INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

2016 EDITION

OUTSIDE SYSTEM CONNECTIVITY WHITE PAPER

OUTSIDE SYSTEM CONNECTIVITY

1. CHARTER

Identify capabilities needed to connect most elements of the internet of everything (IoE) and highlight technology needs and gaps. This includes supporting connection of a broad range of sensors, devices and products and to support information processing and analysis for many applications (i.e. mobility, energy, health, and others) with wireline, wireless and optical interconnect technologies.

2. MISSION

Identify device and technology requirements and research needed to enhance intersystem communication for the next 15 years.

3. SCOPE

The OSC scope includes devices for signal conditioning, transmission devices, coupling and receiver devices and circuits for Cu wiring, wireless RF & Analog and Mixed Signal (AMS), including antennas, and photonic interconnects. The scope also includes identifying emerging material, component manufacturing and heterogeneous integration requirements. RF wireless applications include a wide range of application including WiFi, BlueTooth, Mobile phones, and a wide range of IoT devices. Photonic interconnect applications include local area networks (LAN), data centers, automotive, FTTX, aerospace, and telecommunications.

4. CROSS TEAM INTERACTIONS

OSC will align with IRDS Systems & Architecture, iNEMI and other roadmap efforts on functionality and performance requirements for future communition capabilities.

OSC will align with IRDS More Moore and Beyond CMOS (ERD) on current device and circuit capabilities. OSC will also align with Heterogeneous Integration on integration of active and passive devices and capabilities required to enable efficient assembly of low loss products.

OSC will align with IRDS Design, Test, Metrology, Modeling and Simulation, and Emerging Research Materials (ERM) on capabilities required to enable design, development and manufacturing of future communication capabilities

OSC will also align with ERM and Environmental Safety and Health (ESH) on environmental safety and health requirements and challenges for materials used to manufacture future communication devices and products to ensure they meet requirements through their lifecycle.

5. STAKEHOLDERS

Stakeholders for the OSC include RF, AMS and wireless and photonic component manufacturers, IoT device designers and manufacturers, systems design and manufacturing companies, information processing and communications infrastructure companies (including data centers). RF & AMS and wireless researchers and photonic device and architecture researchers are also stakeholders in the OSC.

6. TECHNOLOGY STATUS, NEW REQUREMENTS AND POTENTIAL SOLUTIONS

The internet is evolving into a very long, complex communications chain from devices at the end of the internet to the data centers and back. Information, for example, can go through an electrical interface, an RF interface, an electrical interface, optical media and back to electrical when it gets to the backplane level in the data center. Then the data communication paths and interfaces reverse when information is sent back to the device. All of these links are potential security leaks potential conflicts and require energy for conversions, not just electronic to photonic, but from one protocol to another.

6.1. Technology Status and Update

The application of RF wireless continues to expand with the introduction of more IoT devices and preparations for cellular 5G technology. Security is becoming a larger issue for wireless devices that access the internet. For photonic interconnects, applications in data centers continues to be the performance and high volume driver that is extending into the server racks and is approaching board level applications. Servers and data centers provide greater functionality per unit volume from improved chip technology and in rack electrical interconnect performance has been adequate. The need for in-rack optical has been delayed because optical the cost/bandwidth/power benefit has not been competitive with conventional Cu interconnects. Recently, the Consortium for On Board Optical Communications (COBO) has been formed to drive development of competitive board level photonic interconnects within data centers and is defining requirements for multi generation adoption.

6.2. New Requirements & Difficult Challenges

6.2.1 RF & AMS Requirements and Difficult Challenges:

Requirements for RF & AMS ICs, devices and passives should not change from the 2015 ITRS 2.0; however, the IRDS will be expanding to include antenna and smart antenna technologies and identify hardware capabilities that may be needed to enable enhanced wireless security. Currently, most security is based on software, such as encryption, however, combinations of software and hardware are being considered to provide security from evesdropping and intrusion. For mobile devices, the primary approach would be to detect anomalies that could identify potential intrusions through spoofed wireless stations, etc.

The difficult challenges RF & AMS continue to be the same as those in the 2015 ITRS 2.0 OSC chapter, as shown in Table 1. The first challenges are to deliver increased performance with technologies integrated on CMOS. Development of "smart" antenna technologies is critical to reducing cost while increasing functionality of mobile devices and IoT devices. Also, development of hardware technologies that could supplement software are needed to enable wireless security solutions for all components of the internet. A potential hardware capability that could enhance security would be to detect anomalies in direction or incoming signal strength or other signitures.

6.2.2 Photonic Interconnect Requirements and Difficult Challenges

The requirements for most photonic interconnect applications have not changed from those in the 2015 ITRS 2.0 Outside System Connectivity Chapter, as shown in table 1; however, requirements inside of a data center have become more challenging. The potential high-volume photonic interconnect application in data centers is the progression to backplane, board, card and package level interconnects. These need to seamlessly connect to the outside of rack interconnects in the data center. For the progression of photonic interconnects to proceed from the backplane to the package level, the cost and energy consumption of photonic circuits must be reduced. This will require more compact photonic devices and routing circuits. Furthermore, low loss/low cost connectors are needed to interface between the board-level photonics and the longer range photonic interconnects in the data center (whether single mode or multimode).

In the longer term, optically based switching and routing will be needed to reduce latency in communication in data centers, so new materials and devices will be need to enable this. Currently, there are no optically switched devices that can operate at high speed. Also, in the future, optical devices need to be made much more compact and this may require building devices and interconnects in 3D. To enable this, devices may need to be fabricated in 3D.

Table 1: Outside System Connectivity Difficult Challenges

Difficult Challenges 2016-2023	***Summary of Issues***
Achieving high performance energy efficient RF analog technology compatible with CMOS processing	Achieving high performance RF required reduced gate resistance which is difficult to achieve Integrating SiGe with CMOS is difficult to achieve high performance heterojunction bipolar transistors (HBT) Integrating III-Vs with CMOS it is difficult to achieve high performance III-V devices Increasing passive device functional density on chip; e.g., resistors, inductors, varactors, and capacitors
Deliver wireless capabilities to support a broad range of applications for IoT devices	Increasing antenna complexity to support multiple applications Security: While solutions to avoid tampering / intercept of RF communications will probably mainly rely on software solutions, and hardware technologies beyond the scope of the Outside System Connectivity Focus Team (e.g., cryptography), we cannot exclude the possibility that security concerns will have an impact on RF technology requirements
Reducing cost of Optical Interconnects	Reducing the large number of components (hundreds) that are expensive Reducing the cost of single mode connected optical devices Increasing optical interconnect density while reducing cost and power Reducing optical device power Increasing Density of MUX/DeMUX and reducing the size of this functionality. Developing low cost joining methods to provide the sub-micron location tolerances needed over the life cycle of single mode structures.
Increase the bandwidth density (bits/mm^2) of Optical Interconnects	Increasing the density of DeMUX with multiple wavelengths, polarizations, etc. Increasing the operating frequency of modulators while reducing power consumption Increasing the operating frequency of detectors while reducing power Simultaneously fabricating and joining multiple parallel fibers or waveguides
Improve the reliability of optical Interconnects	Determine factors that limit the reliability of lasers for single mode OI Improve the reliability of connector technology Determine factors that limit the reliability of modulators, MUXes, DeMuxes
Difficult Challenges 2024-2031	***Summary of Issues***
Agreeing on Optical technology standards	By 2024, multiple optical implementations are likely to be in use implying that standardization could result in cost saving. Will standards emerge or will multiple proprietary solutions prevail?
Processing information in the optical domain	Regenerate digital signals in the optical domain without returning to the electronic domain, a capability that is likely to require non-linear optical materials. Perform logic operations in the optical domain Switch optical streams (circuit switching) in the optical domain.
Establish a System Level Reliability Strategy	Identify a strategy for reliable O/I with point to point connectivity Identify a strategy for reliable O/I with LAN connectivity
Utilize the "Z" dimension more effectively	Optical devices are often linear or planar yet much could be done, especially to reduce size, utilizing the 3 rd. dimension. Design, but specially fabrication in "Z" is "hard". Some type of 3D printing might enable this technical solution.

6.3 Potential Solutions

6.3.1 RF Wireless Potential Solutions:

To improve the performance of RF devices, parasitic resistances in gate and source drain regions must be reduced. The introduction of FinFET structures has the potential to reduce parasitic resistance in MOS devices. Also, the introduction of Ge and III-V devices on silicon has the potential to increase the FET performance. If these higher mobility devices can be fabricated with FIN structures, this could enable lower resistance gates and source/drain structures.

For wireless technology to be effective in anomaly detection, antennas and wireless circuits may need to be able to simultaneously transmit and monitor external transmissions. Furthermore, having the ability to monitor directions of incoming signals and their strength as a function of time may enable enhanced anomaly detection. Anomaly detection may be cost effective in mobile phones, tablets, and notebook computers. Recent research has demonstrated RF circuit designs that can simultaneous transmit and receive signals using a single antenna[RF1, RF2]; however, research is needed on low cost antennas that can dynamically identify incoming signal directions.

6.3.2 Photonic Interconnect Potential Solution:

To reduce cost, increase information density and increase speed, several approaches could be employed including heterogeneous integration or homogeneous integration of optical devices, plansmonic structures for compact routing of photons or nanostructured devices. Progress has been demonstrated in these in the past year.

Heterogeneous integration of devices has been demonstrated and commercial products based on these are being sampled.

Homogeneous integration of optical devices on InP has demonstrated an all optical wavelength router[OI1] that operates at 40Gb/s.

Plasmonic nanostructures have been employed to perform a number of optical functions in compact spaces and enable new capabilities. Plasmonic grating structures have been demonstrated to separate 17 wavelengths with spacing as close as 3.1 nm[OI2]. VCSEL's have been coupled plasmonically to waveguides with a Mach-Zehnder interferometer[OI3], which significantly simplifies integration of lasers with waveguides and other optical elements. The addition of plasmonic nanostructure antennas to lasers has been demonstrated to enhance the spontaneous emission rate with high radiation efficiencies[OI4] and could lead to high data rate LEDs. It has been proposed that properties of plasmons can be modified by the nanostructure[OI5] and possibly the properties of adjacent dielectrics[OI6]. Thus, plasmonic structures have the potential to enable higher density optical devices and circuits in the future.

Nanostructured Passive and Active Devices: As was highlighted in the 2015 ITRS 2.0 Outside System Connectivity Chapter, nanostructured aperiodic structures enable the constructing of high density compact routing and demultiplexing functions in waveguides with single wavelength scales. These nanophotonic structures are fully three-dimensional and multi-modal, have very compact footprints (a few microns long at most), exhibit high efficiency, and are manufacturable. Several of these structures have been experimentally demonstrated[OI7], showing that inverse designed structures can be fabricated and are robust to fabrication imperfections. Also, incorporation of nanostructure in lasers has been used to demonstrate electrically pumped lasers with lasing thresholds of 287 nA at 150K[OI8] which is 1000X less than earlier electrically pumped nanocavity lasers.

7. SUMMARY

The Internet of Everything (IoE) is highly dependent on RF & AMS, wired and photonic interconnects. As the number of users and devices connected to the IoE increases, the volume of data traffic will dramatically increase and the bandwidth of communications through all interconnects will need to increase. To support the increased data rates in communication, RF device performance will need to increase which will require high performance devices and circuits that will require increased use of Ge and III-V and possibly integration of these on Si CMOS platforms. To support increased data rates over the internet, wired and photonic interconnects will need to operate with higher bandwidth that will require higher speed electrical and photonic modulation techniques. For photonics, this will require modulation increased numbers of wavelengths, polaraizations and other properties, which will require new materials and devices. Within data centers, photonics will need to extend into the rack and boards seamlessly which will require development of compact low cost and power photonic devices and compact routing circuits which will require new materials and devices.

Furthermore, security of the IoE is limited by the weakest device or link in a path, so new methods will be needed to secure all links in the data paths. This may require sophisticated software and hardware coupled to detect anomalous sources that are probing remote devices to gain access or attack the IoE. Thus, devices connected through all forms of communications to the internet will need to have protection from intrusion.

8. REFERENCES

RF1. D. Bharadia, E. McMilin and S. Katti. “Full Duplex Radios.” ACM SIGCOMM Computer Communication Review 43 (4), 375-386, 2013.

RF2. D Bharadia and S Katti. “Full Duplex MIMO Radios.” 11th USENIX Conference on Networked Systems Design and Implementation, pp. 359-372, USENIX Association Berkeley, CA, USA, 2014.

OI1. X. Zheng, O. Raz, N. Calabretta, D. Zhao, R. Lu, and Y. Liu. “Multiport InP monolithically integrated all-optical wavelength router.” Optics Letters 41, pp.3892-3895, 2016.

OI2. Y. Tsur and A. Arie. “On-chip plasmonic spectrometer.” Optics Letters 41, pp. 3523-3526, 2016.

OI3. C.P.T. McPolin, J.-S. Bouillard, S. Vilain, A.V. Krasavin, W. Dickson, D. O’Connor, G.A. Wurtz, J. Hustice, B. Crbett, and A.V. Zayats. “Integrated plasmonic circuitry on a vertical-cavity surface-emitting semiconductor laser platform.” Nature Communications 7, 12409, pp. 1-8, 2016.

OI4. K.L. Tsakmakdis, R.W. Boyd, E. Yablonovitch, and X. Zhang. “Large spontaneous-emission enhancement in metallic nanostructures: toward LEDs faster than lasers.” Optics Express 24, 17916, pp.1-12, 2016.

OI5. A. Genc, et. al. “Tuning the plasmonic response up: Hollow cuboid metal nanostructures.” ACS Photonics, 2016.

OI6. W. Cai and M. Brongersma. “Plasmonics gets transformed.” Nature Nanotechnology 5, pp. 485-486, 2010.

OI7. A. Y. Piggott, J. Lu, T. M. Babinec, K. G. Lagoudakis, J. Petykiewicz, and J. Vuckovic, “Inverse design and implementation of a wavelength demultiplexing grating coupler”, *Scientific Reports* 4, 7210 (2014). DOI: 10.1038/srep07210.

OI8. B. Ellis, M. Mayer, G. Shambat, T. Sarmiento, E. Haller, J. S. Harris, and J. Vuckovic. “Ultralow-threshold electrically pumped quantum-dot photonic-crystal nanocavity laser”. Nature Photonics **5**, pp. 297-300 (2011). DOI: 10.1038/nphoton.2011.51.

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