Secure, Efficient Key Management for False Data Detection in Wireless Visual Sensor Networks using Dynamic Key Chaining

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Outline

1. Motivation
2. Assumptions
   - Network Topology
   - Intrusion Detecting Process and Attack Scenarios
3. False Data Detection
   - Message Authentication Code (MAC)
   - Dynamic Key Chaining
   - False Data Detection and Recovery Protocol (FDDR)
4. Performance Analysis
5. Limitations
6. Conclusion

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Motivation

Secure, Efficient Wireless Visual Sensor Networks (WVSNs)

- Terminology
  - **wireless** limited power in computation, memory and energy
  - **VSNs** a large amount of data to handle and transfer for intrusion detection
- Objectives
  - **secure** to be robust against false data injection (FDI) by T compromised wireless nodes
    - Origin and data integrity
    - How to detect and if FDI actually occurs, then how to recover?
  - **efficient** to reduce additional energy consumption and computation, memory and communication overhead

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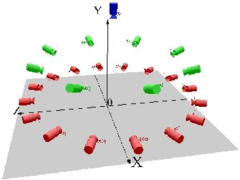
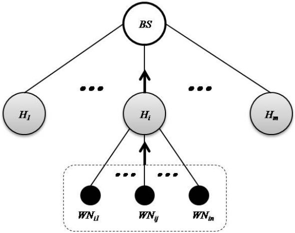
Network Topology

- Cluster-based densely deployed network
- One-hope communication allowed
- *BS* (Base Station) and *H*s (Heads) wired and strongly trusted
- *WN*s (Wireless Nodes) for sensing in rotation for energy efficiency
- *H*s for sensing and data aggregating
- *BS* for data aggregating





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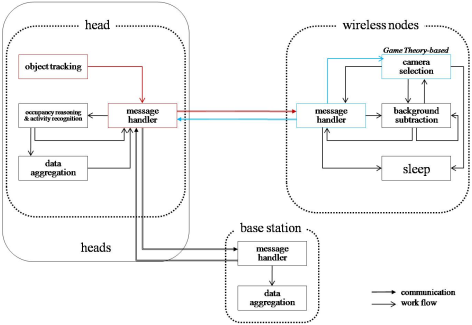
Vulnerability of WVSNs

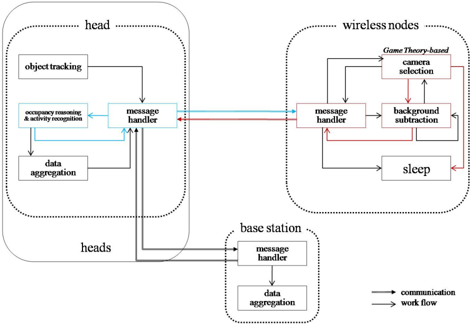
- Types of attacks
  - Physical node capturing: Attackers could steal cryptographic keys
  - Communication channel attacks: Attackers could know some frequently used channels
  - Sybil attacks: Attackers could pretend legitimate nodes
- Potential attacks
  - Since *BS* and *H*s never compromise, only channel attacks occur during broadcasting from them
  - All the attacks could take place during reporting from *WN*s

Case 1: Channel Attacks



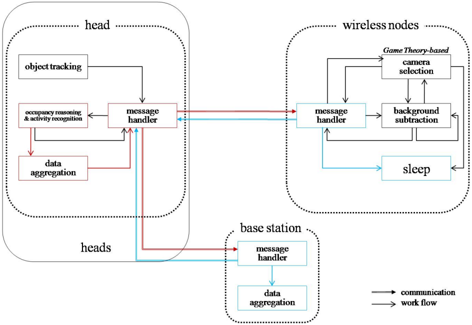
1. Before any intrusion occurs, H_i's all neighbours WN_{ij}s sleep
2. Once H_i perceives an abnormal event, it broadcasts that to all WN_{ij}s by sending message **activate** while stopping its sensing
3. Each WN_{ij} checks the message and selects a minimal set of cameras that should be turned on; if the verification is unsuccessful, it recommends H_i to use another frequency because the current one is unsecured

Case 2: Node Capturing and Sybil Attacks



1. Each WN_{ij} sends the following three types of messages in situations
   - after *camera selection*, reports **the IDs of selected cameras**
   - after *background subtraction*, sends **the resulted image**
   - after seen no objects to observe, forward message **no objects**
2. H_i do a semantic check on the message; if the verification is unsuccessful, H_i drops the message and announces it to all WN_{ij}s since the key being used is disclosed

Case 3: Channel Attacks



1. After receiving **no objects** from all selected WN_{ij}s, H_i broadcasts them to sleep, and then reports the lastest activity recognition result to *BS*
2. Same as in Case 1, against undesirable verification result, WN_{ij} warns H_i to use another frequency for transmission
3. After checking the message's integrity, *BS* broadcasts all H_is the received message; if the verification is unsuccessful, *BS* requires H_i to use another frequency

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Message Authentication Code (MAC)

- Origin and data integrity using MAC
  - Generally, to check message integrity, a MAC generating, hash function which is easy to compute, but hard to reverse is used
  - If a sender sends M and $MAC_K(M)$ using shared key K with its receiver, the receiver verifies if the received M produces the same MAC as the received $MAC_K(M)$
  - Most of channel attacks can be detected by using MAC
- Limitations on using mere MAC
  - What if collisions occur?
    - Collision: $MAC_K(M) = MAC_K(M')$ for $M \neq M'$
    - There could be more than 15,000 packets to deliver per image assuming a packet includes 32 bytes
    - $|MAC| = 4\ bytes$, $P(two\ match) = 1 - e^{(-7{,}500 \times 14{,}999/2^{32})} \approx 0.0259$
  - What if a key used to produce the MAC value is disclosed?
    - An attackers can replace message M with message M' by sending M' and $MAC_K(M')$ with disclosed key K

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Assumptions

- Every node has the same encryption/decryption (symmetric) function, MAC function and one-way function to generate a key chain
- Only pairwise key is used to communicate and all they are pre-distributed before communication
- Saying K_{ij} key between H_i and WN_{ij}, H_i securely requires every WN_{ij} to produce a key chain of certain length l using the one-way function by $f_{K_{ij}}(KC_{t+1}) = KC_t$ before starting to communicate[1]

[1] SPINS: Security Protocols for Sensor Networks, Perring et al., *Wireless Networks*, (8)521-534, 2002

Key Management: Dynamic Key Chaining

- Commitment KC_c: the last key of the current key chain
- A sender (either H_i or WN_{ij}) computes MAC for time interval t using the commitment, and sends M and $MAC_{K_t}(M)$ by employing session key $K_t = K_{ij} \oplus KC_c$ to its receiver while erasing KC_c from the key chain for the receiver
- The receiver verifies and decrypts the message, and then erase KC_c from the key chain, too
- When there is no commitment left, they compute another key chain setting that K_{ij} is the last commitment
- When a key (KC_c, K_{ij} or K_t) is stolen, they generate another key chain setting that the next commitment is the seed K_{ij} for the chain

Formal Results

Lemma 1

This dynamic key chaining guarantees no collision with high probability since a key to produce MAC is employed only once in each delivery.

- Each time to generate a key chain a different key is taken as the seed, and thereby, the resulted keys are different from those previously produced with high probability

Formal Result

Lemma 2

This dynamic key chaining is resilient against any size of compromised node set with high probability, while requiring every wireless node to store $O(|K|(l+2))$ keys, to transit only $|MAC|$ additional bytes and to do $O(|MAC|(\alpha+\beta)+|K|(l+1)(\frac{\alpha}{l+1}+\beta))$ more computation for the number of legitimate data packets α and the number of false data packets β.

- Since only individual, pairwise communication is allowed, any size of compromised set hardly discloses others' secure information
- Setting the key size is big enough as $|K| = 32$ *bytes*, the complexity of breaking a key is $\Omega(2^{39})$[2]
- Only known either the current commitment or the shared key, the session key is not revealed easily
- Once any key being used is disclosed, a new, intractable key chain is computed by the one-way function since the seed is hardly obtained

[2] Key Recovery Attacks of Practical Complexity on AES Variants with up to 10 Rounds, Biryukov et al., *ePrint Archive*, 2010

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FDDR against Cases 1 and 3

1.	$S \Rightarrow R_i$s	$E_{K_t}(D)$ and $MAC_{K_t}(E_{K_t}(D))$
2.	R_i	verify if the receive message generates $MAC_{K_t}(E_{K_t}(D))$
3.	$R_i \rightarrow S$	[verified] success [unverified] request to resend the same message using another frequency

- S: BS or H_i
- Rs: Hs or WN_{ij}s
- E: the encryption function
- Since the senders are strongly trusted, only possible FDI is sending $E_{K_t}(D) + FD$ for false data FD; so, this is easily detected by computing MAC

FDDR against Case 2

1.	$WN_{ij} \rightarrow H_i$	$E_{K_t}(D_{ij})$ and $MAC_{K_t}(E_{K_t}(D_{ij}))$
2.	H_i	integrity check and **semantic check**
3.	$H_i \Rightarrow WN_{ij}$s	[verified] success [unverified integrity] request to resend using another frequency [unverified semantic] failure (and request to reselect cameras)

- FDI can take any form of $\{E_{K_t}(D) + FD$, $E_{K_t}(D + FD)$ and $MAC_{K_t}(E_{K_t}(D + FD))$, $E_{K_t}(FD)$ and $MAC_{K_t}(E_{K_t}(FD))\}$
- The first is detected by integrity check computing MAC
- The rest is verified by semantic check according to the types of message as follows
  - IDs of selected cameras/no objects: FDI occurs if $\bigwedge_j D_{ij} \neq D_{ij}$
  - resulted image: FDI occurs by node WN_{ik} if $\forall j \exists k[(act(D_{ik}) = \sim act(D_{ij}) \wedge \sim act(D_i)) \wedge (act(D_i) \rightarrow act(D_{ij}))]$ for the activity recogniser act; then, such D_{ik} is discarded

Formal Result

Lemma 3

A false data packet injected by any compromised node can be detected in one hop communication.

- The verification process occurs every hop
- Against the messages, such as IDs of cameras and no objects, the semantic check perfectly works
- Against the image messages, the semantic check largely relies on the performance of the activity recogniser; if it produces highly accurate recognition, the lemma can be achieved

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Performance Analysis

- Cost comparison with the following three existing studies
  - TRAD: a traditional message authentication scheme;
  - SPINS: SPINS[1] using a key chain in order for broadcasting; and
  - DAA: Data Aggregation and Authentication Protocol[3] employing two different MACs
- in three different measures
  - Memory overhead;
  - Computation overhead; and
  - Communication overhead

[1] SPINS: Security Protocols for Sensor Networks, Perring et al., *Wireless Networks*, (8)521-534, 2002

[3] Integration of False Data Detection with Data Aggregation and Confidential Transmission in Wireless Sensor Networks, Ozdemir and Cam, *IEEE/ACM Transactions on Networking*, 2009

Cost Comparison in Memory Overhead

Size	TRAD	SPINS	DAA	FDDR
MAC	1	1	$4(T+1)$	1
key	$3\leq$	$3\leq$	$2T\geq$	$l+2\geq$

- Other than DAA, all employ only one MAC to authenticate a packet
- DAA requires $2(T+1)$ MACs for one packet in a pair
- TRAD and SPINS allow that a wireless node directly communicates its neighbours, its head and even the base station using pairwise keys, a group key and a key shared with the base station
- In DAA, an aggregator should store every key shared with its T neighbours and T monitors
- In FDDR, a wireless node is allowed to communicate only with its head

Cost Comparison in Computation Overhead

Computation	TRAD	SPINS	DAA	FDDR
MAC	1	1	$4(T+1)$	1
Aggregation	0	0	$T+1$	2
Encryption/ Decryption	2	2	$T+2$	2
Key Generation	0	0	0	$l+1$

- MAC computation has been already discussed before
- To avoid forwarding redundant information, data aggregation is necessarily required; however, only DAA and FDDR where it is achieved in a head and the base station does
- In DAA, encryption/decryption is carried out in every monitor for one packet as well
- Only FDDR dynamically generates keys

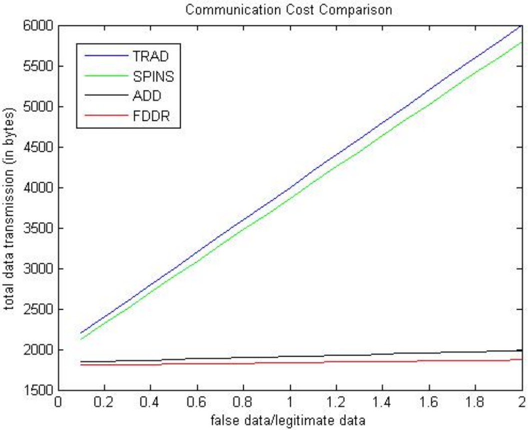
Cost Comparison in Communication Overhead

D_{TRAD}	the amount (in bytes) of data transmission using TRAD of a 8-byte MAC
D_{SPINS}	the amount (in bytes) of data transmission using SPINS of a 6-byte MAC
D_{ADD}	the amount (in bytes) of data transmission using ADD of two 4-byte MACs
D_{FDDR}	the amount (in bytes) of data transmission using FDDR of a 4-byte MAC
L_{tos}	the length (in bytes) of an authenticated and encrypted data packet
α	the number of data packets generated by legitimate nodes
β	the number of false data packets injected by up to T compromised nodes
H_d	the average number of hops between two consecutive data aggregators
H	the average number of hops that a data packet travels in the network
K	the size (in bytes) of key from the key chain
γ	the average number of keys travelled in the network

$$
\begin{aligned}
D_{TRAD} &= (L_{tos} + 8)H(\alpha + \beta) \\
D_{SPINS} &= ((L_{tos} + 6)H + \gamma K)(\alpha + \beta) \\
D_{ADD} &= (L_{tos} + 4)(\alpha H + \beta H_d) + T(L_{tos} + 4)(\alpha + \beta) + \frac{4T}{T+1}(\alpha + \beta) \\
D_{FDDR} &= (L_{tos} + 4)(\alpha H + \beta)
\end{aligned}
$$

Simulation Result for Communication Cost Comparison

- $L_{tos} = 32$, $H = 50$, $\underline{H_d = 1}$, $\underline{\gamma = 1}$, $K = 32$, $\underline{T = 1}$ and $0.2 \leq \beta/\alpha \leq 2$



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Limitations

- Given a limited bandwidth available to a wireless node, FDDR might not recover from a number of channel attacks
- During repeating camera selection, FDDR could result in losing some invaluable data of the occurring event
- There needs to adjust the length of key chain, appropriately, considering tradeoff between memory and computation overhead
- FDDR deals only with the network that contains **a non-negligible portion of wired nodes**
  - At least one node in an area should do much more computation, such as occupancy reasoning and activity recognition based on multiple images
  - At least one node should constantly monitor its area of responsibility for accurate object tracking
- Once the current commitment is revealed, its previous keys are also disclosed (even though deleting all previous keys used so far)

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Conclusion

- No collision occurs even though the network have to handle a large pool of data packets
- For additional, but reasonable memory consumption to store a key chain, higher security is guaranteed with high probability
- Adjusting the length of key chain, relatively less memory, less computation and less transmission overhead can be assured