Dimensional Reduction Analysis for Physical Layer Device Fingerprints with Application to ZigBee and Z-Wave Devices

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Overview

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- **Methodology**
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  - **GRLVQI Device Discrimination**
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- **Results**
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- **Future Work**
  - **Extend to Additional Classifiers**
  - **Develop Additional DRA Methods for RF Fingerprinting**

Problem Statement

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Investigate Suitability of p-Values and Test Statistic Based Dimensional Reduction Analysis (DRA) Methods for Device Fingerprinting Using Radio Frequency Distinct Native Attribute (RF-DNA) Features.

Background

ZigBee & Z-Wave Devices

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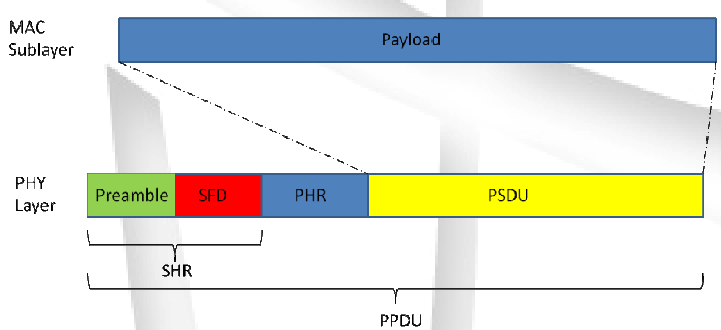
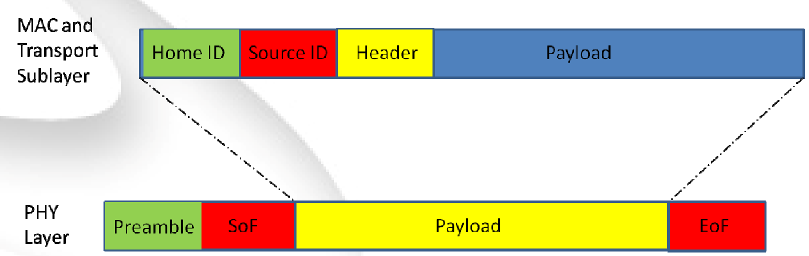
	ZigBee	Z-Wave
Standard	IEEE	Proprietary
Frequency	2.4 GHz	906 MHz
Bit Rate	250 Kbits/s	40 Kbits/s
Security	IEEE 802.15.4 Standard	None: 200 and 300 Series AES 128: 400 Series
Latency	50 to 100 mSec	~1000 mSec
Range	10 to 100 m	30 to 100 m
Message Size (Bytes)	127 (max)	64 (max)





Methodology

ZigBee Emission Processing [2, 13, 14]

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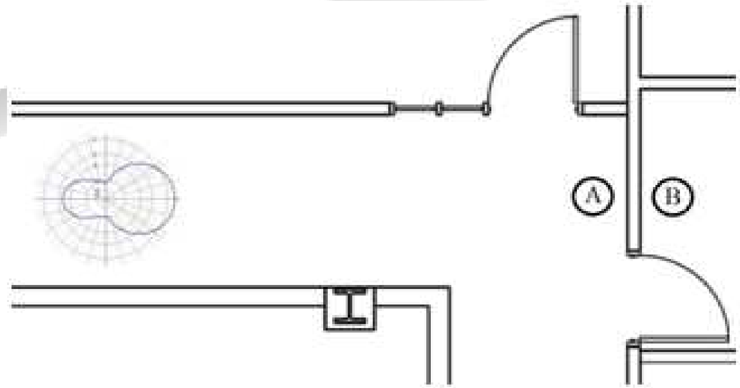
- **Experimentally Collected ZigBee Emissions**
  - **10 Like-Model Devices**
- **Collection Environments**
  - **CAGE – Anechoic Chamber**
  - **LOS – Hallway Line-of-Sight (LOS)**
  - **WALL – Through Wall Propagation**
- **Authorized Devices**
  - **Emissions Collected in CAGE, LOS, & WALL for 4 of 10 Devs (Dev 1 – Dev 4)**
  - **N_C = 4 Like-Model Auth Devs, Different Ser #s**
- **Rogue Devices**
  - **N_{Rog} = 9 Like-Model Rogue Devs, Different Ser #s (Dev 5 – Dev 10)**
  - **Emissions Collected in Selected Environments (See Table)**



ZigBee Experimental Collection Setup for LOS (A) & WALL (B) Environment Emissions [19,54]

ZigBee ID	CAGE	LOS	WALL
Dev5		X	X
Dev6		X	X
Dev7		X	X
Dev8	X		
Dev9	X		
Dev10	X		

ZigBee Rogue Device ID and Collection Environments [19,54]

Methodology

AFIT's RF-DNA Fingerprinting Process [7]

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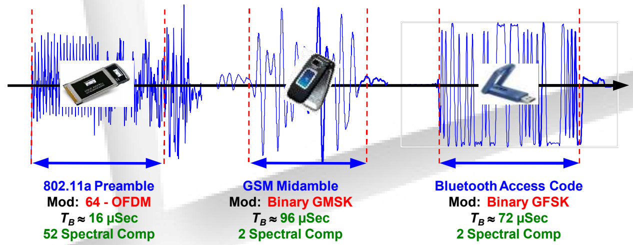
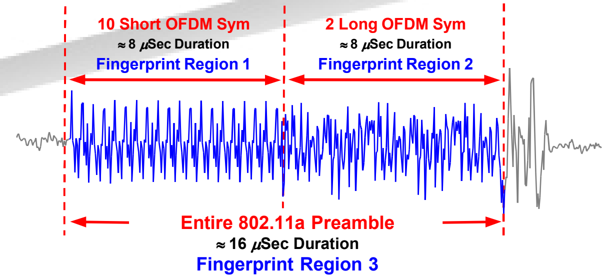
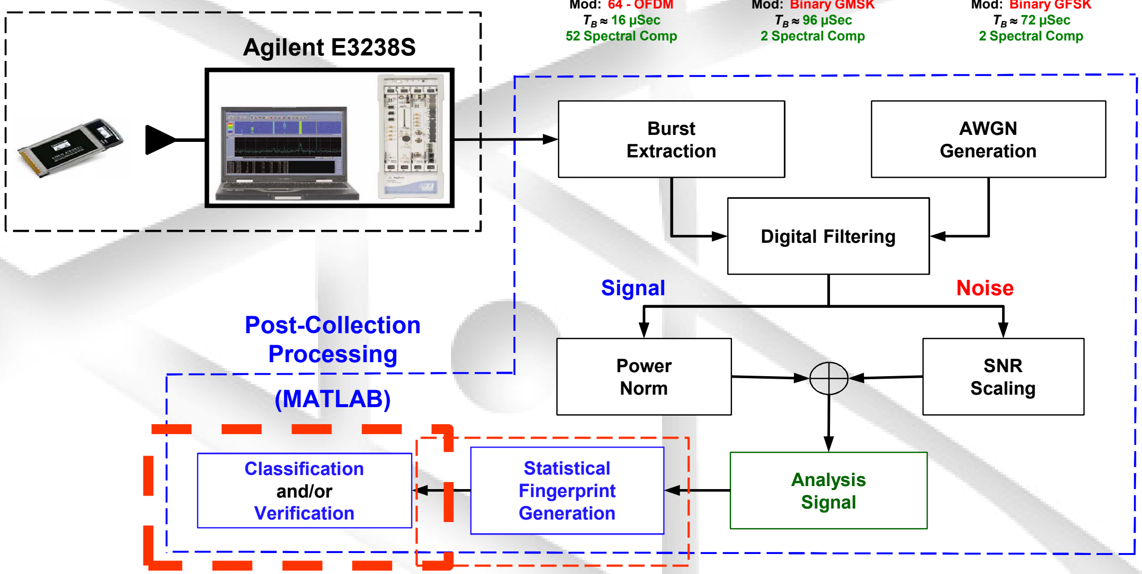
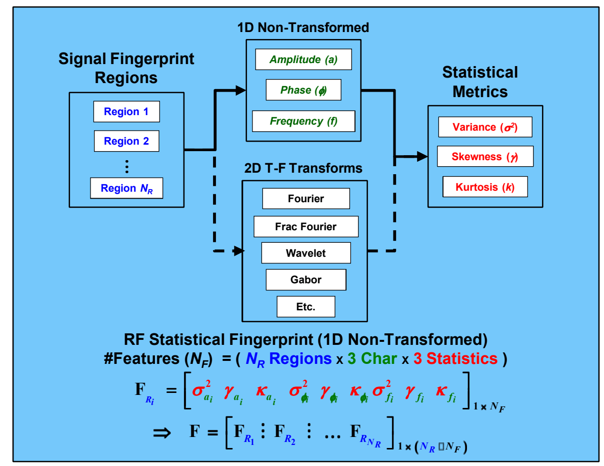
(A) Agilent E3238S (RFSICS)
(A) Nat'l Instruments (NI)
(B) Riscure Inspector



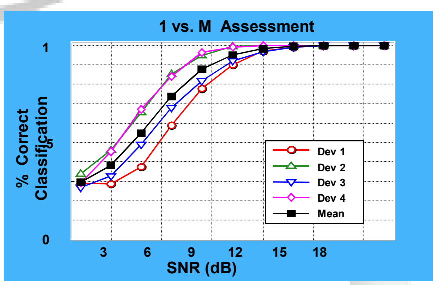




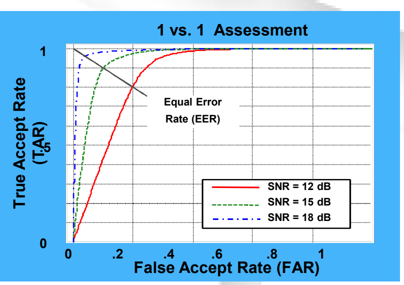
RF Statistical Fingerprint Generation



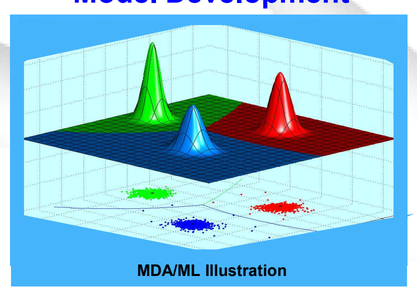
Device Classification



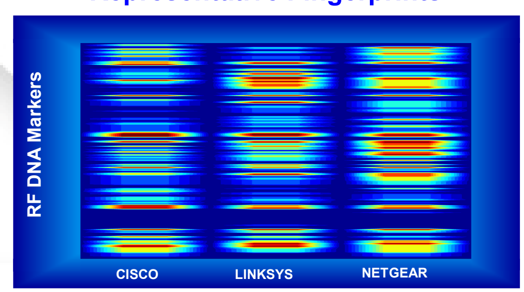
ROC Verification



Model Development



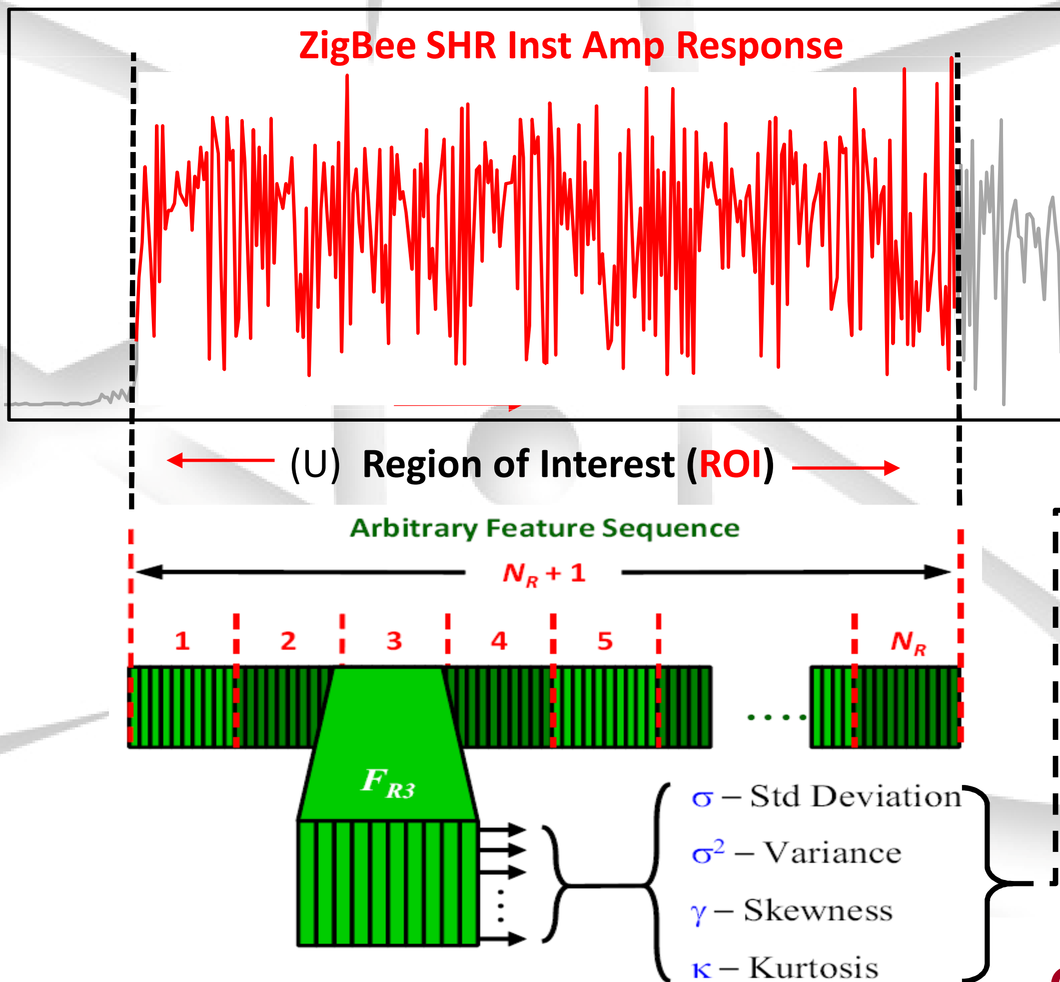
Representative Fingerprints



Methodology

ZigBee Emission Processing [2, 13, 14]

Time Domain (TD) RF-DNA Fingerprint Generation



Non-Transformed Instantaneous:

(a) Amplitude

(b) Phase

(c) Frequency

$$\mathbf{F}_{R_i} = \begin{bmatrix} \sigma_i & \sigma_i^2 & \gamma_i & \kappa_i \end{bmatrix}_{1\times 4}^{i^{\text{th}}\,\text{Region}}$$

Composite Fingerprint

$$\begin{bmatrix} \mathbf{F}_{R_1} \vdots \mathbf{F}_{R_2} \vdots \cdots \vdots \mathbf{F}_{R_{N_R}} \end{bmatrix}_{1\times 4\times N_R}$$

Fingerprints Input to

Classifier Model Development

Methodology

Device Classification: GRLVQI

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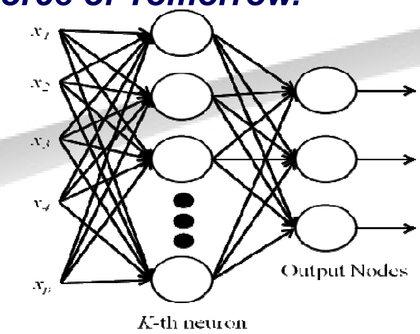
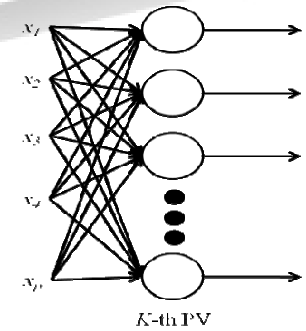
- **LVQ-Based Classifiers**
  - Gradient Descent & Prototype Vector (PV) Approach for Classification
  - Gradient = 1st Derivative of Cost Function
  - Iteratively Examines PV-to-Data Distances
    - Correctly Classified PVs … Move Toward data
    - Incorrectly Classified PVs … Move Away From Data
- **GRLVQI … LVQ Extension [2, 9, 14]**
  - G = *Generalized* … Sigmoidal Cost Function
  - R = *Relevance* … Gradient Descent Feature Relevance Ranking
  - I = *Improved* … Improved Logic, PV Freq, Add'l Learn Rate, Etc.
- **No Explicit *Assumption* / *Knowledge* Required for Data Distribution (PDF)**
  - Appropriate PV Initialization Required
  - Normal PVs ⇒ Standardized Data

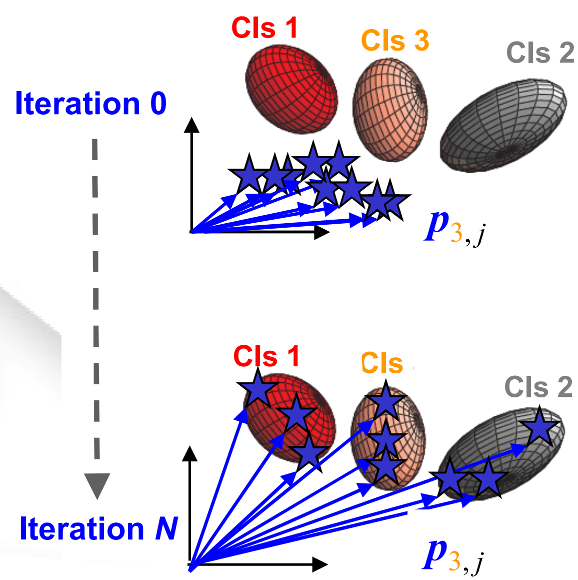


Artificial Neural Net (ANN)



Learning Vector Quant. (LVQ)

LVQ Update



Methodology

Dimensional Reduction Analysis (DRA)

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- **Method #1:** ***(Distribution Based)*: Two Sample Kolmogorov–Smirnov (KS) [13,14, 17]**

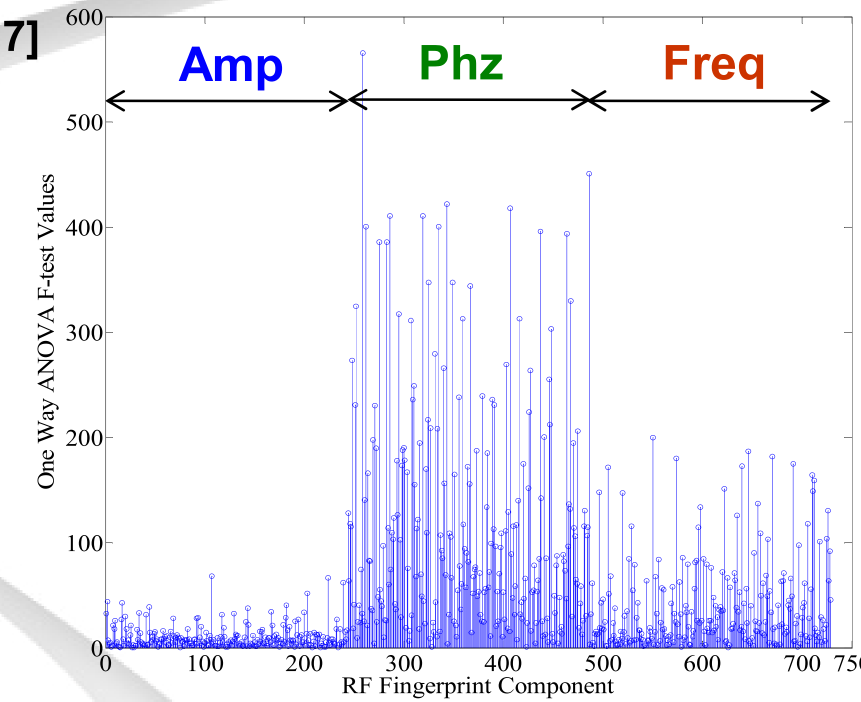
$$KS = \max\left(\left|F_1(x) - F_2(x)\right|\right)$$

- **Method #2:** ***(Distribution Based)*: ANOVA F-Statistics** [18]

$$F_{0(i)} = \frac{MS_{Feature(i)}}{MSE_{Model(i)}}$$

- **Method #3:** ***(Classifier Based) GRLVQI Relevance*** [9]

- **Method #4:** ***Dimensionality Assessment*** [18, 21]



Amplitude (*a*) : ZigBee Feats #1 - #243
Phase (ϕ) : ZigBee Feats #244 - #486
Frequency (*f*) : ZigBee Feats #487 - #729

Methodology

DRA: Dimensionality Assessment

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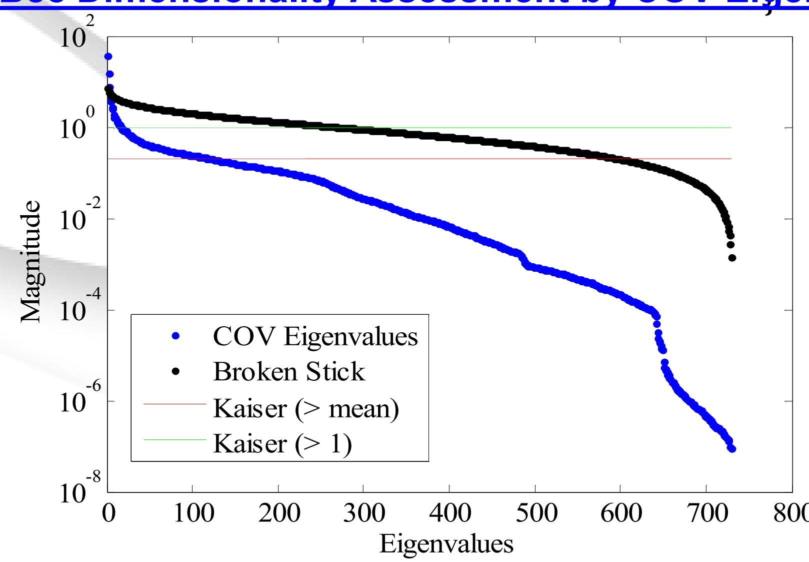
- **Selecting quantity of features in subsets non-trivial**
- ***Qualitative* DRA**
  - ***Previously Considered [13,14]***
  - $N_{DRA,\ ZigBee}$ **= [25, 50, 243]**
- ***Quantitative* DRA**
  - **Introduced Here**
  - **Removes Subjectively**
  - **Intrinsic Data Dimensionality**
- **P-value and Data Eigenvalue methods considered**
  - **P-values Overestimate Required** N_{DRA}
  - **Data Eigenvalue Methods Yield** N_{DRA} **Consistent with Prior Work**
  - $N_{DRA,\ ZigBee}$ **= [17, 123]**
  - $N_{DRA,\ Z\text{-}wave}$ **= [7, 34]**

ZigBee Dimensionality Assessment by Significance Level

SNR (dB)	Method	Significance Level 0.1%	1%	5%	10%
0	F-TEST	196	264	350	402
	KS-TEST (ΣP-VALUES)	37	74	130	160
10	F-TEST	589	639	674	688
	KS-TEST (ΣP-VALUES)	337	414	512	557
18	F-TEST	706	713	720	722
	KS-TEST (ΣP-VALUES)	666	692	711	716
30	F-TEST	718	725	727	728
	KS-TEST (ΣP-VALUES)	727	729	729	729

ZigBee Dimensionality Assessment by COV Eigenvalues



Methodology

DRA: Test Statistics vs p-Values

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- **Recent RF-DNA DRA Research Focused on p-values for feature relevance ranking** [1, 2, 13-14, 28-29]
  - **Test Statistic to p-Value Conversion Req'd**
- **Computing Test Statistic Values**
  - **Ratio between quantities or a simple relationship**
- **Test Statistics vs. P-Values**
  - **p-Values Represent Area Under a Probability Curve**
- **Computing p-Values Requires** [26]

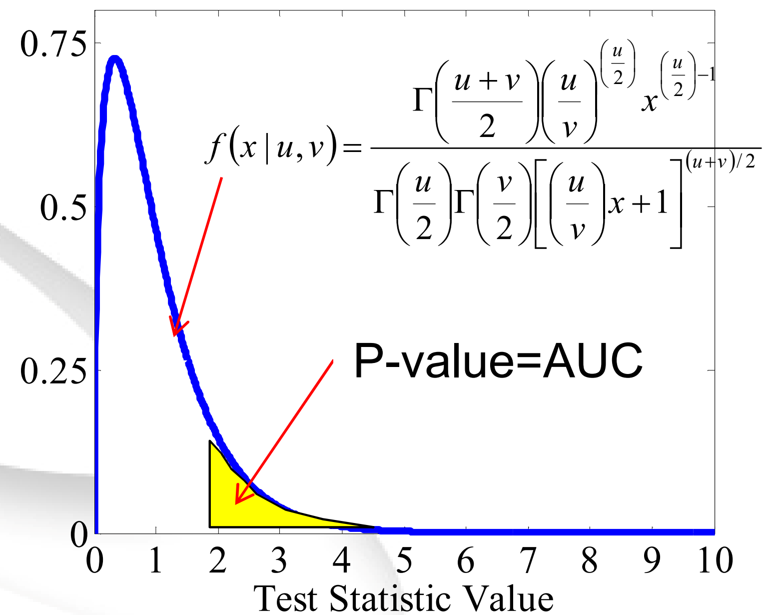
1. Stated Hypothesis Test
2. Test Statistic Value
3. Degrees of Freedom
4. Distributional Assumption
5. Reference Distribution

(Not all are always considered / stated in DRA, e.g. [1, 2, 13, 14])

- **The mapping between test statistic and *p*-value is typically nonlinear**
- **Simple F-Test Stat.** [18]

$$F_{0(i)} = \frac{MS_{Feature(i)}}{MSE_{Model(i)}}$$

- **Complicated F-Test p-value** [18]



- **The KS-test involves a similar nonlinear mapping** [17]

Methodology

ZigBee DRA: Test Statistics vs P-Values

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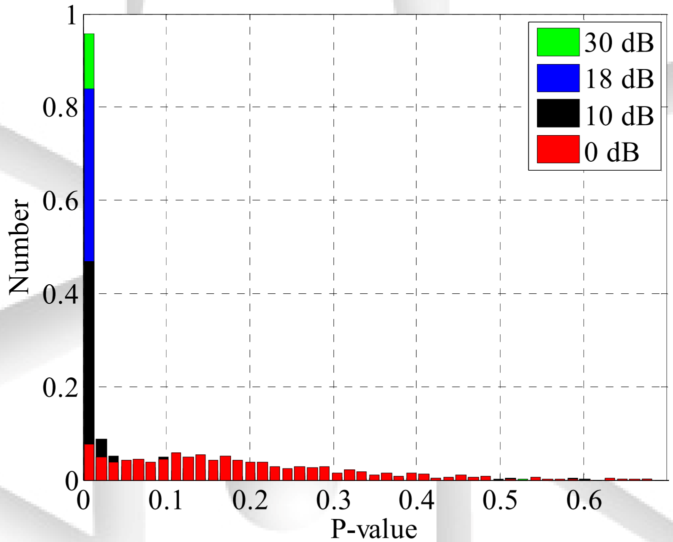
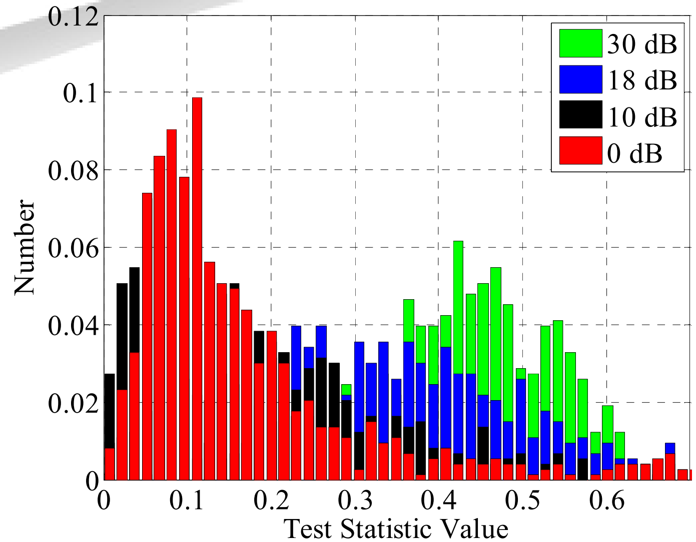
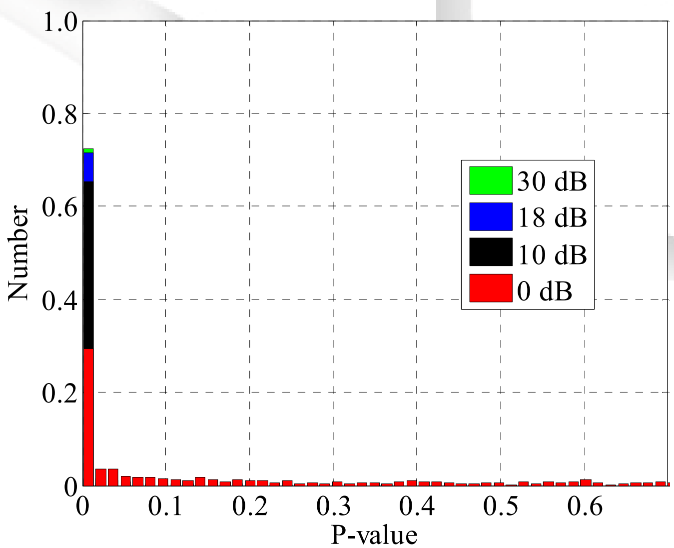
p-values | **Test Statistic Values**

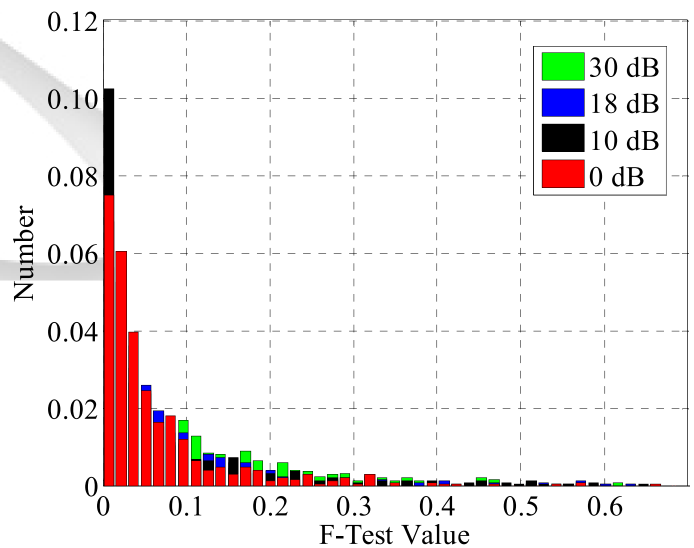
KS-test





F-test





Methodology

ZigBee DRA: Test Statistics vs P-Values

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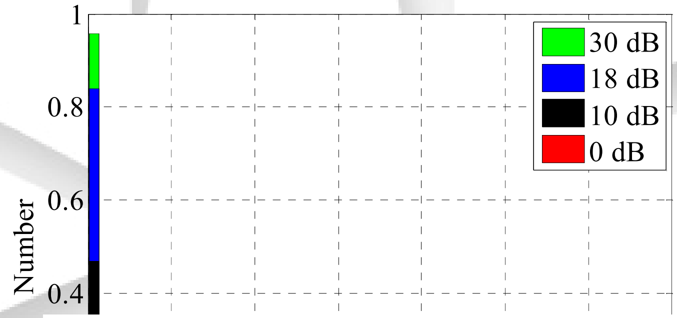
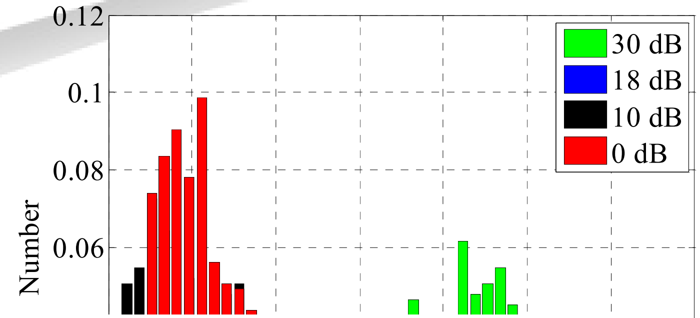
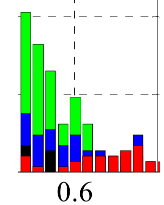
p-values | **Test Statistic Values**

KS-test

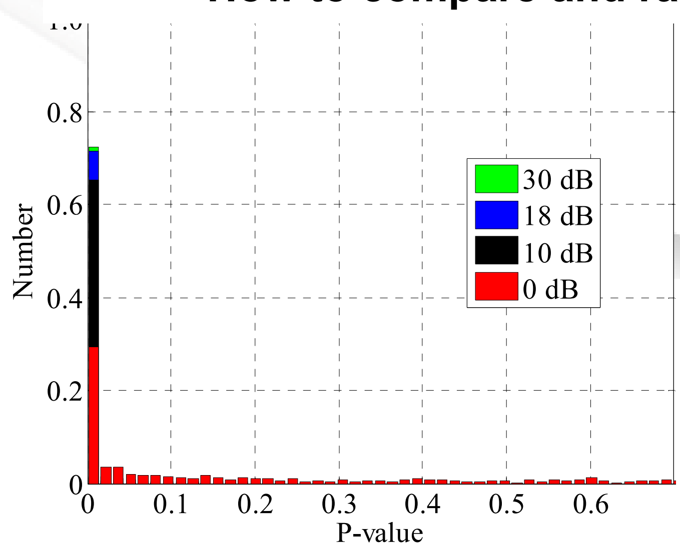


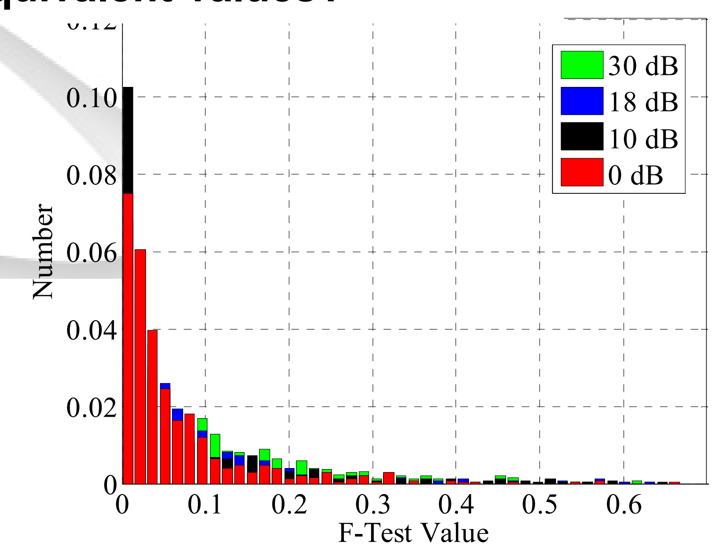




- **With large datasets, p-values tend towards zero**
  - **Hence resolution is lost when converting to p-values**
- **Interpretation/procedural issues also remain**
  - **How to compare and rank equivalent values?**

F-test





Results

Device Classification: ZigBee & Z-Wave

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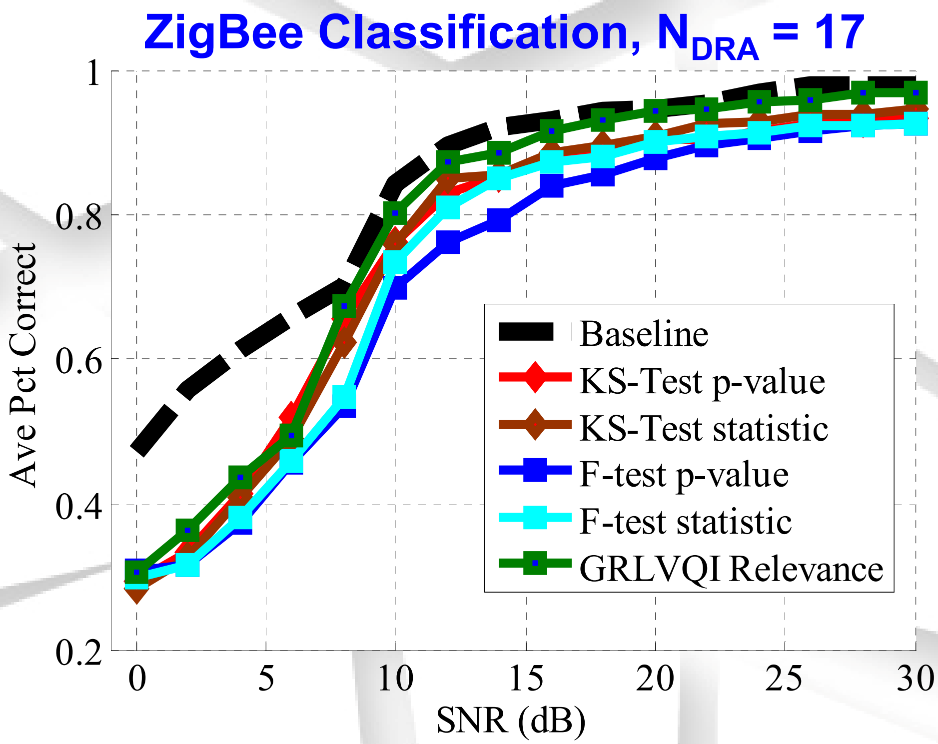
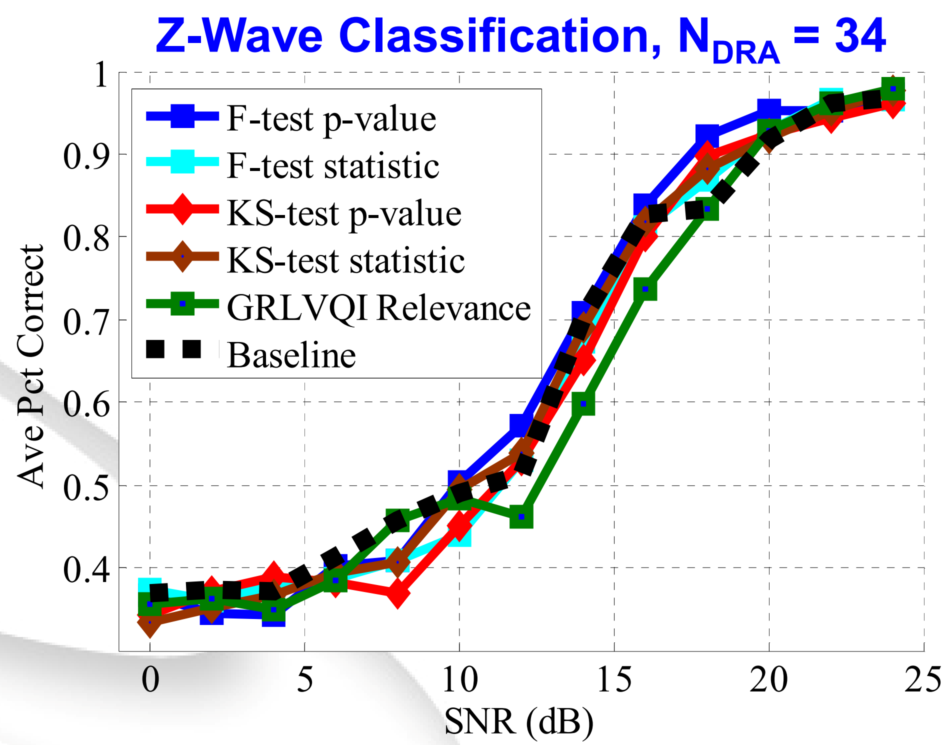
- Test statistic methods offer comparable or better performance to *p*-value based methods





Results

Device ID Verification: ZigBee

- Based on "one vs one" claimed identity scenarios
- Presented as:
  - *%TVR = True Verification Rate*
  - *% RRR = Rogue Rejection Rate*
  - Bold Entry - Best or Statistically Equivalent Performance

DRA Method	KS test Statistic			KS ΣP-value		
N_F	***17***	***50***	***123***	***17***	***50***	***123***
TVR	0%	0%	0%	0%	0%	0%
RRR	8.33%	8.33%	0%	**52.8%**	2.78%	0%
DRA Method	F Test Statistic			F Test P-value		
N_F	***17***	***50***	***123***	***17***	***50***	***123***
TVR	0%	0%	0%	**25%**	0%	0%
RRR	8.33%	5.56%	0%	38.9%	19.4%	0%
DRA Method	GRLVQI					
N_F	***17***	***50***	***123***			
TVR	**25%**	**50%**	**50%**			
RRR	**52.8%**	**66.7%**	**72.2%**			

Results

Device ID Verification: ZigBee

The AFIT of Today is the Air Force of Tomorrow.

- Based on “one vs one” claimed identity scenarios
- Presented as:
  - *%TVR = True Verification Rate*
  - *% RRR = Rogue Rejection Rate*
  - Bold Entry - Best or Statistically Equivalent Performance

DRA METHOD	KS TEST STATISTIC			KS ΣP-VALUE		
N_F	***17***	***50***	***123***	***17***	***50***	***123***

- **Distribution-based DRA offers poor verification performance with non-linear GRLVQI classifier**

DRA METHOD	F TEST STATISTIC			F TEST P-VALUE		
N_F	***17***	***50***	***123***	***17***	***50***	***123***
TVR	0%	0%	0%	**25%**	0%	0%
RRR	8.33%	5.56%	0%	38.9%	19.4%	0%

DRA METHOD	GRLVQI		
N_F	***17***	***50***	***123***
TVR	**25%**	**50%**	**50%**
RRR	**52.8%**	**66.7%**	**72.2%**

Conclusions & Future Work

Conclusions

- **Introduction of F-test for DRA in RF Fingerprinting**
- **Test Statistic Methods vs *P*-values**
  - ***P*-values Susceptible to Converge on 0** [26]
  - **Test Statistic DRA Offers Robustness**
- **Introduction Quantitative Dimensionality Assessment**
  - **N_{DRA} = 123 (quantitative) better than N_{DRA} = 243 (qualitative) of [14]**
- **Comparison of 5 DRA Methods for RF Fingerprinting**
- **First Look RF-DNA Fingerprinting Using Z-Wave Devices**

Future Work

- **Expand Z-Wave Assessments to Include Rogue Devices**
- **Reevaluate with an MDA-based classifier**

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