LEDS: Providing Location-aware End-to-end Data Security in Wireless Sensor Networks

Kui Ren, Wenjing Lou
Worcester Polytechnic Institute

Yanchao Zhang
University of Florida
Introduction: Wireless Sensor Networks

- A wireless sensor network (WSN) is composed of a large number of sensor nodes
- Sensor nodes are typically small, low-cost, low-power devices
- Sensor nodes perform the following functionality:
  - Sense/monitor its local environment
  - Perform limited data processing
  - Communicate on short distance
- A WSN usually also contains a “sink” node(s) which collects data from sensor nodes and connects the WSN to the outside world
- Various sensing tasks
  - military sensing and tracking, remote sensing in hazardous venues, real time traffic monitoring, real time weather monitoring, wild animal monitoring and tracking, fire/flood detection, inventory control, etc.
An Exemplary WSN
Security issues in WSN

- Many applications in WSNs require communication to be highly secure
- Main security challenges:
  - Sensor nodes are resource constrained – computation, memory, communication bandwidth, energy, etc.
  - Sensor nodes are not temper resistant, are subject to compromise
  - Radio link makes attack easier – eavesdropping / false data injection, etc.
- General design guidelines
  - Lightweight: lightweight cryptographic tools, efficient protocol design for communication and storage efficiency
  - Resilient: be resilient against compromised nodes
  - Scalable: de-centralized, localized protocol
Related Work

- **Statistical En-route Filtering (SEF)** – Ye, Luo, Lu, and Zhang, *INFOCOM* 2004
- **Interleaved Hop-by-Hop Authentication (IHA)**
- **Resilient Security** – Yang, Ye, Yuan, Lu, and Arbaugh, *ACM Mobihoc* 2005
  
  Vulnerable to report disruption attack and selective forwarding attack!

- **Location-based Compromise-tolerant Security**
  
  Based on ID-based public key cryptography.
End-to-end Data Security

• Hop-by-hop vs. End-to-end
• Data Confidentiality
  – Intermediate relaying nodes should not read the event reports to the sink: end-to-end encryption
• Data Authenticity
  – The message has not been altered during the transmission: MAC.
  – It was indeed from the claimed source: collaborative endorsement.
• Data Availability
  – Resilient to selective forwarding attack and report disruption attack: one-to-many forwarding, secret sharing
  – In-network false data filtering: interleaved hop-by-hop filtering
LEDs: Two Observations

- **Stationary and location-awareness**
  - Many WSN applications require sensor nodes to be aware of their locations.
  - It is not difficult for each node to know its location and their neighbors’ locations -- GPS based, GPS-free, sensor self-positioning algorithms, etc..

- **Communication pattern**
  - one-to-many: sink-to-node broadcast
  - many-to-one: node-to-sink data collection
LEDS: Cell-based geographic routing

- Geographic routing – No routing overhead
- Predictable routes
- One-to-many forwarding scheme – more resilient to node failure and compromise
LEDS: Location-aware key management framework

- System Secret $K^I_M, K^II_M$
- Each node computes a set of keys
  - Unique secret key
    \[ K^1_u = H(K^I_M | u | I_u | 0), \quad K^2_u = H(K^I_M | u | I_u | 1) \]
  - Cell key shared among all the nodes in the cell:
    \[ K^I_{I_u} = H(K^I_M | I_u) \]
  - Authentication keys shared with nodes along the routing path
    \[ H(K^II_M | (x_1, y_1) | (x_c, y_c)) \]
- Dynamic node addition
  - Nodes delete system secret but keep: $SK_u = H(K^II_M | I_u)$
  - New addition: $K^I_{I_u, I_w} = H(H(K^II_M | I_u) | I_w)$

Location information is embedded into each node’s cryptographic keys. The damage caused by compromised nodes is minimized – a compromised node cannot launch attacks at locations other than where it actually is.
LEDS: End-to-end data security mechanism

- Local communication is protected by the cell key
- A data report is encrypted by the cell key
- Each participating node contributes a share of the encrypted data report

\[ C_u = \mathcal{F}(K_u^1, K_u^2) = \sum_{0 \leq i \leq t-2} a_i (K_u^1)^{i+1} + a_{t-1} (K_u^2)^t \mod p, \]

- Each node contributes a MAC for interleaved cell-by-cell false data filtering
  - Computation of authentication keys: If \( I_v \) is an upstream (closer to sink) cell of \( I_u \), every node in \( I_u \) has the authentication key \( K_{I_u \neq I_v} \) with at least one node in \( I_v \); if the two cells are exactly \( i+1 \) cells away, every node in \( I_v \) shares the authentication key with every node in \( I_u \)

- Sink does the final verification
LEDS: An example

Formed at node $m$

$$\{I_u, m, s, u, C_m, C_s, C_u, Mac_{K_{I_u,m}}(C_m|C_s|C_u),$$

$$Mac_{K_{I_u,m}}(C_m|C_s|C_u)\}.$$  

Sent at node $v$

$$\{I_u, m, s, u, C_m, C_s, C_u, Mac_{K_{I_u,v}}(C_m|C_s|C_u),$$

$$Mac_{K_{I_u,v}}(C_m|C_s|C_u)\}.$$  

Received at node $z'$

$$\{I_u, m, s, u, C_m, C_s, C_u, Mac_{K_{I_z,v}}(C_m|C_s|C_u),$$

$$Mac_{K_{I_z,v}}(C_m|C_s|C_u)\}.$$  

Received at sink

$$\{I_u, m, s, u, C_m, C_s, C_u, Mac_{K_{I_{sink},sink}}(C_m|C_s|C_u),$$

$$Mac_{K_{I_{sink},sink}}(C_m|C_s|C_u)\}.$$  

$event\ cell\ I_u = I_m = I_s$ report-forward route
Security Analysis: Data Confidentiality

- End-to-end encryption: the confidentiality of a data report is compromised only when at least one node in the event cell is compromised.

Fig. 4. Data confidentiality in LEDS under random node capture attacks
Security Analysis: Data Authenticity (1)

- Adversaries have to compromise at least $t$ nodes in a single cell to fabricate a data report associated with that cell.

Fig. 5. Data authenticity in LEDS under random node capture attacks, where $N = 10,000$, $n' = 10$ and $(t, T) = (4, 5)$. 
Security Analysis: Data Authenticity (2)

- High efficiency in false data filtering due to deterministic cell-by-cell en-route filtering

Fig. 6. Expected filtering position vs. number of compromised nodes with respect to different distances to the sink
Security Analysis: Data Availability (1)

- One-to-many forwarding to defend against selective forwarding attack

Fig. 8. Data availability in LEDS under selective forwarding attack
Security Analysis: Data Availability (2)

- Threshold secret sharing to defend against report disruption attack

Fig. 7. Data availability in LEDS under report disruption attack
Performance Analysis

- Key storage overhead:
  - 2 unique keys
  - 1 cell key
  - 2 upstream authentication keys
  - Less than $(T+1)(T+2)/2$ downstream authentication keys
  - 1 half-key to accommodate node addition

- LEDS is also both communication- and computation-efficient
  - localized and independent key generation
  - based on symmetric key cryptography.
Conclusion

- We introduced a novel methodology of key establishment, which takes advantage of location awareness and communication pattern of a WSN.
- We designed LEDS, a lightweight, resilient and highly scalable end-to-end data security solution.
- WSNs are typically task or application specific, customized solutions might be the way to optimize the performance!
Thanks!

Questions?