

Energy-Aware Computing Systems

Energiebewusste Rechensysteme

VI. Cyber-Physical Systems

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2019-06-06



Agenda

Preface

Terminology

Dynamic System Structure

Partitioning

Cross-System Control

Cyber-Physical Systems

Resource Demand

Communication

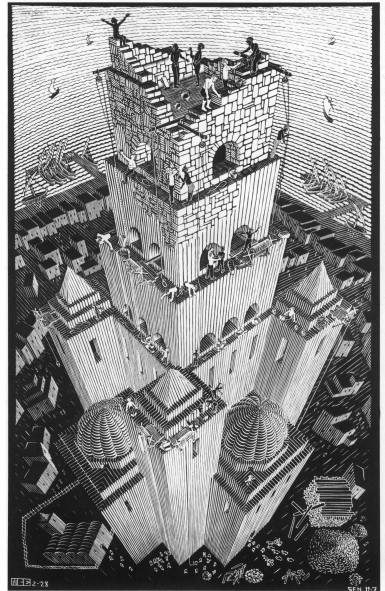
Control

Summary



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)

March 17, 1953

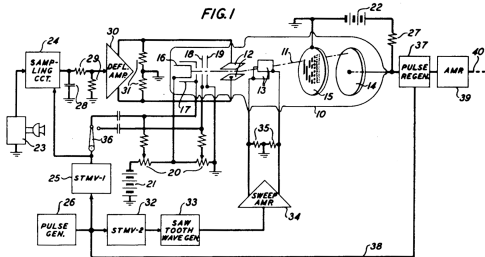
F. GRAY

2,632,058

PULSE CODE COMMUNICATION

Filed Nov. 13, 1947

4 Sheets-Sheet 1



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.

March 17, 1953

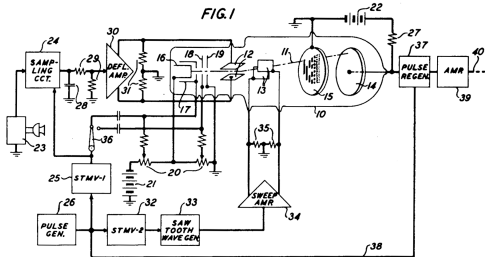
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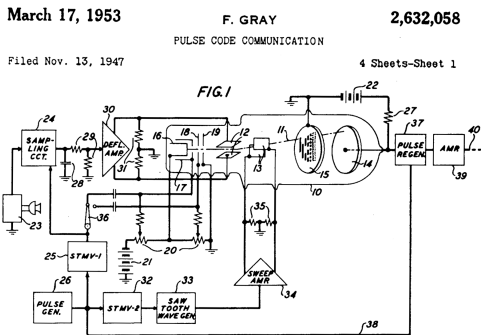
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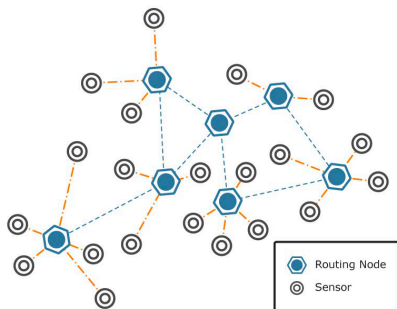
Abstract Concept: Cyber-Physical Systems

- **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

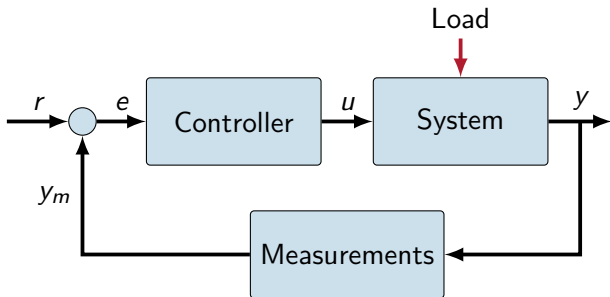
- composition of system is dynamic
- variable system structure depends on **time and location**
 - spontaneous joining and resignation of devices
 - overload and breakdown detection
- heterogeneous **network links**
 - wired and wireless links with variable channel conditions
→ propagation, delay loss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



Nunes et al.



- measurement-based analysis with a feedback control system



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



- 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

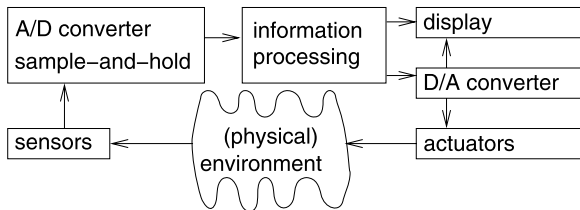


Figure 3.2. Hardware in the loop

Nested Cyber-Physical System

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

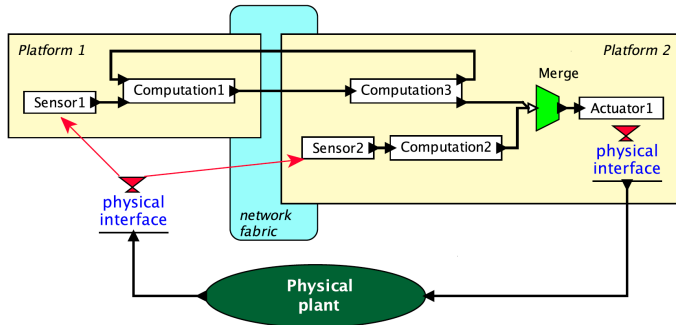


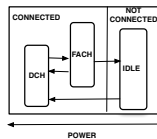
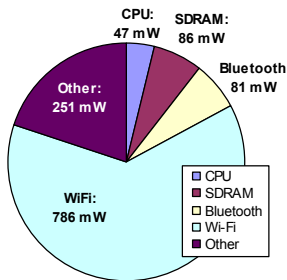
Figure 1.1: Example structure of a cyber-physical system.

Lee & Sanjit: Introduction to Embedded Systems [2]

- **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 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)



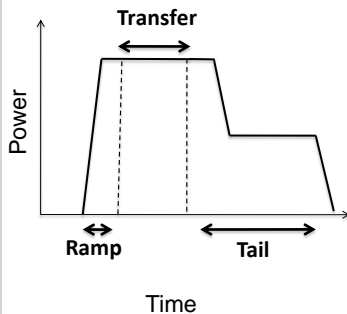
(a)



(b)

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

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



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

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

- 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





LARN: Context

- ▶ 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>

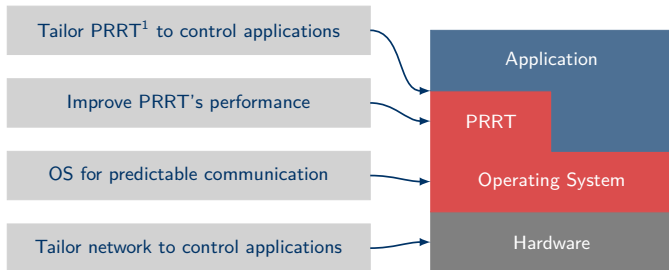
- ▶ Target scenario: control applications
 - ▶ system control in industrial facilities (e.g. BMW etc.)
 - ▶ low-latency control loops for medical applications
 - ▶ wireless sensors and network transports

- ▶ 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>





LARN: Overview and Project Goals

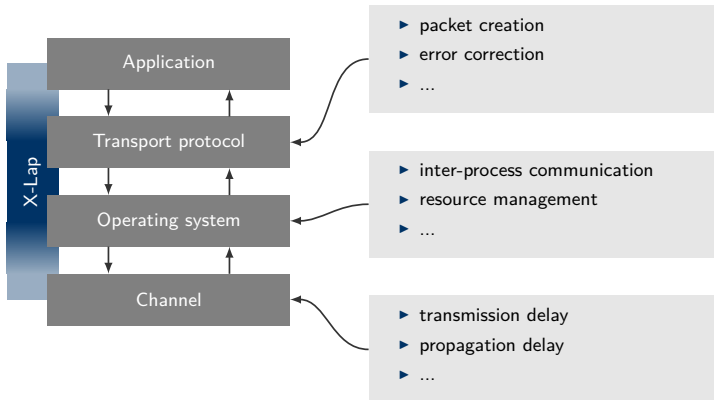


¹predictably reliable real-time transport





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





X-Lap | Architecture

online analysis at run-time

- ▶ timestamping functions
- ⇒ timestamps
- ▶ C implementation

offline analysis

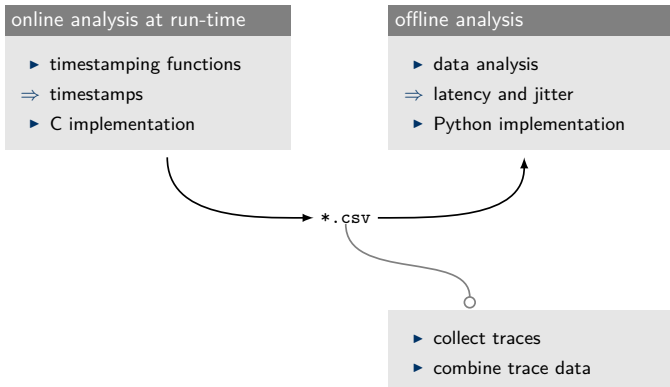
- ▶ data analysis
- ⇒ latency and jitter
- ▶ Python implementation

- ▶ trace every packet
- ▶ embedded into transport protocol code





X-Lap | Architecture





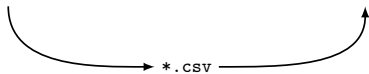
X-Lap | Architecture

online analysis at run-time

- ▶ timestamping functions
- ⇒ timestamps
- ▶ C implementation

offline analysis

- ▶ data analysis
- ⇒ latency and jitter
- ▶ Python implementation



▶ single-packet traces

▶ jitter amongst packets

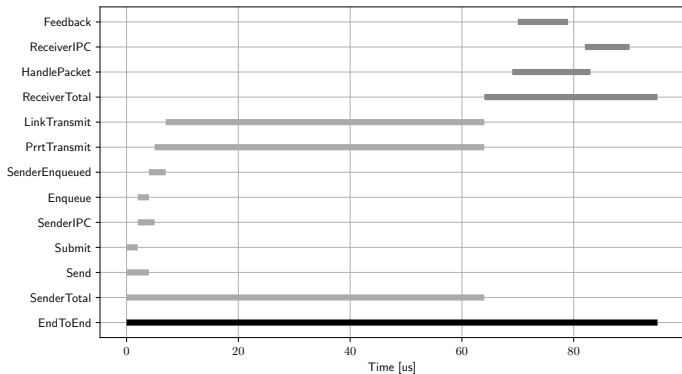
▶ outlier analysis

▶ correlation analysis



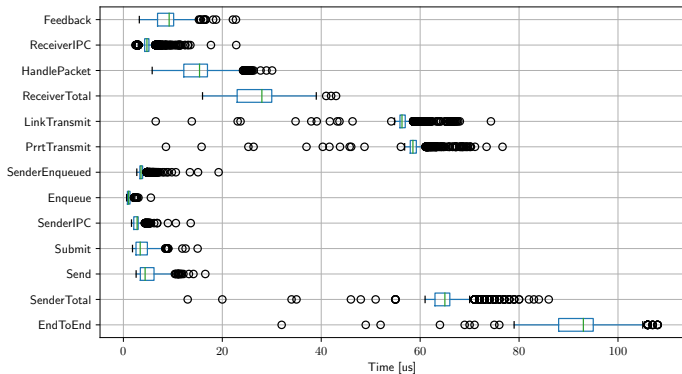


X-Lap | Packet Trace





X-Lap | Trace Jitter

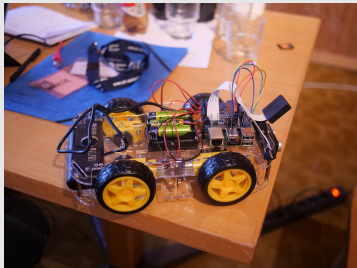




Evaluation Platform

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**



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)





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



- 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. –
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