OFC

The future of optical networking and communications

Post-show Report

An Overview of the Market

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Introduction

15,400
REGISTRANTS FROM
70 COUNTRIES

683
EXHIBITORS

1/3
OF REGISTRANTS
ARE BASED
OUTSIDE THE
UNITED STATES

21%
OF EXHIBIT
REGISTRANTS ARE
C-LEVEL

Source: OFC 2019
Registration Data

The Optical Fiber Communication Conference and Exhibition (OFC) is the leading venue for learning and discussing market trends, innovations, business opportunities and industry-shaping technologies. It is the world's largest conference and exhibition for optical communication and networking professionals that covers the entire ecosystem—where it is today and where it is going tomorrow in terms of research, technologies and product solutions.

15,400 from 70 countries convened at OFC 2019 to present, discuss and debate optical technology. Topics included using AI to manage and control networks, understanding the impact of 5G networking across the supply chain, and what innovations are allowing the network to reach speeds beyond 400Gbps in order to keep pace with the spectacular growth of cloud computing and services. Experts explored numerous global trends, including advances in coherent optical transmission, developments in data center networking, and new approaches in disaggregated network design.

Occupying 189,607 net square feet, OFC 2019 featured 683 exhibits from major international corporations such as II-VI, Acacia, Alibaba, Broadcom, Ciena, Corning, Finisar, Huawei, Infinera, Inphi, Juniper Networks, Lumentum, Semtech, Sumitomo Electric Device Innovations and more. Technologies on display included new compact modular WDM equipment designed for disaggregated network architectures, 16nm semiconductors for 400Gbs transmission and beyond, the latest optical technologies for 400GbE, network and test equipment, fiber cables and specialty fiber manufacturers and the latest in Indium Phosphide and silicon photonics optical components.

Three theaters on the show floor featured 30 sessions of business-focused programming providing high-level takes on the state of the industry, hot topics and perspectives on current and future challenges and solutions. Presentations by experts from major global brands included Acacia, Alibaba, Arista, AT&T, Equinix, Facebook, Google, Intel, Microsoft, Netflix, NTT, Verizon and many others as well as key industry organizations such as COBO, The Ethernet Alliance, OIF and TIP to name a few.

Over the past 40+ years, OFC has been the one must-attend show for companies to showcase the most noteworthy developments in the optical industry and make pivotal product and technology announcements. This report highlights and summarizes the 2019 developments in these areas.

- Inside the Data Center
- Advances in Coherent Technology
- Compact Modular Evolution
- Open and Disaggregated Networks
- Optical Technologies for 5G and MSO Access

1 Inside the Data Center

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The next major stop on the road to faster speeds in the data center is 400Gbps Ethernet, and activity at OFC2019 centered on making this speed a feasible commercial option. Companies across the show floor demonstrated advanced 400GbE semiconductors and optics that, once perfected, will catalyze yet another transition to faster Ethernet technology.

Production of 400GbE optical solutions exist today, but costs do not compare favorably against 100Gbps Ethernet, particularly after the massive drops in 100GbE CWDM and PSM module costs over the past two years. Cloud provider Google is taking advantage of one 400Gbps enabling technology—PAM-4—to deploy 200Gbps Ethernet today. But this is a solution that will not be adopted by the mass market, which is standing by waiting for the cost per bit of 400GbE to drop below 100GbE.

Ramping 400GbE Volume

Based on the production schedules of new products at the show, this situation will change around the end of 2019. The key enabling technology is 100Gbps per wavelength operation, which will effectively quadruple the amount of data transmitted per wavelength versus 100GbE technology. The 100Gbps Lambda MSA industry consortium championed this approach and built upon the work of the IEEE. Based on the amount of 400GbE optical modules demonstrated at OFC, 100Gbps Lambda MSA is a resounding success.

In the first half of 2020, Broadcom will sample its latest Ethernet switch chip, which will double switch density yet again. This device provides 25.6Tbps of switching capacity, providing 64 ports of 400GbE with 256 ports of 112Gbps I/O. In the past, the magic 64-port threshold was the point where rapid adoption of new Ethernet speeds takes place. Andy Bechtolsheim of Arista pointed out that 100Gbps I/O eliminates the need for a 50 to 100Gbps gearbox in the module,

1

yielding cost and power savings and making 400GbE more compelling. Provided all goes to plan, 2020 will be the year widespread 400GbE adoption begins.

Beyond 400GbE
OFC attendees felt greater challenges exist at speeds beyond 400GbE, particularly as switching density grows and the conventional approach of using electrical interconnect and pluggable optics consumes too much power. Stopgap solutions such as parallel or on-board optics offer only incremental improvements and have yet to achieve commercial success, despite appearing to align well with the needs of high-volume cloud data center operators.

Based on what OFC attendees said and where companies are investing, a more radical approach is needed. As switches reach 50Tbps of capacity, low power on-chip optics will become the only way to transmit signals to/from the switch silicon efficiently. And now even the largest companies (Cisco, Juniper, and Intel) as well as some startups have bet big on this concept. OFC2019 unofficially marked the start of the race to make data center switch and optics integration a high volume, commercially viable technology.

Making 400GbE Optics Cheaper

At OFC2019 there was an avalanche of announcements and demonstrations of products aimed at bringing 400GbE optical specifications to production. Most of the announcements were about how three single-mode fiber specifications will lead the transition to volume deployment:

> "We believe that continued expansion of router/switch capacity will require some level of integration of silicon/optics, and we want to start that investment now."
>
> BILL GARTNER – CISCO

- 400Gbps FR4 – 2km single fiber 4x100Gbps CWDM transmission
- 400Gbps DR4 – 500m 4x parallel fiber 4x100Gbps transmission
- 100Gbps DR1 – 500m single fiber 1x100Gbps transmission; four modules can connect with DR4 to provide breakout of individual 100Gbps signals.

PAM-4 Silicon
All 400GbE client specifications leverage PAM-4 signaling and 50Gbaud transmission to provide 100Gbps capacity per wavelength. This signaling requires multi-level transmission and receive-side DSP, and these functions are provided by PAM-4 silicon sourced from several suppliers. These chips sit inside the module and bridge

1

the 50Gbps electrical signals to 100Gbps for optical transmission. The availability of these chips at the right price and power has been one of the limits to making 400GbE affordable. OFC2019 was a chance for these suppliers to provide a progress report.

Inphi has long led the industry in providing the required driver and retimer functions inside optical modules at lower 100Gbps and 200Gbps speeds. At OFC, the company demonstrated its latest PAM-4 development, the Porrima Gen2 PAM-4 DSP, which integrates the laser drivers and the receive amplifiers into a single CMOS package. Shown in conjunction with Mitsubishi's DFB lasers, the solution demonstrated a sub 10-watt QSFP-DD solution for FR and DR4.

Inphi faces competition from several PAM-4 DSP and retimer vendors including Maxlinear and MACOM, but Broadcom is thought by attendees to be the greatest rival. Broadcom is the leader in shipments of Ethernet switches (the Tomahawk series) and has both the expertise and investment capital to pursue complex 7nm silicon designs. The company announced general availability of its PAM-4 DSP (BCM87106), comparable to the Inphi solution.

In the past, Broadcom pursued a successful business strategy by bundling chips with its switches – if you wanted the switch, you had to buy the retimers and PHYs too. This approach doesn't work as well today as the retimers/DSPs are now inside the optical modules, a business Broadcom jettisoned when it purchased Avago. Broadcom still sells the optical components that reside in these modules, and it will offer a full kit of PAM-4 DSPs and optical components to companies focused only on assembling and testing modules. Inphi, on the other hand, has long positioned itself as a neutral supplier, without any interest in competing with its optical customers who make lasers.

This market competition is beneficial for customers, who now have two large and trusted suppliers of 400GbE PAM-4 silicon both trying to offer customers a differentiated solution. This dynamic should guarantee a competitive supply chain for 400GbE module makers trying to ramp production at the end of the year.

Plenty of 400GbE Optics

The number of demonstrations of FR4, DR4, and DR1 modules was too many to count; yet another indication that the 400GbE ecosystem is healthy and preparing to provide a compelling upgrade from existing 100GbE speeds. These modules were everywhere, in QSFP-DD form factors but also OSFP. There was also a handful of VCSEL based 400GbE SR8 solutions on the floor from companies such as Finisar and HG Genuine.

Mitsubishi is already in production with DR4 modules and working its way towards a webscale-level run rate. It appears to be the only company besides Innolight that is supplying volume DR4 modules at this point. A DR4 to DR1 solution is the top application for 400GbE and allows the connection of four servers with 100GbE interfaces via parallel fiber to a single 400GbE DR4 module in a top-of-rack Ethernet switch. It turns out the killer app for 400GbE will first be a high-density 100GbE interface, not true 400GbE. Expect DR4 and associated lower speed DR1 modules to be the first 400GbE formats to reach high volume.

Intel, a proven and successful disruptor of the 100GbE module market, demonstrated DR4 modules and intends to be in volume production by the end of the year. The company also plans to extend its silicon photonics approach to FR4, although like virtually every other company at OFC, Intel feels that DR4 will be the first 400GbE market to lift off. MACOM joined Intel in announcing a silicon PIC-based FR4 solution.

Following the use of 400GbE as a high density 100GbE interface, data center switching architectures will evolve to use native point-to-point 400GbE interconnect. Lumentum demonstrated one of these 2km FR modules and Fujitsu Optical Components showed a 10km LR4 400Gbps solution for campus interconnect. Most of the other major component companies had demos as well, but these longer-reach higher-speed solutions won't see strong demand until late in 2020.

Joining the traditional optical component vendors in the race to deliver 400GbE optics are several companies focused only on module assembly and test. Jabil AOC,

1

Delta, HG Genuine, AOI, and Innolight, none of whom have fundamental laser and semiconductor expertise, purchase these components from Lumentum, Finisar, Mitsubishi, and Sumitomo. Designs are built specifically for large cloud operators, 3rd party resellers, or for re-labeling by equipment OEMs.

Data Center Optics Industry Roadmap

Data center optical module disaggregation is on the rise, as component companies increasingly focus on device engineering and innovation while leaving assembly and test to others. This change in the module supply chain is a result of the turbulent demand cycles of data center customers along with tough pricing and the presence of numerous suppliers.

The data center client optics industry direction runs counter to that of coherent optics, in which the most successful companies pursued aggressive vertical integration by designing all the components in a module in order to optimize costs and time to market. The 400GbE market stands in the opposite now, with disaggregation of components and assembly as the norm.

Module assembly is a labor-intensive business with lots of fixed assets that require a steady and sizeable revenue stream for justification. When 100Gbps components were oversupplied and prices dropped, these fixed assets became liabilities. Component companies today don't want to experience the same difficulties with 400GbE that they had with 100GbE, and they are happy to offshore the cyclical manufacturing risks to module assemblers.

Lumentum is exiting the client-side module business and selling off its operating assets to CIG, another example of a traditional component company struggling to find a business case for the module assembly business. Broadcom chose to exit the business when it purchased Avago, and steep pricing declines in the 100GbE module market forced many suppliers to abandon the vertically integrated component design and module manufacturing approach.

Yet, all of this will change once again in the future. The technical challenges of 50Tbps switching densities and the new and substantial investments made by large incumbent companies support this view. These future high-density switches will demand entirely new approaches to the traditional pluggable optics and central silicon switch model.

Getting Ready for 50Tbps Switching

The industry had multiple sources of 12.8Tbps Ethernet switches in 2019. 2021 will herald the production of 25.6Gbps switch silicon. If this development cadence holds, by 2023 there will be switching chips capable of over 50Tbps of capacity, a theory put forth by a number of panel participants at OFC. These panelists generally agreed that the conventional approach of pluggable optics could be a viable solution for the coming 25.6Gbps switch silicon, but beyond this the status quo approach will encounter significant technical barriers.

Of these barriers, the biggest by far is power consumption. Switching density per chip is increasing at a faster rate than switching capacity per watt. Specifically, the efficiency of the electrical connection between the switch silicon and pluggable modules is not improving. The obvious solution is to eliminate the electrical I/O altogether and replace it with optical I/O.

Putting optical modulators directly on the Ethernet switch chip is too ambitious—the expensive 7nm or 5nm silicon becomes encumbered with technology that will decrease yield and has no need for such advanced silicon geometry. Another approach would be to co-package the switch silicon with silicon photonic optical engines—referred to by many as optical 'chiplets.' These chiplets move the optics from the front panel right into the package of the switch chip itself, thereby eliminating almost all of the power consumed by the electrical connection across the board. Some companies like Rockley Photonics and Finisar propose using chiplets with the existing DR4 specifications, while others like Acacia make the case that this could even be a short reach coherent connection.

NTT, Rockley, and Ayar Labs are making

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chiplets an R&D focus, and it is likely other major semiconductor companies are working on them unannounced. More surprising is that the big incumbent equipment companies are also making investments in this area.

Equipment Vendors Get in the Game

A few months before OFC, Cisco announced the acquisition of Luxtera, a data center optics company focused on silicon photonics integration. Several years back, Juniper announced the acquisition of Aurrion, another silicon photonics company building active laser structures on silicon devices. Why were equipment companies, which increasingly allocate larger portions of R&D towards software, making investments in optics—a challenging industry known for low margins?

The answer is clearer now. While Luxtera makes optical modules, Cisco is far more interested in the fundamental design, test, and assembly expertise of the company than selling QSFPs. In the coming years, when optical interconnect from chip-to-chip is required to build state-of-the-art data center equipment, companies like Cisco don't want to rely on silicon photonics technology from Broadcom or Intel. Cisco expressed at OFC that it believes this expertise is required to be a vendor of cutting-edge hardware and not a reseller of white box systems built on others technology.

> "For a new network speed to be adopted in volume, it has to be more cost-effective than the current generation networking technology."
>
> ANDY BECHTOLSHEIM – ARISTA NETWORKS

Juniper also took the opportunity at OFC to announce its silicon photonics technology based on Aurrion and plans to offer standards-compliant 400GbE QSFP-DD modules. Juniper plans to integrate this technology into future packet engine designs, and not just be another vendor of pluggable optics. This is a similar strategy as Intel, that is using pluggable optics as a real proving ground for more complex, more valuable, and higher volume applications.

Key Takeaways:

- 400GbE adoption to date has been slow due to the high cost relative to 100GbE. New single lambda 100Gbps solutions are reaching production this year and will catalyze adoption.
- Inphi and Broadcom each offer PAM-4 DSP customers a unique value proposition. Again, the competition should be good for customers and accelerate adoption.
- 400Gbps DR4 and DR1 modules will lead the volume ramp of 400Gbps in the data center as a means of providing high-density 100GbE interconnect. Demand for FR will follow.
- Traditional optical component companies are abandoning the module test and assembly business and focusing on building only the laser and detector components. This is an attempt to outsource cyclical manufacturing risk to ODMs.
- The arrival of 50Tbps Ethernet switches in 2023 will force a fundamental re-imagining of how conventional Ethernet switches are architected. The power consumption of I/O to connect switch silicon and pluggable optics is too high at this density. A more radical approach of integrating optics onto the switch via 'chiplets' is the approach most attendees are expecting.
- Component and equipment companies realize this could be a disruptive change and are making investments or acquisitions in anticipation of retaining technical leadership.

2 Advances in Coherent Technology

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Coherent announcements and roadmaps at the show focused on two themes: lowering the power of coherent technology for use in pluggable applications and increasing baud rates to raise the maximum capacity of a single wavelength beyond 600Gbps. Every coherent component announcement concerned either 400ZR or beyond 600Gbps operation. And despite few new ROADM announcements, there was a spirited debate about future ROADM architectures.

Pluggable Coherent—ZR/ZR+

OFC attendees were excited to discuss the massive scale of 400ZR activity, R&D progress, and network operator plans for deploying the technology. 400ZR development has catalyzed the development of new products targeting additional applications.

The 400ZR development ecosystem can now be partitioned into three distinct markets:

- 400ZR – 400Gbps for 100km DCI interconnect in a pluggable QSFP or OSFP format, standardized by the OIF.
- 400ZR+ - Variable multi-haul speeds of 100 to 400Gbps for metro regional reach (up to approximately 1200km) in larger CFP2 or OSFP modules, standardized by OpenROADM.
- 100ZR – 100Gbps for 80km applications at the network edge, designed as a 50Ghz compatible upgrade for 10G WDM, standardized in the IEEE & CableLabs.

Each of these three applications represents different market opportunities and entail different timelines. The opportunities for 400ZR are well understood but constrained to a few high-volume situations with cloud operators. The opportunities for higher performance pluggable 400ZR+ are less clear, but it could potentially displace most of the existing coherent technology

2

shipping today. A standardized coherent pluggable like 400ZR+ could also disrupt the standalone hardware market by allowing operators to deploy coherent WDM in switches and routers more easily.

Microsoft and Google presented at the OFC Data Center Summit and were most interested in 400ZR for metro DCI applications with intent to begin deployment in the late 2020 timeframe. Tad Hofmeister of Google presented the architecture it plans to deploy, with 400ZR pluggables used for all applications in which they could deliver the needed reach. Microsoft, which pioneered the pluggable Metro DCI architecture with the Inphi ColorZ, intends to replace ColorZ with a 400ZR equivalent. Microsoft indicated that it likes the ZR+ concept as an upgrade path for the CFP2-ACOs it currently uses in its Arista equipment. The key determinant for the success of ZR+ in Microsoft's network will be cost/reach relative to non-pluggable 600Gbps and 800Gbps solutions.

A dozen companies are investing upwards of $500M in total to bring 400ZR and its derivatives to market. Some of these companies are focused on a portion of the opportunity, while four vendors (Acacia, Inphi, Ciena, Infinera) are pursuing a fully vertically integrated strategy. If history of the coherent market is a guide—in which vertically integrated equipment companies have shipped 75% of all ports to date--these three vendors should be well positioned for future success.

Glenn Wellbrock of Verizon envisions using 400ZR to interconnect the company's two regional hubs which operate in large cities with select peering points, but not for the hundreds of other nodes Verizon operates in the same city. For those applications, Verizon requires coherent optics capable of multi-haul, or reaching a wide range of possible distances. Pluggable ZR+, used within Verizon's new unified routing architecture based on Juniper, is a better solution for this portion of the network.

Behind closed doors, both Inphi and Acacia demonstrated silicon photonics prototypes that will be paired with 400ZR DSPs scheduled to sample later this year. Both companies plan to sample complete modules this year.

Ciena also made 400ZR a part of its coherent roadmap announcement and committed to building a 400ZR module both for use in its own equipment as well as for sale as a standalone component. The company indicated it would offer multiple module formats and have commercial availability in the first half of 2020. Infinera hinted that it planned to provide pluggable 400Gbps solutions as well.

Finally, the optical module format debate over 400G has been re-ignited. Several operators we spoke to preferred QSFP DD but expressed concern about the risks of bringing 400ZR to market in this format rather than the less constrained OSFP module. These operators anticipate a tiered introduction of 400ZR, with the availability of OSFP earlier than QSFP DD and with better performance. These operators also expect a broader supply chain of OSFP module suppliers and therefore more attractive

VENDOR COMPONENT	DSP	TROSA	OPTICAL MODULE
Acacia	Yes	SiPho	QSFP DD
Finisar		InP	QSFP DD
Fujitsu		InP	QSFP DD
Inphi	Yes	SiPho	QSFP DD
Intel		SiPho?	Maybe
IPG Photonics	Maybe	Maybe	Maybe
Lumentum		InP	QSFP DD
MACOM		Maybe	Maybe
NEL	Yes	SiPho & InP	
Neophotonics		InP	
Sumitomo Electric Equipment		Yes	QSFP DD
Ciena	Yes	Yes	Yes
Cisco	Maybe	SiPho?	Maybe
Huawei	Yes		QSFP DD
Infinera	Yes	InP	Yes
Nokia	Maybe		Maybe

400ZR and ZR+ Development Ecosystem

pricing. While Google and Arista are the only companies to commit to using the OSFP format, other 400ZR consumers are now taking another hard look.

Multiple attendees who visited the Ethernet Alliance demo booth felt that the risks of QSFP DD were clear, as careful inspection of the test equipment showed that OSFP 400Gbps client optical modules operated at lower BERs than QSFP DDs with the same optical parameters.

Faster Speeds Beyond 600Gbps

The current generation of 600Gbps DSPs from Acacia, Huawei, and Nokia that will reach market in 2019 are so efficient that they allow transmission to approach the Shannon Limit, the theoretical maximum capacity of optical fiber. Improvements to spectral efficiency via more complex modulation schemes have now reached the point of diminishing returns.

Consequently, the remaining means of improving coherent links is to raise the baud rate and increase the number of symbols sent, rather than making symbols more complex. This approach allows a single wavelength to transmit more bandwidth over a given distance, but the drawback is that these higher baud rate signals will occupy more optical spectrum. This means bandwidth per wavelength is increasing with higher baud rates, but bandwidth per fiber is reaching a ceiling.

The business case for faster baud rates on a single wavelength isn't about improving the transmission capacity of fiber, it's about improving transmission efficiency and cost per bit. The argument for higher baud rates is that fewer DSPs and optics are needed to deliver the same amount of bandwidth as earlier generations of coherent technology. Given that system cost is proportional to the number of wavelengths, this approach should continue to drive the cost/bit of transmission down. However, the issue of spectral efficiency and the lack of improvement to fiber capacity remains, and it compels operators to lease or deploy more fiber once the spectrum of a fiber is exhausted.

All told, these latest generation coherent products represent stunning engineering challenges, requiring new packaging

techniques and electronics to enable symbol rates approaching or even exceeding 100Gbps. Even if these challenges are surmounted, the reward is found in lower costs, not additional capacity. Some equipment vendors and operators were skeptical that these solutions would prove compelling in many high-volume applications when compared to standardized, commoditized 400ZR+ solutions. Given the massive investment and effort required, a substantial cost/bit reduction with these new 800Gbps solutions will be the most important metric of success.

Company Announcements

In the weeks leading up to OFC, both Ciena and Infinera announced their roadmaps for the next generation of coherent technology. Both companies' announcements focused on new DSPs and optics designed to reach maximum speeds of 800Gbps, but more importantly to deliver speeds of 200Gbps and 400Gbps over longer distances than existing solutions. Like 400ZR, these DSP chips use the latest generation (and most expensive) 7nm silicon processes and cost tens of millions of dollars to design and prototype.

Infinera announced the ICE6, an 800Gbps solution that it had only hinted of during last year's OFC. This year, the company demonstrated the ICE6 InP photonic integrated circuit that contained two full sets of transmit and receive optics operating at up to 800Gbps speeds. In terms of bandwidth density, this 1.6T PIC offers roughly a 2.5x improvement over the ICE4 PIC (1.6T bidirectional vs 1.2T unidirectional), which reached volume production last year. Infinera also announced that the 7nm DSP designed to work with the PIC would prototype in 3Q19 and power ICE6 samples by the end of the year. The company expects ICE6 based 800G systems to ship in the second half of 2020.

Ciena announced the WaveLogic 5 Extreme (WL5e), a solution capable of 800Gbps but optimized for higher performance 400Gbps long haul and 600Gbps metro regional transport. Like the Infinera solution, the WL5e is designed to outclass the 600G hardware reaching the market this year: Ciena claims a 20% improvement in spectral efficiency over these solutions. The company also highlighted strategic decisions giving it more ownership of foundational electro-optics component technologies. Ciena expects systems using the WaveLogic 5 Extreme will be in production by the end of 2019, which would limit the market window for competing solutions.

Huawei did not announce any new coherent products but indicated that it continues to invest in higher baud rate DSPs and coherent solutions. The company has 600Gbps technology based on its H6 oDSP and low power 200Gbps pluggable coherent solutions based on its G6 oDSP.

Coherent Component Innovation

The only component company to announce coherent optoelectronic components with the 50Ghz bandwidth required to enable 800Gbps links was Neophotonics. These included a high-performance narrow linewidth laser, modulator and coherent receiver, and all of these follow the company's earlier success with a previous generation of components that power many of the 600Gbps systems reaching production today.

Lumentum announced successful interoperability of its CFP2-DCO with Acacia, thereby creating a second supply source for customers who are looking to reduce the risk of purchasing solely from one supplier (Acacia). Cisco is using the CFP2-DCO across multiple systems, and other router companies such as Nokia and Arista make use of this format. Other companies such as IPG Photonics and Jabil AOC also introduced 200G CFP2-DCOs, as they seize on the growing interest among switch and router vendors to integrate pluggable coherent optics.

Finisar was the first company to demonstrate a component addressing the new OIF IC-TROSA specification, which is a single integrated component containing all the optical functions needed for a coherent link. This IC-TROSA is key to enabling commodity ZR+ pluggable CFP2-DCO modules, and perhaps even 400ZR modules in OSFP form factors. Other companies including Neophotonics announced such devices, but

2

Finisar was the only one with functioning devices on the show floor.

Finally, Huawei and Fujitsu presented technology designed to increase the capacity of fiber, rather than just increase the speed of the wavelengths. Fujitsu demonstrated its TransLambda solution which can map the entire C-band of wavelength to L-Band and eliminate the need for L-band specific transponders. Huawei introduced super C-band technology, which extends the amplification and operating windows of the conventional C-band to increase fiber capacity.

ROADM Architecture Debates

New ROADM component and equipment announcements were sparse, but the debate about the direction of ROADM architecture was spirited. At last year's OFC, there were extensive discussions and presentations about a new wavelength selective switch (WSS) designed to replace the multi-cast switch (MCS) and amplifiers required to implement contentionless ROADMs. Lumentum was at the center of this debate as the sole supplier of this new MxN WSS switching component.

This year, ECI introduced a new CDC ROADM based on Lumentum's unique technology and highlighted the advantages of this architecture. ECI's message echoed that of other equipment vendors like Huawei and Ciena, who have already announced open line systems that use this component.

Informal discussions with equipment and component makers indicate that cloud network operators are making MxN based ROADMs a centerpiece of their new long haul WDM networks. These operators deeply value automation, and the unconstrained ROADMs make networks more efficient and easily reconfigurable through software.

Other more traditional operators were not so sure. The MxN WSS is single sourced from Lumentum, and other WSS suppliers are hesitant to invest in the technology only to see margins and pricing for this challenging component collapse. Operators are concerned about the large up-front cost required to deploy the MxN based

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architecture, and those with smaller nodes prefer the lower first-in cost of MCS.

Molex (via its Nistica acquisition) is seeing demand for its smaller ROADMs in access and 5G networks in which operators use the optical switches for remote protection, monitoring and troubleshooting. II-VI announced a small port count WSS this year aimed at addressing this same application.

One thing is clear according to equipment vendors—demand for WSS and MCS components is exceptionally strong and no customer can get the volume needed to meet demand. Lumentum indicated that it sees strong demand for its unique MxN product as it ramps production mid-year. MCS component suppliers also say demand has never been stronger. The tight supply situation is exacerbated by further demand in China, where Huawei is aggressively ramping production of ROADMs based on both MCS and MxN architectures.

Key Takeaways:

- Component developments originally targeted at 400ZR are now being repurposed to address additional adjacent markets beyond the original 400Gbps 80km DCI specification. These markets radically increase the addressable market for 400ZR development and reduce market risk for the companies making substantial investments in this area. The availability of pluggable, standardized coherent technology is likely to have a major impact on network design and equipment architecture.
- Proposed 800Gbps solutions should lower the cost/bit of coherent transport, particularly for longer reaches. They do not improve spectral efficiency, though, and they don't solve the problems of operators whose capacity is constrained due to a lack of fiber. The cost and complexity of these developments are such that only a few component and equipment companies can justify the investment needed to bring them to market.
- There is no consensus on CDC ROADM architectures, as divided operators prefer either the traditional MCS based approach or the new MxN approached based on their requirements.

3 Compact Modular Hardware Evolution

3 Compact Modular Hardware Evolution

The compact modular form factor has grown in popularity since its introduction in 2014 as a stand-alone transponder option. Traditionally, compact modular hardware has been defined as a shelf one or two rack units tall and dedicated to a single optical function (transponder, amplifier, ROADM) without many options to change the functionality or configuration. These platforms were initially employed by webscale operators for data center interconnect (DCI) for their simplicity and ability to perform exactly—and only—the functions necessary to move bandwidth between two locations.

Most optical hardware vendors have introduced their own versions of compact modular systems, and customers now include traditional network operators as well as cloud and colo. Compact modular systems are now deployed beyond simple DCI applications and can address any application that requires large bandwidth interconnection. As the number of applications has grown, compact modular hardware has evolved to address a larger customer base.

Examples of Compact Modular Systems

Cisco NCS 1000

Ciena Waveserver Ai

ADVA Teraflex

Fujitsu 1FINITY T100/T200

Huawei OSN902

Infinera Groove G30

Nokia PSI-2T

Evolution to Modularity

Compact modular platforms have transformed beyond simple monolithic systems to include modularity (via "sleds" rather than "cards", but the concept is the same) enabling a single shelf to be used for multiple network functions. Transponders can be combined with amplifiers, ROADMs, and a variety of switch fabrics to tailor the compact modular configuration for an application. Testing capabilities such as OTDRs and network monitoring can also be included. While disaggregation does not require compact modular systems (a disaggregated network can still be deployed with traditional equipment), compact modular systems are a big part of most operators' disaggregation strategy. Therefore, all compact modular systems include open interfaces for management by standard controllers.

Modularity eliminates the up-front cost of buying all the hardware on Day 1, which is

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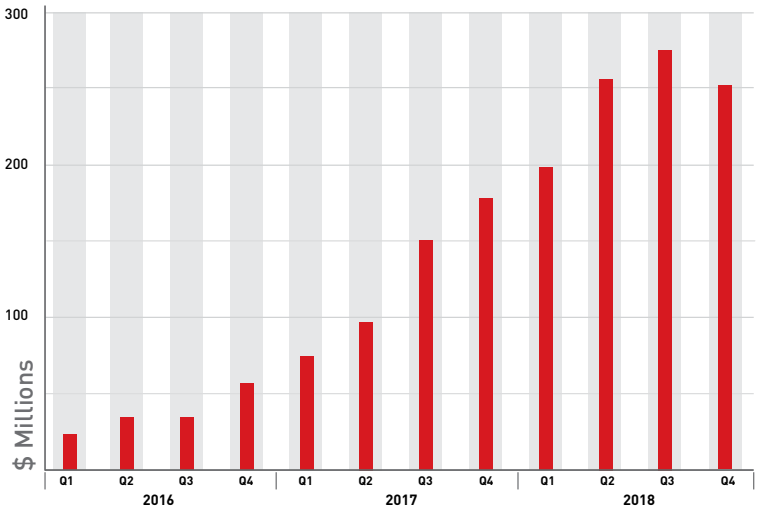
especially important to service providers. Upfront cost was not an issue for initial webscale customers (who could use all the bandwidth immediately upon deployment) but it is a concern for operators who have grown bandwidth over time and prefer to pay-as-you-grow.

As the concept of IP-over-DWDM (colored optics used directly in routers and switches in lieu of standalone transponders) gains traction with operators, the compact modular open line system (OLS) is growing in popularity. In a presentation, Tom Williams of Acacia labelled compact modular open line systems the stepping stone to IP-over-DWDM and claimed a 40% reduction in system power will be achieved by using ZR pluggables directly in switches for 80km applications. At the same time, Vijay Vusirikala of Google stated that while his company embraces the IP-over-DWDM concept, it will continue to use compact modular systems for any optical form factor that does not already fit into Google's routers (i.e., anything other than QSFP) as doing so reduces operational complexity in the network.

Multiple hardware vendors demonstrated their latest compact modular platforms at OFC 2019. There were announcements of field trials, commercial availability, and roadmaps for future deployment of transponder-based systems, open line systems, and even switching systems all built around the compact modular concept.



Compact Modular Sales Worldwide

Source: Cignal AI 4Q18 Optical Applications Report.

Compact Modular Market Overview

As network traffic moves towards a more universal packet-based architecture, the compact modular concept continues to gain traction as a way to simplify the optical layer. Compact modular sales currently represent roughly $250 million in revenue per quarter, or about 6% of the total optical hardware market. However, compact modular is the fastest growing segment in optical hardware and will grow as a percentage of the overall market as adoption accelerates. The recent drop in 4Q2019 is primarily due to loss of sales as a result of the Infinera/Coriant merger, and compact modular sales are expected to recover and continue to increase in 2019.

600Gbps Systems Reach Commercial Availability

The promise of faster-than-400Gbps compact modular platforms became more real at OFC this year. While Ciena's Waveserver Ai 400Gbps platform has been the only 400Gbps platform shipping in 2018, more solutions operating at 400Gbps and above are arriving in early 2019.

Fujitsu announced the commercial availability of the 600Gbps 1Finity T600, based on the NEL DSP. Several other vendors announced products based on Acacia's 600Gbps DSP, including compact modular hardware from ADVA (FSP 3000 Teraflex) and Cisco (NCS1004) as well as ECI's TM1200 card for the Apollo platform. These systems will be commercially available in the first part of 2019, and most are already in commercial trials.

- On the show floor, Fujitsu demonstrated T600 600Gbps operation over 80km on SMF and over 120km using OFS's TeraWave ultra-low-loss (ULL) fiber. Fujitsu claims to have more than a dozen trials in place across all verticals – service provider, cable/MSO, and cloud network operators.
- ADVA's 600Gbps Teraflex, based on the Acacia AC1200 module, will be commercially available in early 2019. The Teraflex is one of the newer sled-based compact modular systems, designed with three slots that support up to 1.2Tbps each (one AC1200 module). As with

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many of the newer systems, the Teraflex supports open management interfaces for integration into a disaggregated, SDN-based optical network architecture.

- Cisco's strategy is focused on evolving compact modular systems to be more flexible with features such as removable sleds, replaceable power supplies, and transponders with L1/L2 switching. Cisco and Verizon conducted a trial with the NCS 1004 demonstrating the benefits of the programmable line rate. A similar trial with research network AARNet in Australia was conducted.

The Roadmap to 800Gbps Compact Modular Systems

Ciena, Infinera and Acacia presented roadmaps to next generation compact modular systems at OFC 2019.

- Ciena announced that it will integrate WaveLogic Ai 5 into the popular Waveserver compact modular platform by the end of the year, leading the technology race to next generation 800Gbps coherent systems.
- Infinera reconciled its Coriant/Infinera product line by displaying the former Coriant Groove platform based on the Acacia DSP as its current third generation coherent compact modular platform and halting development of ICE5-based CX platforms despite successful field tests with customers. Going forward, Infinera will return to internal DSP development and integrate its upcoming ICE6 across its product line during the second half of 2020.

New Form Factors, Functions, and Features

Compact modular open line systems and optical switching platforms were introduced at the show, with Ciena displaying its Reconfigurable Line System (RLS) and Ekinops showcasing its RM ROADM series. The Edgecore Cassini Open Packet Transponder was a part of several demonstrations of open optical networking.

ADVA's FSP 3000 OLS is designed to be an open line system for data center operators who need to support both direct-detect optics as well as coherent optics. Although still a compact modular platform, the OLS is a modular design which allows mixing and matching filters and amplifiers and further pushes compact modular closer to

the original card-based system model. It is also specifically designed to migrate ColorZ-based networks to 400ZR.

The Ekinops RM ROADM-H4-WB and ROADM-H10-WB are promoted as "white box" open line compact modular systems that can operate in any standard open-source environment. Combined with Ekinops' transponder solutions based on the company's own optics development and multiple DSP options, Ekinops offers several compact modular systems as part of its disaggregated networking strategy.

Most of the announcements and demonstrations at OFC 2019 were based on products from large optical equipment manufacturers introduced at previous shows. However, the compact modular concept has extended deep into the optical ecosystem with some interesting twists shown at this event.

SmartOptics showed its DCP-M system designed to support Inphi's PAM-4 100Gbps optics and make deploying direct detect 100Gbps transmission simple for smaller operators. Optelian displayed its MPX-9103 hardened 100Gbps muxponder, a compact modular system designed to be deployed in outside cabinets. PacketLight introduced the PL-2000T, a 4x200Gbps addition to its line of 1RU metro and long-haul optical solutions. Each of these unique approaches expands the addressable market for compact modular hardware.

Key Takeaways: Compact Modular Hardware Evolution

- The compact modular market continues to be the fastest growing segment of the optical hardware market and will accelerate as the number of applications and customers increase.
- Compact modular hardware evolved from monolithic, single-function devices to flexible, sled-based systems that are like the traditional hardware shelves that they are replacing. While some still refer to these systems as "DCI boxes", the service providers are now driving part of the roadmap for functions other than simple DCI.
- Ciena's 400Gbps+ platform, which was commercially available in 2018, is being joined in 2019 by competing platforms from Fujitsu, ADVA, Cisco, Infinera, ECI, and others that were demonstrated at OFC2019.
- Compact modular systems from major optical vendors such as Ciena, Infinera, Cisco, and ADVA are being augmented by new concepts by smaller companies like Ekinops, Optelian, PacketLight, and SmartOptics.

4 Open and Disaggregated Networks

4 Open and Disaggregated Networks

Open and disaggregated network equipment, software, and standards were a common theme on the floor and in presentations at OFC this year. Vendors showcased disaggregated hardware and open software interfaces, standards bodies and industry groups proposed updates to recommendations and standards and network operators debated the benefits and challenges of implementing open and disaggregated networks.

Definitions of Open and Disaggregated

The definitions of open networks and disaggregated networks have evolved since their introduction, and many vendors have a variety of optical networking offerings that fit into one category or the other. While disaggregated does not necessarily require open and open does not necessarily imply disaggregated, these concepts are usually tied together as they both come from the same motivation—to make networks more interoperable and purpose-built for the applications that they support.

Open networks typically refer to equipment and services that are interoperable and can be controlled by generic third-party software via standards-based interfaces. Industry groups like OpenROADM work to develop standards for physical interoperability as well as a common control language (typically YANG data models and NETCONF interfaces) so that equipment from many sources can be easily deployed in the same network. These efforts go much further than previous approaches such as SONET and TL-1 or SNMP by making interoperability more transparent at the physical layer and by abstracting complexity into a standard model at the control layer.

The concept of disaggregated hardware began as strict separation of network functions into distinct hardware components: switches, transponders, amplifiers, etc.

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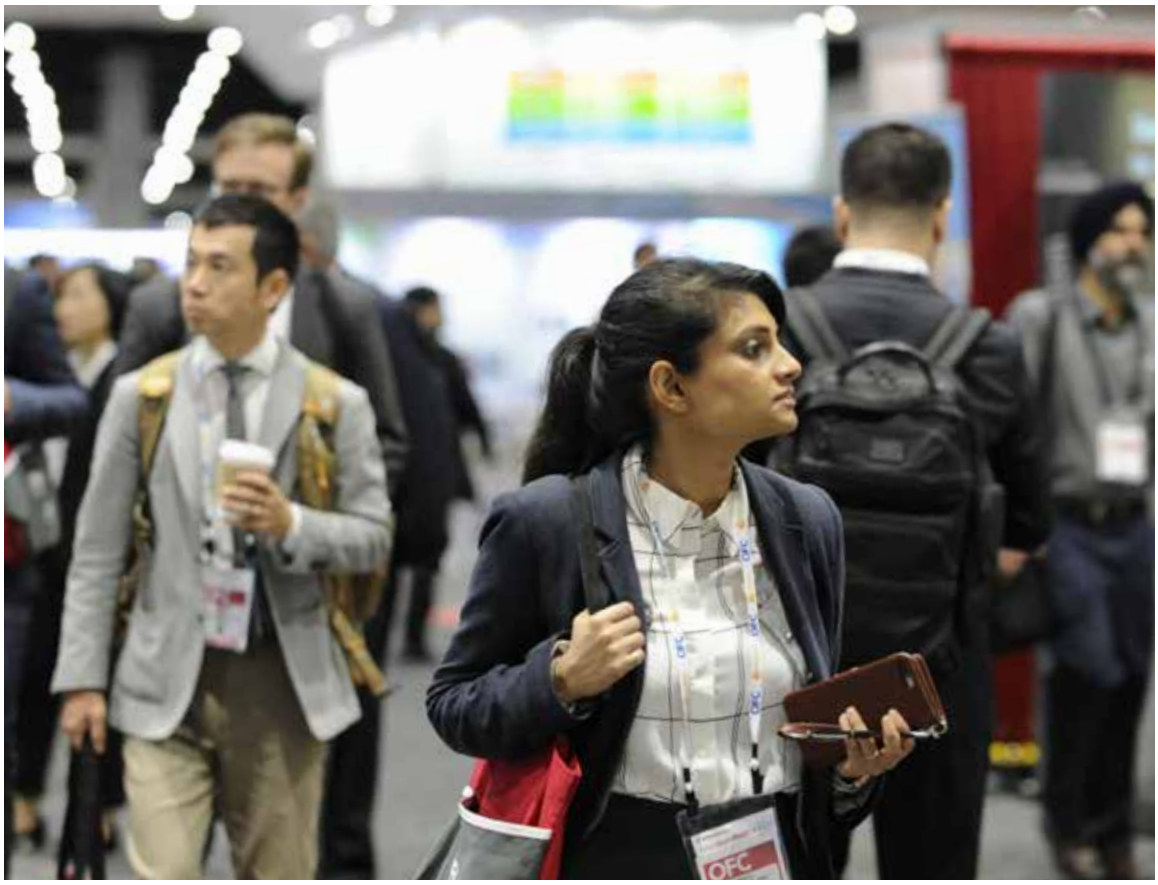

With a disaggregated network, operators could pick exactly the functions needed for any application and would not be forced to deploy unwanted features or leave slots empty in shelves. Since its introduction, the concept has evolved based on operator feedback, and disaggregated systems can now include multiple functions (e.g. switching for efficiency in filling bandwidth on a transponder shelf). The challenge is that network complexity isn't reduced, but instead shifted from the hardware to the software layer, requiring an operational shift for network providers.

Software is always the hardest piece to complete in an open and disaggregated design, especially as hardware becomes more flexible. The capability of multi-haul optical interfaces to adjust to line conditions or demand adds another layer of complexity to traditionally static optical infrastructure. Flexible optical capabilities such as ROADMs, open line systems, interoperable coherent interfaces, and programmable coherent modulation have great promise if the standard APIs, control interfaces, and software can be designed to make them easy to implement.

Parallel to disaggregation, the concept of IP-over-DWDM was widely discussed at OFC by both vendors and operators. IP-over-DWDM combines several functions into a single element (e.g. switching and optical), but the goal of reducing network complexity is the same. With IP-over-DWDM, colored optics are deployed directly in switching hardware, eliminating the need for a separate transponder system. IP-over-DWDM has gained popularity due to the reduced size of high-speed optics allowing higher faceplate density and the development of standard APIs for control of the Layer 1 functions within complex coherent optical modules. Both Acacia and Google mentioned the benefits of IP-over-DWDM in presentations at OFC.

Neither disaggregation nor open networking is the same as the concept of "white box" systems, which were also on display at OFC. White box is a concept taken from packet networking, where generic processor and/or switch hardware are deployed and application-specific software downloaded

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91%
OF EXHIBITORS ARE LIKELY TO EXHIBIT AGAIN

Source: 2019 OFC Post-Conference Survey

45%
OF EXHIBIT ATTENDEES SPENT 10+ HOURS ON THE SHOW FLOOR

Source: 2019 OFC Post-Conference Survey

68%
OF EXHIBIT REGISTRANTS HAVE A ROLE IN BUYING DECISIONS

Source: OFC 2019 Registration Data

51% OF EXHIBIT REGISTRANTS HAVE PURCHASING BUDGETS OF $1M OR MORE

Source: OFC 2019 Registration Data

to make the hardware perform as intended. This concept does not translate well to optical hardware, as software cannot change the physical layer, but the idea of generic hardware being assembled by a third party (e.g. the TIP Voyager project) has been of academic interest. A few vendors and industry groups promoted their "white box" concepts on the show floor, including Edgecore's Cassini packet transponder and Ekinops' white box open line systems.

Operator Viewpoints

Cloud and colo operators were the first to adopt open networking and disaggregation. Open networking allows them to integrate optical control into their data center control model and disaggregation allows them to purchase bulk bandwidth for data center interconnect without any of the other service-provider functions that they do not need.

Traditional service providers seek ways to improve interoperability and manageability but encounter difficulty bringing disaggregation and open networking into their networks. Their legacy equipment, more diverse customer base, and their variety of service offerings present difficulties. These service providers generate revenue from the connectivity itself (whereas optical networking is the connectivity that enables the revenue-generating content that a webscale operator provides) and, therefore each have different priorities for network builds.

During OFC, Cisco mentioned it is seeing fewer requests for disaggregated networks from service provider customers as the challenges of implementing those networks become more apparent. On the other hand, IP-over-DWDM is gaining popularity to reduce network costs without adding complexity. Cisco, Nokia, and Tejas, all mentioned in conversations that a shift to packet-based transport and IP-over-DWDM was underway with their customers. ZTE had a different perspective and stated that the concept has yet to take hold in China, and operators like China Mobile prefer to keep the optical and switching functions separate. The China Mobile model is a conceptually disaggregated model (optical and switching separate) if not a purely disaggregated model in which all functions exist on separate platforms.

During the OFC Data Center Summit event, operators Google, Facebook, Verizon, and Alibaba detailed their approaches to open networks. Google believes the primary goal of open networking is to adopt and deploy new technology faster. The supply chain diversity that open networks deliver is secondary to the purpose of more rapid technology integration. Key elements to this Google's approach are disaggregation (including a move to compact modular systems), zero touch management, and programmability. Google acknowledged it is easier for cloud operators than for traditional service providers to embrace the additional complexity this approach requires at the operational and software control. Facebook's and Alibaba's approaches are very similar to Google's, although Facebook is not interested in a radical disaggregation of the common equipment layer.

> "Innovation radically reduces cost, standardization provides only incremental gains."
>
> DAVE WELCH – INFINERA

Verizon's view on disaggregation has always been at odds with that of the webscale providers, as Verizon believes that the capex and operational savings from combining functions into the same hardware outweigh most of disaggregation's benefits. Verizon described its definition of open networking as standard northbound interfaces for intelligent network management. Beyond that, the Verizon network is much more complex than a webscale network, and the concepts of open and disaggregated are much harder to implement.

Open Networking Standards

Standards bodies and industry groups such as TIP, the OIF and OpenROADM were all present at OFC 2019. They gave

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updates and showed demonstrations of the physical and control interfaces that enable open networking.

OpenROADM is the industry group spearheaded by AT&T to encourage interoperability at the optical layer in metro networking. It had both a live demonstration and a collection of static equipment from participating vendors. Ciena's and Fujitsu's optical equipment was in a live demo with interoperable 100Gbps transponders as well as ROADM/OLS line system, all controlled via an open source OpenDaylight controller developed by the University of Texas, Dallas (UTD). The OpenROADM 100Gbps coherent physical layer specification was also on display in the OIF Demonstration booth and the Coherent Transceiver interoperability demonstration.

The Telecom Infra Project (TIP) is an industry group started by Facebook tasked with creating new approaches to network infrastructure. The TIP Open Optical and Packet Transport (OOPT) group demonstrated a solution built around the Edgecore Cassini "Open Packet Transponder" system, an open source white box switch platform that can be deployed with optical interfaces from several vendors. Coherent modules from Lumentum, Fujitsu Optical Components, and Acacia were used in a Cassini white box running the IP Infusion OcNOS operating system. The entire demonstration was managed via the ONF's ONOS open source SDN network operating system. Not demonstrated, but mentioned in the TIP literature, was the ability to use ONOS to talk directly to the transceivers via the OIF-defined T-API interface.

The Optical Interworking Forum (OIF) sponsored several interoperability and progress demonstrations featuring the progress of OIF's 400ZR project, the interoperability of the latest CEI-112G 112Gbps electrical interface specifications, and advances in FlexE implementation. The OIF presented a session on the 400ZR standard as well as updates on OIF Open Optical Networking projects, including the T-API interface mentioned above.

Open and Disaggregated Hardware and Software

Nearly every optical hardware announcement at OFC used the terms open and disaggregated to describe the solution. However, the definition of open and disaggregated varies from vendor to vendor including compact modular hardware.

OFC presentations and demonstrations showed real world examples of the steps taken since the last OFC towards implementing open, controllable hardware, including:

- ADVA demonstrated a SDN-controlled 600Gbps transmission with automated line rate and modulation adjustment based on link conditions which was designed specifically to meet the needs of disaggregated webscale customers. This capability allows operators to get the

maximum possible bandwidth out of an optical link without manual intervention via open NETCONF/YANG interfaces.

- Prior to OFC, Infinera and Telia Carrier demonstrated a fully autonomous intelligent transponder operating on a live 1500km route in Telia Carrier's backbone network using prototype Infinera hardware. The demonstration simulated impairments such as interference, aging, and channel add/drop, highlighting the ability of the coherent interface to change modulation to match link conditions automatically.
- ECI introduced its "As You Like It" optical networking portfolio based on standard interfaces and flexible, disaggregated hardware. The hardware can be designed by the customer as needed and supports NETCONF/YANG open and interoperable interfaces for control.
- Ciena, Fujitsu, and Cisco all demonstrated compact modular disaggregated hardware platforms with open software interfaces.

Software is the key element to make open and disaggregated networks work. An IEEE- panel (Innovation Opportunities in Transport Networks from Network Analytics and Machine Learning) featured presentations from Google, Facebook, Ciena, and ADVA on how intelligent software will be used for everything from determining fiber type to anomaly detection to fault management and automatic service restoration. The key to these new applications is the open hardware supporting the control interfaces necessary for the software to communicate with the network.

Key Takeaways: Open and Disaggregated Networks

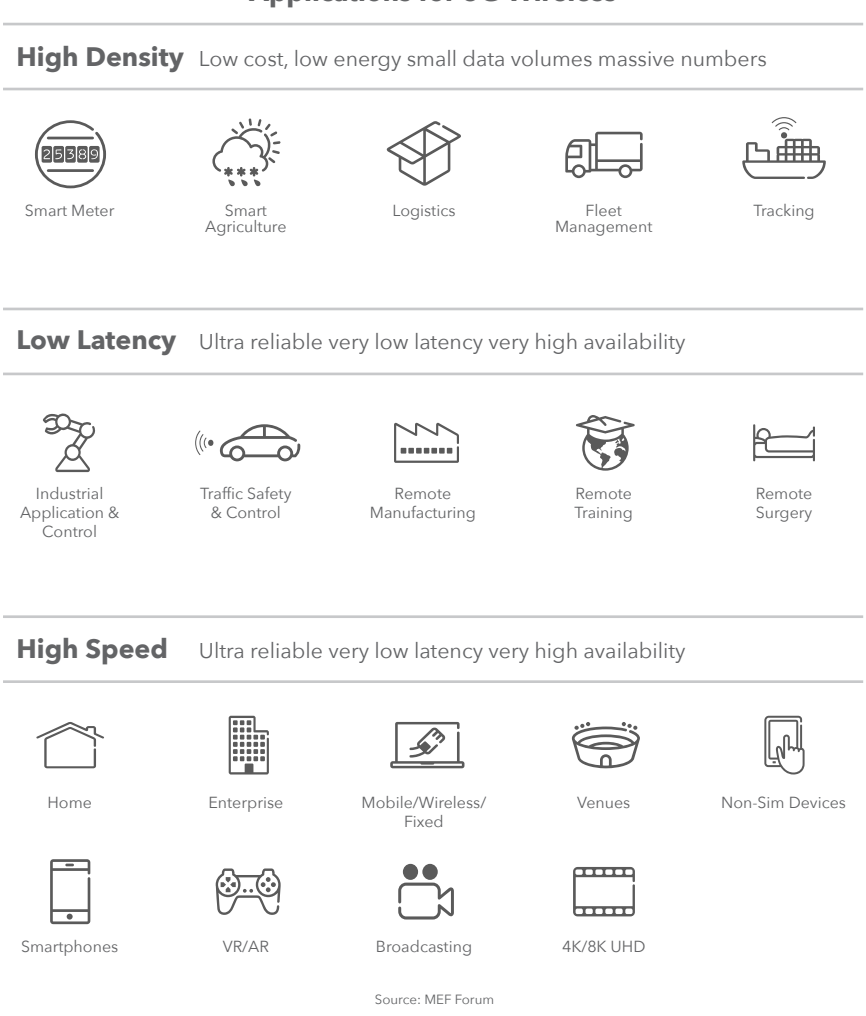
- Open and disaggregated networks continue to be very popular among optical equipment vendors and operators, although there is wide variation in their definitions. Nearly all optical hardware can claim some level of openness and disaggregation, as evidenced by many announcements at OFC supporting these concepts.
- All operators agree with the goal of the open and disaggregated movements: to make networks more interoperable and cost-effective for the services that they carry. However, actual implementations vary widely, especially between traditional service providers and webscale network operators.
- Software to make open and disaggregated networks simple to install and operate is key, and progress is being made in both the standard interfaces as well as the network applications and intelligence needed.

5 Optical Technologies for 5G and MSO Access

5 Optical Technologies for 5G and MSO Access

5G mobile technology and the cable/MSO initiative Fiber Deep are generating interest in new and unique optical networking solutions. Both are pushing more bandwidth to the edge of the network by increasing wireless capacity with 5G and by extending the fiber portion of the HFC network further into the access with Fiber Deep. There were two separate programs on the OFC show floor focused on 5G (a Market Watch panel and a Network Operator Summit panel), numerous component and equipment announcements about 5G and MSO access, and the term "5G" prominently displayed on booths from testing equipment to hardware vendors.

Applications for 5G Wireless



Source: MEF Forum

The Promise of 5G and Fiber Deep

5G Mobile Architecture

5G mobile is just beginning to roll out around the world, with early trials in the US, Japan, China, and South Korea. It promises a major upgrade in wireless technology and will spur optical spending in the access portion of the network. 5G offers more than just an increase in speed, it also improves network latency and enables massive connectivity for IoT applications.

At the Market Watch panel, "Market Projections for Wireline and Wireless Technologies to Support 5G", representatives from Cisco, Futerwei, the MEF Forum, and Cignal AI presented an overview of the new applications that are enabled by 5G, the technology's current status, and its expected impact on optical networks at the edge and in the core. 5G requires a new access network in order to realize the full array of low latency, high bandwidth, and massive connectivity applications. New packet-based eCPRI interfaces connecting radios to baseband units (BBUs) are critical, with Ethernet rates of 25Gbps and 50Gbps targeted. While the access equipment (FTTP, CPRI, fiber, and passives) will see notable increased demand, the overall impact to the metro and long haul network will be minimal. These areas, which deploy traditional optical equipment

5

(DWDM, ROADM), will experience a slow 5G rollout and only moderate additive bandwidth requirements deeper into the network.

At the Network Operator Summit panel, "5G Applications and Networks: Real-world Operator Case Studies," representatives from Deutsche Telekom, Zayo, British Telecom, and Verizon showcased their plans to support 5G rollouts over the next year. The operators plan to disaggregate radio access networks (RANs) in order to centralize the processing necessary for applications like mobile edge computing (MEC). MEC is one of the technologies that will enable new, processing-intense applications at the edge, and it requires improved optical connectivity between remote sites. For now, dark fiber is being deployed to radios by wholesale operators to support third party (i.e., not owned by the wireless carrier) backhaul. Meanwhile, wireless operators that own backhaul fiber are deploying PON (NG-PON2 for Verizon) to capitalize on their existing fiber infrastructure.

MSO Fiber Deep Architecture

The recently developed Remote PHY Distributed Access Architecture (DAA) standards from CableLabs push fiber and optics deeper into the network by using digital solutions rather than the more traditional MSO analog optics. MSOs view fiber as the means to enhance and re-condition their last mile networks, as fiber architectures are inherently higher bandwidth and are easier to manage than the existing copper-based networks. This current shift in network architecture opens the door for a variety of products from traditional optics vendors like Cisco, Ciena, and Nokia that are well-positioned to take advantage of new "fiber deep" architectures.

Operators currently deploy multiple 10Gbps WDM links to support the bandwidth requirements of Fiber Deep architectures, but they would like to get away from the complexity and costs of WDM access when possible. WDM requires coordination and provisioning of wavelengths, additional mux/demux units, and multi-channel monitoring. Costs rise as the number of wavelengths increases. CableLabs recently published a request for a low-cost 100Gbps coherent technology to enable its fiber deep architecture, and components manufacturers

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Source: OFC 2019 Media Report

on the show floor displayed their progress towards enabling low-cost, hardened optics for the cable industry. The goal is a single wavelength solution at 100Gbps that costs less than 10x the current 10Gpbs, but in the interim, other solutions addressing operational issues are being proposed.

Components for 5G and MSO Access

OFC components announcements and demonstrations for 5G and Fiber Deep focused on temperature hardening, ease of management, and achieving bandwidth rates required for eCPRI and backhaul. Advances in component hardware are designed to lower operational and capital costs, which then enable large scale deployment in access networks. While performance is key for the high speed 400Gbps+ coherent components announced at OFC, ease of use and cost are higher priorities for the access area as the amount of components deployed are an order of magnitude higher than in the core of the network. Therefore, access announcements involved either innovations in simple gray optics or lower cost 100GHz grid-compatible DWDM optics.

Several vendors announced optical solutions designed for 5G eCPRI and MSO Fiber Deep applications at OFC.

- **Finisar** has a set of low cost, industrial temperature pluggable 25Gbps transceivers for 5G networks in SFP28 format. Both bi-directional tunable and short-haul Fabry-Perot pluggables were shown on the show floor. Finisar promotes the ability of its tunable optics to automatically discover free channels as a means of greatly reducing WDM's operational complexity in the access network.
- **Sumitomo** announced its development of hardened SFP28 25Gbps modules in conjunction with Semtech's low power bi-directional CDR, designed to operate over 10km. Sumitomo also showcased its SFP+ DWDM extended temperature 10Gbps solution for Remote PHY.
- **Source Photonics** announced volume shipments of its 25Gbps and 50Gbps modules designed to support 5G eCPRI. These include 25Gbps SFP28 duplex modules, single wavelength modules, and DWDM modules supporting reaches from 2km to 20km as well as 50Gbps QSFP28 duplex modules supporting 10km and 40km reaches. Source Photonics also has a 100Gbps QSFP28 supporting up to 10km.
- **Intel** demonstrated its 100Gbps industrial temp CWDM4 solution for 5G. This module, originally announced in September, has a 10km reach and is expected to be used in cell-site routers for aggregation of eCPRI and other local signals.
- **II-VI** announced WSS modules, O/E-band interleavers, and wideband WDM filters designed for use in optical access networks. These solutions are optimal for the 100GHz/low port count/high cost sensitivity requirements inherent in optical access.

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Hardware for 5G and MSO Access

The hardware on display at OFC for 5G and Cable access focused on 5G fronthaul and cell site gateway switching. 5G solutions announced or demonstrated at OFC included WDM and packet-based solutions for 5G xHaul as well as Radio Access Network (RAN) disaggregation solutions. There were no highlighted announcements related to Cable Fiber Deep applications at the show, but much of the optical access technology shown applies to both network architectures. Some specific 5G and Fiber Deep solutions included:

- **Fujitsu** announced two lines of xHaul (fronthaul, midhaul, and backhaul) solutions: one based on transparent WDM transport and one based on Ethernet switching. The Flexihaul WDM solution includes 25Gbps transponders supporting bi-directional eCPRI connections. The Ethernet-based solution is a hardened switch supporting 25Gbps and 100Gbps interfaces and time-sensitive networking (TSN) for latency and timing-dependent 5G networks. The M6424-R version also includes PHY-LOW processing to allow 4G CPRI conversion to eCPRI at the cell site, enabling a simpler migration from 4G to 5G.
- **ADVA** and **Infinera** both demonstrated support for the Telecom Infra Project (TIP) Disaggregated Cell Site Gateway (DCSG) specification with TIP DCSG-compliant solutions. The project is intended to allow software to be disaggregated from the hardware, which allows operators to choose the optimal solution for their networks.
- **Ciena** and **British Telecom** announced that Ciena's Waveserver compact modular platform is supporting the carrier's 5G and FTTP rollout. As access networks become more packet-based and disaggregated, compact modular platforms like the Waveserver are attractive options for delivering bandwidth in the access.

Key Takeaways

- The new access technologies required for 5G and Fiber Deep architectures will generate demand for lower cost, temperature-hardened optical solutions as fiber is deployed to extend bandwidth deeper into the access network. In the access, cost is key.
- According to network operators, virtualization and disaggregation are key to lowering costs for access networks by deploying lower-cost, purpose-built 5G and Remote PHY networks.
- A few hardware solutions are being developed and deployed today which support 25Gbps and 50Gbps optics and packet switching for 5G xHaul, but it is very early in the 5G rollout cycle. Expect to see more packet and DWDM solutions from other vendors over the next year.

Conclusion — Outlook for 2019

Through its many meetings, discussions, and presentations among customers, vendors, and engineers, OFC sets the stage for the coming year. Here's what you should watch:

400GbE Narrows the Cost Gap

100GbE will remain the speed of choice for almost all data center operators throughout 2019. There will be a broad competitive ecosystem of silicon and optical component suppliers advancing 100Gbps single lambda technology. By the end of the year, DR4 optics will be available in volume and at attractive prices, which will trigger a move to 400GbE client optics in 2020 among the large cloud data center operators. Further out, expect both component and equipment companies to invest in photonic integration in order to resolve the 50Tbps switching interconnect problem.

Coherent Technology Evolves Towards Higher Speeds and Pluggability

2019 is the year that 400 and 600Gbps coherent technology transitions from a sole source to a multi-sourced technology which provides a compelling alternative to existing 200Gbps coherent solutions. Speeds faster than 600Gbps won't reach production until 2020, but there will be widespread R&D activity and lab demonstrations as the year ends. Expect the 400ZR ecosystem to expand as component companies seek to capitalize on a pluggable coherent future and optical equipment companies improve their offerings in order to defend existing network architectures.

Compact Modular Moves Out of the Data Center

Compact modular systems are now deployed in applications beyond simple DCI, and they can address any network need for large bandwidth interconnection. The design of compact modular systems continues to change based on feedback from traditional service providers. These systems represent

the leading edge of supplier R&D and are the first to incorporate the latest technology, including 800Gbps speeds in 2020.

Open and Disaggregated Networks

Individual operators will define the meaning of open networking and disaggregation based on the context of their own specific architecture and customers. Cloud operators already embrace this approach, and new 5G and Cable MSO network initiatives will inspire fresh network design approaches. There will be no "standard" implementation– the degree of openness will vary by operator. OpenROADM, TIP, and the OIF continue to drive standardization of components in the network allowing operators to pick and choose what works for them.

5G and MSO

5G and MSO applications compliment open and disaggregated networking, and they will drive demand for hardware that is tailored to high volume access deployments. Expect to see incumbent equipment and component suppliers build dedicated solutions for this market, but don't be surprised to see new companies capitalize on this new high volume market.

Questions?

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