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

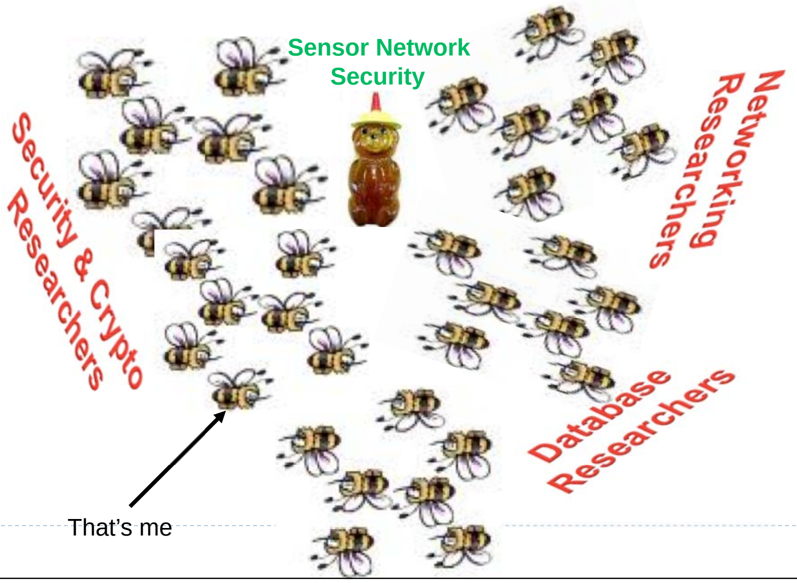
    or
  - Event driven

    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)

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
  - 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

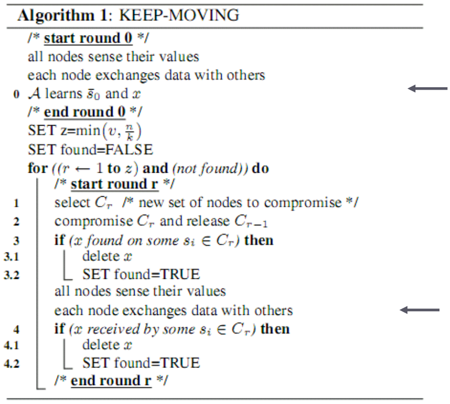
- Adv Goal: Search-and-erase
  - Looks for target data in compromised sensors

- 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   $\mathcal{A}$ learns $\bar{s}_0$ 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 learns target data at round 0

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

Nodes exchange messages

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

- 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

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

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

Keep Moving – Frantic

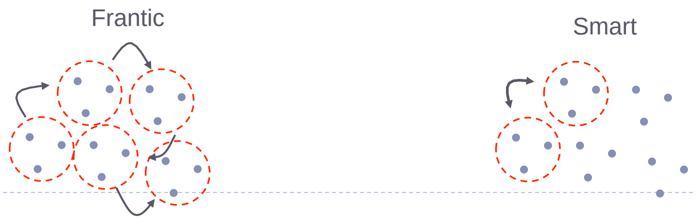
- Select a new random k-set at each round
- Two chances per round
- Probability that data survives v rounds:

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

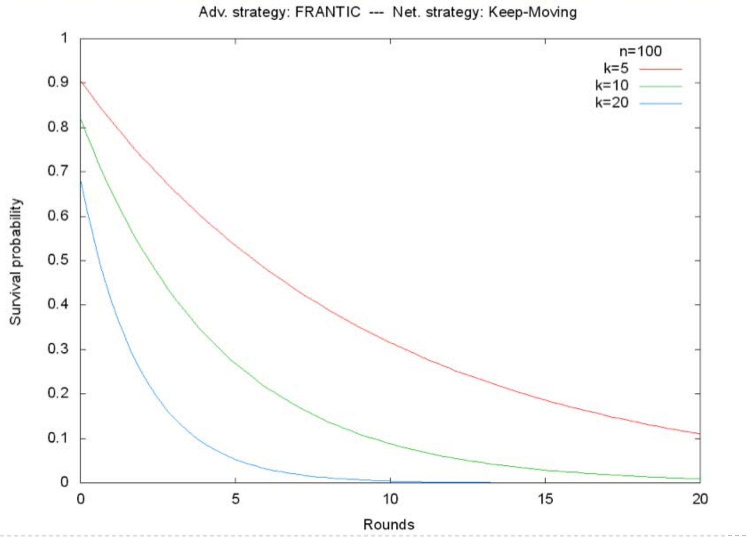
$$P_1 = \frac{k}{n} + \left(1 - \frac{k}{n}\right)\frac{k}{n} = \left(1 - \frac{k}{n}\right)^2 \qquad P_2 = 1 - \frac{k}{n} \qquad P_3 = 1 - \frac{k}{n-k}$$

Keep Moving – Smart

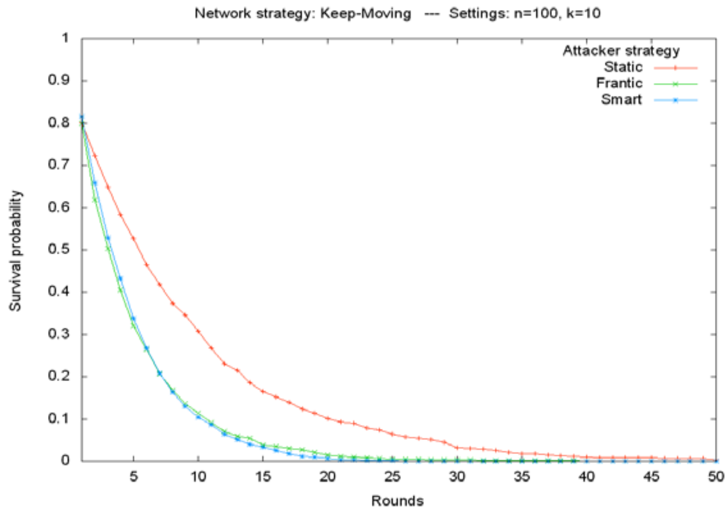
- Moves between two fixed (non-overlapping) set of nodes
  - No matter what adversarial strategy, data recipient node is always chosen according to an uniform distribution
  - Same survival probability!



Results


Adv. strategy: FRANTIC --- Net. strategy: Keep-Moving

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

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

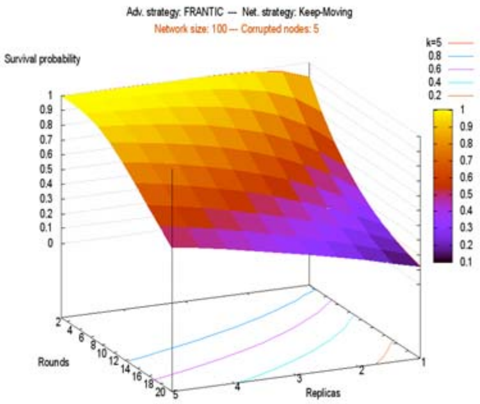
$$\overline{P_R^v}=Pr[X_{1,v}=0\wedge\ldots\wedge X_{R,v}=0]=Pr[X_{1,v}=0]^R=$$

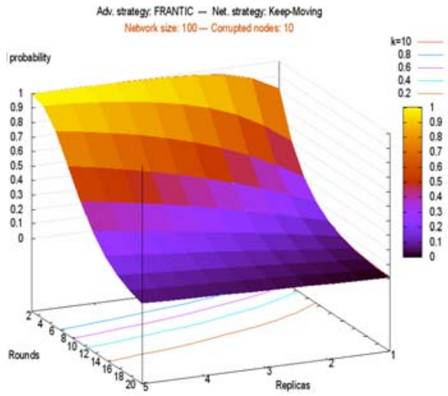
$$=(1-Pr[X_{1,v}=1])^R=(1-P_1\cdot P_2^{v-1}\cdot P_3^{v-1})^R$$

- Prob. that information survives:

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

Results





Replication:

- Increases survival probability
- Requires more storage and power
- Given enough rounds, **Adv always wins**

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:

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

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

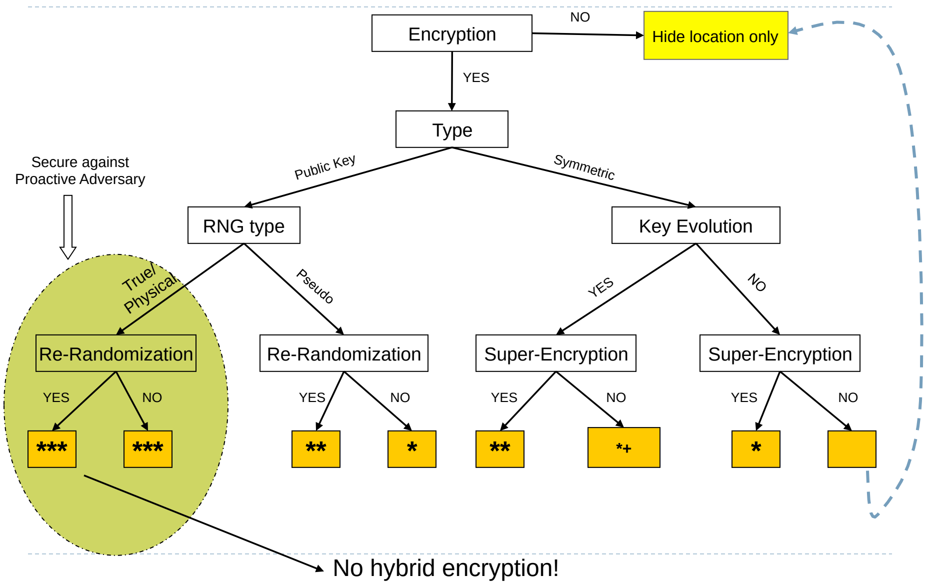
Symmetric Encryption

- 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^r_i

“Crypto Flowchart”



Encryption

NO

Hide location only

YES

Type

Public Key

Symmetric

Secure against Proactive Adversary

RNG type

Key Evolution

True/ Physical

Pseudo

YES

NO

Re-Randomization

Re-Randomization

Super-Encryption

Super-Encryption

YES NO YES NO YES NO YES NO

*** *** ** * ** *+ *

No hybrid encryption!

END PART 2

Question:

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

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

IEEE SRDS’08

Motivation

- Curious ADV: wants to learn sensor-collected data in UWSN
- 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:

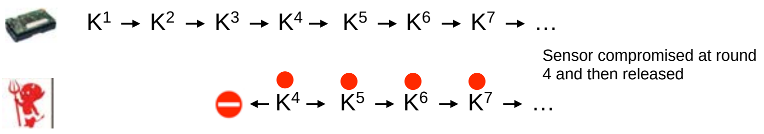
(1) Collected Before Compromise

(2) Collected During Compromise

(3) Collected After compromise (3)

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
    - $K^{r+1}=H(K^r)$
- But, after compromise, ADV can mimic key evolution process



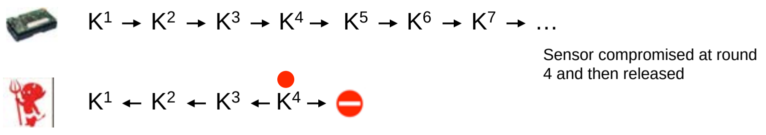
$K^1 \rightarrow K^2 \rightarrow K^3 \rightarrow K^4 \rightarrow K^5 \rightarrow K^6 \rightarrow K^7 \rightarrow \ldots$

⛔ $\leftarrow \overset{●}{K^4} \rightarrow \overset{●}{K^5} \rightarrow \overset{●}{K^6} \rightarrow \overset{●}{K^7} \rightarrow \ldots$

Sensor compromised at round 4 and then released

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



$K^1 \rightarrow K^2 \rightarrow K^3 \rightarrow K^4 \rightarrow K^5 \rightarrow K^6 \rightarrow K^7 \rightarrow \ldots$

$K^1 \leftarrow K^2 \leftarrow K^3 \leftarrow K^4 \rightarrow$ ⛔

Sensor compromised at round 4 and then released

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 key 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)

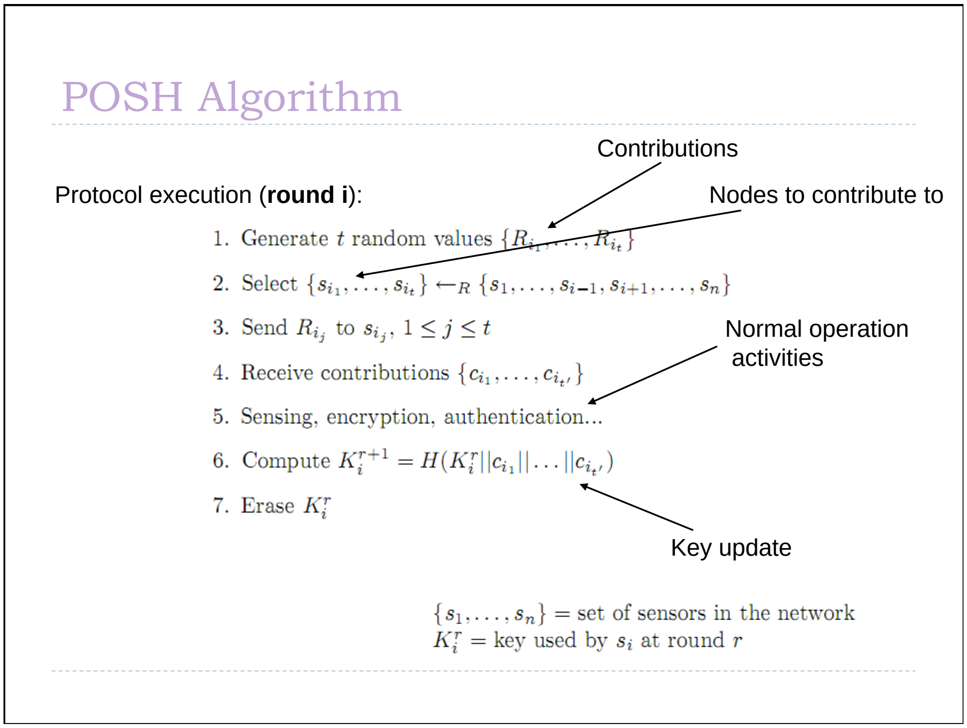
Adversarial model 1/2

- **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

Contributions

Protocol execution (**round i**):

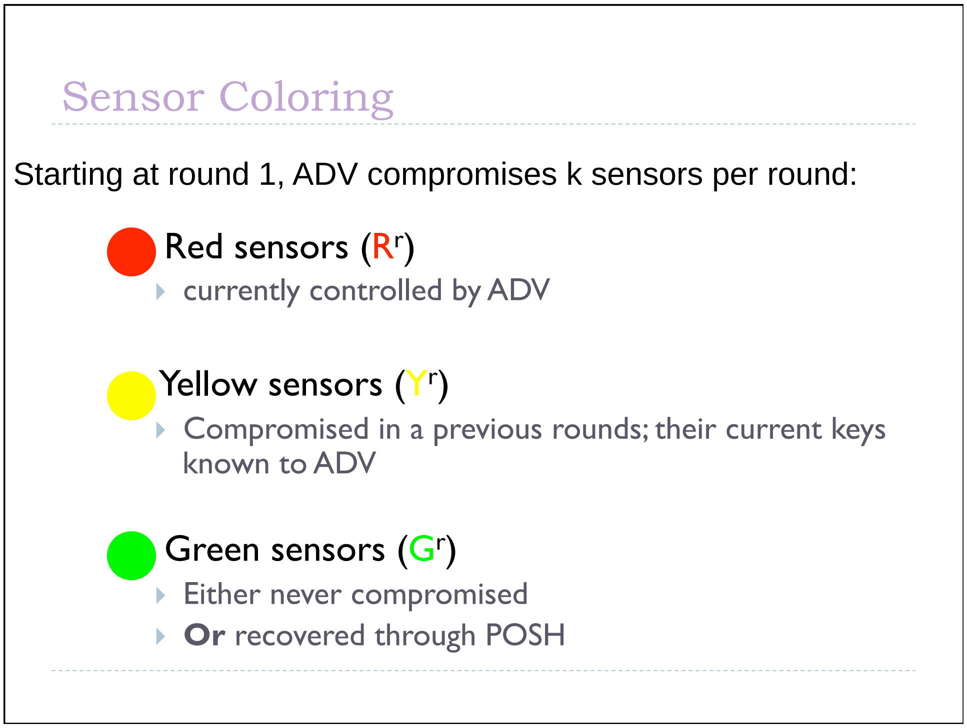
Nodes to contribute to

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

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:

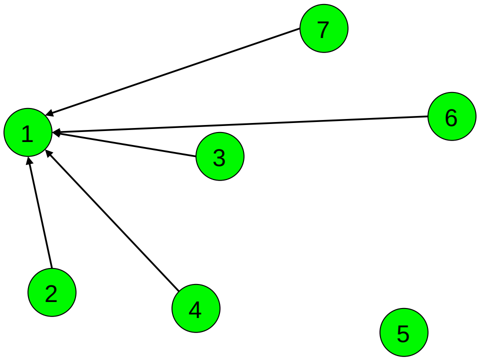
🔴 Red sensors (R^r)
- currently controlled by ADV

🟡 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

r = 3



Sensor 1

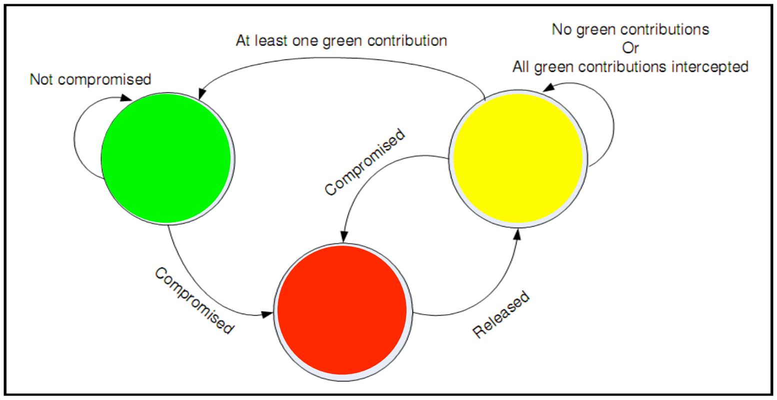
K^1

K^2=H(K^1 || c_3 || c_6)

K^3=H(K^2 || c_2)

K^4=H(K^2 || c_4 || c_7)

Sensor transition diagram



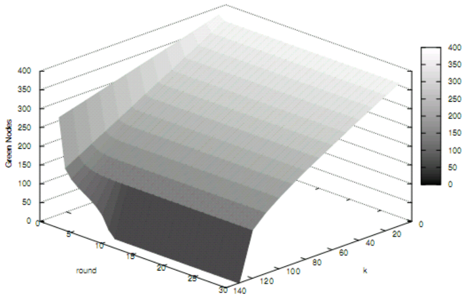
- |R|=k
- ADV's goal – maximize |Y|+|R|
- WSN goal: |G|=n-2k

Two kinds of ADV

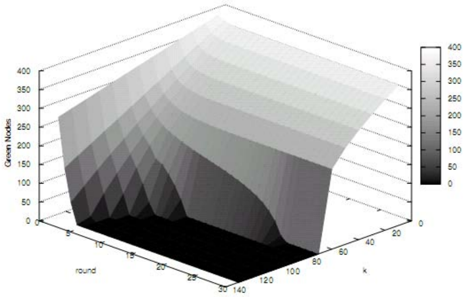
- INF-ADV is always aware of G
  - Unrealistic but very powerful
  - Used as benchmark

- 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



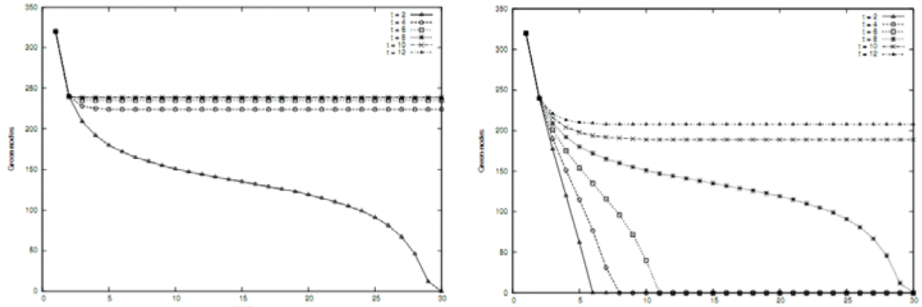
(a) $n = 400, t = 6, p = 0.2$



(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”

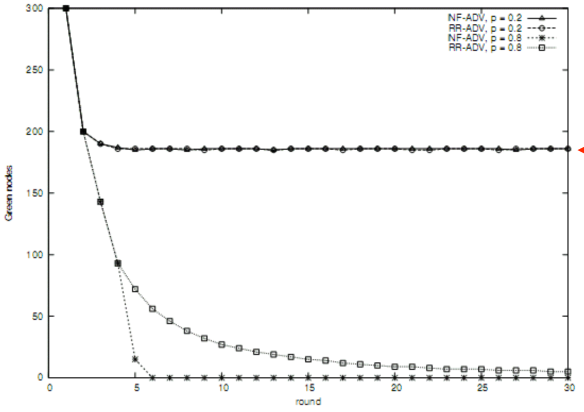


(a) $n = 400, k = 80, p = 0.2$

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

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

INF-ADV vs RR-ADV



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

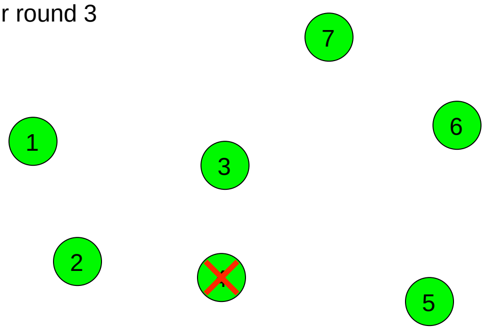
No difference if |G| is close to its optimal value

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



Sensor 1

K^1

$K^2=H(K^1 || c_3 || c_6)$

$K^3=H(K^2 || c_2)$

$K^4=H(K^2 || c_4 || c_7)$

Sink

K^1

$K^2=H(K^1 || c_3 || c_6)$

$K^3=H(K^2 || c_2)$

$K^4=H(K^2 || ? || c_7)$

K^4 requires sensors 4 and 7 / K^1 is shared

Sensor 1 will have contributed to other peers…

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?

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- **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.

Finally… the end!

- Questions?
- Comments?