Rooting out the Rumor Culprit in Online Social Networks

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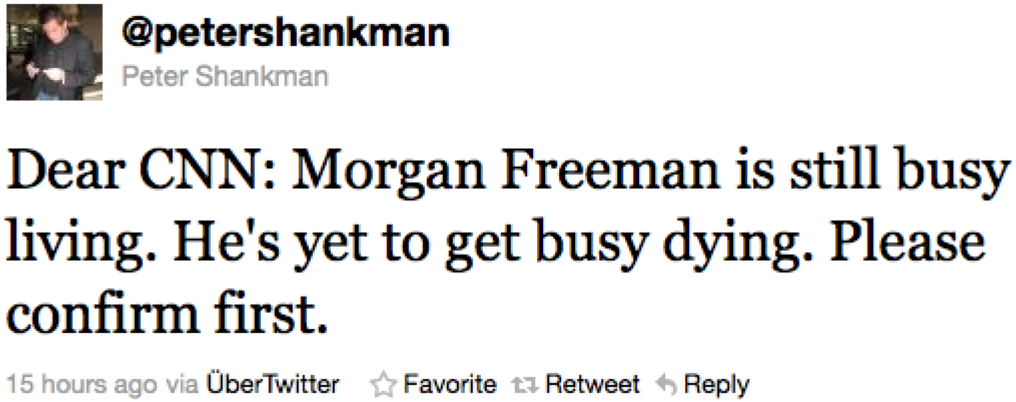
The Fourth International Workshop on M2M Technology
30 Ausgust, 2014

Motivation

Rumors



Peter Shankman, Twitter

Source: Google

Motivation

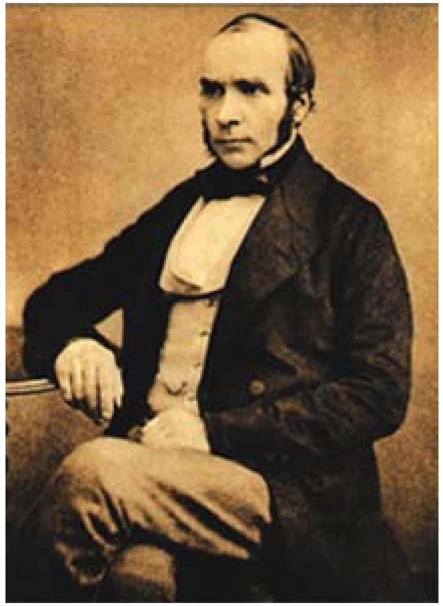
Rumors

Source: Bloomberg

Motivation

1854 London Cholera Epidemic

Outbreak source

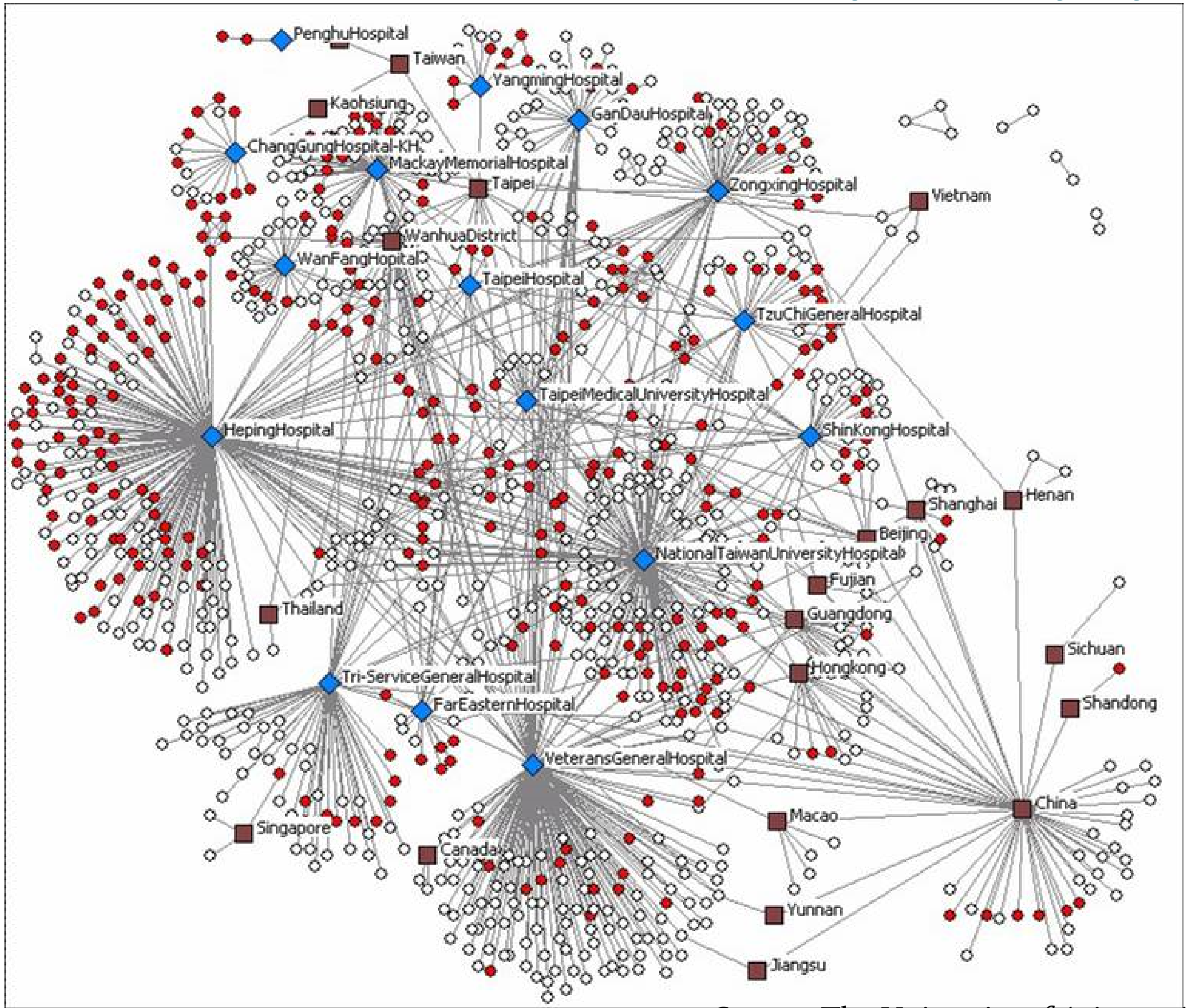


Dr. John Snow

Source: Wikipedia

Motivation

2003 SARS (severe acute respiratory syndrome)



Source: The University of Arizona Artificial Intelligence Lab

Motivation

2003 SARS Rumor

Epicenter of Hong Kong SARS

329 Infected
42 killed

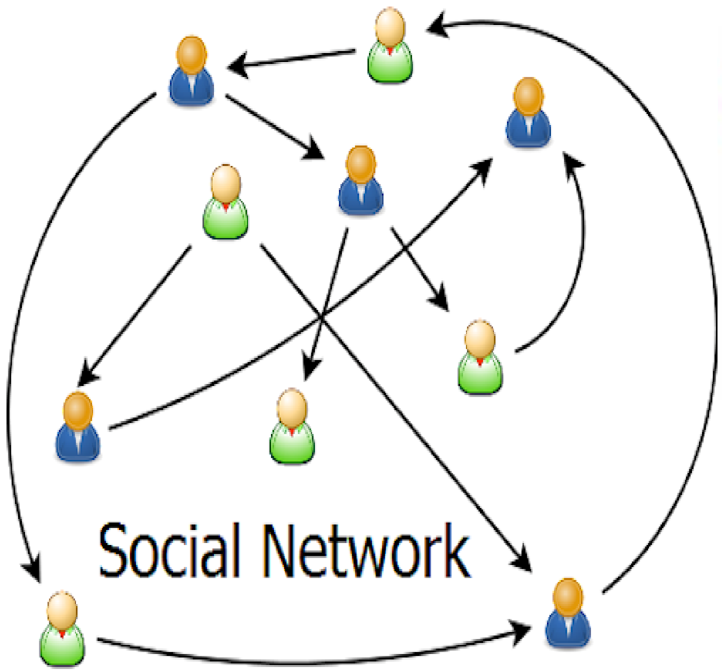
- Rumor: “Entire City was poised to be quarantined”
- 14 year-old boy arrested for creating fake news page

Source: http://edition.cnn.com/2013/02/21/world/asia/hong-kong-sars-anniversary

Rumor and panic spread faster than virus. Nothing spreads like fear!

Motivation

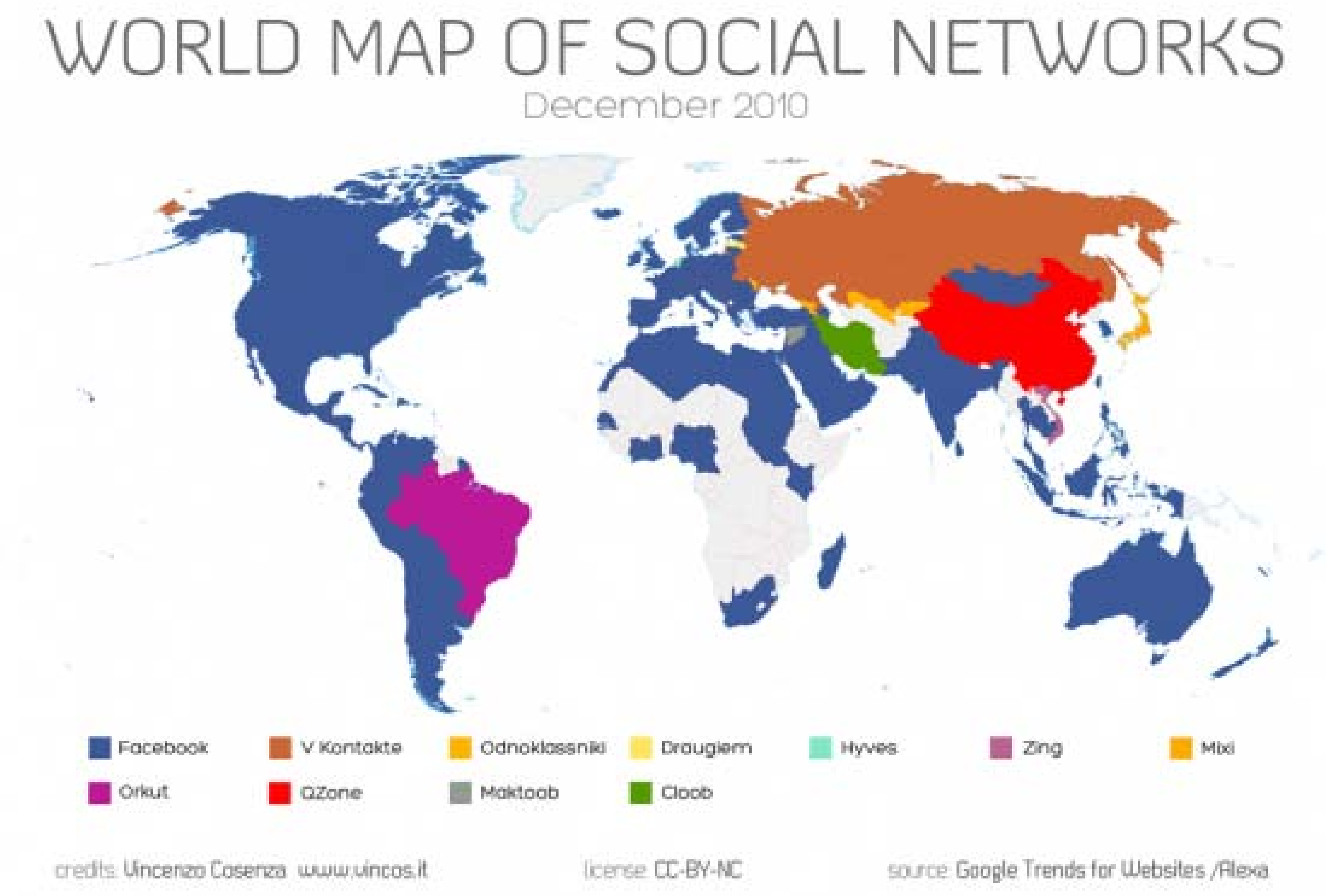
Growth and Expansion of Online Social Networks



- Smartphone revolution 2007
- Twitter 2006
- Tencent Weixin 2012

Motivation

Reach of Online Social Networks



Motivation
National Grand Challenges

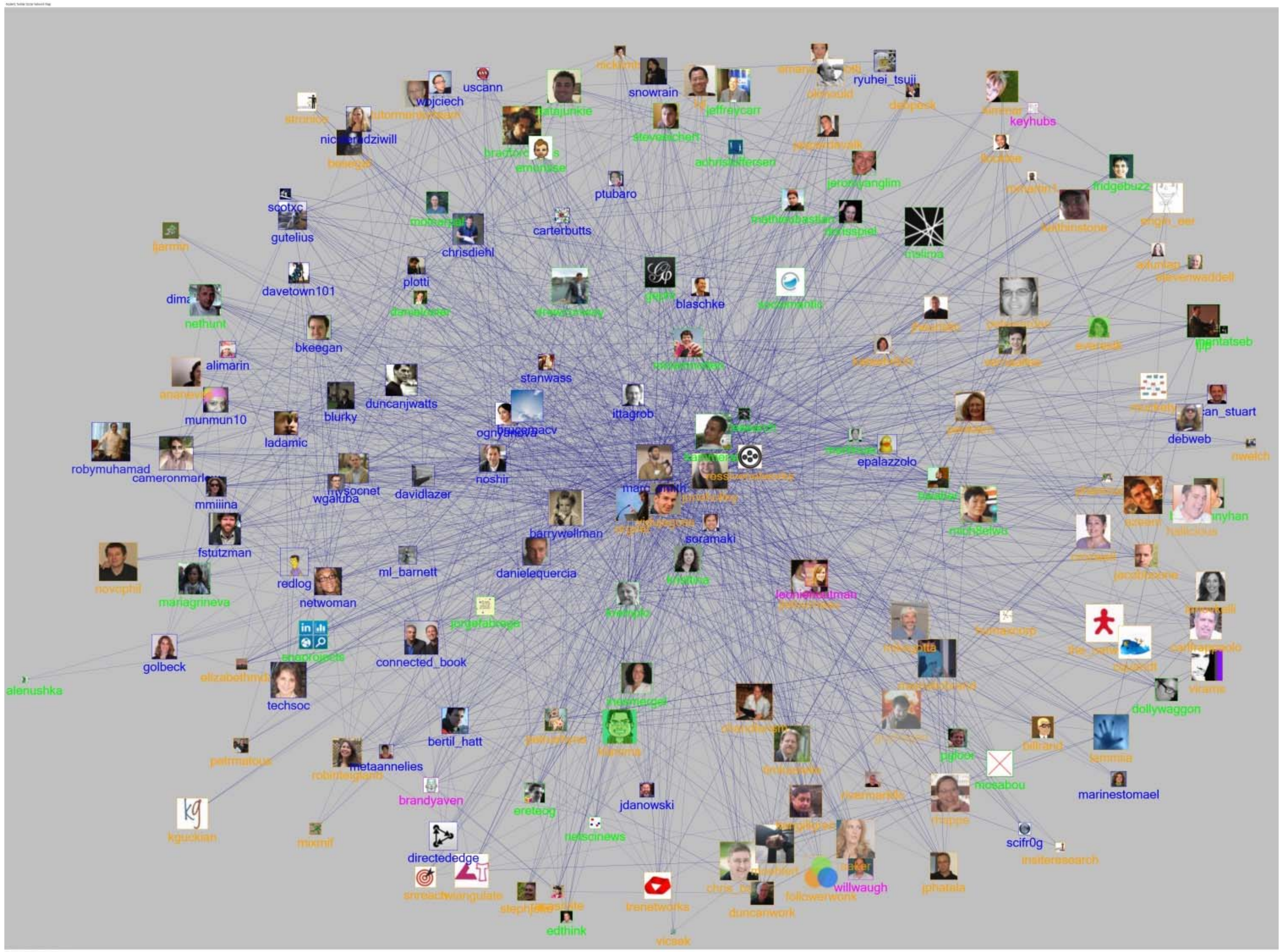
NAE GRAND CHALLENGES FOR ENGINEERING

All engineering approaches to achieving security must be accompanied by methods of monitoring and quickly detecting any security compromises. And then once problems are detected, technologies for taking countermeasures and for repair and recovery must be in place as well. Part of that process should be new forensics for finding and catching criminals who commit cybercrime or cyberterrorism.

– US National Academy of Engineering Grand Challenges 2008

– Challenge No. 11: Secure Cyberspace

Rumor Spreading in Online Social Network

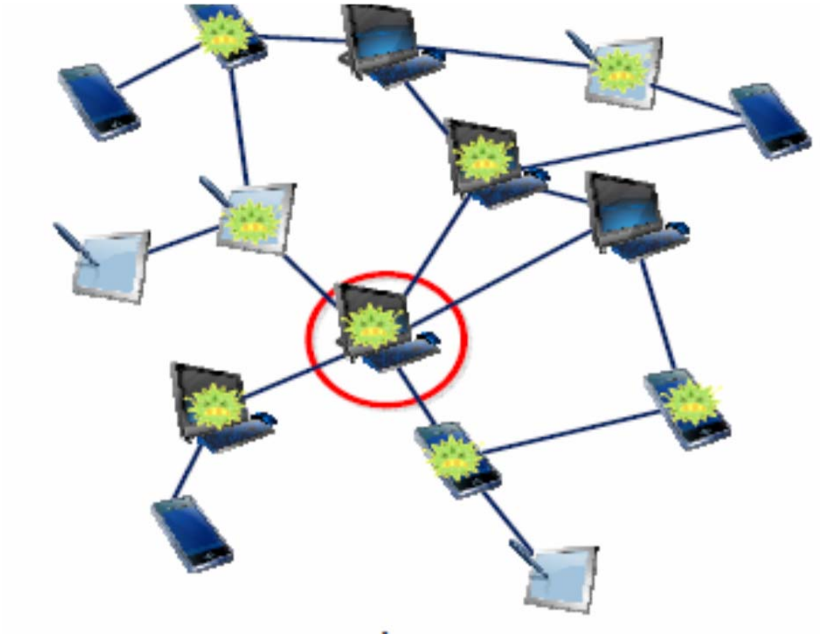


- Outbreak of infectious virus
- Diffusion of viral Information in Network
- Cause of outbreak

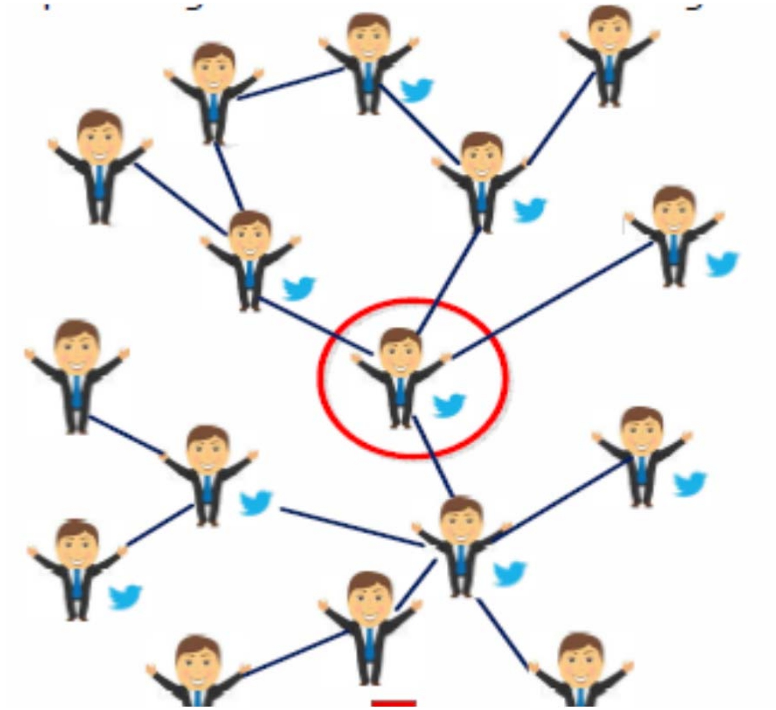
- Epidemic-like information flow = rumor spreading in a network.

Who is the culprit?

- **Spread of computer virus**



- **Tweeting and Retweeting in Twitter Network**



- A rumor, originating from a suspect set, spreads on a network.
- We only know the prior suspect set and infected nodes.
- Can we find the single rumor source?

Outline

- **Related Work and Spreading Model**
- **Rumor Centrality**
- **Detection in Tree Network**
- **Detection in General Network**
- **Cybersecurity Forensics**
- **Conclusion**

Literature

----Research on epidemic outbreak/rumor spreading

- understand impacts of network structure and infection/cure rates

  [Moore—PRE’00, Pastor-Satorras—PRL’01, Newman—PRE’02]

- learn network parameters and predict propagation characteristics

  [Streftaris—IWSM’02, Okamura—ISSRE’07, Gomez-Rodriguez—SIGKDD’10]

- extract influential source nodes

  [Kempe—SIGKDD’03, Chen—SIGKDD’09, Dong—Allerton’12]

– **Rumor source estimation problem has only been recently studied.**

Literature

----estimation of rumor source

- identification of single rumor source using SI model

  [Shah—TIT'11, Shah—SIGMETRICS'12]

- geometric trees, random graphs

  [Shah—arXiv'11, Shah—TIT'11]

- identification of multiple rumor sources (SI model), identification of single rumor source (SIR model)

  [Luo—TSP'13, Zhu—ITA'13]

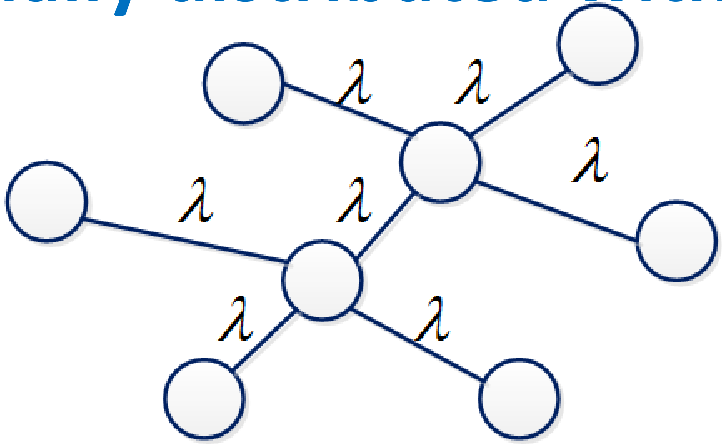
- noisy estimation of a single rumor source

  [Pinto—PRL'12]

– **Important features such as suspects, no. of observations, topology has not been considered.**

SI Spreading Model (Kermack & McKendrick 1927)

- **SI (susceptible-infectious) model**
  - An infected node keeps the rumor forever
- **Uniform probability of any node in a prior suspect set being source**
  - $P_s(\text{source} = s) = |S|^{-1}, s \in S$ ➡ S consists of suspect nodes
- **Time to infect neighbor is independent and exponentially distributed with rate λ**



SI Spreading Model

- **Vertex of a graph G to model the susceptible and the infected node (person)**
- **An edge in G models the relationship between two nodes**
  - **Two persons connected as Facebook Friends or Twitter Follower**

Let G_t be a subgraph of order t of G.

G_t is composed of t infected vertices

G_1 rumor source

$|G_t + 1| = |G_t| + 1$

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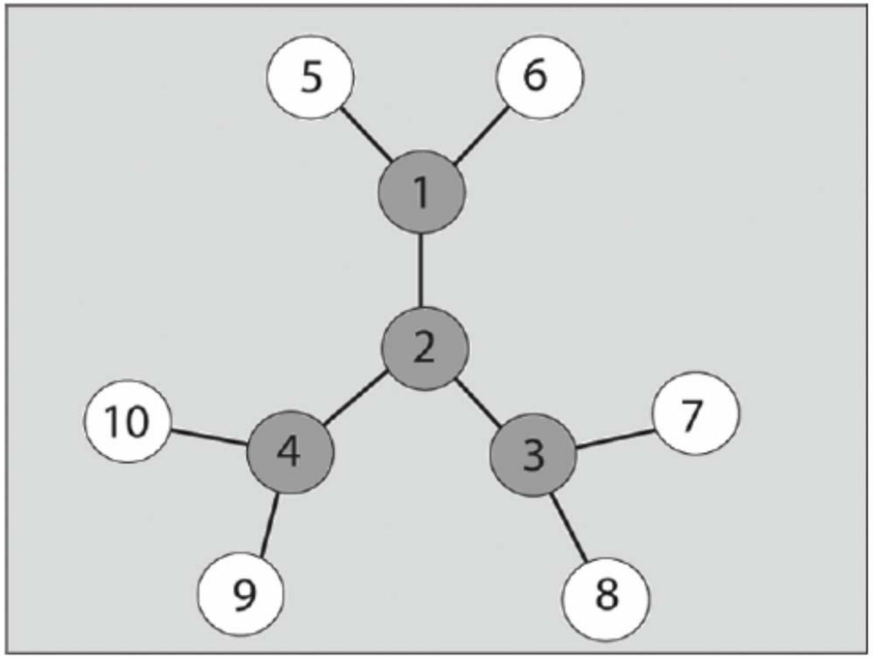
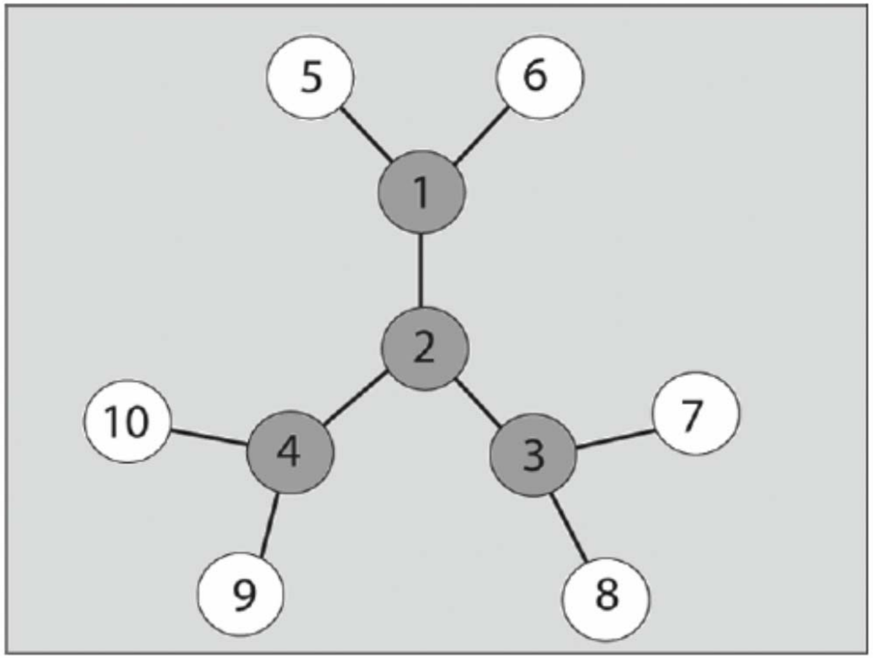
Toy Example

- **Counts the number of permitted permutation to spread a rumor**



Toy Example

- **Suppose Source 1**
  - **Two permutations: {1,2,3,4}, {1,2,4,3}**
- **Suppose Source 2**
  - **Six permutations: {2,1,3,4}, {2,1,4,3},{2,3,1,4}, …**

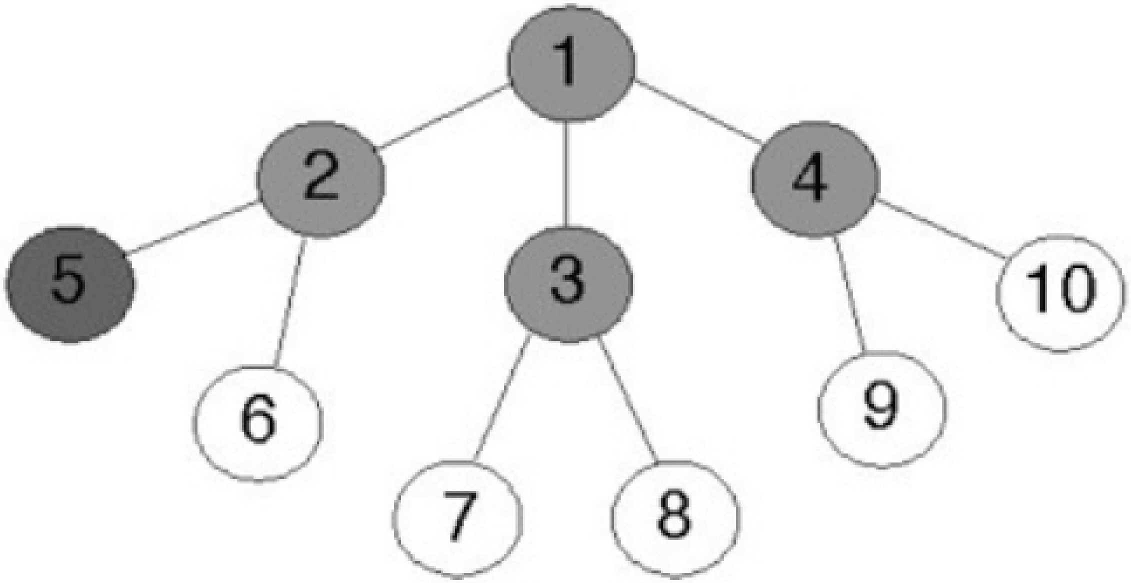


Inference in Tree

- Let T be a tree :
- let G_n be the subtree of T at time n
- $P(G_n|v^*)$ is the probability that view v^* as the source
- Let σ_i be the possible infecting order
- $S(v^*, G_n)$ be the collection of all σ_i where v^* is viewed as the source

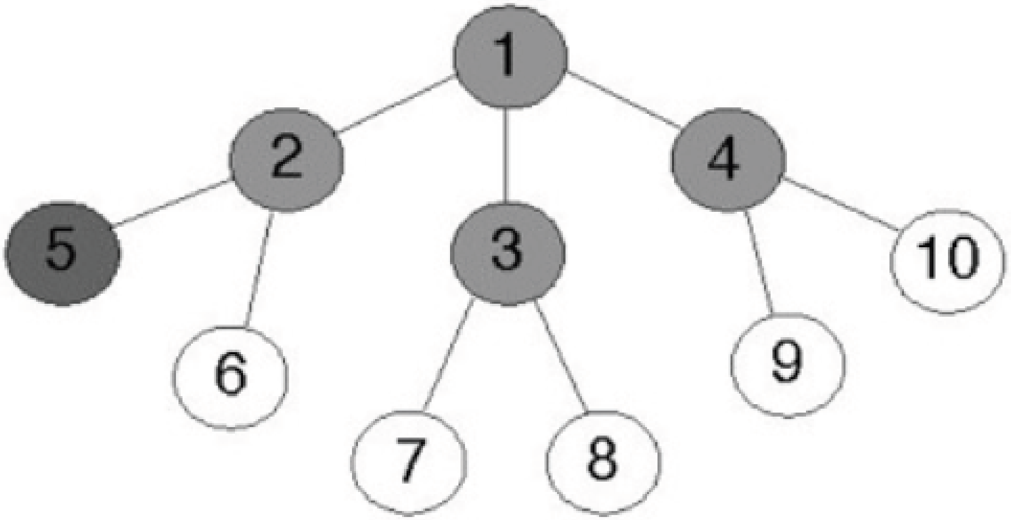
$$P(G_n|v^*) = \sum_{\sigma_i \in S(v^*, G_n)} P(\sigma_i|v^*).$$

Toy Example



Toy Example

Suppose Node 1 is Rumor

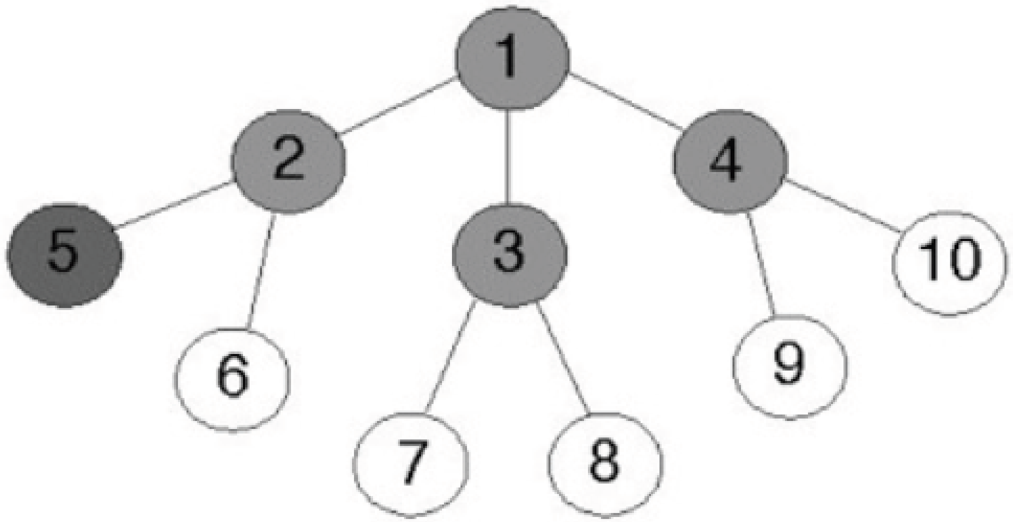


$\sigma_1 = v_1 \rightarrow v_2 \rightarrow v_3 \rightarrow v_4$ $\sigma_2 = v_1 \rightarrow v_2 \rightarrow v_4 \rightarrow v_3$ $\sigma_3 = v_1 \rightarrow v_3 \rightarrow v_2 \rightarrow v_4$

$\sigma_4 = v_1 \rightarrow v_3 \rightarrow v_4 \rightarrow v_2$ $\sigma_5 = v_1 \rightarrow v_4 \rightarrow v_3 \rightarrow v_2$ $\sigma_6 = v_1 \rightarrow v_4 \rightarrow v_2 \rightarrow v_3$

Toy Example

Suppose Node 1 is Rumor

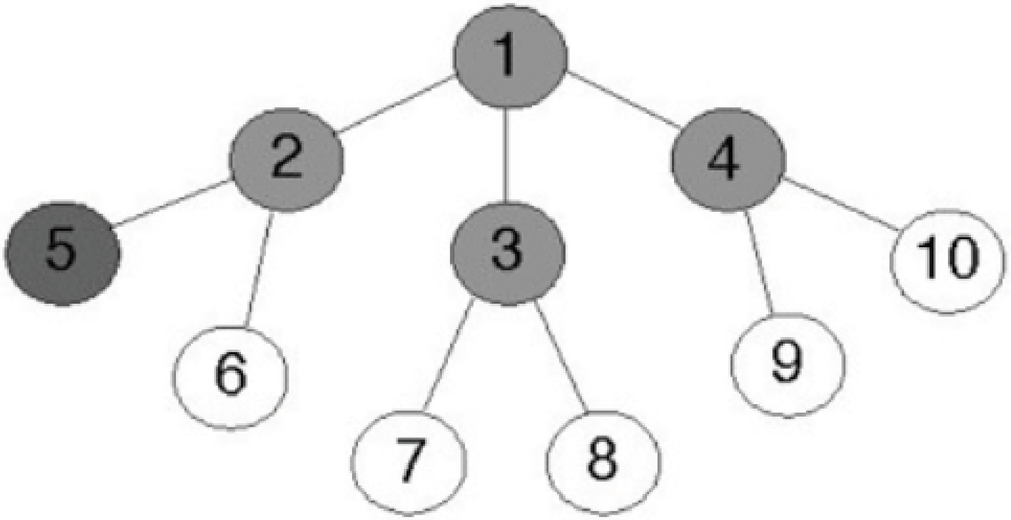


Let's calculate the probability of σ_1

$$P(\sigma_1|v_1) = \frac{1}{3} \cdot \frac{1}{4} \cdot \frac{1}{5}$$

Toy Example

Suppose Node 1 is Rumor



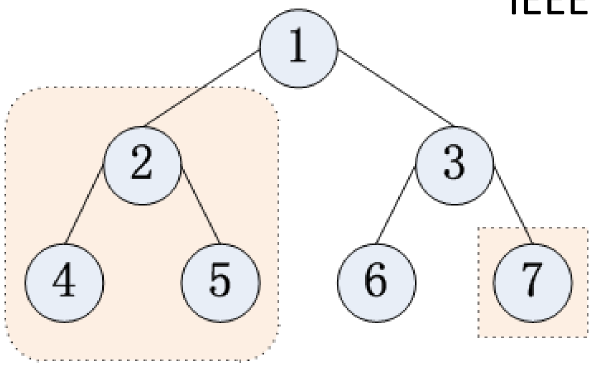
$$P(\sigma_i|v_1) = \frac{1}{3}\cdot\frac{1}{4}\cdot\frac{1}{5} \quad \text{for } i = 1,2,3,4,5,6$$

Rumor Centrality

- **Rumor centrality counts the number of permitted permutation to spread a rumor**

$$R(s,G_n) = n! \prod_{u \in G_n} |T_u^s|^{-1}$$

Shah and Zuman
IEEE Transactions on Information Theory 2011



subtree T_u^s

$|T_2^1| = 3$ $|T_7^1| = 1$

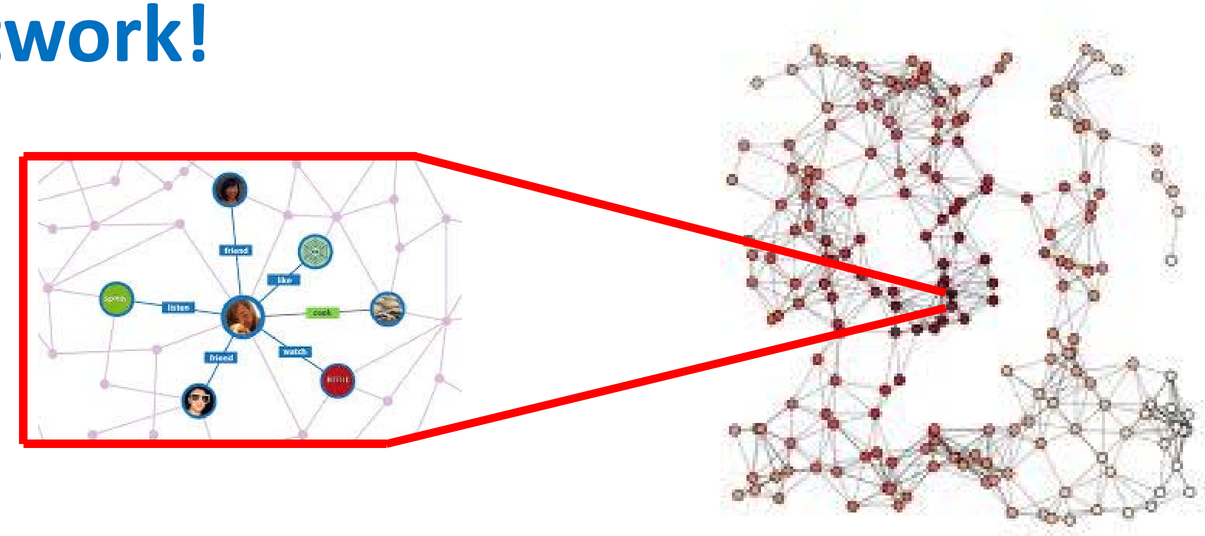
Rumor Center

- **ML (maximum likelihood) estimator** [Shah—TIT'11]

$$\widehat{v} = \arg\max_{v \in G_N} \mathbf{P}(G_N | v^* = v)$$

$$= \arg\max_{v \in G_N} R(v, G_N)$$

- **Most likely source is at the "center" of the network!**



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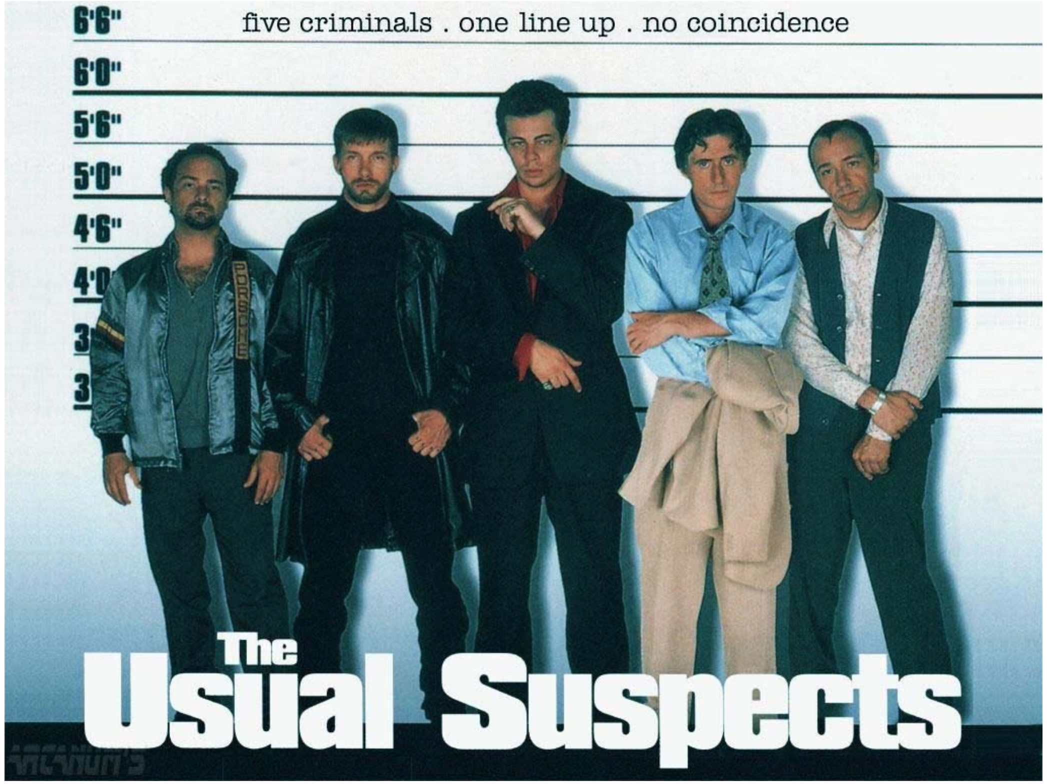
Detection with Suspects

- **Why consider suspects?**
  - Not all infected are suspects
  - spread of infectious disease from cities to cities

    (frequent travellers)
  - infection of rumors or computer viruses in cyberspace

    (vulnerable hosts)



– **Suspect characteristics significantly affect detectability and add an interesting dimension to identifying the source reliably.**

Detection with Suspects

- **What's new with suspects?**

Finite regime:

– at most vs. at least 0.5 detection probabili

Asymptotic regime:

– 0.307 vs. 1 best detection probability

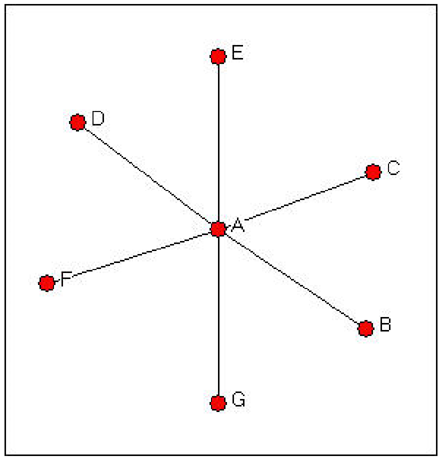
Insightful monotonicity and averaging results

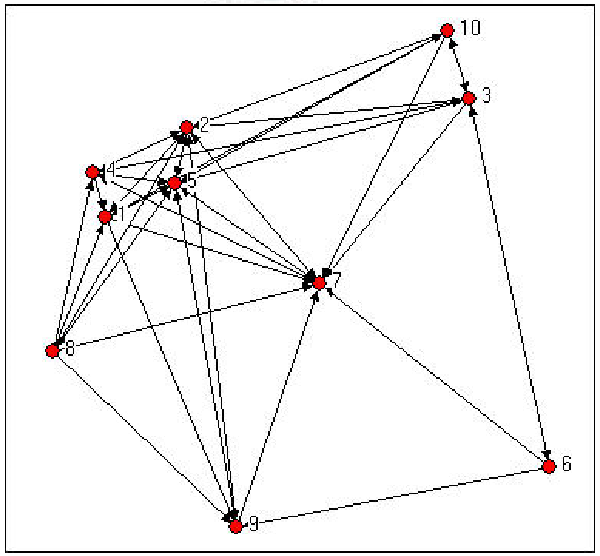
Dong, Zhang and Tan
Proc. of IEEE Symp. on Information Theory 2013

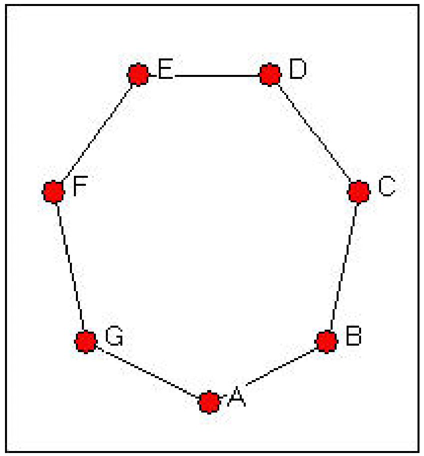
Zhao, Dong, Zhang and Tan
ACM SIGMETRICS 2014

Detectability









– Detectability is graph constrained. Network connectivity matters!

MAP Rumor Source Estimator

- **MAP (maximum a posteriori) estimator**
- A prior suspect set S
- An observation of n infected nodes G_n

$$\hat{s} = \arg\max_{s \in \{S \bigcap G_n\}} \mathrm{P}_G\{s \mid G_n\} = \arg\max_{s \in \{S \bigcap G_n\}} \mathrm{P}_G\{G_n \mid s\}$$

MAP Rumor Source Estimator

- **For regular tree-type networks**

$$\hat{s} = \arg\max_{s \in \{S \bigcap G_n\}} R(s, G_n)$$

- optimal MAP estimator
- focus on regular trees

- **For general tree-type networks**

$$\hat{s} = \arg\max_{s \in \{S \bigcap G_n\}} R(s, G_n)$$

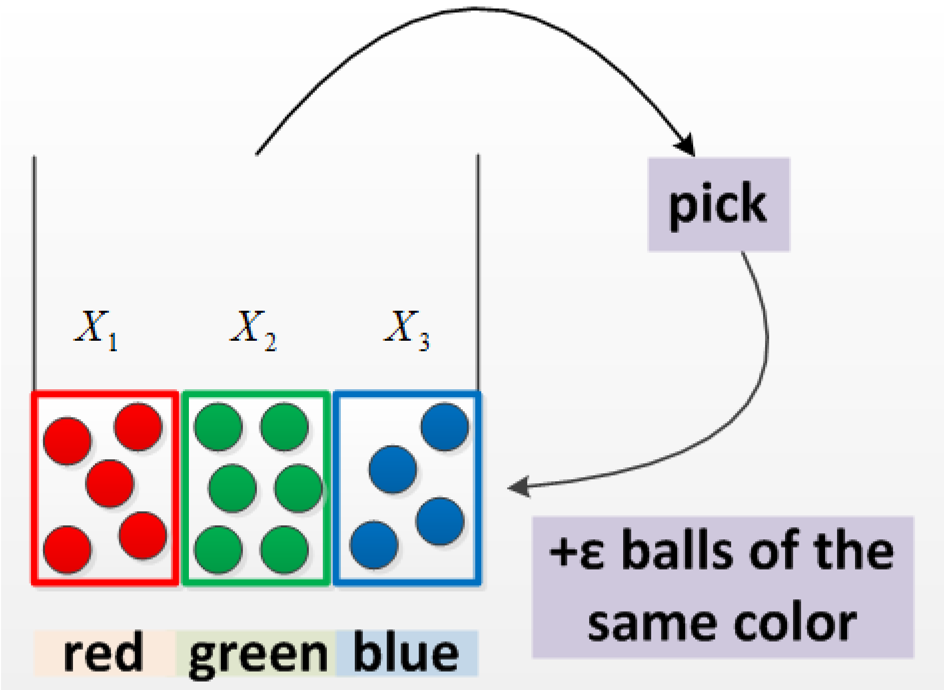
- Analyze the correct detection probability upon observing *n* infected nodes

$$\mathrm{P}_c(n) = \mathrm{Prob}\left[\hat{s} = s^*\right]$$

- **For general networks**

$$\hat{s} = \arg\max_{s \in \{S \bigcap G_n\}} R\left(s, T_{\mathrm{bfs}}(s)\right)$$

Pólya's Urn Model



[Johnson—JWS'97]

- Joint distribution

$$\mathrm{P}_G\left[\bigcap_{j=1}^{\delta}\left(X_j = x_j\right)\right]$$

- Marginal distribution

$$\mathrm{P}_G\left[X_1 = x_1\right]$$

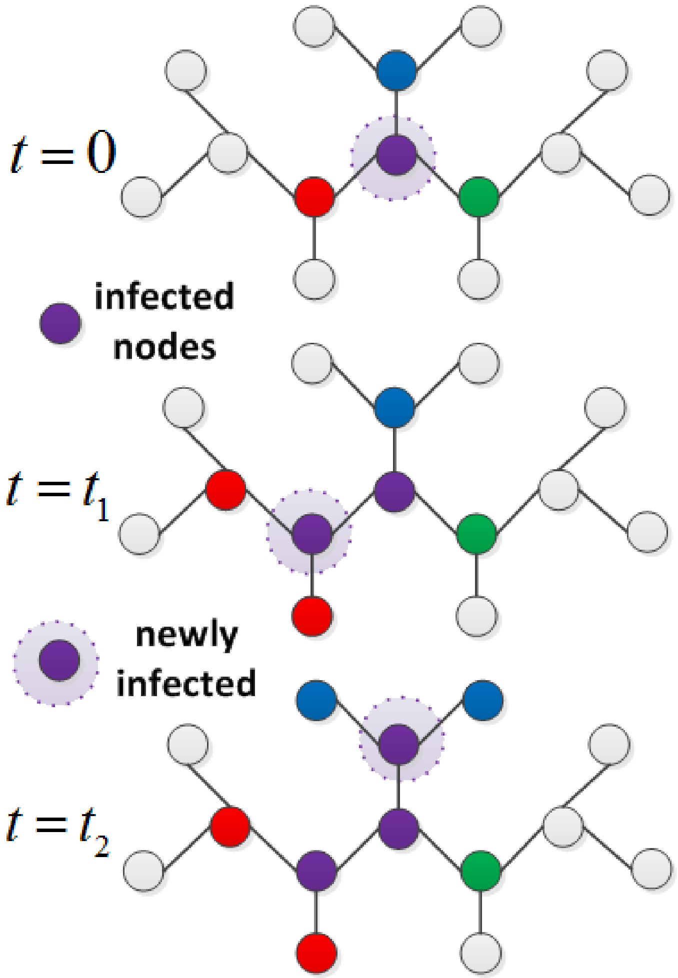
- Limit distributions

$$\lim_{n\to\infty}\mathrm{P}_G\left[\bigcap_{j=1}^{\delta}\left(\frac{X_j}{n} = y_j\right)\right]$$

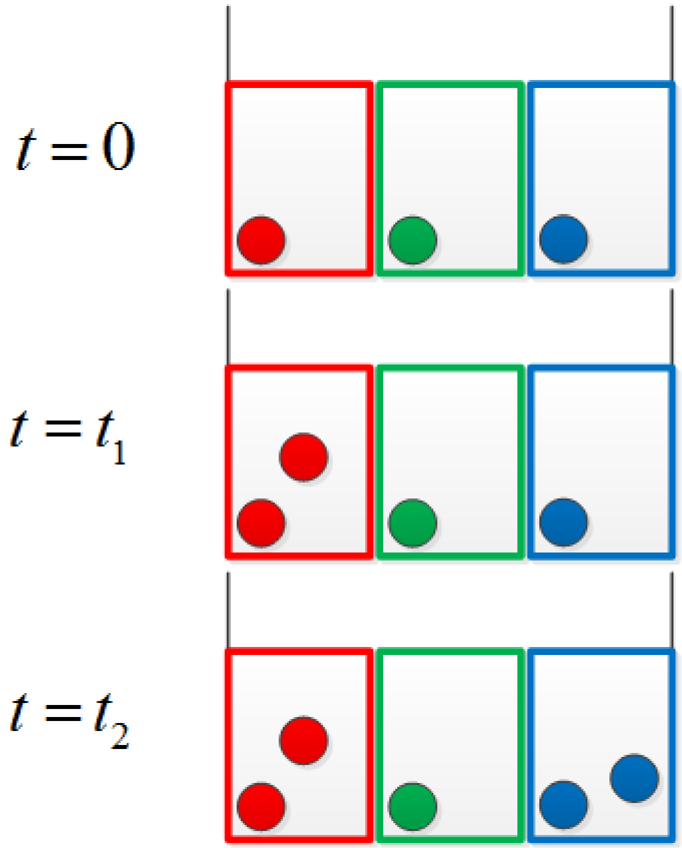
$$\lim_{n\to\infty}\mathrm{P}_G\left[\frac{X_1}{n} = y_1\right]$$

Equivalence to Pólya’s Urn Model

- **Rumor spreading process**



- **Ball drawing process**



$$s=\delta-2$$

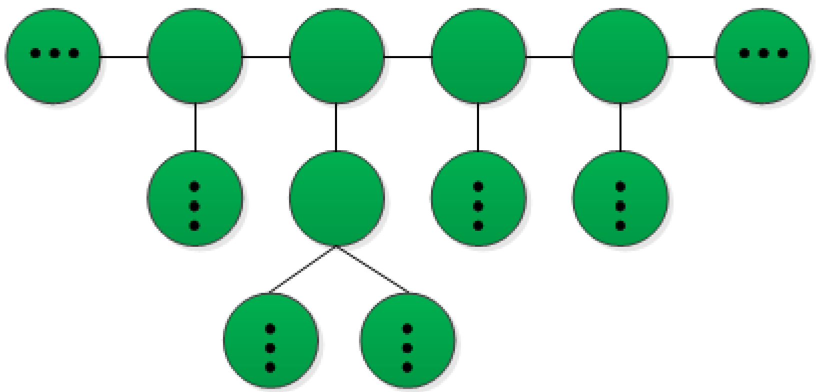
Suspecting all Nodes

----main results

Case 1

– Any infected node might be the rumor source.

[Shah—TIT'11, Shah—SIGMETRICS'12]



– **The detection probability is asymptotically upper bounded by 0.307.**

Main results

- node degree $\delta = 2$

$$P_c(n) = \frac{1}{2^{n-1}} \binom{n-1}{\lfloor (n-1)/2 \rfloor} \sim O(1/\sqrt{n})$$

- node degree $\delta = 3$

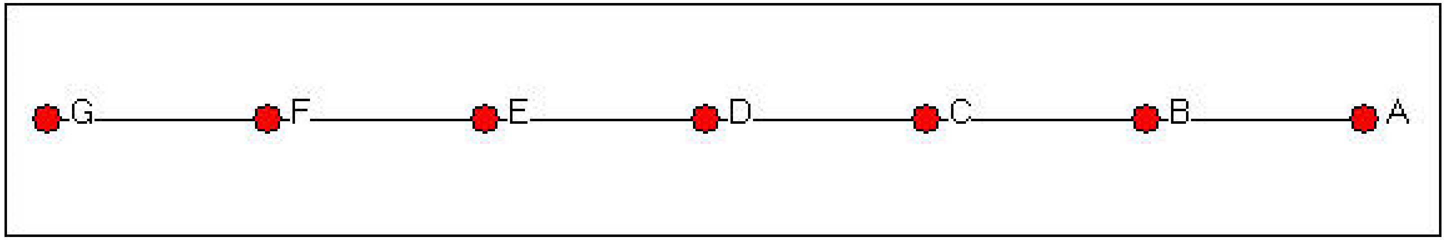
$$P_c(n) = \frac{1}{4} + \frac{3}{4} \frac{1}{2\lfloor n/2 \rfloor + 1} \sim \frac{1}{4} + O(1/n)$$

- node degree $\delta > 3$

$$\lim_{n\to\infty} P_c(n) = 1 - \delta\left(1 - I_{1/2}\left(\frac{1}{\delta-2}, \frac{\delta-1}{\delta-2}\right)\right) \to 0.307$$

- Monotonicity: Detection probability increases with degree and decreases with *n*

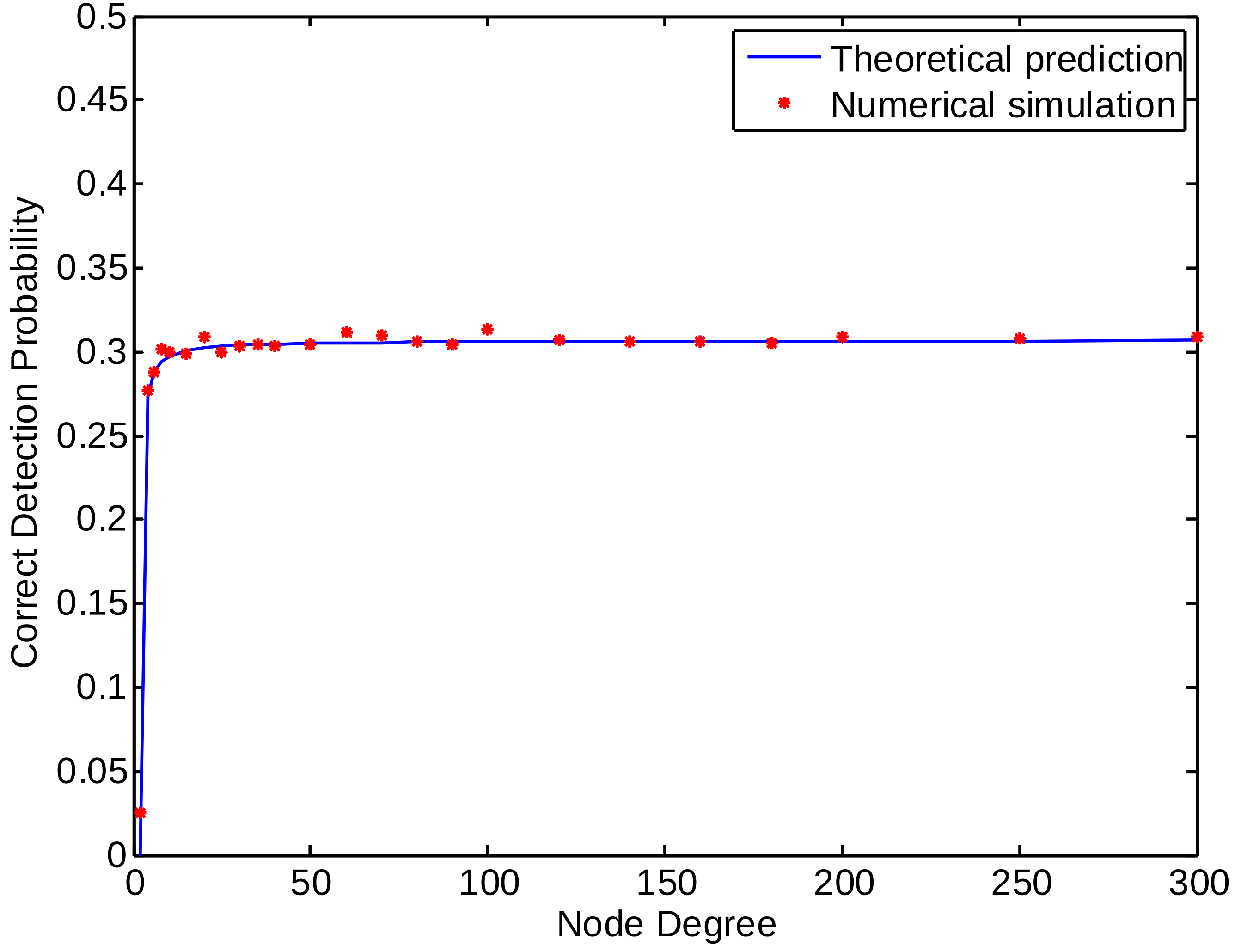
Minimum Detectability



- Line Network is undetectable!
- Can multiple observations help?

Suspecting all Nodes

----validation experiment

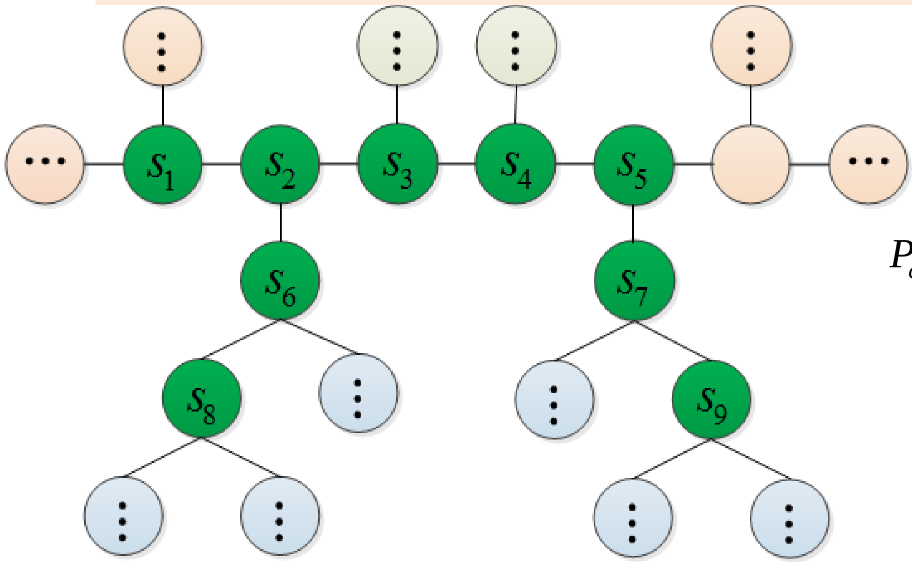


Connected Suspects

----main results

Case 2

– All suspect nodes form a connected subgraph.



– **The performance is significantly improved and reliable detection can be achieved.**

Main results

- node degree $\delta = 2$

$$P_c(n) = \frac{1}{k}\left(1 + \frac{k-1}{2^{n-1}}\binom{n-1}{\lfloor (n-1)/2 \rfloor}\right) \sim \frac{1}{k} + O(1/\sqrt{n})$$

- node degree $\delta = 3$

$$P_c(n) = \frac{k+1}{2k} + \frac{k-1}{k}\frac{1}{4\lfloor n/2 \rfloor + 2} \sim \frac{k+1}{2k} + O(1/n) \geq \frac{1}{k} + \frac{k-1}{2k}$$

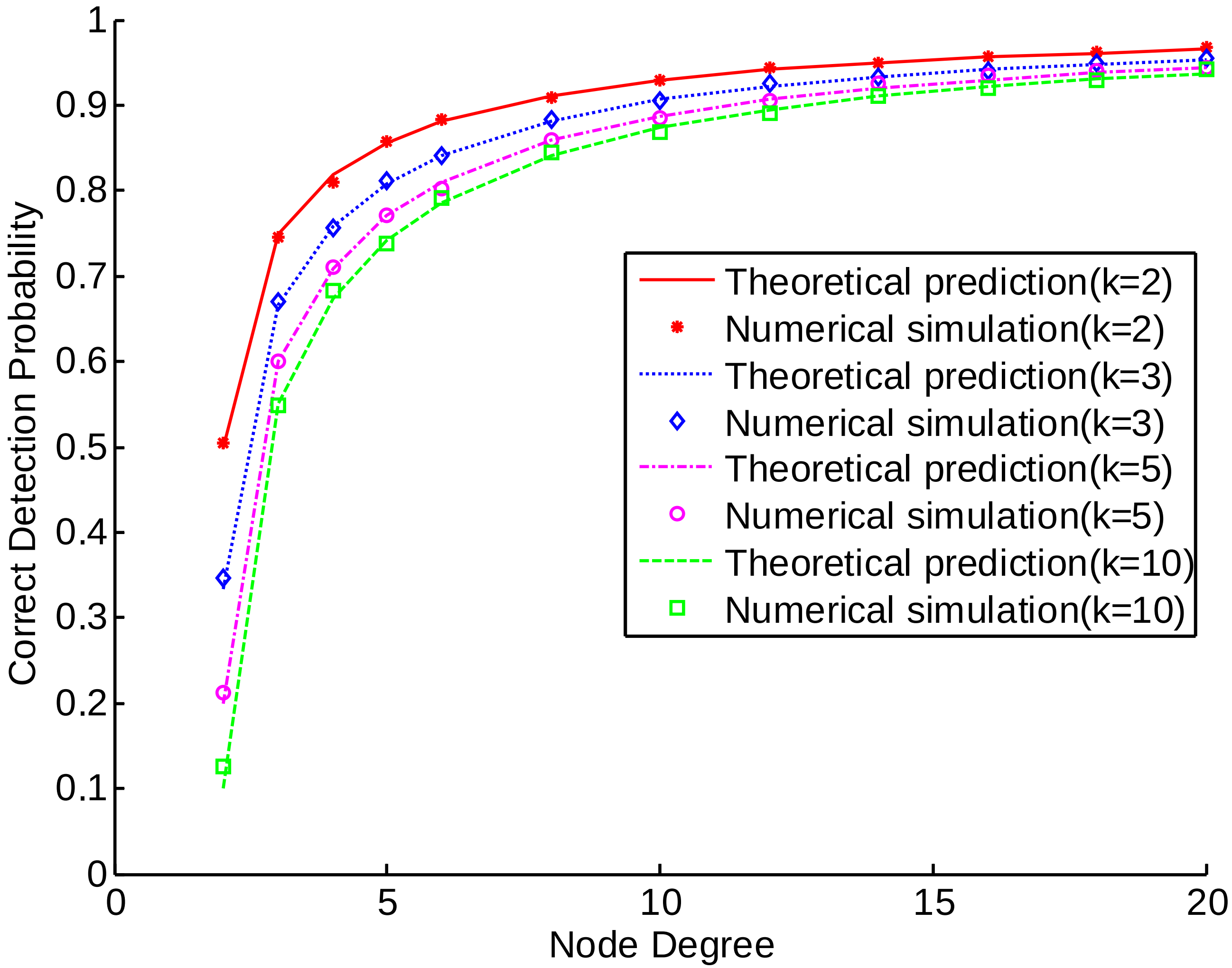
- node degree $\delta > 3$

$$\lim_{n\to\infty} P_c(n) = 1 - \frac{2k-2}{k}\left(1 - I_{1/2}\left(\frac{1}{\delta-2}, \frac{\delta-1}{\delta-2}\right)\right) > \frac{1}{k} + \frac{k-1}{2k} \to 1$$

- Monotonicity: Detection probability increases with degree and decreases with *n*

Connected Suspects

----validation experiment



Connected Suspects

----with vs. without prior knowledge

Closer-up look at case 2

- node degree $\delta > 2$

$$\lim_{n\to\infty} P_c(n) = 1 - \frac{2k-2}{k}\left(1 - I_{1/2}\left(\frac{1}{\delta-2}, \frac{\delta-1}{\delta-2}\right)\right)$$

- exceed prior probability

$$P_c(n) \geq \frac{1}{k} + \frac{k-1}{2k}$$

- at least 0.5-detection

$$P_c(n) \geq 2I_{1/2}\left(\frac{1}{\delta-2}, \frac{\delta-1}{\delta-2}\right) - 1 \geq 0.5$$

- achieve reliable detection

$$\lim_{\delta\to\infty}\lim_{n\to\infty} P_c(n) = 1$$

Comparison with case 1

- node degree $\delta > 2$

$$\lim_{n\to\infty} \mathrm{P}_c(n) = 1 - \delta\left(1 - I_{1/2}\left(\frac{1}{\delta-2}, \frac{\delta-1}{\delta-2}\right)\right)$$

- non-trivial positive value

$$P_c(n) > 0$$

- at most 0.5-detection

$$P_c(n) \leq 0.5$$

- upper-bounded by 0.307

$$\lim_{\delta\to\infty}\lim_{n\to\infty} P_c(n) = 0.307$$

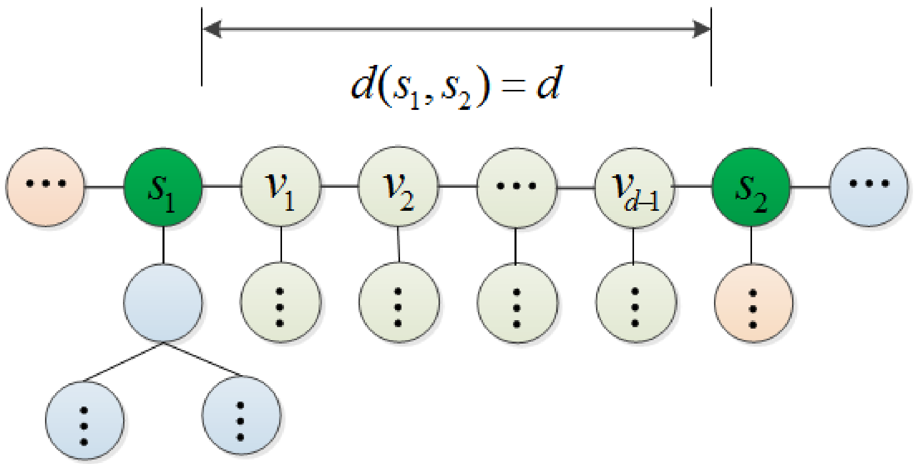
– **Suspect characteristics (connectivity) bring about new ingredients.**

Two Suspects

----main results

Case 3

– Two suspect nodes is separated by *d*.



– **Identifying the rumor source is more difficult if the two suspects are closer.**

Main results

- node degree $\delta = 2$

$$P_c(n) = \begin{cases} \frac{1}{2} - \sum_{z=(n-d-1)/2}^{(n+d+1)/2} \binom{n-1}{z}, (n-d) \text{ is odd} \\ \frac{1}{2} - \sum_{z=(n-d)/2}^{(n+d-2)/2} \binom{n-1}{z}, (n-d) \text{ is even} \end{cases}$$

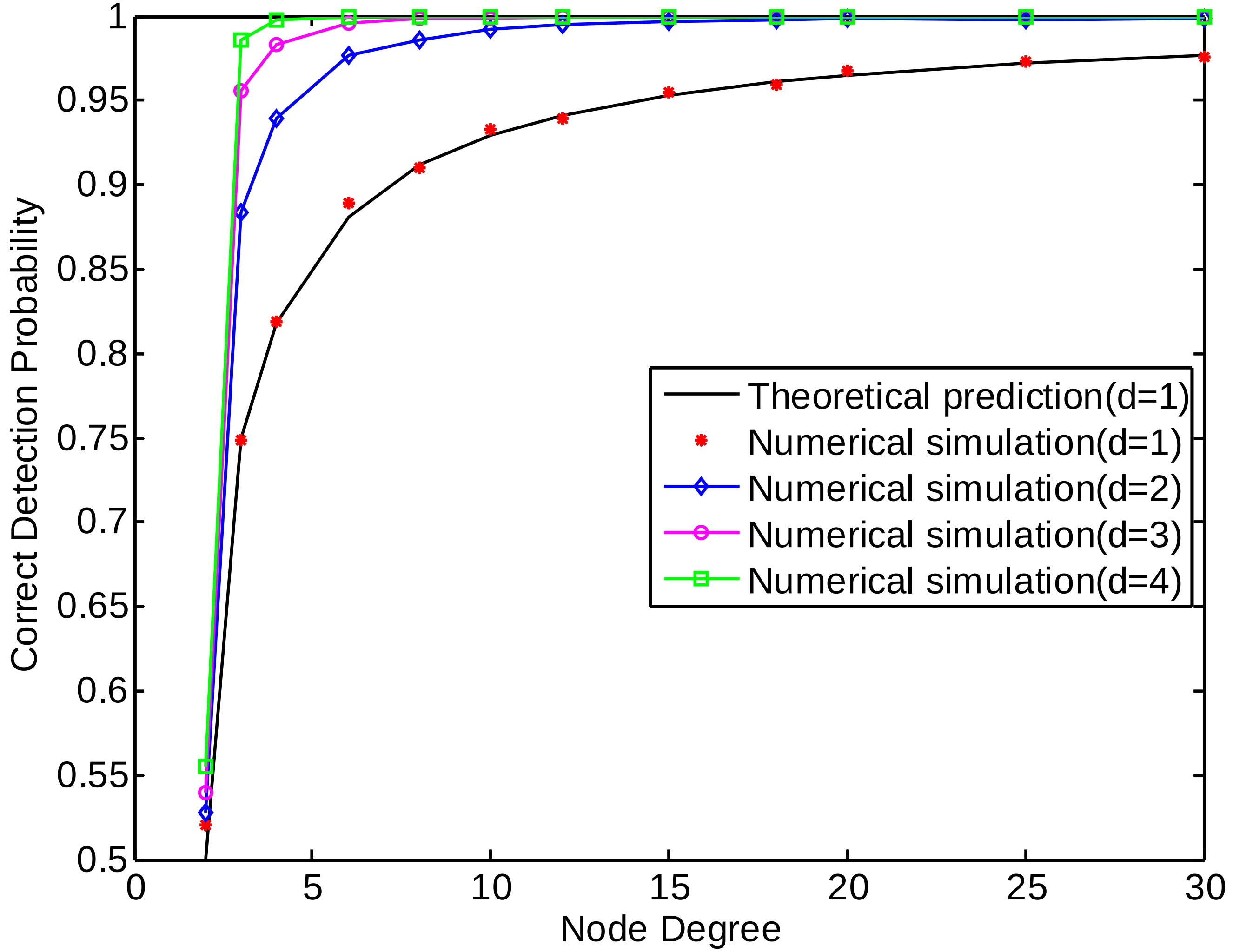
- node degree $\delta > 2$

$$\lim_{n\to\infty} P_c(n) = I_{1/2}\left(\frac{1}{\delta-2}, \frac{\delta-1}{\delta-2}\right) \geq 0.75, d = 1 \to 1$$

- Monotonicity: Detection probability increases with *d*

Two Suspects

----validation experiment



Detection in General Network

- Still an open problem
  - How to deal with loops?

- Breadth-First-Search (BFS) Heuristic Algorithm
  - BFS tree approximates *diffusion tree*
  - Rumor centrality algorithm on BFS tree

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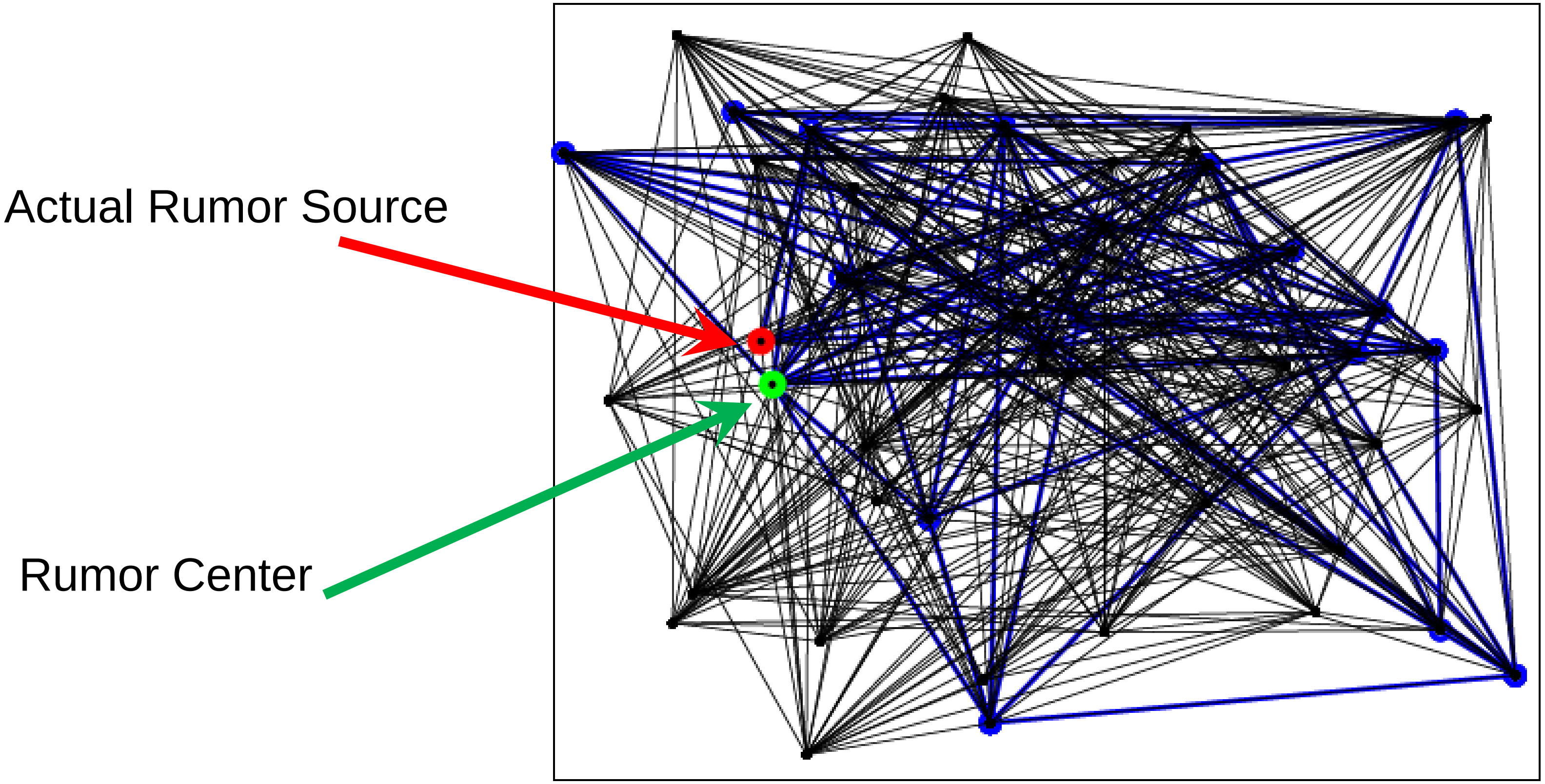
Detection in General Network

- Erdos-Renyi random graph (*N=50, K=20, p=0.4*)

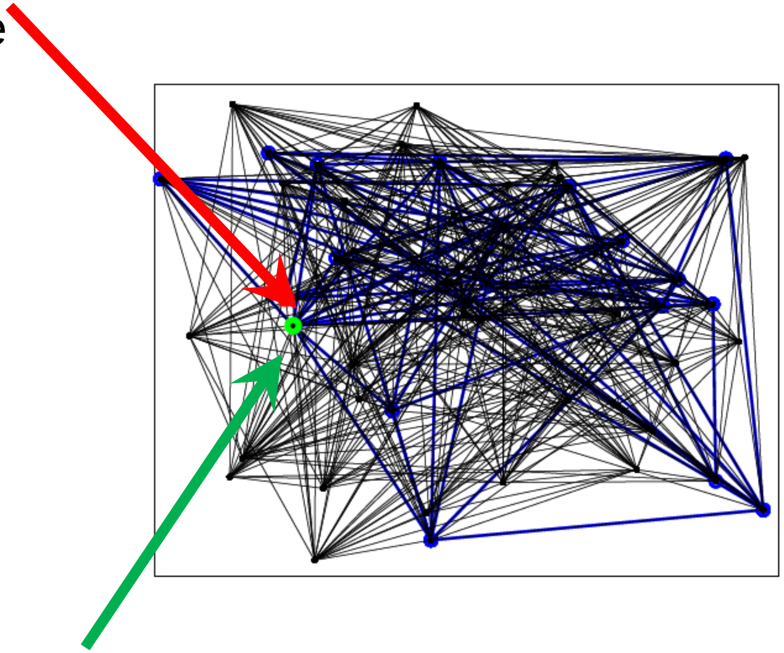


1) Start with N isolated nodes;
2) Add an edge between two nodes with probability p.

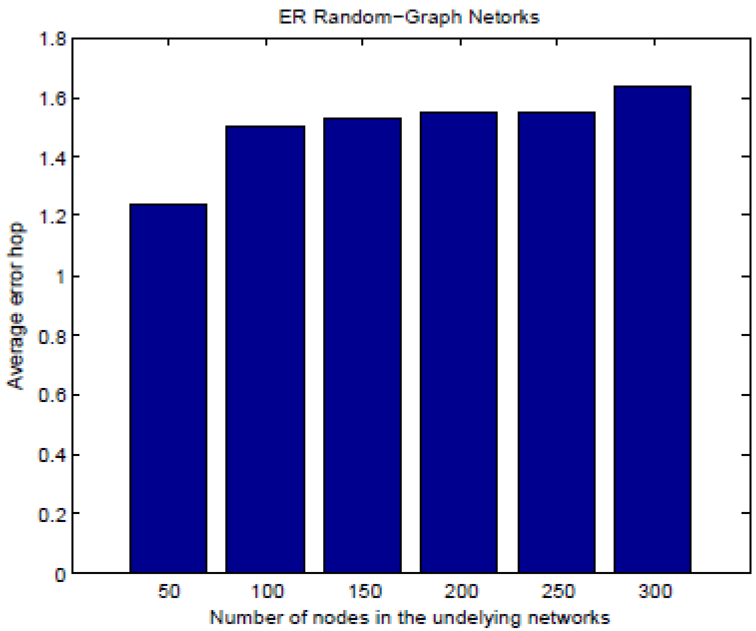
Detection in General Network

- Erdos-Renyi random graph

Actual Rumor Source

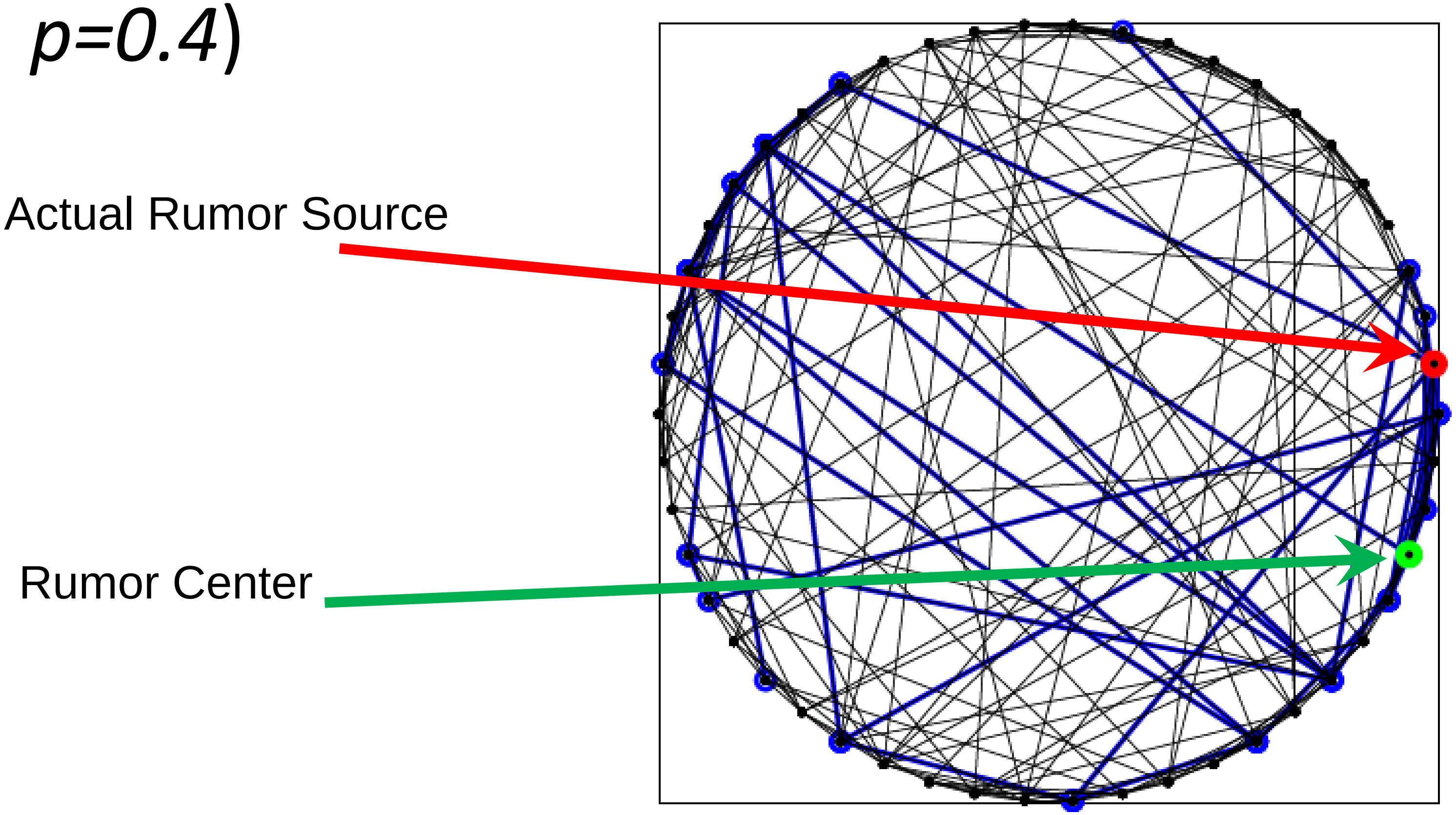


Rumor Center



Detection in General Network

- Newman-Watts small world (*N=50, K=20, m0=4, p=0.4*)

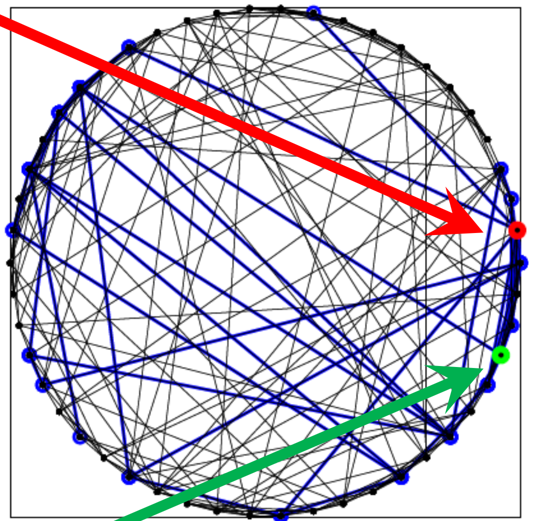


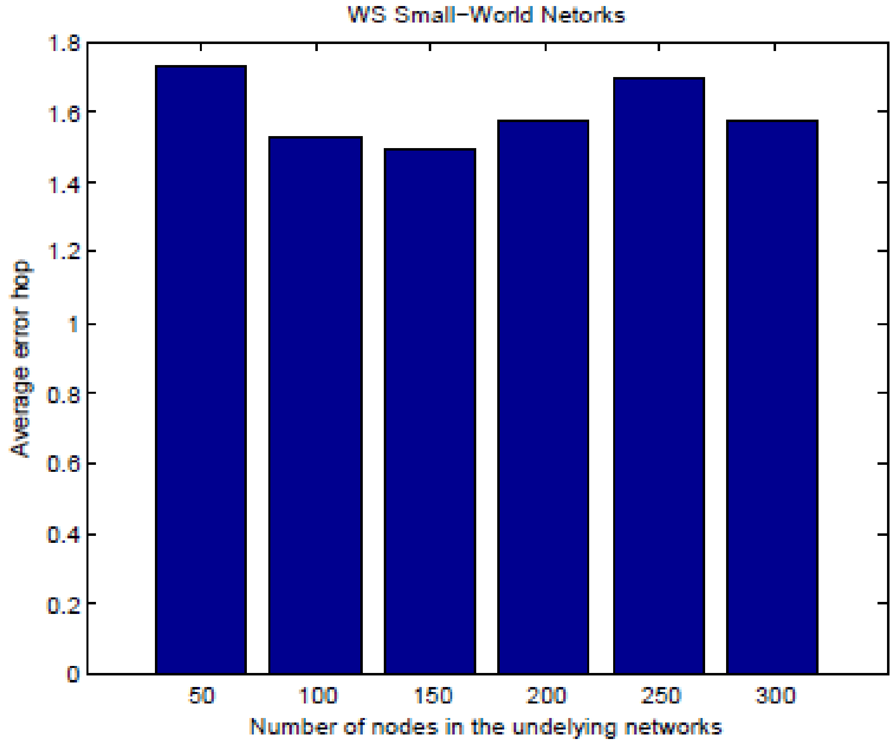
1) Start with a ring-shaped network with N nodes, in which each node is connected to its $2m_0$ neighbors, where $m_0 > 0$ is a (small) positive integer.
2) Add an edge between two nodes with probability p.

Detection in General Network

- Newman-Watts small world graph

Actual Rumor Source



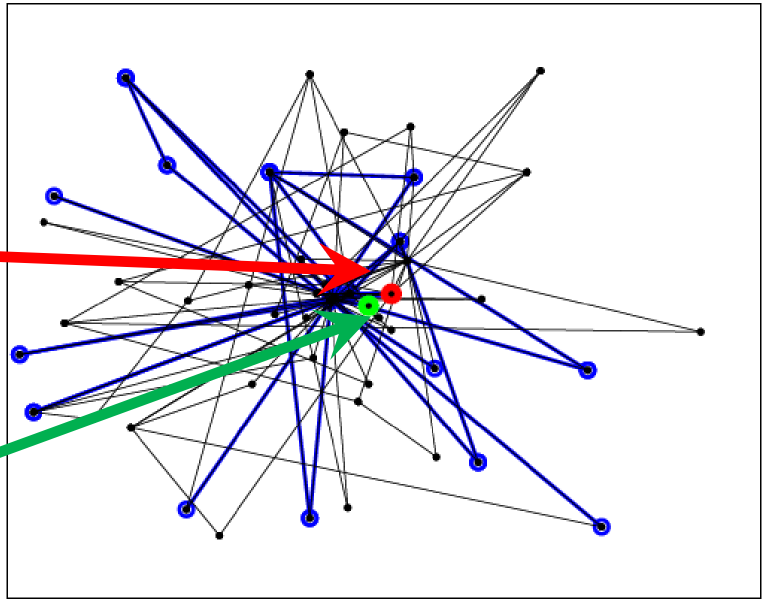


Rumor Center

Detection in General Network

- Barabasi-Albert scale-free graph (*N=50, K=20, m0=4,m=2*)

Actual Rumor Source



Rumor Center

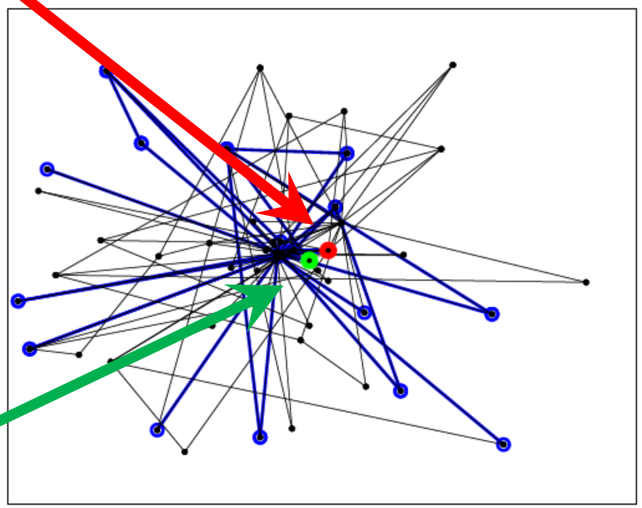
1) Growth: start with a small fully-connected network having $m_0 \geq 1$ nodes, and add one new node to the network each time by connecting to m existing nodes, where $(m \leq m_0)$.
2) Preferential attachment: The new node is connected to an existing node i of degree d_i according to the following probability:

$$\Pi_i = \frac{d_i}{\sum_{j=1}^{N} d_j}.$$

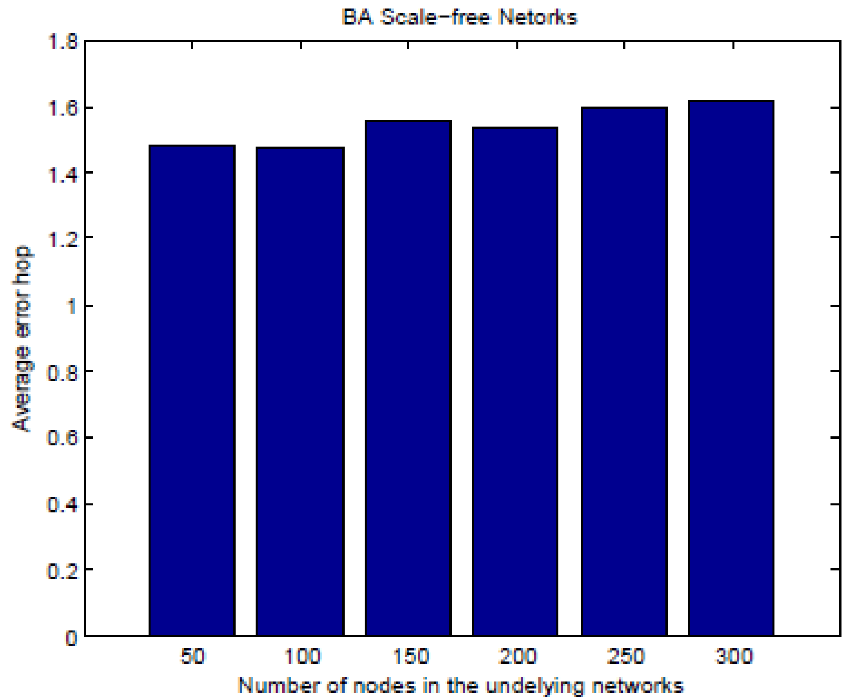
Detection in General Network

- Barabasi-Albert scale free graph

Actual Rumor Source

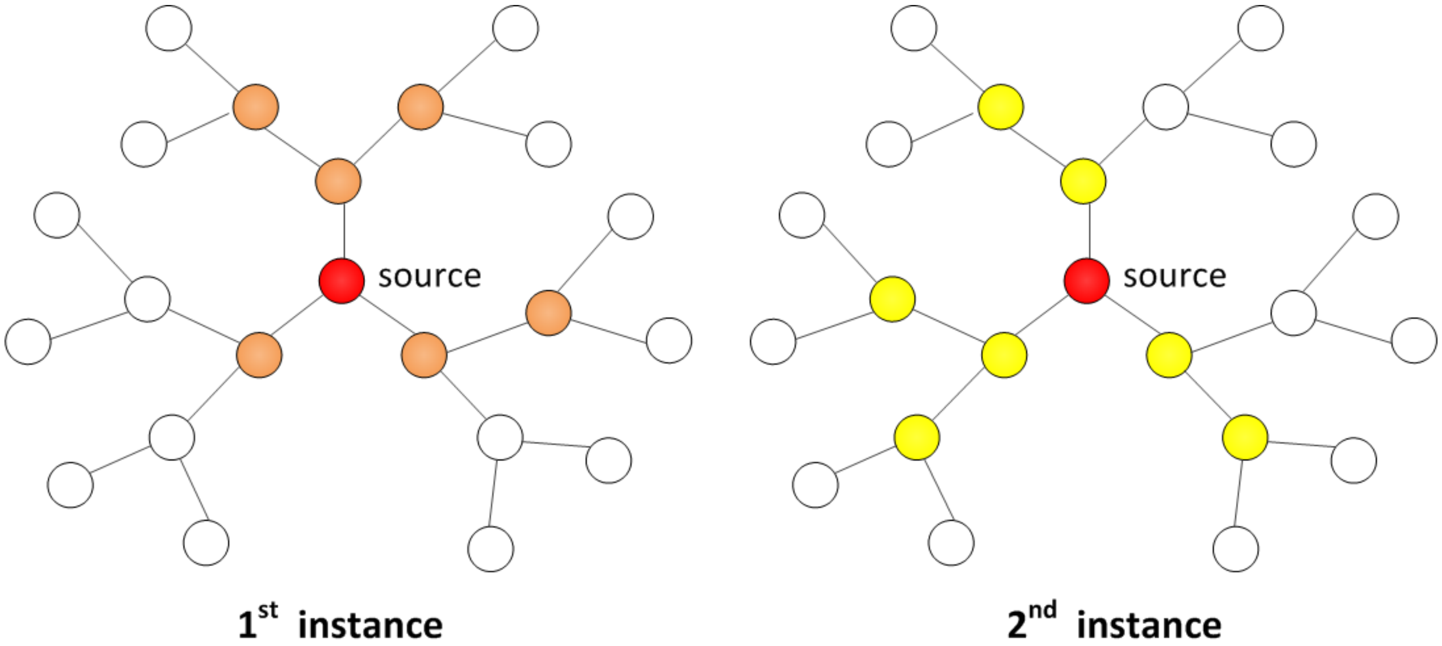


Rumor Center



Detection with Multiple Observations

- **A source may initiate multiple instances, e.g., email spam, recurring malcodes.**
- **Can diversity help? How many observations to take?**



Zhao, Dong, Zhang and Tan, ACM SIGMETRICS 2014

Performance results

➢ **For regular tree**

- **Case 2**

$\delta = 3,\ K = 2$ Given G_{n_1}, G_{n_2}

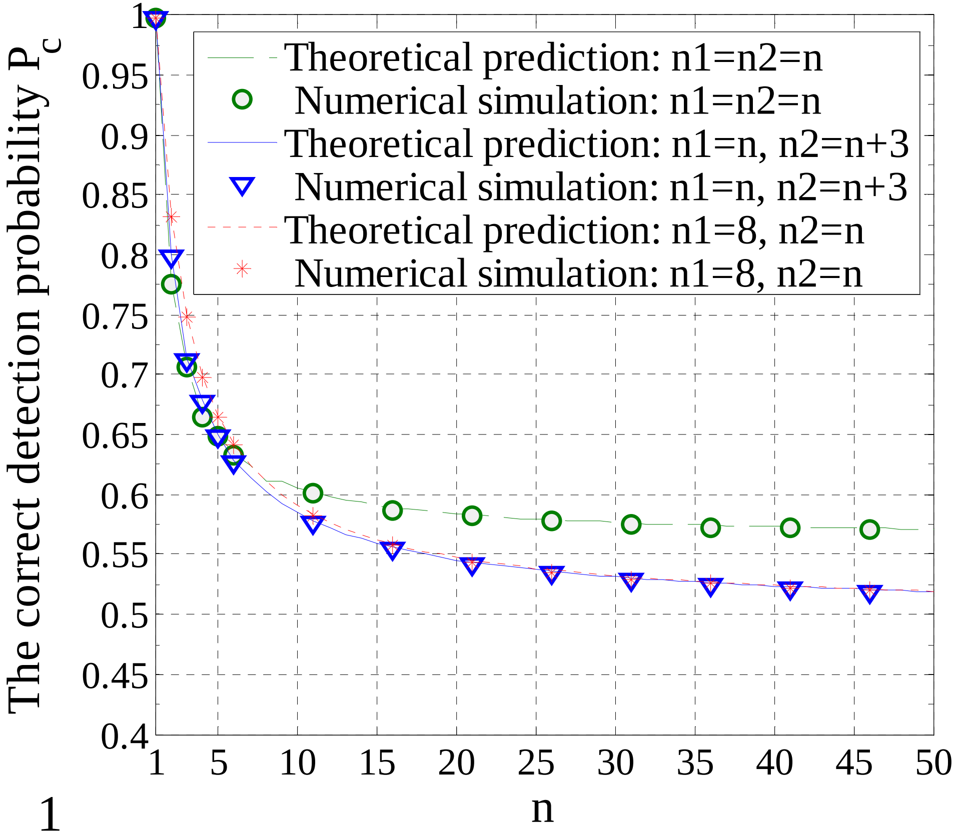
■ (1) $n_1 = n, n_2 = qn\ (q \in Z^+)$

$$\mathrm{P}_c = \frac{qn + q + 2}{2(qn+1)}$$

■ (2) $n_1 = n, n_2 = qn + 1\ (q \in Z^+)$

$$\mathrm{P}_c = \frac{qn + q + 2}{2(qn+1)}$$

■ (3) $n_1 = n, n_2 = qn + t\ (q \in Z^+), t < n$



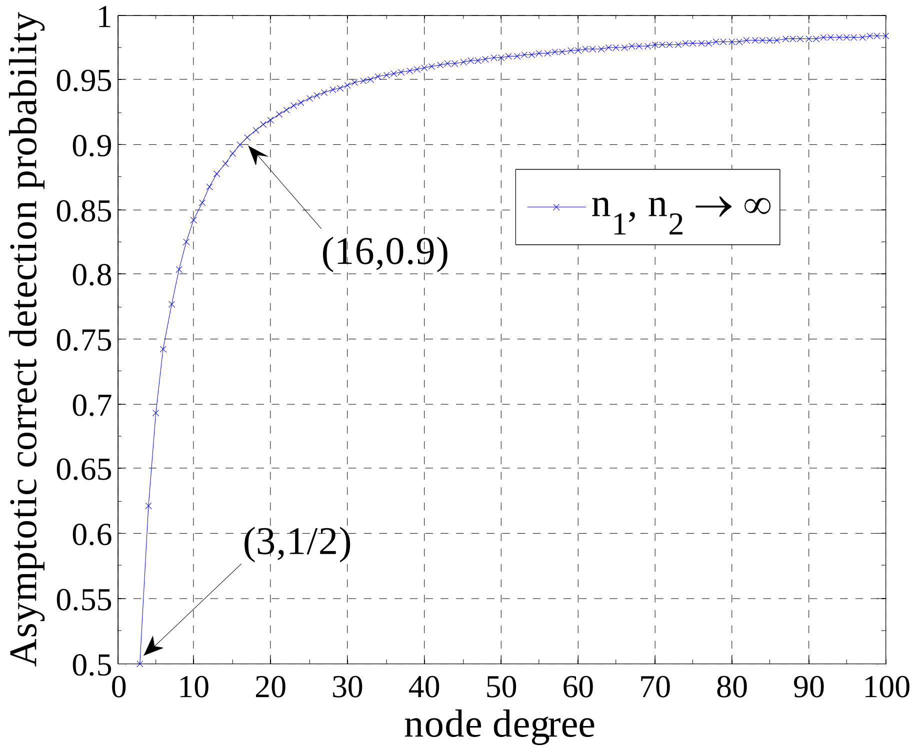
$\delta = 3$

$$\mathrm{P}_c = \frac{qn + q + 2}{2(qn+1)} + \Delta\mathrm{P}_c \quad \text{with} \quad \Delta\mathrm{P}_c < \frac{1}{2(qn+1)}.$$

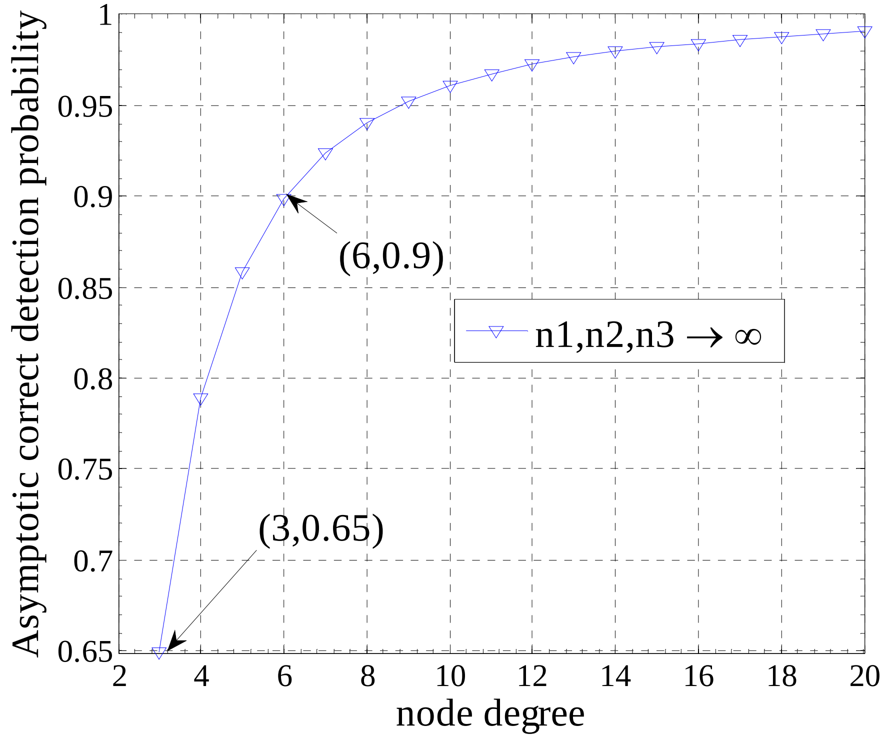
As $n \to +\infty$, $\lim\limits_{n \to +\infty} \mathrm{P}_c = \dfrac{1}{2}$

Performance results

----Detection performance with multiple instances:



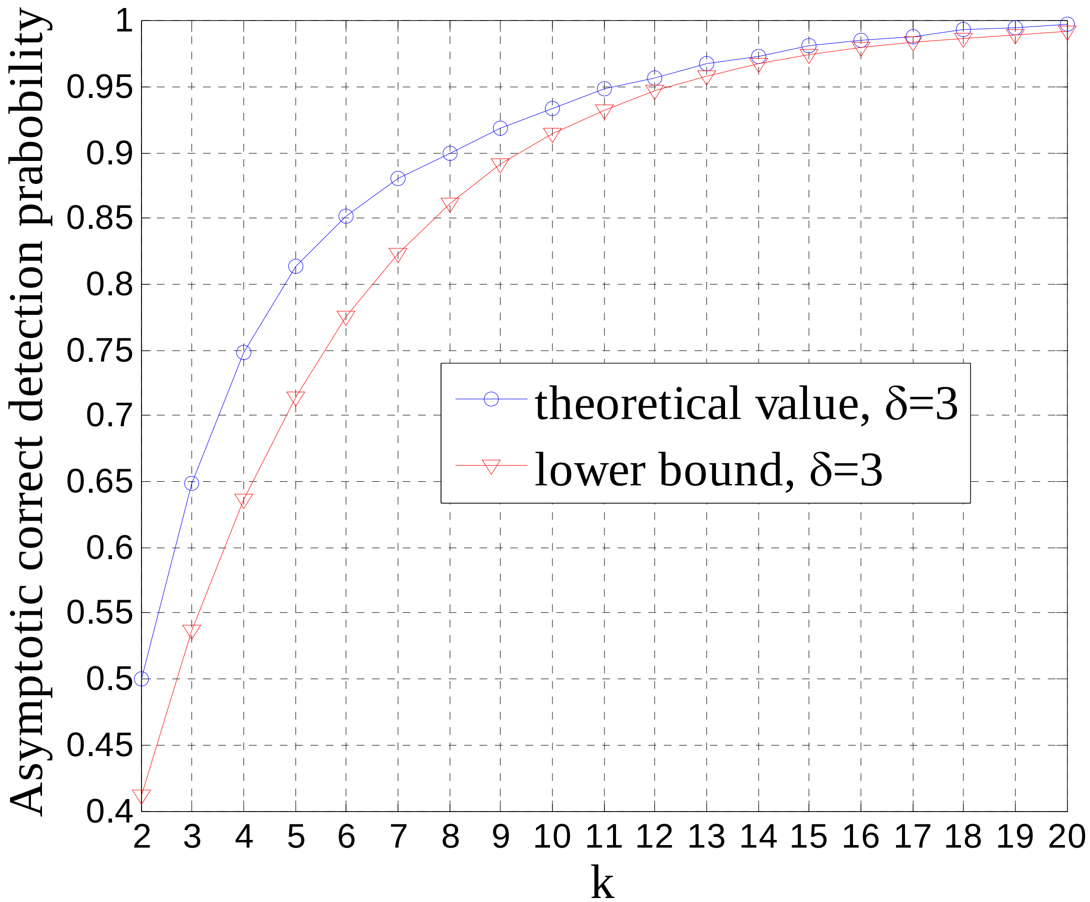
K=2



K=3

Performance results

----Detection performance with multiple instances:



$$\phi_K(\delta)\ \ vs\ \ K, \delta = 3$$

Outline

- Related Work and Spreading Model
- Rumor Centrality
- Detection in Tree Network
- Detection in General Network
- Cybersecurity Forensics
- Conclusion

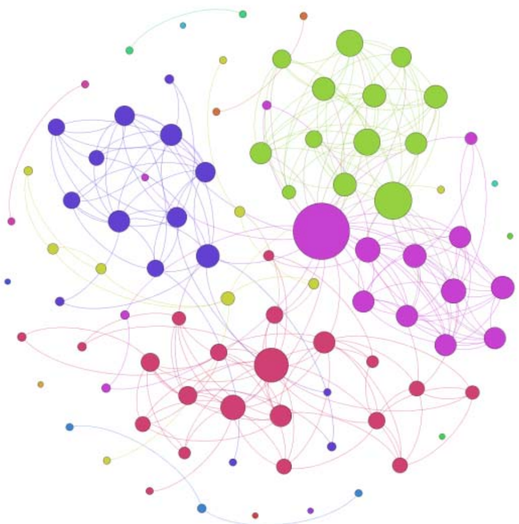
Forensics in Online Social Networks

Network Cyber Security Forensics

- Many interactions over online social networks that are recorded and available from API service to glimpse social relationship of users
- Provide clues for rumor source detection and other cyber-security forensics algorithms
- How to even obtain a single snapshot observation of the graph?
- Bridge deep gulf between theory and practice
  – There is nothing more practical than a good theory!

Forensics using Facebook Graph

- Rate-constrained data scraping
- Access control for privacy and security
- How to use semantics to infer the possession of a rumor?
- How to link social graph with technological graph?



Conclusion

- **Rumor Centrality**
  - **Center of a Network**
- **Network features: Suspects, Connectivity, Observations**
- **Detectability and Detection**
  - **Statistical inference, probability theory, graph theory, Information theory**
  - **Scalable algorithms**
- **Numerous Open Issues:**

– Heterogeneous connectivity and spreading models

– Real-world data traces

– Practical network forensics protocol in online social networks

Thank You

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