On Energy-Aware Communication and Control Co-design in Wireless Networked Control Systems

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Introduction

Motivation

- **Energy is a key issue** in Wireless Networked Control Systems (NCS).
- Up to **80%** of the total power is **consumed by the radio unit**.
- **Reliability** and **latency** can be balanced to **save energy** and to meet **control requirements**.

Goal of this work

Literature survey to identify **how energy can be saved** in Wireless Networked Control Systems.

Approach

Focus on energy-aware communication and control.
Use of a four layers architecture, the NCS stack:

- **Physical layer** – Radio modulation,
- **Data Link (MAC) layer** – Medium sharing,
- **Network (routing) layer** – Data routing,
- **Application layer** – Source coding and control.

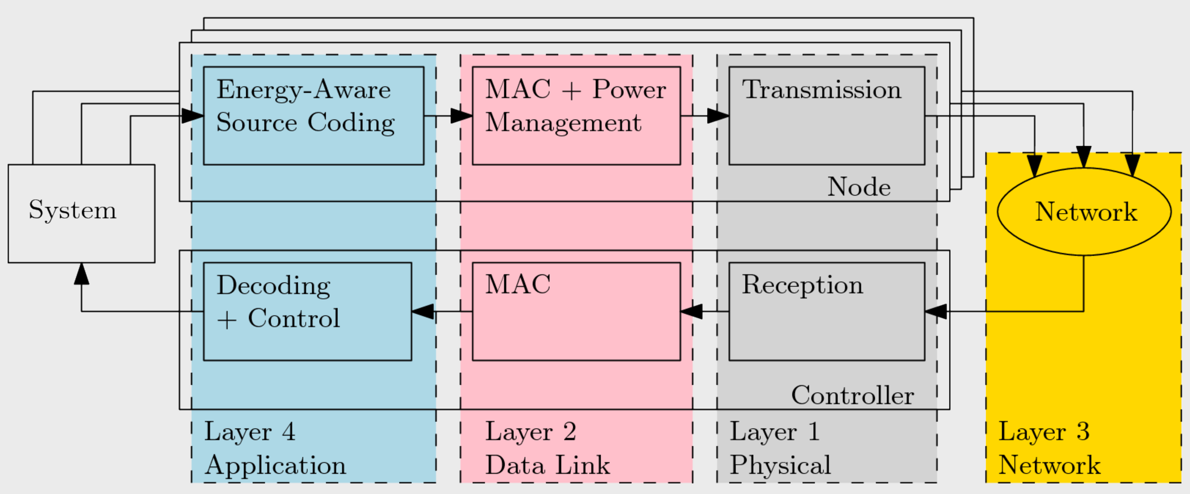

Fig. 1 – *Four layers of the NCS stack on a control block diagram of a NCS*

Physical layer

Power control [1,2,3]

Change transmission power to improve communication quality.

Objective
- Increase reliability
- Limit interferences
- Face a varying channel

Limitation
Extra communication for the control may cost more than the saved energy

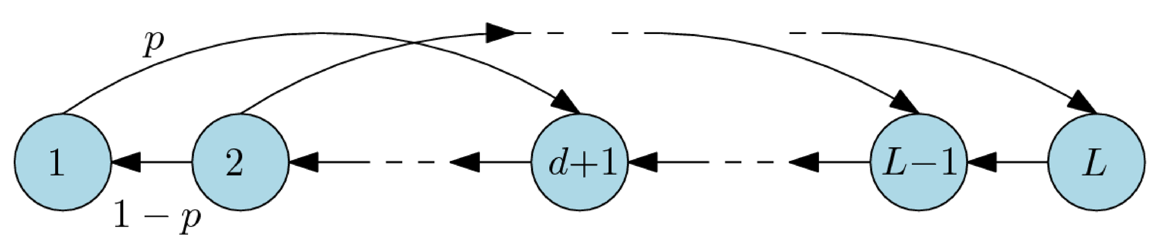

Fig. 2 – *Markov chain model of the MIAD power control algorithm from [1]*

Bit rate control [4,5]

Switch modulation characteristics.

Objective
- Decrease error rate
- Same energy consumption

Limitation
- Synchronization of transmitter and receiver
- Increase latency

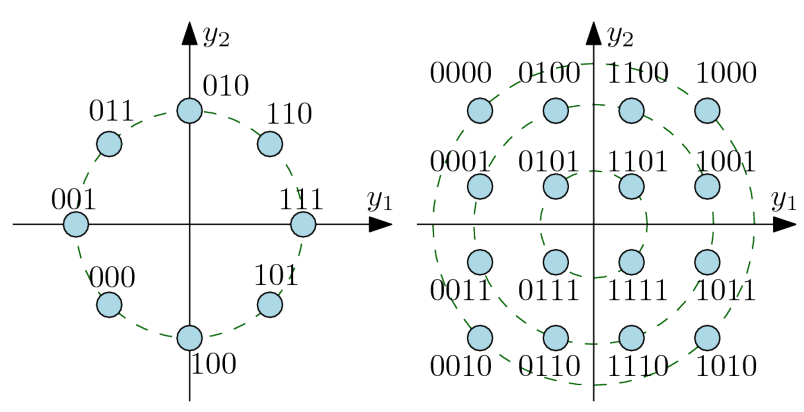

Fig. 3 – *Modulation constellations in the complex plane for 8-PSK (left) and 16-QAM (right) schemes*

Data Link (MAC) layer

Activity mode management [6]

Activity mode is a state of activity of the node (ON, Idle, OFF) where some components are turned off.

Objective
- Trade-off energy/awareness
- Avoid idle-listening state

Limitation
- TDMA scheduling not scalable
- Control is not trivial

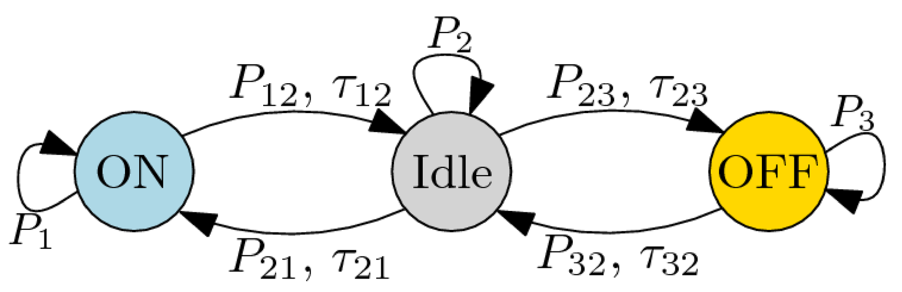

Fig. 4 – *Three activity modes switching automata, including power costs and time transition costs*

MAC protocol tuning [7,8,9,10]

Adapts parameters of the protocol (*e.g.* slot length, sleep and listening times).

Objective
- Balance reliability and latency to meet control requirements
- Minimize energy consumption

Limitation
No existing protocol dedicated to NCS

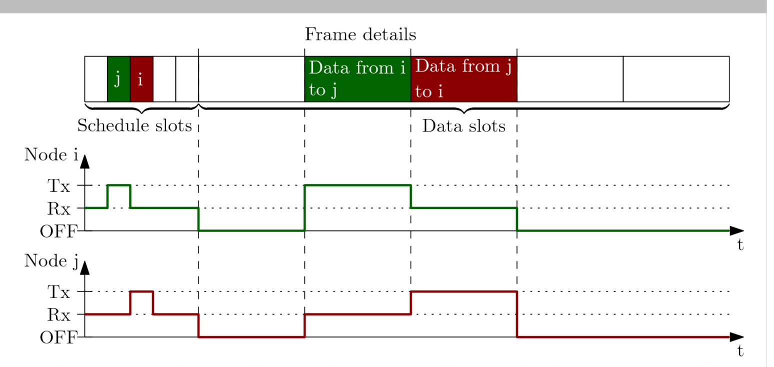

Fig. 5 – *Time view of TDMA-based sleeping policy*

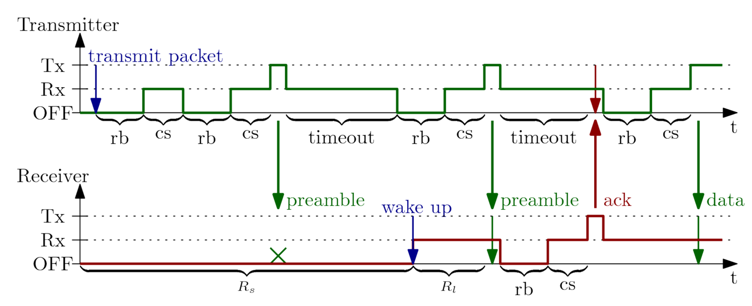

Fig. 6 – *Time view of CSMA-based sleeping policy with preamble messages*

Network layer

Energy efficient routing [11,12]

Efficiency metric is the network life-time.

Objective
- Choose the less costly path
- Ensure quality of service

Limitation
- No existing protocol dedicated to NCS
- No consideration about the application

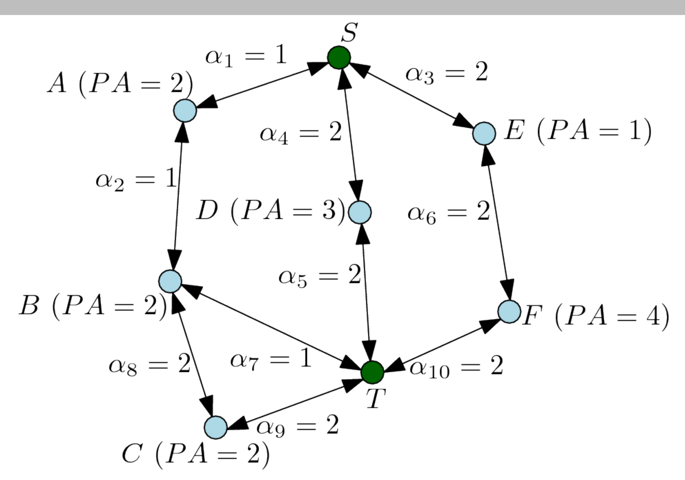

Fig. 7 – *Network topology from [12] illustrating several routing decisions*

Network coding [13]

Nodes perform some processes on the data before relaying it.

Objective
- Limit the amount of data in the network
- Recover from network failures

Limitation
- Not common in NCS
- Strongly depends on data type and application

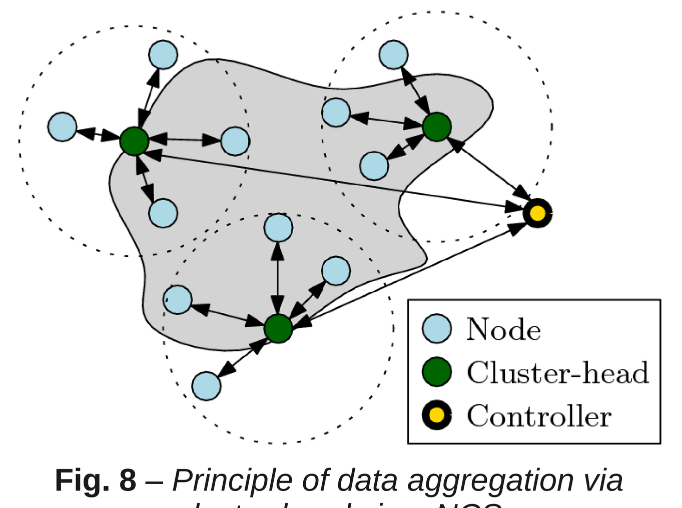

Fig. 8 – *Principle of data aggregation via cluster-heads in a NCS*

Application layer – Quantization and source coding

Quantization and rate constraints [14,15]

Quantization from analog phenomena to digital data introduces loss. Traffic is bounded in a network.

Problem
- Stability can be lost in practice
- Quantization and rate constraints cannot be ignored in the design

Limitation
Trade-off between data rate and control performances

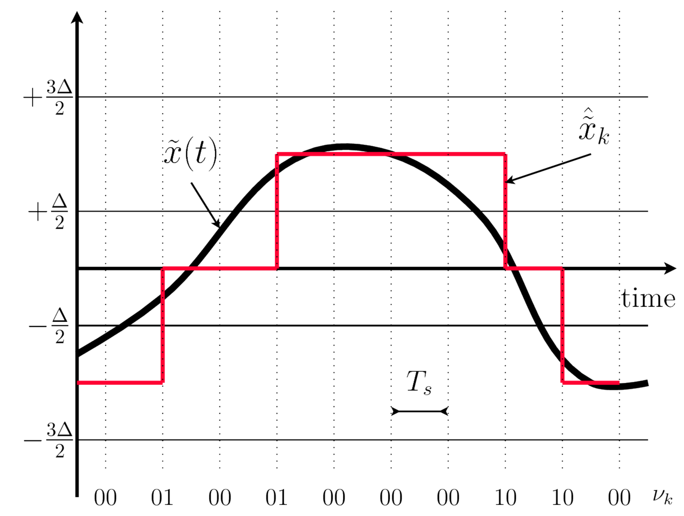

Fig. 9 – *Time view of 3-levels coding scheme [15], embedding quantization*

Source coding [15,16,17]

Compress the data measured by the sensor.

Objective
Limit the amount of data and/or the occurence of communication

Limitation
Conflict between source coding and channel or network coding

Input	Period	Output
01	Ts	000
10	Ts	001
00 01	2Ts	010
00 10	2Ts	011
00 00 01	3Ts	100
00 00 10	3Ts	101
00 00 00	3Ts	110
unused	-	111

Table 1 – *Run-Length Encoding, from [15]. Ts is the sampling time.*

Conclusion and future directions

Conclusion

Cross-layer design is imperative to satisfy application requirements with limited energy resources.

Such designs already exist (RFID wake-up hardware, Network Aware Source Coding, Distributed Source Coding, battery aware MAC protocols).

But almost **no work considers the four layers** in the NCS stack. There is a **need for a protocol dedicated to NCS**.

Future directions

Management of activity modes in the framework of NCS:

- *Focus:* adapt the activity modes to **meet the control requirements** (trade-off between energy and performances),
- *Goal:* avoid **waste of energy** caused by **idle-listening** state.

Application layer – Asynchronous control

Split sensing and control [18,19,20]

The sensor is responsible for deciding when to send measurements to ensure stability, minimizing energy. The controller must be designed to tackle aperiodic sampling arrivals.

Objective
- Limit data traffic
- Aperiodic control

Limitation
Standard methodologies do not consider asynchrony nor intermittence

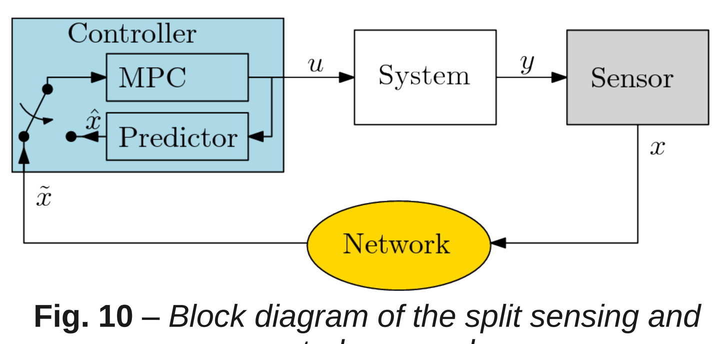

Fig. 10 – *Block diagram of the split sensing and control approach*

Cooperative sensing and control [21,22]

The sensor processes the data and sends parameters. The controller generates control inputs using pre-constrained profiles depending on the sensor's parameters.

Objective
- Share control burden
- Limit further data traffic

Limitation
- Few existing works
- Open issues remain (multiple sensors, real channel influence)

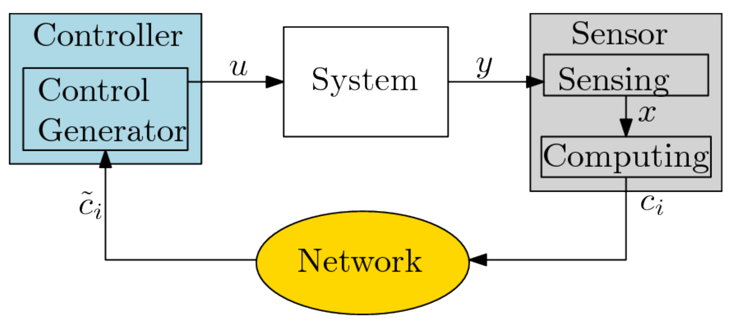

Fig. 11 – *Block diagram of the cooperative sensing and control approach*

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