Modelling Power Saving Strategies in ICT Systems

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16th EUNICE International Workshop and IFIP WG 6.6 Workshop,
EUNICE 2010, Trondheim, Norway, June 28 - 30, 2010

Overview

1 Power Consumption in ICT

2 Energy Information Networks - The Information Spine of Power Grids

3 Energy Efficiency in Mobile Communications

4 Performance Modelling of Power Saving Solutions

5 Power Grids - The Conflict Between Transparency and Privacy

1. Power Consumption in IT

1.1 Observations on Power Consumption in IT

1.2 Examples of Wasted Power Consumption

1.3 Causes and Development Options

1.1 Observations on Power Consumption in IT (1)

Moore’s Law **Doubling of Device Performance every 18 Months**

by **Integration Density: Microtechnology → Nanotechnology**
Switching Speed: Microseconds → Nanoseconds → Picoseconds
Semiconductor Technology: Si → Ge/Si → GaAs
Bipolar → CMOS

Power Consumption

$$P \sim C_S \times V_{DD}^{2.3\ldots2.6} \times f$$

clock frequency
power voltage
switch capacitance

Consequences **Cooling Systems (Air → Water)**
Massive Parallelization
Performance Limitations by Power Constraints

1.1 Observations on Power Consumption in IT (2)

Measurements (Annual Electricity Consumption)

- **US year 2000:**

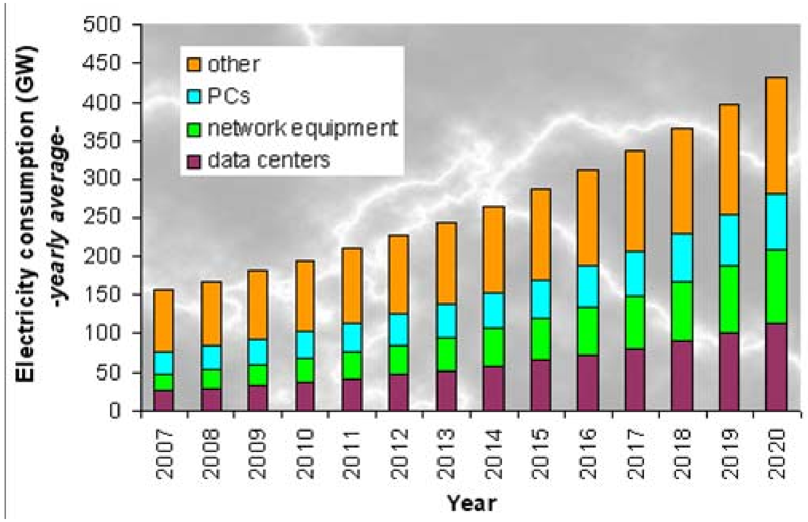
Device	Est. Numbers	Cons. TWh	Costs	Equiv.
Hubs	93.5 Mio	1.6		
LAN-Sw.	95.000	3.2		
WAN-Sw.	50.000	0.2		
Router	3.257	1.1		
Total (US)		6.1	10^9 US $	1 Nucl. Reactor
Total (World)		144		

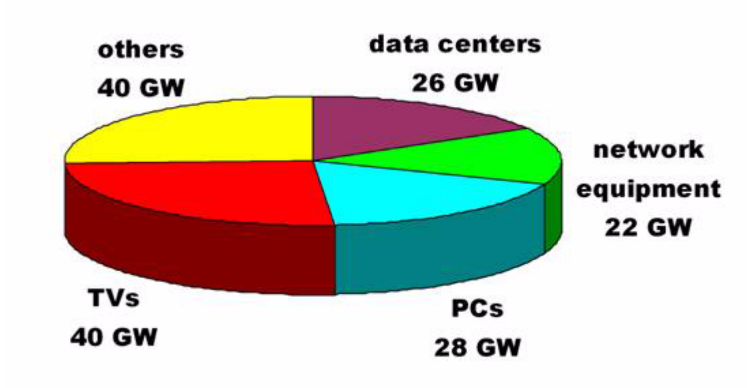
➥ Annual increase in networking power consumption in this decade (estimated) US: 1 TWh

- **Total power consumption of IT ≈ 10% of all power consumption!**

1.1 Observations on Power Consumption in IT (3)

- Annual Electricity Consumption in IT in Germany (2007-2020; 2010)





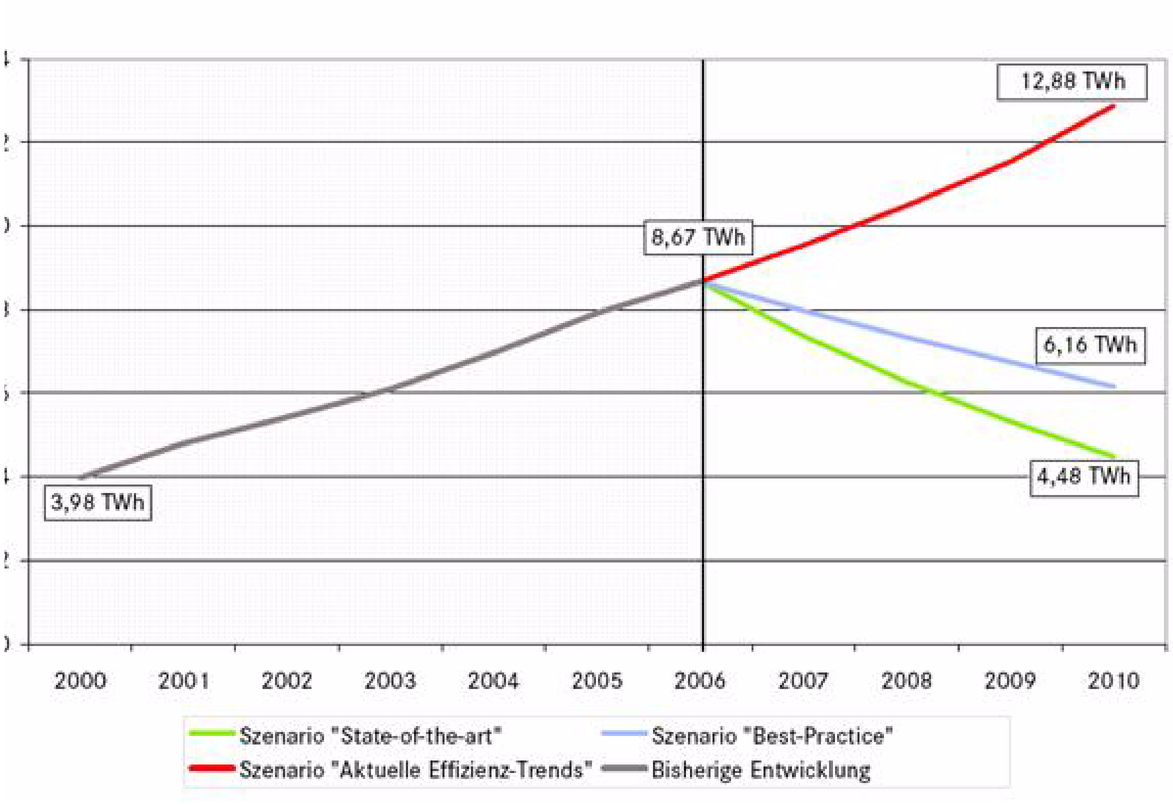
Note: **P (Power Consumption) in Gigawatts (= 10^9 Watts)**

Annual Energy Consumption = $P \cdot \frac{8760\text{h}}{\text{a}}$ = 8.760 x P $\frac{\text{TWh}}{\text{a}}$

1 Nuclear Reactor Provides Typically 6 TWh

1.1 Observations on Power Consumption in IT (4)

- Annual Electricity Consumption in Computing Centers in Germany



1.2 Examples of Wasted Power Consumption

	Type	Examples
(1)	Device Power Consumption	Current Leakage
(2)	Inefficient Operation	Design for Maximum Performance
(3)	Cooling Systems	Power Consumption of Cooling, Waste of Heat
(4)	Ineffective Power Management	No Systemwide Power Control
(5)	Wasted Power Consumption ("Always-On")	Permanent Activation
(6)	Massively Redundant Data Storage	Useless Data Replications
(7)	Highly Redundant Network Traffic	CC, Exploders, Provisional Downloads

1.3 Causes and Development Options (1)

1.3.1 Device Technology

- Device Power Consumption

Example: IBM Blades	Power Supply	20%
	Processing and Caching	55%
	Memory	10%
	I/O Subsystems	5%

- End of Moore’s Law → New Technologies

Reduction of Leakage

➥ Replacement of Silicon Oxyde by Carbon Nanotubes

➥ Nanowire Devices

➥ Molecular Electronics

➥ Spin Devices (Quantum Computing)

1.3 Causes and Development Options (2)

1.3.2 "Green Computing" - Set of activities to reduce power consumption

- **IBM Announcement "Big Green":**
  (2007) 1 Billion US $/a reallocated
  Long-term strategy committment
  CO_2 reduction and computer power increase
  Effective cooling and waste heat usage
  Operational changes
  Virtualization
- **NSN Announcement:**
  (11-20-2007) Design for Environment (DfE)
  Environmental Management System (EMS)
  Recycling of devices and products
  Energy-efficient telecom solutions
  see: *www.nokiasiemensnetworks.com/*
- **EU:**
  (7-17-2007) Code of conduct on energy consumption of broadband equipment (version 2)
  see: *EU Document Renewable Energies Unit*
  Broadband Equipment Code of Conduct

1.3 Causes and Development Options (3)

Power Limitations for Broadband Terminal Equipment (as of 12-31-2009)

Source: EU Document Renewable Energies Unit, Broadband Equipment Code of Conduct (7-17-2007)

Terminal Equipment	**Off State**	**Low Power State**	**On State**
ADSL/VDLS Modem	0 W	0.8 W	1.5 W
VDLS Modem einschl. Ethernet Port, Router und Firewall	0.3 W	2.0 W	6.0 W
Optical Network Termination	0.3 W	(offen)	12.0 W
WLAN Access Point 802.11	0.3 W	2.0 W	6.0 W
VoIP Device	0.3 W	2.0 W	5.0 W
Network Equipment/Port			
ADSL 2+	-	0.8 W	1.2 W
VDSL 2	-	1.2 W	1.6 W
Wakeup Time	-	≤ 1 s	≤ 1 s

1.3 Causes and Development Options (4)

1.3.3 Coordinated Sleeping - The Benefits of Doing Nothing

Example 1: System Power Management Support IBM POWER6 MP
see: *IBM J. Res. & Dev., Vol. 51, No 6, November 2007, pp. 733-745*

- On-Chip Support by Sensors, Actuators, Thermistors (Energy Scale^{TM}-Architecture)
- Thermal and Power Management Device
- Principle: Make use of application dependent power consumption
- Measures:
  - Pipeline Trottling (run/hold, instruction)
  - Multiple voltage domains
  - Voltage and frequency scaling
  - Processor idle modes
  - Dynamic memory modes
  - Overheat protection by sensor technology (on-the-chip)

1.3 Causes and Development Options (5)

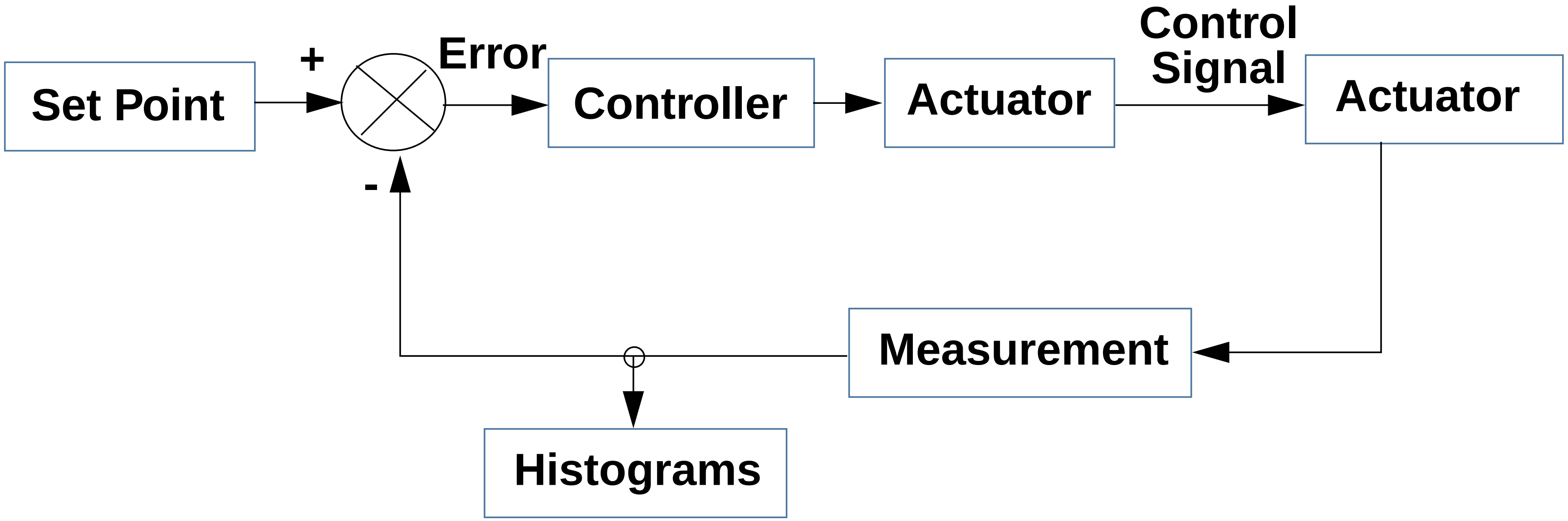
Example 2: Sleep Mode of Telecommunication Equipment

IP-Phone:	5-10 W Continuous Power Consumption
Analog Phone:	≈ 0 W Silence Period 6 W Connection Period
PC Online:	100s W Always-On Mode
Router:	40 kW
***Question*:**	When and how to sleep? Coordinated Sleeping
see:	*"Greening of the Internet"* *ACM SIGCOMM'03, Aug. 25-29, 2003, Karlsruhe*
Measure:	Dynamic Control of Low Power Mode

1.3 Causes and Development Options (6)

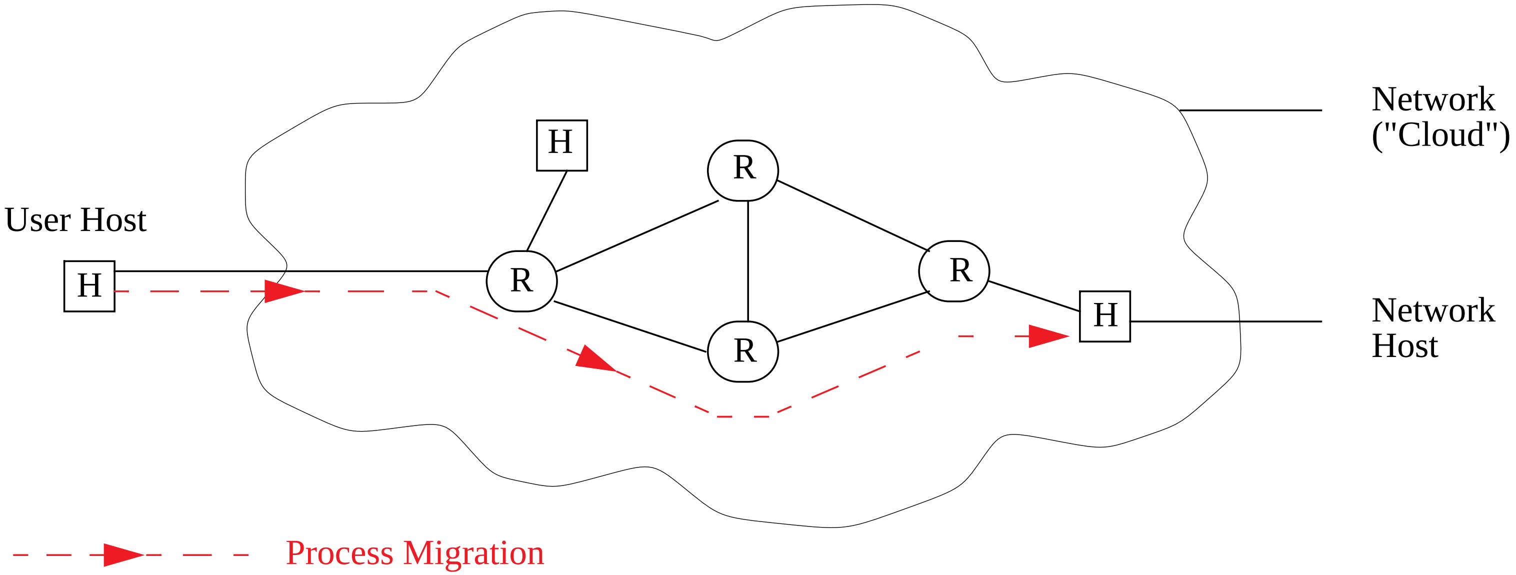
1.3.4 Power Control - Positive Results from Negative Feedback

Example: EnergyScale^{TM} for IBM POWER6 Microprocessor
see: *IBM J. Res. & Dev., Vol. 51, No 6, Nov. 2007, pp. 775-785*



1.3 Causes and Development Options (7)

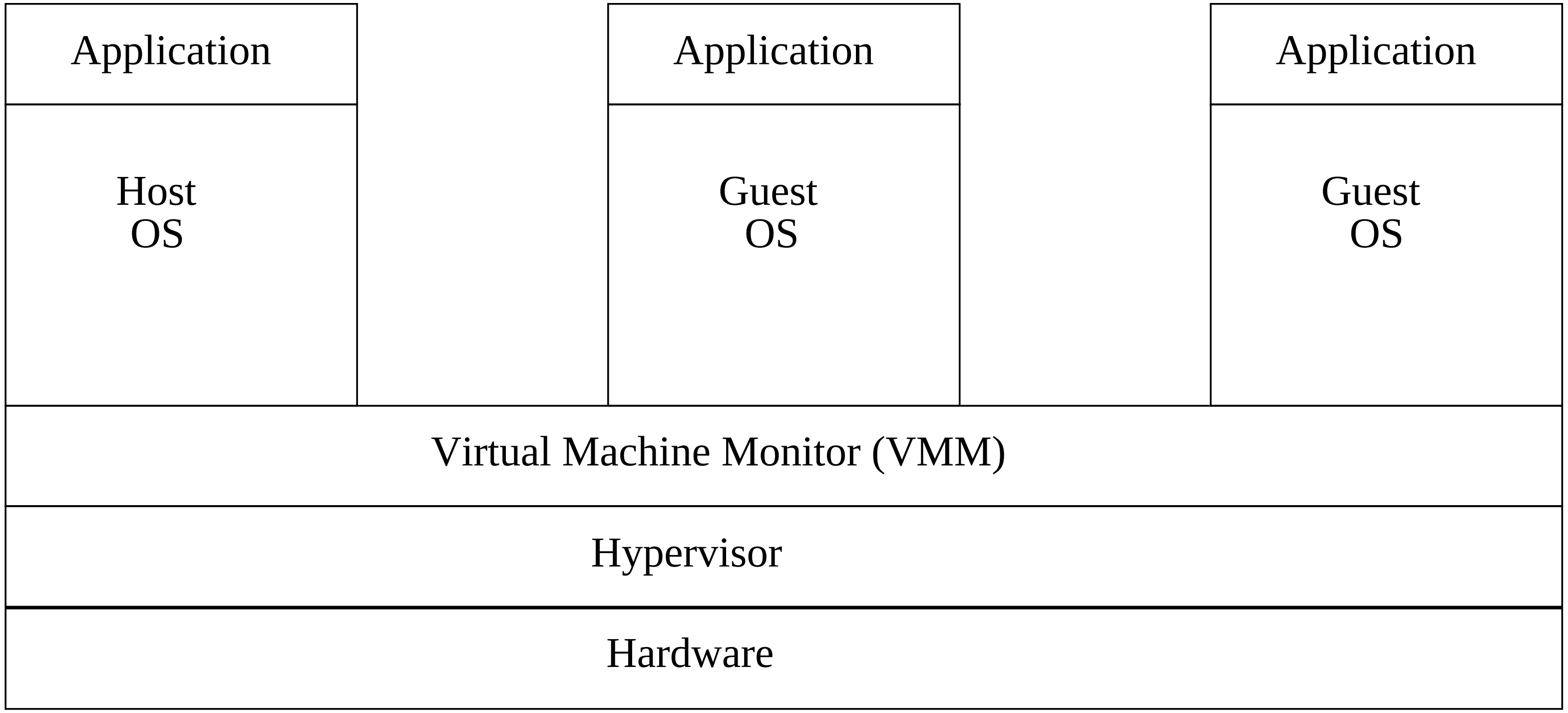
1.3.5 Virtualization



- Dynamic Workload Assignment to Active Resources
- Network Level Multiprocessing through Process Migration
- Workload- and State-Dependent Activation
- Adaptive Scheduling
- Virtualized Resources

1.3 Causes and Development Options (8)

Virtualization



- Emulation of User Host on Guest Hardware Machine
- Adaptive Assignment of Network Resources
- Logical Separation of Migrated User Processes (Security)

1.3 Causes and Development Options (9)

1.3.6 Redundancy Reduction (Storage, Transmission)

- Much Information is Stored on Different Memories / Databases
- Much Information is Distributed to Multiple Destinations (Exploders, Copy Operations, ...)
- Distribution of Reference Links Rather Than Distribution of Data
- Trade-Off Between Storage / Transmission Costs

2. Energy Information Networks - The Information Spine of Power Grids

2.1 Problem Statement

2.2 Smart Metering and Power Grids

2.3 Energy Information Networks

2.4 Power Management

2.1 Problem Statement (1)

- Continuous Energy Demand

- Exhaustion of Traditional Energy Resources (Fossile Combustibles)

- Energy Resources
  - limited availability (wind, sun, water, biomass)
  - have to be used jointly

- Reduction of Energy Demand
  - by improved technologies
  - by adaption between energy production and energy usage

2.1 Problem Statement (2)

- Continuous Energy Demand

- Exhaustion of Traditional Energy Resources (Fossile Combustibles)

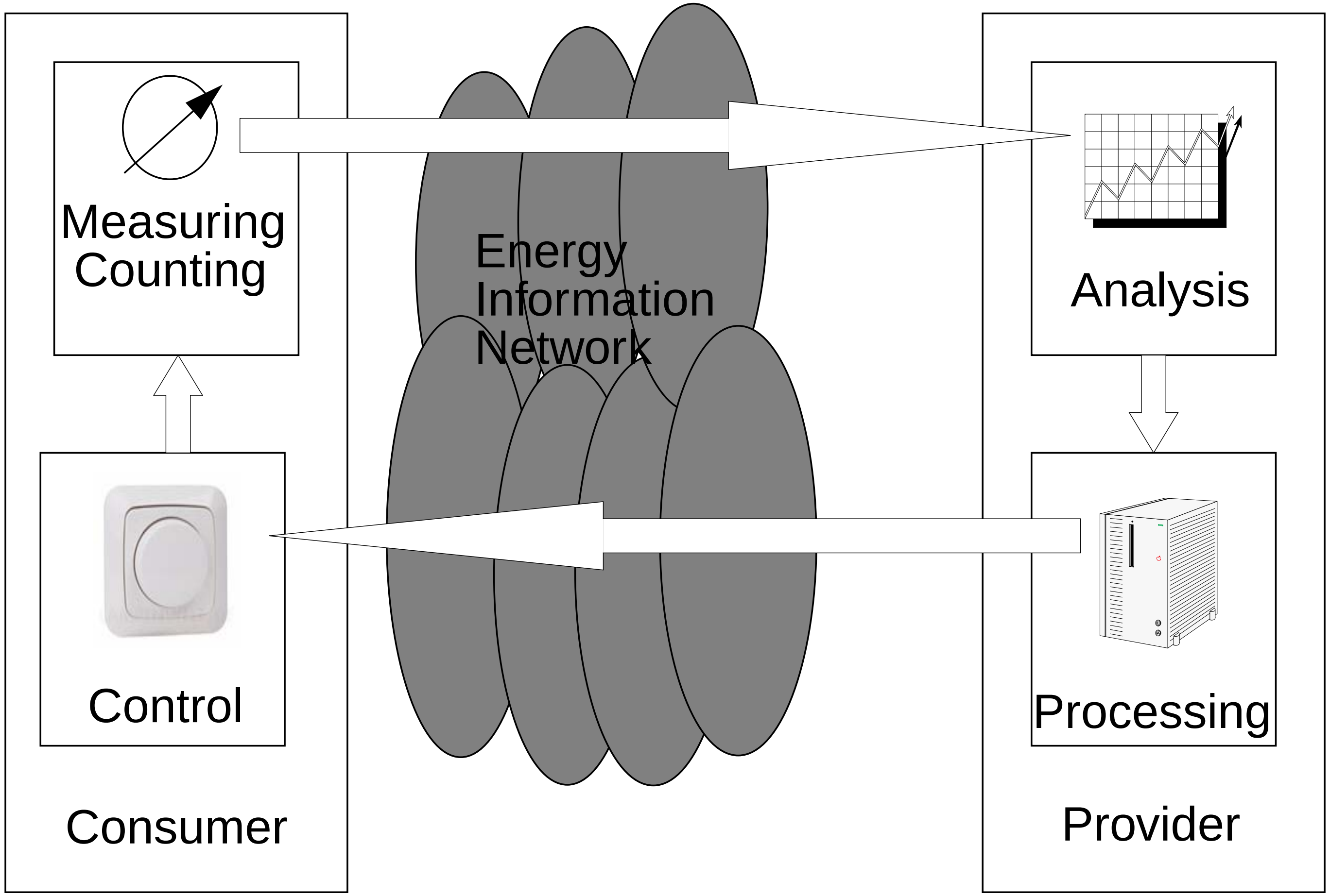
- Energy Resources
  - limited availability (wind, sun, water, biomass)
  - have to be used jointly

- Reduction of Energy Demand
  - by improved technologies
  - by adaption between energy production and energy usage

Intelligent Coupling of
Energy Production / Conversion and Energy Usage

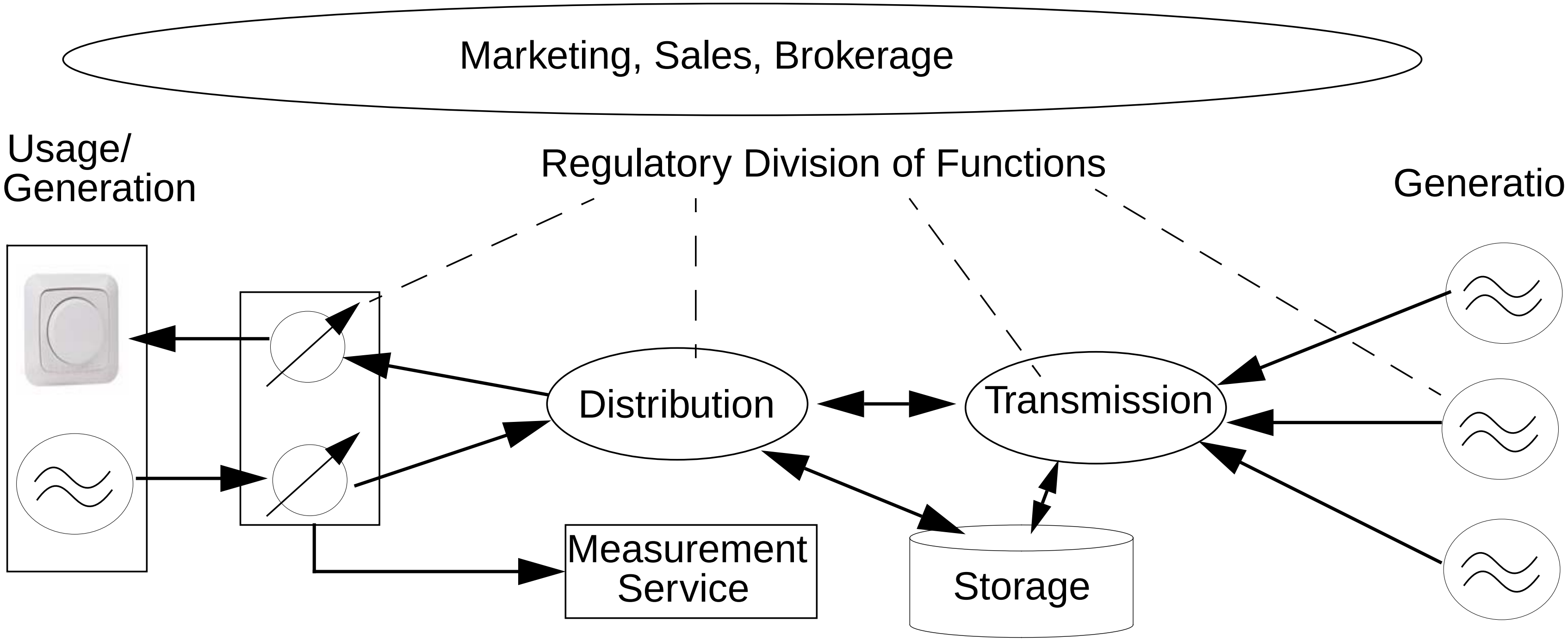
2.2 Smart Metering and Power Grids (1)

Energy Information Network between Producer and Consumer



2.2 Smart Metering and Power Grids (2)

New Role Model



Marketing, Sales, Brokerage

Usage/
Generation

Regulatory Division of Functions

Generation

Distribution

Transmission

Measurement
Service

Storage

2.3 Energy Information Networks (1)

2.3.1 Requirements for an Energy Information Network

- Multiple Interfaces (Sensors/Actors, Network Technologies and Protocols)
- Efficiency (Throughput, Response Time)
- Reliability (Breakdown Protection, Resilience)
- Network Management (Konfigurability, Outage Management)
- Distributedness (Decentral/Central Control, Self-Organization, Distributed Software)
- Controllability (Multi-Parameter Control System)
- Context Sensitivity (Detection of Situation by Sensors, Sensor Fusion)
- Security and Privacy (Access Rights, Protection of Personal Data)
- Energy Efficiency (Sensors/Actors, Power Supply)

2.3 Energy Information Networks (2)

2.3.2 Options

- Inhouse Networks
  - Powerline Communication (PLC)
  - Wireless LANs

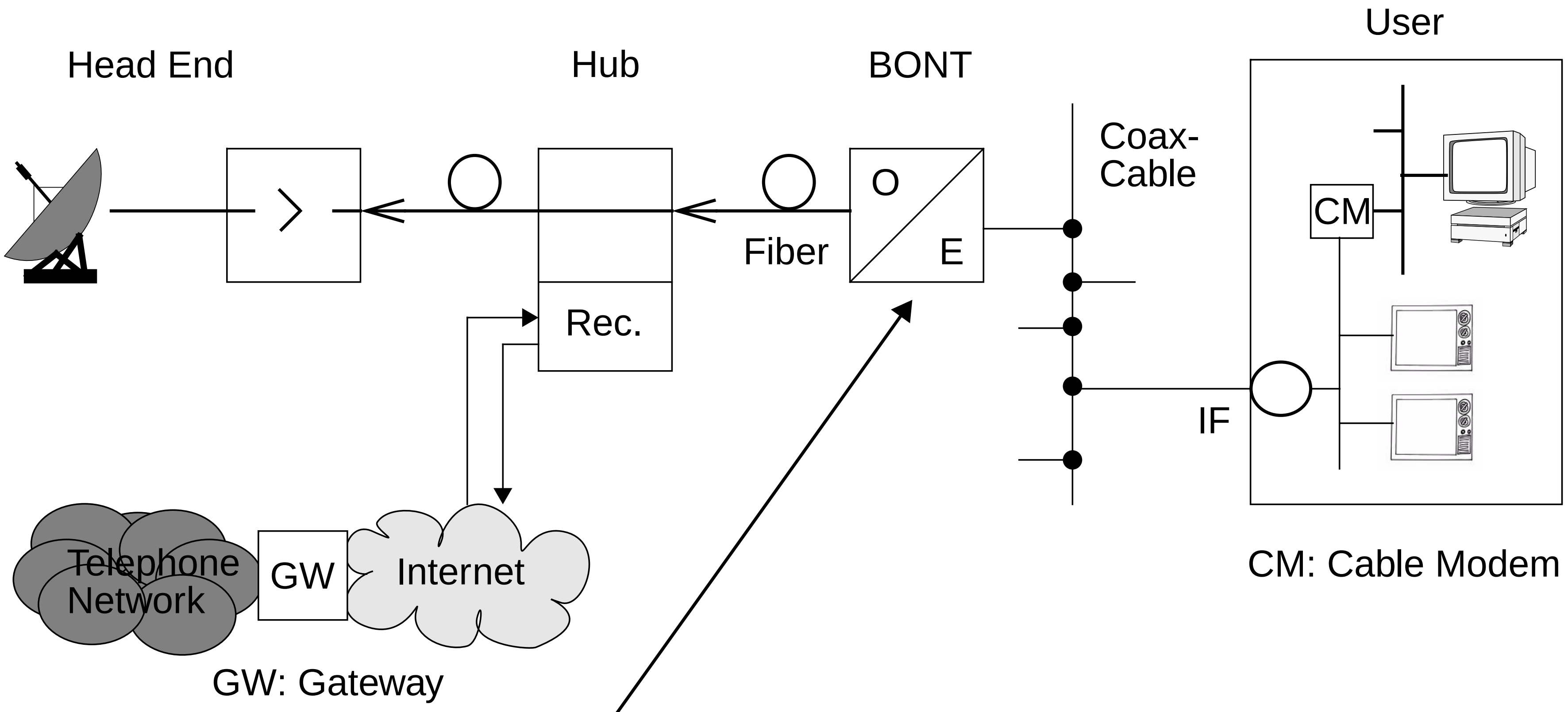
  combined with
  - Integrated Telecommunication and Data Networks

- Access Networks and Wide Area Networks
  - Existing DSL Technologies
  - Future Optical Access Networks
  - Metro / Core Networks
  - Fiber Networks of Energy Providers

  with Gateways to the Internet

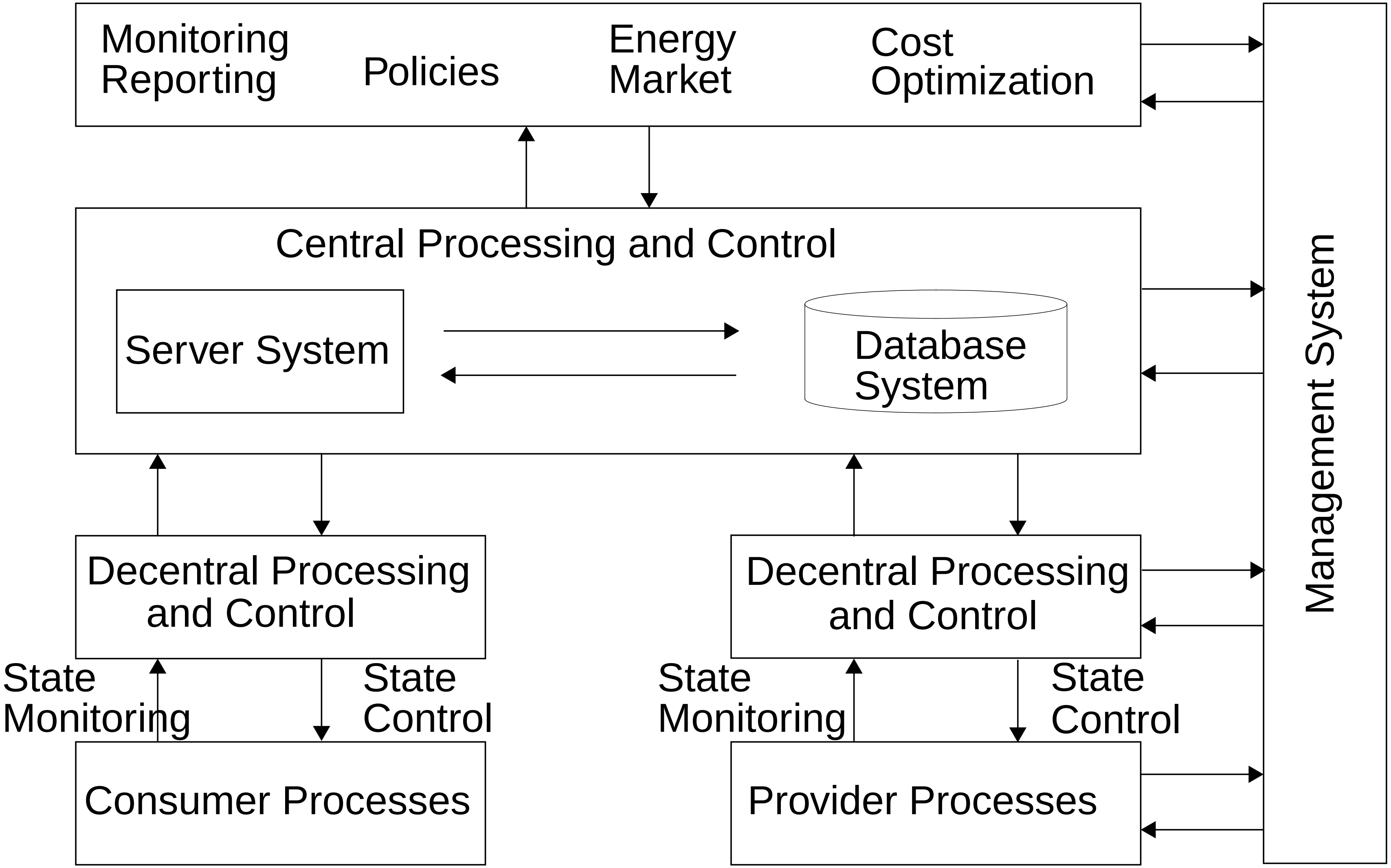
2.3 Energy Information Networks (3)

2.3.2 Example: Hybrid Optical /Coaxial Cable Access Networks



BONT: Broadband Network Termination
IF: Interface between Inhouse Network and Access Network

2.4 Power Management Architecture



Monitoring
Reporting

Policies

Energy
Market

Cost
Optimization

Central Processing and Control

Server System

Database
System

Management System

Decentral Processing
and Control

State
Monitoring

State
Control

Consumer Processes

Decentral Processing
and Control

State
Monitoring

State
Control

Provider Processes

3. Energy Efficiency in Mobile Communications

3.1 Equipment Technology

3.2 Dynamic Resource Allocation

3.3 Protocol and Service Engineering

3.1 Equipment Technology (1)

Low-Power Design

Example: ACM SIGDA Low-Power Technical Committee (LPTC), 2008

www.sigda.org/tech_committee/common/intro/index.php?tc=lowpower

Areas:

- Physical Design
- Logic/RTL-Synthesis
- System-Level Design
- Low-Power Design
- Testing
- FPGA, Configurable Computing
- Verification
- Emerging Technologies
- DFM

Topics:

- Low-Power Busses
- Software (Compiler/OS)
- Synthesis (RTL, FSM, ...)
- Battery-Aware Power Management
- Data Compression
- Clock Gating
- Gate-Level/High-Level Power Estimation
- Clock Routing
- Gate Scaling
- Multi-Processing/Multi-Cores
- Leakage-Aware Design

3.1 Equipment Technology (2)

Mobile Terminals

Topics: RF-Amplifier Design

Application Specific IC Design

Standard/Multi-Core Design

Software Processes (OS, Service Applications)

Display Technology

Radio Base Stations

Topics: Field of Patent Activities
(Power-Saving BS Design)

Example: NSN GSMA Global Mobile Award 2009
(World’s Most Energy-Efficient BS)

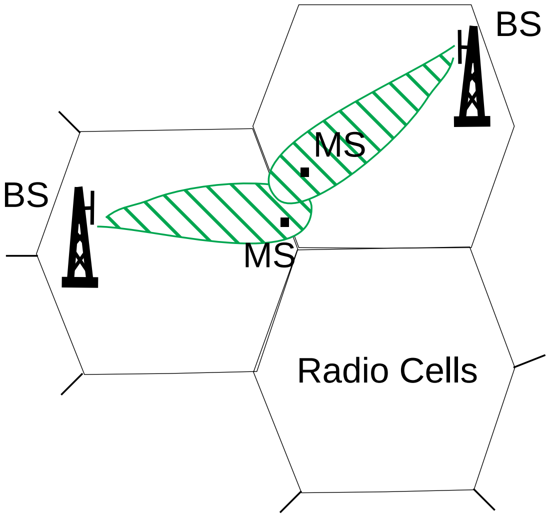
- Single Unit for GSM, 3GPP, WCDMA/HSPA

- Multiradio Technologies

- Only 20 % of Conv. Size, 70 % Power Saving

3.2 Dynamic Resource Allocation

Beyond 3G Mobile Network Evolution



- Cellular Concepts with Sectorized/Beam Antennas, MIMO-Systems
- Adaptive Beam Forming
- Dynamic Assignment of TX Resources (OFDM: Frequency/Time Slots) Dependent on Channel State
- Interference Coordination

3.3 Protocol and Service Engineering

• **Beam Steering:**	Adaptive Control of Angle and Power Dependent on Interference Conditions
• **Error Correction:**	Hybrid ARQ Schemes
• **Signalling:**	Cooperation between BS and MS by Signalling of Channel States and Load
• **Power Control:**	Automatic Sleep Mode Dynamic Activation
• **Traffic Control:**	Resource Allocation Dependent on Service Requirements, Traffic Characteristics, and Quality of Service (X-Layer Optimization)

4. Performance Modelling of Power Saving Solutions

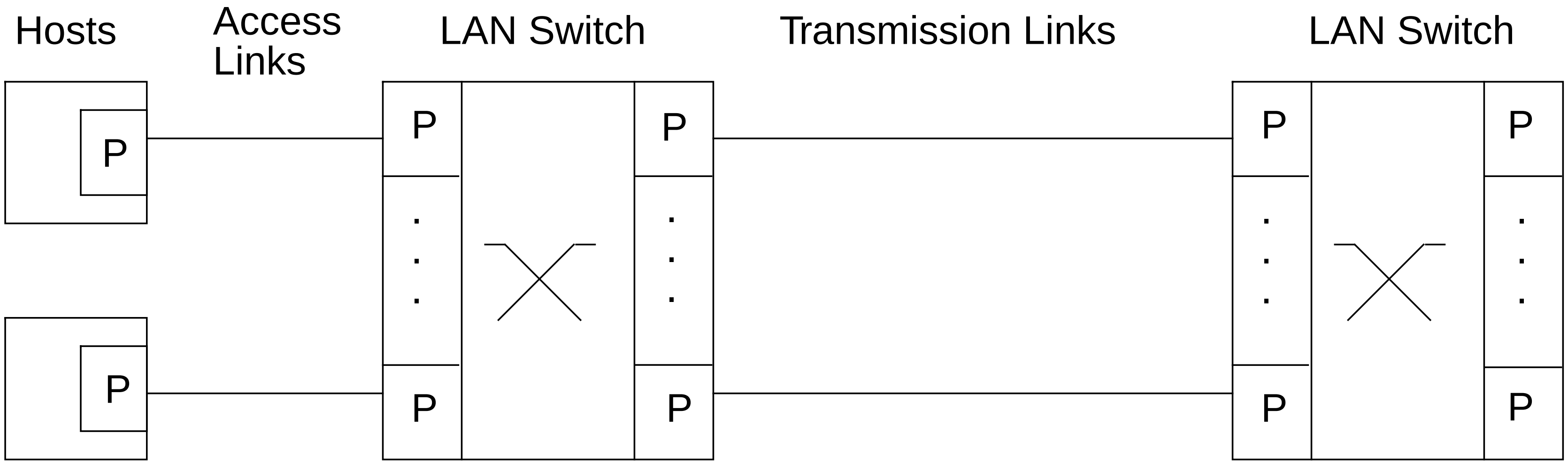
4.1 Concepts of Adaptation of Link Capacity

4.2 Resource-Sharing Models for Adaptive Link Capacity

4.3 Principal Results

4.1 Concepts of Adaptation of Link Capacity (1)

Example: LAN Switching

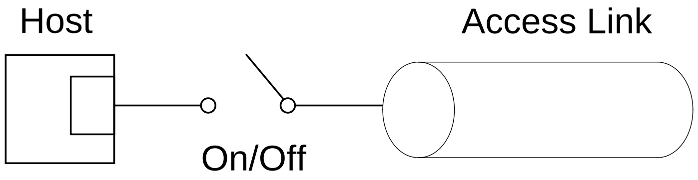


Principles of Adaptation

1. Dynamic Transmission Link Control	-->	Activation/Deactivation of Transmission Link
2. Link Aggregation	-->	Adaptive Link Rate (ALR)
3. Sleeping	-->	Different Sleep States of Resources

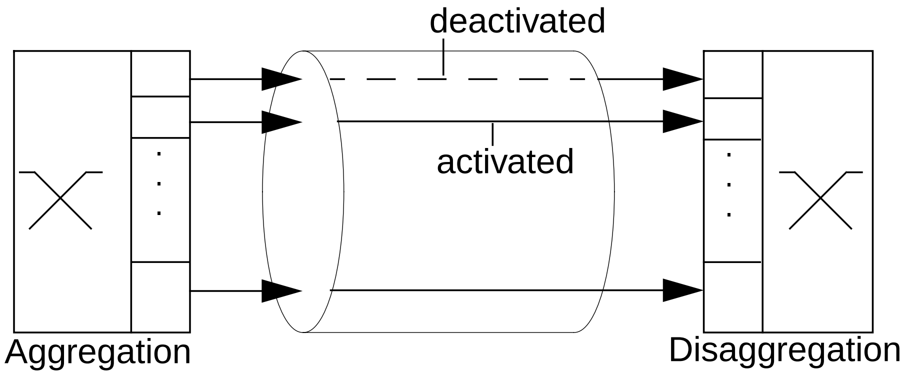
4.1 Concepts of Adaptation of Link Capacity (2)

4.1.1 Dynamic Transmission Link Control



- On/Off Mode
- Adaptive Clock Frequency Mode

4.1.2 Adaptive Link Rate (ALR)



- Activation/Deactivation Dependent on Current Traffic Load
- Negotiation Protocol Required (Bandwidth, Resynchronization)
- Logical Link by Aggregation

- Methods of Activation/Deactivation
  - Load Level Crossing Policy
  - (Dual) State Level Crossing Policy
  - Time-Out Threshold Policy

4.1 Concepts of Adaptation of Link Capacity (3)

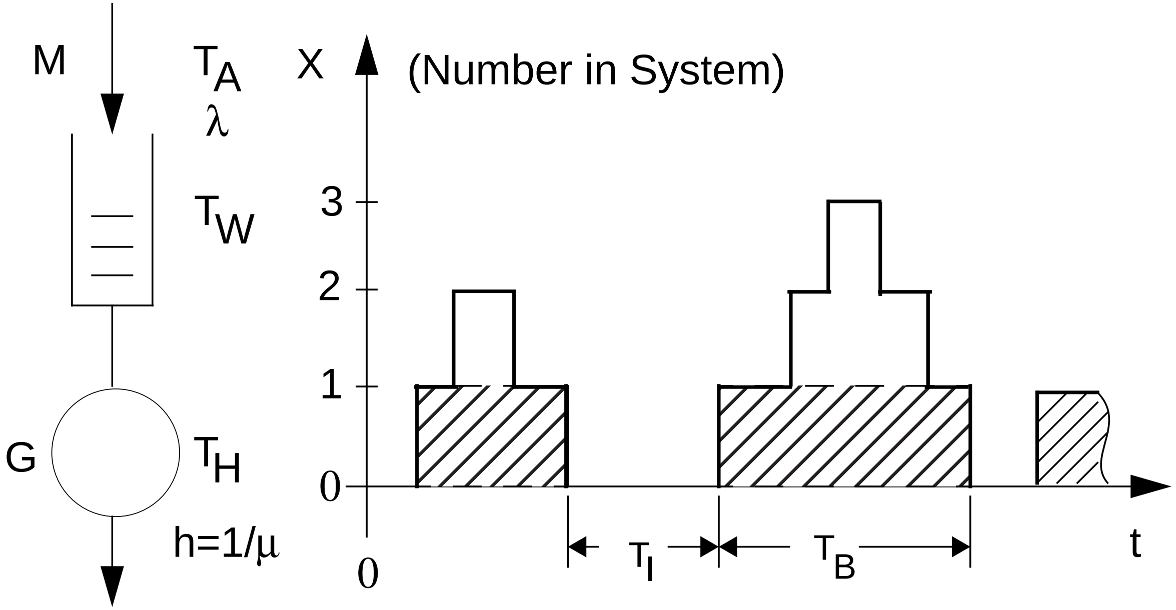
4.1.3 Sleeping Modes

Activity State Model: Activity State = (S_0, S_1, S_2, ..., S_m, Off)

1. Example:	S_0	Fully Activated, Power P_0, Clock Frequency f_0	
(Switch)	S_1, ..., S_m	Operation Clock Levels, Clock Frequencies $f_0 > f_1 > ... > f_m$	
	Off	Deactivated	
2. Example:	S_0	Fully Activated	
(Interface)	S_1	Packet Buffered	--> Activate S_0
	S_2	Packet Loss	--> Activate S_1
	Off	Deactivated	

4.2 Resource-Sharing Models for Adaptive Link Capacity (1)

Ideal Single-Server Model



Idle Period $E[T_I] = 1/\lambda$

Busy Period $E[T_B] = h/(1-A)$

Waiting Time $E[T_W] = \dfrac{A(1 + c_H^2)}{2(1 - A)} \cdot h$

Load Factor $A = \lambda/\mu$

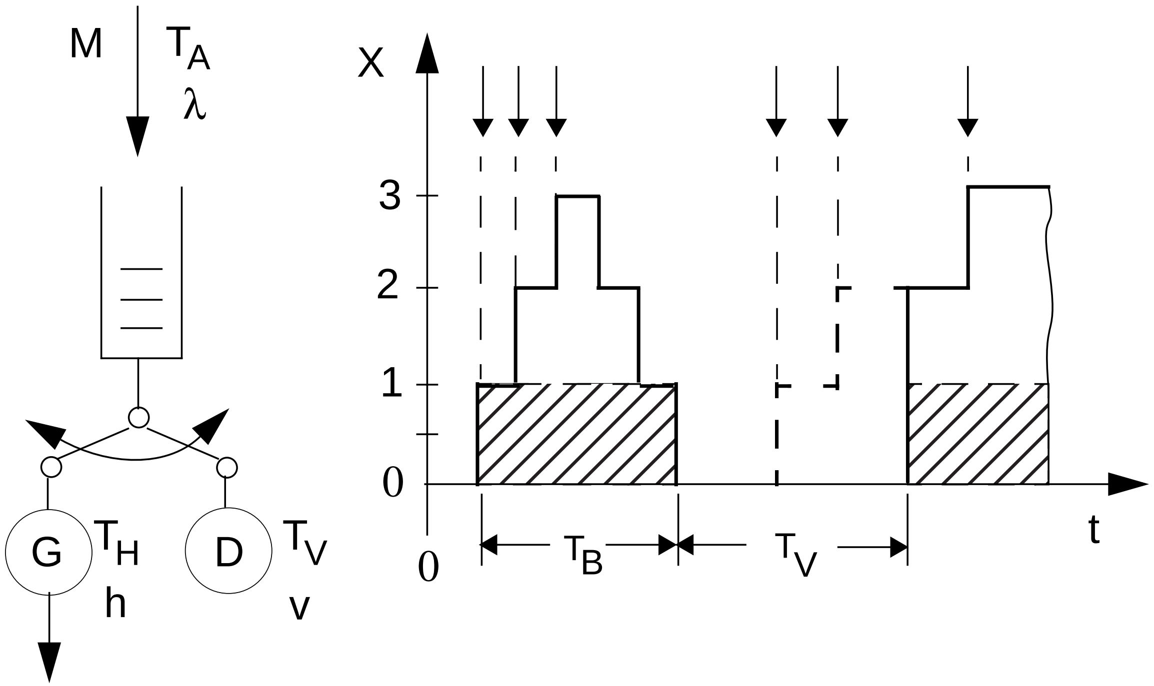
Power Cons. $PC = A \cdot P_0$

Power Saving $PS = (1-A) \cdot P_0$

Problem: Model not Feasible (Overhead for On/Off Server Management)

4.2 Resource-Sharing Models for Adaptive Link Capacity (2)

Single Server Model with "Server Vacation"



VP: $E[T_V] = v$

IP: $E[T_I] = \dfrac{v}{1 - e^{-\lambda v}}$

BP: $E[T_B] = \dfrac{A}{1 - A} \cdot \dfrac{v}{1 - e^{-\lambda v}}$

WT: $E[T_W] = E[T_W]_{M/G/1} + \dfrac{v}{2}$

$$= \frac{A(1 + c_H^2)}{2(1 - A)} \cdot h + \frac{v}{2}$$

- Power Cons. $PC = A \cdot P_0$
- Power Saving $PS = (1\text{-}A)\, P_0$

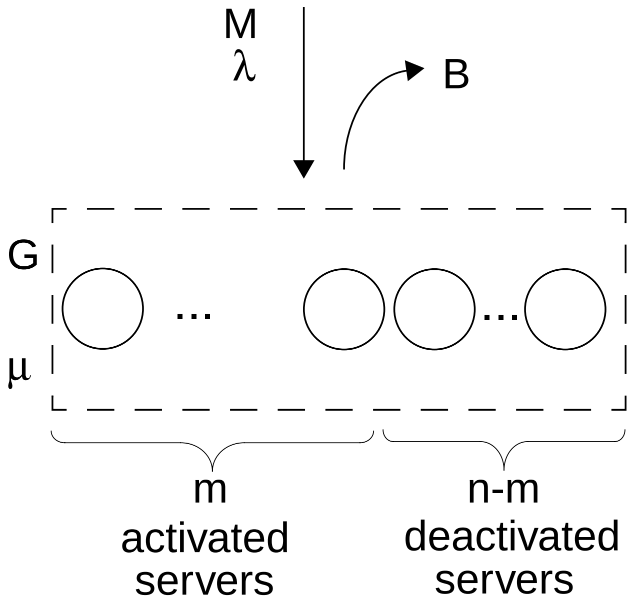
but:

- BP and IP are Stretched by Factor $\dfrac{vh}{1 - e^{-vh}}$
- Mean Waiting Time Increases by v/2

4.2 Resource-Sharing Models for Adaptive Link Capacity (3)

Bufferless Multi-Server Model with Load-Dependent Server Activation

Model



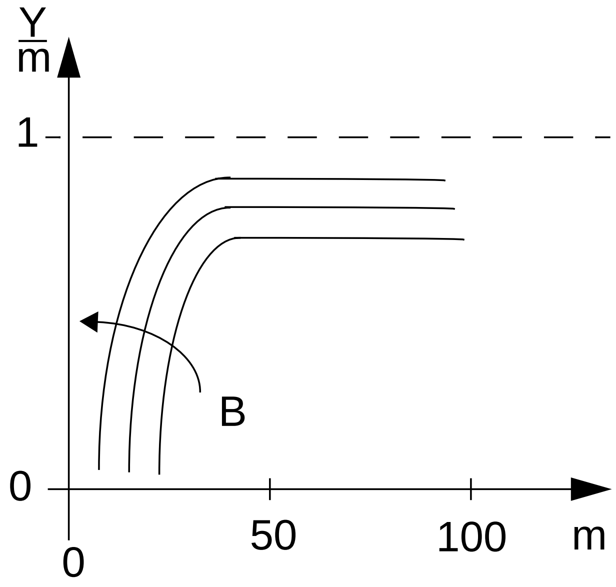
Method

- Activation/Deactivation after Load Change;
  Load Levels A1, A2, ...
- Estimation of Load Level A
  by Measurements within Specified Intervals
- Calculation of Loss Probability acc. to
  Erlang Loss Formula

$$B = E_{1m}(A) = \frac{A^m / m!}{\sum_{i=0}^{m} A^i / i!}$$

- Calculation of Activation Level m acc. to
  $B(m,A) \leq B_0 \ll 1$

4.2 Resource-Sharing Models for Adaptive Link Capacity (4)



- Making Use of the "Economy of Scales" Property

$$\frac{Y}{m} = f(m;B)$$

$Y = A(1-B)$ Carried Traffic

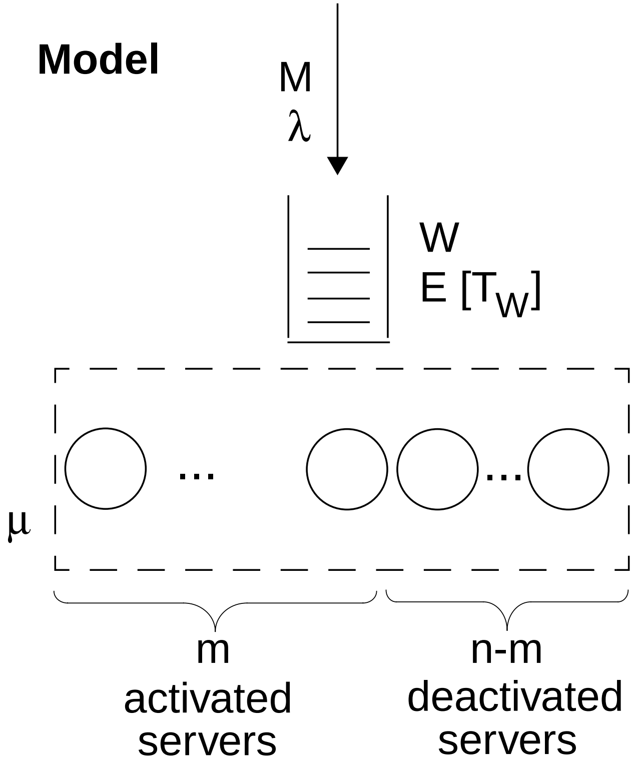
$A = \lambda/\mu$ Offered Traffic

- Power Consumption $PC = m \cdot P_0$
- Power Saving $PS = (n-m) \cdot P_0$

4.2 Resource-Sharing Models for Adaptive Link Capacity (5)

Buffered Multi-Server Model with Load-Dependent Server Activation

Model



Method

- Analogously to Bufferless Model
- Adaptation acc. to Delay Probability W or Average Delay E [T_W]

$$W = f(A,m) \leq W_0$$

or $E[T_W] = g(A,m) \leq E[T_W]_0$

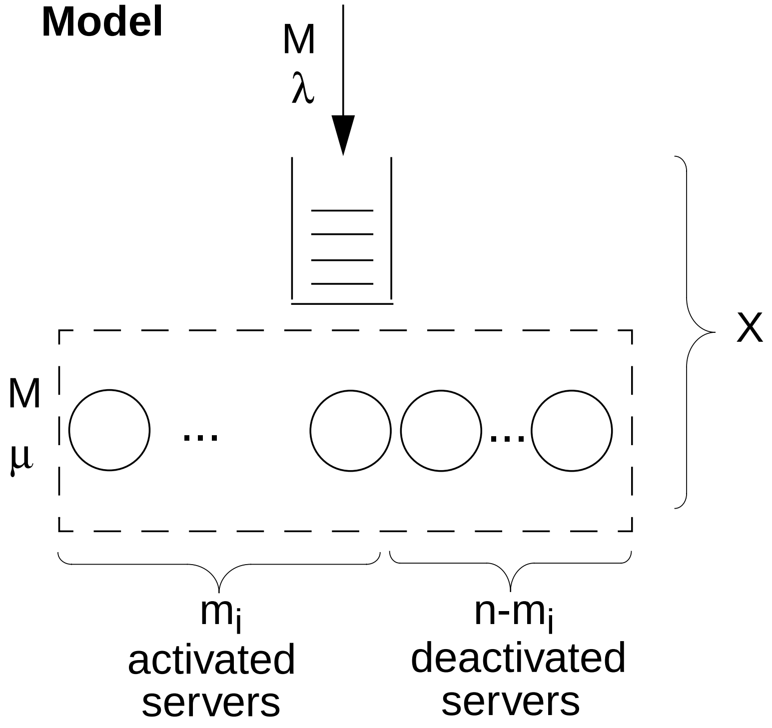
- Erlang Formulas

$$W = E_{2m}(A); \qquad E[T_W] = \frac{h}{m - A} \cdot W$$

4.2 Resource-Sharing Models for Adaptive Link Capacity (6)

Buffered Multi-Server Model with State-Dependent Server Activation

Model



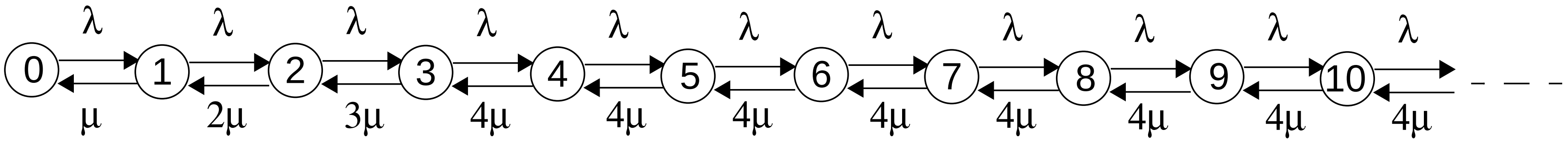
Method

- Add (Drop) Server Activations after Crossing Upper Level X_u (Lower Level X_l) where $X_l < X_u$ (Hysteresis)
- Calculate Activated Number of Servers acc. to Performance Criteria W (or $E[T_W]$) Using Erlang Formula or Birth & Death Process with Variable Service Rates
- Extension to Multi-Level Model (X_{iu}, X_{il}), i = 1, 2, ...
- $PC = m_i P_0$, $PS = (n-m_i)P_0$

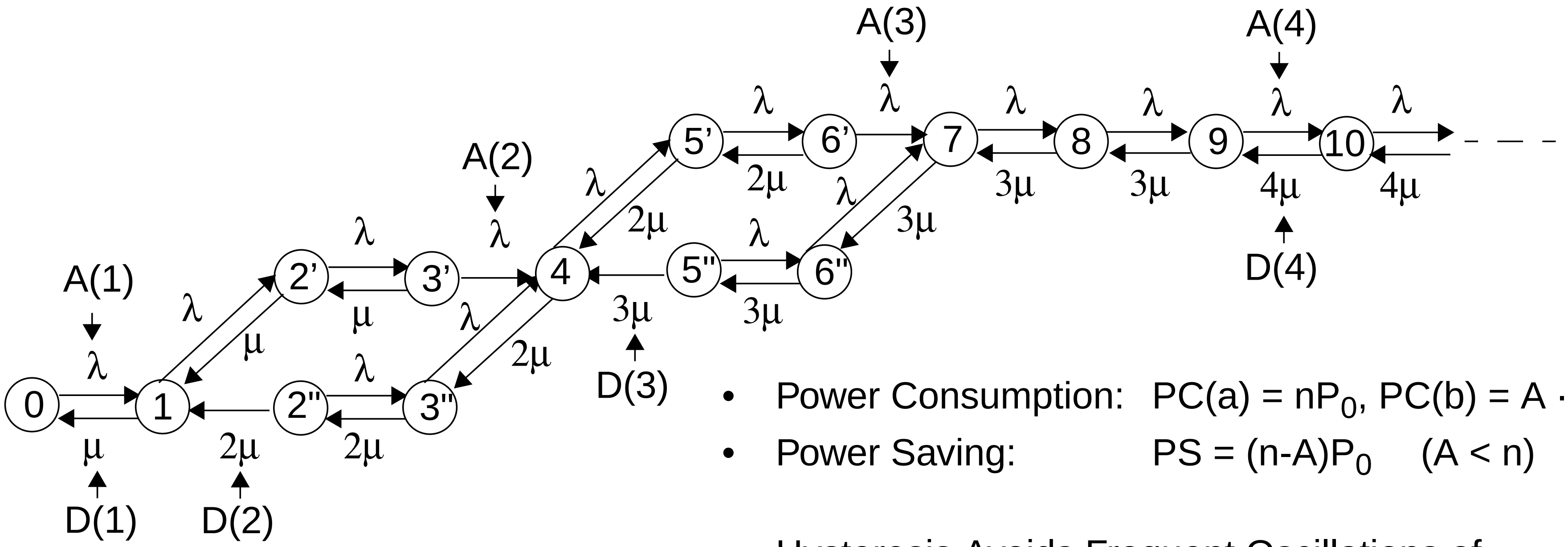
4.2 Resource-Sharing Models for Adaptive Link Capacity (7)

Buffered Multi-Server Model with State-Dependent Server Activation/Deactivation

a) State Transition Diagram for M/M/n Delay Model **without** Adaption:
Example n = 4 Servers



b) State Transition Diagram for M/M/n Delay Model **with** Adaptive Server Activation/Deactivation:

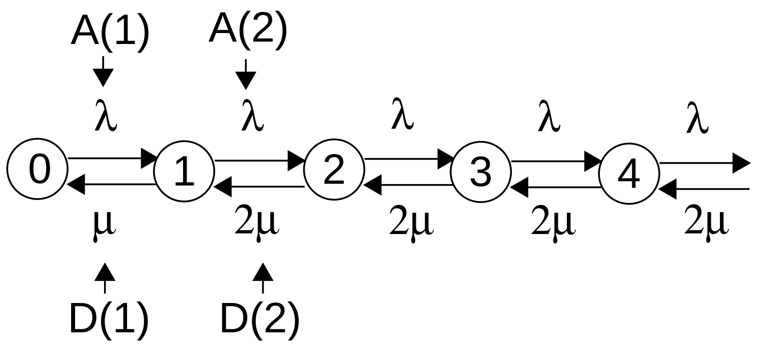


- Power Consumption: PC(a) = nP_0, PC(b) = $A \cdot P_0$
- Power Saving: PS = $(n-A)P_0$ $(A < n)$
- Hysteresis Avoids Frequent Oscillations of Activation/Deactivation

4.2 Resource-Sharing Models for Adaptive Link Capacity (8)

Example: n = 2 Servers with State-Dependent Server Activation/Deactivation

a) **Without Hysteresis**



Power Consumption PC

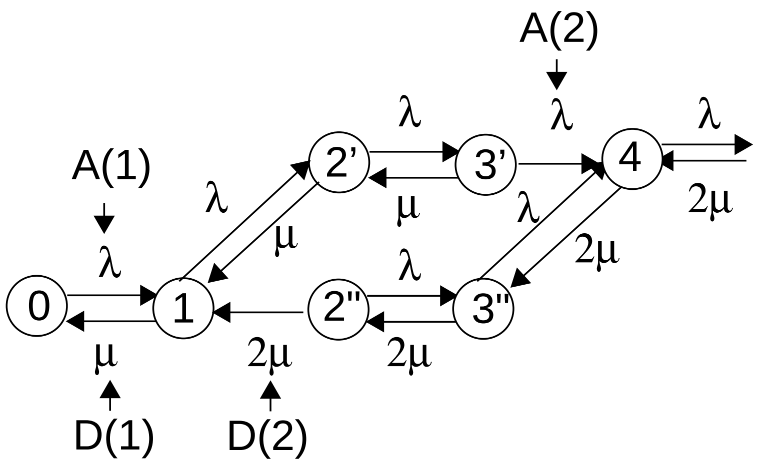
$$PC(a) = PC(b) = A \cdot P_0$$

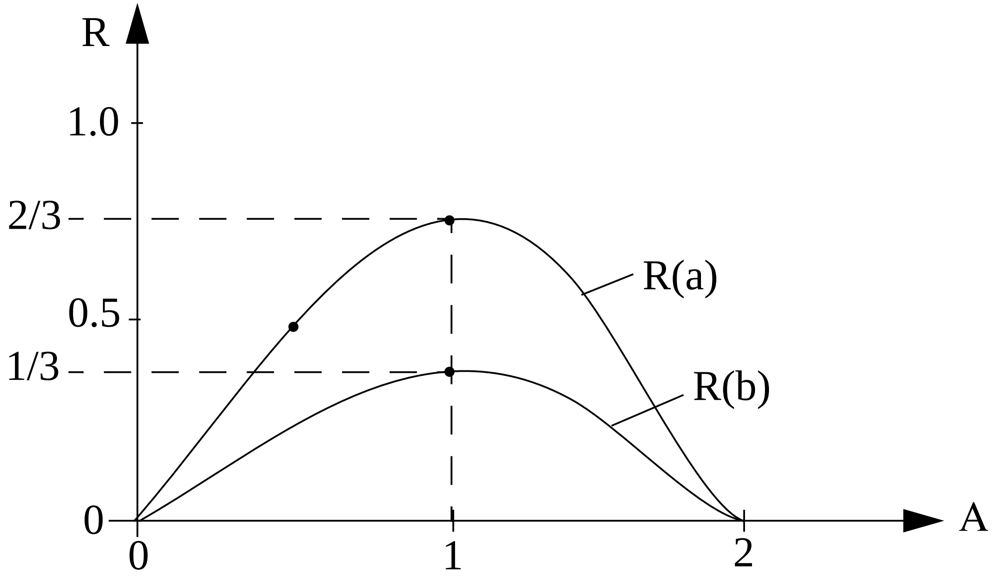
Activation/Deactivation Rate R

$$R(a) = p_a(0)\cdot\lambda + p_a(1)\cdot\lambda = p_a(1)\cdot\mu + p_a(2)2\mu = \frac{2-A}{2+A}\,(A+1)\cdot\lambda$$

b) **With Hysteresis**

$$R(b) = p_b(0)\cdot\lambda + p_b(3')\cdot\lambda = p_b(1)\cdot\mu + p_b(2'')2\mu$$





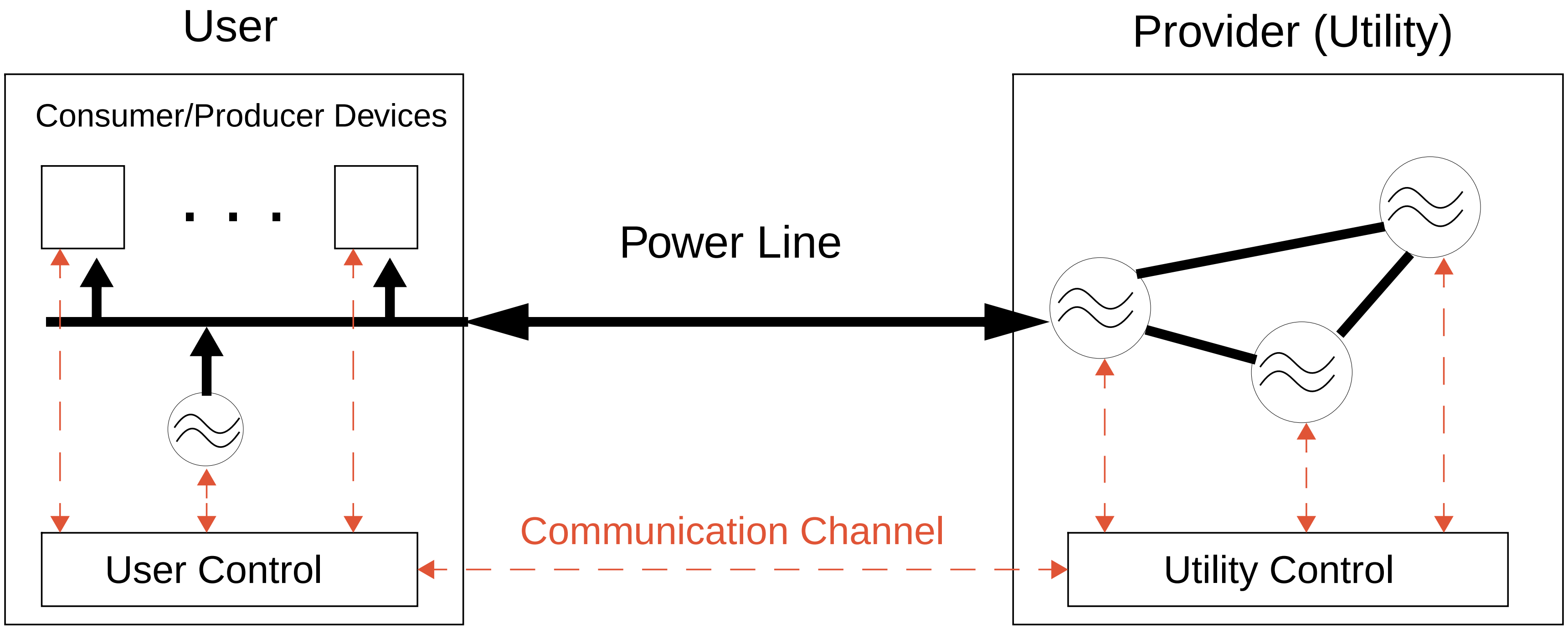
5. Power Grids - The Conflict Between Transparency and Privacy

5.1 Information Transparency in the Smart Grid

5.2 Privacy in the Smart Grid

5.3 The Way Out of the Conflict

5.1 Information Transparency in the Smart Grid



- **Ideal Control** - Transparency of En. Consumption ---> Power Requirement P(t)
  - Transparency of En. Production ---> Power Availability (kW, Tariff, ...)
- **Implementation** - Central Control (Provider)
  - Decentral Control (Consumer)
  - Distributed Control (Cooperation between Provider and Consumer)

5.2 Privacy in the Smart Grid

- **Detailed User Power Consumption Data Underly OECD Privacy Principles**
  - Recording of Smart Meter Data $\Longrightarrow$ Conclusions on Personal/Company Activities
  - Storage Places and Durations of such Data?
  - Access Rights and Control of Usage of such Data?
  - Ownership of such Data?

- **Accuracy, Quality and Control**
  - Accuracy of Measurements or Future Needs
  - Granularity of Energy Consumption Data (Resolution)
  - Completeness and Relevance of Collected Data
  - Application Control (User or Provider?)

5.3 The Way Out of the Conflict (1)

- **Need for Legal Framework**
  - Documentation of Information Types of Collected Data
  - Providing User Notification or User Access to Recorded User Data
  - Limiting the Collected Data to the Required Minimum
  - Limiting the Distribution of Private Consumer Data
  - Limiting the Storage of User Data to the Absolutely Necessary Duration

- **Technical Solutions**
  - Safeguarding of Personal Information Against Unauthorized Access, Disclosure or Copying
  - De-Identifying : Anonymizing / Pseudonymizing of Identities
  - Decentralized Control:

    Smart Power Control Can be Done Completely Decentralized

    Incentives: Online Information about Available Power and Time-Dependent Tariffs

5.3 The Way Out of the Conflict (2)

Further Reading:

"Smart Grid Cyber Security - Strategy and Requirements"

Draft Report of the Smart Grid Interoperability Panel

Cyber Security Working Group

NIST (National Institute of Standards and Technology)

US Department of Commerce

Draft NISTIR 7628, February 2010 (305 Pages)