Smart Dust: Free Space Optical Network

Kavindra Kumar Singh

School of Computer and Systems Sciences
Jaipur National University
Jaipur, Rajasthan (India)

Abstract: Smart dust is a system of many tiny Micro Electro-mechanical systems (MEMS) such as sensors, robots, or other devices, that can detect, for example, light temperature, vibration, magnetism, or chemicals. They are usually operated on a computer network wirelessly and are distributed over some area to perform tasks, usually sensing through radio-frequency identification. Without an antenna of much greater size the range of tiny smart dust communication devices is measured in a few milli-meters.

Keywords: MEMS, Radio Frequency, Communication Devices, Sensors, CCR

1. Introduction

Smart dust is a tiny dust size device with extra-ordinary capabilities. Smart dust combines sensing, computing, wireless communication capabilities and autonomous power supply within volume of only few milli meters and that too at low cost. These devices are proposed to be so small and light in weight that they can remain suspended in the environment like an ordinary dust particle. These properties of Smart Dust will render it useful in monitoring real world phenomenon without disturbing the original process to an observable extends. Presently the achievable size of Smart Dust is about 5mm cube, but we hope that it will eventually be as small as a speck of dust. Individual sensors of smart dust are often referred to as motes because of their small size. These devices are also known as MEMS, which stands for micro electro-mechanical sensors.

2. Background

The Defence Advanced Research Projects Agency (DARPA) has been funding Smart Dust research heavily since the late 1990s, seeing virtually limitless applications in the sphere of modern warfare. So far the research has been promising, with prototype smart dust sensors as small as 5mm.But further scaling down needs advance technological changes. Costs have been dropping rapidly with technological innovations, bringing individual motes down to as little as $50 each, with hopes of dropping below $1 per mote in the near future.

Global Research
Researcher Forum

Journal of Global Research Computer Science & Technology
(JGRCST)
Vol-I, Issue-II, July 2014
ISSN: 2349 - 5170

3. Smart Dust Structure

A smart dust particle is often called motes (Fig. 1). One single mote has a Micro Electro Mechanical System (MEMS), a semiconductor laser diode, MEMS beam steering mirror for active optical transmission, a MEMS corner cube retro-reflector for passive optical transmission, an optical receiver, a signal processing and control circuitry, and a power source based on thick-film batteries and solar cells.
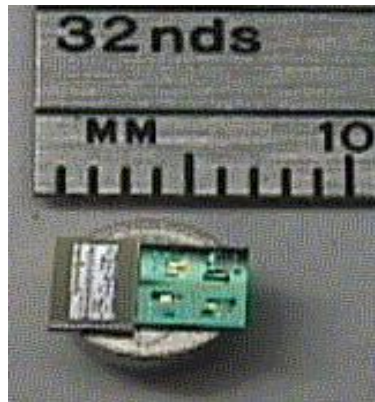

Fig 1.Smart Dust Mote

A major challenge is to incorporate all these functions while maintaining very low power consumption and optimizing the operating life of the mote. The structure of a single moat is shown in Fig 2. Smart dust motes consist of a passive optical transmitter with a micro fabricated corner- Cube Retro-reflector (CCR). This CCR contains three mutually perpendicular mirror fabricated of gold- coated poly-silicon. The CCR reflects any ray of light within a certain range of angles centred about the cube diagonal back to the source.

CCR comprises three mutually perpendicular mirrors of gold-coated poly silicon. The CCR has the property that any incident ray of light is reflected back to the source (provided that it is incident within a certain range of angles centred about the cube's body diagonal). If one of the mirrors is misaligned, this retro-reflection property is spoiled. The micro-fabricated CCR includes an electrostatic actuator that can deflect one of the mirrors at kilohertz rates. It has been demonstrated that a CCR illuminated by an external light source can transmit back a modulated signal at kilobits per second. Since the dust mote itself does not emit light, the passive transmitter consumes little power. Using a micro-fabricated CCR, we can achieve data transmission at a bit rate up to 1 kilobit per second, and over a range up to 150 meters, using a 5milliwatt illuminating laser.
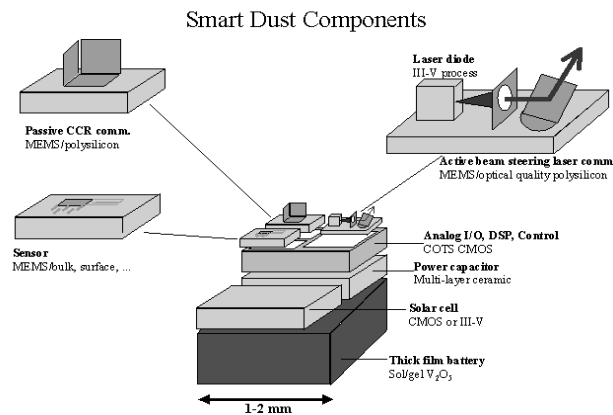
Fig.2 Structural Components of a Smart Dust Mote

The power system consists of a thick-film battery or a solar cell, or both with a charge-integrating capacitor (power capacitor). The thick film battery of sol or gel V2O3 provides as a backup in darkness, while solar cells generate energy from sunlight. Depending on its objective, the design integrates various sensors, including light, temperature, vibration, magnetic field, acoustic, and wind shear, onto the mote. Active transmitters make possible peer-to-peer communication between dust motes, provided there exists a line-of-sight path between them.
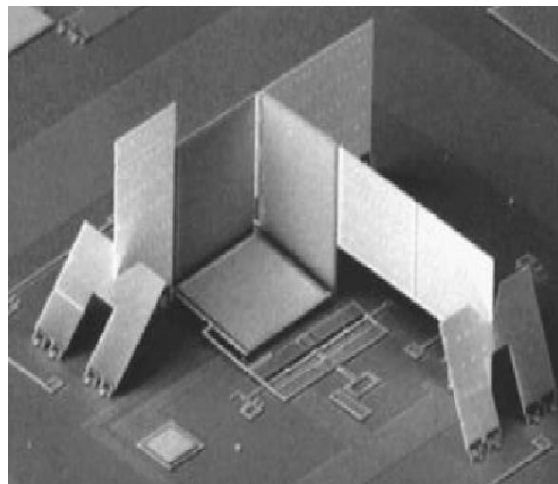

Fig.3 Corner-Cube Retro-reflector (CCR)

4. Corner Cube Retro-Reflector (CCR)

One should note that CCR-based passive optical links require an uninterrupted line-of-sight path. Moreover, a CCR-based passive transmitter is inherently directional; a CCR can transmit to the BTS only when the CCR body diagonal happens to point directly toward the BTS, within a few tens of degrees.

Global Research
Researcher Forum

Journal of Global Research Computer Science & Technology
(JGRCST)
Vol-I, Issue-II, July 2014
ISSN: 2349 - 5170

A passive transmitter can be made more Omni-directional by employing several CCRs oriented in different directions, at the expense of increased dust mote size. If a dust mote employs only one or a few CCRs, the lack of Omni-directional transmission has important consequence on feasible network routing strategies.
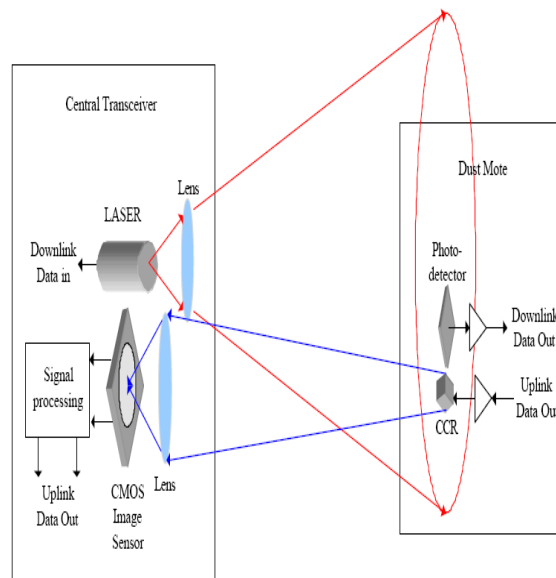

Fig. 4 Free Spaces Optical Network

Fig 4 illustrates a free-space optical network utilizing the CCR-based passive uplink. The BTS contains a laser whose beam illuminates an area containing dust motes. This beam can be modulated with downlink data, including commands to wake up and query the dust motes. When the illuminating beam is not modulated, the dust motes can use their CCRs to transmit uplink data back to the base station. A high frame-rate CCD video camera at the BTS sees" these CCR signals as lights blinking on and off. It decodes these blinking images to yield the uplink data. This uplink scheme achieves several kilobits per second over hundreds of meters in full sunlight. At night, in clear, still air, the range should extend to several kilo meters.

Because the camera uses an imaging process to separate the simultaneous transmissions from dust motes at different locations, we say that it uses space-division multiplexing. The ability for a video camera to resolve these transmissions is a consequence of the short wavelength of visible or near-infrared light. This does not require any coordination among the dust motes, and thus, it does not complicate their design.

5. Challenges

The hardware design has to face many challenges due to the small size of the Smart Dust. First of all, it is hardly possible to fit current radio communication technology into Smart Dust both size wise and energy wise. The present radio communication has large antennas and thus requires larger space. The energy requirements are also high. So, a more size and power efficient passive laser based communication schemes have to be adopted. But it also has its share of disadvantages.

Another factor of concern is the energy consumption by the Smart Dust. With devices so small, batteries present a massive addition of weight. It is therefore important to use absolutely minimal amounts of energy in communicating the data they collect to the central hubs, where humans can access it.

6. Communication Technologies

Primarily, two technologies can be used for Communication between the motes and the BASE station Transceiver (BST), they are as follows:

A. *Radio Frequency Transmission*
B. *Optical transmission technique*

1) Passive Laser based Communication
2) Active Laser based Communication
3) Fibre Optic Communication

6.1 Radio Frequency transmission

It is based on the generation, propagation and detection of electromagnetic waves with a frequency range from tens of kHz to hundreds of GHz. It could be used to function as both the uplink and the downlink. Since RF transceiver typically consists of relatively complex circuitry, it is impossible to achieve the required low power operation using such an approach in a smart dust system. When large numbers of motes are involved in smart dust, RF links may employ alternative multiplexing techniques: time, frequency or code-division multiplexing. Their use leads to modulation, band pass filtering, demodulation circuitry, and additional circuitry, all of which needs to be considered based on power consumption. RF communication can be used for smart dust communication but it poses following problems:

1) Size of the antenna: Since the size of the antenna should be ¼ of the carrier wavelength, if we reduce the size of the antenna (which is very difficult to achieve) the wavelength of the carrier wave will decrease,

thus requiring high frequency transmission. This system will no longer comply with low power consumption requirement of the small dust.

2) RF communication can only be achieved by using time, frequency or code division.

3) Multiplexing (TDMA, FDMA, or CDMA) each having their own complications. For TDMA mote should transfer at high bit rate (as high as aggregate uplink capacity) in absence of other transmission. Beside this, mote should coordinate their transmission with other mote. In FDMA, the accurate control of oscillator frequency is required. Since CDMA operates for a relatively extended time interval, it requires high-speed digital circuitry and it consumes excessive power. Both FDMA and CDMA should avoid coordination between dust motes and they require dust motes to be pre programmed with unique frequencies or codes in order to prevent such coordination.

6.2 Optical Transmission Technique

1) Passive Laser based Communication

The Smart Dust can employ a passive laser based communication scheme to establish a bi-directional communication link between dust nodes and a base station transceiver (BST). For downlink communication (BST to dust), the base station points a modulated laser beam at a node. The latter uses a simple optical receiver to decode the incoming message. For uplink communication (dust to BST), the base station points an un-modulated laser beam at a node, which in turn modulates and reflects back the beam to the BST. For this, the dust nodes are equipped with a Corner Cube Retro Reflector (CCR). The CCR has the property that any incident ray of light is reflected back to the source under certain conditions. If one of the mirrors is misaligned, this retro reflection property is spoiled. The Smart Dust CCR has an electrostatic actuator that can deflect one of the mirrors at kilohertz rates. Using this actuator, the incident laser beam is "on-off" modulated and reflected back to the BST.

This type of design implies a single-hop network topology, where dust nodes cannot directly communicate with each other, but only with a base station. The base station can be placed quite far away from the nodes, since the employed laser communication works over a range of hundreds of meters, provided a free line-of-sight between the BST and the nodes. Communication may suffer from significant and highly variable delays if the laser beam is not already pointing at a node that is subject to communication with the BST. Smart Dust nodes can be highly mobile, since nodes are small enough to be moved by winds or even to remain suspended in air, buoyed by air currents.

Advantage of optical links-

1) Optical transceivers require only simple baseband analog and digital circuitry; no modulators, active band pass filters or demodulators are needed.

2) The short wavelength of visible or near-infrared light (of the order of 1 micron) makes it possible for a milli meter-scale device to emit a narrow beam (i.e., high antenna gain can be achieved).

Global Research
Researcher Forum

Journal of Global Research Computer Science & Technology
(JGRCST)
Vol-I, Issue-II, July 2014
ISSN: 2349 - 5170

3) A base-station transceiver (BTS) equipped with a compact imaging receiver can decode the simultaneous transmissions from a large number of dust motes at different locations within the receiver field of view, which is a form of space-division multiplexing.

4) The CCR makes make it possible for dust motes to use passive optical transmission techniques, i.e., to transmit modulated optical signals without supplying any optical power.

Requirements for Passive Laser-based Transmission:

1) Successful decoding of these simultaneous transmissions requires that dust motes not block one another's line of sight to the BTS. Such blockage is unlikely, in view of the dust motes' small size.

2) A second requirement for decoding of simultaneous transmission is that the images of different dust motes be formed on different pixels in the BTS imaging receiver. For example, suppose that the BTS views a 17-meter by 17-meter area containing Smart Dust, and that it uses a high-speed video camera with a 256 by 256 pixel-imaging array. Each pixel views an area about 6.6 centi meters square. Hence, simultaneous transmissions can be decoded as long as this distance separates the dust motes.

2) Active Laser based Communication

Active optical communication typically uses an active-steered laser-diode based transmitter to send a collimated laser beam to a base station. This system contains a semiconductor laser, a collimating lens and a beam-steering micro-mirror as shown in Figure 2. Active optical communication is suitable for peer-to-peer communication, provided there exists a line of sight path between them. Using MEMS technology, the components of the active communication network can be made to be small enough to fit into the smart dust motes.

One of the disadvantages of the active transmitter is its relatively high power consumption. This leads to the use of active optical communication for short duration burst-mode communication only. In order to minimize the power consumption, the active transmitter should have some protocol to aim the beams toward the receiver, for example, using directional beam and an active beam-steering mechanism. These components would make the design of the dust mote more complicated.

Active communication has the advantage of high power density. This provides capable for optical wireless communication over enormous distances. Using active optical communication one can form multi-hop networks. Burst-mode communication provides the most energy-efficient way to schedule the multi-hop network. The active laser-diode transmitter operates at up to several tens of megabits per second for a few milliseconds.

3) Fibre-optic communication

Global Research
Researcher Forum

Journal of Global Research Computer Science & Technology
(JGRCST)
Vol-I, Issue-II, July 2014
ISSN: 2349 - 5170

Fibre-optical communication employs semiconductor laser, fibre cable and diode receiver to generate, transfer and detects the optical signal. Its most of the characteristics matches with that of passive optical communication. The relatively small size of the optical transceiver is employed with low-power operation. Each dust mote does not need to have an on board light source to transmit the data. By the using MEMS technology, Corner cube retro-reflector is employed on each dust mote to modulate uplink data to base station.

For downlink, a single laser transmitter in base station generates an on-off-keyed signal containing downlink data and commands. The beam splitter divides the interrogating signals into the fibres that are connected to each dust mote. After passing through optical isolator, the signals go into directional coupler. Directional coupler divided them into two fibres. One of them will be passed while the index-matching material blocks the other. Finally, after passing GRIN-rod lens, the signals reach to the receivers of each dust mote. On the uplink, each dust mote is equipped with a CCR. CCR modulates interrogating beams from the base station and reflects these signals back to fibre cable. The directional coupler divides the signals into two fibres. The signals in the fibre that is connected to the optical isolator will be blocked, and the signals in the other fibre will reach to the receiver in the base station.
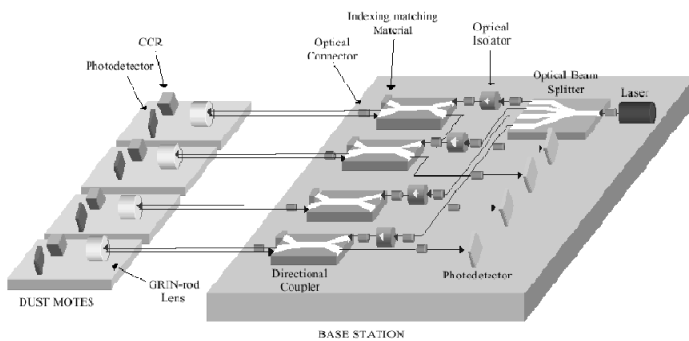

Figure 4: Fibre-optic Communication Setup

Fibre-optic communication has advantages and disadvantages over a passive free-space optical communication. Since optical fibre communication employs fibre cables to transfer and receive optical signals, it does not require the unbroken line-of-sight, the link directionality, and human eye safety from laser is maintained. Each dust mote does not need to employ more than one CCR, and the communication between dust motes and a base station can be guaranteed. In addition, it has a longer range of communication link than that of a free space passive optical communication.

However, fibre-optic communication has a limitation on the application. The optical fibre cables restrict the mobility of dust mote. Since a base station should employ several optical components for fibre connection to each dust mote, it may complicate base station design.

7. Application of Smart Dust

Not only does the Smart Dust remain suspended in the air for hours, the air currents can also move them in the direction of flow. It is very hard to detect the presence of the Smart Dust and it is even harder to get rid of them once deployed. Moreover it does not cost much so can be densely deployed. Due to the above-mentioned features, Smart Dust can be used in varied application fields. These are as follows:

1) Environmental protection (identification and monitoring of pollution).
2) Habitat monitoring (observing the behaviour of the animals in their natural habitat).
3) Military application (monitoring activities in inaccessible areas, accompany soldiers and alert them to any poisons or dangerous biological substances in the air).
4) Indoor/Outdoor Environmental Monitoring
5) Security and Tracking
6) Health and Wellness Monitoring (enter human bodies and check for physiological problems)
7) Power Monitoring
8) Inventory Location Awareness
9) Factory and Process Automation
10) Seismic and Structural Monitoring
11) Monitor traffic and redirecting it

8. Conclusion

There are many on-going researches on Smart Dust, the main purpose of these researches is to make Smart Dust mote as small as possible and to make it available at as low price as possible. Soon we will see Smart Dust being used in varied application from all spans of life.

References

[1] Yunbin Song: "Optical Communication Systems for Smart Dust"

[2] J. M. Kahn, R. H. Katz, K. S. J. Pister: Next Century Challenges Mobile Networking for "Smart Dust"

[3] An Introduction to Microelectromechancal System Engineering:Nadim Maluf, Kirt William

[4] B.A. Warneke, M.D. Scott, B.S. Leibowitz: Distributed Wireles Sensor Network

[5] http://www.coe.berkeley.edu/labnotes