Content discovery in Information Centric Networks

When to flood? Where to flood?

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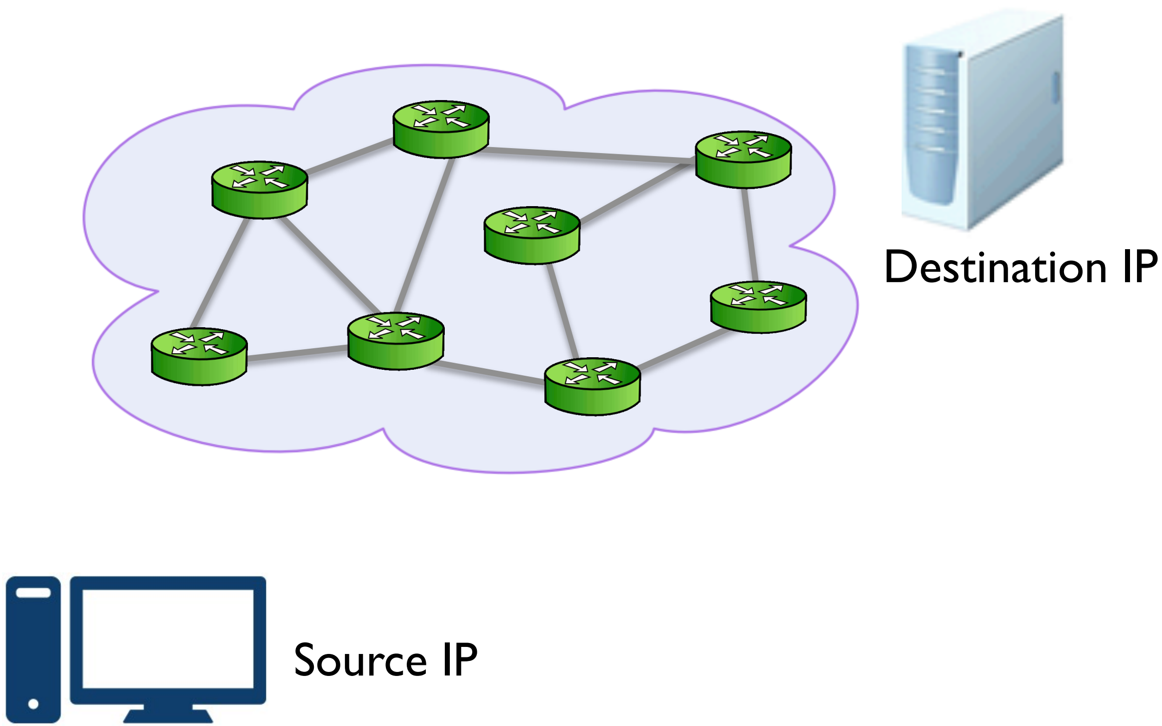
December 28, 2015 Bogazici University, Department of Computer Engineering

Internet Protocol RFC791, 1981

- Host-to-host packet delivery based on IP addresses



RFC 791:

“The internet protocol provides for transmitting blocks of data called datagrams from sources to destinations, where sources and destinations are hosts identified by fixed length addresses”

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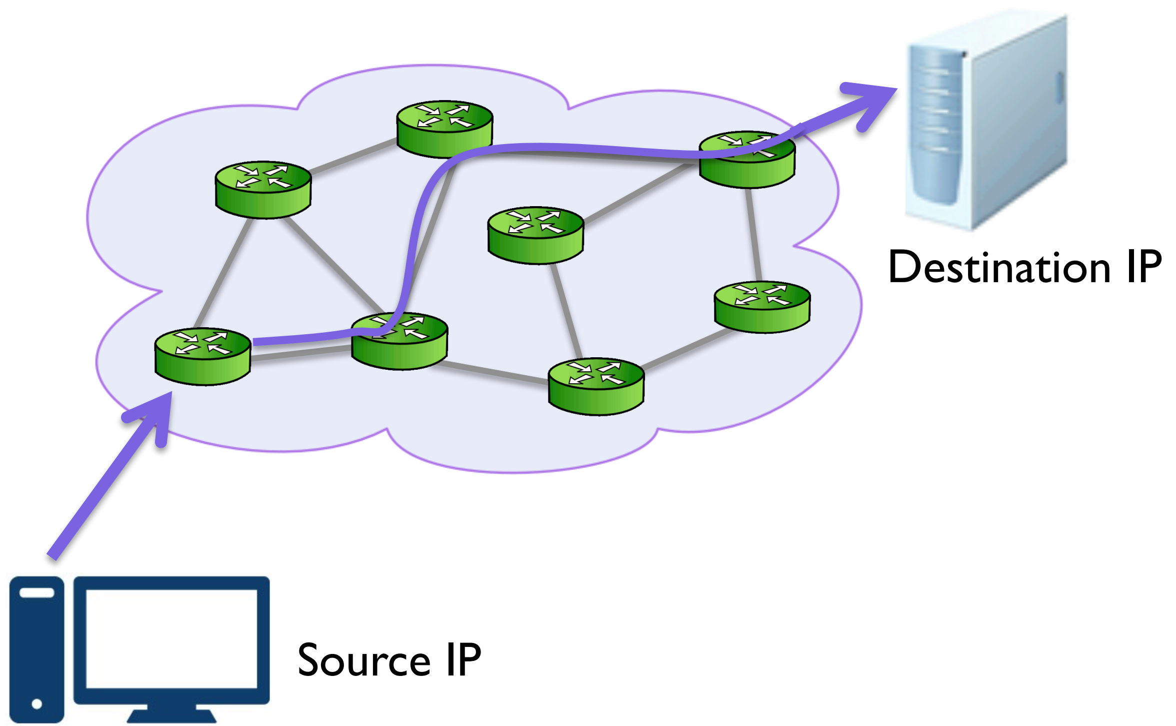

RFC 791:

"The internet protocol provides for transmitting blocks of data called datagrams from sources to destinations, where sources and destinations are hosts identified by fixed length addresses"

Today, some 30 years later

- Different applications, different devices
- Constantly increasing mobile data traffic
- Video (content distribution) is the dominant traffic
- Same content is requested by many users, e.g., Gangham style
- Host-to-content communications

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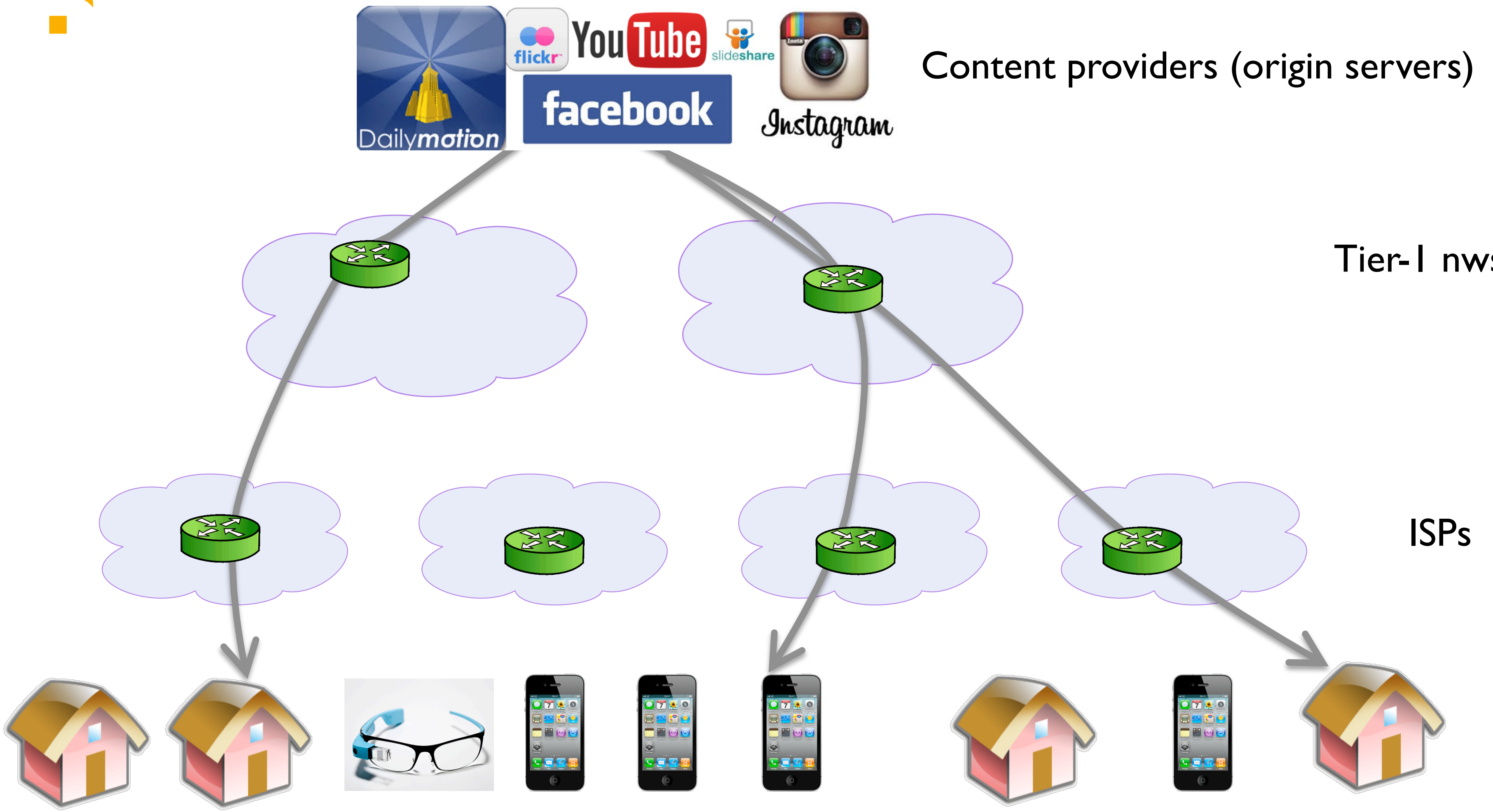

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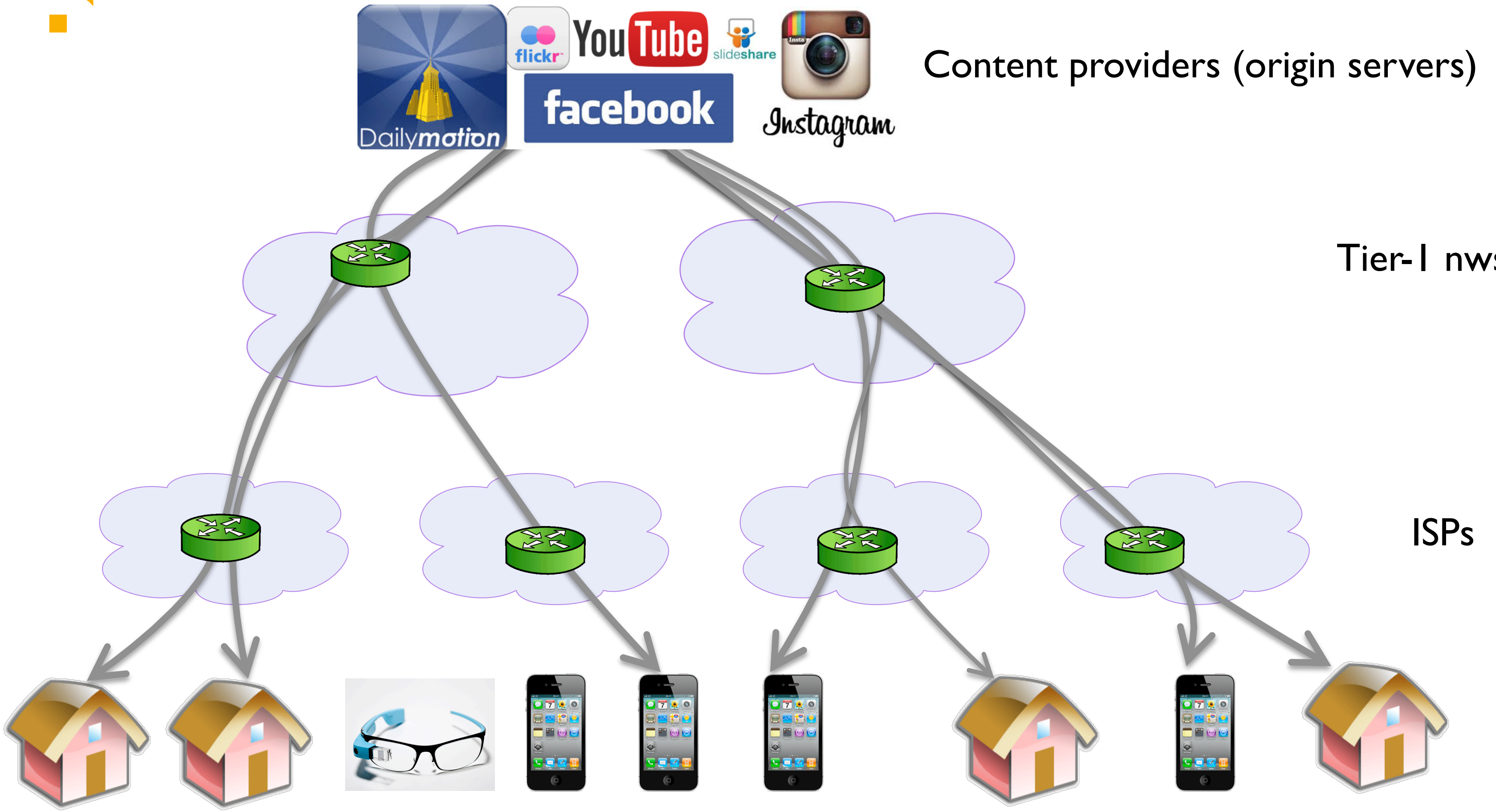
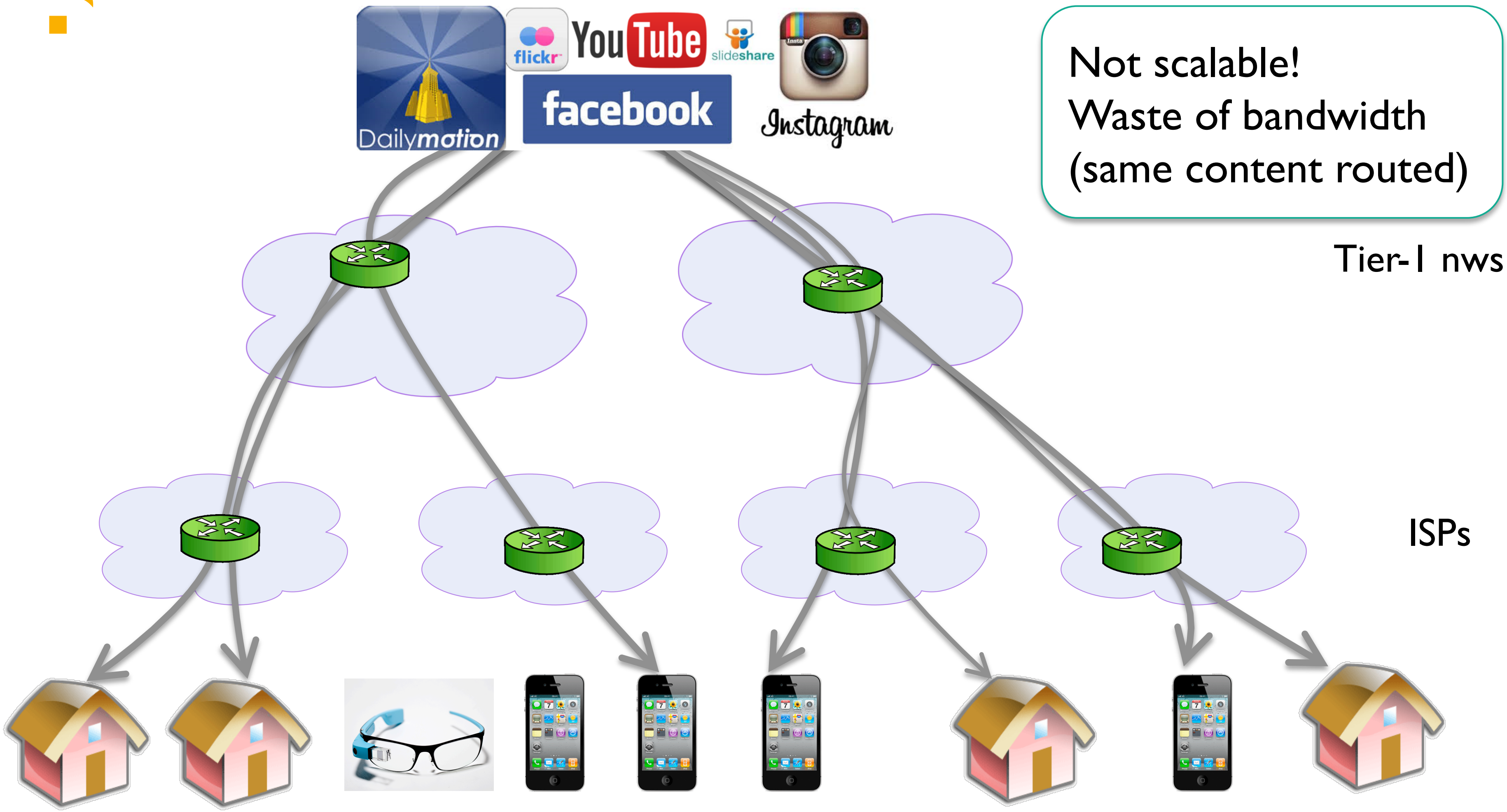
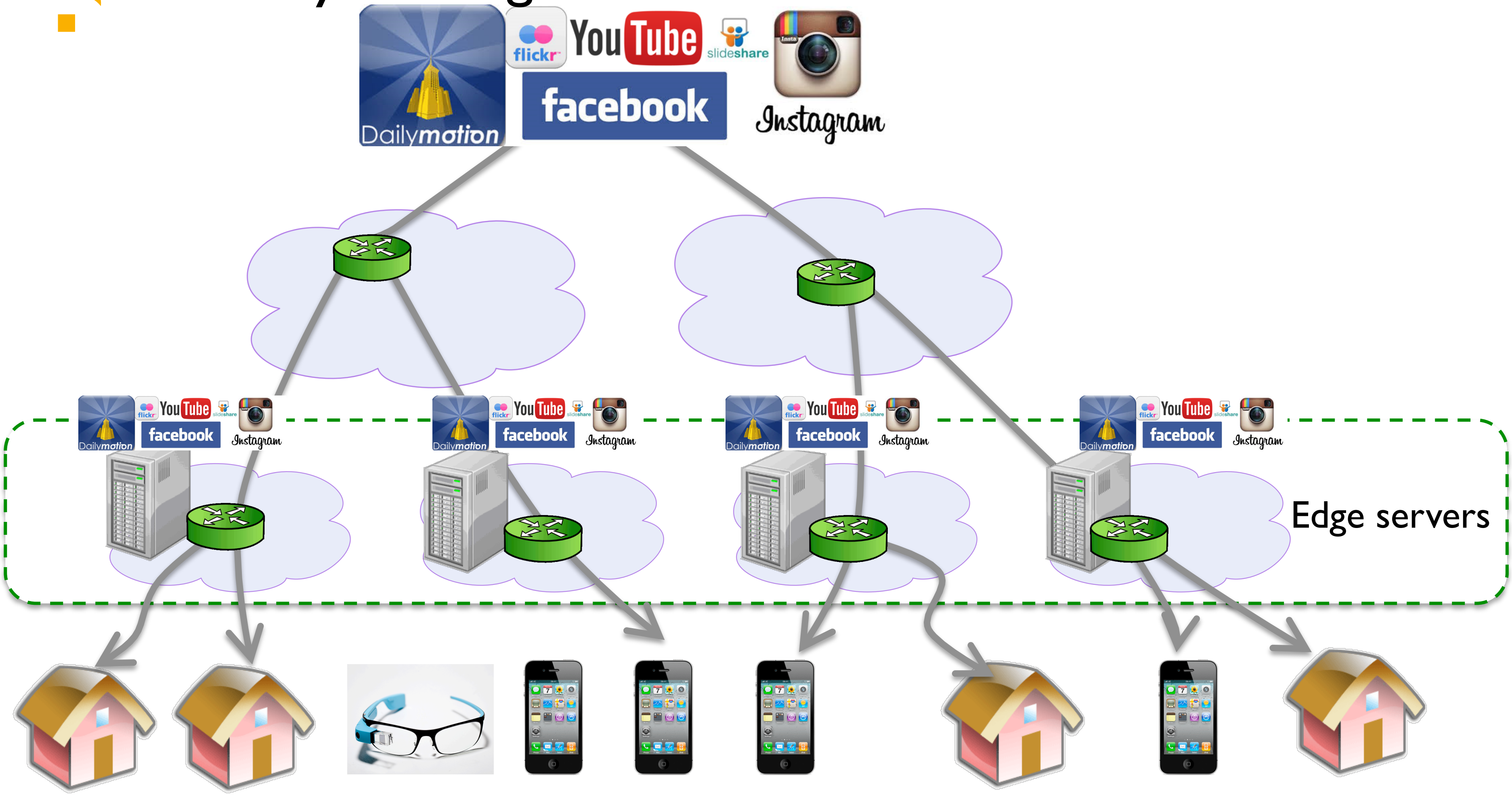


Today, some 30 years later

Not scalable!
Waste of bandwidth
(same content routed)



Content Delivery Networks (CDN): overlay routing over IP



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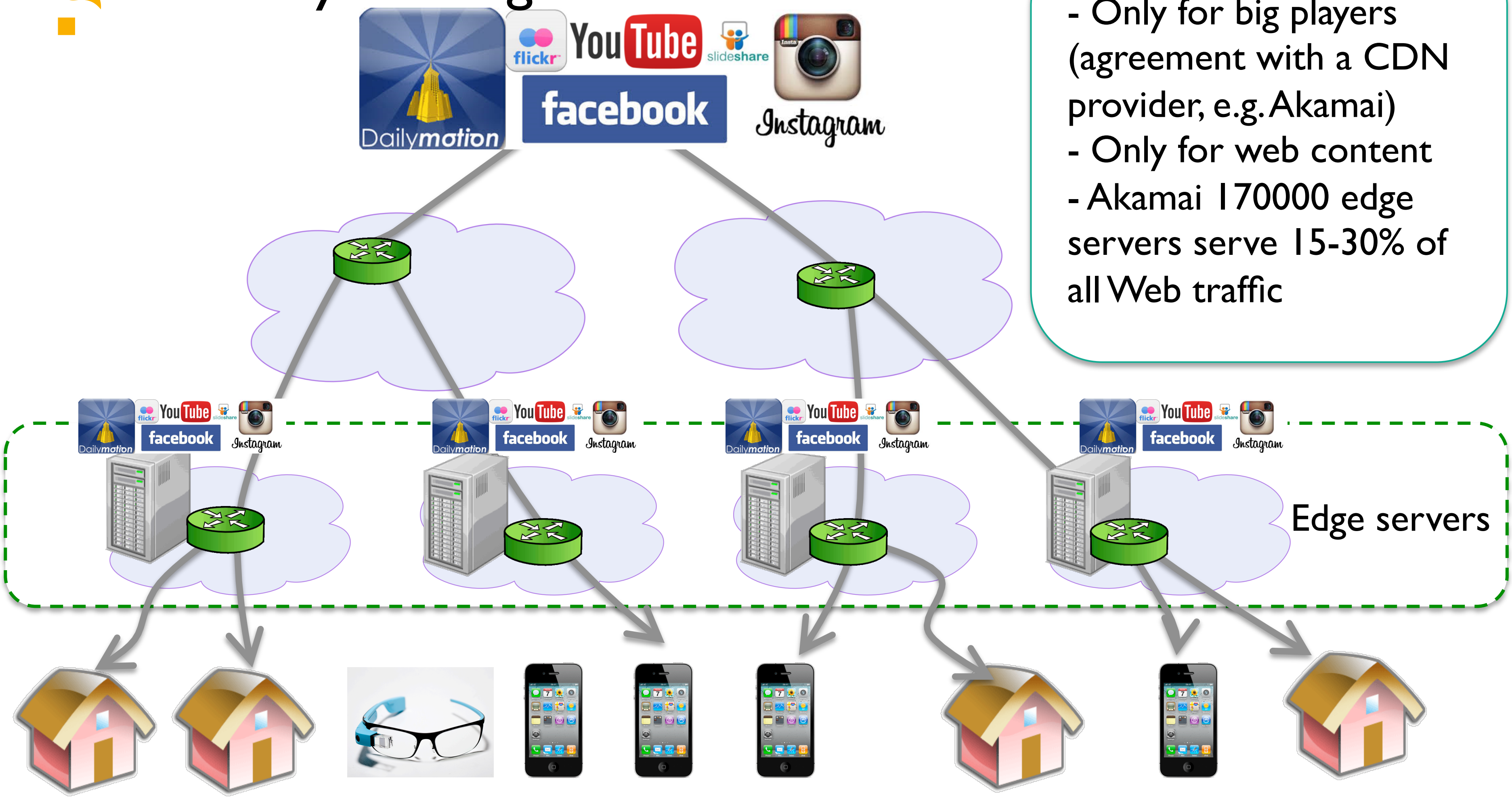
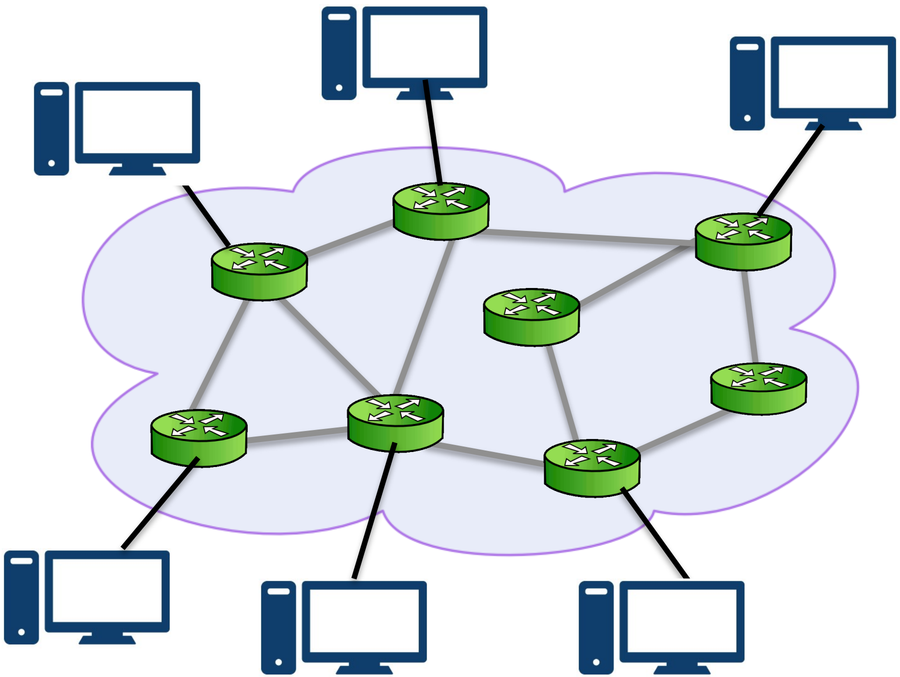


- Only for big players (agreement with a CDN provider, e.g. Akamai)
- Only for web content
- Akamai 170000 edge servers serve 15-30% of all Web traffic

Information-centric Networks (ICN)



- Today's host-centric IP interconnecting *machines*

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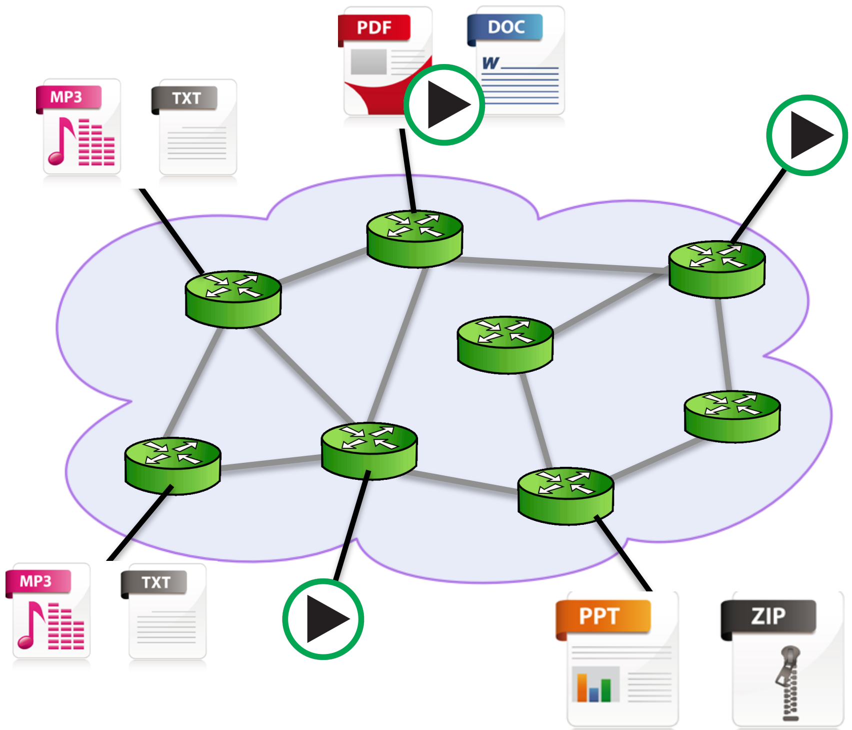

- ICN interconnecting *information*
- Address content (named data objects)

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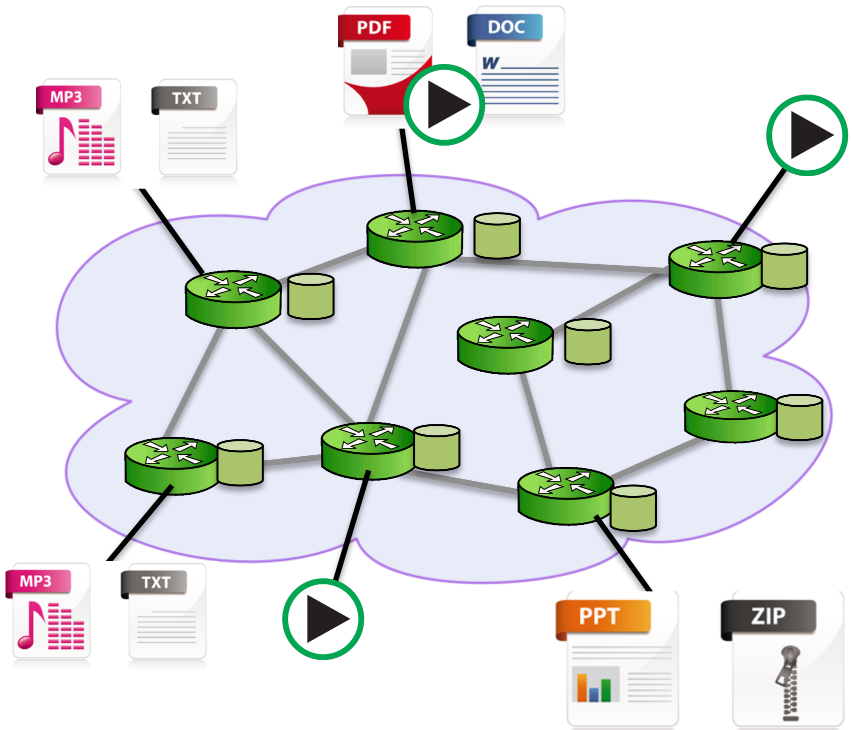
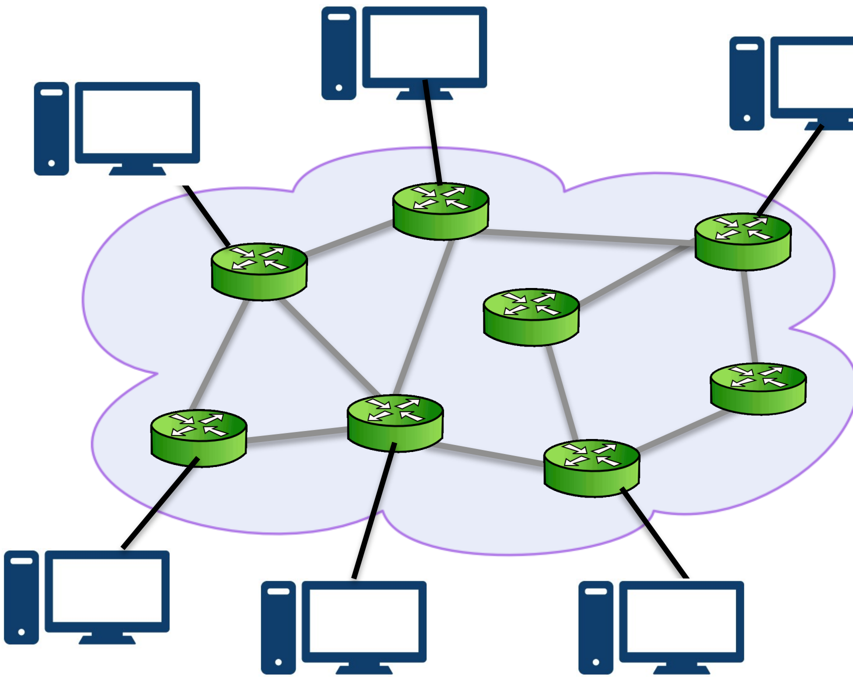
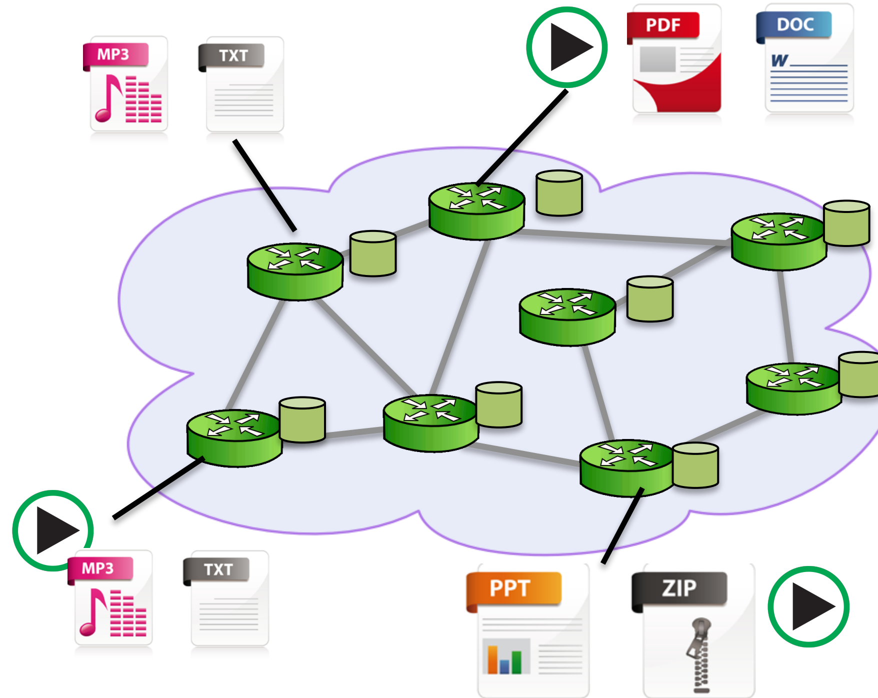


- ICN interconnecting *information*
- Address content (named data objects)
- Add in-network storage everywhere, not only at the edge
- Apply pervasive caching
- Facilitate nearest replica routing

Internet vs. ICN





Host-centric communications (host-to-host)

Content-centric communications (host-to-content)

Internet vs. ICN

	IP	ICN
Addresses	End-host Fixed length IP address	Content Content name (flat or hierarchical)
Interested in	Where is the requested content?	What is the requested content?
Secures	End points and the channel Patch over IP, e.g. IPsec	Each content is signed and authenticated by design
Routers act as	Relays forwarding the same content again and again	Caches serving some content from the local storage
Mobility	Challenging	Easier

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- Quantitative benefits: lower response time, lower network load, lower intra- and inter-ISP traffic
- Qualitative benefits: better security and integrity, better scalability with respect to bandwidth demand, support for mobility, resilience to disruptions and failure

Various ICN architectures

- Content-centric network (CCNx)
- Named-data networking (NDN)
- SAIL - 4WARD - Network of Information (NetInf)
- PSRIP / PURSUIT
- Data-Oriented Network Architecture (DONA)
- …

1 - Content provider/producer 2- Content requestor 3-Content router

Three key questions

- How to address content?
  - – Naming scheme (flat or hierarchical)
- How to retrieve content?
  - – Name resolution (content discovery)
- How to route content?
  - – On-path caching, off-path caching

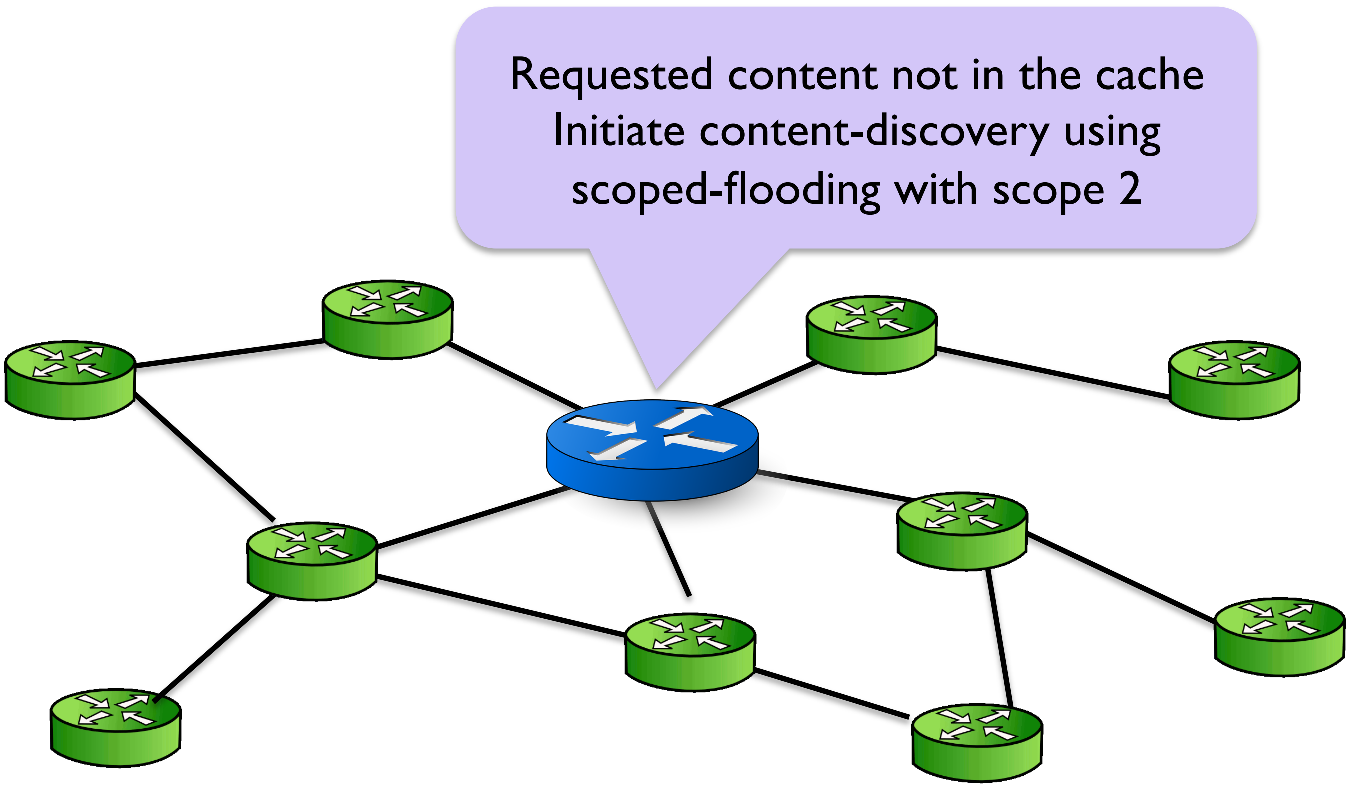
How to retrieve content?

How to discover the requested content?

Scoped-flooding

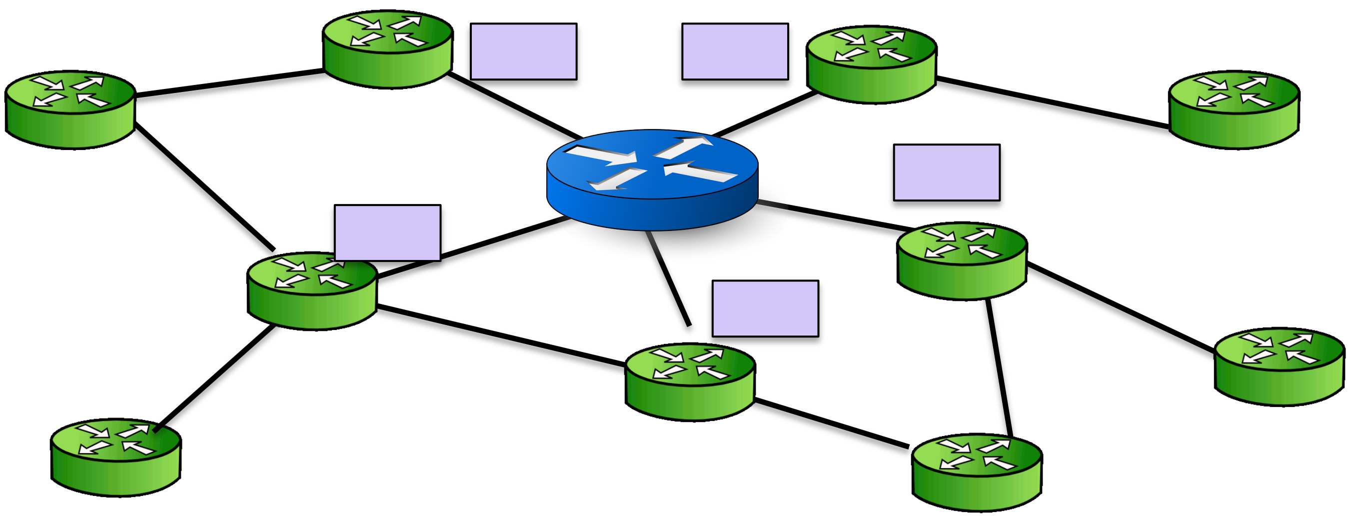
- Propagate the content discovery message in a scope, i.e. number of hops message can travel
- Benefits of (scoped) flooding in the network
  - Low state maintenance, low protocol complexity, etc.
  - A scalable solution or not?

Scoped-flooding



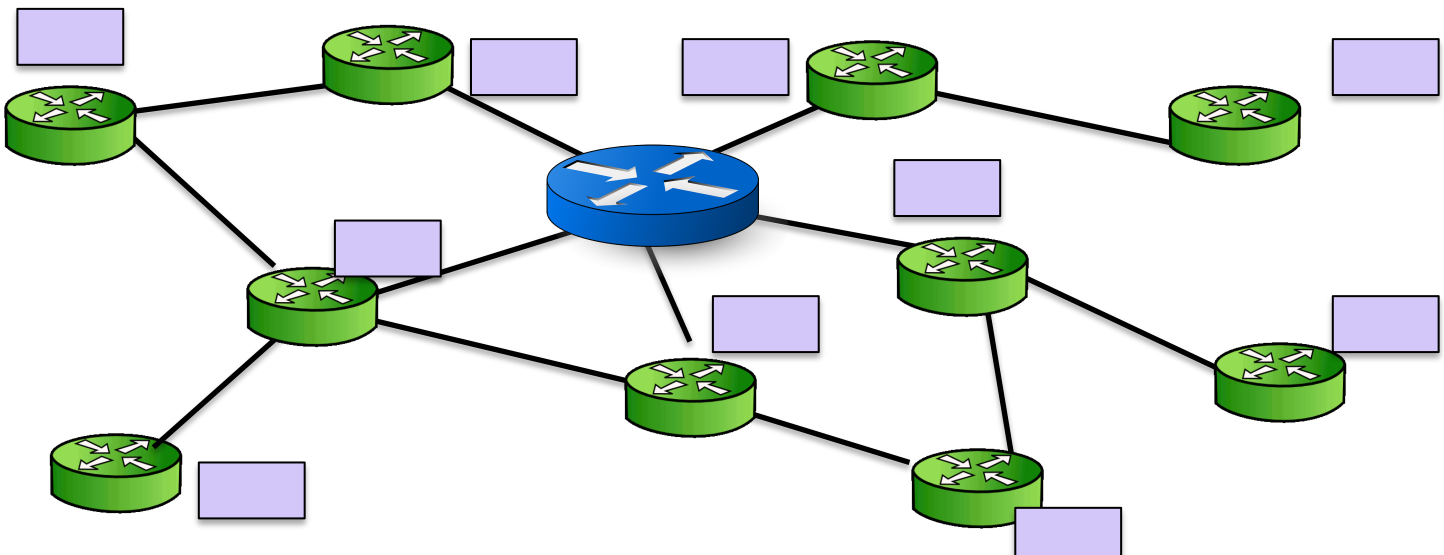
Scoped-flooding

- 1-hop flooding [box] content discovery packet



Scoped-flooding

- 2-hop flooding ▭ content discovery packet



Technically we want to know

- How to set the flooding scope optimally?
- How a network topology impacts the scope?
- How content availability impacts the scope?

In short, we want to flood on the right content at the right place with the right scope.

Pro-Diluvian: Understanding Scoped-Flooding for Content Discovery in ICN

Liang Wang (Cambridge University), Suzan Bayhan (University of Helsinki), Jörg Ott (TU Munich, Aalto University) ,

Jussi Kangasharju (University of Helsinki), Arjuna Sathiaseelan (Cambridge University),

Jon Crowcroft (Cambridge University)

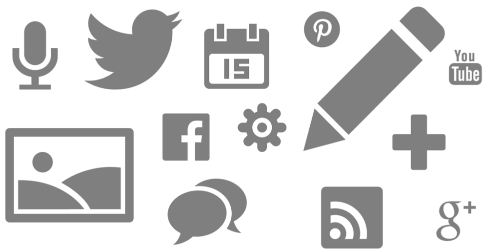
Three key components

Content

- The content (can be anything), only its value matters.

Three key components

Content



Utility= gain-cost

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- The representation of gain/cost as a function of # of nodes and content (value).

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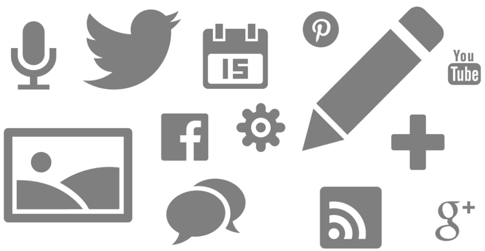

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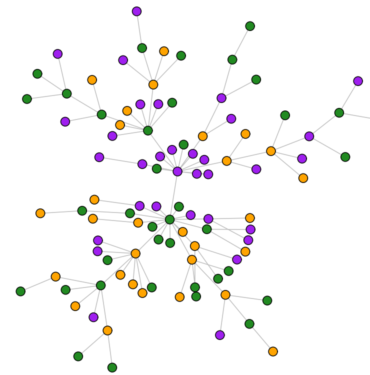
Network topology

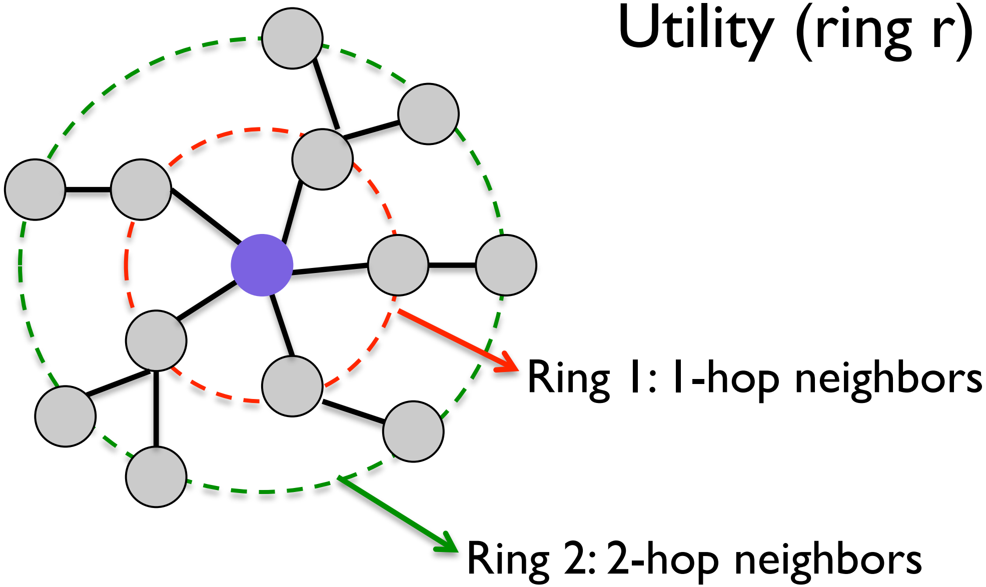


- The content (can be anything), only its value matters.
- The representation of gain/cost as a function of # of nodes and content (value).
- The network model based on which, we can tell how the # of nodes increases as a function of # of hops (scope).

How are these components connected?

A node-centric ring-based model

Utility (ring r) = Gain(ring r) - Cost(ring r)



Utility modeling

Utility = Expected value of content – expected cost of content discovery

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# of total transmissions * cost,
cost: bandwidth, energy, delay

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Total number of nodes receiving the message = n
Content availability = p (uniform distribution)
Gain = $1 - q^n$ where $q = 1-p$

Cost = n*c

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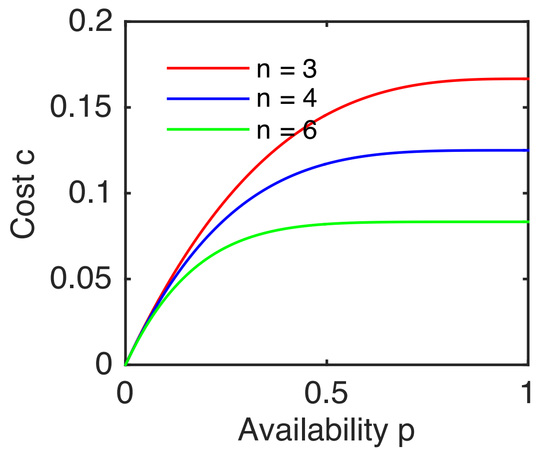
$$U = (1 - q^n) - n \cdot c$$

Effect of p and c on flooding behavior



- What is the critical cost c below which the node will initiate scoped flooding for content with availability p and given n?
  - The lower cost for higher n
  - A node with a large neighborhood is reluctant to flooding

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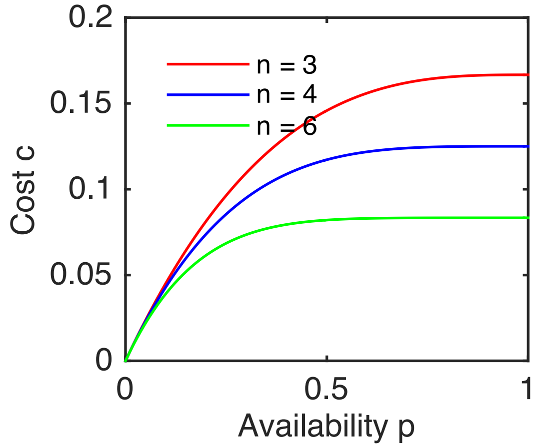

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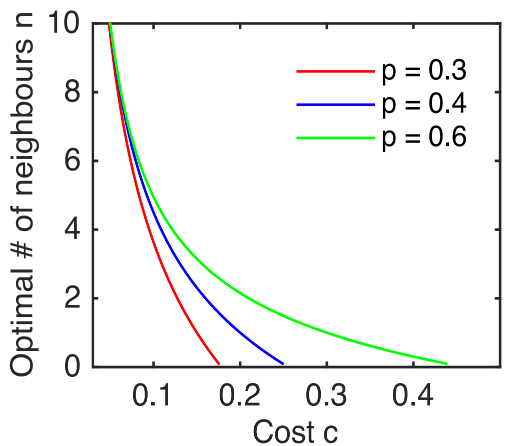


- How does availability p affect flooding?
  - Higher p, worth flooding to more neighbors
  - Lower p, conservative flooding

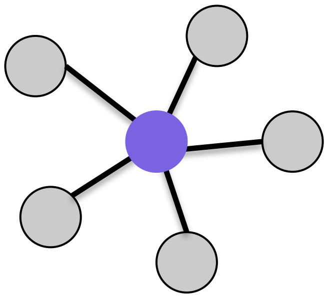
What is the relation between n and r?

- Given scope r, n is the number of nodes that will receive the message:

  $n = f(r)$

- Graph with a given degree distribution ρ, i.e., $G = (V, \rho)$
- h-hop neighborhood of a node: n_h
- $n = \Sigma\, n_h$ where $h <= r$

1-hop neighbors



- <k>: expectation of node degree variable
- ρ_i = Pr(k=i): the probability that a randomly selected node has degree i

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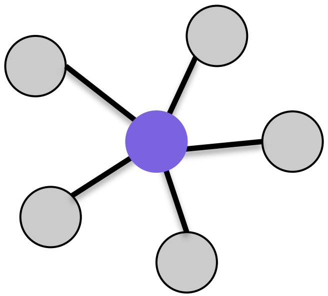

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- Expected number of 1-hop neighbors: $n_1 = \langle k \rangle = \sum_{k=0}^{\infty} k \rho_k$

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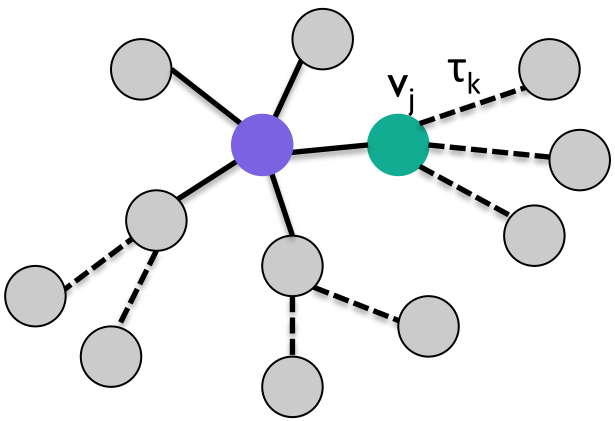

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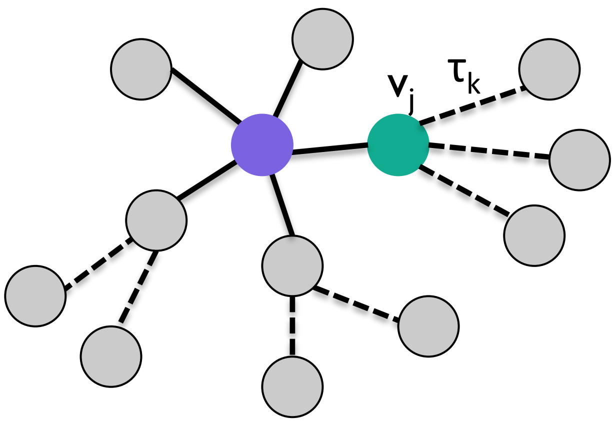

The probability of v_j having k new next-hop neighbours is:

$$\tau_k = \mathbf{Pr}[deg(v_j) = k|\rho] = \frac{(k+1)\rho_{k+1}}{\sum_m m\rho_m}.$$

Therefore, the average number of new nodes from v_j is:

$$\sum_{k=0}^{\infty} k\tau_k = \frac{\sum_{k=0}^{\infty} k(k+1)\rho_{k+1}}{\sum_m m\rho_m} = \frac{\sum_{k=0}^{\infty} k(k-1)\rho_k}{\sum_m m\rho_m} = \frac{\langle k^2 \rangle - \langle k \rangle}{\langle k \rangle}$$

- $<k^2>$: second moment of node degree variable

1-hop, 2-hop, …, r-hops

- Expected number of 1-hop neighbors: $n_1 = \langle k \rangle = \sum_{k=0}^{\infty} k\rho_k$
- Expected number of 2-hop neighbors: $n_2 = \langle k^2 \rangle - \langle k \rangle$
- Expected number of r-hop neighbors:

$$n_r = n_{r-1} \sum_{k=0}^{\infty} k\tau_k = \frac{\langle k^2 \rangle - \langle k \rangle}{\langle k \rangle} n_{r-1} = \left[\frac{\langle k^2 \rangle - \langle k \rangle}{\langle k \rangle} \right]^{r-1} \cdot \langle k \rangle$$

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Neighborhood growth rate

A node can estimate its neighbourhood with 2-hop knowledge.

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- Average network growth rate β
- The ratio of # of ring r+1 nodes to # of ring r nodes

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Neighborhood growth for random graphs

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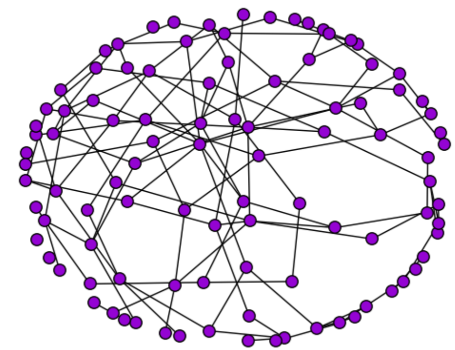
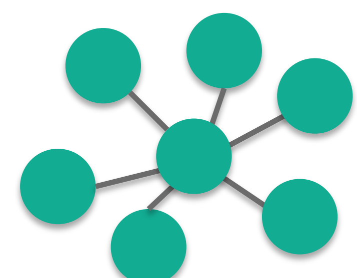
– Erdös-Renyi graph (ER)

- Every node is equally likely to be connected with every other node with prob. p
- Poisson degree dist. for large N, small p



– Scale-free graph

- Some nodes are tightly connected (hub), some have only a few connections
- Power-law degree dist. parameter α



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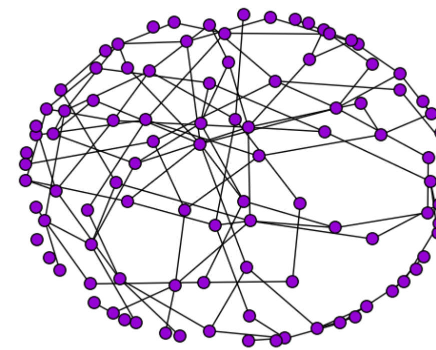

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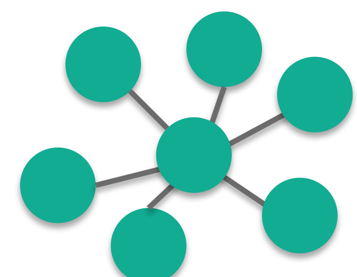
– Scale-free graph $\beta = \frac{1}{\alpha - 3} \quad \forall \alpha > 3$



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How accurate can this model predict?

Synthetic topologies with 10.000 nodes and analyze the largest connected component
Calculate the degree distribution parameters from the actual graphs and find n_r

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Table 1: Overestimation of the model at each hop for various network graphs. V: Number of nodes and E: Number of nodes in the generated instance of the graph, l: average path length. Shaded cells represent the cases where the error is below 0.20.

Id	Topology	V	E	$\langle k \rangle$	l	Clustering	Overestimation of the model				
							$r=2$	$r=3$	$r=4$	$r=5$	$r=6$
1	Random	339	338	1.994	23.07	0	0.327	1.046	2.359	4.692	9.092
2	Random	8030	9761	2.431	12.03	0	0.152	0.371	0.642	0.972	1.399
3	Random	9426	15068	3.197	8.30	0.00040	0.060	0.130	0.212	0.332	0.565
4	Random	9811	20073	4.091	6.75	0.00049	0.023	0.053	0.106	0.259	0.873
5	Random	9928	25060	5.048	5.88	0.00048	0.004	0.017	0.079	0.419	2.79
6	Random	9989	35020	7.011	4.95	0.00066	0.003	0.030	0.229	2.139	54.124
7	Scale-free, α =3.24	7141	9648	2.70	7.88	0.00057	0.093	0.271	0.529	1.069	2.599
8	Scale-free, α =3.35	5869	7347	2.50	8.66	0.00076	-0.115	-0.174	-0.194	-0.16	0.013
9	Scale-free, α =3.50	5960	7357	2.47	8.99	0.00013	-0.356	-0.555	-0.68	-0.757	-0.794

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- Pretty accurately for big networks for 3 - 4 hops (finite network size in contrast to large N in our model).
- Better accuracy for larger networks (small networks, small network diameter)

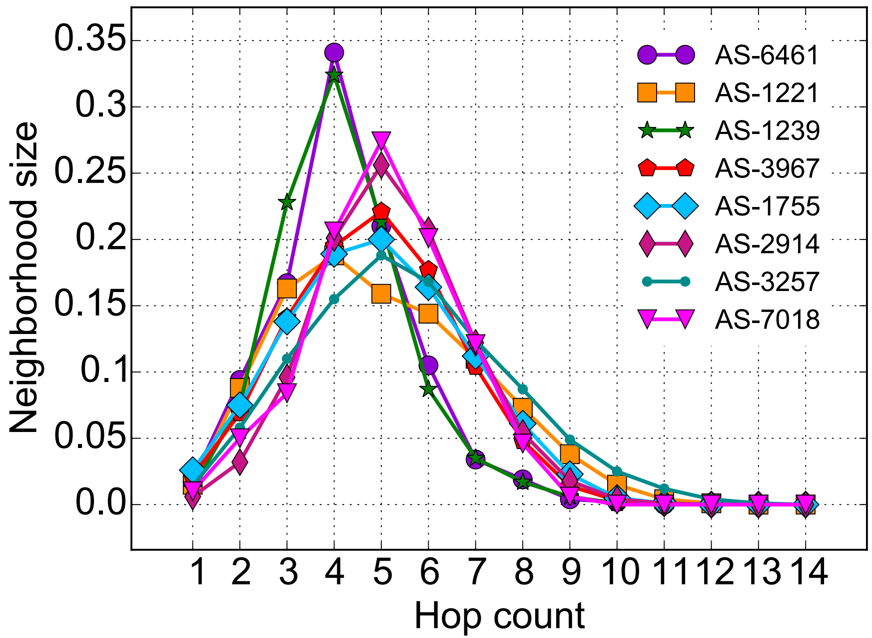
MIND THE GAP

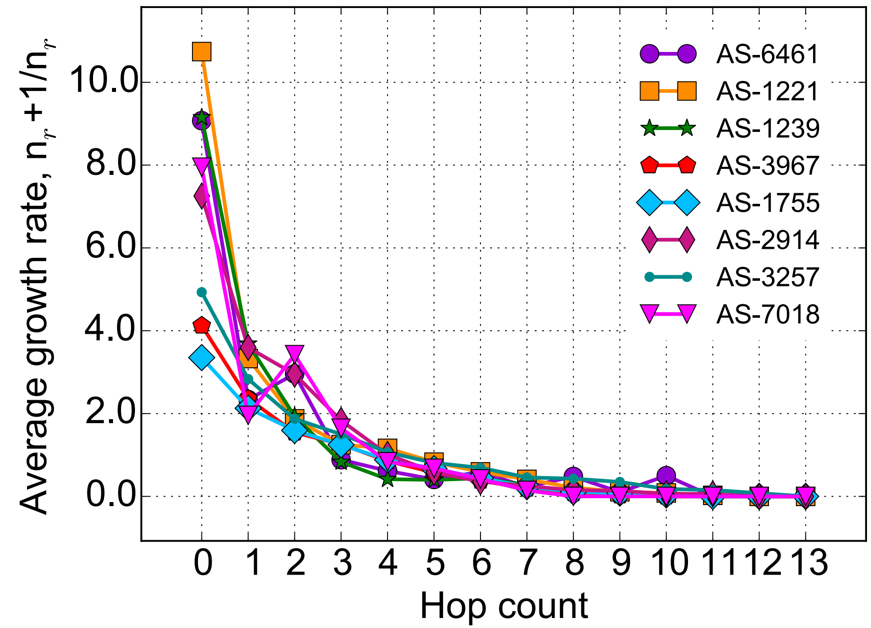
Theory does not always match reality

Test our network growth model with real ISP topologies from Rocketfuel

N. Spring, et al., “Measuring ISP topologies with Rocketfuel,” in SIGCOMM, ACM, 2002.

Accuracy analysis on real ISP topologies





Fast growth till 4-5 hops! Then drops due to limited network size and small diameter.

N. Spring, et al., "Measuring ISP topologies with Rocketfuel," in SIGCOMM, ACM, 2002.

Summary: our model and analysis on real ISP topologies show that neighborhood growth is fast at the first hops

back to content discovery

Q: When to flood?

A: Flood when U>0

$$\boxed{U = (1 - q^n) - n \cdot c}$$

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We have a model for n as a function of r and network topology

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A: Flood when U>0

$$\boxed{U = (1 - q^n) - n \cdot c}$$

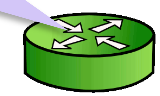
How about q = 1-p?

We have a model for n as a function of r and network topology

Estimating content availability p

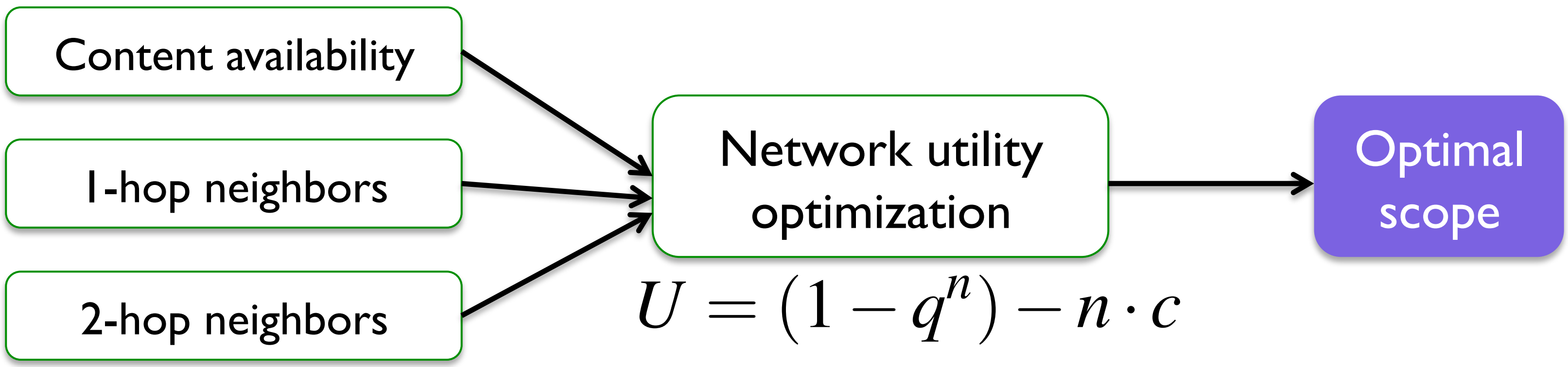
- We consider two cases of a given content set.
  - The availability is given as a priori knowledge.
  - The availability is unknown, so we apply Bayesian inference* to estimate.

What is the availability given that I receive this discovery message with hop count h, i.e., h nodes do not have the content?



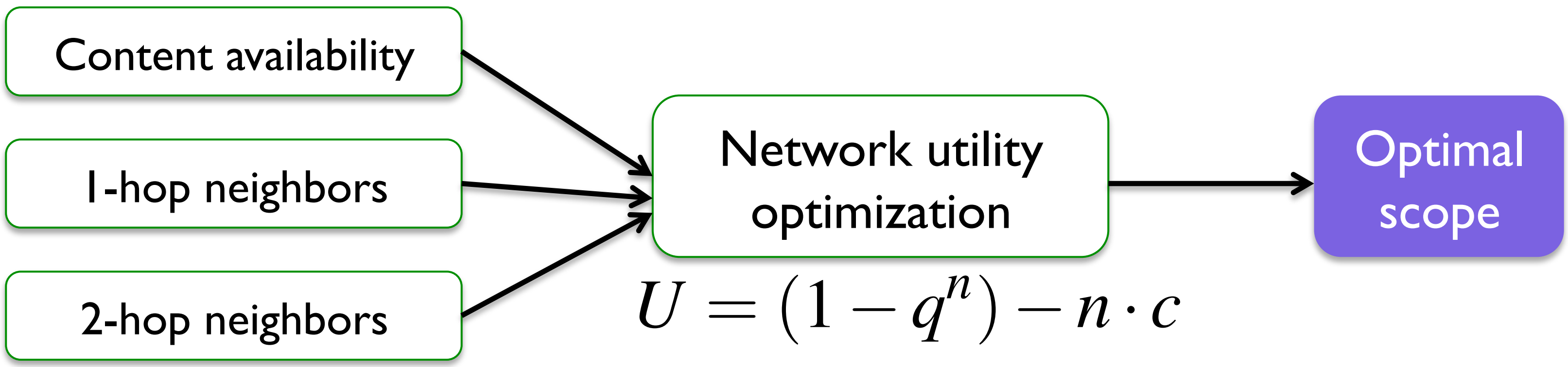
* Esa Hyytiä, S.Bayhan, J.Ott, J.Kangasharju, On Search and Content Availability in Opportunistic Networks, Computer Communications, vol. 73, Part A, Jan. 2016

How to calculate the optimal scope?



$$U = (1 - q^n) - n \cdot c$$

How to calculate the optimal scope?



$$U = (1 - q^n) - n \cdot c$$

A good flooding strategy:

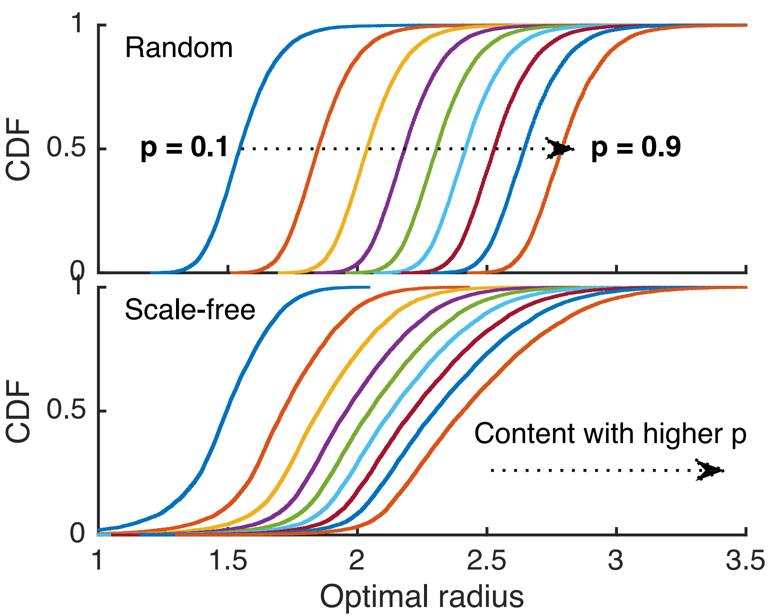
- Node is aware of its neighborhood with an accurate topological inference
- Node is aware of the content's availability with an accurate inference on user requests

Optimal scope for each node or for the whole network?

- Static Flooding (r)
  - Same optimal scope for all nodes
  - A priori knowledge on availability
  - Scope is optimised over the whole network using average # of 1-hop and 2-hop neighbours of the network
- Dynamic Flooding (r_i for node i)
  - Scope calculated for each node based on that node's neighbors
  - With content availability, only flood on popular content
  - Without content availability, always flood 1-hop neighbours by default to infer availability

Do graph generative models matter?

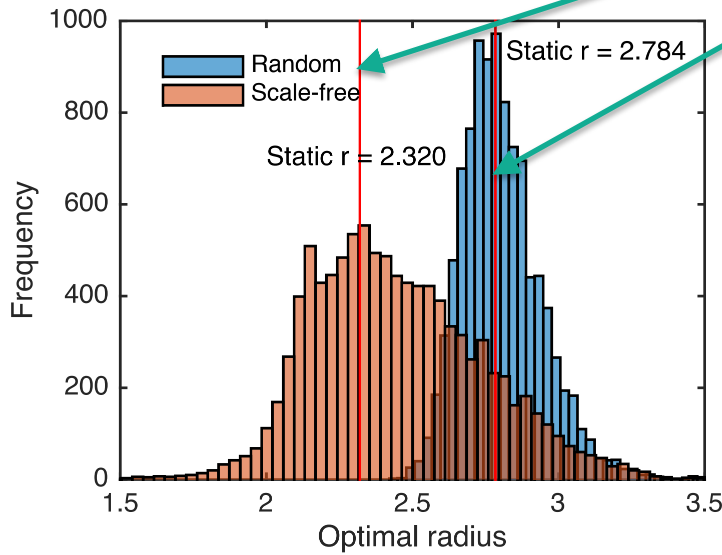
Synthetic graphs with 10000 nodes and 60000 edges



- Optimal scope 1-3 hops
- For higher content availability, scope can be larger as there is a high chance that the content will be in the network
- Nodes in a scale-free network have more diverse optimal scope setting

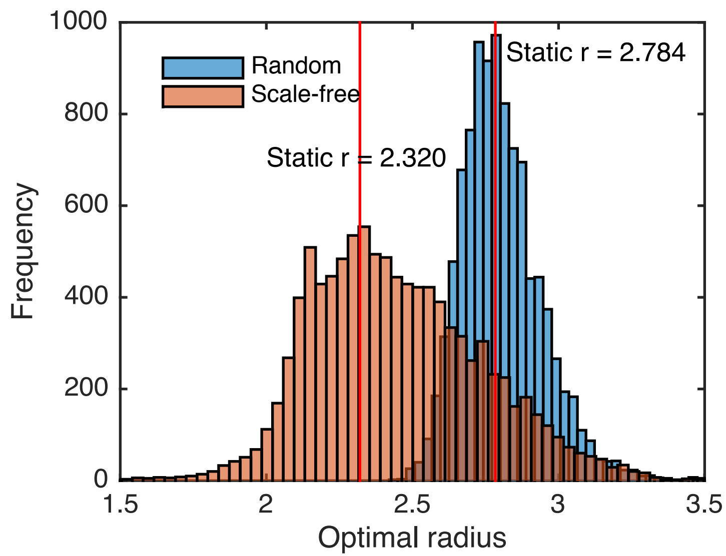
A closer look to the optimal scope

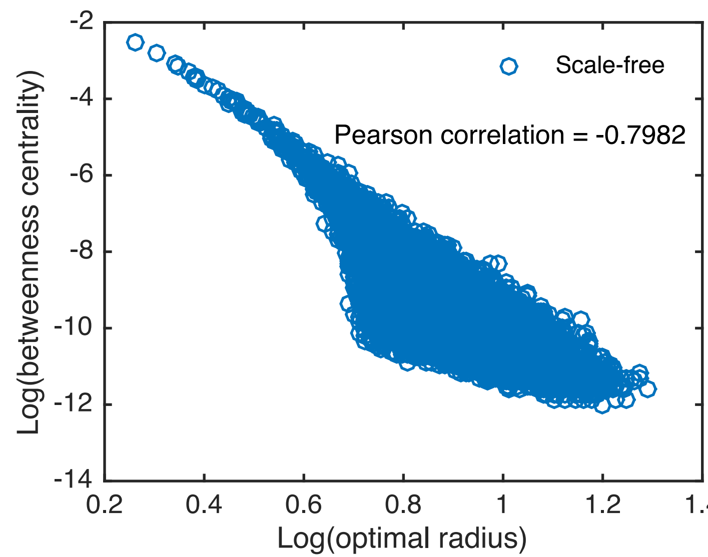
Optimal scope calculated by static flooding



- Scale free: more heterogeneity → divergence from network wide optimal scope.

A closer look to the optimal scope

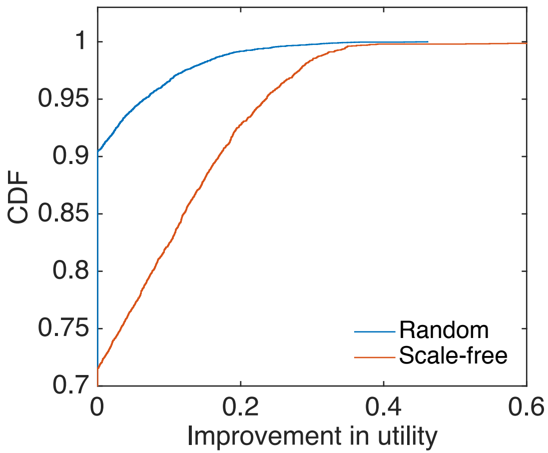




- Scale free: more heterogeneity → divergence from network wide optimal scope.
- Negative correlation → nodes at the network core have smaller optimal scope

Is dynamic flooding always effective?

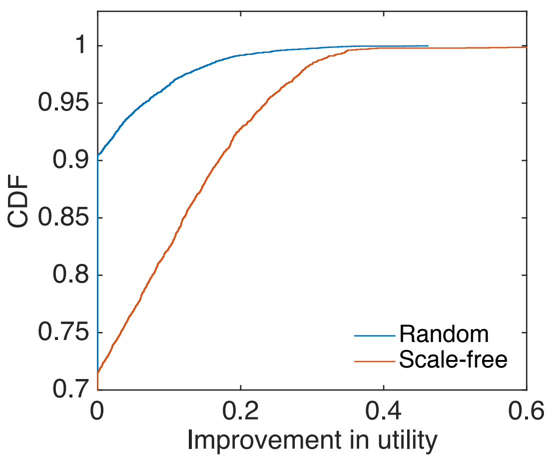
Improvement = (Utility of dynamic flooding - utility of static flooding) / utility of static flooding

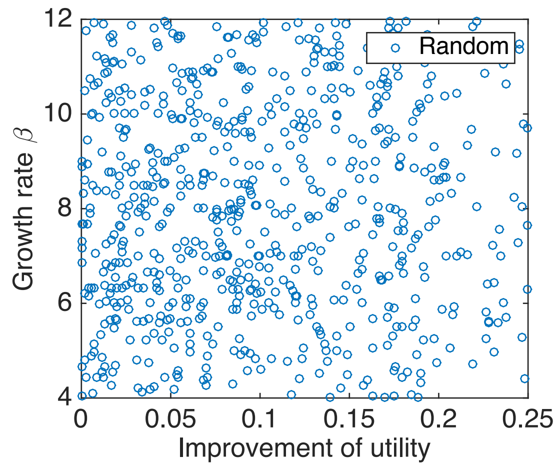


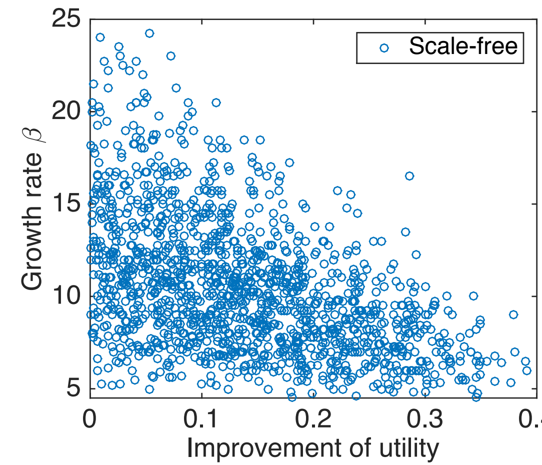
- Very little utility improvement (10% of the nodes) in ER graph because network-wide optimal scope matches node-based optimal scope.
- ER: homogenous structure

Is dynamic flooding always effective?

Improvement = (Utility of dynamic flooding - utility of static flooding) / utility of static flooding



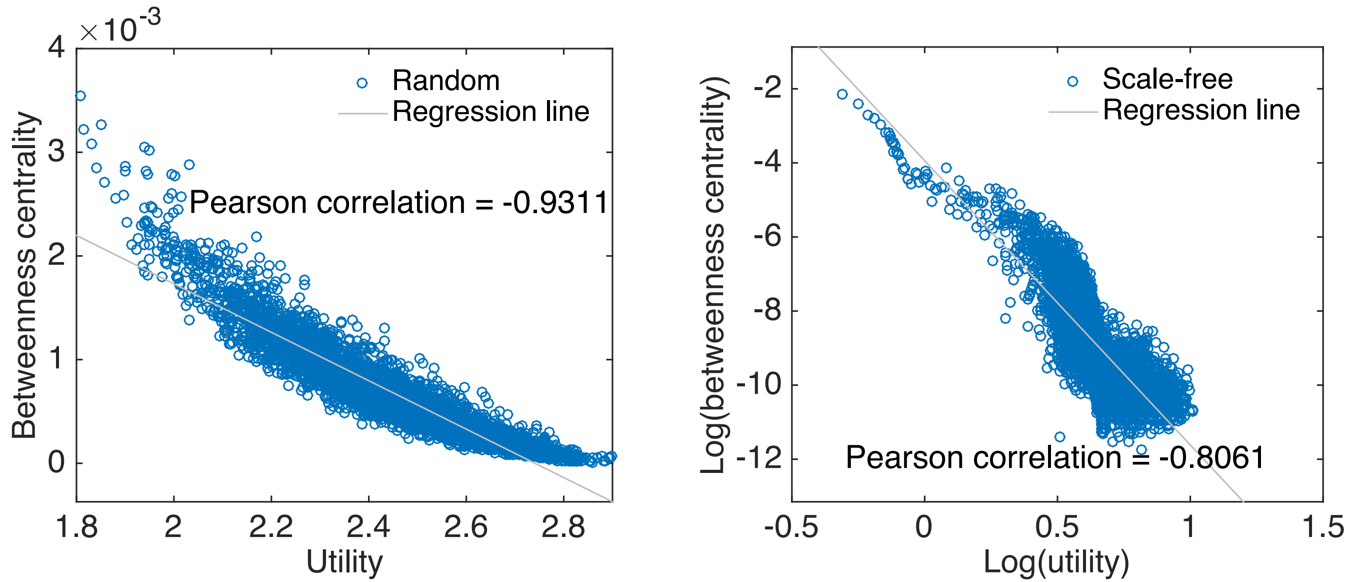




- Correlation between growth and the utility improvement on random network (10% of the nodes) is close to zero, indicating that the significance of improvement is irrelevant of a node's growth rate and its position in the network.

- Correlation on scale-free network (30% of the nodes) is much stronger, with Pearson correlation being 0.53.

How utilities are distributed in the network?



- Strong negative correlation between the utility and betw. centrality.
- In the dense area, a node has a high betw. centrality, it may include more neighbours than necessary (the optimum) even just for 1-hop neighbours.
- In the sparser area, growth rate is lower, so nodes have a better control over the neighborhood size by fine-tuning their scope leading to smaller cost and better utility.

Comparison of dynamic, static, and network-wide flooding

- Four realistic ISP networks and a community network.
- Each node has a 4GB cache with LRU algorithm.
- Content set is based on a Youtube video trace.
- Nodes of degree 1 are clients.
- 10 to 20 servers are randomly selected in a network.
- The collective request trace is generated using a Hawkes process*, which is controlled by both temporal and spatial locality factors.

A. Dabirmoghaddam, et al., "Understanding optimal caching and opportunistic caching at "the edge" of information-centric networks," in ACM ICN'14, 2014

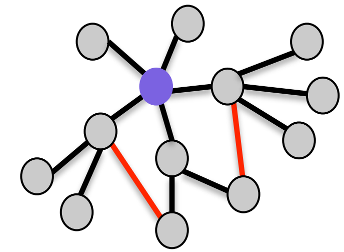
Byte hit rate, cost, and average hops

AS	Byte hit rate			Cost			Avg. hops		
	nw	st	dy	nw	st	dy	nw	st	dy
1239	0.44	0.40	0.43	1.0	0.27	0.28	1.90	1.60	1.62
2914	0.49	0.42	0.47	1.0	0.31	0.32	1.75	1.55	1.58
3356	0.42	0.39	0.42	1.0	0.25	0.27	2.02	1.69	1.74
7018	0.47	0.41	0.45	1.0	0.26	0.28	1.87	1.54	1.63
Guifi	0.51	0.44	0.49	1.0	0.22	0.23	1.71	1.32	1.38

nw: network-wide flooding
st: static flooding
dy: dynamic flooding.

- Network-wide flooding always achieves the best byte hit rate, the improvement is marginal at the price of 2 to 3 times increase cost.
- Dynamic flooding consistently outperforms static one.
- Most content are discovered within 2 hops. Network-wide flooding has the highest values due to its inherent aggressiveness.

What are the limitations of this model?



- Clustering coefficient is not considered in the network model, so it overestimates the neighbourhood growth.
- Cost of retrieving a content is not considered.
- Sublinear growth in gain and exponential growth in cost, this needs to be verified and justified in reality.
- Only evaluated with LRU, we do not know whether other in-network caching algorithms will change our story or not.

Key take-aways

- The neighbourhood (of a medium scope) can be very well approximated with a node's 2-hop information.
- Accurate estimation for 3-4 hops on the network growth
- Analysis on ISP topologies shows the fast network growth
- The choice on static or dynamic flooding depends on the network structure. I.e., random or scale-free networks.
- When to flood: If expected utility is positive, higher content availability
- Where to flood: Better at the network edge

Thanks

The slides and the paper are available at http://www.hiit.fi/u/bayhan/

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