Security and Cooperation in Wireless Networks

http://secowinet.epfl.ch/

# Chapter 6: Securing neighbor discovery

the wormhole attack;
centralized and decentralized wormhole detection mechanisms;

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## Introduction

- many wireless networking mechanisms require that the nodes be aware of their neighborhood
- a simple neighbor discovery protocol:
  - every node broadcasts a neighbor discovery request
  - each node that hear the request responds with a neighbor discovery reply
  - messages carry node identifiers → neighboring nodes discover each other's ID
- an adversary may try to thwart the execution of the protocol
  - prevent two neighbors to discover each other by jamming
  - create a neighbor relationship between far-away nodes
    - by spoofing neighbor discovery messages (can be prevented by message authentication techniques)
    - by installing a *wormhole* (cannot be prevented by cryptographic techniques alone)

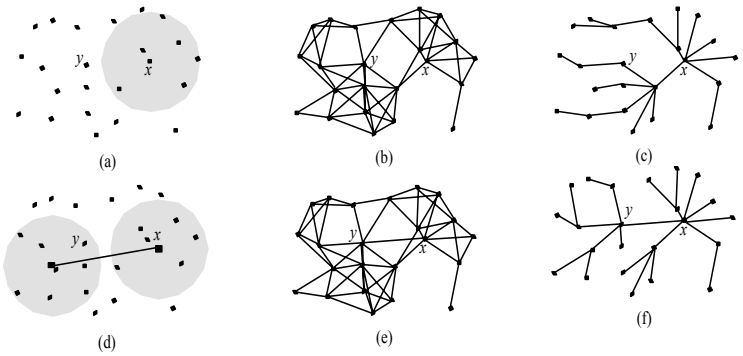
## What is a wormhole?

- a wormhole is an out-of-band connection, controlled by the adversary, between two physical locations in the network
  - the adversary installs radio transceivers at both ends of the wormhole
  - it transfers packets (possibly selectively) received from the network at one end of the wormhole to the other end via the out-of-band connection, and re-injects the packets there into the network
- notes:
  - adversary's transceivers are not regular nodes (no node is compromised by the adversary)
  - adversary doesn't need to understand what it tunnels (e.g., encrypted packets can also be tunneled through the wormhole)
  - it is easy to mount a wormhole, but it may devastating effects on routing



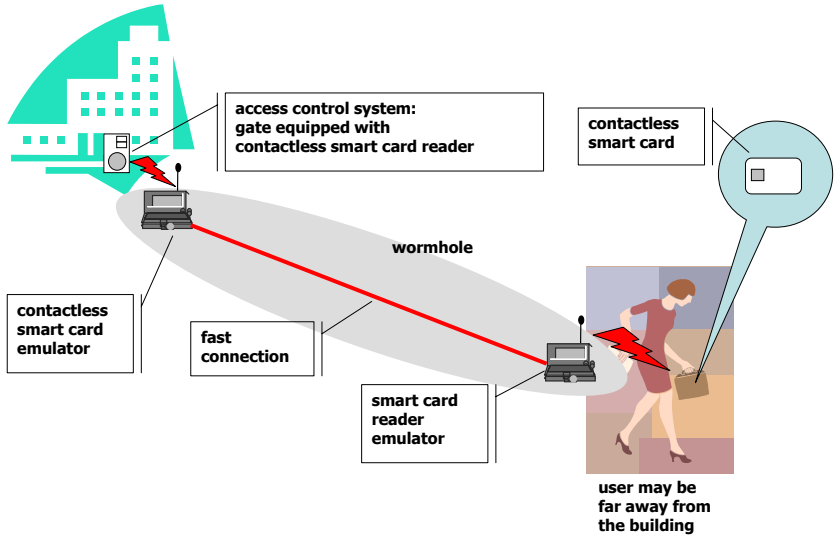
## Effects of a wormhole

- at the data link layer: distorted network topology




- at the network layer:
  - routing protocols may choose routes that contain wormhole links
    - typically those routes appear to be shorter
    - flooding based routing protocols (e.g., DSR, Ariadne) may not be able to discover other routes but only through the wormhole
  - adversary can then monitor traffic or drop packets (DoS)

## Wormholes are not unique to ad hoc networks






## Classification of wormhole detection methods

- centralized mechanisms
  - data collected from the local neighborhood of every node are sent to a central entity
  - based on the received data, a model of the entire network is constructed
  - the central entity tries to detect inconsistencies (potential indicators of wormholes) in this model
  - can be used in sensor networks, where the base station can play the role of the central entity
- decentralized mechanisms
  - each node constructs a model of its own neighborhood using locally collected data
  - each node tries to detect inconsistencies on its own
  - advantage: no need for a central entity (fits well some applications)
  - disadvantage: nodes need to be more complex

## Statistical wormhole detection in sensor networks

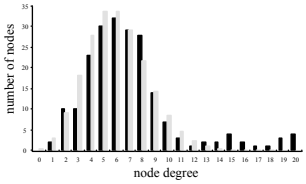
- each node reports its list of believed neighbors to the base station
- the base station reconstructs the connectivity graph (model)
- *a wormhole always increases the number of edges* in the connectivity graph
- this increase may change the properties of the connectivity graph in a detectable way (anomaly)
- detection can be based on statistical hypothesis testing methods (e.g. the $\chi^2$-test)



## Examples

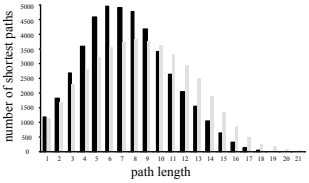
- a wormhole that creates many new edges may increase the *number of neighbors* of the affected nodes

→ distribution of node degrees will be distorted




- a wormhole is usually a shortcut that decreases the length of the shortest paths in the network

→ distribution of the length of the shortest paths will be distorted



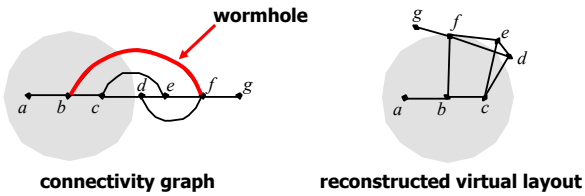
## Multi-dimensional scaling

- the nodes not only report their lists of neighbors, but they also estimate (inaccurately) their distances to their neighbors
- connectivity information and estimated distances are input to a multi-dimensional scaling (MDS) algorithm
- the MDS algorithm tries to determine the possible position of each node in such a way that the constraints induced by the connectivity and the distance estimation data are respected
  - the algorithm has a certain level of freedom in "stretching" the nodes within the error bounds of the distance estimation
- let us suppose that an adversary installed a wormhole in the network
  - if the estimated distances between the affected nodes are much larger than the nodes' communication range, then the wormhole is detected
  - hence, the adversary must also falsify the distance estimation → distances between far-away nodes become smaller
  - this will result in a distortion in the virtual layout constructed by the MDS algorithm

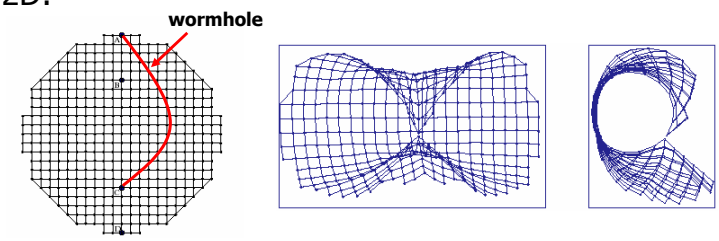


## Examples

- in 1D:




- in 2D:



## Packet leashes

- packet leashes ensure that packets are not accepted "too far" from their source
- geographical leashes
  - each node is equipped with a GPS receiver
  - when sending a packet, the node puts its GPS position into the header
  - the receiving node verifies if the sender is really within communication range
- temporal leashes
  - nodes' clocks are very tightly synchronized
  - when sending a packet, the node puts a timestamp in the header
  - the receiving node estimates the distance of the sender based on the elapsed time and the speed of light

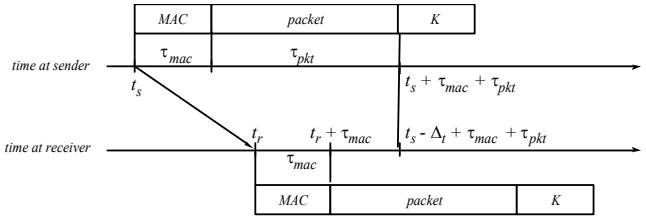
$$d_{est} < v_{light}(t_{rcv} - t_{snd} + \Delta_t)$$

  - note: $v_{light}\,\Delta_t$ must be much smaller than the communication range



## TESLA with Instant Key-disclosure (TIK)

idea: authentication delay of TESLA can be removed in an environment where the nodes' clocks are tightly synchronized




- by the time the sender reveals the key, the receiver has already received the MAC
- security condition: $t_r < t_s - \Delta_t + t_{pkt}$
- note: $\Delta_t$ must be very small or otherwise packets must be very long

## Mutual Authentication with Distance-bounding (MAD)

| $u$ | | $v$ |
|---|---|---|
| | **— initialization phase —** | |
| generate random numbers $r \in \{0,1\}^\ell$, $r' \in \{0,1\}^{\ell'}$ | | generate random numbers $s \in \{0,1\}^\ell$, $s' \in \{0,1\}^{\ell'}$ |
| compute commitment $c_u = H(r\|r')$ | | compute commitment $c_v = H(s\|s')$ |
| | $\xrightarrow{c_u}$ | |
| | $\xleftarrow{c_v}$ | |
| | **— distance-bounding phase —** | |
| the bits of $r$ are $r_1, r_2, \ldots, r_\ell$ | | the bits of $s$ are $s_1, s_2, \ldots, s_\ell$ |
| $\alpha_1 = r_1$ | $\xrightarrow{\alpha_1}$ | |
| | $\xleftarrow{\beta_1}$ | $\beta_1 = s_1 \oplus \alpha_1$ |
| | $\ldots$ | |
| $\alpha_i = r_i \oplus \beta_{i-1}$ | $\xrightarrow{\alpha_i}$ | measure delay between $\beta_{i-1}$ and $\alpha_i$ |
| measure delay between $\alpha_i$ and $\beta_i$ | $\xleftarrow{\beta_i}$ | $\beta_i = s_i \oplus \alpha_i$ |
| | $\ldots$ | |
| $\alpha_\ell = r_\ell \oplus \beta_{\ell-1}$ | $\xrightarrow{\alpha_\ell}$ | measure delay between $\beta_{\ell-1}$ and $\alpha_\ell$ |
| measure delay between $\alpha_\ell$ and $\beta_\ell$ | $\xleftarrow{\beta_\ell}$ | $\beta_\ell = s_\ell \oplus \alpha_\ell$ |
| | **— authentication phase —** | |
| $s_i = \alpha_i \oplus \beta_i$ $(i = 1, \ldots, \ell)$ | | $r_1 = \alpha_1$ and $r_i = \alpha_i \oplus \beta_{i-1}$ $(i = 2, \ldots, \ell)$ |
| $\mu_u = mac_{k_{uv}}(u\|v\|r_1\|s_1\|\ldots\|r_\ell\|s_\ell)$ | | $\mu_v = mac_{k_{uv}}(v\|u\|s_1\|r_1\|\ldots\|s_\ell\|r_\ell)$ |
| | $\xrightarrow{r'\|\mu_u}$ | |
| | $\xleftarrow{s'\|\mu_v}$ | |
| verify $c_v$ and $\mu_v$ | | verify $c_u$ and $\mu_u$ |

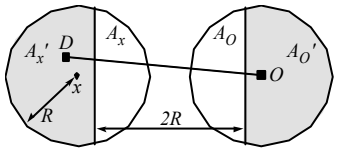
- MAD allows precise distance estimation without synchronized clocks

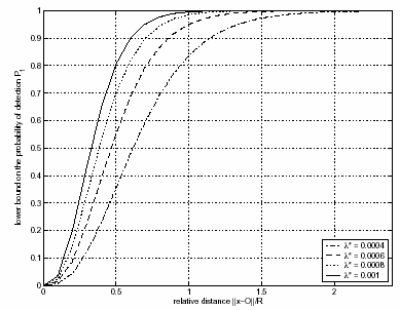


## Using position information of anchors

- anchors are special nodes that know their own positions (GPS)
- there are only a few anchors randomly distributed among regular nodes
- two nodes consider each other neighbors only if
  - they hear each other and
  - they hear more than T common anchors
- anchors put their location data in their messages
- transmission range of anchors (R) is larger than that of regular nodes (r)
- wormholes are detected based on the following two principles:
  1. a node should not hear two anchors that are 2R apart from each other
  2. a node should not receive the same message twice from the same anchor

# Principle 1

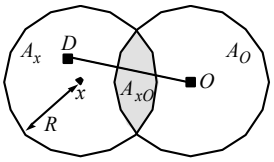


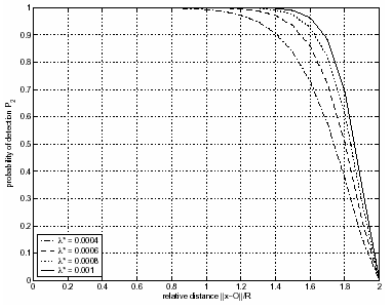




- x hears anchors in $A_x$ and in $A_O$
- $P_1$ is the probability that it hears two anchors that are further away from each other than 2R
- the probability that there is at least one anchor in an area of size S is $(1-e^{-\lambda*S})$, where $\lambda*$ is the density of anchors
- $P_1 \geq (1-e^{-\lambda*S'x})(1-e^{-\lambda*S'O})$, where $S'_x$ is the size of $A'_x$ and $S'_O$ is the size of $A'_O$
- this lower bound is maximum when $S'_x = S'_O$



# Principle 2

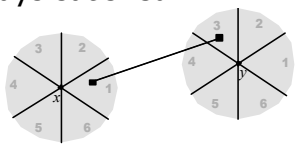


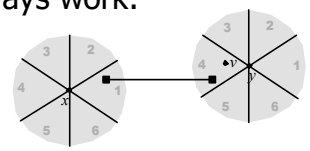

- when x and O are closer than 2*R*, the discs $A_x$ and $A_O$ overlap
- if there is an anchor in the intersection $A_{xO}$, then the messages of that anchor is heard twice by *x*
  - first directly and then from transceiver D who receives it from O through the wormhole
- the probability $P_2$ of detection is equal to the probability that there is at least one anchor in $A_{xO}$
- $P_2 = 1-e^{-\lambda*S_{xO}}$

## Wormhole detection with directional antennas

- when two nodes are within each other's communication range, they must hear each other's transmission from opposite directions
- if nodes x and y communicate through a wormhole, then this condition is not always satisfied:

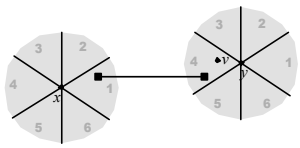



- but this doesn't always work:






## Using verifiers – the idea

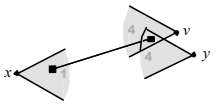



- if y and x were real neighbors and y heard x in zone 4, then every node in y's zone 4 would be a neighbor of x
- if they are not real neighbors, then there may be a node v in y's zone 4 that is not a neighbor of x (v and x don't hear each other from opposite directions)
- such a v can be used by y as a verifier

## Conditions for being a verifier


- if node y hears v in the same zone in which it hears x, then y may hear both x and v through the wormhole

→ for a valid verifier v, y must hear v and x from different zones (i.e., $Z_{yv} \neq Z_{yx}$ must hold)




- if v hears x in the same zone in which y hears x (i.e., $Z_{vx} = Z_{yx}$), then they may both hear x through the wormhole's transceiver
- if, in addition, x happens to hear the other transceiver of the wormhole in zone $\underline{Z}_{yx}$, then x can establish neighbor relationships with both y and v

→ for a valid verifier v, v must hear x from a zone different from the one in which y hears x (i.e., $Z_{vx} \neq Z_{yx}$ must hold too).



## Using verifiers – the mechanism

- y accepts x as a neighbor if
  - they hear each other from opposite zones
  - there's at least one valid verifier v such that x and v hear each other from opposite zones
- how does this detect wormholes ?
  - let us assume that y hears x through the wormhole
  - → one end of the wormhole is near to x, the other end is in zone $Z_{yx}$
  - let us further assume that v is a valid verifier
  - → first condition ($Z_{yv} \neq Z_{yx}$) is satisfied
    - → y hears v directly (since y hears v from a zone different from $Z_{yx}$)
    - → x hears both y and v through the wormhole
  - → second condition ($Z_{vx} \neq Z_{yx}$) is satisfied
    - → x and v cannot hear each other from opposite zones
      - let's assume that $Z_{xv} = \underline{Z}_{vx}$
      - we know that x hears both y and v through the wormhole → $Z_{xy} = Z_{xv}$
      - in addition, we know that $Z_{xy} = \underline{Z}_{yx}$ (otherwise y would not consider x as a potential neighbor)
      - $\underline{Z}_{vx} = Z_{xv} = Z_{xy} = \underline{Z}_{yx} \rightarrow Z_{vx} = Z_{yx}$ (contradicts the second condition)
  - → no valid verifier v exists such that x and v hear each other from opposite zones → y will not accept x as a neighbor

# Summary

- a wormhole is an out-of-band connection, controlled by the adversary, between two physical locations in the network
- a wormhole distorts the network topology and may have a profound effect on routing
- wormhole detection is a complicated problem
  - centralized and decentralized approaches
    - statistical wormhole detection
    - wormhole detection by multi-dimensional scaling and visualization
    - packet leashes
    - distance bounding techniques
    - anchor assisted wormhole detection
    - using directional antennas
  - many approaches are based on strong assumptions
    - tight clock synchronization
    - GPS equipped nodes
    - directional antennas
    - …
- wormhole detection is still an active research area