Leveraging Channel Diversity for Key Establishment in Wireless Sensor Networks

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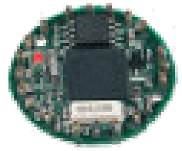
The Promises of Sensor Networks

"Every sweet has its sour"

-Ralph Waldo Emerson



The Sweet	The Sour
Wireless links for easy, quick deployment	Tapping the channel is easier
Cheap and numerous devices	Difficult to avoid physical compromise
Small and energy-efficient devices	Resource constraints on cryptography

How Key Distribution Fits In

- Tapping the channel
  - Keys give confidentiality against eavesdropping
  - Keys avoid unauthenticated data injection
- Physical compromise
  - Distribution should be resilient to node compromise
- Resource constraints
  - Use symmetric key cryptography as much as possible

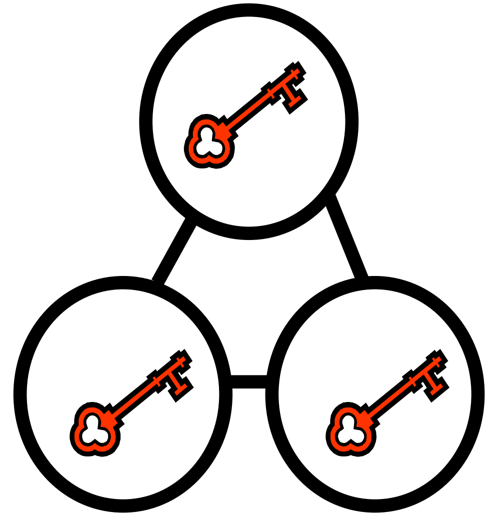
Problem Statement

- After deployment, a sensor needs to establish pairwise symmetric keys with neighbors for confidential and authenticated communication

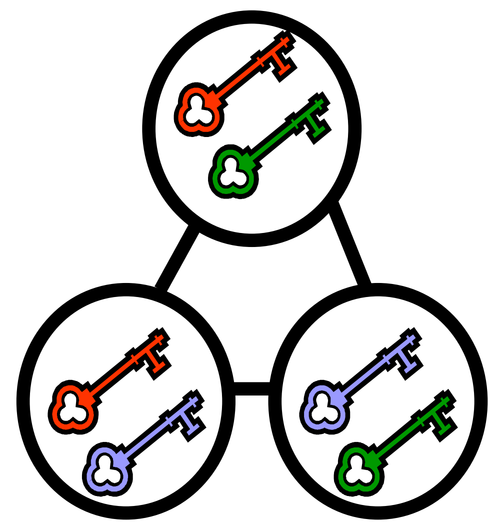
- Applications
  - Secure aggregation
  - Exchanging hash chain commitments (e.g., for authenticated broadcast)

Design Space

- Every node deployed with global key
  - ☺ Minimal memory usage, incremental deployment is trivial
  - ☹ If one node is compromised, then all links are compromised



- Separate key for each node pair
  - ☺ One compromised node does not affect the security of any other links
  - ☹ Required node storage scales linearly with network size



Related Work

- Each sensor shares a secret key with a trusted device (*T*) [Perrig02Winet]
  - *T* used as intermediary for key establishment
  - *T* must be online and may become bottleneck
- Key Predistribution [Eschenauer02CCS]
  - Sensors pre-loaded with subset of keys from a global key pool
  - Tradeoff in connectivity and resilience to node compromise
  - Each node compromise reduces security of the global key pool

Related Work

- Transitory key [Zhu03CCS]
  - Sensors use global key to establish pairwise key and then delete global key
  - Node compromise prior to deletion could compromise entire network
- Using public keys (e.g., Diffie-Hellman)
  - High computation cost
  - But, is it worth it when this cost is amortized over the lifetime of a long-lived sensor network?

Related Work

- Broadcast plaintext keys [Anderson04ICNP]
  - If an eavesdropper is not within range of both communicating sensors, then the key is secure
  - Assumes very small number of eavesdroppers
  - No way to improve link security if eavesdroppers are in range
  - We propose using the underlying wireless channel diversity to greatly improve this solution domain

High Level View of Our Work

High Level View of Our Work

- Given c channels:

  Pr(Eve hears Bob's packet | Alice hears Bob's packet) = $1/c$

- If Alice hears M of Bob's packets, then the probability that Eve heard *all* of those packets is $(1/c)^M$

- As $(1/c)^M \rightarrow 0$:

  The packets Alice heard can be combined to create Alice and Bob's secret key

Threat Model

- Adversary's primary objective is to learn pairwise keys
  - Can compromise node and learn its known keys
  - Can overhear broadcast keys
- Adversary's radio capability is similar to that of sensors [Anderson04ICNP]
  - Receive sensitivity
  - One radio
- Multiple adversary devices may collude in their knowledge of overheard keys
  - Collusion in coordination of channel listening is future work
- Denial-of-Service is beyond the scope of our work

Protocol Overview

- Predeployment
  - Give each sensor a unique set of authenticatable keys
- Initialization
  - Broadcast keys to neighbors using channel diversity
- Key Discovery
  - Find a common set of keys shared with a neighbor
- Key Establishment
  - Use this set to make a pairwise key that is secret with high probability

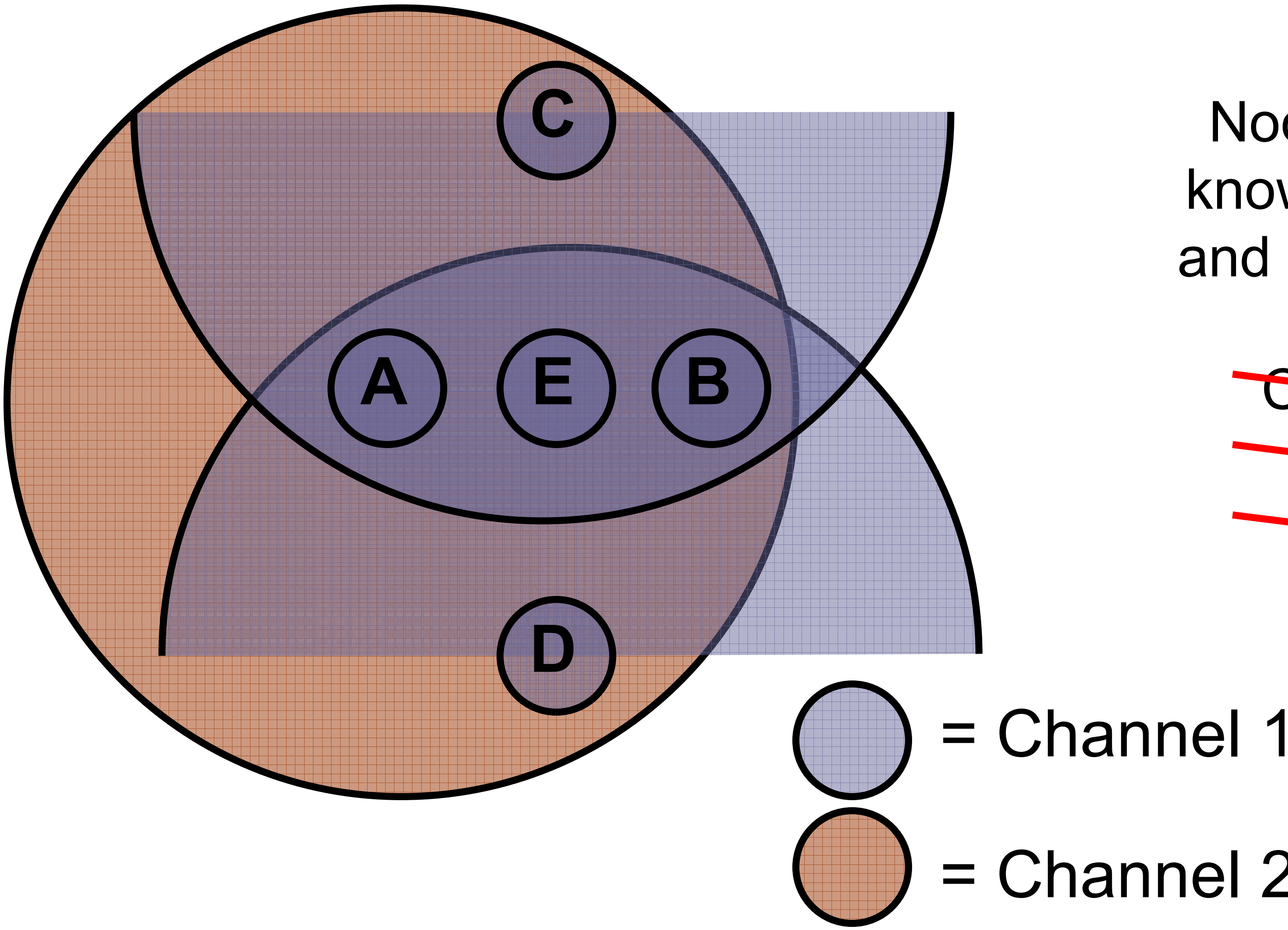
Phase 1: Predeployment

- Each sensor is given λ keys by a trusted entity
  - Keys are unique to sensor and *not* part of global pool
  - λ presents a tradeoff between overhead and security
- The trusted entity also loads the Merkle tree hashes needed to authenticate a sensor's keys
  - O(lg *N*) hashes using Bloom filter authentication
  - O(lg λ*N*) hashes using direct key authentication

Phase 2: Initialization

- Each sensor follows two unique non-deterministic schedules:
  - When to switch channels
    - Chosen uniformly at random among *c* channels
  - When to broadcast each of its λ keys
- Thus, each of a sensor's λ keys is overheard by *1/c* neighbors on average
  - Different subsets of neighbors overhear each key
- Sensors store every overheard key

Initialization Example



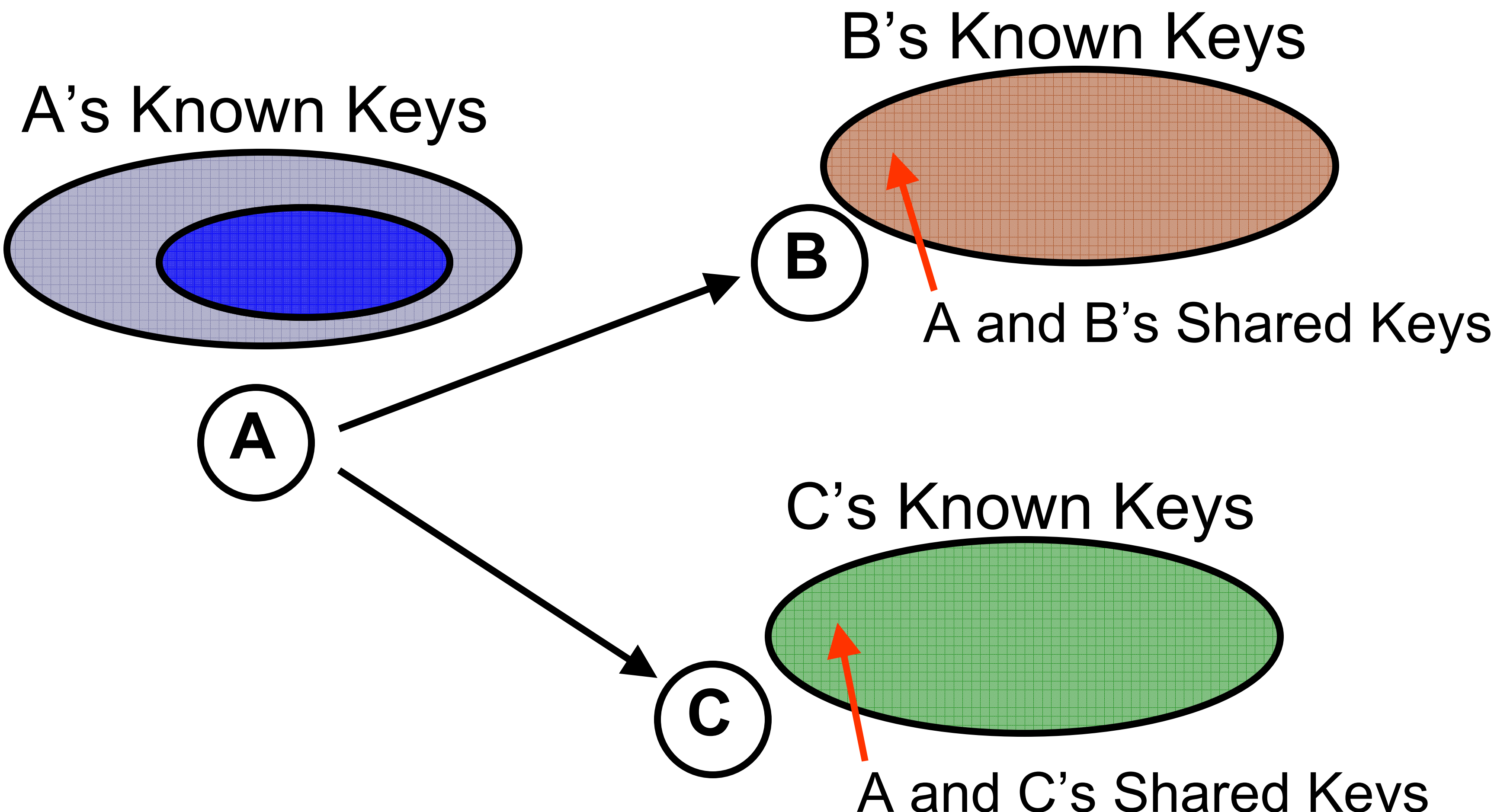
Nodes that know all of A and B's keys:

~~C, D, E~~
~~C, E~~
~~E~~
Ø

Phase 3: Key Discovery

- Goal: Discover a subset of stored keys known to each neighbor
- All sensors switch to common channel and broadcast Bloom filter with β of their stored keys
  - Bloom filter for reduced communication overhead
- Sensors keep track of the subset of keys that they believe they share with each neighbor
  - May be wrong due to Bloom filter false positives

Key Discovery Example

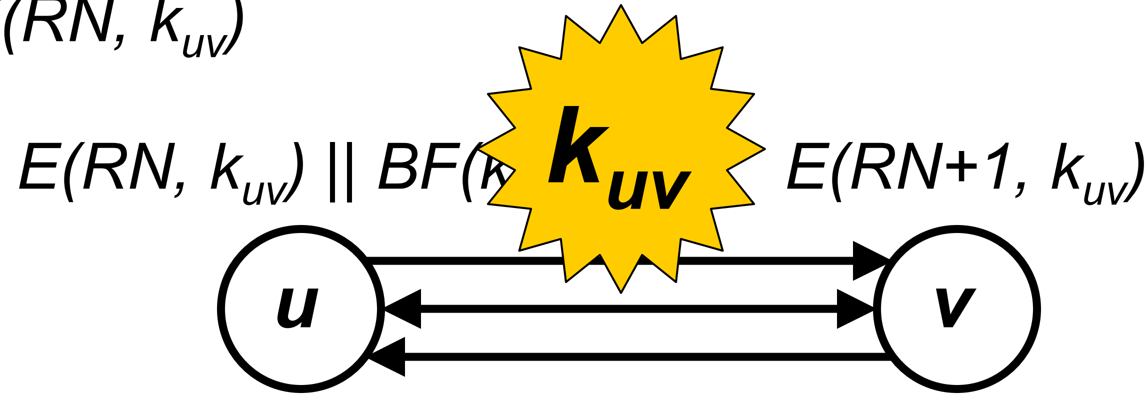


Phase 4: Key Establishment

u's believed set of shared keys with *v* = $\{k_1, k_2, k_3\}$

1. Generate link key: $k_{uv} = \text{hash}(k_1 \,||\, k_2 \,||\, k_3)$
2. Generate Bloom filter for k_{uv}: $BF(k_{uv})$
3. Encrypt random nonce (*RN*) with k_{uv}: $E(RN, k_{uv})$

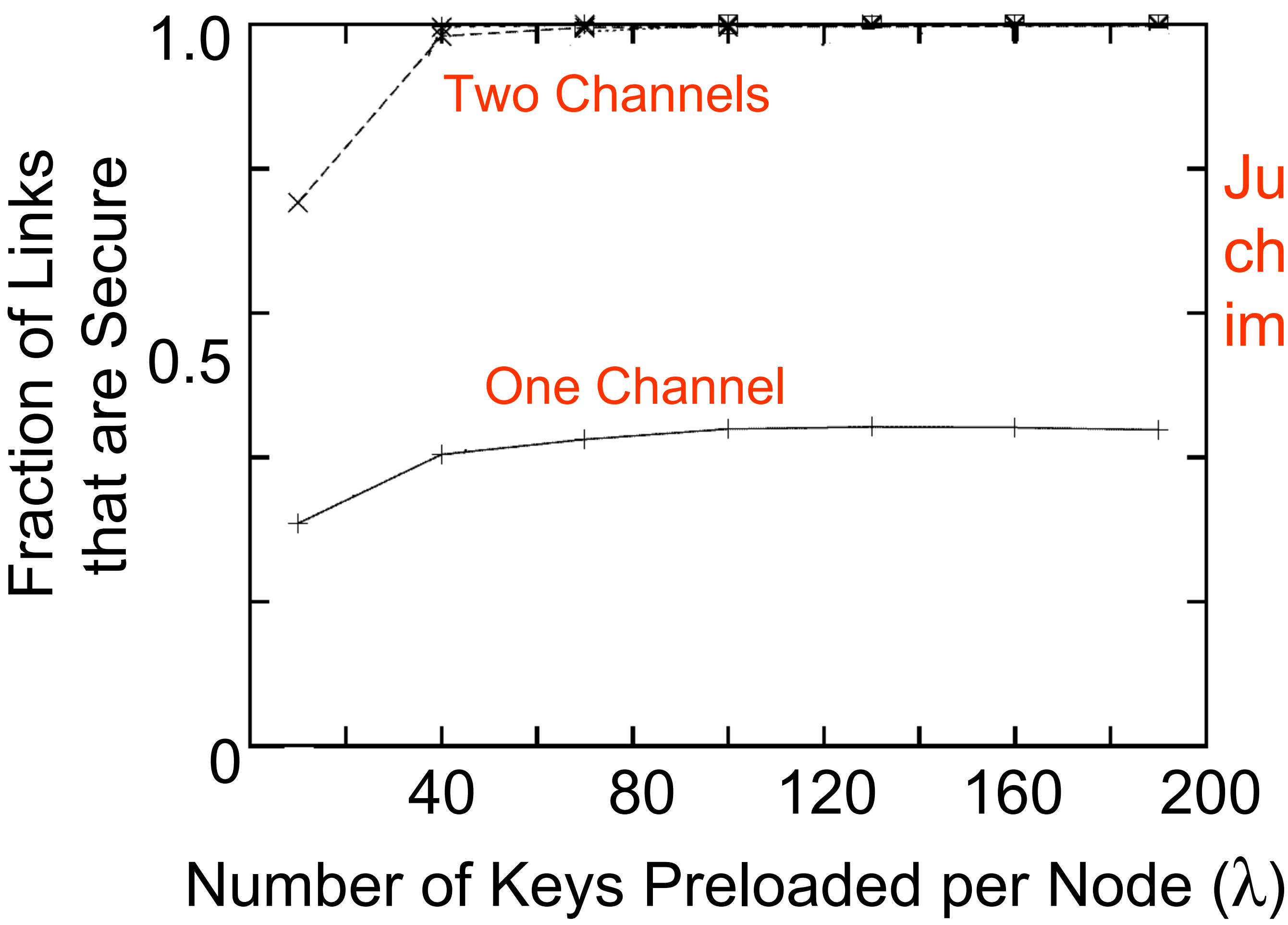
1. Find keys in $BF(k_{uv})$
2. Use keys from Step 1 to generate k_{uv}
3. Decrypt $E(RN, k_{uv})$
4. Generate $E(RN+1, k_{uv})$



Simulation Setup

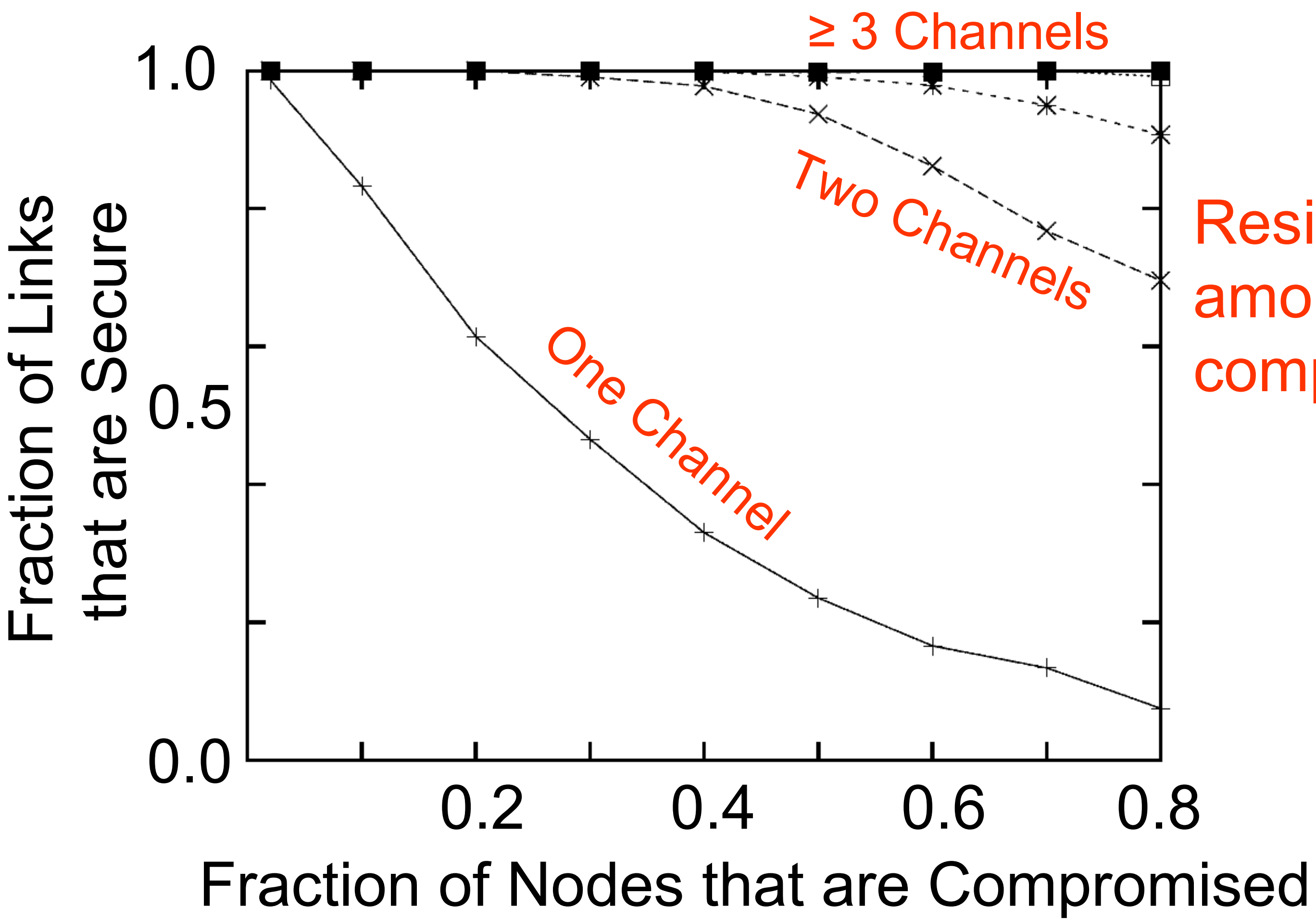
- Use *ns*-2 simulator
- 50 nodes
- Density of 10 expected one hop neighbors
- By default, 15 nodes are adversaries and collude in their key knowledge
- By default, λ is 100 keys/sensor

Results: The Advantage of Channel Diversity



Just one extra channel significantly improves security

Results: Resilience to Compromise



Resilient to large amount of node compromise

Summary

- Key distribution is important for sensor networks
- Many distinct solutions have been proposed
  - No “one size fits all” approach emerges
- Our work is the first to propose using channel diversity for key distribution
  - Results show significant security gains when even *one* extra channel is used

Thank You!

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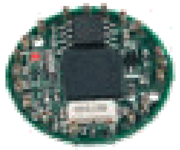
Wireless Channel Diversity

- Radios typically have multiple non-interfering, half-duplex channels
  - 802.11b: 3 channels
  - 802.11a: 12 channels
  - Zigbee (used on Telos motes): 16 channels
- At any given time, an interface can listen to at most one channel

Design Considerations

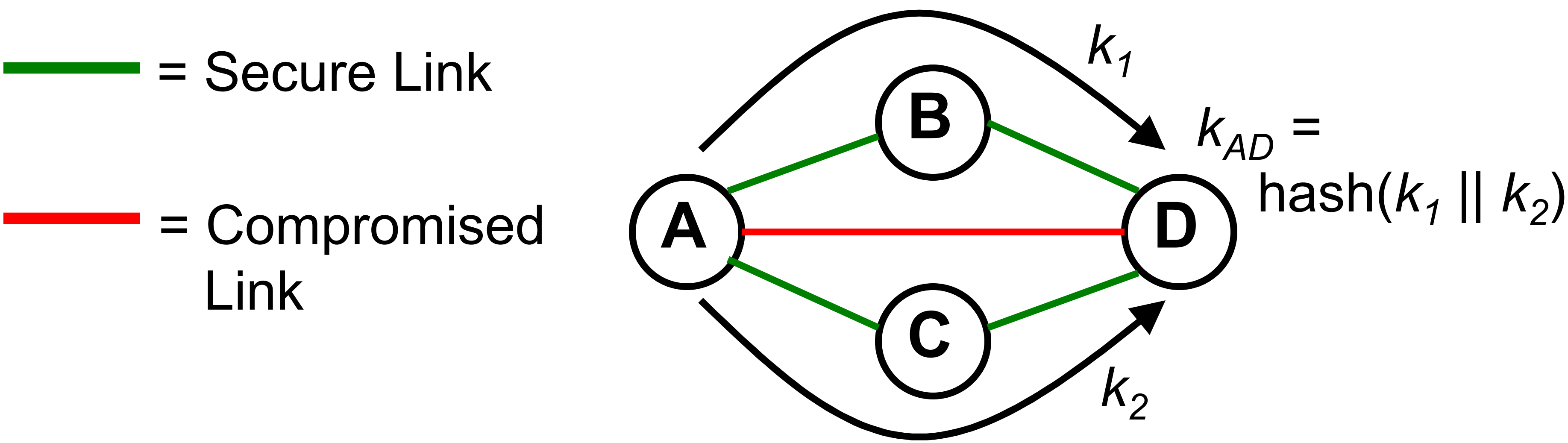
- Resource constrained
  - Energy, computation, memory, bitrate

- Large scale deployments
  - May need thousands (or more) of devices
- Topology may be uncontrolled
  - Specific device's location unknown in advance

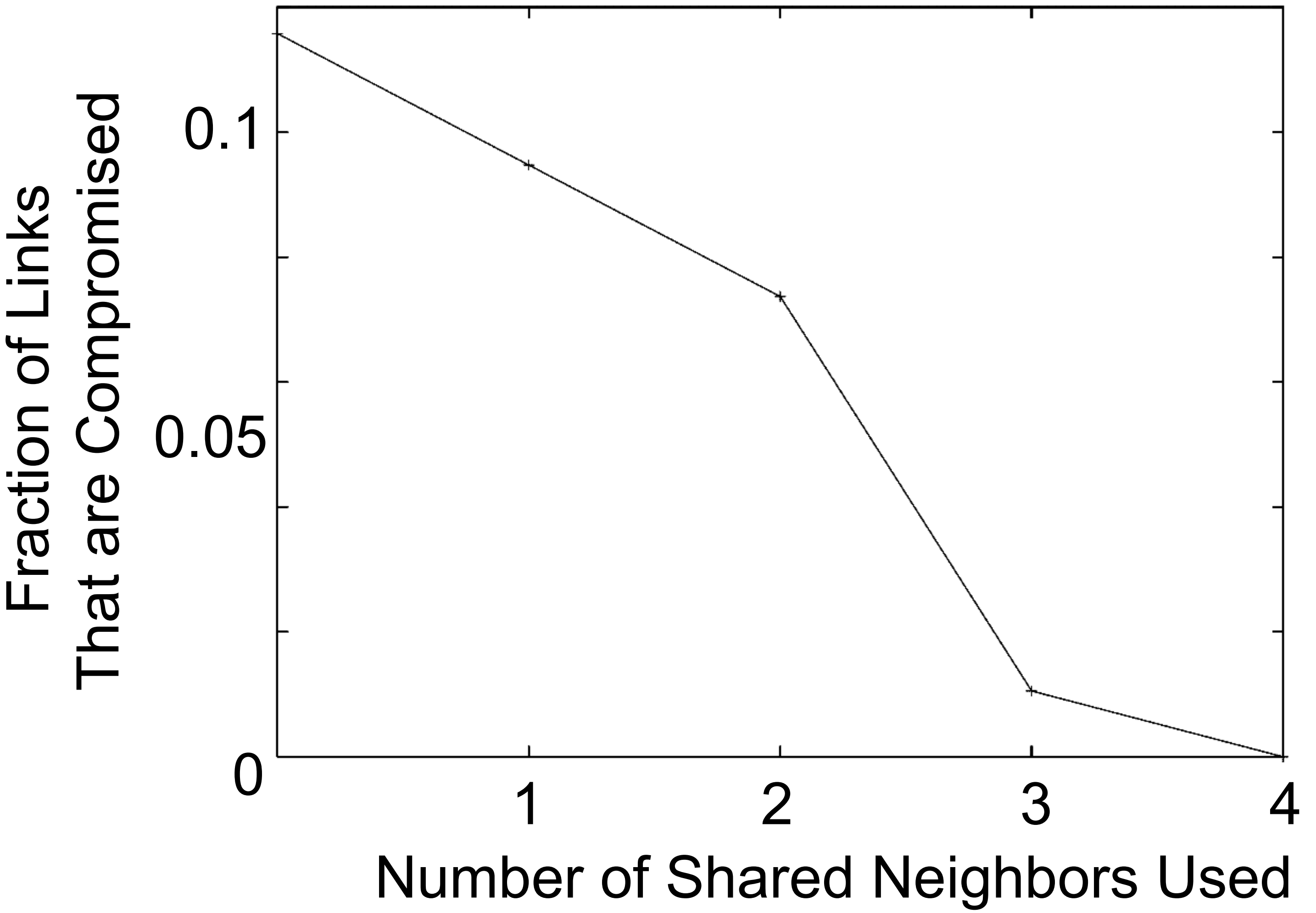


Using Path Diversity

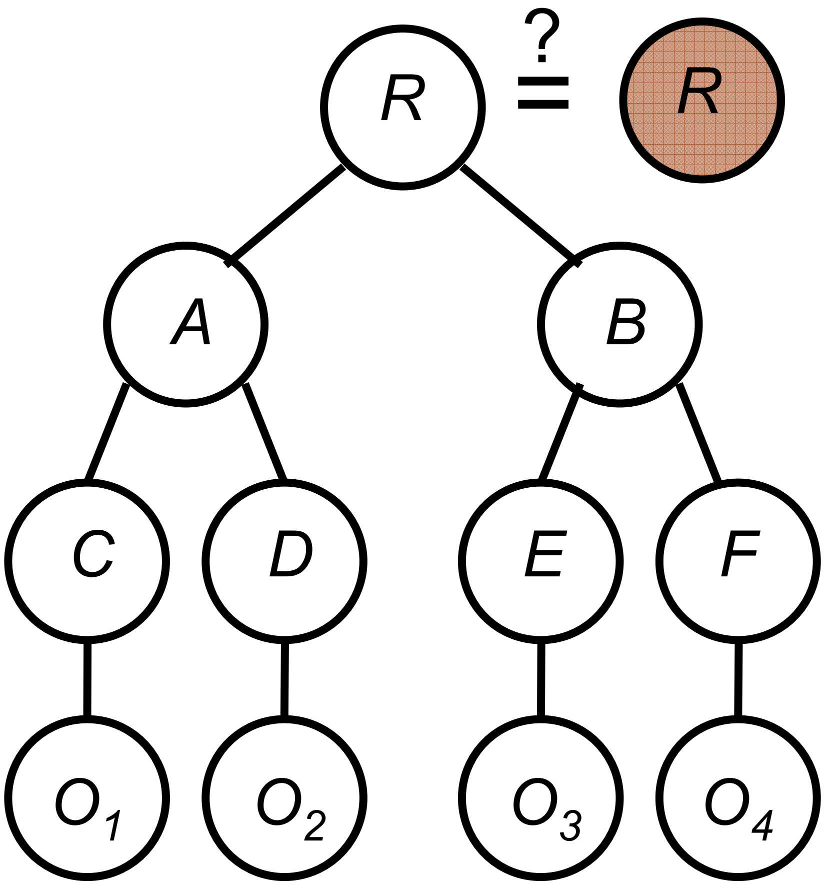
- Path diversity can be used to get a small number of compromised links to zero
- Similar to multipath reinforcement proposed elsewhere
  - Node disjoint paths needed to combat node compromise
  - Only link disjoint paths needed to combat eavesdroppers



Simulation Results for Example Topology



Merkle Tree Authentication



C = hash(O_1)

A = hash(C || D)

R = hash(A || B)

Each sensor given *R* and O(lg *N*) other hashes