HETEROGENEOUS INTEGRATION ROADMAP

2020 Edition

Chapter 3: Internet of Things (IoT)

http://eps.ieee.org/hir

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Chapter 3: Heterogeneous Integration for the Internet of Things (IoT)

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Executive Summary

According to the report of WHO (the World Health Organization, https://covid19.who.int/), the COVID-19 confirmed cases have exceeded 80 million worldwide by the end 2020. Due to this global pandemic, there have been major lifestyle changes. For example, we now use verbal greetings instead of physical contact greetings, and may work from home instead of gathering at offices. We can easily visualize more IoT usage in our daily lives. In this 2020 chapter revision, updates include some new electronic packaging technique achievements, such as a thin-film battery for IoT microsystems and a sensor-platform for medical IoT. In addition, we discuss some IoT platform cases which demonstrate precise monitoring of vital signals and potential to save human lives.

1. Introduction

From IEEE IoT Magazine's article "Towards a definition of the Internet of Things (IoT)"[1], the definition of IoT is "A network of items – each embedded with sensors – which are connected to the Internet." Wikipedia[2] notes that "The Internet of Things (IoT) is a system of interrelated computing devices, mechanical and digital machines provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction." The definition of the Internet of things has evolved due to the convergence of multiple technologies, real-time analytics, machine learning, commodity sensors, and embedded systems. Traditional fields of embedded systems, wireless sensor networks, control systems, automation (including home and building automation), and others all contribute to enabling the Internet of things. In the consumer market, IoT technology is most synonymous with products pertaining to the concept of the "smart home", covering devices and appliances (such as lighting fixtures, thermostats, home security systems. cameras, and other home appliances) that support one or more common ecosystems, and can be controlled via devices associated with that ecosystem, such as smartphones and smart speakers. There are a number of serious concerns about dangers in the growth of IoT, especially in the areas of privacy and security, and consequently industry and governmental moves to address these concerns have begun. This chapter will articulate the difficult challenges and potential solutions linking IoT development and use to the other chapters in the Roadmap.

According to a Cisco report, 500 billion devices are expected to be connected to the Internet by year 2030 [3]:

- Each device includes sensors that collect data, interact with the environment, and communicate over a network.
- The Internet of Things (IoT) is the network of these connected devices. These smart, connected devices generate data that IoT applications use to aggregate, analyze, and deliver insight, which helps drive more informed decisions and actions.

By 2030, consumers anticipate an IoT experience that is omnipresent, seamless and personalized:[4]

- Consumers expect to see this by 2030 everywhere in their lives, with a wide array of use cases at home, at work, outside, for healthcare, automotive services and commercial drones.
- However, trust remains a key hurdle to overcome if consumers are to be completely accepting of these new and emerging technologies and as such, most are willing to pay for guaranteed security.

For IoT to be productive and useful, it is important and necessary to integrate multiple devices with functions of sensing, connectivity for sending and receiving, power, and perhaps data analytics and actuation. This is where heterogeneous integration technology brings the promise and power of IoT into service for humanity from enterprise, energy, manufacturing, transportation, health, agriculture, consumer and many other aspects of society.

Between 2018 and 2025, the GSMA IoT report [5] predicts the number of global IoT connections will triple to around 25 billion in 2025 compared to 9.1 billion in 2018, while global IoT revenue will quadruple to US$1.1 trillion in 2025, as shown in Figure 1. It indicates that there will be around 13 billion new IoT connections within these five years. The top three applications based on the number of connections can be ranked as connected industry (12.5Bn), smart home (5.4Bn), and consumer electronics (3.4Bn). It will continue to grow in the future in areas like smart cities, connected industry, connected vehicles, consumer electronics, and smart home. Three key application areas where forecasters expect a large IoT impact in the coming 10 years are digital manufacturing, smart mobility/transportation and smart medtech. These key areas are often mentioned: Industrial IoT (IIoT), Smart Cities, Healthcare, Connected Cars, and AI devices.

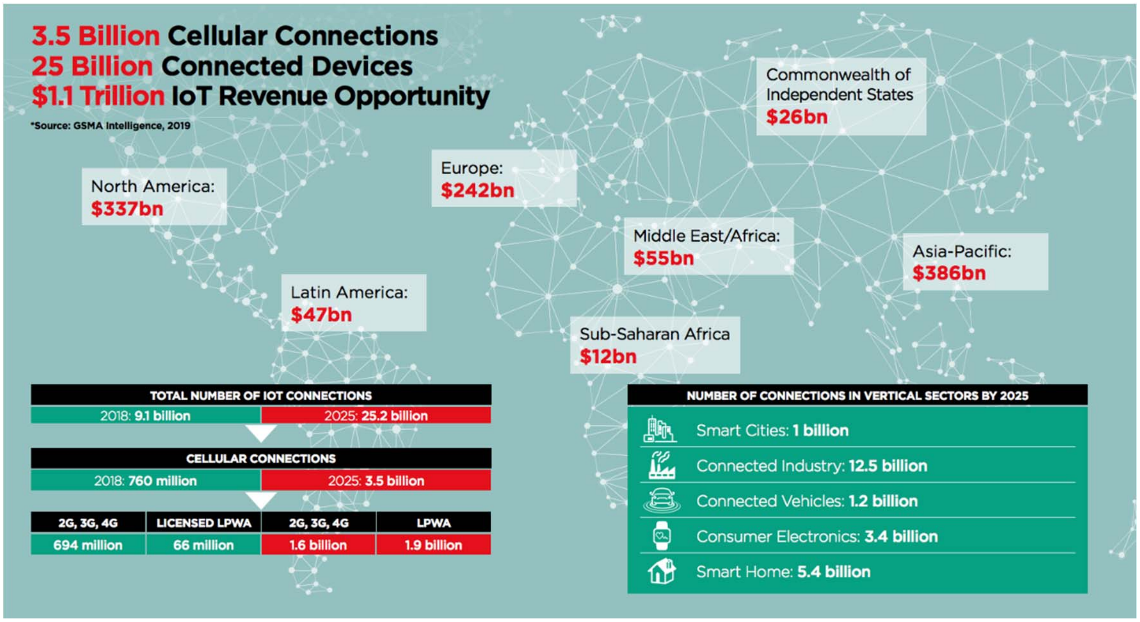


Figure 1. Internet of Things (IoT) by 2025 [5]

Another article, "Unlocking the potential of the internet of things" [Ref. 6], from McKinsey Global Institute, has a similar forecast for the applications potential and the same scale of revenue by 2025, as shown in Figure 2.

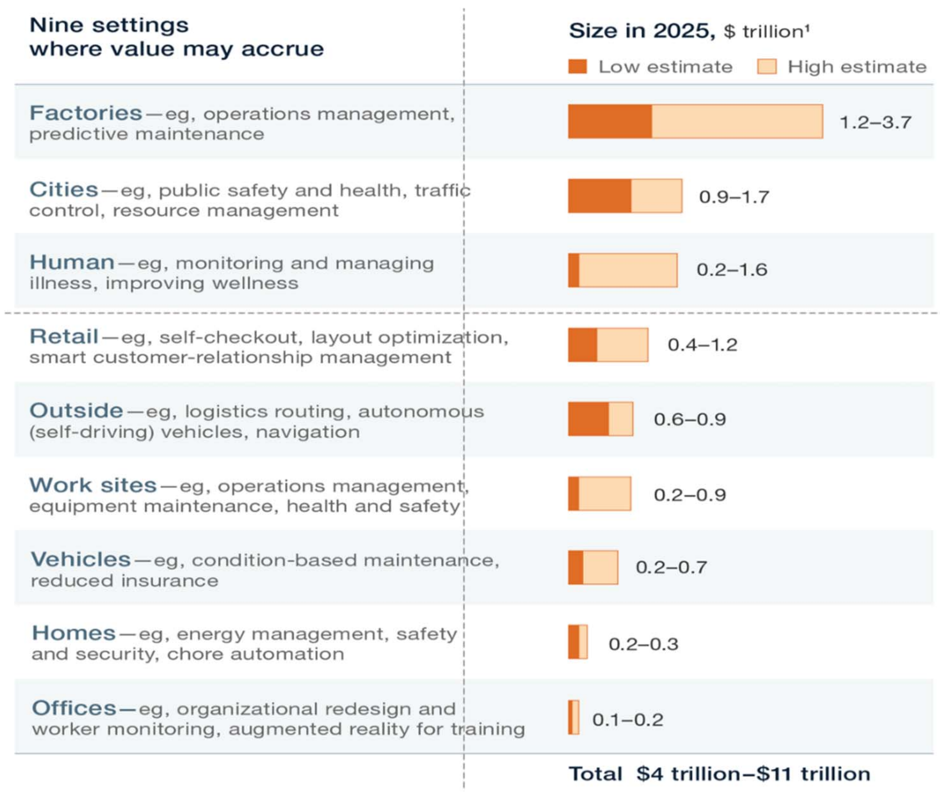


Figure 2. Internet of Things (IoT) by 2025, in US$ [6]

As the McKinsey report shows, the ranking of where value will be generated in the future highlights the importance of digital manufacturing, smart city, health, energy, and human applications. This heterogeneous integration roadmap chapter on IoT focuses on the high-value applications.

For the 5G IoT module and component market[7], Mckinsey expects total revenues for 5G IoT modules to increase from about $180 million in 2022 to almost $10 billion by 2030. During the first years of 5G, standard modules will probably be more popular than special-purpose and 5G Low-Power Wide-Area (LPWA) modules and thus generate the highest revenues. 5G LPWA modules should be the largest growth driver after 2025 and account for almost 30 percent of total 5G IoT module revenues in the B2B sector by 2030. As module sales increase, component providers will benefit. The greatest gains will go to providers of radio chips and application processors – the active components – with B2B revenues for this group expected to reach about $560 million by 2025 and $4.1 billion by 2030. Next in line should be providers of passive components, such as antennas; they will likely see revenues rise from $188 million to $1.3 billion over the same period. Providers of testing, assembly, and packaging should also see revenue increases.

Requirements from the Enterprise IoT sector including the Industrial Internet of Things (IIoT) have been one of the driving verticals for the design and development of new 5G concepts and technologies. The notion of ultra-reliable low-latency communications and massive machine-type communications are reflecting the primary communication types needed within the Enterprise IoT domains. In addition, we also see the emergence of fog and edge computing from the IIoT domain in the past few years, which also drives the architectural evolution of 5G infrastructures.[8]

2. Benefits of IoT

IoT concepts and related technologies are now proven and well understood. The focus now shifts from proof of concept to establishing proof of value (PoV) – either saving costs or increasing revenue. In 2020, more than ever, business and technology leaders need to view IoT as one of many tools in their toolbox and learn how to use it in conjunction with other equally important tools, such as analytics, to derive value from it.

Connected devices could account for as much as 3.5% of global energy consumption by 2027. However. IoT can also help make companies more energy-efficient. One example is Schneider Electric, which incorporated sensors into its Lexington manufacturing lines and reduced energy consumption by 12% as a result.

Typically, IoT devices send data to a cloud server where an algorithm analyzes it and triggers an action. 'Edge' technology, however, lets devices or nearby gateways compute and analyze data locally, with limited and sometimes no connection to the cloud. The industry has started talking about IoT at the edge and can expect to see fast growth in deployments of IoT edge tools.[9]

Energy harvesting (EH) technology allows small, standalone sensors to function continuously for extended periods of time – decades, even – without power-line connections or battery replacements. This technology greatly enhances the problem-solving capability of low-power sensors and its use is growing rapidly.[10]

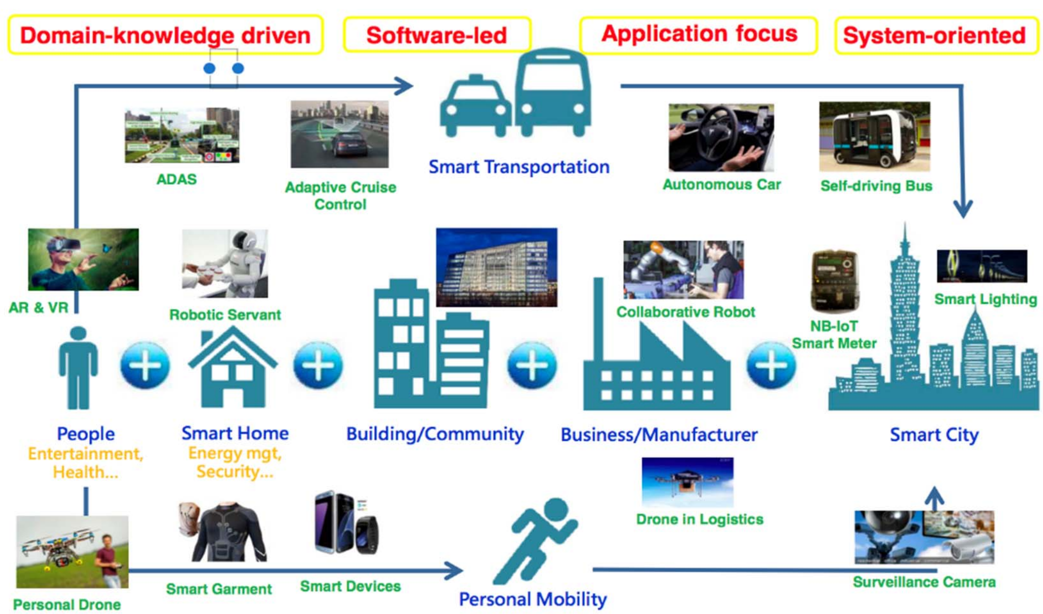


Figure 3. IoT endpoints and vertical-dependent use cases [11]

As shown in Figure 3, IoT endpoints and vertical-dependent use cases are categorized into different segments – people, smart home, smart building/community, business/manufacturer, and smart city. For many industrial IoT early adopters, the current and future generation of wireless communications technologies include Wi-Fi, 2G, 3G, 4G and even 5G. Industrial companies will choose the connectivity solution that delivers the features and performance that are required and at the lowest cost.

3. Challenges for IoT

5G is now upon us, bringing with it the promise of a host of exciting new services. As the boundaries between mobile and the wider digital ecosystem continue to blur, and as data monetization poses a continued challenge, many operators are moving beyond their traditional telco businesses to explore new opportunities in a fast-changing competitive landscape.[12] 5G and LTE will co-exist. The private LTE and 5G network market is expected to reach $4.7 billion in annual spending by the end of 2020, and $8 billion by 2023.[13] Three key developments may affect how the demand for connectivity and the buildout of new networks could reach equilibrium: continued growth in online video consumption; massive growth in machine-to-machine connections; and significant adoption of augmented and virtual reality.[14]

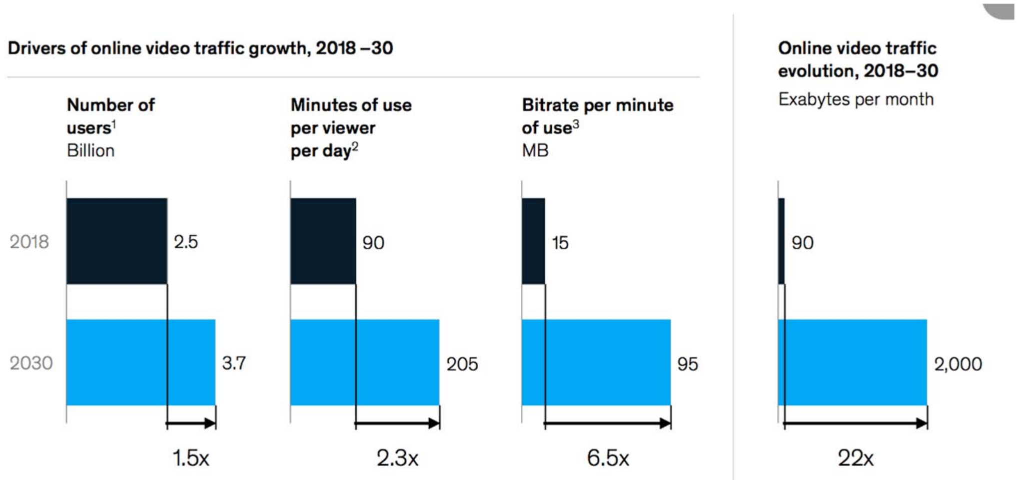


Figure 4 Drivers of online video traffic growth, 2018–2030 [14]

The first development would be a continuation of existing trends, with internet traffic from online video growing 22 times larger over the next decade (Figure 4). The majority of this stems from the transition from today's relatively low-resolution content (SD/HD) to higher-definition content. We also expect to see significant growth in the number of online viewers and more time spent viewing per user. New networks will have to accommodate rising demand for speed and capacity. Much of it will come from the same top 20 percent of power users who consume the majority of video content today; they are likely to be the early adopters of new connectivity technologies such as high-band 5G. New networks would be cheaper to operate due to higher spectrum efficiency – and crucially, they can accommodate a variety of services on the same infrastructure.

Frost & Sullivan's analysis, "Top End User Priorities in Digital Transformation, Global" [15] measures the current use and future decision-making behavior toward IT and communications, monitors the status of digital transformation (including the implementation plans for emerging technologies such as AI, IoT and blockchain), and evaluates drivers behind investments and challenges across verticals and regions. Key findings include: The retail (44%) and transportation (43%) sectors are ahead of others in their digital transformation. More than two-thirds of companies feel that the sales and marketing department will be the most impacted department by their digital transformation. Enhancing customer experience, digital presence, and sales and marketing effectiveness are the three major drivers for IT/telecom investment over the next two years. Improving operational efficiencies is a top priority in Asia-Pacific and Latin America, while upgrading customer experience and satisfaction is the most important corporate goal in North America and Europe for 2020. Cyber security is our greatest concern. [Further discussion on cyber security can be found in the Cyber Security chapter.] For 41% of companies, malware remains the greatest security threat, followed by security misconfiguration and hacking. Malware is common in both smartphone and desktop platforms. The Internet of Things is being used by 65% of companies. Almost 42% of organizations are developing IoT through a third-party service provider. Government is the predominant developer of IoT in-house. IT and communications, finance, banking, and insurance are the top industries implementing artificial intelligence. Cost of integration remains a major setback for the adoption of new digital technologies. The most common problems that companies face with IIoT solutions is cost.[16,17]

There are nine main security challenges for the future of the internet of things (IoT) which are: Outdated hardware and software; Use of weak and default credentials; Malware and ransomware; Predicting and preventing attacks;

Difficulty in finding whether a device is affected; Data protection and security challenges; Use of autonomous systems for data management; Home security; and lastly, Security of autonomous vehicles.[18]

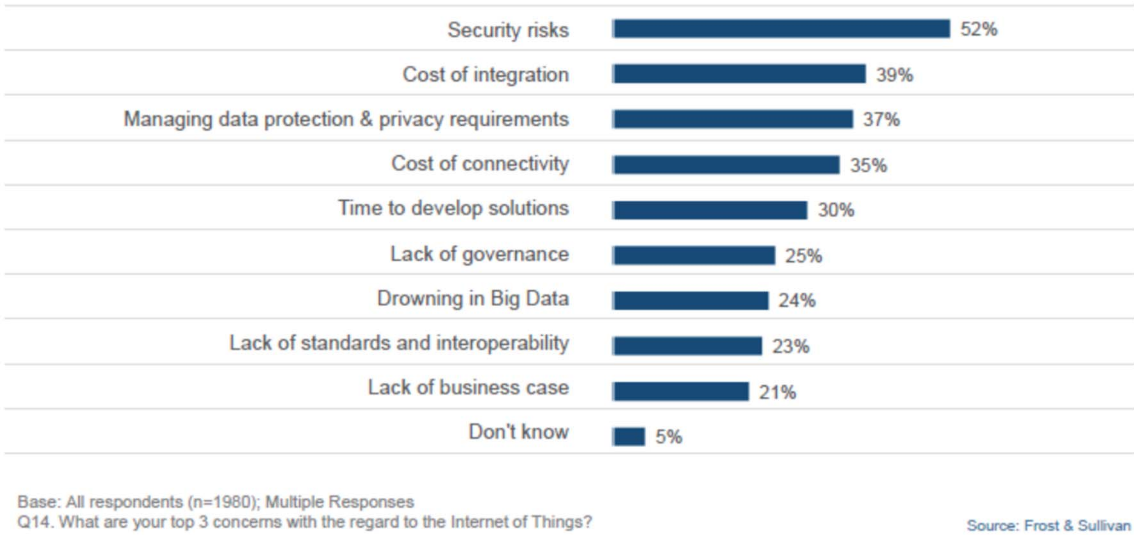


Figure 5. Top Concerns for IoT Deployment [15]

Top Challenges for IoT deployment are security risks, cost of integration and connectivity, data protection and privacy, and time to develop solutions. All the major challenges found by Frost & Sullivan are summarized in Figure 5.

- Gartner's 2016 IoT Backbone Survey [19] found that internally focused IoT projects, particularly those addressing operational efficiencies, topped the priority list for organizations.
- Leveraging thousands of sensors within the data center, collecting data such as temperatures, power, pump speeds, and using DeepMind reinforcement learning, reduced Google's data center cooling bill by 40%, improving computing power around 3.5 times, while using the same amount of power consumption.[20]

4. Difficult Technical issues

Based on the previous section on challenges of IoT, most of the approaches for different applications cannot be solved by the tranditional single packaging technology or regular SiP. Packaging solutions for IoT products need to include light weight, small form factor, low-profile, low power consumption, good electrical performance and low cost. Therefore, the approaches of integrated multiple chips through heterogenous integration technology will be the best candidate to meet the requirements of IoT. For a hardware heterogeneous integration solution, IoT can be realized through useful deployment of multiple approaches that cover the domains of hardware, software and extremely robust applications around various industries and operating sectors. This Section presents the technology areas enabling IoT and will identify the research and development challenges and outline a roadmap for future research activities to provide practical and reliable solutions.

Some of the key technology areas that will enable IoT are: identification technology, IoT architecture technology, communication technology, network technology, network discovery technology, software and algorithms, hardware technology, data and signal processing technology, discovery and search engine technology, relationship network management technology, power and energy storage technology, security and privacy technologies, and standardization. Some of these key technology enablers are discussed briefly in the following subsections.

Figure 6 shows sensing, connectivity, and data I/O with a basic description of key elements of IoT and relative device functions. To illustrate the major difficult challenges and technical issues, we selectively address connectivity, IoT home devices, wearables, sensors, and edge AI devices.

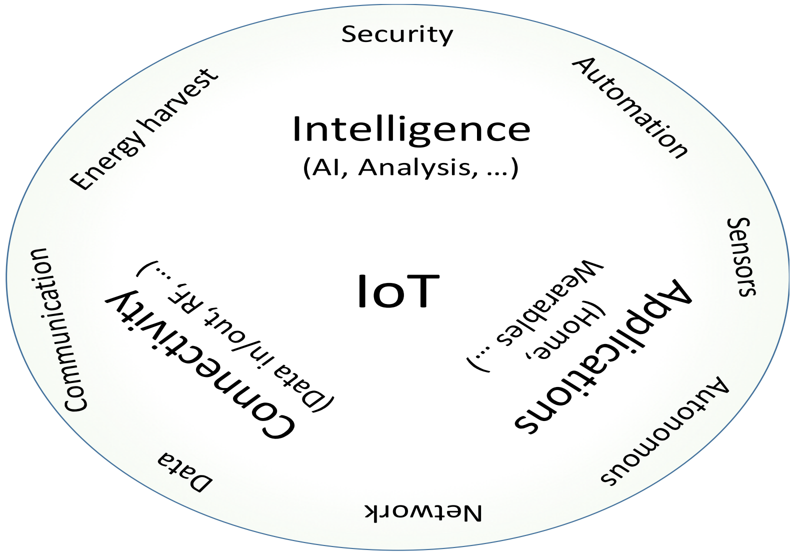


Figure 6. Key elements of IoT

Connectivity:

Limitations of the current Internet architecture in terms of mobility, availability, manageability and scalability are some of the major barriers to IoT. Particularly for upcoming 5G, there is a need to design beamforming antennas to send radio frequency (RF) signals to different network and client devices. In addition, suppression of electromagnetic interference (EMI) and prevention of noise from affecting different working functional areas are other considerations.[21] Addressing connectivity, there is a need to design beamforming antennas and for noise reduction. For additional details, refer to the RF/5G and Mobile chapters.

IoT home devices:

The demand for IoT devices (e.g., smart TVs, smart speakers, smart toys, and so on) has increased dramatically and keeps growing. The challenges for future IoT devices with even more functionality are the requirement for ever denser interconnects, a smaller package size, better electrical performance, and more cost-effective solutions.[23]

IoT and wearables:

To meet the increasing demand for IoT and wearables products, the challenges of heterogeneous integration are how to reach wafer-level system miniaturization with a smaller form factor, higher performance and increased functionality without compromising manufacturing cost.[24]

Sensors:

In the IoT era of smart manufacturing or of autonomous driving, highly integrated and low-cost sensor packaging solutions are required. The challenges of different sensors – including MEMS packaging, biosensor packaging, optical sensor packaging and RF/mmWave packaging – come from stress-sensitive and fragile membranes, the necessity for direct environmental access to this membrane, temperature-dependent monitoring, and other considerations.[25]

Edge AI devices:

In general, AI systems are running on high-performance graphics processing units (GPUs) using software-defined algorithms mostly in cloud environments. High power consumption is a major issue in such systems. However, intelligent and autonomous IoT systems can be realized by using edge-located AI processing power. Compared to high performance computing (HPC) applications, the computation within the IoT device is dramatically reduced when compared to on-board AI systems. A major challenge to implementing new autonomous IoT systems is how to develop low-cost and high-density packaging technologies through 3D stacking.[22]

As shown in Figure 3, with all those IoT devices and technology, considerable unstructured data will be generated all around us – data gathered from shopping online, interactions, study – all done through modern channels of communication such as social media. This data is unstructured and vague and provides very little information for analysis; it is necessary to have this data converted to structured data. The Artificial Intelligence of Things (AIoT) represents the use of Artificial Intelligence (AI) technologies within Internet of Things (IoT) infrastructure (platforms, servers, devices, chipsets, software, etc.) to improve IoT operations, improve human-machine interactions, and enhance data management, analytics and decision-making capabilities. One such AI technology, machine learning, provides IoT networks/systems with the ability to learn from data, transforming IoT-enabled assets into "learning machines". AI also transforms IoT data into useful information, facilitating improved decision making. Accordingly, AI is a foundation technology for moving towards IoT Data-as-a-Service (IoTDaaS).

The key is for the two technology sets (AI and IoT) to work together in a mutually beneficial, reciprocal value-added manner:[26]

- AI adds value to IoT – through machine learning and improved decision making
- IoT adds value to AI – through connectivity, signaling, and data exchange

This will require interoperability at the device level (such as chipsets), software level (operating systems and programs), and platform level. Since many early implementations of AI are rather monolithic and vertical-solution oriented, there will ultimately be a need for Application Programming Interfaces (API) to open up interoperability between devices, software, and platforms for more horizontal leveraging of Artificial Intelligence of Things capabilities.

Energy Harvesting

Today's state-of-the-art RF harvester typically requires a received energy of at least -30 dBm. More importantly, the desired application must be low power enough to operate with the harvested energy. Bluetooth Low Energy SoCs are being designed to operate with microwatt active power and microwatt-level average power in low-duty-cycle applications. Combined with an integrated RF energy harvester, this BLE SoC can create a full-function and yet battery-free Bluetooth solution. Potential applications can be grouped into three categories: proximity, table top, and room.[27]

5. Convergence of AI and Big Data with IoT

- IoT's missing driver is a killer application; AI's missing driver is data. They complement each other.
- Three phases of AI adoption for IoT projects: image/speech-related applications, transfer learning from these applications, and real digital transformation with machine learning and reinforcement learning.
- By 2022, more than 80% of enterprise IoT projects will have an AI component, vs fewer than 10% today.

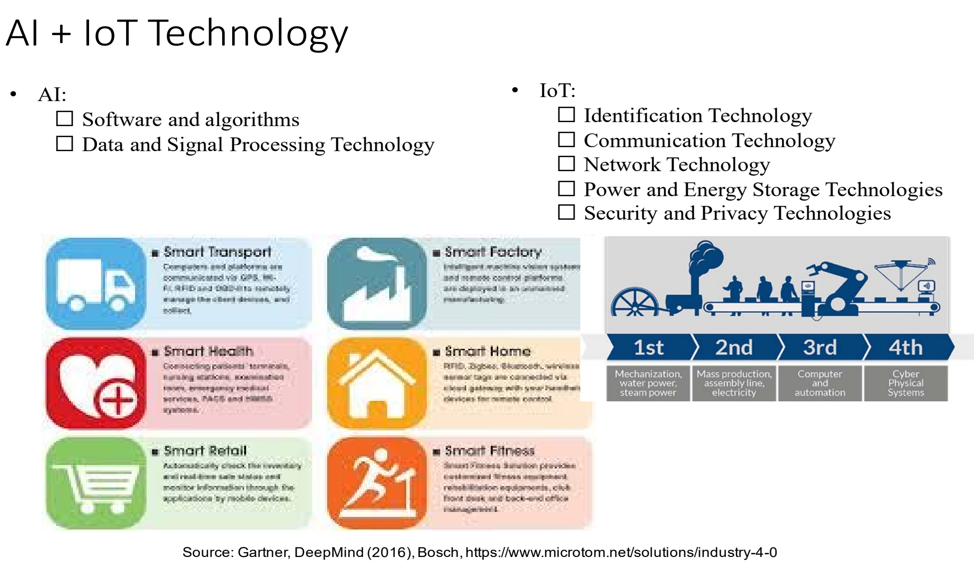


Figure 7. Key elements of AI & IoT Technology [28]

By adopting big data from inspection as an example within the enterprise IoT domain, defect detection is very critical for ensuring product quality and root cause analysis. With the widespread use of cameras and the availability of machine vision systems, automatic optical inspection (AOI) generates huge amounts of image data each day. Considering the cost consistency, accuracy and repeatability of the AOI system, this method has replaced most human inspection originally done by operators. Although the AOI system has become convenient and much more efficient than human inspection, the reality on the production line is that the false alarm rate of an AOI system is still too high because of the strict parameters set to avoid a high escape rate. Therefore, there are two to four verify-and-repair systems (VRSs) deployed after each AOI station to perform labor-intensive manual inspection. The solution for solving these kinds of production issues in daily manufacturing is to converge AI and IoT as an AIoT platform or so-called IoTDaaS (Figure 7).

Based on the convergence of big-image data with installed IoT sensors, a new AIoT system (auto-VRS) can integrate machine learning technology into an AOI system to filter AOI-reported defects from real defects, reducing AOI false alarms to 20%. It can also reduce VRS operator requirements. The new system mainly uses two technologies, namely a fast circuit comparison algorithm and deep learning-based defect classification algorithms. The fast circuit comparison algorithm is used to find the region of interest (ROI) of the AOI defect image, improve the accuracy of defect classification, and reduce the escape rate of real defects. Deep learning techniques classify defects to improve defect recognition and classification accuracy. The implementation of the proposed system is a software module, which can be easy deployed on a cloud server, AOI machine or VRS without any additional equipment.

As shown in Figure 8, the new AIoT system installed as one of the edge devices becomes a solution for the digital transformation of IIoT. With connectivity becoming increasingly commoditized, mobile operators are looking to expand their role in the value chain – from providing essential tools and capabilities for ecosystem partners to building IoT solutions, to becoming end-to-end IoT solution providers themselves.

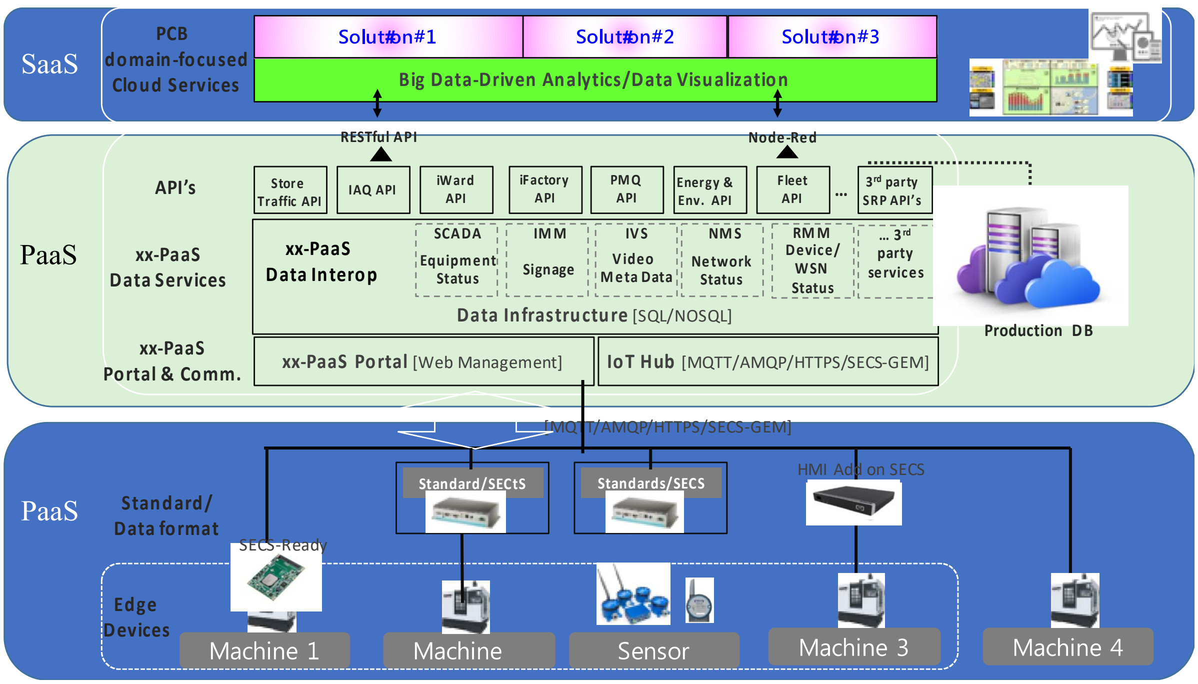
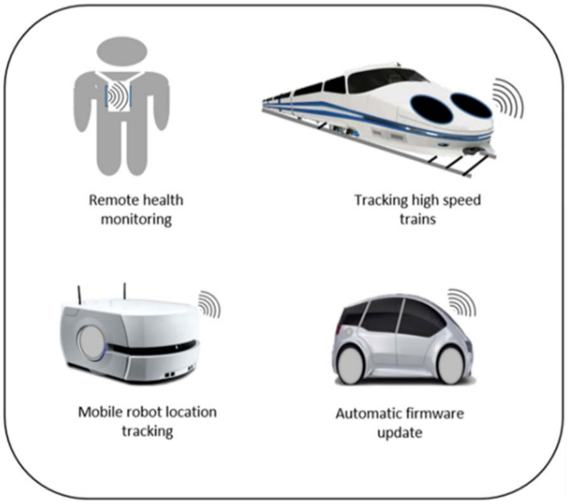


Figure 8. Digital Transformation of IIoT [29]

Many devices and machines used in diverse applications require ubiquitous connectivity to the Internet through a cellular network, as shown in Figure 9. These devices have different requirements in terms of their location, data rates, mobility, energy consumption, latency, complexity, power output level, spectrum, and security. These criteria impose specific requirements on the network infrastructure. While some Internet of Things enabling technologies exist today that may be able to address the wide area coverage requirement of the IoT devices, they fall short as compared to the 3rd Generation Partnership Project (3GPP) technology in terms of coverage, scalability, interoperability, Quality of Service (QoS), and security. 3GPP Release 13 introduced two categories of IoT technologies called LTE-M and narrow band IoT (NB-IoT). In LTE releases 14 and 15, the enhancements of LTE IoT continued to provide cellular IoT connectivity to more IoT devices and in more diverse applications. The evolution from Release 13 to 15 (a rich technology roadmap toward 5G) for multiple different use cases is shown below, and the technology requirements that need to be met for each specific application are listed.[30]



	Cat-M1 R13	Cat-M1 R14	LTE-M R15	Cat-NB1 R13	Cat-NB2 R14	NB IoT R15
Max DL BW (MHz)	1.4	1.4	5	0.2	0.2	0.2
Max UL BW (MHz)	1.4	1.4	5	0.2	0.2	0.2
Max DL TBS (b)	1000	2984	4008	680	2536	2536
Max DL Data rate (Mb/s)	<1	1	> 4	0.025	0.127	> 0.127
Max UL TBS (b)	1000	2984	4008	1000	2536	2536
Max UL Data rate (Mb/s)	<1	3	> 7	0.062	0.159	> 0.159
Max HARQ	8	8	10	1	1 or 2	2

Figure 9. Some IoT use cases achieved by LTE IoT enhancements. [30]

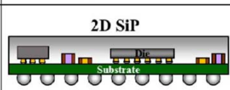
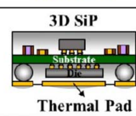
3GPP Release 16 (5G Phase 2) which was completed in June 2020 further focuses on industrial IoT, connected vehicles and expansion into unlicensed spectrum to broaden IoT capabilities, for example for private networks.[31] The proposed enhancements in Release 16 further increase the battery lifecycle, device density, and link budget.

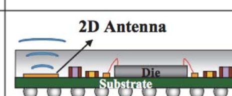
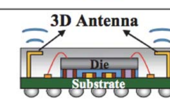
6. Examples of Heterogeneous Integration Solutions for IoT

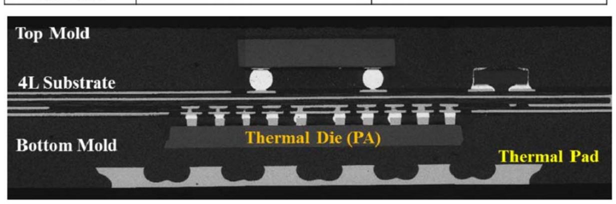
[Refer to other Roadmap chapters on 2D/3D, SiP, WLP, 5G, etc, for good examples of HI solutions for IoT.]

A. Connectivity

- A small form factor and high thermal performance are required for IoT and 5G [refer to the 5G/RF chapter] – see Figure 10.
- A 3D System-in-Package (3D SiP) including double-sided molding and antenna in package (AiP).

Item	2D SiP	3D Double Side SiP
Dimension	8 x 8mm	6 x 6mm
Package Structure		
Passive Component	Side by Side	Double Side Assembly
Thermal Solution	NA	Thermal Pad Design

Item	Traditional SiP	New TV SiP
Dimension (mm)	16 x 12	12 x 12
Package Structure		
Passive Component	Side by Side	Die Stacking on Passive
Antenna Integration	2D Antenna Structure	3D Antenna Structure



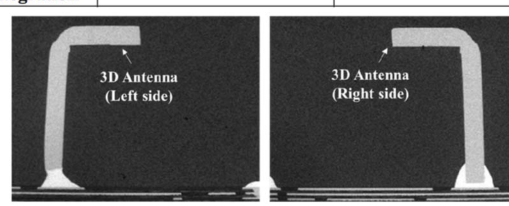
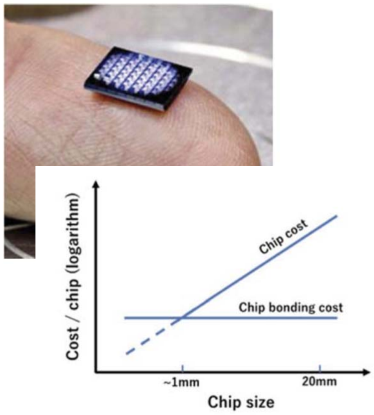


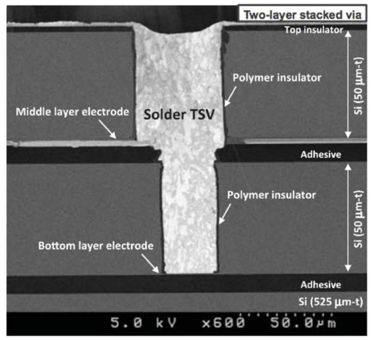
Figure 10. 3D System in Package (3D SiP) [32]

B. Autonomous IoT systems

More intelligent and autonomous IoT systems can be realized by equipping devices with AI, as shown in Figure 11.

- An ultra-small IoT system, which is smaller than a grain of salt and having low cost
- Future small IoT systems with AI devices comprising an intelligent sensor network, high density, and low-cost packaging technologies [refer to the SiP and Module chapter]





	ViaS	conventional TSV (via-Middle)
Wafer bonding	permanent	temporary
Wafer thinning	Yes	Yes
Lithography for TSV	Yes	Yes
Silicon deep etching	Yes	Yes
Liner deposition	VDP @RT (less expensive)	ALD or CVD (expensive)
Seed metal deposition	(under evaluation)	Yes (+ barrier layer)
Cu plating	No (alternative IMS)	Yes
CMP	No	Yes
Backside via opening	No	Yes
Backside bumping	No	Yes
Chip to Wafer bonding	No	Yes

Figure 11. Small IoT systems with AI devices [22]

C. Edge AI device

Fan-out (FO) packages are widely used in handheld, mobile consumer, and Internet of Things (IoT) devices due to the facility they provide for greater I/O density and the integration of multiple components in a single package, as shown in Figure 12.

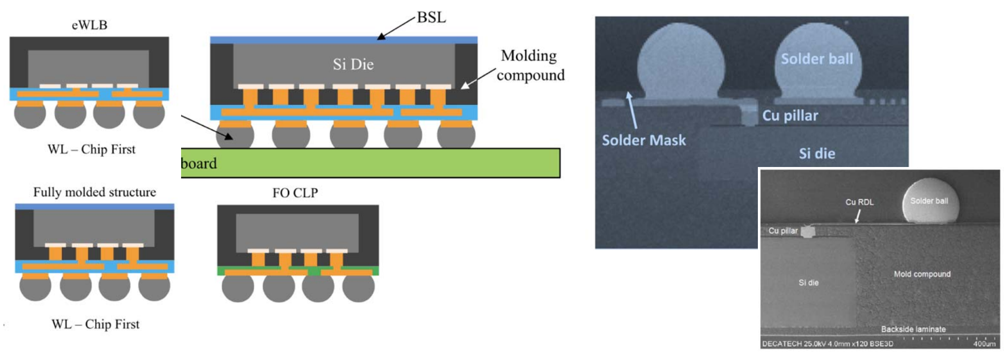


Figure 12. Fan-out (FO) packages [23]

[Note: Fan-Out packaging technology can also be applied to A. Connectivity and B. Autonomous IoT Systems, above, and E. Sensors, and is not limited to Section C. Edge AI Devices.]

D. IoT and Wearables

Common IoT packaging requirements include low cost, good power dissipation (low power for the silicon portion), and good RF shielding in packages that support multiple RF standards such as BTLE, Wi-Fi, or ZigBee [Refer to the Medical, Health and Wearables chapter]. Miniaturization will drive the need for packages that provide greater functionality in thinner and smaller spaces for both medical-grade and consumer-grade-based health monitors, as well as implantable and other medical devices, as shown in Figure 13. The adoption and continued innovation in flexible hybrid electronics (FHE) is expected to drive this industry in the years to come.

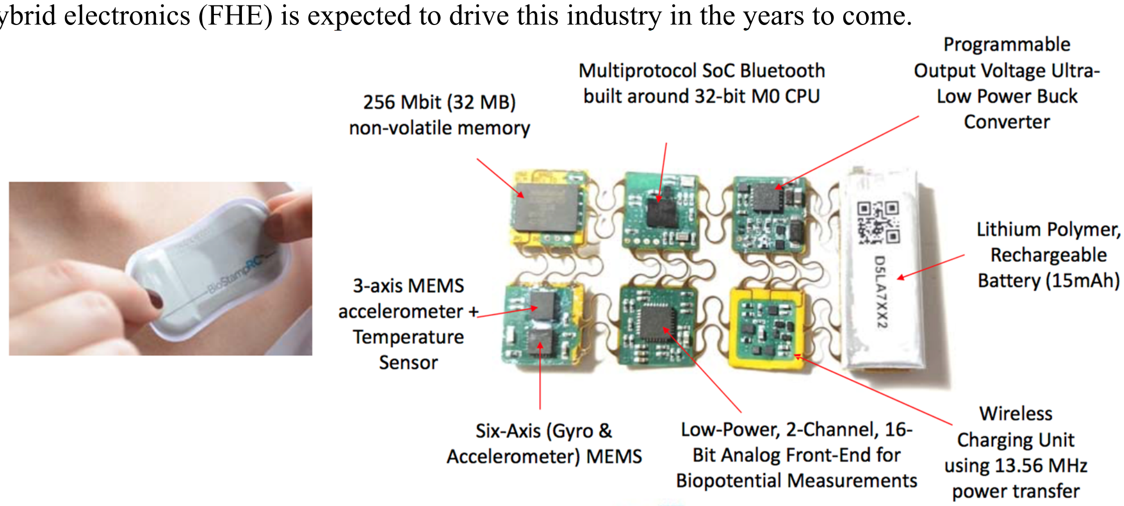


Figure 13. Wearable electronics [Refer to Wearables chapter]

IoT packages must also be production-ready, since waiting for a new custom package is often not an option due to time-to-market constraints. Finally, regardless of whether the solution is discrete or integrated, the footprint must be small. The integration SiP technology offers is especially valuable for products like wearables, smart lights, or smart home applications, where space and size are important. It illustrates several SiP design options that could include wafer-level packages, 2.5D or 3D structures, flip-chip, wire bonding, package-on-package, and more.[33] Cavity-based solutions are popular when sensors are involved, especially when there are stimulus delivery requirements such as portholes for microphones. A SiP can also include embedded passives, conformal shielding, filters, and an antenna. Insightful package integration can reduce the size of an IoT solution. Figure 14 shows a new sensor development kit which combines sensor technology and optimized power consumption to provide a ready-to-use prototyping platform for developing IoT applications with lasting battery life.[36]

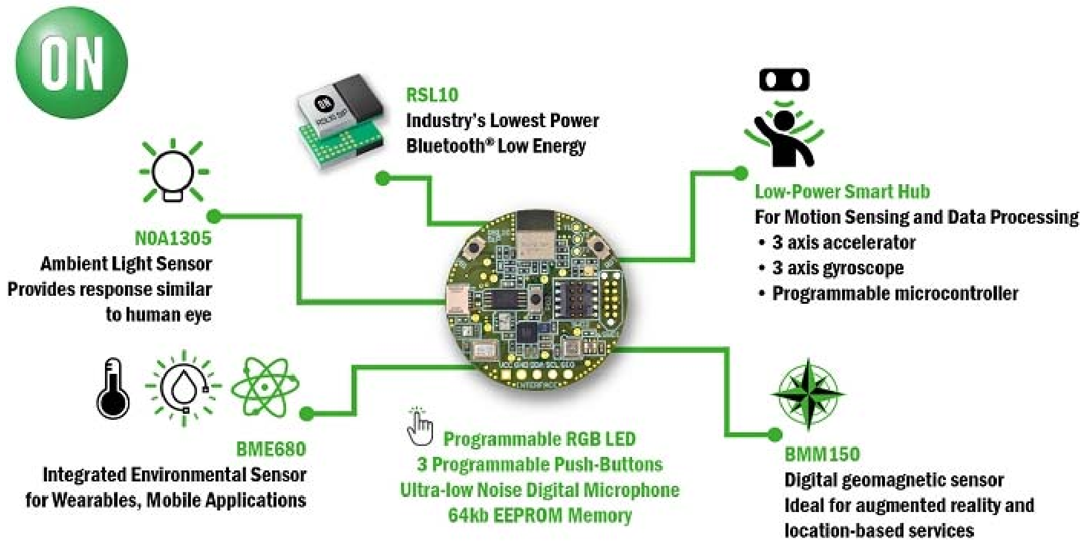


Figure 14. New Sensor Development Kit for Low Power Wearable IoT Applications [36]

E. Integrated Sensor Packaging

Highly integrated and low-cost sensor packaging solutions are required for smart manufacturing or for autonomous driving. Fan-out Wafer Level Packaging (FOWLP) is currently the hottest packaging trend in microelectronics for IoT applications, as shown in Figure 15.

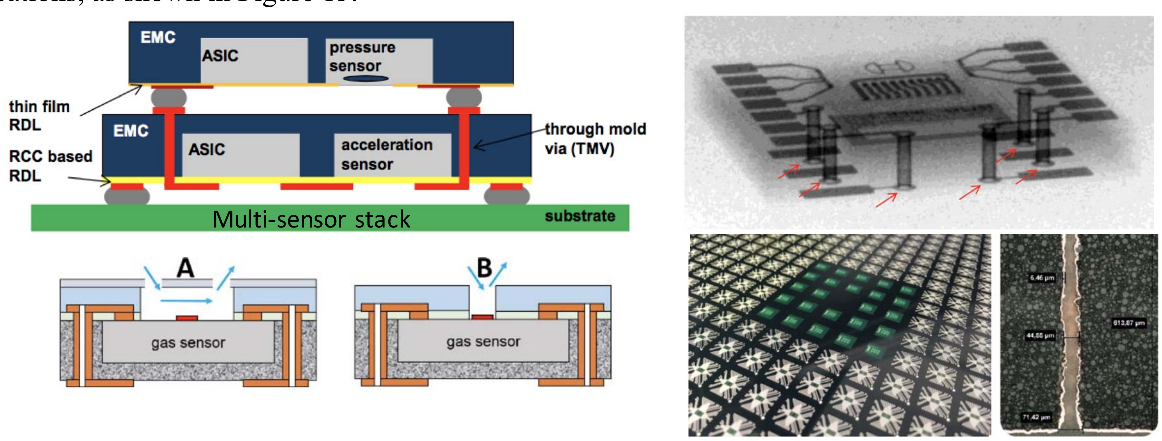


Figure 15. Fan-out Packaging (FO) [25]

F. Heterogeneous Integration of IoT Basic Elements

Figure 16 illustrates a highly integrated package for IoT applications. The same functions had a footprint of 10-mm^2 with discrete packages, but only 6-mm^2 is required with the integrated package solution – a reduction of 40%. Further space saving would be achieved by signal routing in the integrated solution.[6]

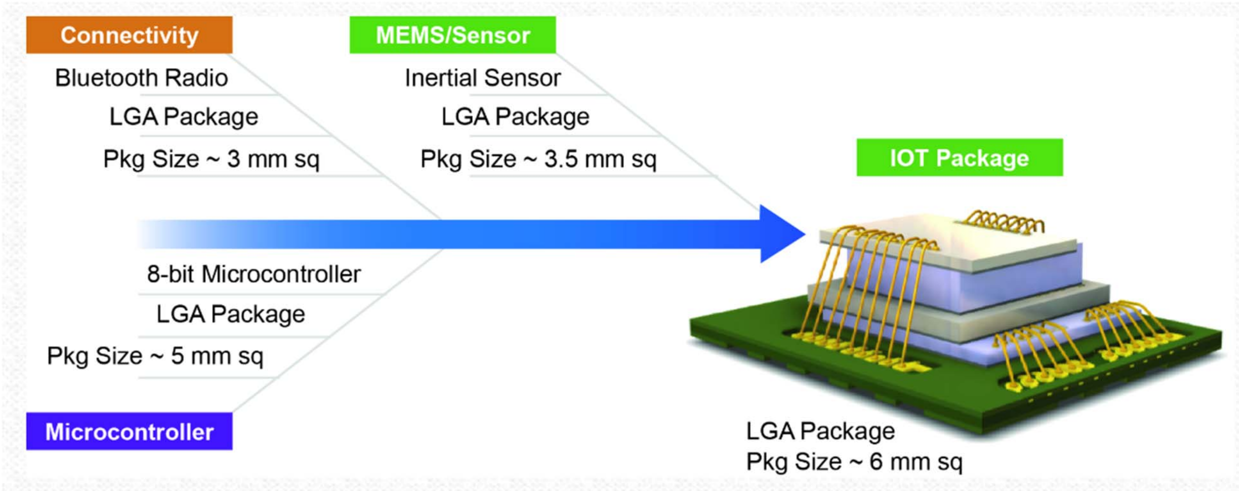


Figure 16. Heterogeneous Integration of IoT Basic Elements [33]

G. Heterogeneous Integration of Thin-Film Battery for IoT Microsystems

Demand for a micro-battery sized energy solution has been increasing rapidly because of emerging low-power microsystems for various Internet-of-Things applications.[34] Figure 17 illustrates an integrated process for IoT applications. The solid-state Thin-Film Battery (TFB) is a stacked structure, prepared by sequentially depositing thin films on the substrate and with a dielectric substrate on bottom and/or top. The thin films include current collector, cathode, electrolyte, anode and current collector. Precision trenches were etched by the programmable mask-less laser milling method around the TFB cells. Injection-molded-soldering was employed for overmolding to create a sealed TFB as small as 2.5mm x 2.5mm x 100µm.

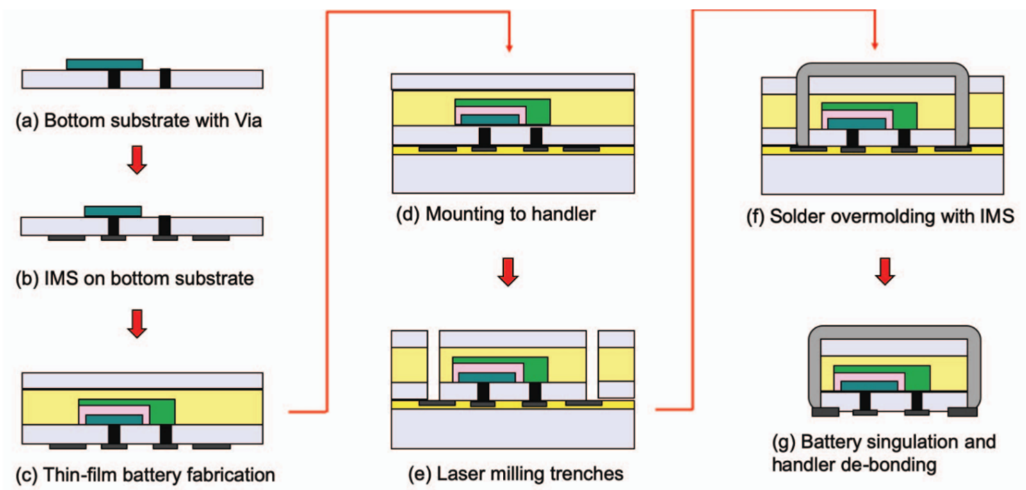


Figure 17. Process flow of the panel packaging approach for micro thin-film battery [34]

H. Heterogeneous Integration of Sensor Platform for IoT Medical Applications

The ability to rapidly detect multiple metabolites has the potential to reduce diagnosis time and cost. Figure 18 illustrates a system for IoT biomarker detection applications. Multi-sensor elements can be used to create a multimodal sensor on a single COMOS chip for use in biochemical assay by analyzing correlated data. The system enables chemiluminescence, colorimetric, SPR based and electrochemical measurements of the same analyte, all of which have been experimentally evaluated.[35] The system's ability to quantify urea, cholesterol and urate within the human physiological range can be successfully demonstrated.

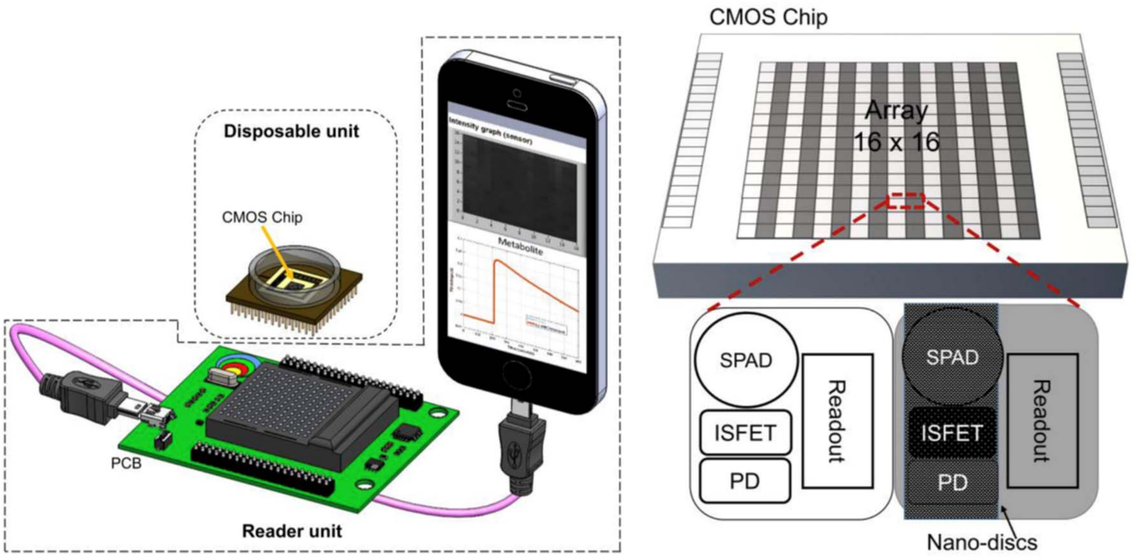


Figure 18. A system comprises a disposable cartridge containing the CMOS chip and a reader connected to a smart phone. Layout of the CMOS chip integrating 16x16 elements (SPAD, ISFET, PD). [35]

7. IoT Ecosystem[37] and Heterogeneous Integration Influence in HI Technology Development

Among the HI technologies, some of the latest make use of Wireless Sensor Networks (WSNs), which have been applied successfully to fields such as train monitoring [38], telemetry [39,40], Industry 4.0 [39,40,41,42] or public safety [43,44]. At this time, ZigBee is arguably the most popular technology for creating WSNs and it has been included in some of the latest commercial [45] and academic home automation developments.[46,47,48,49,50,51,52] Other researchers have also proposed home controllers and gateways for home automation systems that support only WiFi [52,54,55], only ZigBee [49] or both technologies [50,51,52]. Most of them [49,50,51,52] do not use open messaging systems but rather proprietary ad hoc protocols, while some of the latest use MQTT [56,57] or Extensible Messaging and Presence Protocol (XMPP) [53].

IoT has becoming an application-oriented platform which includes a multi-layer architecture: eg. cloud, network, and end-device. It requires a combination of various transmission technologies and network infrastructure to apply these technologies to achieve various scenarios in different application domains. Driven by declines in cost and the popularity of smart phones, the IoT platform and ecosystem have gradually formed. Based on booming cloud technology, IoT is enabling the development of wireless communication technologies, low-power computing technology (eg. low power MCUs), diversified sensor technology, and low-power management chips and memory.

In general, IoT devices require multi-function processing and low power consumption to extend standby time. To distinguish according to function, semiconductor devices for IoT devices can be categorized into five functional blocks, namely MCU, Sensor, PMIC (Power Management IC), Memory, and Connectivity. Each of these five functional blocks corresponds to the required wafer-level integration process technology. In terms of processor and memory, wafer level packaging (WLP) can be a good candidate to meet the requirement of low power consumption and small form factor. The newly developed Fan-Out WLP can further achieve a thinner structure by eliminating the organic substrate, and can lower the cost by adopting integrated molding process. System-in-package (SiP) and Fan-Out WLP can also be stacked in PoP (Package-on-Package) format, the most popular packaging solution for area-saving integration in mobile devices. Since the memory is stacked on top of the processor, lower power consumption (shorter paths) and higher transmission speed (better SI and PI) can be achieved. Another alternative technology to shorten the transmission path is 3D-IC and TSV technology; it can connect the stacked ICs with the shortest path, thereby achieving vertical integration of the stacked chips and meeting the industry's high-frequency requirements. Due to cost limits, it is mainly used for high-end memory (high-bandwidth Memory, HBM) and stacked image sensor module applications.

In terms of the low power requirements of connectivity and PMIC, which have lower pin counts, chip embedded technology can be effectively applied for integrating passive components and the PMIC into an organic carrier/substrate. The remaining area on the top or bottom surface of the carrier/substrate is designed for other chips or passive components with different functions, to form an embedded SiP module. Finally, in terms of sensors, there are many needed to monitor external environmental conditions in smart manufacturing, smart city and smart life applications. Wafer level packaging is very suitable for MEMS and sensors driven by strong demands from IoT applications.

A. Example of Regional IoT Development in Taiwan

Taiwan is planning to build an innovative ecological environment through rapid economic development, which can make Taiwan a new base for global networks, big data, and Internet of Things. Taiwan's Internet of Things promotion program has established seven major alliances, including: Taiwan Internet of Things Alliance; Asia IoT Alliance; IoT by GT Alliance; Taiwan Wisdom Taiwan Smart City Solution Alliance; Cloud Computing and IoT Association in Taiwan; IoT Intelligent Sensing Industry Alliance; Taiwan Internet of Things Industry Technology Association; and IoT Technology and Industry Association.

Taiwan's Internet of Things market is divided into nine major categories:

- smart transportation
- smart logistics
- smart manufacturing
- smart energy efficiency
- environmental monitoring
- smart business
- smart home
- smart agriculture
- smart healthcare

Known as the semiconductor Silicon Island, Taiwan is becoming a trial field for a variety IoT applications. Taiwan's IoT economic opportunity is set to increase global market share from 3.8% in 2015 to 4.2% in 2020, and to 5% in 2025. At the end of 2018, the value of Taiwan's IoT grew by 19% to US$39.1 billion, accounting for 4.24% of the global Internet of Things (Figure 19).

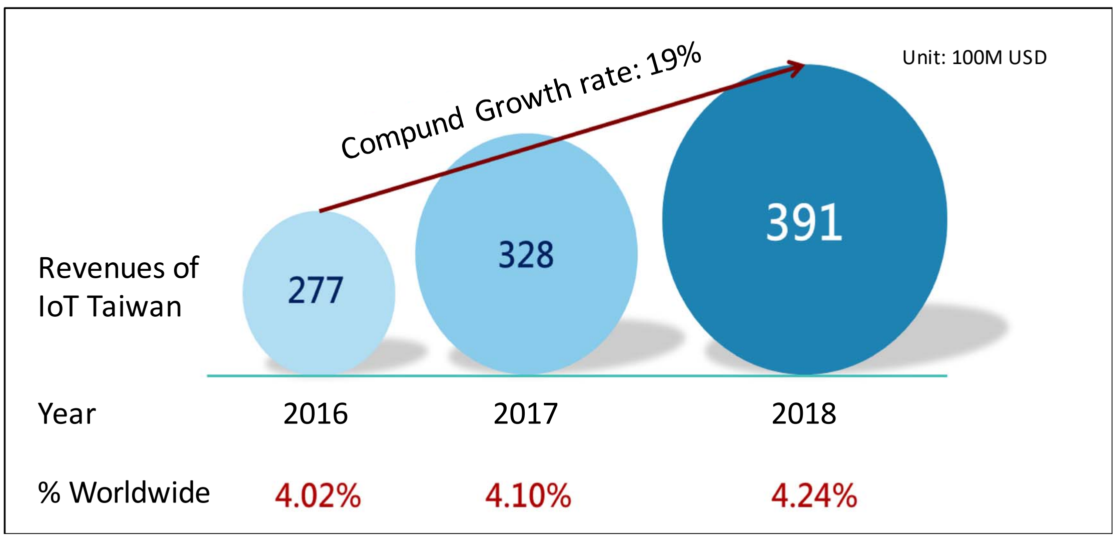


Figure 19. Taiwan's Internet of Things market, Source: ISTI of ITRI (2019)

A pioneer in healthcare cloud-computing technology[58] can be used for patient monitoring that precisely records the physiological data of patients so as to optimize healthcare services. The company's multifunctional cloud patient monitoring system is a health information system (HIS) solution for hospitals and clinics, designed to measure and automatically upload the physiological data of patients, such as blood pressure, oxygen saturation, pulse, respiration, and body temperature, to designated databases at hospitals or clinics. This saves handwriting time, upgrades the quality of medical care, enhances work efficiency, and lowers associated expenditures. This innovative blood pressure monitoring system has proven to be as precise as mercury sphygmomanometer and is well recognized by major hospitals in Taiwan.

The system is also expandable to include "remote healthcare" programs to allow patients to input and upload data collected at home to the medical record databases at hospitals or clinics for professional diagnosis and regular observation. Figure 20 shows its application to heartbeat frequency, heart valve status, and coronary artery analysis for warning of myocardial infarction and heart conditions.

Anti-bacteria cuff	Anti-bacteria cuff to prevent from inter-infection.
Heart Spectrum function	With the patented Cardio Spectrum functions, it's able to present the irregular heartbeat noise.
Tube length	Standard 1.8m/3.6m ; max. can extent to 50m (for Tomography)
First aid use	Water resistant design on 5 sides , it's able to use on outdoor
Sterilization operation	With infection control protection, allow 0.6% bleach and 75% alcohol disinfection
Military Spec.	Blood press measurement 0~305mmHg, Pulse 20~240/minute
Auto-calibration patent	The sphygmomanometer can detect itself accuracy Built-in-test system BIT and auto-test function
Low temperature operation	Celsius -20℃ is normal use (Tibetan hospital using), Celsius +50℃ is normal use
Alpine use	High altitude of 4,500 meters normal use, auto-correction technology (Tibetan hospital using)
Transmission function	Can transfer the measurement information to the iCloud server through a variety of ways, integrated care system with electronic medical records

Figure 20. Heart monitor function of AIoT remote healthcare system [58]

B. Smart IoT Chip and Design Platform Solution

The future Intelligent Internet of Things (AIoT) is expected to dramatically change lives and work, enabling people in this ecosystem to connect to each other easily and to use information more quickly, intelligently and efficiently. The three most important benefits of using AIoT are improving operational efficiency, increasing annual compensation, and improving quality performance.

For example, smart phones and smart speakers, which have been popular in the past two years, include Apple, Xiaomi, Amazon and Google, all of which have launched related products. The market response is also very enthusiastic, and related applications have formed an ecosystem.

Among smart IoT devices, the products with large output value or rapid growth are smart TVs, automatic driving assistance systems (ADAS), intelligent security monitors, smart watches and smart speakers. The output value in 2023 is expected to reach US$3,446 million, $2,802 million, $2,705 million, $1,964 million and $850 million, respectively. The compound annual growth rates from 2018 to 2023 were 7%, 199%, 62%, 16% and 44% respectively.

C. IoT application Platform

AIoT platform I: for smart home, smart city and smart factory:[59]

AP chip solutions with high-speed AI edge computing capability will help accelerate the development of the IoT industry chain, providing solutions for smart home, smart city and smart factory, assisting artificial intelligence technology and the Internet of Things. The platform's powerful AI recognition capabilities will provide technical support for face-identification and payment for unstaffed stores, as well as face access for smart buildings and company attendance systems. In smart factories, it can assist unstaffed vans to automatically identify obstacles to avoid accidents. In sports and fitness applications, through the 3D human body posture recognition function on the platform, not only can it provide the user correction suggestions for fitness posture, but also can automatically detect dangerous postures in life and work, so as to issue early warnings.

AIoT platform II: for smart home

Standard ARM-core MCUs, plus power-saving 802.11b/g/n Wi-Fi, are suitable for use in a variety of IoT products, such as smart sockets, smart appliances, low power consumption wireless cameras, home security, and environmental sensing devices. These are particularly suitable for battery-powered products because of their low power consumption.

AIoT platform III: for COVID-19 [60]

Taiwan established its National Health Insurance system in 1995, and uses a reimbursement system to guide and prioritize the nation's healthcare organizations. There are two forms of information technology to be used for pandemic preparedness and control. The first is the NHI Smart Card that allows all providers real-time access to upload patient records and claims. The other is the MediCloud system, developed in 2018, that provides providers and patients real-time access to health records, including diagnostic imaging and prescriptions. This allows providers to obtain patients' travel history, occupation, contact history, and clustering at mass gatherings in real-time, enabling efficient triage and rapid and accurate diagnoses while keeping them safe. Another IoT technology for Taiwan's contact-tracing and quarantine monitoring is a GPS-based information system called Intelligent Electronic Fences System (IEFS). It is a collaboration between the Central Epidemic Command Center and mobile phone carriers that was developed in early February 2020. Based on an individual's mobile phone signals and nearby cell towers, it triangulates the location of quarantined individuals. It monitors the nation's entire quarantined population and any potential people that they may come into contact with. Thanks to effective epidemic control measures, Taiwan maintains relative normalcy during the pandemic.

D. IoT and Agriculture

Agriculture, one of the oldest endeavors of mankind, represents a major opportunity for AIoT in this ancient industry, including cultivating and havesting living plants, raising animal live stock, and aquaculture. With AIoT incorporating data, AI and ML, there is great opportunity to bring about a widely adopted data-base and AI knowledge based IoT-driven agricultural revolution.

Figure 21. Illustration of IoT and Agriculture. Source: IEEE Internet of Things Magazine December 2019 cover page

In a special issue of IEEE Internet of Things Magazine, guest editor Raffaele Giafreda has selected specific papers from around the globe illustrating the high complexity, difficult challenges, and need for research and innovations, and the great opportunities for benefit across the whole agriculture ecosystem in this time of climate change and global sustainability issues. He said "IoT technology has a huge role to play in such a landscape, as it can provide an unprecedented source of monitoring data at a very detailed granularity level; with this huge amount of data comes the ability to interpret it for a meaningful and business-viable purpose." The article "Energy Neutral Machine Learning based IoT Device for Pest Detection in Precision Agriculture" by D. Brunelli et al, points to a need for LPWANs (Low Power Wide Area Network technologies) to cover large rural areas as opposed to Smart Cities. One example of "edge computing" is an affordable way to monitor for pests (such as the codling moth) occurring in apple orchards and send a signal on the network only when the moth image is recognized and verified. In another article, "Precision Aquaculture," F. O'Donncha and J Grant described data acquisition from sensors deployed in ocean waters and the atmosphere. The hundreds of interconnected sensors then store and serve data, interact with other sensors and devices, and connect with a fog and cloud ecosystem. Mathematical models enable the implementation of a precision aquaculture concept to provide data-driven insight and decisions that promote ecologically sustainable intensification of aquaculture. These two examples demonstrate the vast breadth for IoT application innovation and fascinating variety of application platforms.[61,62,63,64]

8. The future of IoT

Three major categories including security and privacy, data format, and sensing are addressed here for researchers approaching the challenges for the future needs of IoT.

Security and Privacy: how to make an effective and cheap security and privacy solution for IoT

Identification is the first step for security. The vast majority of traditional security controls and discovery tools don't yet exist for IoT devices. Although well-established identification for desktops, laptops and servers exists, the same concept hasn't been applied to IoT. Although an IP address can be applied to an IoT device, it doesn't show what the device is, where it sits, what it's connected to, whether controls are running on it, and if there are any vulnerabilities.

Secondly, an IoT device can also act as a gateway to access internal and previously segregated networks. This lack of visibility results in security teams being completely unaware of the risks they pose and where they have vulnerabilities that can be exploited by hackers. There is also the threat of physical damage, which has gone unaddressed. This may not be a problem in a factory setting, but a medical diagnostic device in a hospital that isn't working correctly could result in a loss of life. Thirdly, security hasn't been incorporated during the design phase. There have been some recent advances in standards, with the passing of a law in the UK which states that all consumer smart devices sold in the UK should adhere to the three basic security requirements for IoT, but we are still very much in the infancy of IoT security. Finally, many IoT devices have not even been configured to receive or run software updates, and some devices are running on battery so they don't have the resources to run security controls.

One focus for future research should be to assure that every IoT device is counted and evaluated, hardware is protected, and there are continual software updates.

Data format: data integration

All the sensing behaviors, including the variety of different applications, data sources, exchange formats, and transport protocols require a high level of flexibility and scalability.[64] IoT devices need to exchange data with each other and with other users on the Internet. Semantic annotation of the data can provide machine-interpretable descriptions about what the data represents, where it originates, how it can be related to its surroundings, who is providing it, and what are the quality, technical, and non-technical attributes. IoT data usually originates from a device or a human, and refers to attributes of a phenomenon or an entity in the physical world. The data can be combined with other data to create different abstractions of the environment, or it can be integrated into the data processing chain in an existing application to support context and situation awareness. Besides data integration, a number of semantic approaches remain to be taken into account.

Newer and more sophisticated methods for data integration and aggregation are required to enhance the value of real-time and historical IoT data. The pervasive nature of IoT data presents a number of privacy threats because of intermediate data processing steps, including data acquisition, data aggregation, fusion and integration. How to deal with data in IoT applications is an important topic for addressing different systems on sharing and integrating data and information. The privacy threat of information linkage and how to address it by technical and legal approaches in a heterogeneous IoT ecosystem is another research interest.

Sensing: autonomous and sensor fusion

The threat of widespread diseases and viral pandemics is likely in our future. Applying IoT technology to reduce or isolate the contact between a contagious virus and people during the diagnosis, analysis/measurement, treatment and recovery through M2M (machine to machine) interactions is a key approach in the research of IoT sensing. In terms of sensing, more unique functions of sensors should be developed to strengthen or improve the five human senses: vision, hearing, smell, taste and touch. For example, next-generation artificial tiny nose systems or cubic smelling gadgets can, in real-time, analyze chemicals, foods, or even diseases. Beyond mimicking the mammalian system, future artificial noses may not only combine cross-reactive sensor arrays with pattern recognition algorithms to create robust odor-discrimination systems, but also interact and communicate with other sensors directly. This may result in autonomous IoT sensing systems.

9. Summary

In summary, IoT is the key to digital transformation. IoT technology starts with connectivity, but it is in digitization that applications get interesting. All companies, big and small, can transform into digital companies by using an IoT platform able to digitize their physical products. IoT will combine AI technology into AIoT which represents the use of Artificial Intelligence (AI) technologies within Internet of Things (IoT) infrastructure (platforms, servers, devices, chipsets, software, etc.) and big data to improve IoT operations, improve human-machine interactions, and enhance data management, analytics and decision-making capabilities.

Consumers, anticipating an IoT experience that is omnipresent, seamless and personalized by 2030, expect to see this everywhere in their lives, with a wide array of use cases at home, at work, outside, for healthcare, automotive services and commercial drones. However, trust remains a key hurdle to overcome if consumers are to be completely accepting of these new and emerging technologies and as such, most are willing to pay for guaranteed security. Heterogeneous integration should play an important role as enabler in enabling IoT devices and systems implementation to fulfill the above mentioned challenges and hurdles.

10. Key Contributors

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