SR3: Secure Reputation-based Resilient Routing

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Conclusion
Challenges of secure routing in WSN

Security for routing in wireless sensor networks is hard, but necessary:

- Low memory, computing power, energy consumption
- Wireless medium is inherently vulnerable
- Compromise nodes: easy
Two main types of attacks

*Packet-level* attacks, *e.g.*

- Data messages alteration
- Creation of new data or control messages

Routing-level attacks, *e.g.*

- Compromised nodes drop packets (blackholes, select forwarding)
- Attackers attract traffic using out-of-band channels (wormholes)
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Routing-level attacks, e.g.
- Compromised nodes drop packets (blackholes, select forwarding)
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Our protocol is resilient against this type of attacks

Resiliency “Capacity of a network to endure and overcome internal attacks” [EOKMV11]
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Main ideas

SR3: Secure Reputation-based Resilient Routing

- Convergecast routing from all sensors to the sink (server)
- Reinforced random walk
  - Built with a reputation mechanism
  - Based on unconditionally trusted information
A chooses the next hop among its neighbors, according to its confidence on them.
▶ A chooses the next hop among its neighbors, according to its confidence on them.

▶ The sink answers with an ACK that tries to follow the reverse of the path of the message.
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The sink answers with an ACK that tries to follow the reverse of the path of the message.

If A gets a valid ACK, it increases its confidence in the neighbor who previously routed the corresponding message.
SR3: Packet-level attacks

Messages: $E_{k_{src}}(Data||N)$, $H(N)$, $Src$

ACK: $N$, $Src$

- Attacker who listens to the data
- Attacker who replays acknowledgements
- Attacker who alters or creates messages
- Attacker forging ACKs
SR3: Packet-level attacks

Messages: $E_{k_{src}}(Data || N)$, $H(N)$, $Src$

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  → Add $\mathcal{H}(N)$ and check that it matches the ciphertext part

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- Attacker who alters or creates messages
  $\rightarrow$ Add $H(N)$ and check that it matches the ciphertext part

- Attacker forging ACKs
  $\rightarrow$ Keep the nonce secret until delivery, and reveal it in the ACK
SR3: Keep track of messages using $L_{Queue}$

- When A generates a new message with a nonce $N$, it chooses the next hop B, and stores a trace of this choice in $L_{Queue}$, a bounded size FIFO list.

$L_{Queue}$: $[(N', D)]$
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$L_{\text{Queue}}$: $[(N', D), (N, B)]$

- Decrypt
- Check validity
- Build ACK
SR3: Keep track of messages using $L_{Queue}$

- When A generates a new message with a nonce $N$, it chooses the next hop B, and stores a trace of this choice in $L_{Queue}$, a bounded size FIFO list.

- Upon reception of an ACK which contains $N$,
  - If A is not the final destination for that ACK, A routes it,
  - Else, if it recalls the corresponding message using $L_{Queue}$, it reinforces A's trust in B.
  - Otherwise, A drops the ACK.

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$L_{Queue}$: $[(N', D)]$
SR3: Reputation

- Trust in a node is the number of identifiers of that node in a bounded FIFO list, $L_{Routing}$, initially empty.
- Messages are routed probabilistically according to the node’s $L_{Routing}$.

$$Pr(X = n) = \frac{|L_{Routing}| n + \delta^{-1}}{|L_{Routing}| + 1}$$

F’s $L_{Routing}$, max size = 3:

$$[\ , \ , \ ] (\star)$$

$$P(X = C) = \frac{0 + 0.5}{1} = 50\%$$

$$P(X = D) = \frac{0 + 0.5}{1} = 50\%$$
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\[
Pr(X = n) = \frac{|L_{Routing}|_n + \delta_v^{-1}}{|L_{Routing}| + 1}
\]

F’s \( L_{Routing} \), max size = 3:

\[
\left[ C, \quad , \quad \right] (\star)
\]

\[
P(X = C) = \frac{1 + 0.5}{2} = 75\%
\]

\[
P(X = D) = \frac{0 + 0.5}{2} = 25\%
\]
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F’s $L_{Routing}$, max size = 3: [C, D, ] (*)&

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$F$’s $L_{Routing}$, max size = 3:

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$$P(X = C) = \frac{2 + 0.5}{4} = 63\%$$

$$P(X = D) = \frac{1 + 0.5}{4} = 37\%$$
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Altisen et al. (VERIMAG)

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F’s $L_{Routing}$, max size = 3: [D, D, D] (⋆)

$$P(X = C) = \frac{0 + 0.5}{4} = 12\%$$

$$P(X = D) = \frac{3 + 0.5}{4} = 88\%$$
SR3: $L_{AckRouting}$ and routing acknowledgments

- Messages leave a trail of entries in a FIFO bounded-size list $L_{AckRouting}$ on the routing nodes.

```
A ---- B ---- C ---- Sink
  |      |      |
$L_{AckRouting}$  $L_{AckRouting}$
  |      |      |
∅      ∅      ∅
```
SR3: $L_{\text{AckRouting}}$ and routing acknowledgments

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Diagram:

$$\mathcal{E}_{k_{A}}(\text{Data}||N), \mathcal{H}(N), A$$

A ----> B ----> C ----> Sink

$L_{\text{AckRouting}} (\mathcal{H}(N), A)$  
$L_{\text{AckRouting}} \emptyset$
SR3: $L_{\text{AckRouting}}$ and routing acknowledgments

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\[\mathcal{E}_{k_A}(\text{Data} \parallel N), \mathcal{H}(N), A\]

\[\mathcal{E}_{k_A}(\text{Data} \parallel N), \mathcal{H}(N), A\]

\[A \xrightarrow{} B \xrightarrow{} C \rightarrow \text{Sink}\]

\[L_{\text{AckRouting}} (\mathcal{H}(N), A) \]

\[L_{\text{AckRouting}} (\mathcal{H}(N), B) \]
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- ACKs follow those indications, and are routed randomly when they cannot.
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\[
\begin{align*}
\epsilon_{k_A}(\text{Data} \| N), \mathcal{H}(N), A & \\
\end{align*}
\]

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\]
Lost and forged acknowledgements

\[ N_l, F \]

\[ I \]

\[ \text{Sink} \]

\[ \text{A} \]

\[ \text{B} \]

\[ \text{C} \]
Lost and forged acknowledgements

ACKs therefore have a $\frac{1}{Nb}$ probability of being dropped at each retransmission, with $Nb$ an upper bound on the number of nodes.
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Security properties and proofs

- Nonce confidentiality before delivery
- Data confidentiality, even after delivery
- Packet unforgeability (implies authentication and integrity)
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These proofs are done using games, which evaluate the probability that an attacker breaks the property (its advantage), depending on the primitives used and the attacker capabilities.
Security properties and proofs

- Nonce confidentiality before delivery
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These proofs are done using **games**, which evaluate the probability that an attacker breaks the property (its **advantage**), depending on the **primitives** used and the attacker **capabilities**.

Using game reductions, we are then able to find an upper bound on the advantage of **any attacker**, which we can then use to find the right compromise between costs and the level of security.
Modeling the protocol

Hash function
We model it as a random oracle $\mathcal{H} : \{0, 1\}^{\eta_n} \rightarrow \{0, 1\}^{\eta_h}$. The number of times the adversary calls $\mathcal{H}$ is denoted $q_H$.

Nonces
Nonces are modeled as truly random numbers of size $\eta_n$.

Block Cipher
A block cipher $\mathcal{F}$ is a set of permutations of $\{0, 1\}^{\eta_c}$, indexed on keys. We assume that the block cipher is $PRP-CCA$-secure, which is the property we rely on for security.

$Gen_{src}^{O(\cdot)}(Data)$
The function which generates a packet produced by $src$ containing $Data$, using $O$ as a block cipher, and drawing a new nonce $N$. 
Data confidentiality

Let $\mathcal{A}$ be an adversary running in two phases ($\mathcal{A}_1$ and $\mathcal{A}_2$).

Experiment $\text{Expt}^{FG}_F(\mathcal{A})$:

1. $k_{src} \overset{\$}{\leftarrow} \text{Init}(K)$
2. $(\mathcal{O}, \mathcal{O}^{-1}) \leftarrow (F_{k_{src}}, F_{k_{src}}^{-1})$
3. $(Data_0, Data_1, state) \overset{\$}{\leftarrow} \mathcal{A}_1 \text{Gen}_{src}^{\mathcal{O}(\cdot), \mathcal{H}(\cdot)}()$
4. $b \overset{\$}{\leftarrow} \{0, 1\}$
5. $(\langle C, h, src \rangle, N) \overset{\$}{\leftarrow} \text{Gen}_{src}^{\mathcal{O}(\cdot)}(Data_b)$

If $b = \mathcal{A}_2 \text{Gen}_{src}^{\mathcal{O}(\cdot), \mathcal{H}(\cdot)}(\langle C, h, src \rangle, N, state))$

- Return 1
Else
- Return 0
Advantage and bounds

The find-then-guess advantage of $A$ against $F$ is defined as the probability of $A$ winning the game (i.e. $Pr[\text{Expt}_{FG}^{F}(A) = 1]$) minus the probability of winning for an adversary that outputs a random bit:

$$\text{Adv}_{FG}^{F}(A) = Pr[\text{Expt}_{FG}^{F}(A) = 1] - \frac{1}{2}$$

We then use Cryptooverif [Bla07]\(^1\), an automated prover of cryptographic properties in the computational model, to get an upper bound on this advantage.

\(^1\)http://prosecco.gforge.inria.fr/personal/bblanche/cryptoverif/
Advantage and bounds

For all adversaries $A$ making $q_G$ queries to $Gen$ and $q_H$ queries to the hash function, there exists an adversary $B$ (making $q_G + 1$ queries to $O$ in its game) such that:

\[
\text{Adv}^F_{FG}(A) \leq \frac{2q_G^2 + 2q_G}{2^{\eta_c}} + \frac{2q_G^2 + 4q_G + 2}{2^{\eta_n}} + 2\text{Adv}^F_{PRP-CPA}(B)
\]
Advantage and bounds

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From this, we can choose our parameters to achieve the desired security bound. For instance, if we use a $\eta_c = 128b$ block cipher and a $\eta_n = 96b$ nonce, and we allow the attacker $q_G = 2^{20}$ oracle calls and answers, we get:

$$\text{Adv}^{FG}_F(A) \leq \frac{2 \times (2^{20})^2 + 2 \times 2^{20}}{2^{128}} + \frac{2 \times (2^{20})^2 + 4 \times 2^{20} + 2}{2^{96}} + 2\text{Adv}^{PRP-CPA}_F(B)$$

$$= \ldots = 2^{-54.999} + 2\text{Adv}^{PRP-CPA}_F(B)$$
Choosing the block cipher and final bound

\[
\text{Adv}_F^{FG}(A) \leq 2^{-54.999} + 2\text{Adv}_F^{PRP-CPA}(B)
\]

If we use AES-128 as block cipher, the best attack known to this day needs \(2^{126.1}\) operations. Therefore, we can expect \(\text{Adv}_{AES-128}^{PRP-CPA}(B)\) to be much smaller than \(2^{-54}\) for any adversary \(B\).
Choosing the block cipher and final bound

\[ \text{Adv}_F^{FG}(\mathcal{A}) \leq 2^{-54.999} + 2 \text{Adv}_F^{PRP-CPA}(\mathcal{B}) \]

If we use AES-128 as block cipher, the best attack known to this day needs \(2^{126.1}\) operations. Therefore, we can expect \(\text{Adv}_{AES-128}^{PRP-CPA}(\mathcal{B})\) to be much smaller than \(2^{-54}\) for any adversary \(\mathcal{B}\).

- Using nonces of 12 bytes and hashes of 8 bytes,
- Using a correct blockcipher of 16 bytes (e.g. AES-128),
- With an attacker that has \(2^{20}\) packets with chosen data, hash function calls, and validity queries,

The probability of the adversary breaking one of the three properties is less than \(2^{-50}\).
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Comparison points

Protocols with different underlying mechanisms

- Uniform Random Walk
- Gradient Based Routing (GBR) plus variants built for enhanced resiliency [EOKMV11]
  - RGBR (randomly select a lower height neighbor each time)
  - PRGBR (send to the same height with $p = 0.4$)
  - PRDGBR (PRGBR + duplication at each node)
- Greedy-Face-Greedy (geographical)
Simulation parameters, models and topologies

- Sinalgo\(^2\), from ETH Zurich
- Asynchronous network (FIFO links)
- Every honest node generates messages, random intervals
- From 50 to 400 randomly positioned sensors, one centered sink
- Topology: Unit Disk Graphs, average degree from 8 to 32
- Connectivity: connected graphs only
- Overall, around 15k simulations, sending over 6 billion messages.

\(^2\)http://www.disco.ethz.ch/projects/sinalgo/
Chosen attacks

- Safe networks
- **Blackholes (10%, 20% and 30%)**
  - Selective forwarding (10% and more, overall less impact than blackholes)
    - From 0 to 100% of messages transmitted
- **5% Wormholes→Blackholes + 5% Blackholes**
  - Direct link to the sink, switch behaviors at one third of the simulation
- **Sybil nodes (10% and more, not significantly better than blackholes)**
  - From 1 to 5 identities

All attackers are randomly positioned.
30% Blackholes, degree 8

![Graph showing average delivery rate vs. number of nodes for different network topologies. The graph includes lines for GFG, GBR, RGBR, PRGBR, PRDGBR, RW, and SR3, with data points indicating performance at various node counts.](image-url)
Resiliency and performances

30% Blackholes, degree 32

![Graph showing average delivery rate vs. number of nodes for different network configurations: GFG, GBR, RGBR, PRGBR, PRDGBR, RW, and SR3. The graph illustrates the performance of these configurations under varying network sizes.]
30% Blackholes, degree 32, 200 nodes

Distribution of the delivery rate (in %) for each node

Altisen et al. (VERIMAG)
No attackers, degree 16

For 400 nodes, RW is around 600 hops.
5% WH->BH, 5% BH, 200 nodes, degree 8, over time

The x\textsuperscript{th} message has been processed (either delivered or lost)

Altisen et al. (VERIMAG)
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Conclusion and future work

- SR3, Secure Reputation-based Resilient Routing
- Proved secure packet format using CryptoVerif
- Resilient against multiple attacks
- Efficient algorithm on both small (<50 nodes) and large (>400 nodes) networks, sparse (average degree 8) and dense (average degree 32) networks

Future works:
- Dynamicity and mobility of nodes
- Implementation and energy measurements planned in ARESA2
Thanks for your attention.

Questions?

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http://www-verimag.imag.fr/~rjamet/SR3/

20% Selective Forwarding, 200 nodes, degree 8, varying $p$
10% Sybil, 200 nodes, degree 8, varying number of identities