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

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Outline

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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?

$$\begin{aligned} 1. \quad & V \overset{challenge}{\longrightarrow} P: \quad N_V \in_{\mathrm{R}} \{0,1\}^n \\ 2. \quad & P \overset{response}{\longrightarrow} V: \quad h_K(N_V) \end{aligned}$$

- 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

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Brands-Chaum distance bounding protocol

P		V
$m_i \in_R \{0,1\}$		$C_i \in_R \{0,1\}$
	$\xrightarrow{commit(m_1,m_2,\ldots,m_k)}$	
	Start of rapid bit exchange	
	$\xleftarrow{C_i}$	
$R_i = C_i \oplus m_i$		
	$\xrightarrow{R_i}$	
	End of rapid bit exchange	
$m = C_1 \vert R_1 \vert \ldots \vert C_k \vert R_k$		
	open commit, sign(m)	
		verify commit
		verify sign(m)

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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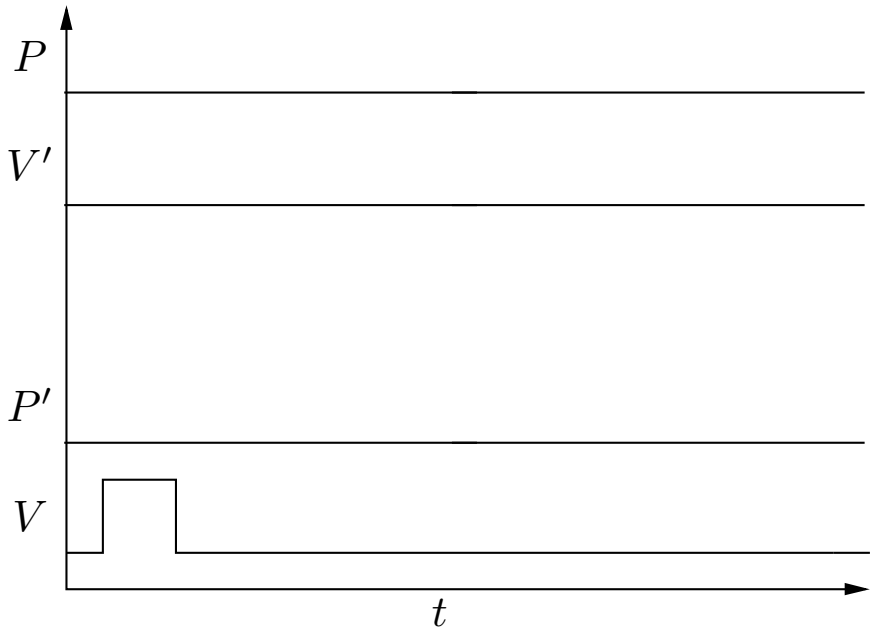
Relay attack with slow medium



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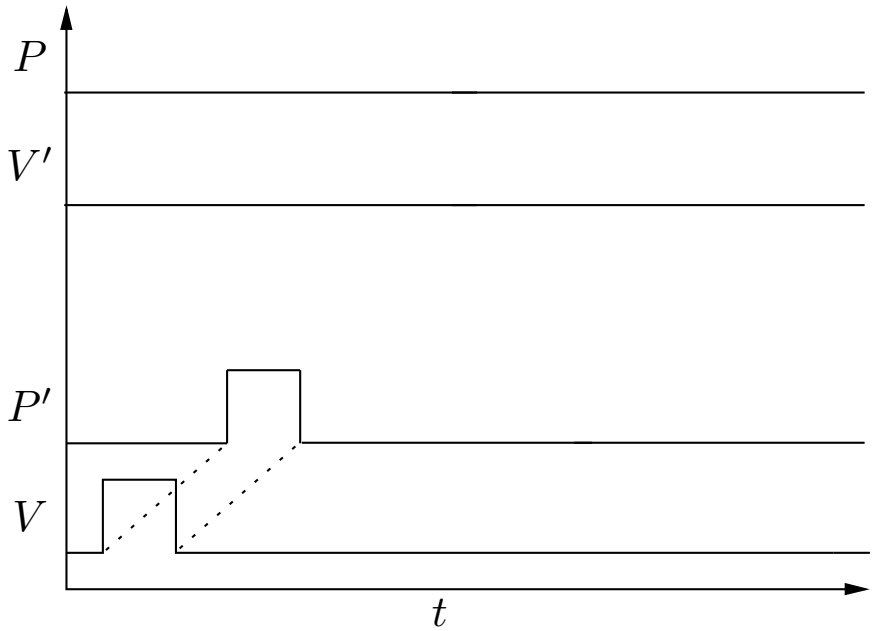

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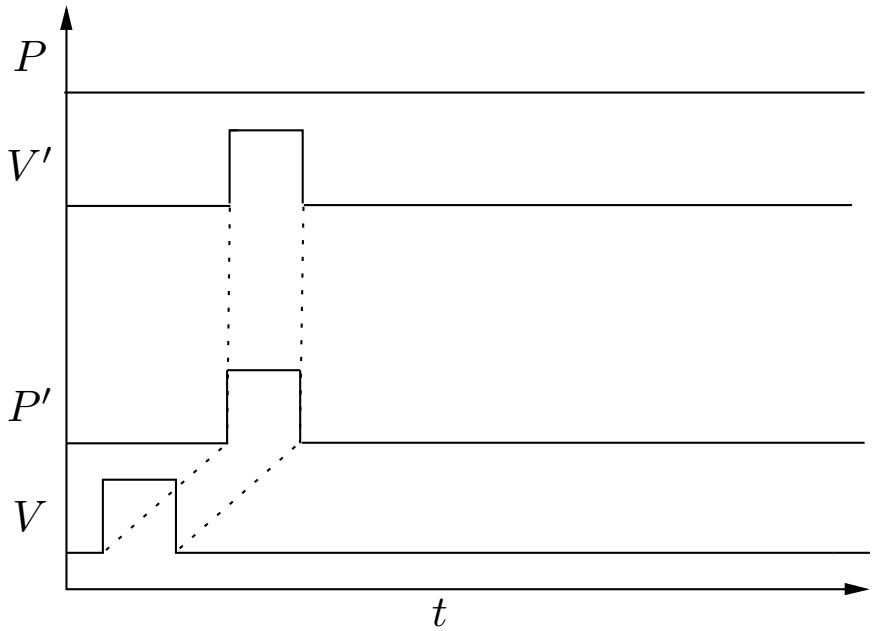

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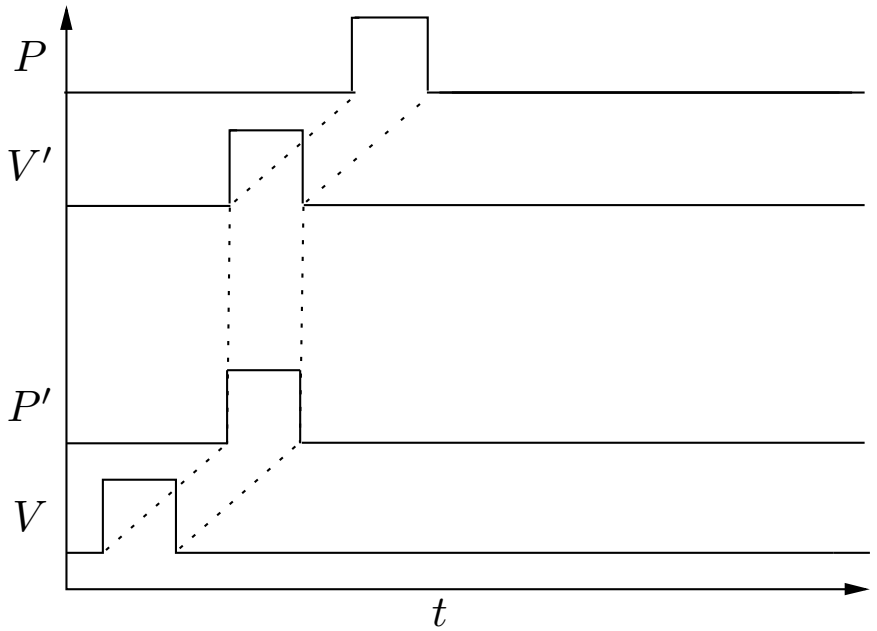

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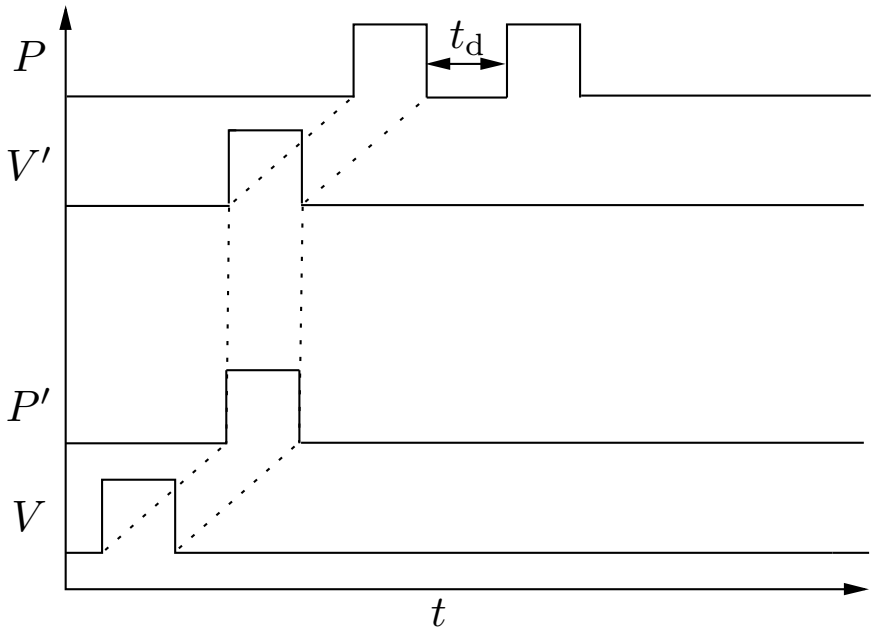

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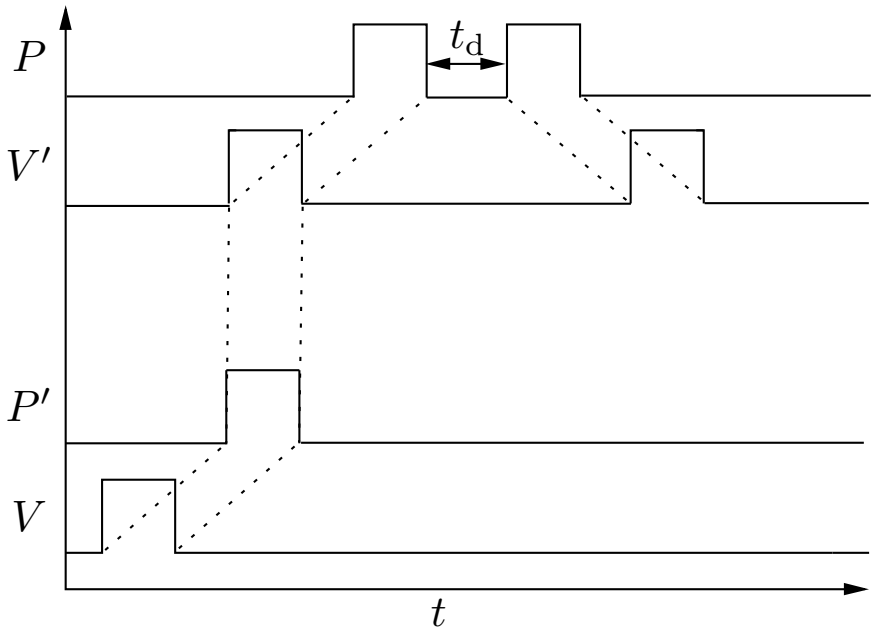

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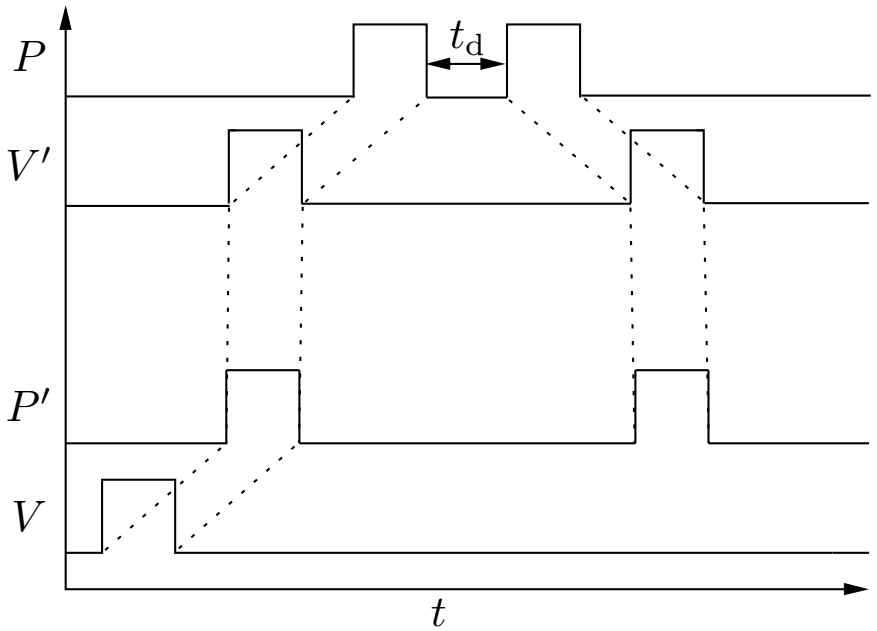

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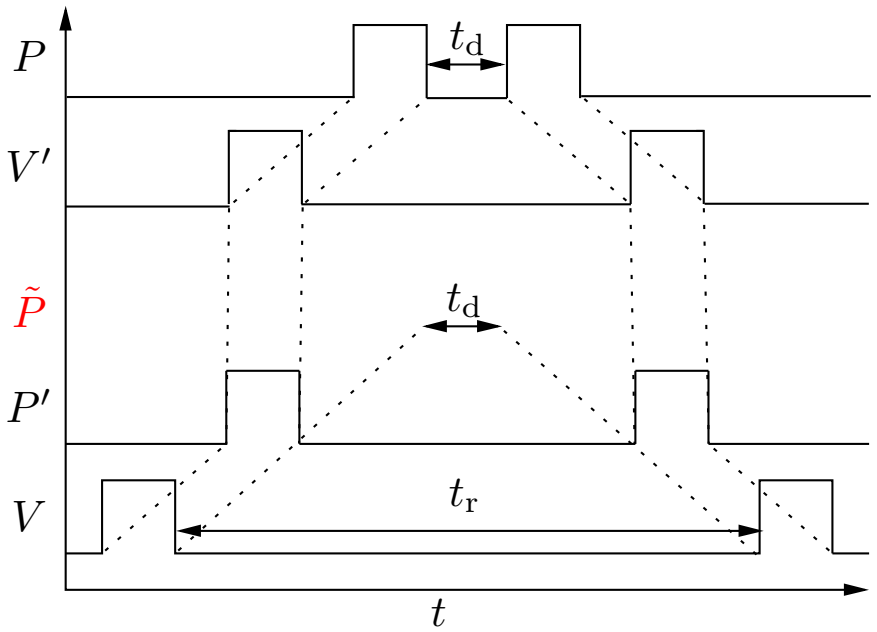

- The shortened round-trip-time t_r yields a closer perceived position $\tilde{P}$

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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 $C_1|\ldots|C_n$ and the prover responds in reverse order $R_n|\ldots|R_1$
  - An attacker can guess the last bit R'_n and preemptively transmit $R'_n|R_{n-1}|\ldots|R_1$

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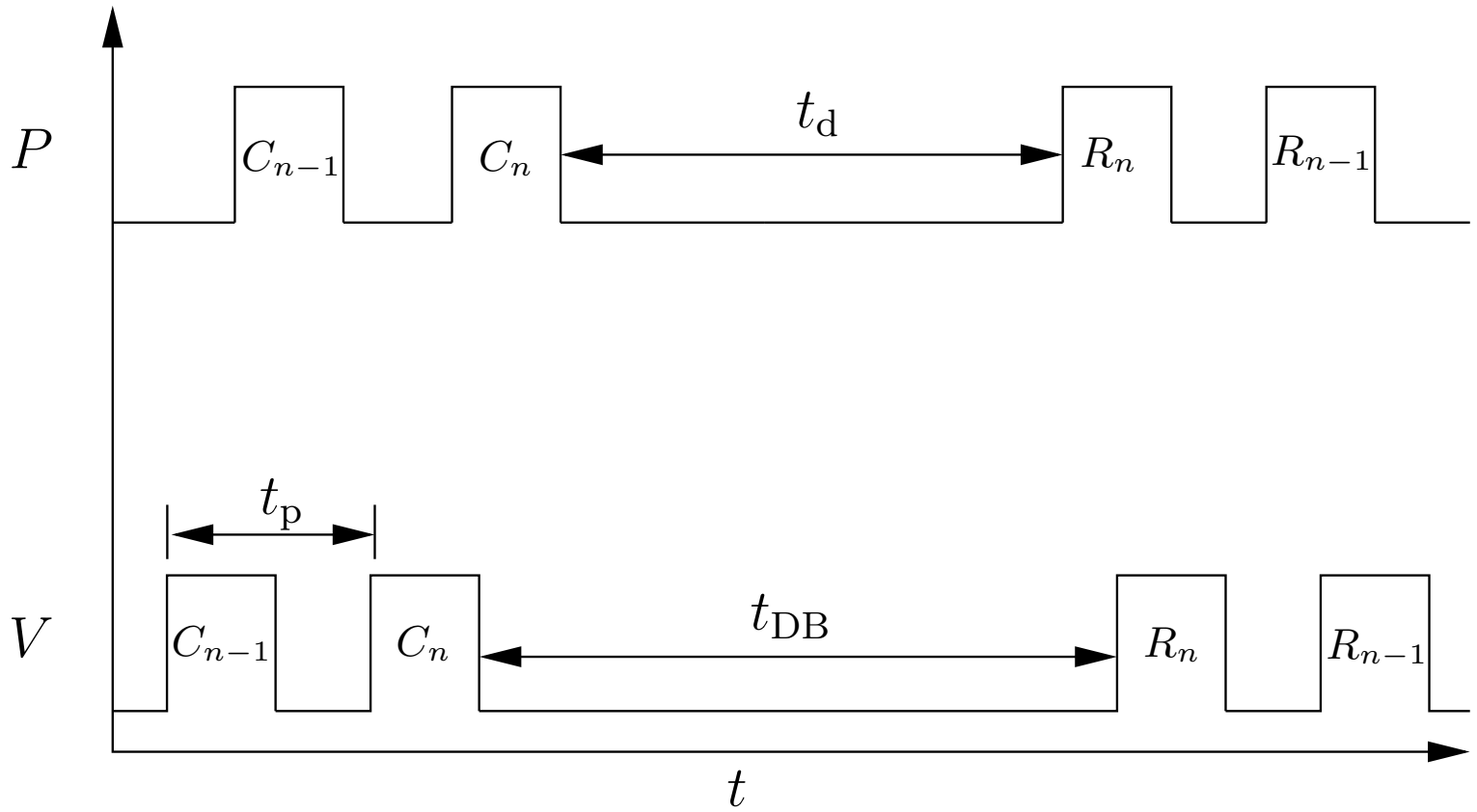
Packet-based challenge-response protocol



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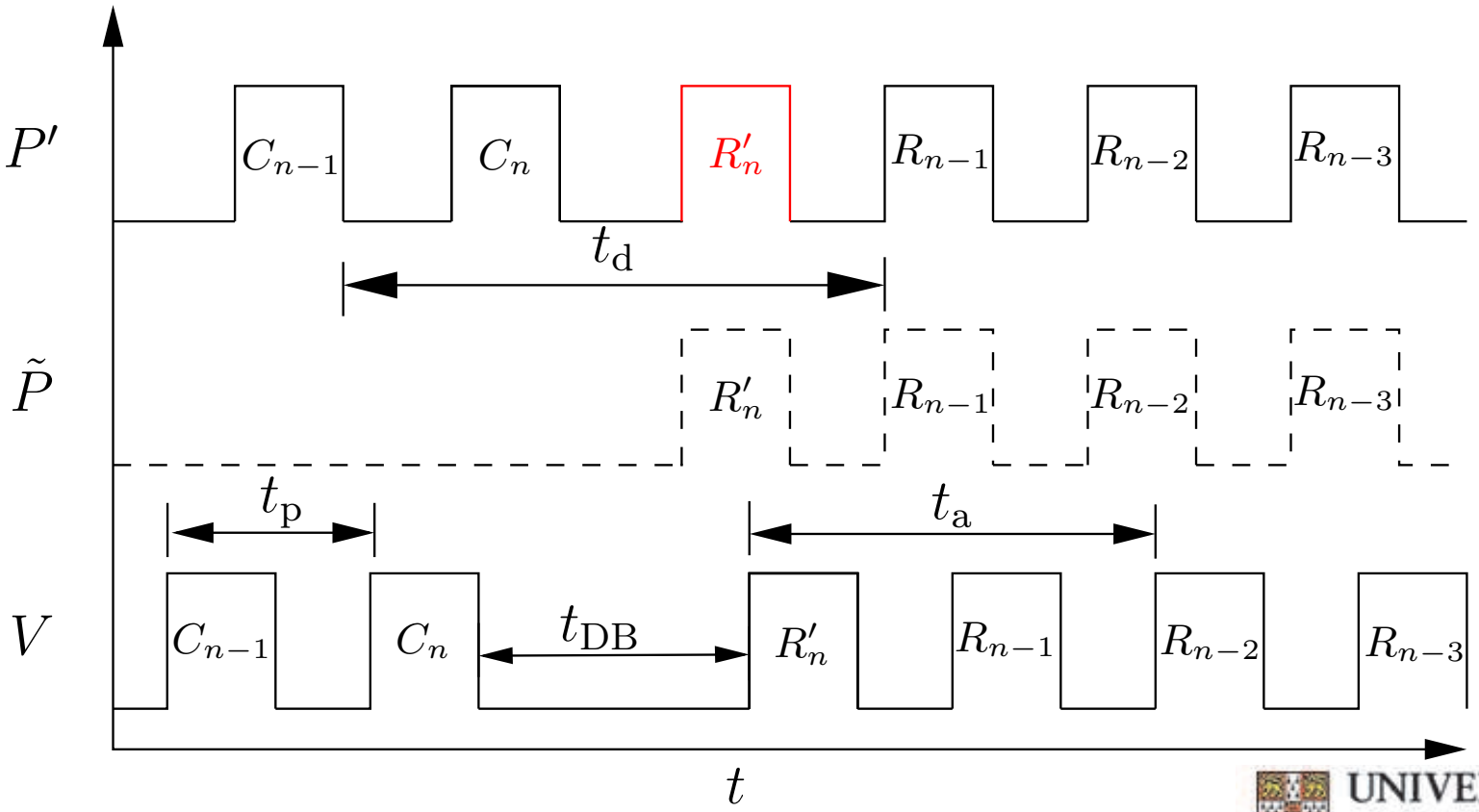

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Comparison to Sastry et al.'s guessing attacks on packet-based challenge-response protocols

- 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

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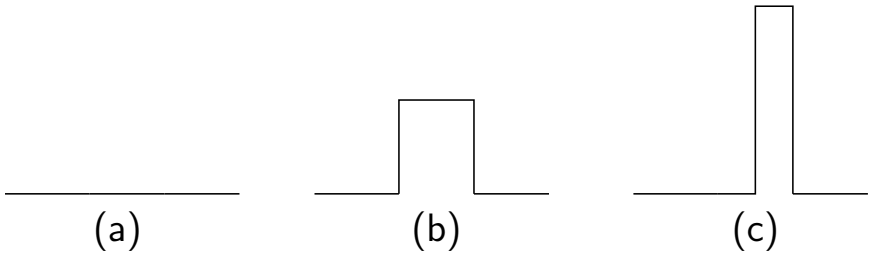
Deferred bit signalling



- 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

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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.

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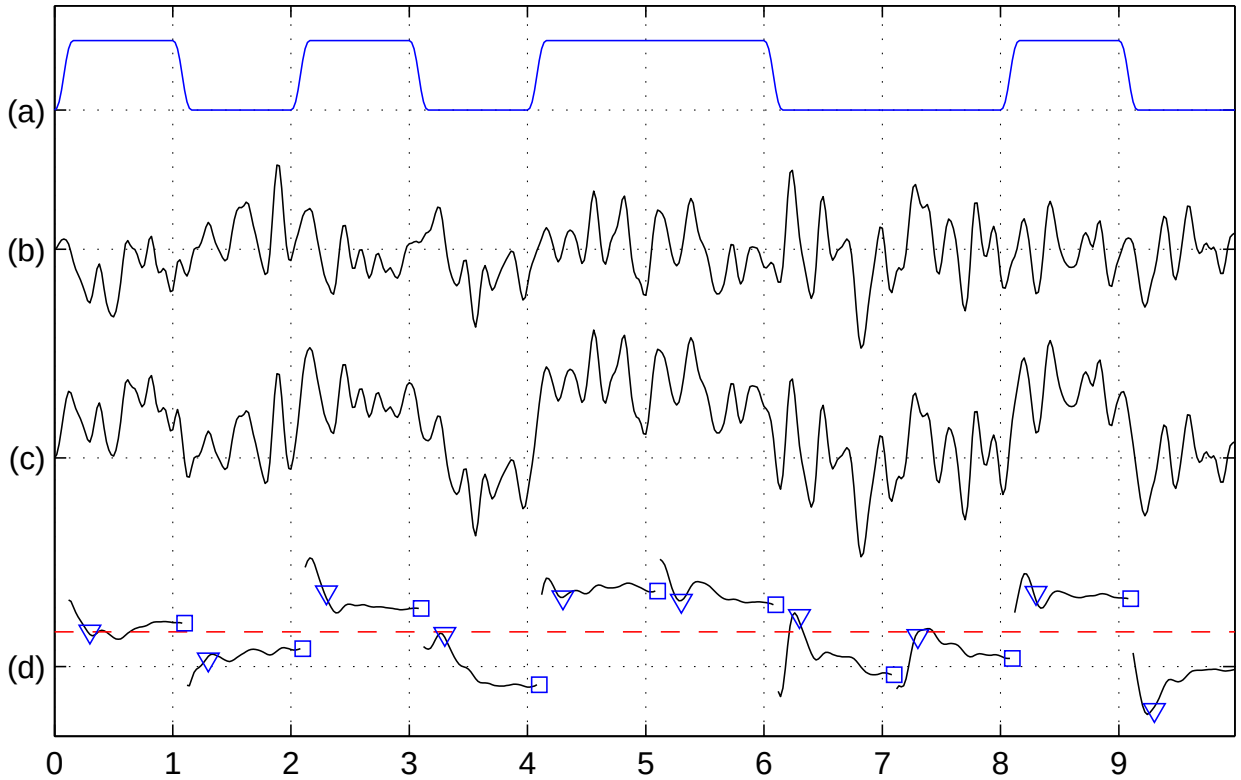
Early decision decoder example



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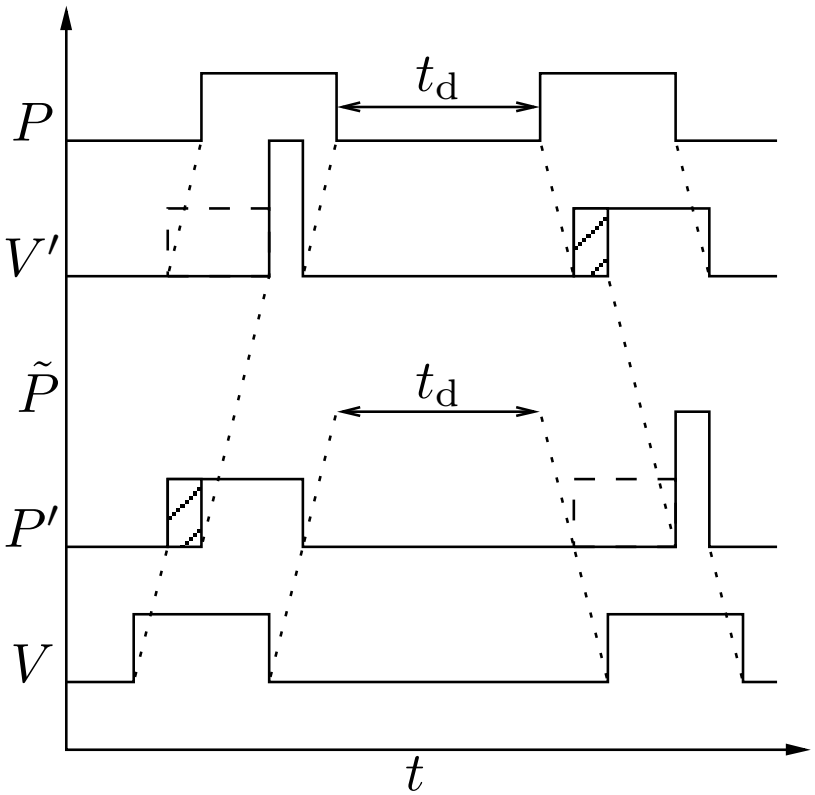
Combining early bit detection with deferred bit signalling



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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/`

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