Hold The Door! Fingerprinting Your Car Key to Prevent Keyless Entry Car Theft

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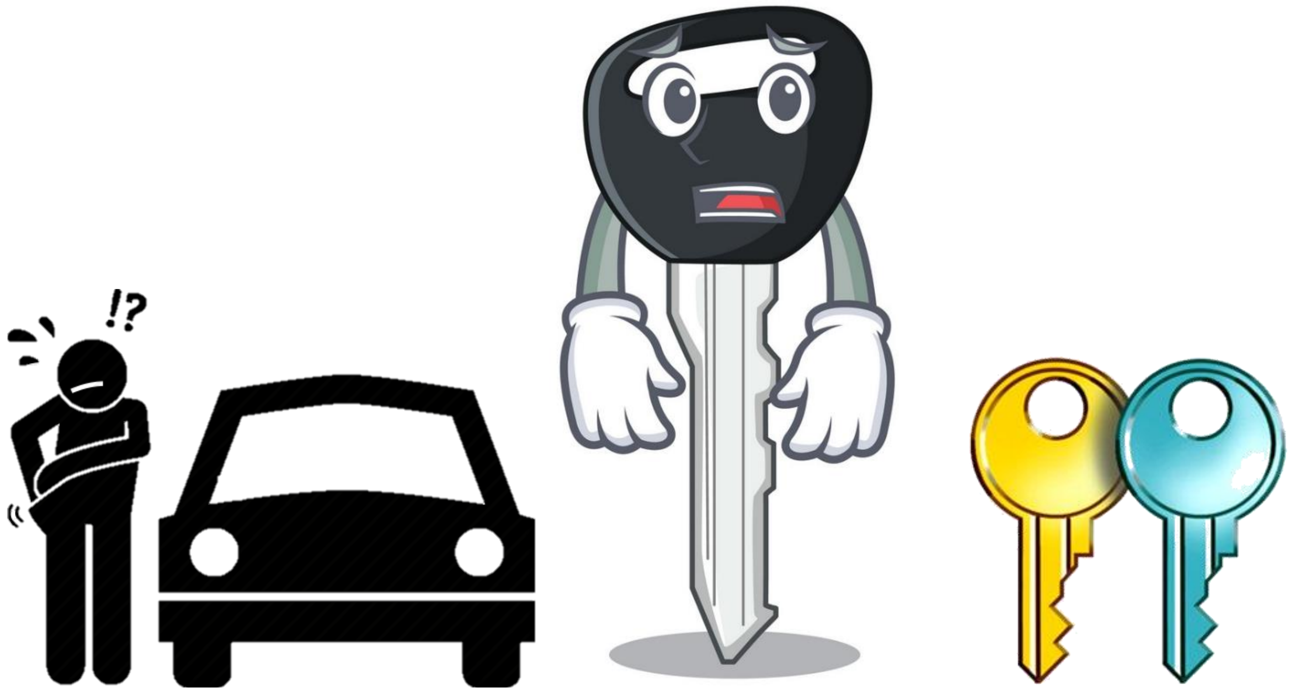
Outline

- Introduction
- Attack Model
- Our Method
- Evaluation
- Discussion
- Conclusion

Introduction

- Traditional system
  - Physically insert a key into the keyhole
  - Inconvenient
  - Vulnerable to key copying

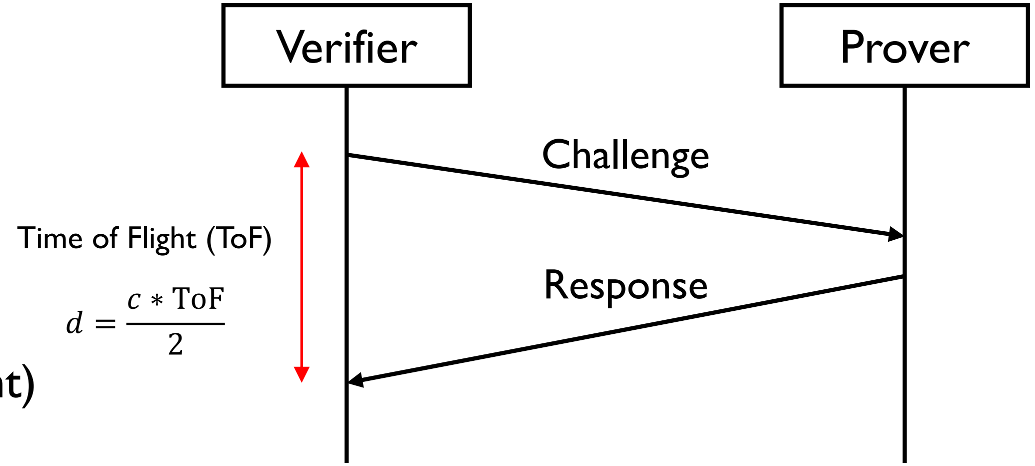


Introduction

- Keyless Entry System
  - Remote Keyless Entry (RKE) System
  - Passive Keyless Entry and Start (PKES) System
- Attacks on Keyless Entry System
  - Cryptanalysis
  - Relay Attack
  - etc. (e.g., Roll-jam)

Introduction

- Countermeasures
  - Distance bounding protocol
    - Sensitive to timing error (Propagates at the speed of light)
  - UWB-IR Ranging System
    - Efforts are underway (IEEE 802.15.4z Task Group) [1-3]
    - Requires an entirely new system
- Motivation
  - Device Fingerprint: Exploits hardware imperfection
  - PHY-layer signal analysis



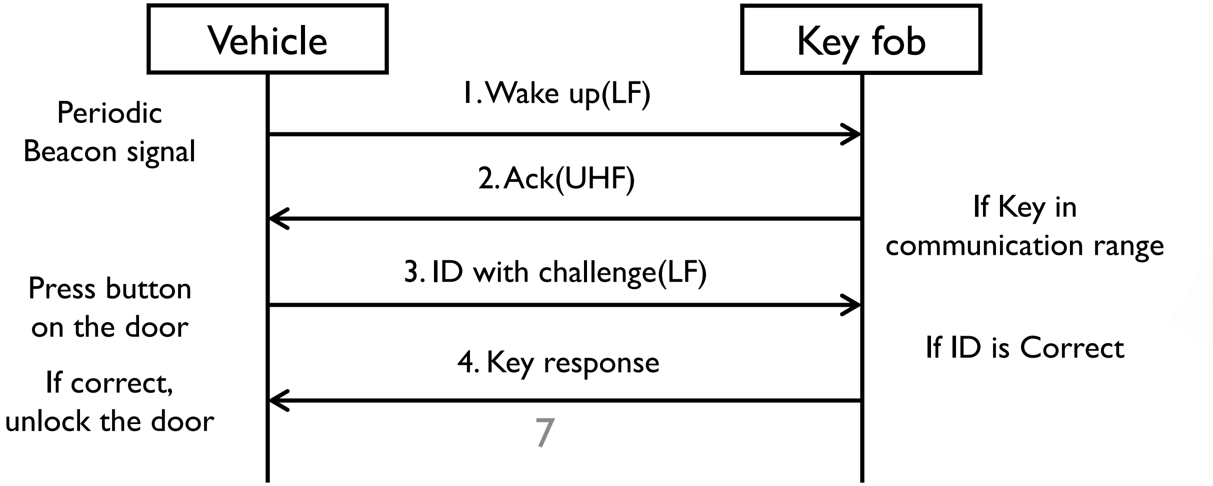
[1] UWB with Pulse Reordering: Securing Ranging against Relay and Physical Layer Attacks (M. Singh et al.)
[2] UWB-ED: Distance Enlargement Attack Detection in Ultra-Wideband (M. Singh et al.)
[3] Message Time of Arrival Codes: A Fundamental Primitive for Secure Distance Measurement (P. Leu et al.)

Introduction

- Contributions
  - New attack model
    - Combines all known attack methods; our attack model covers both PKES and RKE systems
    - Single/Dual-band relay attack, Cryptographic attack
  - No alterations to the current system
    - Easily employed by adding a new device that captures and analyzes the ultra-high frequency (UHF) band RF signals emitted from a key fob
  - Evaluations under varying environmental factors
    - Temperature variations, NLoS conditions (e.g., a key fob placed in a pocket) and battery aging

Introduction

- Passive Keyless Entry System
  - LF band (125~135 kHz, Vehicle)
    - 1 ~ 2 meter communication range
  - UHF band (433, 858 MHz, Key fob)
    - ~100 meter communication range)
  - Shared cryptographic key between the key and the vehicle



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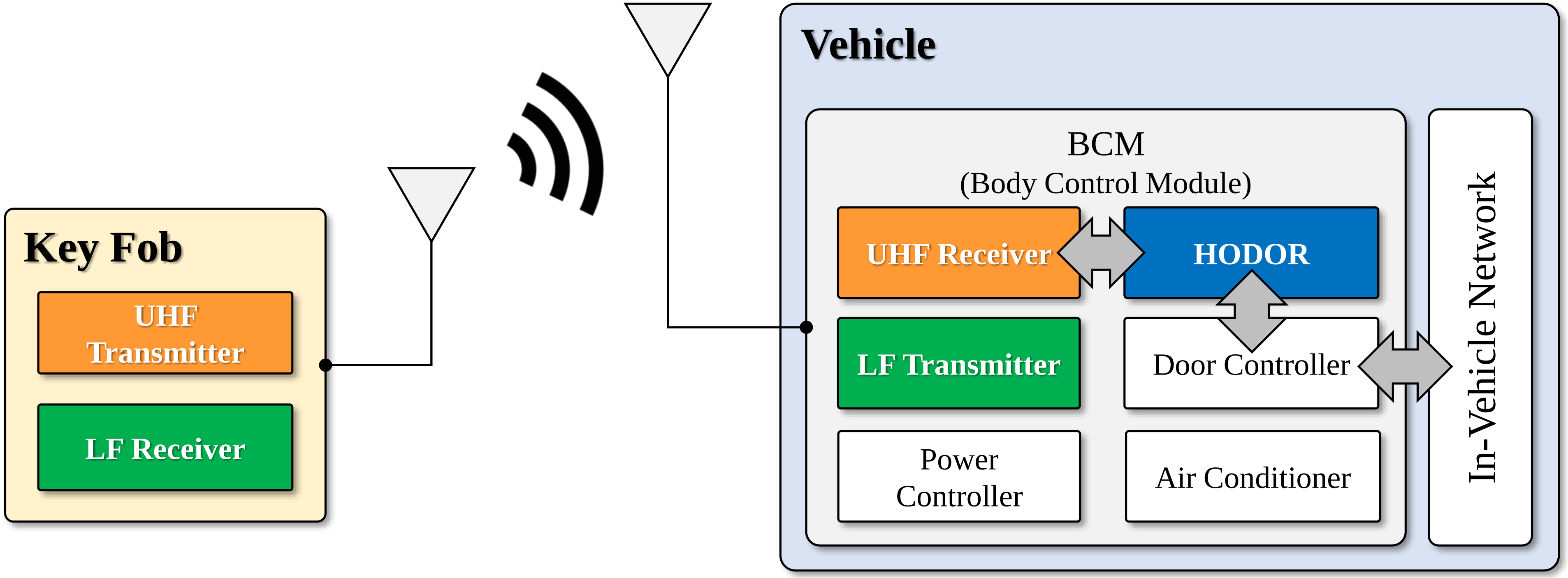
Introduction

- System Model



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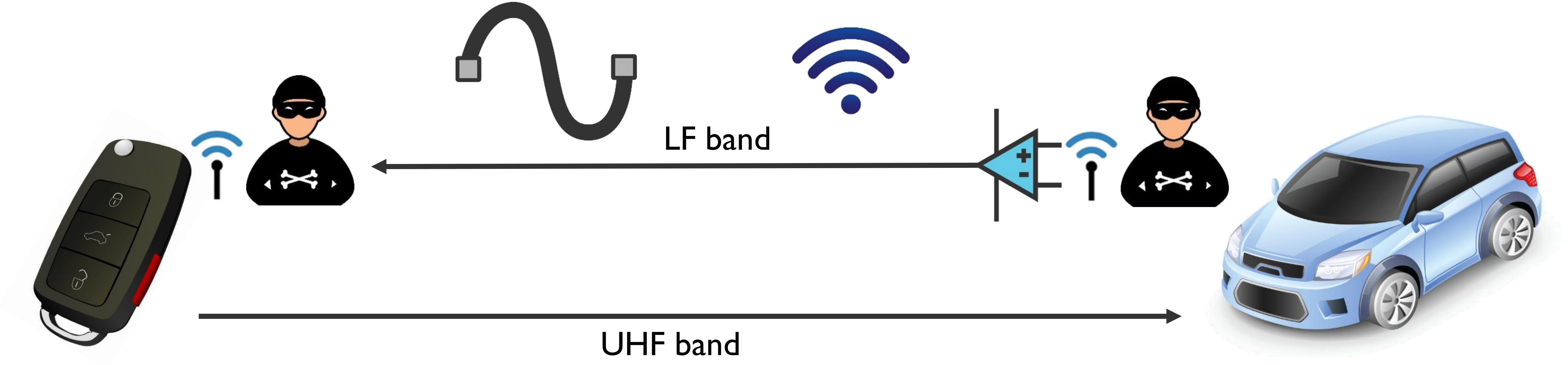
Attack Model

- Coverage
  - Attacks on PKES and RKE systems implemented with the LF/UHF band RFID communication
- Main Objectives of adversary
  - Unlocking a vehicle
- Out of Scope
  - Excluded other functions, such as an engine start message
  - Physical damage to a vehicle

Attack Model

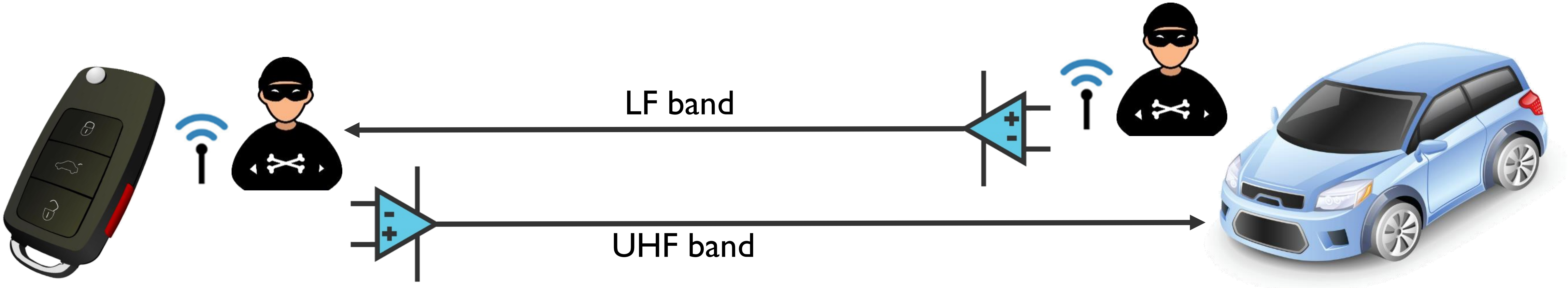
- Single-band Relay Attack [*]
  - Manipulate LF band signal only
  - Wired / Wireless Attack



[*] Relay Attacks on Passive Keyless Entry and Start Systems in Modern Cars (Aurelien Francillon et al.)

Attack Model

- Dual-band Relay Attack (Ⅰ.Amplification Attack)
  - Receives LF band signal and forward to the adversary at the key fob side
  - Injects LF band signal to the key fob
  - Amplifies UHF band signal and injects to the vehicle



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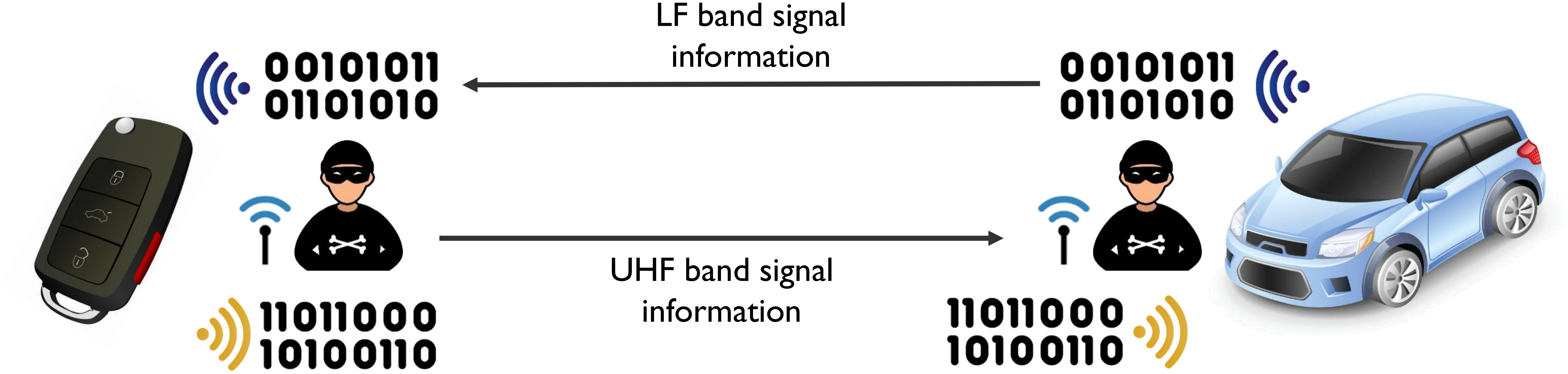
Attack Model

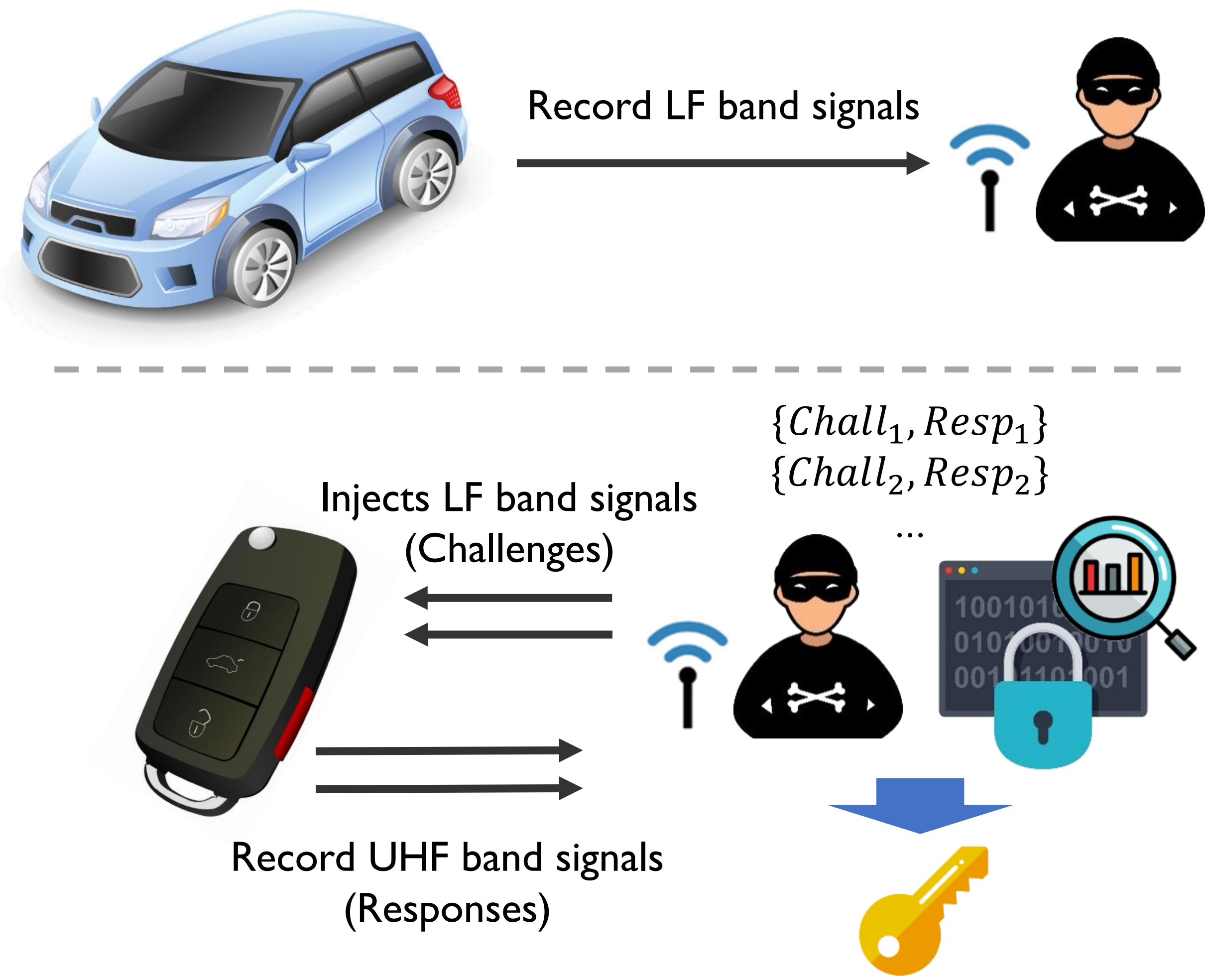
- Dual-band Relay Attack (Ⅱ. Digital Relay Attack) [*]
  - Demodulate LF/UHF band signal
  - Relay binary information



[*] Car keyless entry system attack (Yingtao Zeng et al.)

Attack Model

- Cryptographic Attack [*]
  - Single adversary
  - Injects LF band signals to the key fob
  - Records valid responses and extract secret key
  - Exploits weaknesses of cryptographic algorithm



[*] Fast, Furious and Insecure: Passive Keyless Entry and Start Systems in Modern Supercars (Wouters et al.)

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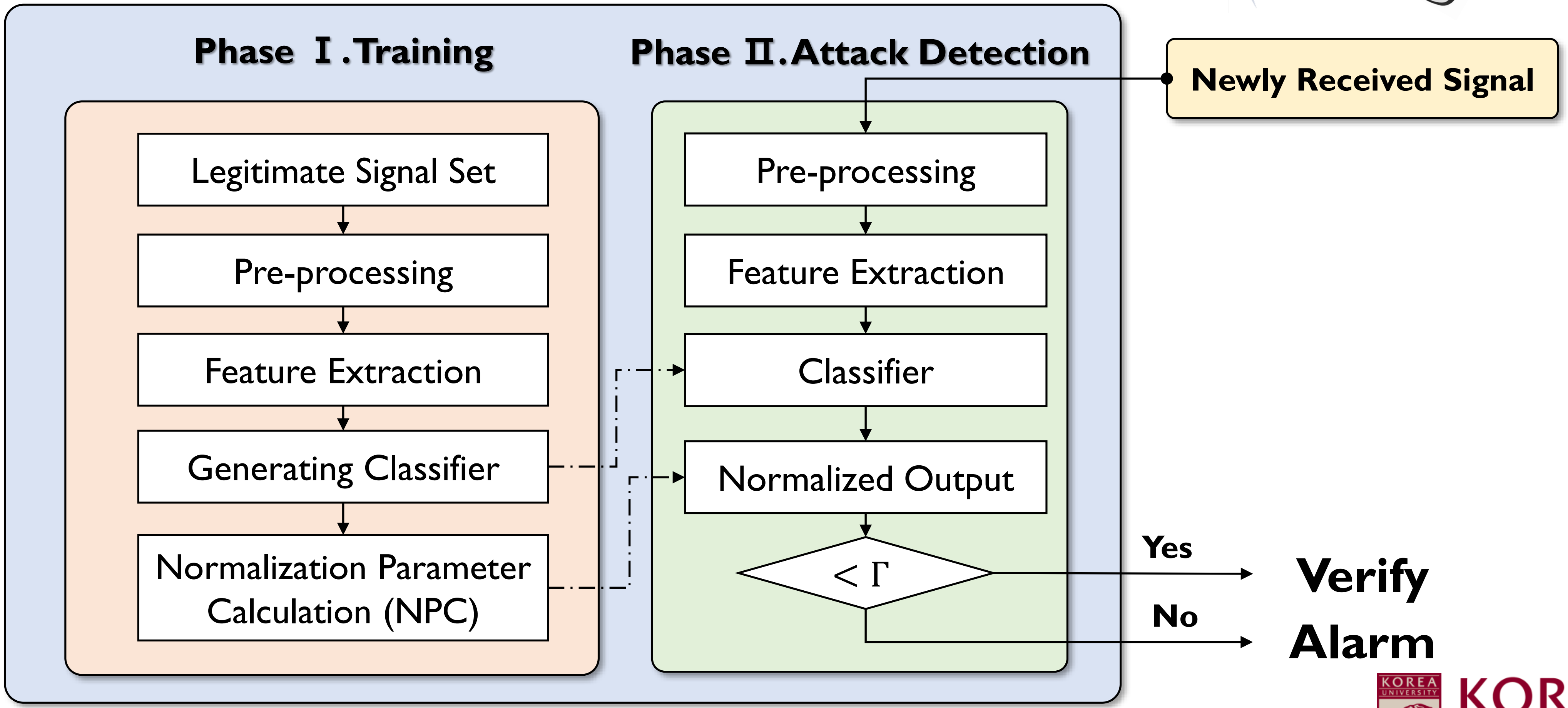
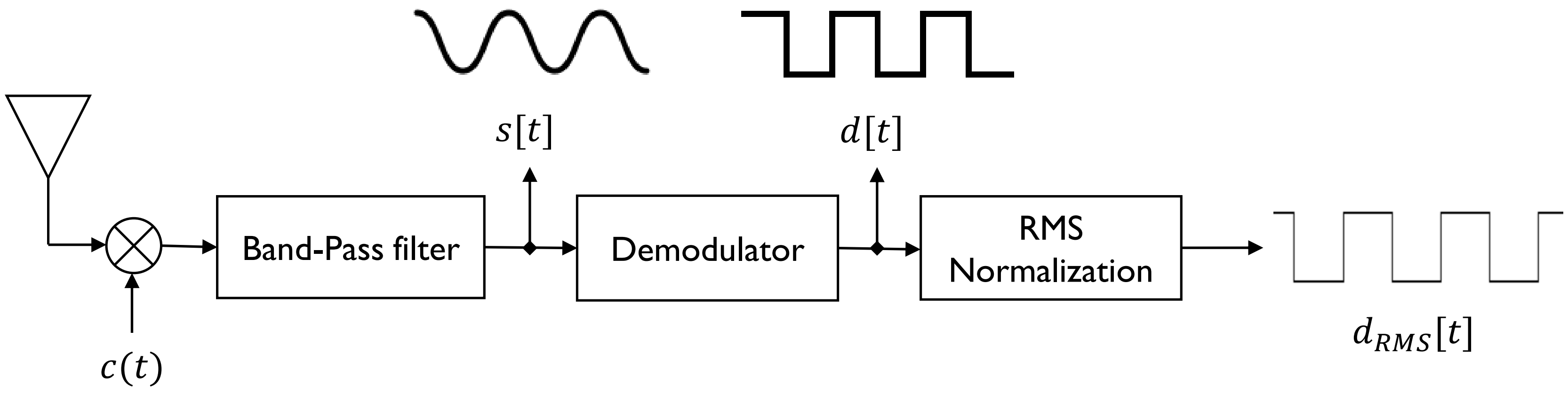
Our Method

- Overview (HODOR)

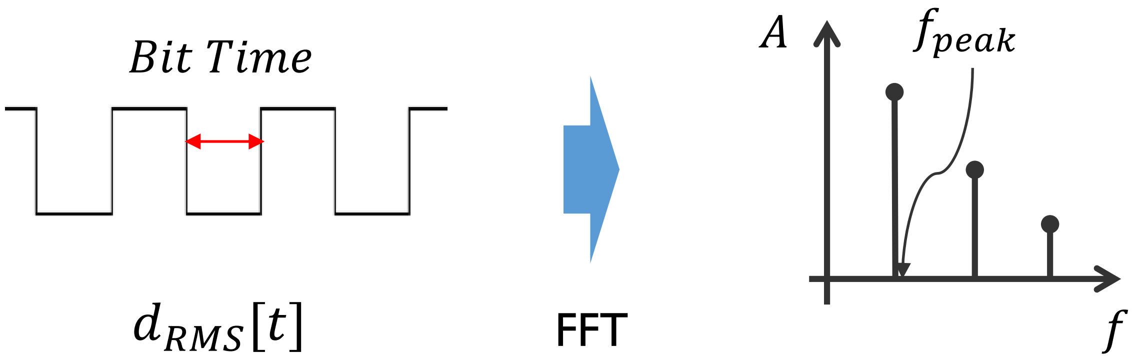


Our Method

- Preprocessing

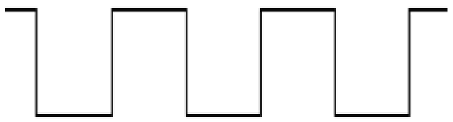


- Feature Extraction



Our Method

- Feature Extraction (Continue)



$d_{RMS}[t]$

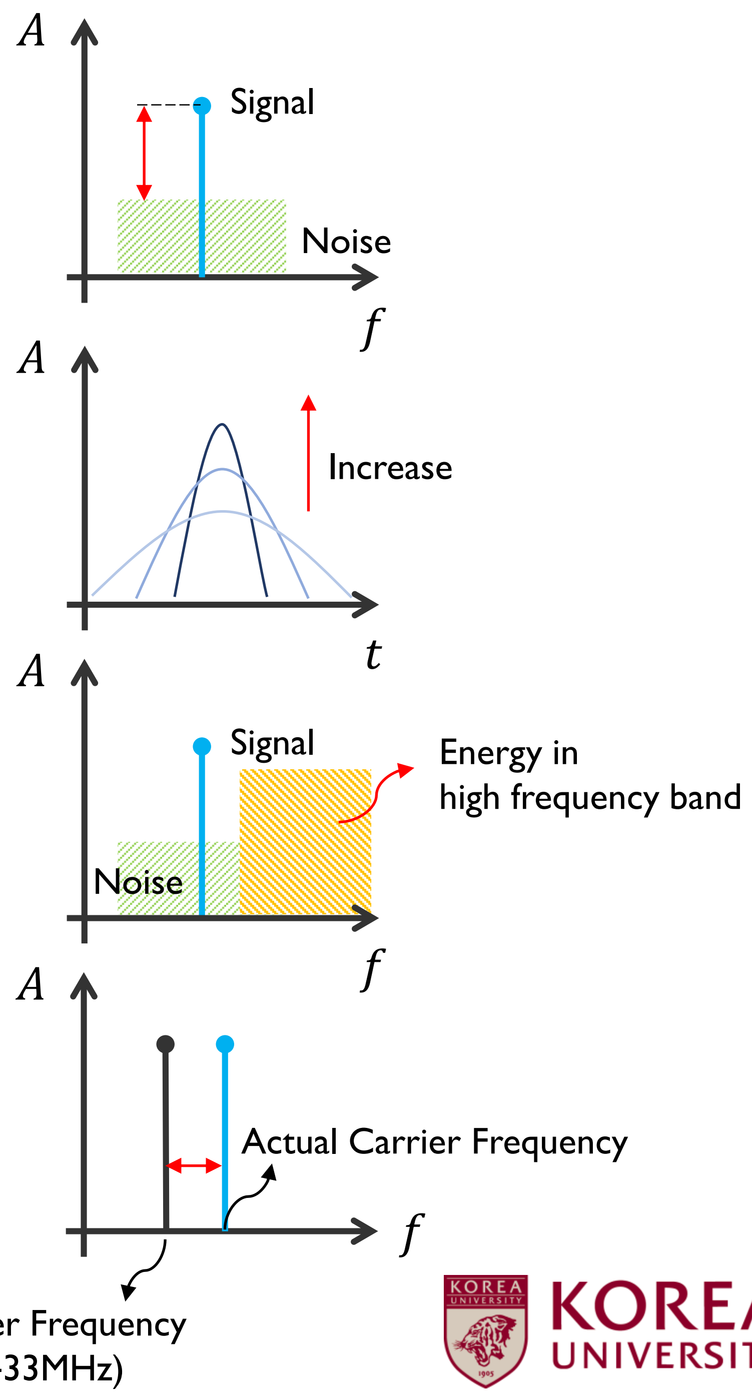
SNR_{dB}

Kurtosis

Spectral Brightness

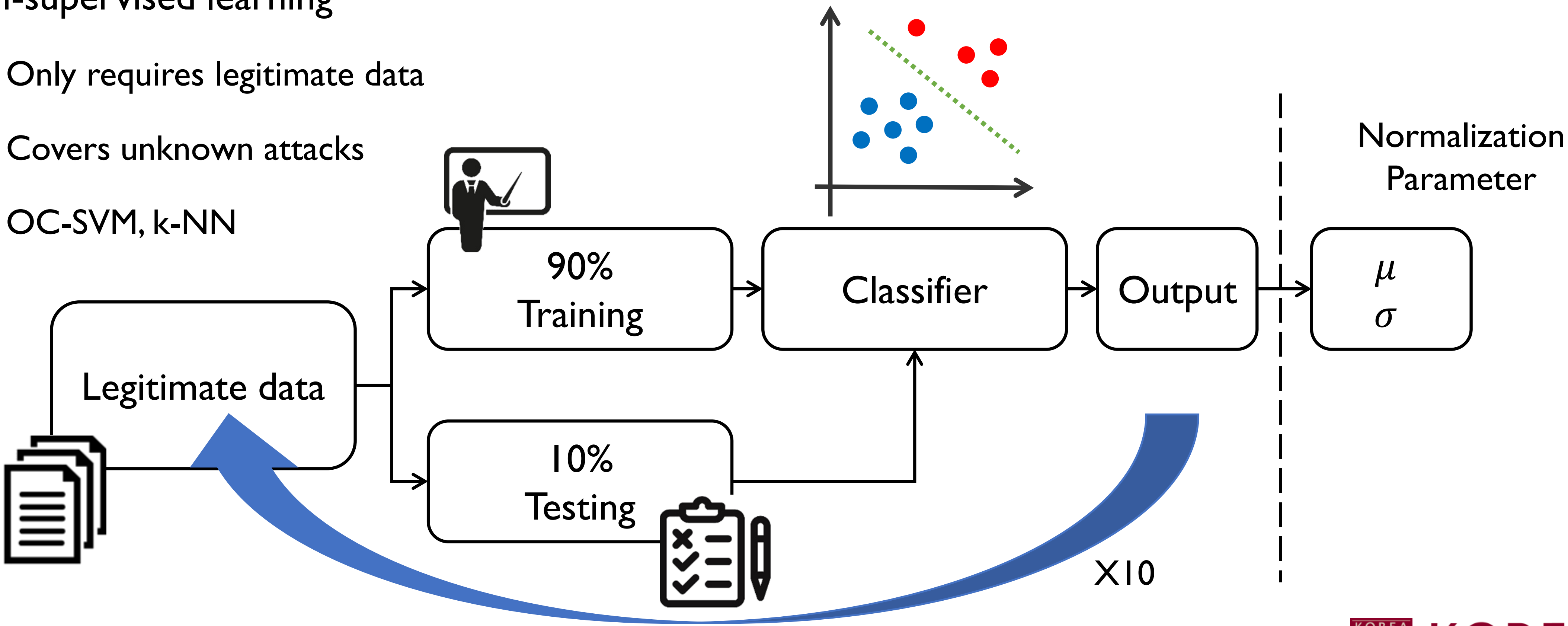
$s[t]$

Carrier Frequency offset



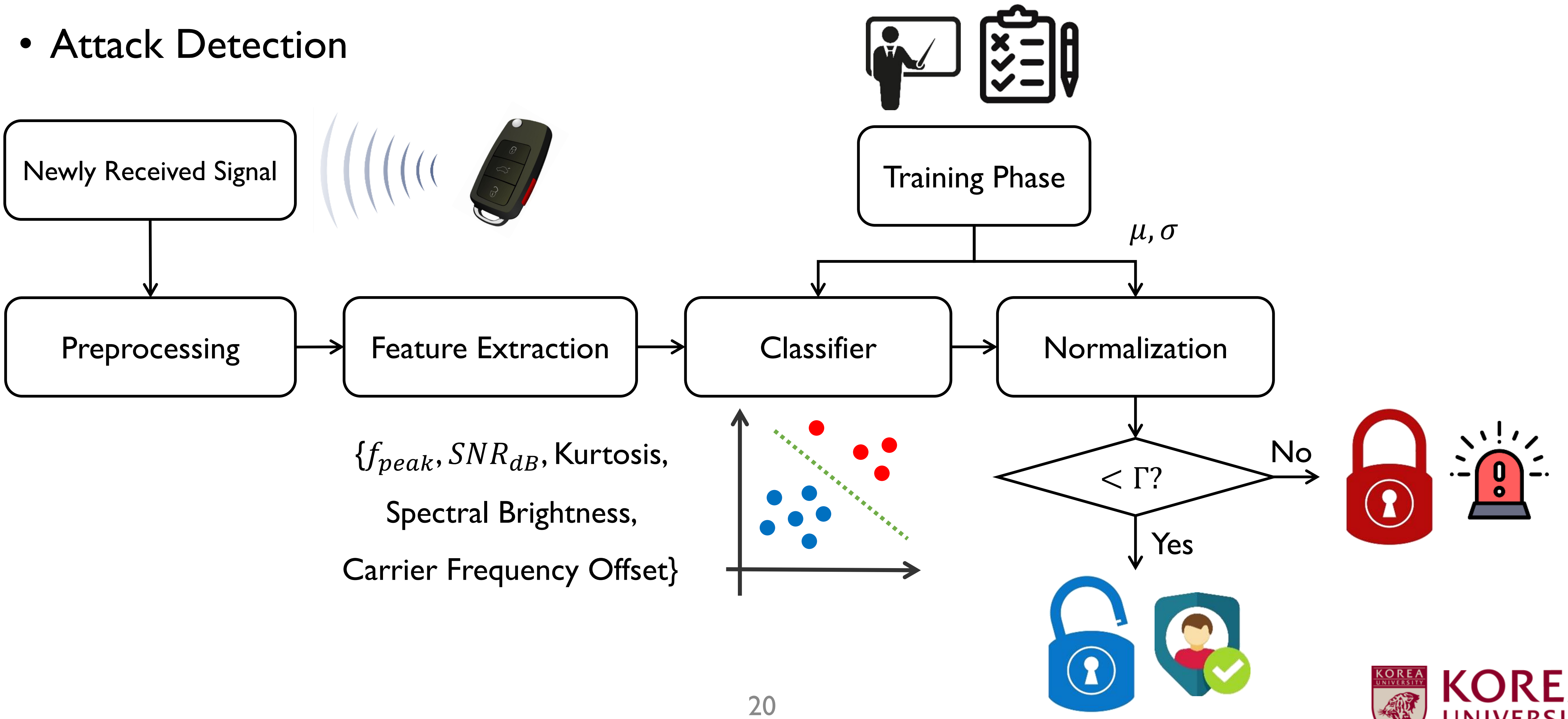
Our Method

- Training
  - Semi-supervised learning
    - Only requires legitimate data
    - Covers unknown attacks
    - OC-SVM, k-NN



Our Method

- Attack Detection



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Evaluation

- Experimental Setup
  - Cars: KIA Soul, Volkswagen Tiguan
  - SDRs: HackRF One, USRP X310
  - SW: GNURadio
  - Loop Antenna, SMA Cable (Relay LF band signal)

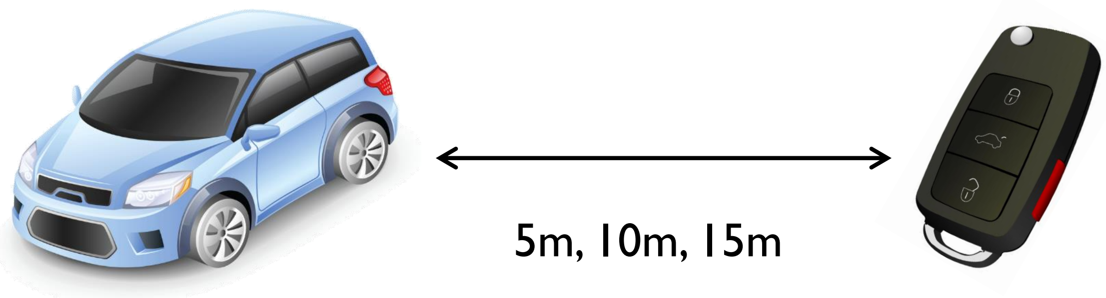
GNURadio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

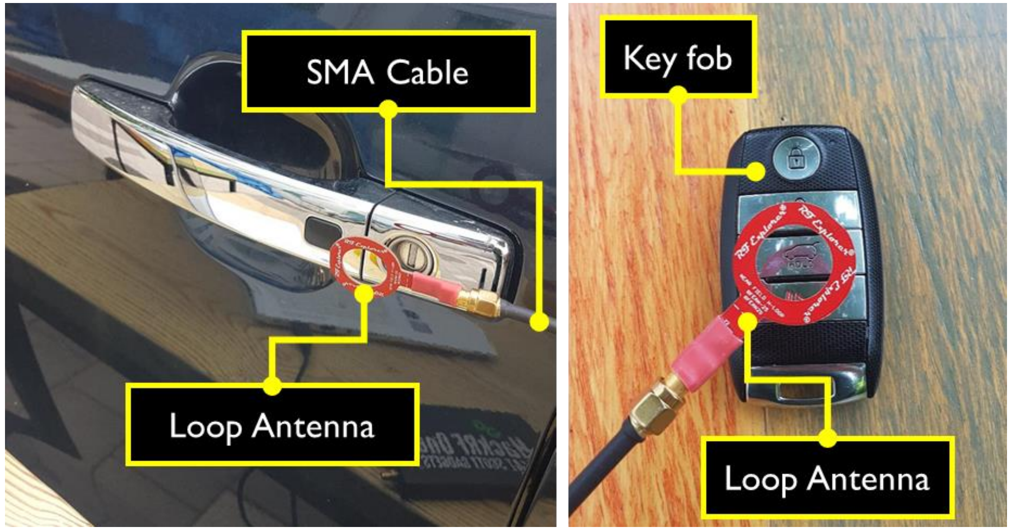
Evaluation

- Selected Classification Algorithms
  - One-Class SVM (OC-SVM) with Radial Basis Function (RBF) kernel
  - k-NN with Standardized Euclidean Distance
  - MatLab implementation
- Performance Metric
  - Assume False Negative Rate (FNR) as 0%
  - Calculate False Positive Rate (FPR)

Evaluation

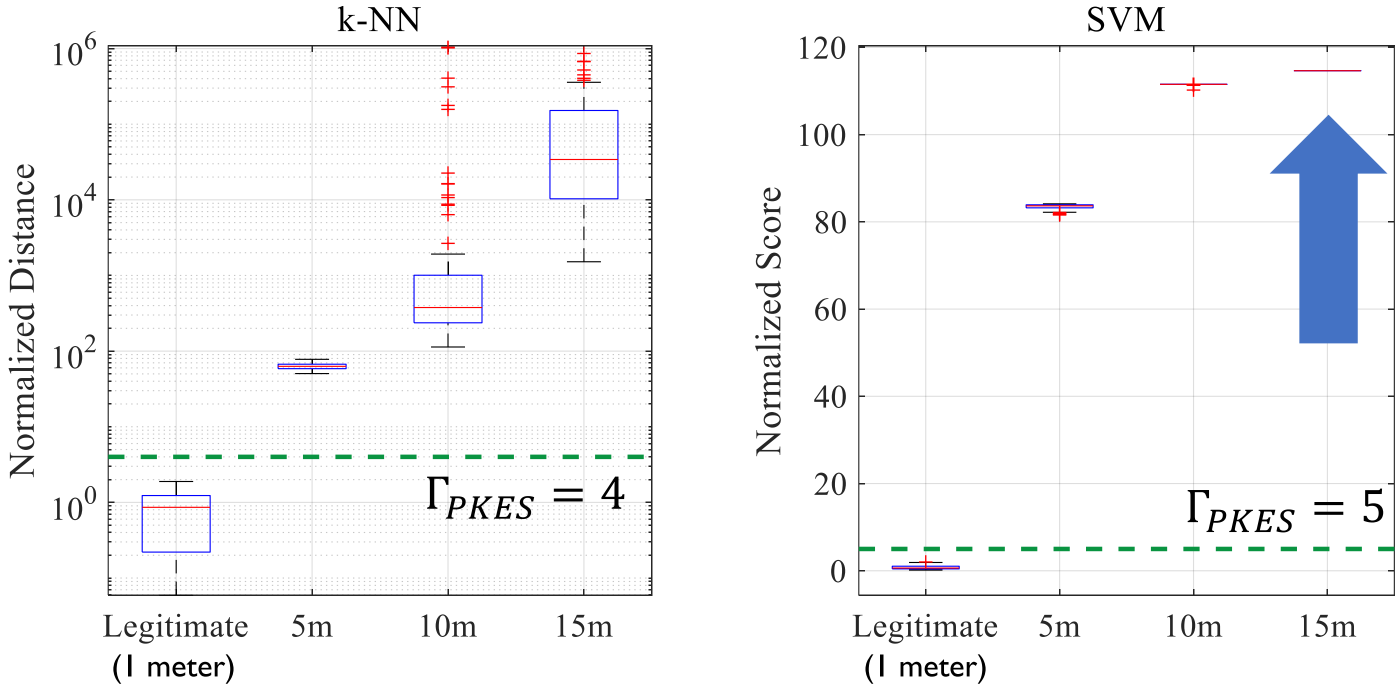
- Single-Band Relay Attack Detection





Experimental Setup

(LF band signal relay)



Results

(0% FPR in both algorithms)

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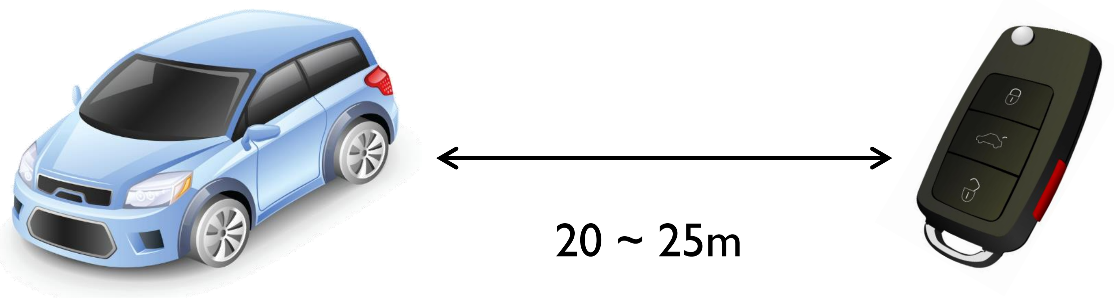
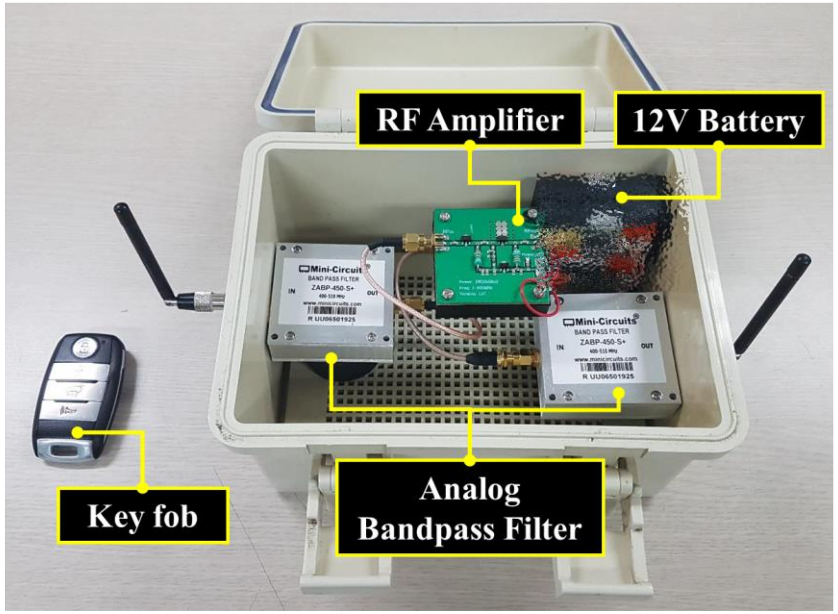
Evaluation

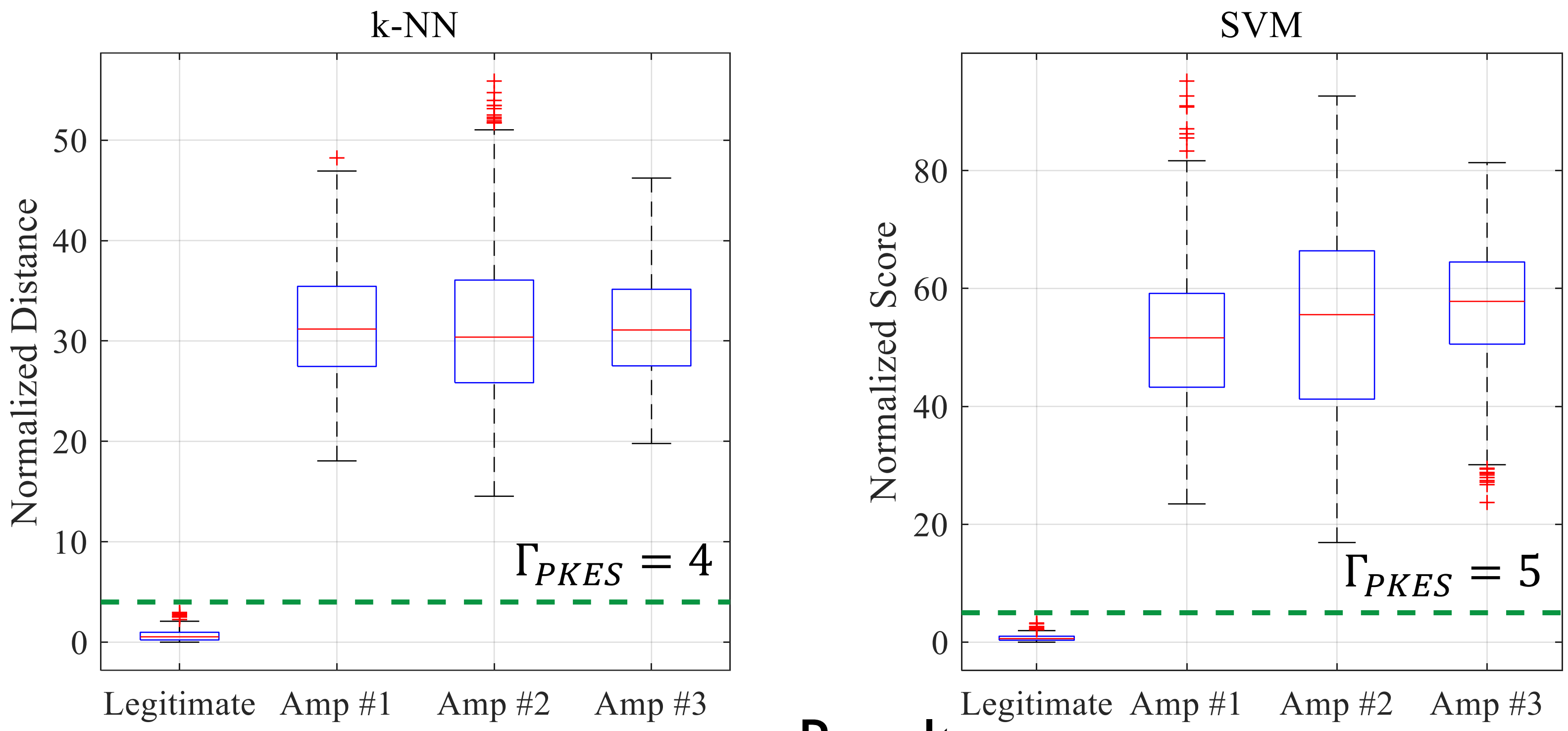


- Dual-Band Relay Attack Detection
  - Amplification Attack



Experimental Setup

(UHF band amplification)

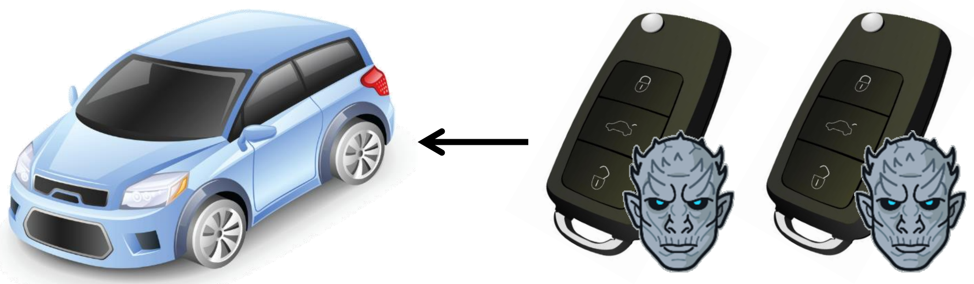


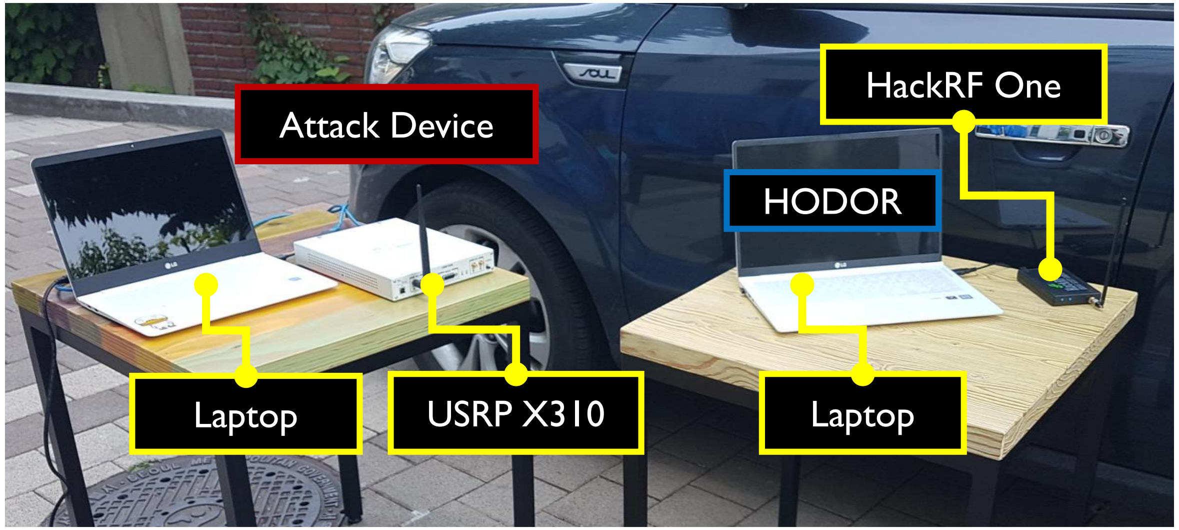
Results

(0% FPR in both algorithms)

Evaluation

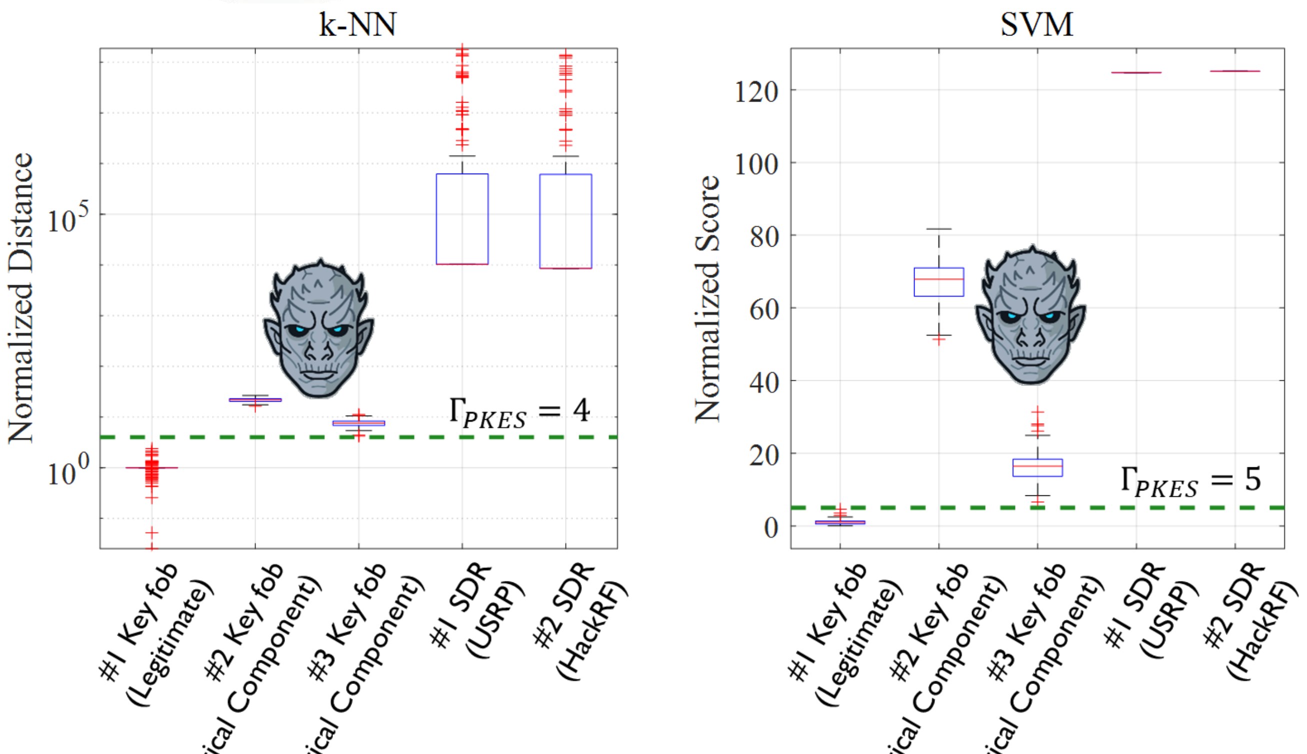
- Dual-Band Relay Attack Detection
  - Digital Relay/ Cryptographic Attack





Experimental Setup

(Cryptographic Attack)



Results

(Average FPR k-NN: 0.65%, SVM:0.27%)

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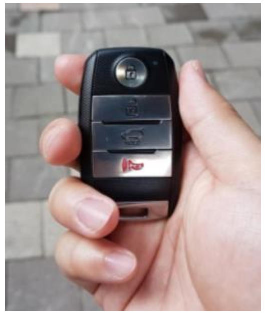
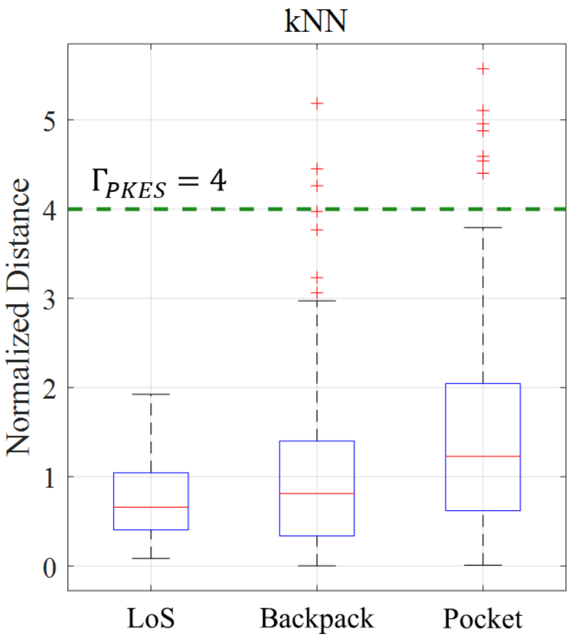
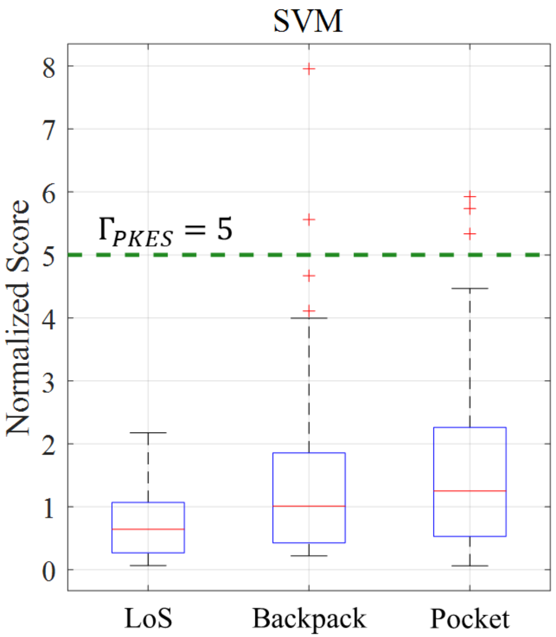
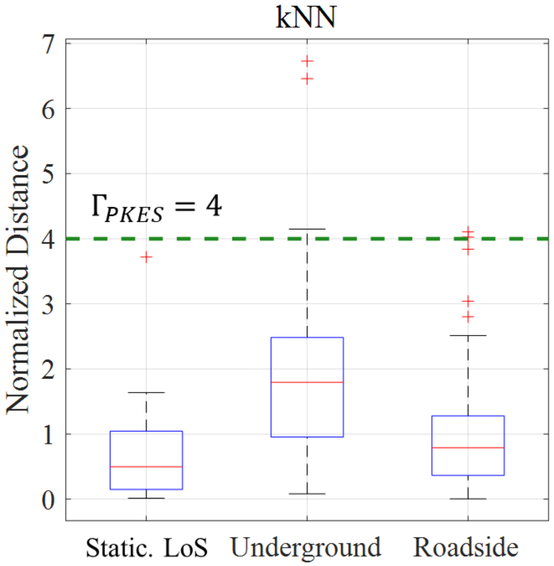
Evaluation

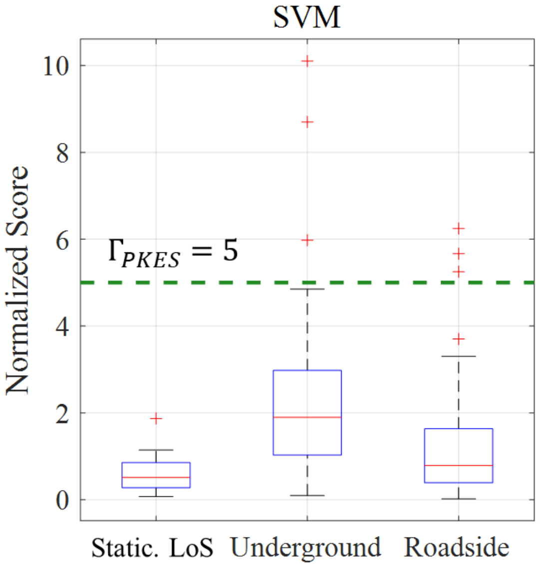
- Environmental Factors
  - Non-Line of Sight (NLoS) conditions, Dynamic Channel Conditions











Backpack: FPR k-NN: 1.32%, SVM:1.35%

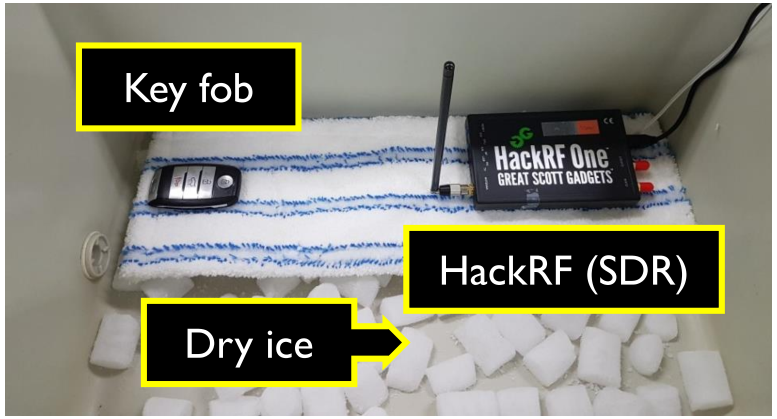
Pocket: FPR k-NN: 1.71%, SVM:1.67%

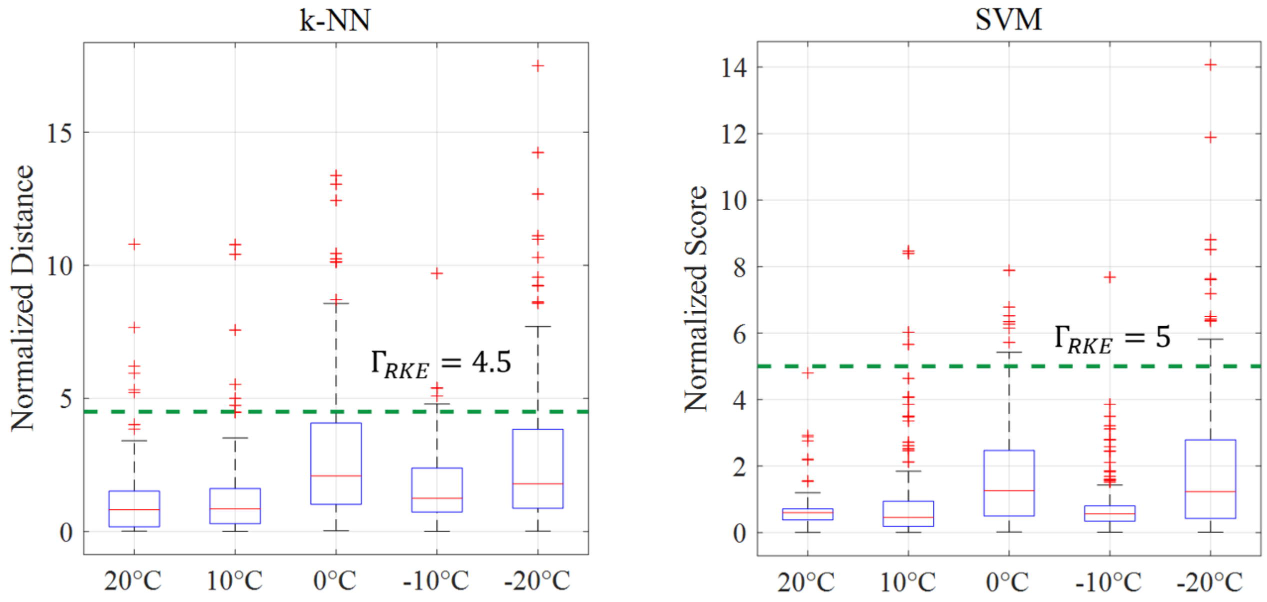
Underground: FPR k-NN: 5%, SVM:4%

Roadside: FPR k-NN: 2%, SVM:3%

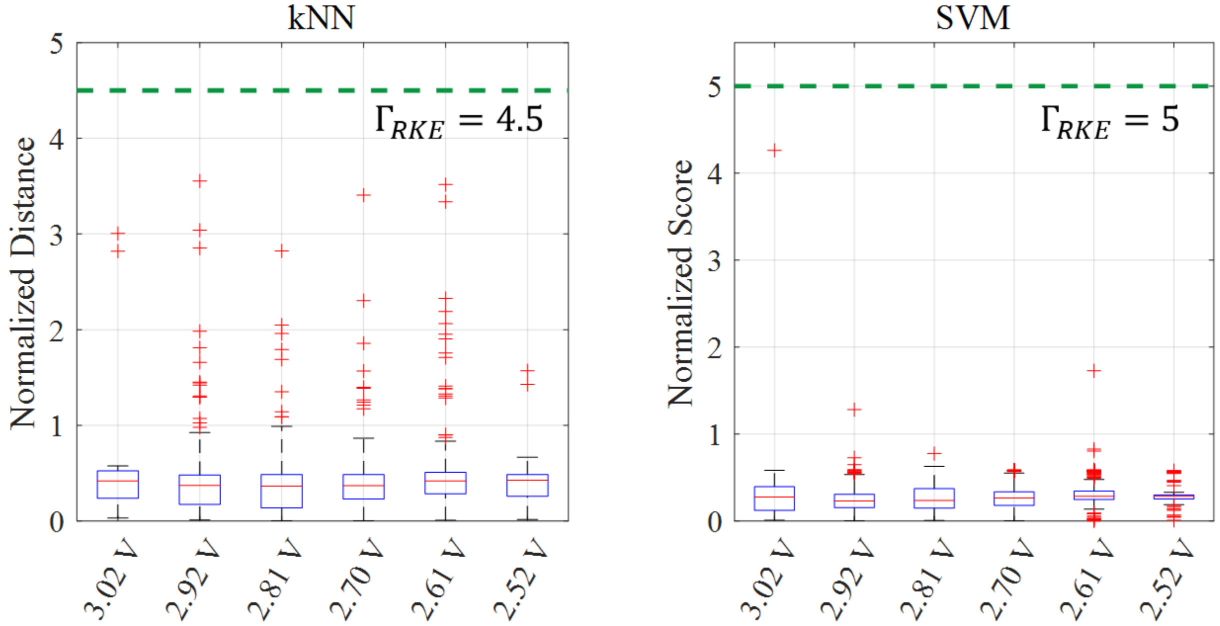
Evaluation

- Environmental Factors
  - Signals from RKE system





Average FPR k-NN: 6.36%, SVM:0.65%



Average FPR k-NN: 0%, SVM:0%

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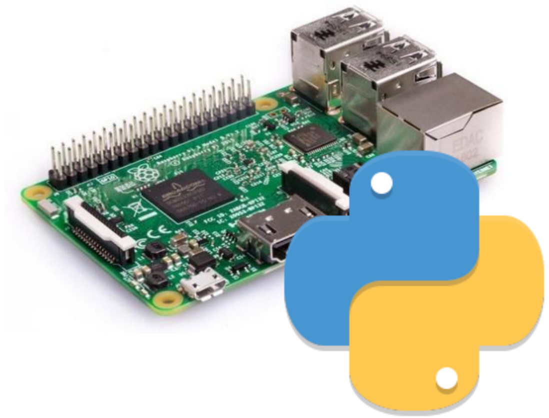
Evaluation

- Execution time
  - Implementation on Raspberry Pi
    - 1.4Ghz Core, 1G RAM
  - Python Code



Phase		Algorithm	
		k-NN	SVM
Feature Extraction (FSK / ASK)	f_{peak}	$4ms$ / $3.85ms$	
	f_c^{offset}	$4ms$ / $3.55ms$	
	SNR_{dB}	$130ms$ / $94ms$	
	$Kurtosis$	$20ms$ / $16.2ms$	
	$Spec.Brightness$	$5ms$ / $3.73ms$	
Attack Detection (FSK / ASK)	$\mathbb{C}_{PKES}$	$4.8ms$ / $4.94ms$	$.038ms$ / $.04ms$
	$\mathbb{C}_{RKE}$	$3.8ms$ / $4ms$	$.04ms$ / $.07ms$

Total Execution Time

K-NN: 163.8ms and SVM: 159.038ms

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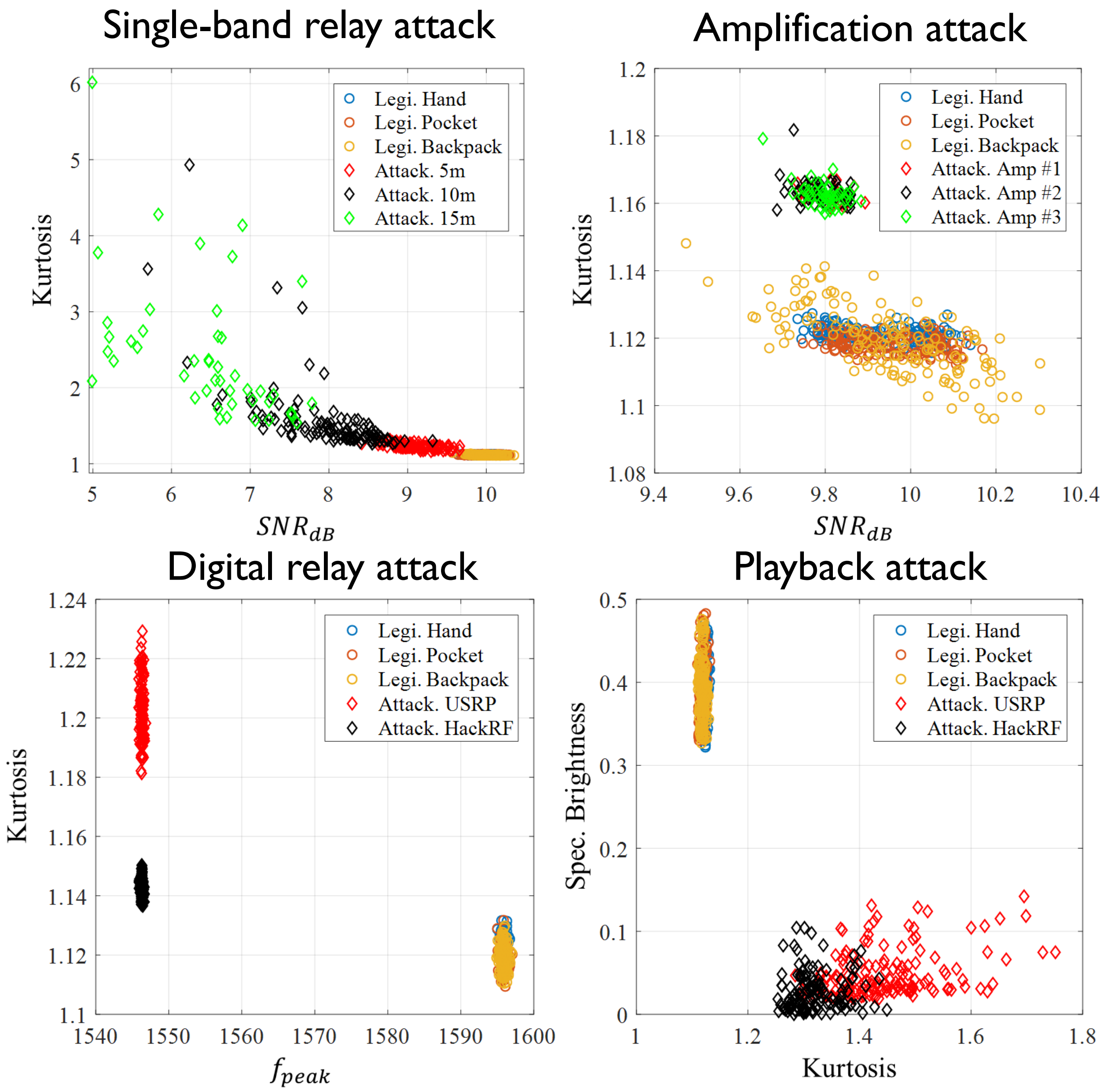
Evaluation

- Feature Importance

Attack Scenario		Single-band Relay Attack	Amplification Attack	Digital Relay Attack	Playback Attack
Rank	1	**SNR**	**Kurtosis**	f_{peak}	**Spec. Brightness**
	2	Kurtosis	SNR	Kurtosis	Kurtosis
	3	Spec. Brightness	Spec. Brightness	Spec. Brightness	f_{peak}
	4	f_{peak}	f_{peak}	SNR	SNR



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Discussions

- HODOR and Security
  - Threshold is a trade-off parameter in HODOR
  - Small threshold leads to the false alarm; a large threshold leads to the false-negative (attack success)
- Feature Impersonation
  - Adversary must impersonate the whole feature at the same time
  - Impersonating a specific feature leads to a distortion in other features
- Practicality
  - Develop additional features and algorithms that properly operate even in extreme environments

Future Work

- Robustness
  - Comprehensive experiments against feature variations
    - IEC certified facilities (Temperature, Humidity, Impact)
  - Incremental/ Decremental learning
    - Cope with a feature variation (a.k.a Concept drift)
- Scalability
  - Feature collision
  - Defense against strong attacker equipped with signal-generator
- Performance optimization
  - Low sample rate, memory usage

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Conclusion

- Proposed a sub-authentication system
  - Supports manufacturer-installed support systems to prevent keyless entry system car theft
- Effectively detect simulated attacks that are defined in our attack model
  - Reducing the number of erroneous detection occurrences (i.e., false alarms)
- Found a set of suitable features in a number of environmental conditions
  - Temperature variation, battery aging, and NLoS conditions

HODOR!

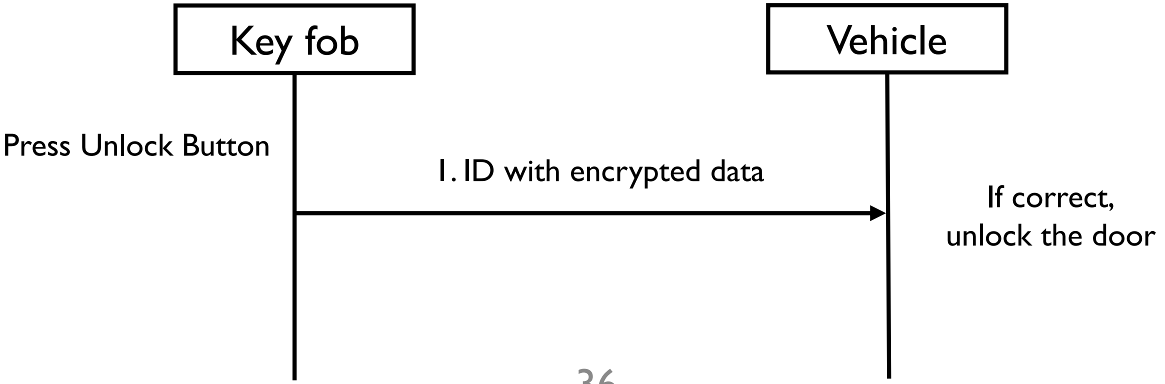
(Thank you!)

Q&A

SAMSUNG This work was supported by Samsung Electronics

Appendix

- Remote Keyless Entry System
  - Unidirectional
  - UHF band (433MHz, 868MHz)
    - ~100 meter communication range
  - FSK or ASK Modulation
  - Shared cryptographic key between the key and the car



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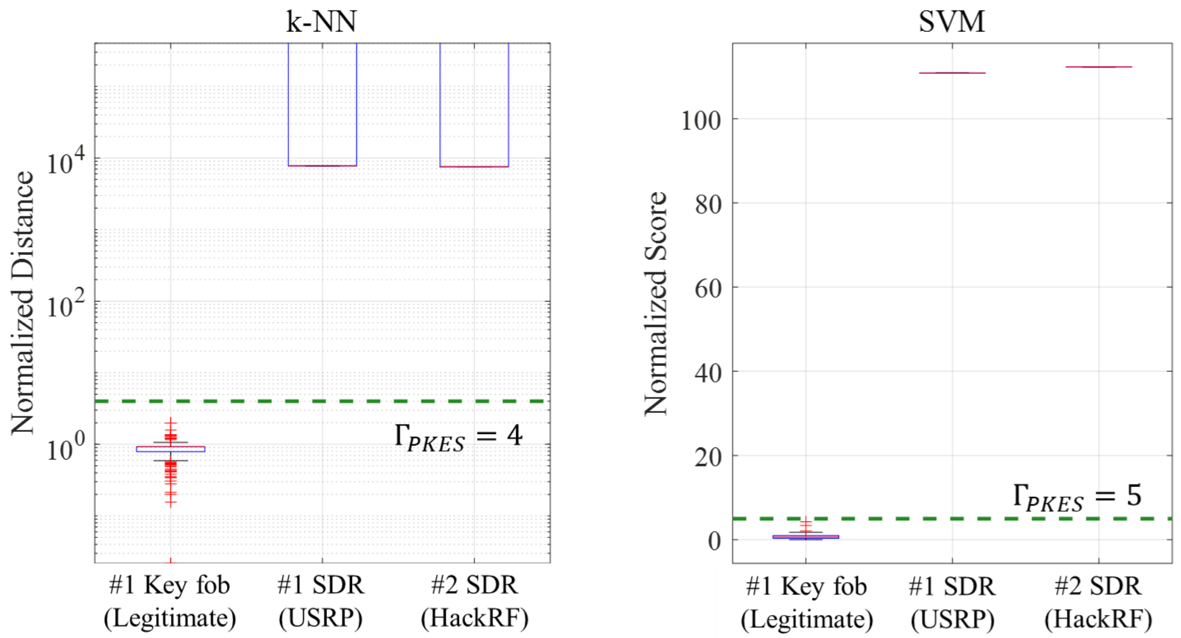
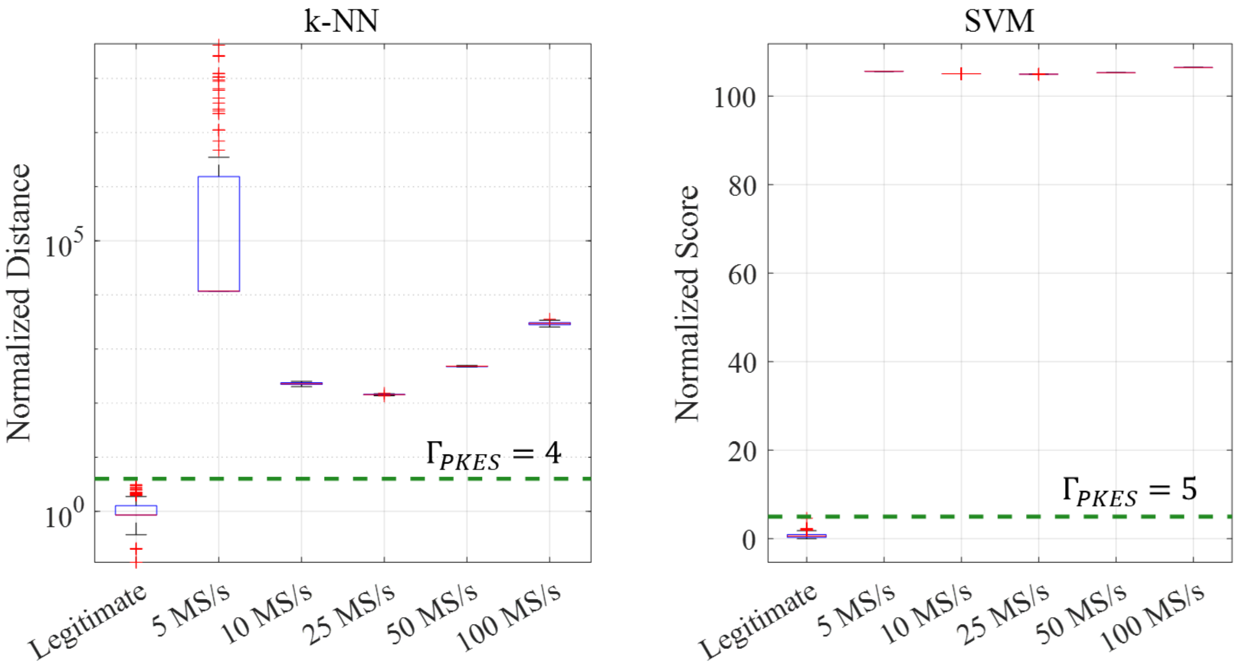
Appendix

- Playback Attack Detection



Experimental Results

(SDR with 5MS/s)



Experimental Results

(USRP with various sample rate)