

Security and Privacy in Unattended Sensor Networks (or How to Cope with a Mobile Adversary)



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Current Research

<http://sprout.ics.uci.edu>

- ▶ **Privacy-Preserving Techniques**
 - ▶ PSI, PPIT and Secret Handshakes
 - ▶ Location Privacy in MANETs/VANETs
 - ▶ Private Querying in WSNs
- ▶ **Security of Personal and Embedded Devices**
 - ▶ **Unattended WSNs**
 - ▶ Security for Embedded Devices
 - ▶ Distance Bounding
 - ▶ Usable Security (wireless device pairing, personal RFIDs)
- ▶ **Internet Security**
 - ▶ Privacy-agile Name Service
 - ▶ Phishing and Typo-squatting Countermeasures
 - ▶ DTN security

Security Research in General

▶ **Reactive**

1. Identify existing security problem and adversary
2. Suggest fixes

OR:

1. Spot problems in existing solutions
2. Expose them



▶ **Proactive: a 4-step process...**



Step 1: Invent *plausible* and *scary* new adversary



Step 2: If needed, postulate new exciting (and *viable*) habitat for scary new adversary



Step 3: Develop *credible, effective and practical* weapons against adversary



Step 4: Market your fairy tale

Roadmap

- ▶ Introduction & Motivation
 - ▶ Naïve defense strategies
 - ▶ Cryptography?
 - ▶ Distributed Self-healing
 - ▶ (if time permits) Mobility & Attestation
 - ▶ Conclusions
-

Wireless Sensor Networks



Many real, alleged and imagined applications



- ▶ **Networking**
 - ▶ Sensor-to-sink communication (opt. sink-to-sensors)
 - ▶ **Collection method**
 - ▶ Periodic collection
 - or
 - ▶ Event driven
 - or
 - ▶ Query based = on-demand
 - ▶ **Online Sink**
 - ▶ Real-time off-loading of data
-

Lots of Prior Work

Sensor Network Security



Lots of Prior Work

Sensor Network Security

Security & Crypto
Researchers

Networking
Researchers

Database
Researchers

That's me



Recent WSN Security Topics

- ▶ Key management
 - ▶ Secure routing
 - ▶ Secure broadcasting/multicasting
 - ▶ Secure querying
 - ▶ Secure data aggregation / statistics
 - ▶ Efficient cryptographic primitives
 - ▶ Various attacks counter-measures, e.g. denial-of-message, cloning, sleep deprivation...
-

Prior Work on WSN Security

- Almost all prior work (pre-2008) assumed that the WSN is supervised by a TTP/Collector/Sink/Base-Station/etc.
 - Is this always so?
 - What if WSN is unattended most of the time?
-

Unattended Wireless Sensor Network (UWSN)

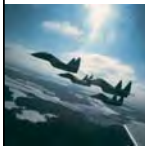


- ▶ Hostile deployment environment

- ▶ No constantly present sink
 - ▶ Itinerant, visits periodically



- ▶ Periodic data sensing
 - ▶ Nodes might retain data for a long time
 - ▶ Data is valuable



- ▶ Nodes are mostly left on their own
 - ▶ Adversary roams around with impunity
 - ▶ Adversary has **lots of time**

- ▶ **Challenge: Data Security**

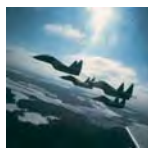
Examples



- ▶ WSN deployed in a recalcitrant country to monitor nuclear activity



- ▶ Underground WSN monitoring sound and vibration produced by troop movements or border crossings



- ▶ Anti-poaching WSN in a national park tracking/recording firearm discharge

UWSN Mobile Adversary (1)

Adv defined by: goal + operation + visibility

Goal:

- Targeted
 - Search-and-erase
 - Search-and-replace
- Non-targeted
 - Curious
 - Polluter
 - Eraser

Operation:

- Reactive
- Proactive

Visibility:

- Stealthy
- Visible

UWSN Mobile Adversary (2)

- ▶ Well-informed
 - ▶ Knows network topology and network defense strategy
- ▶ Mobile
 - ▶ Migrates between sets of nodes between sink visits
- ▶ Erratic
 - ▶ Unpredictable and possibly untraceable movement
- ▶ Data-centric
 - ▶ No interference with sensing or network operation
- ▶ Powerful but not omnipotent
 - ▶ Compromises up to a fixed # (k out of n) of nodes

UWSN Mobile Adversary (3)

- ▶ Previously considered adversaries capable of corrupting fixed number of nodes (k) overall
 - ▶ Solutions focused on detection
 - ▶ Once detected, on-line sink can mitigate attacks
 - ▶ e.g., exclude compromised nodes
- Our adversary is ***MOBILE***
 - Roams and compromises different subsets of sensors
 - Given enough time, can subvert entire WSN
 - Sink is off-line: real-time detection does not help
 - Adv can reach its goal and leave with impunity (remain undetected)

17 ▶

Assumptions

- ▶ Scheduled (per round) data sensing/collection
 - ▶ Max v rounds between sink visits
 - ▶ Adv round = UWSN round
- ▶ Adv compromises at most k (out of n) nodes per round
 - ▶ Compromised nodes not necessarily contiguous
 - ▶ Reads all storage/memory
 - ▶ Listens to all incoming and outgoing communication
- ▶ Adv knows what data to target and when it was sensed
 - ▶ Receives external signal at collection time
 - ▶ Target node identity + collection round
 - ▶ Possibly knows the target value
- ▶ UWSN knows nothing... → Equal protection for all data

This might sound familiar

**Cryptographic Mobile Adversary
in Proactive Threshold Cryptography [1]**

- ▶ Proactive Cryptography: Decryption and Signatures (e.g., RSA, DSA)
- ▶ Adversary wants to learn a shared global secret (or wants to sign/decrypt with it)
 - ▶ Corrupts at most k out of n nodes per round
 - ▶ Moves atomically at end of each round
- ▶ Our setting is different
 - ▶ No global secret
 - ▶ Meager resources
 - ▶ New solutions required

[1] Ostrovsky & Yung, How to Withstand Mobile Virus Attacks, [PODC 1991](#)

- ▶ And lots of related literature since then...



END PART 1

Stealthy Search-and-Erase Adv



IEEE Percom'08

What if sensors have no crypto capability?

- ▶ **Ultra-cheap sensors**
 - ▶ No cryptographic abilities
 - ▶ Can only try to hide data location
- ▶ **Data Migration strategies**
 - ▶ Move Once
 - ▶ Keep Moving
- ▶ **Adv Goal: Search-and-erase**
 - ▶ Looks for target data in compromised sensors
- ▶ **Adv strategy:**
 - ▶ Lazy
 - ▶ Frantic
 - ▶ Smart

Move Once

- ▶ Data off-loaded to a random peer recipient
 - ▶ Kept there for subsequent rounds ($<v$), until sink visit
- ▶ Adversary wins in at most $\left\lceil \frac{n}{k} \right\rceil$ rounds
 - ▶ Round 0
 - ▶ Learns originating node (data not there any longer)
 - ▶ Round i
 - ▶ Move to next set
- ▶ At most $\left\lceil \frac{n}{k} \right\rceil$ rounds to find and erase

Keep Moving

Algorithm 1: KEEP-MOVING

```

/* start round 0 */
all nodes sense their values
each node exchanges data with others
0 A learns  $s_0$  and  $x$ 
/* end round 0 */
SET  $z = \min(v, \frac{n}{k})$ 
SET found=FALSE
for ( $r \leftarrow 1$  to  $z$ ) and (not found) do
    /* start round r */
    1 select  $C_r$  /* new set of nodes to compromise */
    2 compromise  $C_r$  and release  $C_{r-1}$ 
    3 if ( $x$  found on some  $s_i \in C_r$ ) then
    3.1     delete  $x$ 
    3.2     SET found=TRUE
    all nodes sense their values
    each node exchanges data with others
    4 if ( $x$  received by some  $s_i \in C_r$ ) then
    4.1     delete  $x$ 
    4.2     SET found=TRUE
    /* end round r */
    
```

Adv looks for target data in the new set of compromised nodes → 3

Adv looks for target data in the messages received by corrupted nodes → 4

← Adv learns target data at round 0

← Nodes exchange messages

- ▶ Adv has two chances per round
 - ▶ Before data exchange
 - ▶ After data exchange

Keep Moving – Lazy

- ▶ Exploit data being always on the move
- ▶ Two chances at round 1; one chance each new round
- ▶ Prob. data survives to v rounds

$$P_L(v) = P_1 \cdot P_2^{v-1}$$

$$P_1 = \frac{k}{n} + \left(1 - \frac{k}{n}\right) \frac{k}{n} = \left(1 - \frac{k}{n}\right)^2 \quad P_2 = 1 - \frac{k}{n}$$

Keep Moving – Frantic

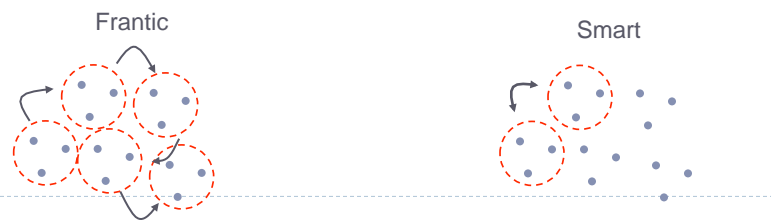
- ▶ Select a new random k -set at each round
- ▶ Two chances per round
- ▶ Probability that data survives v rounds:

$$P_F(v) = P_1 \cdot P_2^{v-1} \cdot P_3^{v-1}$$

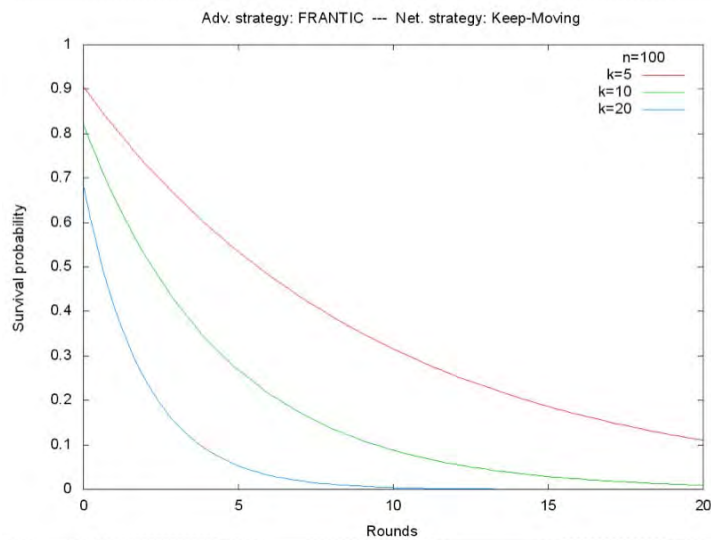
$$P_1 = \frac{k}{n} + \left(1 - \frac{k}{n}\right) \frac{k}{n} = \left(1 - \frac{k}{n}\right)^2 \quad P_2 = 1 - \frac{k}{n} \quad P_3 = 1 - \frac{k}{n-k}$$

Keep Moving – Smart

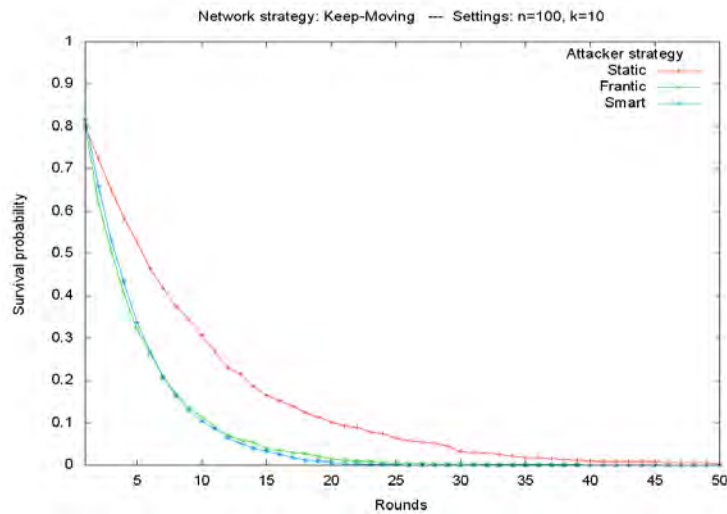
- ▶ Moves between two fixed (non-overlapping) set of nodes
 - ▶ No matter what adversarial strategy, data recipient node is always chosen according to an uniform distribution
 - ▶ Same survival probability!



Results



Keep Moving



Replication

- ▶ Each sensor produces R copies of each data
 - ▶ Data survives as long as one copy survives
- ▶ $X_{i,j} = 1$ if replica i survives up to round j

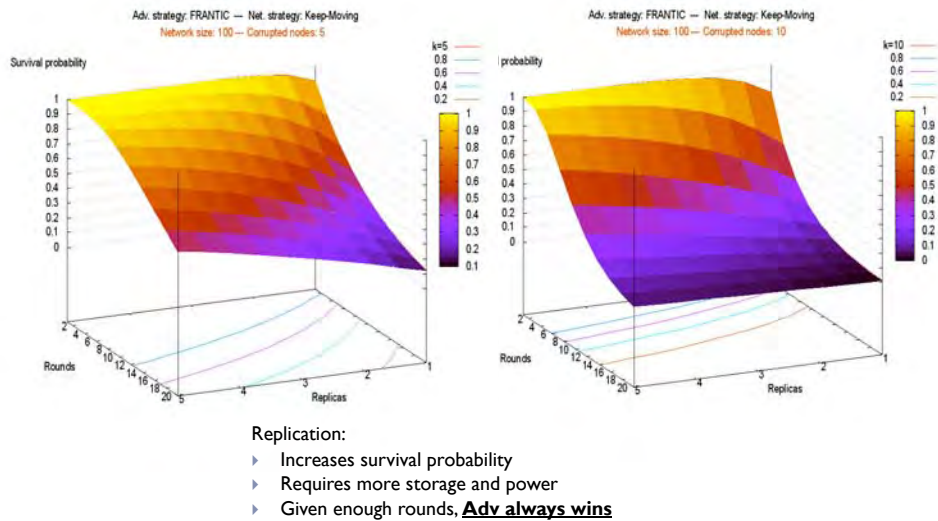
$$Pr[X_{1,j} = 1] = P_1 \cdot P_2^{j-1} \cdot P_3^{j-1}$$

$$\begin{aligned} \overline{P}_R^v &= Pr[X_{1,v} = 0 \wedge \dots \wedge X_{R,v} = 0] = Pr[X_{1,v} = 0]^R = \\ &= (1 - Pr[X_{1,v} = 1])^R = (1 - P_1 \cdot P_2^{v-1} \cdot P_3^{v-1})^R \end{aligned}$$

- ▶ Prob. that information survives:

$$P_R^v = 1 - \overline{P}_R^v = 1 - (1 - P_1 \cdot P_2^{v-1} \cdot P_3^{v-1})^R$$

Simulation Results



Encryption

- ▶ hides data contents and origin
 - ▶ Adv can not decrypt
- ↓
- ▶ Adv can't identify data to erase
 - ▶ Public Key vs. Symmetric key
 - ▶ Randomized Encryption
 - ▶ Distinct random value involved in each encryption operation
 - ▶ Given two ciphertexts encrypted under the same key, infeasible to determine whether two corresponding plaintexts equal

Public Key Encryption

- ▶ Each node knows sink's public key PK_S
- ▶ Data sensed by s_i at round r stored as:

$$E_i^r = E(\underbrace{PK_S, r, s_i, d_i^r, R, etc.}_{\text{plaintext}})$$

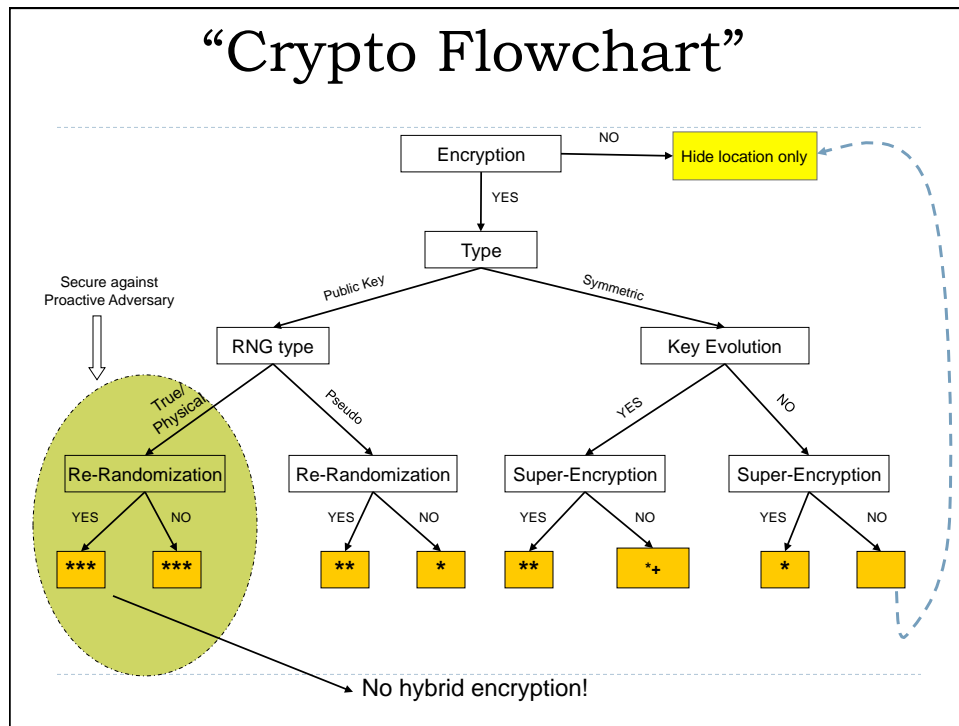
- ▶ Adv can only brute-force guessing plaintext
 - ▶ Good quality randomness makes plaintext guessing infeasible
 - ▶ But, where does R come from?
 - ▶ Dirty little secret...
-

Symmetric Encryption

- ▶ Each s_i pre-shares k_i with sink
- ▶ Data sensed by s_i at round r stored as:

$$E_i^r = E'(K_i, r, s_i, d_i^r, etc.)$$

- ▶ No security...
 - ▶ Adv breaks in, learns k_i and decrypts E_i^r
-



● ● ●

END PART 2

Question:

- ▶ How to recover from mobile adversary compromise without per sensor TRNGs?
-

POSH:
Proactive co-Operative Self-Healing
in Unattended Wireless Sensor
Networks

IEEE SRDS'08

Motivation

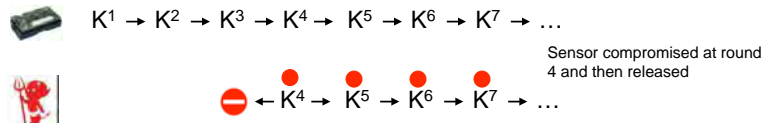
- ▶ Curious ADV: aims to learn sensor-collected data
- ▶ Encryption does not really help
 - ▶ Symmetric keys exposed with node compromise
 - ▶ With public key encryption, ADV can GUESS plaintext
 - ▶ Randomized public key encryption helps but only with a TRNG
 - ▶ TRNG neither available nor foreseeable on ultra-cheap sensors
- ▶ Can we protect category (1) and (3) data?

Sensor-collected data:

- (1) Before Compromise
- (2) During Compromise
- (3) After compromise

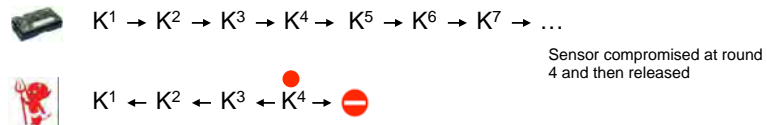
Forward Secrecy

- ▶ Even if ADV learns current key, cannot derive PREVIOUS round keys
- ▶ Per-round key evolution
 - ▶ At each round, key is evolved using a one-way function
 - ▶ $K^{t+1} = H(K^t)$
- ▶ But, after compromise, ADV can mimic key evolution process



Backward Secrecy

- ▶ Even if ADV learns the current key, cannot derive FUTURE round keys
- ▶ Based on assisted per-round key evolution
 - ▶ Requires online TTP or secure hw (same as distributed TTP)
- ▶ Not suitable for UWSNs
 - ▶ Our sink is offline



POSH: Main Idea

- Forward secrecy through key evolution
- Backward secrecy via sensor cooperation
 - Initial observation:
 - A sensor can securely generate a key unknown to ADV, if it obtains at least one contribution from a non-compromised peer sensor

Network Assumptions 1/2

▶ Periodic data collection

- ▶ Time divided in fixed collection rounds
- ▶ Each (of n) sensors collects single data unit per round

▶ Unattended Operation

- ▶ Itinerant sink periodically visits to collect data
- ▶ v – maximum # collection rounds between successive sink visits

▶ Communication

- ▶ UWSN always connected
 - ▶ Any two sensors can communicate either directly or via peers
-

Network Assumptions 2/2

▶ Storage

- ▶ Each sensor has enough storage for $O(v)$ data

▶ Cryptographic Capabilities

- ▶ Cryptographic hashing, e.g., SHA-2
- ▶ Symmetric encryption
 - ▶ unique initial secret key shared with sink
- ▶ Pseudo-Random Number Generator (PRNG)
 - ▶ unique (secret) seed shared with sink

▶ Re-initialization

- ▶ During each visit, sink re-initializes ALL sensors (ADV not present):
 - ▶ New (or old?) software
 - ▶ New secret key
 - ▶ New secret seed
 - ▶ Empty storage (secure erasure)
-

Adversarial model 1/2

▶ **ADV Goal**

- ▶ learn as many secrets as possible (keys and/or other keying material).

• **ADV Compromise Power**

- Can compromise at most $0 < k < n/2$ sensors at any round.
- Reads all storage/memory and listens to all communication of a compromised sensor.

• **ADV Periodic Operation**

- At the end of each round, picks a subset of up to k
 - At the start of each round, **atomically** releases current sensors and compromises new subset
-

Adversarial model 2/2

▶ **Topology Knowledge**

- ▶ Knows the entire topology

▶ **Minimal Disruption**

- ▶ Does not interfere with sensor behavior
- ▶ Perhaps, in order to remain undetected

▶ **Defense Awareness**

- ▶ Fully aware of any scheme or algorithm used by the UWSN
-

POSH Algorithm

Protocol execution (round i):

1. Generate t random values $\{R_{i_1}, \dots, R_{i_t}\}$
2. Select $\{s_{i_1}, \dots, s_{i_t}\} \leftarrow_R \{s_1, \dots, s_{i-1}, s_{i+1}, \dots, s_n\}$
3. Send R_{i_j} to s_{i_j} , $1 \leq j \leq t$
4. Receive contributions $\{c_{i_1}, \dots, c_{i_t}\}$
5. Sensing, encryption, authentication...
6. Compute $K_i^{r+1} = H(K_i^r || c_{i_1} || \dots || c_{i_t})$
7. Erase K_i^r

Contributions

Nodes to contribute to

Normal operation activities

Key update

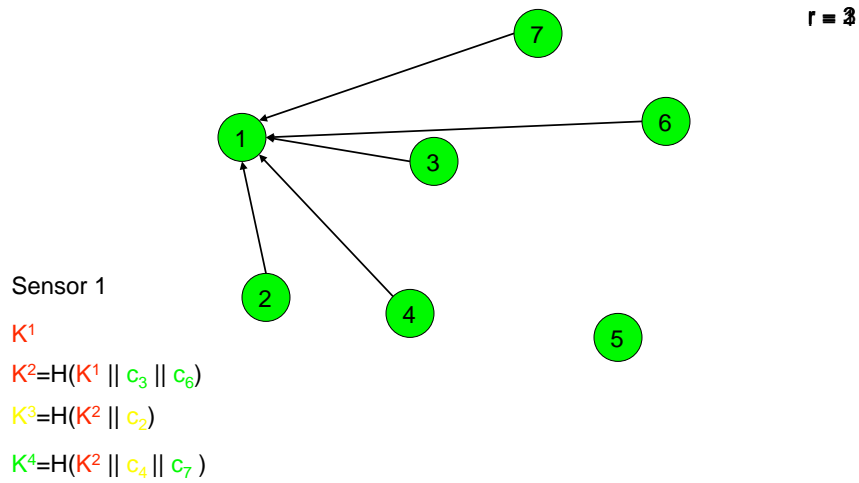
$\{s_1, \dots, s_n\}$ = set of sensors in the network
 K_i^r = key used by s_i at round r

Sensor Coloring

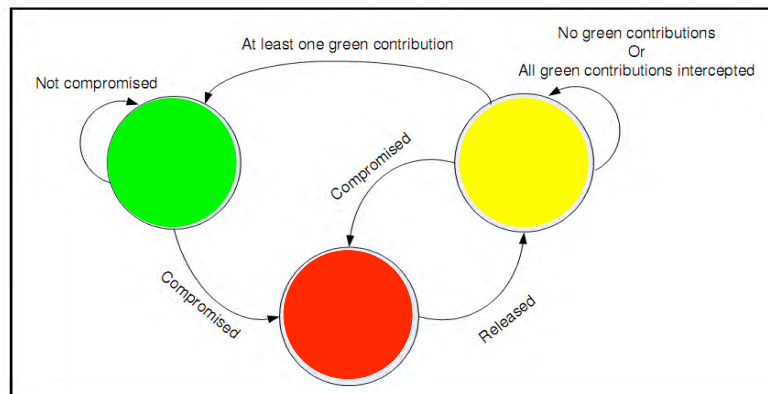
Starting at round 1, ADV compromises k sensors per round:

- **Red sensors (R^r)**
 - ▶ currently controlled by ADV
- **Yellow sensors (Y^r)**
 - ▶ Compromised in a previous rounds; their current keys known to ADV
- **Green sensors (G^r)**
 - ▶ Either never compromised
 - ▶ **Or** recovered through POSH

Example



Sensor transition diagram



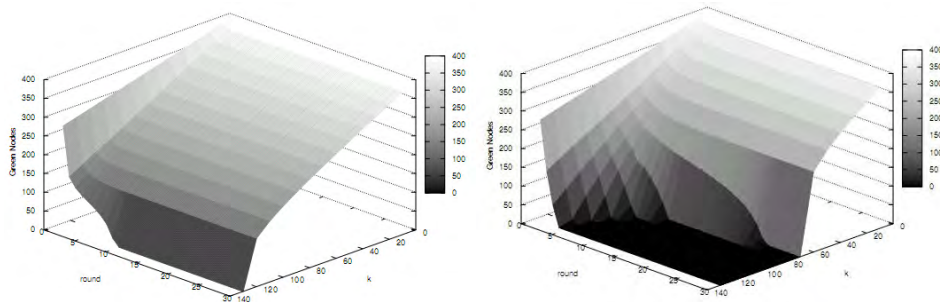
- $|R|=k$
- ADV's goal – maximize $|Y|+|R|$
- WSN goal: $|G|=n-2k$

Two kinds of ADV

- ▶ INF-ADV is always aware of G
 - ▶ Unrealistic but powerful
 - ▶ Used as benchmark

- RR-ADV moves through subsets in round-robin fashion
 - Time based heuristic...nodes that have been in Y for a long time could have since moved to G
 - Realistic but possibly weak
 - Might choose to compromise a yellow sensor

Results: |G| vs INF-ADV

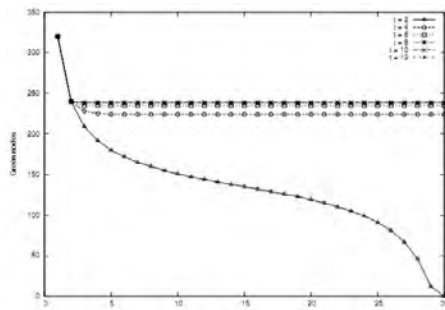


(a) $n = 400, t = 6, p = 0.2$

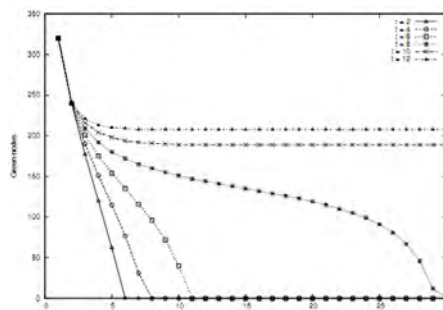
(b) $n = 400, t = 6, p = 0.8$

- p = ADV eavesdropping prob.
- $t = 6$ results in each sensor receiving at least one green contribution, on average
- Threshold phenomena:
 - e.g. for $p=0.2$, |G| remains stable for $k/n < 80/400$
 - That is 20% per round!!!

Effect of "t"



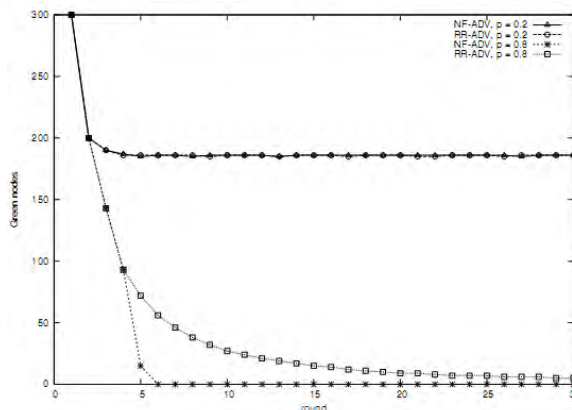
(a) $n = 400, k = 80, p = 0.2$



(b) $n = 400, k = 80, p = 0.8$

- Increasing t when $|G| \sim n-2k$ does not help
 - Also, messages are expensive!

INF-ADV vs RR-ADV



$n = 400, k = 100, t = 6$

Dealing w/ real world

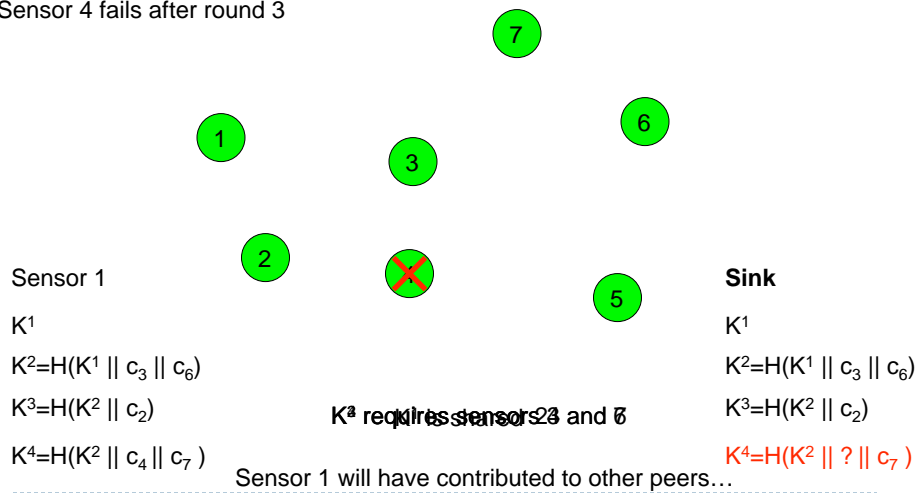
- ▶ **Message delivery failure**
 - ▶ Sink synchronization
 - ▶ Sensor must store IDs of all “contributors” (per round!)

- ▶ **Sensor failure**
 - ▶ If sensor fails, its key history cannot be reconstructed
 - ▶ Other sensors’ secrets might depend on failed one

- ▶ **Public Key helps here...**
 - ▶ Encrypt round key with sink’s PK
 - ▶ Use round key for everything else

Example

Sensor 4 fails after round 3



Conclusion

- ▶ UWSN security represents new problem domain that calls for new solutions
 - ▶ No cryptography means no security
 - ▶ Cryptography helps but not as much as expected
 - ▶ Cooperation helps a lot
 - ▶ Role of randomization in UWSN not completely characterized yet
-

Summary & Directions

- ▶ Contributions:
 - ▶ New kind of network - UWSN
 - ▶ New mobile UWSN adversary
 - ▶ Simple approaches simply don't work!
 - ▶ Lots of interesting problems
 - ▶ Ongoing and Future work:
 - ▶ Mobility?
 - ▶ New adversarial models and flavors
 - ▶ What if Adv interferes with networking and/or sensing?
-

Bibliography

- ▶ **Intrusion-Resilience in Mobile Unattended WSNs**, IEEE INFOCOM 2010
 - ▶ **Data Security in Unattended Sensor Networks**, IEEE Transactions on Computers, Vol. 50, No. 11, 2009.
 - ▶ **New Adversary and New Threats: Security in Unattended Sensor Networks**, IEEE Network, Vol. 23, No. 2, 2009.
 - ▶ **Playing Hide-and-Seek with a Focused Mobile Adversary in Unattended Sensor Networks**, Ad Hoc Networks, Vol. 7, No. 8, 2009.
 - ▶ **Collaborative Authentication in Unattended Sensor Networks**, ACMWISEC 2009.
 - ▶ **DISH: Distributed Self-Healing in Unattended Wireless Sensor Networks**, SSS 2008.
 - ▶ **POSH: Proactive co-Operative Self-Healing in Unattended Wireless Sensor Networks**, IEEE SRDS 2008.
 - ▶ **Catch Me (If You Can): Data Survival in Unattended Sensor Networks**, IEEE PERCOM 2008.
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Finally... the end!

- Questions?
 - Comments?
-



Mobile UWSNs

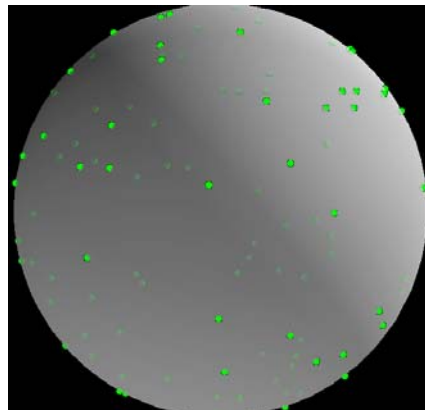
- ▶ UWSNs
 - ▶ No online sink
 - ▶ Static sensors

 - ▶ Sensor movement issues
 - ▶ Non-security related tasks
 - ▶ Coverage, Routing, etc.
 - ▶ Random Waypoint (fixed speed)
 - ▶ Random Walk (fixed speed)
 - ▶ Random Jump (variable speed)
-

Playground

Spherical surface

- ▶ Uniform node density
 - ▶ Tunable via # nodes or node comm. range
 - ▶ No border effect

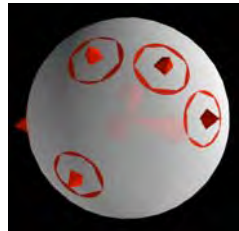
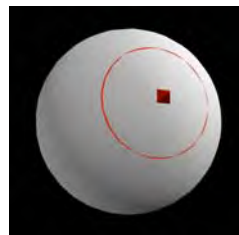


Adversary

- ▶ Controls a portion of the sphere
 - ▶ Sensor jumps in → compromised
 - ▶ Sensor jumps out → released but still yellow
 - ▶ Goal: learn sensor secrets
 - ▶ Once secrets are exposed no crypto works...
 - ▶ ...even if sensor is released!!!
 - ▶ Forward security does not help
 - ▶ Backward security?
 - No secure HW
 - No TRNG
 - No TTP
-

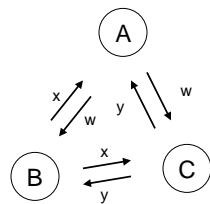
Adversarial flavors

- ▶ Focused vs non-Focused
 - ▶ After one target sensor
 - ▶ or after all of them
- ▶ Monolithic vs Distributed
- ▶ Static vs Mobile
 - ▶ Static \neq static set of compromised nodes



Collaborative Self-Healing

- ▶ Sensor proactively exchange (broadcast) random contributions w/ neighbors
- ▶ Contribution taken from a PRNG
- ▶ A contribution of secure randomness can *heal*!



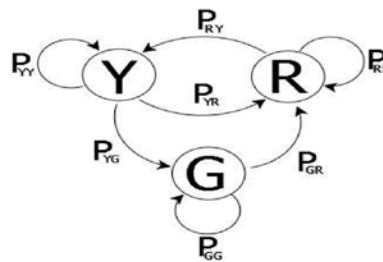
$$K_A^{r+1} = H(K_A^r, x, y)$$

$$K_B^{r+1} = H(K_B^r, w, y)$$

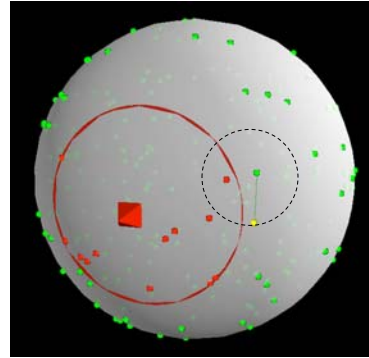
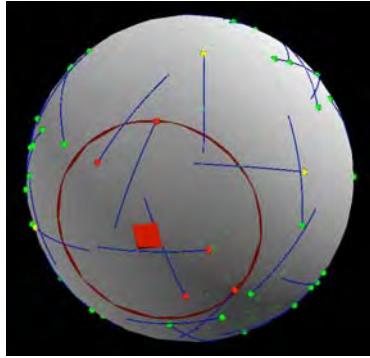
$$K_C^{r+1} = H(K_C^r, x, w)$$

System Abstraction

- ▶ **Red**
 - ▶ Within Adv's area
 - ▶ Any contribution is heard by the adversary
 - ▶ No much can be done for them / can't contribute for others
- ▶ **Yellow**
 - ▶ Came out of Adv's area
 - ▶ Adv knows their secret state
 - ▶ A safe contribution would heal them
 - ▶ Their contributions cannot heal
- ▶ **Green**
 - ▶ Adv does not know their secret state
 - ▶ Can heal peers with safe contributions



Simulation



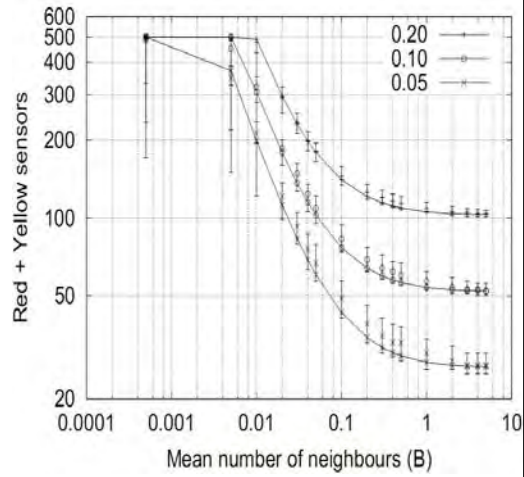
- ▶ Movement
 - ▶ Contribution Exchange
 - ▶ State update
-

Security Metrics

- ▶ **Non-Focused Adv**
 - ▶ Number of green sensors
 - ▶ **Focused Adv**
 - ▶ Time To Compromise
 - ▶ Time it takes for target sensor to become red
 - ▶ Time To Heal
 - ▶ Time it takes for target sensor (once red) to become green
 - ▶ **Cooperative protocol**
 - ▶ Depends on the size and *quality* of neighborhoods
-

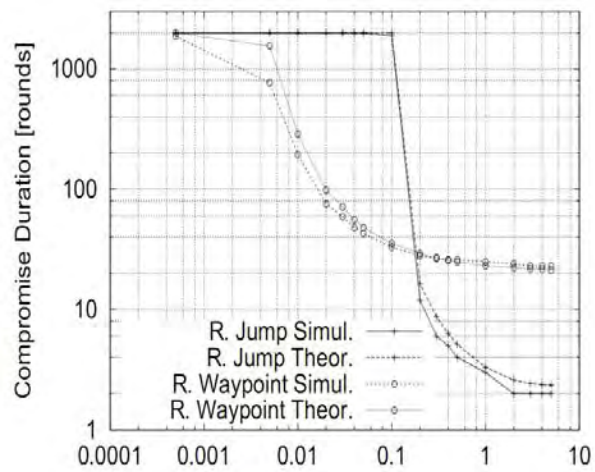
Non-Focused Adv

- ▶ **Adv**
 - ▶ Static
 - ▶ Monolithic
 - ▶ 20%, 10% and 5% coverage
- ▶ **500 Sensor**
 - ▶ Random Waypoint



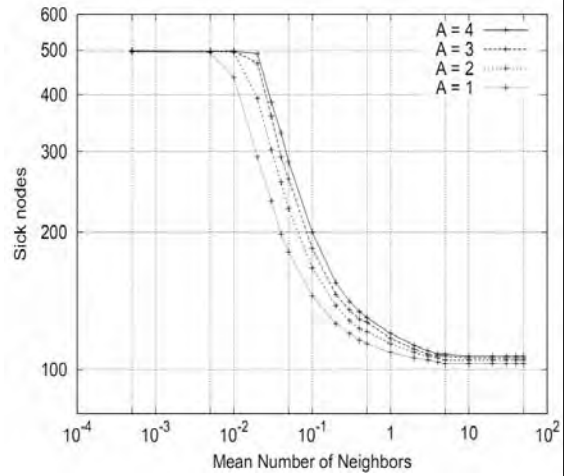
Focused Adv (Time to Heal)

- ▶ **Focused Adv**
 - ▶ Static
 - ▶ Monolithic
 - ▶ 20% coverage
- ▶ **500 Sensor**
 - ▶ Random Waypoint

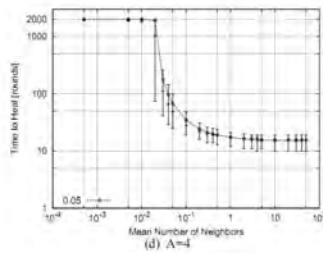
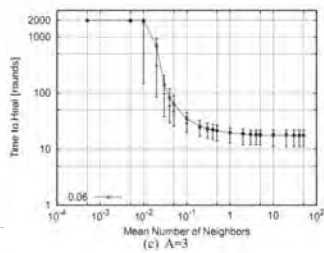
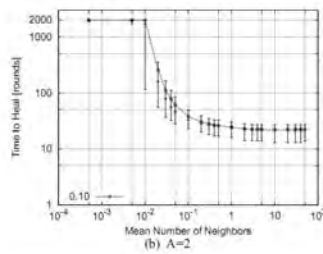
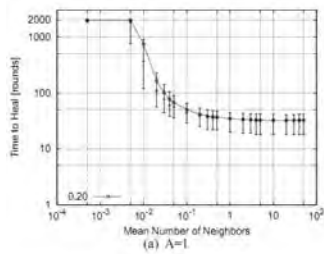


Non-Focused Adv

- ▶ Adv
 - ▶ Static
 - ▶ Distributed (1 to 4)
 - ▶ 20% coverage (total)
- ▶ 500 Sensor
 - ▶ Random Waypoint



Focused Adv (Time to Heal)



Roadmap

- ▶ Explore full spectrum of mobility models, for both sensors and Adv
 - ▶ Characterize neighborhood quality
 - ▶ Use variable sensor TX power to increase cooperation (based on Time To Heal)
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