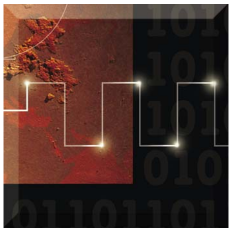

Future Trends in Miniaturization for Wireless Applications

M. Ann Garrison Darrin, Bliss G. Carkhuff, and Thomas S. Mehoke

The future of miniaturization of wireless networks is described from the viewpoint of today's trends in miniaturization, such as microelectromechanical systems and nanotechnology, along with the move away from computer processing–centric systems to distributed networks. The complexity, convergence of technologies, and connectivity of the remote wireless sensor known as the "mote" are discussed in relation to distributed networks. The growth of this technology is compared with growth predicted by Moore's law, which charts a linear progression of technology such as size of a resistor, as well as by the technology S-curve, which charts a logarithmic growth such as that seen by the Internet. We show that growth in the number of applications for motes is likely to more closely follow the predictions of the S-curve. The capabilities of this technology, in terms of functionality, have the potential for the log-linear growth experienced in the modern microcircuit world.

INTRODUCTION

The next generation of wireless technologies is being driven by the rapid convergence of three key technologies: microelectromechanical systems (MEMS), digital circuitry, and the explosive growth of wireless communications. Common to all three are reductions in size, weight, power consumption, and cost associated with the large number of units produced, as well as reductions in complexity (and functionality). Newly emerging technologies based on such convergence include "smart dust" systems,[1] "dots,"[2] and "motes."[3] Motes are tiny, self-contained, powered computers or sensor systems with radio or optical links that enable them to communicate and exchange data with one another and to self-organize into *ad hoc* networks. They form the building blocks of wireless sensor networks, which the Laboratory has become involved in, from small embedded nodes to passive optical transmitters. The emerging field of motes is an excellent place to observe and compare different rates of technological progress.

WIRELESS COMMUNICATIONS

The current approach to wireless communications has been to directly replace circuit switching, such as one finds in a hardwired system, with the desired wireless system. Circuit-switched voice networks are similar to hardwired circuits, with the straightforward addition of receivers, transceivers, and support technology such as antennas where required. The drive today is to add more and more similar technologies or functionality until the field of convergent technologies is reached where handheld devices exist. These point solutions, such as the ubiquitous Blackberry portable device, merge a portable laptop computer and a wireless phone into one package. The current generation of convergent technologies includes home area networks, which interconnect a multitude of devices in the home (e.g., cordless phones, smart toys, pen tablets, remote controls, TVs, VCRs). Many of these devices are mobile and thus well suited to wireless connectivity; even nonmobile devices benefit from wireless connections by eliminating the need for an installed wired infrastructure. These wireless networks represent a sharp change from current wireless solutions in that they do not replace traditional hardwired components with corresponding wireless counterparts.

Now we come to the next generation of wireless technology with the micro- and nanotechnologies that will enable the smart spaces of the future. One such technology that can be used in creating these smart spaces is the mote. Future mote networks will incorporate a high level of integration as well as low-power operation in a small physical package. Features of the new platforms will include modular hardware and software design, system power management, and low-cost, high-volume production potential.[3]

COMPLEXITY AND CONVERGENCE

Rising complexity in a shrinking footprint has proven that Moore's law[4] is viable for MEMS devices. Moore's law states that the transistor density on integrated circuits doubles every couple of years (see the boxed insert). This exponential growth and the ever-shrinking transistor size result in increased performance and decreased cost. Elements such as microbatteries, capacitors, and transistors have all grown progressively smaller, following the trend of Moore's law. However, when all of these elements are combined in a mote, the progressive decrease in the size of the mote falls behind Moore's law over time because of the connections that must be made and because of the base that all of the different components sit upon. Nevertheless, while reductions in the size of the mote fall behind Moore's law when considering the rate of progress of its various components, the convergence of all the various components of the mote results in a highly versatile piece of technology that can interconnect all kinds of existing technology to improve its existing functionality.

Technology with the potential to be this widespread has already been witnessed with the rise of the Internet. The growth in applications for the Internet followed the technology S-curve (Fig. 1). Growth was initially very slow, but once commercial development opened up, growth was exponential as an enormous number of applications were developed, most of which could never have been foreseen. This exponential growth can also be expected with the rise of wireless distributed networks of motes.

MOTES

Figure 2 shows a typical conceptualized wireless mote and its diverse components based on work ongoing at the University of California, Berkeley, in the Smart Dust project.[5] This mote concept illustrates the challenges of packaging these next-generation wireless devices. The power requirements drive the energy storage volume of the packing. Although the devices are low power by design, increased power densities will require good thermal management. In this example, the solar cell area requires exposure to the environment. Atmospheric exposure is a major driver in many sensor applications.

PREDICTED TRENDS IN DENSITY

In 1957, Dr. Gordon Moore co-founded Fairchild Semiconductor Corporation in Mountain View, California. In July 1968, he co-founded Intel Corporation with the intention of developing and producing large-scale integrated products, beginning with semiconductor memories. Shortly thereafter, Intel produced the world's first microprocessor. In an observation made in 1965, often referred to as Moore's law, Dr. Moore described how the number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented. Moore predicted that this trend would continue for the foreseeable future. In subsequent years, the pace slowed a bit, but data density has doubled approximately every 18 months, and this is the current definition of Moore's law, which Moore himself has blessed. Most experts, including Moore, expect this trend to hold for at least another two decades.

In the same time period another visionary, Richard P. Feynman, gave his classic talk entitled "There's *Plenty* of Room at the Bottom: An Invitation to Enter a New Field of Physics" [italics added] on 29 December 1959 at the annual meeting of the American Physical Society at the California Institute of Technology.[4] Dr. Feynman's discussion defined elements of the new frontier in smallness, indicating that the size of things could be decreased in a practical way. He was the first to describe what is possible in principle—in other words, what is possible according to the laws of physics.

In the 1960s, when Dr. Moore made his observation relative to future densities, Intel was producing integrated circuits with 60 transistors on a chip. Today the Laboratory commonly uses devices with over 10 million gates, and will shortly start incorporating devices with over 1 billion transistors in the next-generation SRAM (static random access memory)-based logic devices. Since the early 1960s, the debate has shifted from whether Feynman's vision is plausible to a discussion of when such new fields will come to be. In the same time frame, the impact of Moore's law has been demonstrated in almost every aspect of our daily lives.

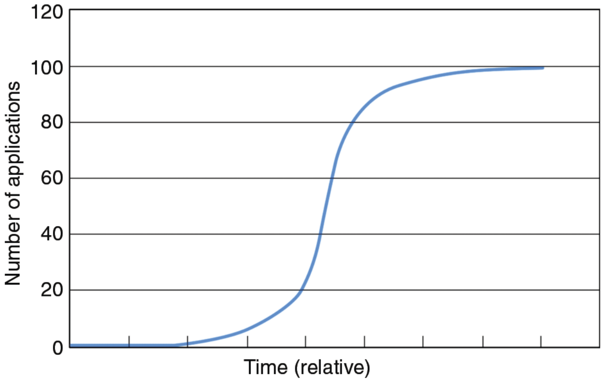

Figure 1. The technology S-curve.

The mix of technologies in this mote, which includes analog and digital systems, MEMS, and laser and power management systems, dictates its size and dimensions.

The conceptualized mote node in Fig. 2 demonstrates the first level of integrations with numerous separate chips. This approach may be advantageous, especially for stacking and packaging micromachined structures. Free-space optical communication may be used to facilitate a more energy-constrained approach. Optical radiators can be more efficient and allow higher-gain antennas at millimeter scales. Optical transmitters are more power-efficient at low power because of reduced overhead and because received power drops only as the inverse of the square of distance d ($1/d^2$), compared with drops at $1/d^4$ for RF transmissions subject to multipath fading.[5]

Ideally, the ratio of the area of active interest to the area of the total package should be relatively large. Packaging challenges for these future motes and distributed wireless networks are numerous and directly related to achieving functionality over mission life. Application-oriented concerns must address the environment and method of deployment of the end item. The ideal in the micro-scale has led to speculation about more nontraditional deployment techniques for setting up the networks, including dropping or propelling them into position, parasitically attaching them to other entities, deploying them in natural flows (water, air, oil), or having them self-install. Traditional concerns are amplified with concerns about *in situ* and deployment threats such as shock, vibration, acoustic damage, moisture, other contaminants, and pressure and temperature ratings. Design for manufacturing may require that subsystems be individually tested before final assembly, where the ability to produce large quantities for scalability would be key.

CONNECTIVITY AND GROWTH POTENTIAL

Remote sensors such as motes are under development at APL, and potential applications seem boundless. One example is the wireless embedded sensor platform (WESP) shown in Fig. 3. This is a core technology around which multiple sensors can be integrated for measuring a variety of environmental variables. Today, the WESP is being developed to monitor corrosion in concrete bridge decks. The WESP becomes known as a smart aggregate (SA) when sensors are added to specifically monitor the bridge deck. The devices are small enough to allow placement throughout the infrastructure without compromising structural integrity. Placement can be tailored for each application, thus allowing more information to be collected from areas of greatest concern.

Figure 4 shows WESP units being buried in the gutter area of the Johns Hopkins Road bridge over Maryland Route 29 near APL. The gutter is an area where deicing salts tend to concentrate and will potentially show the first signs of corrosion activity.

Because of their inaccessibility and long operational life expectancy, the WESP/SA units have no onboard power supply. Most of the time they are dormant. The WESP/SA receives power from an externally generated induction field and transmits the sensor data via a short-range RF transmitter. This requires an operator to "sweep" the structure with a handheld device to collect data (Fig. 5). Interrogation

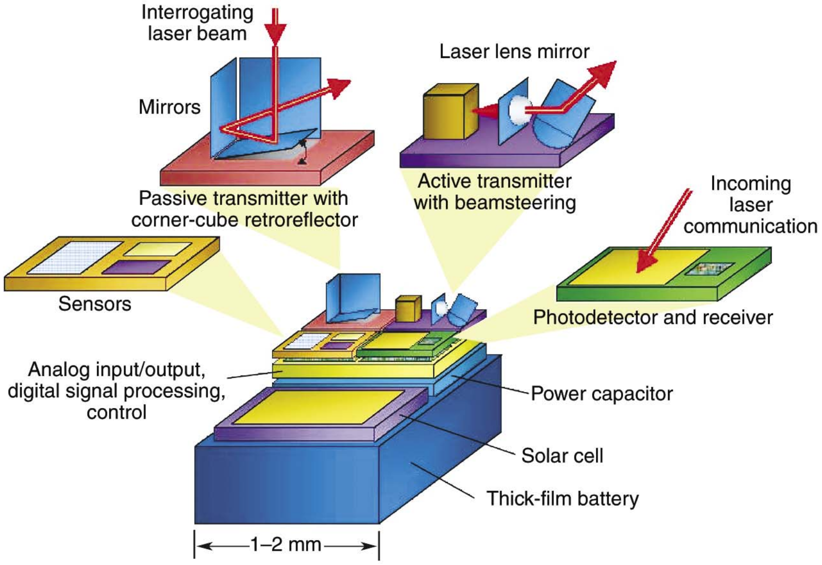

Figure 2. Smart Dust conceptual diagram. (Reproduced, with permission, from Ref. 5.)

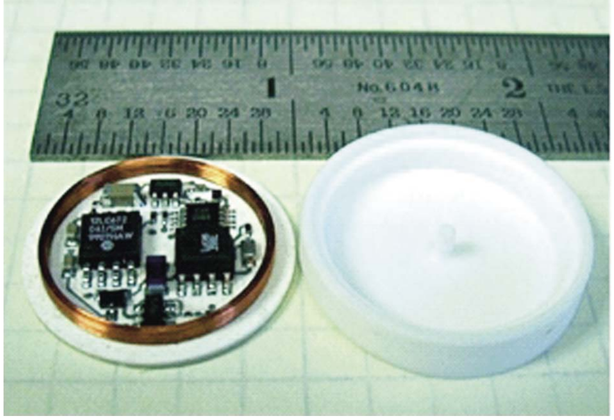

Figure 3. The wireless embedded sensor platform (WESP).

Figure 4. Deployment of WESP Smart Aggregate (WESP/SA) units in a concrete bridge deck.

of WESP/SA units can be expanded to detect vibration, stress, temperature swings, cracking, etc., all of which would help maintenance personnel identify problems long before they become critical.

A look at the commercial technology industry easily reveals the results of Moore's law. Demand for cell phones, notebook computers, handheld devices, and remote sensors has increased dramatically in recent years, and that demand necessitates the production of smaller and faster technologies. As both the volume of users and applications increase, demand increases for the more efficient allocation of spectral frequency ranges, requiring improved transceivers. Portable transceivers benefit greatly from the reduction of elements to the MEMS scale as opposed to mesoscale components. Specific MEMS devices include tunable micromachined capacitors, integrated high-Q (quality factor) inductors, low-loss micromechanical switches, and microscale vibrating mechanical resonators with Q values in the tens of thousands.[6]

Figure 5. Interrogation of WESP/SA units. Blue dots indicate device locations.

CONCLUSIONS

The incorporation of complex components into motes will initially prevent them from reaping the benefits of efficiencies and increases in functionality that have been seen in monolithic components as they track Moore's law. For a complex system to achieve the dramatic benefits of monolithic elements, it would need to evolve to systems on a chip incorporating all of the numerous elements. Power densities of batteries, a key technology, have not followed Moore's law and will thus limit advances of the entire system. However, while this early growth will be limited, when the technology becomes more widely researched and used, the number of applications will grow exponentially as uses that were never imagined are developed.

The emerging field of motes is an excellent place to observe and compare different rates of technological progress. Large numbers of diverse sensors can be attached to motes. Their very small size and ability to quickly form *ad hoc* networks allow them to be used in a huge variety of applications, ranging from space missions to environmental monitoring or even military or counterproliferation applications (Fig. 6). As each of these fields develops custom applications to meet specific needs, the different uses for motes will likely expand exponentially.

Distributed wireless sensor systems are similar to the emerging Internet of 30 years ago, growing at a breakneck pace with widespread applications. Advances in the number of applications, reduction in cost, and reduction in size will be more akin to the rapid growth up the technology S-curve that was seen with the Internet, while functionality growth will be a linear progression up the curve following Moore's law.

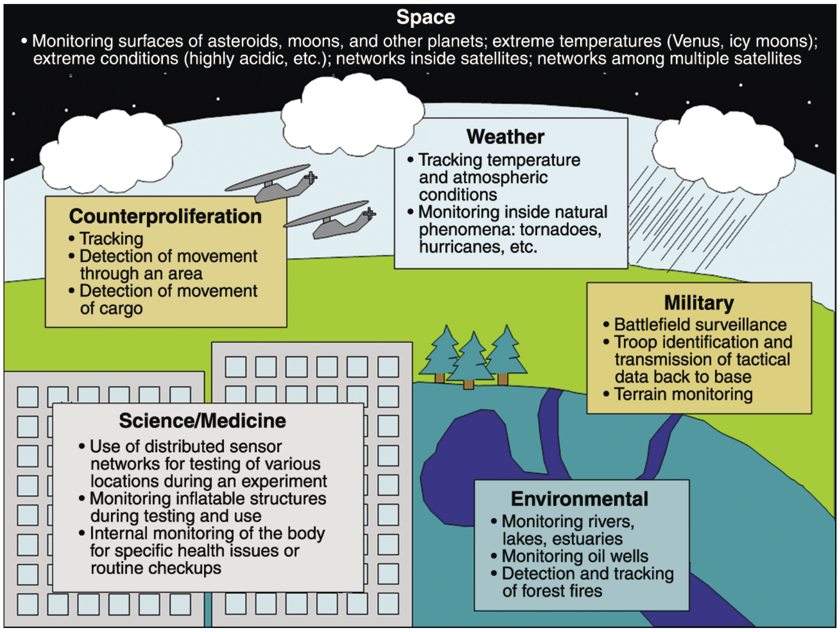

Figure 6. Potential mote applications.

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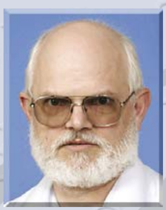
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