

So Near and Yet So Far: Distance-Bounding Attacks in Wireless Networks

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Outline

- 1 Introduction & background
- 2 Attacks on time-of-flight distance-bounding protocols
- 3 Conclusions

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Introduction

- Distance-bounding protocols are specialized authentication protocols that determine an **upper bound** for the physical distance between two parties
- Distance-bounding protocols prevent two parties from appearing closer together than they actually are
- Security is often tied to proximity (e.g., access tokens, contactless wallets)
- Applications to wireless network security
 - Preventing relaying attacks
 - Secure neighbor discovery
 - Component for secure localization
 - Preventing wormhole attacks



Secure location services vs. distance bounding

- Secure location services
 - Provides relative or absolute location of nodes within a network
 - Requires the ability to calculate distances or angles **and** collaboration between several nodes, e.g., ‘anchor’ or base station nodes providing trusted reference locations
- Distance bounding
 - Involves just two parties, a **prover** and **verifier**
 - The verifier places an upper bound on the distance to the prover
 - Distance bounding relies exclusively on the protocol and communication medium to ensure security—no ‘trusted anchors’ allowed!

Location-finding techniques

- Available techniques
 - **Received Signal Strength (RSS)**: Exploits the inverse relationship between signal strength and distance to estimate the distance to other nodes
 - **Angle-of-Arrival (AoA)**: Examines the directions of received signals to determine the locations of transmitters or receivers
 - **Time-of-Flight (ToF)**: Measures elapsed time for a message exchange to estimate distance based on the communication medium's propagation speed
- Suitability to distance bounding
 - RSS inappropriate since attackers can easily amplify and attenuate signals
 - AoA inappropriate since attackers can easily reflect or retransmit from different directions
 - This leaves RF and ultrasound time-of-flight mechanisms

Simple time-of-flight authentication protocol

- Why not use a challenge-response protocol?

$$1. \quad V \xrightarrow{\text{challenge}} P : N_V \in_{\mathbb{R}} \{0, 1\}^n$$

$$2. \quad P \xrightarrow{\text{response}} V : h_K(N_V)$$

- The verifier V times the round-trip time for the prover P 's response
- Distance bound is sensitive to delay t_d , which makes cryptographic operations infeasible

Brands-Chaum distance bounding protocol

P

$$m_i \in_R \{0, 1\}$$

$\xrightarrow{\text{commit}(m_1, m_2, \dots, m_k)}$

Start of rapid bit exchange

$\xleftarrow{C_i}$

$$R_i = C_i \oplus m_i$$

$\xrightarrow{R_i}$

End of rapid bit exchange

$$m = C_1 | R_1 | \dots | C_k | R_k$$

open commit, sign(m)

V

$$C_i \in_R \{0, 1\}$$

verify commit

verify sign(m)



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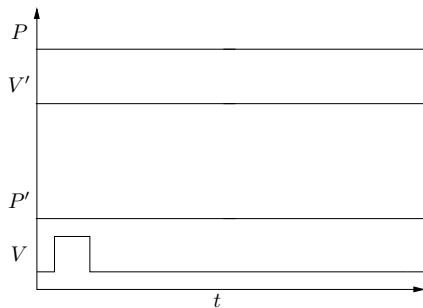
Discussion

- Delay t_d minimized by only using bitwise XOR with pre-committment
- Alternative construction due to Hancke-Kuhn uses a pre-computed table lookup
- Accuracy determine by:
 - Resolution of timing mechanism
 - Pulse width
 - Bit period t_p
 - Processing delay t_d
- Bit errors

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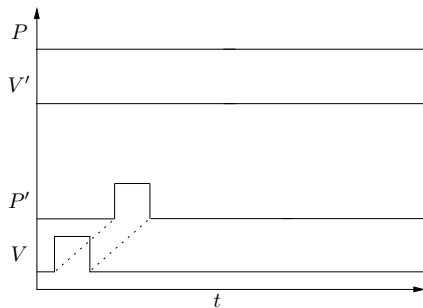
Relay attack with slow medium



- Vertical axis indicates node position; horizontal axis time
- 2 good nodes P and V ; 2 bad nodes P' and V'
- P & V transmit over ultrasound, but P' & V' use RF



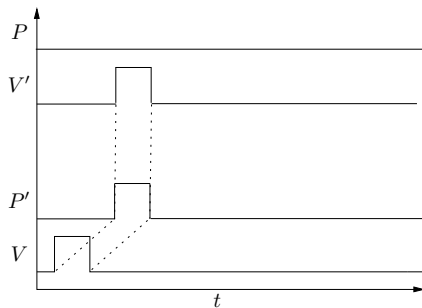
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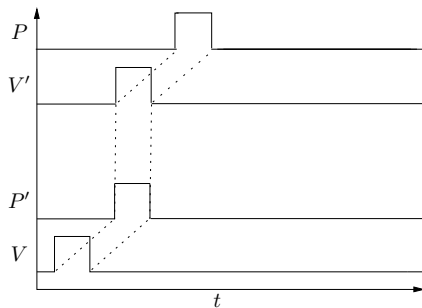
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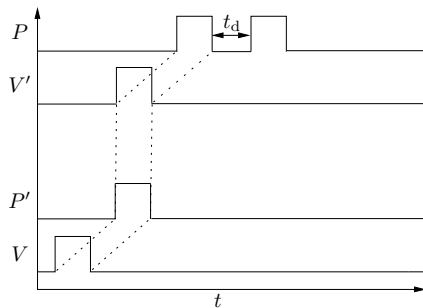
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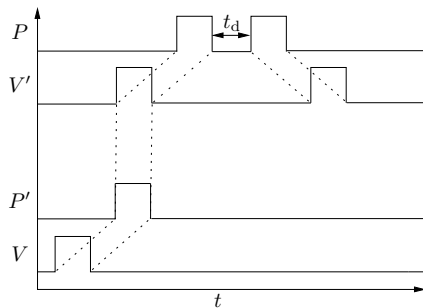
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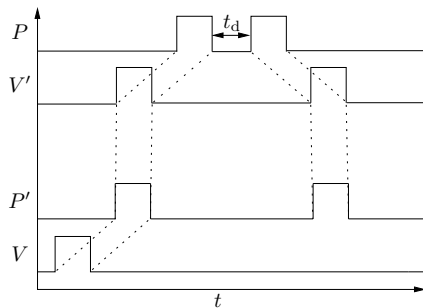
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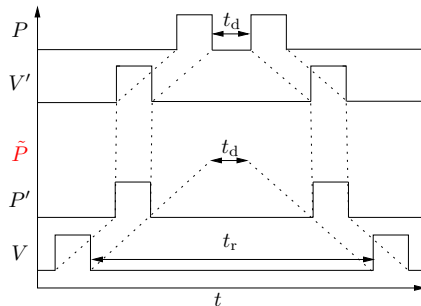
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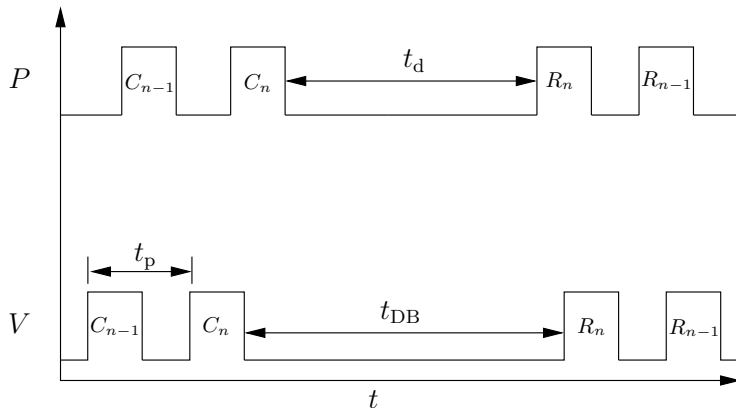


- The shortened round-trip-time t_r yields a **closer** perceived position \tilde{P}

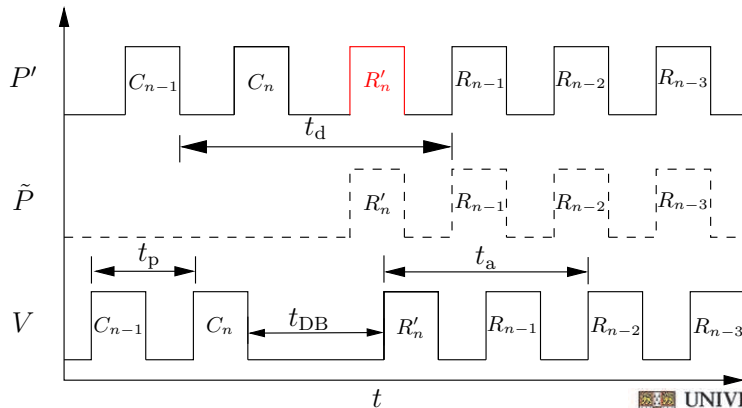
Guessing attacks on packet-based challenge-response protocols

- Braunds-Chaum times **multiple** single-bit exchanges between a prover and verifier
- Others have subsequently proposed timing a **single** packet-based exchange
 - For example, in Čapkun-Hubaux (2005, 2006), a verifier transmits an n -bit challenge $C_1 | \dots | C_n$ and the prover responds in reverse order $R_n | \dots | R_1$
 - An attacker can guess the last bit R'_n and preemptively transmit $R'_n | R_{n-1} | \dots | R_1$

Packet-based challenge-response protocol



Guessing attacks on packet-based challenge-response protocols

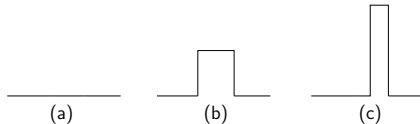


Comparison to Sastry et al.'s guessing attacks on packet-based challenge-response protocols

- Sastry et al. describe a guessing attack where the adversary (potentially distinct from the prover) shortens the perceived distance between the prover and verifier by exploiting differences between bitrates of in and out channels
- The attack can be addressed if the verifier chooses when to start and stop timing packet transmission
- In the guessing attack we describe, a malicious prover can shorten the perceived distance to the verifier independent of the bitrate
- Crucially, this **cannot** be addressed by choosing when to start and stop timing packets
- Multiple timings must be taken



Deferred bit signalling



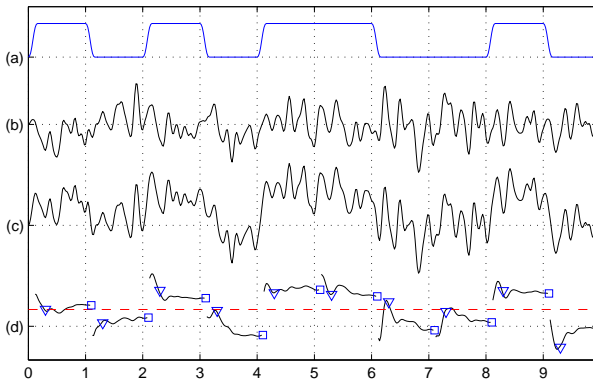
- If waveform (a) is the symbol for 0 and waveform (b) the symbol for 1, then what should waveform (c) be decoded as?
- Compare the received waveform with the two candidate symbols and integrate the differences over the duration of the symbol
- In effect, we can defer transmitting to extract a time advantage

Early bit detection

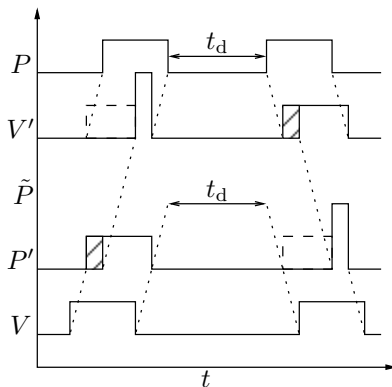
- Using a modified receiver, an attacker can preemptively determine which symbol a waveform represents
- If the attacker's receiver has an m -times better signal-to-noise ratio than a regular receiver, then the attacker's receiver can terminate the integration after observing $\frac{1}{m}$ -th of the symbol's energy (after about $\frac{1}{m}$ of the bit's transmission time)
- The attacker can save $\frac{m-1}{m}$ of the symbol's transmission time compared to using a regular receiver.



Early decision decoder example



Combining early bit detection with deferred bit signalling



Principles for secure time-of-flight distance-bounding protocols

- **Principle 1:** Use a communication medium with a propagation speed as close as possible to the physical limit for propagating information through space-time (the speed of light in vacuum). This excludes not only acoustic communication techniques, but also limits applicability of wires and optical fibers.
- **Principle 2:** Use a communication format in which only a single bit is transmitted and the recipient can instantly react on its reception. This excludes most traditional byte- or block-based communication formats, and in particular any form of forward error correction.



Principles for secure time-of-flight distance-bounding protocols (cont'd.)

- **Principle 3:** Minimize the length of the symbol used to represent this single bit. In other words, output the energy associated with a bit in as short a time as is feasible to distinguish the two possible transmitted bit values. This leaves the attacker no room to shorten this time interval much further.
- **Principle 4:** As the previous criterion may limit the energy that can be spent on transmitting a single bit, the distance-bounding protocol must be designed to cope well with substantial bit error rates.

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Conclusions

- Distance-bounding protocol design is severely constrained by tight timing requirements
- Anything less than timing several single-bit exchanges is prone to manipulation by a clever adversary
- Minimize symbol width (e.g., by using ultra-wideband) to limit exposure to early bit detection and deferred bit signalling attacks
- For more, visit:
<http://www.cl.cam.ac.uk/~twm29/>