Smart Dust

UH ISRC Technology Briefing
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1 Introduction

"Smart Dust" is an emerging technology made up from tiny, wireless sensors or "motes." Eventually, these devices will be smart enough to talk with other sensors yet small enough to fit on the head of a pin. Each mote is a tiny computer with a power supply, one or more sensors, and a communication system (Hsu, Kahn, and Pister 1998, p. 1).

Commercially available motes do not yet fit on the head of a pin; some are about the size of a deck of cards and others are as small as a stack of a few quarters (Eng 2004). Smart dust motes are typically outfitted with environmental sensors which can monitor things like temperature, humidity, lighting, position, and acceleration (Crossbow 2004a). And one vendor, SkyeTek, sells a sensor that can read RFID tags (SkyeTek 2005).

Dust mote battery life ranges from a few hours to 10 years, depending on the size and capabilities of the device (Bigelow 2004). Future motes will be smaller and have longer battery lives. Already, researchers at the University of California, Berkeley (UC Berkeley) have developed a mote roughly the size of an aspirin tablet (Yang 2003). For power, future motes could be supplemented by solar cells or even be powered by *"vibrations in the wall – a bit like a self winding wristwatch"* (Manjoo 2001).

There are numerous applications for smart dust technology, and as motes become smaller, cheaper, and better understood many other uses will emerge. Three potential applications of smart dust technology are illustrated here – one involving a forest service organization, another for a chemical plant, and one for a provider of lighting and power.

A forest service could use smart dust to monitor for fires in a forest (Eng 2004). In this scenario, forest service personnel would drop the dust from an airplane and then count on the sensors to self-organize into a network. In the event of a fire, a mote that notices unusual temperatures in its zone would alert neighboring notes that would in turn notify other motes in the network. In this way the network of motes would notify a central monitoring station of the fire and the location of the mote that noticed it. Equipped with prompt notice of the fire and its approximate location, firefighters could race to the scene and fight the fire while it is small. By linking similar networks of motes to a central fire reporting system, the system can be extended to monitor an enormous region in a national forest.

Motes will be applied in industrial settings to reduce plant downtime and enhance safety. Consider the scenario of a chemical plant that utilizes pipes to transport acidic or abrasive liquids. The chemical contents of the pipes can gradually weaken them so, to prevent accidental chemical releases, plant operators must periodically inspect piping and other *"components that may be susceptible to wall thinning caused by erosion/corrosion"* (Jonas 1996). Today, this inspection process is labor intensive for pipes covered with insulation and for pipes located in confined areas. In the future, smart dust could be employed to facilitate inspections. With this, a plant operator would place several corrosion-detecting motes on piping throughout the plant and then configure a central monitoring station to receive status updates from the motes. And because the motes can be installed under pipe insulation, plant personnel would no longer need to manually remove insulation to evaluate the condition of a pipe (Gibbons-Paul 2004). With this system, the plant manger benefits from having up-to-date status information of all piping while avoiding the costs of manual inspections.

In business, smart dust will be applied in similar innovative ways to improve services and save money. One such scenario involves a local lighting and power organization. Today, in order to determine which of thousands of street lights, are out or in need of service the power company periodically surveys the lights after sunset or waits for a customer complaint. But imagine if the organization monitored its service area with thousands of cheap, light-sensor equipped motes. The firm can now immediately pinpoint the location of non-working lights without incurring the labor and transportation costs of a physical survey. Repairs can be organized in a more systematic manner, complaint calls can be reduced, and customers will be more satisfied (Wired 2003).

This paper focuses on business applications of smart dust. It begins with an executive overview of the technology which is followed by a discussion of current and potential business applications. Also, the cost of smart dust technology and a list of vendors is presented. Before concluding, the paper highlights problems and issues associated with smart dust.

2 Overview of Smart Dust

This section describes smart dust, beginning with a summary of early development work at UC Berkeley. Also presented are two notable smart dust applications completed in the beginning stages of smart dust history. This is followed by a description of current smart dust offerings and expected trends for the technology.

2.1 History

Smart dust was conceived in 1998 by Dr. Kris Pister of the UC Berkeley (Hsu, Kahn, and Pister 1998; Eisenberg 1999). He set out to build a device with a sensor, communication device, and small computer integrated into a single package. The Defense Advanced Research Projects Agency (DARPA)[1] funded the project, setting as a goal the demonstration *"that a complete sensor/communication system can be integrated into a cubic millimeter package"* (Pister 2001). (By comparison, a grain of rice has a volume of about 5 cubic millimeters.)

In the early stages of the project, the team gained experience by building relatively large motes using components available *"off the shelf"* (Pister 2001). One such mote, named "RF Mote," has sensors for *"temperature, humidity, barometric pressure, light intensity, tilt and vibration, and magnetic field"* and it is capable of communicating distances of about 60 feet using radio frequency (RF) communication[2] (Pister 2000). If the mote operated continuously, its battery would last up to one week (ibid).

[1] DARPA is the agency that funded the research that became the basis for the Internet (Johnson 2003).
[2] RF communication is a common communications scheme that is found in household products such as the cordless telephone.

One of the issues that the UC Berkeley team faced in building smaller motes involved powering the device. Small batteries help minimize the size of the resulting mote, but they contain less energy than traditional, larger batteries and thus, they have shorter life spans[3] (Yang 2003). However, long battery life is critical to applications where it would be costly, inconvenient, or impossible to retrieve a smart dust mote in order to replace its batteries. This would be true, for example, with temperature and humidity-monitoring motes placed inside the walls of a building during its construction (Eisenberg 2002, cf. Pescovitz 2001).

Faced with the trade-off between miniaturization and long battery life, early smart dust developers leaned toward miniaturization. The Smart Dust project Web site states that *"[t]he primary constraint in the design of Smart Dust motes is volume, which puts a severe constraint on energy since we do not have much room for batteries or large solar cells"* (Pister 2001). However, the team applied tactics to conserve the available energy to prolong battery life. One approach, taken by Dr. David Culler, was to design *"software that enabled the motes to 'sleep' most of the time yet 'wake up' regularly to take readings and communicate"* (Schmidt 2004). This allows for energy conservation during the sleep period.

The UC Berkeley team equipped some of their early motes with optical communication systems in order to reduce power consumption and allow for a smaller device (Warneke et al. 2001). With this scheme, a mote designated as *"active"* was equipped with a transmitting device similar to what is found in the laser pointers used by presenters in business presentations (ibid, p. 48). Another energy-saving approach the researchers explored was passive transmission (Hsu, Kahn, and Pister 1998). A mote with a passive communication system does not have an *"onboard light source"* but instead it uses a series of mirrors controlled by a small electrical charge (Warneke et al. 2001, p. 47). When a laser is pointed toward the mote, it can rapidly adjust the position of its mirrors to send messages encoded in pulses of light; the message could then be read by a special optical receiver. This passive communication system proved effective in reducing energy consumption, but it has limitations because passive motes in a network cannot directly *"communicate with one another"* and instead have to *"rely on a central station equipped with a light source to send and receive data from other motes"* (ibid, p. 48).

A common mote communication scheme utilizes radio frequency (RF) signals to communicate over relatively short distances.[4] This allows designers to minimize mote size and power consumption (Webb 2003). When communicating, the devices compensate for this by passing each message to a neighboring mote which, in turn, passes the message on to another nearby mote, and so on, until the message reaches the destination – the central monitoring station

"The important part of this is that it's incredibly reliable because if one node goes down, another picks up the slack."

- Robert Conant, V.P. and co-founder, Dust Networks, quoted in *Signal Magazine* (Lawlor 2005)

[3] Solar cells have a similar design trade off. Large solar cell systems provide more energy than small ones.

[4] The maximum distance motes can transmit using RF communications is approximately 30 to 160 feet; the exact value for a particular type of mote depends on its design (Webb 2003, cf. SkyeTek 2005).

associated with the group of motes (ibid). This is not unlike a gossip grapevine (Vogelstein 2004). As implemented, the networks formed by motes are fairly robust; that is, a network of motes continues to perform even if some of its communication paths fail to operate. And once a mote is placed in an existing network, it adapts to blend in with the other nodes to form a larger network; and when a mote fails, the other devices in the network take over its load (ibid). The operation of motes in a mesh network has been described as analogous to the way a soccer team passes the ball until it reaches its destination (Kharif 2004).

During the course of the Smart Dust project, Professor David Culler and a team of researchers at UC Berkeley created the TinyOS operating system (Yang 2003). Once installed on a mote, this software is responsible for operating the device, managing its power consumption, and facilitating communication with other motes (ibid). The software is open-source and available at *http://www.tinyos.net* (Webb 2004).

The Smart Dust project resulted in laboratory and field demonstrations of a few generations of motes with names like Clever Dust, Deputy Dust, Daft Dust, and Flashy Dust (Pister 2001). More importantly, it spurred the interest of numerous other academic and corporate researchers. Two examples of their work are provided in the following section.

2.2 Early Applications

In a demonstration, smart dust was used to detect vehicles traveling through an isolated desert area in Palm Springs, California. The experiment, conducted with the U.S. Marine Corps, began when an unmanned airborne vehicle (UAV) flew over the area, dropped 8 motes (which were wrapped in protective foam) and then departed (Hill 2003). After deployment, the motes organized themselves into a network and then began to lookout for moving vehicles[5]; when a vehicle was detected, the mote recorded tracking information about the event. Eventually, the UAV plane flew over the scene and retrieved each node's tracking data and then, finally, returned to its home based to deliver the data it collected. The experimenters successfully downloaded the vehicle tracking information from the plane for display on a personal computer. In doing so, they showed how smart dust can be used by military and law enforcement personnel to unobtrusively monitor movement within a region.

Scientists at the University of California at San Diego approach smart dust from a biotechnology perspective to produce motes from chemical compounds rather than electrical circuitry (Sailor, Bhatia, Cunin 2002). While not yet commercially available, their motes have proved useful in laboratory environments (Link and Sailor 2003). One experiment demonstrated the use of smart dust to detect the presence of hydrocarbon vapors from approximately 65 feet away (Schmedake, T. A. et al. 2002). In this *"standoff detection,"* the researchers placed *"porous silicon 'smart dust' particles"* in a gas dosing chamber and monitored the experiment from a distance (ibid, p. 1270). Using a laser to illuminate the smart dust and a telescope outfitted with measurement equipment, the team detected the hydrocarbon vapors based on the changes in the light reflected from the smart dust after it had chemically reacted with the hydrocarbon vapors. While the experiment was limited to hydrocarbon vapors, the researchers predict that *"with appropriate chemical modification,"* the smart dust sensors used *"can specifically detect biomolecules, explosives, (and) chemical warfare agents*

[5] According to the author describing the study, the smart dust used sensors called *"magnetometers to detect deviations in the magnetic field caused by metal contained in the vehicles"* (Hill 2003).

such as Sarin" (ibid, p. 1270). As such, the standoff detection capability of smart dust will be of value to military and international weapons monitoring agencies.

2.3 Smart Dust Today

Tiny, ubiquitous, low-cost, smart dust motes have not yet been realized, however, some reasonably small motes are commercially available. One of these, the MICA2DOT[6], is available from Crossbow Technology, Inc. The unit becomes a mote once a small sensor board, coin battery, and antenna are added to the product (Crossbow 2004b). In addition, Crossbow sells larger motes (about the size of a deck of cards), which are compatible with more types of sensors. Other commercially available motes are sold by Dust Networks. This company offers motes which are *"about the size of a matchbook,"* operate on two AA batteries and have a 5-year battery life (Metz 2004).

Many of the sensors available for smart dust motes are micro-electromechanical systems (MEMS) (Hoffman 2003). MEMS contain microscopic devices, *"usually with a moving part,… integrated together with at least some electronic circuitry"* (Clarke 2002). MEMS are in use today in modern automotive airbags. These are *"dot-sized motion sensors… (that) measure deceleration"* and provide its data to a small computer which decides when to deploy an airbag (Eisenberg 1999).

In late 2003, UC Berkeley announced a revolutionary mote called "Spec." The device is complete with sensors and a communication system yet, without its battery and a few additional mote components, Spec is about the size of an aspirin tablet.[7] Because the device fits on a single chip, it costs less to produce and thus, according to Professor David Culler, "*opens the path to very low cost deployments of a large number of motes*" (qtd. in Yang 2003). Additionally, the mote operates with low power consumption – its transmitter requires *"1,000 times less power than a cell phone"* (ibid). This is possible because the device is configured only to talk to nearby motes rather than across a room to a base station.

2.4 Future Trends

Smart dust vendors and researchers indicate that motes sold in the future will be smaller and cheaper (Johnson 2003, cf. Bigelow 2004). Also, motes will likely have revolutionary power sources such as fuel cells or the ability to *"'scavenge' energy to make smart-dust devices run longer"* by *"drawing off the ambient vibration energy generated by an industrial machine or gathering energy from low levels of light"* (Hoffman 2003).

Even as the price of smart dust falls, revenues for the vendors of these devices are expected to increase. According to an estimate published in *Business Week Online*, the worldwide market for wireless sensor networks is expected to grow from $347 million in 2004 to $7 billion by 2010 (Kharif 2004)[8].

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[6] The name MICA refers to a platform for motes whose components are *"sandwiched together to form an integrated wireless smart sensor"* (Horton et al. 2002). This is analogous to the naturally occurring mica mineral material which splits into sheets.

[7] The mote lacks *"an inductor, an antenna, a… watch crystal and a power source. The (UC Berkeley) researchers said these components will add little to the size of the mote"* (Yang 2003).

[8] Another estimate by In-Stat, a digital communications market research firm, forecasts that the market for wireless sensors is expected to be up to $625 million by 2006 (cited in Dragoon 2005).

3 Applications for Business

Off the shelf mote systems can be configured with sensors for numerous properties including temperature, humidity, barometric pressure, light intensity, acceleration (vibration), magnetism, and acoustic levels (Crossbow 2004a). And some mote sensors can determine their locations using the national Global Positioning System (ibid). The combination of some of these capabilities in a well-designed sensor network yields numerous potential applications. To illustrate, this section will review some recent commercial and experimental applications.

3.1 Demonstrated Applications

Energy company BP is experimenting with motes on the Loch Rannoch, an *"885-foot oil tanker,"* to determine if they are useful in predicting failures of onboard machinery. (Economist 2004). The firm placed 160 motes near some of the ship's equipment to measure things like *"vibrations in the ship's pumps, compressors, and engines"* as an indicator of potential failure (Takahashi 2004). The configuration is set up to initiate an alert if it detects unusual vibration or motion. Technicians responding to the alert could fix the problem before it results in a more serious condition. Since ships carry limited amounts of onboard tools and spare parts, catching a problem before it becomes serious could help BP avoid the costs and delays associated with delivering parts to the ship. If motes perform as expected and also survive the harsh marine environment, BP will likely outfit more of it assets with smart dust (ibid). Their experiment demonstrates the use of relatively low cost motes to help protect expensive machinery.

> ***"We have some very expensive equipment on those ships, and now we can monitor the status of that equipment 24 hours a day."***
>
> - Harry Cassar, Technology Director, BP, quoted in *San Jose Mercury News* (Takahashi 2004)

Recently, Accenture Technology Labs installed a wireless sensor network at Pickberry Vineyards in order to demonstrate the benefits of its "Remote Sensor Network" (Accenture 2004). The experiment required placement of motes *"across a 30 acre area to continuously sense humidity, wind, water, and soil and air temperature"* (ibid). The system designers made the mote data available on the World Wide Web to authorized users by configuring the system to upload the sensor data from the mote base station to the Internet via a cellular telephone link. The sensors provide information that will allow Pickberry personnel to, based on *"soil moisture and air humidity,"* optimize *"watering schedules for a specific area"* (ibid). Also, the setup provides prompt notice of *"events such as frost, disease, and pests"* (ibid). Armed with this information, Pickberry management may be able to improve the yield of its crop and lower its costs.

In 2002, motes were applied by John Anderson, a field biologist, to solve an environmental monitoring problem (Schmidt 2004). Dr. Anderson wished to determine the needs of a species of seabirds (Leach's Storm-Petrels) that nest on Great Duck Island, Maine. This is a challenge because the birds only return to their burrows at night, after a feeding at sea during the day (eNature 2002). In order to learn more about the birds, Dr. Anderson *"has had to get down on his stomach and stick an arm into the burrows, which scares the petrels and threatens the survival of their young"* (Schmidt 2004). Now, he can simply hop on the Internet. He and his team installed a smart dust network with sensors that detect the presence of the birds and also monitor the *"temperature, humidity, and barometric pressure"* in a region (Schmidt 2004). The sensors transmit their readings to a nearby base station which is connected to the Internet. Because of smart dust, researchers may now gather real time habitat data from the Internet[9] without intruding on the nesting birds.

Dan Bertocchini, an energy manager for supermarket chain Supervalu, Inc., is experimenting with 19 motes (from Dust Networks) in one of the chain's Minneapolis stores (Dragoon 2005). Over two-thirds of the chain's stores do not have *"submeters"* to *"pinpoint the energy usage of specific pieces of equipment such as refrigeration racks and condensers"* (ibid). By placing wireless sensors on individual devices in the store, Mr. Bertocchini can pinpoint the energy use of specific pieces of equipment and use the information to root out energy waste by targeting specific machines for repair or adjustment. His approach is unique because he does not necessarily plan to put sensors in every store; instead, he will simply move a set of sensors from store to store to perform energy consumption studies. Given that refrigeration is a significant expense for grocery stores, the experiment is well positioned to improve the profits of Supervalu (ibid).

3.2 Potential Applications

Steve Glaser, an associate professor at UC Berkeley is investigating the usefulness of smart dust in evaluating the structural soundness of buildings and other structures (Pescovitz 2001). The approach employs motes equipped with seismic accelerometers to detect slight movements in building support beams and columns. Data from these motes would be of value after a building is suspected of sustaining earthquake damage because the data could be used to certify the structural soundness of the building. An alternative means of identifying *"beam buckling and structural bruises"* are *"tearing down downs of sheetrock"* (ibid). Clearly, a relatively small investment in smart dust motes could pay off if a building could be deemed safe for reentry in a matter of hours rather than closing the building *"for months to undergo a detailed inspection"* (ibid).

Science Applications International Corp., a government contractor, is using smart dust to develop an *"advanced perimeter security system… for the U.S. military"* (Eng 2004). The system will provide an inexpensive means of *"persistent surveillance"* that is easy for soldiers to install and maintain (ibid). This project illustrates how smart dust can be used to implement a security system. Similar technologies could be used to build low cost home and office security systems which can be installed easily and quickly (Bigelow 2004).

Smart dust lends itself to energy saving initiatives. An office building could be outfitted with hundreds of motes that sense light and temperature levels as well as determine when people are present in a room or region (Manjoo 2001). The smart dust network would then provide information to a controller that could turn off the lights when a room was empty and adjust the air conditioning or heating to save costs in a region that is vacant. And since the system would be automatic instead of relying on a human to remember to flip a switch, savings are maximized. Mike Horton, CEO of Crossbow, summed up the benefits in an interview with a newspaper columnist: *"We think on air conditioning costs, motes could save 20 percent on electrical bills, and they're 50 percent to 80 percent cheaper to install than wired sensors"* (qtd. in Takahashi 2004).

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[9] The habitat monitoring data is available via *http://www.greatduckisland.net*.

In another application, motes will soon be used for remote environmental monitoring in an effort to preserve the painted walls and ceilings of Buddhist temples located in caves near the Chinese town of Dunhuang (Pescovitz 2003, cf. Weintruab 2004). Conservationists presently monitor the caves' environments to identify the conditions causing deterioration of the paintings. The issue is that to get information from the existing weather station, technicians have to *"enter the caves to gather the data, and their very presence adds to the degradation"* (Weintruab 2004). Steven Glaser, Assistant Professor of Civil and Environmental Engineering at UC Berkeley, and his team will install motes that monitor *"temperature, barometric pressure, humidity, and vibration"* (Pescovitz 2003 p. 1). The benefit of the dust motes is that now, a technician can take readings *"without unlocking and entering the caves"* (ibid, p. 2).

4 Cost and Availability

Smart dust products are available to early adopters in the form of wireless sensors that become part of a communication network. As discussed in section 2.3, these motes are not dust-sized – they range in size from that of a stack of three U.S. quarters to the size of a deck of playing cards.

Several manufacturers offer prepackaged solutions for building controls, industrial monitoring, and security; these include, but are not limited to: Dust Networks, Millennial Net, and Sensicast. Each has similar offerings of hardware and the associated software required to operate it, but the later two target their product lines to original equipment manufacturers and system integrators (such as management and technology consulting firms). Another vendor, Ember, sells computer chips and embedded software to meet the needs of mote manufacturers (Ember 2005).

Experimenters and researchers with interest in smart dust may purchase products from Crossbow Technology and MicroStrain. Crossbow's motes can be outfitted with sensors that detect phenomena such as acceleration, barometric pressure, position, light intensity, sound, magnetic field, humidity, and temperature (Crossbow 2004a). MicroStrain's motes can be used for industrial monitoring; that firm offers wireless sensors which perform the functions of an accelerometer, strain gauge, or thermocouple (MicroStrain 2005).

SkyeTek, Inc. offers an RFID reader, the SkyeRead M1-Mini, that connects with the Crossbow MICA2DOT wireless sensor platform to form an RFID reader mote (Goode 2004). A columnist describing the configuration noted that *"[t]he sensor and the reader are each about the size of three stacked quarters"* and that *"[t]he MICA2DOT can run up to seven years on a coin cell battery"* (ibid). The resulting RFID reader mote is compatible with multiple brands of RFID tags and it would be useful in applications where the reader is close to the tag -- the product data sheet indicates that when operating, the reader must be within approximately 3" of the tag (SkyeTek 2005). This range doubles if an external antenna is added to the reader, but this would make the mote configuration larger. However, the mote platform itself interacts with its communication base station in a normal fashion; the base station can be up to about 160 feet away from its motes (ibid).

Prices for smart dust implementations vary depending of the desired mote capabilities, installation requirements, and the volume of the purchase. For example, a recent Sensicast installation which monitors industrial motors in a California nuclear power plant cost about

$500 per mote plus an additional *"$500 each for installation to cover the paperwork and analysis that must precede any change in a nuclear power plant"* (Dragoon 2005). But a simple Sensicast building control application would only cost about $250 to $350 per mote (ibid).

The price for motes from Crossbow is about $150 each, but for volume purchases, the price per unit plummets to as low as $40 (Bigelow 2004). The CEO of Crossbow expects prices to drop to about $10 or less per unit *"in the near future"* (qtd. in Bigelow 2004). Also, for about $2000, experimenters may purchase a kit from Crossbow which includes 8 mote platforms, 5 sensors, and a base station board (Crossbow 2005). The base station board is in the form of a computer card which can be installed in a typical personal or laptop computer.

One factor to consider when estimating the costs of smart dust networks is ease of installation. Battery operated motes do not require the installation of additional electrical wiring and their installation simply requires a screwdriver (Dragoon 2005). In comparison to traditional wired sensors, a smart dust mote requires no wiring and this results in both lower labor and materials costs.

Clearly, early adopters have several commercial smart dust products available to them in the price range of a few hundred dollars. Late adopters can expect lower prices as the price per mote falls. This is supported by an Intel report excerpt:

> *"Researchers at Intel expect that, with re-engineering, Moore's Law and volume production, motes could drop in price to less than $5 each over the next several years"* (Intel 2005).

The Intel report utilizes Moore's Law, which postulates that *"the number of transistors on a chip roughly doubles every two years, resulting in more features, increased performance and decreased cost per transistor"* (ibid). Based on this law, the assumption of a $5 mote in the year 2010, and of the price halving every 18 months, the price of a smart dust mote should reach about 65 cents in 2015 and 5 cents in 2020. This is depicted in figure 1.

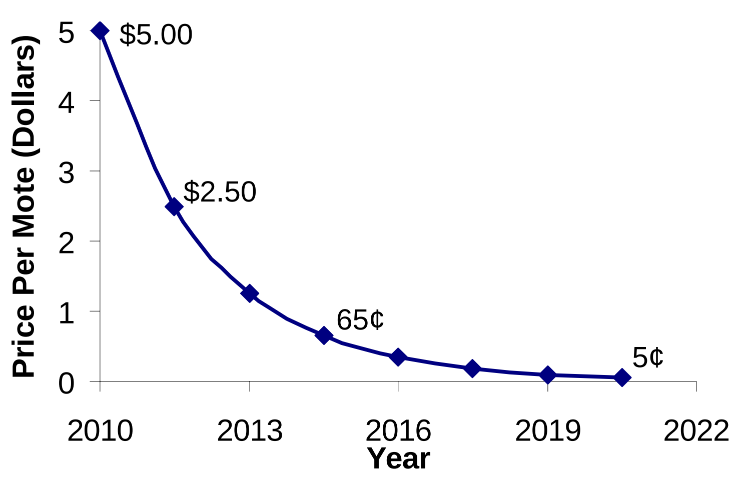

Figure 1. Price Trend Estimate for Smart Dust Motes.

Another indicator of future prices is the aspirin-sized "Spec" mote. Dr. Jason Hill of JLH Labs estimates that, when produced in large quantities, Spec and its associated components can be produced for a total of about 62 cents per mote (Hill 2005). Once commercially available, Spec is well positioned to appeal to later adopters with its low price and small size.

5 Issues

The development and use of smart dust raises some issues and concerns for stakeholders. These include privacy issues, potential system security weaknesses, the need for standards, and the environmental impacts of smart dust. Each of these issues is discussed below.

5.1 Privacy

It's easy to imagine that tiny smart dust sensors could be used for mischievous, illegal, or unethical purposes. Corporations, governments, and individuals could use motes to monitor people without their knowledge. And smart dust could become the tool of choice for corporate espionage. Privacy issues such as these have been raised before. In one case, during an interview with smart dust inventor Kris Pister, a reporter asked about the *"dark side"* of the technology. Dr. Pister replied, *"I believe that the benefits will far, far outweigh the drawbacks, but I'm hardly unbiased"* (qtd. in Edwards 2001). These issues are not easily resolved, but as smart dust becomes smaller, cheaper, and more prevalent, privacy concerns are likely to increase.

5.2 Security

Smart dust motes, as networked computing devices, are susceptible to security concerns similar to that of computers on the Internet. One of these susceptibilities is due to the fact that motes in a network are reprogrammable. This feature allows an administrator to update the software on a single mote and then command it to pass the update along to all the other motes in the network (Culler and Mulder 2004). Although the mote identity verification algorithms in the TinyOS operating system would make it difficult, this mote software feature could be exploited by hackers and eavesdroppers (ibid). In applications that gather sensitive data, system designers should be aware that there is a risk that the data could be compromised.

5.3 Standards

As interest in smart dust increases and more manufacturers produce motes, end users will have more choices when building a system. However, not all smart dust devices would work effectively together without standards. Fortunately, a set of standards is forthcoming -- an alliance of industry leaders has proposed the ZigBee[10] standards (Economist 2004). Once agreed upon by industry and released by the Institute of Electrical and Electronics Engineers (IEEE), the standards will apply to *"residential, industrial, and building controls"* (ibid). And the alliance is well positioned to draft additional standards should the need arise due to the discovery of new applications for the technology.

5.4 Environmental Impacts

After smart dust is sprinkled in a remote or desolate area to accomplish a monitoring function, it is not easily or inexpensively retrieved. If a mote fails and is consequently abandoned by its owner, there is an environmental impact. A mote's environmentally unfriendly components include integrated circuits, a battery, and a printed circuit board. Clearly, motes have environmental impacts that should be considered by users. It is somewhat ironic that negative environmental consequences could arise from the use of smart dust for an environmentally sound purpose such as protecting a forest from fires.

[10] ZigBee is named after "the zigging and zagging of bees, which are individually simple organisms that work together to tackle complex tasks" (Wired 2003).

Some environmental concerns might be raised about motes that draw on radioactive power sources. At this time, commercially available motes do not use radioactive power sources, but a limited amount of research in the area has been completed (Webb 2004). The appeal of these special power sources is the amount of energy that a very tiny battery can produce. This has been demonstrated by Cornell University scientists who developed an isotope-based *"cubic millimeter-sized battery*" that could supply power to a mote *"for decades"* (ibid, p. 30). An atomic scientist, Stephen Schwartz, said in an article that motes with these types are batteries *"aren't likely to be very dangerous unless you ate them, or threw them in the fire and inhaled the smoke"* (qtd. in Eisenberg 2002). However, employees and consumers may object to living and working in proximity to radiation sources. And there are no guarantees that used motes with radioactive power sources would be retrieved and disposed of properly. These issues would need to be worked out before radioactive power sources could be used in commercially available smart dust devices.

6 Conclusion

Smart dust technology provides wireless, remote monitoring solutions. It is available today from vendors such as Dust, Inc., Crossbow Technology, and Sensicast in the form of motes which range in size from that of a short stack of quarters to the size of a deck of cards. These motes have battery lives of up to 10 years and they support various types of sensors. Due to promising university research, future motes will likely be smaller, cheaper, and have longer useful lives.

This paper has presented examples of numerous business applications for smart dust. These examples have ranged from the use of motes to reduce energy costs in a supermarket to the application of dust motes at a vineyard to maximize crop yield while minimizing resource costs. Clearly, there are innovative uses for dust technology; and as smaller, cheaper, and longer-lasting motes become available, their use becomes feasible for additional business challenges.

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