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Short Communication

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"Smart Dust" & Internet of Things (IoT): Progress & Challenges

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The breath taking progress in CMOS scaling over last five decades has made it possible to shrink complex digital integrated circuits (ICs), such as a microprocessor into dimensions that are approaching a dust particle (<1 mm). For example, the latest 10 nm CMOS product is expected to have ~ 100 million transistors/mm^2 (1). This makes fabrication of highly advanced smart dust equipped with a low-power (μW) micro-processor a reality and at a cost of less than a dime! Such unimaginable cost reduction is achievable because a 300 mm Si wafer can easily accommodate over 100,000 advanced ICs on a foot print of <0.8 mm × 0. 8 mm. This allows the recent emergence of Internet of Things (IoT) to be expanded using the "smart dust". Continued proliferation of IoT is expected to exploit advances in smart dust and low-power wireless communication technologies in conjunction with progress in data security. The impact of IoT in monitoring and controlling various environments, such as agricultural fields, medical, healthcare, manufacturing plants, transportation systems and sending continuous streams of accurate and real-time data can be truly transformational (Figures 1 and 2).

The market potential of IoT is phenomenal as shown in Figure 1. It is expected that 10s of billions of devices will be connected for IoT related applications within next 3-5 years. Even more impressive will be the impact of IoT on transactional business as a whole. There are several projections from very respectable sources (IDC, CISCO, Goldman Sachs, McKinsey) which indicate that the overall market for IoT will grow at a 12.5% CAGR from over a $1 trillion in 2013 to several trillions by 2020 (Figure 2).

One key challenge, however, for IoT technology is the security of the transferred and received data, and its authentication. This is the hot topic of IoT research today. The most sought after implementation of data security aims at incorporating encrypted authentication and security software in the IoT device itself. In addition to security challenge, the ubiquity of smart dust or IoT in our daily lives will rely on breakthroughs in wireless communication and powering of ICs at ultra-low power (in the μW range). There are two main technologies for wireless communication: (i) radio frequency (RF) based, and (ii) a light source based. In this editorial we discuss pros and cons of both of these communication approaches.

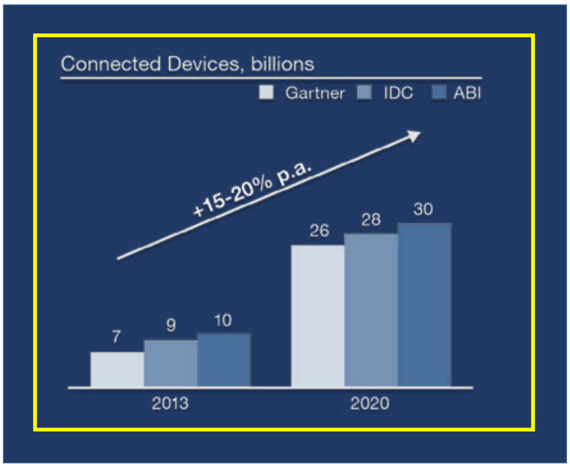

Figure 1: IoT to connect billions of devices.

RF Communication

RF transceivers are attractive for IoT because these do not require a direct line of sight for communication unlike their counterpart optical transceivers. However, RF circuits are typically larger than those which are optics based and operate at power levels in the multi-milliwatt range with a relatively large foot print (a cm or greater). Connectivity among large numbers of smart dust for IoT application by RF may further require additional circuitry for time, frequency or code-division multiplexing which will lead to even higher power consumption. Since the typical size of a RF antenna is relatively large (should be at least be a good fraction of the carrier wavelength), use of very short wavelengths/high frequencies (75-100 GHz) may be compatible with the smart dust dimension. However, in this frequency regime, RF communication will consume higher power. Furthermore, a smaller antenna will reduce both the RF communication sensitivity as well as its energy efficiency.

Optical Communication

Optical interconnects are becoming indispensable in state-of-the-art data centers for providing high band-width data transfer (10s of Gb/s) between and within servers at lower power than electrical connections for distances longer than a few centimetres. The optical transmitter and receiver technologies developed for data centers can

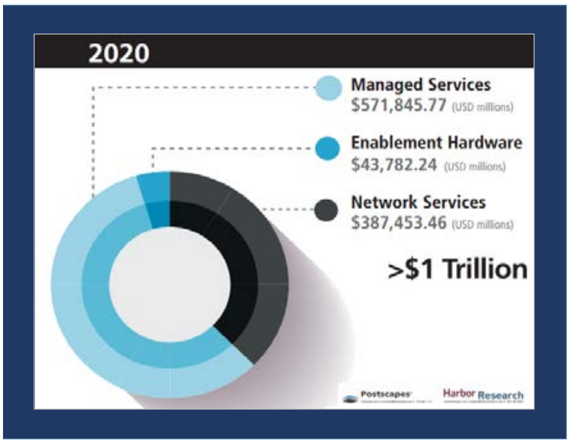

Figure 2: IoT to create trillion dollar market.

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also benefit the development of optical communication for smart dust devices. In particular, connectivity among a large body of tiny (<1 mm) smart dust or IoT devices distributed in free space via ulta low-power optical communication can be a game changer.

Compared to RF devices, semiconductor lasers, LEDs, and detectors require a relatively small foot print (<1 mm) to transfer and detect optical signals and are more amenable to low-power operation (<1 mW). In optical communication, 1 GHz frequency can be easily obtained from a sub-millimeter aperture, whereas RF communication may require several inches long antenna to produce collimation for a 1 GHz radio frequency signal. Furthermore, optical transceivers require relatively simple baseband analog and digital circuitry. The short wavelength (400-800 nm) laser makes a sub millimeter-scale device capable of emitting data via a narrow beam at the μW power level. LEDs can be made much smaller [1-3]. Also, a compact imaging receiver may be sufficient to decode simultaneous transmission from a large number of IoT devices distributed at different locations. Despite its low power and small foot print requirements, optical communication in free-space has two major challenges to overcome: (i) line of sight communication, and (ii) narrow beams for accurate pointing. Development of clever technologies and algorithms are required for smart dust/IoT applications to live up to their true potential to impact many aspects of our lives.

Energy Harvesting

Successful implementation of smart dust/IoT technologies requires autonomous, on-board energy harvesting. The most effective method for energy harvesting is based on solar cells, especially if smart dust/IoT devices are distributed in an outdoor environment [4]. These cells can be engineered to generate requisite power (μW to mW) on a target foot print by using high efficiency solar cells based direct band gap III-Vs. If an application requires smart dust/IoT devices to remain in dark or in low-light environment, power can be generated by shining light on the solar cell by an external light source of an appropriate wavelength.

Storage of the energy generated by a solar cell attached to the smart dust/IoT devices requires an efficient micro-battery. Achieving high storage capacity, e.g., 1 mAh, in a foot print of <1 mm × 1 mm for low-cost IoT devices is extremely challenging and has been the subject of active research. The front up approach for energy storage currently focuses on the Li-ion based solid state battery with high volumetric energy density [5]. This topic is rather broad in scope and will be discussed in a future editorial.

Summary

Spectacular progress has been made in the last decade to establish infrastructure for design and fabrication of IoT/smart devices addressing a multitude of applications including agricultural, medical, manufacturing, and pharmaceutical and many others. The economic impact of IoT once fully exploited for the real-time acquisition and analysis of data will be in trillions of dollars. However, there are two key challenges yet to be overcome: (i) developing a high energy density micro-battery that is capable of providing sufficient power on a few hundred microns foot print to enable various communication protocols for duration of several hours, and (ii) an efficient, low power optical and/or RF communication system that can overcome the line-of-sight limitation.

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