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Designing Secure and Reliable Wireless Sensor Networks

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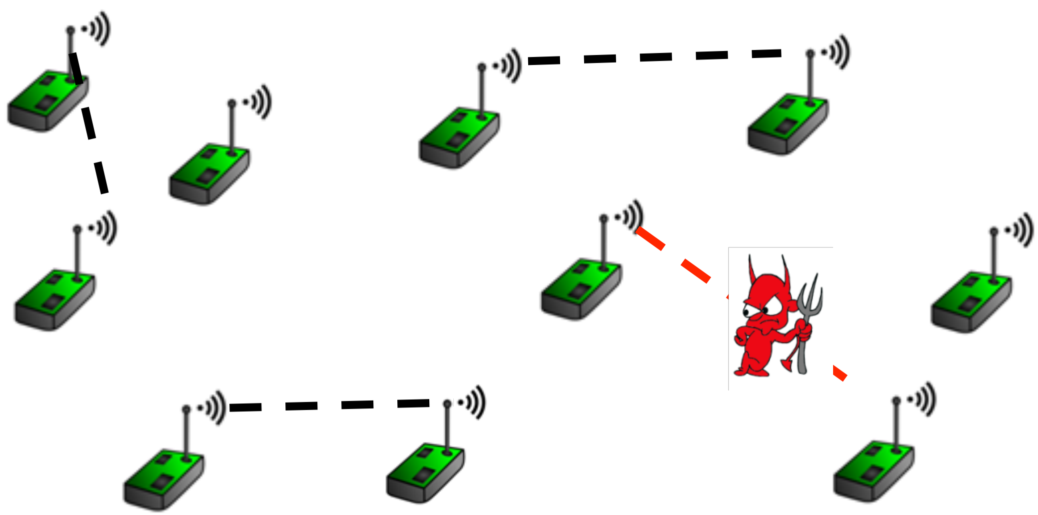
Wireless Sensor Networks

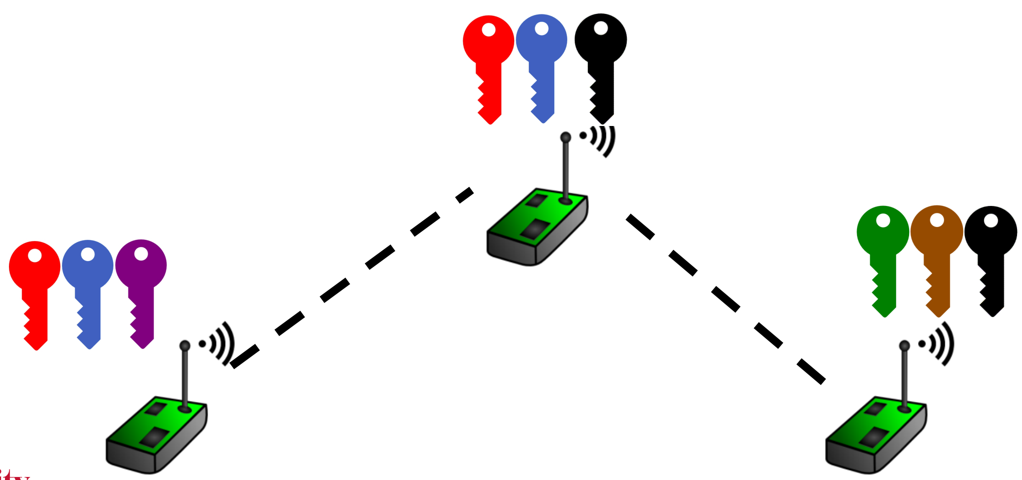
- Distributed collection of sensors: low-cost, resource-constrained, and often deployed in a **hostile environment**
- Wireless communications
  - Monitored **and** modified by an adversary
  - Cryptographic protection is needed
  - Proposed method: **Random** key predistribution (since topology is often unknown before deployment)



Random key predistribution

1. The Eschenauer–Gligor (EG) scheme [ACM CCS '02]

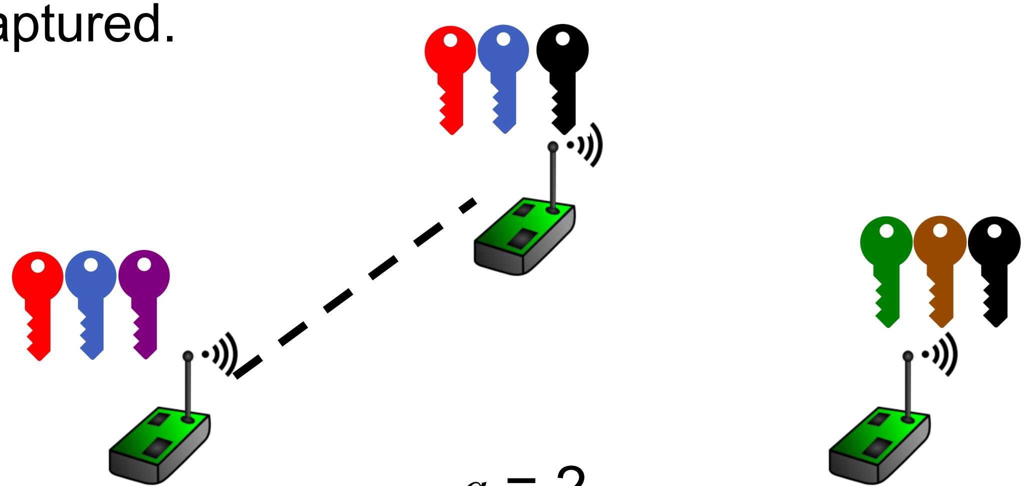
- For a network with ***n*** sensors:
  - A large pool of ***P*** cryptographic keys
  - For each sensor, sample ***K*** keys uniformly at random
  - Example values: ***n*** = 10^4 , ***P*** = 10^5 , and ***K*** = 10^2
- Two sensors can **securely** communicate over an existing wireless link if they have **at least one common key**



A simple extension of the EG scheme

2. The q-composite scheme [Chan–Perrig–Song IEEE S&P ‘03]

- Same initial construction with the EG scheme;
- For any two sensors, secure communication over an existing wireless link if they share at least ***q*** keys (***q>1***)
- **Advantage:** Improved resilience against node capture attacks when ***few*** sensors are captured → Worse than EG if a large number sensors are captured.



$q = 2$

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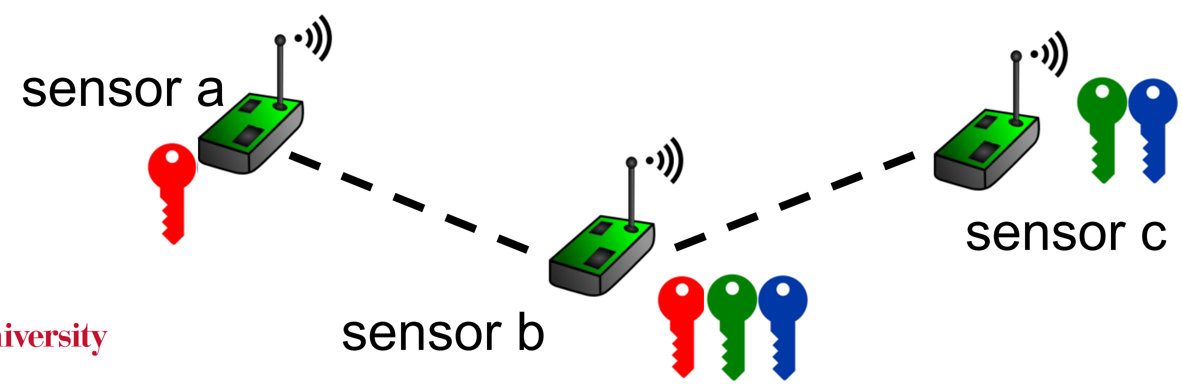
An alternative method

3. The pairwise scheme [Chan–Perrig–Song IEEE S&P ’03]

- Each sensor is paired (offline) with ***K*** distinct **nodes** which are randomly selected from amongst all other nodes.
- For each sensor and any sensor paired to it, a unique (pairwise) key is generated and assigned only to those two nodes.
- **Advantage:** Node-to-node authentication and quorum-based key revocation are possible without requiring a trusted third party.

With ***K***=*1*, *S_a={b}*, *S_b={c}*, and *S_c={b}* where *S_i* is the set of nodes selected by node *i*:



The Main Question

Given the **RANDOMNESS** involved in

- Distribution of cryptographic keys
- Physical location of sensors, due to random deployment (& **mobility)**

How do we ensure that the network has **end-to-end connectivity** that is **reliable** against

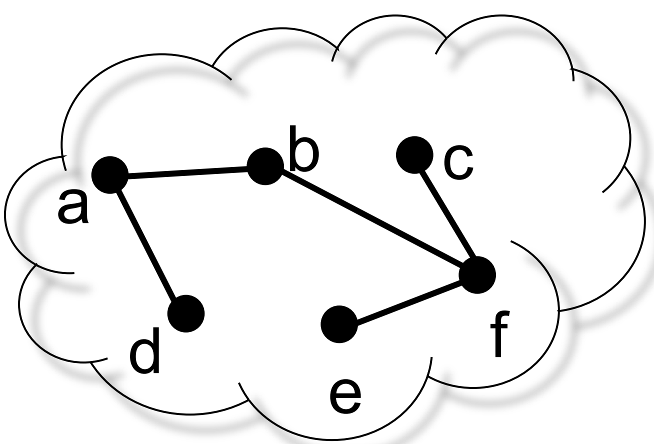
i) Sensor failures due to adversarial attacks, battery depletion, product malfunctioning; and

ii) Link failures due to sensor mobility, environmental conditions, product malfunctioning?

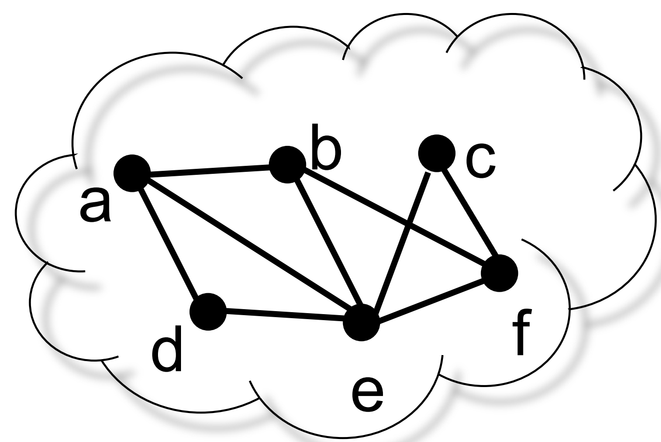
A Reliability Metric: k-connectivity

- Connectivity
  - At least 1 path between any two nodes
- *k*-Connectivity
  - At least *k* mutually disjoint paths between any two nodes
  - Equivalent definition: **Remains connected despite the removal**

  –**of any (*k*−1) nodes or edges**
  - Addtl. advantages: multi-path routing, achieving consensus, etc.



Connected



2-Connected

Our Goal

For a desired level of reliability specified by the parameter *k*,

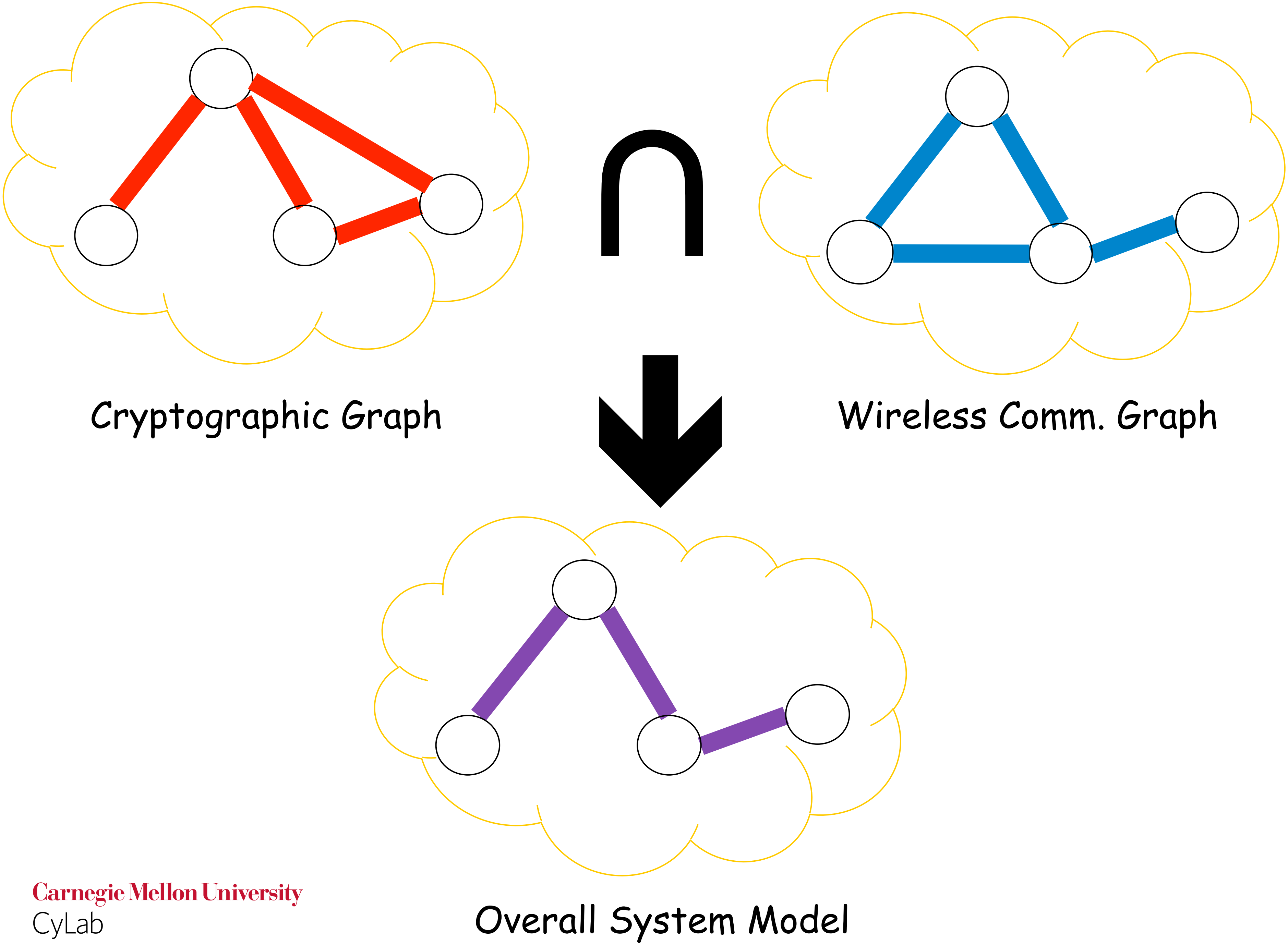
- Determine the probability that the resulting network is *k*-connected as a function of all **network parameters** involved -- This will be done under
  - i) Three key predistribution schemes, and
  - ii) Two wireless communication models

Approach: Random Graph Modeling & Analysis

Random Graph Modeling

Random Graphs = Graphs generated by a random process

- **Communication Graph:** E.g., the disk model
  - An edge $i \sim j$ exists if $\|x_i - x_j\| \le r$ → transmission range
- **Cryptographic Graph:** Induced by the key predistribution sch.
  - An edge $i \sim j$ exists if sensors i and j have **q** keys in common. (For EG and Pairwise *q=1*)
- **System Model: Communication Graph ∩ Cryptographic Graph**
  - $i \sim j$ if $\|x_i - x_j\| \le r$ ∧ have **q** keys in common.
  - Links represent sensors that can securely communicate



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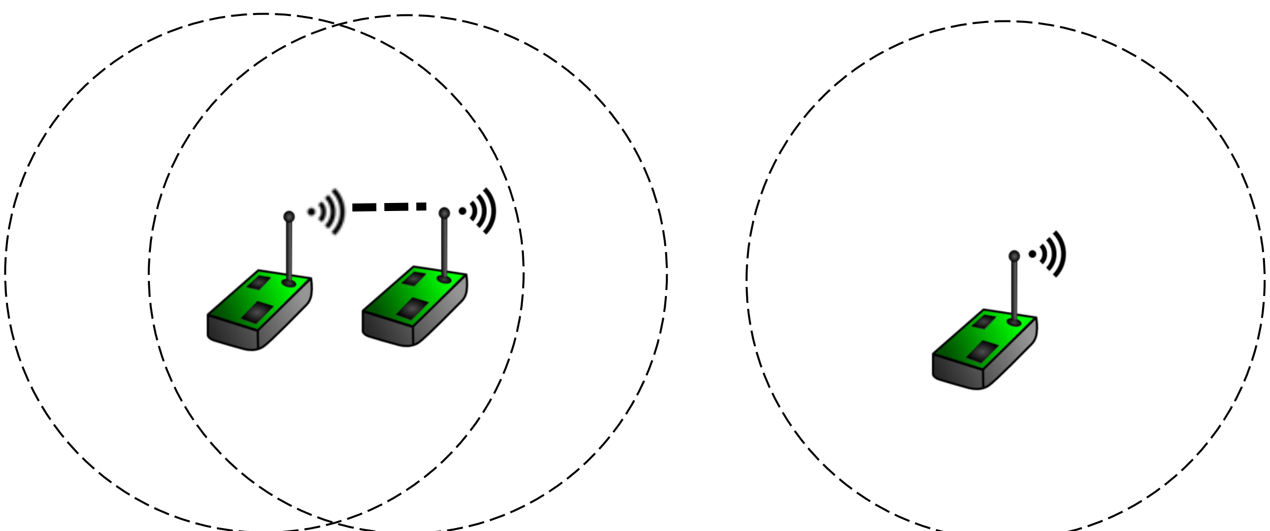
Preliminary Wireless Comm. Models

- On/Off channel model
  - Each channel either on with prob. p_n or off with prob. (1–p_n)
  - Unreliable links due to barriers / environments / wireless nature
- Disk model
  - Only two sensors within some distance r_n can communicate
  - Transmission range r_n is directly related to sensor transmit power



System Models to be Considered

Scheme/Comm. Model	Graph
EG scheme	Random key graph
q-composite scheme	q-composite key graph
Pairwise scheme	Random K-out graph
on/off channel model	Erdős-Rényi graph
disk model	Random geometric graph

Cryptographic Graphs

Communication Graphs

WSN	Graph
$\mathrm{WSN}^{\mathrm{EG}}_{\mathrm{on/off}}$	random key graph ∩ Erdős-Rényi graph
$\mathrm{WSN}^{\mathrm{EG}}_{\mathrm{disk}}$	random key graph ∩ random geometric graph
$\mathrm{WSN}^{q\text{-composite}}_{\mathrm{on/off}}$	q-composite random key graph ∩ Erdős-Rényi graph
$\mathrm{WSN}^{q\text{-composite}}_{\mathrm{disk}}$	q-composite random key graph ∩ random geometric graph
$\mathrm{WSN}^{\mathrm{pairwise}}_{\mathrm{on/off}}$	random K-out graph ∩ Erdős-Rényi graph
$\mathrm{WSN}^{\mathrm{pairwise}}_{\mathrm{disk}}$	random K-out graph ∩ random geometric graph

A Representative Result

- EG scheme : Random Key Graph
  - n sensors, each equipped with K_n keys selected uniformly at random from a pool of P_n keys.
  - An edge between two nodes (sensors) if and only if they share at least 1 key
  - Notation: $G_{\text{RKG}}(n, K_n, P_n)$
- On-off channel model : Erdős–Rényi graph
  - n nodes
  - An edge between two nodes appear independently with prob. p_n
  - Notation: $G_{\text{ER}}(n, p_n)$
- System Model:

$$\text{WSN}_{\text{on/off}}^{\text{EG}} = G_{\text{RKG}}(n, K_n, P_n) \bigcap G_{\text{ER}}(n, p_n)$$

Zhao, Yagan, Gligor: IT 2014

Theorem 1. For $\text{WSN}^{\text{EG}}_{\text{on/off}}$ modeled by $G_{\text{RKG}}(n, K_n, P_n) \cap G_{\text{ER}}(n, p_n)$ with $P_n \geq 3K_n$ for all n sufficiently large, let sequence α_n for all n be defined through

$$\alpha_n = n\, p_n \frac{K_n^2}{P_n} - \ln n - (k-1)\ln\ln n,$$

If $P_n = \Omega(n)$, then as $n \to \infty$,

$$P\left[\text{WSN}^{\text{EG}}_{\text{on/off}} \text{ is } k\text{-connected}\right] \to \begin{cases} \boxed{e^{-\frac{e^{-\alpha}}{(k-1)!}}, \text{ if } \lim_{n\to\infty} \alpha_n = \alpha \in (-\infty, \infty),} \\ \boxed{0, \quad \text{if } \lim_{n\to\infty} \alpha_n = -\infty,} \\ \boxed{1, \quad \text{if } \lim_{n\to\infty} \alpha_n = +\infty.} \end{cases}$$

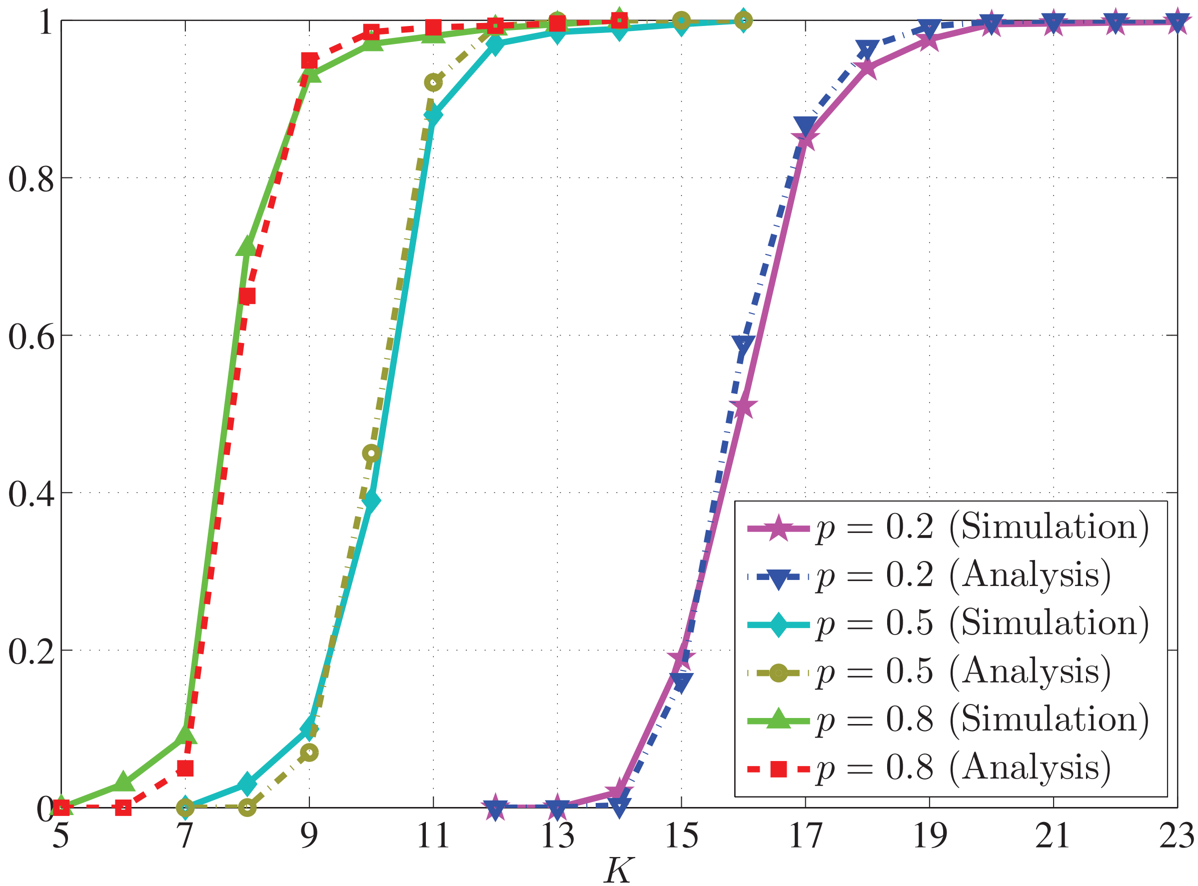
Exact prob.

A zero–law

A one–law

➢ **A precise characterization of *k*-connectivity in wireless sensor networks under the EG scheme**

Simulations with finite number of sensors



Probability that WSN is 2-connected with *n = 2,000*, *P = 10,000*

Contributions thus far

Model	**Results for *k*-connectivity**
EG scheme ∩ on/off channels	Zero-one law + Asymp. probability (ISIT 2013, IT, others in submission)
q-composite scheme ∩ on/off channels	Zero-one law + Asymp. probability (ISIT 2014 – best paper award finalist)
Pairwise scheme ∩ on/off channels	Zero-One law (ISIT 2014, IT, ICC 2015)
EG scheme ∩ disk model	Zero-One law (Allerton 2014)
q-composite scheme ∩ disk model disk model	Zero-One law (In submission)

Applications beyond wireless sensor networks

- Random key graphs ∩ random geometric graphs and Random K-out graphs ∩ random geometric graphs
  - Frequency hopping in wireless networks (keys can be used as an input to pseudo-random number generators, whose output give frequency-hopping sequence)

- Random key graphs
  - Trust networks
  - Cryptanalysis of hash functions
  - Recommender systems using collaborative filtering

- Random key graphs ∩ Erdős-Rényi graphs
  - Common–interest relations in online social networks

Thanks…
Questions??

For references: www.ece.cmu.edu/~oyagan