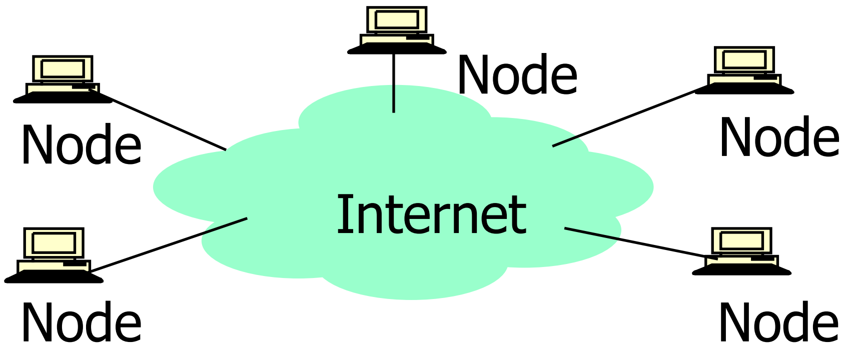
Emergence of Superpeer Networks: A New Perspective

Bivas Mitra

Department of Computer Science & Engineering

Indian Institute of Technology, Kharagpur, India

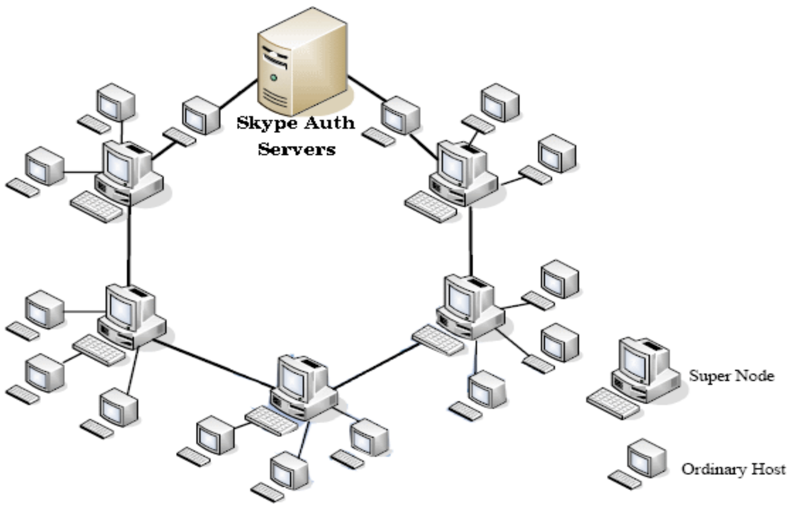
Peer to Peer architecture

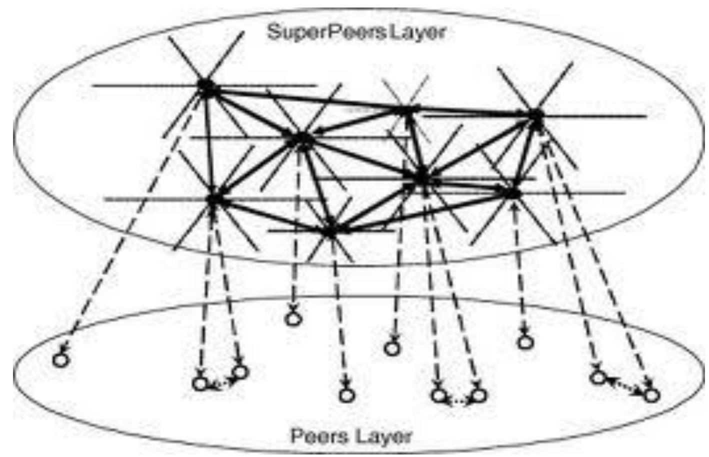


- All peers act as both clients and servers
  - Any node can initiate a connection
  - Provide and consume data
- No centralized data source
- Superpeer network (Gnutella 0.6, KaZaA, Skype) emerges as most widely used network

Superpeer Topologies

- Two Layer Topologies in certain networks like Skype, Gnutella





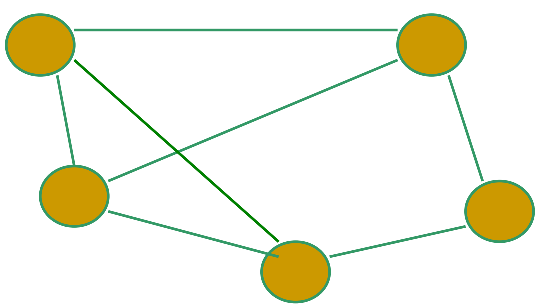
Top Layer --- Resourceful nodes (Superpeers)

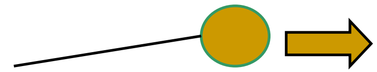
  - High Bandwidth, Storage Space, Computational Power
  - Provides Search, Indexing and Storage Services to the nodes in the network

- Bottom Layer --- Ordinary nodes

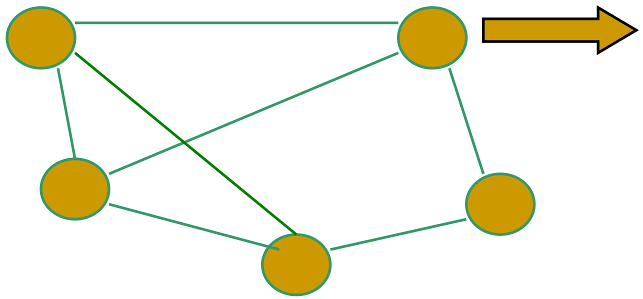
Image Sources: techblessing.com and Lua et al.
Comp. Comm. 31(3), 2008

Dynamics in superpeer networks



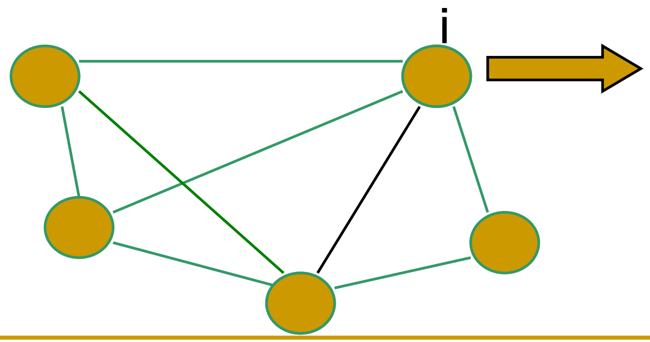


Node joins through bootstrapping protocol



Node removal

Node leaves the network due to churn and attack

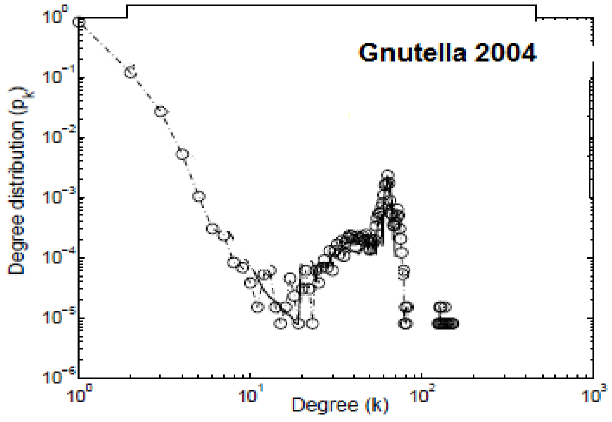


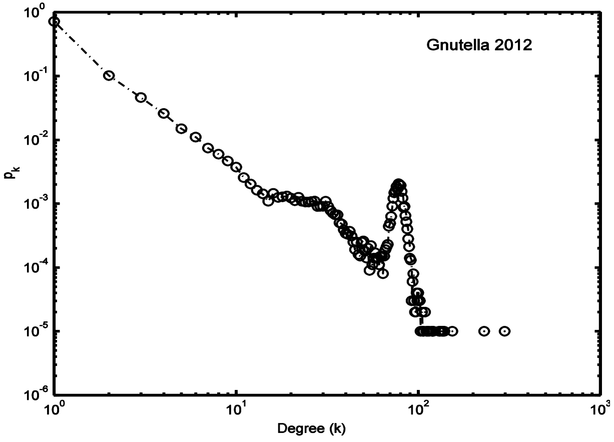
Node initiated rewiring

Rewiring of links

Superpeer networks

- Topology of the superpeer networks are modeled by degree distribution p_k
  - p_k specifies the fraction of nodes having degree k





Degree distribution of Gnutella

- Superpeer network
  - Small fraction of nodes are superpeers and rest are peers
  - Can be modeled using bimodal degree distribution

Research Question

- **Why** does bootstrapping protocol result in bimodal distribution in superpeer networks?
- Literature shows that preferential attachment of nodes results scale free network
  - Inclusion of the 'fitness' and 'rewiring of links' do not changes the nature
  - But superpeer networks (Gnutella, Skype) exhibit bimodal degree distribution
- **How** does the bootstrapping affects network topology
- Can this understanding may help the design engineers to improve p2p networks?

Outline

IEEE INFOCOM 2010, IEEE INFOCOM 2013 (Mini conference)

- Modeling the bootstrapping protocols
- Development of an **analytical framework** to explain the appearance of bimodal network
- Investigating the effect of various bootstrapping parameters on network topology (fraction of superpeers etc.)
- Study of the Gnutella network in light of the developed formalism

Modeling the bootstrapping protocols

- Each node joins the network with
  - Node weight (processing power, storage space etc)
  - Finite bandwidth (determines the cutoff degree)
- Newly arriving peers
  - Preferentially attach to known powerful peers (via Webcache)
  - 'Powerful' node is defined by the 'node weight' and current 'node degree'
  - Random connections also exist (parameterized by ε)
- Model
  - Preferential as well as Random attachment by the nodes
    - Attachment Probability $\propto (k + \varepsilon)$, w
      - k = Degree of the existing node
      - ε = randomness parameters
      - w= node weight

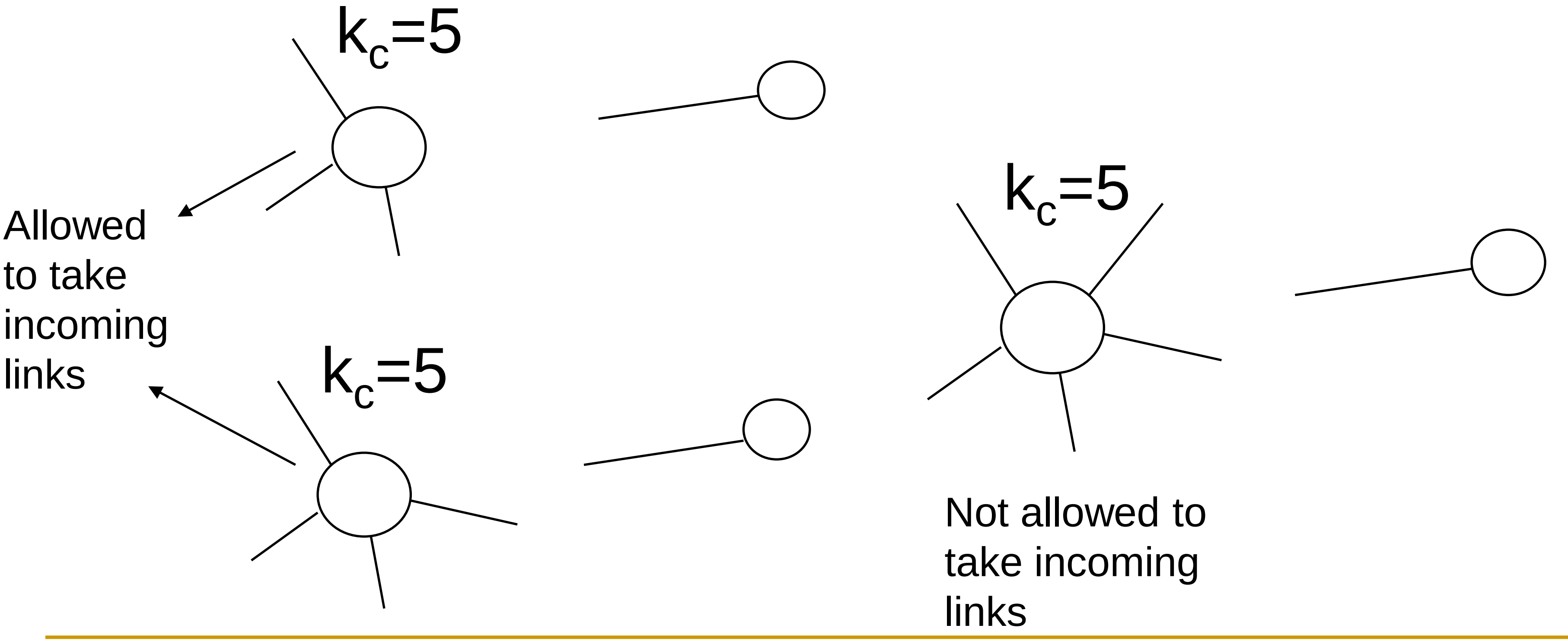
Bootstrapping Constraints

Concept of cutoff degree

- Bandwidth constraints of the nodes
- Implication
  - A node can take at most k_c number of connections
  - Further connection request will be rejected

Concept of finite bandwidth/cutoff degree

Cutoff degree of a node is k_c



Bootstrapping Constraints

Concept of cutoff degree

Two different assumptions

- **Simple :** All the nodes join with same cutoff degree k_c
- **Realistic :** Nodes join with individual cutoff degree.
  - $q_{kc(j)}$ fraction of nodes joins with cutoff degree kc(j).
- All nodes join with degree - m

What do we aim to observe?

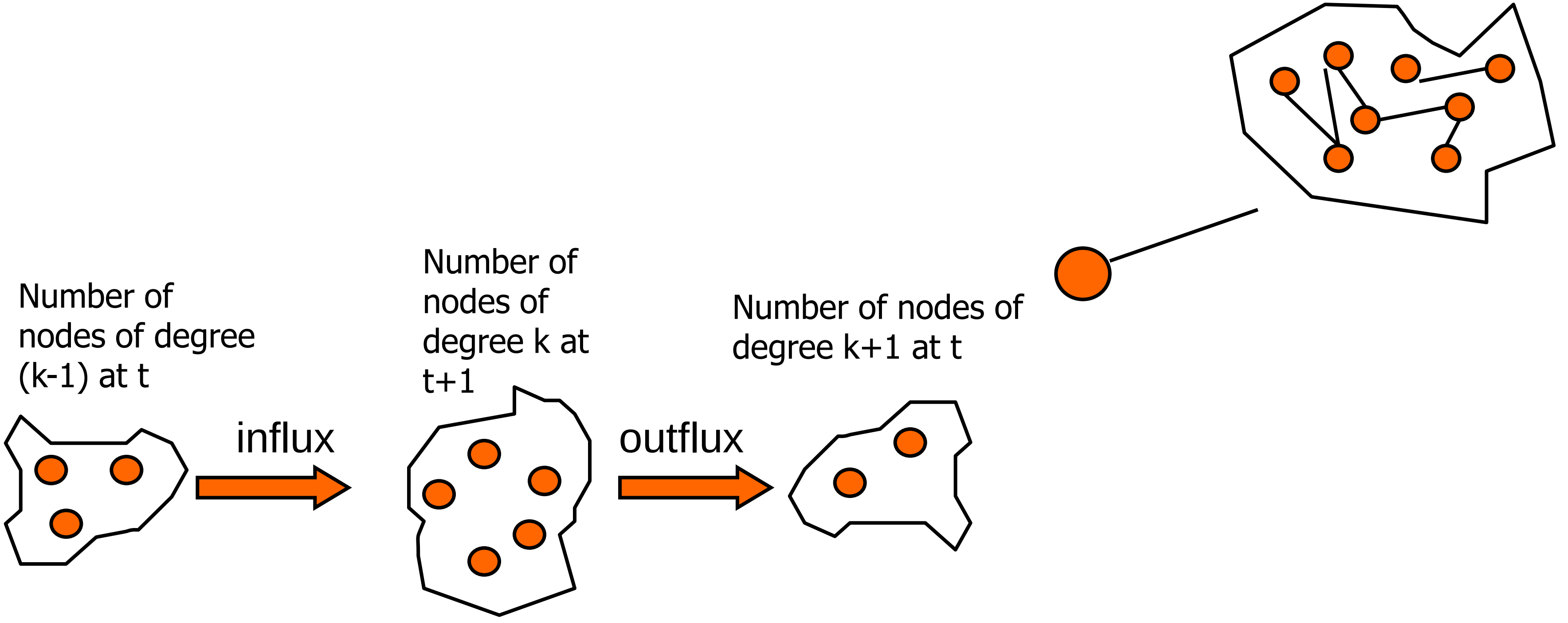
- Effect of bootstrapping parameters
  - *ε (randomness factor)*
  - w (resource)
  - k_c (cutoff degree)
  - *m (joining degree)*

- On the network topology
  - Fraction of superpeers p_{kc}
  - Fraction of lowest degree nodes p_m and
  - Prominence of superpeers
    - Denoted as Superpeer Demarcation Ratio (SDR)=$p_{kc}/(p_{kc}-1)$

Development of the analytical framework

Joining of a node results

- the shift in the k degree nodes to (k+1)
- The shift in the (k-1) degree nodes to k



The Degree Distribution

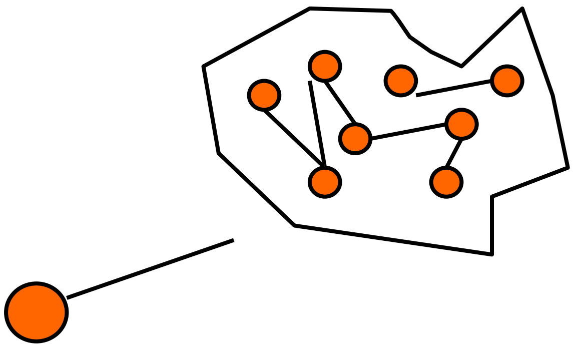
- When a new node arrives

p_k - probability that a node is of degree k

Asymptotically -- $DD_{(n+1)} \approx DD_n \rightarrow p_{k,n+1} \approx p_{k,n} \approx p_k$

The Degree Distribution

- Let $\delta_{k->k+1}$= average no. of nodes that changes from degree *k* to *k+1*. Then
  - $\Delta n_k = \delta_{k->k+1} - \delta_{k-1->k}$



The Degree Distribution

m $m < k < k_c$ k_c

Rate equation at $k = m$

$\delta_{k-1\to k} = 1$ and $\delta_{k\to k+1} = \frac{(k+\epsilon)p_k}{\xi f}$,

$$\Delta n_k = \delta_{k-1\to k} - \delta_{k\to k+1}, \qquad p_m = \frac{\xi f}{m+\epsilon+\xi f}.$$

Rate equation at $k = k_c$

$\delta_{k\to k+1} = 0$ and $\delta_{k-1\to k} = \frac{(k+\epsilon-1)p_{k-1}}{\xi f}$,

$$\Delta n_k = \delta_{k-1\to k} - \delta_{k\to k+1}, \qquad p_{k_c} = \frac{(k_c+\epsilon-1)p_{k_c-1}}{\xi f}$$

Rate equation at $m < k < k_c$

$$\Delta n_k = \delta_{k-1\to k} - \delta_{k\to k+1}, \qquad p_k = \frac{k+\epsilon-1}{k+\epsilon+\xi f} p_{k-1}.$$

$$p_k = \frac{(k+\epsilon-1)(k+\epsilon-2)\cdots(m+\epsilon)p_m}{(k+\epsilon+\xi f)(k+\epsilon+\xi f-1)\cdots(m+\epsilon+\xi f+1)} = C_1\frac{B(k,\epsilon+\xi f+1)}{B(k,\epsilon)}.$$

p_k heavily depends on Beta function B(a,b) $\Rightarrow$ ε

The Degree Distribution (Approx)

For m < k < k_c $\quad p_k = \frac{k+\varepsilon-1}{k+\varepsilon+\xi f} p_{k-1}$ $\quad$ and $\quad p_{k_c} = \frac{k_c+\varepsilon-1}{\xi f} p_{k_c-1}$

- Low values of ε ($\varepsilon << k_c$)

$$p_m = \frac{\xi f}{m+\varepsilon+\xi f}$$

  - When $m < k < k_c$

$$p_k \approx \frac{\xi f}{m+\varepsilon+\xi f} m^{\xi f+1} k^{-(\xi f+1)}$$

  - When $k=k_c$

$$p_{k_c} \approx m^{\xi f} k^{-\xi f}$$

- Higher values of ε

$$p_m = \frac{\xi f}{m+\varepsilon+\xi f}$$

  - When m <k < kc

$$p_k = C(k+\varepsilon)^{-(\xi f+1)} e^{-\frac{(\xi f+1)(\xi f+0.5)}{k+\varepsilon}}$$

  - When k = k_c

$$p_{k_c} = \frac{C}{\xi f}(k+\varepsilon-1)^{-\xi f} e^{-\frac{(\xi f+1)(\xi f+0.5)}{k+\varepsilon-1}}$$

The Degree Distribution

For m <

- Low v

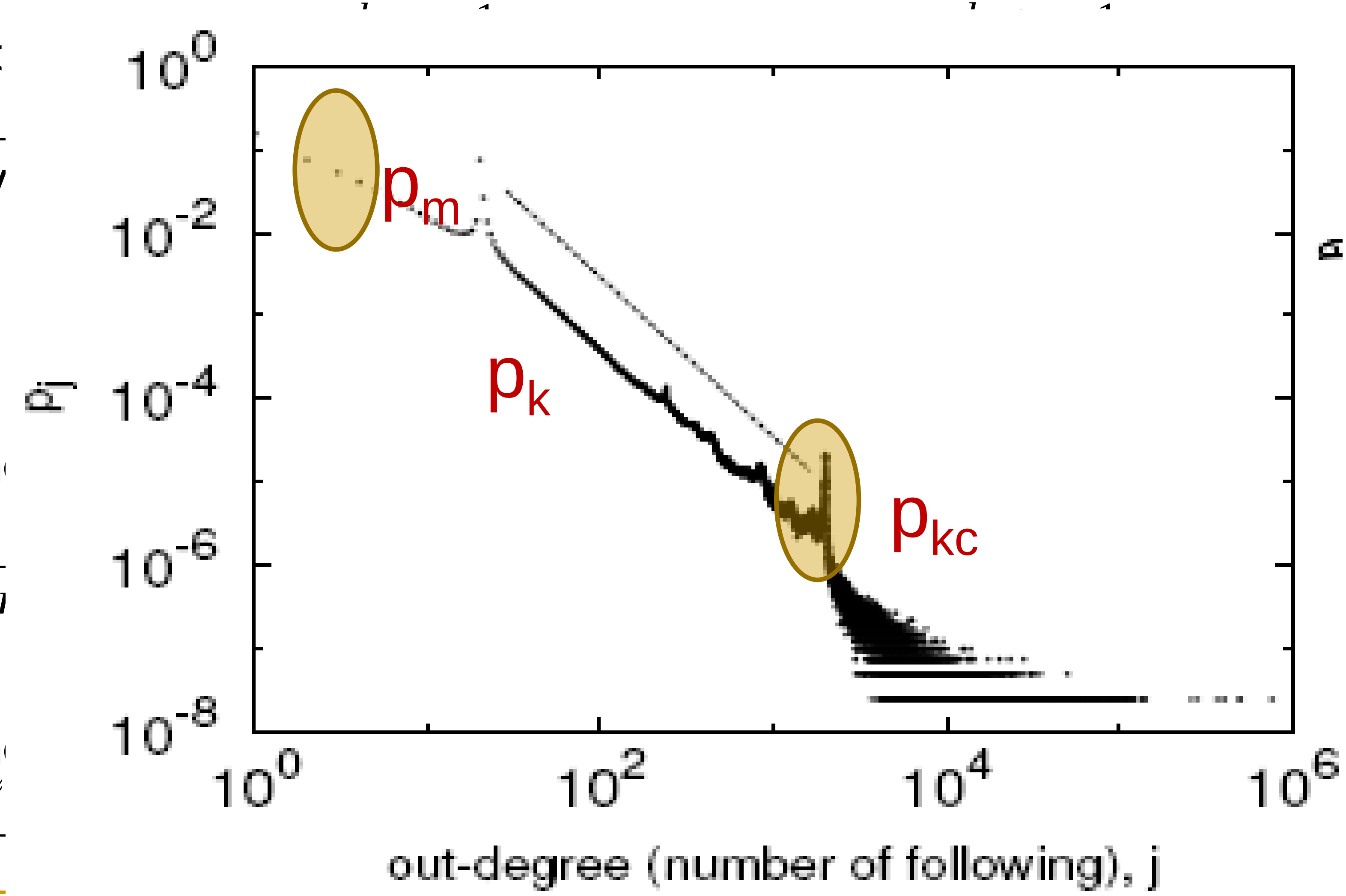
  $p_m =$

  - Wh

  $p_k \approx$

  - Wh

  $p_{k_c} \approx$



The Degree Distribution

For m < k < k_c $p_k = \frac{k+\varepsilon-1}{k+\varepsilon+\xi f} p_{k-1}$ and $p_{k_c} = \frac{k_c+\varepsilon-1}{\xi f} p_{k_c-1}$

- Low values of ε ($\varepsilon << k_c$)

$$p_m = \frac{\xi f}{m+\varepsilon+\xi f}$$

  - When $m < k < k_c$

$$p_k \approx \boxed{\frac{\xi f}{m+\varepsilon+\xi f} m^{\xi f+1} k^{-(\xi f+1)}}$$

  - When $k=k_c$

$$p_{k_c} \approx m^{\xi f} k^{-\xi f}$$

Power law

- Higher values of ε

$$p_m = \frac{\xi f}{m+\varepsilon+\xi f}$$

Deviates from power law

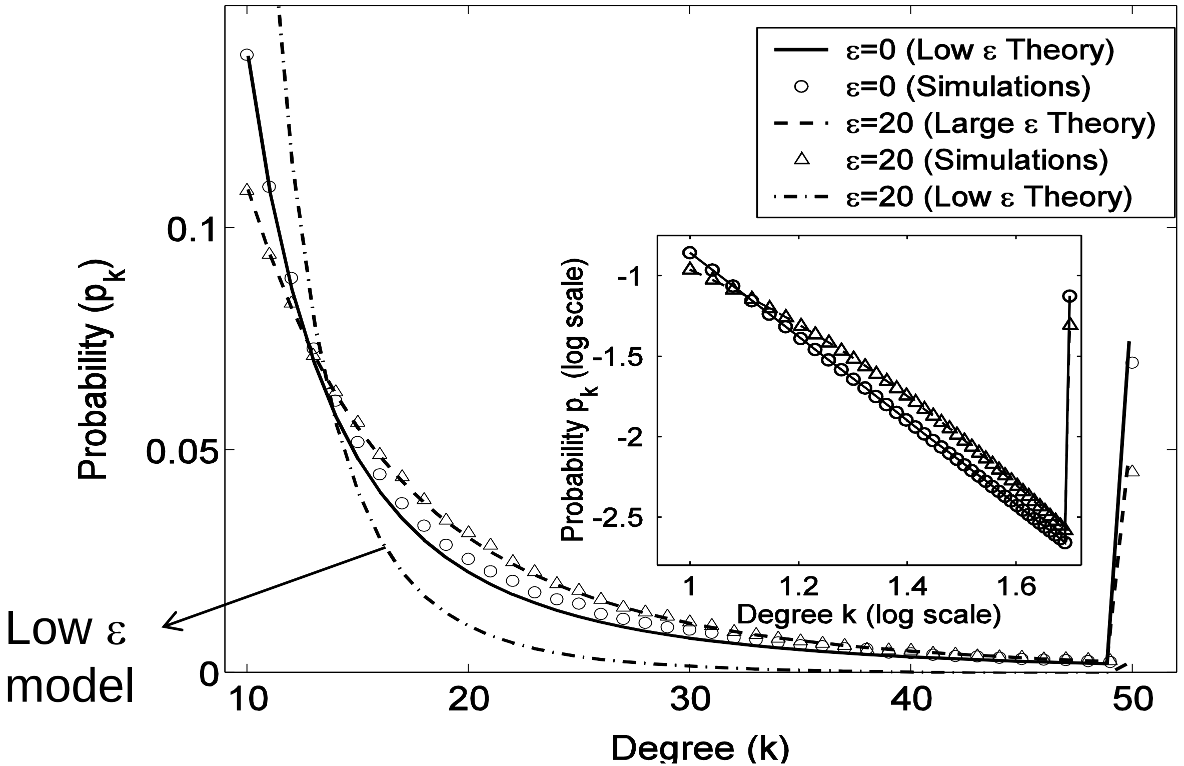
  - When m <k < kc

$$p_k = \boxed{C(k+\varepsilon)^{-(\xi f+1)} e^{-\frac{(\xi f+1)(\xi f+0.5)}{k+\varepsilon}}}$$

  - When k = k_c

$$p_{k_c} = \frac{C}{\xi f}(k+\varepsilon-1)^{-\xi f} e^{-\frac{(\xi f+1)(\xi f+0.5)}{k+\varepsilon-1}}$$

Validation: Impact of epsilon



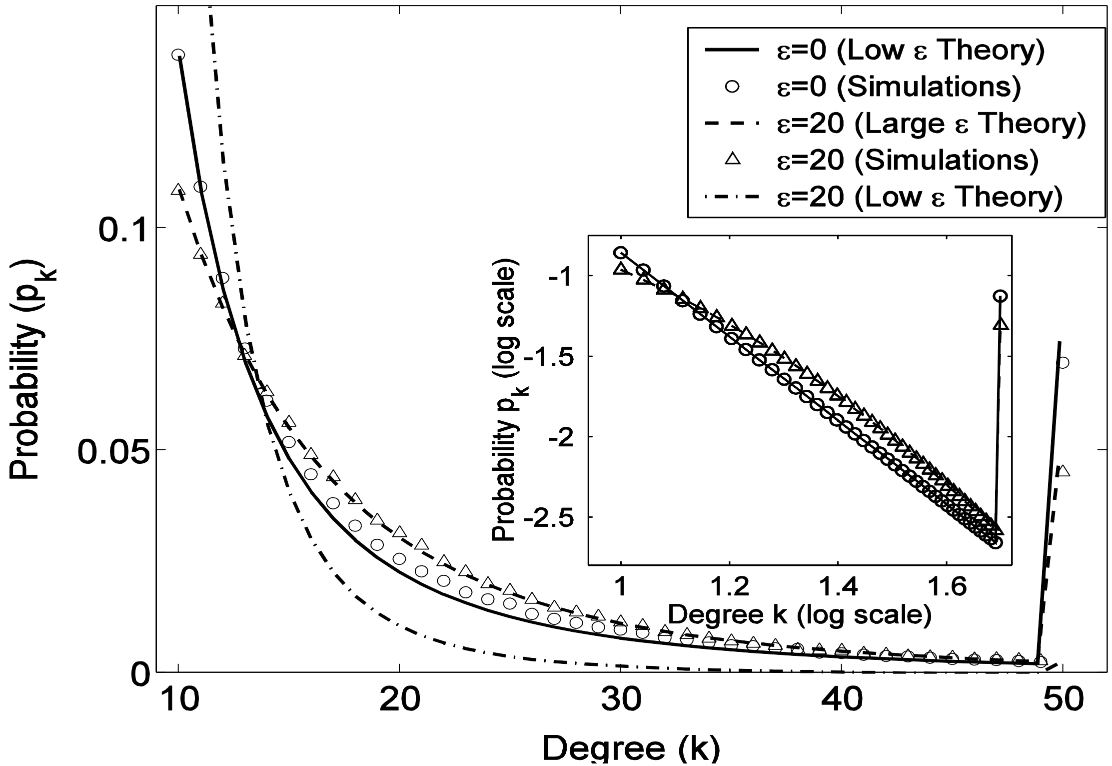
m=10
k_c=50
5000 nodes
500 realizations

Randomness ε adds a new dimension

- Approximation for low ε matches well with simulation for ε=0
  - Does not fit well with ε=20
- Approximation for high ε matches well with simulation for ε=20

For all simulations number of nodes is 5000

Validation: Impact of epsilon



Impact of *ε, k_c and m On*

a) Fraction of superpeers (p_{kc})

b) Fraction of lowest degree nodes (p_m)

c) SDR

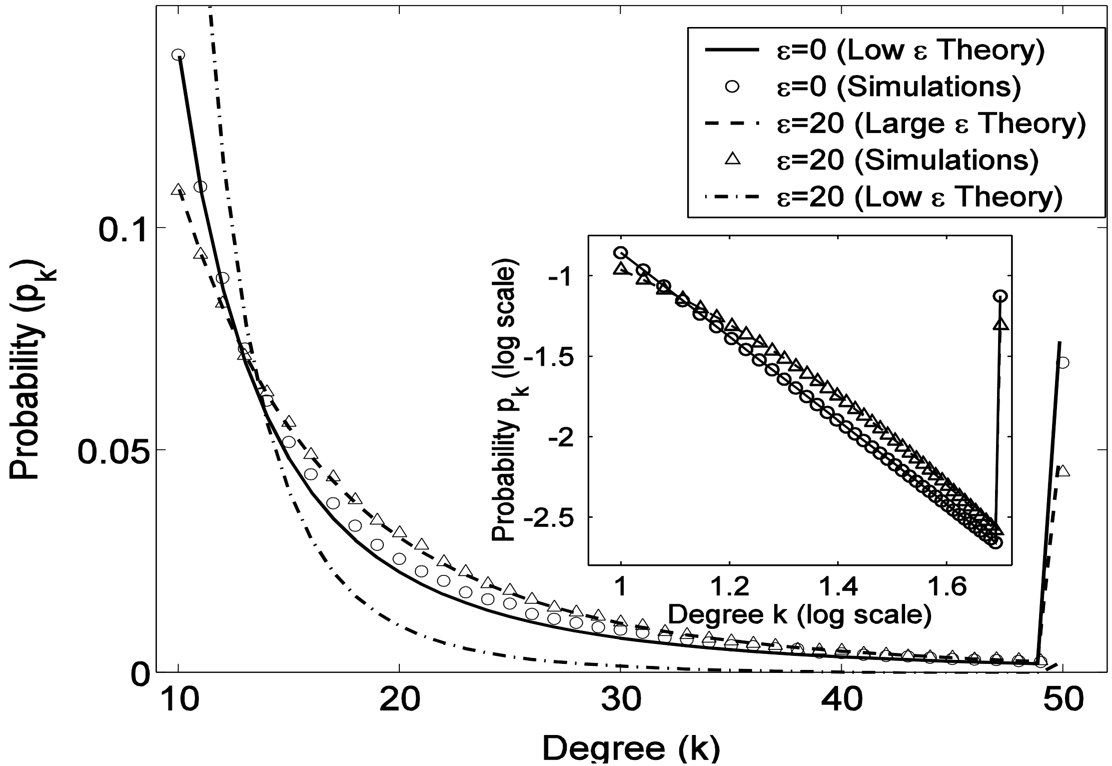
$$\lim_{\epsilon \to 0} p_m = \frac{2f}{m+2f} \text{ and } \lim_{\epsilon \to \infty} p_m = \frac{f}{m+f}$$

Increase in *ε reduces p_m*

Many m degree peers receive connections, results m ⇒ m+1, m+2, etc

For all simulations number of nodes is 5000

Validation: Impact of epsilon



Impact of *ε, k_c and m On*

a) Fraction of superpeers (p_{kc})

b) Fraction of lowest degree nodes (p_m)

c) SDR

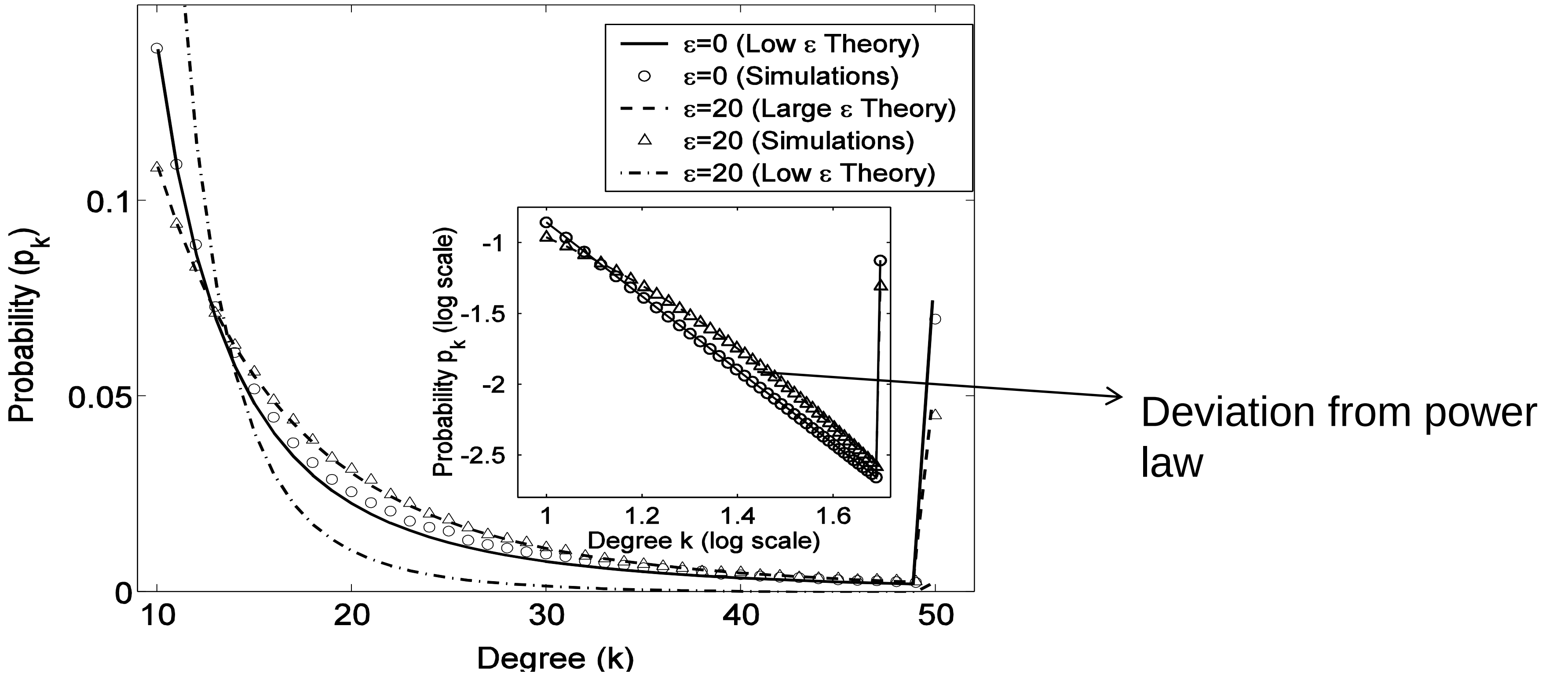
$$p_{k_c} = \frac{k_c + \epsilon - 1}{\xi f} p_{k-1}$$

Increase in ***ε reduces*** $\frac{k+\epsilon-1}{\xi f}$

Hence reduces p_{kc}

For all simulations number of nodes is 5000

Validation: Impact of epsilon



- Impact of epsilon on p_m and p_{kc}
  - Increase in ε **reduces both p_m and p_{kc}**
  - The fraction of intermediate degree node increases

For all simulations number of nodes is 5000

The Degree Distribution

For $m < k < k_c$ $\quad p_k = \dfrac{k+\varepsilon-1}{k+\varepsilon+\xi f}\, p_{k-1}$ and $\quad p_{k_c} = \dfrac{k_c+\varepsilon-1}{\xi f}\, p_{k_c-1}$

- Low values of ε ($\varepsilon << k_c$)

$$p_m = \frac{\xi f}{m+\varepsilon+\xi f}$$

  - When $m < k < k_c$

$$p_k \approx \boxed{\frac{\xi f}{m+\varepsilon+\xi f} m^{\xi f+1} k^{-(\xi f+1)}}$$

Power law

  - When $k = k_c$

$$p_{k_c} \approx m^{\xi f} k^{-\xi f}$$

- Higher values of ε

$$p_m = \frac{\xi f}{m+\varepsilon+\xi f}$$

Deviates from power law

  - When m <k < kc

$$p_k = \boxed{C(k+\varepsilon)^{-(\xi f+1)} e^{-\frac{(\xi f+1)(\xi f+0.5)}{k+\varepsilon}}}$$

  - When $k = k_c$

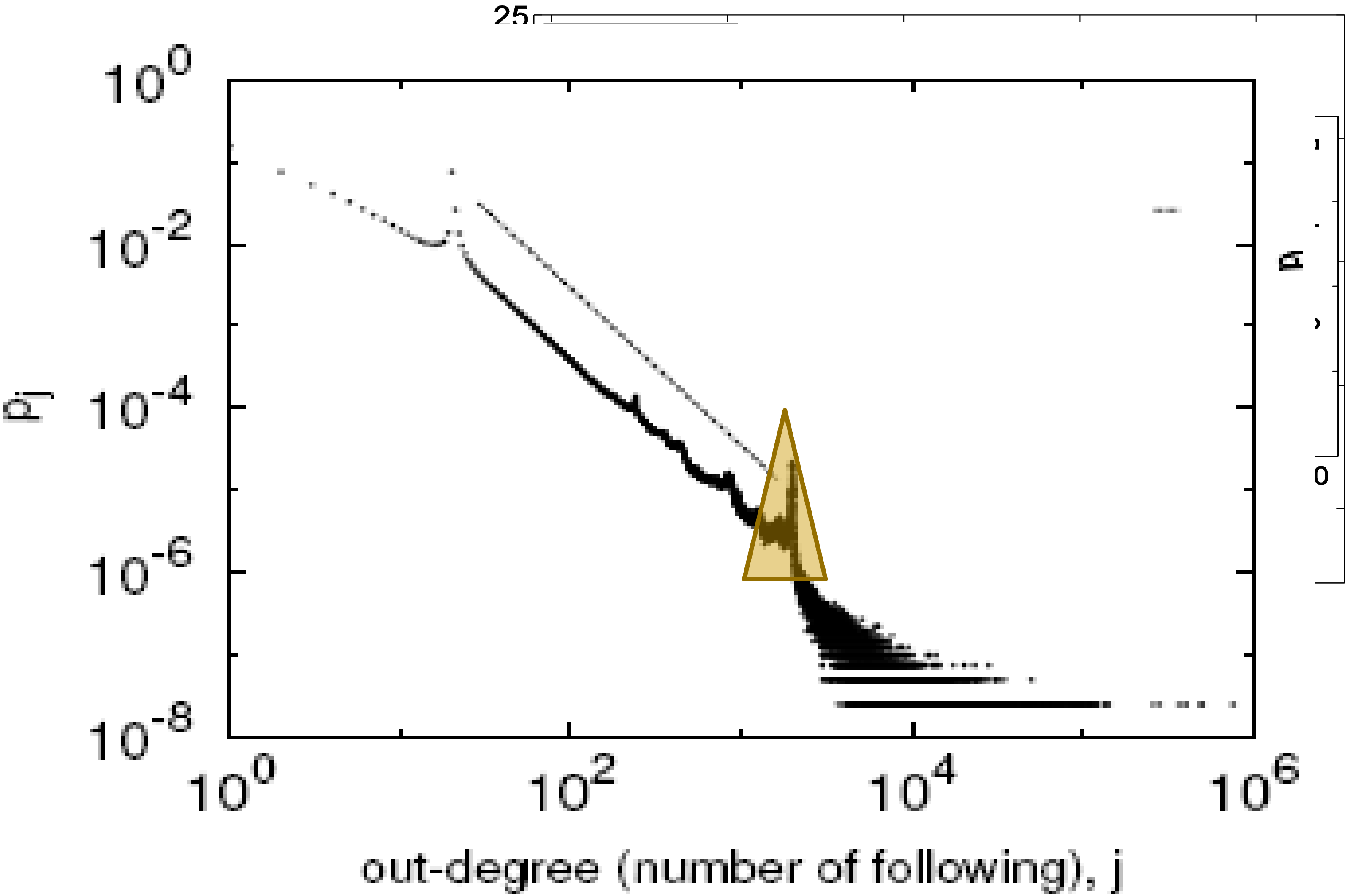
$$p_{k_c} = \frac{C}{\xi f}(k+\varepsilon-1)^{-\xi f} e^{-\frac{(\xi f+1)(\xi f+0.5)}{k+\varepsilon-1}}$$

Impact of ε on SDR (SP demarcation)

- We have

$$\boxed{\frac{p_{k_c}}{p_{k_c-1}}} =$$

- Thus with ir
  - SDR decr
    - $(k_c\text{-}2$
  - SDR incre
    - $(k_c\text{-}2$
- Thus when
  - SDR incre



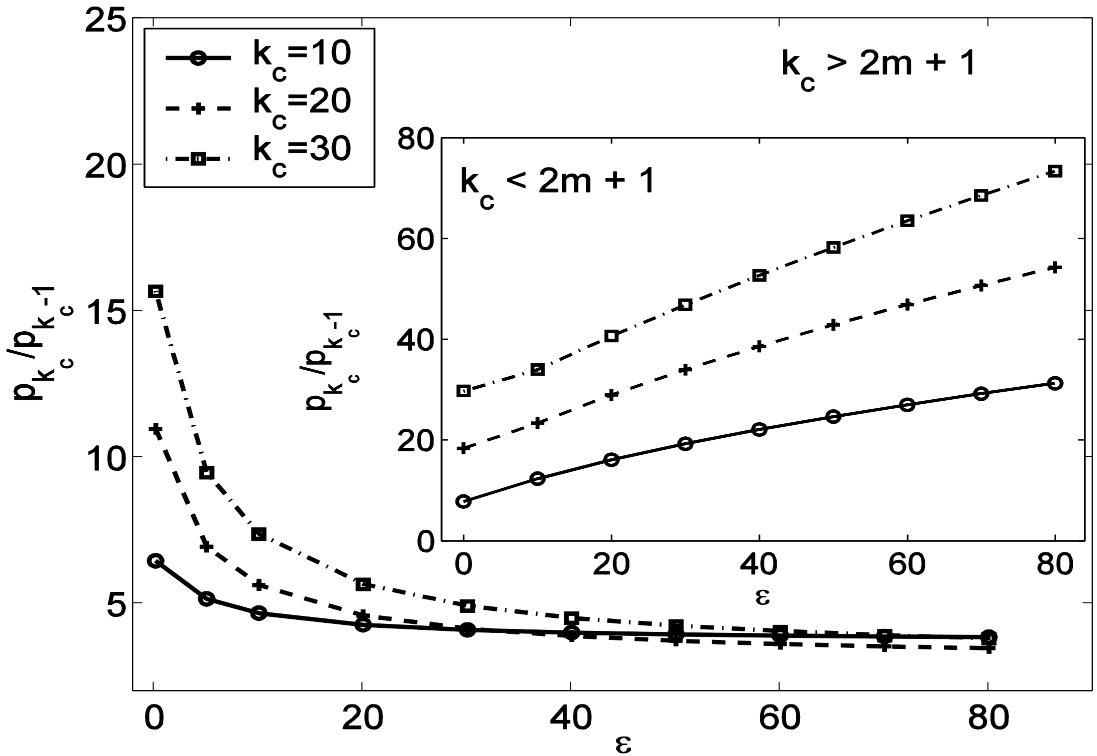
Impact of ε on SDR

- We have

$$\boxed{\frac{p_{k_c}}{p_{k_c-1}}} = \frac{m}{f}\left[\frac{k_c - 2m - 1}{2m+\varepsilon} + 1\right]$$

- Thus with increasing epsilon
  - SDR decreases if
    - $(k_c\text{-}2m\text{-}1)/(2m+\varepsilon) > 0$
  - SDR increases if (inset)
    - $(k_c\text{-}2m\text{-}1)/(2m+\varepsilon) < 0$

- Thus when $k_c < 2m+1$
  - SDR increases with ε



Values of m and k_c

(5, 10), (10, 20) (15, 30)

Impact of ε on SDR

- We have

$$\frac{p_{k_c}}{p_{k_c-1}} = \frac{m}{f}\left[\frac{k_c - 2m - 1}{2m+\varepsilon} + 1\right]$$

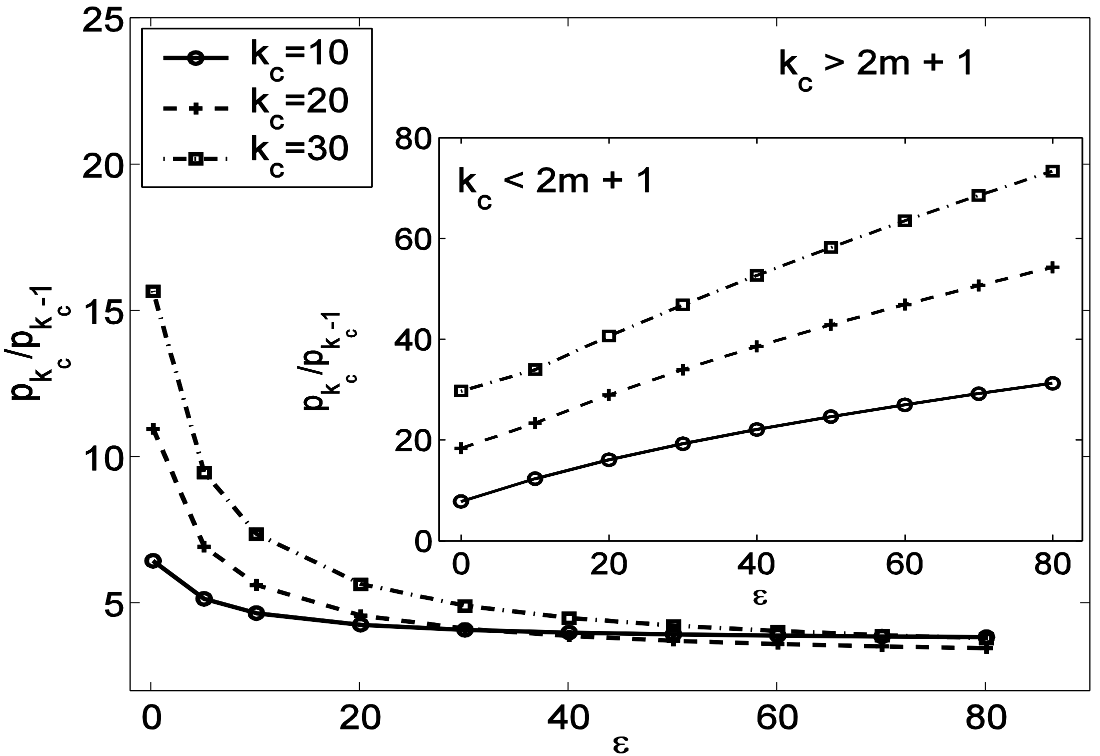
- At $\varepsilon=0$

$$\frac{p_{k_c}}{p_{k_c-1}} = \frac{m}{f}\left[\frac{k_c - 2m - 1}{2m} + 1\right] = \frac{k_c - 1}{2f}$$

- At $\varepsilon=\infty$

$$\frac{p_{k_c}}{p_{k_c-1}} = \frac{m}{f}$$

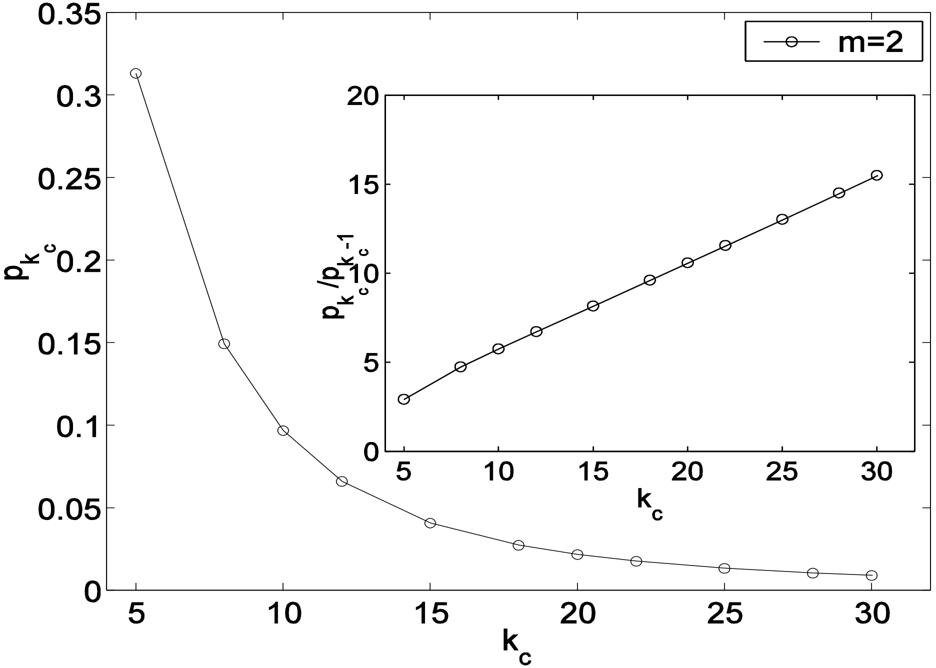
Range of SDR is bounded



Values of m and k_c

(5, 10), (10, 20) (15, 30)

Impact of k_c and m on superpeers

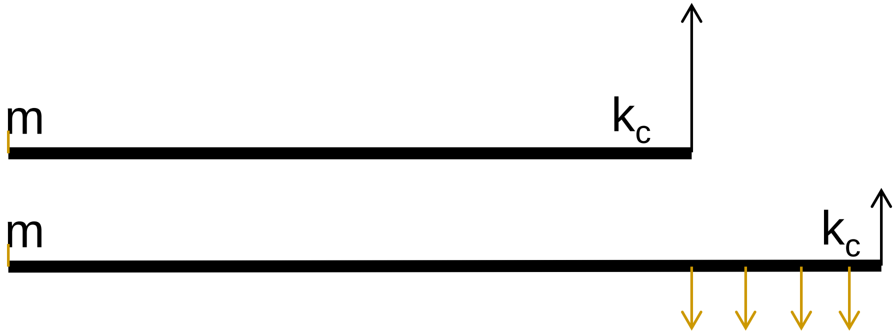


k_c=50 ε=0

- The fraction of superpeers (p_{kc})
  - Decreases with increasing values of k_c

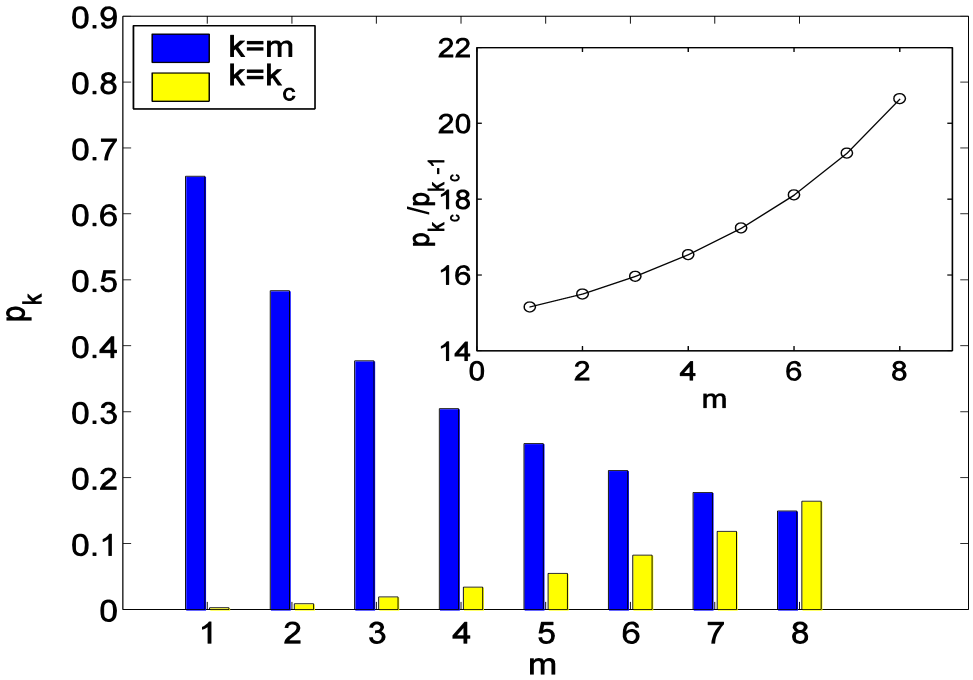
$$p_{k_c} \approx m^{\xi f} k^{-\xi f}$$

Ratio SDR= $\dfrac{p_{k_c}}{p_{k_c-1}}$ increases



Impact of k_c and m

k_c=50 ε=0



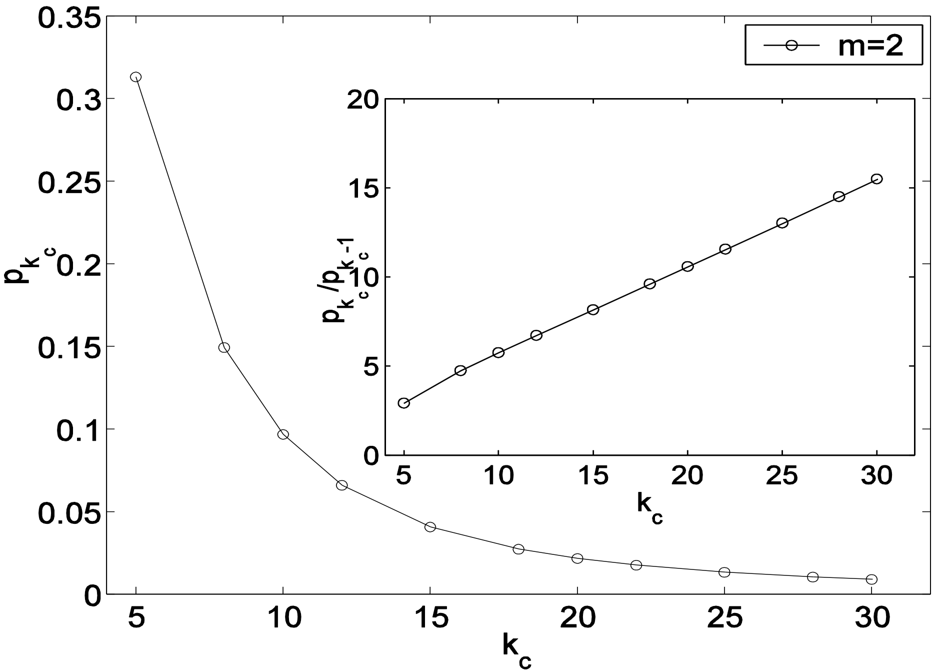
- The fraction of superpeers (p_{kc})
  - Increases with increasing values of m

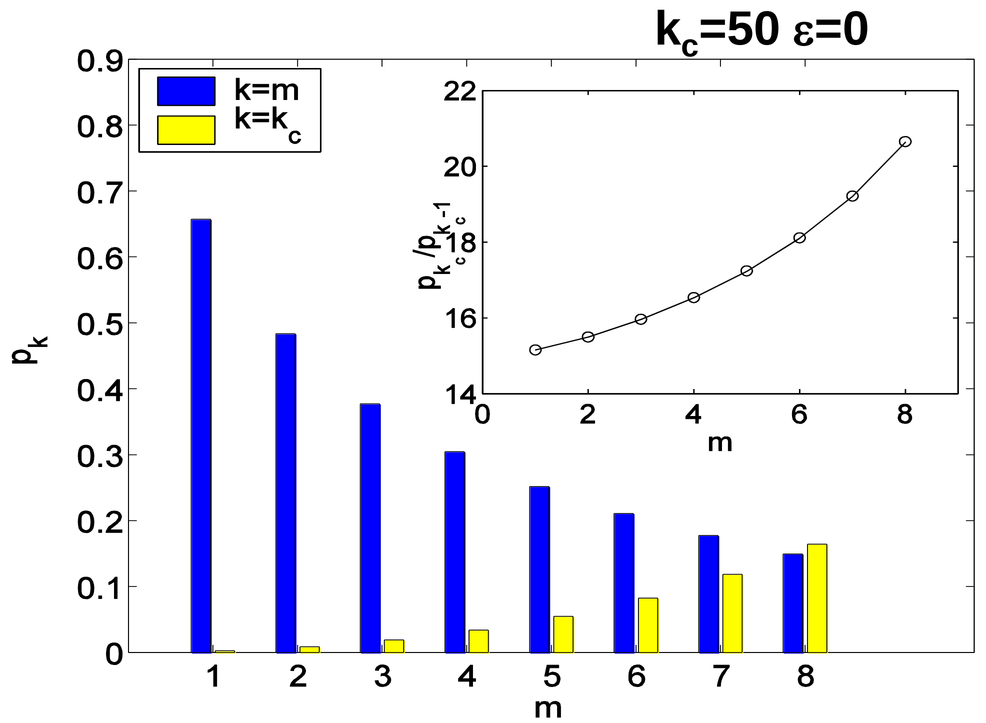
$$p_{k_c} \approx m^{\xi f} k^{-\xi f}$$

- The fraction of low degree peers (p_m)
  - Gets high value for low m

$$\lim_{\epsilon \to 0} p_m = \frac{\xi f}{m + \epsilon + \xi f} = \frac{\xi f}{m + \xi f}$$

Impact of k_c and m





- The fraction of superpeers (p_{kc})
  - Decreases with increasing values of k_c
  - Increases with increasing values of m
- The SDR
  - Increases with increasing values of both m and k_c

What do we aim to observe?

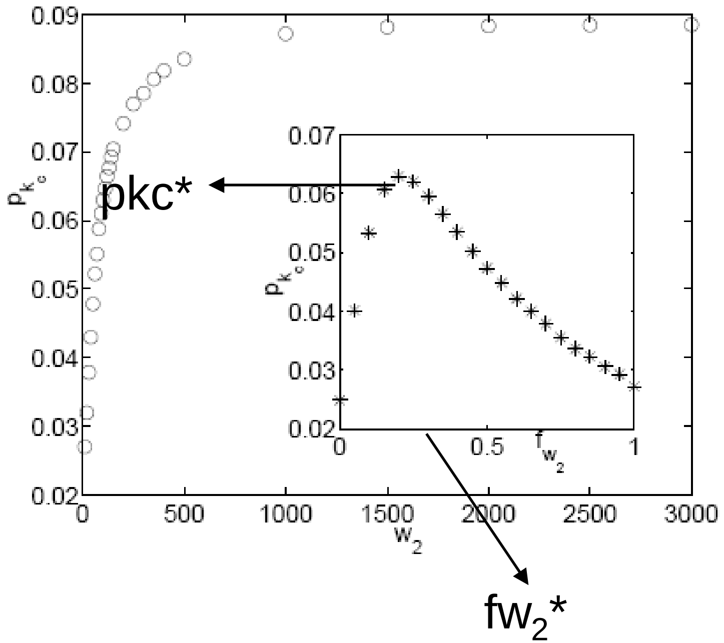
- Effect of bootstrapping parameters
  - *ε (randomness factor)*
  - **w (resource)**
  - k_c (cutoff degree)
  - *m (lowest degree)*

f_w fraction of nodes of weight w

- On the network topology
  - **Fraction of superpeers p_{kc}**
  - Fraction of lowest degree nodes p_m and
  - Prominence of superpeers
    - Denoted as Superpeer Demarcation Ratio (SDR)=$p_{kc}/(p_{kc}-1)$

Impact of node weight (w)

- Consider a bimodal weight distribution
  - nodes join with two weights w_1 and w_2 with individual fraction fw_1 and fw_2.
- We take w_1=10, fw_1=0.8. w_2 varied from 10 to 3000.



Observations (1)

1. Initial increase in w_2 increases the amount of superpeers (pk_c) rapidly.
2. After a certain threshold, pk_c stabilizes

Observations (2) - Inset

1. Initial increase in fw_2 increases p_{kc}.
2. After reaching maximum value (p_{kc}*), p_{kc} decreases
3. Existence of optimum fw_2 (fw_2*)

Impact of node weight

Some suggestions to the network engineers

- Resource (w) of a machine can be exploited only upto a point
  - Enhancing resource (w) is not always cost effective to increase the number of superpeers

- Putting many high resource machines (f_{w2}) in the network can in fact be detrimental
  - May reduce the superpeer fraction

Nodes joining with individual cutoff degree

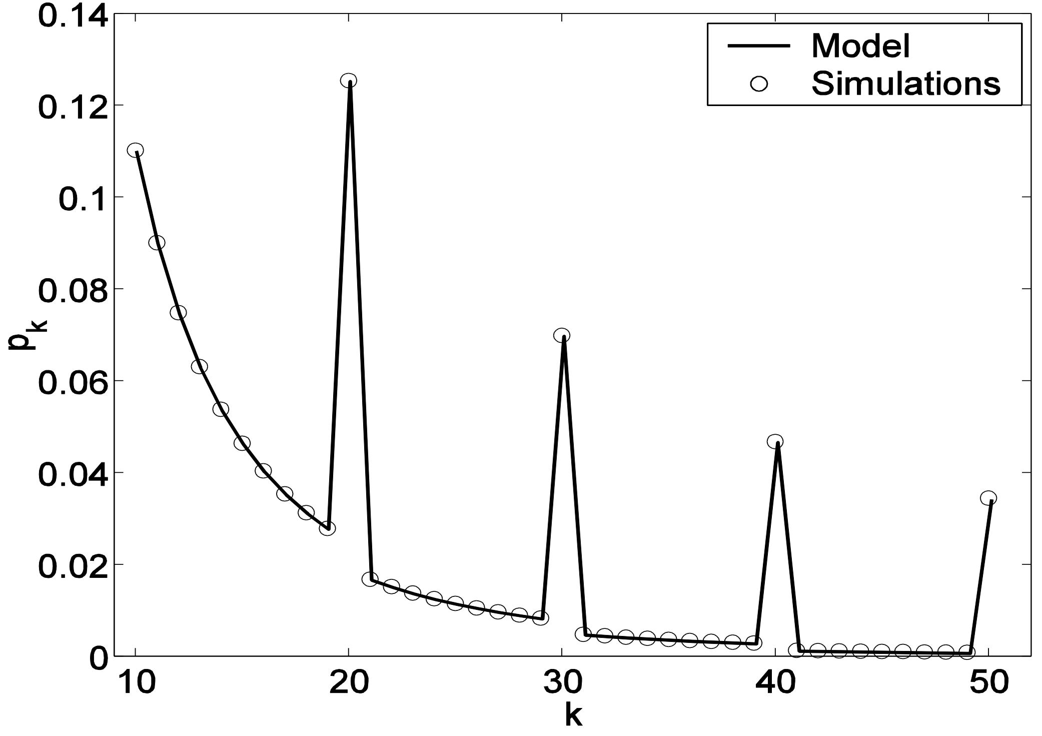
Different users have different capacity

-- Dial-up, leased line, mobile broadband, DSL

Model

Probability that node j joins with cutoff degree $k_c(j)$ is $q_{kc(j)}$; $k_c(\min) \leq k_c(j) \leq k_c(\max)$

Different cut-off degrees



❖Nodes joined with cut-off degrees 20, 30, 40 & 50

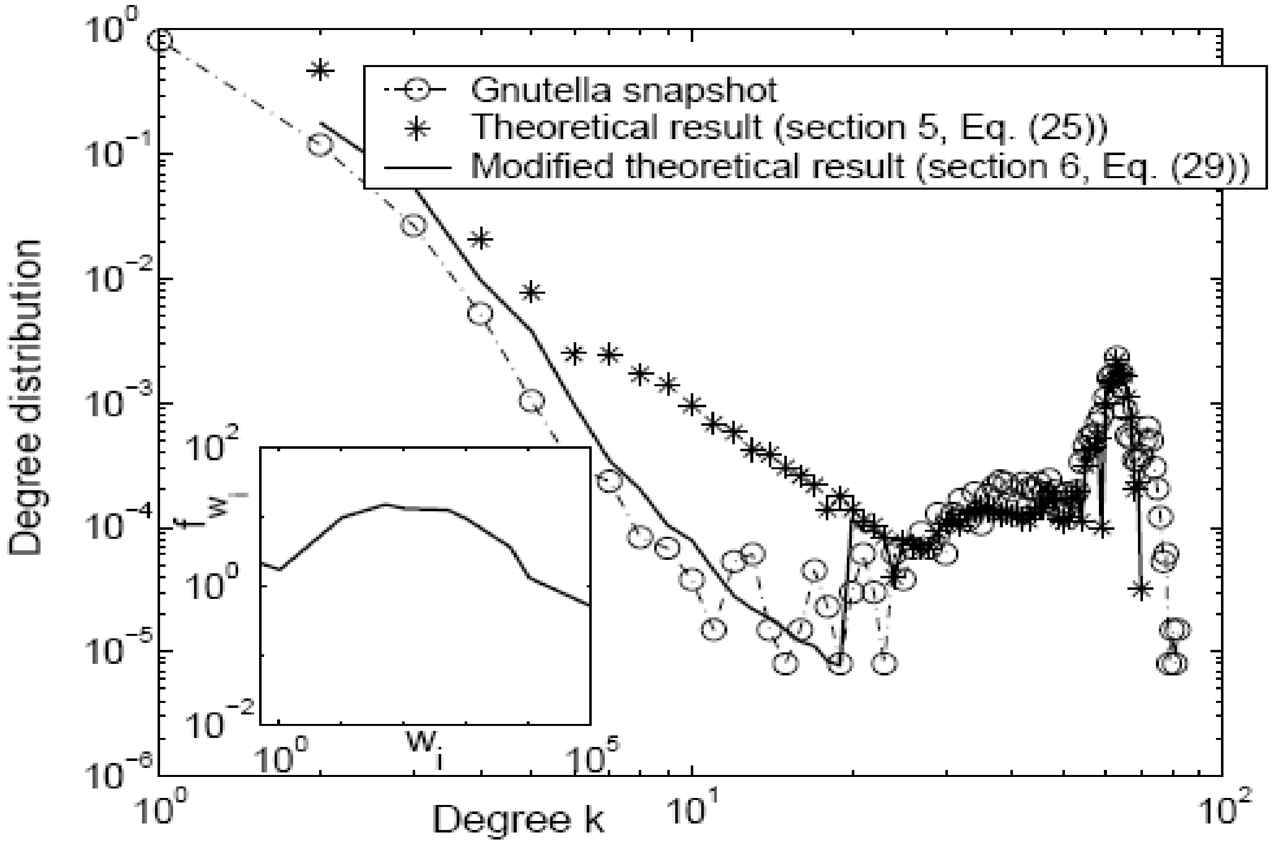
❖Each with a probability 0.25

- Spikes at each cut-off degrees
- Power-law between each cut-off degrees

Case study : Gnutella

- Experiment performed based on the real world network data
- Gnutella network snapshot obtained from the Multimedia and Internetworking research group, University of Oregon, USA
- Size of the network 131,869 nodes
- Compare the theoretical degree distribution with real trace

Case study : Gnutella



Deviation specially for the low-middle degree nodes

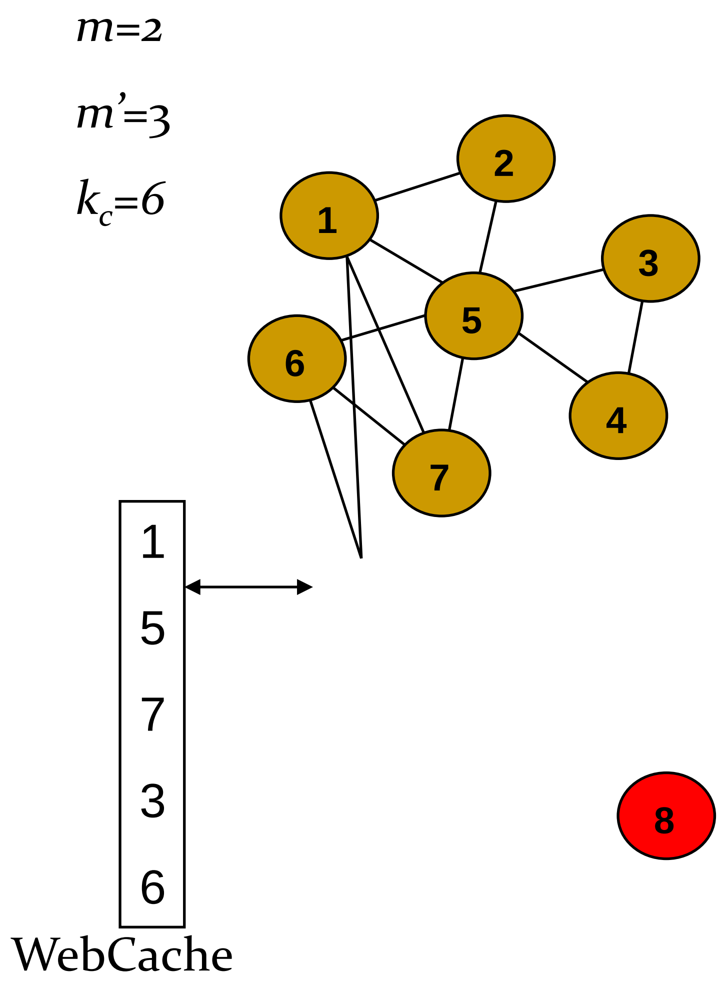
Role of Webcache

- Finite Size Caches (new nodes contact Webcache)
  - Limited information availability about the superpeers
- Implication
  - Information about only a small fraction of nodes (mostly of high degree) are stored and propagated

- Peers having low degrees do not receive connections from the incoming peers
  - Most of the low degree nodes remain in the low degree
  - Subsequently the amount of low degree nodes in the Gnutella network is less than the theoretical calculated value

Revisit the bootstrapping protocol

- A newly arriving peer initially contacts a WebCache
- The Webcache provides a list of ***M*** peers.
- The peer contacts ***m < M*** peers and attempts to connect to them
- A peer on receiving a connection request accepts the request if it has not reached its cutoff degree



Model finite sized Webcache

IEEE INFOCOM 2013 (Mini conference)

- Assumptions
  - Nodes having degree ≥ m' ($m' < k_c$) will ALWAYS be in cache
  - Prob. that a node having degree k ($m<k<m'$) will be in cache is γ

- We model the web cache with tuple $\{\gamma, m'\}$

Average number of k degree nodes in the web cache acquires links from incoming node

$$\delta_{k\to k+1} = \frac{\gamma(k+\epsilon)p_k}{\xi_c f_c},$$

$$\xi_c = \frac{1}{m}\left(\sum_{k=m}^{m'-1}\gamma(k+\epsilon)p_k + \sum_{k=m'}^{k_c}(k+\epsilon)p_k\right),$$

$$f_c = 1 - \frac{(k_c+\epsilon)p_{k_c}}{\sum_{k=m}^{m'-1}\gamma(k+\epsilon)p_k + \sum_{k=m'}^{k_c}(k+\epsilon)p_k}.$$

We take

$\frac{\xi_c}{\gamma}$ as ϕ

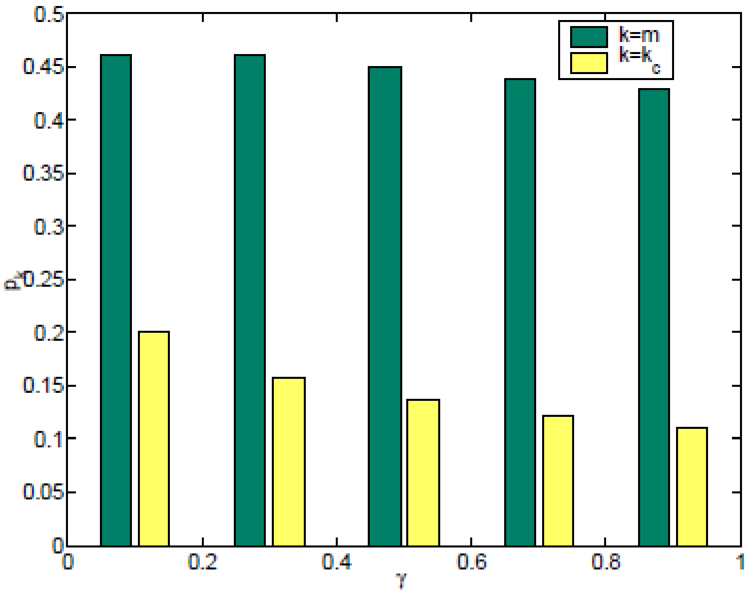
Assume low epsilon

Degree Distribution with Web Caches

- At m $$p_m = \frac{\phi f_c}{m + \varepsilon + \phi f_c}$$
- When $m < k <$ m′ $$p_k \approx \frac{\phi f_c}{m(\phi f_c + 1)} \left(\frac{k}{m} \right)^{-(\phi f_c + 1)}$$
- When k = m′ $$p_{m'} = \frac{\gamma C_{m'}(m' + \varepsilon - 1)}{m' + \varepsilon + \xi_c f_c}$$
- When $m' < k < k_c$ $$p_k \approx \frac{\gamma C_{m'}(m' + \varepsilon - 1)}{m'(\varepsilon + \xi_c f_c)} \left(\frac{k}{m'} \right)^{-(\xi_c f_c + 1)}$$
- When $k = k_c$ $$p_k \approx \frac{\gamma C_{m'}(m' + \varepsilon - 1)}{\xi_c f_c} \left(\frac{k}{m'} \right)^{-\xi_c f_c}$$

All terms except k are constant

Effect of γ on the Degree Distribution



p_{k_c} depends on $\left(\frac{k_c}{m'}\right)^{-(\xi_c f_c)}$

$(\xi_c f_c)$ increases with γ

p$_{kc}$ varies inversely with γ

Simulations Parameters

ε = 0

m' =7, *m*=2, *k$_c$*=25

Effect on p$_m$

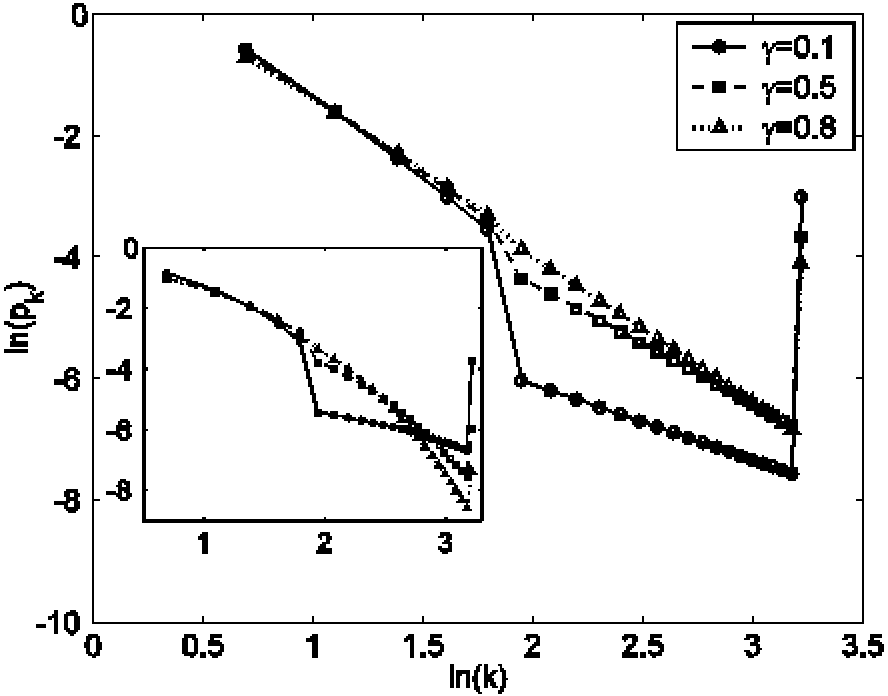
$$p_m = \frac{\phi f_c}{m + \varepsilon + \phi f_c}$$

p$_m$ deceases slowly with γ

Since $\phi f_c = \frac{1}{m}\left(\sum_{k=m}^{m'-1}(k+\epsilon) + \frac{1}{\gamma}\sum_{k=m'}^{k_c-1}(k+\epsilon)p_k\right)$

ϕf_c decreases slowly with increasing γ

Effect of γ on the Degree Distribution



Two regimes in Degree distribution

1. One at $m \leq k < m'$ (*γ independent*)
2. Other at $m' \leq k < k_c$ (γ dependent)

Simulations Parameters

- ε = 0, In inset ε=50
- m'=7, m=2, k_c=25

- In low γ, webcache is populated by high degree nodes
- Nodes in this region aggressively accept new links and move to pk_c
- Decreasing γ, fractions p_m and p_{kc} both increases
- The depth of the pit in the in region $m' \leq k < k_c$ increases with the decrease in γ

Polarization effect

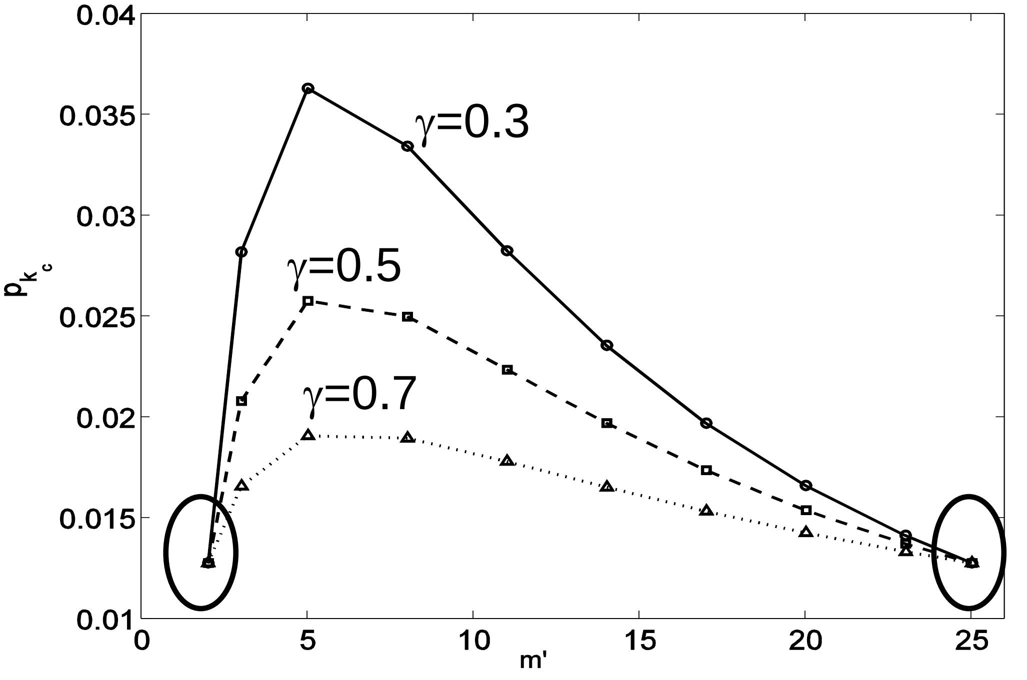
Effect of m' on the Degree Distribution

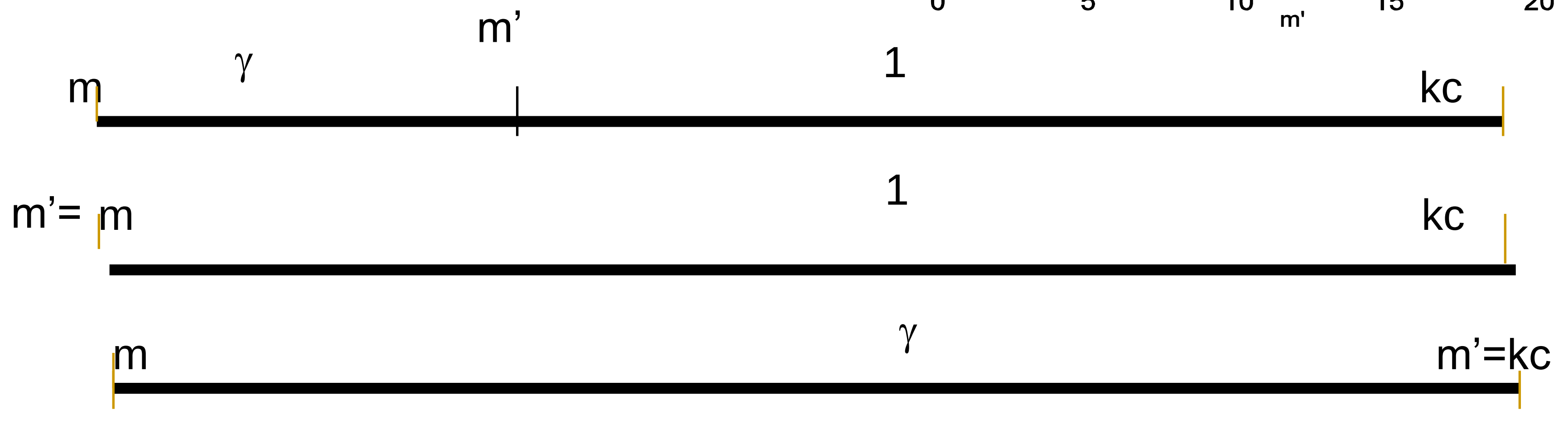
Simulations Parameters

ε=0

m=2, k_c=25

- Effect of m' on p_{kc}
  - For $m'=m$ or $m'=k_c$, superpeer fraction p_{kc} remains same (irrespective of γ)





Degree Distribution with Web Caches

- At m $$p_m = \frac{\phi f_c}{m + \varepsilon + \phi f_c}$$
- When $m < k <$ m′ $$p_k \approx \frac{\phi f_c}{m(\phi f_c + 1)} \left(\frac{k}{m}\right)^{-(\phi f_c + 1)}$$
- When k = m′ $$p_{m'} = \frac{\gamma C_{m'}(m' + \varepsilon - 1)}{m' + \varepsilon + \xi_c f_c}$$
- When $m' < k < k_c$ $$p_k \approx \frac{\gamma C_{m'}(m' + \varepsilon - 1)}{m'(\varepsilon + \xi_c f_c)} \left(\frac{k}{m'}\right)^{-(\xi_c f_c + 1)}$$
- When $k = k_c$ $$p_k \approx \frac{\gamma C_{m'}(m' + \varepsilon - 1)}{\xi_c f_c} \left(\frac{k}{m'}\right)^{-\xi_c f_c}$$

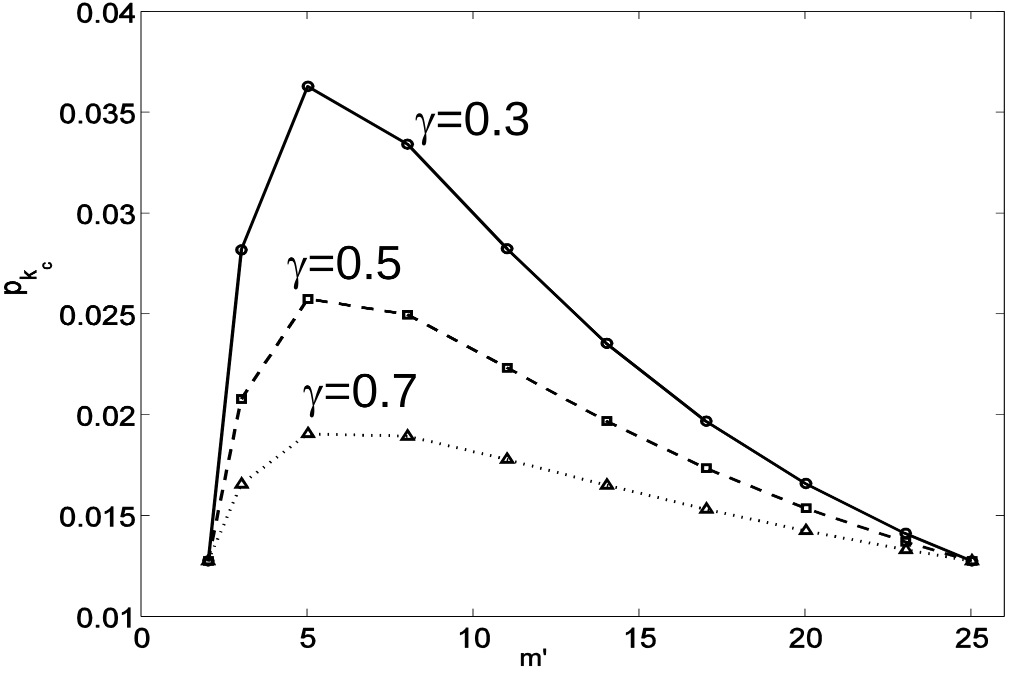
Substituting m′=m and m′=kc $$p_{k_c} \approx m^{\xi f} k^{-\xi f}$$

Effect of m' on the Degree Distribution

Simulations Parameters

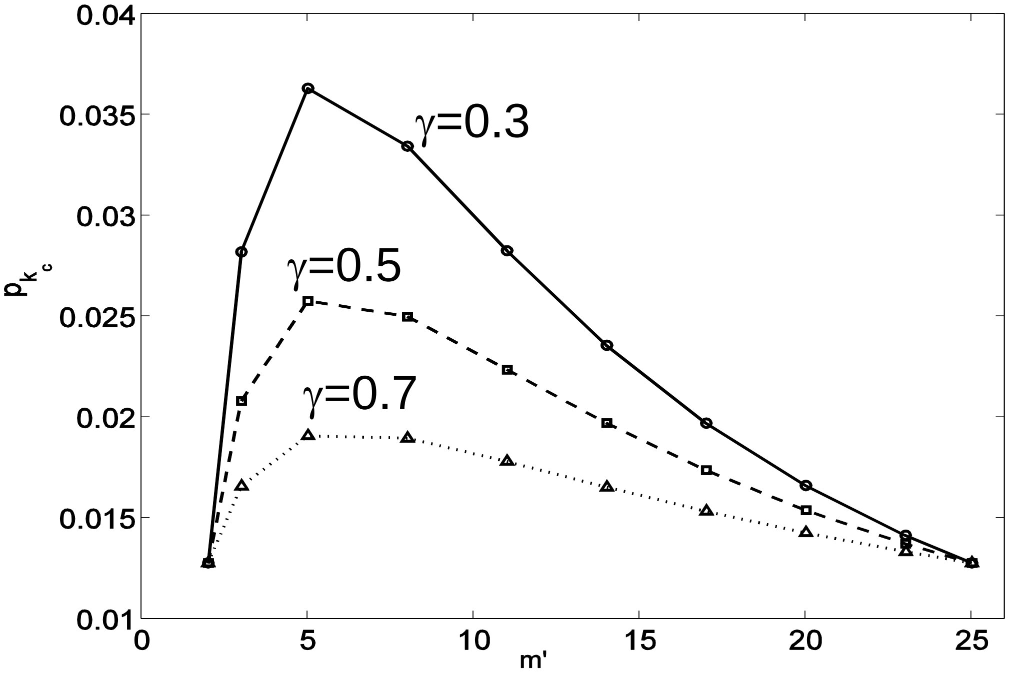
•ε=0

•m=2, k_c=25



- Effect of m' on p_{kc}
  - For $m'=m$ or $m'=k_c$, superpeer fraction p_{kc} remains same (irrespective of γ)
  - **For $m<m'<k_c$, there exists an optimal value of m' for which p_{kc} is maximum**

Effect of m' on the Degree Distribution

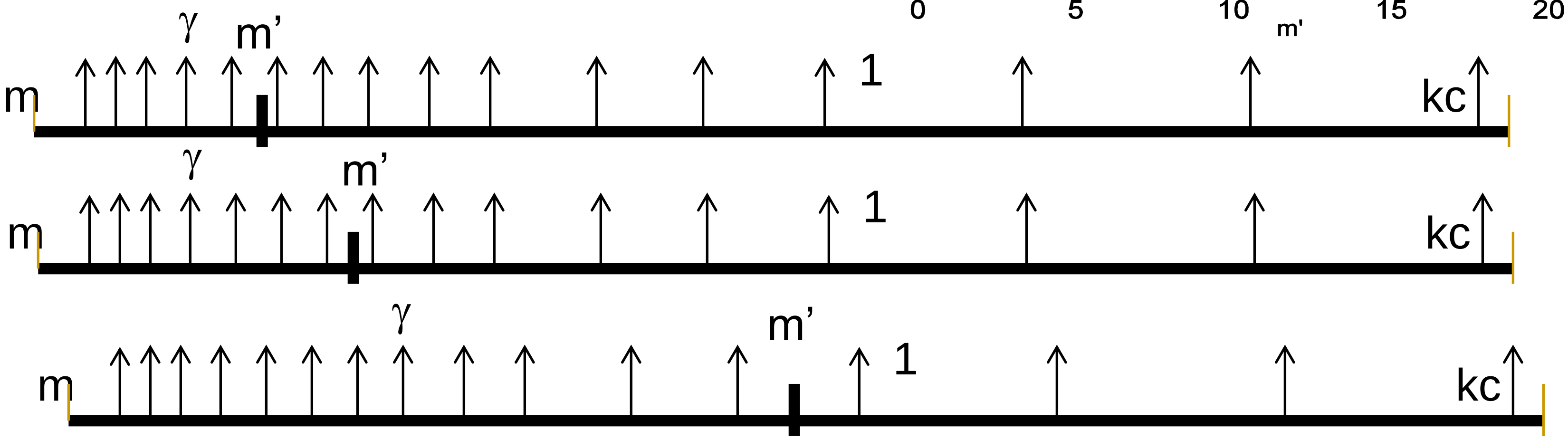


Simulations Parameters

•ε=0

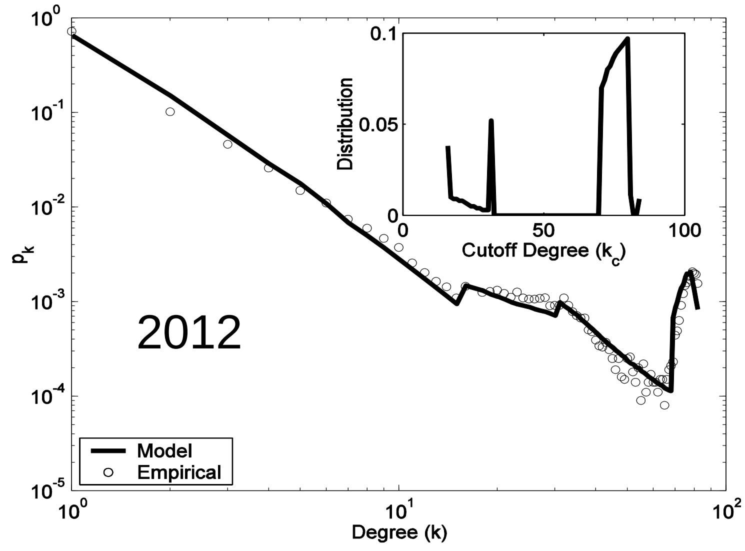
•m=2, k_c=25

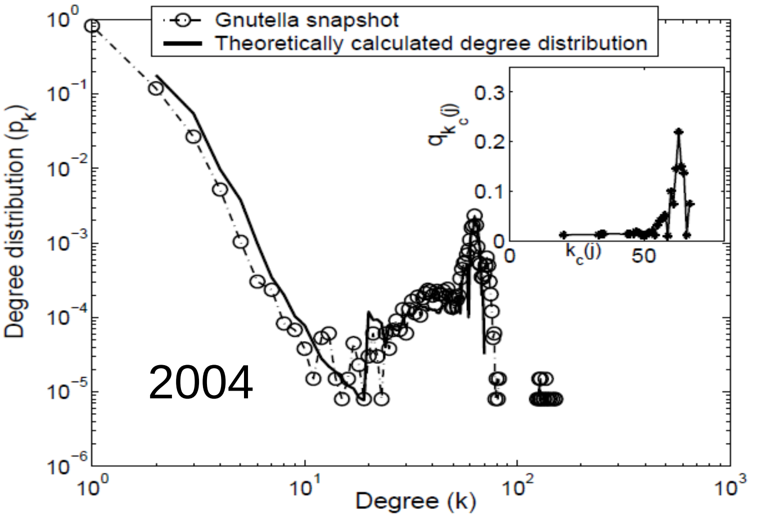
- Effect of m' on p_{kc}
  - For m'=m or m'=k_c , superpeer fraction p_{kc} remains same (irrespective of γ)



Application of the model: Gnutella Networks

- Gnutella Network Data Size
  - Data Size 100,000 nodes (2012)
  - Data Size 1,31,869 nodes (2004)
- Best fit observed for
  - γ=0.42, m'=15 (2012)
  - γ=0.37 and m′=18 (2004)
- Webcache is mainly populated by the high degree nodes (>15)
  - Only 40% of low degree nodes present in cache $1 \leq k \leq 15$
- Variable cutoff degrees (Inset)





Conclusion

- Closed form quantitative relationships between
  - Various bootstrapping parameters and the emergent network properties like
    - Fraction of Superpeers
    - SDR
- Obtain certain insights
  - Increasing randomness in connections increases connection uniformity of superpeers
  - Resource optimization (weight)
  - Increasing webcache size (m’) not necessarily increase fraction of superpeers
    - Optimum point

Thank you

Contact: bivas@cse.iitkgp.ernet.in
Complex Network Research Group (CNeRG)
CSE, IIT Kharagpur, India
http://cse.iitkgp.ac.in/resgrp/cnerg/