Wireless Sensor Networks

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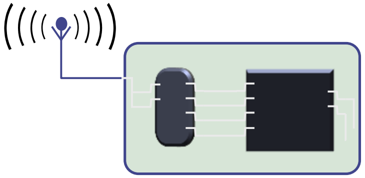
Characteristics and Applications

Wireless sensor networks

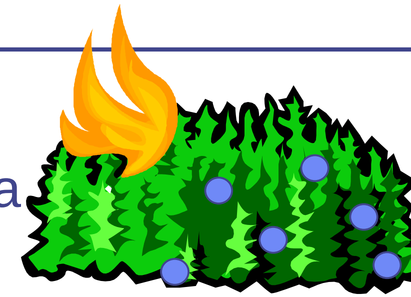
Instead of focusing interaction on humans, focus on interacting with ***environment***

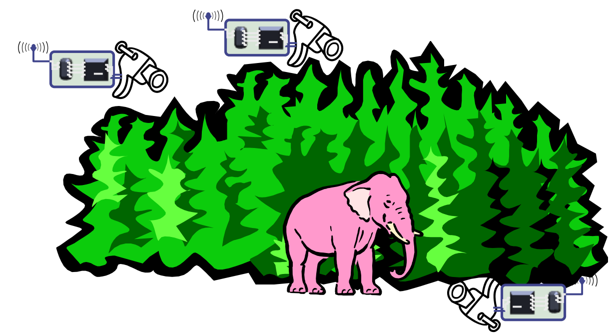
- Network is ***embedded*** in environment
- Nodes in the network are equipped with ***sensing*** and ***actuation*** to measure/influence environment
- Nodes process information and communicate wirelessly

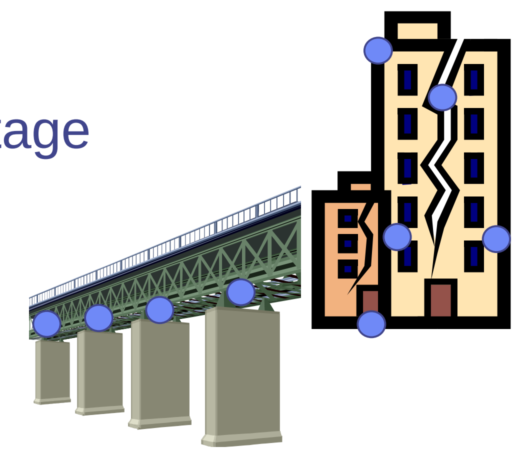


WSN application examples

- Emergency relief operations
  - Drop temperature sensor nodes over a fire to get a "temperature map"
  - Assist paramedic teams on accidents
- Environment monitoring
  - Use sensor nodes to observe wildlife
  - Measurement of pollution levels
- Intelligent buildings and bridges
  - Measurements about room occupancy, temperature, air flow, and reduce energy wastage by proper HVAC control
  - Monitor mechanical stress
- Smart cities
  - Find available parking spots

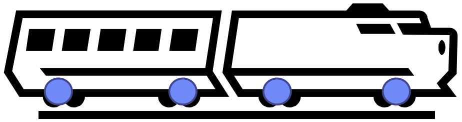






WSN application scenarios

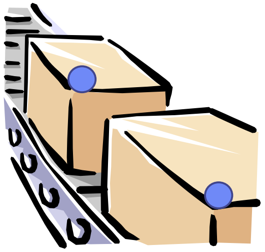
- Medicine and health care
  - Vital signs monitoring using body sensor networks (BSN)
    - Post-operative or intensive care
    - Long-term surveillance of chronically ill patients or the elderly
- Industrial facility management
  - Intrusion detection into industrial sites
  - Monitoring and control of fabrication process, …
- Machine surveillance and preventive maintenance
  - Embed sensing/control functions into places where cables can't go (e.g., tire pressure monitoring)



- Smart grid
  - Monitoring of electric energy consumption of individual domestic/industrial equipments

WSN application scenarios

- Intelligent roadside
  - Provide better traffic control by obtaining finer-grained information about traffic conditions (cars as the sensor nodes)
- Logistics
  - Equip goods (parcels, containers) with a sensor node
  - Track their whereabouts
- Precision agriculture
  - Greenhouses monitoring and control
  - Bring out fertilizer/pesticides/irrigation only where needed



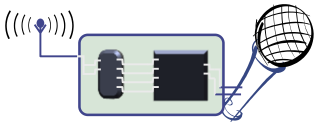
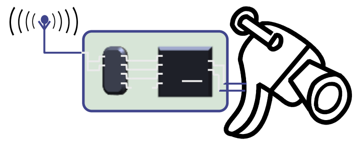
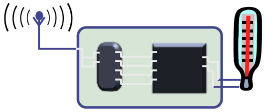
More examples available at:

50 Sensor Applications for a Smarter World

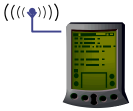
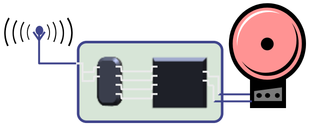
http://www.libelium.com/top_50_iot_sensor_applications_ranking

Roles of participants in WSN

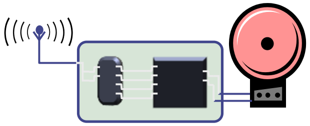
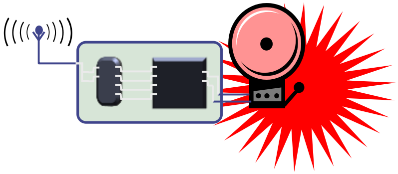
- ***Sources*** of data: Measure data, report them “somewhere”
  - Typically equip with different kinds of actual sensors

- ***Sinks*** of data: Interested in receiving data from WSN
  - May be part of the WSN or external entity, smartphone, base station, gateway, etc.

- ***Actuators***: Control some device based on data, usually also a sink

Deployment options for WSN

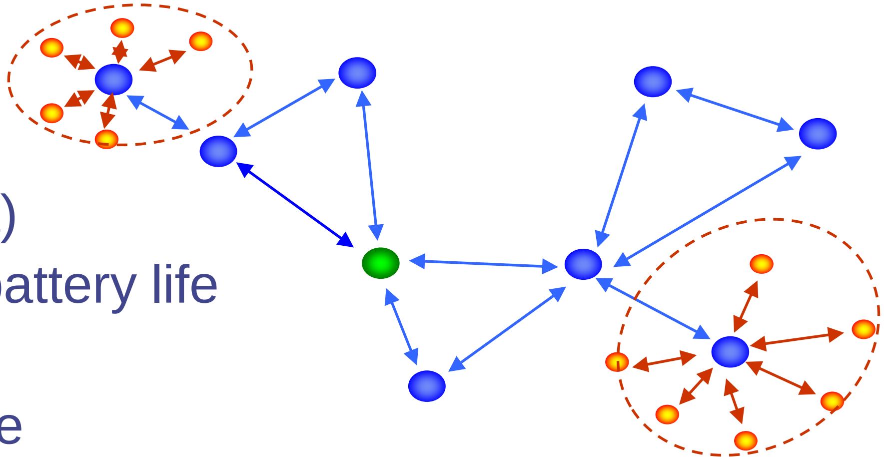
- How are sensor nodes deployed in their environment?
  - ***Random deployment*** (e.g. Dropped from aircraft !)
    - Usually uniform random distribution for nodes over finite area is assumed
  - ***Regular deployment*** (Well planned, fixed)
    - E.g., in machinery maintenance applications
    - Not necessarily geometric structure, but that is often a convenient assumption
  - ***Mobile*** sensor nodes
    - Can be passively moved around by some external force (wind, water)
    - Can move to compensate for deployment shortcomings
    - Can actively seek out "interesting" areas

Traffic Patterns

- ***Interaction patterns*** between sources and sinks, depend on application
  - ***Event detection***: Nodes locally detect events (maybe jointly with nearby neighbors), report these events to interested sinks
  - ***Periodic measurement***
  - ***Query:*** *Local or remote client requests information from sensor nodes on demand*
  - ***Function approximation:*** Use sensor network to approximate a function of space and/or time (e.g., temperature map)
  - ***Edge detection:*** Find edges (or other structures) in such a function (e.g., where is the zero degree border line?)
  - ***Tracking*:** Report (or at least, know) position of an observed intruder ("pink elephant")

Typical WSN characteristics

- Nodes cooperate to achieve a common goal
  - Multi-hop communications
  - Ad-hoc operation
- Low data rate
  - Low traffic load (sensor data)
- Goal: multi-month to multi-year battery life
  - Low power consumption
    - Short transmission range
      - Multi-hop communications
  - Energy efficient protocols
    - Low duty-cycle
- Low device complexity
  - Limited processing and memory capacity
  - Low cost
- High number of nodes



OBS: Some WSNs don’t meet all these characteristics

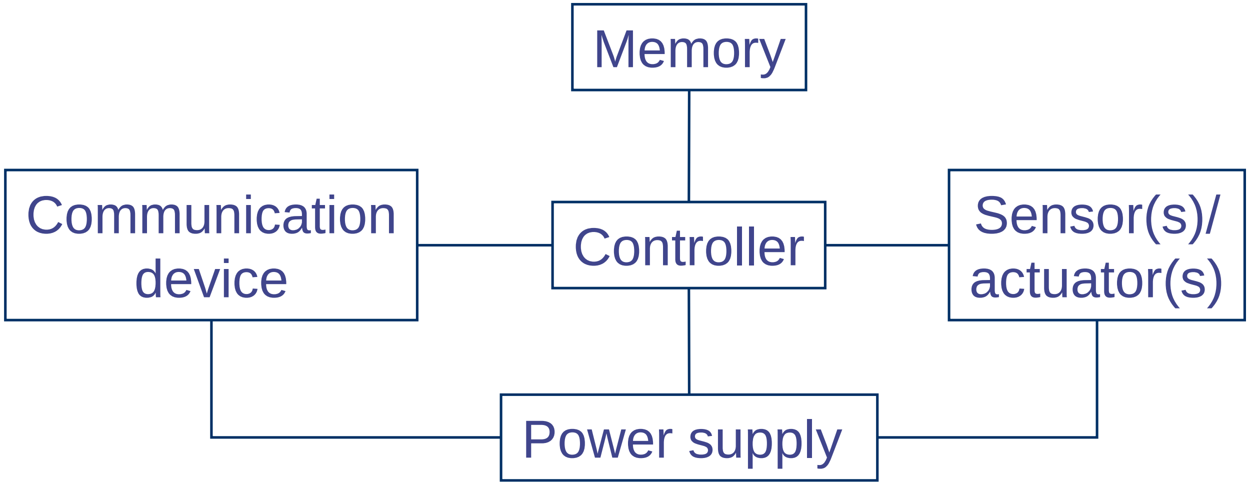
Enabling technologies for WSN

- Cost reduction
  - Wireless communication
  - Processing (microcontroller)
  - Sensing
  - Batteries
- Miniaturization
  - Many applications demand small size
  - “Smart dust” as the most extreme vision
  - Microelectronics and MEMS technologies
- Energy scavenging
  - Recharge batteries from ambient energy (light, vibration, …)
- New communication protocols and standards

WSN Node Architecture

Sensor node architecture

- Main components of a WSN node
  - Controller – processor
  - Communication device(s) – transceiver
  - Sensors/actuators
  - Memory
  - Power supply



Controller

- Main options:
  - Microcontroller – general purpose processor, optimized for embedded applications, low power consumption
  - DSPs – optimized for signal processing tasks
  - FPGAs – may be good for testing
  - ASICs – only when peak performance is needed, no flexibility

- Example microcontrollers
  - Texas Instruments MSP430
    - 16-bit RISC core, up to 4 MHz, versions with 2-10 kbytes RAM, several DACs, RT clock, prices start at 0.49 US$
  - Atmel ATMega
    - 8-bit controller, larger memory than MSP430, slower

Communication device

- Which transmission medium?
  - Electromagnetic at radio frequencies (most relevant) ✓
    - Relatively long range and high data rates, does not require line of sight
  - Electromagnetic, light
  - Ultrasound (suitable for underwater communications)
  - Magnetic induction (only in very specific cases)

- Radio transceivers
  - Transmit a bit- or byte stream as radio wave
  - Receive it, convert it back into bit-/byte stream

Transceiver states

- Transceivers can be put into different operational ***states***, typically:
  - ***Transmit***
  - ***Receive***
  - ***Idle*** – ready to receive, but not doing so
    - Sometimes, some functions in hardware can be switched off, reducing energy consumption a little
  - ***Sleep*** – significant parts of the transceiver are switched off
    - Not able to immediately receive something
    - ***Recovery time*** and ***startup energy*** to leave sleep state can be significant

Transceiver characteristics

- **Capabilities**
  - Interface: bit, byte, packet level?
  - *Supported frequency range?*
    - Typically, somewhere in 433 MHz – 2.4 GHz, ISM band
  - *Multiple channels?*
  - *Data rates?*
  - *Distance range?*
- **Energy characteristics**
  - *Power consumption to send data?*
  - *Power consumption to receive data?*
  - Time and energy consumption to change between different states?
  - Transmission power control?
  - Power efficiency (which percentage of consumed power is radiated?)
- **Radio performance**
  - Modulation? (ASK, FSK, …?)
  - Noise figure? NF = SNR_I/SNR_O
  - Gain? (signal amplification)
  - Receiver sensitivity? (minimum S to achieve a given E_b/N_0)
  - Blocking performance (achieved BER in presence of frequency-offset interferer)
  - Out of band emissions
  - *Provisioning of Carrier Sensing & RSSI (Received Signal Strength Indicator) information*
  - Frequency stability (e.g., towards temperature changes)
  - *Voltage range*

Example radio transceivers

- Almost boundless variety available
- Some examples
  - RFM TR1000 family
    - 916 or 868 MHz
    - 400 kHz bandwidth
    - Up to 115,2 kbps
    - On/off keying or ASK
    - Dynamically tuneable output power
    - Maximum power about 1.4 mW
    - Low power consumption
  - Chipcon CC1000
    - Range 300 to 1000 MHz, programmable in 250 Hz steps
    - FSK modulation
    - Provides RSSI
  - Chipcon CC 2400
    - Implements 802.15.4
    - 2.4 GHz, DSSS modem
    - 250 kbps
  - Infineon TDA 525x family
    - E.g., 5250: 868 MHz
    - ASK or FSK modulation
    - RSSI, highly efficient power amplifier
    - Intelligent power down, “self-polling” mechanism
    - Excellent blocking performance

Energy supply of mobile/sensor nodes

- Goal: provide as much energy as possible at smallest cost and volume/weight
  - In WSN, recharging may or may not be an option
- Options
  - Primary batteries – not rechargeable
  - Secondary batteries – rechargeable, used in combination with some form of energy harvesting
- Requirements include
  - High capacity per volume (J/cm^3)
  - Capacity under load
  - Low self-discharge
  - Efficient recharging (even at low current)
  - Voltage stability
  - Good relaxation properties (self-recharging)

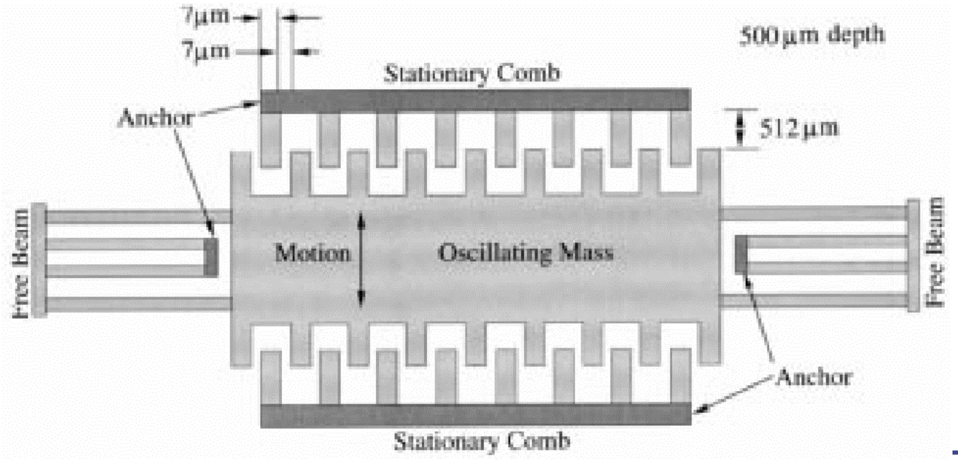
Battery examples

- Energy per volume (Joule per cubic centimeter):

Primary batteries			
Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm^3)	3780	2880	1200
Secondary batteries			
Chemistry	Lithium	NiMHd	NiCd
Energy (J/cm^3)	1080	860	650

Energy scavenging

- How to recharge a battery?
  - A laptop: easy, plug into wall socket in the evening
  - A sensor node? – Try to ***scavenge*** energy from environment
- Ambient energy sources
  - Light ! solar cells – between 10 μW/cm^2 and 15 mW/cm^2
  - Temperature gradients – 80 μ W/cm^2 @ 1 V from 5K difference
  - Vibrations – between 0.1 and 10000 μ W/cm^3
  - Pressure variation (piezo-electric) – 330 μ W/cm^2 from the heel of a shoe
  - Air/liquid flow (MEMS gas turbines)



Energy consumption

- A "back of the envelope" estimation
- Very small battery (~ 1 mm^2 – "smart dust"): 1 J = 1 Ws
- Number of instructions
  - Energy per instruction: 1 nJ
  - Corresponds: 10^9 instructions!
- Lifetime
  - Require a single day operational lifetime = 24x60x60 =86400 s
  - 1 Ws / 86400s = ***11.5 μW*** as average power consumption!
  - No current controller, let alone an entire node (transceiver, sensors), is able to work continuously at such low-power levels
- Way out?

Multiple power consumption modes

- Way out: Do not run sensor node at full operation all the time
  - If nothing to do, switch to ***power save mode***
  - Question: When to throttle down? How to wake up again?
    - Decided by the MAC protocol
- Typical modes
  - Controller: Active, idle, sleep
  - Transceiver: TX, RX/idle, sleep
- Multiple sleep modes possible, "deeper" sleep modes
  - Strongly depends on hardware, e.g.:
    - TI MSP 430: four different sleep modes
    - Atmel ATMega: six different modes

Medium Access Control

Medium Access Control in WSNs

- Medium access in wireless networks is difficult mainly because of
  - Impossible (or very difficult) to send and listen at the same time in the same channel (collision detection is not possible)
  - Interference situation at receiver is what counts for transmission success, but can be very different from what sender can observe (causes the hidden station problem)
  - High and variable error rates
- Requirements
  - As usual: high throughput (efficiency), low overhead, scalability, …
  - Additionally: energy-efficient, handle device sleeping!

Requirements for energy-efficient MAC protocols

- Remembering energy cost for transceivers
  - Transmissions are costly
  - Receiving about as expensive as transmitting
  - Idling can be cheaper sometimes, **but is still expensive**
  - Sleeping is the ideal state
- Energy waste problems
  - ***Collisions*** – wasted effort when two packets collide
  - ***Overhearing*** – waste effort in receiving a packet destined for another node
  - ***Idle listening*** – sitting idly and trying to receive when nobody is sending
  - ***Protocol overhead***
- Always nice: Low complexity solution

Centralized vs. Distributed medium access control

- Centralized control
  - Idea: Have a central station control when a node may access the medium
    - Example: Polling, centralized computation of TDMA schedules
    - Characteristics: Simple, quite efficient (e.g., no collisions), most of the burden is put on the central station
  - **Not directly feasible for large wireless networks**
    - Can be quite useful when network is divided into smaller groups (called clusters)
      - In each cluster, medium access can be centrally controlled

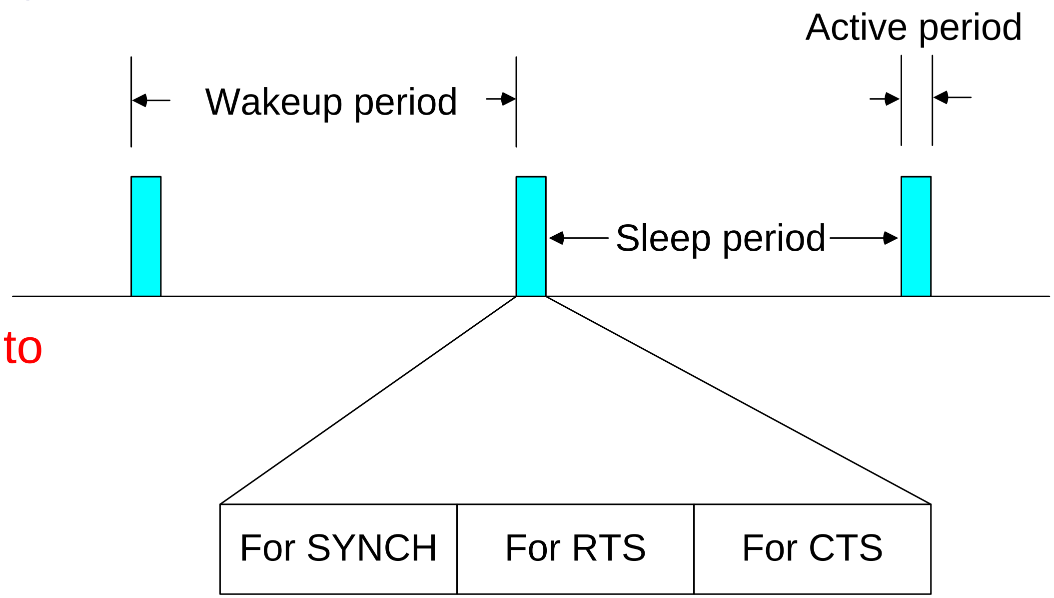
- Distributed control
  - Alternative to centralized control

Schedule- vs. Contention-based MACs

- ***Schedule-based*** MAC
  - A ***schedule*** exists, regulating which participant may use which resource at which time (resource reservation)
  - Typical resource: frequency band in a given physical space
  - Schedule can be ***fixed*** or computed ***on demand***
  - Usually, collisions, overhearing, idle listening no issues
  - Needed: **time synchronization!**
- ***Contention-based*** protocols
  - Risk of colliding packets is deliberately taken
  - Hope: coordination overhead can be saved, resulting in overall improved efficiency
  - Mechanisms to handle/reduce probability/impact of collisions required
  - Usually, ***randomization*** used somehow

Sensor-MAC (S-MAC)

- **Example of a Contention-based WSN protocol**
- MACA's idle listening is particularly unsuitable if average data rate is low (most of the time, nothing happens)
- Idea: Switch nodes off, ensure that neighboring nodes turn on simultaneously to allow packet exchange (rendez-vous)
  - Only in these ***active periods***, packet exchanges happen
  - Nodes need to broadcast synchronization packets to agree on wakeup schedule
  - Synchronization packets need to be sent periodically to overcome clock-drift
- SYNCH, RTS, CTS phases, before packet exchange



Body Area Networks

Rede de Área Corporal (BAN)

- Ou BSN - Rede de Sensores Corporal
- Tipo particular de rede de sensores sem fios
- Dispositivos da rede situam-se:
  - **no interior** (e.g., dispositivos implantáveis e cápsulas endoscópicas),
  - **sobre**, seja incorporados na roupa (*wearable*) ou fixados ao corpo;
  - ou **em torno do corpo humano** (e.g., estação base).
- As BANs possuem aplicações nas áreas de:
  - Cuidados de saúde
  - Desporto
  - Entretenimento

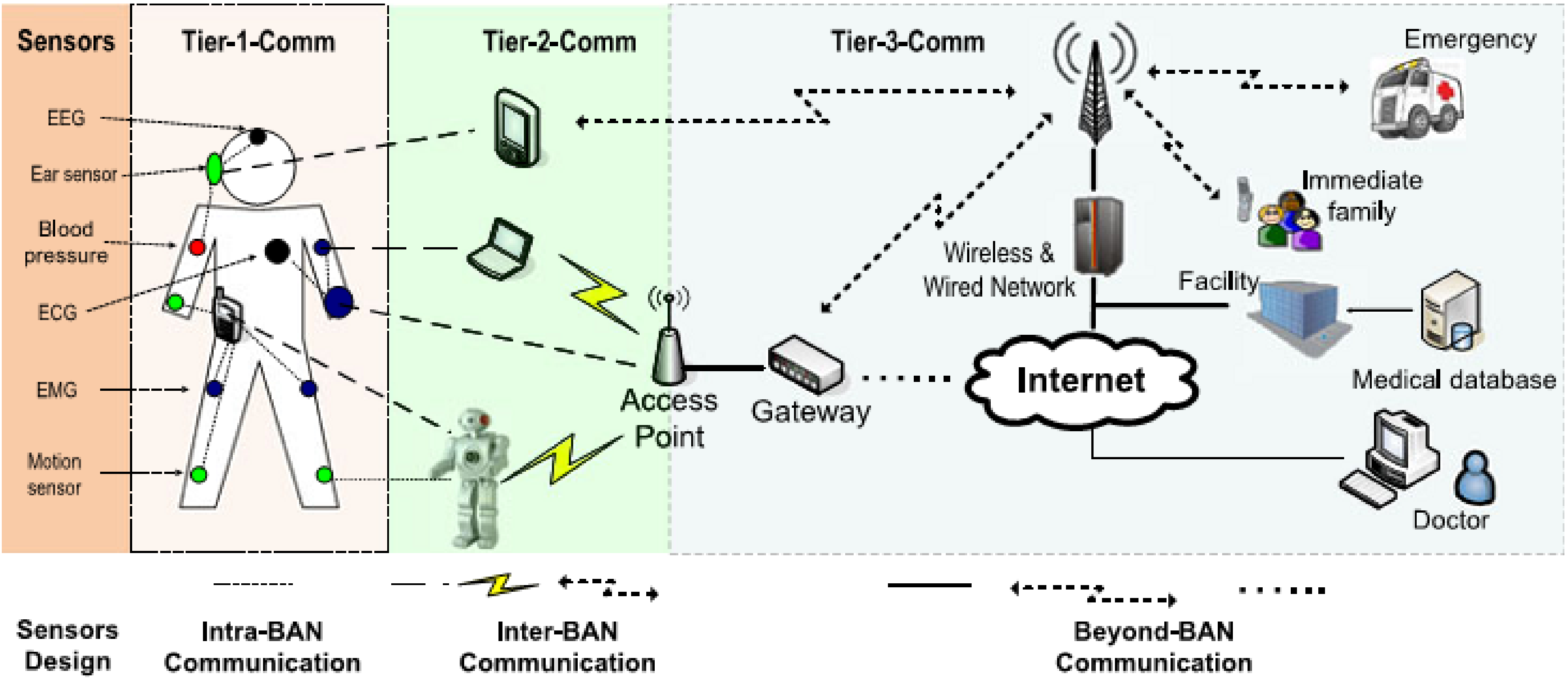
Aplicação em Cuidados de Saúde

- Monitorização contínua de sinais fisiológicos de pacientes
  - Eletrocardiograma (ECG), temperatura, oximetria, pressão arterial, eletroencefalograma (EEG), eletromiograma (EMG), nível de glicose no sangue, etc.
  - Sem restrição à mobilidade e à realização das tarefas normais diárias
  - Potencial de deteção precoce e prevenção de patologias
    - Benefícios para a saúde do utilizador
    - Redução com custos de tratamentos

Aplicação em Desporto e Entretenimento

- Na área do desporto
  - Sensores podem ser utilizados para monitorizar a atividade física:
    - Frequência cardíaca
    - Atividade biomecânica (por exemplo, pelo uso de sensores de torque ou postura)
  - Permite avaliar o estado de saúde e auxiliar na melhoria do desempenho
- Na área do entretenimento
  - Captura de movimentos e controlo de videojogos
  - Transmissão de vídeo, áudio e dados para dispositivos *wearable*

Camadas da Arquitetura de Comunicação



- Camada 1: Intra-BAN. Comunicação entre os nós da BAN no corpo e um dispositivo pessoal, ou concentrador (*hub*), que pode ser de uso geral (e.g., um *smartphone*) ou concebido especificamente para essa função.

Camadas da Arquitetura de Comunicação

- Camada 2: Inter-BAN
  - Comunicação sem fios entre o concentrador e um dispositivo fora do corpo (e.g., estação base, ponto de acesso), passando eventualmente por routers
  - Pode utilizar tecnologias como Wi-Fi, 3G, ZigBee, etc.
  - Pode abranger múltiplos utilizadores
- Camada 3: Beyond-BAN
  - Visa proporcionar o armazenamento, processamento e visualização remota da informação
  - Pode utilizar redes de área alargada, por exemplo, via Internet

Arquiteturas para a Camada Intra-BAN

- Tipo A – Ligação por fios no corpo
  - Entre os dispositivos da BAN e o concentrador
- Tipo B – Ligação sem fios no corpo
  - Entre os dispositivos da BAN e o concentrador
- Tipo C – Comunicação direta para fora do corpo
  - Entre os dispositivos da BAN e um dispositivo fora do corpo
  - Integra também a camada Inter-BAN
  - Dispensa assim o concentrador

Internet of Things

Typical Components of a IoT System

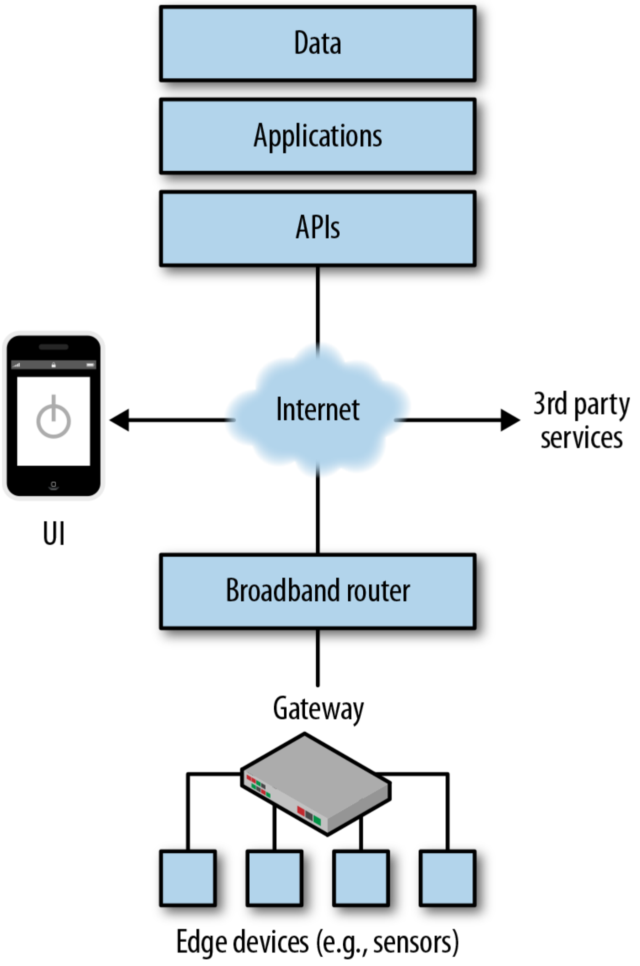
- Embedded devices (the “things” in IoT)
  - Sensors and actuators
- A gateway
  - Required when the embedded devices don’t have native IP connectivity
- An Internet router
  - Shared with conventional (not IoT) applications
- An Internet service
  - Running on a web server
- One or more clients (app or browser based)
  - For the user to interact with the service via mobile phones, tablets or PCs

Embedded Devices Connections

- How embedded devices connect to the Internet
  - Through a gateway (e.g., ZigBee or Z-Wave devices)
    - Example: SmartThings devices
  - Through an smartphone (e.g., using Bluetooth or BLE)
    - Example: wearables
  - Direct connection (e.g., using Wi-Fi)
    - Example: Belkin WeMo devices

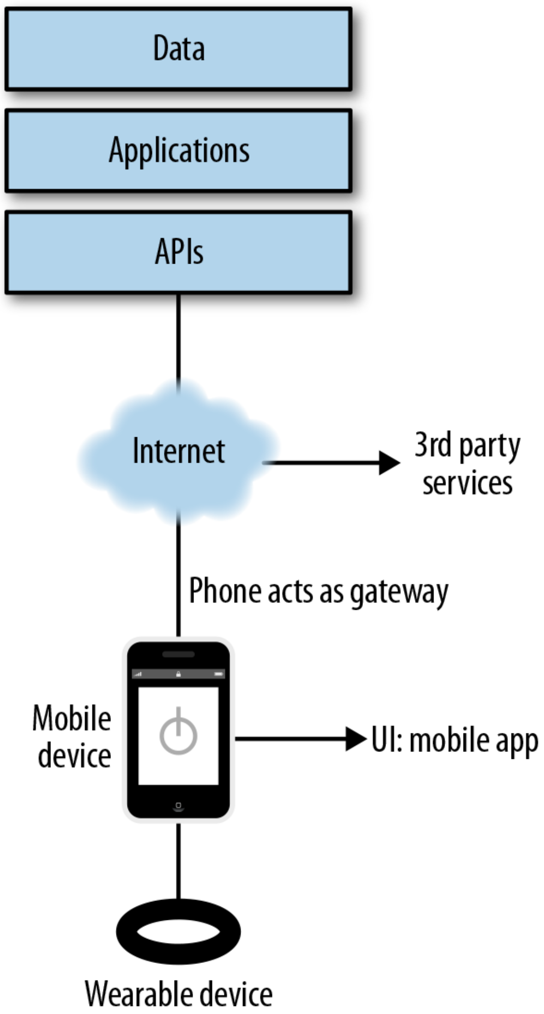
Dedicated Gateway Architecture

- Edge embedded devices use a low-power wireless network protocol such as ZigBee or Bluetooth to talk to the gateway
- Edge devices are not directly accessible on the Internet: all inbound and outbound communications must pass through the gateway
- The gateway translates between the ZigBee protocol and Internet protocols and provides a security firewall, which controls incoming and outgoing communications to protect the edge devices from malicious attacks
- The gateway can also act as a local brain for the system—for example, running the security system or home automation rules



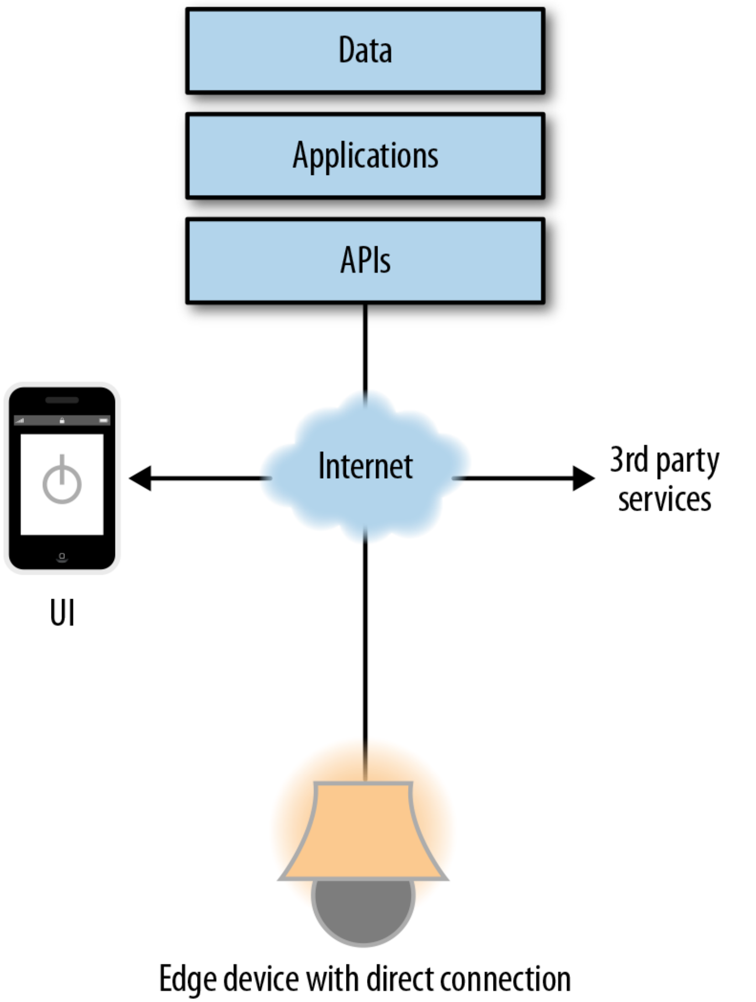
Smartphone as a Gateway

- Common pattern with wearable devices (BANs)
- The wearable device connects to a smartphone using a wireless network technology integrated in the smartphone, such as Bluetooth
- The smartphone has an app that interacts directly with the device
- The smartphone also acts as a gateway to translate between Bluetooth and Internet networking, via cellular or Wi-Fi network
- Using a smartphone as the gateway means it is not necessary to provide a separate gateway device; however, a smartphone is not a suitable gateway for any device that needs connectivity when the user is not around



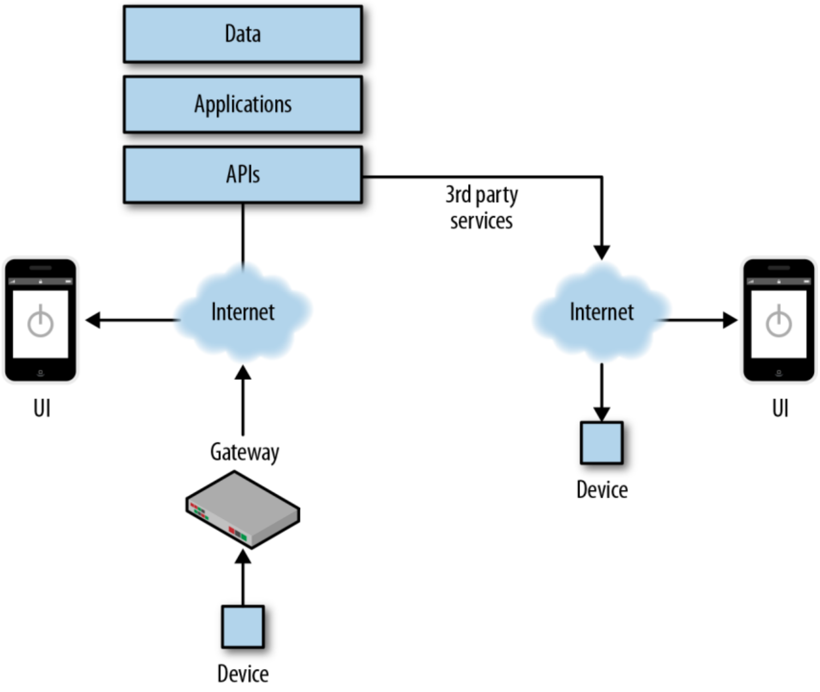
Direct Internet Connection

- Embedded device connects directly to the Internet service via Wi-Fi or cellular network without using a gateway
- Example: Belkin WeMo devices
- Drawback – Wi-Fi uses much more power than ZigBee
  - These devices nearly always need to have mains electrical power



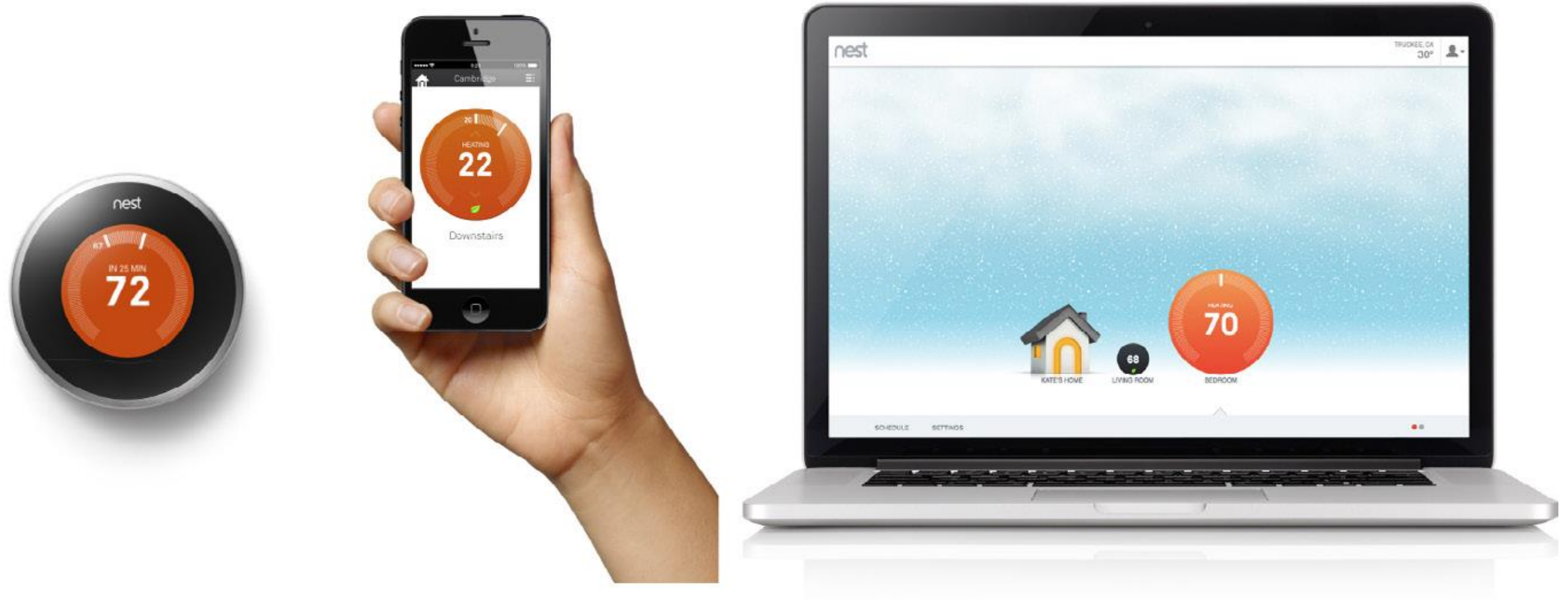
Service-to-Service Connection

- Internet services can connect together over APIs
- Devices from different manufacturers can be integrated without the need of a shared gateway
- Example: a Jawbone activity monitor could spot when you're waking up and notify the Jawbone Internet service. This then notifies the Nest Internet service, which sends a message to your thermostat to turn on and warm up the house.



Extended User Interfaces

- Network connection provides new user interfaces (UI)
- Nest Learning Thermostat - can be controlled by the on-device UI, a smartphone app, or a web app



IoT Platforms

- Closed platforms – Only work with devices of a specific manufacturer
- Open platforms – Enable devices from multiple manufacturers to interoperate
  - Example: Samsung SmartThings connected home platform
    - Supports a range of networks and devices from manufacturers such as GE, Honeywell, Sonos, Philips, Belkin, Withings, etc.