ICT Core Networks: Towards a Scalable, Energy-Efficient Future

June 2013

The Institute for Energy Efficiency
UC Santa Barbara
Acknowledgements

The Institute for Energy Efficiency would like to thank Juniper Networks as the sponsor of this report and lead roundtable sponsor, and also Ciena, Sprint, ESNet, and the US Department of Energy for their supporting sponsorship of the roundtable. We also thank the participants, listed below, who attended and contributed to the discussion and report.

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</tr>
</tbody>
</table>
Table of Contents

Executive Summary .............................................................................................................3

1. Introduction and Roundtable Goal ..............................................................................4

2. Roundtable Methodology ..........................................................................................5

3. Challenges Faced in Core Networks ..........................................................................5

4. Roundtable Recommendations ..................................................................................11

5. Conclusions and Next Steps ......................................................................................16

Appendix ..........................................................................................................................17

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Executive Summary

Aggressive innovation of media and communication services has transformed society in the past decade. Most readers have experienced this revolution, catalyzed by mobile communications, Skype, YouTube, Facebook, and digital music, photography and video. Hardware innovation has provided ever more powerful compute and storage technology, and made it mobile with pervasive wireless coverage. New applications such as cloud storage and computing have become possible with increasing connectivity speeds. This growth in mobility, plus faster pervasive connectivity, is also driving a return to a more centralized computing model. Large data centers providing services to multiple devices in multiple locations are becoming the central office of the 21st century.

This explosion of communication services, coupled with a more centralized computing model that exploits network connectivity, will result in overall transport bandwidth growth of 29%\(^1\) per year with areas such as mobile traffic growing as fast as 78%. Historically, service providers addressed this network demand by exploiting silicon density and performance improvements, riding the benefits of the well-known Moore’s law. Silicon-based VLSI devices are pervasively used today for network traffic computation and switching and for electrical signaling over copper for intra-equipment communication.

The problem is, though absolute performance of compute, storage, and networking elements has improved remarkably, performance per watt of power consumed has not kept pace; speeds continue to rise, but absolute power consumption also continues to rise. Given that bandwidth demand is growing exponentially, new solutions are needed to prevent power consumption from becoming a runaway problem with similar exponential growth.

This is a critical issue; the problem is not just energy efficiency—an argument could be made that pervasive communications save energy—energy usage is a proxy for total cost. There is the cost of electricity, the associated electrical and infrastructure costs for cooling, and providing the redundant systems for supplying this power reliably. More critically, networking system density is limited by power because thermal density is now the limiting design criteria. Since higher densities are critical to keeping equipment affordable as bandwidth needs grow, runaway power consumption is the main barrier to improving costs. Without continued efficiency improvement the availability of greater bandwidth crucial for communication innovation will not be possible.

To address this challenge, UC Santa Barbara’s Institute for Energy Efficiency convened a Technology Roundtable in February 2013, bringing together industry leaders to identify the needed technological and architectural advancements in transmission, switching and routing to develop energy efficient and therefore affordable next generation core networks. Through two days of highly interactive, facilitated discussions, the group recommended the following key advancements:

- Component-level advancements: Increase photonic integration and the use of optics on silicon.
- Use a holistic approach to consider the whole network at once, rather than just optimizing separate components or subsystems.
- Use liquid or other advanced cooling methods.
- Optimize the use of optical switching and dynamic optical bypass.
- Advanced monitoring and control: Use SDN at all layers; expand power monitoring, analytics and control; and explore making network systems proportional in energy consumption to traffic load.

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\(^1\) Cisco VNI Global Forecast 2011-2016
1. Introduction and Roundtable Goal

The past 15 years have been a time of tremendous growth in the availability and fidelity of communication technologies. Pervasive availability and the growing richness of content have resulted in exponential growth of communications traffic related to Internet, multimedia, and cloud computing applications and services. The combined efforts of industry, government, academia, and investors have kept pace with this demand, but the growing cost, heat, and energy requirements challenge the scalability and energy efficiency of future networks.

Most of the progress of the last 15 years was a result of scaling equipment speeds and densities to achieve higher performance at ever-lower cost per bit. Energy efficiency - the linchpin upon which equipment density depends - is a key factor for minimizing the cost, power usage, and density of communication systems. Energy efficiency is an excellent proxy for progress in networking.

One general challenge in many industries is that de-facto technologies and architectures continue to work well up to a certain point, beyond which returns diminish. The challenge is identifying the new architectures and technologies in advance of this point so that the next level of improvements can be realized. An even greater challenge is making the transition from old architecture or technologies to the new as switching costs are typically high. Market participants require that such transitions deliver outsized gains to compensate for the difficulty in navigating and financing the migration.

On February 7 and 8, 2013, UC Santa Barbara’s Institute for Energy Efficiency convened a two-day Technology Roundtable that brought together 27 industry leaders representing vendors, service providers, research institutes, government laboratories, and academics. The roundtable aimed to identify the needed technological and architectural advancements in transmission, switching and routing to develop scalable, energy-efficient, next generation core networks. These recommendations needed to meet the economic reality of the market—either incremental to existing architectures (evolutionary) or revolutionary and delivering much larger gains than the status quo.

The Institute chose to focus discussions on improving the density, scalability and cost of core communication networks. This area of the network is already the most efficient, and therefore the toughest in which to achieve further gains without directed research and new approaches. As improvements are made to the core, this technology will be repurposed for other areas of the network, and benefits will cascade to the smaller and more numerous systems that populate the edges of the network.

This Technology Roundtable was one in an ongoing series hosted by UC Santa Barbara’s Institute for Energy Efficiency, each aimed toward accelerating the development of a different technology driving energy efficiency.
2. Roundtable Methodology

2.1 Meeting Agenda
The roundtable was anchored by three presentations providing background on the following key focus areas: transmission technologies, (Peter Winzer, Alcatel Lucent), switching and routing technologies, (Mark Nowell, Cisco), and core network architecture (Stuart Elby, Verizon). Participants were then divided into a series of smaller breakout groups to engage in further discussion and identify ways to improve the scalability and efficiency of core transmission and switching/routing. Discussion in these groups was unstructured so each participant could independently put forward topics they thought relevant to the discussion. At the conclusion of the breakouts, a representative from each group summarized the discussion for the larger group, sparking further discussion.

2.2 Voting Structure
At the end of the first day, the Steering Committee refined the breakout groups’ findings into a list of 17 actionable recommendations. On the second day, the entire group ranked these recommendations using the following guidelines: Each participant was allocated five votes: three green votes, two blue votes which each counted for 3x the value of a green vote, plus a red marker for items the voter felt needed further discussion. The votes were tabulated by the organizers and immediately presented to the entire group for open discussion. Logical groupings that emerged during the voting were identified and agreed upon by the full roundtable group. This was followed by a wrap-up discussion highlighting the way forward.

3. Challenges Faced in Core Networks
Core network communication equipment has consistently provided exponentially better performance for a fixed cost, which opened the door to new applications that could leverage these gains at no incremental expense to the end-user. Cloud computing and storage would not be possible without the dramatic drop in cost/bit of transport and routing technology. As evidenced by the success of new centralized computing models, improvements in performance of core equipment resulted in exponential increases in Internet traffic. The challenge is whether existing technology roadmaps can keep providing improvements to keep pace with demand, while continuing to drive costs down and lay the footing for new and innovative applications.

3.1 Traffic Growth
Most agree that core network traffic is growing rapidly, but there is no consensus on the rate at which it is increasing. Part of the challenge is that traffic volume varies depending on where in the network it is measured; techniques like caching and multicasting are widely deployed to reduce core network requirements. Also, much of the growth in traffic has taken place on new private networks operated over leased fiber by companies such as Google, Amazon, and Facebook, for which there are no public metrics.

Cisco is the largest provider of core routing equipment in the world to network service providers with 59% global market share in 2012\(^2\). The company is in a unique position to see usage across multiple topologies and maintain relationships with most global service providers. Cisco uses this knowledge to annually publish the Visual Networking Index (VNI), which estimates global bandwidth usage and future growth.

\(^2\) Infonetics Research, Service Provider Routers and Switches, Quarterly Worldwide Market Share Size and Forecasts 4Q12
Over a five-year period\(^3\), Cisco estimates that an additional 19 billion devices will be connected to global networks, average broadband speeds to the home will increase 4x, and Internet users will total 3.4B, with the majority of this growth in the Middle East, Africa, and Asia Pacific. This growth results in a 29% annual increase in network traffic and an increasing shift toward mobile end users via 3G/4G/LTE and WiFi. WiFi offload alone is expected to account for 51% of traffic in 2016.

3.2 Architectural Changes
Overall bandwidth growth from 2011 to 2016 is expected to be roughly 30%, but mobility-driven usage is growing faster. This creates greater demand for core bandwidth to interconnect the data centers that provide a growing share of mobile services.

Data center architecture itself is changing to deal with the growing number of clients, services, and the greater bandwidth used by both. Connectivity among storage and compute assets within data centers is moving from networks that were oversubscribed by design to fully non-blocking mesh architectures connecting hundreds of thousands of machines. This design results from the loss of connectivity affinity in a data center as east-west server-to-server traffic grows. It also provides the deterministic performance and latency across all endpoints needed for data center virtualization.

This elimination of oversubscription between aggregation and core networks within the data center is creating massive pressure on interconnect as a result of higher port counts and the resulting density and power challenges. It forces absolute power higher, while operating at lower utilization levels, decreasing efficiency.

\(^3\) Cisco VNI Global Forecast 2011-2016
But the problem is not only power delivery, it is also heat removal. Current core networking systems are designed to fit within a given power budget. Increases in performance or density—without a corresponding decrease in power—result in technology that cannot improve the economics or efficiency of the system. This trend has increased the importance of multi-chassis systems, as power must now be spread among a wider area than a single shelf or rack in order to effectively cool the equipment.

Advances have been made in areas such as power supply efficiency, airflow architectures, and power monitoring—but systems designed today are ultimately limited by power density and the ability to extract heat from confined spaces. Mechanical rotating fans and HVAC systems to extract this heat already account for 23% of equipment power in datacenter environments.

3.3 Wave and Space Division Multiplexing (WDM and SDM)

Moore’s law—the doubling of silicon density every two years—increased silicon parallelism and enabled exponential improvements in computing and networking performance for the past few decades. Wavelength division multiplexing (WDM), EDFA technology, and later the ROADM were the key optical technologies that brought parallelism to optics and allowed wide area network transport to meet the optical transport demand enabled by Moore’s law.

We can only use the tools that physics gives us; improvements in optical capacity are made by improving performance of one or more physical dimensions: space, polarization, frequency, time, and modulation. Early fiber systems used a single wavelength that operated at the fastest possible electronics rate, maximizing the time dimension. Additional capacity was achieved by adding more fibers, exploiting space division multiplexing (SDM). WDM, EDFAs, and ROADMs were major breakthroughs as frequency became a possible physical dimension and multiple wavelengths at different frequencies could share the same fiber and common equipment.

Following the development of WDM, component technology advanced and enabled time and frequency improvements. Speeds rose from 2.5Gbs to 10Gbs and wavelength frequency spacing tightened. In the past five years, the use of dual optical polarizations and quadrature modulation allowed effective speeds to reach 40Gbs and 100Gbs. Looking forward, additional capacity can be obtained by using more sophisticated modulations such as QAM.

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4 Intel Corporation
The roundtable participants' consensus was that there are minimal gains from advanced serial bit rates (time), 64-QAM (modulation) and gridless architectures (spectrum flexibility). Laboratory experiments already encroach on the nonlinear Shannon limit of fiber, and at the current pace of progress using the technology advances at hand it will be the limiting factor within 5-10 years.

Once this happens, the only physics variable to maximize will once again be space—using multiple fibers, multi-mode transmission, and multi-core fiber—each elements of space division multiplexing.

The urgent issue is that existing optical technology is relatively poor at scaling in the spatial domain, with component costs and power increasing 1:1 as additional fibers or cores are used. Functions such as electronic forward error correction (FEC), chromatic dispersion compensation, and polarization division multiplexing (PDM) can account for 50% of line card power\textsuperscript{5}, and there is no improvement through parallelism.

Though it is clear that spatial multiplexing is the future, the technology that exists today is not well suited to provide it in a power and cost efficient manner. Barring advancements in the efficiency of SDM approaches the rate of efficiency improvements in optical transmission could return to pre-WDM growth rates. That is why research in SDM systems is currently proliferating.

\textsuperscript{5} D. Welch, OFC Workshop, 2012
3.4 Bandwidth Growth Exceeding Efficiency Improvements

Router interface speeds grew at a faster rate than the serial rate capabilities of optical interfaces until 10 years ago. Since then improvements in router port speeds were limited by improvements in the serial speeds of transmission interfaces. The result is that network bandwidth improvements are increasingly addressed using parallel techniques such as link aggregation (LAG). But these SDM techniques do not offer power improvements—the solution is just linear scaling of existing technology. The result is that improvement of bandwidth per watt metrics is slowing.

Figure 3—History of Router, Optical Serial Interfaces, and WDM System Capacity

Switching at layers below OSI level 3 is one solution that has been used. Optical switching via ROADM has been spectacularly successful, with optical switch unit shipments growing at 24% per year since 2007 and expected to grow at a 20% CAGR through 2016\(^6\).

Avoiding the optical regeneration needed for electronic switching achieves large efficiency gains—as a result ROADM equipment is the fastest growing portion of the optical market.\(^7\) Switching at the layer-1 SDH or OTN layer uses significantly more power because of the optical/electrical conversion required, but this is still more power efficient than layer-2 Ethernet or layer-3 IP routing, as shown in Figure 4.

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\(^6\) Infonetics Research, ROADM WSS Component Worldwide Market Size 1H12
\(^7\) Infonetics Research, Optical Equipment Worldwide Market Size and Share 4Q12, Infonetics Research
But Figure 4 also illustrates that efficiency improvements of core networking systems are slowing; energy improvements across all types of equipment have declined to below 20% per year. This is taking place while data traffic continues to increase at a 30% or more annual rate.

Bandwidth growth is now outstripping the rate of core network efficiency improvement. This mismatch between traffic growth and core networking efficiency improvements needed to accommodate it is the fundamental problem which needs directed technology and architectural research in order to meet future demand for bandwidth at economical price points.

Bandwidth is increasing at rates between 20-60% per year (depending on where it is measured) but capital expenditures rose across the service provider landscape at only 2.6% for the past 5 years\(^8\). This was possible only because of past efficiency improvements that provided greater bandwidth at the same cost.

If these improvements do not happen, the business model of service providers—which depends on a fixed revenue-to-capex ratio—will no longer work. This will result in rising prices for consumers, or lower usage of bandwidth, and stifle the continued communication renaissance of the past 15 years.

\(^8\) Infonetics Research, Revenue and Capex by Service Provider Type, Worldwide and Regional Size and Forecast 3Q12
4. Roundtable Recommendations

The roundtable participants recommended 17 advancements to improve the scalability and energy efficiency of core networks (included as Appendix) and voted on those that would yield the most promising improvements. The group’s top recommendations are presented below in order of importance as determined by voting (voting score in parentheses, definition summary in italics).

These recommendations can be clustered into three logical groupings: component level improvements, software-based techniques, and power management—plus several areas of standalone importance.

These rankings in some way reflect the composition of the group and the areas of expertise they represent. For a list of participants, see the beginning of this report.

4.1 Component-Level Improvements

Integration (39 votes): Increase photonic and photonic-electronic integration to reduce power, size, and cost; increase performance; and enable parallelism.

Research in this recommended area would focus on using various manufacturing techniques and material substrates to provide greater physical integration of optical functions such as waveguides, modulators, emitters, and detectors with electrical functions such as drivers, trans-impedance amplifiers, SERDES, and A/D & D/A converters. The benefits of achieving this goal should be large efficiency and cost gains as a result of reduced component count, better thermal control, and the ability to share common components. It was also recognized that if SDM was going to be the primary tool for increasing transmission capacity, some methods were needed to prevent power and cost scaling linearly with additional channels.

The participants agreed that research into new modulation schemes and non-linear signal processing would have limited benefit and various forms of spatial multiplexing would be a key tool to meet increased bandwidth needs. But while parallelism (8 votes) is an important technique for SDM, limited integration of existing optical components results in no efficiency gains. The low vote count for parallelism indicated that without improvements in efficiency it was not relatively valuable.

The power, size, and cost benefits likely to result from using photonic and photonic-electronic integration was seen as the most promising area of efficiency benefit. Performance improvements from photonic integration, such as reduced loss, reduced reflections and improved reliability are also expected. The improved process control of CMOS processing is expected to improve performance, yield, and uniformity, allowing higher levels of integration. Existing protocols and modulations would derive power and cost benefits of additional integration. Various forms of spatial multiplexing would also benefit as parallelism increased at the component level.

The benefits of this approach stretched from straightforward examples such as leveraging common components such as a thermoelectric cooler among multiple optical carriers, to more aggressive examples of integrating separate lasers, receivers, modulators and drivers using a combination of InP and silicon photonics. If the level of integration can be increased by 10X from an existing 100G solution at small or perhaps less incremental cost, and at lower power/bit because of the tighter integration, it will provide an important scalability advantage.

Optics on ASIC (28 votes): Use optical integration on the ASIC to surpass the fundamental electrical IO limit of ICs.
Electrical interconnect between chips, cards, and chassis is now a dominant source of power consumption and occupies a large share of the fixed power envelope system that designs must meet. An alternative is to replace electrical signaling to/from the chip with optics; initially 850nm VCSELs, then moving rapidly to single mode technology for longer distances and wavelength division multiplexing for higher capacity. It is important to develop packaging, connector, and board assembly & manufacturing techniques to implement this at acceptable costs. The intent is to increase I/O capacity and increase power efficiency, lowering total consumption or allowing more power within the package to be dedicated to computation.

Optics on ASIC was recognized by the roundtable participants as a way to resolve the current mismatch of progress in efficiency in silicon and optics; both are improving but the slope of optical improvement is less than that of silicon. But Moore's law does not apply to I/O—silicon switch efficiency is facing constraints as input/output consumes more absolute power as speeds increase. The latest FPGA devices can dissipate up to 50W of power each. But nearly 50% of this power is used for signal I/O—sending and receiving electrical signal in and out of the chip packaging to adjacent cards and components.9

Participants felt that optics, normally a tool designed for longer reaches not attainable with electrical signaling, is a solution for more efficient shorter chip-to-chip links provided that research improves technological and economical feasibility. This recommendation was made with the goal of increasing the absolute I/O throughput from a silicon die and doing this with greater power efficiency. If the power used by interconnect were reduced via optics on silicon, this would create margin within the power envelope for more capacity. Optics on silicon was also viewed as the best tool for improving the fundamental I/O limit of silicon currently constrained by electrical interconnect.

4.2 Holistic Approach

Holistic Approach (25 votes): For energy efficiency the whole network has to be considered at once, not the optimization of separate components or subsystems.

One consistent theme throughout the roundtable discussion was the need for analysis, improvements, and optimizations to take a greater holistic approach. In some cases local optimization of efficiency does not result in absolute improvements but instead just pushes the costs to adjacent areas.

Different customer applications face different constraints, and these customers optimize for different architectures depending on what is expensive and cheap at a given place and time. If transport is relatively efficient from a cost/power perspective, then it is wasted to better utilize storage and compute assets. If transport is expensive then storage and compute assets are moved and duplicated as needed.

Efficiency must be viewed in the same context. Power consumption across the system should be optimized rather than local optimization of individual components. A watt saved at the line card is multiplied by savings upstream in HVAC, backup power, power transmission, voltage conversion—but only if the knowledge that one less watt must be delivered and cooled is communicated from the system to supporting infrastructure.

Some service providers have constructed their own computing and networking equipment after identifying these unavoidable multi-layer and multi-vendor inefficiencies. Inefficiencies included conservative operating temperature ranges that resulted in overly pessimistic power consumption, and the resulting over-design of power delivery and HVAC functions.

9 Xilinx Virtex 7 Specifications
Roundtable participants agreed that cross-platform technology to better monitor and adjust equipment on a facility- and network-wide basis could yield efficiency gains. Data on temperature and power consumption is available within a vendor’s system but often cannot be communicated in fine granularity to a higher layer responsible for overall orchestration.

This recommendation applies to a wider discussion of efficiency, and recognizes the need to improve efficiency among component, equipment, and service providers who frequently have products and organizations in rigid silos.

4.3 Cooling

Cooling (19 votes): *Use liquid and other advanced cooling to reduce energy requirements and create a stable, controlled thermal environment with increased integration density and performance.*

System density is power limited due to heat removal issues, and improvements here would expand the allowable thermal design envelope, improving density. Areas of specific focus included improvements in HVAC design, facility design, thermo-electric techniques, convection cooling, liquid cooling, and energy co-generation/recovery applied to core networking equipment and the areas that contain them.

Cooling is generally characterized by a dogmatic approach of forced air cooling and reflexive resistance to the use of liquid cooling in networking equipment. Participants felt this area of research was neglected and likely ripe for optimization.

Liquid cooling in particular was recognized as having advantages. It lends more thermal stability to a system, allowing operating parameters to be tightened and inefficiencies due to over engineering to wider temperature ranges eliminated. Silicon efficiency is improved at the lower temperatures liquid cooling can provide, and the operating lifetime of silicon and optical components is increased. Liquid cooling infrastructure is also better suited than forced air to reclaim waste heat at a facility level.

While liquid cooling received many votes, general cooling improvements via other means are also worth study. Fans and HVAC consume 23% of the power in datacenters—if convective techniques such as heat pipes were improved, this would reduce the need for mechanical cooling and have large efficiency benefits.

4.4 Optical Switching

Optical Switching (17 votes): *Optimize the use of optical switching and dynamic optical bypass to reduce energy consumption at the cost of granularity.*

The group recommended the use of various techniques to switch photonic circuits instead of electrical equivalents. Optical or wavelength switching can be used for both circuit based and packet based applications, though the latter requires more rapid reconfiguration and optical buffering mechanisms. The value of optical switching is that it avoids the use of costly optical-electrical (OE) conversion, as well as the electronics and interconnect needed to switch traffic.
The success of ROADM-based optical equipment is a market testament to the efficiency of optical switching. Attendees felt that there were a number of other areas where these benefits could be extended, particularly using optical switching and optical bypass of electrical switching nodes. Historically, subwavelength switching and grooming has been necessary. However, as capacity increases, the granularity of switching has increased and switching 10 Gbit/s and higher data streams is necessary. In this case, wavelength switching can provide a dramatic reduction in power, size and cost, while allowing greater flexibility, including colorless, directionless and contentionless switching. This places demands on the size of optical cross connects, but port counts in the hundreds to thousands are possible with low loss.

If optical transport cost is reduced, allowing it to be exploited more at a network level, this in turn will reduce the need for higher order electrical-based switching at intermediate nodes. Nodes at the edge of the network use additional all-optical connections to establish links with other edge nodes instead of relying on intermediate higher order electrical switching nodes in the core.

In the research literature, there are suggestions for using fast circuit switching as well as optical packet switching, but these concepts are still in the early stage of research, and have tradeoffs. Fast circuit switches typically have much smaller nonblocking switch sizes, and packet switches have increased power consumption per bit due to the contention and optical memory requirements.

4.5 Software-Based Techniques

There were several software defined networking (SDN) oriented recommendations identified for further study. SDN is a material manifestation of the popular holistic approach (25 votes) allowing for centralized observation and optimization of the network to maximize utilization and efficiency. SDN was considered by roundtable participants to be path computation as well as applications-initiated network control.

SDN (17 votes): Use SDN at all layers to dynamically optimize the network utilization and maximize efficiency.

SDN is a general technique to identify and remove provisioning inefficiency from the network, allowing for system-wide optimization and increased equipment utilization levels. It also allows for application-driven control of network assets, allowing network configurations to be more closely coupled with application requirements at any given time frame.

Software Based Multilayer Control (11 votes): Use SDN for multilayer optimization, however, avoid unnecessary layer transversals—each transversal takes energy.

It is a well-recognized and accepted industry concept that the lower that the traffic is switched in the OSI layer model, the more energy-efficient and cost-efficient the operation is. Optical switching via ROADM or other technologies (layer 0) is more efficient than electrical based circuit switching (layer 1). Both are more efficient than layer 2 frame switching and the more computationally intensive layer 3 (IP layer). Provisioning of each layer often takes place independently of the others due to historical technology and organizational issues. A mechanism than could evaluate provisioning across all layers would result in elimination of redundant protection paths in separate layers, and reduce the load on the more costly routing layer.

Core networking equipment power consumption is fixed and independent of utilization, therefore directly increasing utilization improves efficiency. SDN techniques can be used to pre-calculate the needed resources and paths for a given network topology and then orchestrate the use of these resources at maximum utilization.
Roundtable presentations and breakout discussions focused on one particular problem often observed in service provider networks—unnecessary multi-layer switching traversals in the network. Network traffic may transit less efficient higher order switching and routing equipment when an express path, which could be all-optical, would be more efficient. Service providers are challenged to identify these situations as there is poor communication between the control planes of the optical and electrical switching equipment.

One proposed recommendation was using SDN techniques to dynamically identify and correct inefficient multilayer transport and switching schemes. This was an attractive solution as it would not require a new architecture to be deployed—an outcome participants universally agreed was not realistic. Multilayer software based control would interface with both the optical and routing layer and optimize path computation on the fly as traffic patterns and usage changed. There are challenges with this approach such as whether control is distributed or centralized, or how dynamic core traffic really is and whether rapid configuration is even needed.

4.6 Power Management

Power Monitoring (15 votes): Expand power monitoring, analytics and control to all components of the network to enable maximizing end-to-end network efficiency, being cognizant of the traffic flow and history. Create metrics to compare efficiencies.

Analysis of power consumption in existing core networks is fractured with no systems capable of aggregating utilization data across all equipment types and locations. Most vendors sample and collect this information on a very granular level but then discard the detail when reporting it to the user.

It is not possible today to measure end-to-end efficiency by overlaying power consumption with network utilization history. Having this capability would allow network-wide power efficiency to be calculated end-to-end, therefore allowing evaluation of new approaches such as software based multi-layer optimization (11 votes) and the impact of more or less optical switching (17 votes). Once in place, network-wide metrics (such as Gbps*km per watt) could be calculated on the fly, allowing for objective measurement of efficiency even between two different networks. Participants agreed that before power utilization metrics can be standardized and various network architectures evaluated for efficiency, a more comprehensive multivendor power data management infrastructure is required.

Energy Proportional Systems (10 votes): Explore making network systems energy consumption proportional to traffic load.

Also explored was the concept of energy proportional systems—core networking systems where energy consumption is proportional to utilization. Networks are currently designed to maximize utilization as current equipment designs have fixed power consumption regardless of load. Some participants felt that using energy proportional systems would lead to less energy usage and network optimization effort while increasing network utilization.

There were some challenges to this approach. Current RFPs from service providers don’t request this feature, as network planning must still be made for peak load. Data centers provision and charge customers for maximum electrical breaker power—there is no variable pricing provided to tenants for electricity. Finally, the historic trend of the power consumption of silicon reducing with shrinking feature size is now slowing down because of increased leakage current. The leakage power is basically independent of the load, which is not helpful for the cause of energy proportionality.

Participants felt that with more sophisticated holistic power monitoring and delivery systems, the benefits of energy proportional systems would be more apparent.
5. Conclusions and Next Steps

Network traffic is growing at such a rapid rate that equipment operating today will account for only a small fraction of the equipment in operation. Therefore, it is tempting to approach the problem of core network efficiency by assuming that it makes economic sense to simply start network planning and deployment from a clean slate, and ignore all legacy requirements. This is exactly what new market participants, particularly in the large data center market segment, have done. This concept works well for new applications and deployments, but is not well suited to incumbents with deep operational experience in existing network architectures.

As a result, further pursuits must focus on evolving existing network architectures through revolutionary components or overlaid control architectures. This is the preference of the consumers of core network equipment and solutions must meet the economic reality of this market. These solutions will require cooperation between academia, carriers, equipment, software and component vendors, and government agencies.

The roundtable proposed a number of next steps to further pursuit of the recommended areas:

- Develop a strategy for approaching funding agencies, for example in areas such as cooling that have been neglected.
- Identify topics appropriate for industry-academic collaborations.
- Work with optical industry advocates, such as OIDA, to conduct optical industry workshops in this area.
- Investigate conducting OFC workshops focusing on a few specific areas identified in this report (for example, energy-efficient cooling techniques, the potential impact of using photonics integration, e.g., silicon photonics, in network equipment, using optical switching to facilitate SDN implementations, and concepts for realizing energy proportionality in transmission and switching equipment).

It was clear that discussion about energy efficiency in core networks covers a very broad range of topics, and touches several domains of expertise. The same group of people cannot be subject-matter experts on all topics covered. Ideally, several of the topics need dedicated study and would benefit from additional follow-up roundtables on subjects such as SDN, photonic integration, and facility cooling and power design.
# Appendix

## Table I—Results of Voting

<table>
<thead>
<tr>
<th>ICT Technology Roundtable—Actionable Recommendations</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integration: Increase photonic and photonic-electronic integration to reduce power, size, and cost; increase performance; and enable parallelism.</td>
<td>39</td>
</tr>
<tr>
<td>Optics on ASIC: Use optical integration on the ASIC to surpass the fundamental electrical IO limit of ICs.</td>
<td>28</td>
</tr>
<tr>
<td>Holistic Approach: For energy efficiency the whole network has to be considered at once, not the optimization of separate components or subsystems.</td>
<td>25</td>
</tr>
<tr>
<td>Cooling: Use liquid and other advanced cooling to reduce energy requirements and create a stable, controlled thermal environment with increased integration density and performance.</td>
<td>19</td>
</tr>
<tr>
<td>Software Defined Networking: Use SDN at all layers to dynamically optimize the network utilization and maximize efficiency.</td>
<td>17</td>
</tr>
<tr>
<td>Optical Switching: Optimize the use of optical switching and dynamic optical bypass to reduce energy consumption at the cost of granularity.</td>
<td>17</td>
</tr>
<tr>
<td>Power Monitoring: Expand power monitoring, analytics and control to all components of the network to enable maximizing end-to-end network efficiency, being cognizant of the traffic flow and history. Create metrics to compare efficiencies.</td>
<td>15</td>
</tr>
<tr>
<td>Software Based Multilayer Control: Use SDN for multilayer optimization, however, avoid unnecessary layer transversals—each transversal takes energy.</td>
<td>11</td>
</tr>
<tr>
<td>Energy Proportional Systems: Explore making network systems energy consumption proportional to traffic load.</td>
<td>10</td>
</tr>
<tr>
<td>Parallelism: Use integrated parallel channels to reduce power consumption and cost.</td>
<td>8</td>
</tr>
<tr>
<td>Virtualization: Use abstraction and virtualization to simplify the control and improve the use of network assets for optimizing network energy efficiency through utilization, protection, and planning.</td>
<td>7</td>
</tr>
<tr>
<td>Clean Slate: Since the network is growing so fast (100x in 10 years), design new systems for optimum efficiency without legacy requirements.</td>
<td>5</td>
</tr>
<tr>
<td>Photonics Roadmap: Create a roadmap for photonics technology performance, similar to the ITRS roadmap.</td>
<td>3</td>
</tr>
<tr>
<td>Efficient Computing: Build faster networks so edge devices and computing resources operate with higher utilization.</td>
<td>2</td>
</tr>
<tr>
<td>Load Balancing: Expand load balancing across network resources and geography at all time scales.</td>
<td>1</td>
</tr>
<tr>
<td>Optical Processing: Use linear and nonlinear optical processing to reduce the DSP power in the receiver.</td>
<td>1</td>
</tr>
</tbody>
</table>