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Goal

- To provide a detailed survey of state-of-the-art and future directions in the usage of formal methods for cross-layer modeling and optimization

- Focus is on wireless networks, where Cross-layering is envisaged to represent a suitable design framework
Table of Contents

- Introduction & Motivation
- Cross-Layer Modeling
- Cross-Layer Design
- 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
Design Issues

▷ **Layered Design (ISO/OSI)**
  ◆ Each layer-$N$ entity is defined in terms of the service it offers
  ◆ Protocols at different layers can be designed independently

▷ **Cross-Layer Design**
  ◆ Weak Cross-Layering
    ◇ interaction among layers of the protocol stack
    ◇ includes “non-adjacent” interactions
  
  ◆ Strong Cross-Layering
    ◇ allows joint design of the algorithms within any entity at any level of the protocol stack
    ◇ individual features related to the different layers can be lost due to the cross-layering optimization
Why Wireless?

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
# Why Wireless?

<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>9.8 - 57.8 Kbps</td>
<td>1.62 bit/s/Hz</td>
<td>5 bit/s/Hz</td>
<td>High</td>
</tr>
<tr>
<td>3G (UMTS)</td>
<td></td>
<td>384 Kbps (mobile) 10.2 Mbps (station)</td>
<td>2.88 bit/s/Hz</td>
<td>100 Mb/s</td>
<td>High</td>
</tr>
<tr>
<td>3G LTE</td>
<td></td>
<td>100 Mb/s</td>
<td></td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Fixed WiMAX (802.16-2004)</td>
<td></td>
<td>10 Mb/s (max up to 70 Mb/s)</td>
<td>1 bit/s/Hz</td>
<td>High</td>
<td>4608 frames, burst and fade mode</td>
</tr>
<tr>
<td>Mobile WiMAX (802.18-2006)</td>
<td></td>
<td>2-3 Mb/s (max up to 150 Mb/s)</td>
<td>1 bit/s/Hz</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>802.11b</td>
<td>Fixed</td>
<td>11 Mbps</td>
<td>5.55</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>802.11a/g</td>
<td></td>
<td>54 Mbps</td>
<td>2.7</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>802.11n</td>
<td></td>
<td>250 Mbps</td>
<td>0.22</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Bluetooth (2.0)</td>
<td></td>
<td>Up to 2.1 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UWB</td>
<td></td>
<td>875 Mb/s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cross-Layer Formalism?

- Several cross-layer approaches currently available in the literature

- No formal (quantitative) characterization of the cross-layer interaction among different levels of the protocol stack

- Our approach: formalize using system theoretic concepts and tools

- Formulate performance $e$ as function of parameters $p$, across the layers
System Design Issues

▷ Utility

◆ “raw” performance metrics $e_i$ will typically be further incorporated into utility functions $U(e)$

◆ express better how valuable the performance metric is to the system owner or user

◆ examples include functions of the system throughput, overall delay or jitter, and system capacity

◆ the utility function can have several forms and shapes

▷ Prices

◆ controllable parameters (factors or resources) will also likely have actual (literal) or virtual prices, say $a$ per unit of design parameter $X$ and $b$ per unit of $Y$
System Design Issues - II

- **System Optimization**
  - Performance/utility targets (e.g., $U(e) > u$)
  - Resource constraints (e.g., $D < d$, $T < t$)
  - Performance/utility maximization (e.g., $\max U(e)$)
  - Max-min and fairness performance targets
  - Service level agreement satisfaction via penalty function minimization

- **Cross-Layer Design Guidelines**
  - the optimal operating point of the system (direct consequence of the optimization process)
  - the proper cross-layer interactions to enable (based on sensitivity of the system)
  - the appropriate signaling architecture to employ (allowing to identify the set of parameters and measurements to use)
Cross-Layer Modeling

- System modeling should be based on mathematical analysis (e.g., Markov analysis, queueing or numerical approximations)

- However, closed form mathematical expressions are often unattainable for real systems, reinforcing the need for the use of empirical methods that include testing, emulation and computer simulation
Experimental CL Sensitivity Analysis

- Naïve estimation as $\Delta e / \Delta p$
- Infinitesimal Perturbation Analysis, IPA
- Accelerated sensitivity analysis via simulation:
  - Score Function (SF) method
  - Fast Importance Sampling-based Traffic Engineering (FISTE)
  - Interchange of mean/integral and derivative
- Stochastic approximation and stochastic optimization via estimated gradients and via non-gradient methods
Cross-Layer Response Surface Modeling

- **Response surface methodology (RSM)**
  - A set of statistical and mathematical techniques used to find optimal settings of parameters ("factors") that minimize or maximize the objective function ("response")

- **IS-accelerated RSM**
  - RSM + Importance Sampling (IS) simulation and testing method
Quantifying Cross-Layering - A Case Study (ITC ‘07)

How to quantify? - by defining factors (parameters) and effects (measurements) across layers in a way common in system science and operations research

“factors” (controllable parameters)

\[ \bar{p}^{TOT} = [\bar{p}^1 \mid \bar{p}^2 \mid \ldots \mid \bar{p}^7] \]

“effects” (performance metrics)

\[ e_i = f_i(\bar{p}^{TOT}) \]

Sensitivity of the system response and interactions

\[ \frac{\partial f_k}{\partial p^j_i} \quad \frac{\partial^2 f_k}{\partial p^j_i \partial p^m_l} \]

Using Quantified Cross-Layering

- Optimize the performance $e_i$ with respect to a subset of $p^{TOT}$ under general constraints
  - by using steepest ascent, stochastic approximation, ridge analysis, stationary points, etc.

- Make *local* steps or decisions at a given operating point
  - in the context of game-theoretic or other economic-driven adjustments

- Control the response $f_k$ over time dynamically (optimal control)
Quantifying Cross-Layering (cont.)

- Quantitative degree of cross-layer interaction and sensitivity should guide decision to actually take a specific interaction into account or not
  - Cross layer designs have implicit disadvantages in terms of cost and complexity

- Need to be cautious [*]
  - A concept that our proposed framework integrates and rationalizes.

Case Study: VoWiFi Capacity

Network Model

- **Problem Statement:** maximum # of VoIP calls, supported in an infrastructure Wi-Fi cell, with satisfactory QoS performance

- **Cross-Layer interactions:**
  Between PHY, MAC, and APP

- **Inputs, Outputs, Constraints**

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Abbreviation</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical data rate</td>
<td>$D$</td>
<td>4</td>
<td>1, 2, 5.5, 11</td>
</tr>
<tr>
<td>Packet Error Rate</td>
<td>$PER$</td>
<td>9</td>
<td>$10^{-9}$, $10^{-8}$, $10^{-7}$, $10^{-6}$, $10^{-5}$, $10^{-4}$, $10^{-3}$, $10^{-2}$, $10^{-1}$</td>
</tr>
<tr>
<td># of retransmissions</td>
<td>$R$</td>
<td>6</td>
<td>0, 1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>Voice packet interval</td>
<td>$I$</td>
<td>9</td>
<td>10, 20, 30, 40, 50, 60, 70, 80, 90</td>
</tr>
<tr>
<td>Constraints</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voice E2E delay</td>
<td>-</td>
<td>-</td>
<td>&lt; 100 ms</td>
</tr>
<tr>
<td>Frame error rate</td>
<td>-</td>
<td>-</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>
Case Study: VoWiFi Capacity (cont.)

▷ Choose and Fit the Metamodel
  ◆ Second order polynomial RSM with interactions ($R^2=0.81$)

\[
N^* = -5.1027 + 1.5575D + 292.8806I + 1.3677R - 157.3738PER \\
+ 5.9569D*I + 0.1980D*R - 5.1210D*PER - 891.6851I*PER \\
+ 3.7706R*PER - 0.1186D^2 - 2710.813*I^2 - 0.2935R^2 + 1644.7405*PER^2
\]

▷ Evaluate the Metamodel: comparison
  ◆ Analysis > Metamodel > Simulation
Case Study: VoWiFi Capacity (cont.)

Cross-Layer Sensitivity and Performance Optimization

\[
dN*/dD = -0.2372D + 5.9569I + 0.198R - 5.1209PER + 1.5575
\]

\[
dN*/dI = 5.9569D - 5421.626I - 891.6851PER + 292.8815
\]

\[
dN*/dR = 0.198D - 0.587R + 3.77PER + 1.3677
\]

\[
dN*/dPER = -5.12D - 891.6851I + 3.77R + 3289.48PER - 157.3774
\]

◆ System is sensitive to:
  ◇ Voice packet interval \(I\) and Packet Error Rate \(PER\)

◆ System is less sensitive to:
  ◇ Data rate \(D\) and Number of MAC layer retransmissions \(R\)
Case Study: VoWiFi Capacity (cont.)

Metamodel properties

- Maximum of $N^*(D, I, R, PER)$ corresponds to
- 20 VoIP calls for $D=11$ Mb/s, $I=70$ ms, $R=5$, $PER=10^{-9}$

For low rates (1 or 2 Mb/s) further retransmissions start to degrade system performance

Violates E2E delay threshold of 100 ms

Model is not sensitive to low PERs

- For $I=0.05$, $PER=10^{-4}$
- For $R=5$, $D=11$ Mb/s
- For $D=1$ Mb/s
- For $D=5.5$ Mb/s
- For $D=2$ Mb/s
Case Study: VoWiFi Capacity (cont.)

Service Provider Perspective

![Utility function:]

\[ U(D, I, R, \text{PER}) = N \cdot \frac{D_{\text{wasted}}}{D} \cdot N \cdot P_{\text{call}} - P_{\text{power}} \cdot (D_{\text{norm}} + \text{PER}_{\text{norm}})^2 \]

- **Operator revenues on per-call basis**
- **Resources required by retransmissions**
- **Resources required to maintain given data and error rates**

- \( P_{\text{call}} \) - Price charged for a single call
- \( P_{\text{power}} \) - Marginal cost of a unit of transmitted power
- \( D_{\text{wasted}} \) - Bandwidth wasted for retransmission in packets/second
- \( \frac{P_{\text{call}}}{P_{\text{power}}} \) - chosen to be equal to 100 which corresponds to a policy to charge $1 per VoIP call while the price paid for power resource is just $1

Maximizing revenues:

- $18.89 with \( D=11 \text{ Mb/s}, I=70 \text{ ms}, R=5, \text{PER}=10^{-9} \)
Mobile Terminal Perspective

- **Objective:** long battery life while providing acceptable call performance

- **Main parameters**
  - transmission data rate $D$
  - maximum number of retransmissions $R$

- **Utility function:**

$$U = \alpha \cdot N^* - \beta \cdot [R + f(D)]$$

where $f(D) = 10^{1.4291 + 0.0515D}$

$\alpha$ and $\beta$ relative weight against costs
Case Study: VoWiFi Capacity (cont.)

- **Design Principles**
  - Limitation on the number of active nodes, and thus a proper Call Admission Control (CAC), is required.
  - Overall system performance depends on many parameters which can be recognized and quantified at different layers.

- This motivates introduction of CAC schemes which exploit metamodel information to provide proper cross-layer parameter setting for run-time system optimization.
Game theory represents a formal tool to describe and analyze interactive decision situations. It provides an analytical framework to predict the outcome of complex interactions among individual rational entities. Rationality is represented by adherence to a strategy based on perceived or measured results. It could be applied to study network behavior (at the moment, still in an early age). Analysis of the interactions among the players and estimation of the outcome of the game are performed by studying the evolution of the game in terms of dynamic or steady-state conditions.

Some Considerations

- Not many works aim at providing a unified yet suitable method to model cross-layering interactions.

- The key issue is represented by the complex interactions among the layers of the protocol stack:
  - Every protocol has a different goal, uses different measurements, ...

- Promising approaches are:
  - “quantifying” approaches (RSM, simulation- or measurement-based)
  - game theory (to capture the interaction among protocols, to explicitly model different goals at each layer)
Conclusions

Cross-layering seems a promising technology to support:
- High performance
- Mobility
- High resource utilization (spectral efficiency)
- QoS

in wireless networks

In some cases, CL design is already employed (e.g., 3G, 3G LTE)

Formal methods will able to support design of effective solutions, but...

... the way is still open to a “unifying theory” of cross-layering
Thank you!