• Paradigm shift from the traditional event-driven model (i.e., go to doctor when sick) to one where we are continuously monitoring a person’s “well-being”
• Monitoring via bio-sensors, smart-home technologies, and information networks.
• This allows us to be more proactive in health maintenance, as well as allowing the health care provider to make more informed decisions with a greater wealth of accurate data.
Basic Terms

- Transducer: a device which converts one form of energy to another

- Sensor: a transducer that converts a physical phenomenon into an electric signal
  – an interface between the physical world and the computing world.

- Actuator: a transducer that converts an electric signal to a physical phenomenon
From Physical Process to Digital Signal

A Measurement and Control System
Sensor Devices

Sensor-to-Signal Interface

• Action of environment on a sensor causes it to generate an electrical signal directly
  – voltage source (V)
  – current (I) or charge (Q) source

• Action of environment on sensor changes an electrical parameter that we can measure
  – resistance changes: $V \sim I$
  – capacitance changes: $V \sim \int I \, dt$, $I \sim dV/dt$
  – inductance changes: $V \sim dl/dt$, $I \sim \int V \, dt$
Signal Conditioning

- Filter for expected frequency regime
- Subtract DC offset (“zeroing”)
- Amplify or attenuate signal (“scaling”)
- Linearize relationship between measured and observed electrical parameter
  - now usually done in software after ADC
- ...

4-channel stereo multiplexed analog-to-digital converter for a sound card

Analog-to-Digital Converter (ADC)

- Many different principles
- Often integrated with microcontrollers
  - in some types, e.g., “successive approximation”, the CPU participates in the conversion process
    - normally want to avoid this
- All involve trade-offs of speed (conversion time), resolution (number of bits), and cost
  \[ Q = \frac{E_{FSR}}{2^M} = \frac{E_{FSR}}{N} \]
- “Flash converter” is the fastest, has the lowest resolution and the highest cost
  - required for video digitization
(One) Classification of Sensors

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Classes</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>Modulating</td>
<td>Thermistor*</td>
</tr>
<tr>
<td></td>
<td>Generating</td>
<td>Thermocouple**</td>
</tr>
<tr>
<td>Output signal</td>
<td>Analog</td>
<td>Potentiometer</td>
</tr>
<tr>
<td></td>
<td>Digital</td>
<td>Position encoder</td>
</tr>
<tr>
<td>Operating mode</td>
<td>Deflection</td>
<td>Deflection accelerometer</td>
</tr>
<tr>
<td></td>
<td>Null</td>
<td>Servo-accelerometer</td>
</tr>
</tbody>
</table>

*Thermistor: a resistor whose resistance changes with temperature.
**Thermocouple: a temperature-sensing element which converts thermal energy directly into electrical energy.

---

Power Supply

- **Modulating**
  - Also known as *Active Sensors*
  - They need auxiliary power to perform functionality
  - Sensitivity can be controlled

- **Self-Generating**
  - Also known as *Passive Sensors*
  - They derive the power from the input
Operating Mode

• Deflection
  – The measured quantity produces a physical effect
  – Generates an apposing effect which can be measured
  – Faster

• Null
  – Applies the counter force
  – To balance the deflection from the null point (balance condition)
  – Can be more accurate but slow

Classification (cont’d)

A better classification would be the Physical Property which we are measuring...
  – Temperature
  – Pressure
  – Humidity
  – Light
  – Microphone (sound)
  – Motion detector
  – Chemical detector
  – Image Sensor
  – Flow and level sensor
  – ... ... ...
Electrical Phenomena

- Resistive
- Capacitive
- Inductive
- Piezo-electric

Pressure Sensing: Principle and Types

- Transduces pressure into electrical quantity

- Pressure exerts force which can be converted to electrical voltage using various methods

- Types
  - Strain gauges
  - Capacitive diaphragms
  - Piezo-resistive or silicon cell
  - Bourdon tubes
  - Glass feed through with silicon cell
Pressure Sensor Types (1 of 2)

- **Strain Gauges**
  - Based on the variation of resistance of a conductor or semiconductor when applied to mechanical stress
  - Made of alloys like constantan, nichrome and also semiconductors
  - Can be bonded or un-bonded

- **Capacitive diaphragms**
  - Diaphragm acts as one plate of capacitor
  - The stress changes the space between capacitor plates
  - Can be made of strain gauge or other metal

Pressure Sensor Types (2 of 2)

- **Piezo-resistive or Silicon Cell**
  - Micro-machined silicon diaphragms
  - Piezo-resistive strain gauges diffused into it
  - Very sensitive to pressure

- **Tubes and Feed-Through Glass**
  - Glass feed through and silicon cell mounted on plastic housing
  - Based on the pressure difference
Humidity Sensing: Principle and Types

- Humidity is defined as the water vapor content in the air or other gases

- Measured as
  - **Absolute Humidity**
    - Ratio of the mass of water vapor to the volume of air or gas
  - **Relative Humidity** or RH
    - The ratio of the moisture content of air compared to the saturated moisture level at the same temperature or pressure
  - **Dew Point**
    - Temperature and pressure at which gas begins to condense into liquids

Humidity Sensor Types (1 of 2)

- **Capacitive RH sensor**
  - Change in dielectric constant is directly proportional to relative humidity in the environment
  - Very low temperature effect
  - 0.2-0.5 pF change in capacitance for 1% RH change

- **Resistive Humidity Sensors**
  - Measure the impedance change
  - Inverse exponential relationship to humidity
  - Mostly used are conductive polymer, salt etc.
  - Ceramic coated to avoid condensation effect
Humidity Sensor Types (2 of 2)

- **Thermal Conductivity** Humidity Sensors
  - Measure absolute humidity
  - Calculate the difference between dry air and air containing water vapor
  - One thermistor sealed in dry nitrogen and another exposed to environment
  - Difference in current proportional to humidity

- **MEMS-based** Humidity sensor
  - Polymide-coated cantilever beam
  - Provided with movable electrode
  - Absorption causes increase in beam mass
  - Deflection causes capacitance change

Temperature Sensing: Principle & Types

- A temperature sensor detects a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change.

Type of Sensing

- **Contact**
  - Sensor is in direct physical contact with the object to be sensed
  - To monitor solids, liquids, gases over wide range

- **Non-contact**
  - Interprets the radiant energy of a heat source to energy in electromagnetic spectrum
  - Monitor non-reflective solids and liquids
A microphone is an acoustic to electric transducer that converts sound into an electrical signal.

Microphones capture sound waves with a thin, flexible diaphragm. The vibrations of this element are then converted by various methods into an electrical signal that is an analog of the original sound.

Most microphones in use today use electromagnetic generation (dynamic microphones), capacitance change (condenser microphones) or piezoelectric generation to produce the signal from mechanical vibration.

In a condenser microphone, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates.

Since the plates are biased with a fixed charge (Q), the voltage maintained across the capacitor plates changes with the vibrations in the air.
Dynamic Microphones

- In a dynamic microphone, a small movable induction coil, positioned in the magnetic field of a permanent magnet, is attached to the diaphragm.
- When sound enters through the windscreen of the microphone, the sound wave vibrations move the diaphragm.
- When the diaphragm vibrates, the coil moves in the magnetic field, producing a varying current in the coil through electromagnetic induction.

Accelerometer Sensor: MEMS

Types
- **Piezo-resistive**
  - Proof mass suspended with piezo-resistive beams
    - Simple structure, fabrication, and readout (low imp. output)
    - Large temp. sensitivity, smaller overall sensitivity than capacitance devices
- **Capacitive**
  - Acceleration is measured by the capacitance between a fixed plate and plate on the proof mass.
    - Stable (temperature, drift)
    - Can be susceptible to EMI.
  - Cost: approx $10.
Accelerometer: Inner Working (1 of 2)

It consists of beams and capacitive sensor with some anchor points

Accelerometer: Inner Working (1 of 2)

On applying the acceleration, the beams deflect and cause the change in capacitance.
Motion Detector: Types

• **Photo Sensor**
  – Beam of light crossing the room near the door, and a photo sensor on the other side of the room. When the beam breaks, the photo sensor detects the change in the amount of light and rings a bell (garage doors).

• **Microwave- or Ultrasonic-based**
  – Burst of microwave radio energy and waits for the reflected energy to bounce back.
  – When a person moves into the field of microwave energy, it changes the amount of reflected energy or the time it takes for the reflection to arrive.
  – The same thing can be done with ultrasonic sound waves, bouncing them off a target and waiting for the echo.

Pyro-electric Infrared Motion Detector

[Diagram of Pyro-electric Infrared Motion Detector]
Sensor Devices

• Sensors fall into three categories:

1. **Physiological sensors**: measure ambulatory blood pressure, continuous glucose monitoring, core body temperature, blood oxygen, and signals related to respiratory inductive plethysmography, electrocardiography (ECG), electroencephalography (EEG), and electromyography (EMG).

2. **Biokinetic sensors**: measure acceleration and angular rate of rotation derived from human movement.

3. **Ambient sensors**: measure environmental phenomena, such as humidity, light, sound pressure level, and temperature.

Psychophysiology

• The branch of physiology dealing with the relationship between physiological processes and thoughts, emotions, and behavior.

• The body responds to psychological processes, e.g., your cheeks get warm when you are embarrassed.

• Psychophysiology is concerned with measuring psychological processes by measuring physical indicators.
History

- Greek and Roman physicians
  - heart rate to index interpersonal attraction
- In China:
  - people used to spit out rice to indicate if someone was lying or not. If the rice was dry, they were lying
- Lie detector:
  - Cesare Lombroso: used the first lie detection test in 1895
  - John Larson: invented the first polygraph
  - Leonarde Keeler: invented current polygraph in the 1920s
- Electroencephalography
  - activity in the human brain.
  - 1924: first electroencephalogram (EEG) recording of brain
- Pulse rate, skin conductance, respiration, temperature, …

Vital Signs

- Temperature, pulse, respiration, blood pressure (B/P) & oxygen saturation are the most frequent measurements taken by HCP.

- Because of the importance of these measurements they are referred to as Vital Signs. They are important indicators of the body’s response to physical, environmental, and psychological stressors.
### Biomedical Measurements

<table>
<thead>
<tr>
<th>Biomedical measurements</th>
<th>Voltage range (V)</th>
<th>Number of users = K (sensors)</th>
<th>Bandwidth (Hz)</th>
<th>Sample rate (samples/s) = (Hz)</th>
<th>Resolution [bitsample]</th>
<th>Information rate [bits]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>0.5-4 m</td>
<td>5-9</td>
<td>0.01-250</td>
<td>1250</td>
<td>12</td>
<td>15,000</td>
</tr>
<tr>
<td>Heart sound</td>
<td>Extremely small</td>
<td>2-4</td>
<td>5-2000</td>
<td>10,000</td>
<td>12</td>
<td>120,000</td>
</tr>
<tr>
<td>Heart rate</td>
<td>0.5-4 m</td>
<td>2</td>
<td>0.4-5</td>
<td>25</td>
<td>24</td>
<td>600</td>
</tr>
<tr>
<td>EEG</td>
<td>2-200 μ</td>
<td>20</td>
<td>0.5-70</td>
<td>350</td>
<td>12</td>
<td>4200</td>
</tr>
<tr>
<td>EMG</td>
<td>0.1-5 m</td>
<td>2+</td>
<td>0-10,000</td>
<td>50,000</td>
<td>12</td>
<td>600,000</td>
</tr>
<tr>
<td>Respiratory rate</td>
<td>Small</td>
<td>1</td>
<td>0.1-10</td>
<td>50</td>
<td>16</td>
<td>800</td>
</tr>
<tr>
<td>Temperature of body</td>
<td>0-100 m</td>
<td>1+</td>
<td>0-1</td>
<td>5</td>
<td>16</td>
<td>80</td>
</tr>
</tbody>
</table>

Bandwidth = $f_{max} - f_{min}$
Sample rate = $S_f = f_{max}$
Information rate = $R_s = $ Resolution \_Sample rate


### Wireless Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>802.15.4</th>
<th>802.15.1</th>
<th>802.11b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network type</td>
<td>WPAN</td>
<td>WPAN</td>
<td>WLAN</td>
</tr>
<tr>
<td>Modulation</td>
<td>DS</td>
<td>FH</td>
<td>DS</td>
</tr>
<tr>
<td>Number of channels</td>
<td>16</td>
<td>79</td>
<td>11</td>
</tr>
<tr>
<td>Channel width (MHz)</td>
<td>2</td>
<td>1</td>
<td>22</td>
</tr>
<tr>
<td>Coverage area (m)</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Data rate (Mb/s)</td>
<td>0.25</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Data service</td>
<td>Unack, ack</td>
<td>Acknowledged</td>
<td>Acknowledged</td>
</tr>
<tr>
<td>Medium access</td>
<td>CSMA/CA</td>
<td>TDMA</td>
<td>CSMA/CA</td>
</tr>
</tbody>
</table>
Clinical Data vs Wireless Technologies

<table>
<thead>
<tr>
<th>Biomedical Data</th>
<th>Type</th>
<th>Typical File Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>EKG recording</td>
<td>Electrical signal</td>
<td>100 kB</td>
</tr>
<tr>
<td>Electronic Stethoscope</td>
<td>Audio</td>
<td>100 kB</td>
</tr>
<tr>
<td>X-Ray</td>
<td>Still image</td>
<td>1 MB</td>
</tr>
<tr>
<td>30s of ultrasound image</td>
<td>Moving image</td>
<td>10 MB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology</th>
<th>Data Rate</th>
<th>Frequency Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>9.6 kbps</td>
<td>900/1800/1900 MHz</td>
</tr>
<tr>
<td>GPRS</td>
<td>171.2 kbps</td>
<td>900/1800/1900 MHz</td>
</tr>
<tr>
<td>EDGE</td>
<td>384 kbps</td>
<td>900/1800/1900 MHz</td>
</tr>
<tr>
<td>3G/UMTS</td>
<td>2 Mbps</td>
<td>1885 MHz – 2200 MHz</td>
</tr>
</tbody>
</table>


Activity Sensors

They can be useful in monitoring patients undergoing physical rehabilitation such as after a stroke.

The Pluto custom wearable designed at Harvard incorporates the TI MSP430 microprocessor and ChipCon CC 2420 radio.

Pluto can run continuously for almost 5 hours on a rechargeable 120 mAh lithium battery.

It has a Mini-B USB connector for programming and to recharge the battery.

The software runs under TinyOS.

Pulse Oximeter

- Non-invasive technology used to measure the heart rate (HR) and blood oxygen saturation (SpO₂).
- The technology used is to project infrared and near-infrared light through blood vessels near the skin.
- By detecting the amount of light absorbed by hemoglobin in the blood at two different wavelengths, the level of oxygen can be measured.
- The heart rate can also be measured since blood vessels contract and expand with the patient’s pulse, which affects the pattern of light absorbed over time.
- Computation of HR and SpO₂ from the light transmission waveforms can be performed using standard DSP algorithms.

Smiths Micro Power Oximeter Board
- Length: 39 mm
- Width: 20 mm
- Height: 5.6 mm
- 6.6 mA at 3.3 V, typical power: 22 mW
- Pulse range: 30-254 bpm
- SpO₂: 0 to 99%
- Data is transmitted from the oximeter board at a rate of 60 packets per second (5 bytes per packet).

Minolta Pulsox-2
- Size: W69xH60xD28 mm
- Weight: approx. 70g (with 2 AAA batteries)
The most common type of EKG involves the connection of several leads to a patient’s chest, arms, and leg via adhesive foam pads. The device records a short sampling, e.g. 30 seconds, of the heart’s electric activity between different pairs of electrodes.

When there is need to detect intermittent cardiac conditions a continuous EKG measurement is used. This involve the use of a two- or three-electrode EKG to evaluate the patient’s cardiac activity for an extended period.

The EKG signal is small (~1mV peak-to-peak). Before the signal is digitized it has to be amplified (gain > 1000) using low noise amplifiers and filtered to remove noise.

The P wave is associated with the contractions of the atria (the two chambers in the heart that receive blood from outside).

The QRS is a series of waves associated with ventricular contractions (the ventricles are the two major pumping chambers in the heart).

The T and U waves follow the ventricular contractions.
IMEC has recently developed a wireless, flexible, stretchable EKG patch for continuous cardiac monitoring. Placed on the arm or on the leg, the same system can be used to monitor muscle activity (EMG). The patch includes a microprocessor, a 2.4 GHz radio link, and a miniaturized rechargeable lithium-ion battery. The total size is 60x20 mm². Data is sampled between 250 and 1000 Hz and continuously transmitted. The battery has a capacity of 175 mAh which provides for continuous monitoring from one day to several days.

EKG Signals

Various sampling rates and quantization levels are used when EKG signals are digitized. In practice, sampling frequencies between 128 Hz and 256 Hz are used. The higher sampling rates and bit rates, e.g. 16 bits, are used to characterize EKG in sufficient detail.
• Detect transient cardiac events for diagnostic purposes
• Detect acute (life-threatening) events and alert
• Correlate cardiac events with activity levels, or other parameters
• Monitor variations in rhythm induced by medications

EMG/GSR

Stress Detection

• Measures muscle tension (EMG) on back which is indicative of “stress”
• Measures “skin resistance” (GSR) which varies with the involuntary production of sweat as a result of stress/emotion
Heart Rate Monitors

<table>
<thead>
<tr>
<th>Products</th>
<th>Feature</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar FS1</td>
<td>displays heart rate and exercise time, has visual &amp; audible target zone alarms. Shows average heart rate of the total exercise.</td>
<td>$69</td>
</tr>
<tr>
<td>Alive Heart Monitor</td>
<td>uses wireless Bluetooth and mobile phone networks to immediately transmit ECG and accelerometer data to a computer, PDA, or central monitoring centre.</td>
<td>$100</td>
</tr>
<tr>
<td>BioHarness-Zephyr Technology</td>
<td>allows a user (or remote person) to view vital signs and status. Uses Bluetooth.</td>
<td>$120</td>
</tr>
</tbody>
</table>

**Electroencephalogram**

- **normal signal**: 0 – 1000 Hz
- **theta band**: 4 – 8 Hz
- **alpha band**: 8 – 12 Hz
- **beta band**: 13 – 30 Hz
- **gamma band**: 30 – 100 Hz
Electroencephalogram

- **Delta (up to 4Hz)**
  - Front in adults, back in children
  - Sleep, babies, during some continuous attention tasks
  - (subcortical lesions, diffuse lesions, ...)

- **Theta (4-8Hz)**
  - Locations not related to task at hand
  - Young children, drowsiness or arousal, idling
  - (focal subcortical lesions, deep midline disorders, ...)

- **Alpha (8-13Hz)**
  - Posterior regions, both sides
  - Relaxed, reflecting, closing eyes, inhibition control
  - (coma)

- **Beta (13-30Hz)**
  - Both sides, symmetrical distribution
  - Alert/working; active, busy or anxious thinking, active concentration
  - (benzodiazepines)
Event-Related Potentials (ERPs)

The raw signal with stimuli presentations leading to the ERP

- Medical application
  - Wearable Monitoring Systems
  - Pulse Oximeter
  - Electrocardiograph (EKG)
  - Electroencephalography (EEG)
  - Electromyography (EMG)

Body Sensor Network
Body Sensor Network

Body Area Networks

- Implantable medical devices
  - Cancer tracking, cardiac pacemakers / defibrillators, neurostimulators, drug pumps, glucose sensor, etc.
- Swallowable
  - Pills for drug delivery and imaging
- Wearable sensors
  - EEG, ECG, blood pressure, body temperature, ...
- Hearing aids
- Wellness / Fitness sensors
- Baby care

Use Case: Drug Delivery

- Pill travels in the gastrointestinal tract and is in periodic wireless communication to an external unit near the body
- Pill lifetime is between 8-72 hours
- Communication range is between 1 and 3 meters

Use Case: Drug Delivery

- Patient at home
  - Pill reports actions and sensor data to portable unit every few seconds or minutes
  - Possibly more than one pill in the patient
  - Can not guarantee portable unit is within range
    - Pill may store data and download when portable unit is found
- Patient in research clinic or hospital
  - Multiple patients on a clinical ward
  - Pill reports actions and sensor data
  - Possible central external unit talking to and commending several pills
- Data rate
  - Generally low: status and simple sensor (e.g., pH) measurements taken on the order of every minute
  - Exception: use of an image sensor where images are taken and transmitted
    - Commercial products exist with data rates as high as 800 Kbps
Use Case: Deep Brain Stimulation

- A treatment of neurological diseases and conditions by an implanted *brain pacemaker* that stimulates different regions of the brain with electrical impulses

![Implanted Pulse Generator (IPG)]

- The IPG needs to
  - Communicate wirelessly with an external unit
  - Communicate wirelessly with an electrode controlling unit

- Requirements
  - Data rate between 128 Kbps and 320 Kbps
  - BER $< 10^{-10}$
  - Stand-by power $< 0.1$ mW
  - Lifetime between 3 to 5 years
  - Range less than 3m

Source: Medtronic, Inc.
Use Case: Cancer Treatment

- Based on sensed data by implanted devices, doctors can change a patient’s treatment or even recalibrate the implanted device.

- Doctors can decide when it is the right time to take the next step in a patient’s treatment.

- Requirements
  - Data rate < 20 Kbps in most cases
  - Range < 3m
  - BER < $10^{-10}$

Use Case: Glucose Level Monitoring

- In patients with diabetes, a body-worn glucose monitor analyzes the level of glucose in the body.

- If the glucose level surpasses a desirable value, the glucose monitor informs the patient and, if appropriate, communicates with the implanted insulin pump to release the right amount of insulin.

- Data rate in the order of 1 Kbps
Use Case: Fitness

- While doing exercise, one could use the same personal device (e.g., MP3 player, cellular phone, etc.) to:
  - Stream music to a wireless headset
  - Receive and display sensing data such as heart rate, glucose level, body temperature, speed, distance, etc.
- Information sensed can be used to set the pace for the rider
- If an abnormal event is detected, an alarm is sent from the personal device to the wireless headset

Use Case: Fitness

- User carries a mobile device (e.g., cellular phone) which controls and displays a number of features:
  - Sensors: body temperature, glucose level, heart rate, etc.
  - Streaming to wireless headset
  - Remote control (e.g., the PDA, personal CD player, etc.)
- Mobile device is also used as a gateway to send remote patient monitoring data to a central database where it can be accessed by the patient’s physician
- Scalable data rate (up to 10Mbps) and power consumption (up to 40mW) requirements
Summary of Some Application Requirements

<table>
<thead>
<tr>
<th>Application</th>
<th>Target data rate</th>
<th>Latency</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drug Delivery</td>
<td>&lt; 16 Kbps</td>
<td>≤ 250 ms</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>Deep Brain Stimulation</td>
<td>&lt; 320 Kbps</td>
<td>≤ 250 ms</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>Capsule Endoscopy</td>
<td>1 Mbps</td>
<td></td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>ECG</td>
<td>192 Kbps (6 Kbps, 32 channels)</td>
<td>≤ 250 ms</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>EEG</td>
<td>86.4 Kbps (300Hz sample, 12-bit ADC, 24 channels)</td>
<td>≤ 250 ms</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>EMG</td>
<td>1.536 Mbps (8kHz sample, 16-bit ADC, 12 channels)</td>
<td>≤ 250 ms</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>Glucose level monitor</td>
<td>&lt; 1 Mbps</td>
<td>≤ 250 ms</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>Audio</td>
<td>1 Mbps</td>
<td>≤ 20ms</td>
<td>&lt; 10⁻⁵</td>
</tr>
<tr>
<td>Video / Medical imaging</td>
<td>&lt; 10 Mbps (e.g., Standard Video)</td>
<td>≤ 100 ms</td>
<td>&lt; 10⁻³</td>
</tr>
<tr>
<td>Voice</td>
<td>50 – 100 Kbps per flow</td>
<td>≤ 10ms</td>
<td>&lt; 10⁻³</td>
</tr>
</tbody>
</table>

Summary of Some Application Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Proposed Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating space</td>
<td>In, on, or around the body</td>
</tr>
<tr>
<td>Data rate</td>
<td>Scalable</td>
</tr>
<tr>
<td>Target bands</td>
<td>Unlicensed and Medical approved bands</td>
</tr>
<tr>
<td>Device duty cycle</td>
<td>Scalable</td>
</tr>
<tr>
<td>Peak Power consumption</td>
<td>Scalable</td>
</tr>
<tr>
<td>Coexistence</td>
<td>Coexistence with legacy devices, primaries, and self-coexistence</td>
</tr>
<tr>
<td>Security</td>
<td>High</td>
</tr>
<tr>
<td>Safety</td>
<td>High</td>
</tr>
<tr>
<td>Topology</td>
<td>Multiple simultaneous links</td>
</tr>
<tr>
<td>Network Setup</td>
<td>Required</td>
</tr>
<tr>
<td>Location information</td>
<td>Desirable</td>
</tr>
</tbody>
</table>

High Authentication, privacy, encryption, etc.

Meet regulation requirements for SAR

Tens of simultaneous links, no single point of failure, and multi-hop support

Secure and under a few seconds

Localization within a radius of a few centimeters
Literature and Technical Survey

From University funded research . . .

...To Medical Application . . .

...To Business Applications.