Brno University Security Laboratory

Two Improvements of Random Key Predistribution for Wireless Sensor Networks

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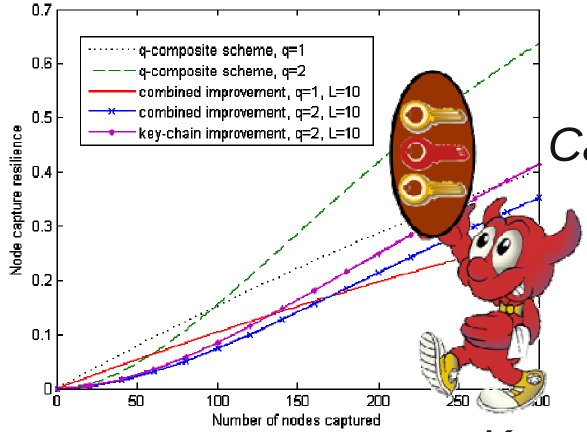
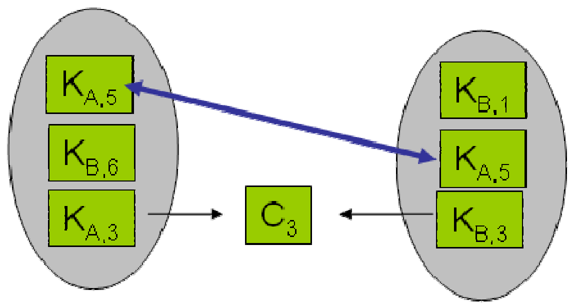
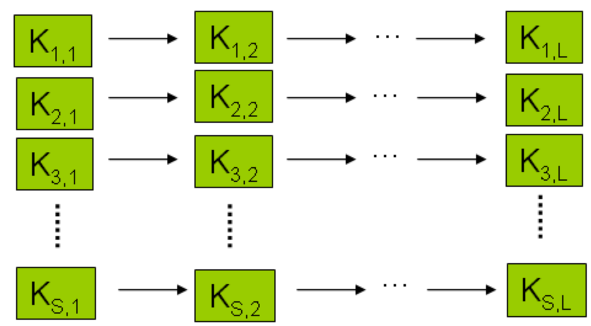


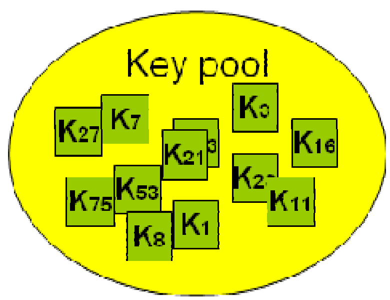
Capture resilience improvements

Collision key improvement

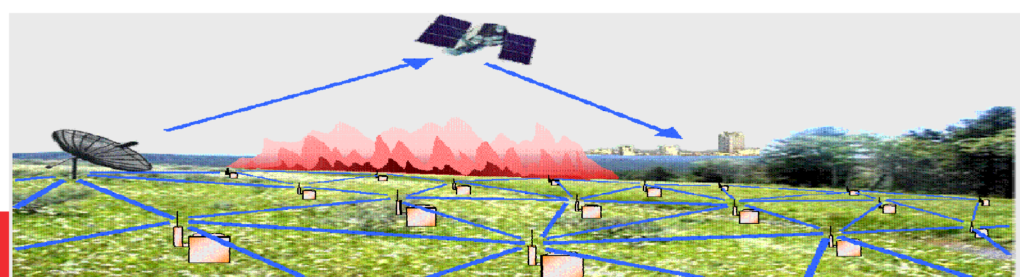


Key-chain improvement





Eschenauer & Gligor 2002
Chen et al. 2003

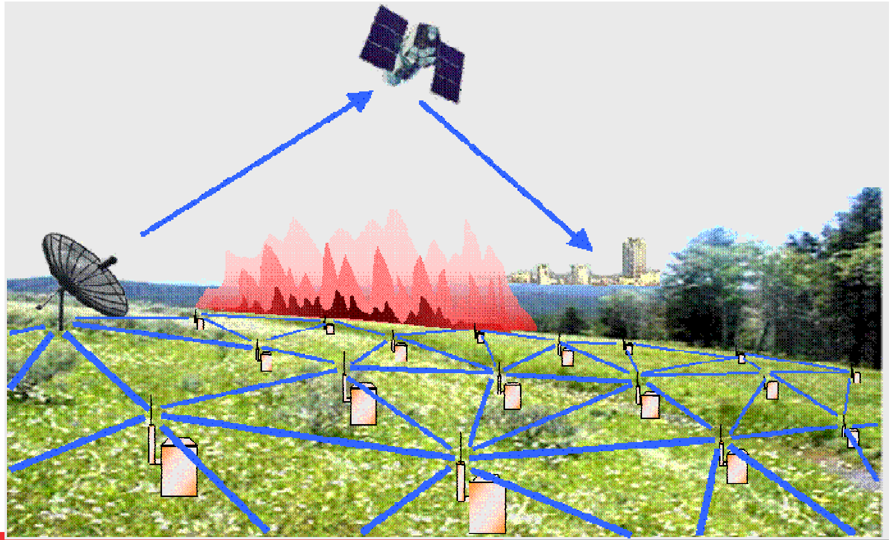


Wireless Sensor Network (WSN)

- Sensor nodes
  - environmental sensors
  - RF transceiver
  - battery powered
  - low computational and memory resources
  - 8-bit processor, 4KB RAM, < 128KB EEPROM
  - number of nodes: 10 – 10^5

- Topology
  - self-organized topology
  - ad-hoc position/neighbors – not known in advance
  - multi-hop communication

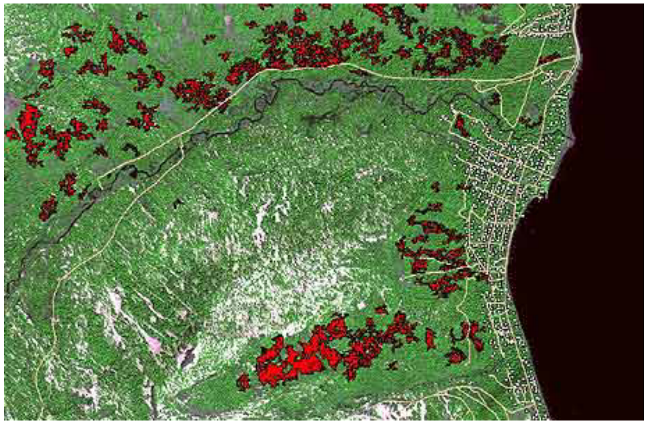
- Base station(s)
  - lap-top capabilities
  - almost unlimited energy resources



Applications of WSNs

Traffic control

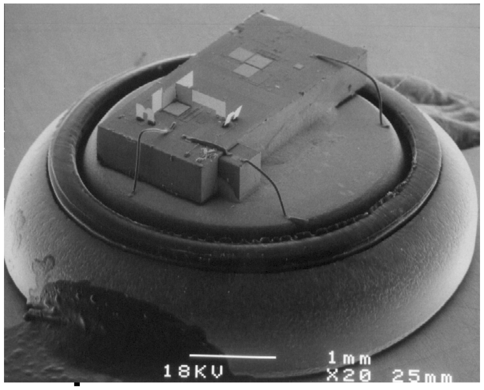
Medical information



Remote fire detection

Combat field control

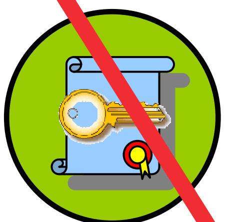
Some differences from standard networks



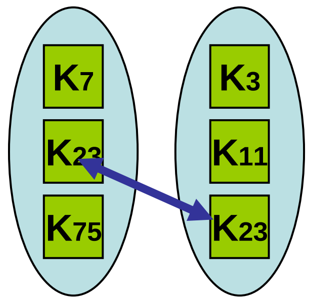
- Running on battery (limited resource)
  - days for personal network
  - years for large scale monitoring network
  - especially communication is energy-expensive
- Relatively limited computation power
  - powerful CPU possible, but energy demanding
- Nodes can be captured by an attacker
  - all secrets can be extracted from unprotected nodes
  - and returned back as malicious node

Many ways how to establish keys

~~Asymmetric cryptography~~

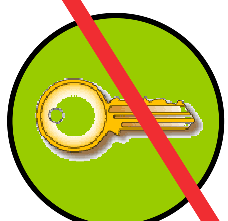


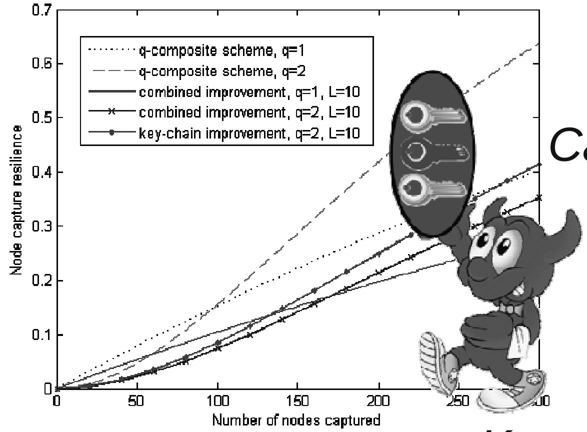
Random key pre-distribution



~~Trusted party~~

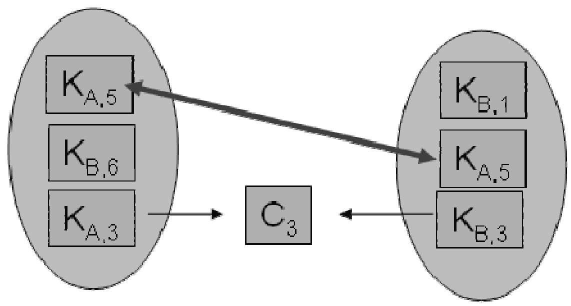
~~Master key, pairwise keys~~



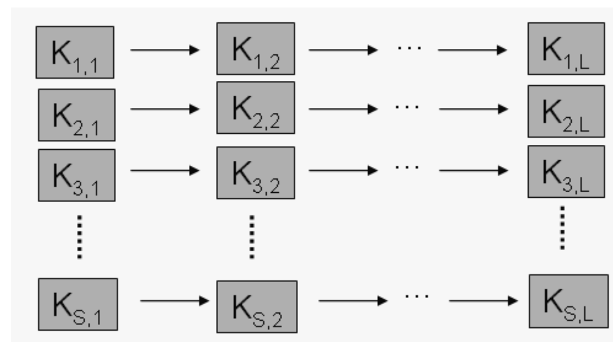


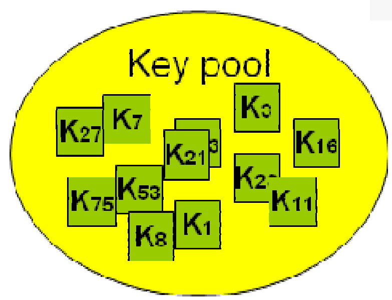
Capture resilience improvements

Collision key improvement



Key-chain improvement





Eschenauer & Gligor 2002
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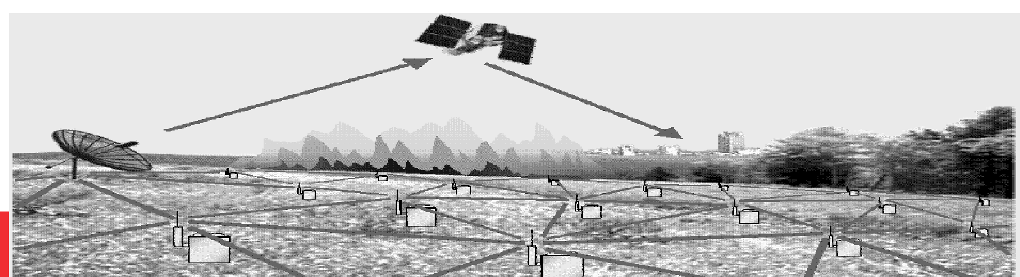
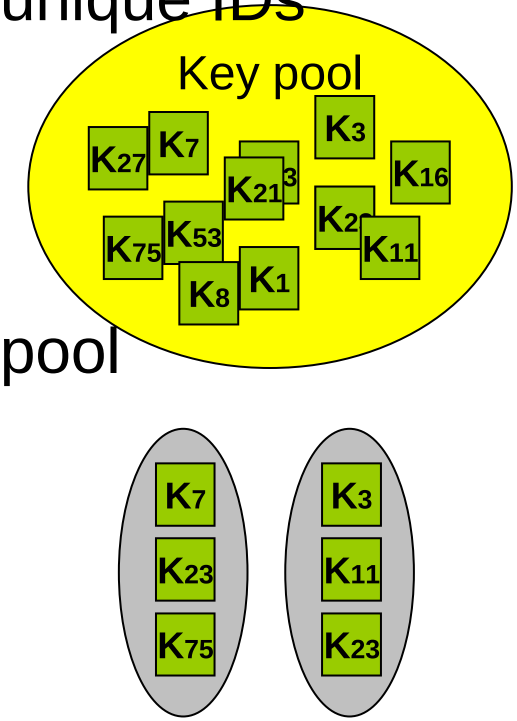
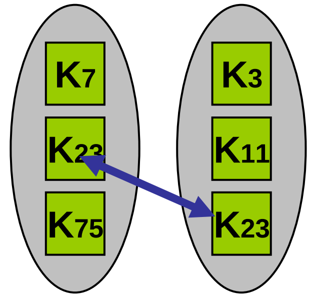


Random key pre-distribution

- *Eschenauer & Gligor 2002, Chen et al. 2003*
- Elegant idea with low memory requirements
  - based on birthday paradox
  - large pool of **S** cryptographic keys with unique IDs used
- For every node prior deployment:
  1. randomly select **m** keys from large key pool
  2. return selected keys back to pool
  3. proceed with next node



Random key pre-distribution (2)



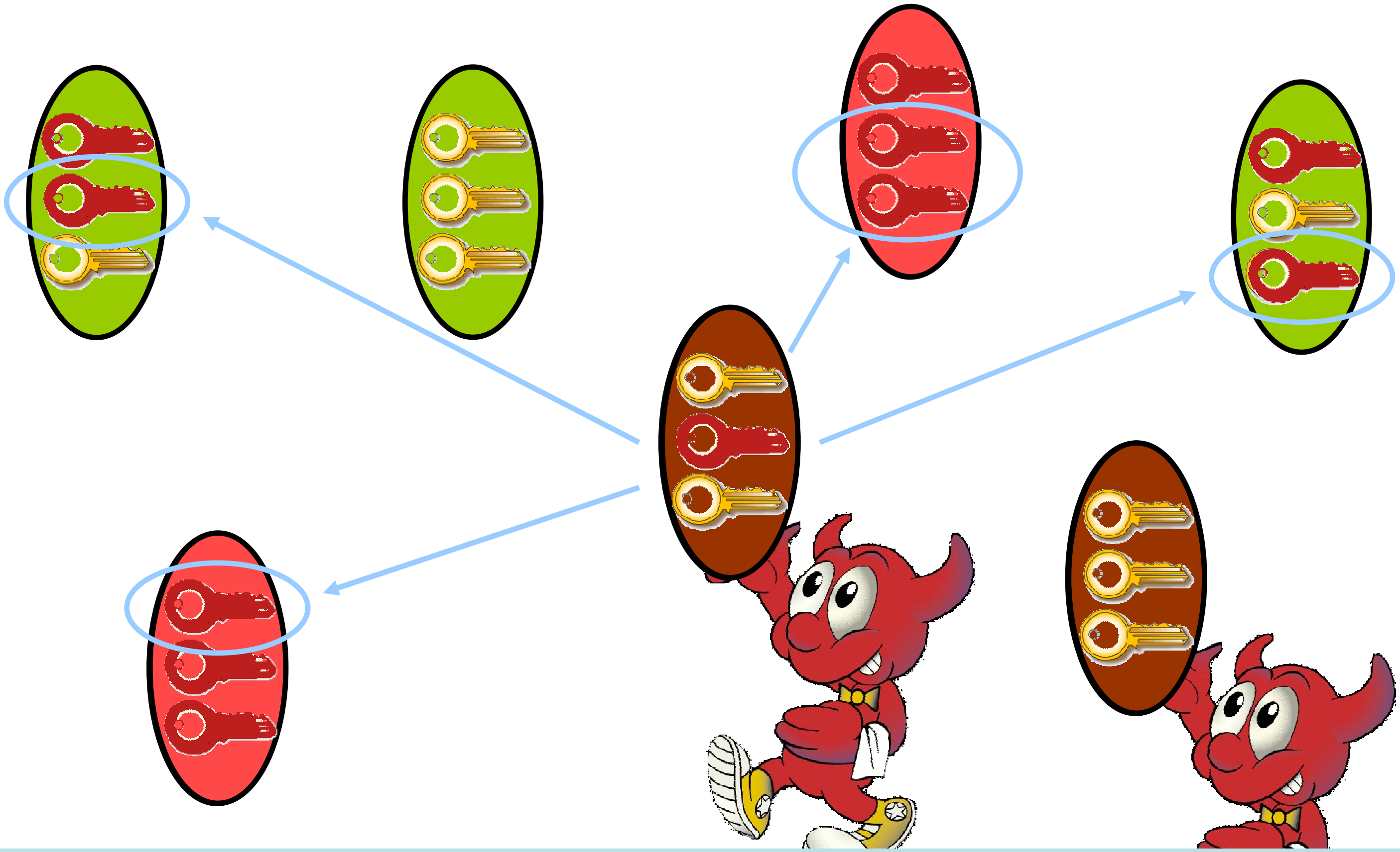
- During neighbour discovery:
  1. neighbours establish radio communication
  2. nodes iterate over their keyrings for shared key(s)
  3. if shared (by chance) key(s) are found, secure link is established

- What is key sharing probability?
  - e.g., 100 keys from 10000
  - 64% probability at least one key shared

- *q*-composite scheme – at least *q* keys shared

- Not all nodes can establish secure link
  - but sufficient connectivity probability can be set

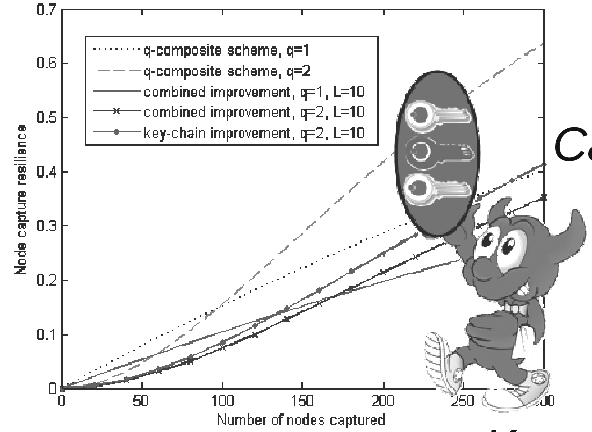
How random key pre-distribution fails



- Keys from uncaptured nodes compromised as well
- Good tradeoff between memory and security

Random key pre-distribution - parameters

- S … key pool size
- m … key ring size
  - node memory limitation
- P … probability that two nodes share at least q keys
  - dependent on m , key pool size S and q
  - we can calculate minimal P required so the network graph remains connected
- *ncr* … node capture resilience
  - assume attacker randomly captured n nodes
  - fraction of secured links between uncaptured nodes that are compromised using keys from captured nodes



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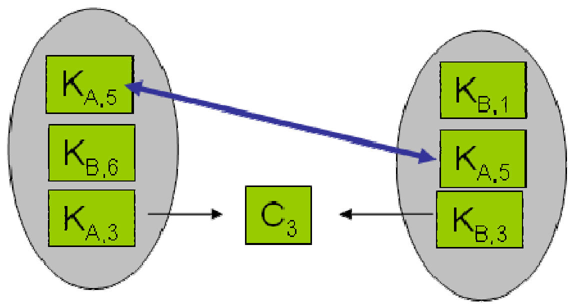

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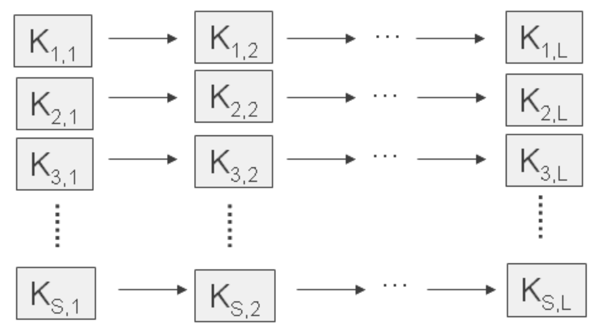

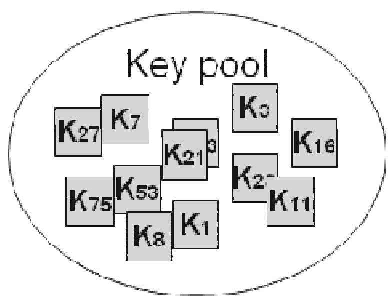

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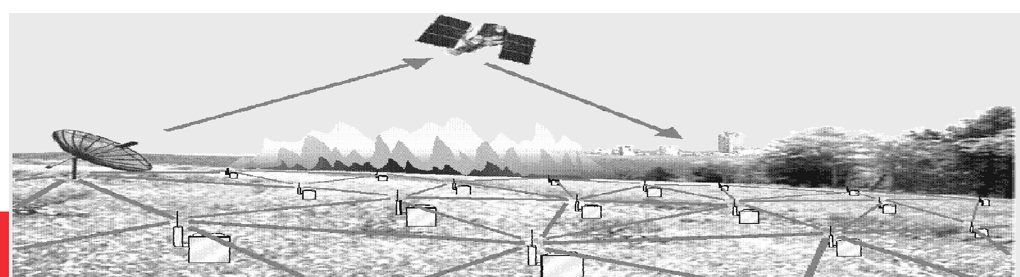
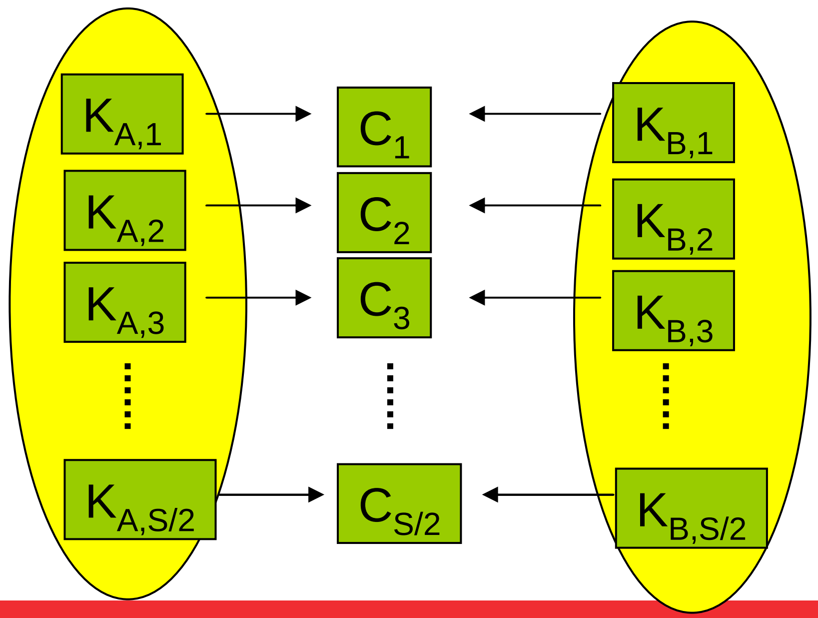


Collision key improvement

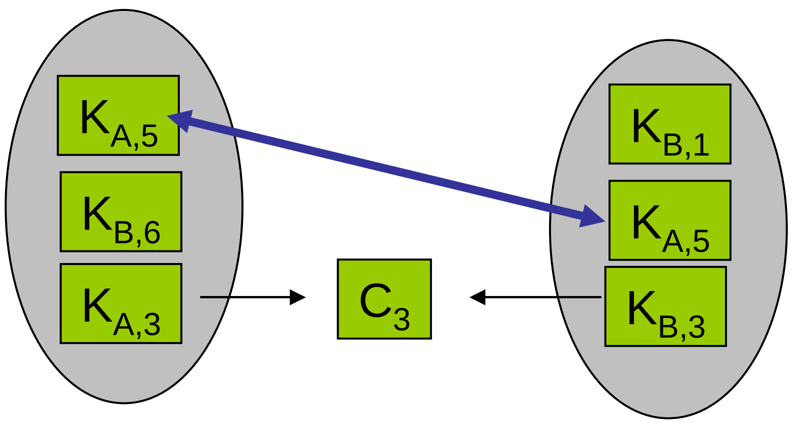
- Key pool created using ***S/2*** related key pairs K_A, K_B
- **$C = H(K_A) = H(K_B)$**
- H is cryptographically secure hash function with a limited input/output length, e.g. 80 bits
- Such collisions can be found with moderate computational power



Collision key improvement (2)

- For every node prior deployment:
  1. randomly select ***m*** keys (***no related key pair*** is allowed)
  2. return selected keys to a key pool
  3. proceed with next node
- During neighbor discovery:
  - beside normal keys, also collision keys can be shared
  - probability of link key establishment is higher

$C_3 = H(K_{A,3}) = H(K_{B,3})$

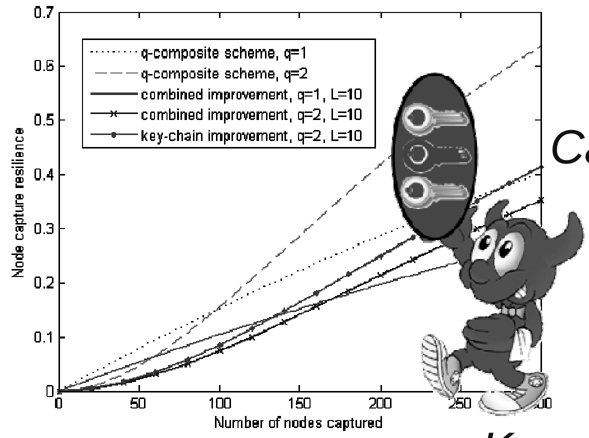


Key pool construction

- To find an n-bit collision approx. $2^{n/2}$ hash operations are needed
- To find c^2 collisions, approx. $c * 2^{n/2}$ hash operations are needed

- Goal: to find 80-bit collisions in SHA-2
- Method: Van Oorschot and Wiener's parallel collision search
  - time-memory trade-off approach
- Hash operations computed: approx. 2^{47}
- Over 2^{12} collisions found - enough for key pool

- Aggregate time spent on single 3GHz core: 19 000 hours
- We have used BOINC framework and approx. 1000 cores
  - Final time: approx. 19 hours
  - GPUs could bring significant speed up



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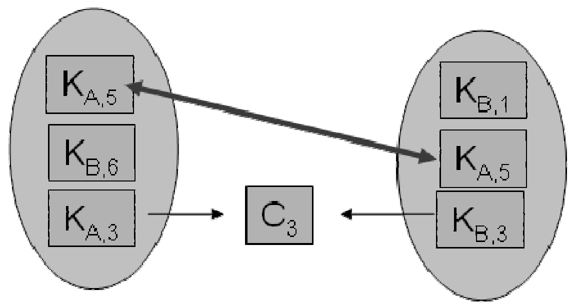

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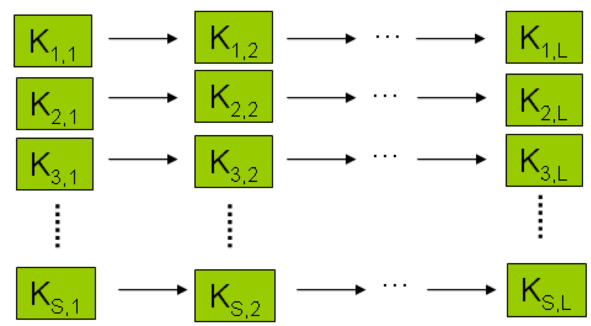

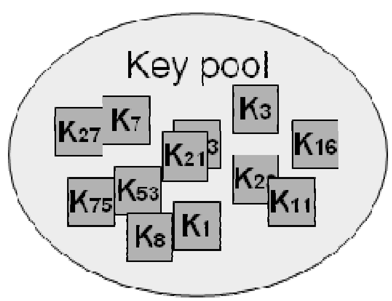

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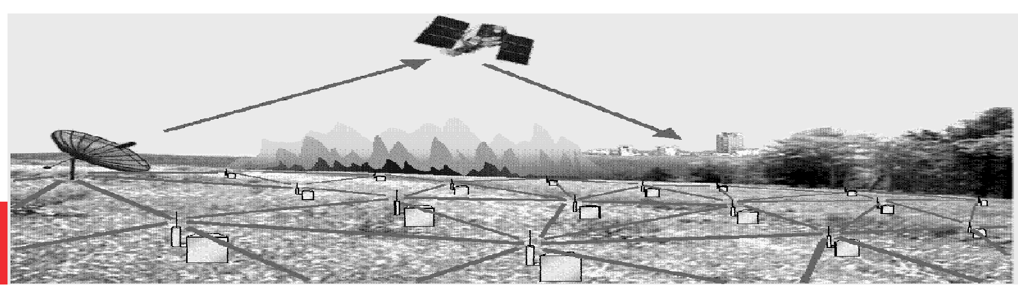
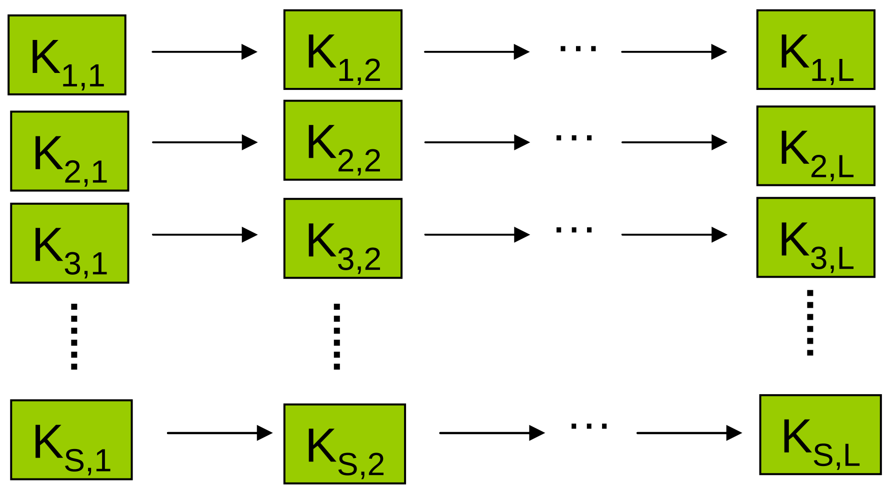


Key-chain improvement

- Key pool created using ***S*** hash chains of a length ***L***



- For every node prior deployment:
  1. randomly select **m** hash chains
  2. randomly select single key from every selected chain
  3. return selected chains (keys) back to pool
  4. proceed with next node

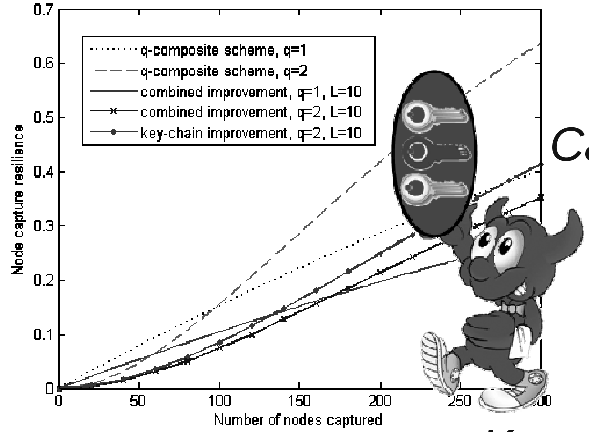
Key-chain improvement (2)

- During neighbor discovery:
  - two nodes can calculate shared key if they posses keys from the same hash chain (with index *i*)

$$K_{i,1} \rightarrow K_{i,2} \rightarrow K_{i,3} \rightarrow K_{i,4} \rightarrow K_{i,5} \rightarrow K_{i,6}$$

- Probability of key establishment remains as in original design
- Node capture resilience improves
  - attacker may capture keys that are further in the chain
  - slightly better than in collision key improvement

- Hash chains for key predistribution used also in *Ren et al. 2006*
  - different key ring construction, keyed hash function used



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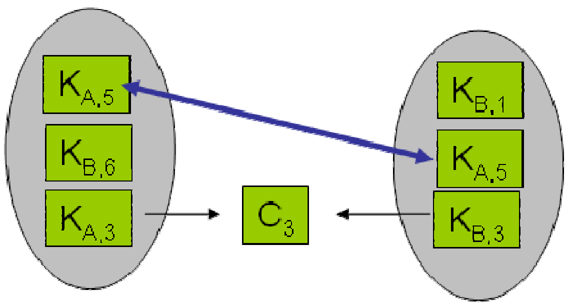

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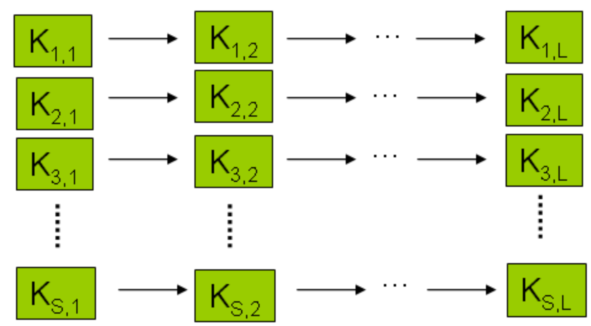

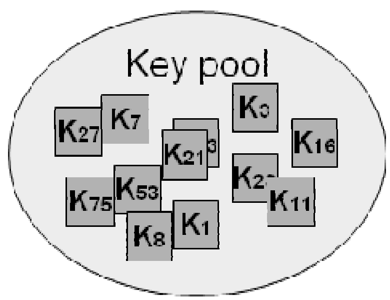

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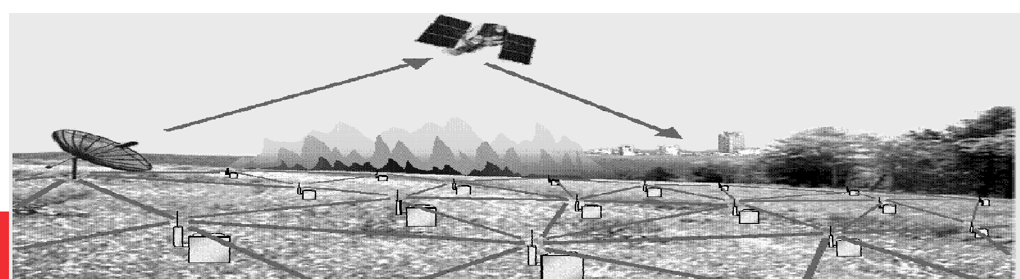
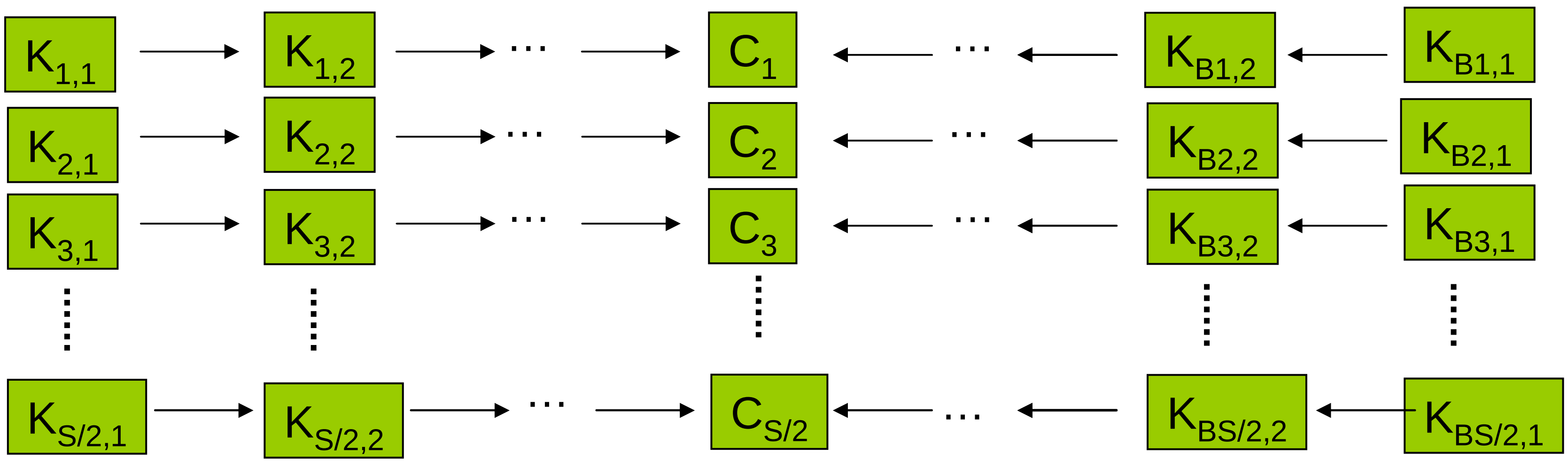
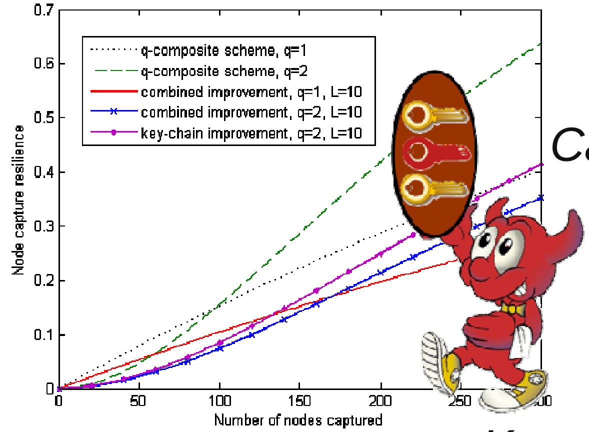


Combination of improvements

- Both improvements can be easily combined
- Collision search produces colliding hash chains





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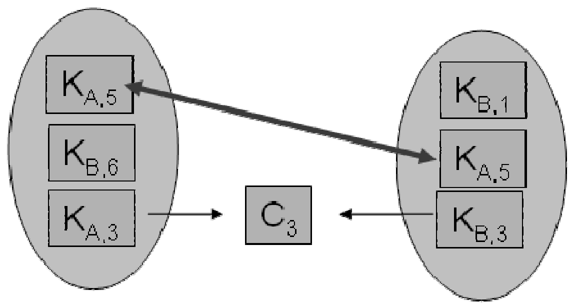

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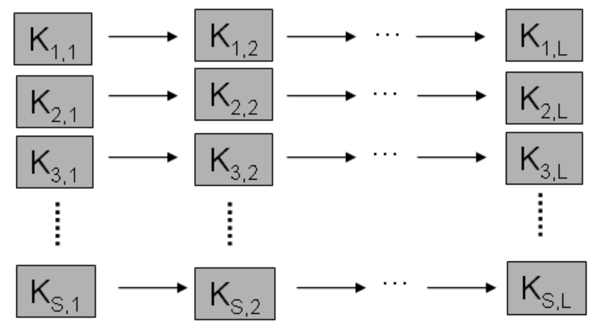

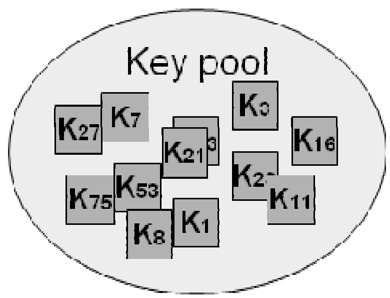

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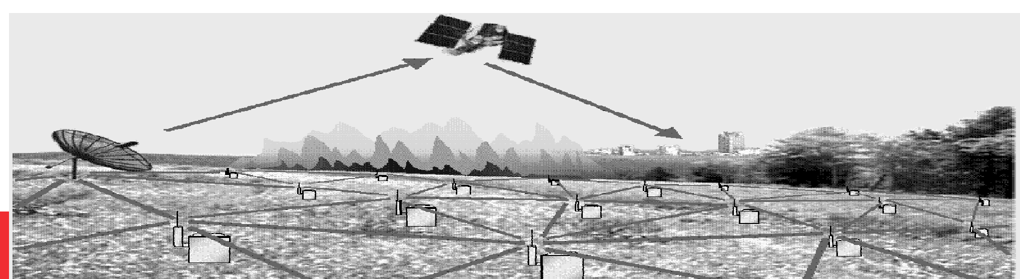
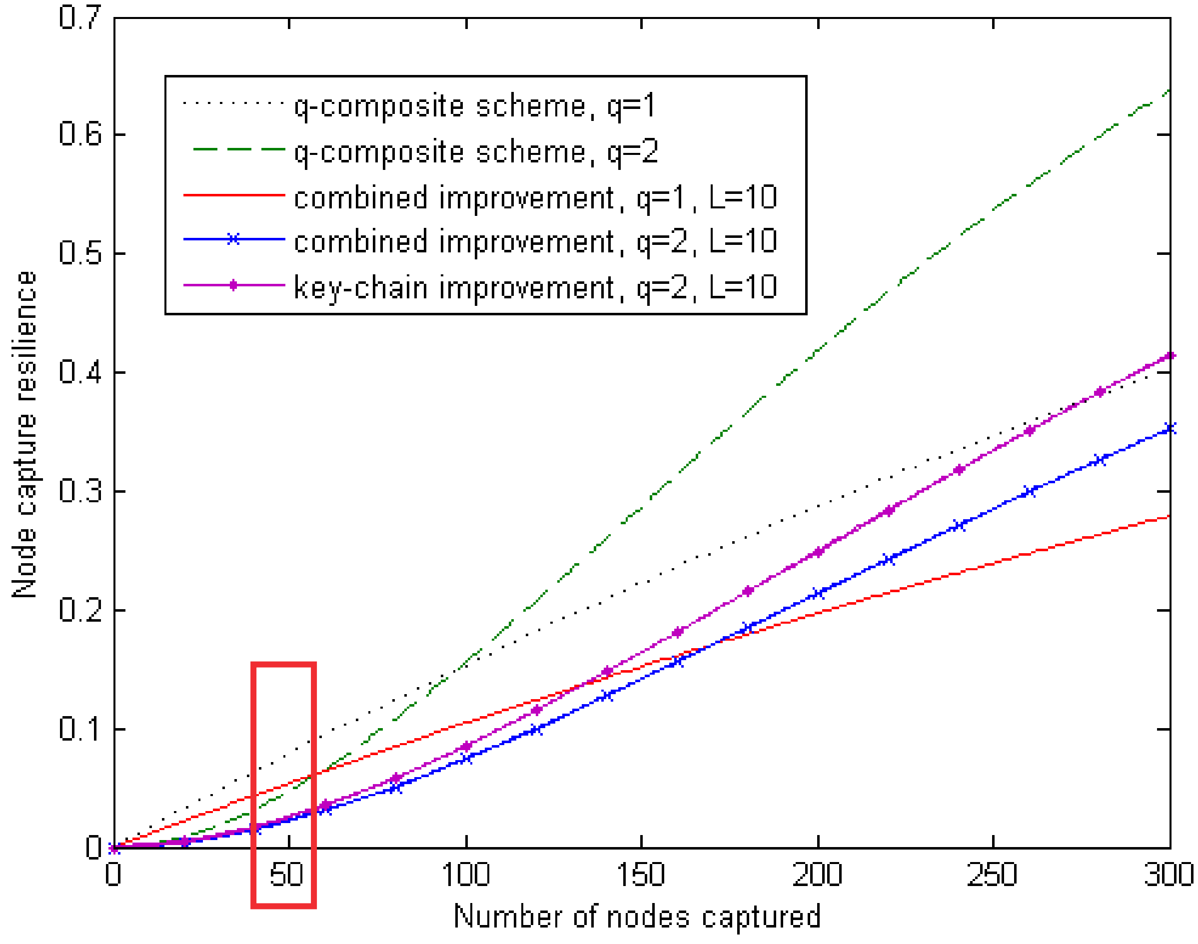


Combination of improvements - evaluation

- *P = 0.33, m = 200*

- *For q = 2 and n = 50*
- *q-composite: ncr = 4.7%*
- *Collision key: ncr = 2.7%*
- *Key-chain: ncr = 2.5%*
- *Combined: ncr = 2.2%*

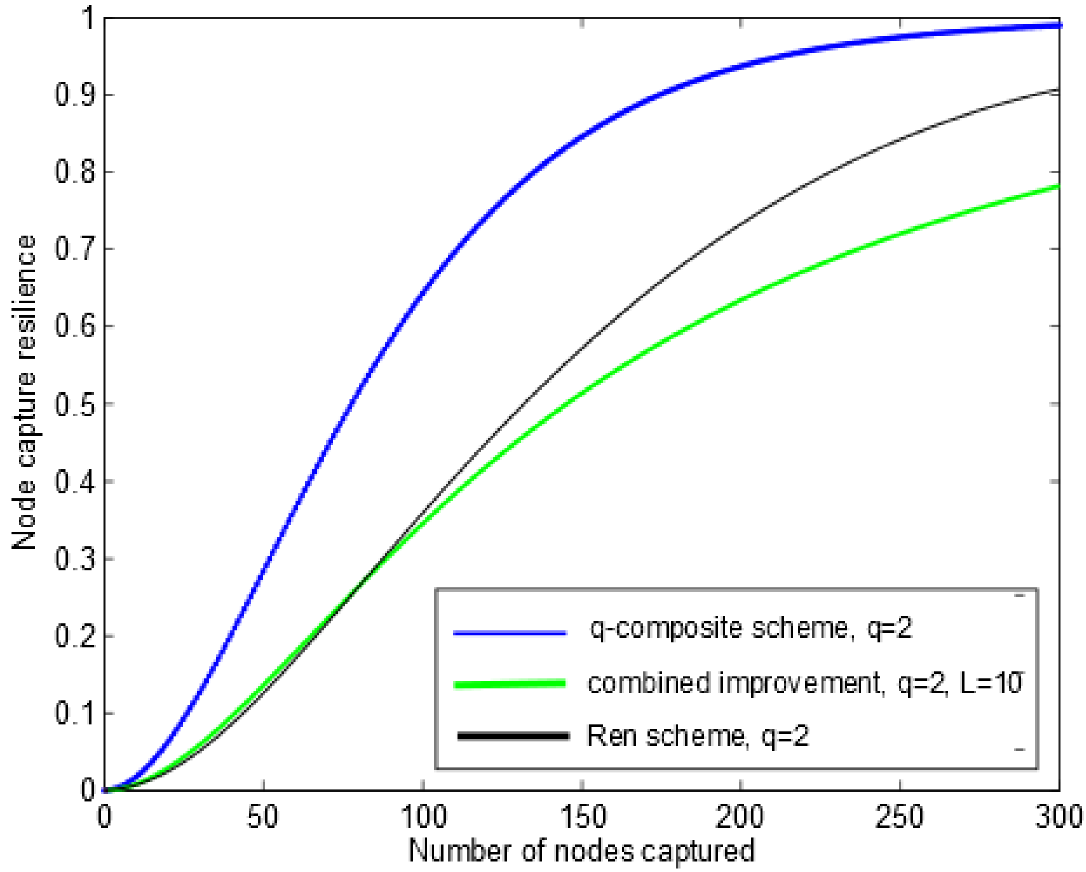


Comparison with Ren et al.

- *Ren et al. 2006*, random key predistribution based on keyed hash chains

- *P = 0.5, m = 90*
- Ren scheme setting
  - R_0 = 10, R_1=79,
  - L=1 000, K=100 000

- Combined improvement outperforms Ren scheme if number of nodes captured is high



Summary

- Eschenauer & Gligor 2002 is one of core schemes
  - many existing schemes extends or builds on it
- Two improvements of this core scheme proposed
  - security performance of extensions also influenced
- Hash collisions can be used in favor of security
  - limited length collisions with moderate CPU resources
- Unkeyed hash chain instead of single key used
- Both improvements combinable
- Results verified both analytically and with network simulator

Thank you for your attention.

Any questions?

References

[Eschenauer & Gligor 2002] Eschenauer, L., Gligor, V.D.: A key-management scheme for distributed sensor networks. In: 9th ACM conference on Computer and Communications Security, CCS'02, pp. 41-47. ACM, New York (2002)

[Chan et al. 2003] Chan, H., Perrig, A., Song, D.: Random key predistribution schemes for sensor networks. In: Symposium on Security and Privacy, 2003, pp. 197-213. IEEE, (2003)

[van Oorschot & Wiener 1999] van Oorschot, P.C., Wiener, M.J.: Parallel collision search with cryptanalytic applications. Journal of Cryptology, 12(1):1-28, (1999)

[Ren et al. 2006] Ren, K., Zeng, K., Lou, W.: A new approach for random key pre-distribution in large-scale wireless sensor networks. Wireless Communications and Mobile Computing, 6(3):307-318, (2006)

Key-chain length

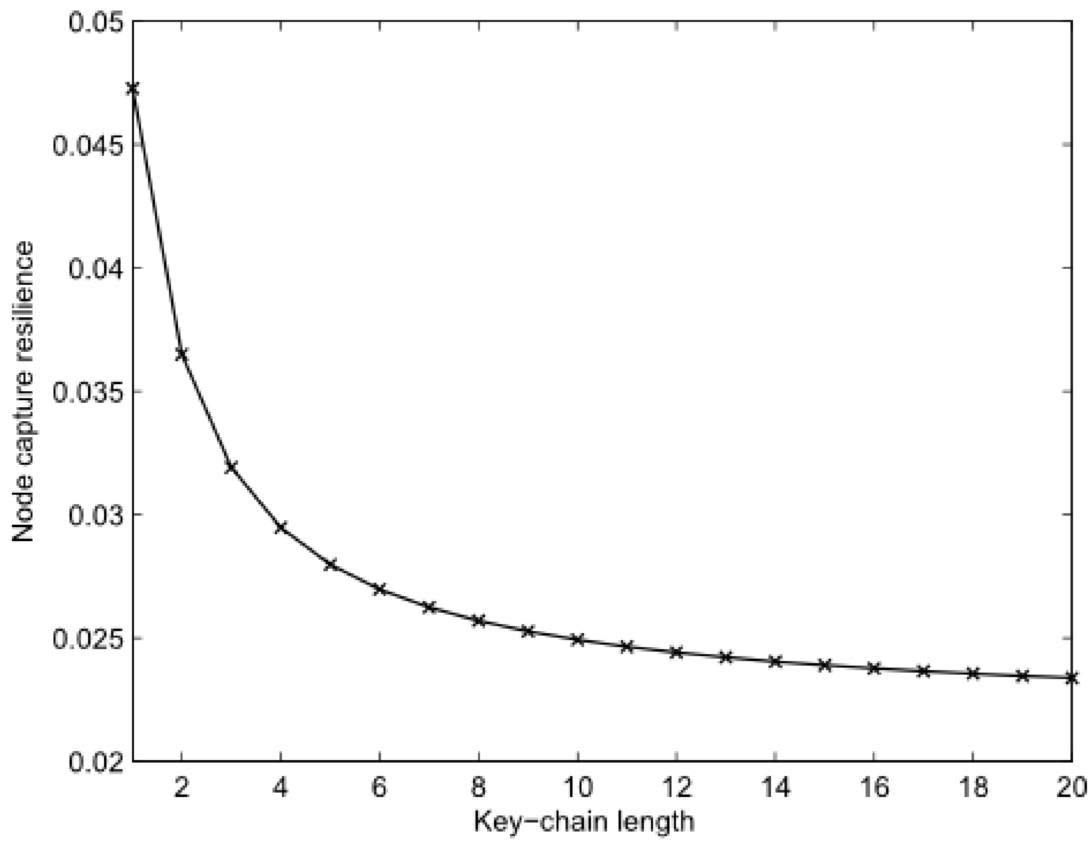
- The longer the chain the better the resilience, but …
- Effective chain le…
  - number of di…
    assigned to s…
  - dependent o…
- Practical value i…

P=0.33

m=200

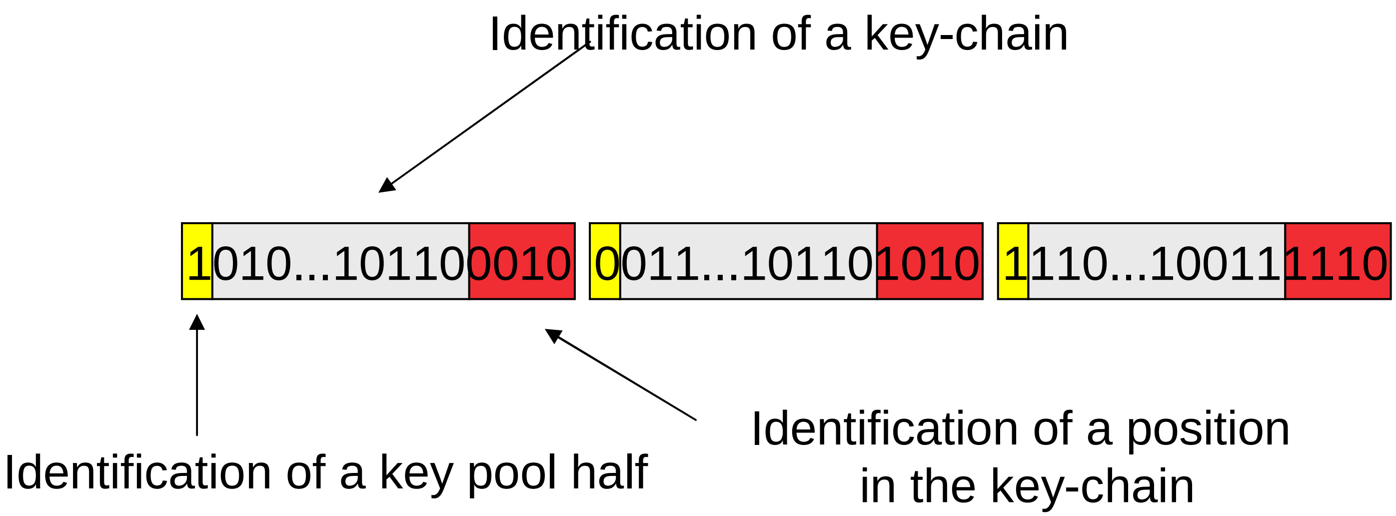
q=2

n=50



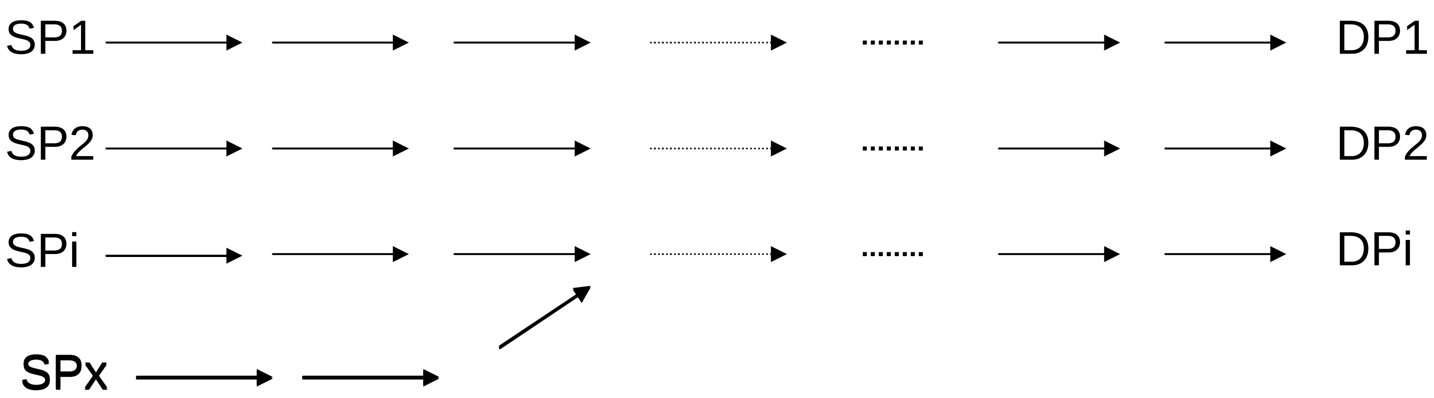
Seed based predistribution

- Generate pseudorandom stream using neighbor ID and pseudorandom number generator



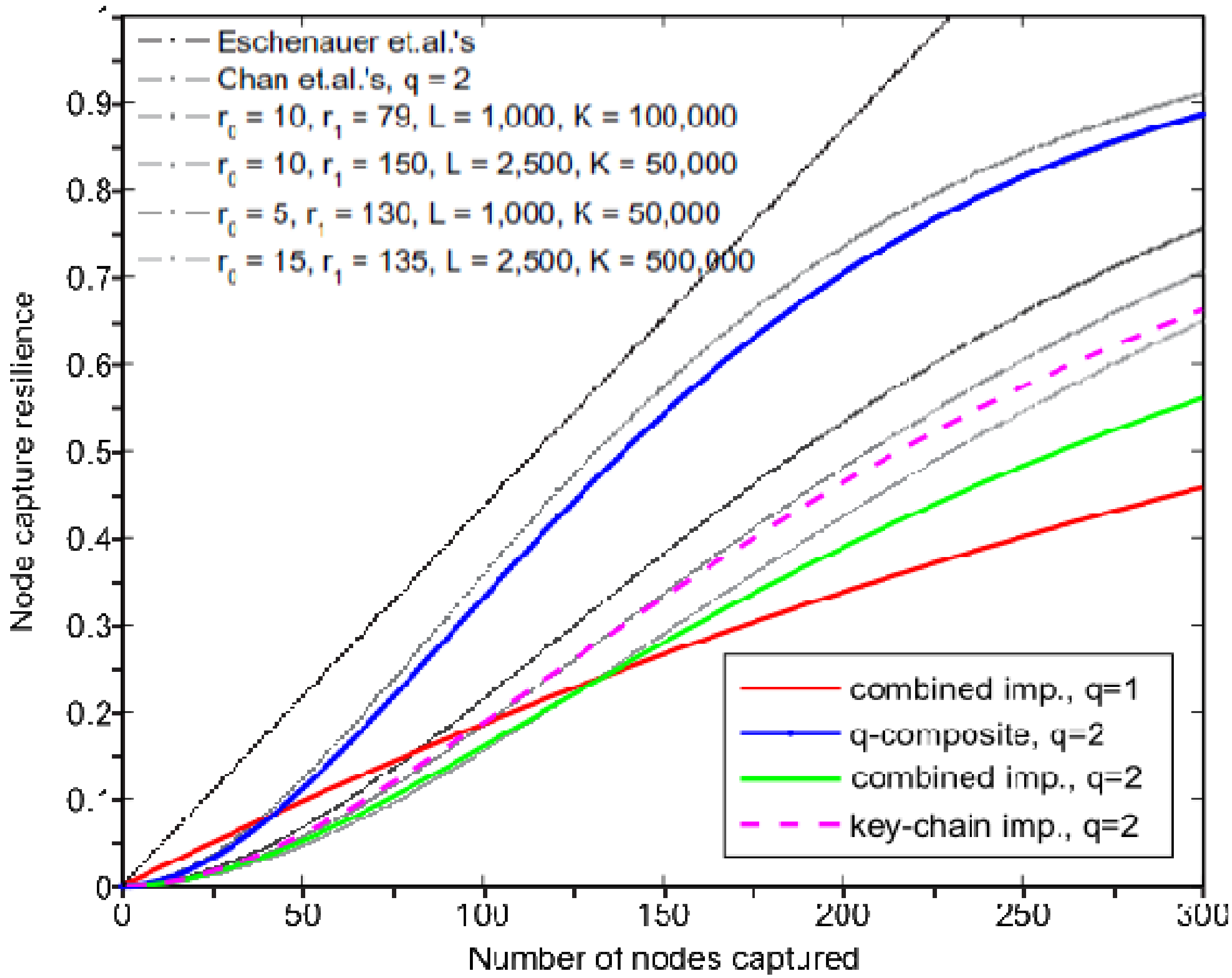
Key pool construction

- Van Oorschot and Wiener's parallel collision search
  - time-memory trade-off approach
- SP – random 80-bit starting point
- DP – 80-bit distinguished point, fixed number of leading zeros
- (SPi,DPi) pairs stored in memory



Comparison with Ren et al.

- *P = 0.5, m = 161*



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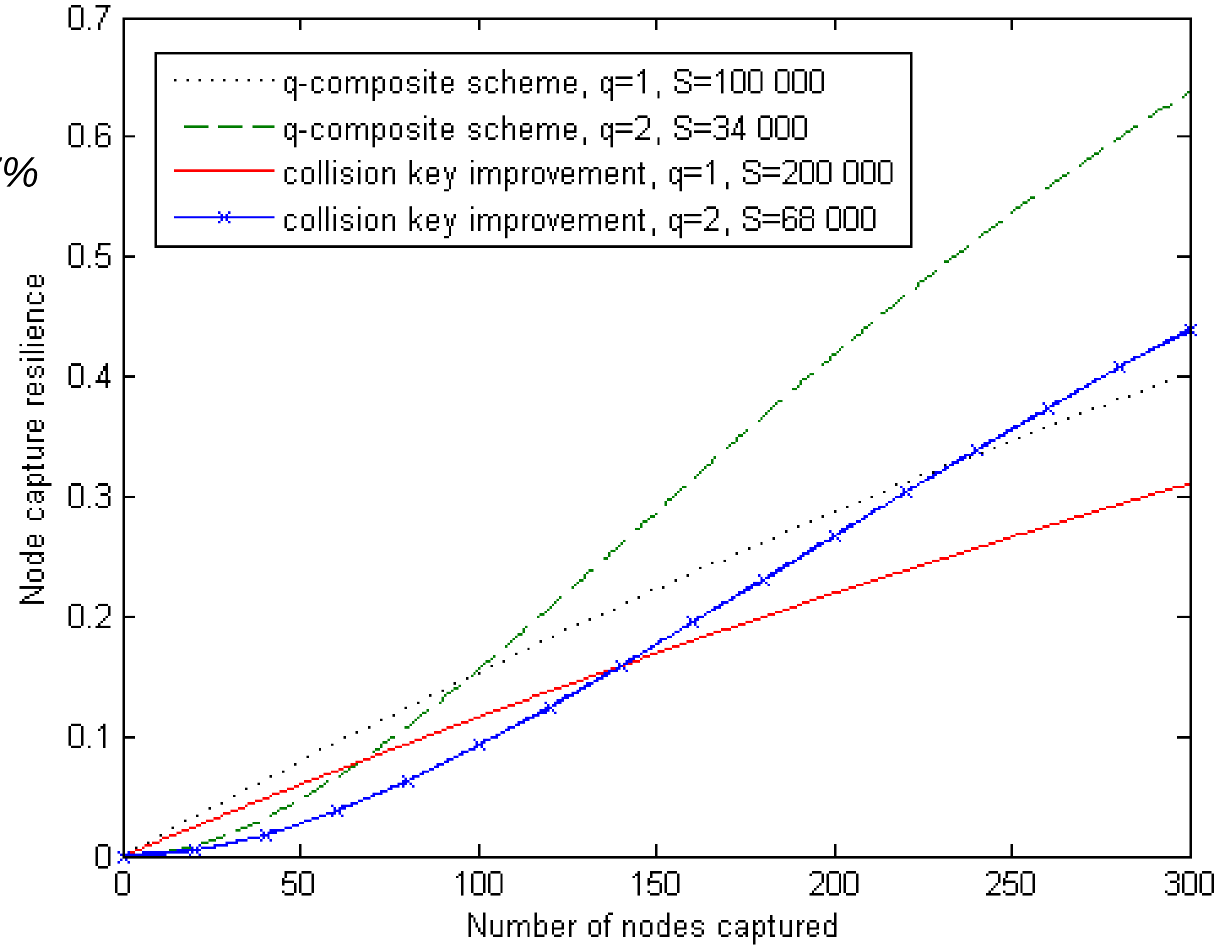
- *P = 0.33, m = 200*

- *For q = 2 and n = 50*
- *q-composite ncr = 4.7%*
- *Improved ncr = 2.7%*



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- *Improved ncr = 2.5%*