CS60055: Ubiquitous Computing

Energy Harvesting

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Low Power Autonomous Devices

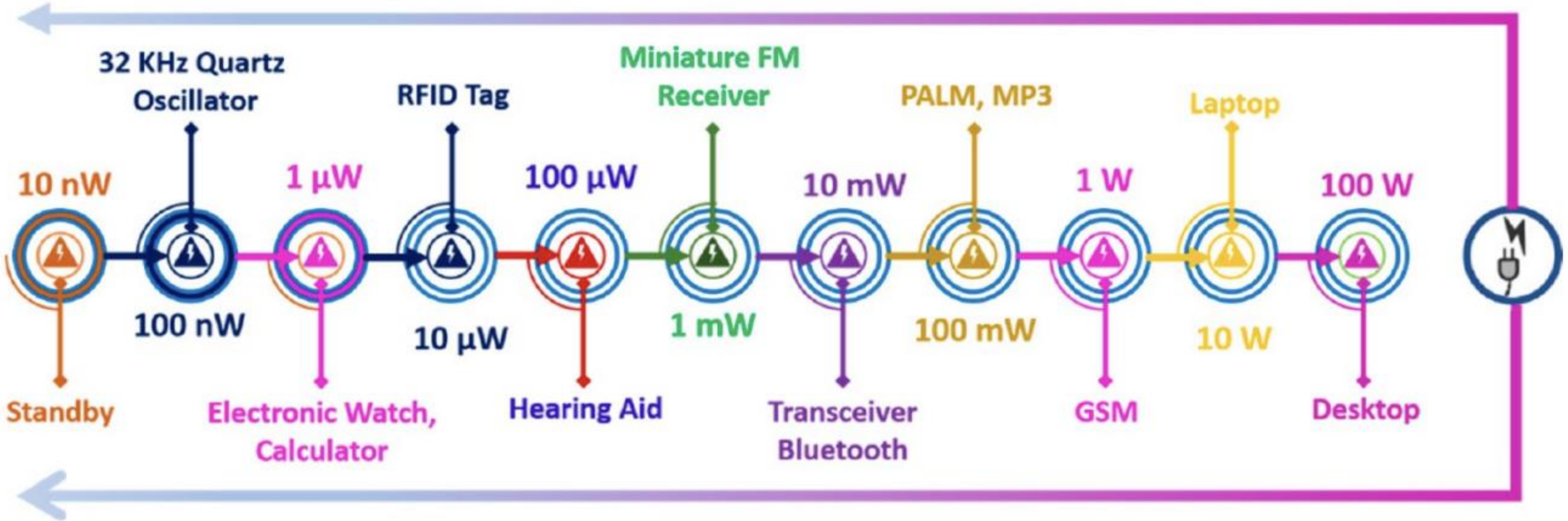
- Connected low-powered devices are the backbone behind majority of the ubiquitous systems
    - Sensing and actuation (Conventional IoT devices)
    - Supports on-board ML for inferences (TinyML)
    - Edge devices with GPU support (Nvidia JetSon)

- Powered by on-device power supply
    - Currently realized by various types and sizes of batteries depending on the application requirements

- Power sources become one of the major performance bottleneck
    - batteries store a finite amount of energy – needs recharging or replacement

Low Power Autonomous Devices

- Various applications demand constant power sources which are unlikely to be available
  - Example: Biodiversity monitoring (animals in a forest, fishes in the sea)
- Given the limited lifespan of batteries, we need alternative power sources
- Power requirements for typical IoT devices:



MK Mishu et al (2020)

Power Autonomy Challenges

- Use non-conventional energy sources (along with harvesting)
  - Example: Solar energy
- Energy harvesting as a potential energy source
  - Thermal energy harvesting
  - Solar energy harvesting
  - Vibration (piezoelectric) energy harvesting
  - Kinetic (mechanical) energy harvesting
  - Inductive (electromagnetic induction) energy harvesting
  - Ambient Light Energy Harvesting (Indoor Light Harvesting)
  - Electrostatic Energy Harvesting
  - Magnetic Field Energy Harvesting
  - RF (Radio Frequency) Energy Harvesting
  - ...

Radio Frequency Energy Harvesting

- Captures ambient radio frequency energy and converts it into usable electrical power

- Use the available RF devices for energy harvesting
  - GSM Antennas
  - Radios
  - WiFi devices
  - TV Broacast
  - …

- Typically used in a scenario where many RF sources are available in the area
  - Advantage: "Free" energy source
  - Challenges: Low power density and variable/unpredictable power

How RF Energy Harvesting Works

- **Antenna:** Responsible for capturing RF signals from the surrounding environment
  - Typically captures a specific predefined frequency (say, 5GHz WiFi)
  - Multiband antennas can capture signals from multiple frequency bands

- **Matching Network: C**onnects the antenna to the rectifier and maximizes power transfer
  - Adjusts impedance to ensure that the maximum possible RF power is delivered from the antenna to the rectifier

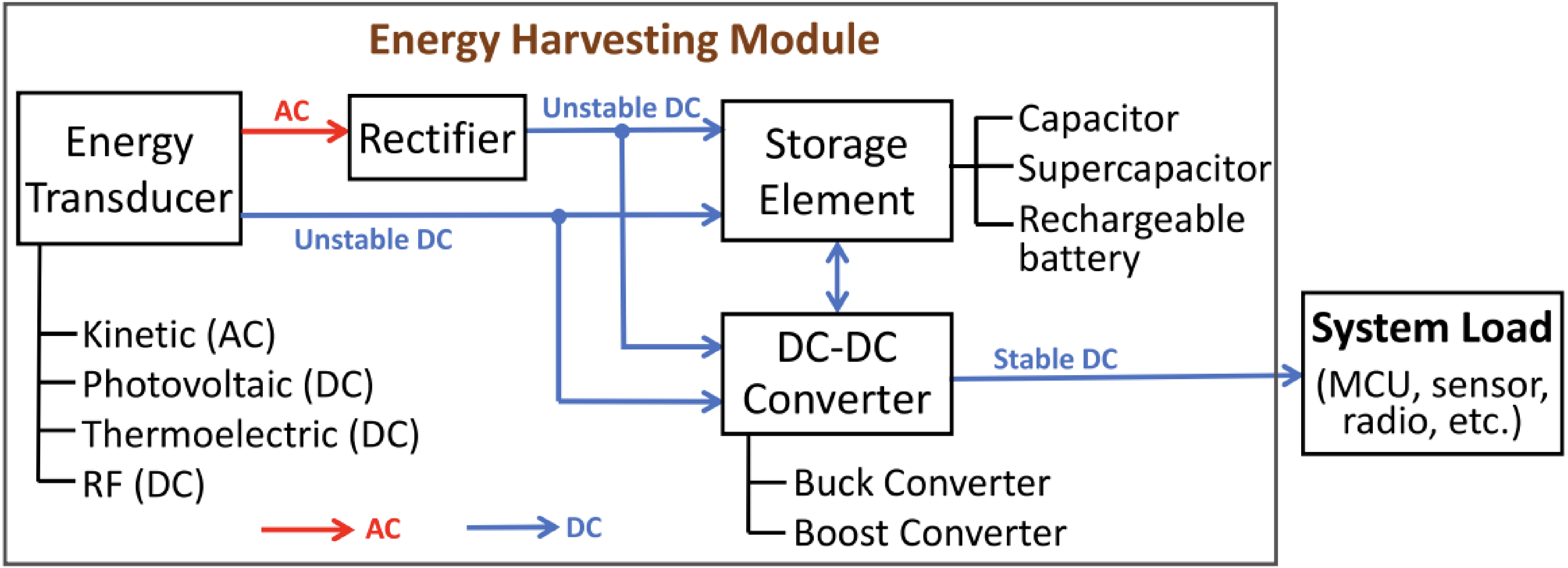
- **Rectifier (AC-to-DC Conversion)**: Converts the captured RF signal into DC power
  - RF energy is AC, while most electronic devices require DC

How RF Energy Harvesting Works

- **Energy Storage/Management Circuit**: The harvested energy is typically stored in a small capacitor, rechargeable battery, or supercapacitor to provide stable power to a device
  - Regulates the power output and ensures stable voltage for the device.

- **Loads (Device):** The device or circuit that uses the harvested energy

Energy Harvesting Network



Source: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8944276

Principle of RF Energy Harvesting

- The power received by an RF energy harvesting antenna depends on several factors
  - Distance from the RF source
  - frequency of the signal
  - …
- *Friis Transmission Equation* provides the power received (P_r) by an antenna from an RF source:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2}$$

  - P_t is the transmit power of the RF source in watts
  - G_t is the gain of the transmitting antenna
  - G_r is the gain of the receiver antenna
  - λ is the wavelength, and d is the distance between the transmitting and the receiving antennas

Principle of RF Energy Harvesting

- The antenna efficiency (η) affects the power delivered to the rectifier
- The Effective Power Captured by the antenna (P_{ant}) is:

$$P_{ant} = \eta P_r$$

  - In practice, an impedance matching network is used to maximize power transfer from the antenna to the rectifier
  - If the antenna and rectifier are perfectly matched, the maximum power is transferred; otherwise, power is reflected, reducing efficiency.

- The rectifier converts the AC signal received from the antenna into DC power. The **DC Power Output** after rectification is computed as,

$$P_{DC} = \eta_r P_{ant} = \eta \eta_r P_r$$

η_r is the rectifier efficiency

Principle of RF Energy Harvesting

- To calculate the power available to the load or device, we consider both the rectifier's output and any energy stored in capacitors or supercapacitors

- Let C be the capacitance of the storage capacitor, and V be the output voltage across it. If the capacitor is charged to a voltage V over time t, the stored energy (E) is:

$$E = \frac{1}{2}CV^2$$

- If the capacitor discharges to power a load, the average power delivered (P_{out}) can be computed as,

$$P_{out} = \frac{E}{t} = \frac{1}{2}CV^2/t$$

Battery-free Wireless Sensing

- Use the wireless signal for joint sensing and energy harvesting
  - The received signal can be used for analyzing the environment as well as the DC component of the signal can be used for energy harvesting

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REHSense: Towards Battery-Free Wireless Sensing via Radio Frequency Energy Harvesting

Tao Ni[*], Zehua Sun[*], Mingda Han[†], Guohao Lan[‡], Yaxiong Xie[¶], Zhenjiang Li[*], Tao Gu[§], Weitao Xu[*✉]
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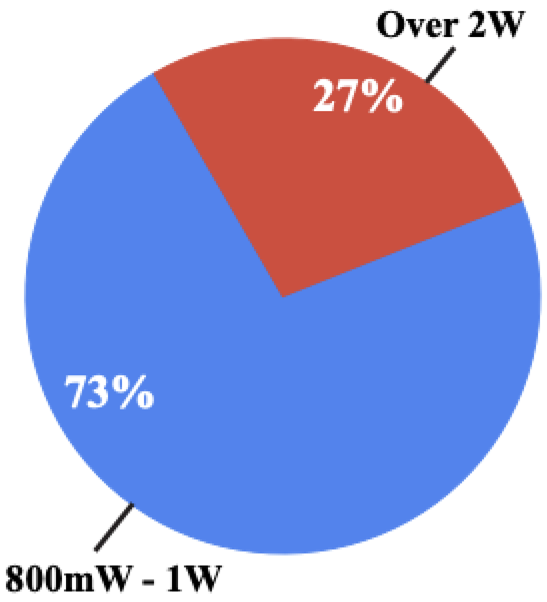
ACM MobiHoc 2024

Challenges with WiFi Sensing

- Not all WiFi cards support CSI extraction
  - Most of the CSI-extractable NIC cards are no longer adopted by the latest Wi-Fi devices
  - Needs additional hardware on the WiFi devices for CSI extraction

- WiFi NICs consume a good amount of power



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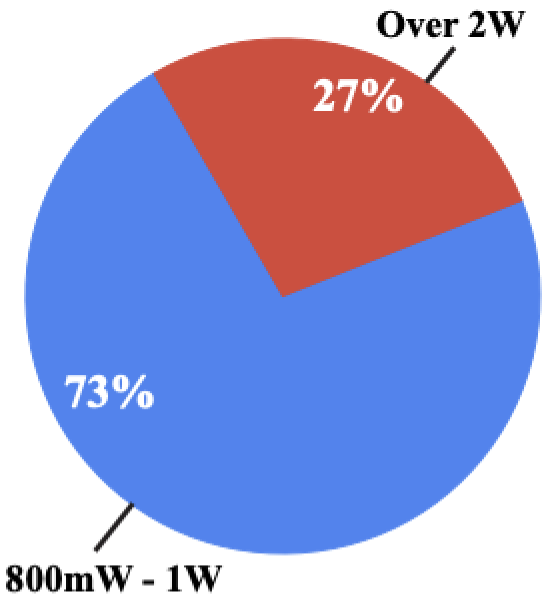
Use an energy harvester to power the NIC and sensing can be performed by extracting CSI information from the same RF signal



Core Idea

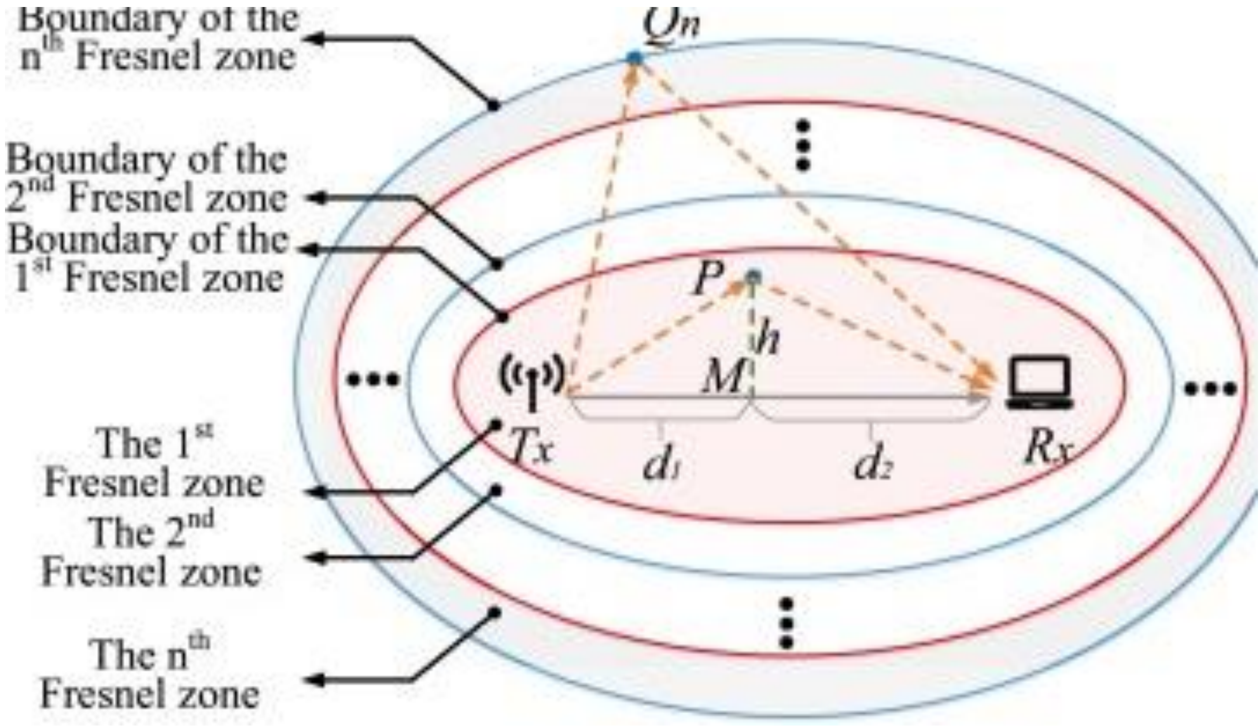
- Human activity significantly affects the amount of energy that the harvester captures from the ambient RF signals
  - Depending on the position and the pose of the human, the signal reflecting off the human body may superimpose constructively or deconstructively with multipath signals in the propagation environment at the harvester
  - Leverage the RF energy harvester as a novel battery-free activity sensor

- Measure the time-varying harvested power (voltage) as the sensing signal
  - Apply a deep neural network to recognize various human activities

Fresnel Zone Diffraction Model

- Divides the area around the direct LoS path between a transmitter and a receiver into a series of ellipsoidal zones called Fresnel zones
  - Each zone represents an area where electromagnetic waves travel with different path lengths, resulting in constructive or destructive interference based on the phase differences at the receiver

- Describes how obstacles in the Fresnel zones affect signal transmission
  - Helps predict the signal strength and attenuation caused by diffraction, which occurs when an electromagnetic wave encounters an obstacle along its propagation path



Fresnel Zone Diffraction Model

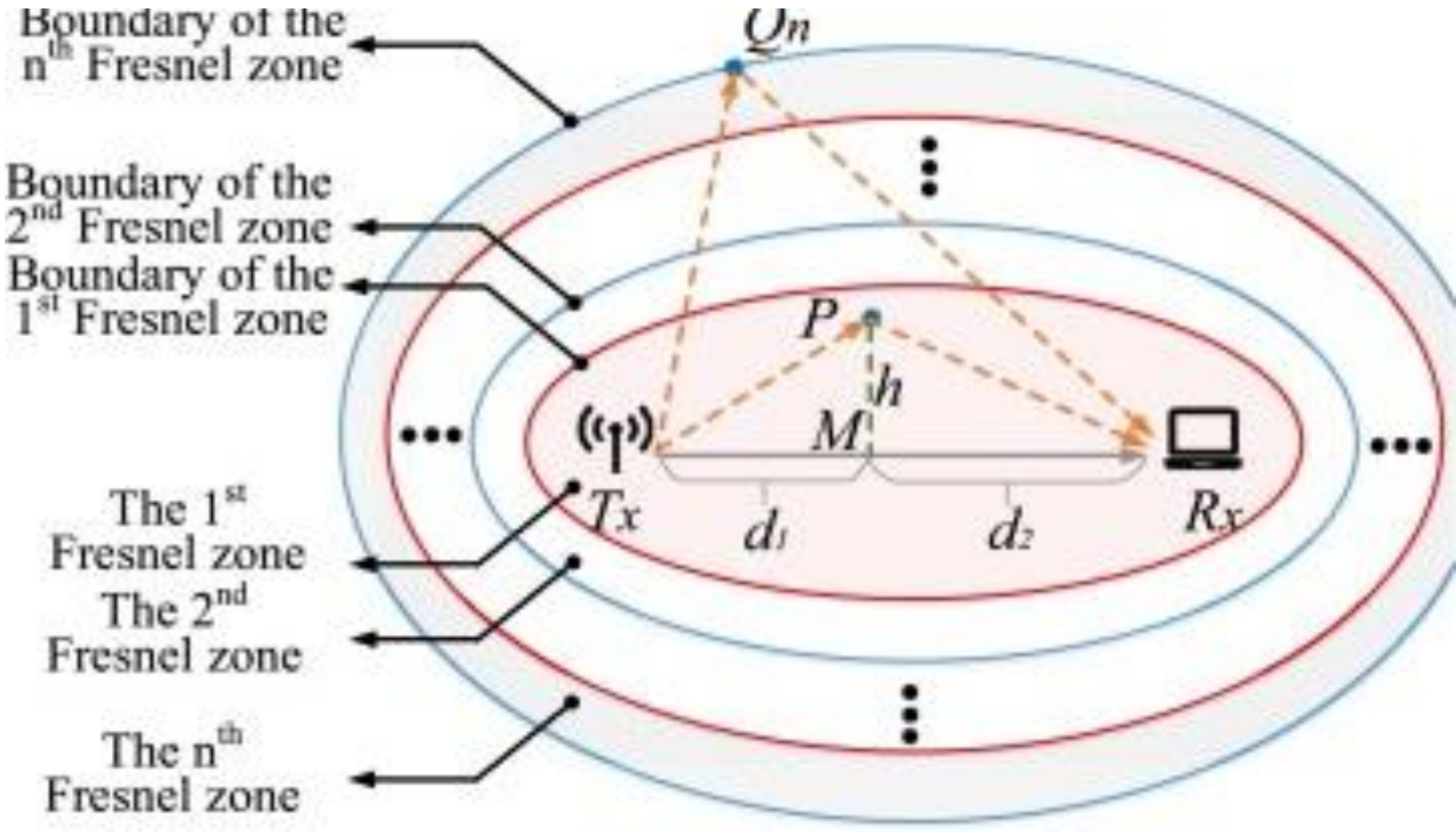
- **First Fresnel Zone (FFZ):** Contains most of the transmitted energy
  - Keeping the first Fresnel zone clear of obstructions minimizes diffraction losses and allows for a stronger received signal

- **Higher-order Fresnel Zones:** These alternate between causing constructive (odd-numbered zones) and destructive interference (even-numbered zones)
  - Signals passing through these zones can interfere with each other at the receiver, depending on the path differences

Fresnel Zone Diffraction Model

- The radius of the first Fresnel zone at any point along the path between the transmitter and receiver can be calculated using

$$F_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}}$$



Fresnel Zone Diffraction Model

- To estimate signal attenuation due to diffraction, the model uses a parameter called the **Fresnel-Kirchhoff diffraction parameter** (ν), which quantifies the impact of an obstacle on the signal:

$$\nu = \frac{h\sqrt{2(d_1 + d_2)}}{\lambda\sqrt{d_1 d_2}}$$

  - h is the height of the obstacle in meters

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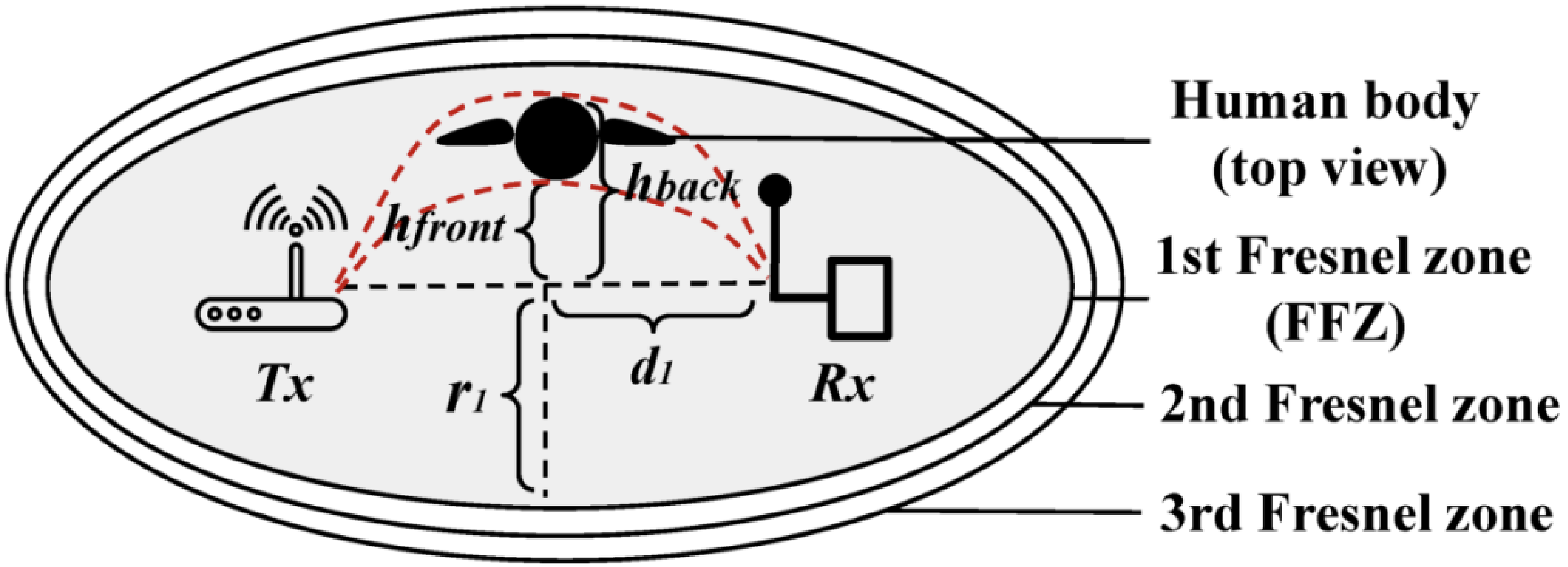
- If ν <0.7: Minor obstruction, minimal diffraction loss.
- If $\nu \approx 1$: Moderate obstruction, potential for significant diffraction loss.
- If $\nu > 1$: Severe obstruction, high diffraction loss, substantial signal attenuation.

Impact of Human Subjects on the FFZ

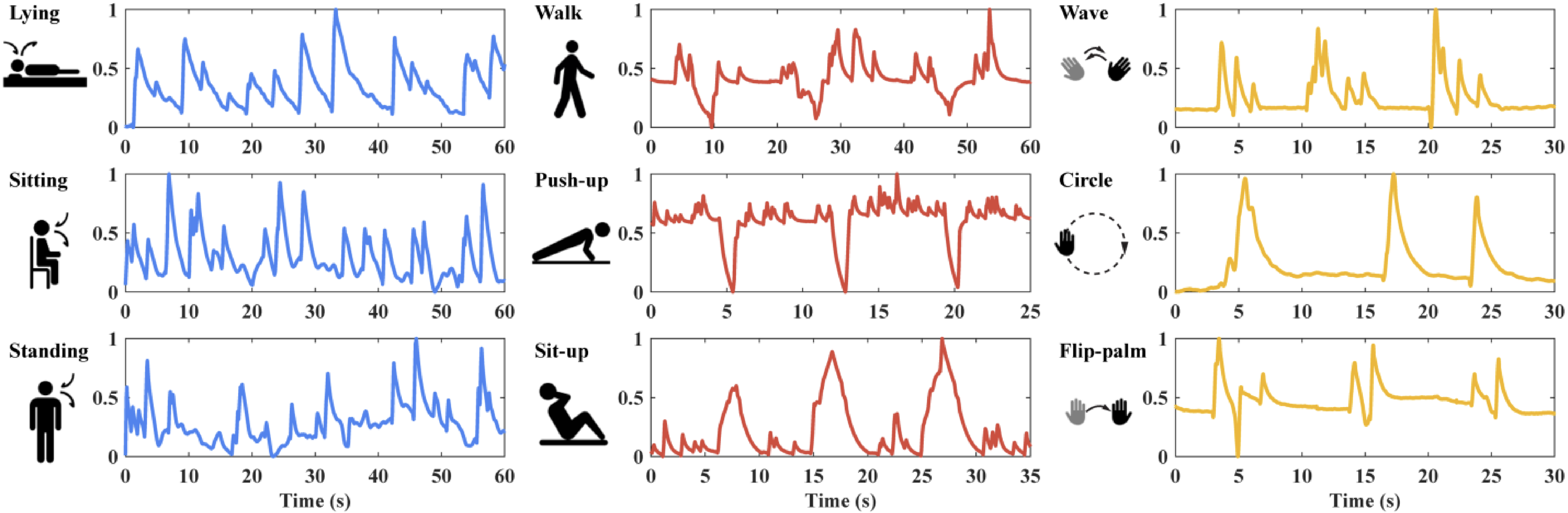
- Human subject on the FFZ will create signal diffraction
  - The diffracted signals from the human body will attenuate with the Friis gain at the RF harvester



Impact of Human Subjects on the FFZ

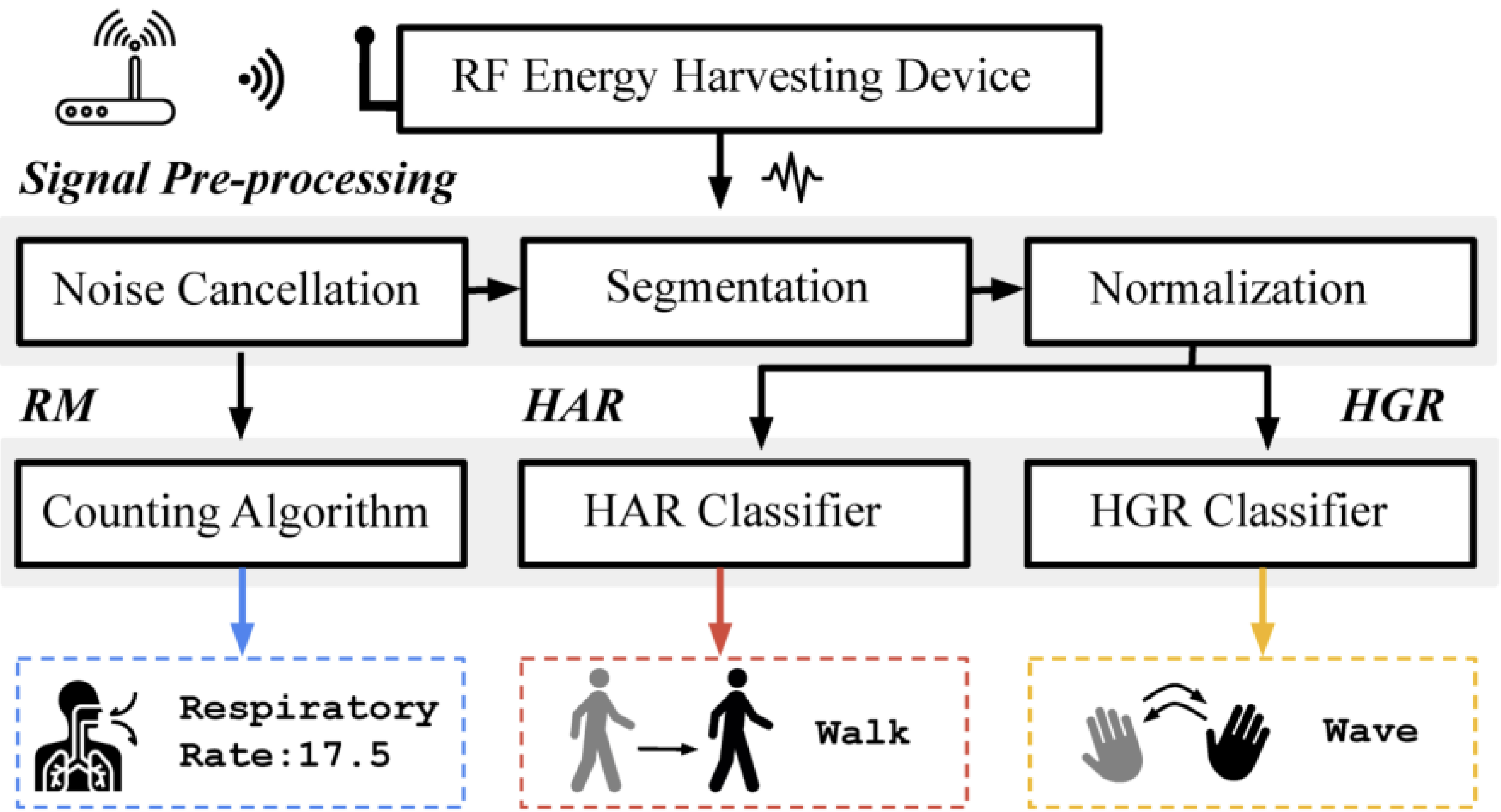
- The energy generated by the RF energy harvesting device is the combination of three factors
  - Friis Gain (Free-space propagation)
  - Diffraction Gain (Constructive attenuation from the FFZ)
  - Path loss from the other objects (Constructive/destructive attenuation from other objects in the surroundings)

Harvested Voltage Signals for Variuous Activity Recognition Tasks

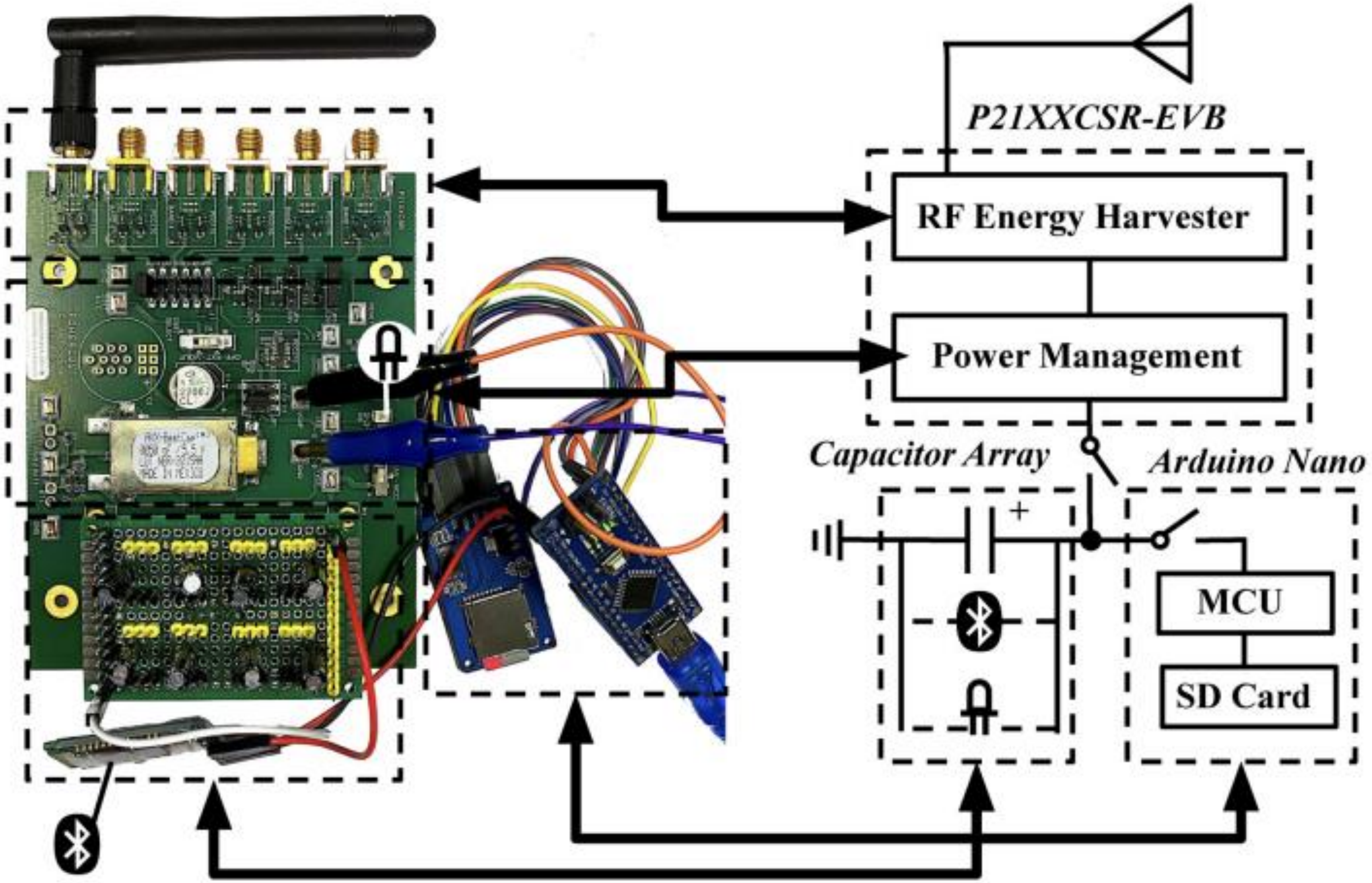


(a) Respiration monitoring.
(b) Human activity recognition.
(c) Hand gesture recognition.

Overview of REHSense



Battery Free Sensing System



Happy Learning!

Some resources related to this topic