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EECE5155: Wireless Sensor Networks and the Internet of Things

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Module T4: Data Communication

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Outline

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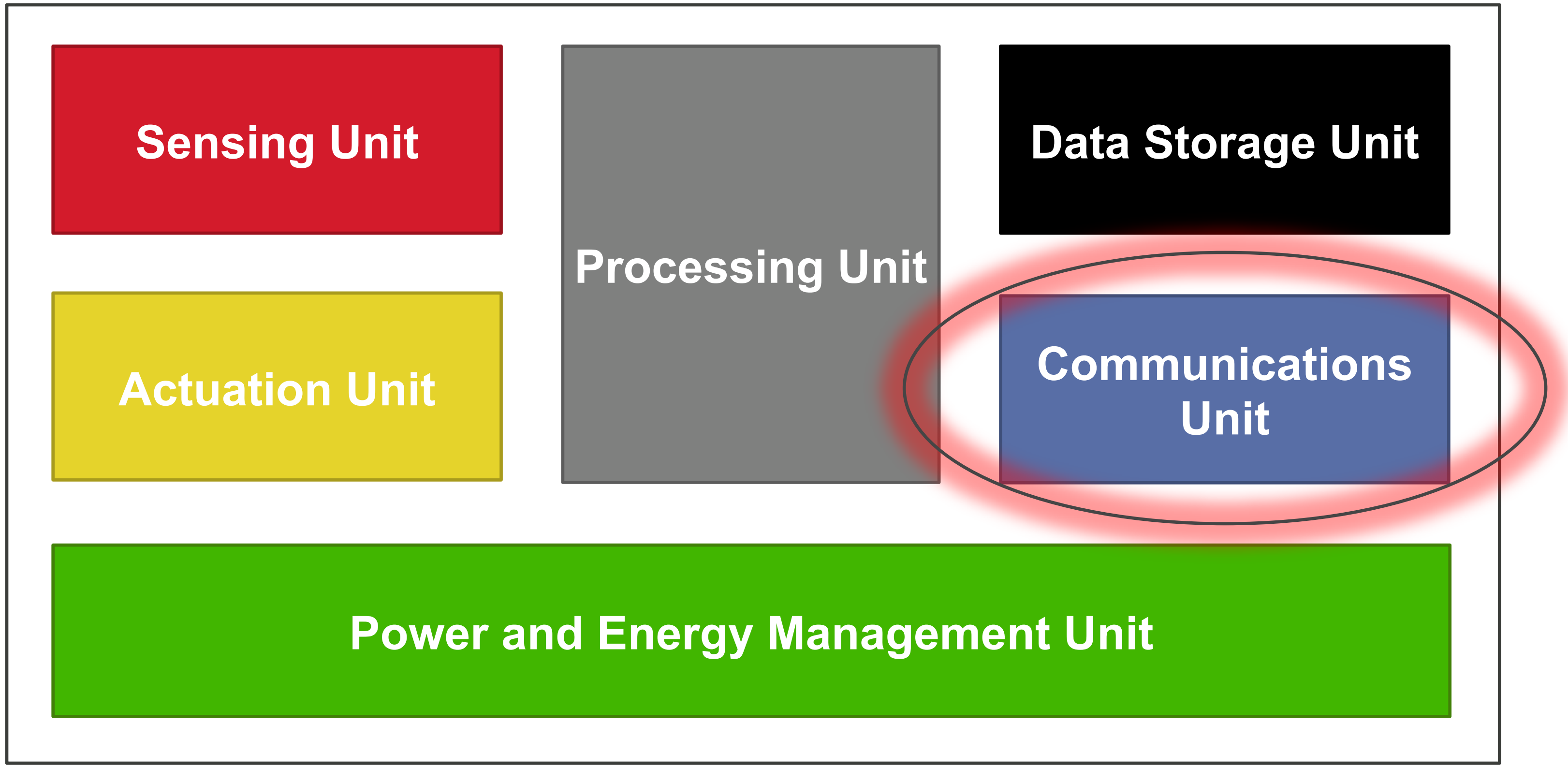
- **Part 1: The Communications Unit**
- **Part 2: Protocols and Standards for the IoT**

Part 1


Sensing Unit
Processing Unit
Data Storage Unit
Actuation Unit
Communications Unit
Power and Energy Management Unit

Part 2

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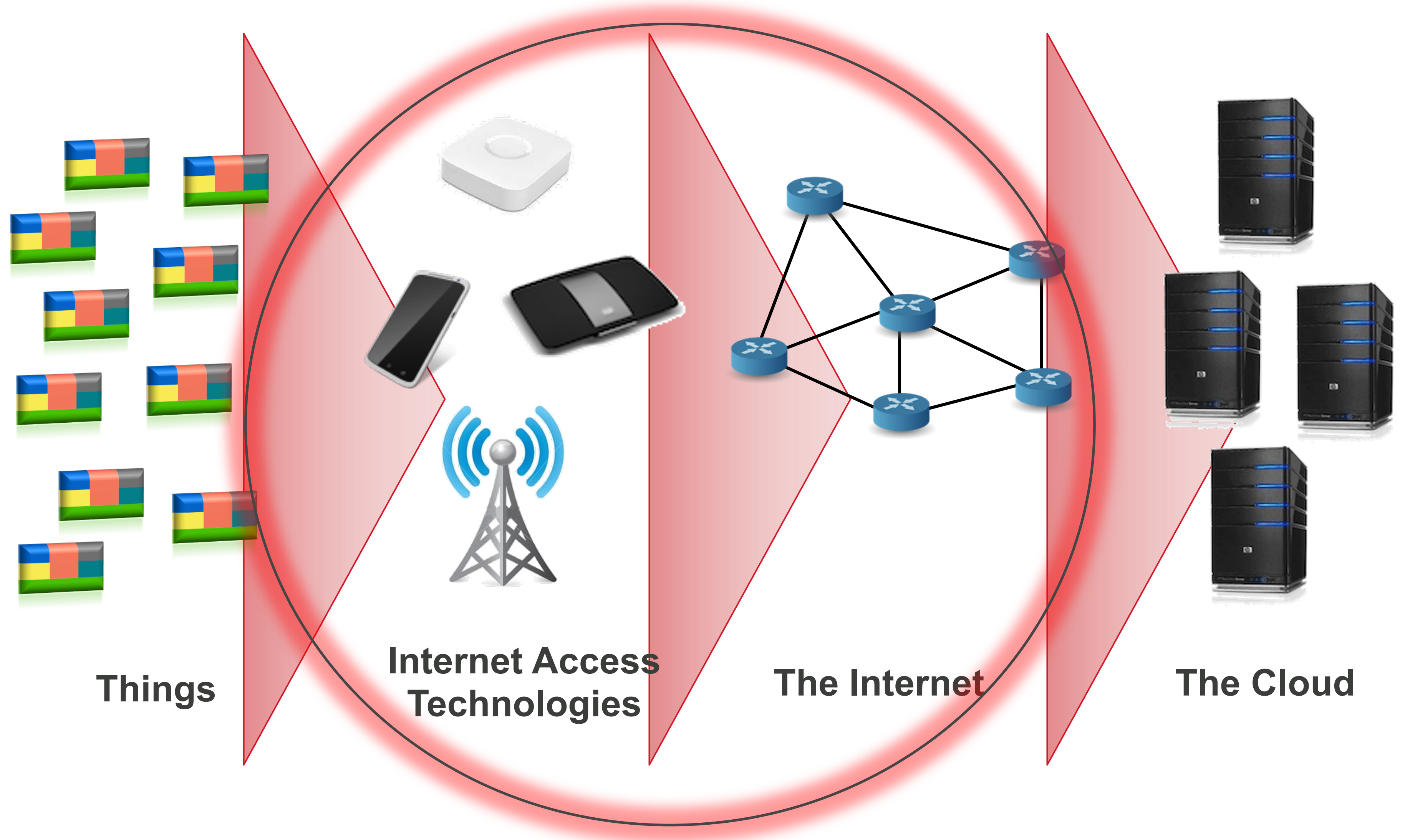

Part 1: The Communication Unit

Part 1: The Communication Unit

Introduction

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- In the majority of IoT applications (not all), "Things" are wireless connected to the Internet
- There are different physics that support wireless communications:
  - **Electromagnetism**
    - Near field communication through magnetic induction
    - Radiowaves, microwaves, millimeter waves, terahertz waves
    - Infrared, visible and ultra-violet optical signals
  - **Acoustics**
    - Sound, ultra-sound signals
  - **Molecules**
    - Ions, hormones, pheromones
  - ..

Transceivers and Antennas

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- **Transceiver = Transmitter + Receiver**
  - The required hardware needed to generate (in transmission) and process (in reception) wireless signals
  - Building blocks:
    - Signal generators
    - Modulators or Mixers (mix in the information)
    - Amplifiers
    - Filters
    - …
- **Antenna:**
  - The element that converts an electrical current in a propagating electromagnetic wave and vice versa

The Communication Unit

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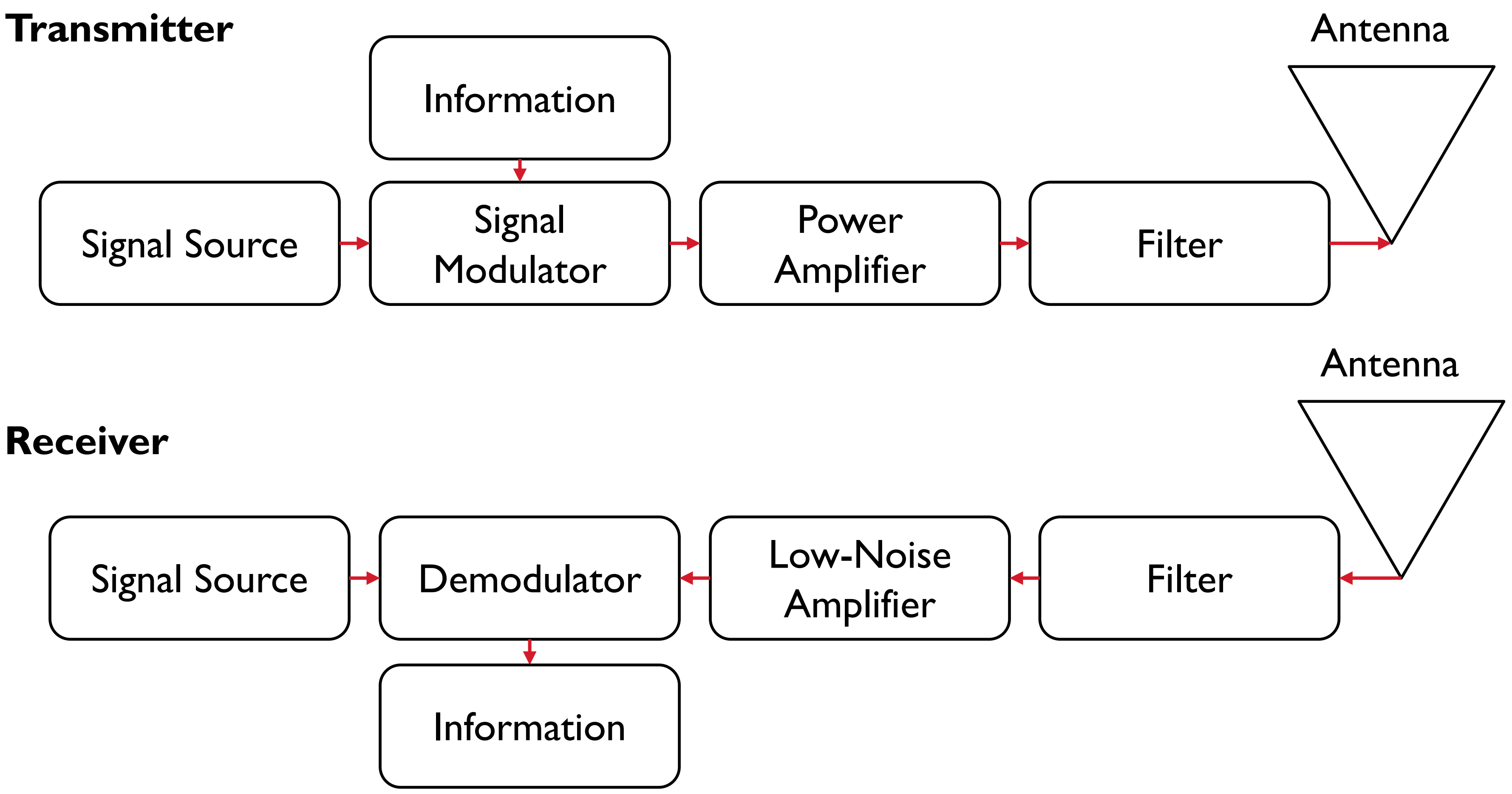

Some Examples

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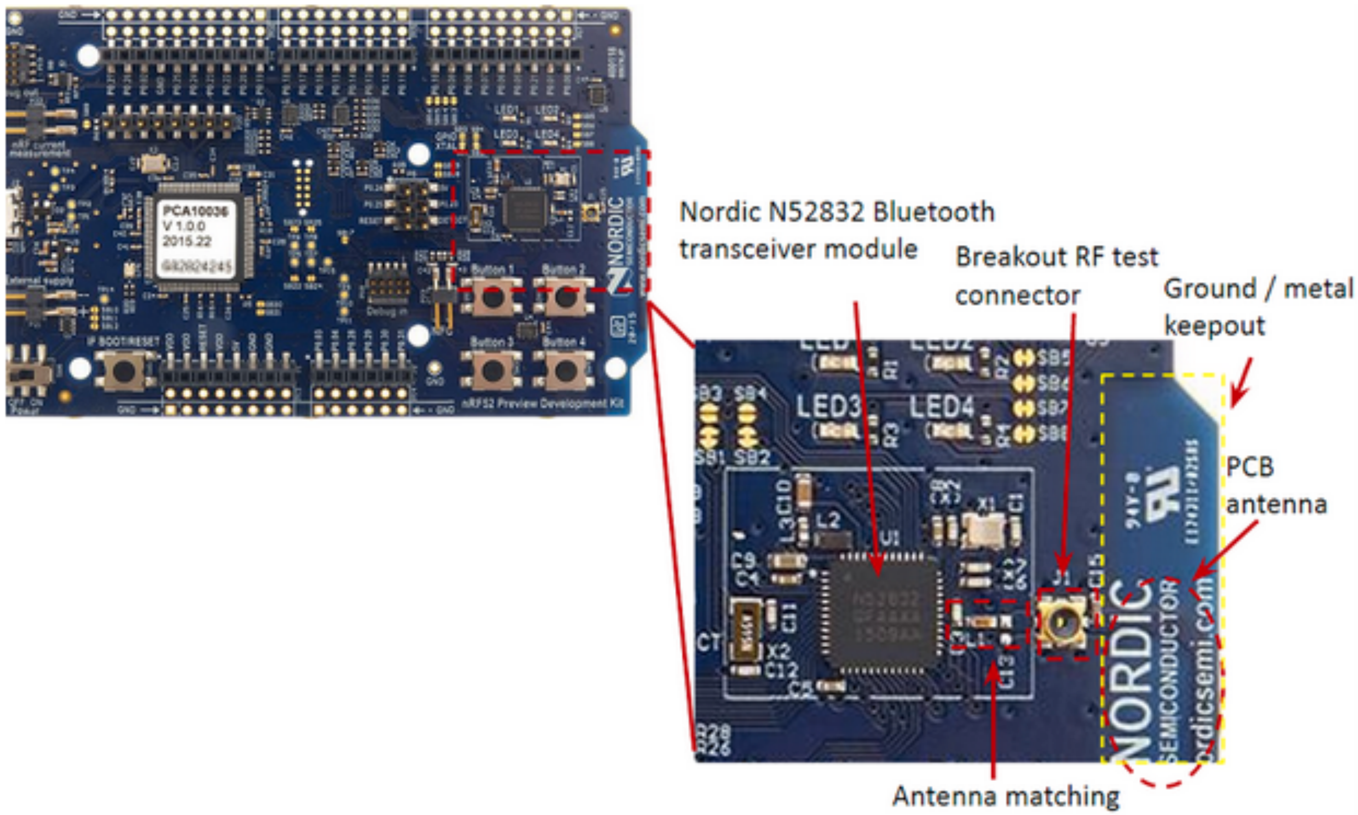
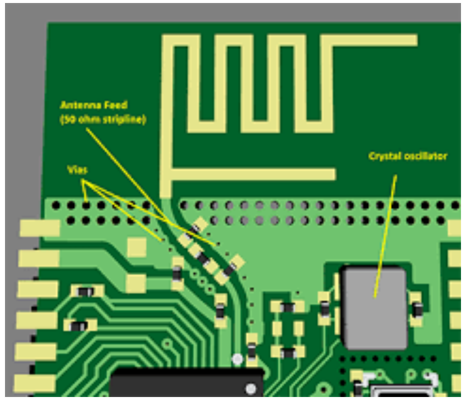


On-chip Antennas

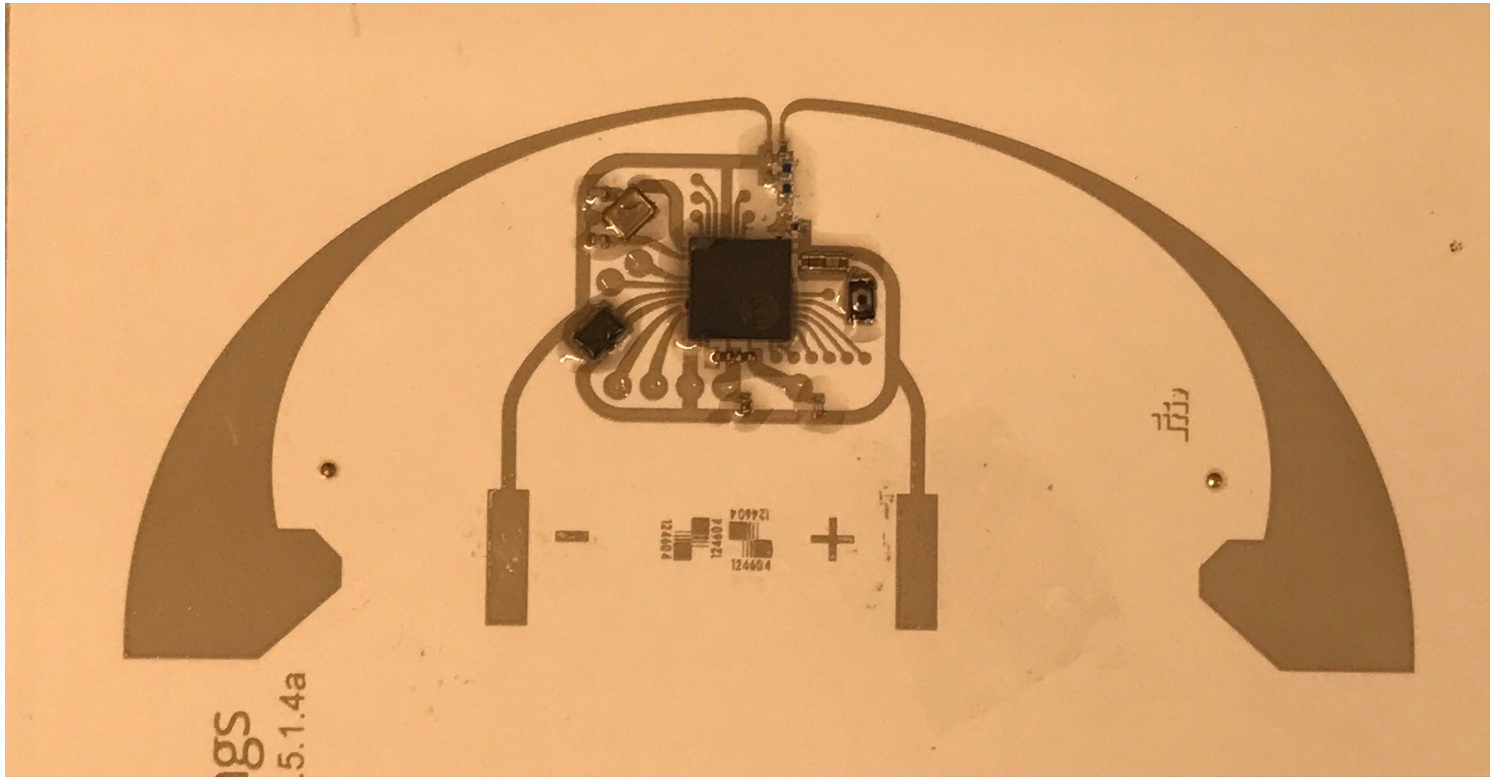


Off-chip Antennas

Some (cooler) Examples

- Paper-printed Electronics

NanoThings



Nano-transceivers and Nano-antennas

- How could we make transceivers and antennas that are:
  - Smaller?
  - Non-invasive?
  - Non-perceptible?

- By leveraging the tools provided by nanotechnology to:
  - Manipulate new materials, including graphene (remember Module T3)
  - Leverage new physics, such as plasmonics

- Applications:
  - The Internet of Nano-Things

Nano-transceiver and Nano-antennas

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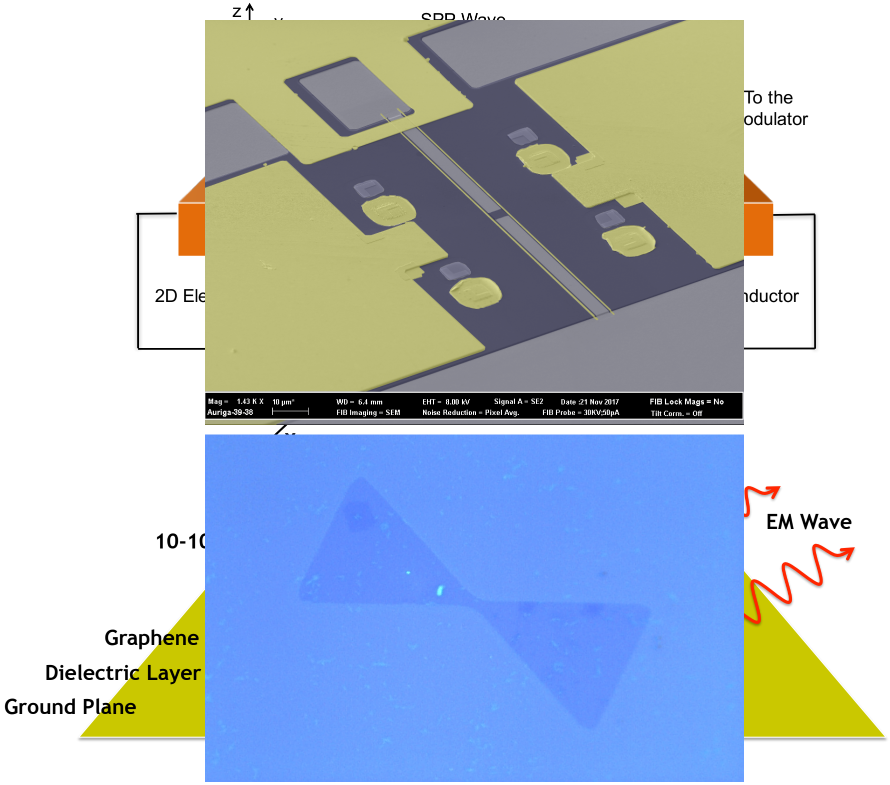

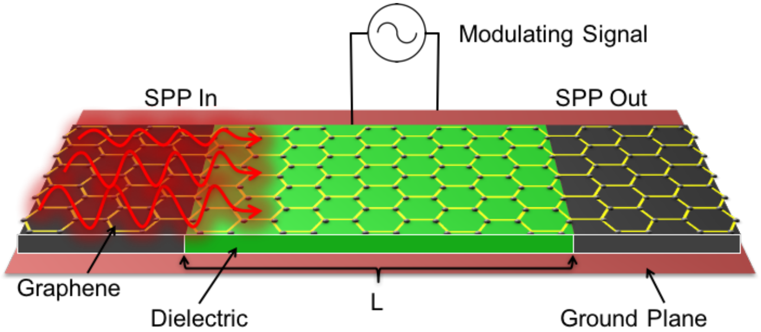

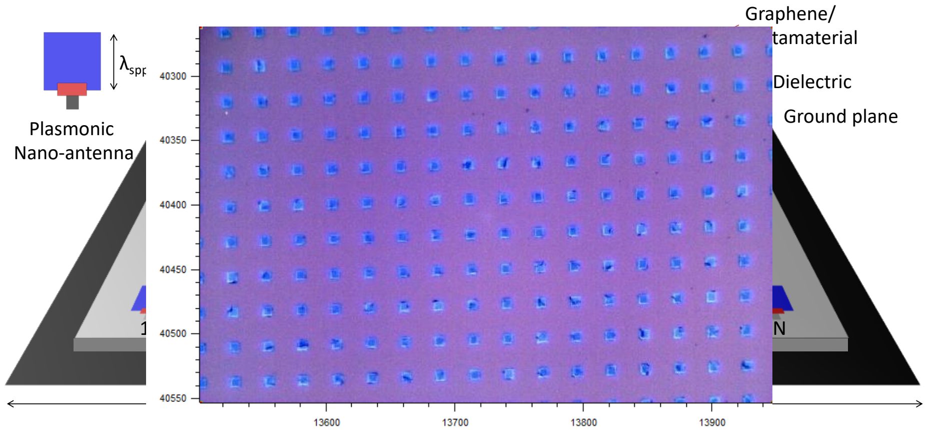

Transceiver: J. M. Jornet and Ian F. Akyildiz, "Graphene-based Plasmonic Nano-transceiver for Terahertz Band Communication," in Proc. EuCAP, 2014. U.S. Patent No. 9,397,758 issued on July 19, 2016.

Modulator: P. K. Singh, G. Aizin, N. Thawdar, M. Medley, and J. M. Jornet, "Graphene-based Plasmonic Phase Modulation for THz-band Communication," in Proc. EuCAP, 2016. U.S. Patent Application filed on April 9, 2018 (Priority date April 9, 2017).

Antenna: J. M. Jornet and I. F. Akyildiz, "Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks," IEEE JSAC, 2013. Shorter version in Proc. of EuCAP, Apr. 2010. U.S. Patent No. 9,643,841, issued on May 9, 2017.

Antenna Array: I. F. Akyildiz and J. M. Jornet, "Realizing Ultra-Massive MIMO communication in the (0.06-10) Terahertz band," Nano Communication Networks (Elsevier) Journal, June 2016. U.S. Patent 9,825,712 Nov. 21, 2017.

Transceiver and Antenna Specifications

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- Frequency band of operation
- Bandwidth
- Modulations
- Data-rate
- Transmission power
- Antenna gain
- Noise figure
- Sensitivity
- Communication distance / range
- Out of band emissions
- …

Different communication and networking solutions will require different specifications. More in Part 2

Transceiver States

- Transceivers can be put into different operational states, typically:
  - **Transmit**
  - **Receive**
  - **Idle** – ready to receive, but not doing so
    - 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

- **Research issue:** Wake-up receivers – can be woken up via radio when in sleep state

Energy Consumption

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- At this point, we have explained the key elements in the "Things" or embedded systems in IoT applications
- In many IoT applications, the "Things" are battery powered:
  - Their batteries need to be periodically replaced or recharged
    - Energy harvesting systems (e.g., solar, wind, motion) could be utilized
- In all these cases, minimizing the power requirements and the energy consumption is a priority
- Next, let's develop an energy model for "Things" in the IoT

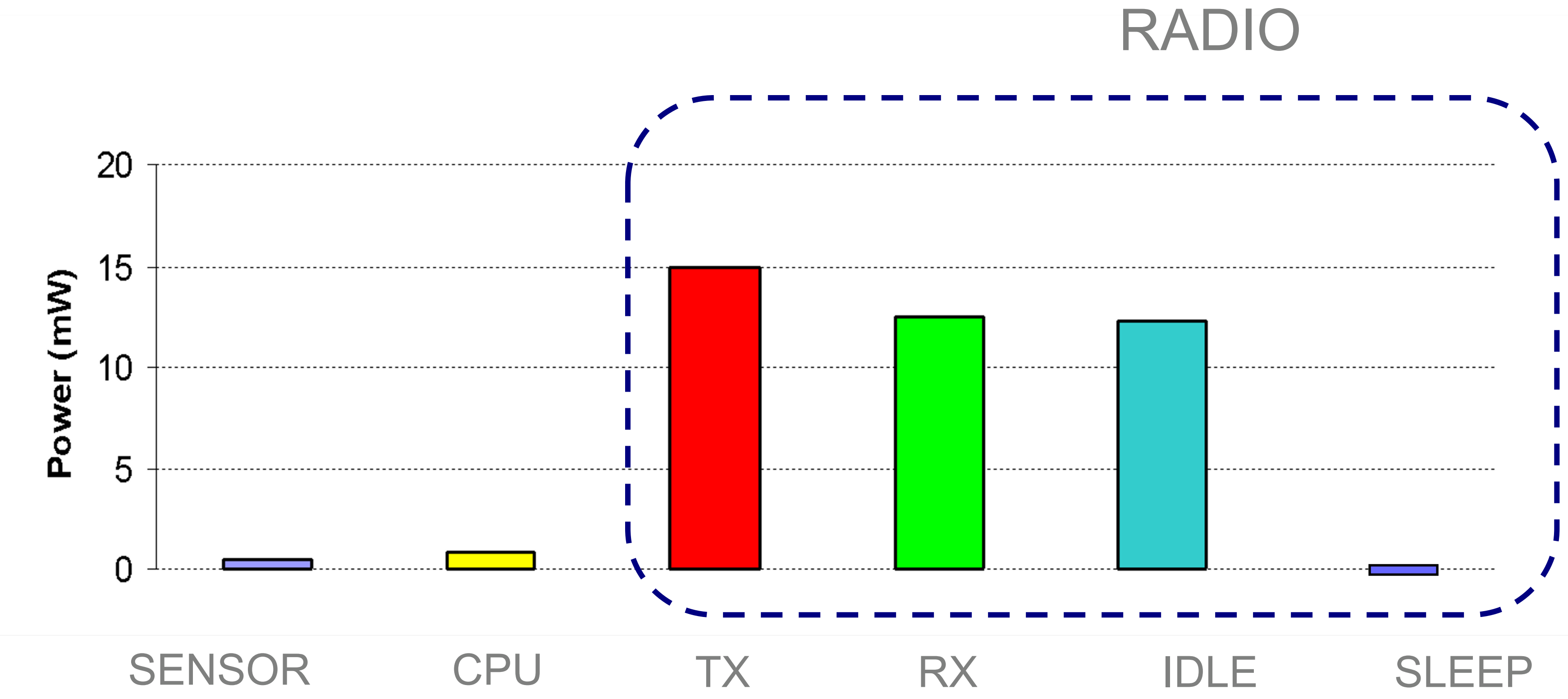
Reminder

- **Power** → Watts
- **Energy** → Joules (Watts*second)
  - Energy = Power * Time

- **Logarithmic units:**
  - Power in dBW = $10\log_{10}$(Power in Watts)
    - E.g., 2 W = 3 dBW
  - Power in dBm (or dBmW) = $10\log_{10}$ (Power in milliWatts)
    - E.g., 1 mW = 0 dBm
  - Power Gain in dB = $10\log_{10}$(Gain – unitless)
    - E.g., 100x = 20 dB

Power & Energy Consumption

- Power/Energy consumption in a sensor network can be divided into three domains
  - Communication
  - Data Processing (Computation)
  - Sen



Energy Consumption in Communication

- A sensor spends maximum energy in data communication (transmission and reception)
- For short range communication with low radiated power (e.g., 0 dbm), the transmission and reception energy costs are approximately the same
- Modern low power short range transceivers consume between 1 and 100 mW of power when sending and receiving
  - The energy consumption then depends on "how long" are they sending and receiving
- Transceiver circuitry has both active and start-up power/energy consumption

Energy Consumption in Communication

$$E_c = N_T[P_{te}(T_{on} + T_{st}) + P_O(T_{on})] + N\_R[P\_re(R_{on} + R_{st})]$$

- P_{te} is power consumed by transmitter
- P_{re} is power consumed by receiver
- P_O is output power of transmitter
- T_{on} is transmitter "on" time
- R_{on} is receiver "on" time
- T_{st} is start-up time for transmitter
- R_{st} is start-up time for receiver

N_T is the number of times transmitter is switched "on" per unit of time

N_R is the number of times receiver is switched "on" per unit of time

Energy Consumption in Communication

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- $T_{on} = L / R$
  - where L is the packet size in bits and R is the data rate in bits/second

- The number of packets being sent and received, N_T and N_R, depend on the protocols being used

- Low power radio transceiver has typical P_{te} and P_{re} values around 10 dBm and P_O close to 0 dBm

Start-up Power and Start-up Time

- A transceiver spends time upon waking up from sleep mode, e.g., to ramp up phase locked loops or voltage-controlled oscillators (VCOs)
- During start-up time, no transmission or reception of data is possible
- "Things" often communicate in short data packets
- Start-up energy consumption (power * time) starts dominating as packet size is reduced
- It is inefficient to turn the transceiver ON and OFF because a large amount of energy is spent in turning the transceiver back ON each time

Energy Consumption VS Packet Size

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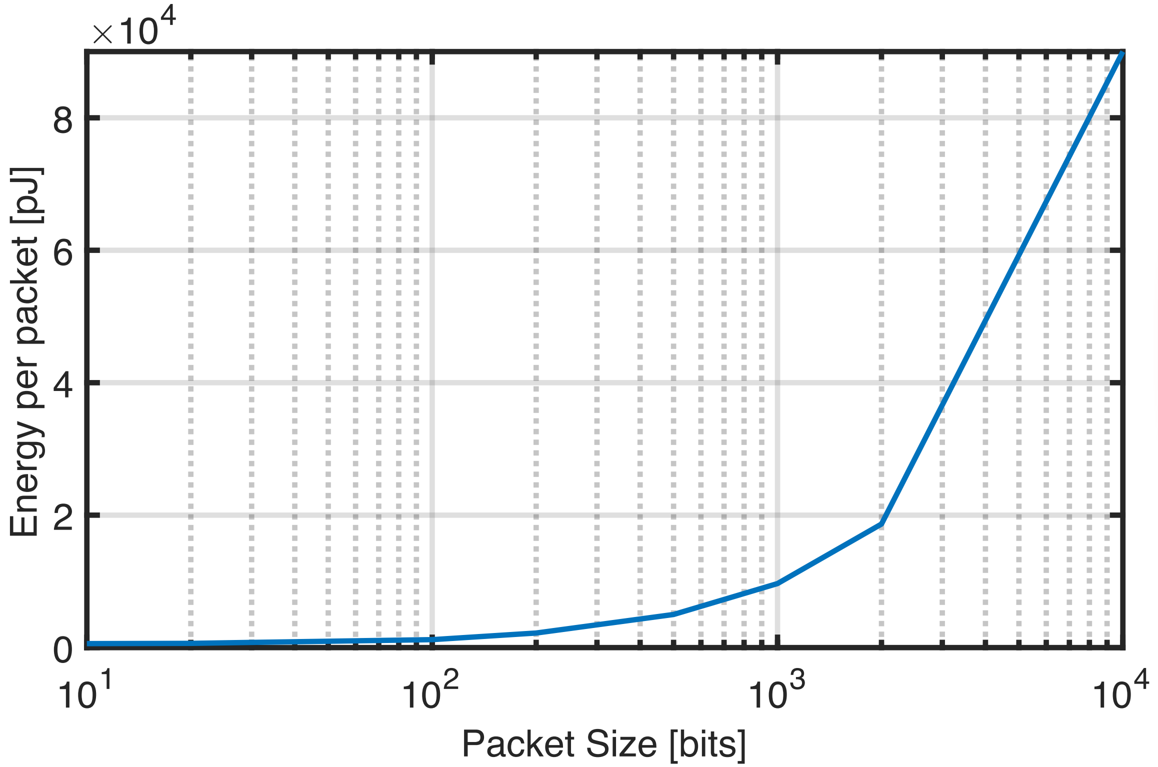

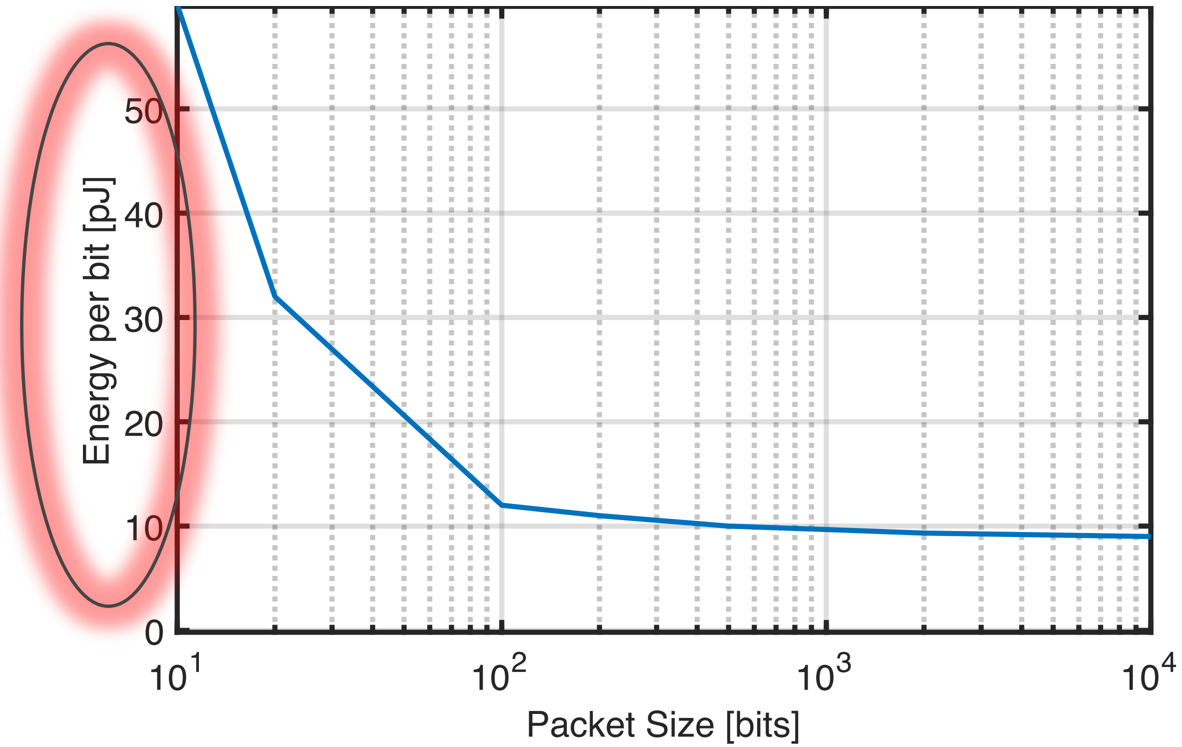

- As packet size is reduced, the energy consumption is dominated by the startup time on the order of hundreds of microseconds during which large amounts of energy are wasted

Start Up and Sleep Mode

- The effect of the transceiver startup time will greatly depend on the type of MAC protocol used
- To minimize power consumption, it is desirable to have the transceiver in a sleep mode as often as possible
- However, constantly turning on and off the transceiver also consumes energy to bring it to readiness for transmission or reception

Trade Off!

What about energy spent during computation?

Energy Consumption in Data Processing

$$E_p = N * C * V_{dd}^2 + \underbrace{V_{dd}\left(I_O e^{\frac{V_{dd}}{n*V_T}}\right)\left(\frac{N}{f}\right)}$$

- N is the number of clock cycles per task
- C is the average capacitance switched per cycle
- V_{dd} is the supply voltage
- V_T is the thermal voltage
- f is the switching frequency

This term represents leakage current

In general, leakage currents account for about 10% of the total energy dissipation

Remember from Module T3:
All these parameters depend on your transistor technology

Energy Consumption in Data Processing

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- The energy consumed in data processing is often much less than the energy consumed in communication
- **Example:**
  - Assumptions:
    - Traditional low-power radio operating at 1-2 GHz
    - Rayleigh Fading wireless channel with losses depending with the fourth power of distance (More in Module T4, Part 2)
  - Result:
    - Energy cost of transmitting 1 kilobyte (KB) at a distance of 100 meters (m) is approximately equal to executing 3 million instructions by a 100 million instructions per second processor
- Performing local data processing is crucial to minimize the total energy consumption of the system!
  - That's the same reason why we try to perform as much processing as possible close to the data source
    - **Edge Computing**

Some Examples

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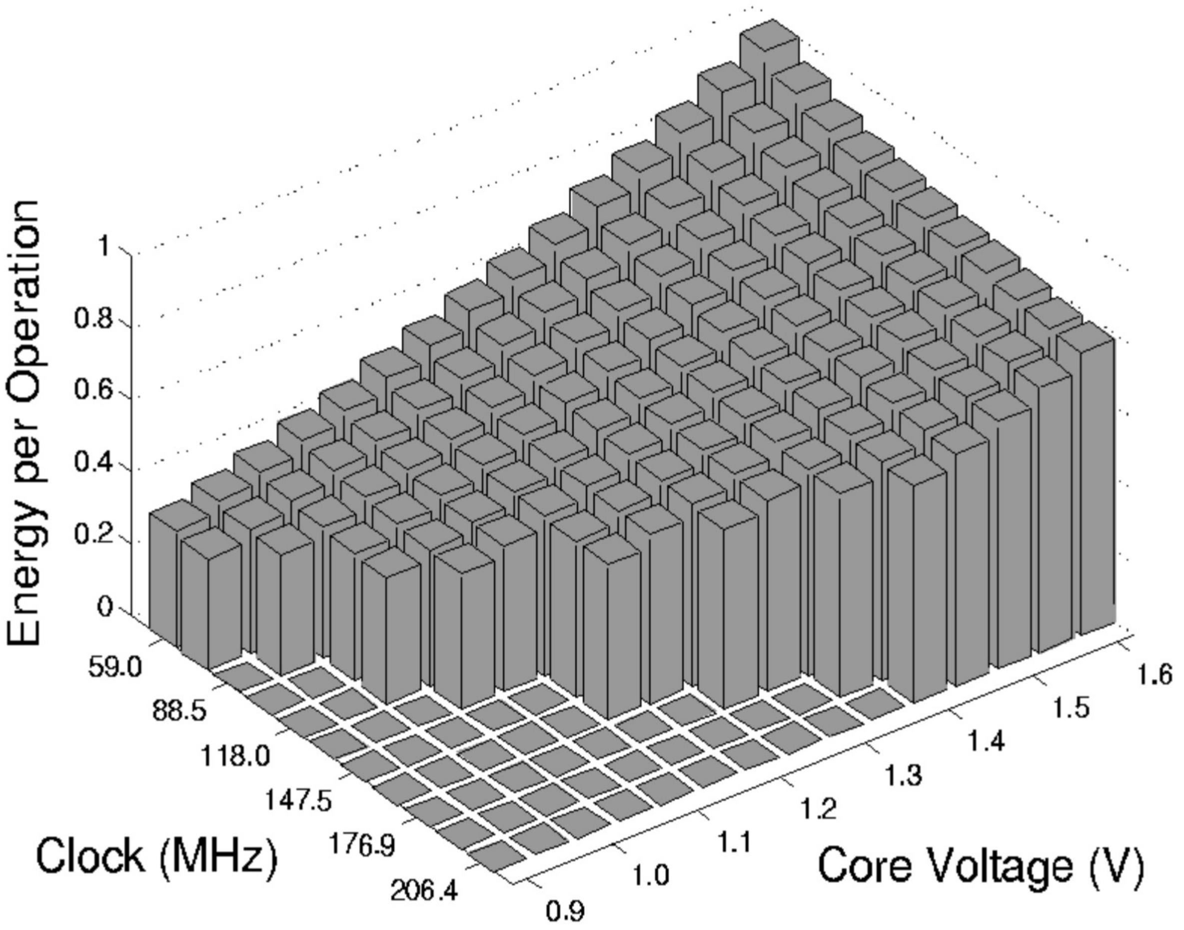
- Commercial Microcontrollers
  - **TI MSP 430 (@ 1 MHz, 3V):**
    - Fully operation 1.2 mW
    - Deepest sleep mode 0.3 μW
      - Only woken up by external interrupts (not even timer is running any more)
  - **Atmel ATMega**
    - Operational mode: 15 mW active, 6 mW idle
    - Sleep mode: 75 μW

Alternative: Dynamic Voltage Scaling

- Rationale:
  - Power consumption P depends on
    - Clock frequency
    - Square of supply voltage
    - $P \sim f\, V^2$
  - Lower clock allows lower supply voltage
  - Easy to switch to higher clock
  - But: execution takes longer



Memory Power Consumption

- **Crucial part:** FLASH memory
  - Power for RAM almost negligible

- FLASH writing/erasing is expensive
  - Example: FLASH on Mica motes
  - Reading: ¼ 1.1 nAh per byte
  - Writing: ¼ 83.3 nAh per byte

Ah = Ampere hour
Multiply by voltage V in volts to obtain Watt hour or Wh
Multiply by 60 seconds/hour to obtain Watt second = Joule

Computation VS Communication Cost

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- **Tradeoff?**
  - Directly comparing computation/communication energy cost is not easy
  - It really depends on the technology being used:
    - 900 MHz RF system
    - 2.4 GHz WiFi/Bluetooth System
    - 3.1-10.6 GHz Ultra-wide-band System
    - 60 GHz mmWave system
    - …
      - Besides the amplifiers in your transceiver, the digital to analog and the analog to digital converters (DACs and ADCs), i.e., the interface between analog signals and your digital computer, are one of the most energy consuming elements

Let's put everything together:

A simple energy model

A Simple Energy Model

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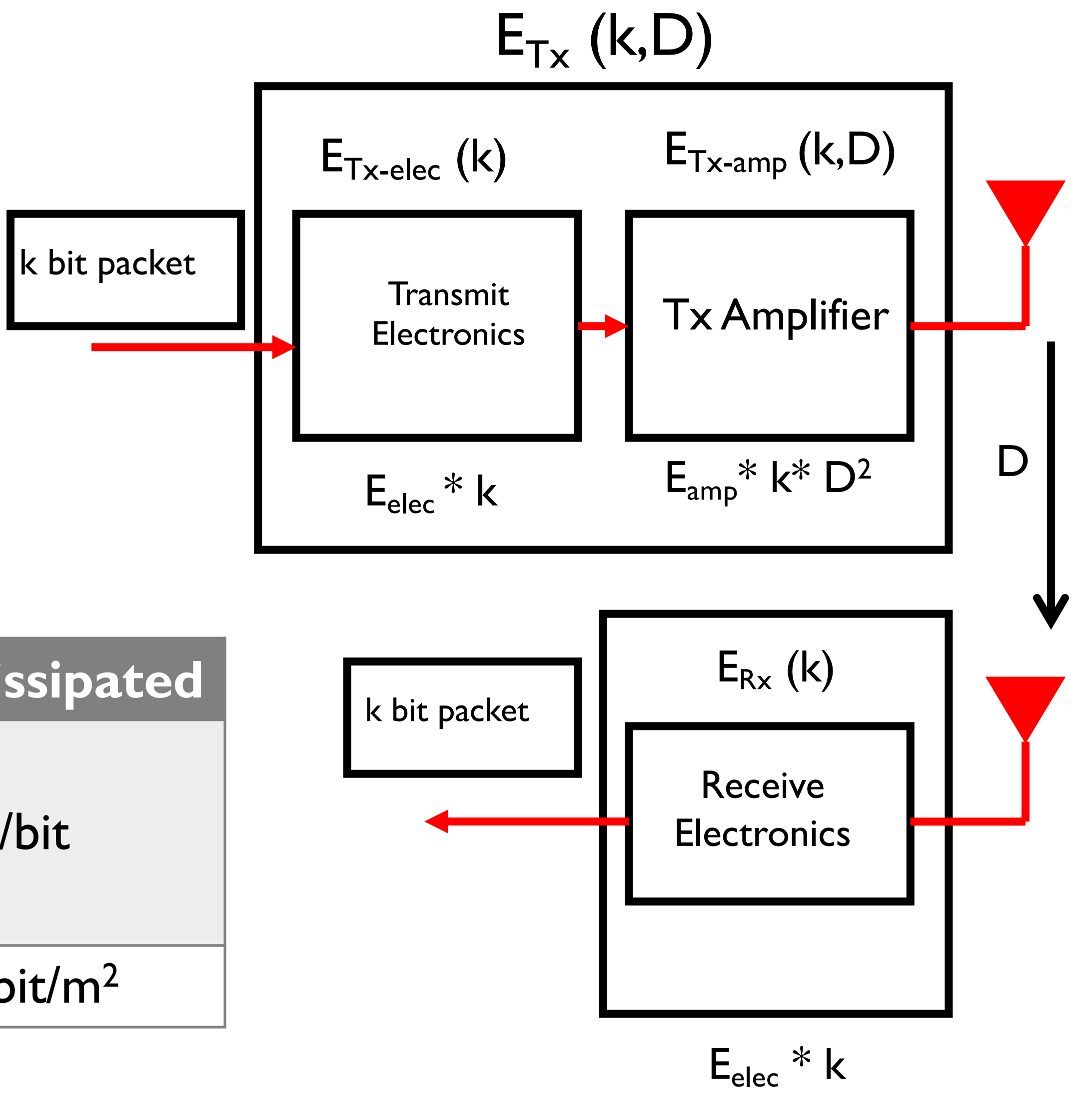
- Consider that a "Thing" is only operating in transmit and receive modes with the following assumptions:
  - **Energy to run circuitry:**
    - $E_{elec} = 50$ nJ/bit
  - **Energy for radio transmission:**
    - $E_{amp} = 100$ pJ/bit/m^2
  - **Energy for sending k bits over distance D:**
    - $E_{Tx}(k,D) = E_{elec} * k + E_{amp} * k * D^2$
  - **Energy for receiving k bits:**
    - $E_{Rx}(k,D) = E_{elec} * k$

A Simple Energy Model

$E_{Tx}(k,D) = E_{Tx\text{-}elec}(k) + E_{Tx\text{-}amp}(k,D)$
$E_{Tx}(k,D) = E_{elec} * k + E_{amp} * k * D^2$

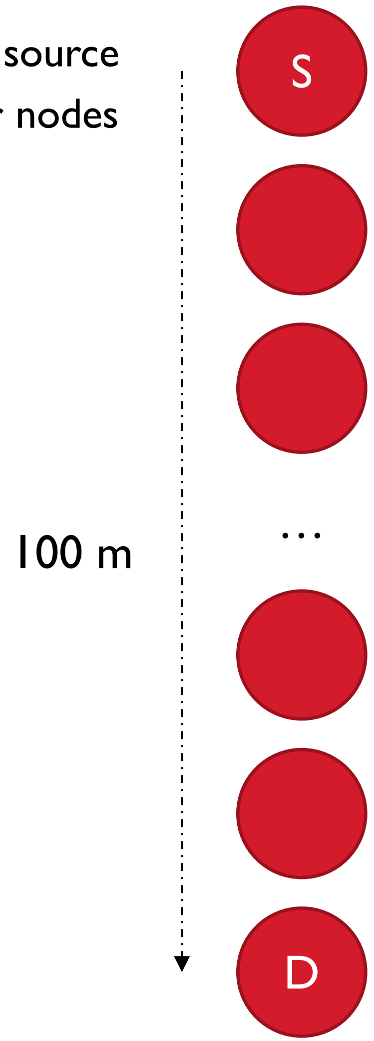
$E_{Rx}(k) = E_{Rx\text{-}elec}(k)$
$E_{Rx}(k) = E_{elec} * k$

Operation	Energy Dissipated
Transmitter Electronics ($E_{Tx\text{-}elec}$) Receiver Electronics ($E_{Rx\text{-}elec}$) ($E_{Tx\text{-}elec} = E_{Rx\text{-}elec} = E_{elec}$)	50 nJ/bit
Transmit Amplifier (E_{amp})	100 pJ/bit/m²



Example Using the Energy Model

- What is the energy consumption if 1 Mbit of information is transferred from the source to the sink where the source and sink are separated by 100 meters and the broadcast radius of each node is 5 meters? Assume the neighbor nodes are overhearing each other's broadcast



Conclusion

- Energy is an extremely important factor in the design of your wireless internet of things
- It is extremely device and application dependent:
  - What type of transceiver do you have?
  - What type of processor do you have?
  - How often are these used?
    - All these also depend on the communication and networking protocols
      - **That's the focus of Module T4 - Part 2**

Next Steps

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- Before every Wednesday, make sure to indicate on the Student Hub whether you want to join the lectures in person or remotely
  - On Thursday, you can then know if you have been approved to come to class the following week

- Finalize the research project team creation and topic selection task:
  - **Due this Sunday!**

- Complete the first computer laboratory assignment (individually or in couples)
  - **Due this Sunday!**