Autonomous Networking

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Some slides in this course are readapted from seminar slides from ***Mauro Piva*** (*Sapienza*)

Today's plan

- Internet of Things (IoT)
- Battery free IoT environments

What is Internet of Things?

What kind of things?

Everything that is "Smart"

- **Smart objects**: everyday ***physical objects*** with some embedded electronics that allow them to ***compute*** and ***communicate***
- Smart watch, smart phone, smart TV, etc
- But also…
- Smart car, smart home, smart building, smart city
- The conventional concept of the Internet as an *infrastructure network to interconnect end-user devices* leaves space to a notion of **interconnected "smart" objects forming pervasive computing environments**

Internet of Things

The term is broadly used to refer to

1. The **resulting global network** interconnecting smart objects by means of extended Internet technologies
2. The **set of supporting technologies** necessary to realize such a vision
3. The **ensemble of applications and services** leveraging such technologies to open new business and market opportunities

Conceptual point of view

- The IoT builds on three pillars, related to the ability of **smart objects** to:
  1. Be ***identifiable*** (anything identifies itself)
  2. To ***communicate*** (anything communicate)
  3. To ***interact*** (anything interacts) – either among themselves, building networks of interconnected objects, or with end-users or other entities in the network

Single component point of view

Smart object definition: Entity that

- Has a **physical** embodiment and a set of associated physical features (e.g., size, shape, etc.).
- Has a minimal set of **communication** functionalities (e.g., the ability to be discovered and to accept incoming messages and reply to them).
- Is associated to at least one **name** and one address.
- Possesses some basic **computing** capabilities (match an incoming message to a given footprint or perform rather complex computations such as network management tasks).
- Possess means to ***sense physical phenomena*** (e.g., temperature, light, motion) or to trigger actions having an effect on the physical reality (actuators).

N.B. The last point is the key one and differentiates smart objects from entities traditionally considered in networked systems (host, terminals, routers)

Smart objects

- include devices considered in RFID research as well as those considered in wireless sensor networks (WSNs) and sensor/actor networks (SANETs)
- RFID
- Sensor and actor networks

Key devices in IoT

- IoT includes devices (in addition to traditional networking devices)
  - With only very basic communication and computing capabilities
  - Do not present a full protocol stack
- IoT is about entities acting as *providers* and/or *consumers* of data related to the *physical world*

Required features (1/2)

Key system-level features that Internet of Things needs to support:

- Devices **heterogeneity** (protocols handling devices with different computational and communication capabilities)
- **Scalability** (naming, communication and networking, information management, service provisioning and management)
- Ubiquitous **data exchange** through proximity wireless technologies (spectrum availability)
- **Energy-optimized** solutions (optimization of energy usage)

Required features (2/2)

Key system-level features that Internet of Things needs to support:

- **Localization** and **tracking** capabilities (many applications require position and movement tracking)
- **Self-organization** capabilities (devices must be able to organize into ad hoc networks)
- **Semantic interoperability** and **data management** (massive data require standardized formats)
- Embedded **security** and **privacy-preserving** mechanisms (key requirement for ensuring acceptance by users and the wide adoption of the technology)

Enabling technologies

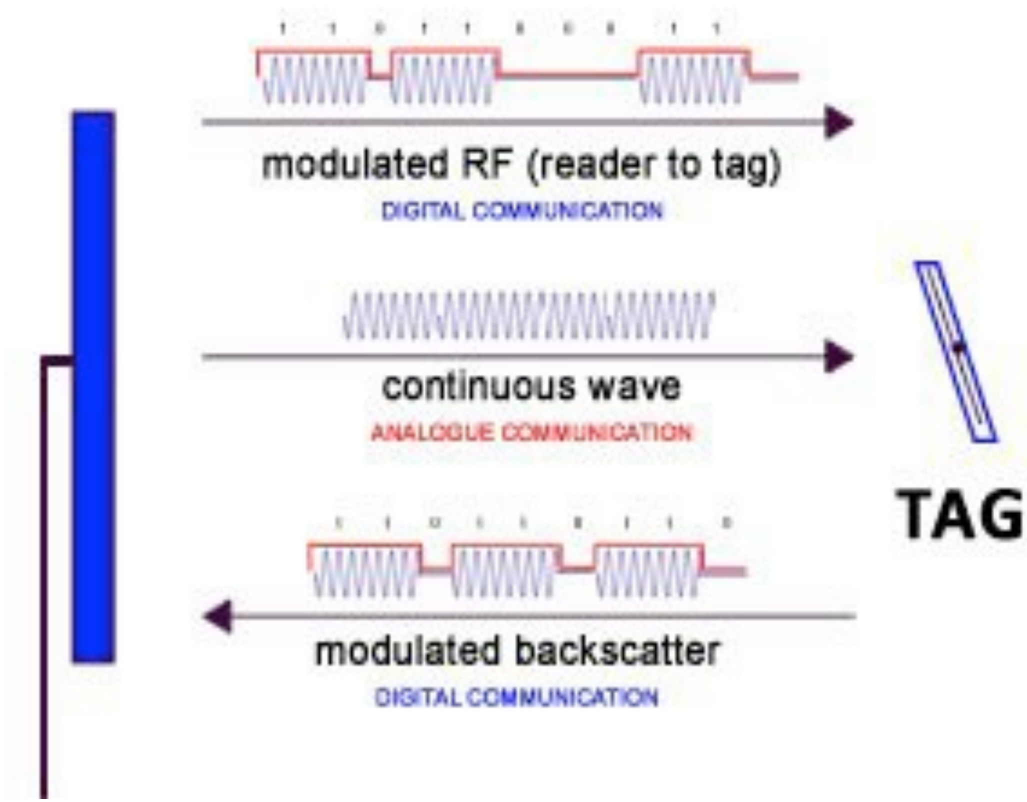
- A key issue for IoT is the development of appropriate means for **identifying** smart objects and enabling **interactions with the environment**
- Smart objects must have capabilities of:
  - Identification
  - Communication
  - Computation
  - Direct interaction with the environment
- Key building blocks are:
  - Wireless sensor networks
  - RFID

A new type of device

- Is it possible to re-design smart objects so that they can work without batteries?
- The answer is **backscattering**
- Backscatter (or backscattering) is the reflection of signals back to the direction from which they came

Battery-free smart objects

Backscattering



A new type of device

- Backscattering allows powering of sensor devices and eliminates the need to have any inbuilt batteries at all
- Several low-power devices can use radio frequency (RF) signals as a power source and use them to **sense, compute, and transmit data** via reflecting the RF signal
- Two backscattering techniques
  - Ambient
  - RF identification (RFID)

Ambient backscattering

Devices harvest power from **signals available in the environment** (e.g., TV, cellular, and Wi-Fi transmissions)

The main **advantage** of ambient back-scattering is the use of existing RF signals without requiring any additional emitting device.

Ambient backscattering

Performance drawbacks

- Achieves **low data rate** (below 1 kb/s)
  - applications that need to transmit data only occasionally, for example, to exchange money between smart cards or detect misplaced objects in a grocery store, but cannot support real-time applications, which need continuous communication.
- The **availability** of signals
  - Although TV towers broadcast signals 24 hours a day without interruption, signal ubiquity cannot be guaranteed, with negative effects on the transmission of data in real time.
  - If the signal is weak, smart devices are not able to accumulate the energy necessary to operate.
- Signals **weaken** significantly in **indoor environments**, even in places where they are supposed to be ubiquitous (e.g., TV signals in metropolitan areas located at a distance greater than a few, 8 to 10, Km from the tower).

RFID backscattering

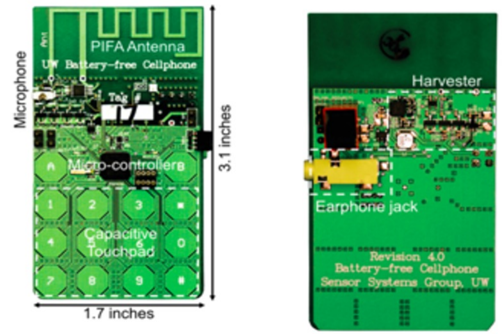
RFID tags harvest power from **signals emitted by the RFID reader**

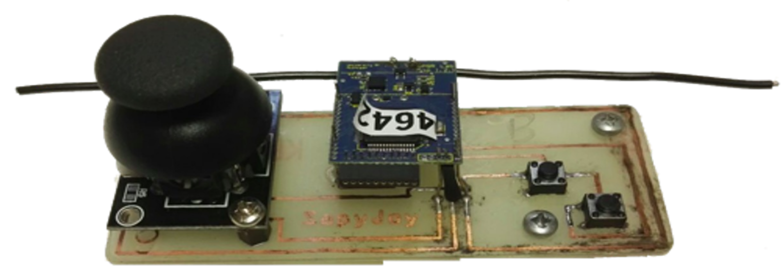
The main advantage is the availability of RFID signal, as the reader is always present in a RFID

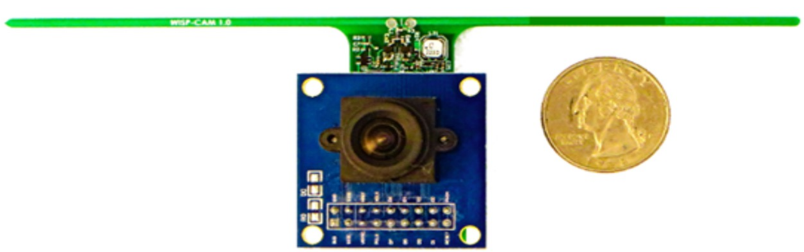
SENSOR-AUGMENTED RFID TAGS

Sensor Augmented RFID Tags

- RFID Tag with sensors embedded:
  - PIR, Camera, Accelerometer…
- No Battery
- Low Power
- Short Distances



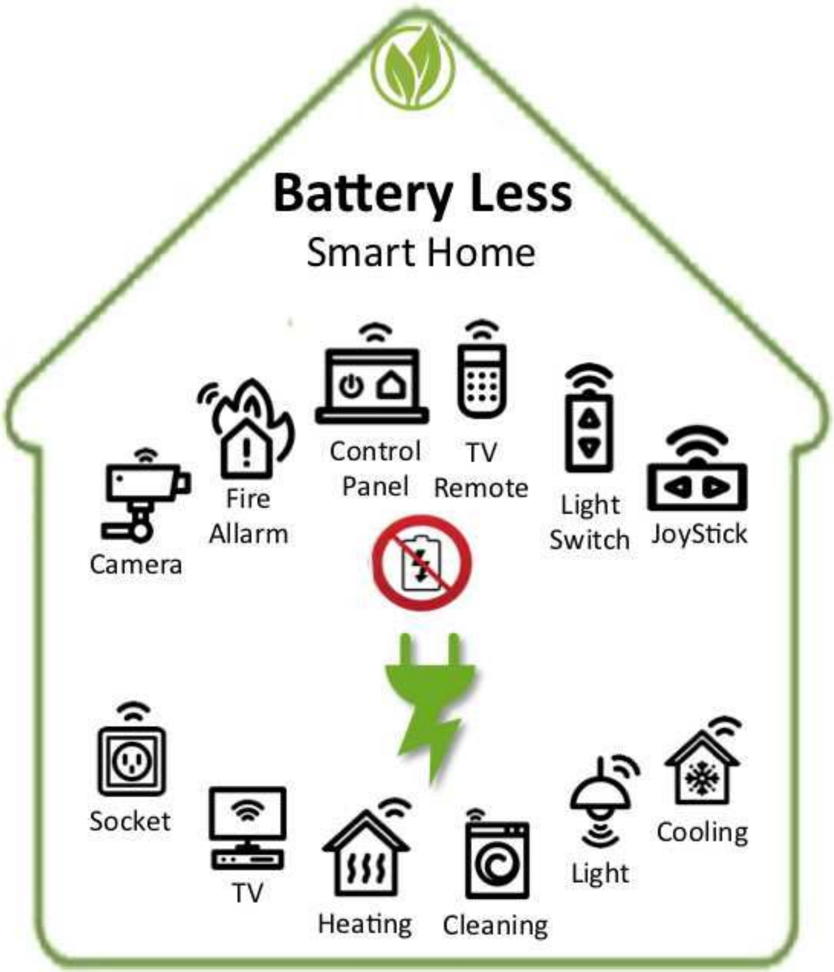




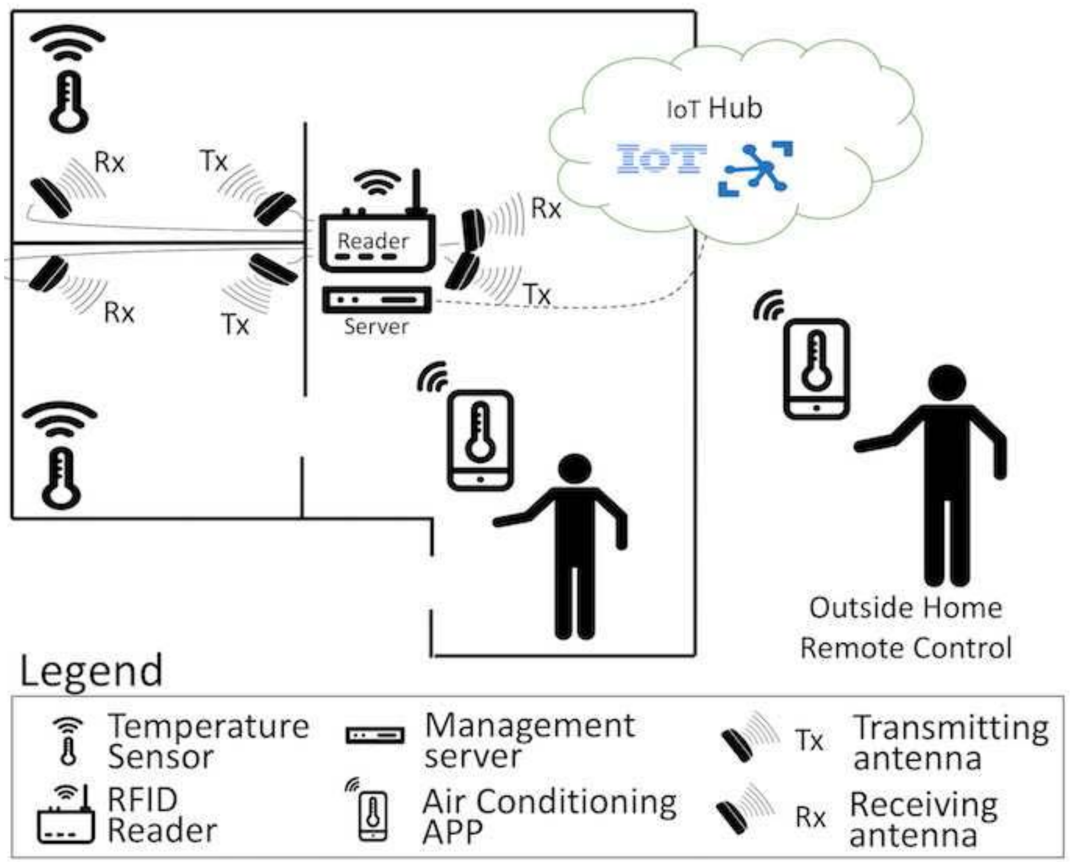
Sensor Augmented RFID Tags: characteristics

- Limited Power
- Limited Operative Range
- Limited Operative Time
- Limited storage
- Low datarate
- **But can run sensors!!!**

Battery free smart home



Deployment



IoT Hub
IoT
Rx
Tx
Rx
Tx
Reader
Server
Rx
Tx
Outside Home
Remote Control
Legend
Temperature Sensor
RFID Reader
Management server
Air Conditioning APP
Tx
Transmitting antenna
Rx
Receiving antenna

Replacing batteries with RFID tags

- We developed a joystick for videogames that uses RFID backscattering for battery-free operation.
- Our joysticks enable consumers to play at every moment without caring about charging.

Developed battery-free devices

Video Game Controller

- Real-time device that is realized by mounting an analog joystick and two buttons on a Moo tag
- Able to interact with several types of video games (e.g., adventure, action, puzzle, and role-playing games)
- a printed circuit board (PCB) connects the analog joystick and the two buttons to the Moo tag, which also has an accelerometer embedded, allowing for complex game experiences.

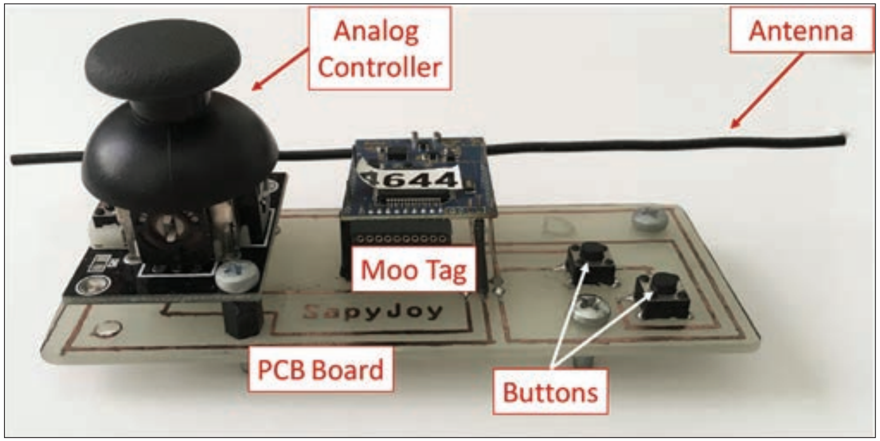


FIGURE 1. SapyJoy videogame controller: A PCB board connects the analog controller and the buttons to the Moo tag.

SapyJoy

Mouse

Mouse: A platform analogous to SapyJoy can work as a wireless and battery-less mouse by interfacing its x and y axes with the pointer on the screen.

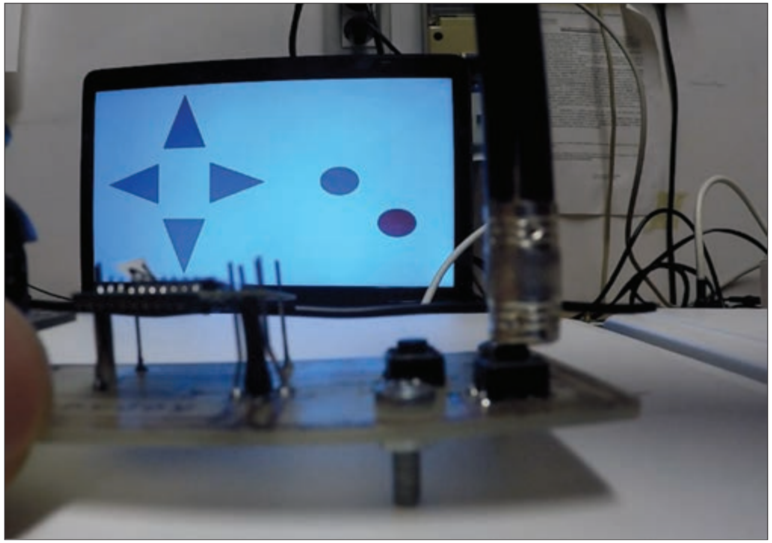


FIGURE 3. Button pressure on the battery-free mouse and corresponding action on the screen.

Developed battery-free devices

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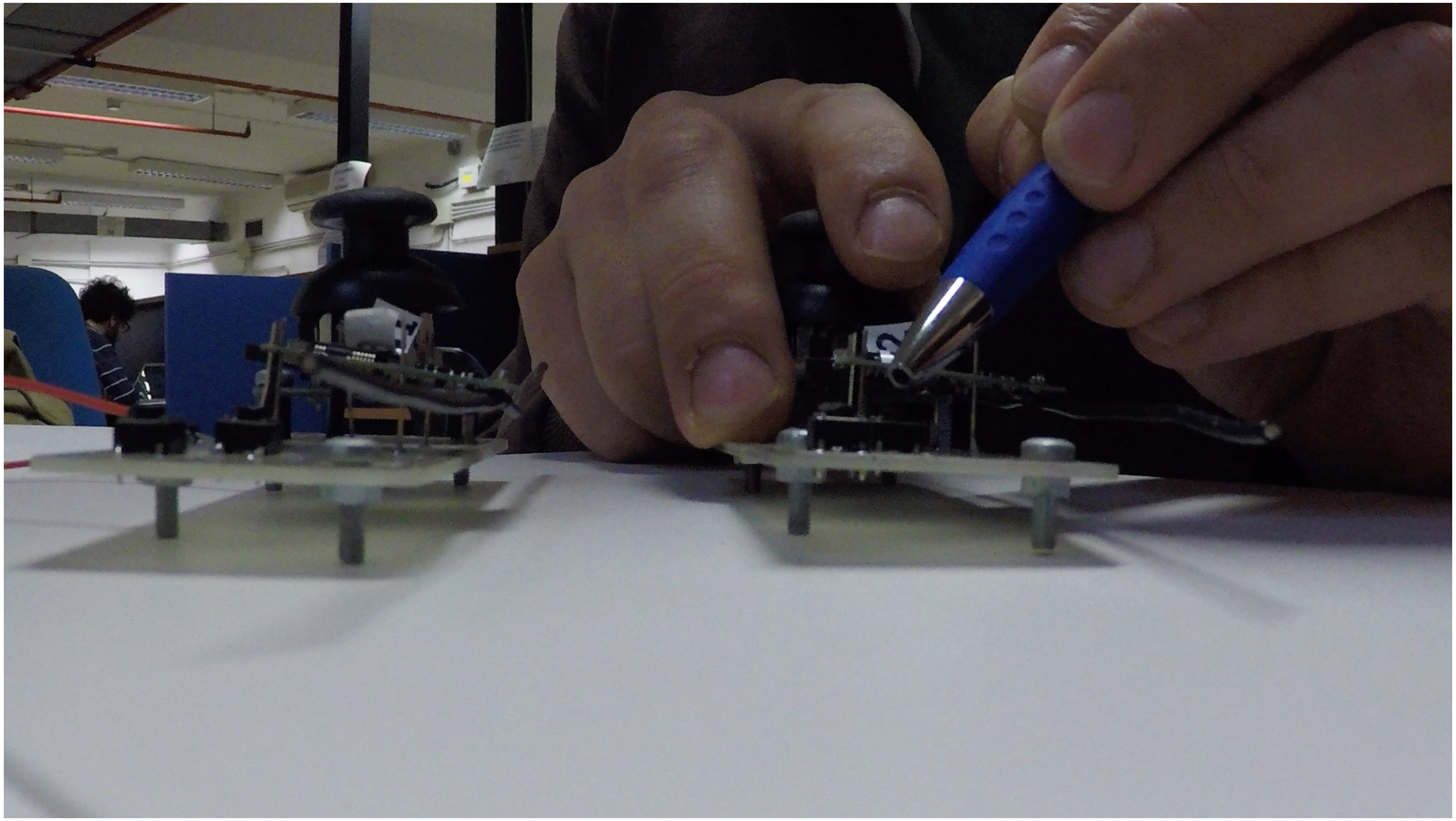
Light Switch

- Event-based device, realized by mounting a button on the Moo Tag
- When the user presses the button on the wireless and battery-less light switch, the system switches on a LED on an actuator
- Depending on the application, it is possible to embed multiple buttons on the same Moo tag to control different lights deployed inside a smart building
- The logical connection between the tag switch and the corresponding light is placed inside the server.

Light Switch

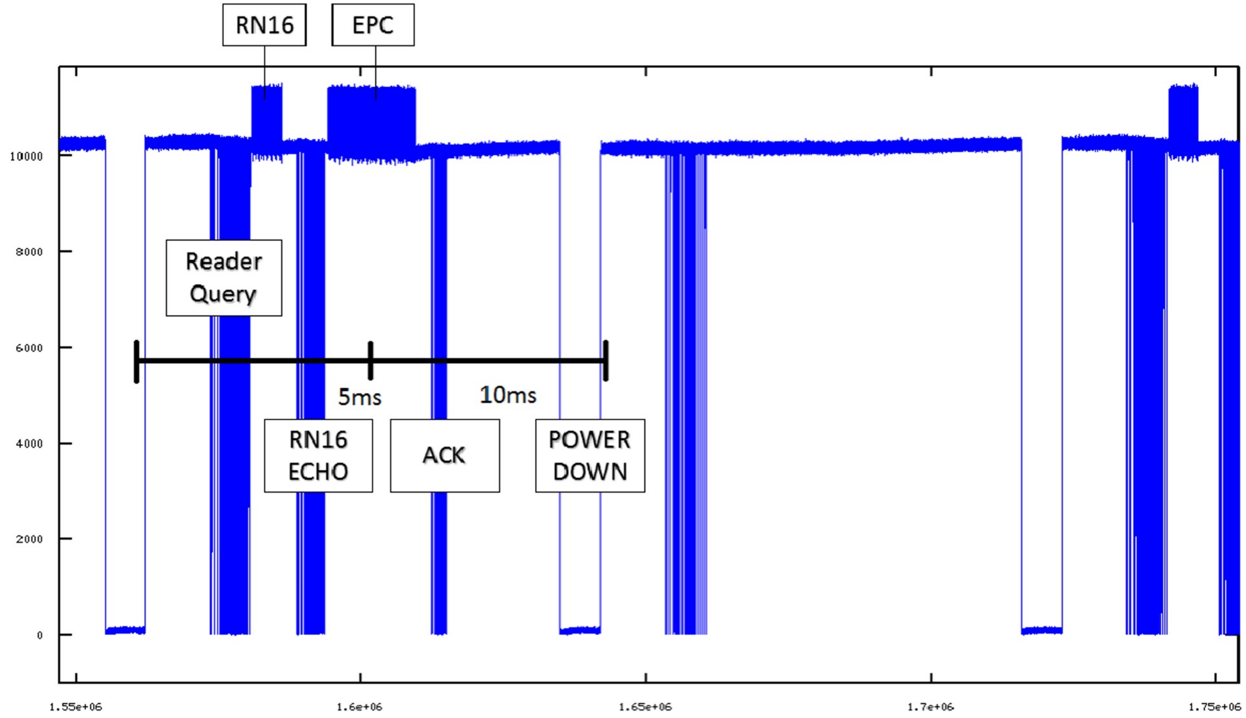


Performance: experiments

- To interact with our prototypes, we use a USRP (Universal Software Radio Peripheral) RFID reader equipped with two RFID antennas, and a server that interconnects the RFID reader with smart home applications
- The Moo tag receives the reader signal and uses it to harvest operating power using the RFID circuit
- The harvested power runs onboard sensing, encoding of measurement data, cyclic redundancy check (CRC) error coding, and backscatter communication to wirelessly send data back to the reader
- The communication protocol between the reader and the tags is based on the EPC Gen 2 Class 1 standard, which has been modified to acquire data from sensors and store them in the buffer that is traditionally used to maintain the tag ID.

Communication

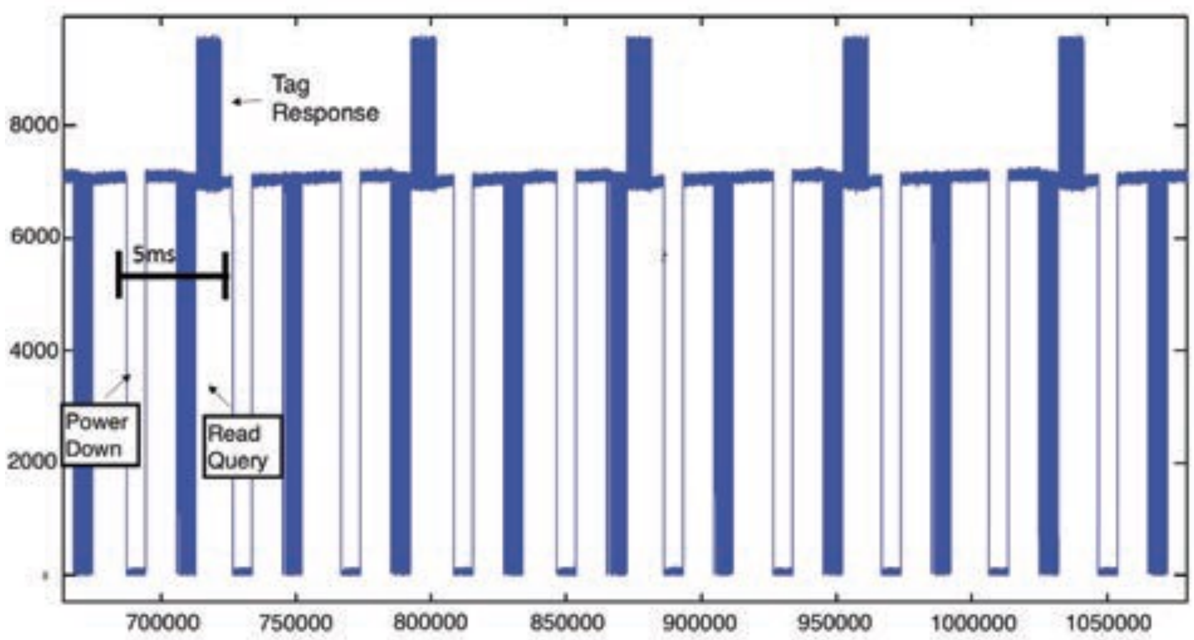
- What is the communication protocol?
- Sensor-augmented RFID tags run EPC Global Standard



How can a tag send sensor data?

- The communication protocol between the reader and the tags is based on the EPC Gen 2 Class 1 standard, which has been **modified to acquire data from sensors and store them in the buffer that is traditionally used to maintain the tag ID**.
- As only a few bits (e.g., 8 bits) are sufficient to represent the tag's ID, the remaining, typically 96 – 8 bits, can be used to send sensed data.
- We limited the data field to **1 byte for tag ID and 6 bytes for data samples (including 4 CRC bits)**. This number guarantees low packet error rate — confirmed by our experimental study — and enough space for data samples for all devices except the camera, which would require data fragmentation even in the case of longer payloads.

EPC modification



Matched filter for SapyJoy

Performance evaluation

- **Reaction time**
  - the time since the generation of new sensor data to the corresponding action on the recipient application.
  - Application layer metric.
  - In the case of the joystick, it measures the time between an action on the joystick (e.g., a button press) and the corresponding event on the video game application.
  - In the case of an environmental sensor, this metric measures the time between the generation of new sensor data and the corresponding reaction on the recipient actuator (e.g., a presence sensor activating a camera).

Performance results

Device	Reaction time (ms)	CI
SapyJoy	92.92	[82.31–102.92]
Commercial controller	104.58	[96.31–112.85]
Commercial mouse	110.41	[103.09–117.74]

TABLE 1. Reaction time for different controllers.

Device	Reaction time (ms)	CI
Light switch	62.91	[67.41–73.41]
Mouse	92.92	[82.91–102.92]

TABLE 2. Reaction time for battery-free light switch and mouse.

Good results but …

Devices have been tested standalone

There is only one device answering to the reader queries

No possibilities for collisions

What if multiple devices coexist?

Interoperability

- Although results clearly show the feasibility of battery-free RFID- based smart objects, whose performance is comparable to that of the battery-powered counterparts, their coexistence cannot be taken for granted.
- When multiple devices operate **simultaneously**, the reaction time increases significantly with respect to the case of a device working alone.

Results with multiple devices

- We run experiments with three devices working at the same time: two environmental sensors — temperature and presence — and a video game controller (our SapyJoy)

- The devices are queried (and hence transmit sensed data) following a time-division multiple access approach, which provides different time slots to different devices in a cyclically repetitive frame structure

- If a device is queried at each slot, the reaction time is clearly shorter with respect to the case in which it is queried once every multiple slots. The outcome of our experimentation is that the **reaction time increases significantly** (i.e., 200 ms) with respect to when it works alone (i.e., 92.92 ms).

- This delay would certainly increase if the number of transmitting devices increases, making interoperability a challenge as the joystick may experience delays that are too long.

Open problem

- **Would an equal assignment of channel resources satisfy devices' needs**?
- Multi-kind multiple battery-free devices, operating simultaneously, have widely varying communication requirements in terms of data transmission, ON/OFF activity, and deadlines.
- Example, a joystick may sense no changes for hours (while it is OFF), and then start sensing new data (while used for playing) at very different rates (from a few milliseconds to one or more seconds), depending on the game type and player activity.
- How to rule channel access?

Readings

Paper available on Elsevier digital library

- D. Miorandi, S. Sicari, F. De Pellegrini, I Chlamtac,"**Internet of things: Vision, applications and research challenges**", *Ad Hoc Networks*, volume 10, issue 7, sept. 2012, pp 1497-1516

Paper available on ieeexplore library

- G. Maselli, M. Pietrogiacomi, M. Piva and J. A. Stankovic, "**Battery-Free Smart Objects Based on RFID Backscattering**," in *IEEE Internet of Things Magazine*, vol. 2, no. 3, pp. 32-36, September 2019

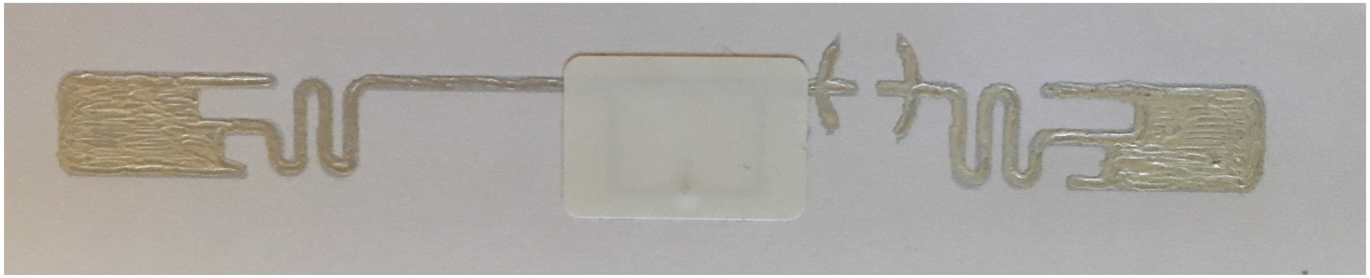
Other developments

- RFID are powerful tools to enable the development of cheap devices

JoyPaperTag

JoyPaper

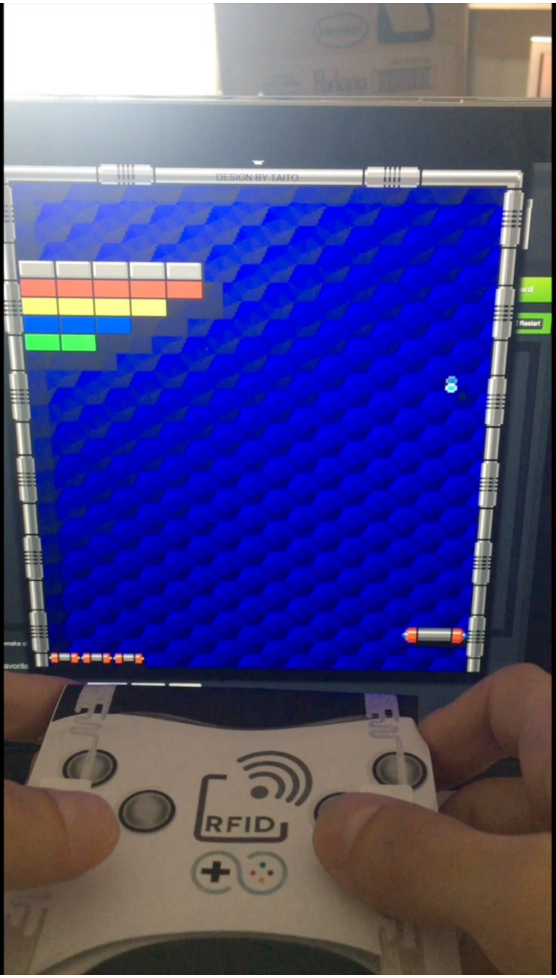
- The process for creating JoyPaper employs only paper, ultra-compact RFID tags in the form of stickers, and pens with conductive ink.
- Small stickers containing commercially available UHF loop integrated circuits (IC) are placed over specifically designed conductive traces, that can be easily drawn by hand using a pen filled with conductive ink



Button pressure on JoyPaper.

- the antenna's continuity is restored and then tag starts to operate again
- When touched the tag becomes an input sensor, able to send its ID to a querying reader.

JoyPaperTag



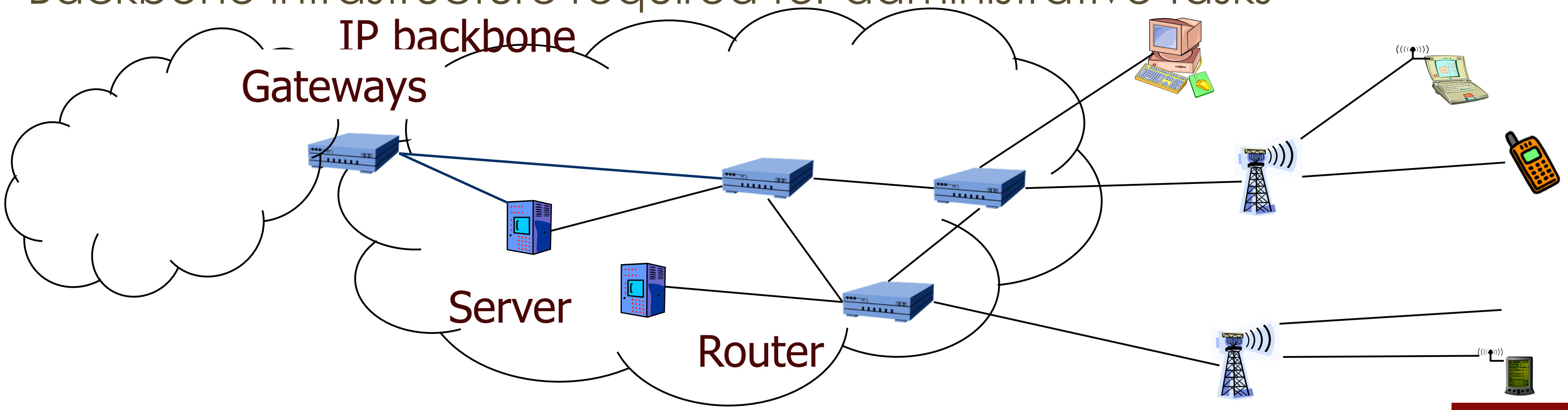
Other wireless networks

- Infrastructure-less wireless networks
  - (Mobile) Ad Hoc Networks (MANET)
  - Wireless Sensor Networks (WSN)

Infrastructure-based wireless networks

Infrastructure-based Wireless Networks

- **Traditional wireless network**: based on infrastructure (GSM, UMTS, …)
- Base stations connected to a wired backbone network
- Mobile devices communicate wirelessly to these base stations
- Traffic between different mobile entities is relayed by base stations and wired backbone
- Mobility is supported by switching from one base station to another
- Backbone infrastructure required for administrative tasks



Limits

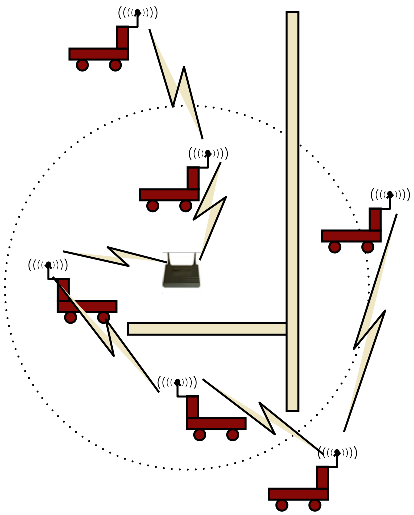
What if…

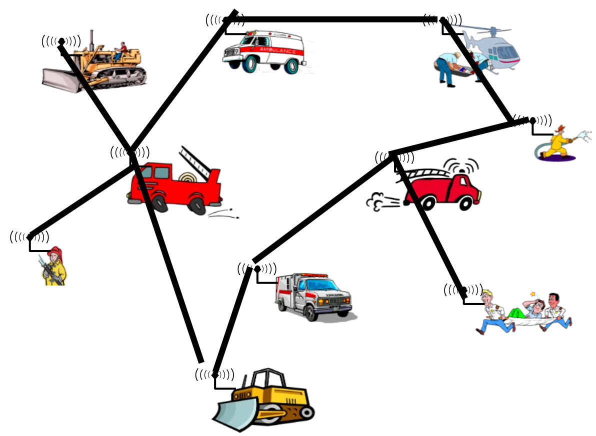
- No infrastructure is available?
  - Disaster areas
- It is too expensive/inconvenient to set up
  - Remote, large constructions sites
  - Houses
- There is no time to set it up
  - Military operations

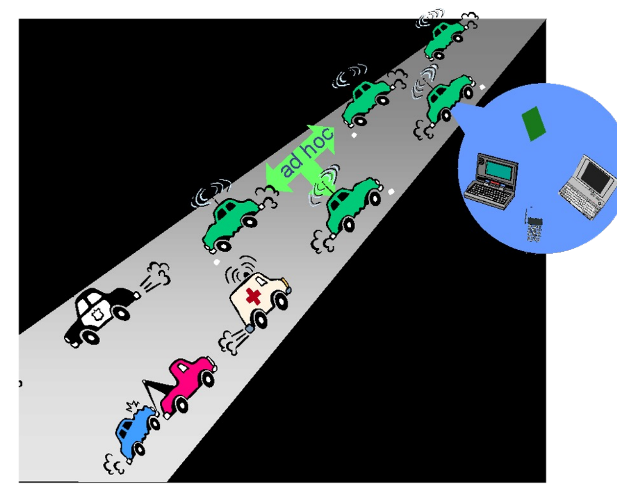
Infrastructureless-based wireless networks: Mobile Ad Hoc Networks

Applications of Infrastructureless networks

- Factory floor automation
- Disaster recovery
- Car-to-car communication





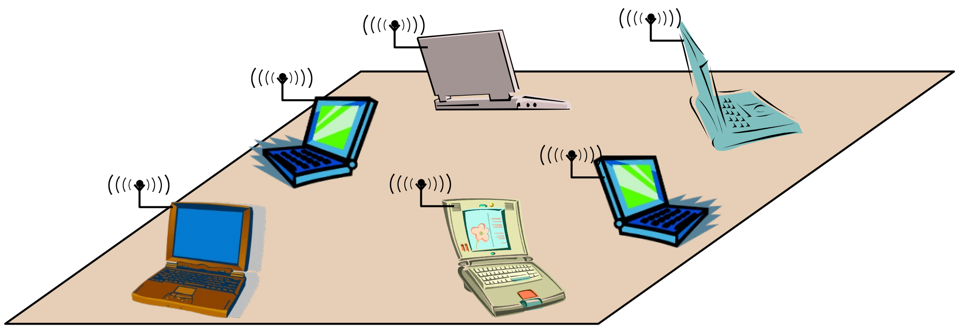


- Military networking: Tanks, soldiers, …
- Finding out empty parking lots in a city, without asking a server
- Search-and-rescue in an avalanche
- Personal area networking (watch, glasses, PDA, medical appliance, …)

Solution: Wireless Ad Hoc Networks

- Build a network without infrastructure, **using networking abilities of the participants**
  - **Ad hoc** network – a network constructed "for a special purpose"

- Example: Laptops in a conference room – a single-hop ad hoc network



Challenges in Ad Hoc Networks

- Without a central infrastructure, things become much more difficult

- Problems are due to
  - **Lack of central entity** for organization available
  - **Limited range** of wireless communication
  - **Mobility** of participants
  - **Battery-operated** devices

Self-organization

Lack of central entity

Without a central entity, participants must organize themselves into a network (self-organization)

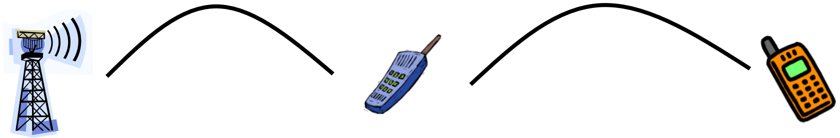
Challenges (among others):

Discovering the presence of neighboring devices	**MAC– no base station can assign transmission resources, must be decided in a distributed fashion**	Finding a route from one participant to another

Limited range of wireless communication

Multi-hop Wireless Networks

- For many scenarios, communication with peers outside immediate communication range is required
  - Direct communication limited because of distance, obstacles
  - Solution: multi-hop network

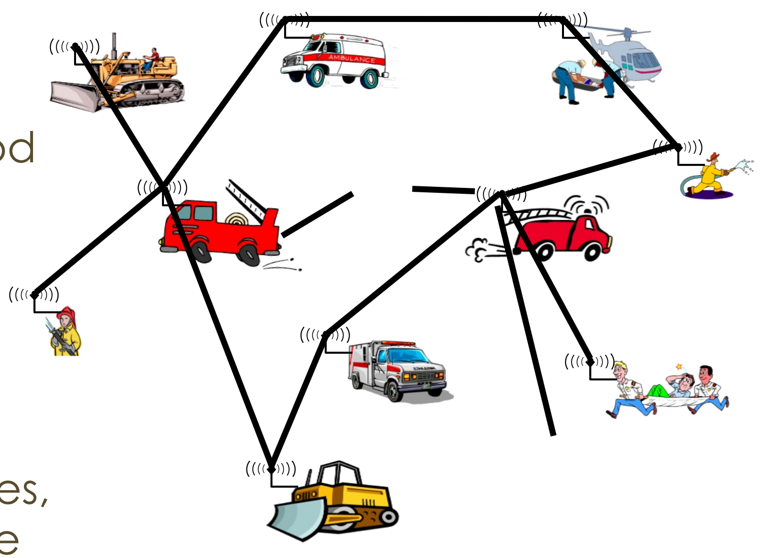


  - Under some circumstances, multi-hopping may help save energy

Mobility

Adaptive Protocols

- In several ad hoc network applications, participants move around
- In cellular network: simply hand over to another base station
- In mobile ad hoc networks (MANET):
  - Mobility changes neighborhood relationship
  - Routes must be reconfigured adaptively
- Complicated by scale
  - When the network size increases, reconfiguration becomes more difficult



Energy-efficient operation

Battery operated devices

Participants in an ad hoc network often draw energy from batteries

Desirable: long lifetime for

- Individual devices
- Network as a whole

Energy-efficient networking protocols

- E.g., use multi-hop routes with low energy consumption (energy/bit)
- How to resolve conflicts between different optimizations?

Mobile ad hoc networks

- A lot of research has been done to address all these challenges
- However a **killer application** for ad hoc networks has never been found
- **Sensor networks** (a special case of ad hoc networks), have had much wider success