NC STATE UNIVERSITY Computer Science

# A Key-Management Scheme for Distributed Sensor Networks

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## Paper Overview

- “A Key-Management Scheme for Distributed Sensor Networks”, Laurent Eschenauer, Virgil Gligor, November 2002.
- Presents a key-management scheme designed to satisfy operational and security requirements of DSNs by selectively distributing and removing keys from sensor nodes as well as re-keying nodes without substantial computations or bandwidth usage.

## Outline

- Background
  - Distributed Sensor Networks
  - Key Management in Distributed Sensor Networks
- Related Work
- Proposed Key-Management Scheme
  - Key Distribution
  - Key Revocation
  - Re-Keying
- Analysis
- Simulation Results and Scenario
- Conclusion and Future Work



## Background: Distributed Sensor Networks

- Collection of battery powered sensor nodes
- Types of nodes:
  - Data-collection nodes: cache data and make it available for processing to application components within the network
  - Control-nodes: monitor the status of and broadcast simple commands to sensor nodes
- Dynamic in nature
- Communication/Computation constraints
  - Limited power and communication range
  - Typical asymmetric (public-key) cryptography too expensive
- Key-Management Issues

# Background: Key-Management in DSN

- Traditional Internet style key distribution
  - Impractical due to unknown topology prior to deployment, communication range limitations, etc.
- Current key-management techniques:
  - Rely on key-predistribution
  - Single mission key
    - Inadequate due to security risks
  - Pair-wise privately shared keys
    - Requires the storage of (n-1) keys in each sensor, n(n-1)/2 per DSN
    - Addition, deletion, or re-keying of sensor nodes becomes very complex
    - Sensor nodes have on-chip memory limitations



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# Related Work

- In the last decade key-management research has been primarily focused on broadcast and group communication.
- Group communication related work:
  - C. Blundo, A. De Santis, A. Herzberg, S. Kutten, U. Vaccaro and M. Yung, "Perfectly Secure Key Distribution for Dynamic Conferences," in Advances in Cryptology – CRYPTO' 92, LNCS 740, Springer-Verlag, Berlin, august 1993, pp. 471- 486.
  - C. Blundo, L. A. Frota Mattos and D. R. Stinson, "Tradeoffs Between Communication and Storage in Unconditionally Secure Schemes for Broadcast Encryption and Interactive Key Distribution," in Advances in Cryptology – CRYPTO '96, LNCS 1109, Springer Verlag, Berlin, August 1996, pp. 387-400.
- Broadcast communication related work:
  - A. Fiat and M. Naor, "Broadcast Encryption," in Advances in Cryptology – CRYPTO '93, LNCS 773, Springer-Verlag, Berlin, August 1993, pp. 480-491.



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## Proposed Key-Management Scheme

- Relies on probabilistic key sharing among the nodes of a random graph and uses a simple shared-key discovery protocol
- Each sensor node has a key ring consisting of randomly chosen k keys from a large pool of P keys.
- Key Distribution
  - Key pre-distribution phase
  - Shared-key discovery phase
  - Path-key establishment phase
- Key Revocation
- Re-Keying



## Key Distribution

- Phase 1: Key Pre-Distribution
  - Consists of 5 off-line steps:
    - Generate a large pool of P keys (2^17 – 2^20 keys)
    - Randomly choose (n times) k keys out of P without replacement
    - Load each set of keys (key ring) into each sensor node
    - Save key identifiers and associated sensor identifiers on the controller nodes
    - Load the identity and shared key (K_ci) of a controller node responsible for a particular sensor node into that node's memory ( shared key can be derived )
- Phase 2: Shared-Key Discovery
  - "Public" method → Each node broadcasts in clear text the key identifiers of the keys on their key ring
  - "Private" method → Each node broadcasts a list of challenges _ encrypted with each key (e.g. E_Ki(_), i=1,…,k)

## Key Distribution cont'd

- Phase 3: Path-Key Establishment
  - Assigns a path key to selected pairs of sensor nodes that do not share a key but are connected by two or more links
  - Path keys need not be generated since after the second phase is finished a number of keys on a key ring are left unassigned.



## Key Revocation

- Necessary when a node is compromised
- The controller node performs the following steps in order to revoke a key(s):
  - Creates a list of k key identifiers that has to be revoked
  - Generates a signature key, K_e, and unicasts it to each affected node by encrypting it with K_ci( the key shared with each node during the pre-distribution phase)
  - Signs the list of k key identifies with K_e and broadcasts it
- Once the keys are removed from the designated key rings, some links may disappear and the affected nodes need to repeat the shared-key discovery phase and possibly the path-key establishment.

## Re-Keying

- Sometimes keys expire and re-keying must take place.
- It doesn't involve any broadcast messages from a controller node.
- After expired-key removal, the affected nodes restart the shared-key discovery and possibly path-key establishment phase.



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# Analysis

- DSN Connectivity with Random Graphs
  - P →total number of available keys.
  - G(n, p) →a graph of n nodes for which the probability that a link exists between two nodes is p.
  - d = p * (n -1) → expected degree of a node (i.e. the average number of edges connecting that node with its neighbors).
- Erdos and Rényi's Equation:
  - Given a desired probability P_c for graph connectivity and number of nodes, n, the threshold function p is defined by:

$$P_c = \lim_{n \to \infty} Pr[\text{G(n,p) is connected}] = e^{e^{-c}}$$

where

$$p = \frac{ln(n)}{n} + \frac{c}{n} \text{ and c is any real constant.}$$



# Analysis cont'd

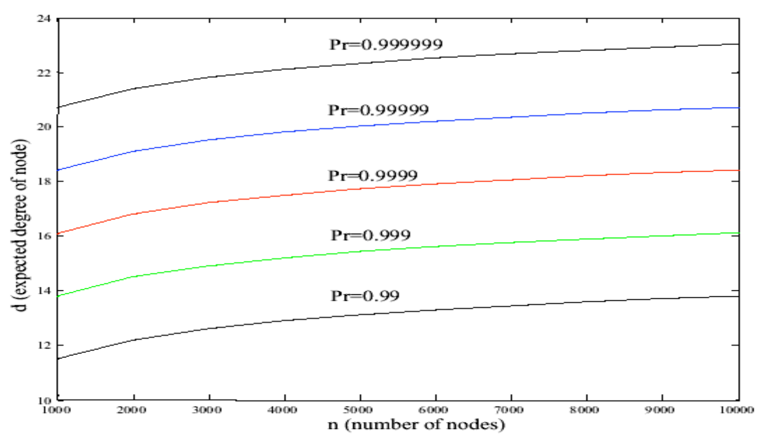



**Figure 1: Expected degree of node vs. number of nodes, where $P_c = Pr[G(n, p)$ is connected]**

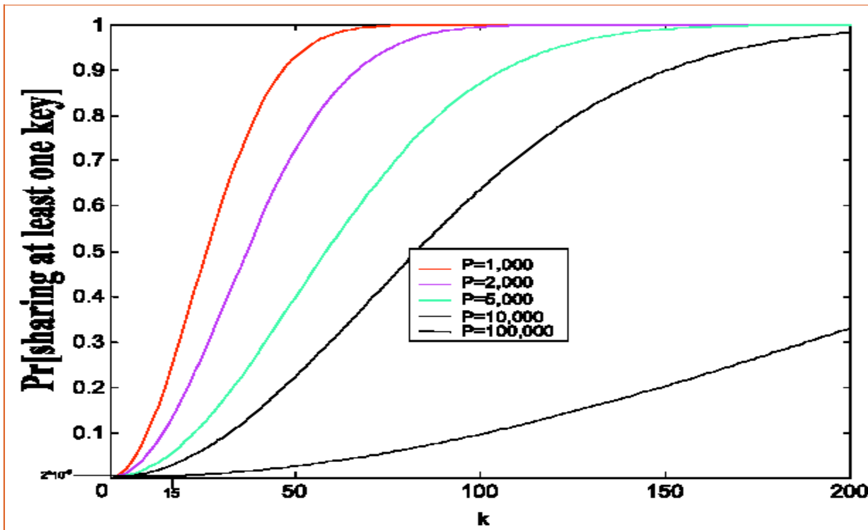
## Analysis cont'd

- Given a neighborhood connectivity constraint requirement n_ and d, the probability of sharing a key between any two nodes in a neighborhood becomes:
  - p_ = d/(n_-1)
  - The following equation represents the relationship between P, p_ and k:

$$p' = 1 - \frac{(1-\frac{k}{P})^{2(P-k+\frac{1}{2})}}{(1-\frac{2k}{P})^{(P-2k+\frac{1}{2})}}$$



## Analysis cont'd



## Analysis cont'd

- Example 1:
  - Assume a DSN has 10,000 nodes and the resulting network should be connected with probability P_c = 0.99999. What is the average number of neighbors that each node is connecting with?
  - Answer:
    - Using Erdos and Rényi formula we get that c =11.5
    - p = ln(n)/n + c/n, we get p = 0.002
    - d = p * (n -1), we get d = 20.7 ≈ 20 nodes.
- Example 2:
  - Given that 75 keys are distributed out of 10, 000 to every sensor node in a DSN, what is the probability that any two nodes share a key in their ring?
  - Answer:
    - p_ = 0.4326 ≈ 43.26%



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## Simulation Scenario and Results

- Purpose
  - To evaluate the efficiency and scalability of the key distribution scheme
- Setup
  - Pool of 10,000 keys
  - A Distributed Sensor Network with 1000 nodes
  - Average density of 40 sensor nodes in a neighborhood
  - Each simulation is run 10 times



## Simulation Scenario and Results

- Effect on the network topology

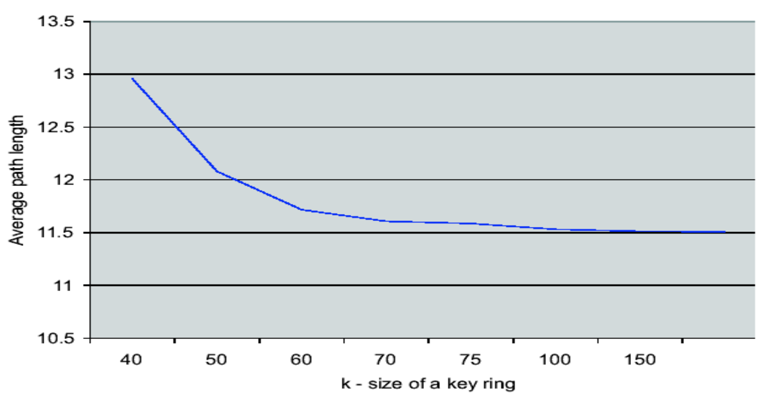



Figure 3: Average path length at the network layer

## Simulation Scenario and Results

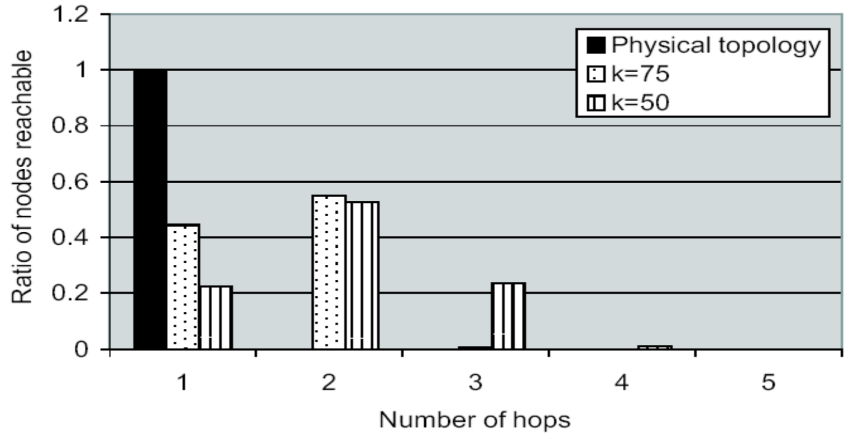
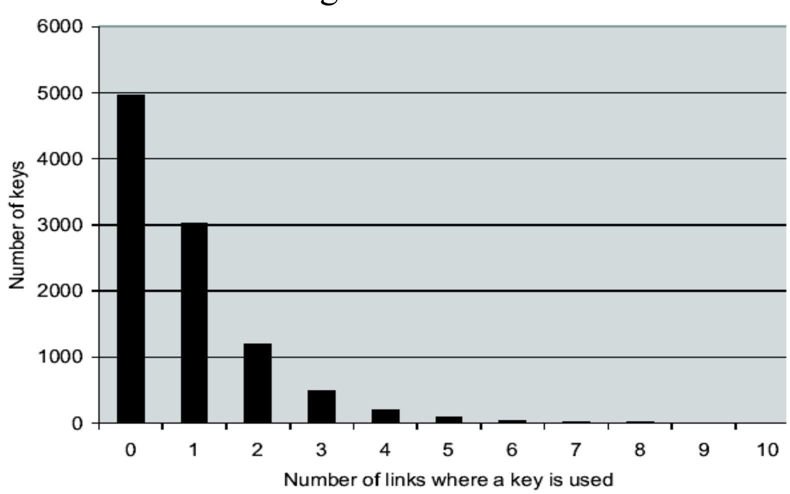



**Figure 4: Path length to neighbors**



## Simulation Scenario Results

- Effect of an attack against unshielded sensor nodes



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## Conclusion and Future Work

- Conclusion
  - The results show that the proposed scheme is superior to the traditional key management techniques.
  - It is scalable and flexible with possible trade-offs between sensor-memory size and connectivity.
  - Provides better overall security given that a sensor node is compromised (i.e. attacker has a k/P chance of successfully attacking a link).
- Future Work
  - More detailed analyzes and simulations can be performed to further refine the relationships between k, the connectivity of the network and the overall pool of keys, P.
  - This scheme can be incorporated in the development of a LHAP for Distributed Sensor Networks.

# Questions?