Optimization of Energy Harvesting Wireless Sensor Networks
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Summary
We design novel communication protocols for wireless sensor networks with energy harvesting nodes. Our main contribution is a machine-learning based communication protocol for an energy-harvesting sensor node that optimizes the total amount of transmitted data without any prior knowledge regarding the energy harvesting process.

Wireless Sensor Networks (WSNs)
A WSN consists of spatially deployed sensor devices that measure physical or environmental phenomena. Sensor nodes transmit their measurements wirelessly to an access point where the data is stored and/or analysed. Applications: health monitoring, earth monitoring, structure monitoring, agriculture, smart homes and many other industrial applications.

Battery Powered Nodes
- The energy stored in the battery is used to operate the sensor node (e.g., to power up sensing device, microprocessors, ADCs and radio frequency amplifiers).
- Much effort has been put into designing low-power communication protocols to extend the lifetime of wireless sensor nodes limited by the battery capacity.
- However, eventually the battery drains and the sensor node becomes useless until the battery is replaced.

Problems
- Batteries are expensive, and take space,
- Batteries eventually die: In large networks it is expensive to change batteries manually.
- In remote or embedded networks it is difficult to access the nodes (i.e., vibration sensors monitoring embedded in a bridge or environmental monitoring).

Energy Harvesting Powered
- Energy harvesting devices and rechargeable batteries complement WSN by allowing, in principle, perpetual operation of the sensor nodes.
- Most of the available energy sources are limited and sporadic.
- New communication protocols that adapt to the randomness of the energy source, and take the maximum out of the scarce energy available are needed.

Problems
- Increasing the amount of harvested energy usually requires to increasing the cost/size of the harvester.
- Storage units may be inefficient and leak energy.
- Fixed or non-intelligent communication protocols for WSNs may waste the energy harvested at the node.

System Model
A sensor node with an energy harvester is usually modeled by:

- Energy harvesting process
- Data arrival process
- Channel state process

The load block depends on:
- Measured data (e.g., amount of data to be transmitted),
- State of the wireless channel (e.g., the channel is blocked or there is line of sight),
- Communication protocol (e.g., modulation scheme, transmit power, ACK-retransmission protocol),
- Electronics of the wireless transmitter (e.g., RF amplifiers and antenna hardware).

Our Wireless Sensor Node Model
- The load block is modeled by a time-varying wireless channel, data measurements of random size, and the communication protocol implemented in the receiver.
- The transducer and energy storage blocks are modeled by an ideal battery in which the energy arrives in packets at random instants.

Wireless Communication Problem
At the beginning of each TS, the transmitter makes a binary decision: to transmit or to drop the incoming packet, with the objective of maximizing the total amount of transmitted data to destination during its activation time:

\[
\max \sum_{t=0}^{\infty} E_t \left( X_t D_t \right),
\]

subject to:

\[
B_{t+1} = \min \{ B_t - X_t E_t, B_{\text{max}} \};
\]

\[
X_t E_t \leq B_t,
\]

\[
X_t \in (0, 1).
\]

Contribution and Results
We find the best wireless communication protocol based on three different assumptions regarding the knowledge about the energy, data and wireless channel states processes at the transmitter.

Offline Optimization
- Everything is known in advance:
  - the instants and amounts of the energy/data arrivals and channel states are known in advance (non-casual knowledge),
  - the optimization problem can be solved numerically using the Branch and Bound algorithm.

Online Optimization
- Statistical knowledge:
  - Energy/data arrival and channel are modeled as Markov processes,
  - Parameters of this processes are known,
  - Optimization problem is solved using Dynamic Programming.

Machine Learning Optimization
- Transmitter has no knowledge:
  - Parameters of the energy/data and channel process are not known,
  - We use Q-learning to find the optimal transmission policy,
  - Q-learning learns iteratively, the statistics of the underlying Markov process and, after some learning iterations, converges to the optimal policy of the online optimization.

The effect of the Learning Time

The Effect of the Harvesting Rate

Conclusions
- Energy harvesting WSNs require communication protocols that can adapt to the scarce and stochastic energy source,
- Energy harvesting process is stochastic: what is known about this process is critical,
- Machine learning optimization is important for practical applications because it optimizes the communication protocols without information regarding the energy source,
- We have shown that Q-learning quickly learns the system parameters and approaches the optimal optimization upperbound.

The Effect of the Harvesting Rate