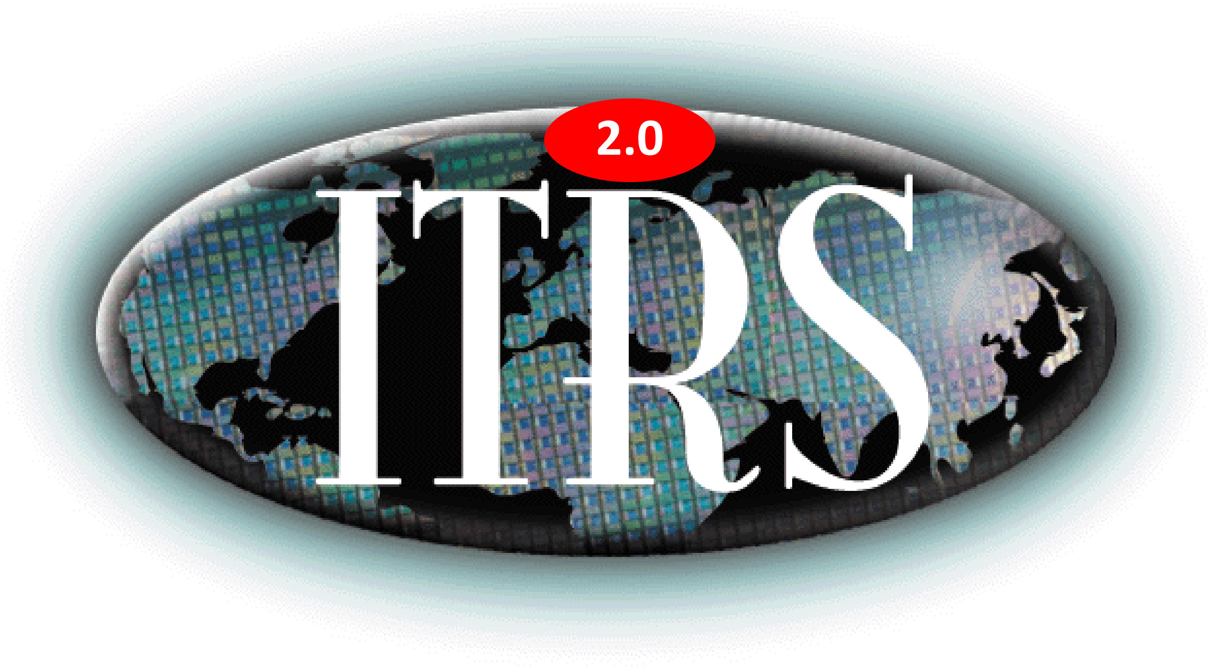

INTERNATIONAL
TECHNOLOGY ROADMAP
FOR
SEMICONDUCTORS 2.0

2015 EDITION

HETEROGENEOUS COMPONENTS

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EXECUTIVE SUMMARY

Heterogeneous Components are electronic devices that are manufactured using micro and nano-fabrication technologies and assembled together into the heterogeneous systems. This chapter of the ITRS2.0 roadmap marks the beginning of our effort to evolve what was formerly the MEMS Chapter of the ITRS Roadmap to address the expanded range of applications of the ITRS2.0 Roadmap. This transition comes as an opportune time, when the MEMS and Sensors Industry Group has joined with the TSensors Initiative to co-organize TSensors Summits. The TSensors Summits, combined with their planned foresight documents, provides an insight into emerging applications driven by health, agriculture, smart global infrastructure, clean environment and clean energy. These emerging applications will define the future requirements for heterogeneous components and their performance specifications. Using these requirements and performance specifications, the Heterogeneous Components Focus Team determines the gaps in the current manufacturing technologies that must be addressed in order to meet those future requirements. This paradigm for roadmapping is what distinguishes the ITRS roadmaps from other industrial roadmaps. Transitioning to ITRS2.0 marks a new journey into developing such a roadmap with no classical Moore’s type law to drive the roadmapping process.

In this first edition of the ITRS2.0 Heterogeneous Components, we continue our discussion on the needs for devices testing and standards. As devices increase in functionality and performance the trend for the cost of device testing should continue to rise yet system integrators expect the prices of heterogeneous components to stay constant or lower. This is opposite to what would be expected since adding more functions and increasing performance should require additional and higher accuracy testing. Standard testing protocols are also needed for defining performance parameters published in manufacturer’s device datasheets. The current ***lack of standardization*** results in the inability of the systems integrator to compare the cost and performance tradeoffs between the manufacturers. The MEMS and Sensors Industry Group is responding to this needs by establishing a ***Standards Division*** that is developing device parameter performance terminologies and device performance testing protocols. The industry group is also developing new standards for device communications by extending the current I2C communications protocols.

As the volume of manufacturing continues to increase, there is a growing interest by members of the industry group to define standard manufacturing process modules. Doing this has the potential to speed up the commercialization of new device technologies while also lowering their manufacturing cost. This discussion has been referred to within the industry group as a paradigm for the “standard drill bit” of a traditional machine shop. Furthermore, discussions coming out from the TSensors Summits show that in order to meet the production volume and cost requirements for reaching an era of Trillions of Sensors manufactured every year will drive the development of large area electronics that could be based on roll-to-roll printing technologies.

Finally, a bottleneck could develop as we move towards the vision of the trillions of sensors that will be used in the era of Internet of Things, IoT, using current wireless communications protocols and sensor data management. While the required number of internet addresses with IPV6 is more than adequate to address the trillions of sensors envisioned by IoT, it’s bright future is shadowed by an inevitable shortage of wireless bandwidth to support the connection of this vast sea of sensors unless a more efficient means for handling that large volume of potential real time data advanced.

1. MISSION

Heterogeneous Components identifies trends in high-market-growth-potential applications, determines the device performance requirements that are needed to enable those applications, and uses this information to discover technology gaps that must be solved in order to produce the future products that are envisioned by the roadmap. This roadmap is produced in collaboration with the MEMS and Sensors Industry Group [[1]], iNEMI [[2]], and the TSensors Initiative [[3]].

2. SCOPE

Heterogeneous Components are devices that do not necessarily scale according to “Moore's Law,” and provide additional functionalities such as sensing and actuating, communications, and power generation and management. Figure 1 below shows a diagram of Heterogeneous Components in a Heterogeneous System. A Heterogeneous Component, for example, could be an accelerometer. A Heterogeneous System, for example, could be a smart phone containing many Heterogeneous Components that must be assembled and packaged together.

The major challenge in developing a Heterogeneous Components Roadmap is that they could potentially include anything that might be assembled and packaged in future electronic products. There could also be many device technologies and designs that might fall under the definition of a single Heterogeneous Component. Micro-device technologies such as Microelectromechanical Systems (MEMS) could be based on surface micromachined or bulk micromachined manufacturing processes, their operation might be based on capacitive, piezoelectric, or thermal conductance effects, and they might be offered as discrete devices or as co-integrated or monolithically integrated with electronics.

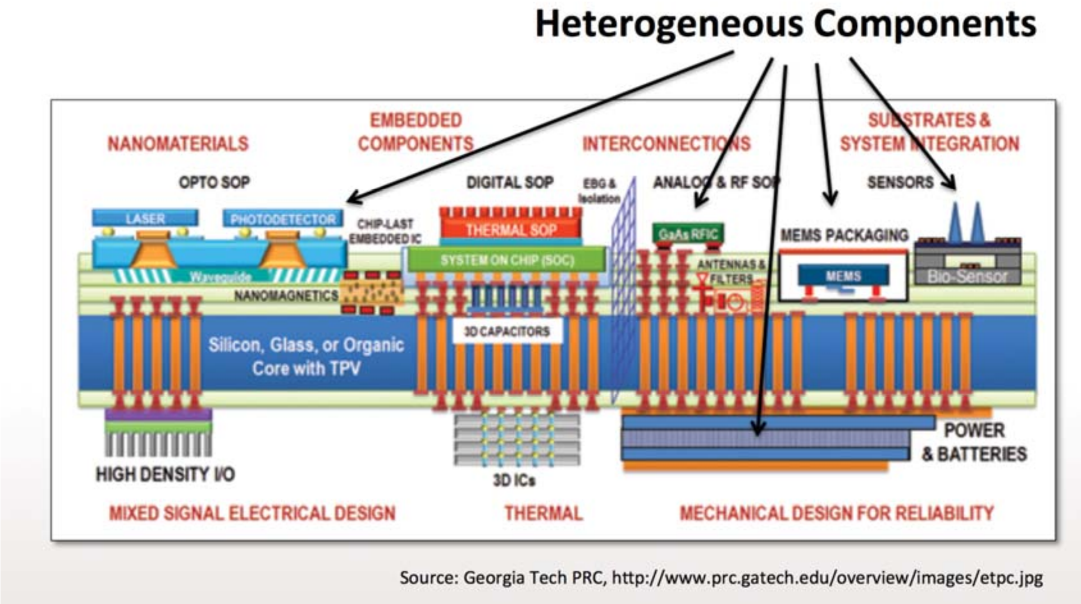
The challenge of roadmapping the virtually infinite diversity of Heterogeneous Components is further compounded because each application may have different performance requirements. For example, an accelerometer in a smart phone could have a lower requirement for reliability, and thus lower unit cost, compared to an automobile where human life could be at stake. The high accuracy and stability performance for inertial guidance applications are often accompanied by a higher cost compared to the requirements for sports and gaming applications.

This edition of the Heterogeneous Components roadmap seeks to define the performance parameters that systems integrators define for systems requirements and establishes the potential for the beginning of the effort to continuously grow the breadth of this roadmap.

3. INTRODUCTION

The advent of hand-held mobile devices, such as smartphones and tablet computers, has driven a rapidly growing market demand for manufacturers to produce miniaturized components with ever increasing performance and functionality. Their performance requirements are driven by systems evolution or new “killer apps” that can emerge unexpectedly into the scene. While the market for smartphones and tablets is expected to continue to grow with continuing advances in product performance and functionality, new markets are also emerging including wearables and applications related to the Internet of Things. These applications fuel requirements, development, and production of Heterogeneous Components.

The ITRS has been refocusing its roadmapping activities to align itself with this evolution of the semiconductor electronics industry. The ITRS established the MEMS Technology Working Group in 2010 and published the first edition of the MEMS chapter of the ITRS Roadmap in 2011. Since then, the MEMS TWG has continued to publish its findings in the ITRS and iNEMI technology roadmaps. The MEMS Chapter included accelerometers, gyroscopes, inertial measurement unites, microphones, and RF MEMS resonators, galvanic switches, and varactors. As the ITRS transitions its roadmapping activities to ITRS2.0, the MEMS TWG has transitioned its efforts to support the Heterogeneous Components Focus Area of ITRS2.0. This provides an opportunity to expands the range of



Source: Georgia Tech PRC, http://www.prc.gatech.edu/overview/images/etpc.jpg

Figure 1 Illustration of Heterogeneous Components in a Heterogeneous System.

applications and device technologies that are currently addressed in the MEMS Roadmap.

A major challenge to roadmapping MEMS technology has been the diversity of applications for MEMS. For example, MEMS devices include pressure sensors, ink jet printer cartridges, accelerometers, digital light projectors, bolometers, gas sensors, surgical tools, microphones, portable medical diagnostic systems, and more. Furthermore, there has been a long history of MEMS of a one-device one-application paradigm, where each device had a unique design and a unique manufacturing process. In order to address challenge, the working group chose to set its focus on applications related to consumer portable, wearable, and automotive.

4. Sources

The MEMS Technology Working Group develops its roadmapping studies working collaboratively with industrial groups, standards associations, as well as other industrial roadmap developed by the ITRS, iNEMI, and TSensors. These groups have developed formal agreements for working together on roadmapping, standards, as well as other activities. The roadmap is a living document, meaning that it is developed and updated incrementally corresponding with each yearly publication by the ITRS and iNEMI. iNEMI publishes their roadmap on odd numbered years, 2015 being that date of the last publication, and the ITRS publishes its roadmap on even numbered years, the 2014 edition being the date of the last one and a 2015 update. This is the first edition of the Heterogeneous Components Chapter of the ITRS2.0 Roadmap.

4.1 MEMS and Sensors Industry Group

Founded in 2001, the MEMS and Sensors Industry Group [1] is the trade association advancing MEMS across global markets. Through conferences, workshops, and collaborative projects (both online and in person), MIG brings together the MEMS supply chain, in a neutral forum to address critical challenges to MEMS commercialization. MIG works to accomplish this mission by enabling the exchange of non-proprietary information among members and by providing access to reliable industry data that furthers the development of MEMS technology and promoting the greater commercial development and use of MEMS and MEMS-enabled devices. The MEMS Industry Group hosts annual meetings of the MEMS Executive Congress and the MEMS Technical Congress.

4.2 IEEE Standards Association

The IEEE Standards Association [[4]] is well known for standards that define communications protocols and device performance specifications. The roadmapping process for MEMS articulated the need and contributed to the development of a consensus within the MEMS Industry Group for the need for standardizing device performance datasheets. The MEMS Industry Group has established the IEEE P2700 Standard for Sensor Performance Parameter Definitions Working Group of the Electron Devices Society's MEMS Standards Development Committee (EDS-MEMS-SDC). The working group published its first standard in 2014 entitled "IEEE Standard for Sensor Performance Parameter Definitions."

4.3 SEMI

SEMI [[5]] is the global industry association serving the manufacturing supply chain for the micro- and nano-electronics industries. SEMI has been active since the late 1990's in developing standard test methods for materials used in manufacturing MEMS devices. These test methods include the measurement of strain, film thickness, elastic modulus, and bond strength. There is discussion and a growing interest within the MEMS Industry Group and within TSensors for the need for standardizing process modules.

4.4 MANCEF

MANCEF [[6]] is an industry group that connects a global community focused on commercializing micro, nano, and emerging technologies through conferences and educational efforts. MANCEF organizes an annual conference for MEMS manufacturers called The Commercialization of Micro-, Nano-, and Emerging Technologies (COMS) and has been active in supporting the TSensors Summits. MANCEF has also published a series of MEMS and nano roadmaps the first entitled "The MANCEF International Micro/Nano Roadmap MANCEF initiated the first two industry roadmapping efforts to much acclaim using second generation roadmapping techniques initiating this activity in 1998. SEMI, KIT, MESA+ and SNL supported these early roadmapping activities. The roadmaps were presented in 2002 and 2005. They have subsequently published other roadmaps using first second and third generation techniques most recently the third generation roadmap technique focusing on the Healthcare industry in 2015," available for purchase on the MANCEF website.

4.5 TSensors Summit

The TSensors Summits [3] are a forum for the world's sensor visionaries to present their views on which sensor applications, sensor types and sensor manufacturing platforms have the potential to fuel sensor market growth to the trillions within a decade. Such forecasted explosion will be a continuation of consumer sensor growth from 10 million units in 2007 (iPhone introduction) to almost 10 billion devices in 2013. These summits provide an opportunity for identifying future requirements for devices that can be used to forecast long-term trends for technology roadmapping.

5. APPLICATION DRIVERS CONSIDERED

The MEMS Technology Working Group (TWG) has chosen its focus on application areas for MEMS devices in Automotive, Consumer Portable, Consumer Wearable, and devices associated with the Internet of Things (IoT). The TWG also recognizes the importance of Medical Diagnostic Applications, and the Microfluidic Devices that are forecasted to see a rapid growth in the next several years.

Heterogeneous components can have use in multiple applications, such as automotive and portable consumer devices, but each of the applications often has different device performance requirements. For example, automotive applications require accelerometers with high reliability and use in extremes in environmental conditions yet accelerometers in mobile devices require low cost and low power consumption. Thus a main requirement for low cost could be traded off with other requirements such as long-term reliability or accuracy. Device performance requirements will need to be developed for each application area that is considered in this roadmap.

Table 1 Examples of heterogeneous components with their key attributes for automotive, smart phone, wearable, and medical applications, exemplifying how their requirements may differ with application.

	Automotive	**Smart Phone**	**Wearable**	**Medical**
Inertial Sensors (accelerometers, gyroscopes and IMUs)	Crash Sensors, Inertial Positioning: reliability, accuracy, large ambient temperature range	Tilt, Movement, Inertial Positioning: low cost, low power.	Movement sensor, heart rate – low cost, low power.	Movement, tilt – reliability, low power, FDA approval
Microphones	Hands free communications	Voice, noise cancellation, ultrasonic communications	Voice, heart rate, ultrasonic communications – low cost, low power	Voice, heart rate - reliability, low power, FDA approval
Pressure Sensors	Tire, manifold, altitude, vapor pressure	Altitude, barometric pressure	Blood pressure – low cost, low power	Blood pressure – reliability, low power, FDA approval
Micro Speakers		Sound reproduction – small size, low power	Sound reproduction – small size, low power	
Conductivity			Perspiration	
Humidity			Ambient environmental conditions	
eNose		Environmental and	Environmental and	

5.1 Automotive

As automobiles become more complex, signal processing technologies are increasingly being used to create the automobile of the future. We are asking a lot from our cars; adapt to changes in driving conditions, provide driving directions, keep in touch with the office and family members, and provide quality audio and video entertainment—all while providing more safety and running more efficiently than ever before. No easy task.

No part of the car exemplifies this more than its safety systems. While most of us know that cars today use MEMS accelerometers to sense rapid deceleration for airbag deployment, what we may not appreciate is MEMS inertial sensor technology is continually evolving and has found many other safety and convenience applications in automobiles beyond airbag systems.

The most common application beyond airbag systems is the almost ubiquitous Automatic Braking System (ABS). Until very recently, most ABS systems did not use an inertial sensor. They simply read wheel speed and apply pulsed braking if the wheels are thought to be skidding. However, most all-wheel-drive systems and some newer high performance ABS systems, look at longitudinal acceleration to determine if the chassis is still moving. This is particularly important for all-wheel-drive equipped vehicles where all four wheels may have lost traction due to the application of drive torque.

The most important performance parameter MEMS accelerometers were able to address for ABS is zero g bias and sensitivity stability. In general, it is assumed that the minimum available deceleration force available (even on slippery surfaces) will be about 100mg (0.98m/s2). So the combination of zero g bias drift and sensitivity variation must not vary more than 100mg over the automotive temperature range. MEMS accelerometers with a typical zero g bias stability of 16mg and sensitivity drift of 0.3% over the automotive temperature range are ideal for this application.

Electronic Stability Control is another application for MEMS sensors that assists the driver in regaining control of the automobile just as it is starting to skid. An ESC system uses a yaw rate sensor (or MEMS gyroscope), a low g MEMS accelerometer, wheel speed sensors (which may also be used by the ABS system) and steering wheel angle input. Wheel speed from each wheel is measured, and the predicted yaw (or turn) rate of the car is compared to that measured by the gyroscope and the intentions of the driver (as predicted by the steering wheel angle). A low g accelerometer is also used to determine if the car is sliding laterally. If the measured yaw rate differs from the computed yaw rate, or lateral sliding is detected, single wheel braking or torque reduction can be used to make the car “get back in line”.

ESC systems require a yaw rate sensor with fairly low noise (typically less than 0.5 degrees/sec) and low sensitivity to mechanical vibration. Just as in ABS, the accelerometer must be very stable over temperature, as small amounts of lateral acceleration must be measured. MEMS gyros and accelerometers have surpassed other technologies on these performance requirements.

Roll over detection systems employ a roll rate sensor to read the roll rate. The roll rate is integrated to determine the roll angle of the vehicle. An accelerometer reading vertical acceleration (Z axis) is also required as large roll angles may be encountered in banked curves with no possibility of roll over. Better roll over detection systems also use another accelerometer to measure lateral acceleration as a vehicle striking a curb or other object while sliding sideways is much more likely to roll over.

MEMS Gyros used for roll over sensing do not require the same resolution as those used in ESC systems, but they must have excellent rejection of external shock and vibration and have a larger dynamic range. MEMS gyroscopes are now commonly used in this application because of their insensitivity to external shock and vibration.

5.2 CONSUMER PORTABLE

This report considers consumer portable devices to be computer systems or peripherals that incorporate MEMS technology to enable and enhance their mobile use. These applications signify the next step in the evolution of computers, which started with the mainframe, and evolved to mini computers, desktop computers, laptop computers, and finally the smart phones and tablet computers. The trend into mobility frees us from the desk and allows us to move into the world while staying connected with each other and with information systems.

The release of the Nintendo Wii in November 2006 can be considered to mark the beginning of consumer portable MEMS device applications. The Wii wireless controller incorporated a 3-axis MEMS accelerometer that determined motion and position of the controller, bringing a new dimension to game playing applications. The remote allows the user to interact with the console using gestures and by pointing at the screen. The accelerometer and optical sensor that are built into the remote enable this functionality.

Apple introduced the iPhone in June 2007. Analogous to how the Wii remote revolutionized gaming, the iPhone can be considered to have revolutionized mobile phones. The iPhone advanced the functionality of mobile telephones by providing a more advanced graphical user interface with Internet browsing and email, among other things. The MEMS accelerometer technology detected the direction of gravity, which enabled the display to rotate so that it was always kept upright, and also provided an interface to game applications that could be purchased from the “app store.”

The MEMS technologies introduced into these applications gained rapid consumer acceptance, evidenced by their rapid growth in sales, Fig. 2, top left, shows relatively flat sales of Nintendo gaming consoles until the introduction of the Wii, lower left, shows Apple sales for iPhones exceeded revenues for their other product offerings within two years of its introduction. The MEMS technologies that supported these consumer portable applications did not require the same levels of accuracy and reliability as the automotive applications from which the technologies evolved. The primary drivers for these applications were cost, size, and low power dissipation.

Another significant component of the consumer MEMS evolution was in the area of packaging. Previous MEMS products, mostly automotive sensors, had a cost structure that allowed the use of mechanically robust, open cavity packages, such as ceramic DIP packages. The benefit of such packages was that the MEMS device could be mounted in an elastically isolated way, decoupling it from package induced stresses. However, such package technologies were much too expensive for the consumer market. Methods for using low cost, plastic packages were required to meet cost targets. This lead to technologies for capping the MEMS device, to allow plastic over-molding and the development of sophisticated die attach and stress relief methods.

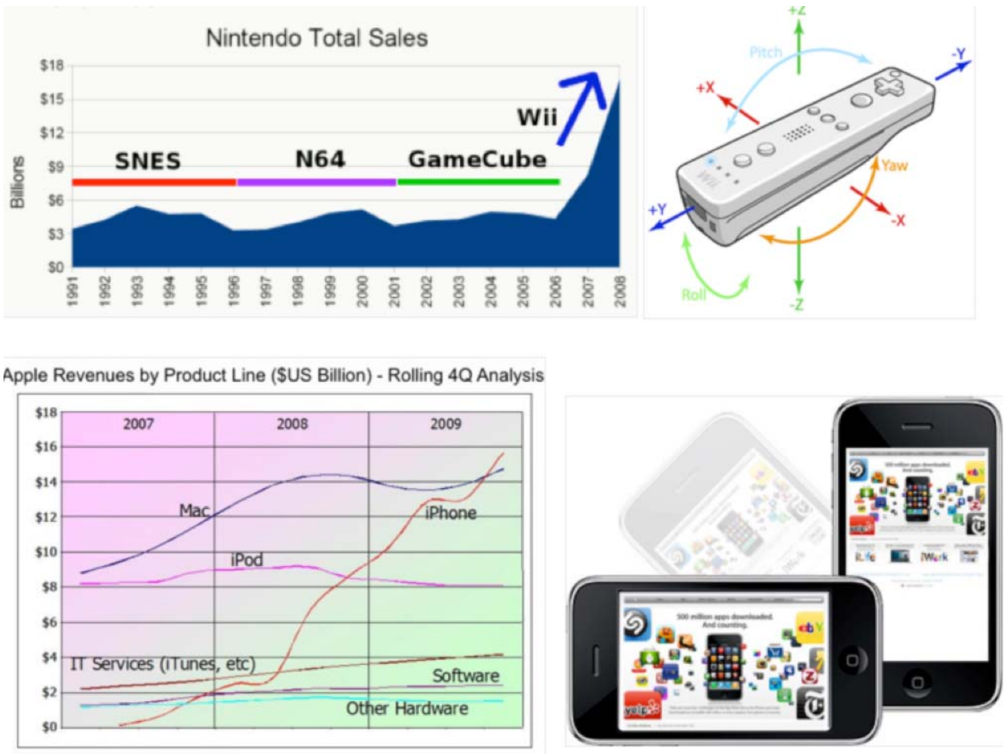


Figure 2 ***Nintendo's annual revenue from 1991 to 2008 (top left) revealing the explosive impact of Wii sales. The Wii wireless remote (top right), which incorporated a 3-axis accelerometer to sense displacement and rotation. Apple’s revenues by product line are shown (bottom left). The functionality enabled by MEMS accelerometers to maintain an upright display is illustrated (bottom right).***

Another important aspect of the evolution of MEMS sensors is the addition of on-board computation. For many years, MEMS sensors were pure analog sensors with a simple voltage (or current loop) output. But as technologies evolved that allowed the connection of a MEMS sense element to a CMOS ASIC, digital functionality became available. At first this functionality was used in a simple way to set sensor parameters or perform self-test operations. But soon the availability of digital logic was used to generate digital output, data buffering, and in time, data computation and sensor fusion. This evolution allows functionality to be moved from a system's central processor to the "smart" sensor, offloading that processor for higher-level functions (or lower cost). Of course, this increased level of functionality requires an increased level of testing. Although the methods for testing a digital ASIC are well understood, testing a mixed signal ASIC which is intended to be connected to an electromechanical MEMS element is much more complex.

The consumer portable MEMS device technologies that this working group has focused on are accelerometers, gyroscopes, and microphones. The working group has also included an assessment of RF MEMS resonators, switches, and varactors in this report. Section 3 of this report lists the key attributes of these device technologies over a 5-year span (2012 – 2017), which are considered short-term needs by iNEMI and ITRS who typically define long term needs to be 10+ years.

A major conclusion drawn from our roadmapping effort has been that the back-end of MEMS manufacturing (packaging and testing) can consume more than 50% of the total manufacturing cost, yet virtually all R&D investment has been in the front-end of manufacturing (devices and process development). The research investment portfolio can be partially attributed to a lack of articulation of the problems faced by the back end of manufacturing, and their importance. The development of a consensus opinion that documents the issues facing the industry, which is the primary output from technology roadmapping, can be used as a tool to optimize R&D investment that meets critical manufacturing needs in a timely manner.

This roadmap considers both the evolution of discrete MEMS devices and integrated MEMS technologies. This term "discrete" MEMS is used to refer to devices that perform one function. For example, a 3-axis accelerometer with an integrated ASIC is referred to as a discrete MEMS device for the purposes of this discussion. Integrated MEMS also referred to as multimode sensors, refer to the integration of sensing functions, such as accelerometer and gyroscope, in the same package.

Discrete MEMS devices are expected to see a continuous incremental increase in performance, and reduction in cost and package size. Fig.3 depicts that size evolution of integrated MEMS microphone chips manufactured by Akustica. The greatest challenges for discrete MEMS are related to packaging; decreasing package size while at the same time drastically lowering cost. There are no known solutions to meet the packaging and cost projections out to 2017.

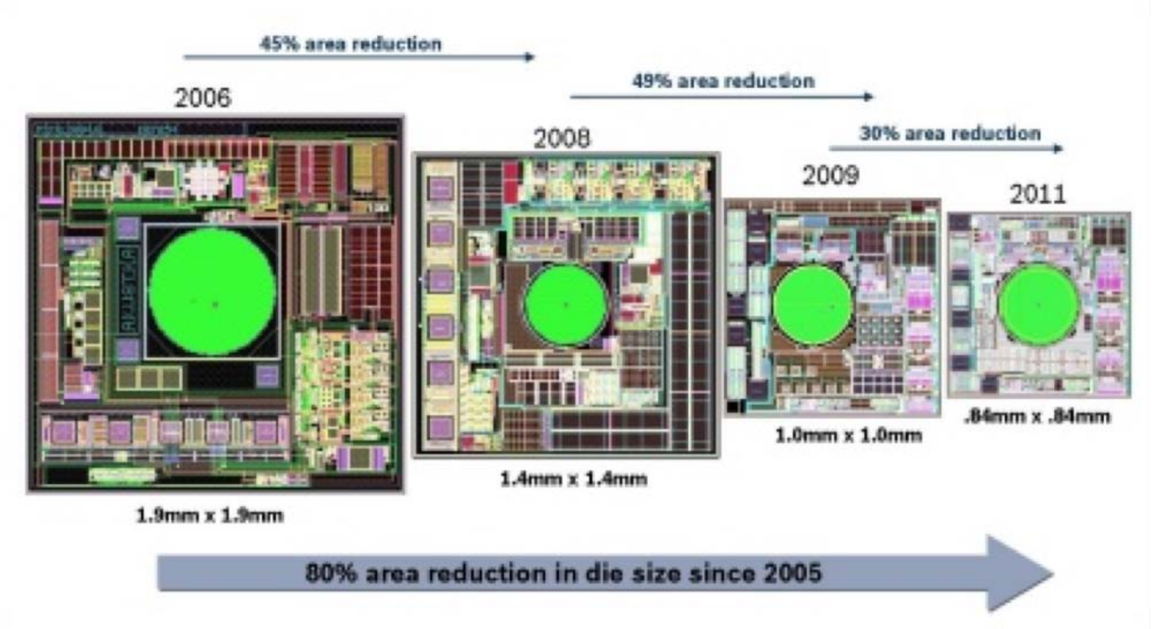


Figure 3 ***Example of the continuous incremental improvement of MEMS devices. The MEMS microphone chip size from Akustica saw an 80% reduction between 2006 and 2011.***

The MEMS TWG sees the greatest challenges for MEMS technologies in relation to their integration path. The integration path towards the Inertial Measurement Unit (IMU) is to integrate a 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer (compass), and a pressure sensor (altimeter). This is referred to as a 10 degree of freedom (DOF) multimode sensor. The TWG focused its attention on the accelerometers and gyroscopes; however, future iterations of the roadmap should include magnetometers and pressure sensors. Pressure sensors are MEMS devices that will be integrated in the future IMUs used in mobile devices. Though magnetometers are not, by definition, MEMS devices, they are inclusive to the More-than-Moore paradigm.

Multimode sensor technologies face challenges in assembly and packaging, especially for integration of the IMU at the package level, yet these are challenges where interim solutions are known. The greatest concern for multimode sensor technologies, with no known solutions, relates to testing. Possible solutions relate to moving as much of the testing as possible to earlier steps in the manufacturing process, such as wafer-level tests. This will require the ability to accurately predict performance at the package-level from the wafer-level tests. Other solutions include advancing know-how for MEMS design for testability and even to develop ways to eliminate testing, referred to as to “design for no test.”

There is a continuing need to extend knowledge of the physics of failure in MEMS. This is especially relevant for RF MEMS devices, where their adoption in many applications has been hindered. Extending knowledge of the physics of failure will enable suppliers to improve their reliability and to develop reliability focused, accelerated test methods. It is recognized that there is knowledge for specific devices that resides with companies; however this knowledge has traditionally been kept secret for commercial advantage. Some sharing of such information may become beneficial at an appropriate later time.

The MEMS TWG examined the near-term technology requirements for the MEMS technologies in this roadmap. While there is a desire to expand discussions to include the long-term, the committee must first reach a consensus on how this will be done. It may be that long-term requirements for MEMS will concern integration path, e.g., integration with multiple sensor technologies; advancing ASIC requirements to microcontroller, package level integration versus 3D staking technologies versus monolithic integration paths. Thus near-term requirements may concern the incremental advances in device performance metrics within the long-term integration cycles.

Roadmapping the integration path will require accurate cost analysis, ensuring that future predictions are consistent with the resources and technology needed to deliver to the market place within cost constraints. This methodology can be usefully employed to cost/price discrete MEMS devices and predict the production developments needed for the immediate future. However, accurately costing future integrated MEMS devices represents a significant challenge. Particularly challenging is: estimating the structure of costs to solve the technical problems in integrating fundamentally different components, the costs of developing cost-effective test equipment and the formidable task of packaging in large scale manufacturing.

5.3 Consumer WEARABLE

The rapid increase of digital data and connected technologies is revolutionizing healthcare. The healthcare system used to be highly centralized, disease oriented and focused on acute care. It is changing today towards keeping people healthy, raising each individual's awareness of their health and inducing efficient behavioral changes. As they become empowered to maintain a healthy lifestyle, a large portion of them is eager to collect data about their health, track trends over time and share their health performance on their social network. Others could have a mild condition that can benefit from continuous monitoring. This growing part of the population with the desire to monitor lifestyle and health is often called the Worried-well. Worried-wells are information seekers. In the last decade, worried-wells were searching the web for symptoms they would experience, looking to correlate them with possible health conditions. In the last few years, websites have been introduced to connect people with similar conditions or symptoms (e.g. patients-like-me). In the future, the worried-wells will have a new army of technologies at their disposal to monitor and improve their health. Silicon and MEMS technologies are making that revolution possible.

Today the mobile phone can already provide a great deal of health information. Accelerometers can track activity and sleep. Built-in optical sensors are available that can sense heart rate when the user is touching the phone. The camera in the phone can be used for purposes as diverse as checking the calorie content of a food item, or identifying your emotions based on facial expression recognition. A broad spectrum of mobile phone apps has been developed to analyze this data, and deliver it to the consumer in an intelligible and actionable manner. A recent survey reported over 16,000 consumer health apps available on the Apple store as of August 2013 and that 66% of Americans would use mobile health apps to manage their health [7].

Not every health parameter can be measured with a mobile phone. They often suffer from the lack of continuous recording and inaccuracy in data interpretation due to the inherent lack of capability in knowing the exact location of the phone at a certain point in time. Wearable sensors, referred to as wearables, are addressing these limitations. Being worn on the body, they allow the user to continuously track health parameters, and to identify possible deviations to one’s normal profile. Their location is typically known, which allows for more accurate and reliable data interpretation. Finally, they enable measurements that would not be possible with the phone alone. Examples of wearables available today include heart-rate sensors such as Polar, Adidas, Sunto and activity monitors such as Fitbit, FuelBand, Jawband and Directlife. Big challenges remain in terms of reducing the size of these devices, reducing power consumption and ensuring reliable performance in all situations of daily life.

The worried-well is a growing part of the population, and the keenest of those information seekers are the ones who are at risk of major health issues. A study by the IBM Institute for Business Value estimates that 1.5B of the word population is overweight, representing a large population at risk of obesity and its indirect consequences: 1B smokers are subject to developing cancer, 600M people suffering from hyper-tension are at risk of cardiovascular diseases and heart failure, and 25M people with sleep apneas are also subject to car and work accidents.

MEMS device manufacturers are presently looking at what are referred to as Wearable Devices as the newest opportunity for market growth. These devices provide information to the wearer but do not claim to be medically diagnostic. Because of that, they are not subject to approval by the FDA and thus have significantly less cost, time, and risk bringing them to market.

Examples of wearable technologies are shown in Fig. 4. Wearable devices are typically worn on the wrist, upper arm, chest, and head. They are used to measure the wearer’s movement, location (GPS), skin temperature, skin conductance, etc. This data is then used to estimate caloric burn, distance and route travelled, sleep efficiency, etc. The wearer can use this information to become aware of how their living habits may impact their state of health. For example, caloric burn can be used as a means to adjust diet in order to control weight gain (or loss). Understanding the quality of sleep may influence the wearer to become aware of and change poor sleeping habits and to arrange an optimal time for sleep.

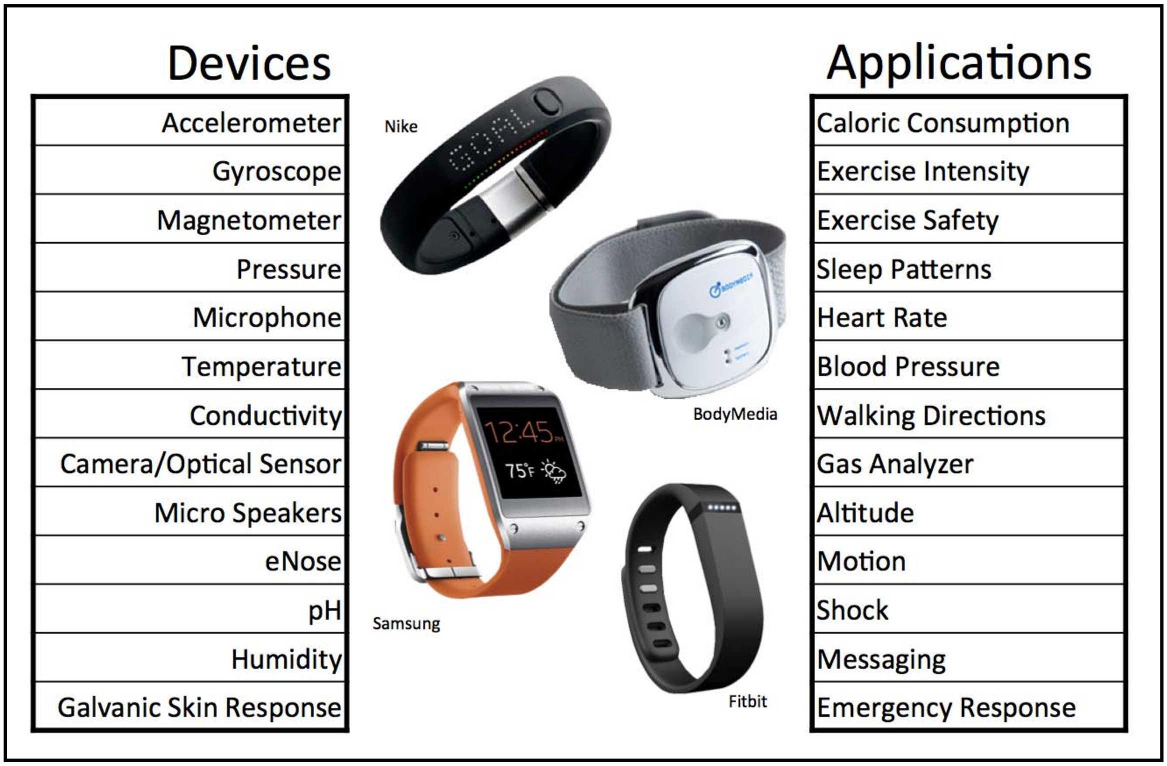


Figure 4 ***Sensors trends for "Wearable" technologies. The column on the left lists the types of sensors that are already in or may be added to wearable devices, and the column on the right lists the types of functions are already or may be added using these sensors.***

The wearer typically uploads their data from their device to a website where it is saved, analyzed, and displayed. The data is uploaded by connecting the device to a computer or by using a wireless connection, often via Bluetooth, to upload by using an application installed on a smart phone. There are other types of devices gaining use that are not worn continuously throughout the day, such as weight scales and blood pressure cuffs, that also use this process to upload data.

Once the data is uploaded the wearer can view a summary and can also observe trends. For example, a daily summary might encourage the wearer to add a workout at the end of the day in order to reach a desired goal for caloric burn. Trends can be extremely useful in helping the wearer become aware of the effects of their lifestyle and diet on the longer-term state of their health. Some websites allow the wearer to join groups to compete with others within their group and allow the wearer to choose to display their results and achievements on social networking sites such as Facebook. This kind of information not only helps the wearer to achieve their fitness goals, but over the longer-term can help change deep-seated habits and thereby develop a healthier lifestyle.

5.4 INTERNET OF THINGS (IOT)

The Internet of Things (IOT) and the subsequent terminology Internet of Everything (IOE) are terms that refer to slightly different things. IOT/E has become household acronyms but where did the terms originate. There is some discussion about who originally coined the IOT phrase. Some say it was Nicolas Tesla. When he stated in 1926

"When wireless is perfectly applied the whole earth will be converted into a huge brain, which in fact it is, all things being particles of a real and rhythmic whole.........and the instruments through which we shall be able to do this will be amazingly simple compared with our present telephone. A man will be able to carry one in his vest pocket."

Other focus on supply chain managers from Safeway but most state that the term Internet of Things was first coined by Kevin Ashton [8] while working at Proctor and Gamble in 1999. The first connected devices where shown in the Netherlands and GE house of the future since the late 1980's and appliances in the 1990's by Sunbeam's toaster and followed most recently refrigerators utilizing Nanodust like sensors. In any case, the future projected for IOT has evolved into a more recent effort to systemize sensor data utilizing the Internet.

The TSensors Initiative is an effort to understand how we can utilize the Internet to systemize small macro, micro and nano sensors to enable a fully connected environment. Peter Hartwell from HP has spoken about the idea of a Central Nervous System of the Earth or CeNSE [9]. He projected that systemized sensors through the Internet would profoundly revolutionize human interaction with the earth. But he and many others have suggested that it would take the equivalent of 1000 Internets as now configured to support even 1 trillion sensors.

The system rather than the sensors is the monetary driver for the trillion-senor world. TSensor Systems at the Commercialization of MEMS (COMS) 2012 meeting initiated an effort for reaching a $1 cost per sensor device costs. This could enable ubiquitous sensing. The number of wearable, grid, biological, infrastructure, automotive, agricultural, water, additive manufacturing and many other based sensors and actuators grew for a future projection trillion to a potential for 50 to 100 trillion. The MEMS and Nano based sensor market could be for 1 to 100 trillion and the systemization or Internet of Things portion including data development and other infrastructure would be at least ten times that amount. Even at the 5 trillion-sensor level the production of sensors is approximately 1/5 of the US GDP (in excess of 17 trillion dollars 2014) and its systemization is 50 trillion dollars compared to the world GDP (2014) of in excess of 77 trillion US dollars. Surely the scope of this is difficult to achieve.

Further, certain aspects of the Internet are also holding this abundant new world back. For example, the first conference IOT occurred in 2008 and the use of the Internet for this many devices were new. More companies and individuals suggested other hurdles like: a need for more Internet addresses, power concerns, the growth in data trafficking, security and bandwidth. The Cloud providers have suggested solutions like data analysis at the edge through Cisco's Fog or other ideas like swarming. Others have suggested the use of alternative local networks.

The first support of the "Internet of Things" came with the available of IPV6 standard in 2011 replacing the IPV4 standard. The IPV4 standard had approximately 4 billion addresses. The new IPV6 has a total of 340 undecillion (10^{36}) IP addresses, which is the equivalent of 3.4 with 38 zeros. This number of addresses will support the optimistic over 100 trillion connected devices in the world by 2030. The required number of Internet addresses is now more than adequate but all other infrastructure commercialization challenges have not yet been solved. One of the issues faced is the possible shortage of wireless bandwidth to support the connection of this vast sea of sensors.

6. Critical DEVICE PERFORMANCE PARAMETERS

This section presents a list of devices that have been considered by the MEMS and Sensors Industry Group for standardization of definition for their performance parameters. These parameters can serve as a measure for technology roadmapping by deriving future device performance requirements from future applications envisioned by the TSensors Initiative.

Table 2 Summaries of Critical Device Performance Parameters for Roadmapping

Accelerometers Full scale range Sensitivity Zero-g offset Cross-axis sensitivity Noise Power consumption
Gyroscopes Full scale range Sensitivity Zero rate bias Cross-axis sensitivity Linear acceleration sensitivity Noise Power consumption
Magnetometers

Full scale range Sensitivity Zero magnetic field offset
Microphones Signal to noise ratio Frequency response Power consumption
Barometers Full scale range Sensitivity Pressure temperature coefficient Power consumption Response time
Hygrometers Full scale range Sensitivity Relative humidity accuracy Power consumption Response time
Thermometers Full scale range Sensitivity Absolute temperature error Power consumption
Ambient Light Sensors Detection range Sensitivity Responsivity vs. angle
Proximity Sensors Sensitivity Power consumption

7. DIFFICULT CHALLENGES

Table 3 below presents a summary of the difficult challenges that are revealed in order for manufacturers to meet future device performance requirements that are being driven by future applications. The subsequent subsections discuss the issues in greater detail.

Table 3 Summary of Difficult Challenges

Difficult Challenges	***Summary of Issues***
Device Testing	Standard testing protocols are needed for defining performance parameters published in device datasheets. The current lack of standardization results in the inability of the

	customer to compare the cost and performance tradeoffs between the manufacturers.
	The cost of testing continues to rise yet system integrators expect prices to stay constant or lower even with increases in performance and function. Increasing performance and adding more functions requires higher accuracy tests and additional tests, which should normally increase testing costs.
	There is a continuing need to extend knowledge of the physics of failure of MEMS devices for accelerated reliability test methods.
Standard Process Modules	There has been a continuing discussion amongst MEMS designers and fabricators for decades about the pros and cons, and the possibility of moving towards standardization in fabrication process modules for MEMS. The discussion and interest on the need for this has been growing within the MEMS Industry Group but it has not yet gained enough momentum to produce specific actions.
Bandwidth for Connectivity	The new IPV6 has a total of 340 undecillion IP addresses, which is the equivalent of 3.4 with 38 zeros. This number of addresses will support the optimistic over 100 trillion connected devices in the world by 2030. However, if the envisioned trillion sensors are to communicate wirelessly there will be a shortage of wireless bandwidth unless new paradigms for managing and transmitting the data are developed.

7.1 CHALLENGE: DEVICE TESTING

Testing MEMS devices is complex, requires sophisticated approaches and entails various challenges. The testing of these sensors involves a series of steps including calibration and validation, which in turn require applying external physical stimulus to perform both parametric and functional testing. Each class of device not only needs a test system capable of providing the required stimuli, but the physics of the stimulus, how it affects the device, and how data is processed and analyzed are key functions of these systems. With these features in mind, modular systems which can be expanded from very small volume engineering systems into high volume production automatic test equipment (ATE) systems is the direction the MEMS test industry is evolving today.

In order to meet the high volume and low cost requirements that are driving the MEMS market, the industry is undergoing a self-assessment in terms of how to reduce cost and become profitable. Being that capital equipment expenditure and test times are among the major drivers of the final device test costs in terms of cost/device, implementation of the design for testing philosophy has become a focal point for MEMS manufacturers. This philosophy is defined by design techniques, which add testability features to products, which in turn enable more efficient development and final product testing.

Standardization of Datasheets – There is a lack of standard testing protocols for measuring device performance metrics reported in datasheets. This lack of standardization results in the inability of the customer to compare the cost and performance tradeoffs between the manufacturers. Instead, the customer must conduct their own performance tests or work with a third party to characterize and compare performance metrics. The MEMS Industry Group has recently published a Standardized Sensor Performance Parameter Definitions terminology document that defines performance parameters for accelerometers, gyroscopes, magnetometers, barometers, hygrometers, thermometers, and ambient light and proximity sensors. The group has created a new IEEE Standards Committee on MEMS Device Testing and published this document as an IEEE Standard. The group is now engaged in developing standard testing protocols for each of the performance metrics.

Cost of test - The cost of testing continues to rise yet system integrators expect prices to stay constant or lower even with increases in performance and function - a non-sustainable situation. MEMS devices need to be stimulated mechanically “shaken, rattled, and rolled”. These added requirements to the traditional electrical tests result in more expensive handlers and longer testing times that result in lower throughput. The handlers also tend to be customized for each manufacturer. Standardizing the handlers may lower costs considerably. The cost of testing is also influenced by the requirements for tests by the customer, which may add expense but may not add any value. Standardizing tests on product performance, reliability, and device data sheets can also dramatically reduce the cost of testing.

Wafer-level testing - A possible solution for lowering the cost of testing may be to move as much of the testing as possible to the wafer level. This will require knowledge and predictive models of and/or eliminate effects from assembly and packaging so that information from wafer level testing can predict the final packaged device performance. The goal would be to make the final tests of the finished device to become a simple verification of the expected performance. Wafer level testing should also be used to feed data forward in the process, including the designer, to improve designs and product yields.

Design for no test - Also referred to as self-test/self-calibration. Another solution to lowering the cost of testing is to advance methods for self-test/self-calibration so that no testing is required. There is presently a lack of know-how for designing for testability and methods for self-test/self-calibration that can reduce the burden of test at the back end of manufacturing. Since design for test is very application dependent, methodologies will need to be developed for each device technology.

Accelerated reliability test methods - There is a continuing need to extend knowledge of the physics of failure of MEMS devices. This is especially relevant for RF MEMS devices, where their adoption in many applications has been hindered due to reliability requirements. Extending knowledge of the physics of failure will enable methods to improve device reliability and to develop accelerated reliability test methods. Specific knowledge of reliability metrics and test methods resides in companies, but this information is not typically shared because it can be a commercial advantage to the company to keep it secret. Otherwise, the possible solution is to share the information that exists, evaluate gaps, and support R&D on developing knowledge on those areas that require it. Then, this knowledge can be applied to the development of standardized accelerated reliability test methods.

7.2 CHALLENGE: STANDARD PROCESS MODULES

Integrated Circuit (IC) designers are accustomed to working in a design environment using design rules and design libraries to develop their complex systems. This so called Meade and Conway [[10]] approach to digital circuit design has been a powerful tool to reduce the complexity of the design process leading to a great reduction in the development time for producing working digital circuits. The approach works because the design and fabrication process of CMOS digital electronics is standardized, enabling the designer to develop circuit designs without requiring knowledge of every step and possible variation of the fabrication process. There has been discussion amongst MEMS designers and fabricators for decades about the pros and cons, and the possibility of having some kind of standardization in fabrication processes for MEMS. All acknowledge what the benefits would be but cringe at the notion of trading off device performance with process standardization. The discussion on the need for this has been growing within the MEMS Industry Group [[11]] but it has not yet gained enough momentum to produce specific actions. It may be that an agreeable approach towards the solution still needs to be articulated.

7.3 CHALLENGE: BANDWIDTH FOR CONNECTIVITY

Since 2012 the Internet has been bandwidth deficient and it has become even more unsecure. We have seen Internet providers like Comcast de-democratize the Internet through their effort to control the use of bandwidth most recently through Comcast charging Netflix’s a premium for bandwidth use. We have seen the “Big Cloud” computing suppliers consolidate. We have seen automotive vehicles hacked and turned off from afar leaving some serious questions about the security of the IOT. All this and we haven’t even approached a trillion sensor world yet. The Internet as currently configured cannot support even a trillion sensors as predicted by HP some time ago. A TSensor world needs a new IOT driven Internet configuration.

We can increase effective bandwidth though the use of power but increasing the power consumption of our remote sensing devices is a maximizing not optimizing solution. The TSensor system group has inquired from many companies were they think the use of sensors will be emphasized. They range from 30% to 70% use being derived lifestyle sensors like wearables to industrial and infrastructure problem solving sensors with the same 30 to 70% use projections like grid safety. The type of sensor, its accuracy requirements, compatibility with local networks, compatibility with computation at the edge, its cloud systems stakeholder specified data requirements among other things will determine load on the Internet system.

Data on the edge through cloud and swarm technologies will help. "Fog" or edge driven analytics are sued to optimize cloud computing. They are developed to bring "Big Data" closer to the users. It is a newer paradigm that supports decreasing wireless data over the Internet. Swarm techniques promote collective behaviors of decentralized self-organized systems and leverage local systems. It promotes the use of Artificial intelligence (AI). Yet these techniques will not be enough to overcome the spectra or bandwidth hurdle.

IOT/E is becoming exceptionally popular and from what Gartner's "Hype" cycle model suggests there will be large customer satisfaction. The heighten expectations that IOT is a panacea for an ever increasingly connected world cannot rely on an Internet system that grew organically rather than being designed. Using increased power to "speedup" Internet is not an answer especially for remote sensing. The TSensor system roadmap is developing a roadmap and seeing if the "Fog" can replace the "Cloud," seeing is new Machine to Machine designs can embrace a world that in moving from Terabytes to Petabytes.

The TSensor Roadmaps are currently looking at multiple critical dimensions such as:

Amount of data that can be streamed in a wireless network (wireless standards, gateways)

Amount of data that can be streamed in a wired network (IP protocols).

Sensor capabilities for data transmission, storage and processing, e.g., M2M protocols.

Sensor energy storage capacity.

Sensor manufacturing costs.

Availability of skilled engineers

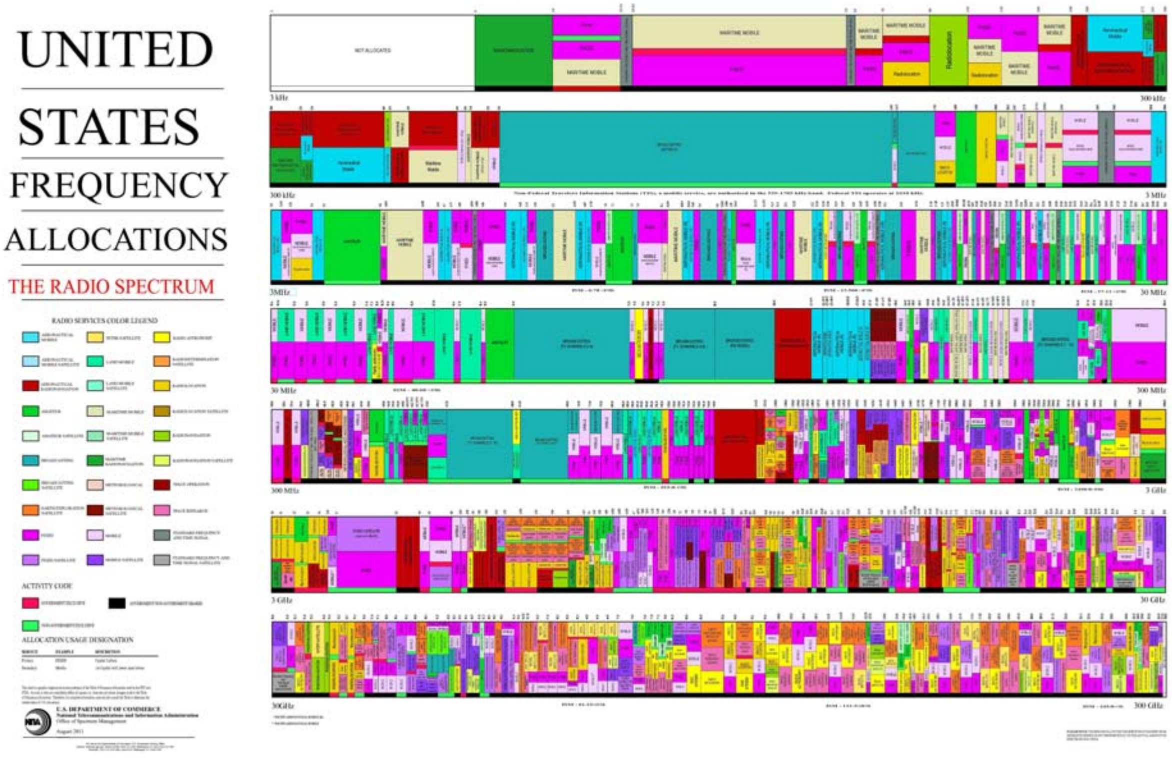


Figure 5 ***Chart of the US radio frequency allocation spectrum as of 2011, from:*** **https://www.ntia.doc.gov/files/ntia/publications/2003-allochrt.pdf**

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