Cyber-Physical Networking

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Internet Applications have changed...

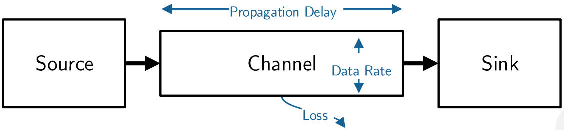
Original Internet used to exchange research results (CERN, ...).

Today's use cases:

- Internet of Things (IoT):
  - Large number and diversity of devices.
  - Large volumes of realtime sensor data.
- Multimedia Applications (VoIP, Teleconferencing, Games):
  - High interactivity / low latency.
  - Large data rates (audio-visual content).
- Time and Safety Critical Processes:
  - Production system automation (low control latency).
  - Remote surgery (low latency, no visual artefacts).

→ Requirements have changed → Demand for new solutions

Transmission Parameters



Facts:

- A: Every physical transmission link is prone to errors.
- B: Every transmission channel has a maximal amount of data it can convey per time.
- C: Transmissions take time that is at minimum the propagation time between sender and receiver.
  - * Propagation delay is dependent on spatial distance.

→ To tackle fact A and provide reliability, error control is required.

Traditional Error Control Mechanisms

Automatic Repeat ReQuest (ARQ):

Reactive scheme that is applied in case a loss is detected.

+ Simple mechanism with little overhead (only requires timer).
− Increases load on the network by resending "old" data.
− Introduces uncertainty as packet might be lost or just delayed.

Forward-Error Correction (FEC):

Proactive scheme that is applied when loss is anticipated.

+ Losses can be compensated after the first forward-trip time.
− Static increase in data rate for redundancy.

Theoretical Limits (Noisy Channel)

Noisy-Channel Coding Theorem (Shannon 1945, Proof by Feinstein 1954)
For every discrete memoryless channel, the channel capacity

$$C_{Shannon} = \max_{P_X} I(X;Y) \tag{1}$$

has the following property. For any $\epsilon > 0$ and $R < C$, for large enough N, there exists a code for length N and rate $\geq R$ and a decoding algorithm, such that the maximal probability of block error is $< \epsilon$.

$[C] = [R] = \frac{bits}{second} \quad ; \quad \epsilon \in [0,1]$

$\rightarrow (1-\epsilon) \propto N \quad \wedge \quad N \propto$ Latency

$\rightarrow$ Reliability $\propto$ Latency

Theoretical Limits (Finite-Blocklength Capacity)

Finite Blocklength Channel Coding Rate (Poor et.al 2010)
Given error probability ϵ, channel capacity C, blocklength N, channel dispersion V and complementary Gaussian cumulative distribution function Q, the maximally achievable data rate is:

$$C_{Finite} = C_{Shannon} - \sqrt{\frac{V}{N}} \cdot Q^{-1}(\epsilon) \tag{2}$$

→ A strong bound on what can be achieved within a given block length and respective time interval.

But current protocols for packet-switched networks perform far from this bound. (Wang et.al 2004)

Intuitive Relation between Latency and Reliability

We can derive:

- **ARQ**:
  - Latency increases by additional round trip times.
  - Waiting times have to be added to compensate for processing delay and jitter.
- **FEC**:
  - Requires computation time for encoding, decoding and data accumulation.
  - When operating at maximum data rate, transmitting redundancy slows down useful data transmission.

$\rightarrow$ Reliability $\propto$ Latency

Novel Error Control Mechanisms

Hybrid-Error Correction (HEC) (Shiozaki et.al 1996)

- Given link's packet loss rate and residual error rate, an FEC parameter set can be generated that is suitable.
- On low-latency links however, ARQ is usually more efficient as it does not require coding.
- HEC combines these approaches to provide the optimal error control for given link parameters.
- Challenges:
  - Finding the optimal parameter set is non-trivial.
  - Link parameters change over time.

→ **Adaptive Hybrid-Error Correction (AHEC)** (Tan 2008)

Novel Transport Layer Protocols

Predictably Reliable Real-time Transport (PRRT) (Gorius 2012)

- Enhance traditional UDP sockets to ensure interoperability with current systems and acceptance by institutions.
- Error Control is done using AHEC scheme on transport layer.
- Evaluate channel state information (latency, loss rate) and try to adhere to application parameters (residual loss, throughput, maximum latency).
- Open Issues:
  - Implementation tuned to multimedia transport only.
  - Optimisation only considering first-order statistics, limiting the statements that can be made about robustness and stability.

Traditional Transport Layer Protocols

User Datagram Protocol (UDP) (IETF RFC 768)

+ Fast; User-controlled throughput; Rudimentary integrity checks using checksums.
- No error control; Can cause congestion and harm TCP streams.

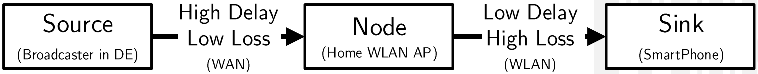
Transmission Control Protocol (TCP) (IETF RFC 793)

+ Full reliability (using ARQ); In-order delivery; Congestion and flow control.
- Very sensitive to loss (assumes congestion and turns down throughput); No way to make it tolerate limited loss events.

→ Both not suited for applications that tolerate loss and prefer partial reliability to ensure timely delivery.

PRRT as a Network Atom

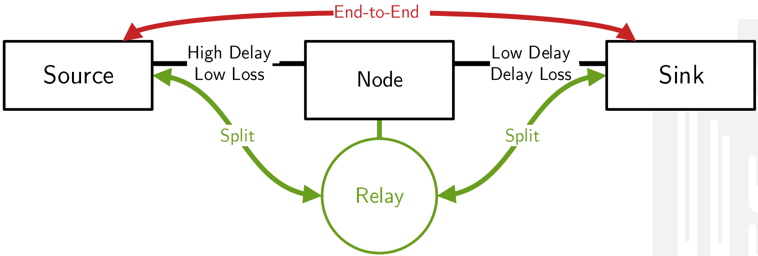
- PRRT := atom to optimise transmissions along segments
- Unmanaged Internet $\rightarrow$ end-to-end is one virtual segment
- Link parameters are merged:



- More segments would allow to fine-tune coding.

$\rightarrow$ Need a means to create multiple segments along a path.

Transparent Transmission Segmentation



- Performance Enhancing Proxies as intermediates. (IETF RFC 3135)
- Create multiple segments without the end-users noticing.
- Measure segments individually and apply optimization locally.

Opportunities

Create multiple domains for certain networking aspects:

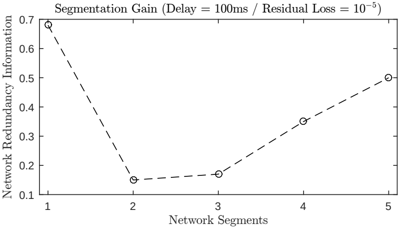
- TCP:
  - Error Control (retransmissions)
  - Congestion Control
  - Flow Control
- PRRT: Tune the FEC and ARQ parameters so that segments are optimally error coded.

→ Where to place how many relays?

Split Dimensioning Problem

Quantitative Dimensioning:

- First considerations using linear integer programming. (Karl 2015)



- Efficiency and quantity are not directly proportional.

Spatial Dimensioning:

- First attempts consider single nodes and neighbors. (Schmidt 2015)
- Distances on link parameters yield promising split candidates.

Programmable Networks

Software-Defined Networking (SDN):

- Separate control plane (routing) from data plane (forwarding).
- Eases integration of relays to optimize transmissions.

Open Networking Testbed:

- TC Lab operates a network testbed for executing evaluations.
- Provides LAN characteristics using local nodes.
- Provides WAN characteristics by cooperation with national and international partners:
  - SmartFactory, Kaiserslautern (DE)
  - Nokia Networks, Munich (DE)
  - Helsinki Institute of Information Technology (FI)

Past Work

SINNODIUM:

- BMBF research project on "Software Innovation for the Digital Enterprise" (2013 - 2015)
- Remote Maintenance Web Application (AV Dashboard)
- Peer-reviewed paper "Vertical Integration and Adaptive Services in Networked Production Environments"; presented at ERP-Future 2015, released in Springer LNBIP

OpenNetworking:

- Testbed Operation
- SDN Analysis Suite (Master Thesis) (*Günter-Hotz-Medaille WS '15/16*)
- SDN-Visualization (Bachelor Thesis) (*FdSI Bachelor-Preis SS '14*)

Current Practical Work

PRRT:

- Develop protocol lib for further optimisation and portability.
- Improve performance and support non-multimedia apps.

Synchronization:

- Add time & clock synchronization to testbed.
- Enable measurement of microsecond precision latencies.

Transparent Transmission Segmentation:

- Evaluate TCP relaying effects in varying scenarios to derive utility of the approach.
- Paper "Improving Network Transmissions from the Network's Core" acceptance to be announced end of this week.

Future Work

Cyber-Physical Networking (Project):

- Accepted Project Proposal: "Latency- and Resilience-Aware Networking (LARN)" (33% acceptance) for the DFG priority programme SPP 1914 (50% acceptance).
- Cooperation with Friedrich-Alexander University Erlangen, to develop a Reliable Networking Atom (RNA) software component, incorporating PRRT.
- Evaluate transmissions segmentations effects with PRRT.

Information Theory (Thesis):

- Improve prediction of parameters for PRRT transmissions.
- Derive Quality of Communication (QoC) using channel state information, aiming for soft guarantees.

Conclusion

- Cyber-Physical Networks have new demands on networks that have not yet been covered in-depth by research.
- Theoretical limits for communication systems exist, but packet-switched systems are still far away from this bound.
- Providing unconventional transport protocols like PRRT can help to overcome deficiencies of UDP and TCP.
- Targeted disobedience to the Internet's end-to-end principle can benefit individual transmissions and the overall network.

Research Goals:

- Improve PRRT and broaden its applicability.
- Systematically investigate transmission segmentation.

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