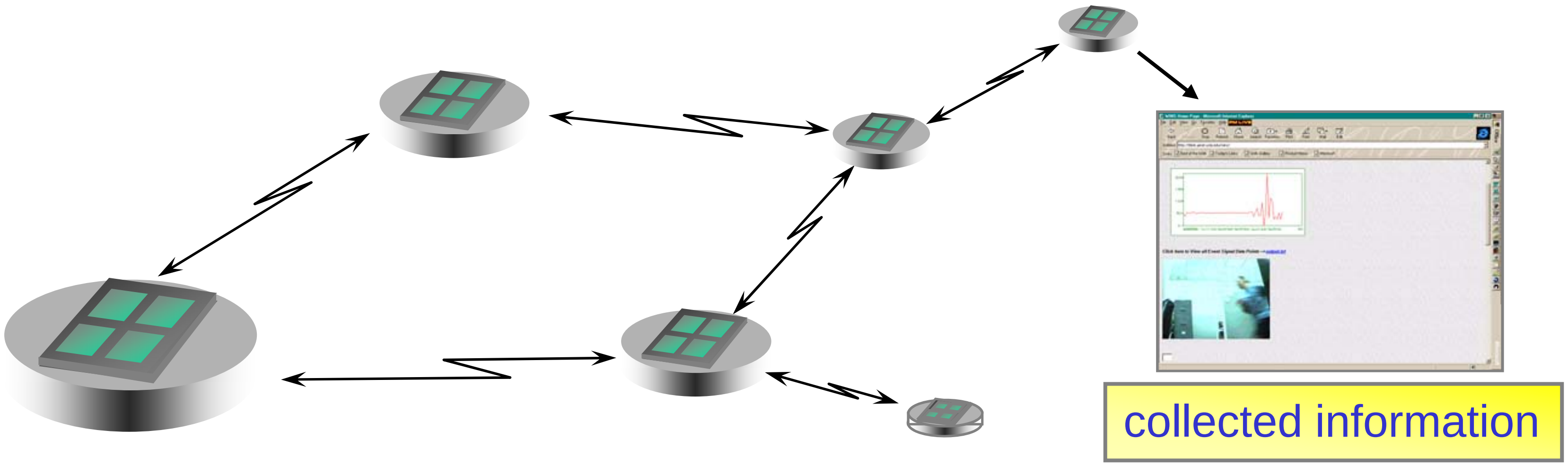
Introduction to Machine-to-Machine Network (IOT, WSN)

林宗賢

GIEE/NTU

Introduction

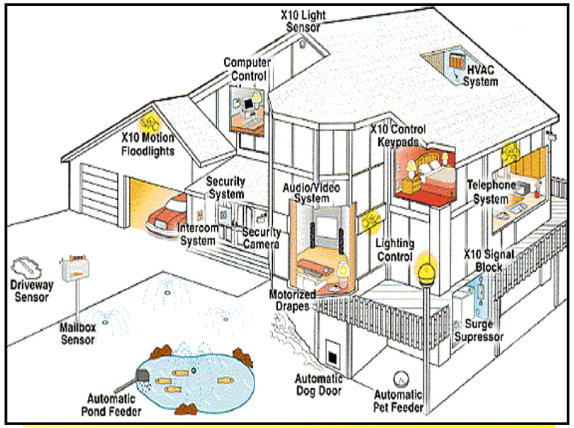
- A **wireless sensor network** (WSN) gathers information through densely distributed nodes
- Each smart sensor node contains multiple functions: sensing, signal processing (computing), networking, communication, etc.



- ***Twister*** (starring Bill Paxton and Helen Hunt as tornado chasers, 1996): in the movie, the scientists tried hard to place numerous small wireless devices into a F5 tornado to collect data. Well, that's the idea!
- ***i-Robot*** (Will Smith, 2004)

Applications

- Situation awareness
  - Biomedical monitoring
  - Environmental monitoring (土石流監控)
  - Building control
  - Home security
  - Automobile monitoring/control
  - Manufacturing automation
  - Condition-based maintenance
  - Battlefield application



Home/Building controls

Industrial controls

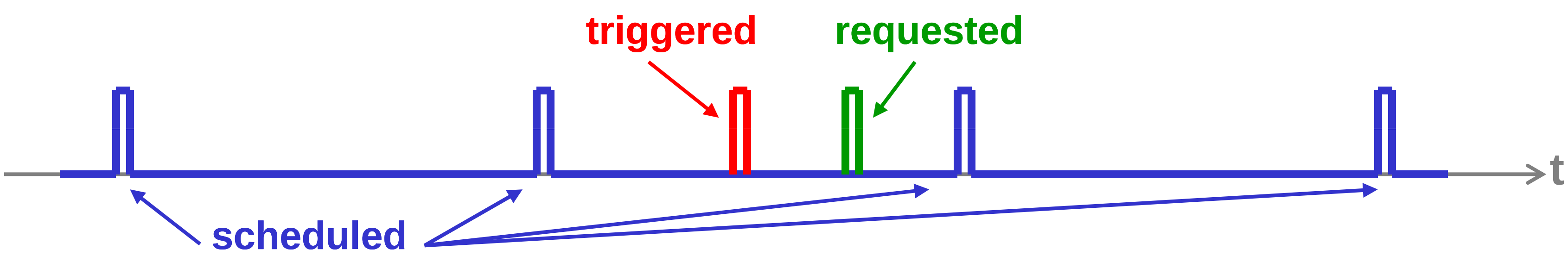
Sensor Network Characteristics

- Characteristics
  - Dense distribution
  - Each node must be low power (average power or energy), low cost, and compact
- Approaches for low-power
  - Low duty cycle operation
    - sensor nodes are in sleep mode most of the time
  - Short-distance multi-hop communication
    - Short-range and low bit rate communication provide link budget advantage, reduce radio power consumption
  - In-node signal processing $\Rightarrow$ analyzed information is conveyed in the form of *short message* rather than *large amount of raw data*
  - Collaborative decision making with neighboring nodes (the sniper detection system)

Low-duty Cycle Operation

- Information is provided only when,
  - Scheduled
  - Requested
  - Triggered (after something happened)
- Mainly refer to the communication module, the sensing module may be continuous (depends on the applications)

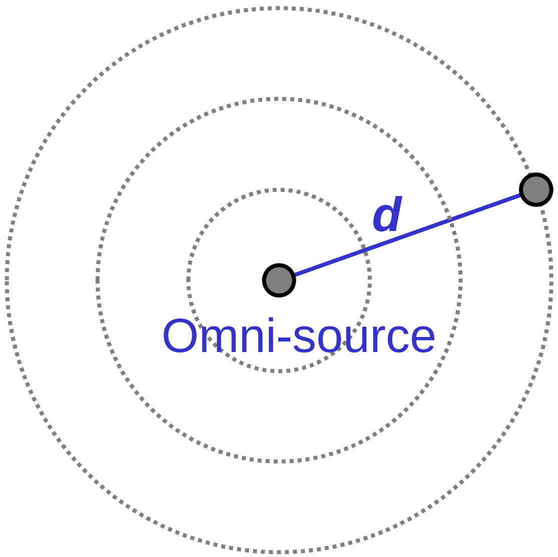
Communication module operation



⇒ Reduce average power (energy) consumption

RF Path Loss

- Free space: a channel region free of all objects that might absorb or reflect RF energy



Power density (P) on a sphere at a distance ***d***

$$P = \frac{P_t}{4\pi d^2} \quad watts / area$$

Power (P_r) extracted with a receiving antenna

$$P_r = A_{er} \times P$$

(A_{er} is the effective area of the receiving antenna)

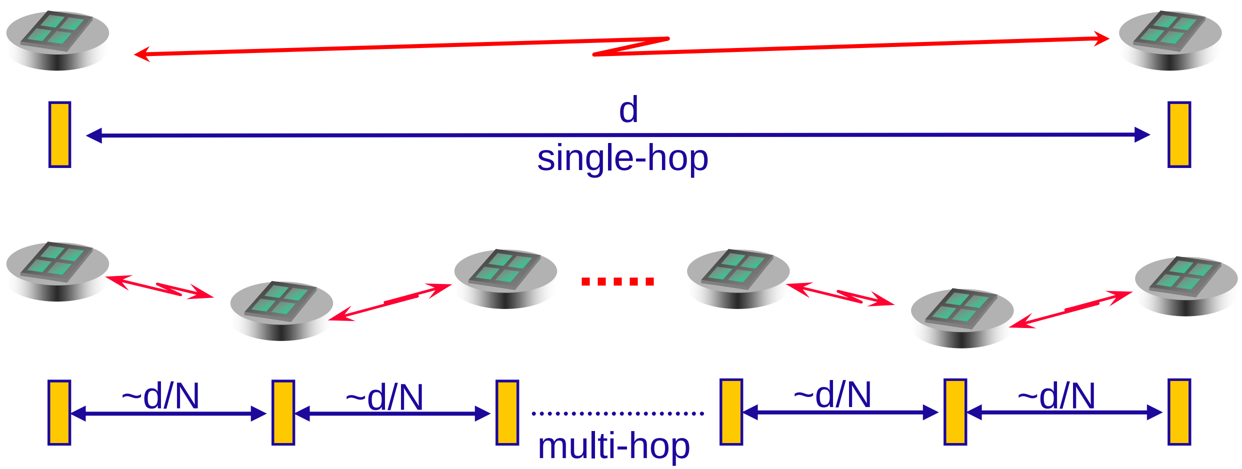
$$A_{er} = \frac{\lambda^2}{4\pi} \qquad \text{(for isotropic)}$$

$$P_r = \frac{P_t}{(4\pi d / \lambda)^2} \Rightarrow \boxed{Path\ Loss = (4\pi d / \lambda)^2}$$

- Free space condition rarely exists
- For a practical "d^n-model" (n: loss exponent), n is larger than 2

Multi-hop Communication

- By breaking a long range transmission into segments of short hops, aggregated system power is reduced



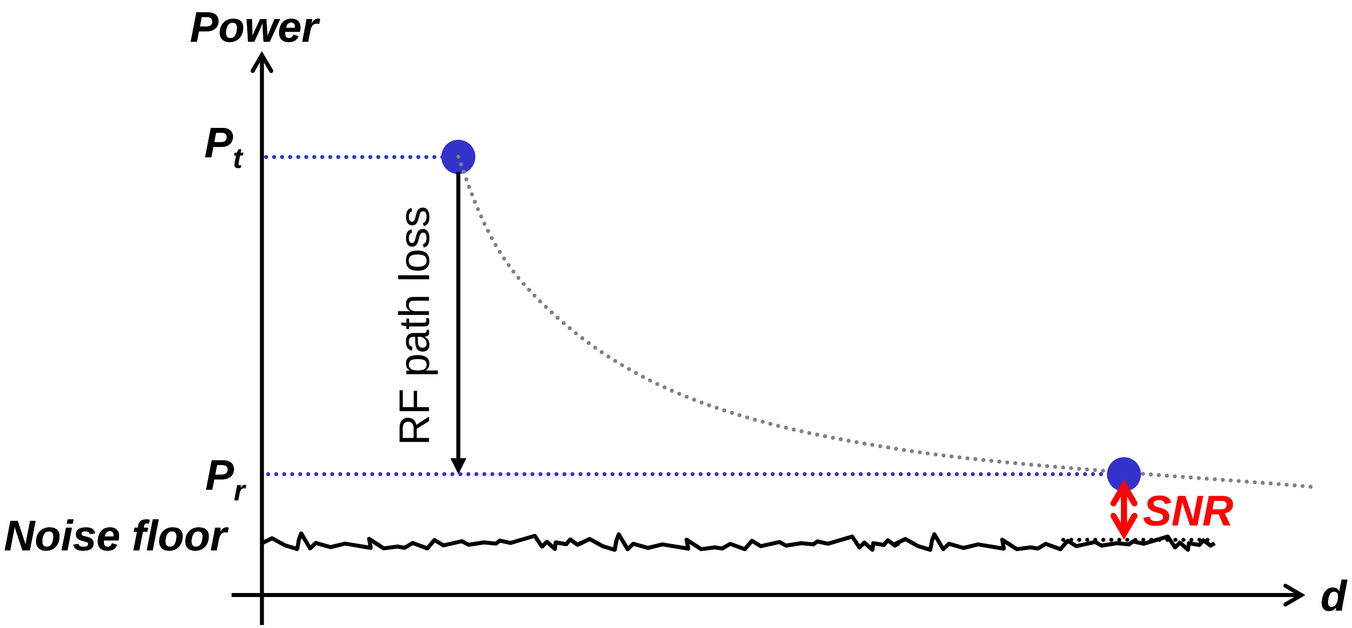
Received power due to RF path loss $\Rightarrow \; P_{rec} \propto \dfrac{1}{d^{\alpha}} \; (\alpha \approx 3-5)$

Relative power saving for N hops $\Rightarrow \; \dfrac{P_{total}(N)}{P_{total}(1)} \propto \dfrac{1}{N^{(\alpha-1)}}$

- Must also consider networking overhead and repeaters

Link Budget

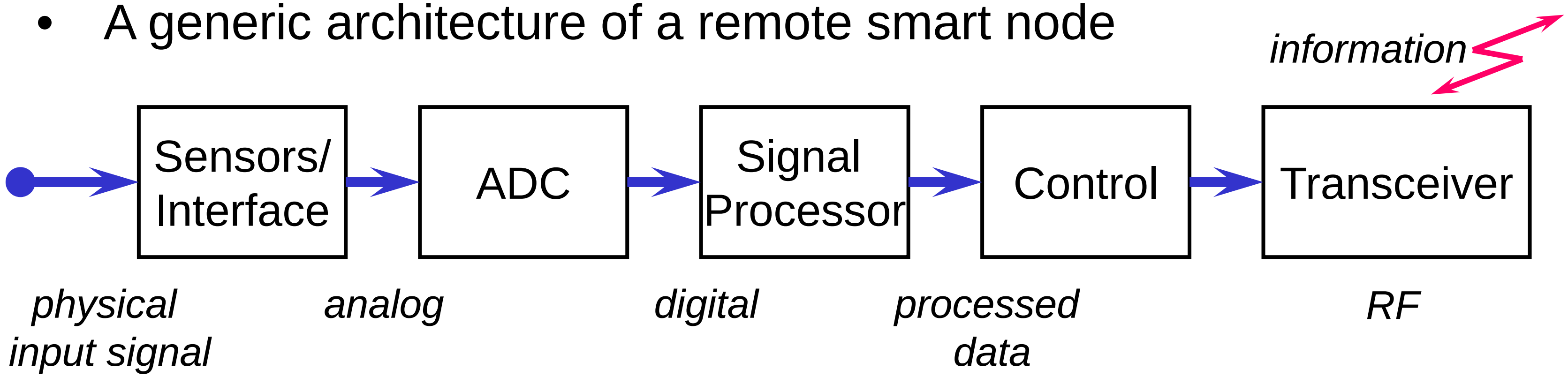
- The receiving device must have sufficient signal-to-noise ratio (SNR) in order to properly retrieve the data.
- The goal is to analyze the link between point ***A*** and ***B***, and see if a proper SNR can be achieved.



- SNR can be easier met with shorter distance and smaller bandwidth.

Wireless Sensor SOC

- A generic architecture of a remote smart node



- Local intelligence requires:
  - Energy sources
  - Sensors (infrared, seismic, acoustic, magnetic, imaging, etc.)
  - Interface circuitry
  - Analog/digital signal processing
  - Wireless communication
  - Networking
  - Distributed computation

Energy Sources

- Power is supplied by compact batteries (such as Li cells) or scavenged from environment
  - Batteries
    - Rated current capacity: define the peak current allowed for the node (drawing higher current than the rated value leads to a reduction of battery life)
    - Relaxation effect: the idle period allows partial capacity recovery of batteries; favor duty-cycle operation
  - Scavenged from environment (essential in certain M2M applications)
    - MEMS micro-vibrator
    - Piezoelectric bi-morphs
    - Photovoltaic
    - RF induced energy
  - Typically, require efficient regulators for practical use

Sensors - MEMS

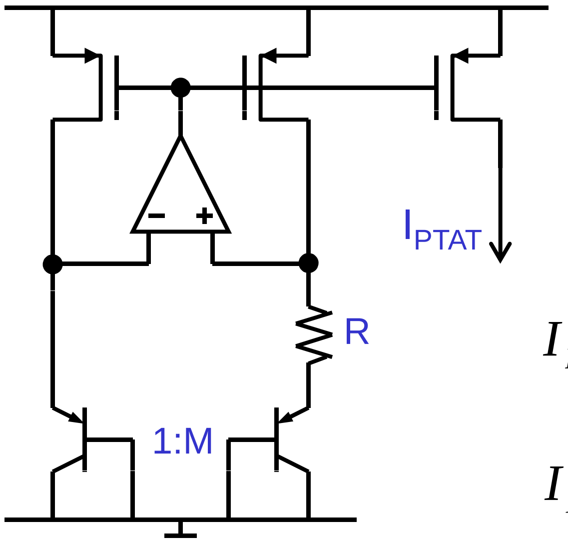
- Various sensing principles can be applied
  - Capacitive
  - Piezoresistive, piezoelectric
  - Thermal (TC), pyroelectric, thermoelectric, thermal expansion
  - Hall effect
  - Sound waves
- MEMS sensors: as physical size shrinks, sensor performance often degrades, but frequency response is usually improved
- Mature MEMS products
  - Airbag accelerometer
  - Blood pressure monitoring sensors
  - Inkjet printer head

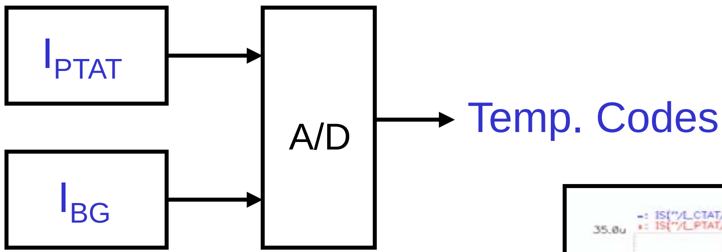
Sensors - Electronics

- Use electronics (circuits) to sense
- Electronic sensors
  - Temperature sensor
    - Standard CMOS process provides certain bipolar devices
  - Image sensor
    - Require some process modification to improve photon-responsivity and reduce dark current
  - Ranging/location sensor (UWB)
    - Radar

Example: Temperature Sensor

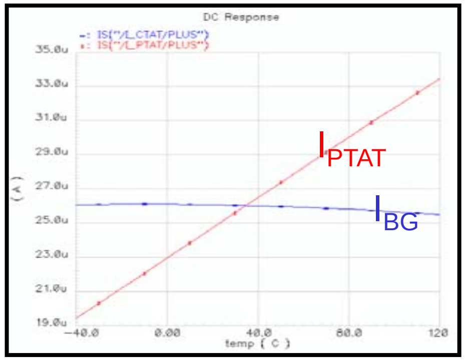
- Measure chip temperature or approximate ambient temperature if the chip itself generates little heat
- Based on the temperature dependence of V_{BE} and ΔV_{BE}
- Compare a PTAT current with a BG current to measure temperature (**CTAT?)**
- Parasitic lateral bipolar devices compatible with CMOS processes





$$I_{BJT} \cong I_S \exp\left(V_{BE}/V_T\right)$$

$$I_{PTAT} = \frac{\Delta V_{be}}{R} = \frac{V_T \ln(M)}{R} \propto T$$

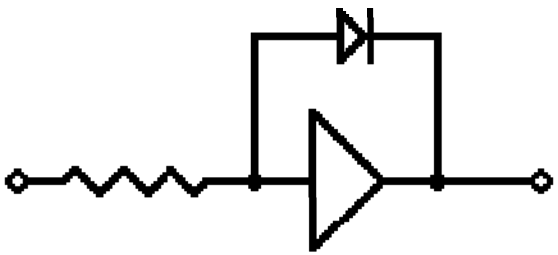


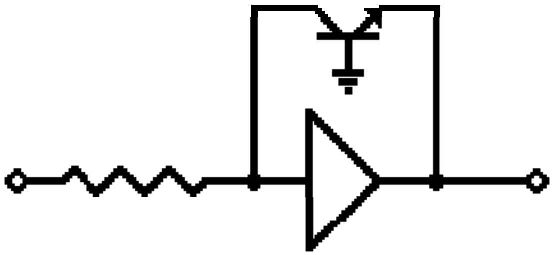
Interface Circuitry

- The desired signal is usually weak with large background noise
- Flicker noise and offset in CMOS circuits
- Sensor interface circuits in general require low noise, high resolution, high dynamic range, and low power
- Examples
  - Low-noise amplifiers
  - Logarithmic response circuits
  - Readout circuitry for photo-detector
  - Measurement circuitry for capacitive sensors
  - Noise and offset reduction techniques
    - Auto-zeroing technique
    - Chopper stabilization
  - Delta-sigma converters

Logarithmic Response Circuits

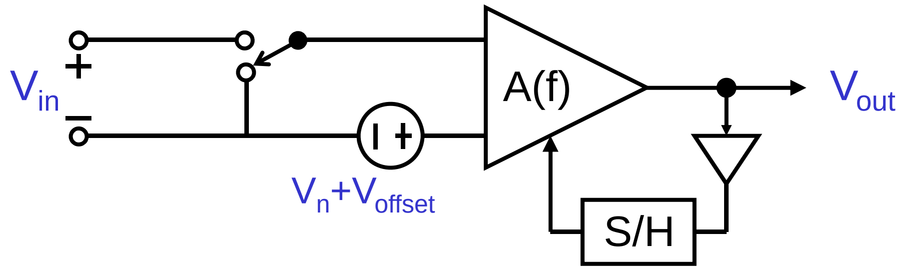
- Sometimes we do not want a linear response from an op amp circuit. For example, what if we want the output voltage to represent the natural logarithm of the input voltage?



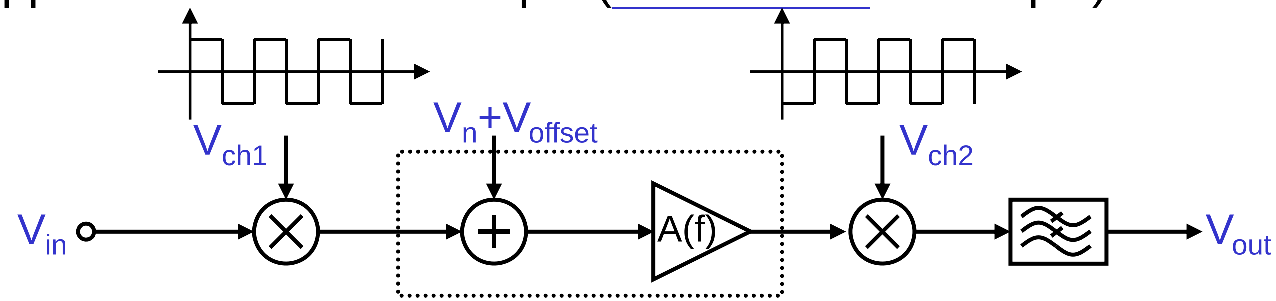


Interface Circuitry Examples

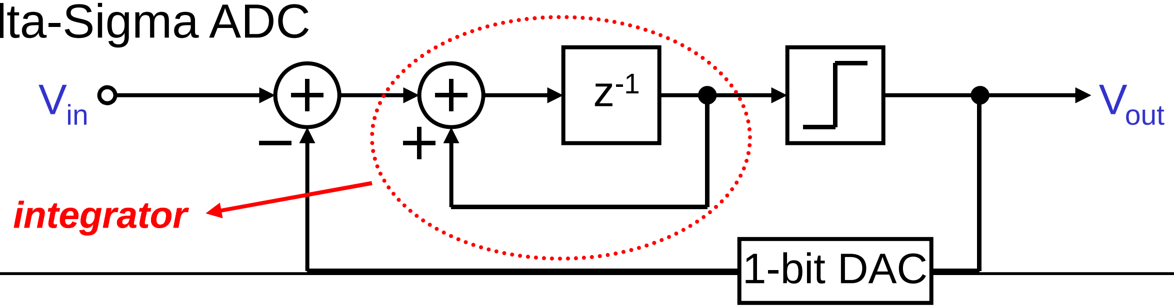
- Auto-zeroing technique (**sampling** technique)



- Chopper stabilization technique (**modulation** technique)



- Delta-Sigma ADC



Digital Signal Processing

- DSP digests raw data into information $\Rightarrow$ send less bits over radio
- Desired information ranges from event detection to event recognition
- Several approaches for information extraction (classification)
  - Time domain
    - threshold detection
    - correlation
  - Frequency domain
    - filter banks
    - spectrum analyzer (FFT or swept analyzer)
  - Time-frequency domain
    - Wavelet
  - Hilbert-Huang transformation

Wavelet, HHT

- The **wavelet** is a wave-like oscillation with an amplitude that starts out at zero, increases, and then decreases back to zero. It can typically be visualized as a "brief oscillation" like one might see recorded by a seismograph or heart monitor. Generally, wavelets are purposefully crafted to have specific properties that make them useful for signal processing.

- The **Hilbert–Huang transform (HHT)** is a way to decompose a signal into so-called intrinsic mode functions (IMF), and obtain instantaneous frequency data. It is designed to work well for data that are non-stationary and nonlinear. In contrast to other common transforms like the Fourier transform, the HHT is more like an algorithm (an empirical approach) that can be applied to a data set, rather than a theoretical tool

HHT Applications

- 哈佛醫學院用 HHT 來測量心律不整
- 約翰霍普金斯公共衛生學院用它來測量登革熱的擴散
- 美國聯邦調查局用 HHT 來辨識發言者的身分
- 海軍用它來探測潛艇
- 聯邦公路管理局研究中心測量公路、橋梁的安全
- 地震工程、地球物理探測、衛星資料分析
- 潛艇設計、結構損害偵測
- 血壓變化和心律不整
- 潮汐、波浪場等各項研究

(Ref: 謝志敏教授)

Low-Power Digital Circuits

- Performance metrics: power, energy, energy-delay product
- Power consumed by digital circuitry can be classified into static, dynamic, and leakage parts
- Static: typically not significant ($I_{DC} \times V_{DD}$)
- Dynamic: switching activities ($\propto fCV_{DD}^2$)
  - Lowering clock frequency
  - Reducing capacitance
  - Dynamic voltage scaling (V_{DD} and voltage swing)
- Leakage: gate leakage and substrate leakage
  - Device selection
  - Require low-leakage design methodologies

Wireless Connectivity

- Wireless interface options
  - Wi-Fi (WLAN, IEEE 802.11 a/b/g/n)
  - Bluetooth (IEEE 802.15.1)
  - UWB (IEEE 802.15.3)
  - Zigbee (IEEE 802.15.4)
  - WBAN (IEEE 802.15.6)
  - IEEE P1451.5
  - Proprietary solutions

- Some issues in selecting wireless standards for a low-power sensor network
  - Communication overhead
  - Latency requirement

Proprietary Wireless Solution

- Issues:
  - Frequency band: unlicensed ISM bands
  - Modulation scheme: constant envelop modulation
  - Data rate: higher data rate tends to be more power hungry, but too low may not be beneficial
    - Dynamic modulation scaling
  - Diversity (spatial/time/frequency) approaches
  - Multiple access schemes (TDMA, FDMA, CDMA, etc.)
  - Duplexing schemes (TDD, FDD)
  - Equalization
  - Coding

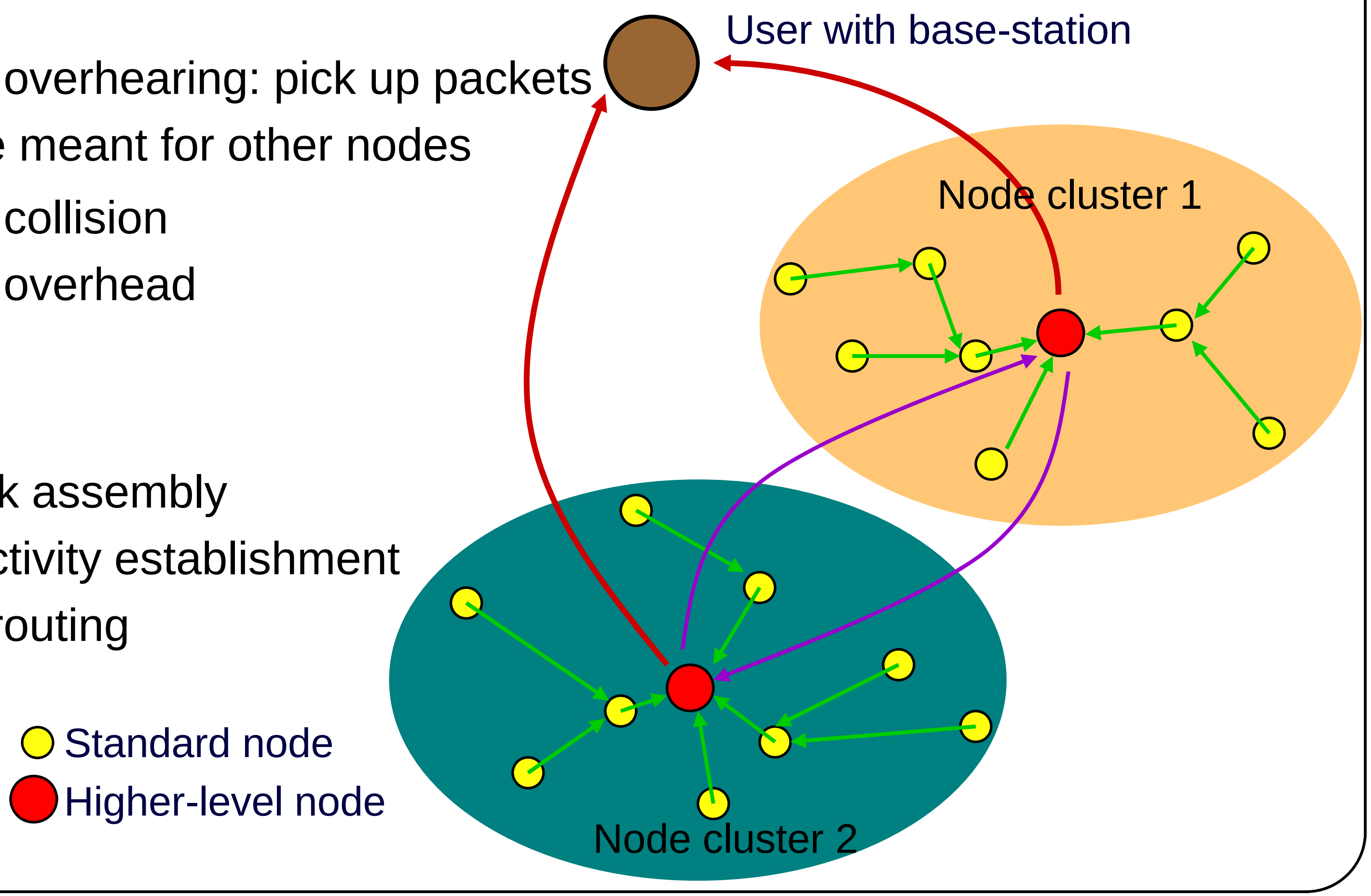
Low-Power Radio

- Short distance and low bit rate relax the link budget
- Low power radios
  - Transceiver architectures
    - Picoradio (UCB)
    - Super-regenerative
    - Impulse radio
    - Conventional architectures
  - Fast startup
  - Low-power circuit techniques
  - Mixed-mode calibrations
  - **Low-drift low-power oscillator (low frequency)**
  - Integrate (or inexpensive off-chip) high-Q components
- Average power consumption is likely dominated by the frequency synthesizer rather than the PA

Networking

- Main sources of energy waste in a network
  - Packet overhearing: pick up packets that are meant for other nodes
  - Packet collision
  - Packet overhead

- Issues
  - Network assembly
  - Connectivity establishment
  - Traffic routing

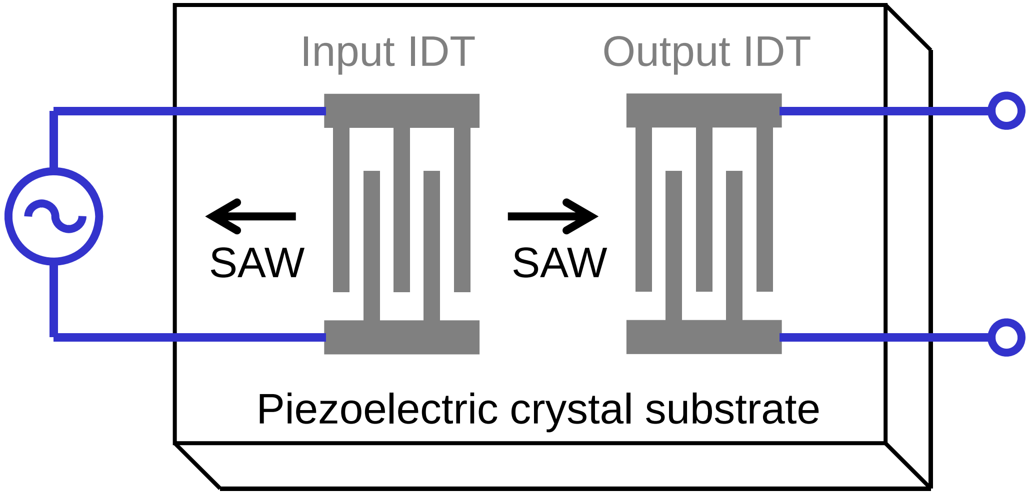


Passive Components

- Other than conventional passive components (Rs, Ls, and Cs) available in standard processes, alternative technologies may provide performance advantage in low-power design. Several component candidates are:
  - SAW (surface acoustic wave)
  - FBAR (film bulk acoustic resonator)
  - MEMS
  - LTCC (low-temperature co-fired ceramic)
  - Discrete chip components
- Tradeoffs among design complexity, performance, integration, and cost are to be studied

SAW

- The input signal is converted into SAW that propagates along the substrate, and converted back to the electrical signal at the output transducer

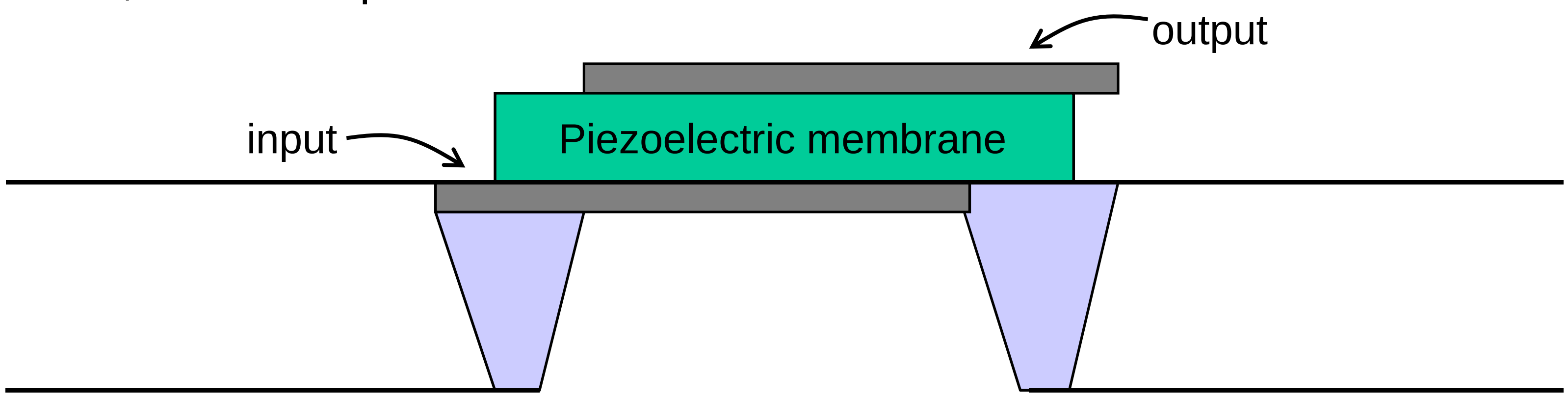


IDT: InterDigit Transducer

- Touch screen application

FBAR

- FBAR: thin **F**ilm **B**ulk **A**coustic **R**esonators
- Inherently a better choice (better power handling capability, less sensitive to surface quality, concentrated electric field)
- But, difficult to produce



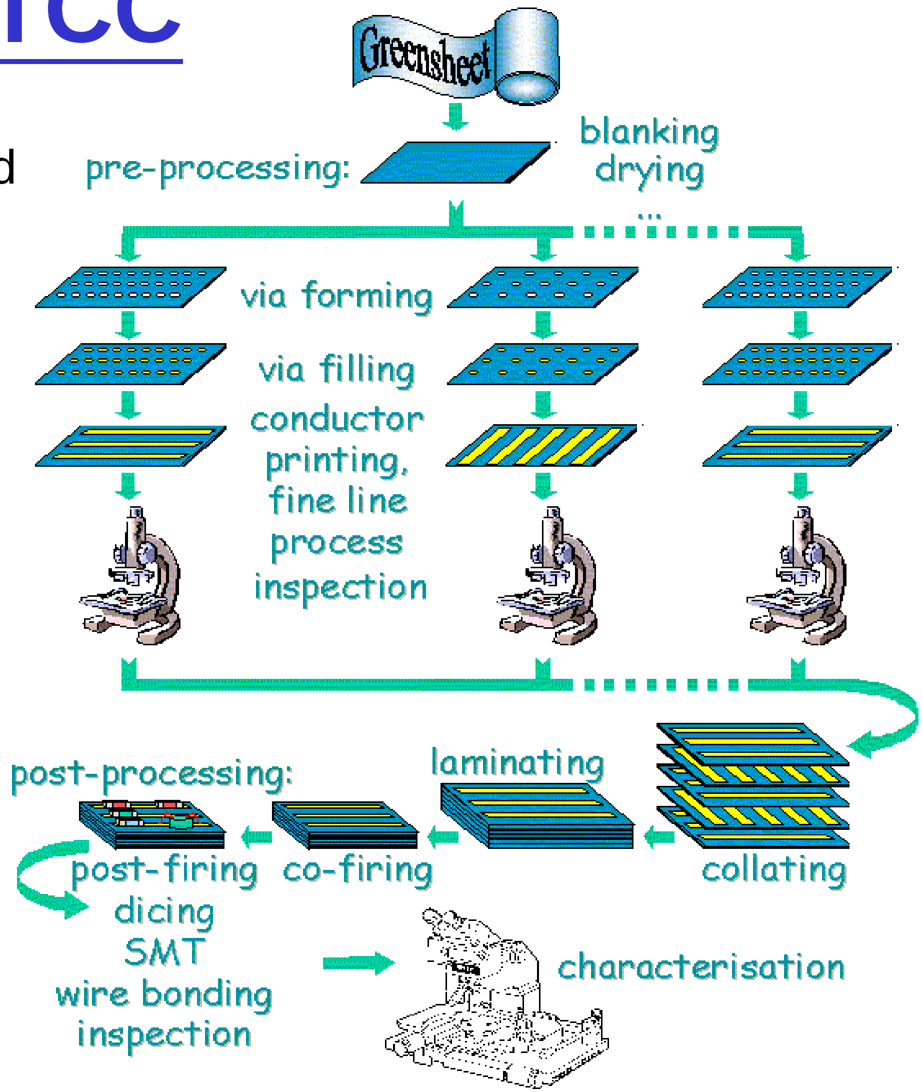
- Large acoustic impedance mismatch must exist on both sides of the piezoelectric (reduce mechanical damping)
- Lower parasitics

MEMS/NEMS

- MEMS – **M**icro-**E**lectro**M**achanical **S**ystems
- Technologies:
  - Surface micromachining
  - Bulk micromachining
  - LIGA
- Research areas:
  - RF-MEMS
  - Optical-MEMS
  - Bio-MEMS (Protein sensor; Prof. 黃榮山)
- NEMS – **N**ano-**E**lectro**M**achanical **S**ystems

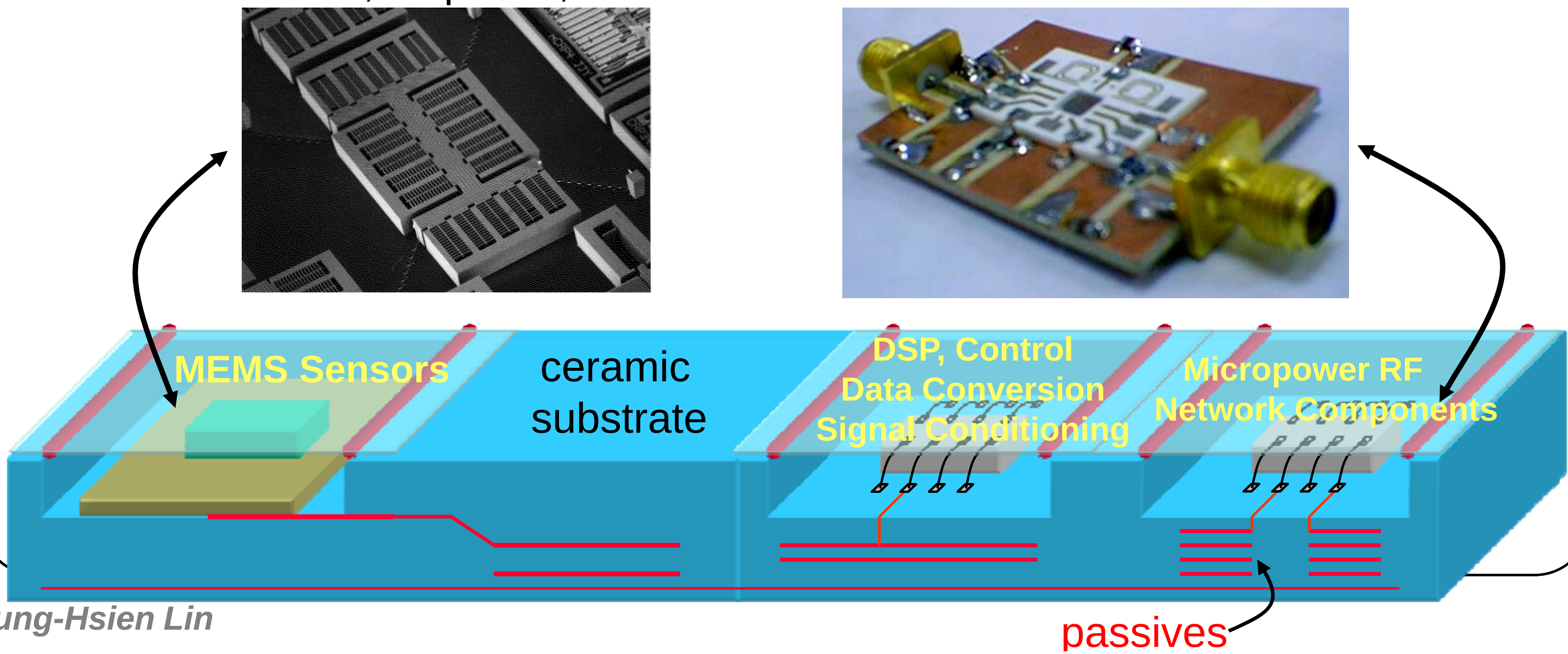
LTCC

- LTCC: **L**ow-**T**emperature **C**o-fired **C**eramic
  - Fine lines and space
  - Low resistance metallization
  - Excellent high frequency characteristics
- However:
  - Shrinkage control
  - Mechanical strength
  - Thermal conductivity
- cf. HTCC



System Integration

- System-on-a-chip/System-in-a-module/System-in-a-package
- One example: LTCC integration
  - Low loss substrate, high quality conductor
  - Not a good thermal conductor (not a main concern for low power)
  - Suitable for implementing passives such as, balun, matching network, loop filter, antenna and T/R switch



Summary

- Multiple research disciplines involved
- Require research efforts from system/network level all the way to circuit/component design
- Various applications
- Potential industrial interests
- An important link to bio-medical research

Sensor Network Related Research Activities

- Many research organizations have some sort of sensor network projects going on, each with different emphases. The project (or research group) acronyms are shown in parentheses.
  - UCB (Smart Dusts, Pico Radio, NEST)
  - MIT (μAMPS)
  - UCLA (WINS, LECS, NESL)
  - USC (SCOWR, SCADDS)
  - Georgia Institute of Technology (SensoNet)
  - DARPA (Smart Modules)
  - NIST (Wireless Ad Hoc Network Projects)
  - PARC/XEROX (Smart Matter Integrated Systems)
  - CSEM (Wisenet)
  - KAIST (MICROS)
  - Others (Rutgers, Washington….)

References

- [UCB] J. Rabaey, J. Ammer, T. Karalar, S. Li, B. Otis, M. Sheets, and T. Tuan, "PicoRadios for Wireless Sensor Networks: The Next Challenge in Ultra-low Power Design," *ISSCC Digest of Technical Papers*, pp. 200-201, Feb. 2002.
- [UCB] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, "System Architecture Directions for Network Sensors," *in Proc. of ASPLOS*, pp. 93-104, Nov. 2000.
- [MIT] R. Min, M. Bhardwaj, S.-H. Cho, E. Shih, A. Sinha, A. Wang, and A. Chandrakasan, "Low-power Wireless Sensor Networks," *VLSI Design*, pp. 205-210, *2001*.
- [UCLA] V. Raghunathan, C. Schurgers, P. Sung, and M. Srivastava, "Energy-aware Wireless Microsensor Networks," *IEEE Signal Processing Mag.*, pp. 40-50, Mar. 2002.
- [UCLA] G. Asada, M. Dong, T. S. Lin, F. Newberg, G. Pottie, H. O. Marcy, and W. J. Kaiser, "Wireless Integrated Network Sensors: Low Power Systems on a Chip," in *Proc. ESSCIRC*, pp. 9-16, Sep. 1998.
- [USC] W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Netowrks," *In Proc. INFOCOM,* pp. 1567-1576, June, 2002.
- [Georgia] I. Akyildiz, W. Su; Y. Sankarasubramaniam, and E. Cayirci, "A Survey on Sensor Networks," *IEEE Commun. Mag*., pp. 102-14, Aug. 2002.