The Cross-Layer Paradigm In Next Generation Internet: Open Issues & Future Perspectives

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Goal

- To provide a survey of cross-layering solutions in today’s networks
- To analyze the cross-layer paradigm and identify the key issues
- To outline promising scenarios where cross-layering could be successful
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- Layering & Cross-Layering
- Current penetration of CL
- Key Issues
  - Signaling
- A promising scenario
  - Distributed protocol stacks
- Conclusions
Layering & Cross-Layering

Layering (ISO/OSI – TCP/IP)
- Enable fast development of interoperable systems, but…
- … limited performance of the overall architecture, due to the lack of coordination among protocols

Cross-Layering
- A recent design principle: allow coordination, interaction and joint design of protocols crossing different layers
- It seems appropriate for specific scenarios, such as wireless, where independent layer design may be sub-optimal
- Advantages demonstrated per case and “ad hoc” but not systematically
Which is the penetration of cross-layering in current networks?

- “Implicit” in all IP networks:
  - ARP
- “Explicit” in wireless networks
  - Layered paradigm works poorly in wireless networks, due to:
    - User / Node Mobility
    - Limited data transfer performance
    - Low energy efficiency
    - Quality of Service (QoS) requirements
  - Tighter integration among the layers is required for QoS, congestion control, handover
## The wireless scenario

<table>
<thead>
<tr>
<th>Technology</th>
<th>Mobility</th>
<th>Data transfer performance</th>
<th>Energy consumption/battery life</th>
<th>Quality of Service</th>
<th>Cross-Layer Design Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2G (GSM)</td>
<td>Global roaming</td>
<td>Physical rate: 9.6 – 57.6 Kb/s, Spectrum efficiency: 2.52 bit/s/Hz</td>
<td>Days</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>3G (UMTS)</td>
<td>Global roaming</td>
<td>Physical rate: 384 Kb/s (mobile), 2 Mb/s (static), Spectrum efficiency: 2.88 bit/s/Hz</td>
<td>Days</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>3G-LTE</td>
<td>Global roaming</td>
<td>Physical rate: 100 Mb/s (mobile), 5 Mb/s (static), Spectrum efficiency: 0.01 bit/s/Hz</td>
<td>Days</td>
<td>High</td>
<td>High</td>
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<tr>
<td>Mobile WiMAX (802.16e-2005)</td>
<td>Fixed</td>
<td>Physical rate: 10 Mb/s (max up to 70 Mb/s), Spectrum efficiency: 0.007 bit/s/Hz</td>
<td>Days</td>
<td>Medium</td>
<td>Medium</td>
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<tr>
<td>802.11b</td>
<td>Fixed</td>
<td>Physical rate: 11 Mb/s, Spectrum efficiency: 0.0065 bit/s/Hz</td>
<td>Hours</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>802.11a/g</td>
<td>Fixed</td>
<td>Physical rate: 54 Mb/s, 12 Mb/s, Spectrum efficiency: 0.0027 bit/s/Hz</td>
<td>Hours</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>802.11n</td>
<td>Fixed</td>
<td>Physical rate: 250 Mb/s, Spectrum efficiency: 0.0022 bit/s/Hz</td>
<td>Hours</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>Bluetooth (2.0)</td>
<td>Fixed</td>
<td>Physical rate: Up to 2.1 Mb/s, Spectrum efficiency: 0.0014 bit/s/Hz</td>
<td>Hours</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>UWB</td>
<td>Fixed</td>
<td>Physical rate: 875 Mb/s, Spectrum efficiency: 0.0002 bit/s/Hz</td>
<td>Hours</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Possible Cross-layer Interactions
Key Issues

- Cross-layering vs. layering
  - Need to be cautious [*]
  - Cost-benefit analysis
  - Dependant on the scenario

- Design framework
  - No “unifying theory”
  - No formal modeling

- Signaling
  - Internal or network-wide

CL Signaling Architectures

a) Packet structure

b) Cross-layer Interfacing

c) Cross-layer networking

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## CL Signaling Architectures

<table>
<thead>
<tr>
<th>Cross-Layer Signaling Method</th>
<th>Scope</th>
<th>Propagation Latency</th>
<th>Communication Overhead</th>
<th>Processing Overhead</th>
<th>Direction of signaling</th>
<th>Packet Dependant</th>
<th>Requires Standardization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interlayer Signaling Pipe</td>
<td></td>
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<tr>
<td>Packet Headers</td>
<td>Local</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Path dependant</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Packet Structures</td>
<td>Local</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Path dependant</td>
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<tr>
<td>Direct Interlayer Communication</td>
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<tr>
<td>ICMP messages</td>
<td>Local</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Path independent</td>
<td>×</td>
<td>✓</td>
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<tr>
<td>Callback functions</td>
<td>Local</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Path independent</td>
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<td>×</td>
</tr>
<tr>
<td>Central Cross-layer Plane</td>
<td>Local</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Path independent</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Network-wide Cross-layer Signaling</td>
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<td>Packet Headers</td>
<td>Local/Network-wide</td>
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</tbody>
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Distributed Cross-Layering

- **Idea:** Extend the idea of protocol stack modularity making it network-wide – Distributed Protocol Stacks

- **Details**
  - Each functional block of the protocol stack (a protocol layer or its part) can be abstracted into a separate module and implemented at a different node in the network.
  - Communication between host protocol stack and removed module is performed using a custom “lightweight” protocol.

- **Application**
  - Move protocol stack functions that generate high communication overhead into the network core behind the bottleneck link.
  - Caution: not all the protocol stack functions can be abstracted and separated.
3G LTE background

File Server → IP network → Base station → User Terminal

Transport
  Output() → TCP data

Network

Link

Physical

Module running environment
  TCP ACKs

ACK gen

TCP ACKs

Custom protocol

Physical

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ARQ Proxy – Packet Identification

- 3G LTE: Hash values
- WiFi: Frame Sequence Numbers

Hybrid ARQ (HARQ-ACK)

Enhanced Node B (eNB)

User Equipment (UE)
Conclusions

- Cross-Layering represents a promising design paradigm, especially in wireless networks.
- Fine tuning and optimization in complex scenarios require some sort of cross-layering, at the expense of interoperability.
- Cross-layer signaling has a high potential:
  - “Distributing” the protocol stack
  - Cognitive networking