Hiding Traffic with Camouflage: Minimizing Message Delay in the Smart Grid under Jamming

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Outline

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Smart Grid Vision

The Smart Grid: the next-generation power grid.

- Power infrastructures with information technologies.
- National Institute of Standards and Technology (NIST): Roadmap and Guidelines. [NIST'09,10,11]

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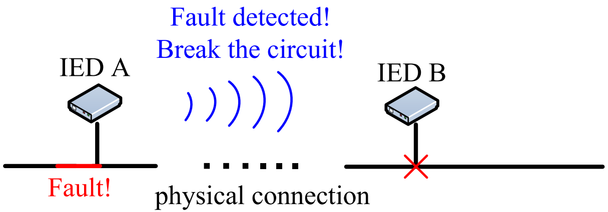
Wireless networks for power control applications [NIST'11].

- Efficient
- Low-cost
- Convenient network access

Power Applications over Wireless

Example: A generic protection scenario over wireless networking [Cleverland'07,Kanabar'09,El-Khattam'10].



- IED: Intelligent electronic devices
- A needs to tell B: break your circuit!
- The message has a strict delay requirement.
  - Example: 3ms/10ms for substation protection [IEC 61580].

Threat of Jamming Attacks on Power Applications

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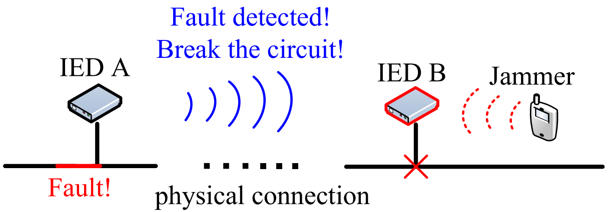

A jammer can disrupt the time-critical messaging, leading to

- denial-of-service, as it does in conventional wireless networks.
- physical damages to power infrastructures.

Existing Anti-Jamming Works: Methods and Issues

Communication theory: Spread spectrum technologies

- frequency hopping (FH) or direct sequence (DS)
- building multiple frequency and code channels.
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  - Widely-adopted models: memoryless, periodic, reactive, *et al* [Xu'02, Bayraktaroglu'08].

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- Worst-case methodology is vital to smart grid security design.

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In this paper, given fixed network setups, we find a new way to minimize the message delay under worst-case jamming attacks.

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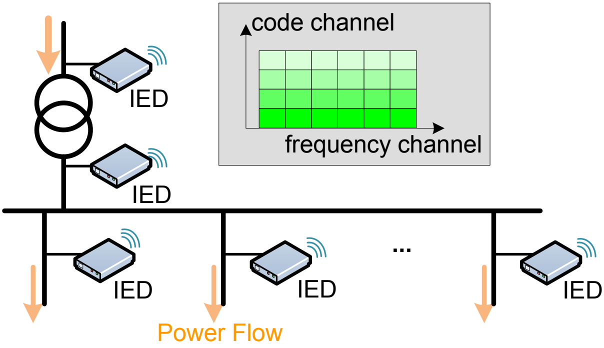
Network Model

A local-area power system over a wireless network with m nodes, N_f frequency and N_c code channels.



Time-Critical Message Transmission Model

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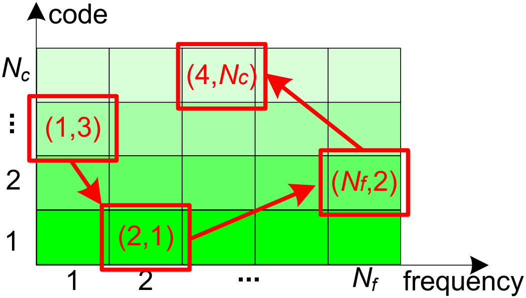

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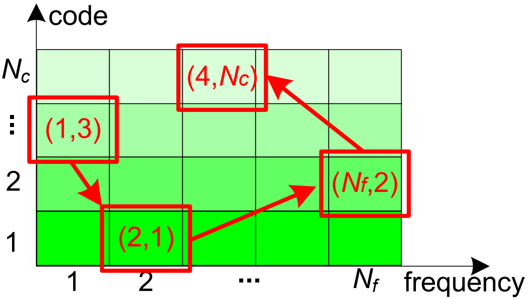

The secret channel selection pattern is not known to the attacker.

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Question: How to adopt the worst-case analysis of jamming attacks

1. Define a generic model to cover most existing models.
2. Find out what is the worst case induced by the generic model.

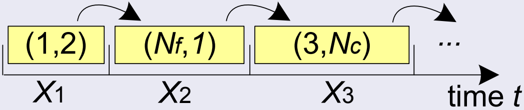
Jamming Attack Model

It's vital to use worst-case analysis rather than case-by-case one in the smart grid.

- no particular jamming model.

Definition (Generic Jamming Process)

A jammer's jamming process is denoted as a Markov-renewal process $((F, C), X) = \{(F_k, C_k), X_k | k = 1, 2, \cdots\}$.

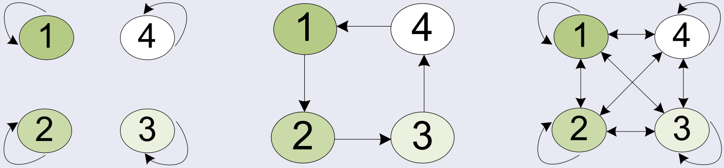


- X_k is the interval for the k status.
- (F_k, C_k) is the targeted frequency-code channel.

Generic Jamming Model: Markov-Renewal Process

Why is $((F, C), X)$ Markovian?

- Two associated transition matrices $\mathbf{Q}_F$ and $\mathbf{Q}_C$.



constant jamming sweeping jamming uniform jamming

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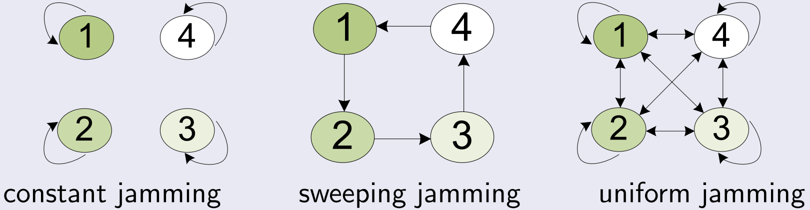

Reactive or non-reactive? Manipulate the jamming interval X_k

- Non-reactive (jam all the way): X_k is randomly distributed.
- Reactive (sense then jam): $X_k = \tau + S_k \mathbf{1}_A$.
  - τ: constant channel sensing time.
  - $\mathbf{1}()$ is the indicator function.
  - A: event that the channel is busy, S_k the jamming interval.

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2. Attempt to minimize the worst-case $\mathbb{P}(D > \sigma)$.

Outline

Theorem: Worst-Case Delay Bound

Theorem (Worst-Case Delay Performance)

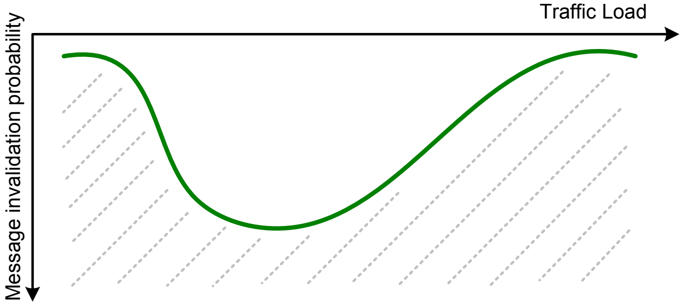
For a wireless local-area network $\mathcal{N}(m, N_f, N_c)$, the worst-case delay performance at node k is always induced by the reactive jamming and bounded by

$$\mathbb{P}(D_k > \sigma) \leq \left(1 - \left(1 - \frac{1}{N_f N_c}\right)^{T_L(1-\rho)\gamma_k} \left(1 - \frac{T_L}{\frac{\tau N_f N_c}{1-\rho} + \rho T_L^2 \gamma_k}\right)\right)^{\sigma/T_L},$$

where T_L is the message transmission duration, σ is the message delay threshold, $\gamma_k = \sum_{j=1, j\neq k}^{m} \lambda_j$, and λ_j is the traffic rate at node j.

Theoretical Indication for Practical Security Design

Theoretical results tell us



Jammer's achievable region

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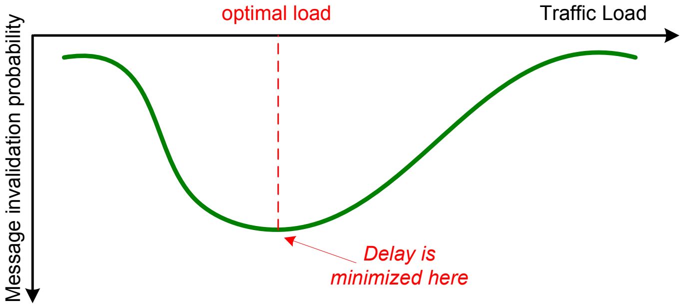

There exists an optimal network traffic load to minimize worse-case delay/message invalidation probability.

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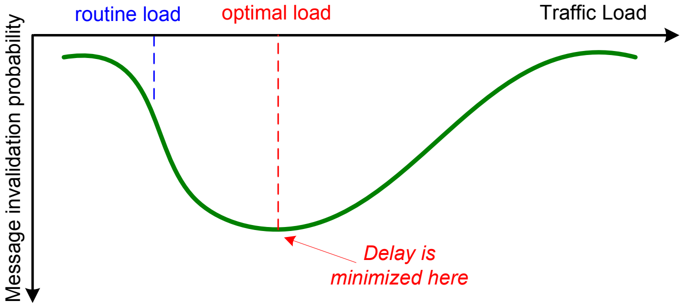

In the smart grid, network traffic is usually highly unsaturated for reliable monitoring and control.

- Example: wireless monitoring for substation transformers only needs to transmit a message every second [Cleverland'07].

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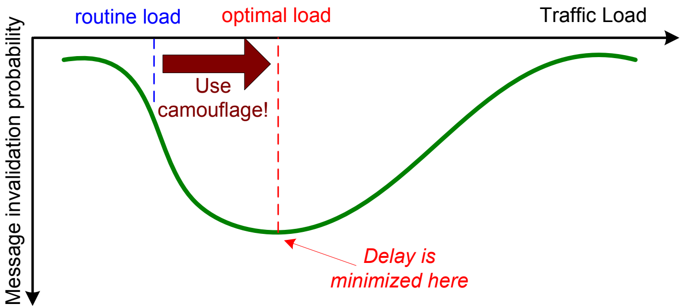
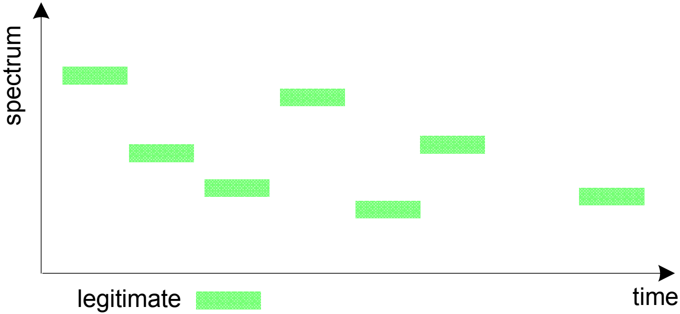


This implies that we need to transmit redundant traffic to optimize the traffic load. We call such traffic camouflage.

Intuition of the U-shaped Phenomenon



A reactive jammer can sense channels every fast: if there is no traffic, then go to next channel!

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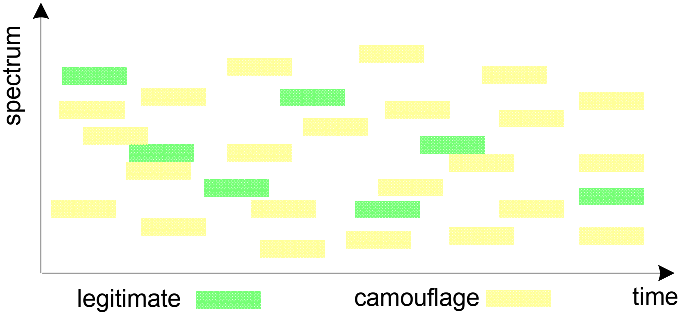


A reactive jammer is busy in jamming camouflage, giving a chance for legitimate traffic to pass through.

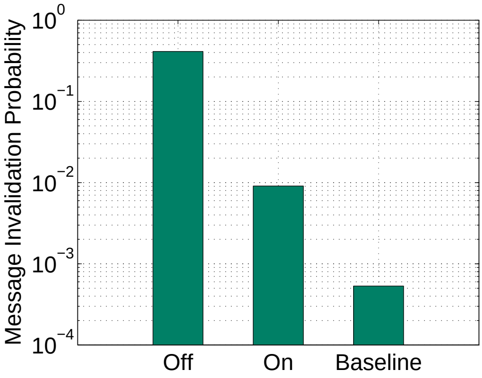
Experimental Setups

We set up an wireless anti-islanding network in the FREEDM systems center in North Carolina State University.

- Spread spectrum: frequency hopping with 8 channels.
- Bandwidth: 125KHz per channel.
- Number of nodes: 5 USRP-based IEDs.
- Jammer: USRP-based reactive jammer, scanning channel one by one.
- Routine traffic: 1 message/second.
- Message length: 400 bytes.
- Anti-islanding message timing requirement: 150ms.

Experimental Results

Routine traffic: 1 message/second.
Optimal camouflage traffic load: 14 messages/second.



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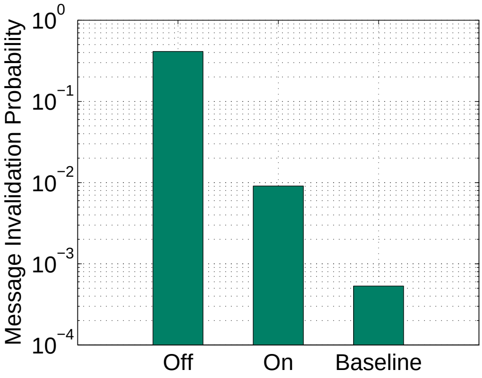

Transmitting camouflage traffic will improve the performance in order of magnitude!

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Conclusion

- We defined a generic jamming process, and show the worst-case delay bound is due to reactive jamming and exhibits a U-shaped function of network traffic load.
- There exists an optimal load to minimize the worst-case delay, therefore transmitting camouflage traffic can in fact help improve the delay performance.
- We illustrated via experiments that camouflage traffic can substantially improve the delay performance for smart grid applications under jamming attacks.

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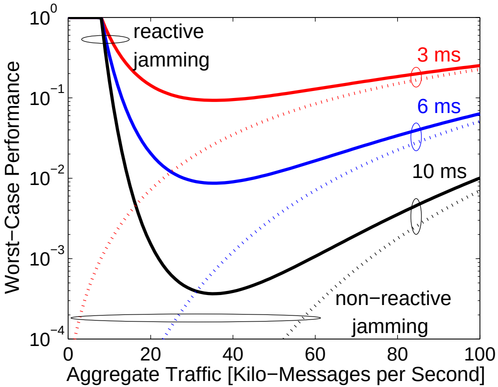
- We illustrated via experiments that camouflage traffic can substantially improve the delay performance for smart grid applications under jamming attacks.
- Future work
  1. Consider the case of multiple attackers.
  2. Lift the assumption that the secret pattern between a transmit-receive pair is already set up.

Thank you!

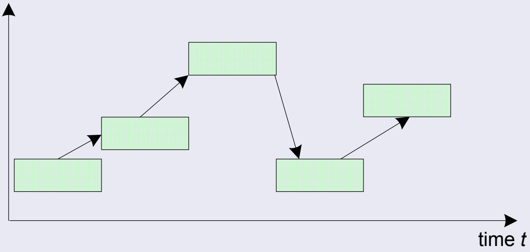
Backup 1: Reactive vs Non-reactive



The delay bound $\mathbb{P}(D_k > \sigma)$ versus aggregate traffic γ_k at node k for time-critical applications with delay thresholds of 3–10ms. ($N_f = N_c = 10$, $T_L = 1$ms, $\rho = 0.1$, and $\tau = 100\mu$s for reactive jamming)

Backup 2: Interference Model

When a transmission fails



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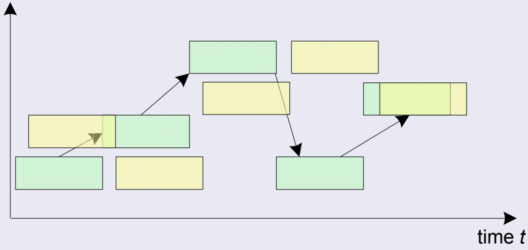

Interference model

A transmission on the (i, j)-th channel fails only if at least a portion $\rho \in (0, 1)$ of the transmission is

- either disrupted by jamming
- or collided by other legitimate traffic.

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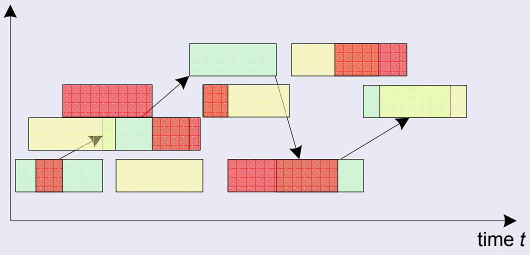

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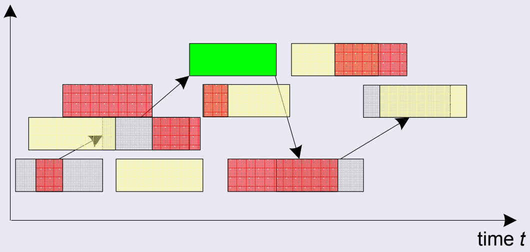

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