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

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Outline

1 Motivation

2 Preliminaries
   - Modeling for Time-Critical Transmission
   - Modeling for Jamming Attacks
   - Performance Metric

3 Main Results
   - Analytical Modeling
   - Experimental Evaluation

4 JADE: Jamming Attack Detection based on Estimation

5 Conclusion
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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).
Exiting Works and Issues

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100% packet delivery ratio ≠ Message can be delivered on time
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- Jamming detection: requires the knowledge of the jamming impact to accurately identify significant attacks. (Xu’02, Wood’07)
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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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Requirements for Time-Critical Transmission

Time-critical messages require

- Highest priority,
- Low processing delay,
- No buffering and queuing.

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.
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  - Simple retransmission mechanism: no any flow control.

![Diagram showing the layers of a communication stack with a time-critical message at the Application layer.]
Modeling for time-critical transmission.

- A direct map from the application layer to MAC layer.
- Retransmission of a failed packet until the deadline.
Various jamming models available in the literature (Xu'02, Bayraktaroglu'08)

- Random jamming
- Periodic jamming
- Reactive jamming
Models for Jamming Attacks

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

- Random jamming
- Periodic jamming
- Reactive jamming with probability $p$

In this paper, we consider reactive jamming as it is the primary focus in existing work.
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 $\sigma$, 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.
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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: A dumb transmitter always re-sends a transmission-failed packet until it is successfully delivered to the receiver.

- The number of retransmissions $N$ can go to infinity.
- Enables asymptotic analysis. (Malone’07, Bayraktaroglu’08)
Assumption: Dumb Transmitter

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- The number of retransmissions $N$ can go to infinity.
  - enables asymptotic analysis. (Malone’07, Bayraktaroglu’08)

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.

- Part of the motivation is to formulate some problems in gambling.

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**Gambler’s ruin**

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

<table>
<thead>
<tr>
<th>Initial fortune</th>
<th>Win the goal</th>
<th>Bankruptcy</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 dollars</td>
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<td>50 dollars</td>
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What is the probability that the gambler can win the game?

If the jamming process can be mapped to a similar gambling game, we are done.

100 dollars 0 dollar 50 dollars

Initial fortune Win the goal Bankruptcy
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Gambler’s ruin

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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 \( J(p) \), 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 Alliance’09, Kanabar’09, Akyol’10)
- Jammer: USRP with RNU Radio.
- Time-critical messages: 4 GOOSE applications.

- **200ms** for anti-islanding (Kanabar’09).
- **16ms** for transfer trip protection (Kanabar’09).
- **10ms** defined in IEC 61850 (Type1/P2).
- **3ms** defined in IEC 61850 (Type1/P1).
Experimental Results: Message Invalidation Ratio

GOOSE messaging between a transmit-receive pair under jamming.

- Type1/P1 (3ms)
- Type1/P2 (10ms)
- Transfer Trip Protection (16ms)
- Anti-islanding (200ms)
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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: $p^* = 0.3$. 
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.
**Experimental Results of JADE**

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<tbody>
<tr>
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<td>54ms</td>
<td>109ms</td>
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<td>JADE:</td>
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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.

| 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%   |
| LLR Test :                                   | 91.3%  | 92.1%  | 92.5%  | 91.6%  |

- The LLR Test has a **model mismatching problem** in dealing with a practical time-vary jammer.
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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!