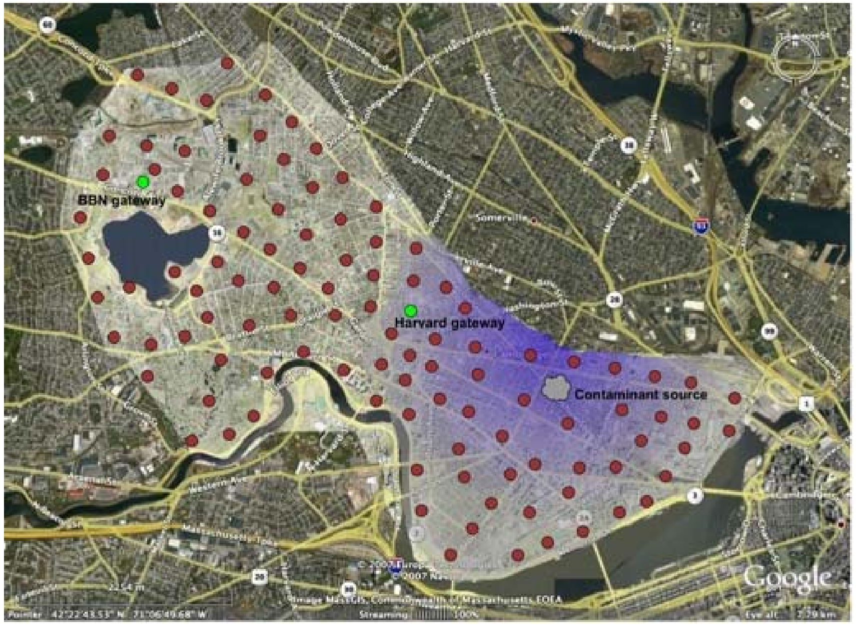
Centre for Research in Photonics (CRPuO) at the University of Ottawa

Cyrium Technologies Inc.

Solar-powered wireless sensor network

N. Yastrebova, K. Hinzer, D. Masson, S. Desgreniers, H. Schriemer, B. J. Riel, S. Fafard, T. J. Hall



May 3, 2007

Characteristics of the Wireless Sensor Network

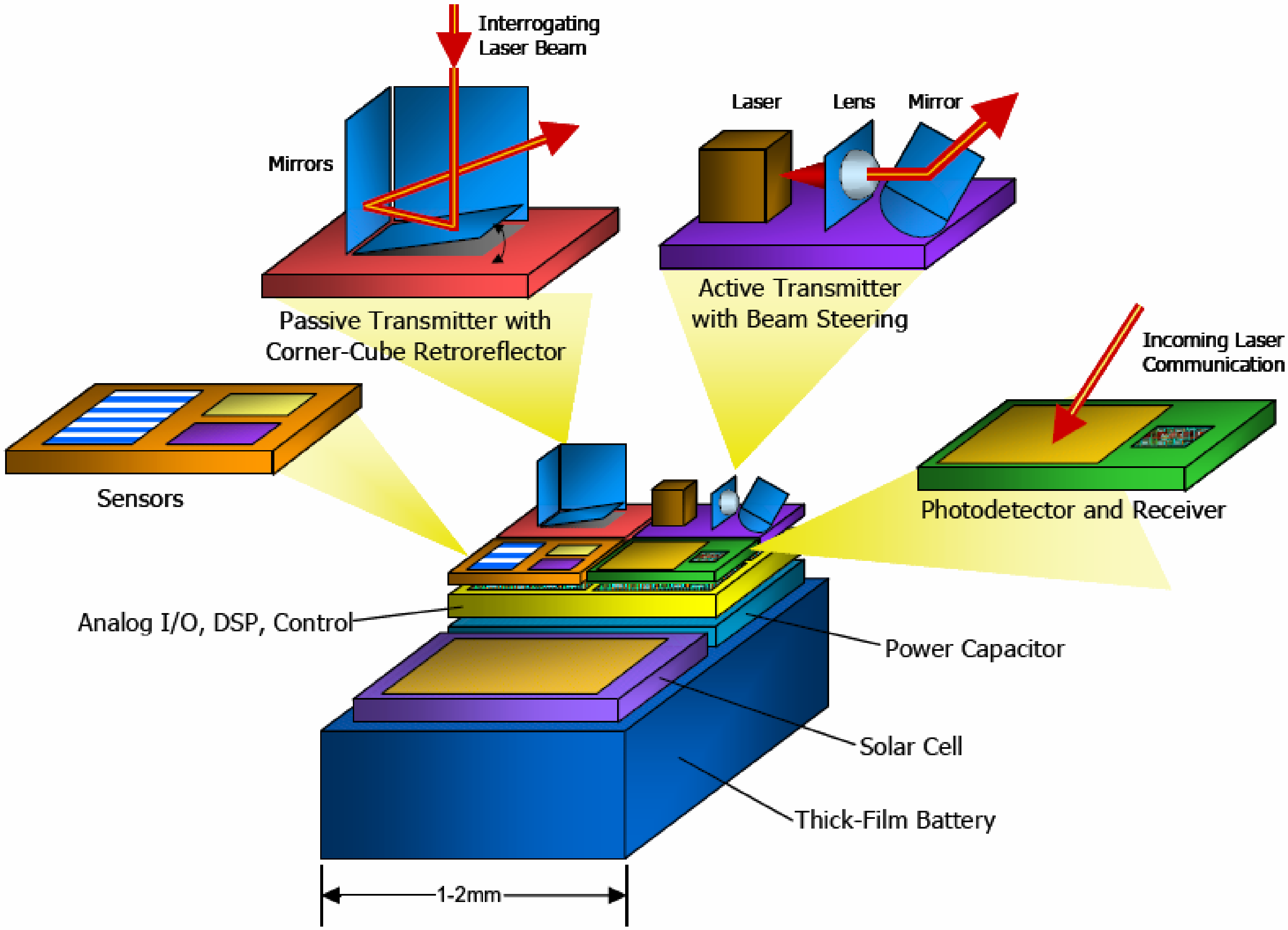
✓Wireless Sensor Networks (WSN) are ad hoc networks (wireless nodes that self-organize into an infrastructureless network).

✓In contrast to other ad hoc networks:

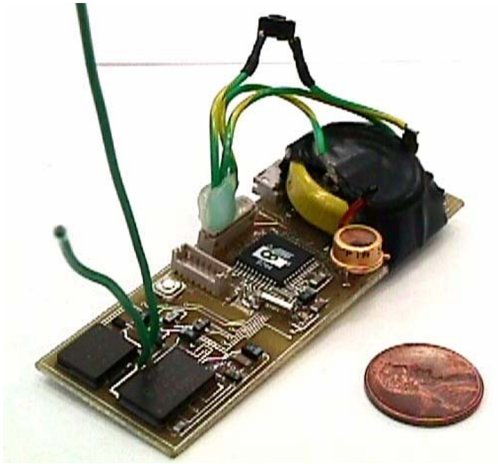
- WSNs have many more nodes and are more densely deployed;
- Sensing and data processing are essential;
- Hardware must be cheap;
- WSNs operate under very strict energy constraints;
- The communication scheme is many-to-one (data collected at a base station) rather than peer-to-peer;
- Bandwidth and resources scale with network size.

✓Limitation of energy supply has constantly impeded the progress of WSN towards large scales and true autonomous operations.

WSN node's design [1]



History

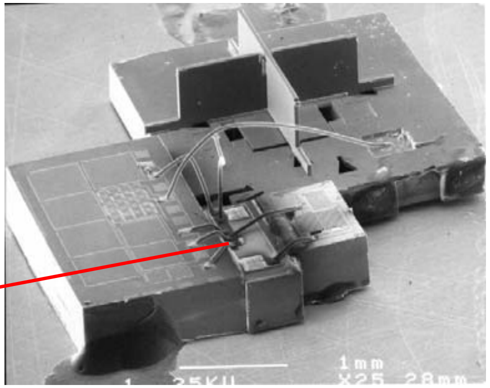


RF Mote 2000

University of California, Berkeley

(*Image courtesy: Seth Hollar*).

- Sensors for temperature, humidity, barometric pressure, light intensity, tilt and vibration, and magnetic field;
- communicating distances of about 60 feet using RF;
- battery lasts up to one week of continuous operation.

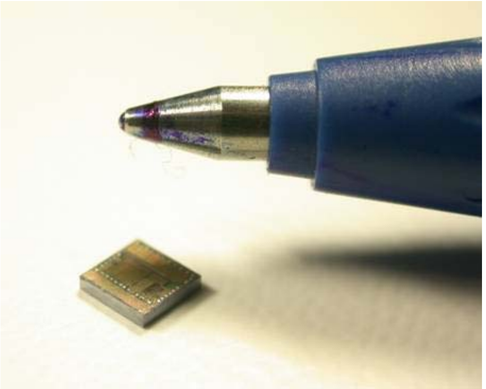


Smart Dust 2001

UofC, Berkley

(Image courtesy: Kris Pister).

- Solar powered mote;
- Bi-directional communication;
- Sensors for acceleration and ambient light;
- ~4.8 mm3 total displaced volume.



"Spec" 2003

next to the tip of a ball point pen.

(*Image courtesy: Jason Hill*).

Full-custom CMOS chip containing processor, memory, sensors and RF communications.

Power budget

✓Constrained by energy, computation, and communication;

✓Small size implies small battery;

✓Low cost & energy implies low power CPU, transceiver with minimum bandwidth and range;

✓Ad-hoc deployment implies no maintenance or battery replacement;

✓To increase network lifetime, no raw data is transmitted.

✓The lifetime of sensor nodes can be increased through improvements in power generation, power conservation, and power management.

✓Power sources:

- Lithium battery
- Thick film battery
- Photovoltaic
- Vibration
- Acoustic noise
- Thermal conversion
- Nuclear reaction
- Fuel cells

Integrated circuit:

- ✓ Sensor signal processing
- ✓ Communication
- ✓ Control
- ✓ Data storage
- ✓ Energy management

Energy-optimized microprocessor: 1pJ/instruction (32-bit);

Analog-to-digital converter: 1nJ/sample.

Sensors:

- ✓ Temperature, humidity, pressure, flow
- ✓ Position, acceleration, vibration, strain, force
- ✓ Tactile/contact, proximity
- ✓ Sound
- ✓ Gases
- ✓ Bio-agents
- ✓ Passive infra-red

Temperature, humidity, light: 4nJ/sample;

Accelerometer: 0.5nJ/measurement.

Wireless communication:

RF:

- ✓ – IEEE 802.15.1: Bluetooth
- ✓ – IEEE 802.15.4 and ZigBee
- ✓ – TinyOS

Optical

- ✓ Passive - MEMS corner-cube retroreflector
- ✓ Active - semiconductor lasers and diode transceivers

Bluetooth: 100nJ/bit [<100m];

GSM: 40uJ/bit [<10km];

Optical transmitter (laser): 1nJ/bit [→ 10km];

20pJ/bit [→180m]

Photodiode receiver: 0.1nJ/bit

Solar-power supply

✓**Solar radiation**: - one of the most abundant available sources of energy (14TW/hour);

- it is particularly amenable to a system that needs line-of-sight for optical communication;

✓**Solar cell**: - fairly compact;

- capable of efficiently generating multiple potentials;
- compatible with other processes;
- a well-developed technology compared to other energy harvesting techniques.

✓**Reservoir capacitor**: - stores scavenged energy;

- allows the solar panel to run close to its maximum power point.

✓**Solar cell** (~15% efficiency) **generates**: Outdoors: ~0.1 mW/mm^2, ~1 $J/day/mm^2$;

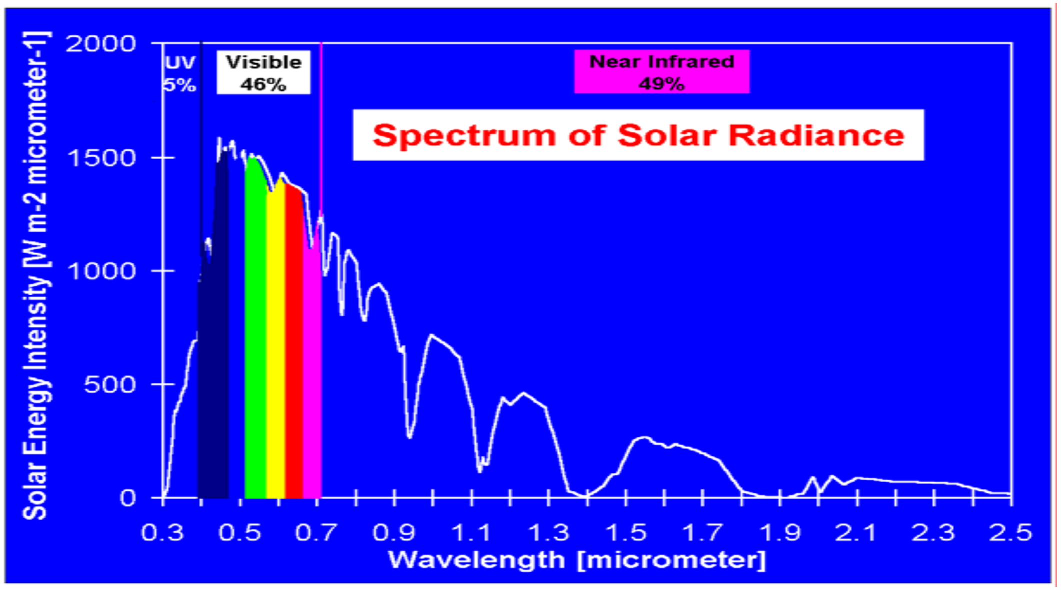
Indoors: 0.1-10 $\mu W/mm^2$, 1-100 $mJ/day/mm^2$.

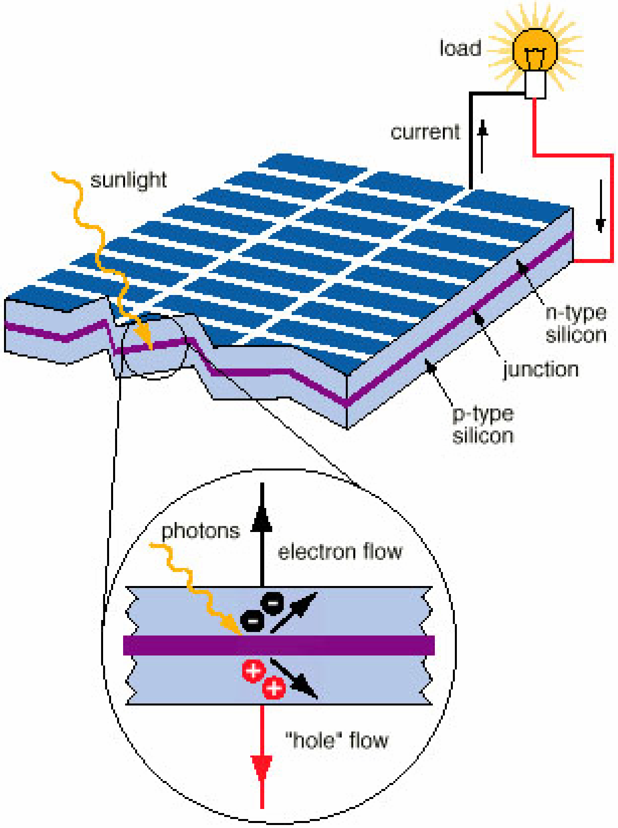
Storage: Batteries ~1J/mm^3;

Capacitors ~10mJ/mm^3.

Given our 1 mJ per day of energy from indoor lighting, each second we can sample a sensor, think about the result, and transmit some data.

Photovoltaic basics





•Absorption of light (hν >ΔEg);

•Release of positive and negative charge-carriers;

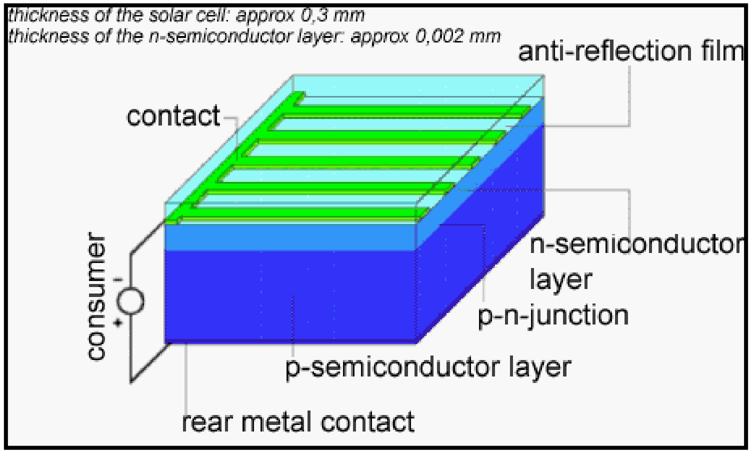
•Separation of carriers;

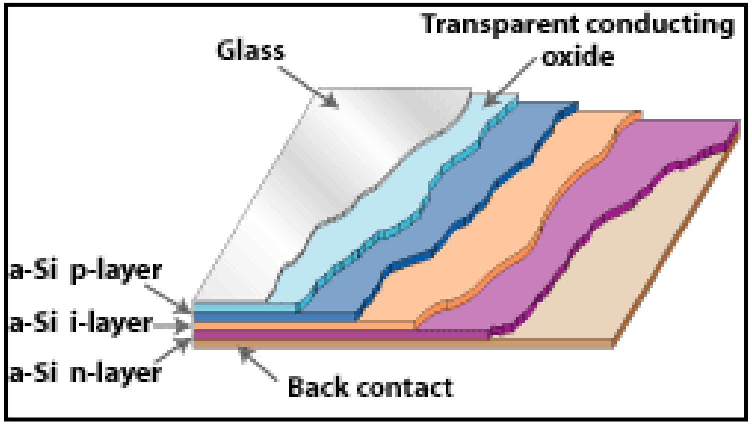
•External current.

3 generations of solar cells

Bulk solar cells:

- are better suited to high light conditions and the outdoors spectrum.
- efficiency ~ 15% - 20%;
- poly-crystalline Si is cheaper, but less efficient than single-crystalline silicon :
- increases in efficiency tend to be matched by the cost of increased design/processing complexity.

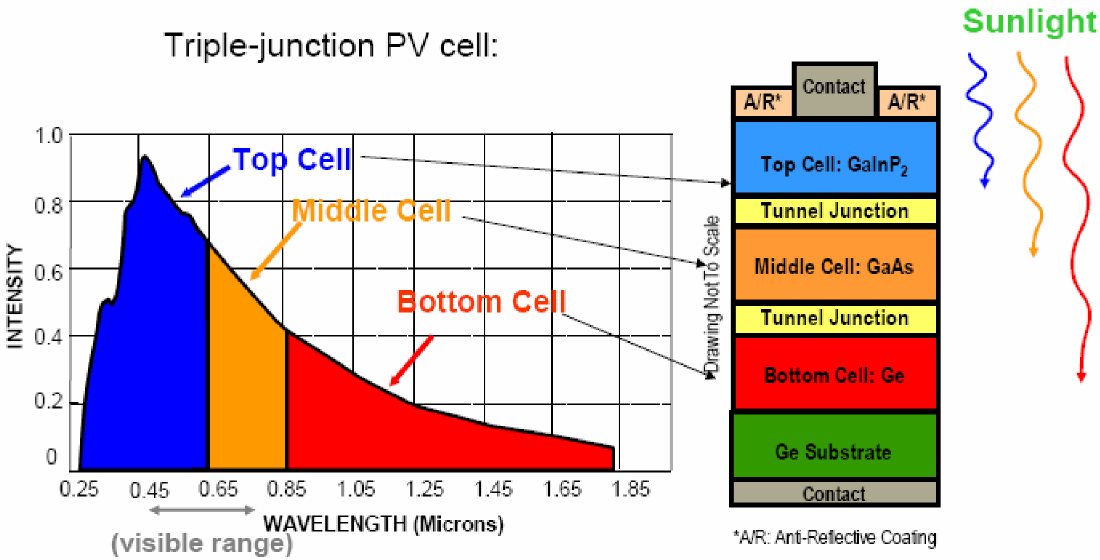


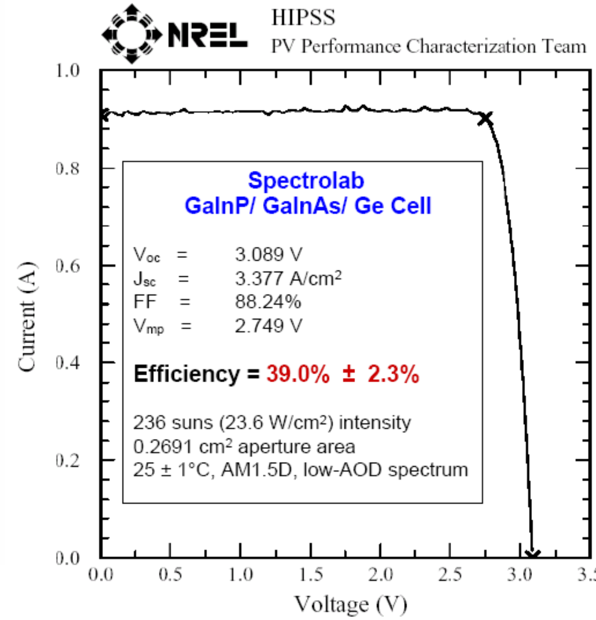


Thin-film solar cells:

- spectral response more closely matches that of artificial indoor light.
- amorphous Si present conversion efficiencies are ~5-10%;
- CdTe cells, with good PV potential, give rise to environmental concern.

III-V-compound multi-junction solar cells [2]





•Multi-junction solar cells absorb each colour of light with a material that has a band gap equal to the photon energy;

•Each junction adds voltage; current between junctions is matched in monolithic cells;

•Present-day highest efficiency - 40.7%.

•Multi-junction approach is limited by existence of materials with suitable band gaps and which can be feasibly incorporated into a solar cell or system.

The efficiency of the present-day triple-junction solar cell can be improved by:

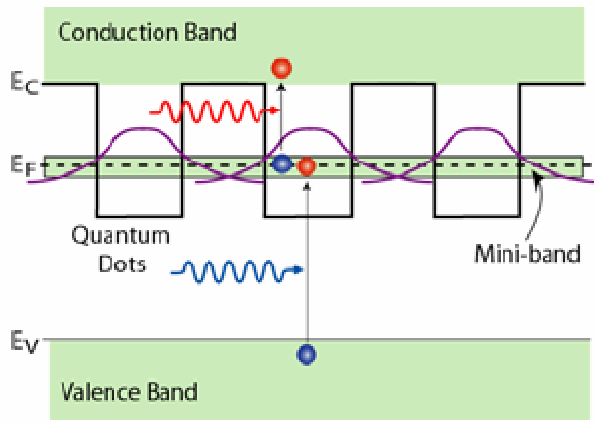
- Design optimization of each subcell;

- Increasing the number of junctions:

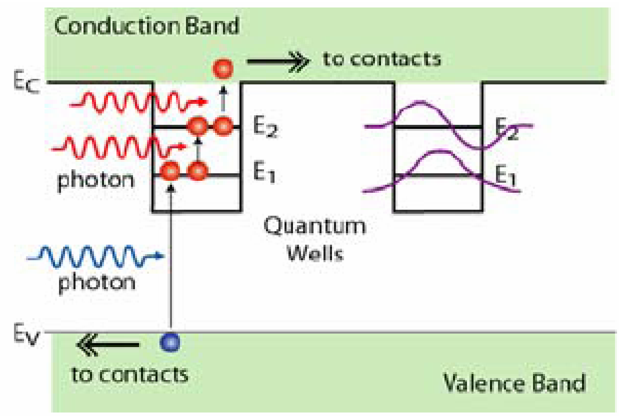
- Use of nanostructures (quantum wells, quantum wires, superlattices, nanorods, nanotubes…):

  size-dependent electronic structures → tunable optoelectronic properties → tailoring the properties of existing materials → higher photovoltaic efficiency;

- A mixture of QDs of different sizes can be used for harvesting the maximum proportion of the incident light (up to the peak theoretical efficiency - 86.8%).



continuous mini-bands [3]



localized energy levels [3]

Applications

✓Meteorological monitoring

✓Geophysical & biological research

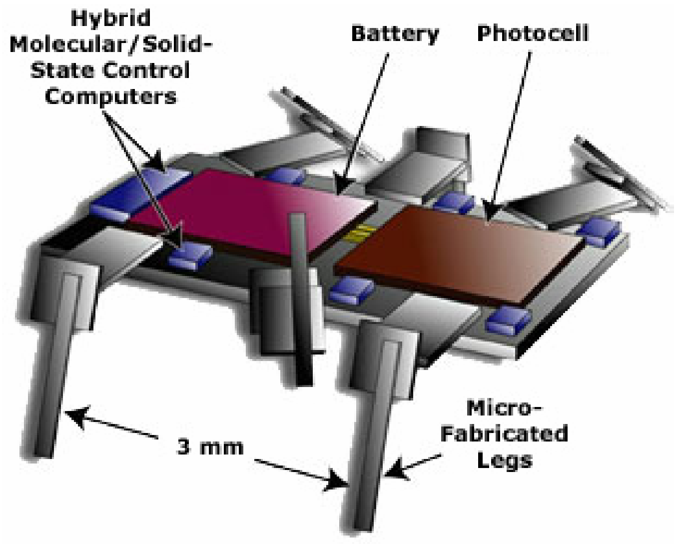
✓Structure maintenance & inventory control

✓Industrial processing

✓Monitoring of a hostile environment

✓Perimeter survelliance

✓Detecting the presence of chemical & biological agents



Millirobot of the MITRE Corporation

✓Medical applications

✓Constructing smart-office spaces

✓Energy conservation

✓Providing interfaces for the disabled

✓Virtual keyboards

Sensor-web Experiment at 29 Palms Marine Base

- Deploy a sensor network onto a road from an unmanned aerial vehicle (UAV);
- Detect and track vehicles passing through the network;
- Transfer vehicle track information:
  - from the ground network to the UAV;
  - from the UAV to an observer at the base camp.

Monitoring of disaster area in Japan

- The Japanese Ministry of Internal Affairs and Communications started developing a system that allows for detailed information gathering about a disaster area;
- RFID tags equipped with heat, infrared, and vibration sensors are sprinkled from the sky .

Protection of expensive machinery

- Energy company BP uses motes on an 885-foot oil tanker for predicting failures of onboard machinery;
- 160 motes are placed 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.

Structure maintenance example: Golden Gate Bridge

•Measures vibration and structural stresses;

•Real-time accelerometers;

•About 200 motes.

Environmental control in office buildings:

•A distributed WSN system can be installed to control the air flow and temperature in different parts of the room;

•Can reduce energy consumption by two quadrillion BTUs in the US, which amounts to saving of $55 billion per year and reducing 35 million metric tons of carbon emissions [8];

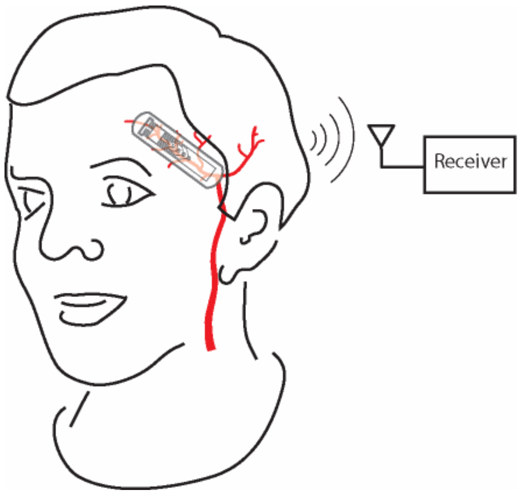
•Additionally, seismic monitoring is available.

Chemical plant: reducing downtime and enhancing safety

•The chemical contents of the pipes can gradually weaken them and cause accidental chemical releases;

•Today, this inspection process is labor intensive for pipes covered with insulation and for pipes located in confined areas

•With this system installed under pipe insulation, the plant manger benefits from having up-to-date status information of all piping while avoiding the costs of manual inspections.



Health applications

•Telemonitoring of human physiological data;
•Tracking and monitoring doctors and patients inside a hospital;
•Drug administration in hospitals;
•A ‘‘Health Smart Home’’ was designed in the Faculty of Medicine in Grenoble to validate the feasibility of such systems;
•Intel deployed a 130-node WSN to monitor the activity of residents in an elder care facility: patient data is acquired with wearable sensing nodes.

Increasing the crop capacity of the Pickberry Vineyards

•Accenture Technology Labs installed a wireless sensor network at Pickberry Vineyards across a 30 acre area to continuously sense humidity, wind, soil moisture and air temperature;
•The information is wirelessly transmitted to a centrally located PC that analyzes the data within seconds;
•WSN allows farmers to more accurately determine how to best manage their crops.

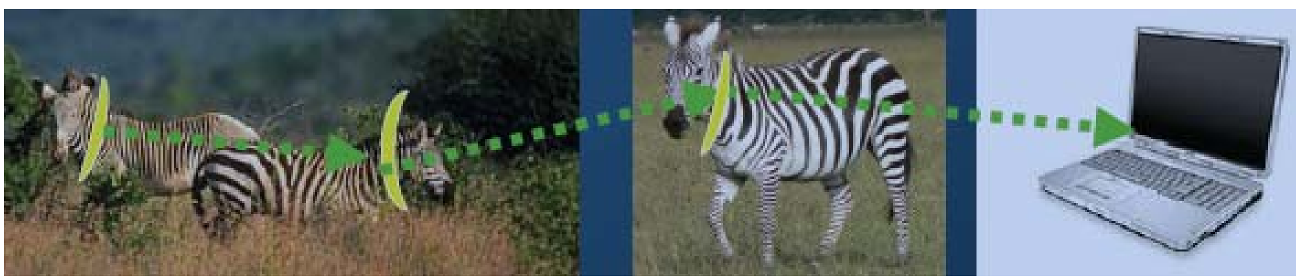
Environmental monitoring problem

•Great Duck Island off the coast of Maine, scientists seek to identify the breeding patterns of Leach’s storm petrels, without disturbing the birds and disrupting their nests;

•Intel’s WSN detect the presence of the birds and also monitor the temperature, humidity, and barometric pressure in a region;

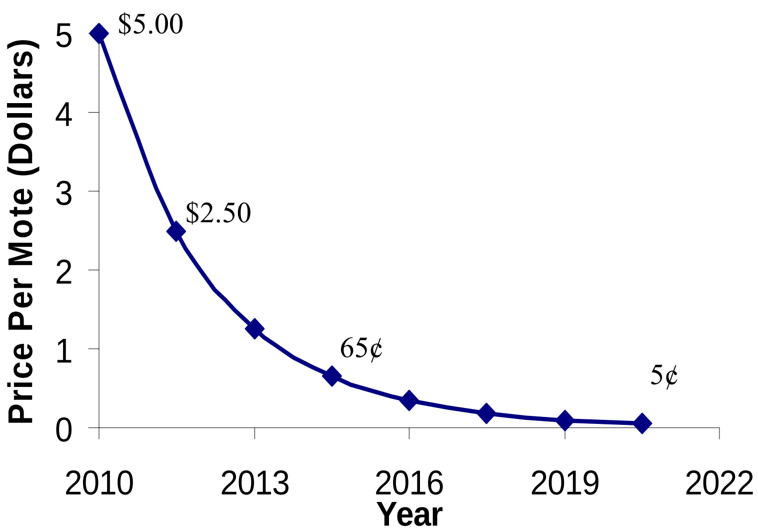
•The sensors transmit their readings to to the Internet.

WSN to study the behavior of zebras



- Special GPS-equipped collars were attached to zebras;
- Data exchanged with peer-to-peer info swaps;
- Coming across a few zebras gives access to the data.

Cost and availability



Price Trend Estimate for Smart Dust (Intel) [5].

✓Crossbow Technologies
✓Dust Networks
✓Millenial Net
✓MicroStrain
✓Sensicast
✓Nanotech
✓SkyeTek
✓Intel

•"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" [6].

•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 [7].

•Current prices: from $40 (Crossbow, for volume purchase) to $1000 (Sensicast, price of motes with installation at California nuclear power plant).

Issues

"I believe that the benefits will far, far outweigh the drawbacks, but I'm hardly unbiased."

Dr. Pister, founder of "Smart Dust" project.

- ✓ **Privacy**

"How would you like it if, for instance, one day you realized your underwear was reporting on your whereabouts?"

Debra Bowen, California State Senator, at a 2003 hearing.

- ✓ **Security**
- Software feature could be exploited by hackers and eavesdroppers;
- Updating the software on a single mote can command it to pass the update along to all the other motes in the network;
- The mote identity verification algorithms in the TinyOS operating system.

- ✓ **Environmental impact**
- A mote's environmentally unfriendly components include integrated circuits, a battery, and a printed circuit board.
- A million tiny motes – a total volume of one liter.

- ✓ **Standards**
- ZigBee
- IEEE 1451
- Wibree

Research focus

- By the example of the photovoltaic devices developed by Cyrium Technologies for space applications, we are planning to demonstrate the possibility of using GaAs on Ge solar cells as a micro-mote's renewable energy source.

- Numerical modeling of solar cell junctions and significant characterization of solar cell materials and devices will take place.

- The planned deliverables are two prototypes of III-V solar cells on Ge substrates for possible applications in micromote network sensors.

- We will elaborate on the specifications that these solar cells have to actually be able to power micro-motes.

- The specifications will also be done keeping in mind the possibly to further integrate the laser and the photoreceiver on the same platform.

- This type of work is original and should advance the research's community insight on solar cell use in the very early stages of micro-mote technology.

Conclusion

- ✓The flexibility, fault tolerance, high sensing fidelity, low-cost and rapid deployment characteristics of WSN create many new and exciting applications for remote sensing.
- ✓Realization of sensor networks needs to satisfy the constraints introduced by factors such as scalability, cost, hardware, topology change, environment and power consumption.
- ✓Photovoltaics is a well-developed technology that uses the most accessible environmental energy source.
- ✓Solar cells are fairly compact, capable of efficiently generating multiple potentials, compatible with other processes.
- ✓Most efficient photovoltaic cells use multiple III-V-semiconductor materials with bandgaps spanning the solar spectrum.
- ✓As technology progress, cubic millimeter scale nodes will be able to survive on scavenged solar power.
- ✓In the future, a wide range of WSN application areas will make sensor networks an integral part of our lives, the information about the physical world will be more ubiquitous.

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