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
  - Event driven
  - Query based = on-demand

- Online Sink
  - Real-time off-loading of data
Lots of Prior Work

Sensor Network Security

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

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### 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


And lots of related literature since then...
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 \( \left\lfloor \frac{n}{k} \right\rfloor \) rounds to find and erase

Keep Moving

```plaintext
Algorithm 1: KEEP-MOVING

1/* start round 0 */
all nodes sense their values
each node exchanges data with others
0 A learns a and x
1/* end round 0 */
SET found=FALSE
for (r = 1 to n) and (not found) do
    1/* start round r */
    select C_i. new set of nodes to compromise */
    compromise C_i and release C_{i-1}
    If is found on some a_i C_i then
    2 delete x
    3 SET found=TRUE
    all nodes sense their values
    4/* end round r */
    each node exchanges data with others
    If is received by some a_i C_i then
    4/* end round r */

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

Nodes exchange messages

Adv learns target data at round 0
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

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

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

Keep Moving – Frantic

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

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

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

Frantic

Smart

Results

![Graph showing survival probability over rounds for different values of k and n.](attachment:graph.png)
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 \( j \)

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

\[
Pr_R = Pr[X_{1,1} = 0 \land \ldots \land X_{1,R} = 0] = Pr[X_{1,j} = 0]^R =
\]

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

- Prob. that information survives:

\[
P_R^* = 1 - Pr_R = 1 - (1 - P_1 \cdot P_2^{i-1} \cdot P_3^{i-1})^R
\]
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:

$$E_i^r = E(PK_s, r, s_i, d_i^r, R, etc.)$$

- 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 $E_i^r$
"Crypto Flowchart"

- Encryption
  - YES
  - NO Hide location only

- Type
  - Encryption
  - RNG type
  - Key Evolution

- Re-Randomization
  - YES
  - NO

- Secure against Proactive Adversary

- Public Key
  - Symmetric

- Re-Randomization
  - YES
  - NO

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

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

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

- 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**

Protocol execution (round i):

1. Generate $t$ random values $\{R_1, \ldots, R_t\}$
2. Select $\{s_1, \ldots, s_t\} \leftarrow_R \{s_1, \ldots, s_{t-1}, s_{t+1}, \ldots, s_n\}$
3. Send $R_j$ to $s_j$, $1 \leq j \leq t$
4. Receive contributions $\{c_1, \ldots, c_t\}$
5. Sensing, encryption, authentication...
6. Compute $K_{t+1}^i = H(K_t^i || c_1 || \ldots || c_t)$
7. Erase $K_t^i$

Nodes to contribute to

Contributions

Normal operation activities

Key update

\{s_1, \ldots, s_n\} = set of sensors in the network

$K_t^i = key used by s_i at round r$

**Sensor Coloring**

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

- **Red sensors** ($R'$)
  - currently controlled by ADV

- **Yellow sensors** ($Y'$)
  - Compromised in a previous rounds; their current keys known to ADV

- **Green sensors** ($G'$)
  - Either never compromised
  - Or recovered through POSH
Example

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

- $p =$ 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”

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

INF-ADV vs RR-ADV

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

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**Example**

Sensor 4 fails after round 3

1. Sensor 1
   - $K^1$ = H($K^1 || c_3 || c_6$)
   - $K^2$ = H($K^2 || c_2$)
   - $K^3$ = H($K^2 || c_4 || c_7$)

2. Sink
   - $K^1$
   - $K^2$ = H($K^1 || c_3 || c_6$)
   - $K^3$ = H($K^2 || c_2$)
   - $K^4$ = H($K^2 || ? || c_7$)

$K^2$ requires sensors 2 and 6

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?
Bibliography

- Intrusion-Resilience in Mobile Unattended WSNs, IEEE INFOCOM 2010

Finally... the end!

- Questions?
- Comments?