Battery Lifetime Distributions

Boudewijn R. Haverkort
Design and Analysis of Communication Systems
Faculty for Electrical Engineering, Mathematics and Computer Science
University of Twente, the Netherlands
`http://dacs.cs.utwente.nl/`

50th IFIP WG 10.4 Meeting
June 29–July 2, 2006, Annapolis, MD

Who am I?

- since 2003: full professor, Design and Analysis of Communication Systems, University of Twente
- 1995–2002: associate professor, Performance Evaluation & Distributed Systems, RWTH Aachen
- 1991–1995: lecturer, Tele-Informatics and Open Systems, University of Twente
- spring 1993: visiting researcher, Teletraffic Research Centre, University of Adelaide

Did I do Dependability?

- Ph.D. on performability evaluation, 1991
- DCCA-2 in Tucson, AZ, 1991
- started performability workshop series, 1991
- organized EWDC in Twente in 1995
- almost all PDS conferences since 1995 (PC chair in 2005)
- all (but one) performability workshops (since 1991): //www.pmccs.net/
- QEST conference series, since 2004: //www.qest.org/

Design and Analysis of Communication Systems

- 5 tenured faculty (1/2/2), 2 industrial affiliates
- 3 postdocs, around 10 PhD students (funding: NWO, STW, EZ, EU)
- active in courses on Telematics, Computer Science, Electrical Engineering (BSc+MSc) and Security, Embedded Systems (only MSc)
- classes on systems:
  networking, mobile & wireless, fault-tolerant, distributed computing
- classes on evaluation: performance and dependability evaluation, quantitative evaluation of embedded systems

DACS = Dependable Ambient Communication Systems?

- **management and measurement on operational networks**: capacity planning, TCP measurements, SMTP, web-service management, λ-switching, intrusion detection (anomaly based)

- **design and implementation of mobile/wireless access networks**: ad hoc routing (power-aware), context-aware networking, service discovery, QoS protocols, prototyping and simulation

- **modelling and evaluation of networked embedded systems**: formal specification of protocols, including time, model checking for performability, batteries, tool development

Dependability Becomes Important in the Netherlands!

- 3 TU (Twente, Eindhoven, Delft) will become a federation as of 2007

- 50 MEU to stimulate the convergence process:
  - 12 MEU to NIRICT (//www.nirict.nl/)
  - half of this (6 MEU) to CeDAS (for 5 years)

- CeDAS = Centre of Excellence for Design, Analysis and Synthesis of Dependable Systems

- distributed centre in which 3×6 chairs cooperate on dependability issues (in the broadest sense)

- research programme currently being set up, coordinated by me; hope to be agenda-setting for large funding programs

so far for the background

let's talk about batteries!

About Batteries (I)

- more and more systems become battery powered (see the *IEEE Computer* November 2005 special issue)
- low power consumption becomes of utmost importance to have long system lifetimes (think of sensor networks, but aldo PDAs, and so on)
- low power design as such is very important, but not enough, as batteries tend to have very interesting non-linear behaviour
- this asks for "battery awareness" at various layers in the system design
- it is not just the amount of power that is used, but also the extraction pattern of power that is of importance

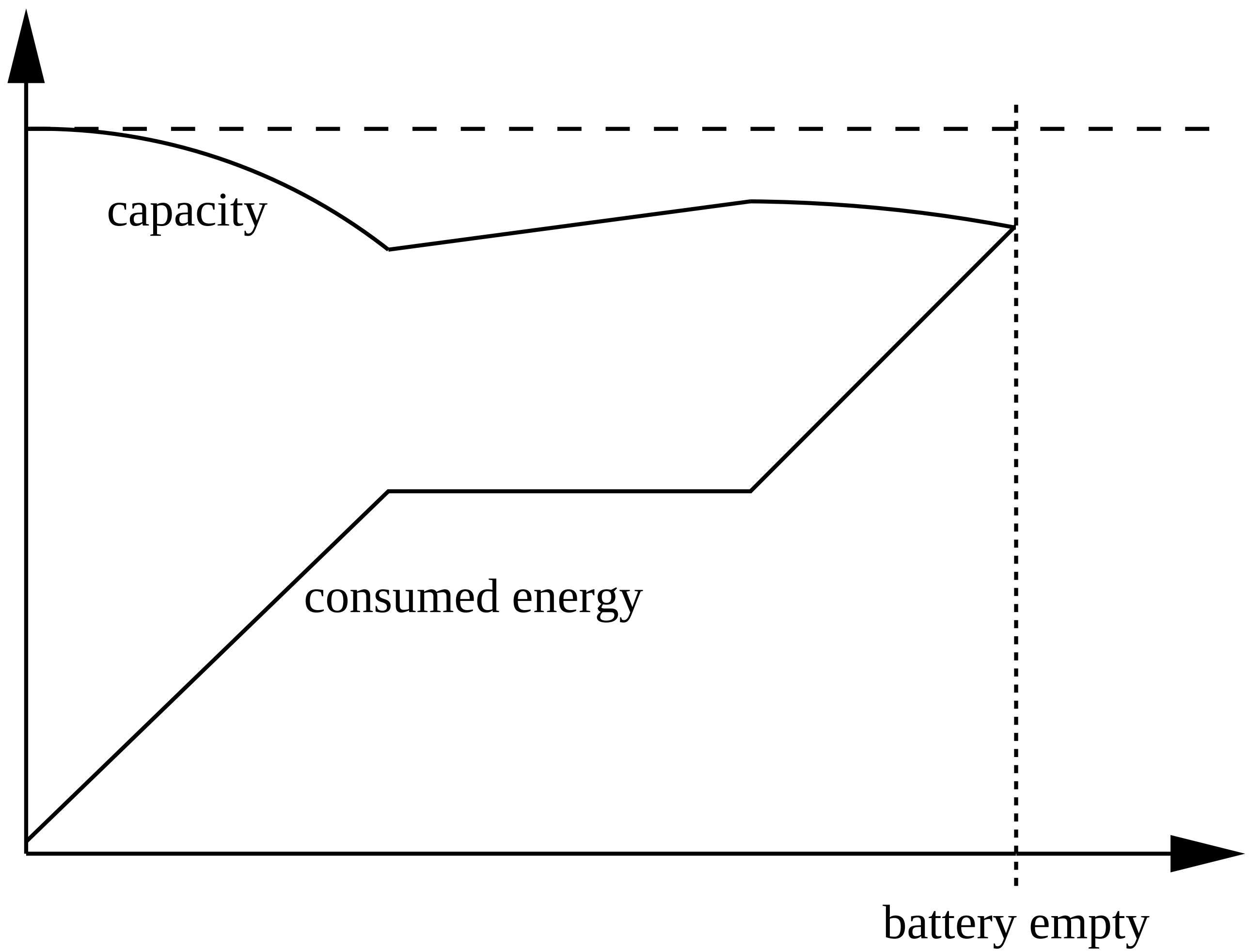
About Batteries (II)

- variety of types of models has been developed: electro-chemical and electrical, but none of these are used in a true systems context
- first approaches using stochastic models appeared recently
- voltage (Volt, V) and capacity C (Ampere-hour, Ah)
- energy stored is product of voltage and capacity
- capacity is not the same under all types of load; voltage drops under high load, and capacity is smaller under high load
- ideally: lifetime $L = C/I$, with I the employed current

Battery Recovery and Saturation Effects

- **recovery**: at high loads, the internal ion flow (Li^+) (between anode and cathode) can not keep up with the speed of the current drawn externally so that voltage drops
- at lower loads, this backlog of ions is recovered from
- **saturation**: with long-lasting loads, there might be too little ions at the cathode to react with
- the outside of the cathode becomes saturated even though internally there are ions available; some ions simply become unreachable

Non-Linear Effects in Battery Usage



What is the Lifetime of a Battery-Powered Device?

- depends strongly on the usage pattern, hence, device application workload
- the battery characteristics
- model this as a non-homogeneous Markov reward model (MRM):
  - transition matrix $\mathbf{Q}$ describes the system/application workload
  - reward rates can depend on time and on the battery content left
  - two reward rates per state: one for usage, one for restoration effects
- two accumulative reward variables:
  - $Y_1(t)$ for power used (initially 0) up to time t
  - $Y_2(t)$ for the remaining battery capacity at time t (initially C)

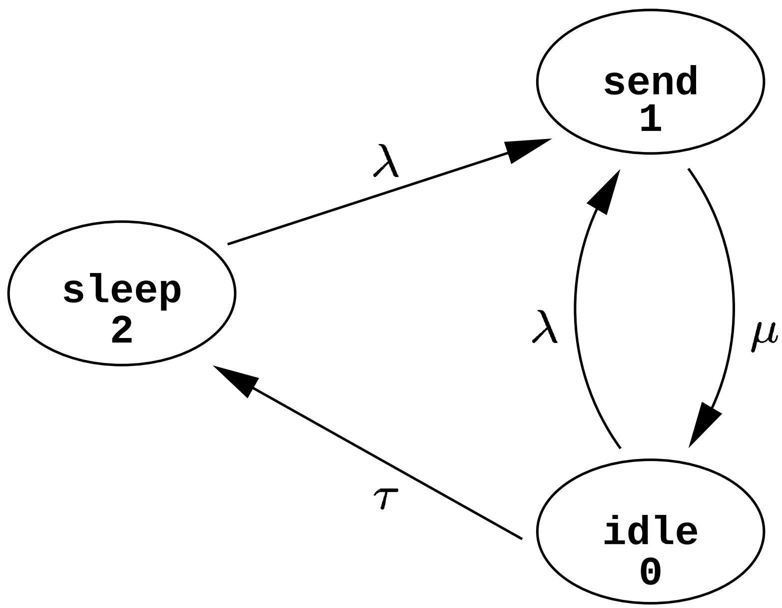
Reward Specification

- power consumption: fixed non-negative reward rates $r_{i,1}$
- for the capacity restoration effects, we need to distinguish two cases:
  - $r_{i,1} = 0$: $r_{i,2} = c$, as long as $C - Y_1$ is not exceeded
  - $r_{i,1} > 0$: $r_{i,2} = -r_{i,1} \cdot \dfrac{1}{Y_2 - Y_1}$
- there is modelling freedom here
- $\Pr\{\text{battery empty at time } t\} = \Pr\{Y_1(t) \geq Y_2(t)\}$
- in essence: performability distribution in non-homogeneous MRMs

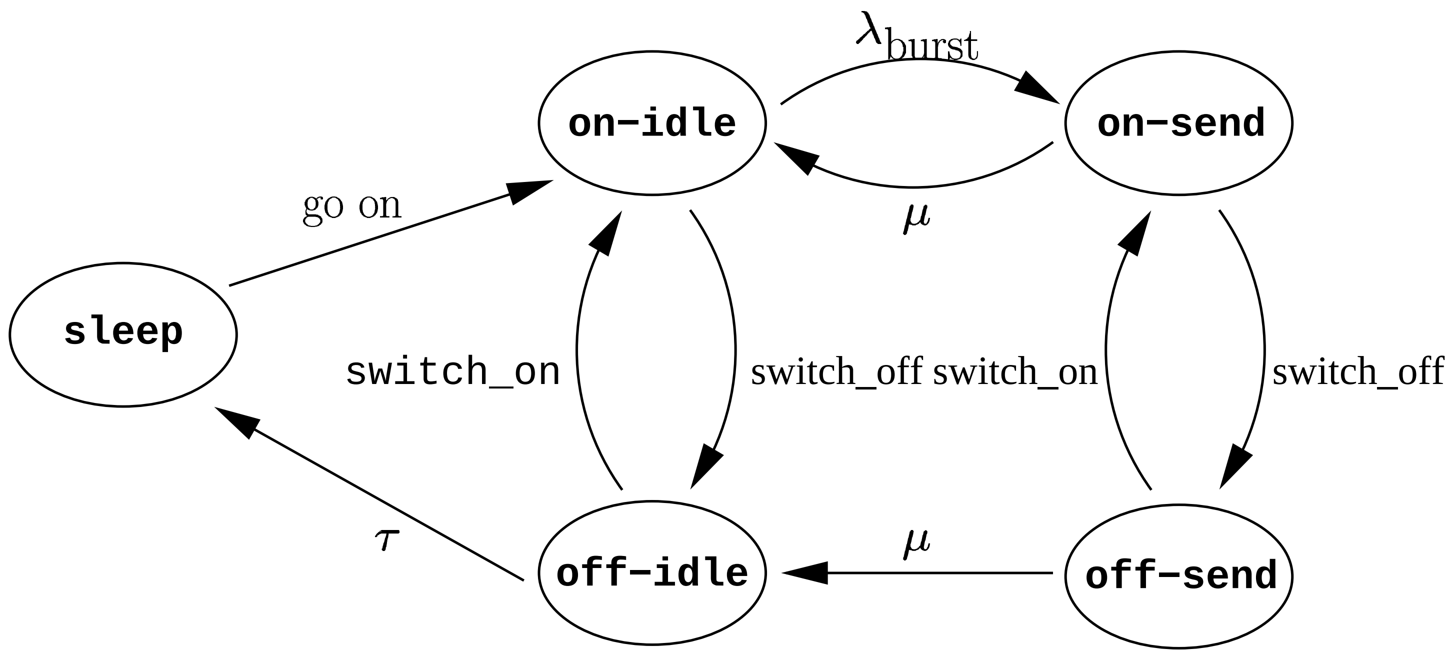
Example Modelling Study

- two workload models (3 and 5 state) with same average workload, but one more bursty than the other
- 800 mAh battery; rates such that you can sleep 110 hours or send 4 hours
- to allow for longer restoration periods, it might be benificial to collect packets and send in burst (with high energy consumption)

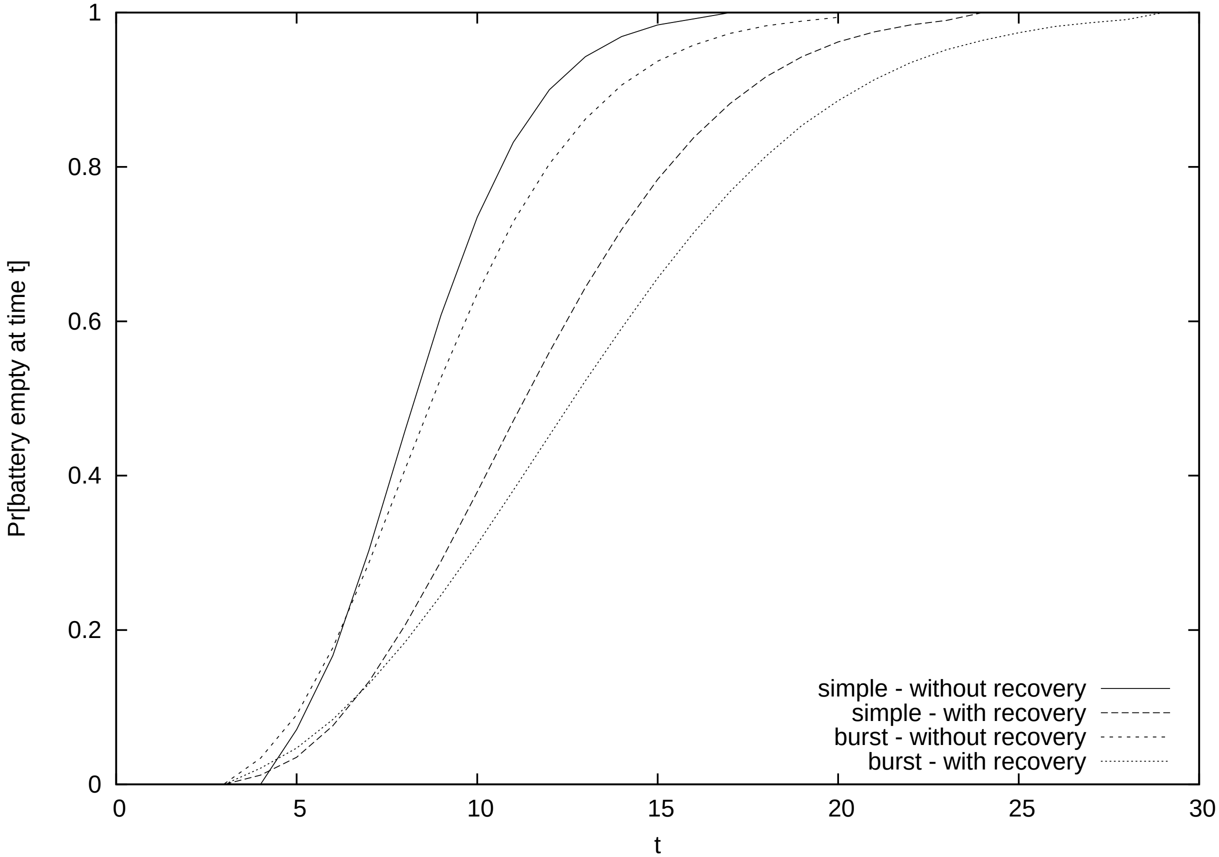
Simple Workload Model



Bursty Workload Model



Typical Result: Lifetime Distribution



Employed Algorithms

- no exact algorithms available
- two algorithms: Markovian approximation, and discretisation
- space complexity: $\mathcal{O}\left(N \cdot \frac{y_1}{\Delta} \cdot \frac{y_2}{\Delta}\right)$
- time complexity: $\mathcal{O}\left(N^2 \cdot t \cdot \frac{y_1}{\Delta} \cdot \frac{y_2}{\Delta}\right)$
- Δ is a Markovian discretisation parameter

To Conclude

- batteries become important: battery empty $\Rightarrow$ failure
- first approach to model batteries in a true system context
- new algorithms were needed (and need to be further developed)
- simulation (Spice models) or true experimental platform needed for model evaluation

thank you for your attention