NanoRFID/Computers: Developments and Implications

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***Abstract*—True nano RFID/Computers (NRs) will represent a major change in the way many things are done. This technology will truly enable fulfillment of the promise of the Internet of Things (IoT).**

NR's could have as transformative impact on the world as the Internet and personal computer have. They could provide the foundation for realizing the vision of the "Internet of Things" or "Internet of Everything" by "wiring up" the world, from inanimate objects to living organisms. From the environment of the individual to the global ecosystem, we could "know" and interact with our environment on real-time basis down to a nanoscale, such as human cells and molecular structures of objects. This would enable humans to have a far greater understanding and awareness of and control over the world around them – viewing our world with much "higher resolution". The benefits could range from huge gains in improving human health while reducing costs to far greater efficiencies in the use of natural resources to enhance prosperity and environmental sustainability.

These nanoscale devices can do much more than tracking. They can be embedded in any material, and thus serve as a platform to both acquire data from the material and to send information or instructions to the material. Beyond two-way data transmission, NRs would not just be tracking devices but complete computing and data acquisition systems. Through the application of ultra-miniaturization, distributive computing and nano antennas, the acquisition and processing of analytical data can become massively parallel.

Keywords*—Nanoscale; Internet of Things (IoT); Internet of Everything; RFID; nano-computers; nano RFID/Computer (NR)

I. Introduction

NR's could have as transformative impact on the world as the Internet and personal computer have. They could provide the foundation for realizing the vision of the "Internet of Things" or "Internet of Everything" by "wiring up" the world, from inanimate objects to living organisms. From the environment of the individual to the global ecosystem, we could "know" and interact with our environment on real-time basis down to a nanoscale, such as human cells and molecular structures of objects. This would enable humans to have a far greater understanding and awareness of and control over the world around them – viewing our world with much "higher resolution". The benefits could range from huge gains in improving human health while reducing costs to far greater efficiencies in the use of natural resources to enhance prosperity and environmental sustainability.

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This technology will change many things currently done with larger systems making them more efficient and less costly. However, it will make possible things today that only appear in science fiction, such as the manipulation of blood cells, monitoring and making decisions on failure of operational items, allowing food, water and air to send messages on their quality, a global information system available from day-to-day items like walls, clothing, and nearly any surface. NRs could provide tracking and monitoring nearly everything that is made or modified. They could even create a global computer linking every item and in Pierre Teilhard de Chardin's Omega Point where "*no evolutionary future awaits anyone except in association with everyone else*."

NRs would be invisible to the naked eye. They would be about 150 nm in width and a few microns long and be produced by the billions and embedded by the thousands in any given object, which would enhance both their collective capability and their reliability. They could be manufactured by the billions using current computer chip "fabs" with great economies of scale. Such devices could have significant cost savings over existing sensors and computing systems.

NRs could have mobile applications. Consider clothing, embedded with such devices. Add the potential for nano Wi-Fi and it may be possible that future smart phones no longer need to be encased but rather would be distributed in clothing. A simple voice-actuated system with an ear device could be used to access the device. The video portion of the now nano smart phone could be provided by an optical system like Google Glass.

Surfaces could become a portion of an interactive system. Billions of NRs could be applied to surfaces, which would include sensors and decision algorithms, which could interact with an external operational system capable of changing the system. The possibilities of NR applications are endless. The devices would become a new "platform" like the Internet or smartphone apps.

In the biomedical area, applications in diagnostics, drug delivery, neural interface, microsurgery, and metabolic monitoring will open a new era in providing personalized, effective, and lower-cost medicine.

II. Technology

The original RFID was conceived in July 1969 and patented in May 1970 and issued January 1973. Since then, hundreds of billions of RFIDs have been produced and used for tracking, inventory and other related purposes. The impact of RFID has been multifaceted since inception in 1969, with applications in transportation, logistics, medicine, agriculture, retail, manufacturing, military, architecture, finance, real estate, and security (to list a few general areas) [1], [2].

One overarching trend in the development and proliferation of RFID is scaling and miniaturization, while also increasing their capabilities [3], [4]. Now we are at a point in technological development where it is possible to build a far-smaller NR that includes a nano computer that is as small as 150 nm in width and several microns in length and is imperceptible to the human eye. This would allow placing a communication and computer systems even within blood cells, or engine parts, fuel, food, everyday items. Only the imagination would be the limitation on what NRs could do.

Basic functions of an RFID include harvesting of RF energy (antenna), demodulation of incoming RF to provide system power (passive power), decoding of information encoded in incoming RF and encoding of information in outgoing RF (transponder), storage and later retrieval of information (memory) and microcontroller/microprocessor function (logic). Of note is the growing number of sensor systems that potentially could be integrated into NRs [5].

A. What has Size got to do with it?

The trend to sub-millimeter size and smaller RFID devices has several key advantages:

1) Transparency: The user is unimpeded and can be unaware of the presence of RFID

2) Efficiency: Miniaturization enables lower power electronics

3) Cost: High volume manufacture with microlithography techniques allows cost to track on-chip (silicon) real estate, driving smaller scaling through cost reduction.

4) Embedding in almost everything: The low cost and nano-size of NRs make possible capitalizing on usage that so far is impossible, such as embedding in biological cells or paint finishes.

Roll-to-roll fabrication techniques are poised to reduce micro fabrication costs even further. Indeed, the dramatic improvements of microlithography, deposition, etch and planarization enables significant cost reductions through the application of fully depreciated nanofabrication technology, currently in the 15nm node for flash memory (the 10nm node is about to be marketed for high-end logic) [6].

With these well-known advantages for ultra-miniaturization of electronics, it may be surprising that the smallest RFID systems being marketed today are relatively large, with many marketed devices being multi-millimeter scale and elite devices topping out at ½ micron in smallest dimension. PharmaSeq has recently been awarded SBIR funding to create a series of devices starting at 250 microns and decreasing in subsequent generations to be implantable within cells [7]. However, PharmaSeq will be faced with the problem of a suitable antenna system.

The most significant impediment to progress in shrinking the size of NRs is antenna scaling. For 2.4 GHz communications systems, currently one of the standard antenna designs is relatively large, with compact designs down to a few millimeters in the literature [8]-[13]. The "antenna problem" represents an impediment, which must be solved for ultra-miniaturization to progress. As the size of the device decreases the amount of radiated energy the device receives also decreases, thus making communication with the device more difficult and unreliable – and requiring the communicating device to be closer and closer to the material in which the NR resides.

The antenna problem has several potential directions for resolution. Surface plasmon resonance technology has enabled nanoscale antennas to be created that operate from terahertz to optical frequencies. Magnetic particles as well as dendritic conductive oxides also represent technologies that have some potential to aid scaling [14]-[17]. But the key to effective use of these approaches may well be augmentation through the integration of multiple devices as a "swarm"— a coordinated ensemble to form an antenna array *in situ* to improve the communications range, analogous to e-VLBI (Very-Long-Baseline Interferometry) [18]. In this approach, the myriads of NRs would have a multiplier effect with the swarm antennae receiving the radiated energy and distributing it among all the NRs. The antennas individually are on the scale of the micro or nano transceivers. The plurality of antenna and associated transceivers are configured to collectively increase the receiving and transmitting "gain" of electromagnetic (RF, optical) radiation signals. This potentially would enable NRs to extend their communications range and in some cases enable communication with the NRs that otherwise be impossible.

B. Manufacturing of NRs

The smallest RFIDs are currently being manufactured in 90nm CMOS technology and have an area of approximately 2500 um^2. By employing the current most advanced CMOS manufacturing technology – 14nm – these same device capabilities can be shrunk to the size of a red blood cell (~8um diameter), or, with modified layout, to submicron dimensions in width, for example[1]. Fabrication using MEMS techniques

[1] Note regarding size that the red blood cell layout just provides an example for a feasible device size that could navigate within the human body. Using the same area to accommodate the circuitry, but employing a 150nm width, would be achieved in a filament 150nm by 335um long. This layout may even allow antenna fabrication or at least a significant portion of the antenna fabrication during the CMOS flow.

and SOI technology will facilitate sensor integration and device release from the substrate.

The principal challenge will be fabricating suitable antennae for devices in the micron and sub-micron scale. We envision employing techniques such as electroless plating and self-assembly to form and/or connect antennae and potentially ancillary modules to the NR devices. Antennas may incorporate many nodes where NR devices connect, allowing multiple devices and antennas forming synergistic arrays while there is R&D in reducing the size of RFIDs to nano scale the major IP of this team is the introduction of nano “swarm” antenna solutions coupled with the introduction of a distributive nano computer system.

C. Programming of NRs

The NRs would be programmed for specific functions. This could be achieved either by designing the circuitry of the nano devices to function in a specific manner (like pre-programmed ROM) or flashing the memory of the devices with simple code. In some instances, both types of programming methods could be employed for more complex applications. However, the systems that would be employed to achieve this would result from future research and development. Specific functions can be incorporated through a couple of methods. For a single application, ROM can be defined in the CMOS lithographic steps. If a more versatile functionality is required, then one-time programmable memory or multi-time programmable memory can be manufactured with suitable process flows in the CMOS manufacturing.

D. Insertion of the NRs

To obtain detailed information from various components of a complex system, the NR devices may be deployed in a variety of ways, depending upon the type of information and the kind of system. Nevertheless, while medical applications differ from industrial uses in terms of specifics, the strategies for deployment are similar, emphasizing the unobtrusive integration of information handling nodes close to the source of the desired information.

Industrial and consumer applications allow strategies including incorporation into the materials of construction—for example, stress sensors in high-load concrete, vibration sensors in critical aerospace joints, wear monitors in bushings and seals. Other strategies may comprise incorporation into the tape, decals and patches, and adhesive materials, paint, and specialty coatings. Any region that can tolerate a blood cell-sized inclusion at ambient temperature is a candidate location for an NR.

Medical applications would require forms suitable for topical application (static or trans-dermal patches, powder, lotion etc.), inhalation (aerosol), ingestion or injection of NRs devices into a living host. Appropriate formulation analogous to a pharmaceutical, including testing for safety, would be requisite. Truly sub-micron scale devices would be inserted within cells or even organelles using methods analogous to gene transfection technology (biolistic, electroporation, electrospray, etc.).

E. Operation of the NRs

The NRs would be interrogated and operated by means of a transceiver device. In this instance, the transceiver would send out a signal of a specific frequency or frequencies, which would serve to power the system and send and receive data. The most effective frequencies would vary among applications and systems. Near infra-red (near IR) and IR will be useful in medical, industrial and consumer applications for relatively close to the surface applications. Millimeter wave and microwave frequencies have significantly better penetrating ability. It is important to recognize that the size regime of the device is smaller than even millimeter waves, which makes antenna design potentially more challenging.

Dermal and transdermal medical applications may be able to use IR and near-IR light, while deeper insertion of devices into living systems will necessitate the use of longer wave lengths, which have deeper penetration capability. Similarly, for industrial and consumer applications, near-IR and IR would be potentially useful for surface treatments, while longer wavelengths would be necessary for buried or obscured locations. Antenna design and fabrication are therefore intimately related to the specific requirements of the application. Advanced systems of NR devices may rely on relaying information from device to device as a mesh network (like cell phones talking one to another to create a communications system that is not dependent on cell towers) to partially address these concerns. This “swarm” approach should be scalable and tunable to meet the different demands and conditions of various uses of NRs.

Once the NR is powered by the external energy source, operations are straightforward. Encoded in the transmission of power to the device or as a secondary channel, digital instructions would be received and decoded by the NR and sent to an onboard microcontroller, which then would orchestrate the functions of memory, sensing and communications. One key feature of this approach is that advanced systems form networks allowing multiple devices to share information, resources and computing power in a distributive manner. It may be possible that specific NRs in the same “swarm” of NRs have different functionality and logic.

F. Cost of NRs Ecosystem

In considering the application of NRs, it is important that a total ecosystem cost be developed. The cost analysis for this major new technology ecosystem will vary from application to application. In simple applications, such as inventory tracking within a supermarket, the cost of NRs may be much lower than existing systems. In this case, the labels of the various products would have embedded the NRs for both inventory control and check out (replacing UPC codes). Such a system would also reduce the cost of restocking as dates for products are accessed at check out. Moreover, consumers can be charged without the need of clerks. At home, the NRs would enable consumers to monitor what they have within their residences. There are many other possible applications using simple NRs, many of which cannot be foreseen now, just at the ideas and functions behind the more than 1.5 million apps for the iPhone were not imagined by its inventors when the device debuted in 2007.

For the red blood cell-sized NRs manufactured on 300mm wafers, the number of potential die (units) would be on the order of 1 billion. With the cost of a 300mm wafer manufactured in a 14nm flow (est.$10K); the unit RFID cost would be on the order of $0.00001 ($10K/10^9). Post processing for attaching antennae, separation from the substrate, "packaging" and testing, etc., would increase the cost by perhaps a factor of 3. Even with substantially costlier post-fab processing steps, the NR's unit cost would be very attractive.

In more complicated applications, such as auto monitoring and biomedical, the cost would be higher. However, now is not possible to determine the cost of this or for that matter any NRs ecosystems.

III. Possible Applications

Successful ultra-miniaturization of RFID technology has the near certain potential to expand many current applications and open entirely new application that relies on compact packages (i.e., aerospace, security, biomedical), and/or low cost (retail, agriculture, logistics). New applications include swarm-based remote sensing, process control, biological mapping, therapeutics and diagnostics, authenticity verification, ecological monitoring, soil and water analysis, air quality reporting, inventory control, materials QA, and many others.

A. Biomedical

In a biomedical application, it is possible for NRs to collect data on certain vital functions if those devices also contain specific sensory capabilities. At the same time, NRs are possibly the only way to collect this data, as the sensors must be nano sized to collect data on these vital functions. These sensors then can use the communication functions of the NRs to transmit that data to the interrogator. Moreover, the NRs can also be used to deliver specific medications to a designated area within an individual, such as to a cancer cell. Since the device can receive signals, its location can be tracked by the reflected data.

It may be possible for NRs to enter the brain to deliver information, which may have negative as well as positive implications. Biomedical applications include the potential for extracellular as well as intracellular implants for diagnostics and therapeutics. Neuronal implants could yield very precise manipulation of signal processing (i.e. seizures, input-output errors, tinnitus). Man-machine interface may be facilitated in this way, enabling information to be encoded directly (*direct-write*) into the optic and auditory nerves from external sources (potentially direct-write of information into the areas of memory and processing). *Direct-read* of implanted arrays would facilitate detailed extraction of complex representations of information being processed within the brain.

Entire organs may be monitored in three dimensions with suitable miniaturized NR devices introduced intravenously or implanted with the organ. The applications of NRs to vials, petri dishes, microwell plates, cell culture media, and other consumables allows precise tracking. The tracking of medicine can ensure correct doses are administered at correct times with logging of salient data (identity, approval, storage location, inventory, authenticity, ownership, etc.). An audacious proposal is the incorporation of nanopore technology that could enable proteomics and other "omics" data to be acquired locally and compared across organs and entire individuals to map gene expression. Incorporation of antibodies into NRs would enable the self-directed tagging of specific cell types and tissues of every organ. Once tagged, the NRs could assay through onboard sensing and then render treatment at that location for example, a magnetically susceptible tag could be inductively heated to destroy a small volume of tissue with precision. Extensive studies and testing of the long-term effects of insertion of NRs into the human body would be required before these devices could be approved for use in humans.

B. Commercial

In a commercial application of NRs, the potential uses are numerous. These devices can be embedded in the surface of any item. This can provide a means of tracking of those items such as batch number, date of expiration, cost, location, and have the ability for this or similar data to be updated. Therefore, inventory control could become a much simpler task. NRs can be embedded in such things as paint so that it is possible to determine when a room was painted what were the original colors, etc. These devices could also be embedded in many items to determine if they are counterfeit or original.

A possible application of NRs is in the automobile industry. The devices could be implanted in each component of the vehicle. By coupling these devices with sensors, it may be possible for real-time feedback from any of the components of the vehicle. This could include such things as stress levels, failures, need for repair, or other data, which possibly can then be retransmitted to the owner of the vehicle and/or the manufacturer. If the NRs were injected into the fuel, they could potentially provide feedback to the vehicle's control system to adjust the efficiency of the engine's consumption of fuel. The application of these devices would also assist in finding stolen vehicles and external tracking of the vehicles. It may be possible to design LIDAR (Light Detection and Ranging) systems that cover the entire vehicle providing a shell of information of the vehicle surroundings and notifications. Table 1 illustrates potential uses for vehicle smart highways.

Another commercial application of NRs is in the airline industry. Counterfeit parts for commercial airlines are a problem posing especially great safety hazards. Coating of airline parts by a manufacturer in such a way that the coding could not easily be removed, could ensure that the part was genuine. NRs also could be integrated into parts subjected to vibrational stress to identify wear as well as to track the parts from the cradle to the grave, especially those with critical replacement schedules. On engineering test stands, these invisible devices could provide strain gauge, thermal and vibrational measurements with high spatial resolution. Propellant, coolant and environmental systems might include chemical sensing functionality to identify leaks and provide control data.

TABLE I. NANO RFID MODULES FOR A SMART HIGHWAY

Function	**Tagged Materials**	**Advantage**
Building information modeling (BIM)	Infrastructure- mortar, paint, asphalt, moldings and other plastic parts	Precise measurement and survey of infrastructural elements; updates with improvements and modifications.
Maintenance	Infrastructure- mortar, paint, asphalt, moldings and other plastic parts	Logging of installation, repaving, retrofitting, inspection; updates with improvements and modifications.
Hazards awareness	Signage- phosphorescent paint, plastic	Updated aspects of specific hazards- wetting, icing, road closure, detour.
Toll Collections (FasTrak, etc.)	Infrastructure, signage	Updated aspects of fee for use; interactive with vehicular tags & permits.
Parking coordination	Infrastructure, signage	Updated aspects of fee for use; interactive with vehicular tags & permits.
Collision avoidance	License plate- stickers, paint; molded plastic parts	Communications between vehicles and between infrastructure and vehicles for proximity and range data.
Lighting management	Consumable parts, molded plastic, paint	On-demand lighting for traffic to conserve power, especially solar powered installations.
Road markings	Phosphorescent paint, plastic tape	Updated aspects of specific statutes, ordinances, and hazards.
Navigation	Signage	Updated aspects of specific locations- routing, local services, and attractions
Flow (roadway-vehicle and vehicle-vehicle)	Infrastructure, signage	Situational awareness enhanced by vehicles and infrastructure communicating as a "flock", a holistically coordinated group as a moving system.

Security applications for NRs include invisible and difficult-to-remove tracking devices, including providing biometric data to individuals. Specific locations may be unobtrusively marked allowing precise relocation at a later time, with the remote extraction of data. The potential of creating very large arrays of nano-devices (nano e-VLBI) may enable significant range, allowing GPS or analogous systems to provide real time location information. High signal strength, high-resolution interrogation of very large sets of these arrays might be accomplished from mobile platforms (e.g. AWACS) to provide detailed information from the specific territory.

NRs for systems encryption may yield very strong encryption (potentially quantum encryption), and the system's complexity provides a dual challenge to would-be forgers and counterfeiters. Ownership may also be authenticated augmented through biometric data. Munitions and arms, documents, containers, currency, vehicles, personnel, materials, infrastructure, the territory may be tracked and interrogated for data provided by onboard sensing. Highly sensitive systems (CBN systems) may be authenticated. [2] Interlocks may be designed with integrated NR to assure safe operations—an additional feature here is that the historical state of the system (when interlock has been activated and for how long) may easily be tracked, potential capturing biometric data.

NRs directly enable the Internet of Things (IoT) for retail purposes. Packaging can track expiration, storage and quality of contents. A classic example is a refrigerator that monitors its own contents, where each item inside can report to the refrigerator its individual history. This extends to all consumable materials inventories—cold storage warehouses, transportation, displays, production lines. Wearables may coordinate invisible networks of NRs collecting user data. Compatibility of cartridges and modules with the systems they are associated can be assured.

NRs could be employed for a home inventory system. If packages contained information such as use date, buy date, and item information, it would be possible for an external interrogator, such as a refrigerator or pantry device, to quickly assess what buying decisions may be necessary.

C. *Agriculture*

Agricultural applications include on-site soil science (moisture, fertilizer, temperature, minerals), monitoring of plant growth and ripening (ethylene sensing), and tracking of agricultural products for quality. To monitor quality, dilution with sub-standard material could be ascertained by monitoring the concentration of NRs within a freight car of grain, corn syrup, protein concentrate, meat, etc. Similarly, the application of pesticides and fertilizer could be precisely tracked if NRs were incorporated into these materials at constant levels and then assessed as deposited or after. As noted above, the history of storage conditions could be ascertained to ensure safety and food security through reduced spoilage and contamination. Water quality could be determined and monitored through the incorporation of NR-sensors in water storage and delivery systems, for example monitoring arsenic, turbidity, chlorination, etc.

D. *Military*

The military applications of NRs could change warfare as we know it. The obvious uses of these devices for tracking of materials, personnel, and operations can greatly improve the logistic of the military. Many of the commercial uses discussed above are also applicable to military uses. However, consider the application of NRs for "friend or foe" identification. While larger RFIDs can possibly be

[2] This application is analogous to MEMS systems developed at Sandia National Labs in the early 2000s but would be considerably more efficient both in application and cost.

compromised, those embedded in clothing, individuals' skin or for that under the skin of personnel, may be difficult to counterfeit or detect. This would also accommodate more easily identifying personnel who, due to injury resulting in death, otherwise could not be easily identified. The NRs could contain medical data that could be accessed immediately to administer to a wounded, injured or sick person.

The weaponization of NRs may be possible. In this instance, a weapon could be like the medical application where the device delivers a drug that debilitates or kills combatants without their knowledge that they have been injected with deadly or debilitating NRs. However, the international laws may prohibit certain applications of weaponized devices – and in fact, the NR community could lead the way in proposing international bans on such weapons under the Biological Weapons Convention (BWC) and the Chemical Weapons Convention (CWC).

E. Environmental

Environmental monitoring could be an application. Air and water transport could be monitored downstream from an upstream release. NRs could be used directly, or mounted on aerodynamic assist systems (dandelion seed, insect, MEMS). As discussed above, array enhanced signals could allow for the significant standoff in the case of monitoring or assessing hazardous environments.

F. Other

Many of the applications above are process control applications. Industrial processes may be monitored in detail by use of NRs. Circulating coolant can report temperature at key locations, potentially mapping turbulent systems. Conditions within bioreactors might be mapped in 3-D (pH, lactate, Ca++, etc.). Fluid flow, loading, temperature, vibration are ubiquitous data in chemical engineering that may be captured with high resolution. Reporter-NRs might be incorporated in drug intermediates in the process and be used to track reaction rates, the process time for the batch, etc.

IV. Neutralization and Destruction of NRs

Magnetic extraction could be very useful for removing NRs from fluids (assuming magnetic susceptibility of the NRs). EMP or focused radiation may be useful for destroying or deactivating unwanted NRs. Indeed, corollary countermeasures would be valuable to control for unintended information propagation for many of the above applications. Incorporation of specific vulnerability (self-destruct code, specific poison, magic frequency, etc.) into NRs may also be very helpful for some applications. (What about "dead" nano RFIDs in the environment – as we have seen the concern about nanoparticles ending up in the ocean and in fish?)

We will need to seriously consider both the positive and negative aspects of various uses of NRs to society, including the implications for privacy, for health from use in the human body, and for the impact of the distribution of NRS throughout the environment. Being at the forefront of developing NRs to harness the potential for good, should enable us to also be at the forefront of efforts to ensure such devices are not misused, intentionally or inadvertently.

References

[1] http://www.rfidjournal.com/articles/view?392

[2] https://www.transcore.com/sites/default/files/History%20of%20RFID%20White%20Paper.pdf

[3] http://www.energyharvestingjournal.com/articles/1283/light-powered-microtransponders-for-miniaturized-rfid-tracking

[4] http://www.nsf.gov/news/newsmedia/2015_BIO_Innovation_Zone_NSF_media_guide.pdf

[5] http://www.rfidjournal.com/search?q=sensor&x=0&y=0

[6] http://www.sandisk.com/about-sandisk/press-room/press-releases/2014/sandisk-announces-15-nanometer-technology,-world's-most-advanced-nand-flash-manufacturing-node/

[7] http://www.pharmaseq.com/index.php/company/news-events/press-releases/26-2013/87-nsf-awards-sbir-grant-to-pharmaseq-to-develop-a-radio-p-chip-for-intercellular-sensing

[8] http://electronics.stackexchange.com/questions/18826/whats-the-technical-limit-to-how-small-rfid-like-system-antenna-can-be

[9] http://www.jpier.org/PIERL/pierl26/12.11080306.pdf

[10] http://www.snopes.com/photos/technology/smartdust.asp

[11] http://www.hitachi.com/New/cnews/070213c.html

[12] http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6559513&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6559513

[13] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.73.5757&rep=rep1&type=pdf

[14] http://scitation.aip.org/content/aip/journal/jap/104/9/10.1063/1.2973198

[15] http://www.ncbi.nlm.nih.gov/pubmed/25958501; http://www.onecentralpress.com/wp-content/uploads/2014/12/CHAPTER-1-MG-14-CORRECTED.pdf

[16] http://link.springer.com/chapter/10.1007%2F978-1-4419-1011-0_7#page-1; https://www.osapublishing.org/aop/viewmedia.cfm?uri=aop-1-3-438&seq=0

[17] http://arxiv.org/abs/cond-mat/0104104; http://m.sciencemag.org/content/329/5994/930.short

[18] http://www.jive.nl/astronomers-demonstrate-global-internet-telescope