data Center applications. This was the largest switch demonstrated to date.

We collaborated with OIDA (the Optoelectronics Industry Development Association) to organize annual CIAN-OIDA road-mapping workshops for establishing metrics and standards for our industrial sectors. These workshops were well attended by industrial, academic, and National Labs researchers. We advanced fundamental knowledge in Photonics and published over 20 *Nature/Science* articles.

From the start, CIAN has had strong diversity in its faculty, students, and staff and has continuously enhanced its diversity through targeted recruitment efforts and by strengthening its partnerships with underrepresented minority-serving institutions. CIAN’s rich diversity is reflected in its core values as expressed through REU and RET programs that target not just underrepresented minorities but also veterans. It has been most satisfying to see the fruits of our outreach efforts in African American, Hispanic, and Native American communities using our multi-institutional resources. A particular source of pride, CIAN has inspired interest in science and engineering in a generation of young Native American students.

Initially we tried to fill the positions of Education Director and Industrial Liaison Officer with faculty members. This approach failed miserably, since busy faculty were only able to allocate a small part of their time to these tasks. We quickly changed course and filled these positions with professional staff members whose main responsibilities were to the ERC. This change was instrumental in putting our Center on the right path to successfully implementing our education, outreach, and industrial collaboration activities. Another challenging aspect of our leadership was to be able to fit all our plans and activities within the budget allocated, especially in the early and later years when the NSF funding was substantially reduced.

To lead the CIAN ERC was challenging but very satisfying. For both of us it has been one of the best experiences of our faculty lives. It was very rewarding to successfully lead a 200+ member-strong organization. We viewed it like running a company with a well-defined vison/mission and specific “products” and reporting to a “Board of Directors,” which in our case was the NSF program directors and their annual site visit review team. The “products” were our graduate and undergraduate students, postdocs, and researchers and their journal publications, conference presentations, and patents—some of which led to startups and industrial commercialization.

A final note on a common complaint of ERC leaders: We found that preparing the annual reports was a burdensome task, but not an unreasonable one considering the big investment that NSF was making in the ERC and the many benefits that the ERC experience produced both personally and professionally for our faculty, students, staff, industrial members, and ourselves.