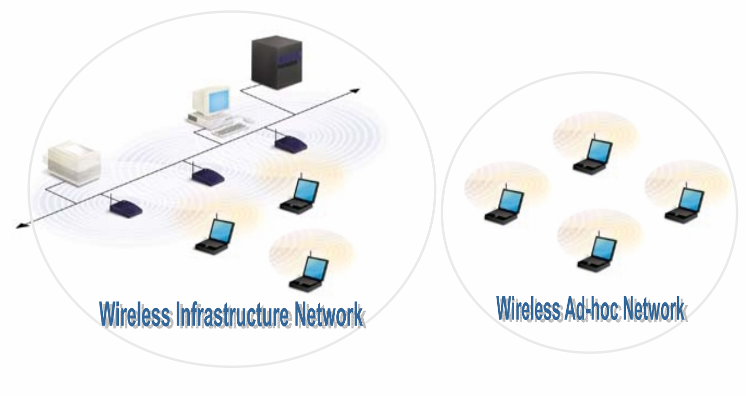
Extending the Lifetime of a Network of Battery-Powered Mobile Devices by Remote Processing:
A Markovian Decision-based Approach

Peng Rong and Massoud Pedram

University of Southern California
Dept. of EE
Los Angeles CA 90089

June 5, 2003

Wireless Network Topology

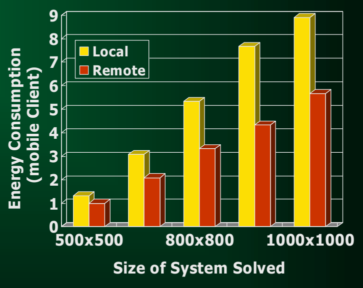


Outline

- Introduction
- Background
- System Modeling
- Policy Optimization
- Experimental Results
- Conclusion

Introduction

- Employ Wireless Remote Processing to Save Energy
  - Migrate a task from an energy-constrained mobile host to an AC-powered base station
  - Wireless communication results in power consumption
  - Applications:
    - ✧Task detection and recognition
    - ✧Voice recognition
    - ✧Large-scale numerical computations
    - ✧Simulation
    - ✧Compilation



Power savings for remote execution of Gaussian solution of a system of linear algebraic equations

[Rudenko-98]

Prior Work

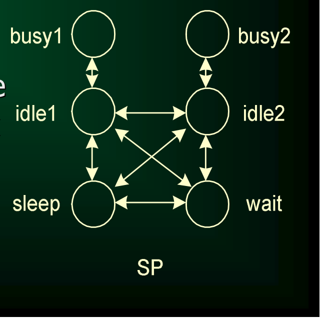
- A remote processing framework that supports process migration at the operating system level [Othman-98]
- An adaptive decision-making policy based on CPU measurements for a repetitive task [Rudenko-99]
- A compilation framework for remote processing [Kremer-01]
- An economics-based computation distribution protocol [Shang-02]

Discussion

- The previous works do not
  - consider any task timing constraints
  - discuss how to combine remote processing and power management techniques to achieve further energy saving
- Our work targets a mobile device providing real time services in a client-server wireless network
- Our objective is to minimize power consumption of the mobile host by using remote processing and dynamic power management while meeting some real-time constraints

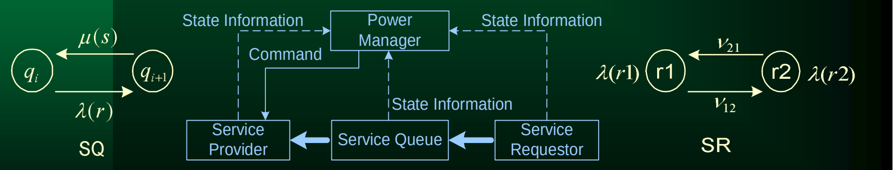
Background I

- Dynamic Power Management (DPM)
  - Selectively shuts down the idle components or slows the underutilized components
- (Controllable) Continuous-Time Markovian Decision Processes (CTMDP) : An Example [Qiu-00]
  - State space
  - Action set
  - Generator matrix
    - ✧Represents the state transition rate
    - ✧Action-based parameterized matrix
  - Cost function components
    - ✧Power consumption
    - ✧Transition energy



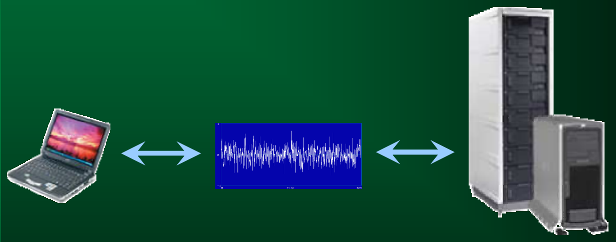
Background II

- Constructing the CTMDP Model of the System
  - State space
    - ✧The Cartesian product of the state space of each component minus invalid states
  - Generator matrix
    - ✧Independent components: tensor-sum method
    - ✧Correlated components: each entry should be computed separately



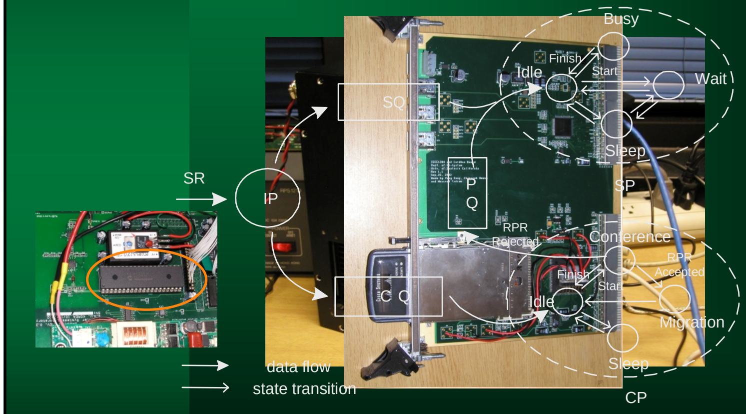
Modeling the Application Scenario

- Components
  - Mobile host (client), wireless channel, base station (server)

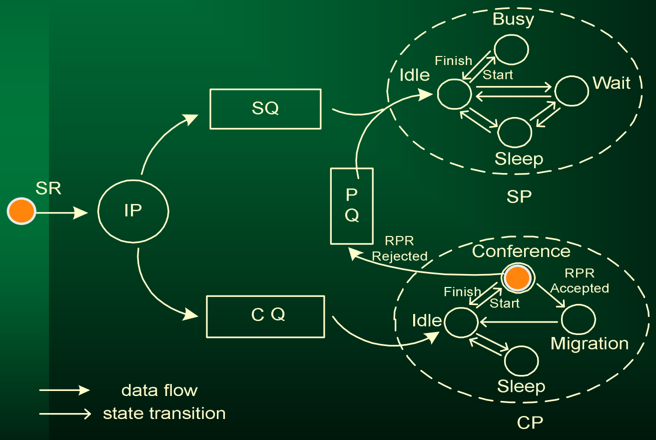


Mobile Client ⟷ **Wireless Channel** ⟷ **Server**

Model of the Mobile Client



Service Flow in the Mobile Client



Assumptions about the Mobile Client

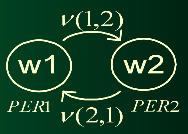
- Continuously executes real-time processes to service the incoming tasks
- Different tasks differ in the task size, which is assumed to be exponentially distributed
- Relationships between the task size, the execution time, and the migration time are known in advance (e.g., profiling)

Remote Processing Procedure

- Step1: Send the Remote Processing Request (RPR)
- Step2: Server responds with ACCEPT or REJECT message
- Step3: If accepted, migrate the remote execution candidate (REC)
- Step4: Start new task or go to sleep
- Step5: Server completes REC
- Step6: Get back results of computation (RES)

Model of the Wireless Channel

- Wireless channel
  - Noisy, bandwidth limited
  - Multi-path fading and shadowing effect
- A two-state CTMDP model
  - State: represents the expected packet error rate
  - State transition: models the slow fading effect

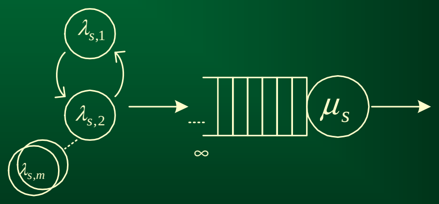


- Data migration time over an error-prone wireless channel

$$t_a = n \cdot \sum_{m=0}^{\infty} t_0 \cdot PER^m = \frac{nt_0}{1-PER} = \frac{t}{1-PER}$$

Model of the Server

- Queuing model
  - An infinite M/M/1 queue with a multi-state task generator



  - The mobile client only needs to know the rejection probability for its RPRs

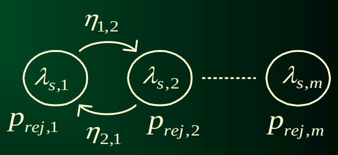
Calculating the Rejection Probability

- The rejection probability Calculation
  - Hard real-time constraint: $t_e + t_w \le c \cdot t_e \ (c \ge 1)$

$$p_{rej}(\lambda_s, \mu_s) = 1 - \sum_{n=0}^{\infty} p_n \cdot \Pr\{t_e(c-1) > t_w\},$$
$$= \frac{\lambda_s}{\mu_s} \cdot \frac{1}{(\mu_s - \lambda_s)E(t_e)(c-1)+1}$$

t_e: execution time of the task on the server
t_w: waiting time of the task to be executed on the server

- Special Cases



  - $c = 1$

$$p_{rej}(\lambda_s, \mu_s) = \lambda_s / \mu_s = 1 - p_0$$

  - Uniform task size distribution and μ_s □ λ_s

$$p_{rej}(\lambda_s, \mu_s) = \frac{1}{c(\mu_s / \lambda_s - 1) + 1} \approx \frac{\lambda_s}{c\mu_s}$$

Optimal Offline Policy

- Formulated as a Linear Programming problem based on the CTMDP model
- Objective function is to minimize the power consumption of the mobile client
- Subject to constraints on
  - Ratio of task loss due to full queues
  - Average task delay: locally executed tasks and remotely executed tasks

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Online Policy

- Based on a 2-D decision table computed off-line
  - Key: (PER, P_{reject})
  - Value: policy
- Parameter prediction
  - PER: predicted packet error rate

$$PER^{(n)} = \alpha \cdot APER^{(n)} + (1-\alpha) \cdot PER^{(n-1)}$$

APER: short-term actual packet error rate

  - P_{reject}: predicted rejection probability

$$P_{reject}{}^{(n)} = \beta \cdot P_{rej}(\lambda_s{}^{(n)}, \mu_s{}^{(n)}) + (1-\beta) \cdot RR_N$$

RR_N: rejected ratio of last N remote processing requests

Experimental Setup

- Component Parameters
  - SP: StrongARM SA1110

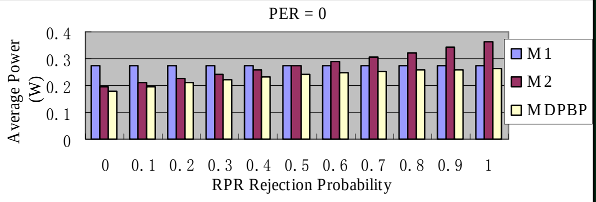
State	Busy	Wait	Sleep
Power (mW)	600	100	0.2
Transition Time	Wait to Busy Busy to Wait	10 us	
	Sleep to Busy	160 ms	
	Busy, Wait to Sleep	90 us	

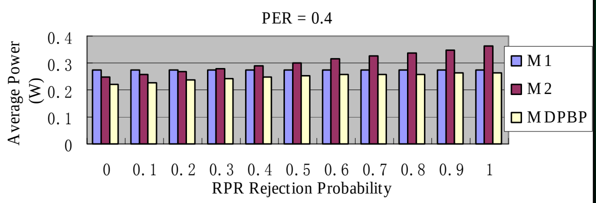
  - CP: Orinoco WLAN Card

State	Transmit	Receive	Sleep
Power (mW)	1400	900	50
Wake-up time (ms)	34		
Sleep-down time (ms)	62		

Experimental Results

- Offline Optimal Policy
  - Non-varying wireless channel and server behavior
    - ✧ **M1:** No RPR; **M2:** Always try RPR first





Experimental Results

- Offline Optimal Policy
  - Server: queuing model
  - Characteristics of the wireless channel and server changed stochastically

PER1	PER2	$\nu(1,2)$	$\nu(2,1)$
0%	20%	1/15000	1/10000
$\lambda_{s,1}$	$\lambda_{s,2}$	$\eta(1,2)$	$\eta(2,1)$
16 per sec.	24 per sec.	1/20000	1/20000

  - Results

Policy	M1	M2	MDPBP
Average Power (W)	0.2742	0.2746	0.2412
MDPBP Improvement	12.0%	12.2%	--

Experimental Results

- Online Policy
  - Server: queuing model
  - Wireless channel: slowly and randomly changing

Policy	M1	M2	MDPBP
Average Power (W)	0.2742	0.2510	0.2310
MDPBP Improvement	15.8%	10.1%	--

Conclusions

- A new mathematical framework for extending the lifetime of a mobile host in a client-server wireless network by using remote processing was proposed
- The client-server system was modeled based on the theory of continuous-time Markovian decision processes
- The DPM problem was formulated as a policy optimization problem and solved exactly by using a linear programming approach
- Based on the off-line optimal policy computation, an on-line adaptive policy was developed and employed in practice
- Experimental results demonstrated the effectiveness of our proposed methods
- Future work will be focused on ad-hoc mode wireless network