INDUSTRIAL INTERNET OF THINGS

Contents

EXECUTIVE SUMMARY

Introduction

Broadly speaking, the IoT is a system consisting of networks of sensors, actuators, and smart objects whose purpose is to interconnect "all" things, including every day and industrial objects, in such a way as to make them intelligent, programmable, and more capable of interacting with humans and each other. Applications of these smart solutions across consumer and industrial markets (IIoT) has been estimated to drive $1.7T investment by 2020, one third of which is in hardware; IoT sensor revenues are predicted to grow at a CAGR of 35% to ~ $47B by 2021, but these estimates keep increasing. IoT applications are being developed for the consumer market (wearables, autonomous vehicles), smart homes, buildings and cities, mobile healthcare, and manufacturing sectors, which will revolutionize how we use the internet and drive rapid industrial growth. Smart Sensors with on board or remote signal processing and artificial intelligence (AI) to trigger automated actions may help enable the next industrial revolution.

Even though other technologies (wireless communication, MEMs and other sensor materials) are already part of the IoT landscape, photonic components and photonic integrated circuits (PICs) have a substantial role to play in expanding the required network capacity and in developing high-performance, miniaturized, smart photonic sensors.

Current Status

The number of devices currently connected to the internet per person is 4~5. Early growth in the consumer market takes advantage of existing network connectivity using cell phone apps to connect wearable devices (smart watches for health care monitoring) and home or office wireless networks for environmental monitoring and control and security monitoring and access. Internet Protocol version 6 (IPv6) together with 5G and narrower band networks are being developed to deal with the anticipated growth in the number of addressable IoT devices and data traffic, and required end-to-end quality of service, (particularly for mission critical applications in health care, autonomous vehicles, security and certain environmental applications).

Main Challenges

IoT is anticipated to grow rapidly to the point where cities will have one smart "thing" per square metre. New wireless cellular networks will need to deal with the density and volume of data, and it is anticipated that the total amount of installed fiber will double in the next 4 years for short access links. E2E QoS must address high reliability, low latency and sufficient data rate to securely handle bidirectional data for each application. Mission critical applications may require round trip data exchange of~ 1ms or less, and managing minimum service interruptions for mobile users (in automobiles and trains) is an additional networking requirement. The photonic components and PICs required for these expanded 5G networks and IoT sensors will need to meet these requirements, taking into account packaging demands on SWaP and price versus volume pressure (- an opportunity for Si Photonics and InP PCIs) as the number of IoT "things" added to the internet could approach 57000 per second and generate ~$9 trillion in sales (part of which depends on these PICs).

Security of the data and network has been recognized as critical for successful adoption of this technology, for example where critical infrastructure is controlled. Blockchain and soft-cryptography will secure data for the time-being, with quantum photonics being a potential longer term solution.

Needs (for photonics)

Fabrication needs for Si photonics and InP have been documented in other sections. If the amount of installed fiber will double mainly to support shorter access links within cities, the required Si photonic and InP PICs will need to be developed with smaller size and lower cost. Sensors which are self-powered (energy harvesting) where appropriate will need to become cheaper, faster and better performance to help drive demand. Sensing functions will also need to be integrated with connectivity and some level of signal processing so standardized information, not raw data, is transmitted through networks.

Sensors are already in development or marketed for: consumer goods (infotainment, wearables, food and water quality), eHealth (blood, breath and other chem-bio sensor analysis), energy and building automation, industrial (manufacturing) automation and structural monitoring, environmental monitoring (oil and gas distribution, drugs, hazardous materials and climate change). In transportation, visible and IR imagers for highway monitoring along with LIDAR and other sensors are already being developed for autonomous vehicles, but they will need to become solid-state, miniaturized, and drastically lower cost for significant consumer market penetration and eventual full autonomy.

Needs:

Short-term Needs <5 years

- Secure data transmission protocols
- Increased network capacity for IoT data
- Higher wireless bandwidth, low latency
- Sensors with sufficient sensitivity, accuracy and specificity
- Routers, as point of entry, must boost security for consumer IoT devices with modest security
- Fund allocation to establish cybersecurity infrastructure, monitoring, preventive technologies and awareness

Mid-term Needs 5 – 10 years

- Localised signal processing
- Low-cost, SWaP
- Miniaturized systems (packaging)
- Portability, power autonomy for mobile applications
- Integrated photonics enables QDK (quantum key distribution)
- Integrated protection of 5G IoT devices connected directly to the 5G network from direct attack

Needs > 10 years

- Real-time data analysis and use of AI
- Localised decision making
- Routine use of integrated photonic QDK for security
- Rigorous protection from malware targeting Distributed Denial of Service (DDoS) attacks on smart cities
- Rigorous protection from machine phishing – infiltration of IIoT and operational networks to manipulate systems with false signals.

INTRODUCTION

The IoT, arguably one of the most exciting and revolutionary technological developments of the internet age, is a key enabler for many emerging and future "smart" applications and technology shifts in various markets. These range from the connected consumer to smart home & buildings, electronic health (eHealth), smart grids, next-generation manufacturing, wearable technology, parking meters, equipment sensors, refrigerators, and smart cities. The IoT is therefore predicted to become one of the most significant drivers of growth in these markets.

The fundamental concept behind the IoT is a network of physical devices that are embedded with technology to give them the ability to sense or measure their environment and then have the capability to store and or programmatically send data through network connectivity. Data from these devices can be sent, stored, or programming actions taken.

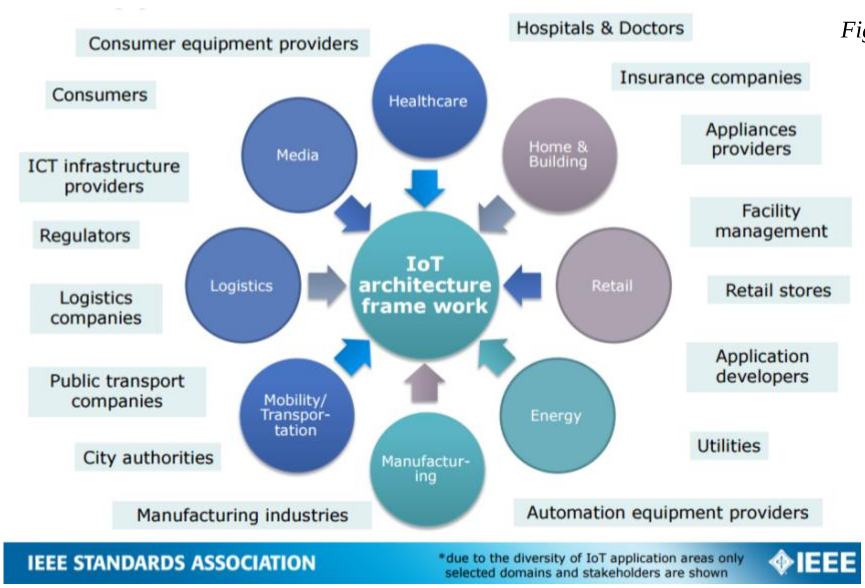

Figure 1. IoT Application Domains & stakeholders

Broadly speaking, the IoT is a system consisting of networks of sensors, actuators, and smart objects whose purpose is to interconnect "all" things, including every day and industrial objects, in such a way as to make them intelligent, programmable, and more capable of interacting with humans and each other. The IoT is loosely defined as connections between devices, cities and people. It is, in essence, the seamless flow between the: BAN (body area network): the ambient hearing aide, smart t-shirts; LAN (local area network): the smart meter as a home interface; WAN (wide area network): the bike, car, train, bus, drone, etc. and; VWAN (very wide area network): the 'wise' city with e-gov services everywhere no longer tied to physical locations. The IoT is actually a collection of vertical markets and industries — and references the way they will be affected by connected devices and consumers. In all - the IoT ecosystem is hard to define, complex, and difficult to capture due to the vastness of possibility and the rapidity with which it is expanding. There is no common definition for the IoT, but it is shaping the evolution of the Internet, creating numerous challenges and opportunities for engineering and science and the success of the IoT depends strongly on standardization, which provides interoperability, compatibility, reliability, and effective operations on a global scale.

The IoT is the subject of a great deal of hype and many bold predictions about where it will eventually take us. Current estimates are that there will be more than 25B IoT devices (some estimates call for more than 50B devices) deployed by 2020. However, there is no question that the IoT is changing the world. In addition to connecting people, anytime and everywhere, it is connecting IoT products to humans and other IoT products, and it is putting these products into service on behalf of humanity. This transformation is well underway and, if the scenario outlined by David Eggers book The Circle is only partially correct, will continue to accelerate. Note that there can be many IoTs. There is the global IoT (evolving from the global Internet) as well as local and private IoTs. The term "IoT" encompasses all of these.

The Internet of Things (IoT) IEEE Ecosystem Study Executive Summary January 2015, noted that "IoT products include devices, apps, and services (e.g., smart phones, tablets, intelligent networks, big-data analytics, and cloud storage). A key aspect of the IoT is the intelligent connectivity of these products. (It is likely that there will be situations where devices will be more rigidly constrained to satisfy safety, legal, and regulatory obligations.)"

INDUSTRIAL IOT (IIOT)

Comparing IoT and IIoT, Price Waterhouse Coopers notes[1] "if you consider the scale of the industrial products sector and its potential for device connectivity throughout the supply chain and with customers, then it's set to dwarf the size of the consumer IoT by several magnitudes. While a few billion consumer devices— wearables, home automation devices, cars—will become Internet-connected during the next five years, the equivalent global growth curve for the industrial IoT is set to rocket towards 100 billion devices as the technology becomes pervasive in industrial sectors worldwide". IDC predicts that the worldwide Internet of Things (IoT) market spend will grow from 689.2 B$ in 2016 to 1.4 T$ in 2021 with a compound annual growth rate (CAGR) of 14.5%. The installed base of IoT endpoints will reach over 36 billion units by the end of 2021[2] Machina Research "comprehensively extends the coverage of its forecasts to include almost the entirety of the Internet of Things revenue opportunity, predicting it will rise from 892 B$ in 2015 to 4 T$ in 2025"[3].

While these projections include all IoT revenue sources (including services), sensors (devices) play a critical role in the overall IoT ecosystem. Hardware accounts for about one third of the projected annual IoT expenditure in 2020[4] (Figure 2), and integrated photonics will also be a critical component both for the sensors and their connectivity through a vastly expanded network. Globally, IoT sensor revenue was estimated at 10.6 B$ in 2016, and is expected to grow to 47.8 B$ in 2021 at a CAGR of 35% [5]. The number of IoT devices is projected to rise from 25 billion in 2020 to 55 billion in 2025[6].

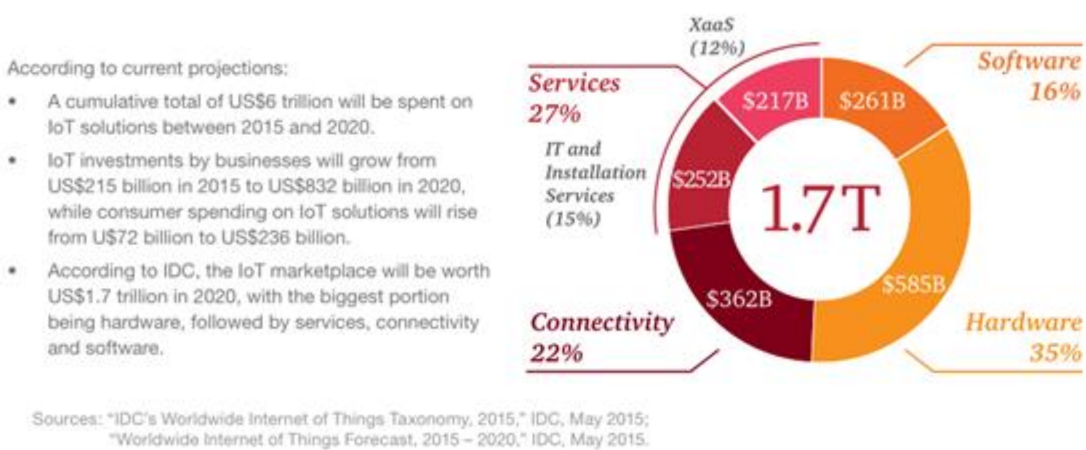

Figure 21. Investment in IoT solutions: an exponential growth path

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[1] IDC, Worldwide Internet of Things Forecast Update, 2017–2021
[2] IDC, Worldwide Internet of Things Forecast Update, 2017–2021
[3] Machina Research, 03 May, 2016
[4] PwC, Leveraging the upcoming disruptions from AI and IoT, 2017
[5] BCC Research, SENSORS FOR THE INTERNET OF THINGS (IOT): GLOBAL MARKETS March 2017
[6] Business Insider, THE INTERNET OF THINGS 2018 REPORT: How the IoT is evolving to reach the mainstream with businesses and consumers Jan 2017

The opportunities for new and improved business and services in all industry segments are almost endless, as indicated in Figure 3[7]. This also means there will be overlap in many other market and application sectors with what is considered IoT, as more and more sensors and products are made “smart”.

Market potential

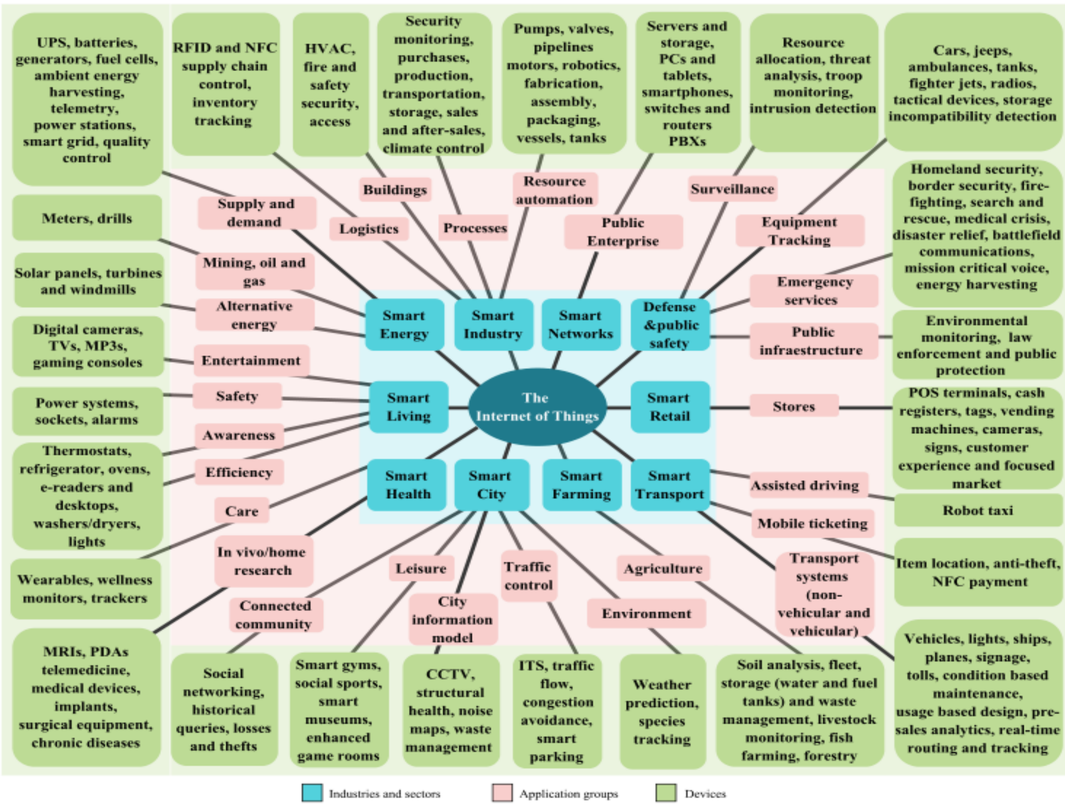

Figure 3. Proliferation of devices and applications in the Internet of Things (IoT)

This “Massive IoT” is driving growth of the different parts of the network, particularly for 5G, where the connection density could reach 10^6 /km^2 (or 1 per m^2) and applications requiring low latency are expected to require front haul round trip times less than 1ms. This densification for smart cities will require an integrated optical-wireless fabric with a much higher density of smaller cells. How quickly this infrastructure can be established, and viable business models put in place for its use remain two of the main challenges. At the 2018 OIDA Workshop on Scalable Integrated Photonics for 5G and IoT, Claudio Mazzali noted one consequence of connecting all these added radio antennas; whereas “*it took about 42 years to deploy 2 billion kilometers of optical fiber…It will take less than 4 years for the next 2 billion kilometers – and most of it will be in the access space…*” [8]. The role of integrated photonics and PICs in building capacity for 5G and other parts of the network to support the data traffic resulting from massive IoT is discussed elsewhere in this roadmap.

Table 1. from the Fifth Generation Mobile Communications Forum[9], illustrates the characteristics and level of network performance required for different applications. Achieving a high quality of service or end-to-end (E2E) user experience for all applications at different data rates is one of the major challenges for 5G, as the number of nodes or connected devices grows rapidly. Security of the network and data is a critical requirement for adoption of this next generation technology, particularly considering recent cyber-attacks and data breaches.

[7] Paula Fraga-Lamas et. al., Sensors 2016, 16, 1644

[9] 5G Mobile Communications Systems for 2020 and beyond, https://5gmf.jp/wp/wp-content/uploads/2017/10/5GMF-White-Paper-v1_1-All.pdf

Table 1. network characteristic requirements

Network characteristic	Requirement	Areas of relevance
End-to-End Quality of Service	low latency & sufficient data rate	Mission critical, e.g. health care, autonomous vehicles (V2V), security
	high reliability	
	Security the data	
Extreme Flexibility	accommodates E2E QoS for all users	
Low Latency	round trip data exchange ~ <1ms	M2M and AR/VR
Max data rate	Streamed 4K video?	Entertainment, Security
User mobility	Max speed of user & minimum service interruption time	Passengers in automobiles, trains
Number of users & connection density	Could reach 1/ m^2	Within the Smart City

In addition to network requirements, the anticipated number of IoT devices suggests the following general characteristics may be important for their design, installation and integration. Ease of installation will often depend on size, weight and power consumption (SWaP), and in cases where wired installation will not be practical, some form of energy harvesting, and energy storage will need to be incorporated into the design. Cost of these "things" is anticipated to go down rapidly as volumes increase exponentially. This follows the trends projected for PICs described in other sections of this roadmap. New materials platforms for integrated photonics such as PICs printed on flexible substrates may emerge for some applications in the future.

THE IOT MARKET AND PHOTONICS

The IoT market is burgeoning but fragmented. Early players are active and currently creating products for which they see a market. These players include government and academia as well as business and industry. In order to get products to market, these players are implementing proprietary solutions, some of which may evolve into de facto standards. Currently, IoT is trending toward vertical applications. Verticals showing early growth are consumer goods, eHealth, transportation, energy and industrial automation. IoT development and deployment are motivated by the desire to provide existing goods and services more efficiently (cheaper, faster and better) and by the desire to create new goods and services that will drive new revenue streams. Connecting things and allowing data to move will open new markets, just as the Internet did. New products and business models will disrupt traditional business models; some of these new products and models will be created by unintended consequences of technologies being deployed.

What might the value of the IoT market be? Let's start at the top. You probably know that John Chambers, former chairman and CEO of Cisco Systems, likes big numbers. In a keynote at the 2014 International CES in Las Vegas, he "pegged the value of the evolving IoT" to be $19 trillion! Chambers, in his keynote, gave many concrete examples: Cities saving money and increasing revenue by monitoring parking, lighting and water systems; connected homes with smart security and entertainment systems controlled by mobile apps; and eventually smart healthcare through an array of monitoring systems. "2014 will be a transformational, pivotal point for the Internet of Everything ... by 2017, it will be five to ten times more impactful in one decade than the whole Internet has been," said Chambers. He described how IoT-based smart cities, for example, could see a direct return on investment through a smarter infrastructure. For quantitative backing, keynote guest speaker Antoni Vives, deputy mayor of Barcelona, Spain, said the city has saved $58 million a year using a smart water system, $37.5 million on smart lighting, and has increased parking revenue by one third through the use of smart parking meters.

According to a new market research report "Optical Networking and Communications Market by Technology (Wavelength Division Multiplexing (WDM), Synchronous Optical Networking (SONET)/ Synchronous Digital Hierarchy (SDH) and Fiber Channel), by verticals (Aerospace and Defense, Government, Manufactures, Submarine, Mining, Transportation, Oil and Gas, Healthcare, Telecom, Energy and Utilities) and by Geography - Global Trends & Forecasts to 2014 - 2020", published by MarketsandMarkets, the total value of optical networking and communications market is expected to generate revenue of $12.55 Billion in 2013 and is expected to reach $25.97 Billion by 2020, at an estimated CAGR of 10.5% from 2014-2020.

Similarly, MarketsandMarkets Internet of Things (IoT) Security Market by Technologies (Network, Cloud and Application Security, Identity Access Management, Analytics, Unified Threat Management (UTM), Intrusion Detection System/Intrusion Prevention System (IDS/IPS), Device Management, Encryption), Industry Verticals and Applications - Global Forecast to 2020 says that the integration of the IoT has provided the control of different connected devices into a single smart device such as a smartphone, personal computer (PC), and tablet and at the same time it has provided the opportunity to infiltrate the entire infrastructure by hacking the controlling device. Therefore, IoT security has become essential for organizations, governments, utilities, and individuals for the protection of their data and infrastructure and is gaining traction in day-to-day deployment. The IoT security market is being driven due to rising security concerns associated with the critical infrastructure to be monitored/connected and strict government regulations and is expected to grow from USD 6.89 Billion in 2015 to USD 28.90 Billion by 2020.

Again, from MarketsandMarkets, the Silicon Photonics Market by Product (photonic wavelength, optical modulators, optical interconnects, Wavelength Division Multiplexing Filters (WDMF), LED, and others), application (telecommunication, data communication, and others) and by geography - global trends and forecasts to 2014 – 2020 suggests that silicon photonics is an emerging technology, which focuses on the ultimate goal of providing the microelectronics world with the ultra-large-scale integration of components at a low cost and without any significant changes in their performance. This can be achieved by producing all-silicon based components and products. Hence, silicon photonics has become an interesting preposition across the globe as it focuses on high-speed transmission, low-cost, and complex integration of various products together such as optical waveguides, modulators, and photo-detectors. The silicon photonics market is expected to grow to $497.53 million by 2020, growing at a CAGR of 27.74% from 2014 to 2020. This rough-order estimate is in line with Yole's prediction that the silicon photonics devices market will grow from less than $25 million in 2013 to more than $700 million in 2024 with a 38% CAGR.

Technological advances are fueling the growth of the IoT. Improved communications and network technologies, new sensors of various kinds, improved—cheaper, denser, more reliable and power efficient—storage both in the cloud and locally are converging to enable new types of products that were not possible a few years ago.

The potential impact of silicon photonics on the optical communications market has captivated the imagination of industry in the last three years. Early success of several optical component vendors in the demonstration of capabilities of this technology and shipping first products led to several mergers and high-value acquisitions. How much of an impact can this technology make on the market?

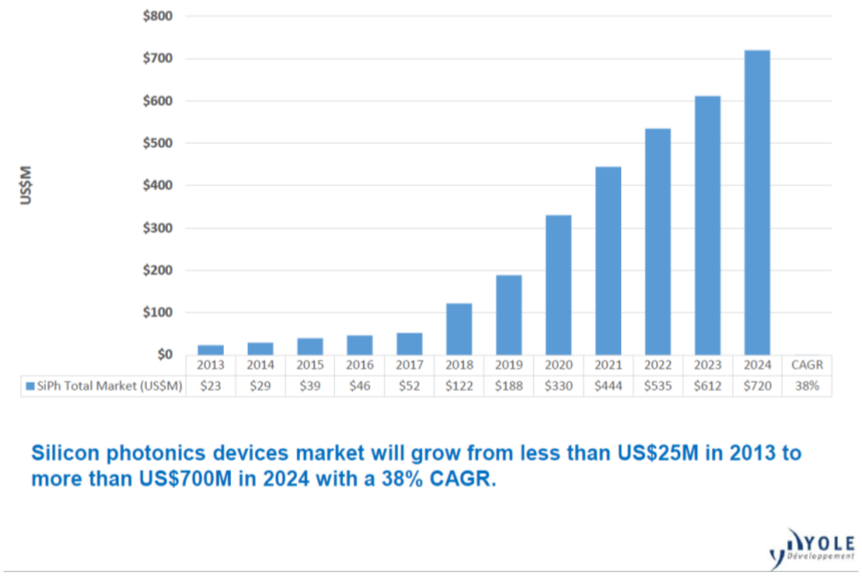

Figure 4. Si phonotnics 2013-2024 market forecast in $M

Integrated photonics is garnering more value due to its various features and wide range of applications. It offers various advantages, such as high-speed data transfer, data integration, and small form factor; moreover, since it is an emerging technology, it has managed to attract new industrial users. The telecommunication application held the highest market share in 2013, but medical applications are estimated to experience larger growth in the near future. Silicon photonics is implemented by various companies in their product portfolios due to its advanced features including high-speed data transfer and the integration of large data into a small device footprint. Various products such as optical waveguides, modulators, and photo-detectors can be integrated within a single device, providing a smaller form factor with the help of silicon photonics. WDMF and Silicon Optical Modulators (SOM) products currently hold the highest share in the North American market. Thus, this shows that the WDMF and SOM products in the silicon photonics market have a great potential to increase over a period of time.

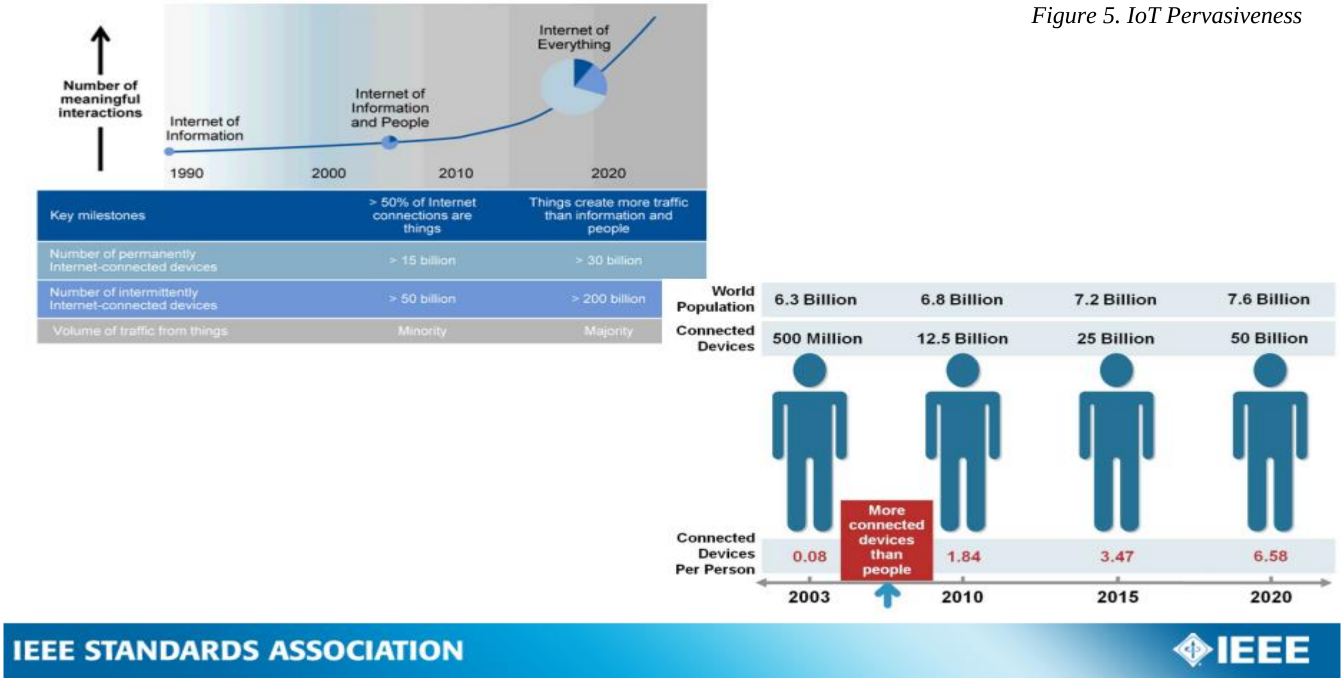

Figure 5. IoT Pervasiveness

The (http://www.reportsnreports.com/Purchase.aspx?name=273791) MarketsandMarkets silicon photonics report says silicon photonics has great potential as it is an emerging technology. This global report gives a detailed view of the market across geographies, namely the Americas, Europe, Asia-Pacific, and the rest of the world (RoW). The North American region dominates the market in terms of the market size; however, the Asia-Pacific (APAC) region has been growing at the highest CAGR in this market. The growing demand to transfer data coupled with government funding in silicon photonics are motivating companies to launch silicon photonics products in the North American market. The competitive landscape of the market presents a very interesting picture. The market is witnessing new product launches as well as large-scale collaborations, agreements and partnerships across the value chain with a number of tier-one players around the globe. The major players in this market include Intel Corporation (U.S.), Hamamatsu Photonics, K.K (Japan), Finisar Corporation (U.S.), IBM Corp. (U.S.), Luxtera, Inc. (California), ST Microelectronics (Switzerland), 3S Photonics (France), Oclaro Inc. (U.S.), Mellanox technologies (U.S.), and Infinera Inc. (U.S.).

SITUATIONAL (INFRASTRUCTURE) ANALYSIS

IOT CONNECTIVITY

IoT is a catchall term for many kinds of connected devices, including sensors, speakers, and cameras—found in cities, remote resources, factories, homes and on your person. These devices often don't need as much bandwidth as smartphones, but the expense of connecting them through existing LTE networks is prohibitive and very inefficient. To address this, many believe those devices need their own dedicated wireless networks. Two new types of networks; Long Term Evolution for Machines (LTE-M) and Narrowband–Internet of Things (NB-IoT); are now being deployed for that purpose. Both are designed for low-power devices that send only a few bits of data at a time. Unlike Wi-Fi, these networks operate in licensed cellular spectrum where there is minimal radio interference. They also provide coverage over tens of kilometers, much farther than local wireless access points or short-range technologies such as Bluetooth and Zigbee.

Specifications for LTE-M and NB-IoT were released in 2016 by the standards body called the 3rd Generation Partnership Project. Since then, carriers have rolled out 28 nationwide LTE-M and NB-IoT networks across 21 countries, including China, Germany, Ireland, Spain, Turkey, Italy and the United States. Of the two network types, LTE-M provides higher throughput and lower latency—filling 1.4 megahertz of bandwidth at data rates of 150 kilobits per second with around 10 milliseconds of latency, compared with NB-IoT, which sends data at about 50 kb/s through 200-kilohertz channels with latency as high as 10 seconds. LTE-M also enables voice transmissions, whereas NB-IoT is best for devices that send infrequent updates. A building alarm, for example, may need to send only five messages of 50 bytes a day.

In addition, silicon photonics is emerging as a commercially available technology, vying for market share in a number of application spaces. For shorter distance applications (within and between racks in data centers) which continue to make up the bulk of HPC and data center links, silicon photonics must compete with the incumbent copper- and VCSEL-based technologies based on form factor, cost and power. Here the functional advantages of Si photonics are more limited, albeit important, providing longer single-mode reach with a cost advantage over more traditional components. This is an expanding market space as both data rates and run lengths increase in flatter high-performance networks. However, this application does not take full advantage of the integration capabilities that Si photonics has to offer. Incipient deployment of optical circuit switched networks based on millisecond scale MEMs switching is beginning to show promise as a component of higher performance networks. Optical circuit switching is an application where silicon photonics can provide unmatchable technology advantages, by integrating a large number of functions on a single PIC, providing nanosecond scale switching times with reasonably large radix and integrated gain. While this application is still many years off, it is not achievable without the integration capabilities of a silicon photonics integrated circuit.

The inexorable rise of big data and the plethora of unstructured data being generated by connected devices and sensors are fundamentally changing data center economics, prompting a growing number of enterprises to consider greater IT virtualization or colocation as they adopt a hybrid cloud approach. Recent market research confirms that data center spending continues to increase. But retrofits are giving way to a growing focus on colocation or cloud services as the cost of building new data centers becomes harder to justify.

Those trends, again driven by big data and the IoT, are also being propelled by practical considerations like reducing latency in the data center as enterprises push data to the edge of networks. Meanwhile, hybrid and solid-state drives and storage are also being implemented as a way to reduce latency. Whatever they are, IoT devices running at the edge are not only communicating wirelessly with the cloud but also communicating with local gateways and, perhaps, working with built-in logic boards to complete a task.

Wearables and home devices are likely to play a lead role in IoT Growth**.** Wearables and home devices are likely to lead growth in the IoT business during the rest of this decade, according to semiconductor companies and industry analysts at the Computex Taipei show (June 2015). In 2015, 72 million wearable devices worth $17 billion will ship, growing in dollar terms at a compound annual growth rate (CAGR) of 18 percent to 156 million units or $39 billion in 2019, according to Bryan Ma, a vice president with market research firm IDC.

But what device is likely to be the wearable of choice? “If I were a betting man, it would be watches,” said James Bruce, director of mobile solutions for ARM, whose chip designs are in 90 percent of the world’s smartphones,” in a Computex presentation. “Wrist based products are definitely going to be one of the leading categories. We’re at the start of that growth.”

It will take time for wearables to become compelling, according to ARM. “It took years for smartphones to develop their various use cases,” Bruce said. “We’re now seeing the same thing with wearables. Three or four years down the line, you’ll see lots of different people using wearables.” For mobile payment or access to a home or a car, a watch with near-field communication (NFC) makes sense because of the ease of use, Bruce said. For home IoT devices, use cases are developing rapidly in China, according to MediaTek, the world’s third largest chip designer. “The home IoT market in China is growing faster than the rest of the world,” said SR Tsai, general manager of MediaTek’s Wireless Connectivity and Networking Business Unit, in an interview with EE Times. The home IoT market worldwide this year will reach 50 million units.

The home IoT market worldwide this year will reach 50 million-unit shipments and 200 million units in the next three years, Tsai said. That forecast converts into a bullish CAGR of 59 percent for the 3-year period. In China, some companies have started adding WiFi controlled smart switches to air conditioners and other home appliances, according to Tsai. China’s Xiaomi, the world’s third largest smartphone maker, and other local handset makers are trying to deploy IoT as part of their business, Tsai said. Helping to stimulate demand, the Chinese government will invest about $200 billion during the next three years in domestic broadband access for fiber-to-the-home at a 10 gigabit per second rate, he added.

Of course, security issues may become a limiting factor in China’s burgeoning home IoT business, according to Tsai. “Their security concerns are lower than in other areas,” he said. “Smartphones are the personal gateway, but you still need a home gateway.” According to research by security software vendor Trend Micro, about 30 percent of the routers in the marketplace have been hacked, Tsai said. MediaTek and Trend Micro have allied to provide security against attacks on home networks. “If your router transfers a lot of data outside, we can stop this kind of attack,” according to Tsai. “Rather than securing the end device, as with laptops years ago, now it’s better to secure at the gate in home routers.” In a smart home, air conditioners, refrigerators and doors are links in the network that could potentially leak valuable personal data to outside hackers, Tsai says. “If they are breached, you are in big trouble.”

SENSORS IN THE IOT

Photonic sensors

Photonic sensing technology incorporates emission of light, transmission, deflection, amplification, and detection by optical components, instruments, lasers, other light sources, fiber optics, electro-optical instrumentation, and sophisticated nanophotonic systems. It provides smaller, cheaper, lighter, and faster components and products, with greater functionality while using less energy. Think this is just hype? Consider the more than 100,000 individual sensors dotting the 1,400-kilometer waterway connecting the Danjiangkou reservoir to Beijing and Tianjin. For the last year, it’s been scanning the canal for structural damage, tracking water quality and flow rates, and watching for intruders, both human and animal.

One might look at the IoT in the context of the internet evolving from a communication platform that provides access to information "anytime" and "anywhere" into a network that integrates "anything" by gathering and disseminating data from the physical world to enable a better understanding of our environment.

The IoT allows us to make inferences about phenomena and take mitigation measures against unwanted environmental effects. The current IoT leverages existing wired and wireless network infrastructures for communications and control - receiving data continuously from local sensors and transmitting it to cloud servers using whatever signal was available at the moment. This could include fiber, Ethernet, 2G, 3G, 4G, Wi-Fi, or Zigbee.. However, as IoT devices continue to proliferate in parallel with higher data rate communications and data services, these existing networks will become increasingly stressed and congested, particularly in remote and underserved regions of the world.

Photonics has been recognized as an enabling technology that impacts, extends across, and underpins a host of industrial sectors, from healthcare to security, manufacturing to telecommunications, energy to the environment, and aerospace to biotechnology. In all these sectors, photonics sensing activity can be recognized via the intelligent application of light either in an entirely novel context such as a new photodynamic medical treatment, or as a replacement to an older, outdated technology such as signage and lighting based on the use of incandescent lamps.

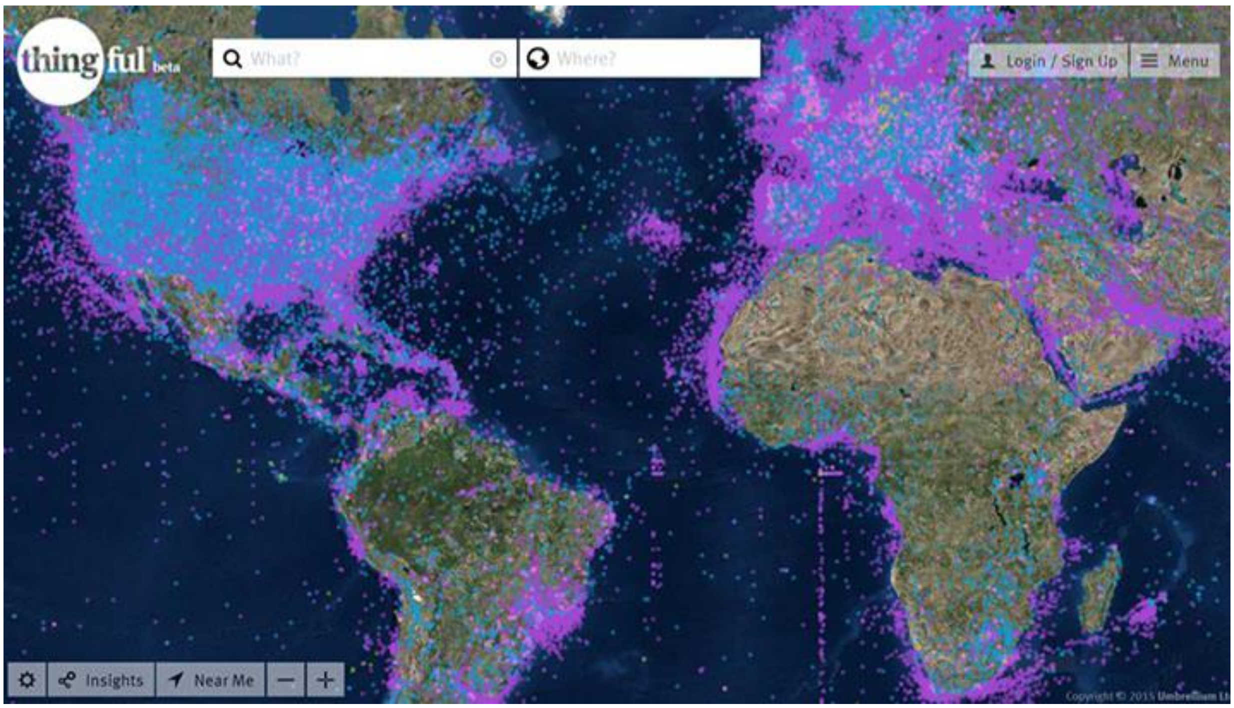

Figure 6. Distribution of sensor nodes over the globe

For example, the IoT fulfills all the technological requirements to be successful in developing countries: it is low-power technology (good for places with unreliable electricity), it does not require a fast internet connection (nodes are sending small amounts of data, and servers can be local), it is low-cost (or getting there) and it has an immediate impact on people's lives. IoT applications can greatly benefit populations in developing countries: weather can be monitored, food safety can be checked, water quality can be analyzed, air quality can be measured, landslides can be detected and mosquitoes can be counted in cities in real time. Furthermore, cheap e-health kits can be shipped to the isolated areas of the developing world to bridge the healthcare gap between urban and rural settings. The picture below showing sensor nodes that publish their data openly on the internet (https://www.thingful.net/) reveals a visibility gap where the North is scattered with nodes while the South is poorly represented. Africa, for example which is home to 1 billion people, has very few sensors.

While individual sensors may require minimal bandwidth, their aggregate contribution to the sea of IoT data may become quite large. As the problems tackled by IoT practitioners not just in developing countries, but around the world fall into categories (air quality, water quality, smart agriculture, healthcare, etc.), it is crucial that networks connecting IoT scientists and practitioners working in their domain be developed.

The network will provide a way to harvest, store and communicate data for analysis and for researchers to share solutions and to collaborate on finding the best solution to their problem.

Due to large numbers of sensors expected to be part of any given network, it will likely be necessary to aggregate multiple sensing streams as one 'virtual' sensor that provides an integrated interface to other functionalities. An example of a 'virtual' mobile sensor could be aggregated traffic flow information on a highway that is derived from multiple vehicle sensors. This, of course, raises additional questions. Which sensors can be aggregated, considering their mobility patterns? How is sensor aggregation and virtual sensing to be implemented, since mobile sensors are by definition mobile, and hence may not be always in proximity of each other? If a sensor moves out of range, can the aggregation be mobility tolerant enough to be recovered through other means?

Biophotonic Sensors

In addition to optical interconnects, several other applications are envisioned for silicon photonics. The technology can also play a role in biosensing applications. A disposable mass-produced sensor would be attractive as it could grow the market for biosensors. Sensor applications are somewhat different from optical communication as there are other very low-cost optical technologies that compete in this space. One likely application area for silicon photonics is the so-called lab-on-a-chip in which both reaction and analysis are performed in a single device.

According to a report by Allied Market Research ("Global Photonic Sensors Market [Type, Technology, Application and Geography] - Global Opportunity Analysis and Forecast - 2013 - 2020"), the global photonic sensor market is forecast to reach $15.2 Billion by 2020, growing at a CAGR of 16.9% during the period (2014 - 2020). The study acknowledges the dominance of fiber-optic sensors and sheds light on the way biphotonic sensors would garner more market share during the forecast period. Based on its application, biphotonic technology is expected to be the fastest growing technology in the photonic sensor market. Military is expected to be the largest revenue-generating segment until 2019, due to the wide-ranging applications of photonic sensors in various defense equipment. Geographically, the North American region is leading, and it would maintain the lead throughout the forecast period.

The Internet of Things Market, while similar to the sensor portion of the BioPhotonic Sensors Market requires integration of the sensor with the communications function because of the vast number of sensors that are anticipated in future IOT and IIOT applications. This roadmap discusses the market needs for biphotonic sensors in a separate chapter.

APPLICATIONS

THE INDUSTRIAL IOT

Building-management, home-automation networks, Internet of Lights (enabled by the success of LEDs in lighting) and a variant of the IoT - the Industrial Internet of Things (IIoT) at its simplest, can be defined as the integration of physical assets (machines, buildings, etc.) with sensors, control networks and intelligent software.

The value propositions of the IIoT are analytics, remote access and management, collaboration, speed and accuracy of intelligence, and the easy capture and transfer of knowledge, not just data. The IIoT is much more demanding than the consumer or human Internet of Things, which is characterized by applications and functions that involve human interaction such as wearable fitness trackers or home thermostats. The more stringent requirements of the IIoT include:

- Autonomous control, or the ability to operate without human intervention — either because the industrial environment is somehow inappropriate for people or because actions must take place too quickly, frequently or reliably to be handled by people.
- Peer-to-peer operation, without interaction with an Internet server or cloud.
- Industrial-strength reliability and industrial-grade security.
- Support for wired as well as wireless connectivity.

An Internet of Lights is formed when all the smart lights in a space are connected by digital networks and are able to communicate with each other, communicate with a server or gateway, and communicate with sensors and controls in proximity of the lights. In such a configuration, the Internet of Lights becomes the backbone of a building-management or a home-automation network. What makes this really attractive is that lights are virtually everywhere, and they already have (electrical) power to the light itself. This power can be used to run other electronic components and devices integrated into, or attached to, the networked lights. Like LED lighting, almost all electronic components used for communication, control and sensors are also low-voltage components that can share the same power supply, reducing the component count and costs.

Sensors and controls can be directly attached to the lights and the Internet of Lights network, or can also be incorporated via short-range wireless connectivity options, such as 6LoWPAN or Bluetooth Smart radios. In this way, the lights become access points for the IoT, where the "things" could have short-range wireless radios with very long battery life due to the proximity of the access points. Hence, as individual lights become smarter and then are networked together and connected to additional sensors, actuators and other devices the Internet of Lights meets the Internet of Things – a new world of opportunities is likely to be created.

Achieving a high quality of service or end-to-end (E2E) user experience for all applications at different data rates is one of the major challenges for 5G, as the number of nodes or connected devices grows rapidly. Security of the network and data is a critical requirement for adoption of this next generation technology, particularly considering recent cyber-attacks and data breaches.

Table 2. Network characteristic requirements

Network characteristic	Requirement	Areas of relevance
End-to-End Quality of Service	low latency & sufficient data rate	Mission critical, e.g. health care, autonomous vehicles (V2V), security
	high reliability	
	Security the data	
Extreme Flexibility	accommodates E2E QoS for all users	
Low Latency	round trip data exchange ~ <1ms	M2M and AR/VR
Max data rate	Streamed 4K video?	Entertainment, Security
User mobility	Max speed of user & minimum service interruption time	Passengers in automobiles, trains
Number of users & connection density	Could reach 1/ m^2	Within the Smart City

In addition to network requirements, the anticipated number of IoT devices suggests the following general characteristics may be important for their design, installation and integration. Ease of installation will often depend on size, weight and power consumption (SWaP), and in cases where wired installation will not be practical, some form of energy harvesting, and energy storage will need to be incorporated into the design. Cost of these "things" is anticipated to go down rapidly as volumes increase exponentially. This follows the trends projected for PICs described in other sections of this roadmap. New materials platforms for integrated photonics such as PICs printed on flexible substrates may emerge for some applications in the future.

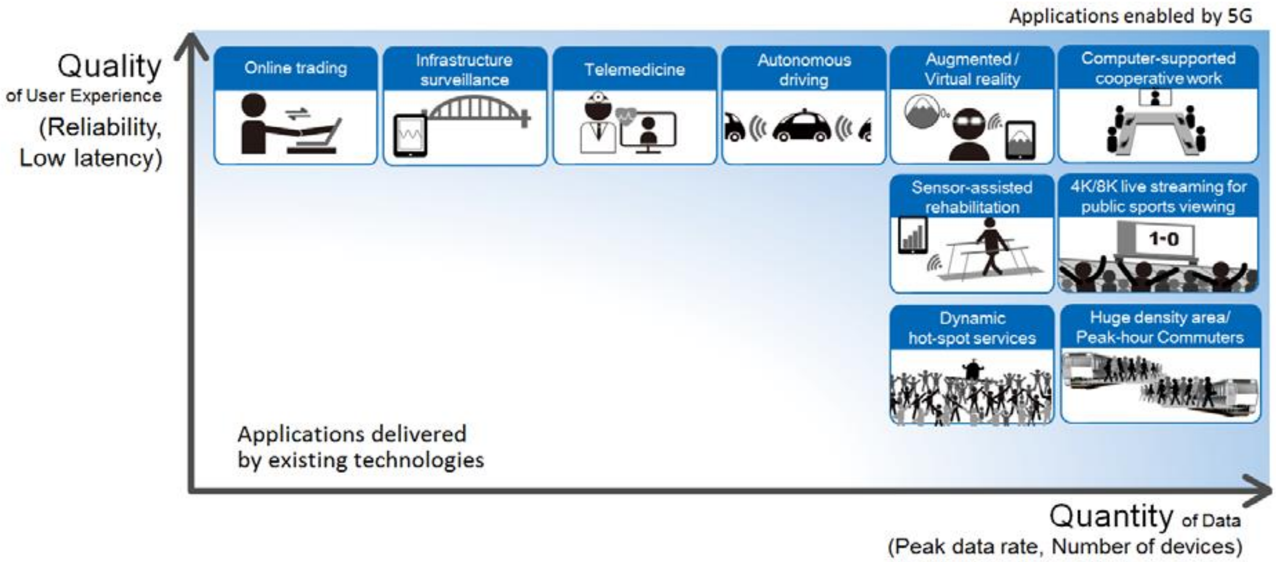

Figure 7. Network performance required for different IoT applications

The overall business model for installing the network infrastructure and developing IoT services and applications is not yet well established. The IoT end-user will also need to be convinced that their personal data is secure and cannot be compromised before widespread adoption is achieved.

Table 3summarizes some of the main applications where photonic sensors are employed in different sectors. Many of these applications, and the use of integrated photonics, are described in other sections of this report. Here we will focus on applications enabled by connectivity via the Smartphone.

Table 3. Main applications where photonic sensors are employed in different sectors

Sector	Application
Energy and Environment	Monitoring air & water quality Sensors in Oil and Gas production & SHM) Agriculture & food quality
Transportation	Autonomous vehicles, traffic control Aerospace (SHM - structural health monitoring)
Healthcare	Diagnostics (blood, OCT, gas/breath monitoring) Fitness trackers, real time monitoring (e.g. ECG) Patient point of care, surveillance, fall detection Food sensors
Security, safety & emergency services	City, Company Offices, Home Monitoring control and security of critical infrastructure
Factories and Supply Chain	Increased automation and use of robotics (sensors + AI) sensor for machines (control, maintenance monitoring) More efficient & shorter manufacturing (lower costs) Automated supply chain network
Consumer	Enhanced mobile access to all sector services and entertainment
Cities	Smart control & use of all infrastructure, transportation, & security More efficient lower cost operation of all services

IoT Connectivity and the Smartphone

The tens of billions of IoT devices expected over the next 10 years will drive huge growth in integrated photonics in the Telecom/Datacom, and data center markets, even if individually their requirements for bandwidth and data storage are small. Development of 5G is being led by several companies, including Samsung, Intel, Qualcomm, Nokia, Huawei, Ericsson, ZTE and others, and South Korea already showcased 5G at the 2018 Winter Olympics, Pyeong Chang. Many other large mobile networks are testing different 5G approaches and first deployments are expected in 2018 – 2019 time frame. Mobile phones are expected to incorporate new IoT capabilities which take advantage of this improved service.

The next generation smartphones will come packed with sensors and provide new UIs (user interfaces) which will enable new IoT applications. The new iPhone X from Apple (Figure 8) can be unlocked with face recognition; "*the TrueDepth camera projects and reads over 30,000 infrared dots to form a depth map of the face, along with a 2D infrared image. This data is used to create a sequence of 2D images and depth maps, which are digitally signed and sent to the Secure Enclave. To counter both digital and physical spoofs, the TrueDepth camera randomizes the sequence of 2D images and depth map captures and projects a device-specific random pattern. A portion of the A11 Bionic processor's neural engine—protected within the Secure Enclave—transforms this data into a mathematical representation and compares that representation to the enrolled facial data. This enrolled facial data is itself a mathematical representation of your face captured across a variety of poses"*[10]. Apple claims Face ID is accurate to 1 in 1 million, which is much better security than the 1 in 50,000 that fingerprint recognition provided.

[10] Apple white paper, https://images.apple.com/business/docs/FaceID_Security_Guide.pdf

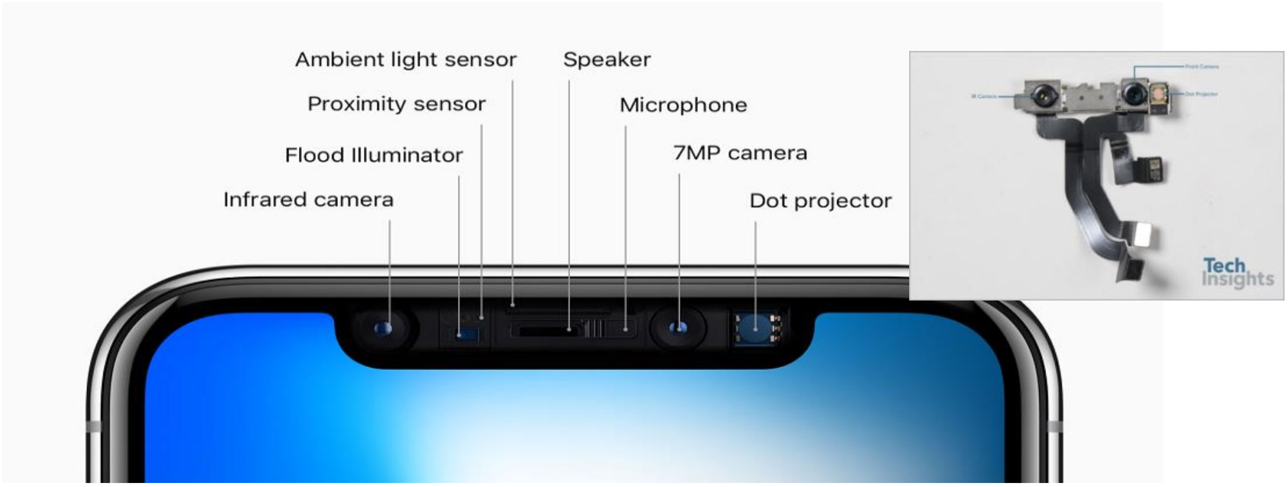

Figure 8. Apple iPhone X

The combination of IR and visible cameras integrated with (VCSEL) IR dot projectors for 2D and 3D imaging, coupled with data processing (analytics, or AI) and (eventually 5G) network connectivity, show how integration of new sensors with smartphones will enable new IoT applications. Another feature this integrated photonics package provides is that of gesture recognition, for gaming or as (part of) a UI for other applications. By combining gesture recognition, Face ID or voice activation when your phone or other “listening” devices (e.g. Amazon Echo, Google Home or Apple Home Pod) recognize you, the user experience can be adapted to almost any requirement via a “touchless interface”.

This will help drive the overall image sensor market (including consumer electronics, automotive and industrial), which “is expected to witness high growth during the forecast period. The overall market is expected to grow from USD 12.78 Billion in 2016 to USD 24.80 Billion by 2023, at a CAGR of 9.75% between 2017 and 2023. The base year considered for the study is 2016, and the forecast period provided is between 2017 and 2023”[11].

[11] Image Sensor Market by Technology (CMOS, CCD), Processing Type (2D, and 3D), Spectrum (Visible, and Non- Visible), Array Type (Linear, and Area), Vertical (Automotive, Consumer Electronics, Industrial), and Geography - Global Forecast to 2023, January 2018 - www.marketsandmarkets.com/Image-Sensors

Other approaches to 3D imaging rely on stereoscopic imaging ortime of flight methods (Figure 9). Which method is appropriate and cost effective may vary with the application, but manufacturing and assembly costs will need to be extremely low in high volumes for consumer applications. According to IHS Markit[12], the True Depth Sensing suite (IR camera and flood illuminator) parts are estimated to cost $ 16.70.

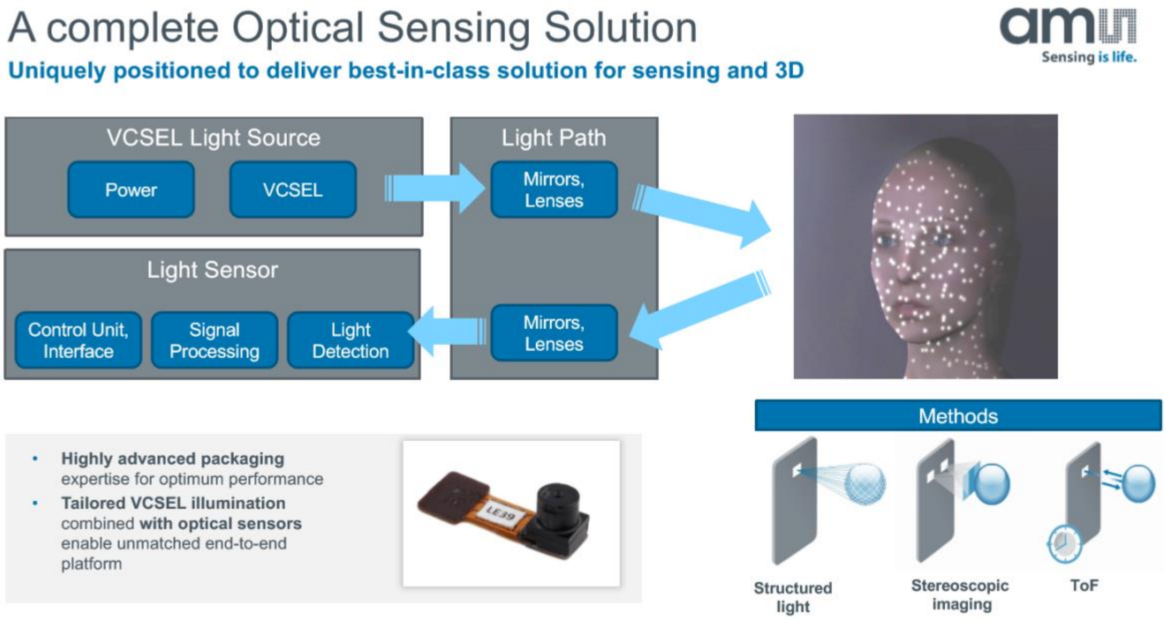

Figure 9. 3D Imaging

The compact components developed for smartphones (proximity sensors, 3D cameras, microphones, speakers) and their low-cost manufacturing are also expected to be incorporated in new wearables; as more sensors and functions are added to the smartphone, their added power consumption may become a consideration and trigger more focus on energy harvesting approaches.

WEARABLE DEVICES

'Wearables' or 'wearable devices' refers to a variety of electronic devices worn on, or near the body. Examples include smart watches, smart glasses, contact lenses, fabrics, headbands, hats, rings, bracelets, and hearing aid-like devices with sensors that are packaged and incorporated in a format that is wearable. Not all of these devices use optical-sensing technology, but many do, and incorporate lasers or LEDs with detectors. If we include in the definition that the sensor data can be transmitted, or communicated, many of these are easily interfaced with smartphones and reuse their well-developed, compact and cheap sensor technology.

The main applications for wearables and the types of sensors used are shown in Table 4. Wearables are expected to play a key role within IoT development, bringing useful information directly to the user in a natural, friendly way as illustrated in Figure 10[13]. From a value perspective, the total market will reach 25.8 B$ in 2018, up 31.2% from the 19.7 B$ in 2017. The main drivers in play here are more vendors, more devices, and slowly growing demand. By 2022, total value will reach 44.0 B$, resulting in a CAGR of 17.5% for 2017–2022.

[12] https://technology.ihs.com/596781/iphone-x-costs-apple-370-in-materials-ihs-markit-teardown-reveals
[13] http://www.yole.fr/IoT_Seminar_Yole_FraunhoferEMFT.aspx#.Wn3r5K6nGos

A current example of a consumable wearable device is the Apple Watch, which became available in 2015. It was rapidly accepted and became a best-selling wearable device. Since its introduction in 2015, the combined sales of all smartwatches have grown into a ~$13 billion market segment that represented more than 40% of the worldwide wearable device business in 2018. According to market research portal Statista, the smartwatch segment alone shall increase another 32% to almost $18 billion by 2021.

Table 4. Applications for wearables and types of sensors

Sector	Wearables Applications	Sensor Tech	Comments
Fitness and exercise monitors	Existing & new wrist band devicesc	MEMS (for IMUs),	
Consumer, infotainment	Gaming, VR, AR	MEMS (for IMUs), 2D and 3D sensors and cameras	Already in portable devices and smartpones - easily adaptable to wearables
Healthcare	Monitoring of temperature, heart rate, ECG, blood flow, blood analysis, breath analysis, other diagnostics and drug delivery	IR thermometers, Photoplethysmography (PPM), Glucometers (electrochemical), CD4 (labelled, fluorescence), molecular absoprtion (tunable DFBs, QCLs, VCSELs)	Most are or will be portable and wearable
Industrial and security	Worker health monitoring, environmental monitoring, video surveillance	Personal healthcare monitoring + local environmental sensors for temperature, gas monitoring, 2D & 3D cameras	For use in hazardous or harsh envirornments, for police, disaster response etc
'New' Wearables	Combinations of new and existing sensors , eg for the visually impaired, supporting assisted living	multiple types	Incoprorates a higher level of data processing and AI. Could enable more user functionality and mobility

Smart wearables' value will rise in 2018, reaching 16.1 B$ and moving further ahead of basic wearables' value of 9.8 B$. Smart wearables' value will continue to increase, growing at a pace of 16.8% each year before reaching 27.2 B$ in 2022. Basic wearables' value, meanwhile, will increase at a slightly higher clip (18.5% CAGR) before reaching 16.8 B$ in 2022[14]. IDTechEx have categorized the various types of sensors incorporated into Wearables, and their projected market share from 2016 in Table 5[15].

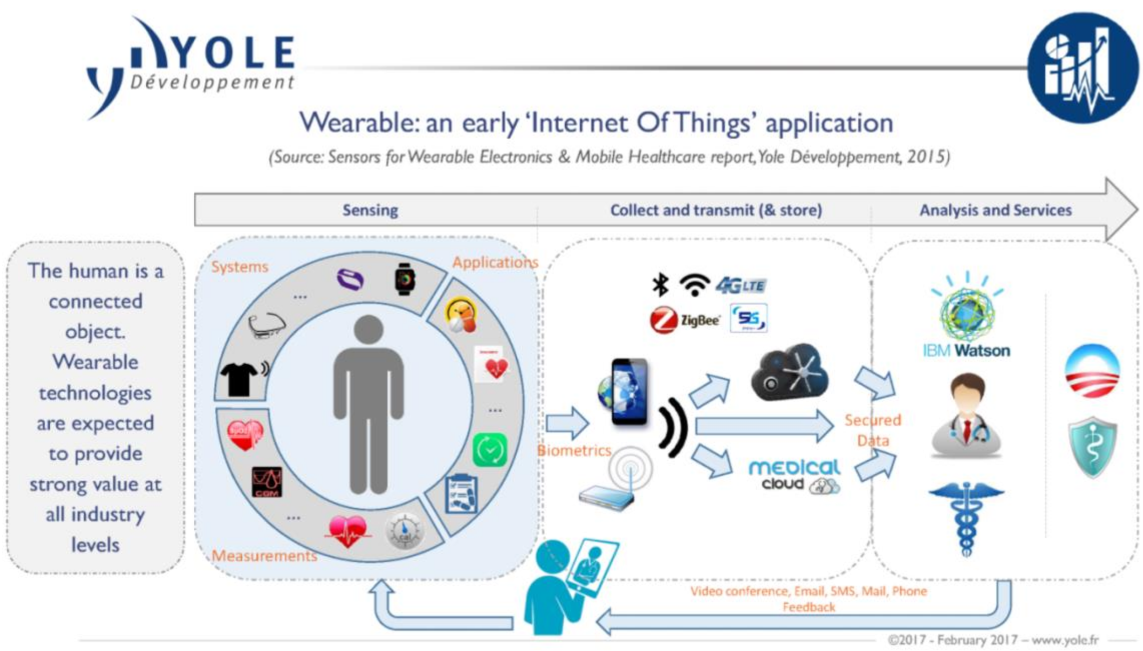

Figure 10. IoT wearable devices

[14] IDC Worldwide Wearable Computing Device Forecast, 2018–2022: CY 1Q18
[15] IDTechEx Wearable Sensors 2016-2026: Market Forecasts,Technologies, Players

Table 5. Market size for each wearable sensor type from 2016-2016, in USD millions

Sensor Type	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	CAGR
Inertial Measurement Unit Sensors	185.1	210.2	237.4	264.9	290.5	312.7	330.8	344.9	355	361.8	377.76	*7.4%*
Biopotential sensors	157	177.6	203.9	234.8	267.8	299.6	327.8	351.3	369.8	383.8	409.58	*10.1%*
Optical Sensors	134.9	148.1	167.2	191.1	218.5	247.2	275	300	321.5	339.3	365.81	*10.5%*
Stretch and pressure sensors	19.4	31.3	49.3	75.1	110.4	156.9	215.9	288.6	375.5	476.9	542.64	*39.5%*
Chemical sensors	265	356.5	493.1	686.7	948.3	1288.4	1716.8	2242.7	2873.9	3616.4	4091.57	*31.5%*
Other	119.6	143.1	169.9	198.6	227.2	253.2	274.9	291.5	303	309.7	328.79	*10.6%*
TOTAL	**881**	**1,067**	**1,321**	**1,651**	**2,063**	**2,558**	**3,141**	**3,819**	**4,599**	**5,488**	**6,116**	***21.4%***

Source: IDTechEx

Combinations of sensors, both optical and other types, are often used in wearable products. This trend, and the incorporation of new types of sensors will contribute to continued market growth Many wristbands and watches use optical sensing, but more sophisticated wearables also benefit from photonics. Companies at the forefront of health wearables include:

- Profusa - pioneering tissue-integrated biosensors scanned by an optical reader to monitor body chemistry
- Artinis - supplies a portable cerebral oxygenation monitoring system based on fNIRS
- CareWear - supplies an FDA-approved wearable therapeutic light patch

ID TechEx now predicts about one third of the 2022 revenue will be associated with optical technology[16]. Wearable IoTs and their applications will remain strongly coupled to smartphones and smartwatches for network connectivity, and to take advantage of existing user interfaces.

Industrial and security

Wearables also play an important role in Oil and Gas industry for Predictive Safety Sensing (Sensor-enabled wearable devices leverage oil & gas predictive analytics to help maintain employee safety). Deloitte noted that *"Vests monitor heartrate, blood pressure, air quality, geolocation, weather conditions, and other safety precaution metrics. Goggles measure eye movement for evidence of fatigue, disorientation, and other signs of visual impairment"*. The accuracy, intelligent analysis, reporting and display of data from multiple sensors will provide new wearables with differentiated value.

HEALTHCARE

The need for portable or wearable devices for medical sensing and monitoring has already been noted in the Healthcare section of this roadmap. Diagnostic and Analytic systems will make use of various types of sensors and spectrometers but combining these with a medically approved personalized point of care device e.g. microfluidics in a lab-on-a-chip for more sensitive biosensors and possibly drug delivery will be challenging.

For such devices to be network connected will add additional requirements. Bringing new devices to the market depends on more than technology development since clinical validation and regulatory approval can be time-consuming.

[16] https://www.idtechex.com/research/reports/wearable-sensors-2018-2028-technologies-markets-and-players-000555.asp

Security of data and its transmission is a major concern for IoT in general and this market segment in particular. Some form of distributed ledger technology (Blockchain) may be needed to protect transmission and storage of personal medical records. IDC have predicted that by 2019, 20% of all IoT deployments will have basic levels of blockchain services enabled[17]

Nevertheless, smartwatches and fitness trackers are merging and adding new capabilities and already transmit and share the data. Heart rate monitoring using Photoplethysmography (PPG - a simple LED-based optical technique which detects volumetric changes in blood in peripheral circulation, and oxygen saturation) is present in most high-end fitness trackers and recording electrocardiograms from the modified wrist band of a Smartwatch[18] or with the aid of a smartphone can now be added. By incorporating some AI in the data analysis, it is hoped to provide early detection and opportunity for treatment of atrial fibrillation, affecting over 30 million people. While this added sensor is not photonics based, it illustrates the potential in this growing market sector.

The existing mobile phone cameras are already being used in developing countries for eye examination to image the optic nerve and retina, and several approaches to adapt them "smartphone spectrometers" are also being explored to address clinical requirements in remote or underservices areas[19],[20]. Other examples of integration of sensors with mobile phones include the use of a visible to near infrared G-Fresnel spectrometer for the analysis of hemoglobin[21]. The resolution of ~5 nm in a wavelength range from 400 nm to 1000 nm can potentially enable new point-of-care opportunities, such as cancer screening. Hyperspectral imaging (HSI)) with mobile phones has recently been demonstrated at VTT by incorporating a MEMS-based Fabry-Perot interferometer tunable optical filter (MEMS FPI) with the existing CMOS camera[22]. This will augment the 2D and 3D imaging capability of mobile phones; the analysis (AI) of these spectrally sliced images will expand their use for applications in food safety, health care (point of care) monitoring and agriculture, where conventional HSI solutions are much more expensive. Commercialization of the technology is underway[23] and could have an impact within 5 years. Smartphones are also being explored for hyperspectral reflectance imaging, for biomedical applications such as tissue oximetry[24].

Compact spectrometers for sensing from visible to mid-IR (2 – 4 µm) range are also being developed in different PIC technologies. As noted in the Healthcare section on Point-of-care Diagnostics, compact ring resonators are already in use for some wavelengths and the need for improved performance, integration with microfluidics, packaging and reduced cost documented. The applications for photonics in Breath Analysis by Trace Gas monitoring have been described in the bio photonics and medical chapter.

The requirements for chemical (liquid and gas) and biological sensors have been recently reviewed by Miller and Agarwal, including the sensor types, their fabrication requirements, technology needs and challenges[25]. The table below shows the key attributes for different time frames from their report.

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[17] CARRIE MACGILLIVRAY, IDC FUTURESCAPE: WORLDWIDE INTERNET OF THINGS 2017 PREDICTIONS, WEB CONF NOV 2016
[18] https://internetofbusiness.com/apple-watch-kardiaband-iot-healthcare/
[19] http://www.mdpi.com/1424-8220/18/1/223, Sensors 2018, 18, 223; doi:10.3390/s18010223
[20] http://dx.doi.org/10.1016/j.bios.2016.09.021
[21] Scientific Reports | 7: 12224 | DOI:10.1038/s41598-017-12482-5
[22] http://www.vttresearch.com/media/news/the-consumer-of-the-future-will-use-a-mobile-phone-to-monitor-his-environment
[23] http://optics.org/news/8/4/28
[24] Jonathan L. Lin et. al. Proc. of SPIE Vol. 10485 104850C-1
[25] Ben Miller and Anu Agarwal, Integrated Photonic Sensors, 2017 Integrated Photonics Systems Roadmap (IPSR), March 2018

Table 6. Roadmap for targeting key attributes required in Chem-Bio sensors

	3-year Roadmap	**5-year Roadmap**	**Beyond 5 years**
Sensing mechanism	Absorption spectroscopy and surface capture; single point, time of flight; Refractive Index	Include detection of changes in fluorescence or colorimetry (visible)	Absorption spectroscopy; changes in RI and fluorescence, polarization etc.
Analyte to be detected by sensor	Chemical with absorption in the 1300 to 1550 nm wavelength range; biomolecules at moderate abundance (≥ ng/mL)	Include detection of chemical with interactions in the visible wavelength range; biomolecules at low abundance (ag/mL)	Chemical sensing over a wider wavelength range; single biomolecule detection
Labeled or Label-free sensing	Label-free	Add functionalization that may be required (e.g. AB-Antigen pair) or other labelling; develop Rochester TAP facilities for this functionality	Label-free and labeled
Material System	Si or silicon nitride waveguides with Ge detectors	Silicon nitride waveguides with Si detectors; silicon nitride with thicker box layer (or other method to support TM; silicon nitride for visible frequency combs, etc.	Thicker nitride for NIR frequency combs; Silicon nitride and silicon waveguides Si and Ge detectors respectively for visible and NIR and perhaps MIR; Ge on Si for long-wavelength; ZnSe, Chalcogenide glass
Analyte delivery	Etching down to silicon waveguide level at SUNY, and analyte delivery via microfluidics, ink jet printing etc. at the Rochester TAP	Etching down to both silicon and silicon nitride levels at SUNY, and analyte delivery via microfluidics, ink jet printing etc. at the Rochester TAP	Developing TAP packaging capabilities for analyte delivery and encapsulation
Light Source	Interposer-based lasers. Backup: VCSELs emitting in the 1300 to 1550 nm range. SOA (broad-band).	On-chip lasers (1310, 1550). Frequency comb sources	More choices in hybrid and integrated light sources across several wavelength ranges. Light sources between 3 to 5 microns, integrated on chip. ZnSe/Cr? Controlled tunable on-chip laser
Detector	Multiple Ge detectors (with different sensitivities). High sensitivity, low-frequency Ge detector particularly important	Multiple Silicon detectors with different sensitivities	On-chip and hybrid Si, Ge and other material system (3-5 micron) photo detectors and imagers with application-specific sensitivities

Spectrometer	Automated AWG design; standard AWG as part of the PDK; FTIR (MZ-based) and ring resonator based; focus on telecom and datacom bands	Add wavelength regions (3-5 micron); increase resolution. Alternative spectrometer designs (echelle gratings)	Broaden wavelength range; add 8-12 micron wavelength region
Filters	Ring resonators	Photonic crystal tunable filters	Coating-based
Light interface	Edge coupler (25 micron pitch) Grating coupler	Tunable gratings	Multimode waveguides
Integration level	Hybrid with flip-chip bonding at Rochester TAP	Hybrid with flip chip bonding and some monolithic where needed, at Rochester TAP	Hybrid and monolithic capability
Coupler	In-plane	In-plane or grating	In-plane or grating with varied material systems
Resolution	Application-specific	Application-specific	Application-specific

IOT AND SMART CITIES, HOMES AND OFFICES

Cities are already becoming “smarter”, driven by the economic benefit of reduced operating and maintenance costs of major infrastructure (water & sewer, power, transportation and security). Smart meters encourage residents to reduce waste, and information from traffic cameras is already “processed” to predict travelling times. Integrating more AI with 2D and 3D visible and IR cameras will expand their use where image or object recognition is required for autonomous control in building access and security. Autonomous vehicles are expected to rely strongly on sensor information from a combination of visible and IR (night vision) cameras, LiDAR and Radar (ADAS) systems.

For smart homes and offices, the transition from incandescent to LED lighting has already made an impact on energy costs, but many more opportunities exist to improve the use of space and reduce operating costs. Integrating new sensors, which are self-powered, with built in wireless connectivity, will make their installation and adoption much easier. Integrated photonics plays a role in many aspects of this emerging business, including energy harvesting (photovoltaics and other technologies), occupancy, motion and temperature (IR) sensors and compact solutions that can be integrated with building control systems are emerging[26].

IOT AND FACTORY AND SUPPLY CHAIN AUTOMATION

In addition to being incorporated in finished goods, IoT sensors are found throughout their manufacture; they provide efficient materials management, manufacturing and assembly, and the on-time delivery of high-quality products by making more use of integrated photonic smart sensors and robotics intelligently networked together. Automated laser machining and welding, vision systems for robotics and assembly, parts tracking (bar code scanning) and material delivery are ubiquitous in automotive manufacturing lines.

The large semiconductor fabs are also an example of how automation has provided better wafer throughout, process control, wafer testing and packaging, and increased yield (lower cost) for manufacture of many of the IoT sensors and chips we use, with reduced “hands-on” labour.

[26] http://www.echoflexsolutions.com/products/sensors

Photonics is an integral part of the automated exposure, alignment and inspection tools, as well as in optical monitoring of deposition and etch tools in our fabs, as well as the loading and transport of wafers. Supply of materials and delivery of finished goods may see increasing use of different types of autonomous vehicles on the road, and the regulatory requirements to allow drones to deliver goods to your door are already being explored. As the costs (sensor cost, installation and network connection cost and time, and software integration cost and time) of bringing IoT solutions to the factory decreases, their increased use will improve the scheduling, efficient operation and maintenance and overall productivity of machines and other assets significantly.

Table 7. Visible light application requirements

Visible light applications	[unit]	5 years	5-10 years	10-15 years
Annual revenue per product? /or total?	[€/year]	2M/50M	10M /250M	50M/ 1000M
Cost price	[€/unit]	1000	500	100
Energy consumption	[W]	1	0.5	0.1
Wavelength range	[nm]	405-640	405-850	405-850
Reliability	[%]	90	99	99,9
Footprint	[mm²]	100	50	10
Output power	[W]	1	2	5
Life cycle	[years]	5	5	5
Bandwidth	[Bps]	NA	NA	NA
Swap time	[seconds]	NA	NA	NA
Speed	[m/s]	NA	NA	NA

STRUCTURAL HEALTH MONITORING (ACOUSTICS)

Opto-acoustics non-invasive technique for characterizing behaviors of biological materials including cells, tissues and organs. The specification required integrated optical functionality (filter), the device cost and its market size are given below.

Possible functions of PICs:
Passive wavelength filter C-band, 4 -16 channels. Cross rejection ratio >60 dB
Same as above but with integrated photodiodes, 10 MHz bandwidth
Integrated laser, tunable over C-band, narrow line width (<1 kHz), high frequency FM modulation (>50 kHz), 15 mW output power, 15 years MTBF Market potential
Total SHM market (optical and electrical): 1.1 B$ in 2016 to 3.4 B$ in 2022

Cost
Passive components: competitive with bulk optics, € 50 - € 100 at 1000s of pieces
Laser: € 500 per piece at 100s, € 100 per piece at 1000s

PHOTONIC GAS SENSING

Real-time gas detection at low concentrations (part per billion level or lower) is conflicting with the need for high sensitivities. Thus, to acquire the needed sensitivity long absorption pathlength are needed (multi-pass cells, high-finesse optical cavities). In optical cavities absorption path lengths can reach hundreds of meters up to a few kilometers, depending on the reflectivity of the mirror coating. In the mid-infrared wavelength region, the mirror reflectivity is less advanced, but is compensated by the stronger absorption line strengths of the molecular transitions.

An additional problem is the detectivity of infrared detectors. While the detectivity for near infrared detectors is very good with quantum efficiencies > 10%, mid infrared detectors have a 5 order of magnitude lower detectivity at room temperature. For supercontinuum lasers the power per wavelength unit is low; as such, their output power must be increased or the Detectivity of the mid-IR detectors must be improved. Currently, several methods are applied for gas monitoring: next to optical detection these are mass spectrometry and electro-chemical sensors. While systems based on mass spectrometry are highly sensitive, they suffer from complexity, large footprint and purchase costs. Electro-chemical sensors are cheap but suffer from low specificity.

There are at least two areas in the natural gas industry in which integrated photonic sensors could play a major role: pipeline monitoring and leak detection at compressor stations. The natural gas distribution industry has an annual estimated profit of ~$15 billion (IBISWorld), but pipeline leaks cost the industry over $2 billion annually. By better detecting and repairing leaks, losses can be eliminated and profits increased by up to 12%. Current pipeline monitoring occurs using manual methods by either (a) walking with a handheld device along a pipeline or (b) driving a vehicle-mounted sensor along a pipeline. The requirement to manually survey the entire pipeline to detect leaks means that current detection is expensive and slow, allowing leaks to go undetected until a worker finally walks or drives by the leak location. Integrated photonic sensors could provide sensitive, specific detection that can be deployed as a network of sensors across the entire pipeline, monitoring the pipeline for leaks in real time.

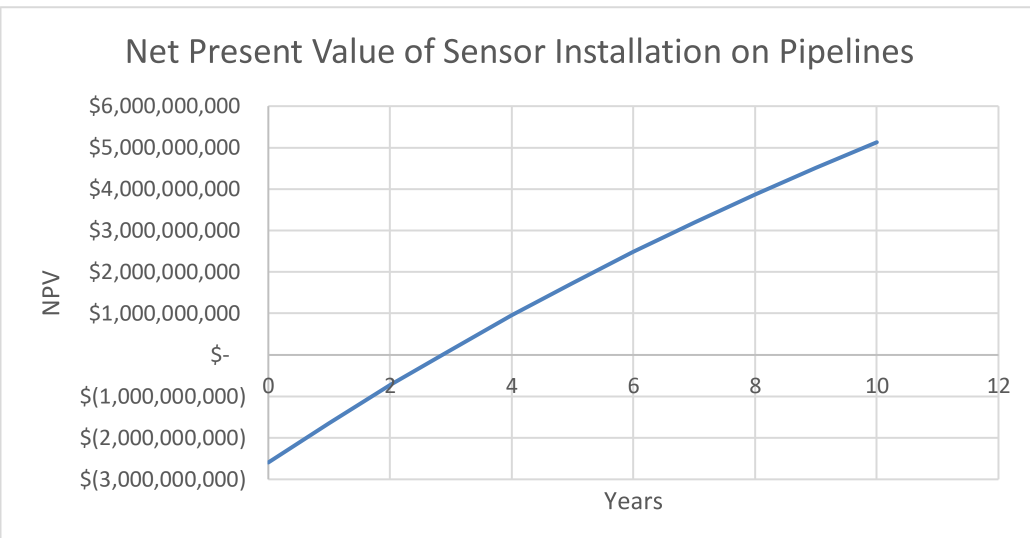

Figure 11. Net Present Value of installing an integrated photonic sensor network on natural gas pipelines to detect leaks.

This change would allow natural gas distributors to identify a leak more quickly and take action to repair it, preventing extra natural gas from escaping and saving the cost of lost gas and potential environmental damage. The requirements for a network of pipeline leak sensors of 10-200 ppm sensitivity, high selectivity, and low power consumption are all metrics met by integrated photonic sensors. By installing a network of integrated photonic methane sensors, the natural gas distribution industry could easily get a net savings of $5 billion over 10 years with a three-year payback period, as shown in Figure 11.

As illustrated in Figure 11, a net savings of more than $5 billion in ten years with a three-year payback period is significant. There are about 1500 compressor stations along natural gas pipelines in the US, with each station repressurizing gas and scrubbing any contaminants (such as liquids) out of the pipeline. These stations are a frequent point of failure in the gas pipeline, so a sensitive sensor that can detect leaks or other problems is important. These stations require several upgrades, so they are essentially rebuilt every 3-5 years, providing an easy entry point for new sensor technology, such as integrated photonics.

There are several gas sensor applications, each with its own technical requirements, such as the types of gases to be detected, sensitivity and selectivity, response time, lifetime and power consumption. Each application also has its own business requirements including regulations, target price, maturity of the market and competition.

There are six main gas sensor market segments:

1. Consumer: Gas sensors embedded in consumer products including home devices, wearable electronics and mobile phones;
2. HVAC: Gas sensors used for indoor/in cabin air quality monitoring;
3. Transport: Gas sensors used for exhaust gas measurement or in engine control for heavy

Duty vehicles;

4. Medical: Gas sensors used for breath analysis in ventilation and point of care;
5. Defense and Industrial Safety; and
6. Environment: Gas sensors used to monitor air quality and pollution peaks.

Gas sensing technology is determined by price, form factor, power consumption, sensitivity and response time. According to Yole “optical technologies have the highest accuracy and longest lifetime but are not widely used in the transport market because cost pressure is high. They are largely used in HVAC, especially Non Dispersive Infrared sensors (NDIR). Further integration will open the way to portable systems for industrial applications.” The advantage of integrated photonic sensors lies in their low Size, Weight, and Power SWaP footprint.

Emission monitoring

Air pollution from emitted by anthropogenic or/and natural sources constitutes a significant risk factor for human health. In Europe, air pollution is estimated to cause more than 300’000 premature deaths each year[27]. The total annual economic cost of air pollution related health impacts is estimated to be more than US$ 1.5 trillion[28]. Today, significant effort is devoted globally to improve air quality through *e.g.* land-use planning strategies, replacement of fossil fuels by clean energy sources and lower level of industrial emission.

27 http://news.bbc.co.uk/2/hi/health/4283295.stm

28 WHO Regional Office for Europe, OECD (2015). Economic cost of the health impact of air pollution in Europe: Clean air, health and wealth. Copenhagen: WHO Regional Office for Europe.

To be successful, these measures need be accompanied by air quality monitoring at large scale to ensure compliance with air quality legislation but also to provide information for political decision-making regarding air quality and safety. Detailed air quality data are needed around urban areas, industrial infrastructures and highways from a dense network of air quality monitoring stations. But also, for remote areas from ships, or case of catastrophic events such as leaks and fires in chemical industry, wildfire and volcanic eruptions.

Common materials and their combustion products

Products / Combustion products	Acrylic	Fire retardant material	Flourinated resins	Melamine resins	Nitrogen containing material	Nylon	Petroleum products	Plastics	Polystyrene	Pylyurethane	Poly-vinylchloride	Rubber	Silk	Sulfur containing material	Wood cotton paper	Wool	Immediately Dangerous to Life or Health Concentrations (IDLH)	
																	ppmv	mg/m3
Acrolein	x						x								x		2	5
Carbon monoxide	x						x				x				x	x	1200	1320
Hydrogen Chloride	x	x						x			x					x	50	70
Hydrogen Bromide		x															30	160
Hydrogen Fluoride			x														30	26
Ammonia				x		x		x					x			x	300	210
Hydrogen cyanide				x	x	x		x		x			x			x	50	55
Acetic acid							x								x		50	125
Formic acid							x								x		30	55
Nitrogen dioxide					x			x									20	36
Phosgene								x			x					x	2	8
Styrene									x								700	3000
Hydrogen Sulfide												x	x				100	150
Sulfur dioxide												x	x	x			100	250
Acetaldehyde								x							x		2000	3600
Formaldehyde								x							x		20	25
Methane															x			

Figure 12. The complex mixture of toxic molecules that can be generated in a fire and that are immediately dangerous to life: IDLH (Immediate Danger to Life or Health) concentrations.

Agro-technology and food

There is an increasing need for a technology that would provide a tool for fast, accurate and non-destructive analysis of the quality status of packaged food products, as well as its package integrity in every stage of the distribution chain, starting from the packaging process at the food producer until storage at the retailer. This technology should be able to measure a range of different volatile components representative for different spoilage processes that could occur in packaged food. Through integrating a photonic based sensor on the inside of packaging materials, it will continuously measure the quality status of the packaged food product as well as the package integrity for modified atmosphere packages containing carbon dioxide with high or low oxygen levels.

Early detection of food degradation and spoilage is important for improved management of the controlled atmosphere conditions (process control), thus preserving food quality at reduced costs and ensuring food safety for consumers. It’s estimated that globally 33% of the edible parts of food produced for human consumption gets lost or wasted[29], losses due to spoilage and degradation during handling, storage and transportation. Important gases are CO_2/O_2 ratio (related to the respiration quotient), ethylene (plant hormone, container transport companies are interested in ethylene detection to prevent early ripening of fruit, vegetables, and flowers), ethanol, acetaldehyde (volatile markers for fermentation), methanol, acetone (rotting process indicators). More specifically, the development of fungal infections (potentially dangerous for the consumer’s health via mycotoxins), during storage may be detected by rotting volatiles in combination with low levels of fermentation volatiles. Therefore, the continuous monitoring of such volatiles is important not only for food quality but also for food safety control.

Other field of applications for photonic-based gas sensing

Gas sensors for residential/commercial buildings, confined environments.
Gas sensors for monitoring biochemical processes in bioreactors

[29] Gustavsson, J., et al., Global Food Losses and Food Waste: Extent Causes and Prevention. 2011, Rome: Food and Agriculture Organization (FAO) of the United Nations.

Detection of prohibited and/or dangerous substances such as drugs, explosives, constituting important means for security assurance and law enforcement. Quality insurance gasses growth conditions semiconductor industry.

ROADMAP OF QUANTIFIED KEY ATTRIBUTE NEEDS

The following is a partial list of quantified key attributes extracted from the Portable Systems Product Sector chapter of the iNEMI 2015 Roadmap. In addition, we have attempted to include specific key attributes unique to integrated photonics.

Table 8. Quantified key attribute needs

Parameter	Metric	2013	2015	2017	2019	2025
PCB Costs						
2 layer flexible	$ per cm2	0.025	0.020	0.015	0.010	0.005
2 layer Rigid	$ per cm2	NA	0.0063	0.006	0.0058	0.005
3 layer flex	$ per cm2	NA	NA	NA	NA	NA
6 layer flex (with micro vias)	$ per cm2	0.065	0.050	0.040	0.025	0.013
4 layer conventional	$ per cm2	0.020	0.008	0.008	0.008	0.008
4 layer - embedded capacitor / resistor	$ per cm2	NA	NA	NA	NA	NA
6 layer conventional	$ per cm2	0.025	0.013	0.012	0.012	0.010
4 layer w/ microvia	$ per cm2	0.040	0.0274	0.0247	0.022	0.018
6layer rigid (with micro vias)	$ per cm2	0.065	0.050	0.040	0.030	0.020
6 layer, blind/buried	$ per cm2	0.085	0.070	0.055	0.035	0.025
8 layer	$ per cm2	0.040	0.016	0.015	0.015	0.012
8 layer w/ microvias	$ per cm2	0.080	0.044	0.040	0.036	0.028
8 layer w/ blind/buried	$ per cm2	0.100	0.080	0.065	0.040	0.030
8 layer colaminated (ALIVH)	$ per cm2	0.120	0.100	0.080	0.050	0.035
10 layer conventional	$ per cm2	0.050	0.028	0.027	0.026	0.020
10 layer w/ microvias	$ per cm2	0.120	0.053	0.046	0.042	0.030
10 layer w/ blind / buried	$ per cm2	0.140	0.120	0.100	0.070	0.038
10 layer colaminated (ALIVH)	$ per cm2	0.140	0.120	0.100	0.070	0.040
Assembly Costs	#REF!					
Average Board Assembly Cost	¢ per I/O	0.035	0.02	0.02	0.01	0.006
Average Final Product Assembly Cost	$/unit	1.15	1.05	0.98	0.9	0.5
Package Costs	#REF!					
IC Package Cost	¢ per I/O	0.15	0.1	0.1	0.08	0.05
Package Cost (High Density Ceramic/w/ Area Connector)	¢ per I/O	0.6	0.5	0.4	0.2	0.1
Package Cost (High Density µvia Laminate w/ Area Connecto	¢ per I/O	0.03	0.025	0.2	0.1	0.05
Connector Cost	¢ per I/O	0.005	0.004	0.003	0.002	0.001
Energy Cost	$/Wh	0.4	0.3	0.25	0.2	0.1
Memory Cost (Flash)	$/MB	0.03	0.015	0.007	0.004	0.002
Memory Cost (SRAM)	$/MB	0.85	0.7	0.55	0.4	0.2
Cost of Test as a ratio to assembly	ratio	0.025	0.02	0.015	0.01	0.005

Parameter	Metric	2013	2015	2017	2019	2025
PCB Costs						
2 layer flexible	$ per cm2	0.025	0.020	0.015	0.010	0.005
2 layer Rigid	$ per cm2	NA	0.0063	0.006	0.0058	0.005
3 layer flex	$ per cm2	NA	NA	NA	NA	NA
6 layer flex (with micro vias)	$ per cm2	0.065	0.050	0.040	0.025	0.013
4 layer conventional	$ per cm2	0.020	0.008	0.008	0.008	0.008
4 layer - embedded capacitor / resistor	$ per cm2	NA	NA	NA	NA	NA
6 layer conventional	$ per cm2	0.025	0.013	0.012	0.012	0.010
4 layer w/ microvia	$ per cm2	0.040	0.0274	0.0247	0.022	0.018
6layer rigid (with micro vias)	$ per cm2	0.065	0.050	0.040	0.030	0.020
Cycle Time						
NPI Cycle Time	Weeks	14	12	10	6	4
Product Production Life (not including spares)	Years	3	3	3	3	3
Reliability						
Temperature Range	Deg C - Deg C	-40 - +85	-40 - +85	-40 - +85	-40 - +85	-40 - +85
Number of Cycles	Cycles to Pass	manuf spec	manuf spec	manuf spec	manuf spec	manuf spec
Vibrational Environment (PWB level)	G^2/Hz	UA	UA	UA	UA	UA
Use Shock Environment	Gs & ms to Pass	20G(20ms)	20G(20ms)	20G(20ms)	20G(20ms)	20G(20ms)
Devices	#REF!					
Number of stacked die (Max)	#	8	10	11	12	20
Sensors	Types	Gyro, Accel, GPS	revious plus Haptic	amera, Context Camera (gesture recognition)		
Number of Die in SiP (max)	#	5	5	6	7	12
Maximum MEMS Power Consumption	W					
MEMS	Types	Gyro, Accel, GPS	Gyro, Accel, GPS	prev+projection	prev+projection	prev+medical
Max. Ohms	ohms / sq. cm	10K	100K	100K	100K	100K
Max. Capacitance	μF / sq. cm	10K	250	500	700	1000
Min. % tolerance	%	10	5	5	2	1
RF Components						
Quality Factor	Q	20	125	400	1000	5000
Capacitance density	nF/sq. cm	0.3	1	10	100	500
Inductance req.	nH	15	30	300	1000	1000
Interconnect Insertion loss maximum	db/cm/GHz	0.05	0.008	0.0025	0.001	0.0002
Photonic Components						

Parameter	Metric	2013	2015	2017	2019	2025
Memory						
Main Memory Type	Type	SRAM	Stack D&S	eDRAM, NVM	eDRAM, NVM	eDRAM, NVM
Main Memory Capacity	MB	256	1 GB	5 GB	10 GB	100GB
Storage Type	Type	Card/Slot	Disk	Disk?	Optical ?	Optical
Storage Capacity	MB	5 GB	20 GB	100 GB	500GB	1TB
Maximum Power	mW					
Minimum Speed	GB/sec					
Components/ Package						
Max Component I/O density	I/O/sq.cm	500	600	700	800	1200
Average Component I/O density	I/O/sq.cm	50	55	60	80	120
Average Component Density	#/sq.cm	30	40	50	80	120
Maximum I/O per package	I/O per part	600	675	725	1000	1400
Average I/O per package	I/O per part	7	7.5	8	9	11
Max Components/sq. cm.	#/sq.cm	55	60	70	75	95
Max I/O for 50 mm square SCM w/ full area array	#	3000	3500	5000	8000	1300
Package I/O Pitch, (area array)	mm	0.4	0.4	0.3	0.3	0.3
Package I/O Pitch for SCM (area array)	mm	0.4	0.4	0.3	0.3	0.3
Package I/O Pitch for MCM (area array)	mm	0.5	0.4	0.4	0.3	0.3
Package I/O Pitch (perimeter)	mm	0.4	0.4	0.3	0.3	0.3
Number of Terminals - Max Digital	#	600	675	725	1000	1400
Number of Terminals - Max RF	#	100	150	200	350	600
Maximum Component Height	mm	1.0 to 2	1.0 to 1.5	0.7 to 1.2	0.4 to 1.0	0.2-0.5
Maximum Body Size (L x W)	mm	38	40	42	50	50
Minimum Terminal Pitch BGA	mm	0.4	0.4	0.3	0.3	0.3
Minimum Terminal Pitch Leadless	mm	0.4	0.4	0.3	0.3	0.3
Minimum Component size (LxW)	mm	0.5	0.5	0.4	0.3	0.3
PCB / Substrates						
PCB Board Size (Min)	sq. cm	0.75	0.5	0.3	0.2	0.1
PCB Board Size (Max)	sq. cm	80	64	52	40	30
Substrate Lines/Spaces	μm	65	65	50	35	20
Substrate Pad Diameter	μm	175	150	125	100	50
Ceramic Thin Film Lines/Space	μm	35	25	20	10	5
PCB Land Diameter With Vias for BGA - Via in Pad (VIP)	μm	300	250	200	150	100
PCB Minimum Plated-thru-via (PTV)	mm	0.15	0.1	0.1	0.075	0.05
Substrate Material	Type	FR4	FR4	FR4	FR4	FR4
PCB Lines And Spaces	μm	300	300	250	250	200

Parameter	Metric	2013	2015	2017	2019	2025
Electrical & Test						
Frequency on Board	MHz	250	300	350	400	500
Impedance Tolerance	%	10	10	5	5	1
Built In Self Test (BIST)	%	50	70	85	90	90
Boundry Scan	%	20	35	50	75	90
Minimum Logic Family Voltage	Volts	2	1.8	1.5	0.8	0.7
Maximum Logic Family Voltage	Volts	3.3	2.85	2.2	1.8	1
Normal Logic Family Voltage	Volts	2.85	2.2	1.8	1.2	0.8
Test pad access minimum	%	25	20	10	5	5
Minimum test pad size	mm²	1	1	0.8	0.7	0.5
Maximum escape rates	DPMO	1000	500	200	100	100
Power	#REF!					
Power	Type	u Polymer, methanol	u Polymer, methanol	u Polymer, methanol	u Polymer, methanol	u Polymer, methanol
Spec. energy	Wh/kg	120	150	200	250	500
Energy dens	Wh/liter	138	150	230	300	500
Cycle life	#cycles-80%	1000	1200	1500	1800	2000
Specific power	W/kg	300	400	500	600	1000
Shelf life	years	3 years	4 years	5 years	8 years	10 years
Run Time Before Recharge	Hours	8	10	15	20	40
Min. and Max. Operating Temperature	Degrees C	-20 to 30	-25 to 35	-30 to 40	-30 to 45	-40 to 50
Battery Cost (Maximum)	$/Wh	0.6	0.5	0.4	0.2	0.1
Battery Recaharge Time (Maximum)	Hours	4	3	2	2	1
Environmental						
Minimum MSL Level	Level #	3	3	2A	2A	2
Max Reflow Temp	Degrees C	260	260	260	260	220
Solder Type	Composition	LF	LF	LF	LF	LF
Hazardous Substance Content	% by weight	0	0	0	0	0
Recycling targets - Recovery, Recyclability	%,%	70/60	75/65	80/70	95/90	95/95
Thermal						
Use Ambient Operating Temperature Range	Deg C - Deg C	-10 to 50	-10 to 50	-10 to 50	-10 to 50	-10 to 50
Thermal Design Power (Hottest Chip)	Watts	40	45	50	60	60
Cooling Method	Passive,Active, None, Both	both	both	both	both	
Number of Chips W/Some Heat Sink	# / Assy or Board	0	0	0	0	0
Device Cooling Air Temperature (Inside the Box)	Deg C	40	40	40	40	40

CRITICAL (INFRASTRUCTURE) ISSUES

IDENTIFY PARADIGM SHIFTS

The IoT – so what can we do that we couldn't do before? Well, users have, in a significant way, taking control of information! As an increasing number of devices are being connected to the Internet, information is evolving from what we know today into a whole new mindset where continuous development and modular authoring is paramount. The production of technical information has for many decades been a fairly routine process. Products are manufactured, documented and marketed, and when they are being sold, the printed documentation is handed over to the owner or gets distributed to service technicians.

With the evolution of the Internet, a paradigm shift began, directing information to displays and less towards printed media. Handbooks are being replaced by apps and user web forums, information about repair and maintenance procedures became available via service portals, accessories and parts systems are digitally distributed and connected to e-commerce websites and business platforms. In addition, a company's product information today is primarily competing with social channels such as YouTube, Wikipedia and Ifixit among others. The users have taken control of the information.

The IoT introduces another paradigm shift and encapsulates the notion that information will likely be completely integrated into products — information content has become an inextricable part of the product itself! The challenge for us — the information authors — is to continuously describe the components of ever-changing products.

Connected things bring new value — all sorts of things as noted earlier — because connected things can intelligently make use of each other in order to make our lives easier and more efficient.

*Figure 13: From "**Smart Dust**" systems that can be embedded (and even **ingested**) all the way to the satellites driving an **Interplanetary Internet** system. The range of hardware devices that will drive an Internet of Things is staggering! IoT will create new winners long before losers find out they're losing.*

TECHNOLOGY NEEDS

The IoT isn't coming soon - it's already here! A typical car produced in 2014 has between 60-100 built-in sensors. The IoT connects the physical world to the Internet. The IoT connects billions of sensors and devices such as every day consumer objects and industrial equipment onto networks. Networked inputs are then combined into bi-directional systems for better decision making, increased efficiency, new services, or environmental benefits. Increasing amounts of data produced by those sensors and connected devices are hence acquired, logged, and stored onto networks. Although the IoT IS already here, it's not evenly distributed!

The IoT paradigm, while not evenly distributed yet, is rapidly connecting the physical world to the Internet. The IoT is inevitable, affecting every industry, every company, every job, and every person. The IoT is going to be huge with over 212 billion devices by 2020 (Samsung IFA 2014 / International Data Corporation (IDC), 2014). IDC predicts that the IoT will generate nearly $9 trillion in annual sales by 2020. Not convinced? Within 6 years, 57,000 new "things" will be added to the Internet every second. For businesses, the IoT requires a mindset shift because it will create and capture value differently. The IoT is both a driver of new product cycles and another leg of cost efficiencies. Products can address needs in a predictive manner, leveraging data and frequent updates. The IoT enables incremental revenue, control points and opportunities for partnerships in the ecosystem. The IoT will create new winners long before losers find out they're losing. It is necessary to understand and leverage this evolution, so that we can face the requirements that will be placed on us, as well as benefit from all the opportunities it creates.

Truly, the sky is the limit in terms of IoT applications:

- Home consumer: Thermostats, Lighting, Remote control appliances, Detection (intrusion / smoke), Energy / water monitoring, Infotainment, Pet feeding
- Health & Body: Patient care, Patient surveillance, Elderly monitoring, Fall detection, Remote diagnostic, Equipment monitoring, Hospital hygiene, Bio wearables, Food sensors
- Cities & Industry: Smart lighting, Waste management, Maintenance, Surveillance, Signage, Utilities / Smart grid, Emergency services
- Transportation & Mobility: Smart car, Traffic routing, Telematics, Package monitoring, Smart parking, Insurance adjustments, Supply chain, Shipping, Public transport, Airlines Trains
- Buildings & Infrastructure: Heat, ventilation and air conditioning, Security, Smart lighting, Transit, Emergency alerts, Structural integrity, Occupancy, Energy credits

IoT revenues predictions are staggering in every category (Source: IDC - Internet of Things Spending Guide by Vertical Market, 2014):

-	BANKING:	2014: $92B	2018: $154B
-	MANUFACTURING:	2014: $472B	2018: $913B
-	RETAIL:	2014: $160B	2018: $326B
-	HEALTH:	2014: $132B	2018: $313B
-	TRANSPORTATION:	2014: $156B	2018: $325B
-	UTILITIES:	2014: $100B	2018: $201B
-	GOVERNMENT:	2014: $301B	2018: $570B
-	OTHER:	2014: $750B	2018: $1.78T

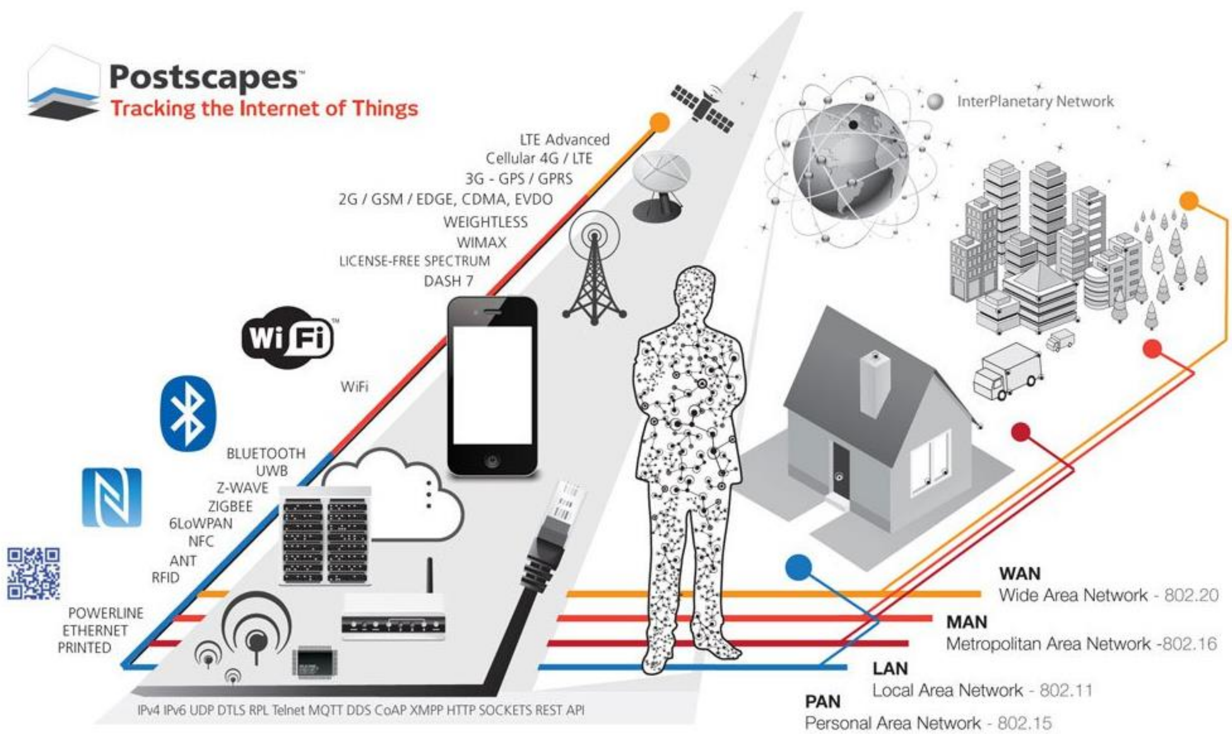

Figure 14. Potential applications of IoT (http://postscapes.com/internet-of-things-technologies#communication)

TECHNOLOGY CHALLENGES

CONNECTIVITY/SIGNALING

There will not be one connectivity standard that "wins" over the others. There will be a wide variety of wired, wireless and free-space photonic standards as well as proprietary implementations used to connect things in the IoT along with connectivity via data centers as required to collect, process and distribute the information. The challenge is getting the connectivity standards to talk to one another with one common worldwide data currency. With connected IoT devices, reliable bidirectional signaling is essential for collecting and routing data between devices. That's where IoT data streams come into play. Devices may be talking to a server to collect data, or the server may be talking to the devices, or maybe those devices are talking to one another. No matter what the use case, data needs to get from point A to point B quickly and reliably. You need to be 100% sure that that stream of data is going to arrive at its destination every time.

How useful IoT devices can be clearly resides not only in local communication, but also in global communication. If at all possible, it is crucial that your IoT networks (LANs, PANs, and BANs) all make use of the suite of Internet Protocols (IP, UDP, TCP, SSL, HTTP, and so on). Furthermore, your networks must support Internet Protocol version 6, as the current IPv4 standard faces a global addressing shortage, as well as limited support for multicast, and poor global mobility. IPv6's addressing scheme provides more addresses than there are insects on earth — some have calculated that it could be as high as 10^{30} addresses per person. Hence, IPv6 will make it easier for an IoT device to obtain a global IP address, enabling efficient peer-to-peer communication.

This said, the sheer volume of data created by the IoT will have unknowable impact on the networking systems used today. Deep analytics will require distributed data centers and real-time response to events. Fast, agile networks are crucial to enable the real-time analysis of sensor data. Given these requirements, it is very unlikely that today's networks will stand up to the demands of 2020. As a potential solution, even software-defined networking only begins to address some of these needs in the cloud data center.

As a final thought, here are some additional things we continue to consider regarding the impact of IoT on data flow and networking. Many IoT applications may differ from current applications like video and search. Data rates will likely be much lower BUT from many more devices. Some data may remain device local, while some will be routed to the cloud to be stored and aggregated. This can add up to quite a lot of data - consider fitbit, Spotify, all the applications on cell phones, etc.

- So, what might be the implication of these traffic changes on the network?
- What will this traffic look like…Into and out of the data center and then within the data center?
- Will it differ by application?
- How might this affect optical networking?
- Will the impact simply be much like todays cell phones and sensors multiplied by X - only increasing aggregate bandwidth?
- *We are working to figure this out - your thoughts are welcome!*

SECURITY

With the amount of data being sent within the IoT, security is a must and data centers need to prepare themselves for increased scale, density, and security. When talks of IoT take place, it won't be just one aspect of the infrastructure that will need to be augmented to support the IoT. It will impact the whole technology stack, including the networks, facilities, cabinets, technology platforms, and system administration. Companies and data centers are already starting to see the effects of the IoT and must ensure they are capable of handling future data requirements. Built-in hardware security and use of existing connectivity security protocols is essential to secure the IoT.

According to Dr. Deepak Kumar, CTO at Adaptiva, “In the coming decade, [the] IoT will cause the bandwidth gap to balloon out of control. Enterprises will see enormous amounts of traffic coming from a massive number of sources. In addition to greater bandwidth, enterprises must plan for bandwidth optimization and enforce stricter traffic management policies. IT departments will need to ensure they have mechanisms that prioritize internet and intranet access to business-critical applications and devices first.” In order to prepare for the influx of data, data centers must enhance their current capabilities as it pertains to infrastructure, scalability, services, storage, and security. IoT producers will be looking for data center-as-a-service providers that understand and are making plans to support the IoT.

Another challenge is simply educating consumers to use the security that is integrated into their devices. Remember - 50 billion Connected Devices by 2020 Security is a huge umbrella, but it’s paramount in IoT connectivity. For example, what good is a smart home if anyone can unlock your doors? The IoT encapsulates significant changes across all industries. Most of the 15 billion devices that have been hooked up to the web over the past few years have not adequately addressed security. These devices use cheap parts, have weak or no password protection, and use obtuse methods for changing passwords. As sensors become more common in the home and at work, it's easy to imagine a future overtaken by connected objects and devices and a network that is unprepared for it. Here are three specifics:

- Authorization: When sending or receiving a stream of data, it’s essential to make sure that the IoT device or server has proper authorization to send or receive that stream of data.
- Open ports: An IoT device is dangerously vulnerable when it’s sitting and listening to an open port out to the Internet. You need bi-directional communication, but you don’t want to have open ports out to the Internet.
- Encryption: You need end-to-end encryption between devices and servers.

The bottom line is that as the IoT evolves and an increasing number of IoT devices enter the network, increased security needs additional emphasis. The more endpoints within a network, the greater the likelihood of the network’s security being compromised, and each IoT device is an endpoint!

POWER MANAGEMENT

Billions of IoT devices signaling and sending data between one another takes a toll on power and CPU consumption. More things within the IoT will be battery powered or use energy harvesting to be more portable and self-sustaining. Line-powered equipment will need to be more energy efficient. The challenge is making it easy to add power management to these devices and equipment. With all this communication, you need minimal battery drain and low power consumption and wireless charging will incorporate connectivity with charge management.

COMPLEXITY

Manufacturers are looking to add IoT connectivity to devices and equipment that has never been connected before. Ease of design and development is essential to get more things connected. The average consumer needs to be able to set up and use their devices without a technical background. Presence detection will also play a role here. It’s important to immediately know when an IoT device drops off the network and goes offline. And when that device comes back online, you need to know that as well. Presence detection of IoT devices gives an exact, up to the second state of all devices on a network. This gives you the ability to monitor your IoT devices and fix any problems that may arise with your network.

BANDWIDTH

In addition to power and CPU, bandwidth consumption is another challenge for IoT connectivity. Bandwidth on a cellular network is expensive, especially with hundreds of thousands of IoT devices on a network sending request/response signals to your server. That’s a huge server issue and requires a large-scale server farm handling all this data. You need a lightweight network that can seamlessly transfer data between devices and servers.

INTERNET OF THINGS ARCHITECTURE

In the near future, these billions of devices connected to form the IoT will include sensors and actuators in smart cities, smart tags on many familiar objects, wearable health monitoring sensors, smartphones, intelligent cars, and smart home appliances. In the not-so-distant future, the IoT will incorporate many types of robots like domestic, flying drones, and even insect scaled flying devices. The changes to our daily life will be immense. *Today's* technology isn't ready for this massive scale and the highly dynamic nature of the future IoT, the huge amounts of data streamed from the physical world, and the new communication patterns it will create. We need new programming, network management and content delivery approaches that is realized with a systems-engineering approach — integrated hardware, software, networking, powering…all talking together from the inception. Today's IoT architectures were designed for small scale IoT closed-looped network "islands" using proprietary protocols. Densely deployed "things" can't collaborate dynamically across these islands to execute distributed tasks that involve sensing, actuating, and computing. *We need to break down the technology silos and create a flexible, event-driven architecture that allows seamless data sharing among applications.*

INTEGRATED PHOTONICS

With so many things connected to Internet, however, there is increasing demand for more network traffic, especially higher capacity in core networks. In addition, the shaping of the IoT is largely dependent on technologies like Internet Protocol version 6 (IPv6), cloud computing, Internet everywhere, and sensors. Most of these technologies are also asking for high-capacity network traffic. In the end, it's all about bandwidth and using technologies and products that can achieve higher network traffic capacity and the desire for higher levels of integration of optics favors the adoption of silicon photonics.

The system-level cost management, integration density, and power limit trade-offs must be carefully considered as development of silicon photonics is pursued.

- Speed & High Bandwidth: Optically transmitted signals run over long distances and at high signal rates superior to any other media - one big obstacle to the IoT.
- Security: Optical networks are the most secure and hack-proof - another big obstacle to the IoT.
- NO Electromagnetic Interference - making optical interconnects a number one choice for the IoT's network.

PRIORITIZED DEVELOPMENT & IMPLEMENTATION NEEDS (< 5 YEARS RESULT)

Critical Milestones		
CMx	**Content title**	**Period < 5 years**
CM1	To be defined	
CM2		
CM3		
CM4		
CM5		
CM6		
CM7		
CM8		
CM9		
CM10		

PRIORITIZED RESEARCH NEEDS (> 5 YEARS RESULT)

Critical Milestones		
CMx	**Content title**	**Period > 5 years**
CM11	To be defined	
CM12		
CM13		
CM14		
CM15		
CM16		
CM17		
CM18		
CM19		
CM20		

GAPS AND SHOWSTOPPERS

To be defined

RECOMMENDATIONS ON POTENTIAL ALTERNATIVE TECHNOLOGIES

To be defined

CONCLUSIONS

The exponential growth in the Internet-of-Things and their present and future impact across almost all market sectors is driving the digital economy and leading us into the next industrial revolution. Integrated photonics plays many key roles in addressing the challenges to enable this transition. The number of nodes connected, and the shear amount of data requires dramatic growth in the network, the cloud and data centers, and means that robust software or artificial intelligence (AI) will be required to manage, process and act upon much of this information with little human intervention. This change in the man- “IoT machine” interface will require new user interfaces.

Early adoption of IoT is taking advantage of existing technologies for connectivity through smartphones. *Sensors* such as 2D and 3D visible and IR cameras developed for smartphones can find applications in other application sectors (wearables, homes, offices, cities and security, automotive, and industrial equipment). *Healthcare* will see new portable and point of care solutions where integration of lasers, detectors, compact spectrometers and microfluidics with other types of sensors are expected to provide more rapid monitoring and easier access than conventional medical facilities. For all of these IoT nodes to function usefully and gain consumer acceptance, sensors with acceptable characteristics (size, weight, performance, power consumption, cost…) will need to be integrated with robust software (AI) for intelligent data gathering and interpretation over reliable networks with secure communications. The network quality of service and data security are big challenges and must be addressed before cities will see fully autonomous vehicles relying on V2V communication for their control. Even if this does not happen quickly, there will be much more photonics in vehicles (including LiDAR).History suggests that all of this new IoT technology will become part of daily lives more quickly than originally anticipated.

The IoT is expected to continually change and evolve — rapidly! More devices are being added every day and the industry is still in its infancy. Many of the challenges facing the industry are yet unknown. Unknown devices. Unknown applications. Unknown use cases. Given this, there needs to be flexibility in all facets of development. Processors and microcontrollers that range from 16–1500 MHz to address the full spectrum of applications from a

MCU in a small, energy-harvested wireless sensor node to high-performance, multi-core processors for IoT infrastructure. A wide variety of wired, wireless and photonic connectivity technologies are needed to meet the various needs of the market. A wide selection of sensors, mixed-signal and power-management technologies are required to provide the user interface to the IoT and energy-friendly designs.

The new technologies that are becoming available must meet these challenges — complexity, connectivity, security, bandwidth, power, and environmental. Key, new processor packaging technologies are being developed with some fundamental changes in the rest of the electronics industry and how it impacts the technology that can be leveraged. With the IoT, a new set of technology will evolve, but often at a much different scale of size, bandwidth and latency than required by typical data centers.

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