Energy Neutral Communications for Pervasive Wireless Networks & IoT

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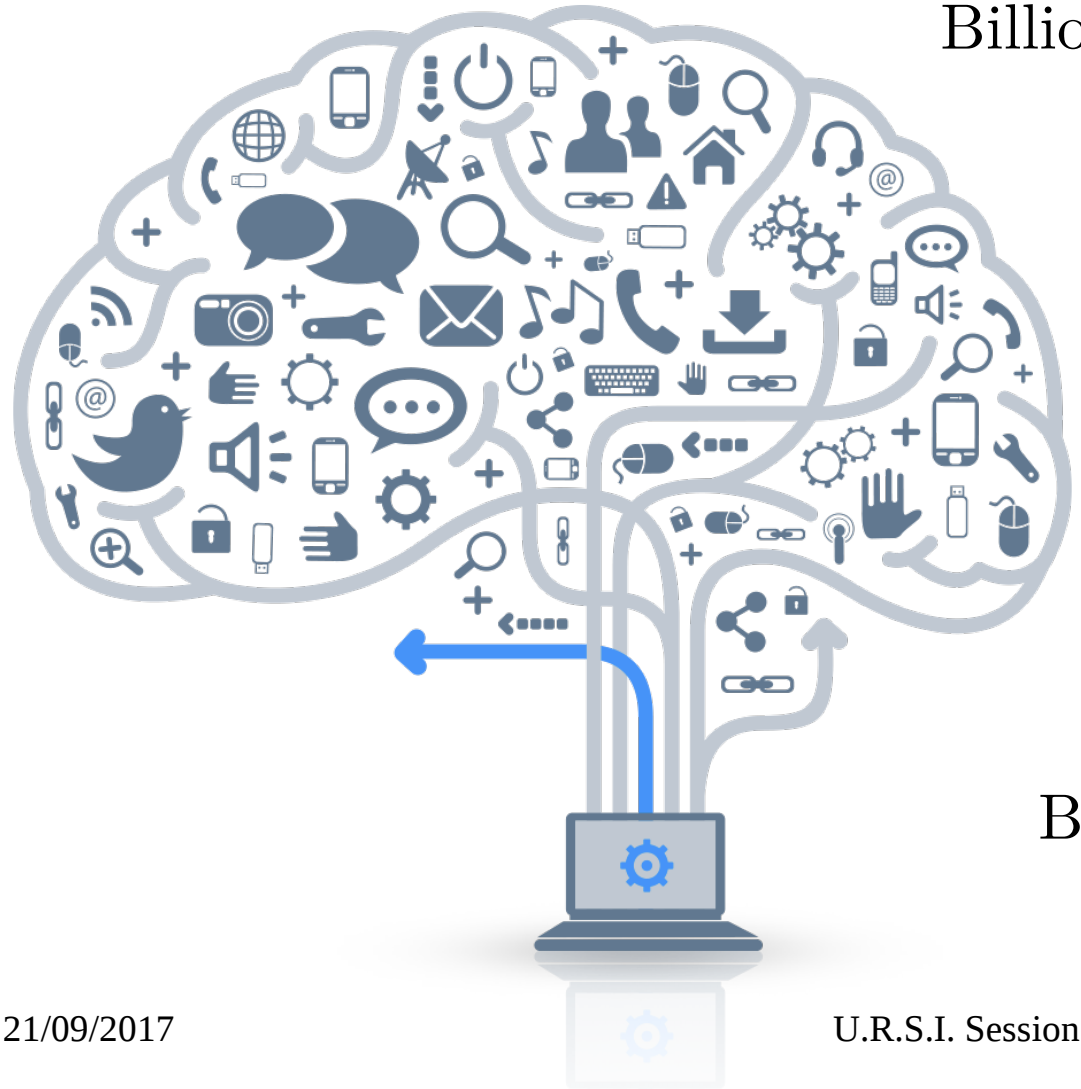
Outline

- Pervasive Wireless Networks & Internet of Things (IoT)
- Energy Neutrality & Radio Frequency Energy Harvesting
- Energy Storage-Aware Communication Strategies
- Research challenges
- Concluding Remarks
- References

Pervasive Wireless Networks & IoT



Billions of Connected Devices

Energy Constraints

Ultra-Low Cost

Pervasive Dislocation

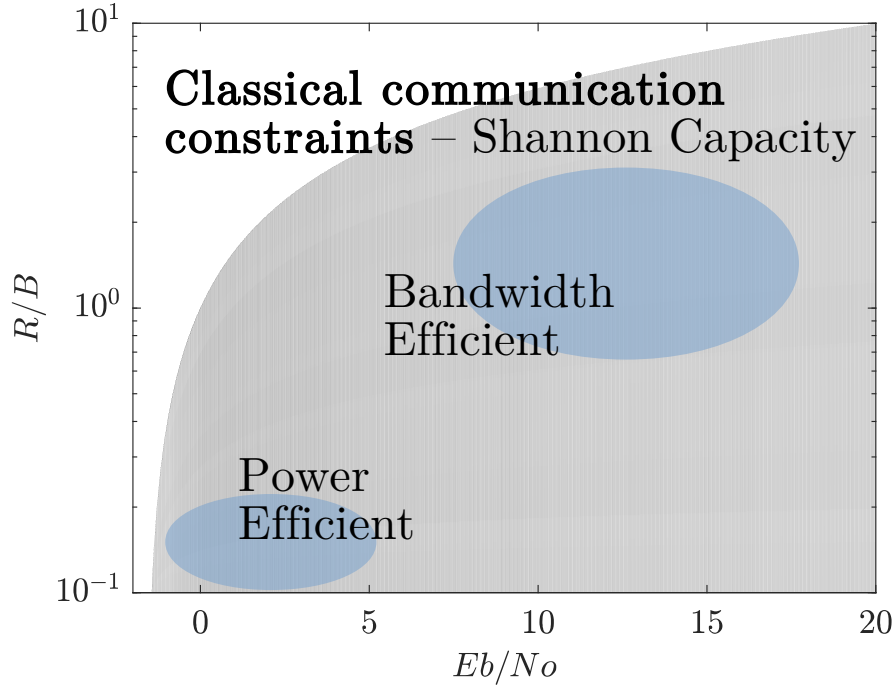
Low Data Rates

Bursty Communication

Pervasive Wireless Networks & IoT

- Radio Frequency Identification (RFID) Systems
- Wireless Body Area Networks (WBANs)
- Monitoring tasks in dangerous fields
- Smart Cities
- Domotics
- Connected Vehicle

Energy Neutrality Paradigm



Energy constrained communication systems

Energy Management

Energy Storage

Wireless Sensors Networks

The energy consumed by the device is always less than or equal to the energy harvested from the environment

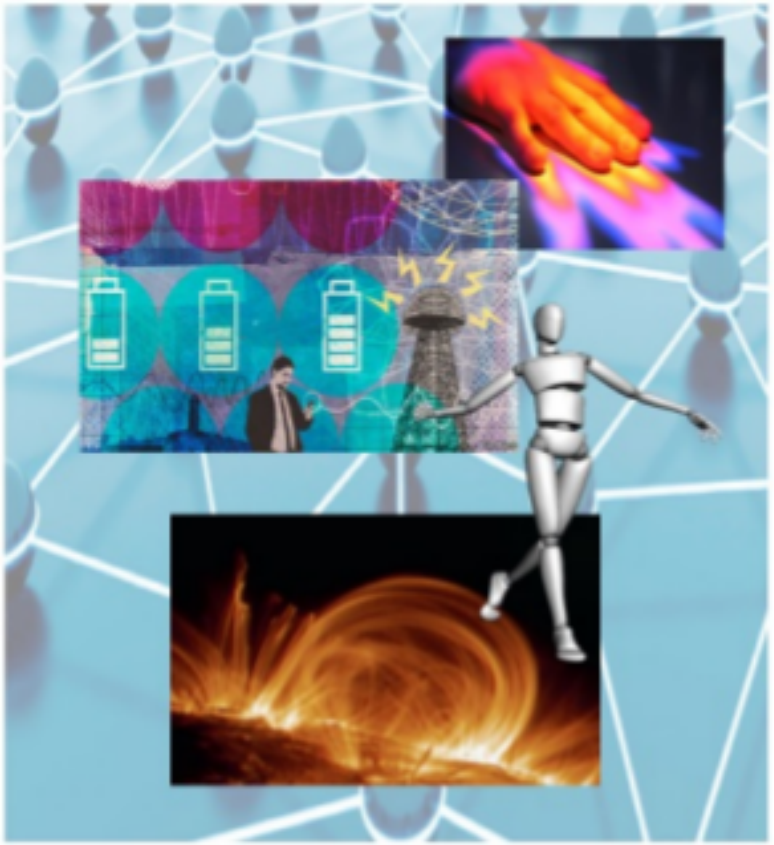
Energy neutral communications

Energy Harvesting

Energy Management

Energy Storage

Energy Neutrality Paradigm – Energy Harvesting



Energy harvesting frees the network from "always-on" energy sources

Energy sources:

- Body Motion
- Body Heat
- Solar Energy
- Wind Energy
- Radio Frequency (RF) Energy
- Etc ...

Energy Neutrality Paradigm – Energy Storage

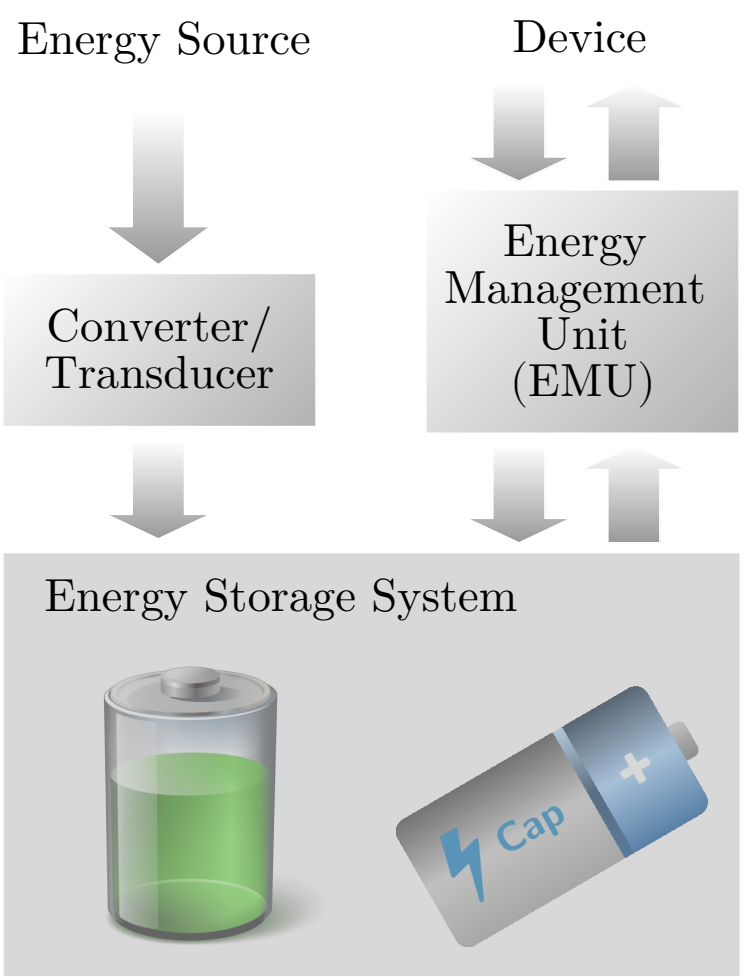
Batteries:

- High charge density
- Low Leakage
- Capacity fading (Aging)

Supercapacitors:

- Low charge density
- High Leakage
- No Capacity fading (no Aging)

Energy Neutrality Paradigm – Energy Management



An Energy Management Unit (EMU) is instrumental for achieving self-sustainability

- Regulates the energy usage
- Controls the energy level trajectory in the storage system:
  - leakage control in supercapacitors
  - aging control in batteries
  - energy acceptance/rejection

RF Energy Harvesting

RF energy harvesting is an appealing solution for pervasive wireless communication systems

- availability
- simplicity
- ease of implementation

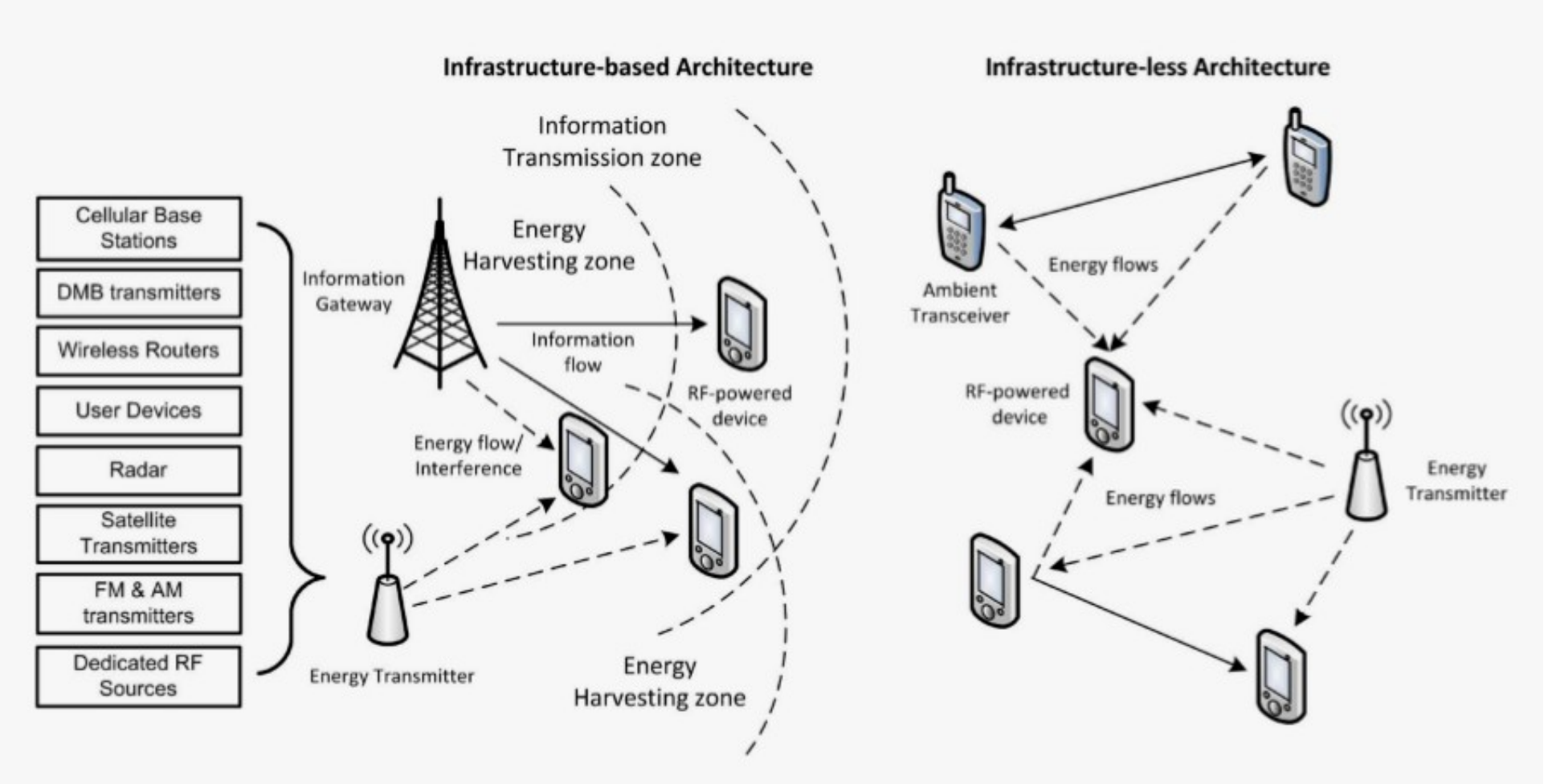
Path-loss

Shadowing

$$P_{rx} = c_0 + 10k_0 \log_{10} d + X + f$$

Multi-path propagation

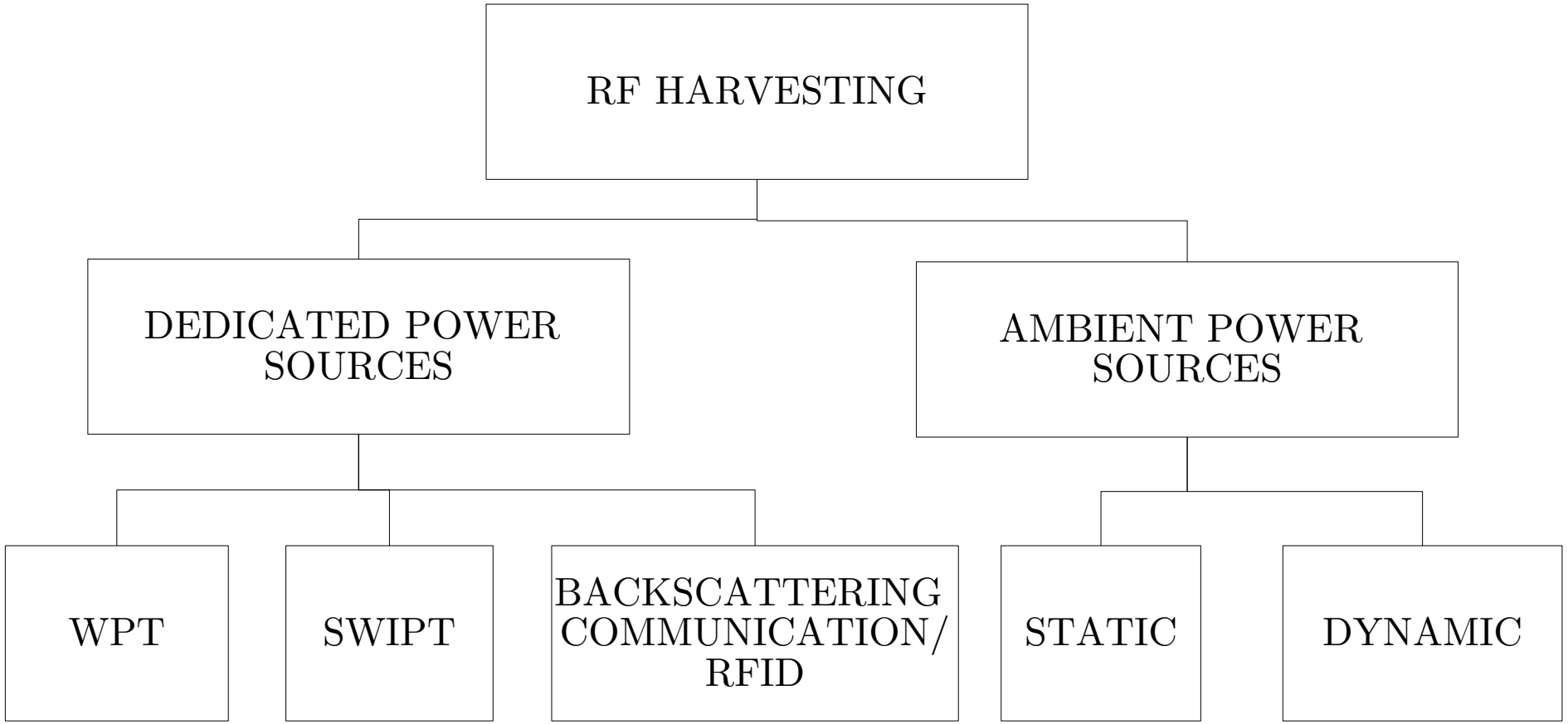
RF Energy Harvesting – Architectures



RF Energy Harvesting – Design Issues

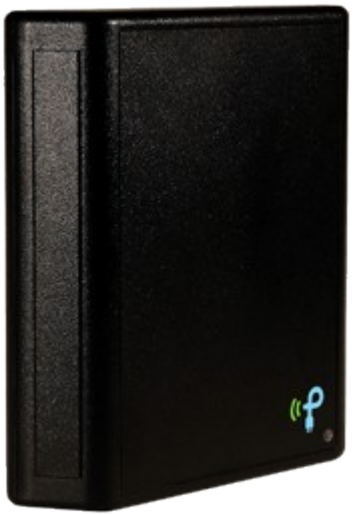
- Circuit Design
  - antennas
  - matching network
  - rectifier
  - receiver architecture
- Multi Antenna Networks
  - energy-Beamforming
- Interference and Cognitive Radio Networks
  - spectrum sensing
  - spectrum access
  - spectrum management
- Communication Protocols
  - MAC protocols
  - routing protocols

RF Energy Harvesting – Classification



Dedicated Power Sources

- highly predictable and stable energy supply
- can operate in the license-free ISM frequency bands



TX91501 POWERCASTER® TRANSMITTER
http://www.powercastco.com
1-3 W RF transmit power @ 915 MHz

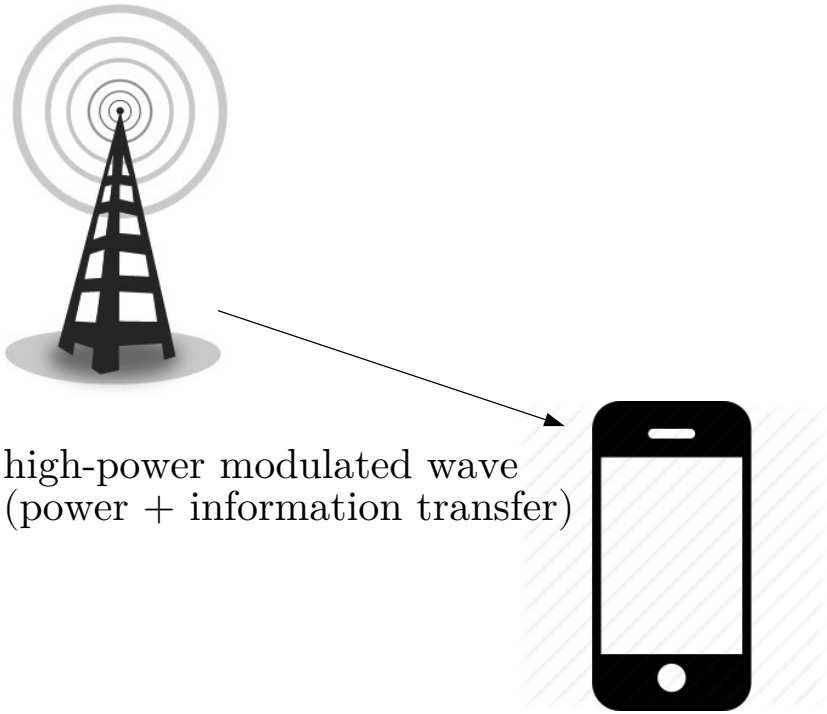
- output power limited by regulations (FCC)

$$P_{tx,MAX} = 4\ W \quad @900MHz$$

$$P_{tx} = 4\ W \quad \rightarrow \quad P_{rx} = 10\ \mu W\ @\ 20\ m$$

- high density deployment → high cost
- mobile dedicated power sources

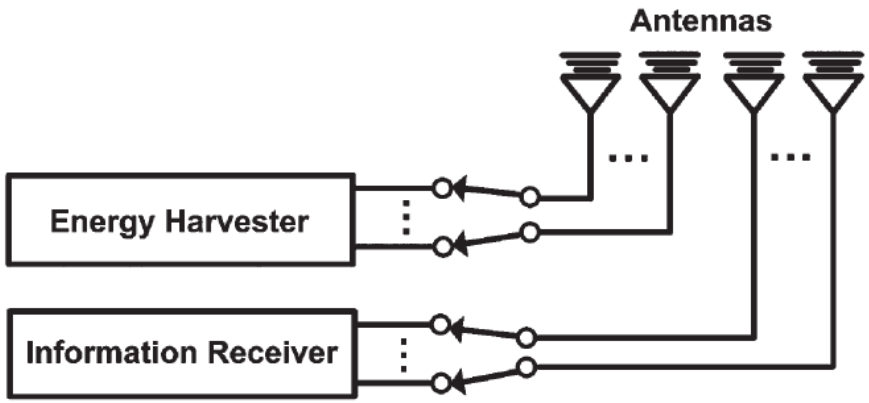
Dedicated power sources – SWIPT

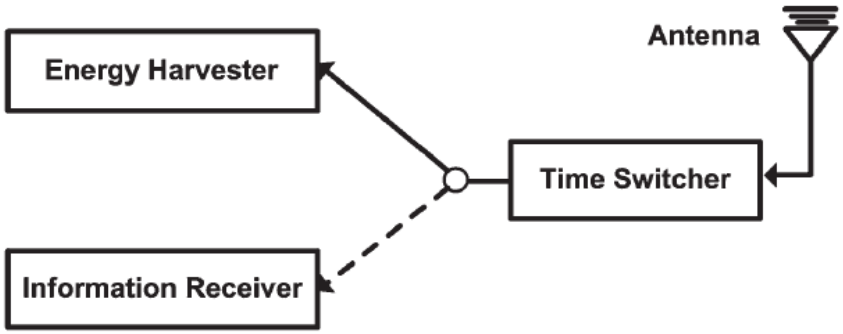


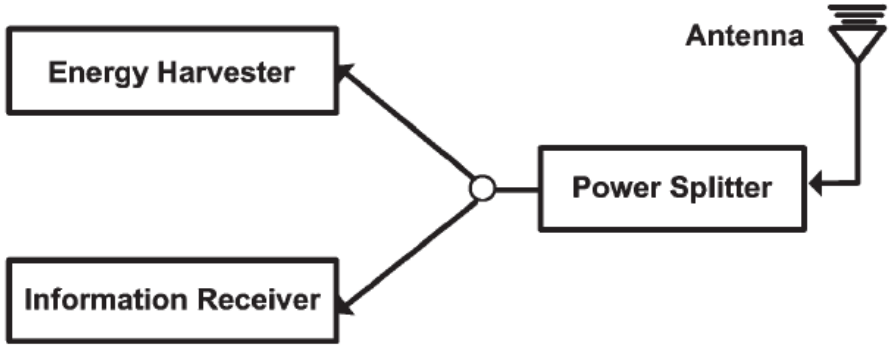
Information can be **jointly transmitted** with energy using the same waveform

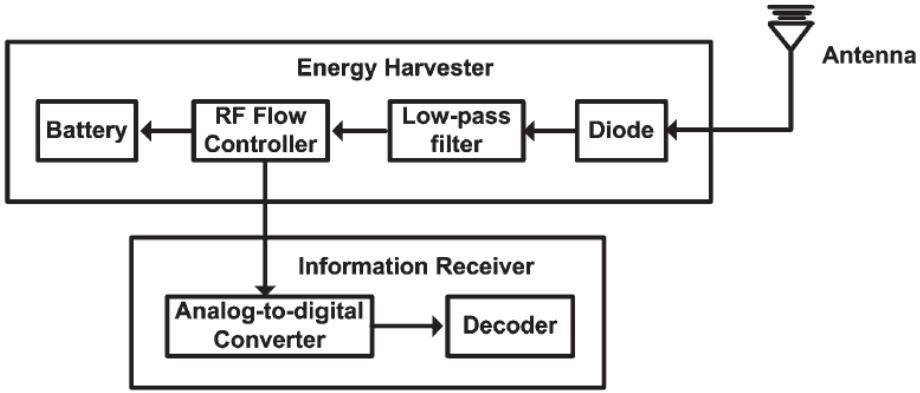
- **Waveform design**:
- optimize **rate-energy tradeoff**
- Bandwidth and hardware constraints
- Mantaining spikiness in multi-path propagation

SWIPT – Receiver Architectures



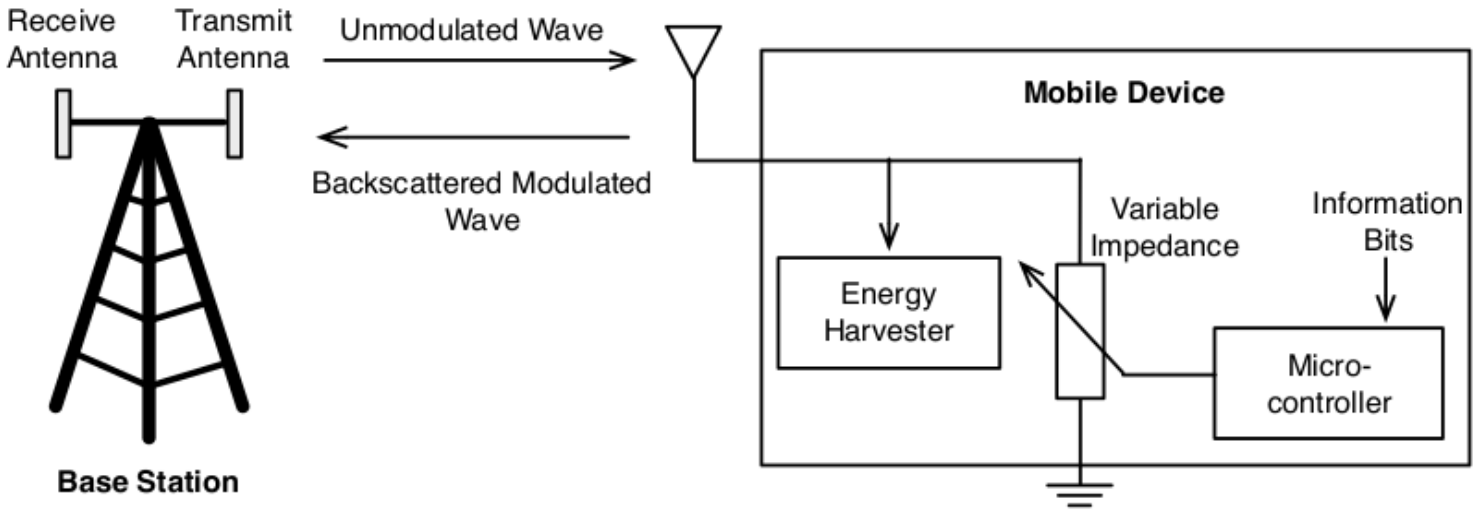






Integrated Receiver Architecture

Dedicated Power Sources – Backscattering Communication



- Allows to power up passive receivers with no active RF components (RFID-like communication)
- Useful basic technique for low-power and low-complexity mobile devices
- Composite fading in the forward and backward links
- Modulation constellation size optimization

Ambient RF Harvesting – Static Sources

- relatively predictable and stable energy supply
- may suffer for **large scale** and **small scale** fluctuations due to service schedule and wireless channel conditions
- small power densities @ different frequency bands

- high antenna gain for all frequency bands
- wide-band circuitry design
- harvesting circuitry efficiency

TV towers

$P_{tx} \sim 10^3\ W$

Base station

$P_{tx} \sim 10\ W$

Ambient RF Harvesting – Dynamic Sources

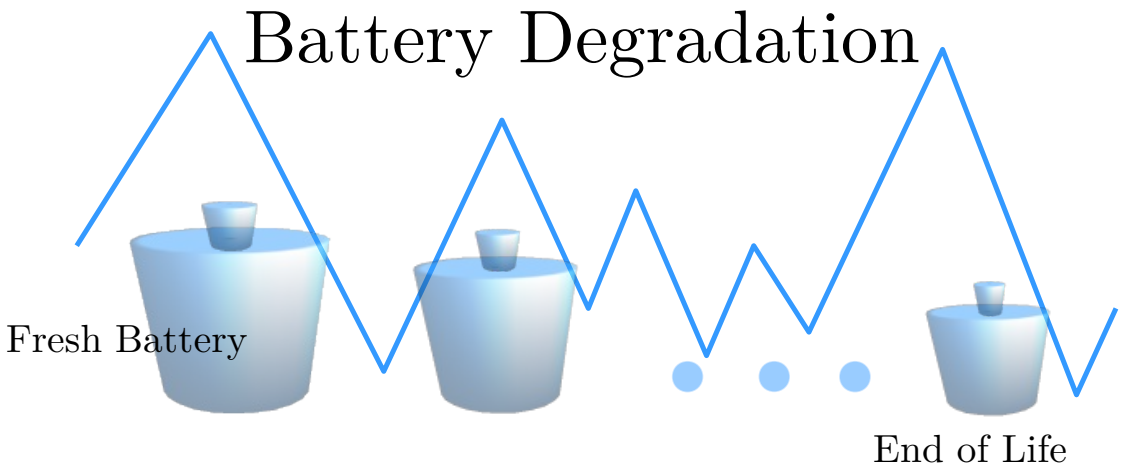
- highly unpredictable
- work periodically (bursty nature) or use time-varying transmit power

- adaptive and intelligent energy harvesting system
- Search for **harvesting opportunities** in a certain frequency band

Wi-Fi access point

$P_{tx} \sim 0.1\ W$

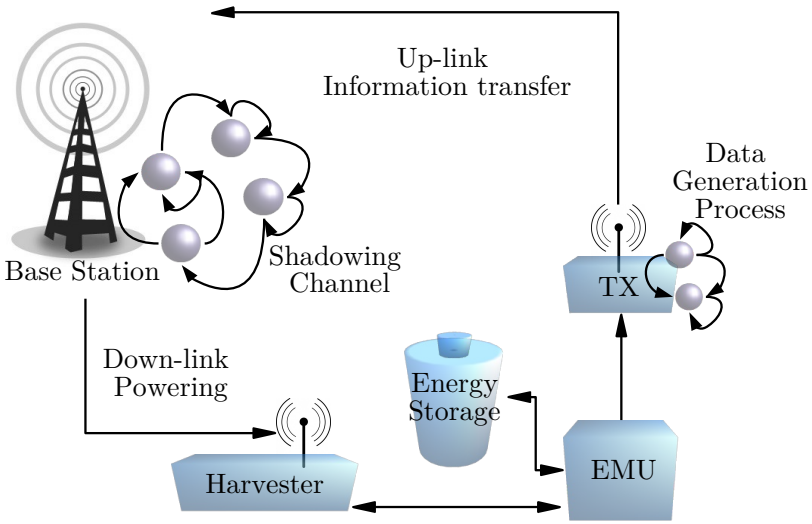
Energy Storage-Aware Communication Strategies



A limitation to the achievement of self-sustainability

- rechargeable batteries are subject to degradation
- battery aging is a core metric for battery-powered wireless systems
- the “capacity fading” process is mainly determined by charging/discharging profiles
- deep charging/discharging cycles result in large battery degradation rates

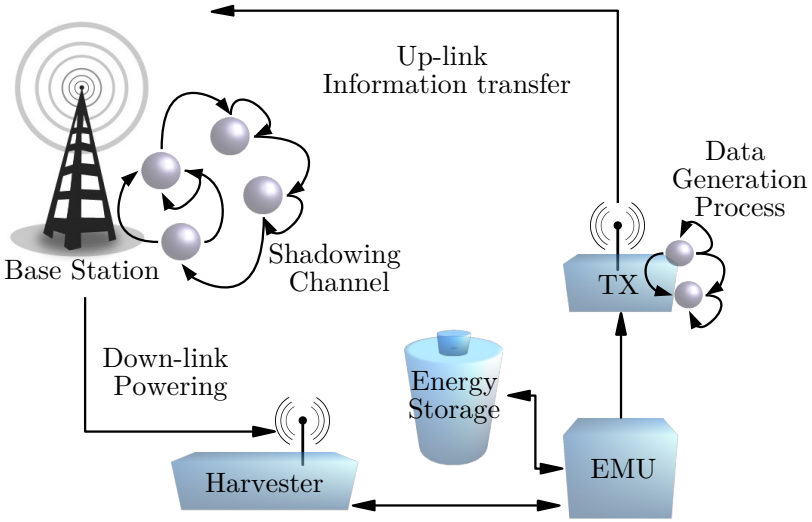
Energy Storage-Aware Communication Strategies



- The stored energy is influenced by energy arrival and consumption processes
- The incoming energy exhibits fluctuations induced by time varying channel or traffic conditions
- Uncontrolled energy trajectories may induce high degradation rate

Development of **battery aging-aware** communication strategies

Aging-Aware Communication Strategies

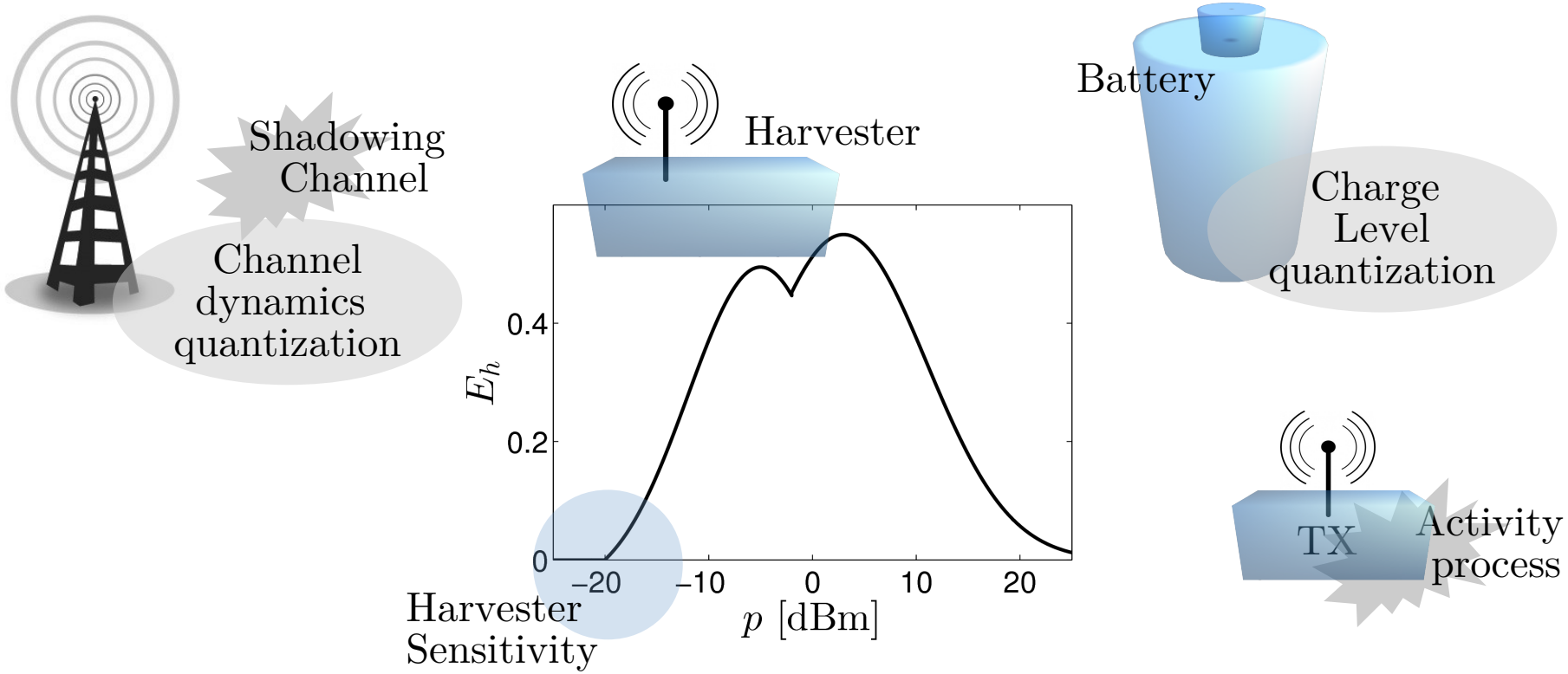


- The composite system state tracks variations in channel gain, battery State of Charge (SoC) and data availability
- Each time, the node selects a transmission power and may reject the incoming energy according to the observed state
- The system state evolves as a controlled Markov process

The battery SoC fluctuations can be controlled introducing a cost function that measure the deviation from a target charge level

Aging-Aware Communication Strategies – System Modeling

$$e(t) = P_n^h \int_0^t \beta[e(\tau)]d\tau$$



From physical behavior to system abstraction

–

“Deep” Cross-Layer approaches

Optimization Framework

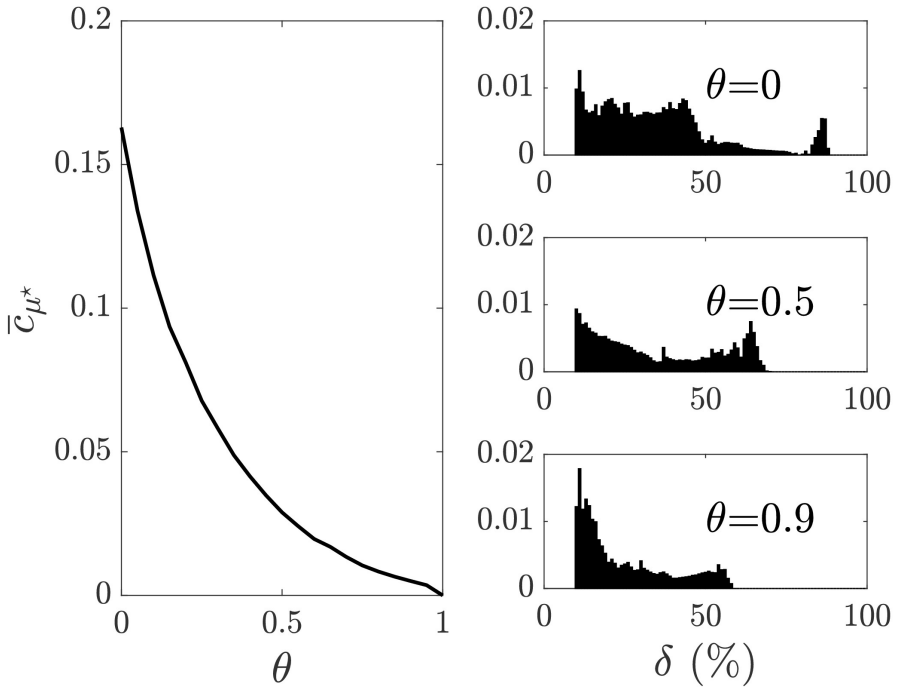
$$\Theta_\mu = (1 - \theta)\overline{\nu}_\mu + \theta(1 - \overline{c}_\mu^\gamma)$$

Weights the importance of throughput maximization VS battery degradation rate minimization

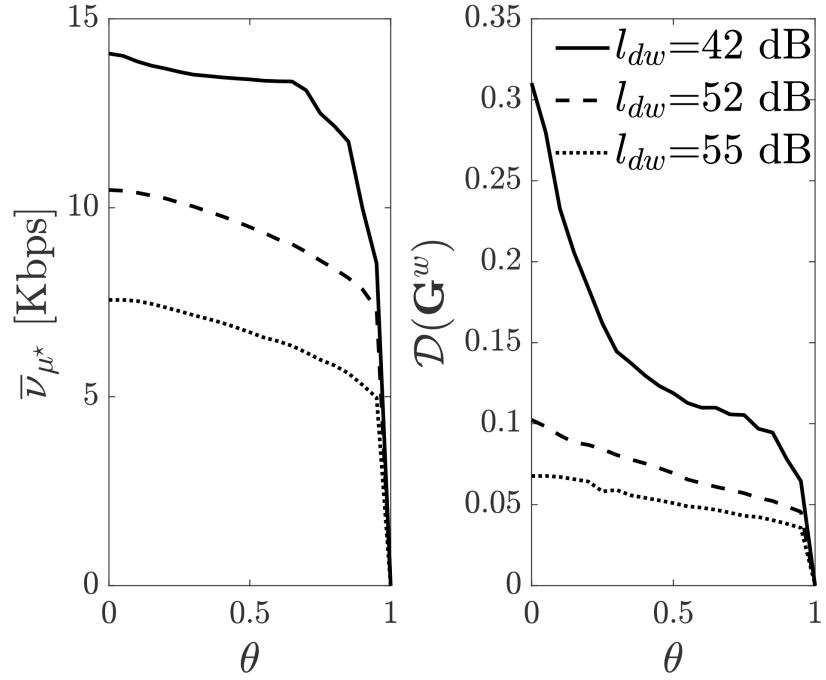
$$\begin{aligned} \underset{\mu}{\text{maximize}} \quad & \Theta_\mu \\ \text{s.t.} \quad & \overline{e}_\mu \leq \gamma \end{aligned}$$

The objective function is a weighted sum of the long-run expected throughput and a cost function that measures the deviation from a charge target point γ.

Optimization Framework

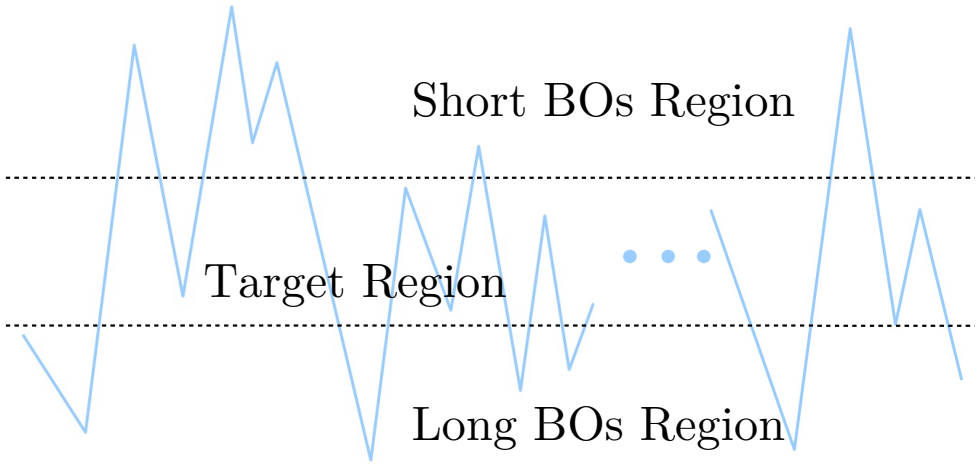


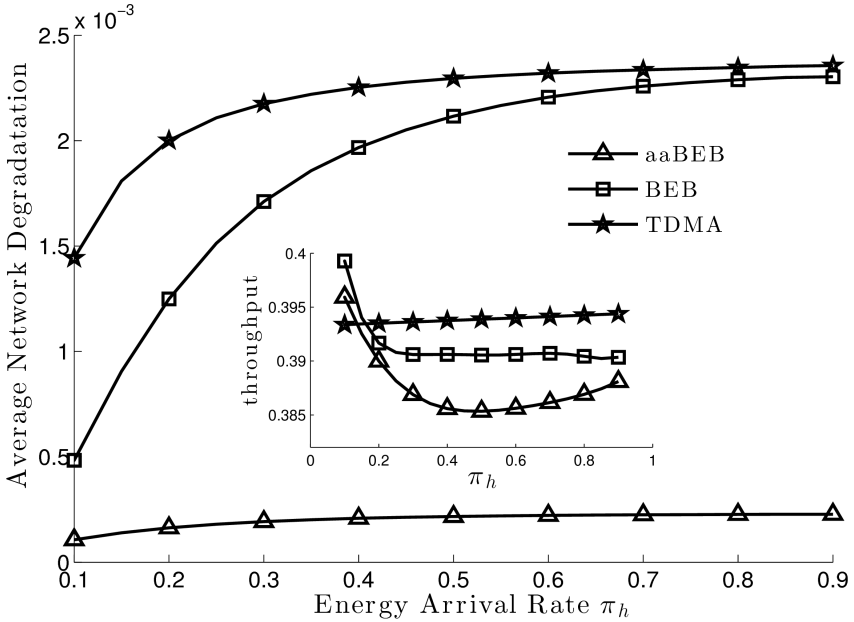
The proposed strategy effectively reduces the occurrence of deep charge/discharge cycles



A trade-off between system throughput and degradation control arises

Aging-Aware MAC protocols





- Adaptive channel access scheme based on SoC
- *High-SoC* region: nodes transmit more aggressively and may reject the incoming energy
- *Low-SoC* region: long backoffs encourage recharge;
- Battery trajectory is "confined" within a *Target-SoC* region.

Research Challenges

- Adaptive communication strategies based on channel state information and energy storage dynamics
- Energy-Beamforming and massive MIMO
- Energy and Information transfer coexistence – Cognitive radio technology
- Cross-Layer Design
- Joint optimization based on propagation, circuitry and communication protocols – Co-simulation
- Health & Safety
- Security

Concluding Remarks

- Energy neutrality paradigm represents a leading concept for the design of next generation pervasive wireless networks and the IoT
- RF energy harvesting represents an enabling technology for energy-autonomous wireless devices
- In this context, communication protocols needs to be storage-aware and a wide range of new research challenges and opportunities arise

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Thank you