Cost-Optimization of IPv4 Zeroconf Protocol

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Ad hoc Networking

Models and Methods

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Outline

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- IPv4 Zeroconf Protocol
- The Model
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  - No answer probabilities
  - Abstrat cost
- Mean total cost
  - Cost function
  - Optimization
- Reliability
- Assesing the protocol
- conclusion

Motivation

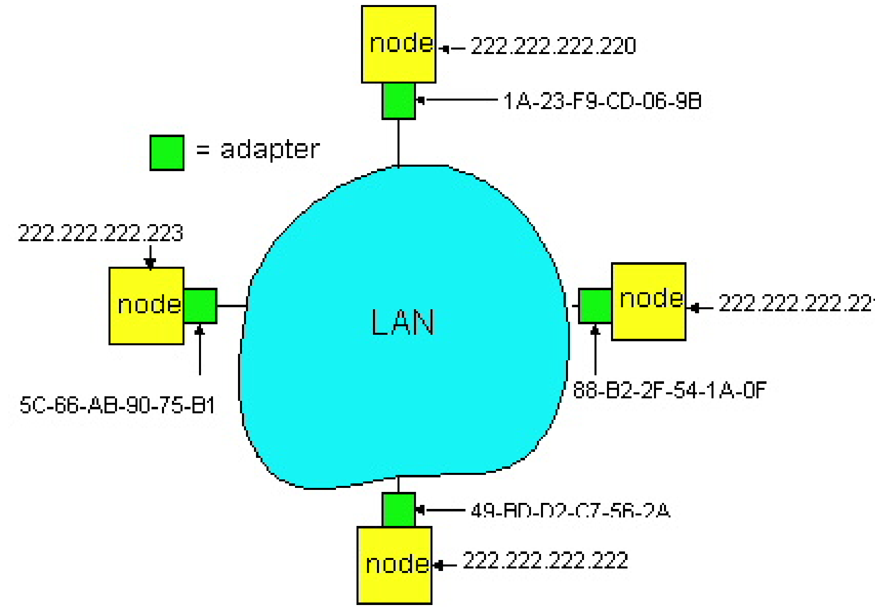
- Electronic devices to get connected via Local network based on IP protocol
- IP protocol required to get upper layer protocols supported (ftp etc…)
- No DHCP server
- No manual configuration
- Problem:
  - How to assign unique IP address?
  - Self-configuring (plug and play) devices

Motivation

- Proposed IPv4 zeroconf Protocol
  - Internet-draft end 2002
  - Randomized assignment of link-local addresses
- We discuss here Costs:
  - Cost during initialization phase
  - Cost when address collision occurs
- Questions to be addressed:
  - How to optimize the cost incurred
  - Trade-off between cost and reliability

IPv4 Zeroconf Protocol

- Based on ARP Protocol:
  - Address Resolution Protocol
  - A knows B's IP address, wants to know MAC address of B
  - A broadcasts ARP query pkt containing B's IP address
    - All machines on LAN receive this ARP query
  - B receives ARP pkt, replies to A with ist (B's) MAC address



IPv4 Zeroconf Protocol

- Zeroconf Protocol:
  - Fresh connected host (A) chooses randomly IP address from within 65024 link-local addresses between 169.254.1.0 and 169.254.254.255 allocated by IANA
  - A broadcasts ARP probe pkt containing chosen IP address
    - All hosts on LAN receive this ARP query
  - A waits for an answer or timeout **r**
    - If no answer, repeats **n** times
    - answer received,
      - A doesn‘t care about MAC addres
      - A knows chosen IP address is used
      - A chooses randomly new IP address and repeats
  - After **n** probes, if no reply, A adopts chosen IP address

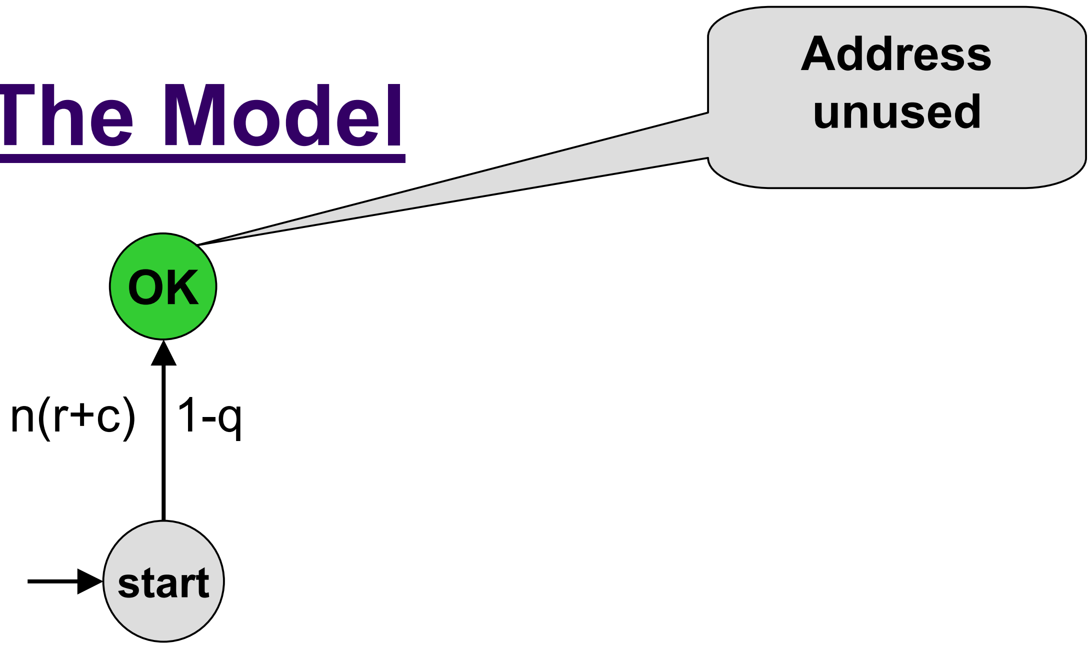
IPv4 Zeroconf Protocol

- Zeroconf Protocol:
  - Suggestions in draft:
    - n = 4,
    - r = 2 sec for unreliable(wireless) networks and,
    - r =0.2 sec for reliable ones
    - user must wait for 8 sec till new (unused) IP address is adopted
  - Decreasing n or r may lead to address collision
    - Cost of collision is very heigh (break active connections)
  - Trade-off between reliability (assigning unique IP address) and not disturbing the user too much
  - Q:What is the probability that a collision occurs for a given n & r?
  - Q:What is the optimal n and r s.t. overall (mean) cost of protocol is minimum?

The Model

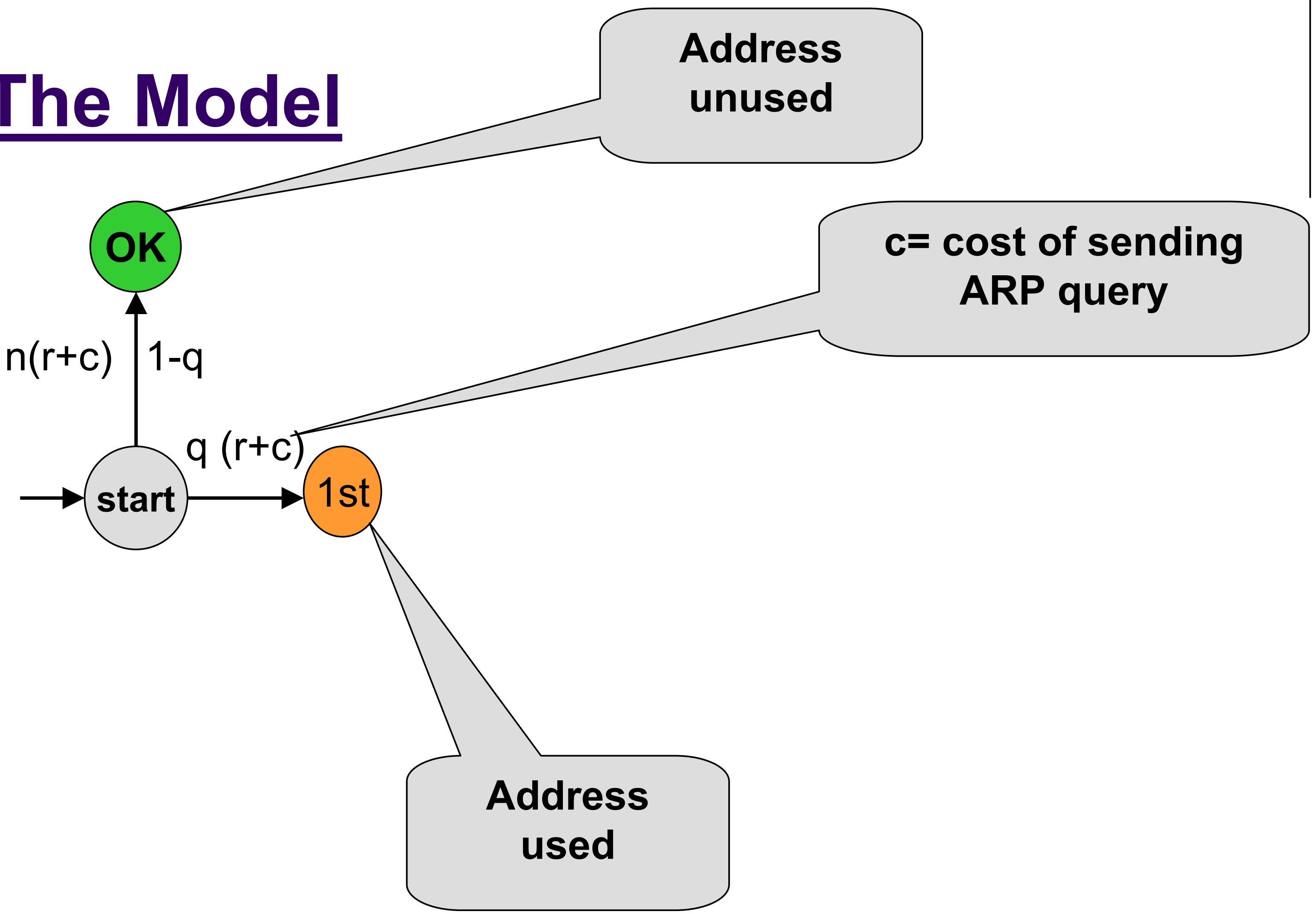
- Consider a single freshly connected device trying to connect to an existing ad hoc network (initialization phase)
- The network consists of m devices
- At most n ARP probes have to be sent to check the chosen IP address
- Time to wait between two queries is set to r
- Assume during initialization other devices neither added nor removed nor trying to get a new address
- Family of dicrete-time Markov reward models
  - Different DTMCs for n = 1,2,3,… with costs associated with transitions as rewards

The Model



q is probability of choosing used IP address q = m/65024

The Model



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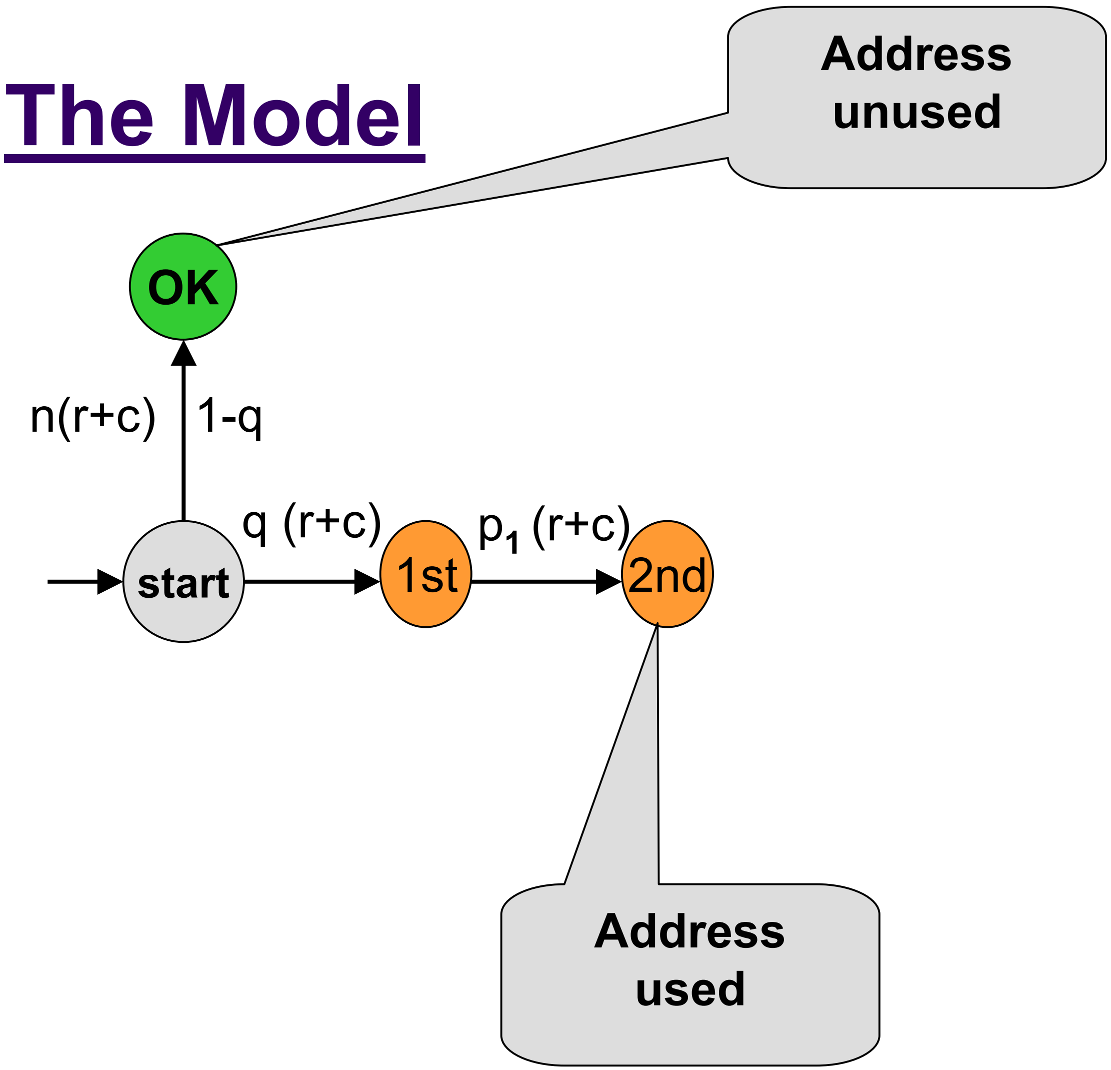

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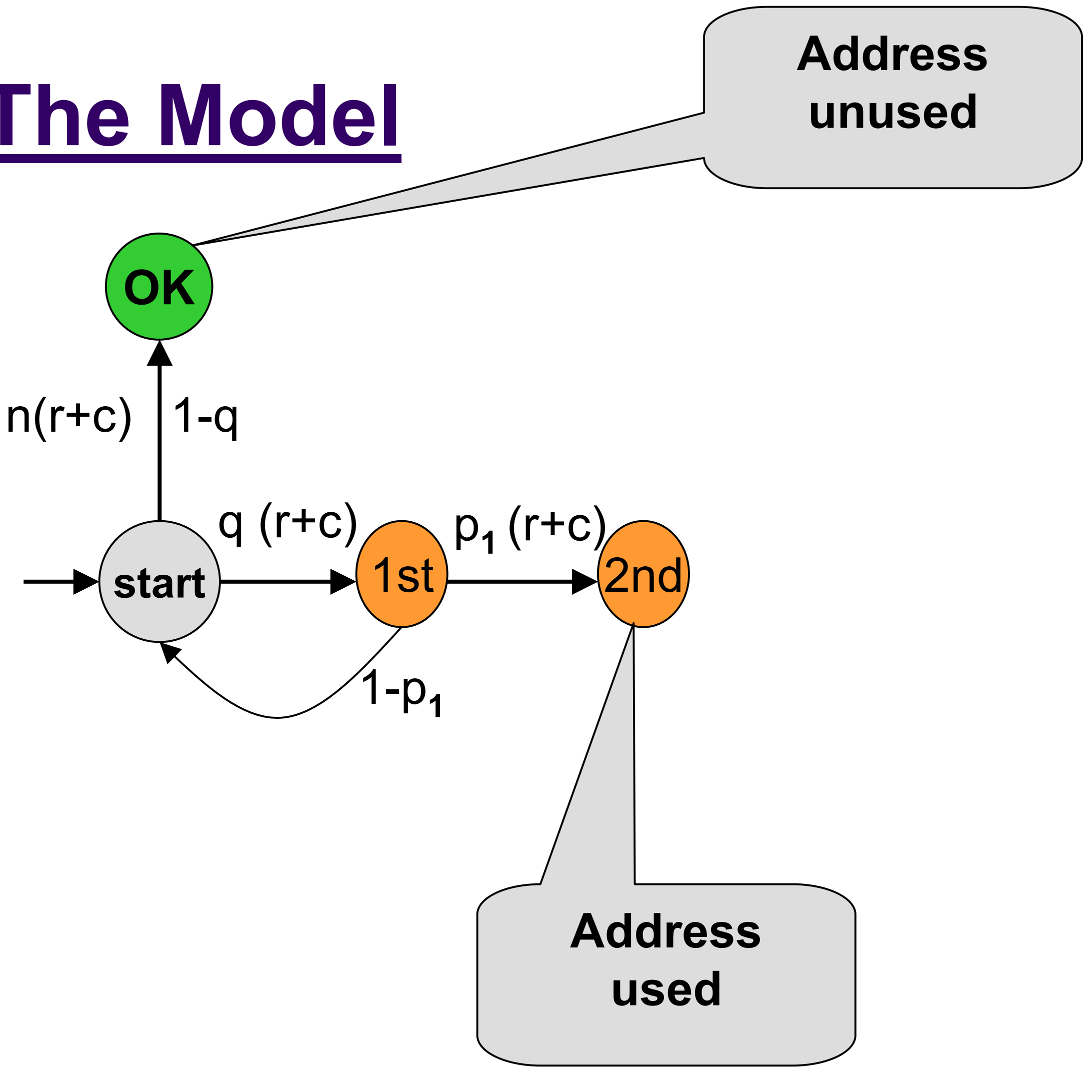
p_1 probability of not receiving a reply of 1st ARP probe after r sec.

The Model



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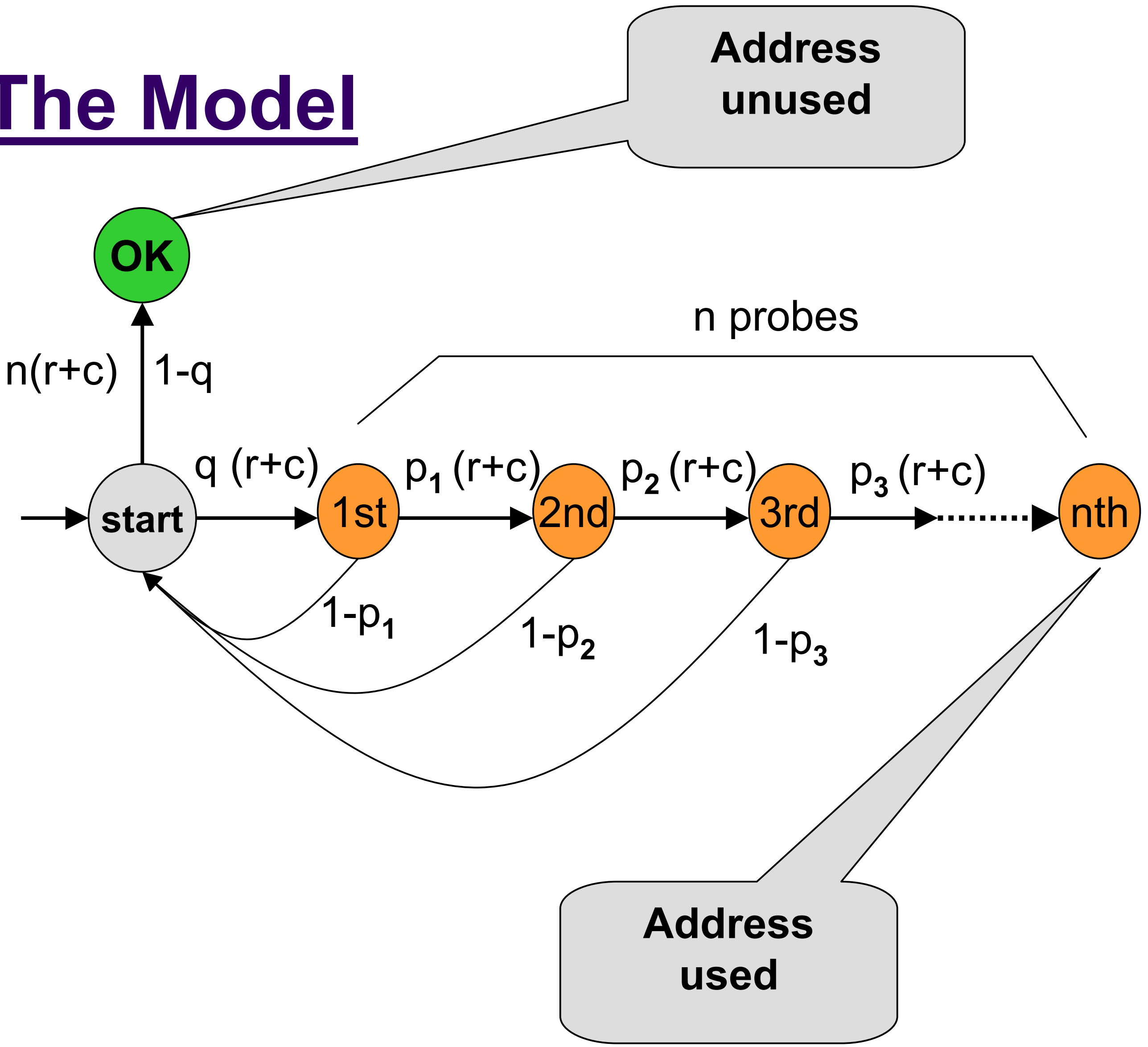
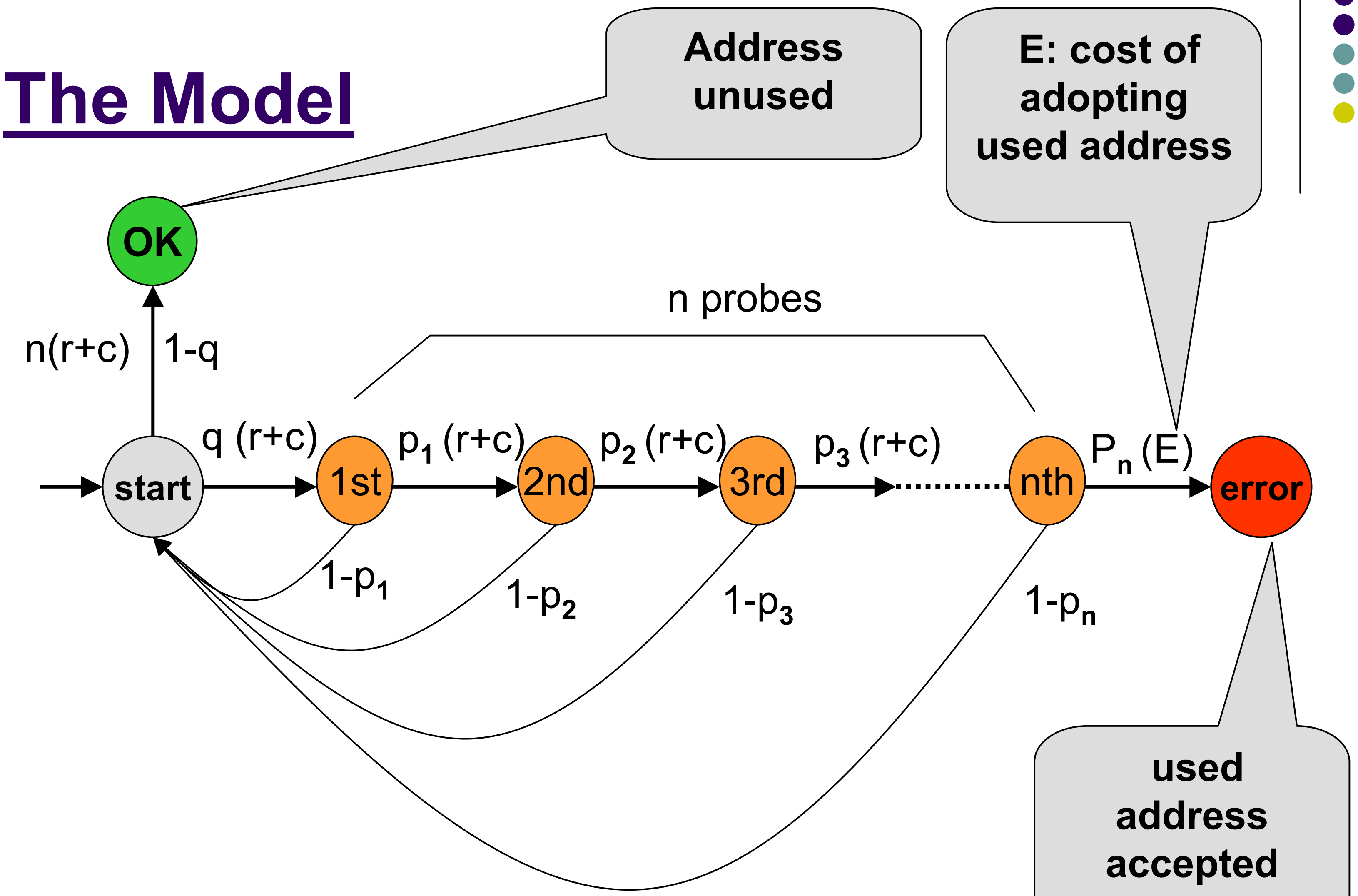


Address unused
OK
n(r+c)
1-q
n probes
start
q (r+c)
1st
p1 (r+c)
2nd
p2 (r+c)
3rd
p3 (r+c)
nth
1-p1
1-p2
1-p3
Address used

The Model



Q: How do we compute $p_1, p_2, p_3, \ldots, p_n$?

The Model: No-answer probability

- P1: Pr(no answer of probe1 received within 0 → r)
- P2: Pr(neither answer of probe1 nor of probe2 received in r → 2r)
- P3: Pr(neither answer of probe1,2 nor probe3 received in 2r → 3r)
- ….
- Pn:

  Pr(neither answer of probe1,2,3,… nor of probe n received in r → 2r)
- $F_X(t) = \Pr(X \le t)$,
  - X : time at which a reply to an ARP probe is received
  - F_X : defective distribution function s.t $\lim_{t \to \infty} F_X(t) = L < 1$

    i.e packets may get lost

$$P(i,r) = \prod_{j=1}^{i} \left(1 - \frac{F_X(jr) - F_X((j-1)r)}{1 - F_X((j-1)r)} \right)$$

The Model: Abstract cost

- Sources of cost:
  - time cost : reprsented by r
  - Network usage cost: c
  - Cost of erroneously accepting already used IP address: E
    - Cost of beaking connections
    - Cost of reconfiguration of both hosts
    - Cost of user dissatisfaction with the product
    - …etc
- The mean total cost of the protocol
  - Mean total cost incurred during initialization
  - Starting from state „start“ ending with steady states „OK“ or „error“
  - Sum up all costs of all possible paths

The Model: cost function

- Probability matrices $\mathbf{P}_n = (p_{ij}^{(n)})$, i,j = 1,2,3,…,n+3 for n=1,2,…
- Cost matrices $\mathbf{C}_n = (c_{ij}^{(n)})$, i,j = 1,2,3,…,n+3 for n=1,2,…

	1 Start	2	3	4	….	n	n+1	n+2 error	n+3 OK
1 Start	0	q (r+c)	0	0	….	0	0	0	1-q (n(r+c))
2	$1-p_1$	0	P_1 (r+c)	0	….	0	0	0	0
3	$1-p_2$	0	0	P_2 (r+c)	….	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮
n	$1-p_{n-1}$	0	0	0	….	0	p_{n-1} (r+c)	0	0
n+1	$1-p_n$	0	0	0	….	0	0	$P_n(E)$	0
n+2 error	0	0	0	0	….	0	0	1	0
n+3 OK	0	0	0	0	….	0	0	0	1

The Model: cost function

- Mean total cost: $\underline{a} = \left(a_1^{(n,r)}, \ldots, a_{n+1}^{(n,r)}\right)^T$
- the mean total cost of state i :

$$a_i^{(n,r)} = \sum_{j=1}^{n+3} p_{ij}^{(n)} \left(c_{ij}^{(n)} + a_j^{(n)} \right) \quad , i = 1,2,3,\ldots,n+1$$

- Let $\mathbf{P'}_n = (p_{ij}^{(n)})$ $\quad , i,j = 1,2,3,\ldots,n+1$

and $\underline{w} = (w_1 , \ldots , w_{n+1})^T$ $\quad , w_i = \sum_{j=1}^{n+3} p_{ij} c_{ij}$

Then $\underline{a}$ can be computed from $\underline{a} = \mathbf{P'}_n \cdot \underline{a} + \underline{w}$

or better $\underline{a} = - (\mathbf{P'}_n - \mathbf{I})$

The Model: cost function

- We consider the mean total cost of state „start“: $a_1^{(n,r)}$

$$C(n,r) = \frac{(r+c)\left(n(1-q) + q\sum_{i=0}^{n-1}\pi_i(r)\right) + qE\pi_n(r)}{1 - q\,(1-\pi_n(r))}$$

where $\pi_i(r) = \prod_{j=0}^{i} p_j(r)$, for $i = 0, \ldots, n$

- Next step:
  - Fix c, q, E and F_X to find **optimal** n and r for minimal cost
  - Fix n and r and perform **sensitivity analysis**

The Model: optimization

Linearly increasing

Polynomialy decreasing

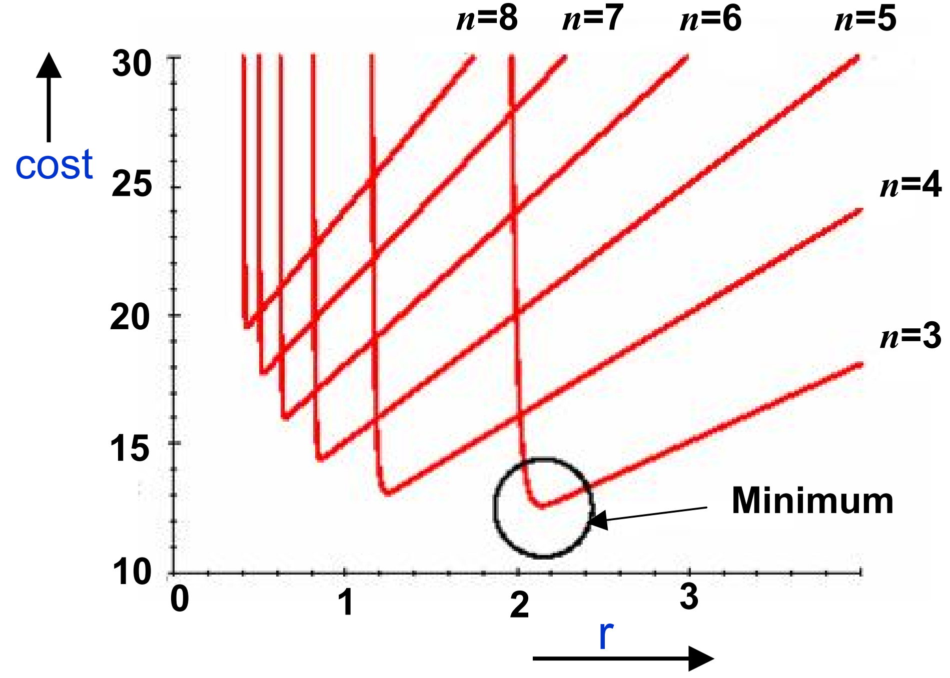
$$C(n\ldots = \frac{(r+c)\left(n(1-q) + q\sum_{i=0}^{n-1}\pi_i(r)\right) + qE\pi_n(r)}{1-q\,(1-\pi_n(r))}$$

- Consider C(… as family of functions $\{C_n(r)\}$
- Compute $r_{opt}^{(n)}$ …umerically such that $C_n(r_{opt}^{(n)})$ is minimal
- r = 0 → $\pi(0) = 1$ → $C(0) = qE$
- $\lim_{r\to\infty} F_X(r) = L$ → $\lim_{r\to\infty} p_i(r) = 1\text{-}L$ → $\lim_{r\to\infty} \pi_i(r) = (1\text{-}L)^i$

$$\Rightarrow \quad A_n(r) = \frac{(r+c)\left(n(1-q) + q\,\dfrac{1-(1-L)^n}{L}\right) + qE\,(1-L)^n}{1-q}$$

The Model: optimization

- Example plots:
  - $F_X(r) = \begin{cases} L.(1 - e^{-\lambda(r-d)}) & \text{for } r \geq d \\ 0 & \text{otherwise} \end{cases}$
  - d = 1 , round-trip delay
  - λ = 10, mean time a reply is received after sending ARP probe d+1/ λ
  - m = 1000, hence q = 1000/65024
  - c = 2 , E= 10^{35}



Cost function for n= 1, …, 8

The Model: optimization

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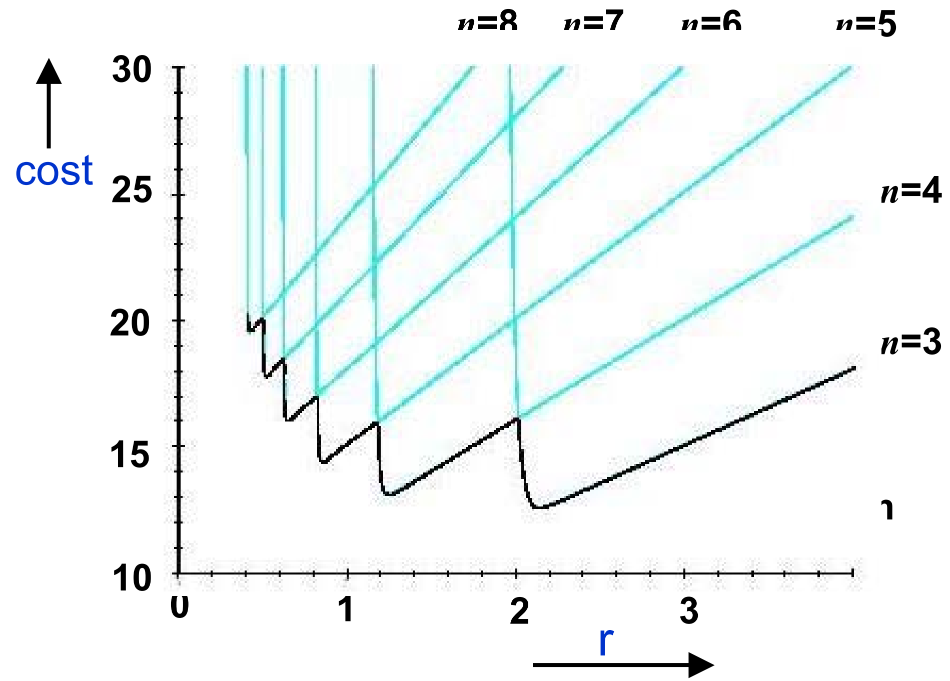


Cost function for n= 1, …, 8

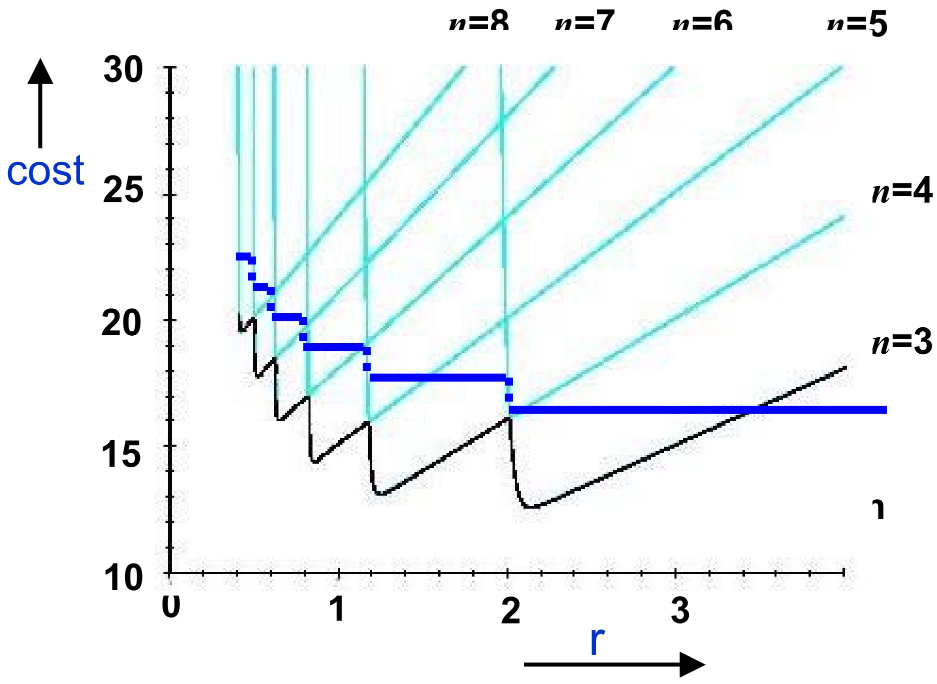
The Model: optimization

- Optimal *n*:
  - Find $N(r)$ such that:

    $C_{min} = C(\ N(r)\ ,\ r\ )$

The lower r is,

the lower the cost is



Cost function for n= 1, …, 8

The Model: optimization

- Optimal *n*:

$$A_n(r) = \frac{(r+c)\left(n(1-q) + q\,\frac{1-(1-L)^n}{L}\right) + qE\,(1-L)^n}{1-q}$$

- Hence, the minimal value of n is:

$$v = \left\lceil -\frac{\log(E)}{\log(1-L)} \right\rceil$$

To minimize the cost this should approach zero

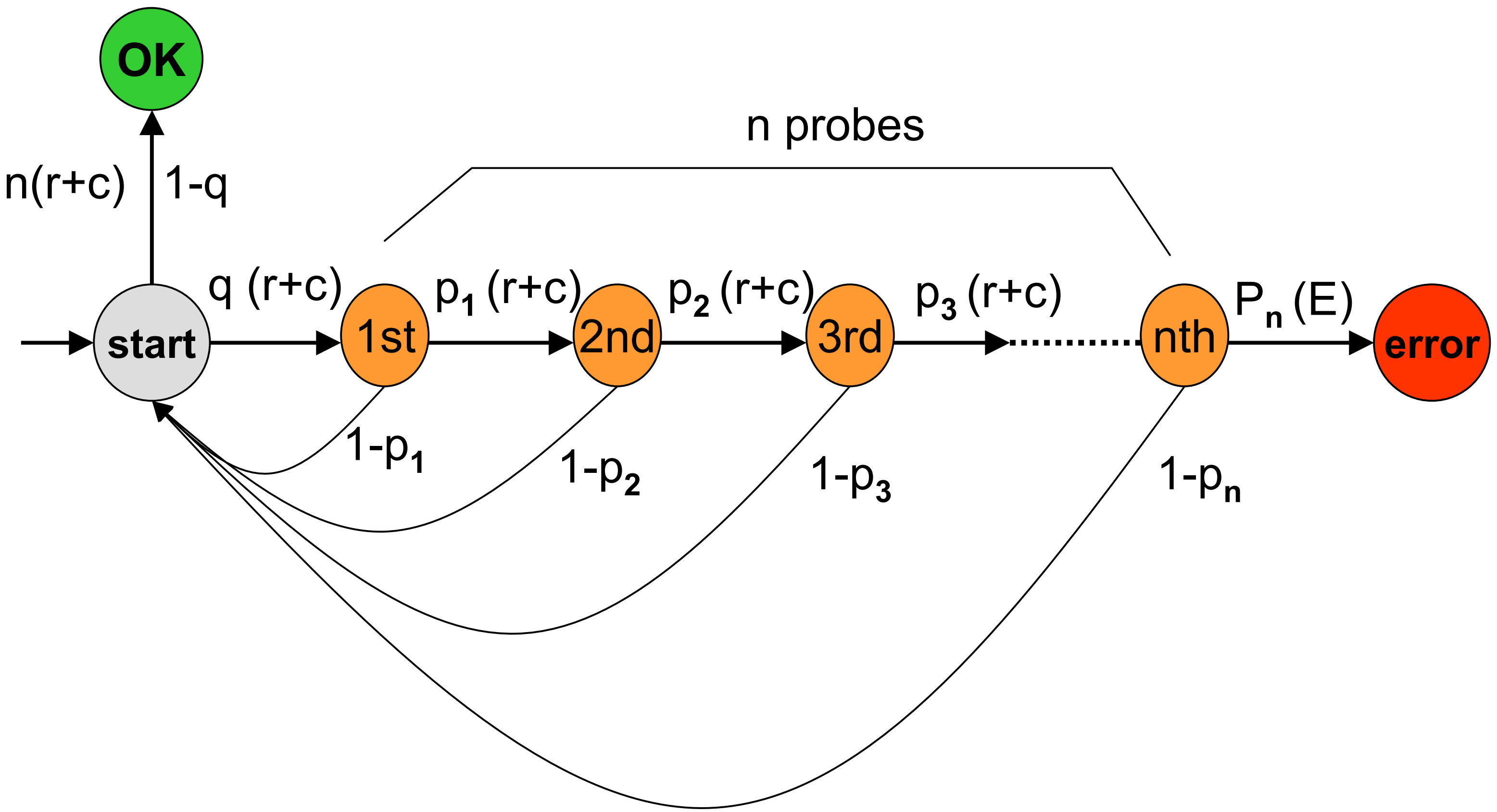
The Model: Reliability

- Reliability: probability that unused IP addressed is selected at the end of initialization phase. i.e probability to end up in state OK

	1 Start	2	3	4	….	n	n+1	n+2 error	n+3 OK
1 Start	0	q (r+c)	0	0	….	0	0	0	1-q (n(r+c))
2	$1\text{-}p_1$	0	P_1 (r+c)	0	….	0	0	0	0
3	$1\text{-}p_2$	0	0	P_2 (r+c)	….	0	0	0	0
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
n	$1\text{-}p_{n-1}$	0	0	0	….	0	p_{n-1} (r+c)	0	0
n+1	$1\text{-}p_n$	0	0	0	….	0	0	$P_n(E)$	0
n+2 error	0	0	0	0	….	0	0	1	0
n+3 OK	0	0	0	0	….	0	0	0	1

The Model: Reliability

- Reliability: probability that unused IP addressed is selected at the end of initialization phase. i.e probability to end up in state OK



The Model: Reliability

- Reliability: probability R(n,r) that unused IP address is selected at the end of initialization phase (probability to end up in state OK).
- We drive 1 – R(n,r)

$$1- R(n,r) = \underline{s}_n \sum_{K=1}^{\infty} (\mathbf{P'}_{\mathbf{n}})^{k-1} \underline{e}_n = \underline{s}_n (\mathbf{I} - \mathbf{P'}_{\mathbf{n}})^{-1} \underline{e}_n$$

$$\rightarrow \quad 1 - R(n,r) = \frac{q\pi_n(r)}{1 - q\,(1 - \pi_n(r))}$$

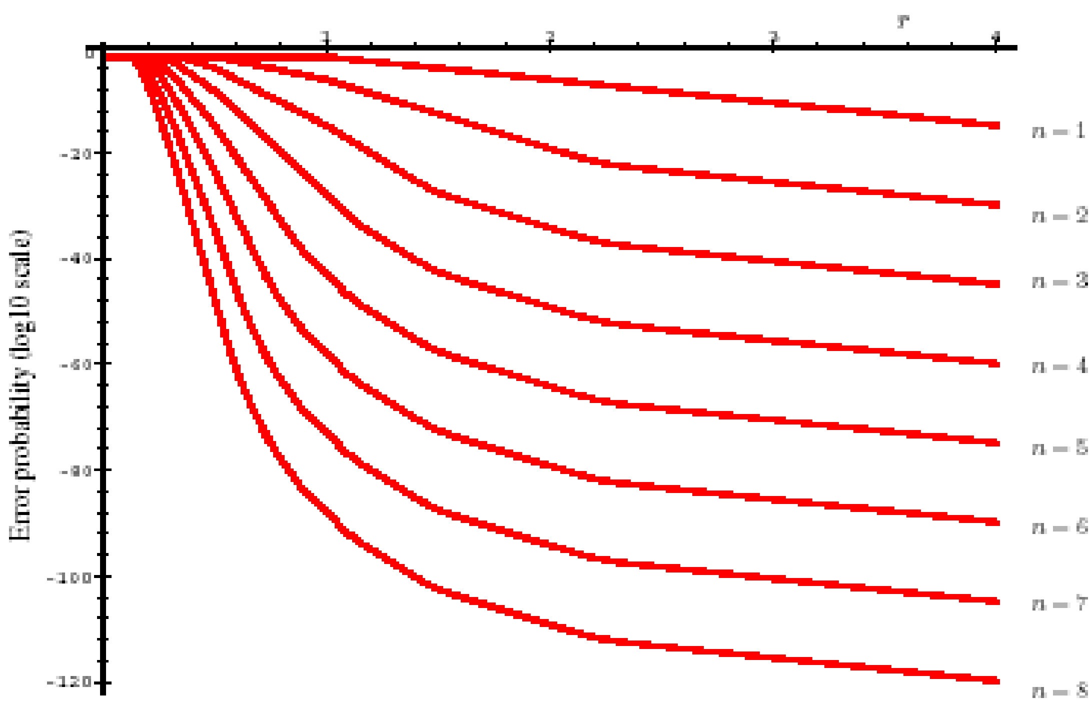
The Model: Reliability

- Error probability (of adopting used IP address)

$$1 - R(n,r) = \frac{q\pi_n(r)}{1 - q\,(1 - \pi_n(r))}$$

r →

Error probability ↑



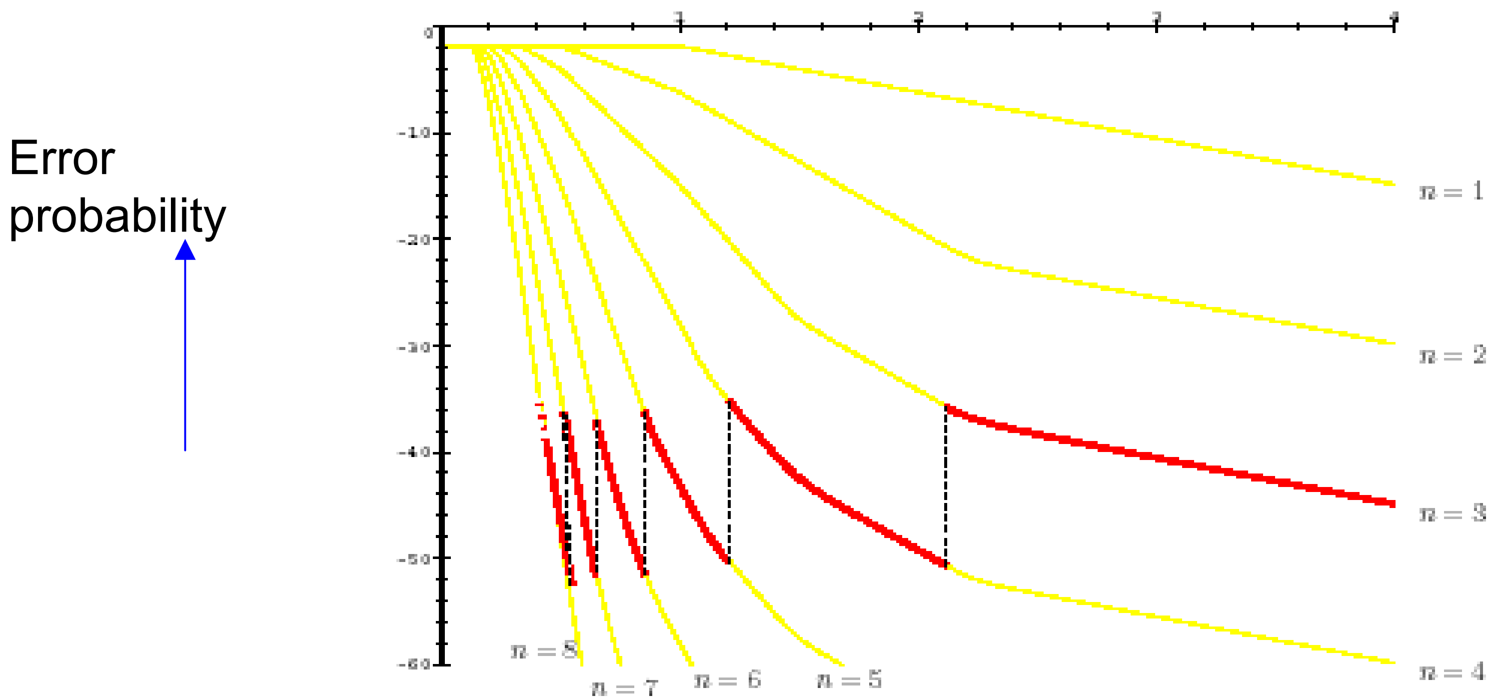
The Model: Reliability

- Error probability (of adopting used IP address)

$$1 - R(N(r),r) = \frac{q\pi_n(r}{1 - q\,(1 - \pi_n}$$

The lower r is,

the lower the reliability is



Summary and Conclusion

- Family of Discrete-time Markov reward models has been used to model the protocol run
- Cost function :

$$C(n,r) = \frac{(r+c)\left(n(1-q) + q\sum_{i=0}^{n-1}\pi_i(r)\right) + qE\pi_n(r)}{1 - q(1-\pi_n(r))}$$

- Optimal parameters can be computed using numerical solutions
  - Optimal n :

$$n > \left\lceil \frac{-\log(E)}{\log(1-L)} \right\rceil$$

- Trade-off between cost and Reliability
  - The lower r is set, the lower the cost become, but also the reliability decreases then