OPERETTA: An Optimal Energy Efficient Bandwidth Aggregation System

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Agenda

• Motivation
• OPERETTA Architecture
• Optimal Scheduling
• Implementation
• Evaluation
• Conclusion and Future Work
Motivation
Motivation

- Exponential increase in mobile data demand
- FCC National broadband Plan
  - 500 MHz of additional spectrum
  - Technical and business innovations that increase efficiency of spectrum utilization
Motivation

• Exponential increase in mobile data demand
• The proliferation of multi-homed or multi-interface enabled devices
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• Current OSs allows you to use only one interface even if more than one is connected to the Internet
Motivation

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- The proliferation of multi-homed or multi-interface enabled devices
- Current OSs allows you to use only one interface even if more than one is connected to the Internet
- Energy awareness
Motivation
Motivation

• Current solutions face a steep deployment barrier
  – Updating servers, application, clients kernel and infrastructure
• Current solutions focus only in maximizing the throughput
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Design Goals

- **Goal 1**: Deployability
- **Goal 2**: Adaptability to system’s parameters
- **Goal 3**: Energy awareness
- **Goal 4**: Optimality
- **Goal 5**: Capture the user preferences
- **Goal 6**: Minimize the user involvement
OPERETTA Architecture
## Scheduling Granularity

<table>
<thead>
<tr>
<th>Connection level scheduling</th>
<th>Packet level scheduling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does not require any server or infrastructure updates</td>
<td>Requires updating the legacy server and/or the network infrastructure</td>
</tr>
<tr>
<td>Utilize the available interfaces while having multiple concurrent connections</td>
<td>Utilize the available interfaces even if only single connection is running on the system</td>
</tr>
<tr>
<td>Achieves high performance gains but not optimal</td>
<td>Can reach the optimal performance</td>
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</tbody>
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OPERETTA Architecture

• Application Characteristics Estimator
  – Qualitative measurements
  – Quantitative measurements
OPERETTA Architecture

• Interface Characteristics Estimator
  – Estimates the available bandwidth and energy consumption rates at each interface
  – Uses destination based estimates in case of OPERETTA-enabled servers
OPERETTA Architecture

- Battery Sensor
  - Senses the available battery level in the device
OPERETTA Architecture

- **User Interface Module**
  - Obtains user’s preferences and interface usage policies
  - Example
    - Selecting scheduling policies
    - Assigning certain Applications to certain interfaces
OPERETTA Architecture

• Mode detection module
  – A background process listening on specific port
  – Specifies whether the server is OPERETTA-enabled or not
OPERETTA Architecture

• Scheduler
  – Schedules the packets and/or the connections on the different network interfaces
OPERETTA Architecture

• Received Data Reordering Module
  – Used only in packet oriented mode
  – Reorder the packets before giving them to the application
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System Model

- Mobile device equipped with $m$ interfaces
- Each interface with data rate $r_j$ and energy consumption rate $a_j$
- The device is running a set of applications sharing the interfaces
System Model

• OPERETTA’s goal is to assign streams to interfaces
  – Minimize the required energy (E)
  – Achieve a desired throughput (T)

• The Mode Detection Module then determines whether the operation mode is connection-based (\( S_n = 1 \)), or packet-based (\( S_n = 0 \)) if the other end is OPERETTA-enabled.
Utility Function

- Used to determine the users required level of throughput ($T_{\text{target}}$)

$$T_{\text{target}} = r_{i_{p_{\text{min}}}} + \alpha \sum_{j \neq i} r_{j_{p_{\text{min}}}}$$

- User utility parameter

- The data rate for the minimum power consuming interface

- The data rate for interface $j$
Objective Function

- Minimize the overall system’s energy consumption

\[
\text{minimize } E = \sum_{j} E_j
\]

- Minimize the energy consumption for both packet-oriented and connection-oriented streams

\[
\text{minimize } E = \sum_{j} \frac{a_j}{r_j} \left( \omega_j \sum_{i=1}^{n} L_i \left(1 - S_i\right) + L_n S_n x_{nj} \right)
\]
System Constraints

• Target Throughput

\[
\forall j, \Delta_j = \frac{\omega_j \sum_{i=1}^{n} L_i (1 - S_i) + \sum_{i=1}^{n} L_i S_i x_{ni}}{r_j} \leq \frac{L}{T_{\text{target}}}
\]

The time needed for interface j to finish its load

The current system load

Each interface has to finish its load before a certain time in order to obtain the required throughput level
System Constrains

• Integral Association

\[ \sum_{i=1}^{m} x_{nj} + (1 - S_n) = 1 \]

If the new stream is connection-oriented, it should be assigned to only one interface
System Constrains

• Packet Load Distribution

\[ \sum_{j=1}^{m} \omega_j = 1 \]

For packet-oriented streams, their total load should be distributed over all interfaces.
System Constrains

• Variable ranges

\[ \omega_j \geq 0, 1 \leq j \leq m \]
\[ x_{nj} \in \{0,1\}, 1 \leq j \leq m \]
Scheduling Algorithm

- Determining $\omega$

$$\omega_j = \min \left( 1 - \sum_{k \leq j-1} \omega_k, \frac{Lr_j - T_{\text{target}} \sum_i L_i S_i x_{ij}}{T_{\text{target}} \sum_i L_i (1 - S_i)} \right)$$

- Throughput maximization in packet oriented mode

$$\omega_j = \frac{r_j}{\sum_i r_i}$$
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Implementation

• OPERETTA Middleware
  – It is implemented as a Layered Service Provider (LSP)
  – It is installed as a part of the TCP/IP stack in Windows OS
  – It intercepts socket-based connection requests and assign proper network interfaces to them or distribute their data across the different interfaces
Implementation

• OPERETTA Monitoring Application
  – It is used to captures the user preferences and interfaces’ usage policies
  – It is also used to monitor OPERETTA middleware and its estimates
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Environment

NIST-NET

WiFi
1 Mbps, 634 mWatt
Bluetooth
0.7 Mbps, 95 mWatt
GSM
2 Mbps, 900 mWatt

6 Mbps
Parameters and Metrics

• Parameters
  – Applications characteristics (small load 22.38KB and large load 285KB)
  – Connections Heterogeneity (13 small connection/sec and 1 large connection/sec)
  – The Ratio of OPERETTA enabled servers (gamma)
  – Network interfaces characteristics
  – User preferences
  – Utility Functions
  – Robustness to estimation errors

• Metrics
  – Throughput
  – Average Energy consumption per unit data
Results

- With as few as 25% of the servers becoming OPERETTA enabled, OPERETTA’s performance reaches the throughput upper bound, highlighting its incremental deployment and performance gains.
Results

- OPERETTA scheduler captures the user’s needs
Results

- Round Robin does not take the interfaces heterogeneity into account
- OPERETTA outperforms weighted round robin since it take the applications characteristics into account
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Conclusion and Future

• OPERETTA is Deployable
• OPERETTA’s high performance gains
  – 150% enhancement in throughput with no changes to the servers
  – Reaches the maximum achievable throughput with 25% of the servers are OPERETTA enabled
• Directions for extending OPERETTA
  – Implementation
  – Objective
  – Environment
Thank you

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