A Graph Theoretic Framework for Preventing the Wormhole Attack in Wireless Sensor Networks

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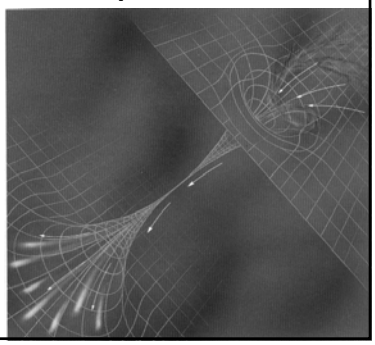
Wormholes – Hope for time travel

Wormhole: A space-time distortion that links two points in the Universe via a shorter path in distance/duration than the direct path.

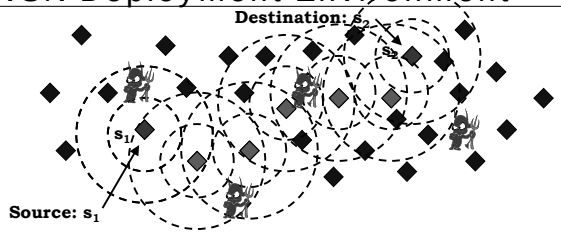
Can be a problem in wrong hands!



Outline

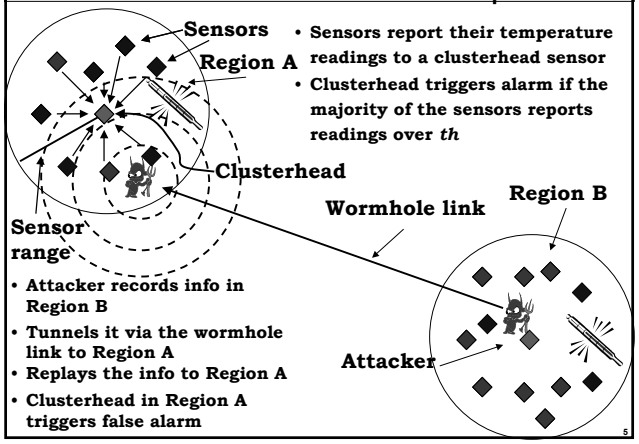
- **The Wormhole threat in Wireless Sensor Networks (WSN)**
- **Graph Theoretic Formulation**
- **Related Work**
- **Our Approach: Local broadcast Keys**
- **Security Analysis**
- **Conclusions**

WSN Deployment Environment



- **Ad hoc mode of communication - Distributed algorithms based on a cooperative principle**
- **Exchange of information locally**
- **Deployment region may be hostile**

Wormhole Attack – Example 1



- Sensors report their temperature readings to a clusterhead sensor
- Clusterhead triggers alarm if the majority of the sensors reports readings over *th*

- Attacker records info in Region B
- Tunnels it via the wormhole link to Region A
- Replays the info to Region A
- Clusterhead in Region A triggers false alarm

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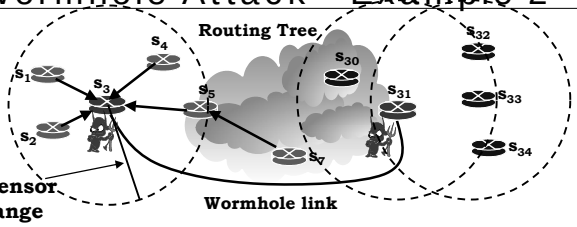
Wormhole Attack – Example 2



- Attacker establishes a wormhole link between s_{31} and s_3.
- s_{31} and s_3 become neighbors in routing tree
- Sensors $\{s_1, s_2, s_3, s_4, s_5, s_7\}$ route through the wormhole link to reach any of $\{s_{30}, s_{31}, s_{32}, s_{33}, s_{34}\}$, and vice versa.
- The attacker controls/observes large amount of data.
- It can selectively drop packets, affect throughput, cause route oscillation.
- Sensor s_3 becomes a sinkhole for the local traffic to $\{s_{30}, s_{31}, s_{32}, s_{33}, s_{34}\}$

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Impact of the Wormhole Threat

- **WSN Applications**
  - **Monitoring**
  - **Access Control**
  - **Localization**
- **Network Protocols**
  - **Routing**
  - **Neighbor discovery**

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Wormhole Attack Properties

- **Type: Replay attack**
  - **The integrity and authenticity of the communication is not compromised**
  - **The success of the attack is independent of the strength of cryptographic primitives.**
  - **Freshness can be guaranteed by a speedy direct link.**

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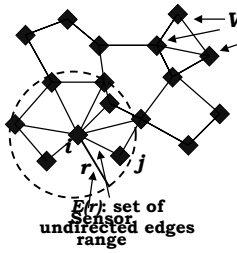
Graph Representation of WSN



WSN represented by a Geometric Graph $G(V, E(r))$

$$e(i,j) = \begin{cases} 1, & if \ \|i-j\| \le r \\ 0, & if \ \|i-j\| > r \end{cases}$$

The Communication Graph $G(V, E_G)$ need not be identical to $G(V, E(r))$, but,

$$E_G \subseteq E(r)$$

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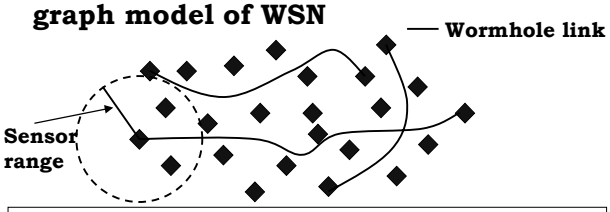
Graph Interpretation of Wormholes

- **Wormholes violate the geometric graph model of WSN**



For a Communication Graph $G'(V, E_{G'})$ with wormholes $E_{G'} \not\subset E(r)$

Wormholes transform $G(V, E_G)$ to a Logical Graph $G'(V, E_{G'})$

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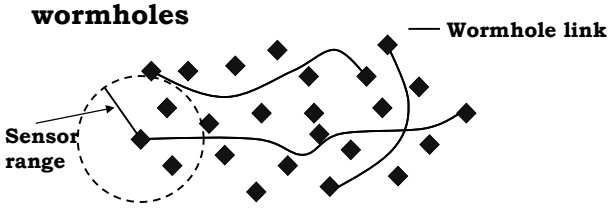
The Wormhole Problem

Given a logical graph $G'(V, E_{G'})$ with wormholes



Extract from G' the communication graph $G(V, E_G)$ with

$$E_G \subseteq E(r)$$

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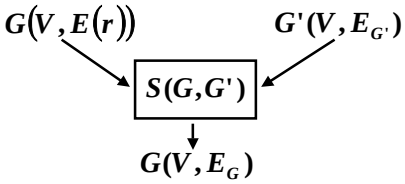
Solving the Wormhole Problem

If $G(V, E(r))$ can be constructed (e.g. known locations of sensors) then:



$S : GxG' \rightarrow G$ a transformation such as XOR operation between the connectivity matrices of G, G'

What if $G(V, E(r))$ is UNKNOWN?

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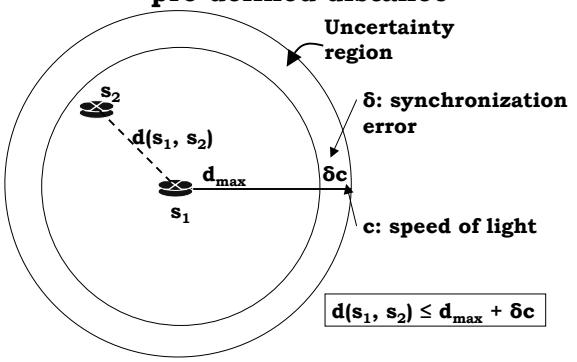
Packet Leashes – Hu et al.

A packet cannot travel further than a pre-defined distance



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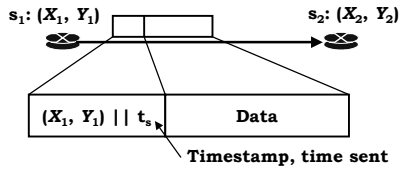
Packet Leashes – Hu et al.

- **Locations of the nodes are known**
  - **Geographical Leashes**



- **s_2: Accept packet if:**

$$d(s_1, s_2) \leq (t_r - t_s + \delta)c$$

Speed of light

Time received

Synchronization error

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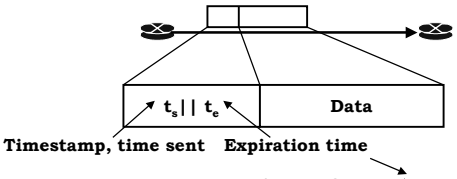
Packet Leashes – Hu et al.

Temporal Leashes: Locations not known



- **s_2: Accept packet if:** $t_r \le t_e$

Time received

$$t_e - t_s = \frac{d_{\max} - \delta c}{c}$$

- **For $t_e > t_s$: $d_{max} > \delta c$**

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Packet Leashes – Hu et al.

- **Packets Leashes can detect (and remove) wormholes if:**
  - **Geographical leashes:** $r \le (t_r - t_s + \delta)c$

    Sensor communication range
  - **Temporal leashes:** $t_e - t_s = +\, r/c - \delta$
- **Requires tight synchronization**

  Eg: For $t_e > t_s$, if δ = 0.5msec → r > 150m

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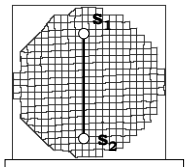
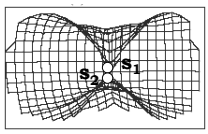
Visualization of Wormholes – Wang

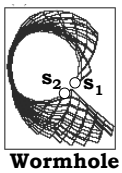
- **Construct a visual representation of the WSN**



Wormhole link



Wormhole between s_1, s_2 (front view)



Wormhole between two nodes (side view)

- **Idea: Wormholes shrink the distance between two points causing wraparound in the visual representation**

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Visualization of Wormholes – Wang

- **Central Authority (CA) collects distance measurements of each sensor to its neighbors.**
- **Using Multi Dimensional Scaling (MDS), CA computes the relative position of each sensor.**

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Our Approach : LBK

- **LBK: Local Broadcast Keys**

You need to be in the neighborhood to speak the same language and understand the message

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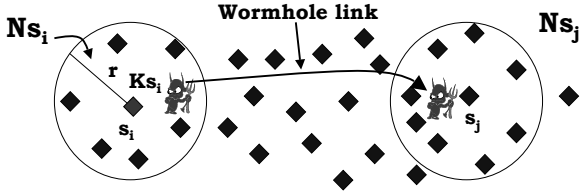
Local Broadcast Keys (LBKs)



- **Each sensor uses a key Ks_i ONLY KNOWN to its neighborhood Ns_i.**
- **Broadcast information encoded with Ks_i, cannot be decrypted outside Ns_i.**

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Correctness of the LBK Solution

- **Imposing LBKs to the "wormhole infected" logical graph $G'(V,E_{G'})$,**

$$e(i,j)=\begin{cases}1, & if \quad j \text{ holds } Ks_i\\ 0, & \text{otherwise}\end{cases}$$

- **Since j holds Ks_i iff j in in the neighborhood of i,**

$$e(i,j)=\begin{cases}1, & if \quad \|i-j\|\le r\\ 0, & if \quad \|i-j\|>r\end{cases}$$

Geometric graph model is satisfied

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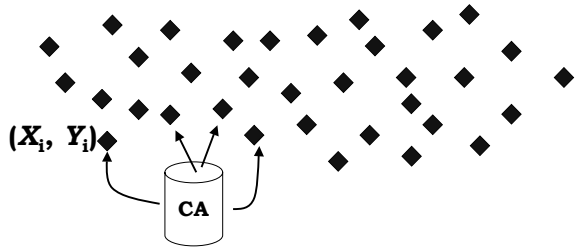
Establishment of LBKs (1)

A) Static Network: Locations of the sensors are known.



A Central Authority (CA) distributes the LBKs to sensors.

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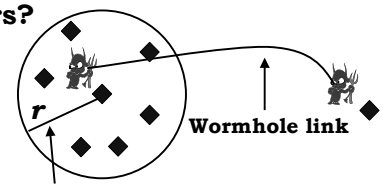
Establishment of LBKs (2)

B) Locations of the sensors are unknown, how do sensors discover their neighbors?



Sensor range

Neighbor discovery schemes are vulnerable to wormholes

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Secure Neighbor Discovery

1. **Perform distance bounding with neighbors – Requires:**
   - **time measurements with nanosecond accuracy**
   - **Nanosecond processing capable hardware**
2. **Perform Secure Localization (SeRLoc)**
3. **Use Power Proximity to infer distance**
4. **Proposed Approach: Use special nodes we call GUARDS.**

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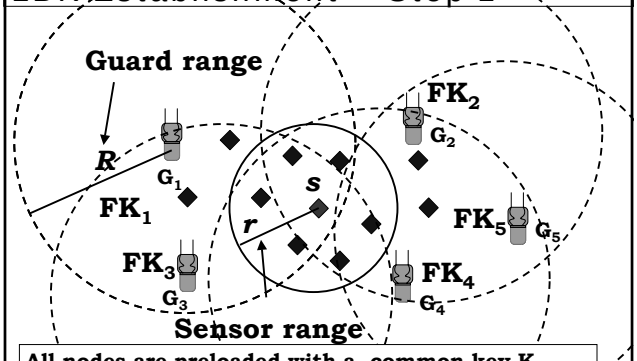
LBK Establishment – Step 1



All nodes are preloaded with a common key K_0
Each Guard G_i broadcasts an encrypted fractional key $E_{K0}\{FK_i\}$

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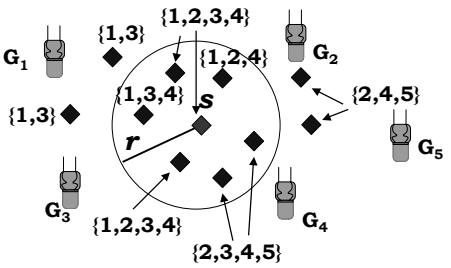
LBK Establishment – Step 1

{i,j,k,…}: indexes of the Guards heard



Sensors collect all the fractional keys they hear.

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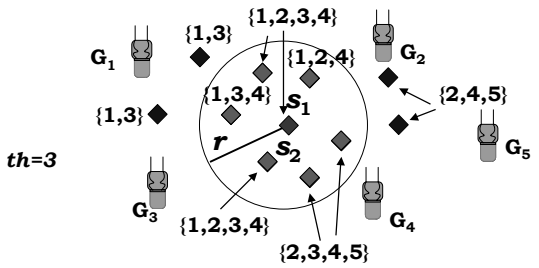
LBK Establishment – Step 2

Every sensor announces the indexes of the fractional keys it hears and a threshold *th*



If a sensor s_i shares more than *th* fractional keys with s_1 → establish pairwise key $K_{s1,si}$

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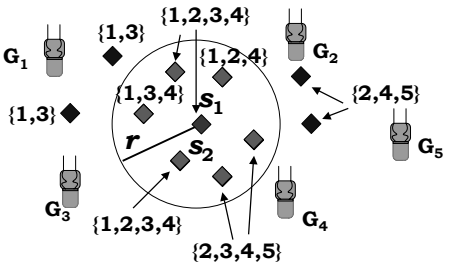
LBK Establishment – Step 2



$K_{s1,s2}$=H(FK_1 || FK_2 ||FK_3|| FK_4}
H: Collision Resistant Hash function

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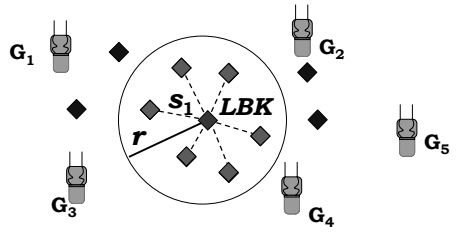
LBK Establishment – Step 3

Sensor s_1 distributes its LBK via unicast to each neighbor s_i, using $K_{s1,si}$.



Each sensor holds its own LBK and the LBks of its neighbors.

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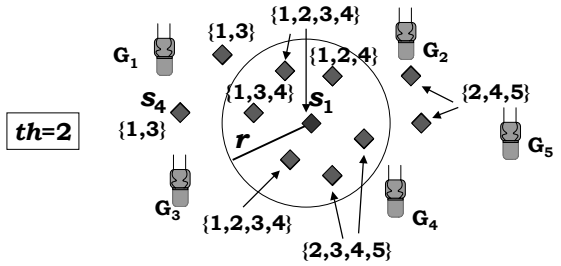
LBK Establishment – non-neighbors

What if a node outside the sensor range shares sufficient keys with s_1?



Threshold must be chosen carefully!
What do we mean by this?

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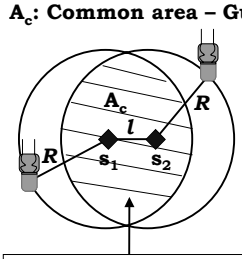
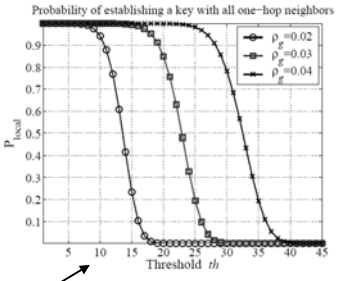
Deciding the Threshold value (1)

R: Guard range, *l*: distance between sensors (l≤r)
A_c: Common area – Guards heard to both s_1,s_2



At least *th* guards need to lay within A_c, $l \le r$



Computed as if all neighbors are at *l=r*

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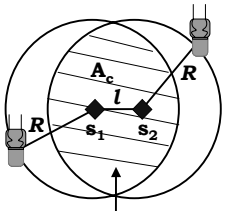
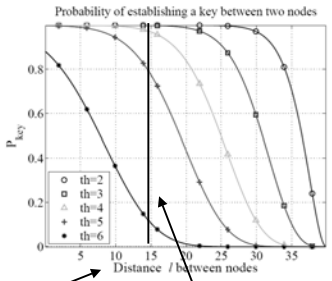
Deciding the Threshold value (2)

Probability of establishing a LBK with non-immediate neighbors



At least *th* guards need to lye within A_c, $l > r$



ρ_g=0.03 **Sensor range**

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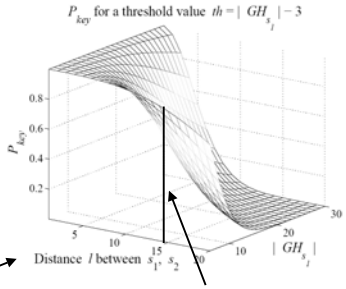
Locally computed Threshold

- **Locally decide for the threshold value *th* based on # of guards heard GH_s.**

- **The threshold is some function of GH_s**
  ***th* = f(GH_s)**



ρ_g=0.03 **Sensor range**

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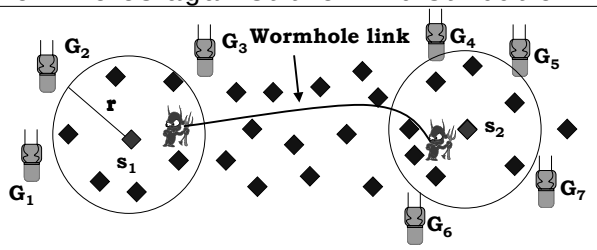
Wormholes against the FK distribution



- **Attacker tunnels the transmissions of the FK via the wormhole link and replays at both ends.**
- **Sensors s_1, s_2 hear set of guards GH_s={G_1...G_7}**
- **s_1, s_2 establish a pairwise key and hence, a LBK**
- **If th >3, s_1 cannot establish an LBK with any of its neighbors**

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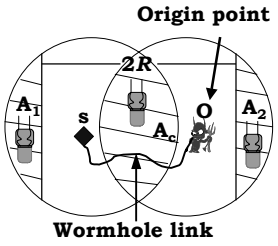
Detecting wormholes during the FK distribution

Guards include their coordinates with every transmission of Fractional Keys (FK).



- **If sensor s hears a FK multiple times it is under a wormhole attack**
- **If sensor s hears two guards more than 2R apart, it is under a wormhole attack**

$$P_{\det} \geq \left(1-e^{-\rho_g A_c}\right)+e^{-\rho_g A_c}\left(1-e^{-\rho_g A_1}\right)^2$$

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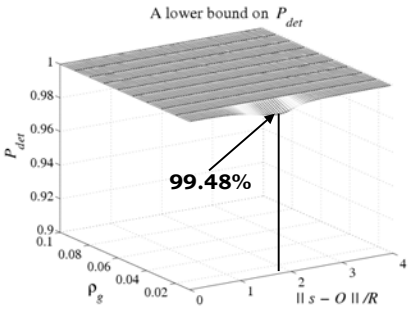
Wormhole Attack Detection

- **P_{det} during the distribution of fractional keys**

Once attack is detected execute challenge-response scheme to identify the closest guard



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Conclusions

- **We showed: Any candidate solution eliminates wormholes if the communication graph produced satisfies the geometric graph constraints**
- **We proposed: A scheme for eliminating wormholes when sensors have unknown location and are not time synchronized**

Main idea behind the solution: If broadcasted information is encrypted at each neighborhood with a different Local Broadcast Key, it cannot be decrypted at some other neighborhood

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