Abstract: This presentation explores optimization of paging and registration policies in cellular networks. Motion is modeled as a discrete-time Markov process, and minimization of the discounted, infinite-horizon average cost is addressed. The structure of jointly optimal paging and registration policies is investigated through the use of dynamic programming for partially observed processes. It is shown that there exist policies with a certain simple structure that are jointly optimal, though the dynamic programming approach does not directly provide an efficient method to find the policies.

Jointly optimal paging and registration policies are identified for a cellular network composed of a linear array of cells. Motion is modeled as a random walk with a symmetric, unimodal step size distribution. Minimization of the discounted, infinite-horizon average cost is addressed. The jointly optimal pair of paging and registration policies is found. The optimal registration policy is a distance threshold type: the mobile station registers whenever its distance from the previous reporting point exceeds a threshold. The paging policy is ping-pong type: cells are searched in an order of increasing distance from the cell in which the previous report occurred. The existence of provably jointly optimal policies for other symmetric networks is addressed, and a connections to isoperimetric inequalities is made.
Viewpoint of the network -- conditional probabilities

- MS is paged
- Paging cost: $4P$
- MS registers
- Registration cost $R$

Dynamic programming formulation

The joint optimization problem can be formulated as a dynamic programming problem on the space of conditional probability distributions (details in H., Mitzel, and Yang, Infocom 2003 paper).

An implication: there exist jointly optimal paging and registration policies specified by reduced complexity laws.

Reduced complexity laws (RCLs) $f$ and $g$

- Paging order $f$: state at last report, elapsed time since last report
- Registration probability $g$: state at last report, elapsed time since last report, current state in $(0,1)$

Write $C(f,g)$ for cost when RCL pair $(f,g)$ is used.

Finding an individually optimal pair of RCLs

Observations about cost $C(f,g)$:

- Given $g$, an optimal $f$ is given by maximum likelihood search
- Given $f$, an optimal $g$ can be found by dynamic programming on a finite state space

Suggests an iterative algorithm: $f^0 \rightarrow g^0 \rightarrow f^1 \rightarrow g^1 \rightarrow f^2 \ldots$

Provides good laws in numerical trials, though a simple example shows result may not be jointly optimal.
Example of suboptimality

Search 4 then 2 if paged at time 1 or 4 or 7 ... (optimal choice)

Suppose 0 < R < b (so a registration costs less than risk of paging one cell one slot later.)

f - search 3 then 5 (at time 2 or 5 or 8 . . . )
g - register in state 4

(f, g) - is an individually optimal pair

f* - search 5 then 3 (at time 2 or 5 or 8 . . . )
g* - register in state 2

(f*, g*) - is a jointly optimal pair

Example of optimality

Suppose:
+ set of states is the set of integers, and that
+ MS takes independent steps with symmetric, unimodal distribution b

f* - ping-pong search from last sighting

g* - distance threshold registration policy, thresholds d and -(d-1), for some positive integer d.

Proposition: (f*, g*) is optimal for some choice of thresholds Proof is outlined on the next five slides.
Let \( m \) and \( n \) be summable vectors of nonnegative numbers. Let 
\[ m[1] \geq m[2] \geq \ldots \]
be the nonincreasing ordering of the \( m \)'s.

**Definition:** \( m \) dominates \( n \), written \( m > n \), if:
- (sum of the \( m \)'s) = (sum of the \( n \)'s)
- \( m[1] + m[2] + \ldots + m[k] \geq n[1] + n[2] + \ldots + n[k] \) for all \( k \geq 1 \).

The vectors \( m \) and \( n \) are equivalent, and \( m \) is said to be a rearrangement of \( n \), if \( m > n \) and \( n > m \).

*Example of optimality (continued)*

Intuitively, \( m > n \) if \( m \) is more concentrated than \( n \).

Transfer principle: If \( m \) is obtained from \( n \) by transferring mass from a smaller value of \( n \) to a larger value, then \( m > n \):

Conversely, if \( m > n \), then \( n \) can be obtained from \( m \) by repeated transfers of mass.

**Definition:** Let \( s(m) \) = mean number of pages needed to find an MS with probability vector \( m \) for optimal search order:

\[
 s(m) = 1 + (1 - m[1]) + (1 - m[1] - m[2]) + (1 - m[1] - m[2] - m[3]) + \ldots
\]

**Lemma:** If \( m > n \), then \( s(m) \leq s(n) \).

Recall: \( b \) is the symmetric, unimodal step size distribution. \( b^* \) is neat.

**Proof of proposition**

Fix an arbitrary registration policy: consider one report cycle

<table>
<thead>
<tr>
<th>Time (t)</th>
<th>Mass removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( b )</td>
</tr>
<tr>
<td>1</td>
<td>( x(1-t)b )</td>
</tr>
<tr>
<td>2</td>
<td>( x(1-t)b )</td>
</tr>
</tbody>
</table>

Idea: Compare to a threshold policy with same mass removed at each stage.
Example of optimality (continued)

**Proof of proposition**

Threshold policy with same mass removed per step

<table>
<thead>
<tr>
<th>t=0</th>
<th>Mass removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>*b</td>
<td></td>
</tr>
<tr>
<td>(x(1-l_p))</td>
<td>(\text{reg}(g))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t=1</th>
<th>Mass removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>*b</td>
<td></td>
</tr>
<tr>
<td>(x(1-l_p))</td>
<td>(\text{reg}(g))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t=2</th>
<th>Mass removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>*b</td>
<td></td>
</tr>
<tr>
<td>(x(1-l_p))</td>
<td>(\text{reg}(g))</td>
</tr>
</tbody>
</table>

By induction, distributions \((w(k))\) of this scheme are neat and dominate those of the original registration policy.

Example of optimality (continued)

Completion of proof of optimality:

The two strategies have same mass removed at each time, so they have the same mean registration cost.

By induction, \(w(k)\) is neat for second strategy \(\rightarrow\) so ping-pong/threshold strategy has smaller mean paging cost.

Thus, ping-pong paging can be used without loss of optimality.

The matching registration policy is fixed threshold type. \(\square\)

Conjectured additional example of optimality

Suppose:

- set of states is plane
- MS takes independent steps with (radially) symmetric, unimodal density \(b\)

\(f^*\) - expanding distance search from last sighting
\(g^*\) - distance threshold registration policy

**Conjecture:** \((f^*, g^*)\) is optimal for some choice of thresholds.

Extension to 2 dimensions requires straightforward extension of concepts to continuous state space. For example:

Given functions \(f, g\) on the plane, nonnegative, integrable,
say \(f\) dominates \(g\) \((f \succ g)\) if for every \(c > 0\):

\[
\sup_{A: \text{measure}(A) = c} \text{integral of } f \text{ over } A \geq \sup_{A: \text{measure}(A) = c} \text{integral of } g \text{ over } A
\]

Say \(f\) is neat if \(f(x)\) is a nonincreasing function of \(|x|\) alone

**Lemma:** If \(f\) is neat, then \(f*b\) is neat.
However, so far we have been unable to generalize one lemma, but each of the following conjectures would imply the one that follows it.

Conjecture A: If \( f >_T \) and \( g >_\bar{g} \) and if \( f \) and \( g \) are neat, then \( f*g >_T \bar{g} \).

Conjecture B: Same as Conjecture A but with \( g=\bar{g} \).

Conjecture C: Expanding disk search and distance threshold registration policy are optimal if \( b \) is neat.

Note: Conjecture A (if true) implies the Brunn-Minkowski inequality for sets \( A, B \) in \( n \) dimensions:
\[
\mu(A+B)^{1/n} \geq \mu(A)^{1/n} + \mu(B)^{1/n}
\]
where \( A+B=\{a+b: a \in A \text{ and } b \in B\} \). (Take the sets to be the supports of the functions.)

Conclusions on Paging and Registration

- Finding/proving joint optimality is hard, subtle
- Finding individually optimal pairs is fairly tractable
- Nevertheless, optimal policies can always be expressed as reduced complexity control laws
- Further analysis, such as exploration of approximate methods of dynamic programming may be useful.
- Models here are extremely simplistic, perhaps takeaway message is that distance based policy may be reasonable. Systems today offer a quickly moving target for modelers.

Related work

C. Rose '96, '99
C. Rose & R. Yates '95
A. Bar-Noy & I. Kessler '93
A. Bar-Noy, I. Kessler, and M. Sidi, '96
U. Madhow, M.L. Honig, K. Stieglitz, '95

For citations and further reading

B. Hajek, IT Workshop, October '02
B. Hajek, K. Mitzel, and S. Yang, INFOCOM '03
www.uiuc.edu/~b-hajek

Thank you.