From Jammer to Gambler: Modeling and Detection of Jamming Attacks against Time-Critical Traffic

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Outline

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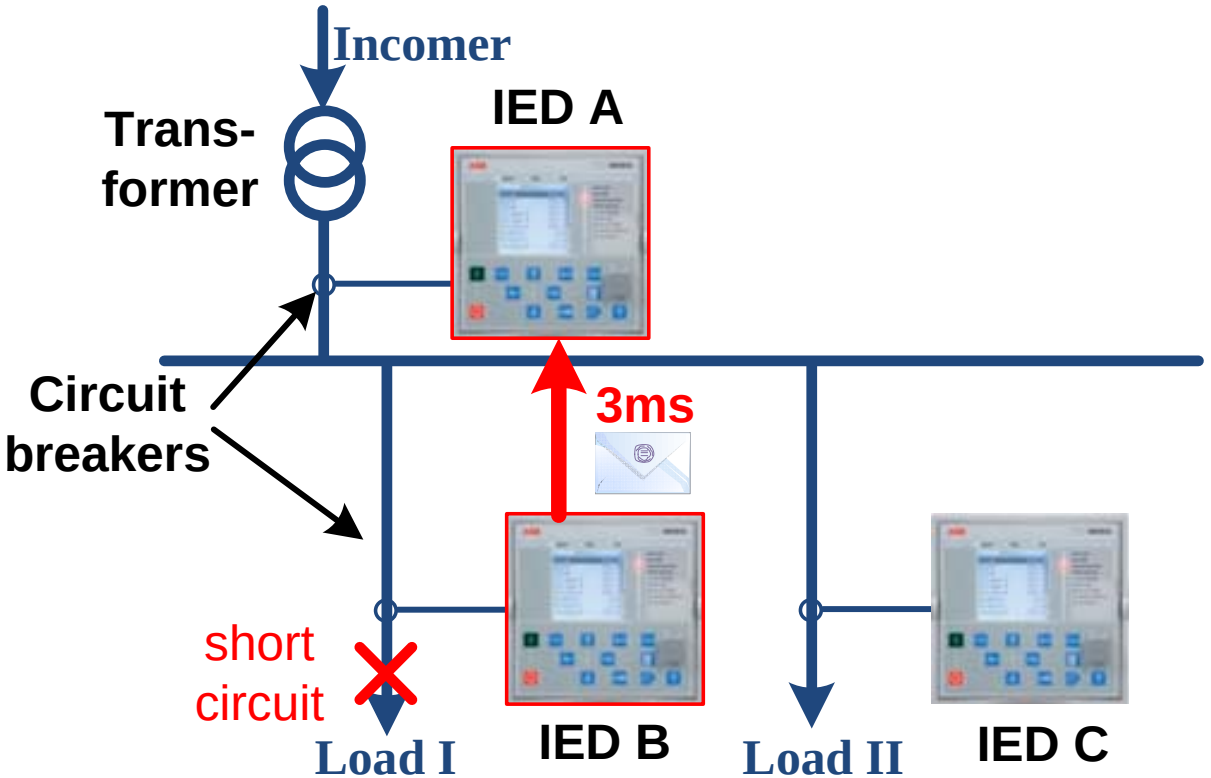
Time-Critical Wireless Networks

Emerging cyber-physical systems (notably the smart grid) have provided a new paradigm for wireless network design.

- Time-critical wireless networks.

Why Time-Critical?

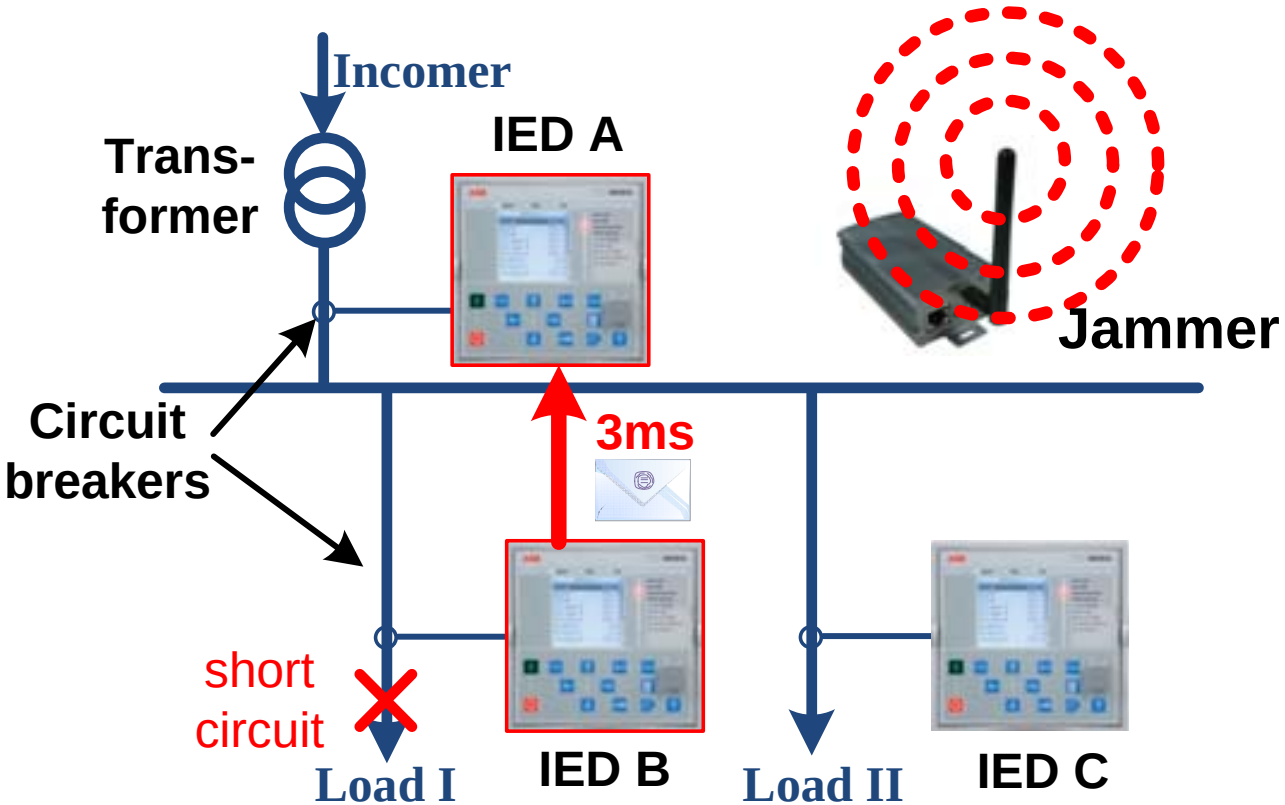
Example: A substation protection scenario.



- IED: Intelligent electronic devices
- B needs to tell A: Do not break your circuit!

Jamming Issue in Time-Critical Networks

Example: A substation protection scenario.



- A jammer can severely disrupt time-critical communication.

Exiting Works and Issues

Existing results can not be readily adopted in time-critical networks.

- Jamming modeling and evaluation: packet delivery/transmission ratios (Xu'02), number of jammed packets (Li'07), network throughput (Bayraktaroglu'08).

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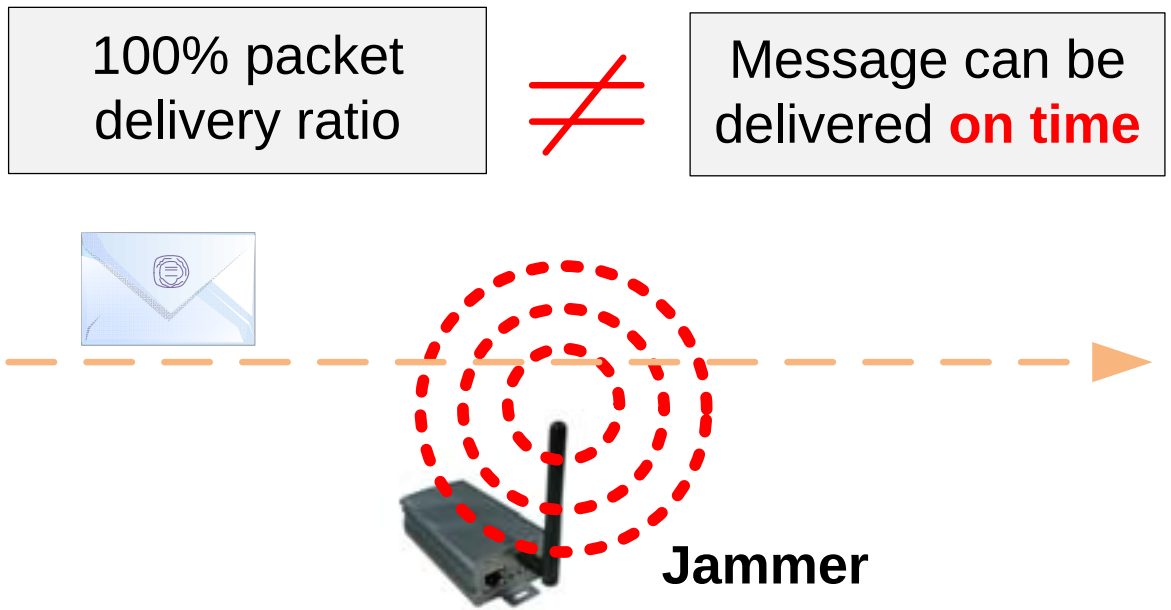

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  With no understanding of jamming impact, it is hard to design efficient detection methods.

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A fundamental question:

How to model and detect jamming attacks against time-critical traffic in wireless networks?

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- Highest priority,
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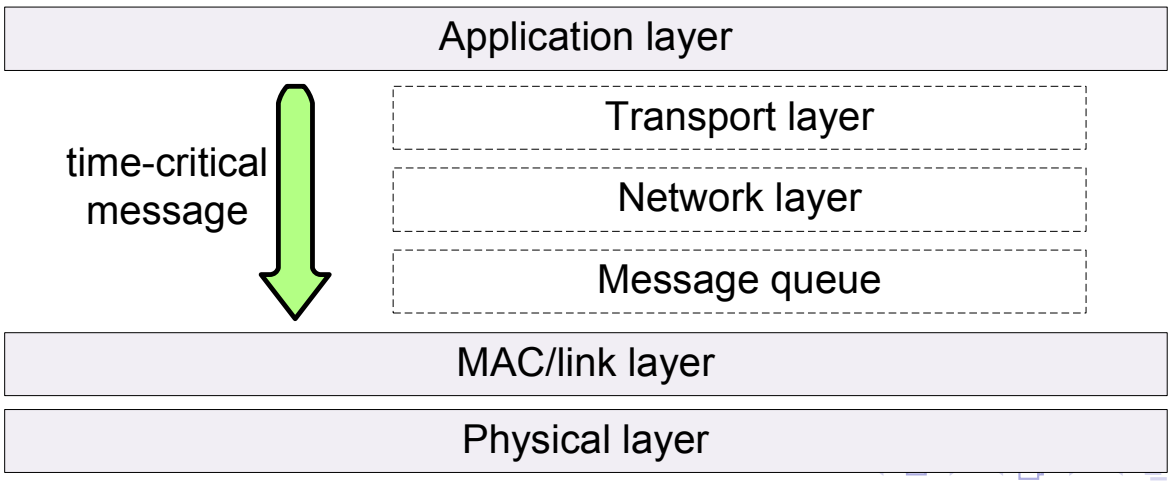
IEC 61850 is a recent standard for power substation communication.

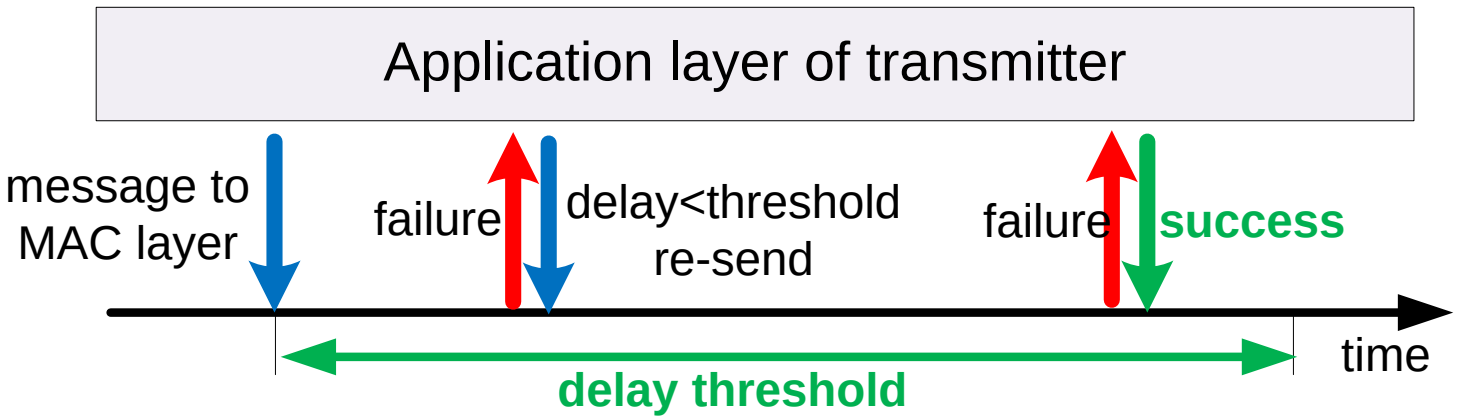
- GOOSE (Generic Object Oriented Substation Events) messages have 3ms and 10ms delay requirements for power device protection.
  - Simple retransmission mechanism: no any flow control.



Modeling for Time-Critical Transmission

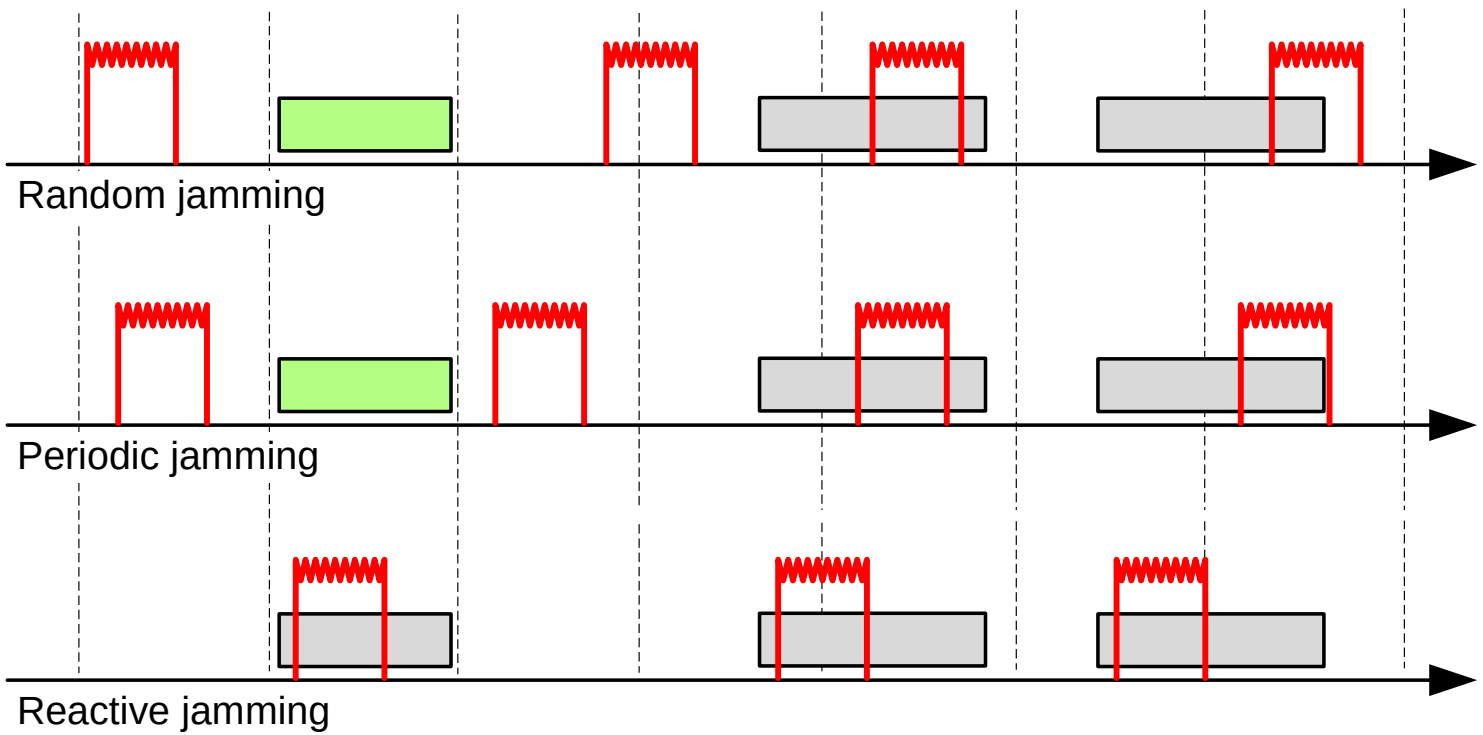
Modeling for time-critical transmission.

- A direct map from the application layer to MAC layer.
- Retransmission of a failed packet until the deadline.



Models for Jamming Attacks

Various jamming models available in the literature (Xu'02, Bayraktaroglu'08)



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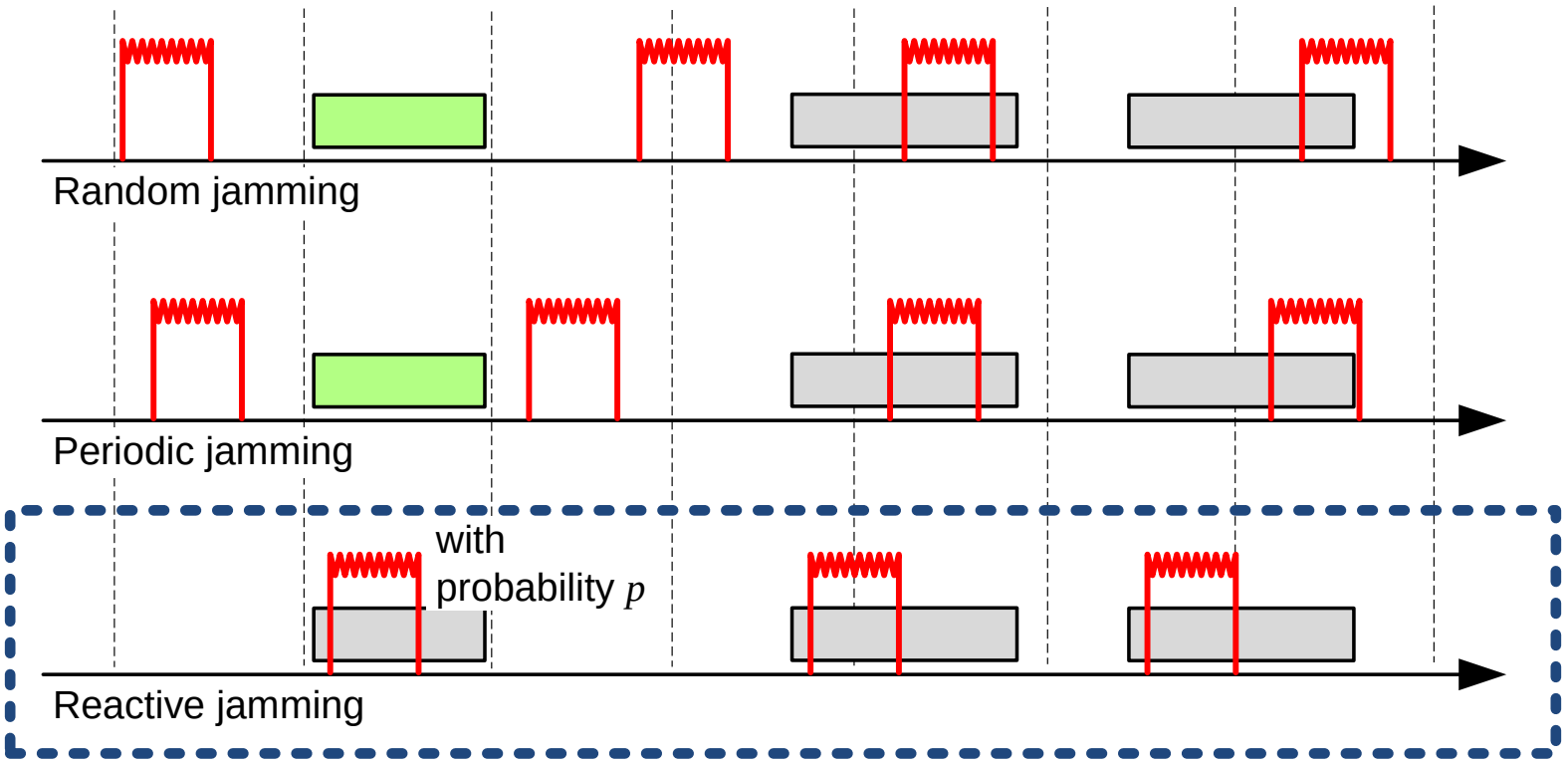
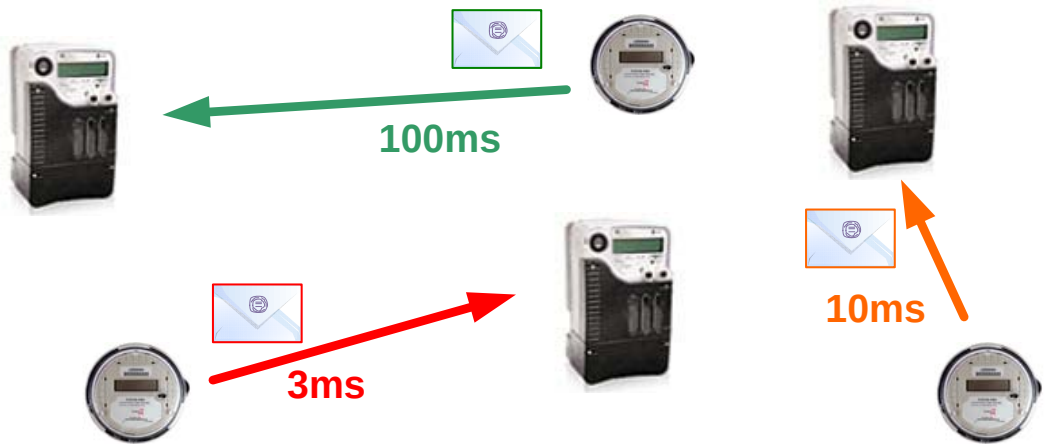


In this paper, we consider reactive jamming as it is the primary focus in existing work.

Performance Metric

The goal of time-critical network is to deliver time-critical messages with specific delay thresholds.



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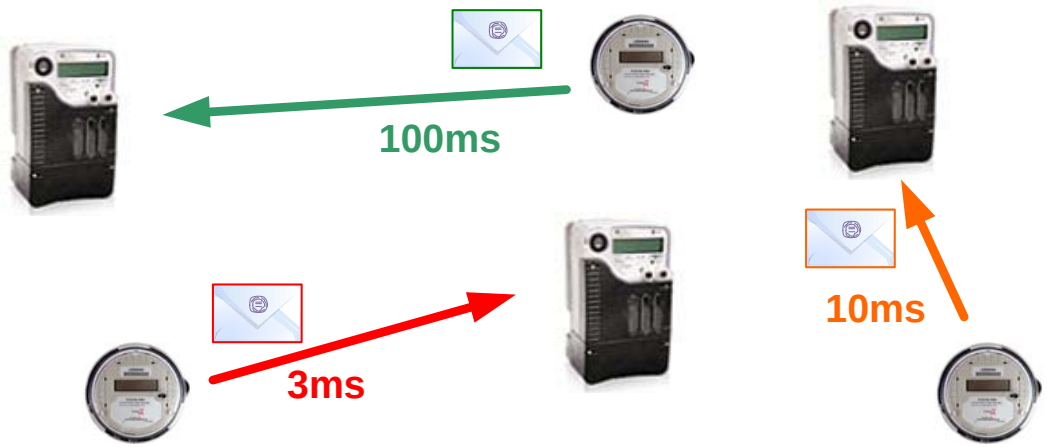

The metric should

1. be message-oriented.
2. directly reflect the delay constraints.

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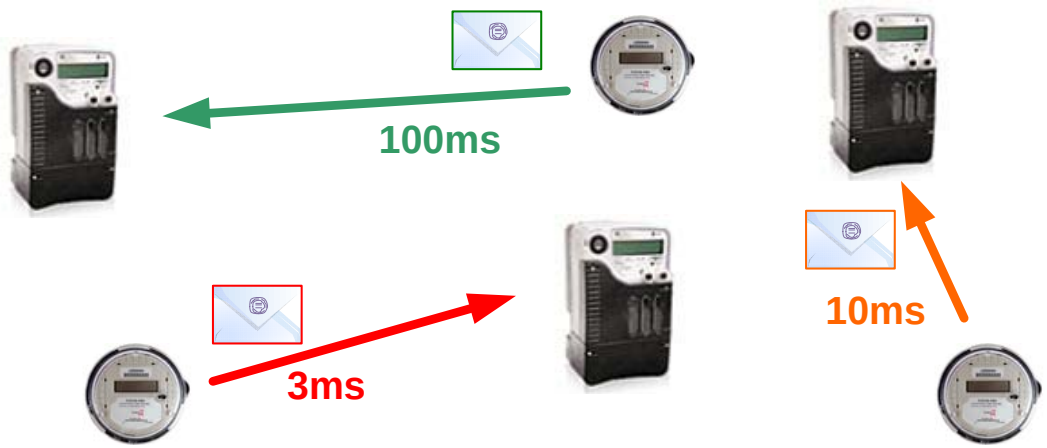


Message Invalidation Ratio

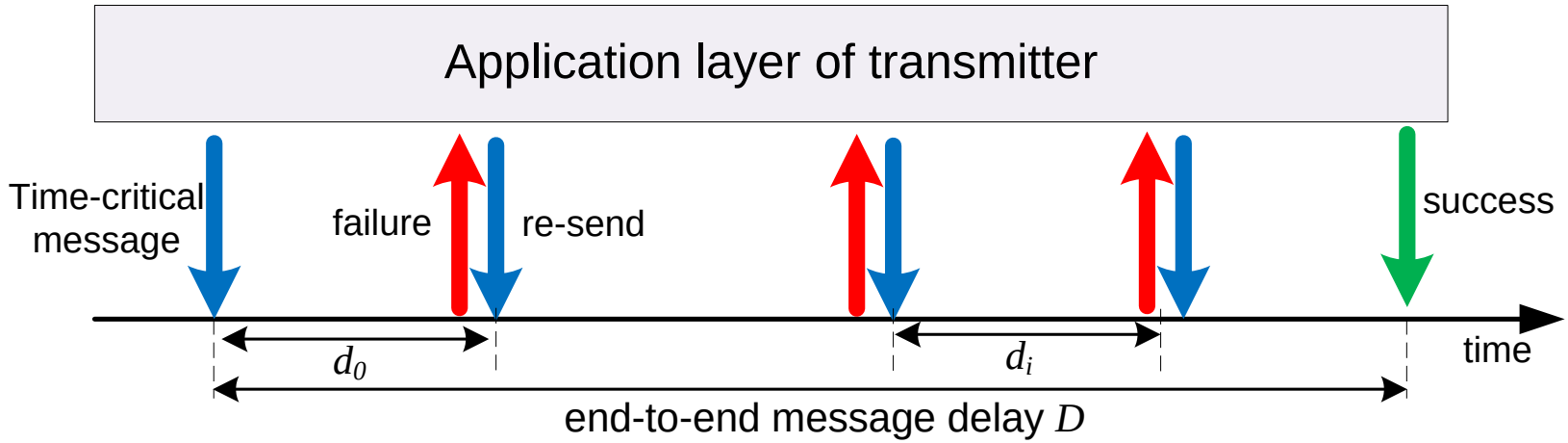
For a time-critical message with delay constraint σ, the message invalidation ratio is defined as

$$r = \mathbb{P}\{D > \sigma\},$$

where D is the end-to-end application-layer delay of the message.

Outline

Problem Formulation for End-to-End Delay



The end-to-end application delay:

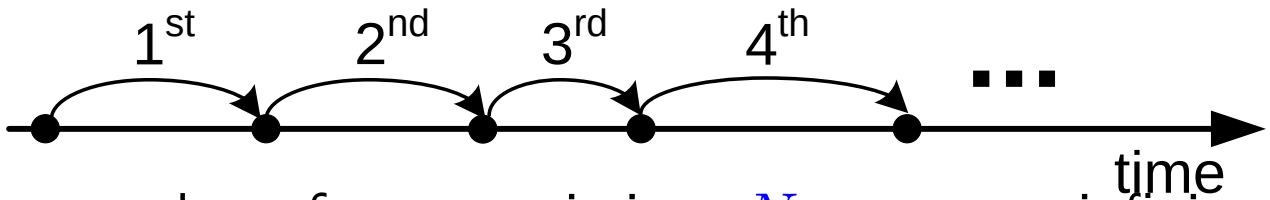
$$D = \sum_{i=0}^{N} d_i,$$

where d_i is the i.i.d. delay for i-th retransmission at the MAC layer, and N is the number of retransmissions.

The message invalidation ratio: $r = \mathbb{P}(D > \sigma)$.

Assumption: Dumb Transmitter

Assumption: A dumb transmitter always re-sends a transmission-failed packet until it is successfully delivered to the receiver.



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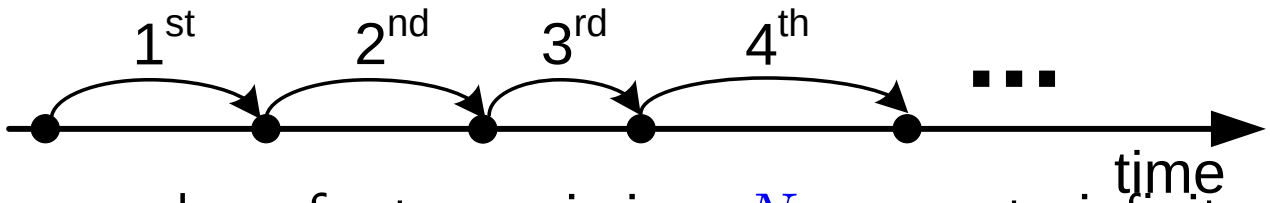

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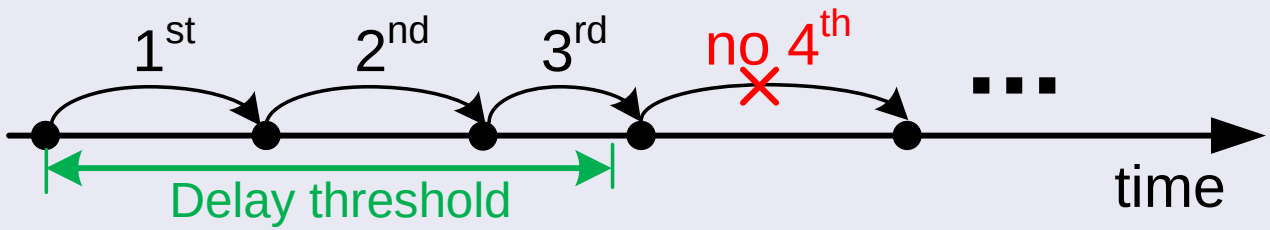
Practical challenge: A message is retransmitted until the deadline.



- N is an upper-bounded random variable dynamically coupled with the cumulative delay in history.
- Mathematically, N is a stopping time. (need non-asymptotic tools!)

Martingale Theory

An effective tool to solve stopping time related mathematical problems.

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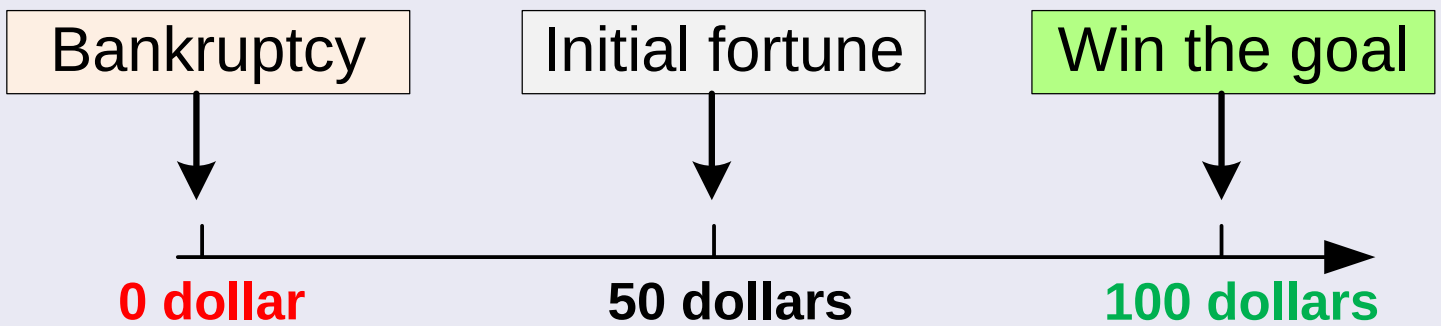
Gambler's ruin

In each play, he wins (or, loses) 1 dollar with probability p (or, $1-p$).



What is the probability that the gambler can win the game?

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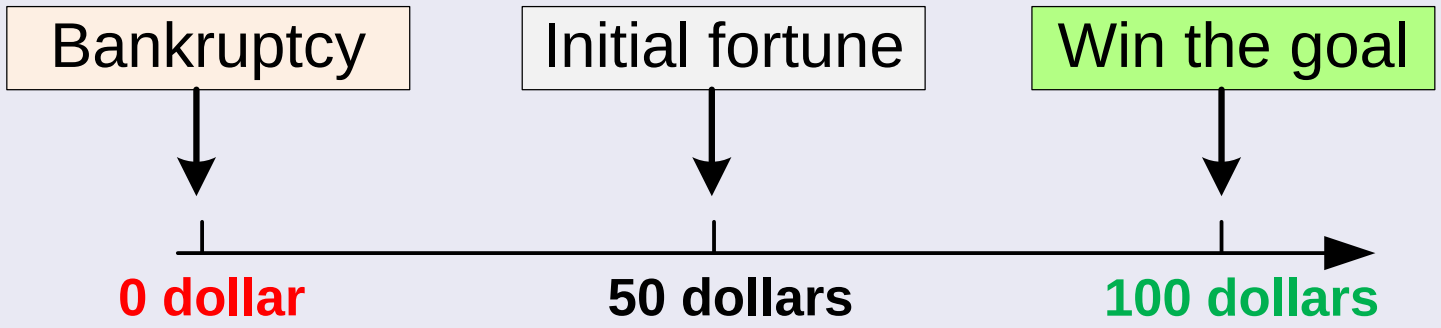

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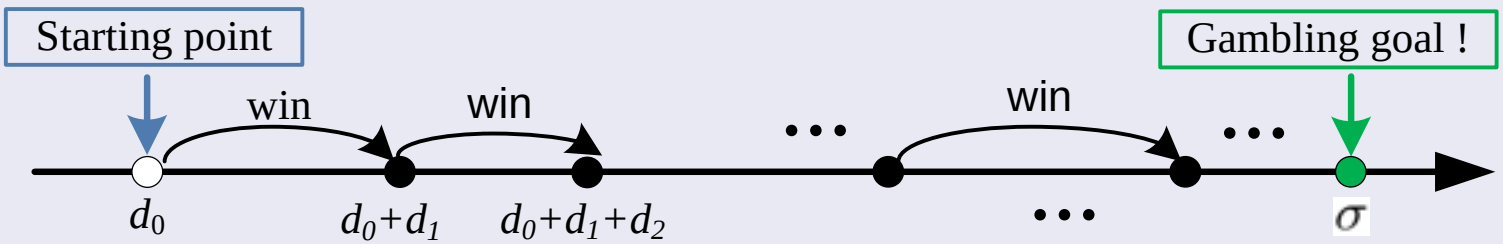
From Jammer to Gambler

The Jammer is a gambler

- Delay $\Rightarrow$ money
- Delay threshold $\Rightarrow$ gambler's winning goal.



- Message invalidation: the jammer keeps jamming each transmission of a message such that the cumulative delay is larger than the delay threshold.
- The gambler wins: the gambler keeps winning each play such that the cumulative money is larger than his goal.

Analytical Results Based on Martingale Theory

Theorem (Message invalidation ratio for general cases)

Given a jamming strategy $\mathcal{J}(p)$, the message invalidation ratio r is

$$r = \frac{\mathbb{E}(D_s) - \frac{c}{1-p_a}}{\mathbb{E}(D_s) - \frac{p_a c}{1-p_a} - \mathbb{E}(D_u)},$$

where $p_a = p^{N_{mac}}$, N_{mac} is the retry number at MAC layer, $c = \mathbb{E}(d_i)$ is the mean of the i.i.d. MAC-layer delay d_i, $D_s \leq \sigma$ is the end-to-end delay of a successfully delivered message, and $D_u > \sigma$ is the delay of failed message delivery.

Theorem (General upper bound)

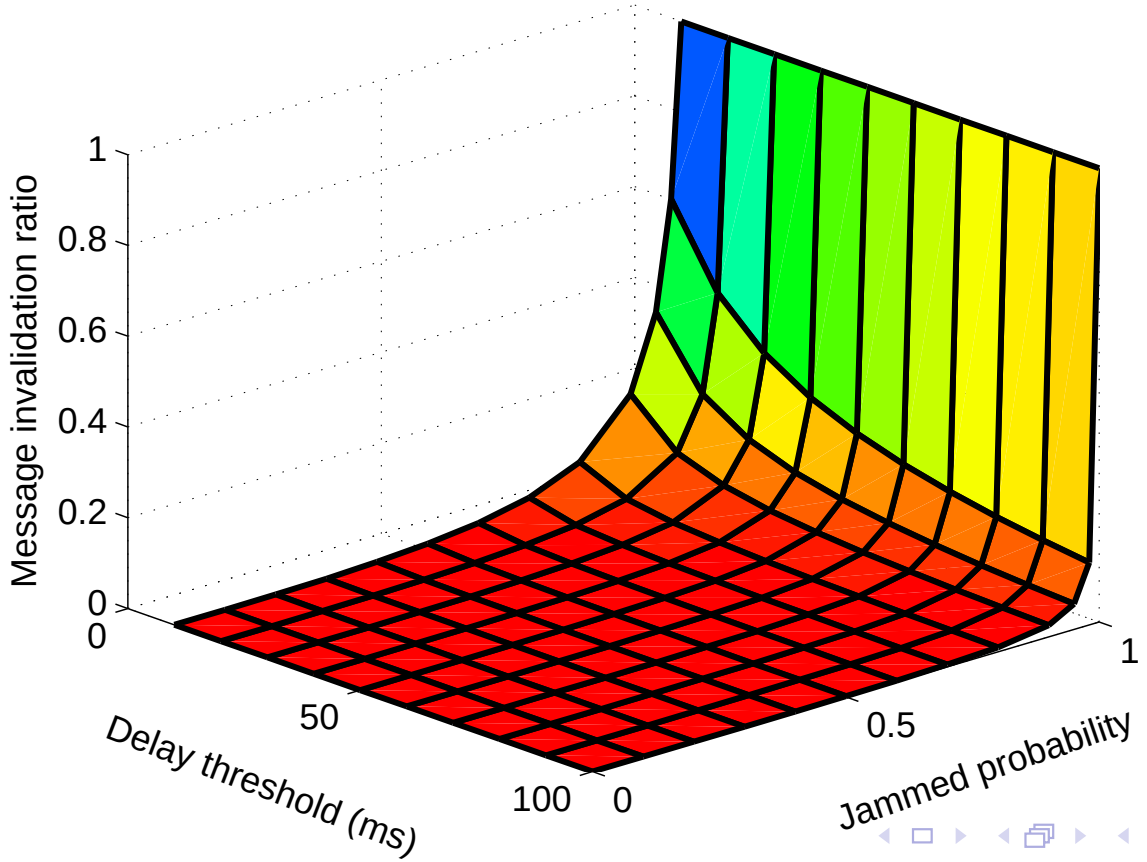
For the message invalidation ratio r in Theorem 1, it satisfies that

$$r \leq \frac{p^{N_{mac}} c}{(1 - p^{N_{mac}})(\sigma - c) + p^{N_{mac}} c}.$$

Indication of Analytical Results

Phase transition for message invalidation ratio:

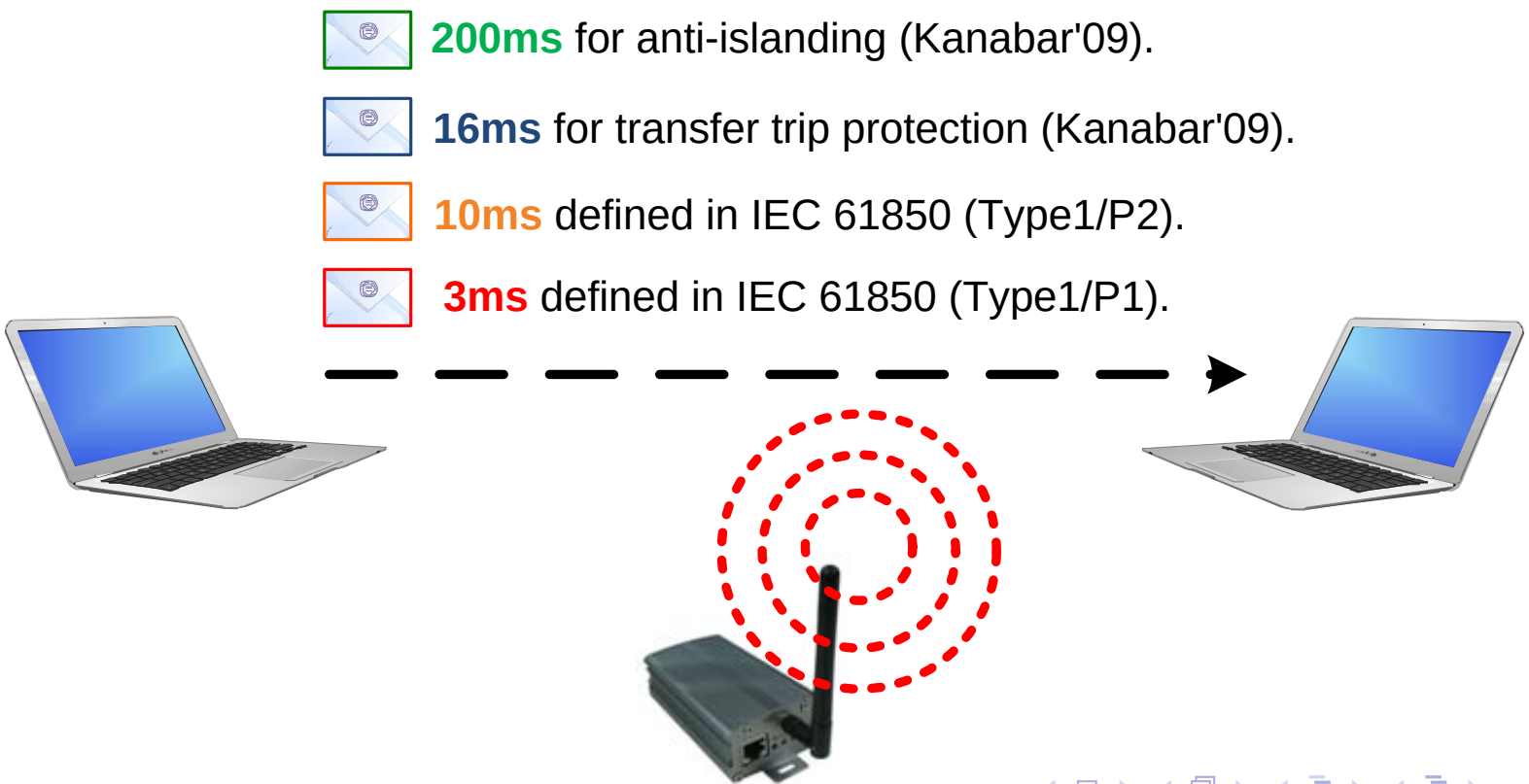
- Slightly-increasing phase: increases negligibly with the increasing of the jamming probability p.
- Dramatically-increasing phase: increases dramatically (and linearly) with the increasing of the jamming probability p.



Experimental Evaluation: Setups

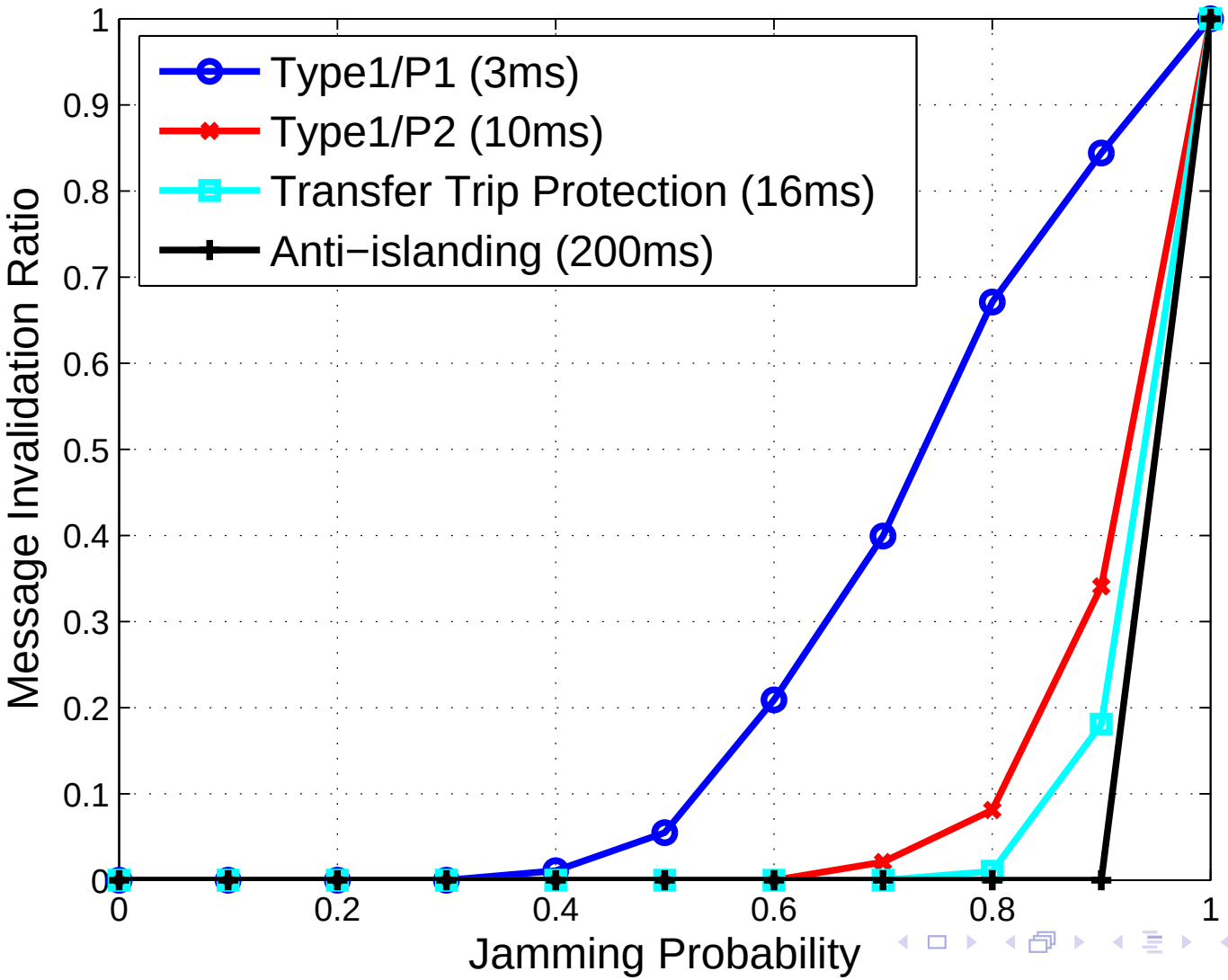
Setups:

- Network: a WiFi-based substation network. (WiFi Aliance'09, Kanabar'09, Akyol'10)
- Jammer: USRP with RNU Radio.
- Time-critical messages: 4 GOOSE applications.



Experimental Results: Message Invalidation Ratio

GOOSE messaging between a transmit-receive pair under jamming.



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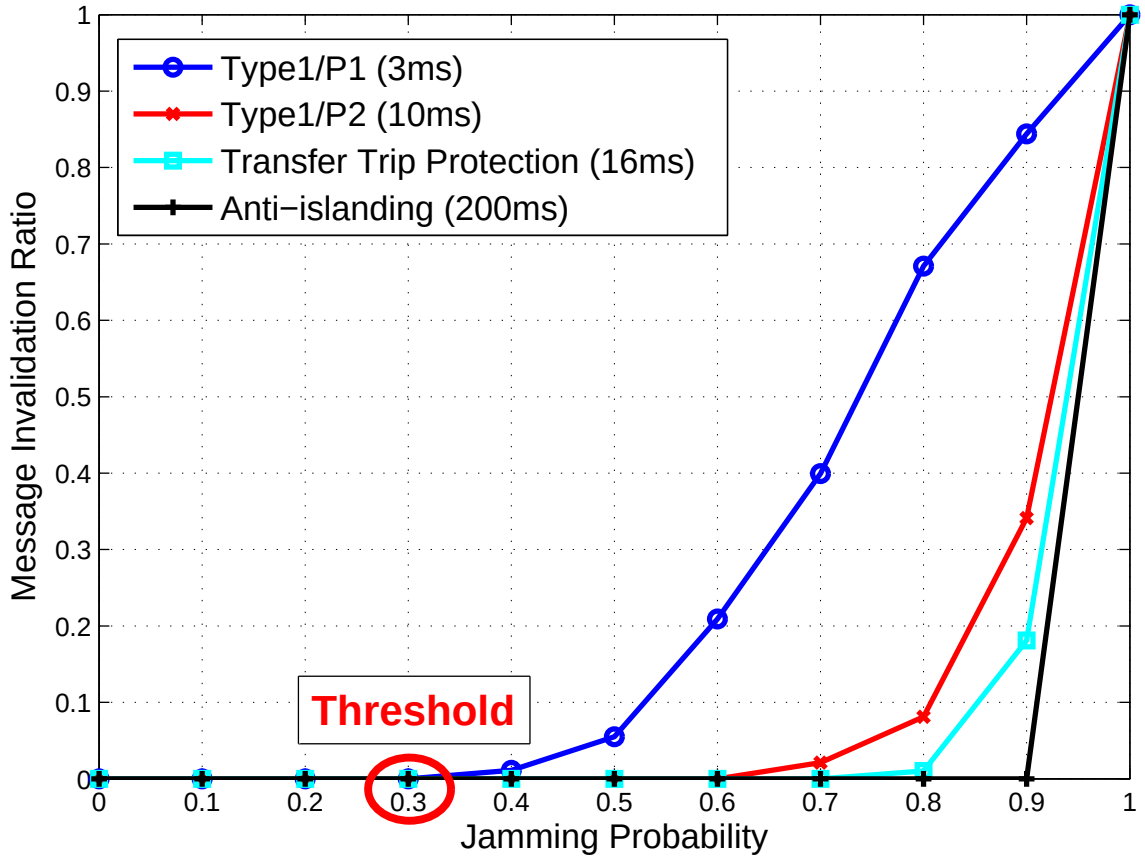
JADE: Jamming Attack Detection based on Estimation



1. Transmit a number of packets.
2. Estimate the jamming probability $\hat{p}$ based on transmission results (e.g. no ACK)
3. if $\hat{p} > p^*$, jamming exists. The threshold p^* is chosen smaller than the transition point: $p^* = 0.3$.

Experimental Results of JADE

Jammer: time-varying with jamming probability p uniformly distributed on $[0.4, 0.9]$.

Benchmark: the Likelihood Ratio (LLR) Test (Li'07) is the theoretically optimal detector for deterministic models.

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Table: Detection Ratios of both JADE and LLR Test

Number of Samples:	50	100	150	200
Detection Time:	54ms	109ms	163ms	218ms
JADE:	98.6%	99.1%	100%	100%
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- The LLR Test has a model mismatching problem in dealing with a practical time-vary jammer.

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Conclusion

1. Motivated by emerging time-critical wireless applications, we introduce the message invalidation ratio to quantify the impact of jamming attacks against time-critical traffic.
   - Theoretical results: Gambling based modeling.
   - Experimental results: GOOSE messaging in IEC 61850.
2. We show a phase transition phenomenon for the message invalidation ratio.
   - Slightly-increasing phase.
   - Dynamically-increasing phase.
3. We developed a JADE system to achieve simple, efficient and robust jamming detection for power substation networks.

Thank you!