Energy-Aware Computing Systems

Energiebewusste Rechensysteme

VI. Cyber-Physical Systems

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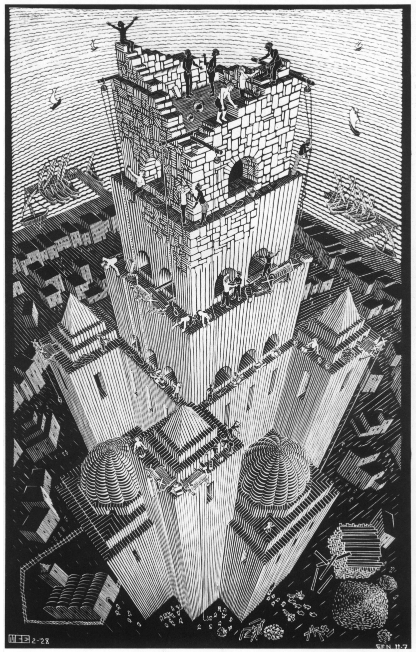
Agenda

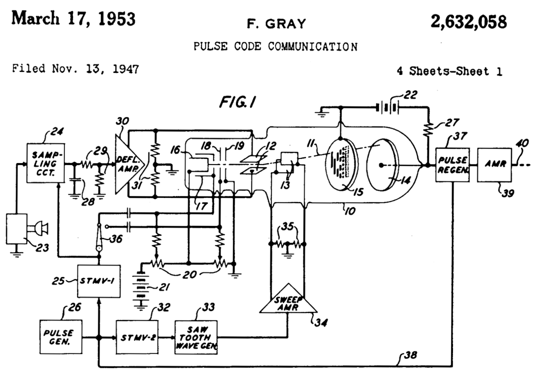
Preface: Pluralism of Systems

- broader perspective
  - introversive perspectives at the level of **individual systems**
  - holistic perspective at a higher level of **compound systems**
- dependence and cooperation
  - individual systems **specialize in specific tasks** of the compound system
  - cooperation between individual systems to form a **(even) greater „whole"**



Abstract Concept: Cyber-Physical Systems

- **cyber**-physical systems
  - digital operations that interface with the physical world
  - **computation**
    - sensing of data
      → pre-processing
    - processing of data
  - **communication**
    - transformation of data
    - data transmission
    - uni- and bidirectional
  - **control**
    - control loops
    - several levels of abstraction (i.e., cruise control, machine control, injection control)

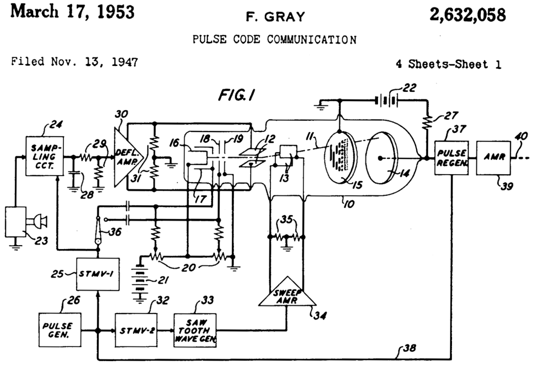


Abstract Concept: Cyber-Physical Systems

- cyber-**physical** systems
  - physical operations that interface with the digital world
  - **natural** systems
    - hydrologic cycle
    - solar system
  - **human-made** systems
    - mechanical systems
      ↪ mechanical energy
    - optical systems
      ↪ light energy
    - electrical systems
      ↪ electrical energy

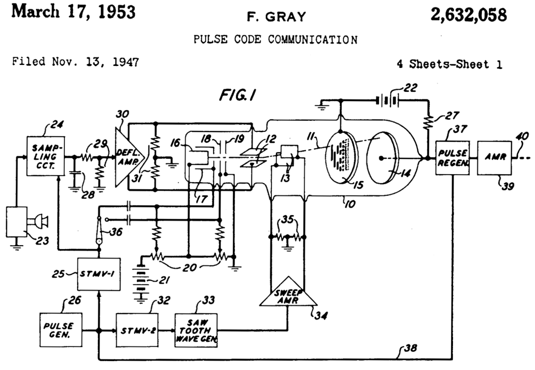
    ⇓

    tools, instruments etc.



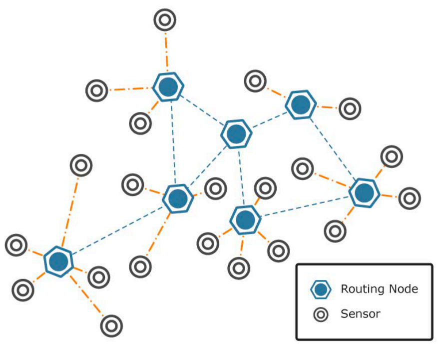
Abstract Concept: Cyber-Physical Systems

- **cyber-physical** systems
  - systems that interlock **cyber** systems with **physical** systems
  - integrate systems
    - combine physical systems and processes
    - incorporate with networked computing infrastructure
  - enhance functionalities
    - augment features of physical systems
    - new capabilities due to computing and communications
  - broad range
    - deeply embedded systems (i.e., pace maker)
    - large scale industry facilities (i.e., power plant)



Dynamic Structures

- composition of system is dynamic
- variable system structure depends on **time and location**
  - spontaneous joining and resignation of devices
  - overload and breakdown detection
- heterogeneous **network links**
  - wired and wireless links with variable channel conditions
    → propagation, delay loss
  - impact of (physical) system components on link quality

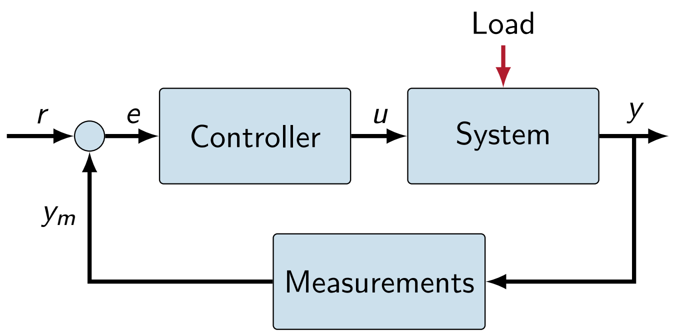


Nunes et al.

Control Theory and Practice

Recap

- measurement-based analysis with a feedback control system



- controller operates system: **closed control loop** ⇒ feedback control
- **control:** control variable u
  measure: process variable y

Cyber-Physical System Control

- cyber-physical control systems: use hardware „in a loop"
  - information on physical environment ← sensors
  - sample-and-hold-circuits and analog-to-digital (A/D) converters: digital representation of physical aspects
  - compute and control → actuators

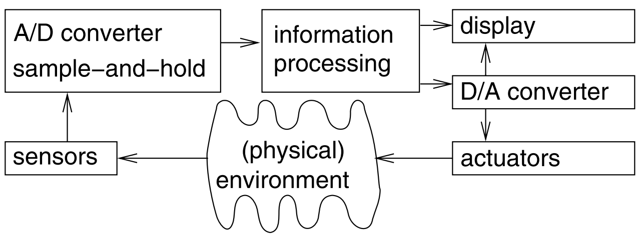


Figure 3.2. Hardware in the loop

P. Marwedel: Embedded System Design [3]

Nested Cyber-Physical System

- nested controls that operate jointly in a broader context
  - control: actuator controls physical plant
  - sense/feedback: physical interface towards sensors

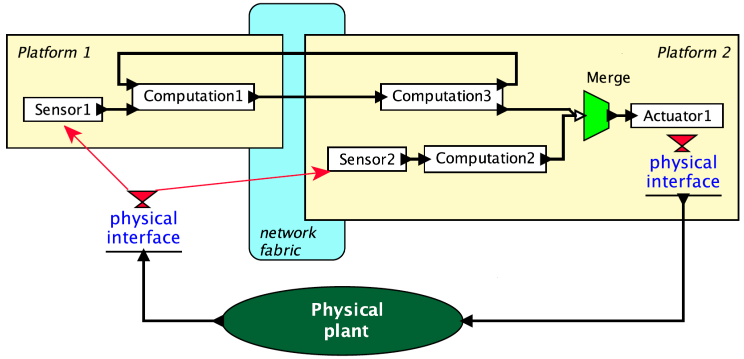


Figure 1.1: Example structure of a cyber-physical system.

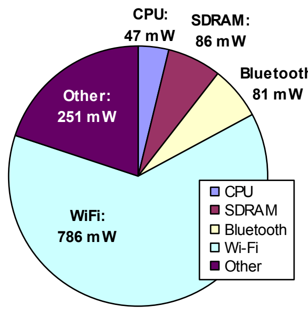
Lee & Sanjit: Introduction to Embedded Systems [2]

Resource Demand

- **energy** as a basic **operating resource** of embedded systems that constitute main parts of a cyber-physical system
- computation
  - general purpose CPUs
  - (re{configur,programm}able) application-specific integrated circuits
- communication
  - transmission power for (wireless) network links → **tail state analysis**
  - (periodic) duty cycles
- control
  - actuators
  - cross-layer operations → **cyber-physical networking**

Network Links and Tail States

- network communication contributes significant shares to the overall energy demand
  - state-dependent power demand
  - activity tracking across different subsystems (i.e., application logic, network stack, hardware)



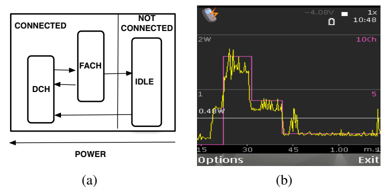
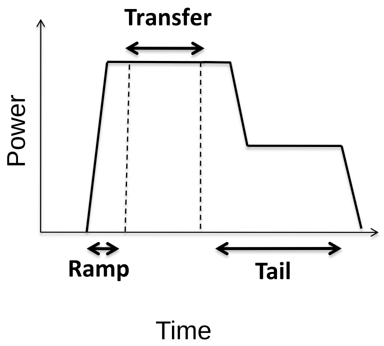


Figure 1: : (a) The radio resource control state machine for 3GPP networks consisting of three states: IDLE, DCH and FACH (b) Instantaneous power measurements for an example transfer over 3G showing the transition time between high to low power state

Balasubramanian et al. [1]

Working with Tail States: TailEnder

- tracking of tail states to schedule the execution of requests (e.g., packet transmission)



TailEnder scheduler (t, r_i, d_i, a_i):

1. Let Δ be the last deadline when a packet was transmitted (initialized to $-\infty$ and reset in Step 3(c)).
2. If $(t < d_i)$
   (a) if $(\Delta + \rho \cdot T < a_i)$, transmit.
   (b) else add the request to queue Q.
3. If $(t == d_i)$
   (a) Transmit r_i
   (b) Transmit all requests in Q and set $Q = null$
   (c) Set $\Delta = d_i$

Figure 10: The TailEnder algorithm decides at time instant t whether to transmit a request r_i with arrival time a_i and deadline d_i. The parameter ρ is set to 0.62 in our implementation.

Control Mechanisms in Cyber-Physical Systems

- Ptides: A Deterministic CPS Modeling Paradigm (UC Berkeley)
- system modeling assumptions
  - synchronized clocks with known bound on synchronization error
  - communication channels with known bounds on latency
  - computations impacting the physical world have known bounds
- Interlude: Latency and Resilience-aware Networking (LARN)
  - pragmatic approach for designing low-latency cyber-physical systems
  - suitable for control applications in cyber-physical systems
  - X-Lap: tool-based cross-layer analysis method

Cyber-Physical Networking

LARN: Context

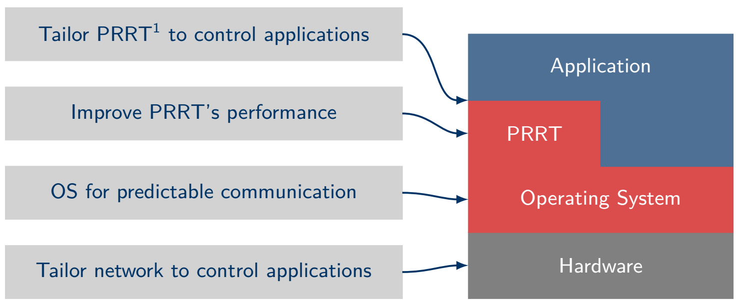
LARN

- DFG Priority Programme Cyber-Physical Networking (SPP 1914)
  - focus: **predictable** latency and resilience in cyber-physical networks
  - interdisciplinary: computer science, electrical and control engineering
  - 11 individual projects, funding for six years (planned)
  - `http://www.spp1914.de`
- Target scenario: control applications
  - system control in industrial facilities (e.g. BMW etc.)
  - low-latency control loops for medical applications
  - wireless sensors and network transports
- Latency- and Resilience-Aware Networking (LARN)
  - operating system: System Software Group at FAU Erlangen-Nürnberg
  - transport protocol: Telecommunications Lab at Saarland University
  - `http://larn.systems`

Cyber-Physical Networking

LARN: Overview and Project Goals

LARN

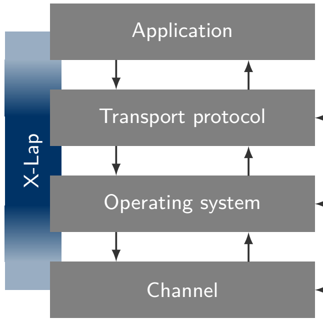


[1] predictably reliable real-time transport

X-Lap | Introduction

LARN

Motivation: identify root causes for latency and jitter in transport protocol.



- packet creation
- error correction
- ...

- inter-process communication
- resource management
- ...

- transmission delay
- propagation delay
- ...

X-Lap | Architecture

LARN

online analysis at run-time

- timestamping functions
- ⇒ timestamps
- C implementation

offline analysis

- data analysis
- ⇒ latency and jitter
- Python implementation

- trace every packet
- embedded into transport protocol code

X-Lap | Architecture

LARN

online analysis at run-time

- timestamping functions
- ⇒ timestamps
- C implementation

offline analysis

- data analysis
- ⇒ latency and jitter
- Python implementation

→ `*.csv` →

- collect traces
- combine trace data

X-Lap | Architecture

LARN

online analysis at run-time

- timestamping functions
- ⇒ timestamps
- C implementation

offline analysis

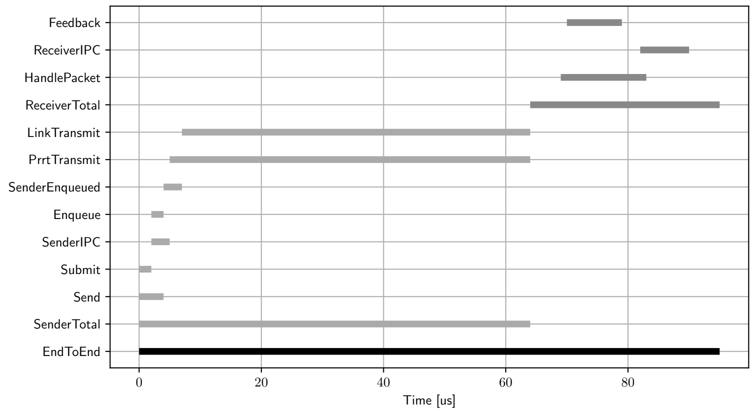
- data analysis
- ⇒ latency and jitter
- Python implementation

→ `*.csv` →

- single-packet traces
- jitter amongst packets
- outlier analysis
- correlation analysis

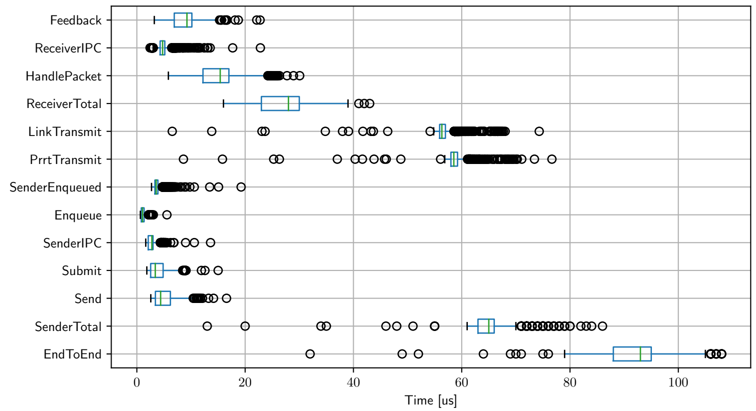
LARN

X-Lap | Packet Trace



LARN

X-Lap | Trace Jitter

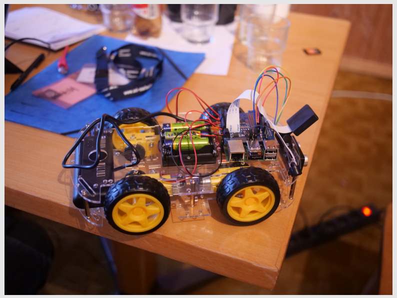


LARN

Evaluation Platform

Autonomous Driving Car using RNAs

- Raspberry Pi 3 (w/ 802.11n)
- camera CCD
- ultrasonic sensors
- chassis and motor



Autonomous Driving (line following)

- camera captures line and transmits video via PRRT
- edge controller extracts line, determines angle, and determines control outputs
- target speed transmitted back and applied on the motor

edge-to-car communication

Platooning (car following)

- first car follows line
- second car follows and keeps distance to first car

car-to-car communication

LARN

Results and Outlook

- Improve cross-cutting system properties
  - focus on **energy efficiency**: impact of runtime adaptations
  - non-functional properties of networked systems (i.e. RNAs)
  - system configuration of individual RNAs (i.e. local scope)

    ⇳

    energy demand/latency of overall system (i.e. global scope)

- Identification and proactive avoidance of bottlenecks within system stack
  - build „strain reliefs" to **avoid emergence of bottlenecks**
  - proactively exploit a priori knowledge (i.e. system design)
  - cooperative system-analysis (i.e. ahead of runtime + at runtime)

Cyber-Physical Networking

Results and Outlook

CCNC 2019 Workshop

IEEE Workshop on Cyber-Physical Networking (CPN'19), January 2019, Las Vegas

http://cpn2019.spp1914.de/

Publications

- Reif, Stefan; Schmidt, Andreas; Hönig, Timo; Herfet, Thorsten; Schröder-Preikschat, Wolfgang: **"Differential Energy-Efficiency and Timing Analysis for Real-Time Networks"**, 16th International Workshop on Real-Time Networks (ECRTS RTN), Barcelona, Spain, July 2018
- Reif, Stefan; Hönig, Timo; Schröder-Preikschat, Wolfgang: **"In the Heat of Conflict: On the Synchronisation of Critical Sections"**, IEEE International Symposium on Real-Time Distributed Computing (ISORC), Toronto, Canada, May 2017
- Reif, Stefan; Schmidt, Andreas; Hönig, Timo; Herfet, Thorsten; Schröder-Preikschat, Wolfgang: **"X-Lap: A Systems Approach for Cross-Layer Profiling and Latency Analysis for Cyber-Physical Networks"**, 15th International Workshop on Real-Time Networks (ECRTS RTN), Dubrovnic, Croatia, June 2017

Considerations and Caveats

- cyber-physical systems
  - complex digital systems that interfere with physical world
  - dynamic system structure
  - embedded systems sense and actuate in a networked compound
- energy demand of cyber-physical systems
  - computation
  - communication → consideration and active exploitation of tail states
  - control → cross-layer analysis

Subject Matter

- cyber-physical systems are a corner stone for large-scale control systems that connect **digital** with **physical components**
- single embedded systems are joining in a dynamic, networked compound to build an **(even) greater „whole"**
- **energy demand** considerations are pervasive → influence on other non-functional properties of the cyber-physical systems (i.e., reliability, resilience)
- reading list for Lecture 7:
  - Andrew Krioukov et al.
    NapSAC: Design and Implementation of a Power-Proportional Web Cluster
    Proceedings of the Workshop on Green Networking (GreenNet'10), 2010.

Reference List I

[1] Balasubramanian, N. ; Balasubramanian, A. ; Venkataramani, A. :
Energy Consumption in Mobile Phones: A Measurement Study and Implications for Network Applications.
In: *Proceedings of the SIGCOMM Conference on Internet Measurement (IMC'09)*, 2009 (IMC '09), S. 280–293

[2] Lee, E. A. ; Seshia, S. A.:
Introduction to Embedded Systems: A Cyber-Physical Systems Approach.
The MIT Press, 2016. –
ISBN 978–02–625–3381–2

[3] Marwedel, P. :
Embedded System Design - Embedded Systems Foundations of Cyber-Physical Systems.
Springer, 2011. –
ISBN 978–94–007–0256–1