CORRELATION BASED CLASSIFICATION OF COMPLEX PRI MODULATION TYPES

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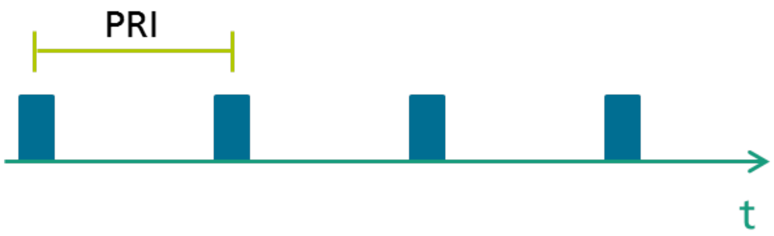
*Since April 2017 Fotios is with Airbus Defence and Space GmbH

Agenda

1. Introduction
2. Problem description
3. Proposed solution
4. Simulated examples
5. Summary & conclusions

Introduction 1/3

- Choice of a radar's **pulse repetition interval (PRI)** has great influence on target detection and tracking performance
- Interval might be constant:



- Or with some modulation:
- (3-level stagger)

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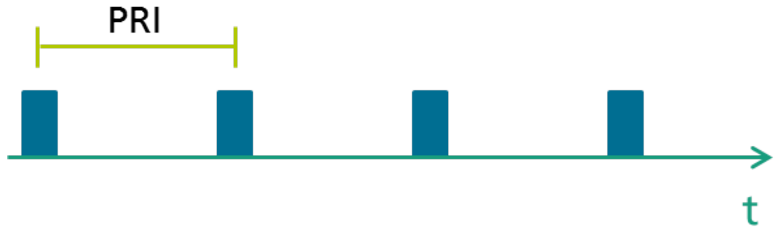

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Introduction 2/3

- Classification of **pulse repetition interval modulation** important for electronic warfare systems:
  - Significant knowledge about the observed emitter
  - Improvement of own electronic warfare system functions
- Literature: Standard PRI modulation types only
  - Dwell & switch, stagger, constant, jittered, complex

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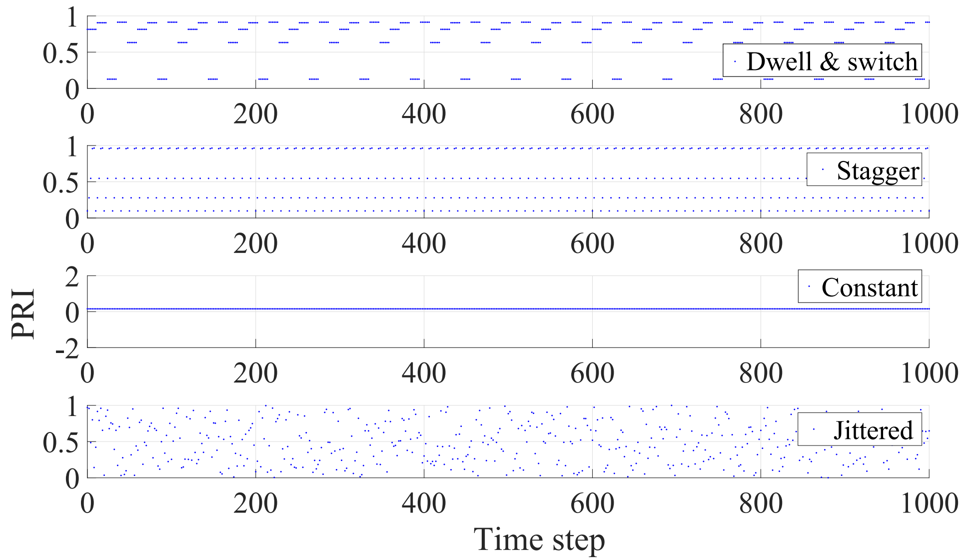
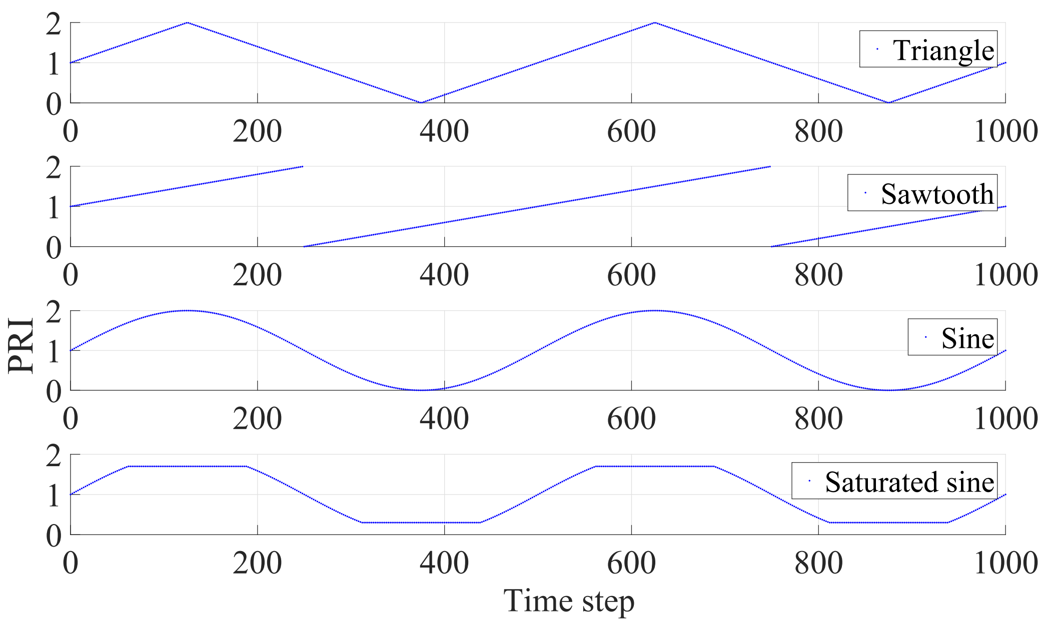


Introduction 3/3

- Automatic classification of **complex PRI modulation sub-types** remains unaddressed
  - Common: Triangle, sawtooth, sine, and saturated sine



Problem description 1/2

Consider a scenario where:

- A receiver observes an area of interest and records pulses emitted from different radars
- The received pulses are deinterleaved, i.e sorted by emitter
  - Deinterleaving is a complex topic itself - not in scope
  - Effects accounted for by considering spurious and missing pulses

Problem formulation:

→ **Does the received signal exhibit a complex PRI modulation?**

→ **If yes, of which sub-type: sawtooth, triangle, sine, or saturated sine?**

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Problem description 2/2

This is essentially a *multi-class classification* or *multiple hypotheses testing* problem:

- Hypothesis H_1: class C_1, i.e. sawtooth modulation
- Hypothesis H_2: class C_2, i.e. triangle modulation
- Hypothesis H_3: class C_3, i.e. sine modulation
- Hypothesis H_4: class C_4, i.e. saturated sine modulation
- Hypothesis H_0: class C_0, i.e. none of the above

We desire high **probability of correct classification**:

$$P_C^j = P(C^* = C_j | C_{\text{true}} = C_j), \; j = 1, \dots, 4$$

and low **probability of misclassification**:

1. Modulation type j is classified as some other type

$$P_{M-v1}^j = P(C^* \neq C_j | C_{\text{true}} = C_j), \; j = 1, \dots, 4$$

2. Some other modulation types are classified as type j

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Proposed solution

Input: TOA difference of pulses Δt, cross-correlation threshold c_{min}
Output: Complex modulation type hypothesis decision $H_j : C^* = C_j,\ j \in \{0, 1, 2, 3, 4\}$

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smooth the lower envelope of Δt and get $\widehat{\Delta t}$ (red line in Fig.)

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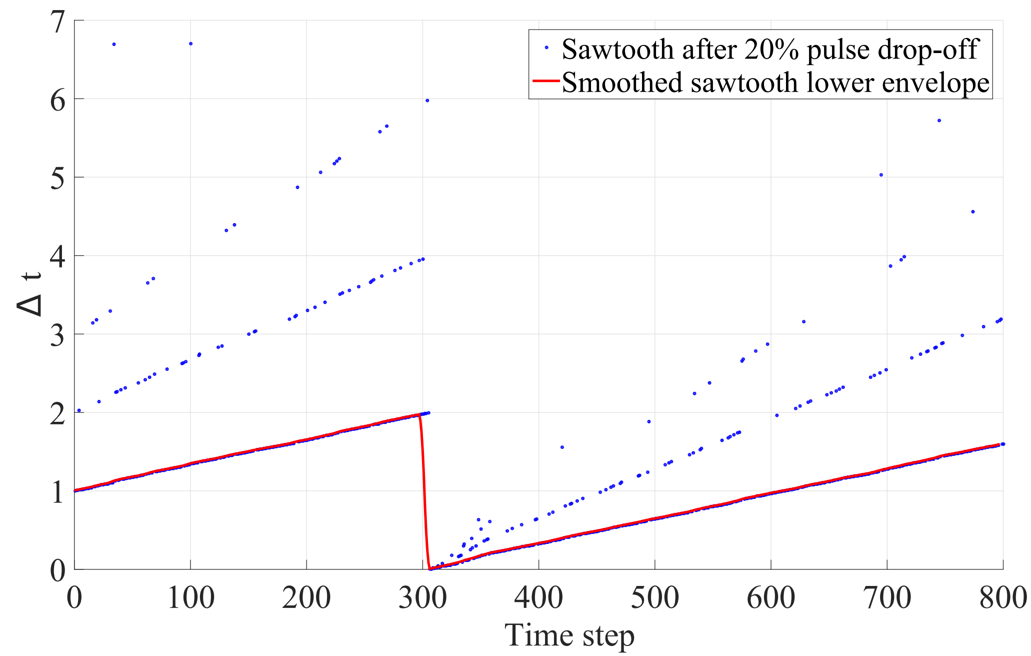
Elimination of the effect of lost pulses



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evaluate $\left(\widehat{\Delta t} \star \widehat{\Delta t}\right)$, i.e. its autocorrelation
find the period of Δt using the peaks of $\left(\widehat{\Delta t} \star \widehat{\Delta t}\right)$

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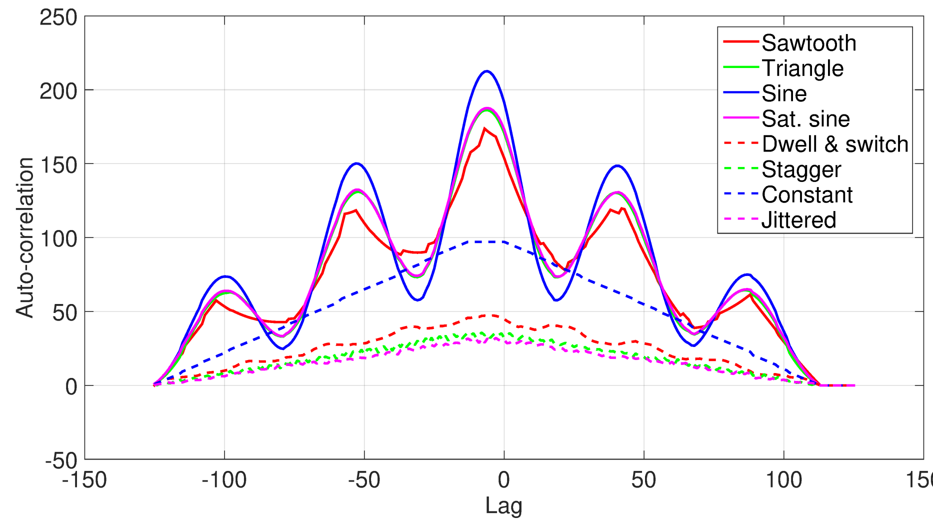
Complex PRI modulation induces distinct peaks



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extract a period from $\widehat{\Delta t}$
create ideal signals $\Delta t_j^*,\ j = 1, \ldots, 4$

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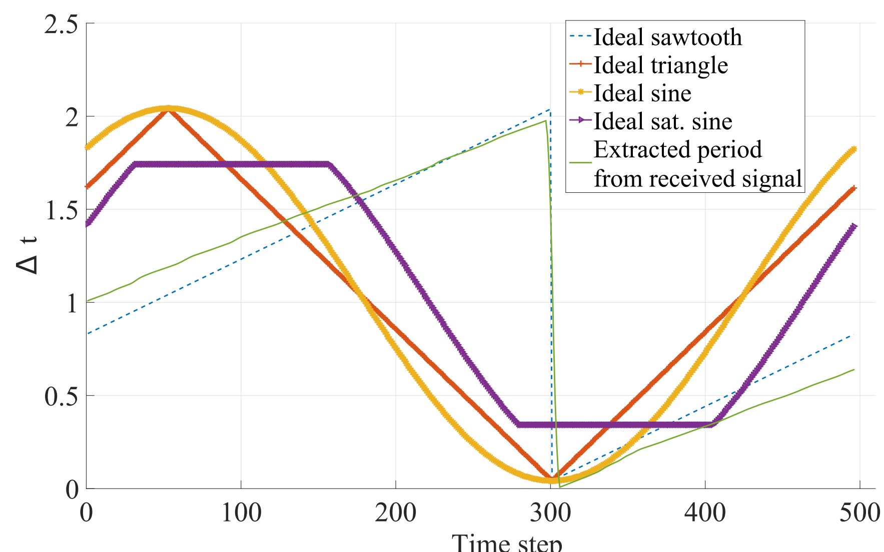
end if



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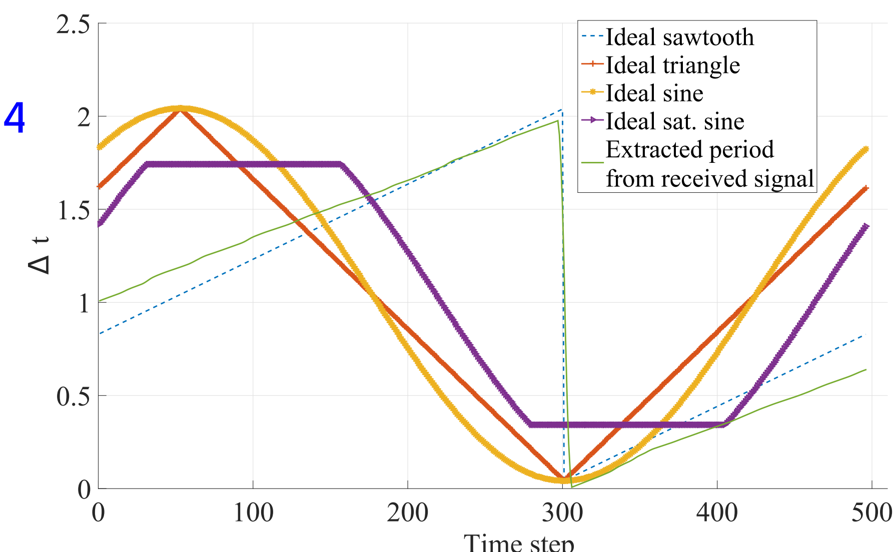
create ideal signals $\Delta t_j^*,\ j = 1, \dots, 4$
find $j^* = \arg\max_j \left[\left(\widehat{\Delta t} \star \Delta t_j^*\right)\right], j = 1, \dots, 4$
if $\left(\widehat{\Delta t} \star \Delta t_{j^*}^*\right) > c_{min}$ **then**
    choose hypothesis $H_{j^*} : C^* = C_{j^*}$
else
    choose hypothesis $H_0 : C^* = C_0$
end if



Simple example 1: Favourable case

In this case we assume **very reliable** prior information:

- Normalized cross-correlation threshold $c_{min} = 0.8$
- Duration of the emitted signal $D = 200$ time units
- We sample 1.8 periods of the signal
- Drop-out ratio of 10%, i.e. 10% of the emitted pulses are lost
- Saturation of sat. sine is known to be 0.7

PRI mod.	$\mathbf{P_C}$	$\mathbf{P_{M-v1}}$	$\mathbf{P_{M-v2}}$
Sawtooth	0.96	0.01	0.0001
Triangle	0.88	0.12	0.22
Sine	0.83	0.17	0.11
Sat. sine	0.84	0.16	0.09

PRI mod.	$\mathbf{P_C}$	$\mathbf{P_{M-v1}}$	$\mathbf{P_{M-v2}}$
Dwell & switch	N/A	0.001	N/A
Stagger	N/A	0	N/A
Constant	N/A	0	N/A
Jittered	N/A	0.0003	N/A

Simple example 2: Unfavourable case 1

In this case we assume reliable prior information but more pulses are lost:

- Normalized cross-correlation threshold $c_{min} = 0.8$
- Duration of the emitted signal $D = 200$ time units
- We sample 1.8 periods of the signal
- **Drop-out ratio of 20%**, i.e. 20% of the emitted pulses are lost
- Saturation of sat. sine is known to be 0.7

PRI mod.	P_C	P_{M-v1}	P_{M-v2}
Sawtooth	0.9	0.05	0.0001
Triangle	0.64	0.36	0.25
Sine	0.79	0.2	0.34
Sat. sine	0.6	0.4	0.22

PRI mod.	P_C	P_{M-v1}	P_{M-v2}
Dwell & switch	N/A	0.007	N/A
Stagger	N/A	0.0008	N/A
Constant	N/A	0	N/A
Jittered	N/A	0.003	N/A

Simple example 3: Unfavourable case 2

In this case we assume unreliable prior information:

- Normalized cross-correlation threshold $c_{min} = 0.8$
- Duration of the emitted signal $\boldsymbol{D} = \mathbf{100}$ time units
- We sample **1.5 periods** of the signal
- **Drop-out ratio of 20%**, i.e. 20% of the emitted pulses are lost
- Saturation of **ideal sat. sine is 0.8** instead of the true value 0.7

PRI mod.	P_C	P_{M-v1}	P_{M-v2}
Sawtooth	0.9	0.07	0.03
Triangle	0.06	0.94	0.02
Sine	0.06	0.94	0.11
Sat. sine	0.9	0.09	0.95

PRI mod.	P_C	P_{M-v1}	P_{M-v2}
Dwell & switch	N/A	0.02	N/A
Stagger	N/A	0.002	N/A
Constant	N/A	0	N/A
Jittered	N/A	0.02	N/A

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In depth look into the performance

The following settings were used:

- Normalized cross-correlation threshold $c_{min} = 0.8$
- Duration of the emitted signal $D = 1000$ time units
- Mean **pulse repetition interval** $PRI \in \{0.1, 0.25, 0.5, ..., 3, 3.5, 4\}$ time units
  - Higher value means less pulses emitted in the same time
- **Number of observed signal periods** $D/T \in \{1, 1.1, 1.2, \ldots, 3\}$
  - Ratio of emitted signal duration D and signal period T
  - Higher value means less pulses per period in the same observation time

In depth look into the performance

The following settings were used:

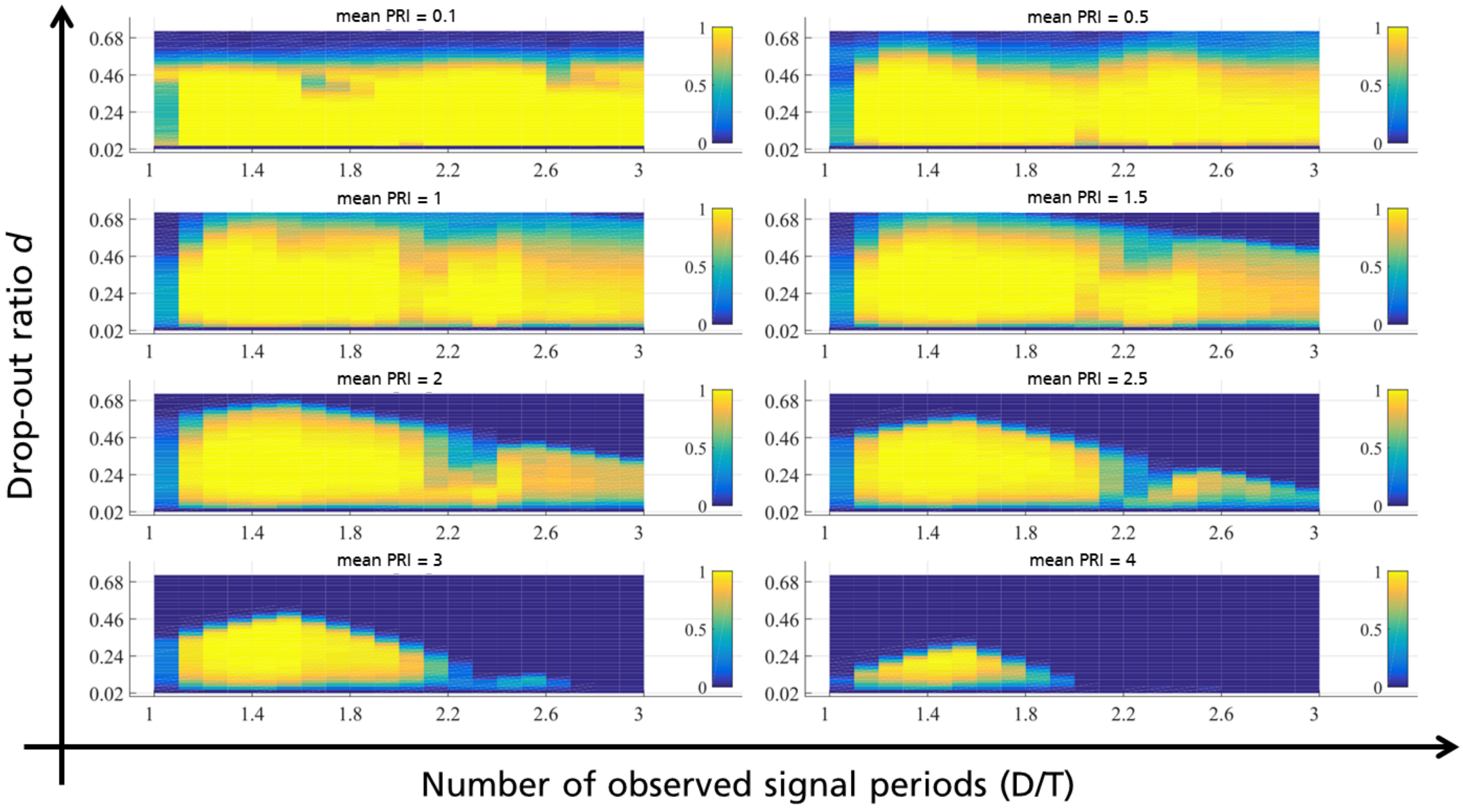
- **Drop-out ratio** $d \in \{0, 0.02, 0.2, \ldots, 0.7\}$
- 1000 Monte Carlo runs
- Pulses randomly dropped at each run based on the drop-out ratio

We examine the:

- Probability of correct classification
- Both definitions of the probability of misclassification

Example: Sawtooth PRI modulation

Very high **probability of correct classification** P_C over a broad range of signal reception settings.



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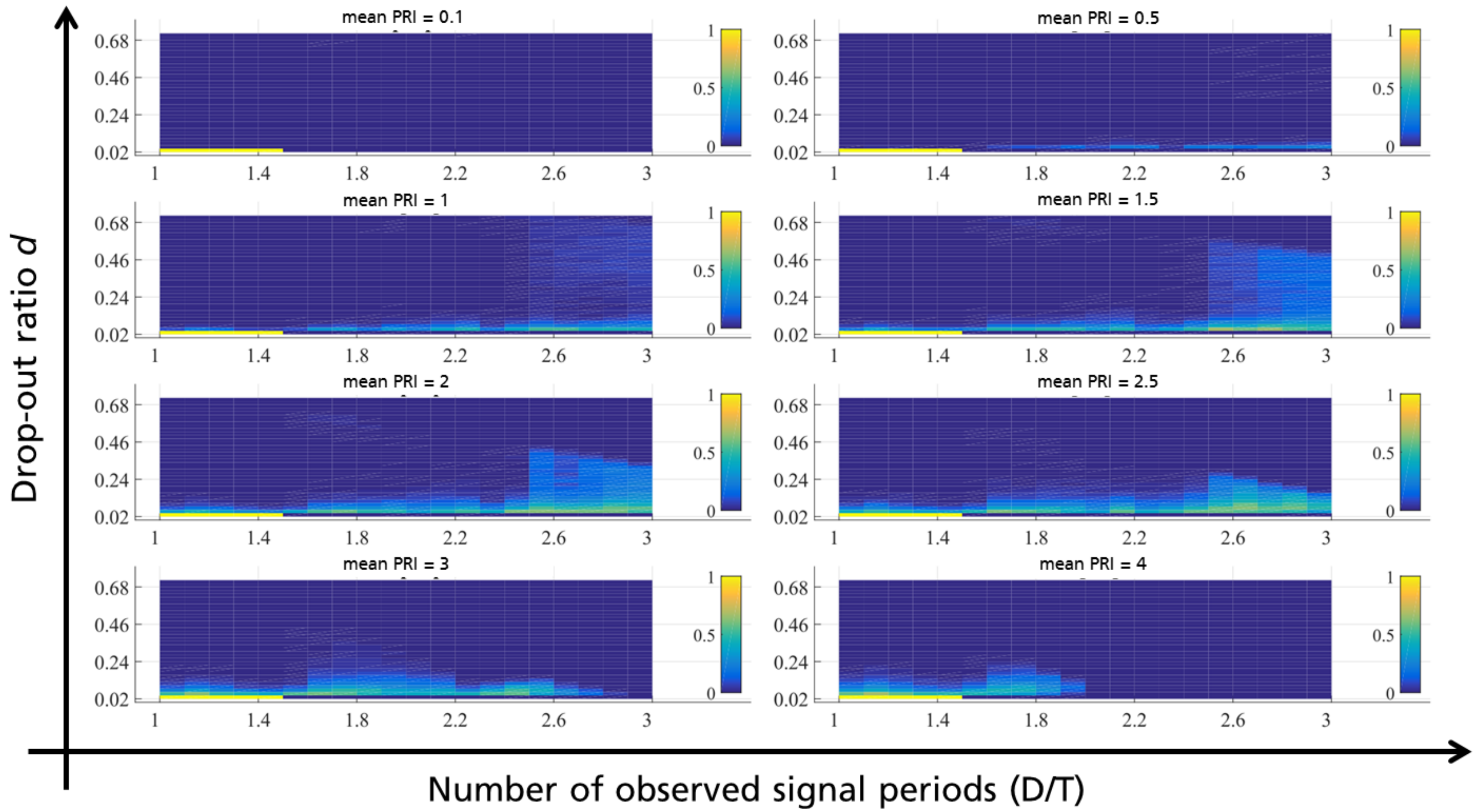
Example: Sawtooth PRI modulation

Very low **probability that sawtooth is classified as another complex modulation type** P_{M-v1} over a broad range of signal reception settings.



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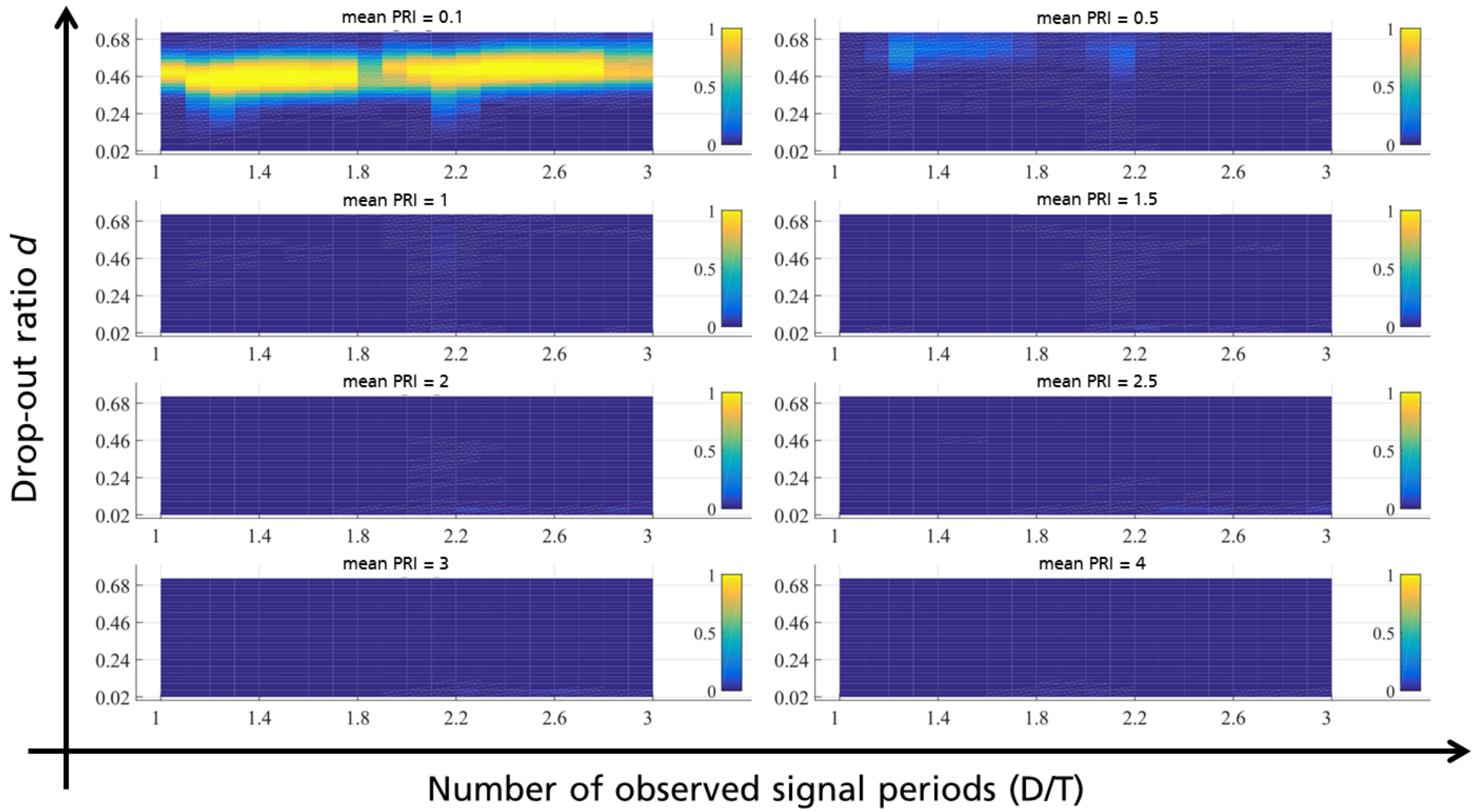
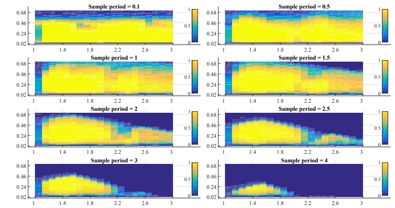
Example: Sawtooth PRI modulation

Very low **probability that other modulation types are classified as sawtooth** P_{M-v2} over a broad range of signal reception settings.



Conclusions



- Sawtooth modulation correctly classified in almost all cases
- Non-complex PRI modulations practically never identified as complex
- Most false classifications of triangle and sine are due to confusion with saturated sine
- Crucial part: Reliable extraction of the lower envelope of the received signal
  - Lower envelope should resemble one of the ideal complex modulation types
  - At least 1.2 periods should be observed
- Best performance for: $D/T \in \{1.2, \ldots, 2\}$, $meanPRI \in \{0.1, \ldots, 2\}$, $d \in \{0.02, \ldots, 0.46\}$
- Prior information about the received signal crucial for its correct classification
  - Knowledge about the signal period can be used for adapting the observation duration
- Significant pulse drop-out ratios can be tolerated
  - Up to 50% under some favourable conditions

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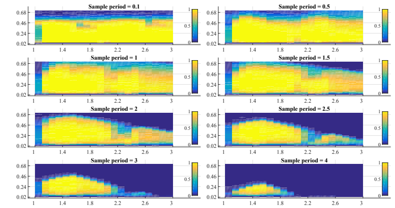

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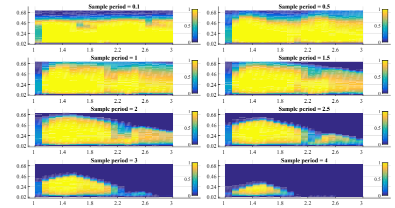

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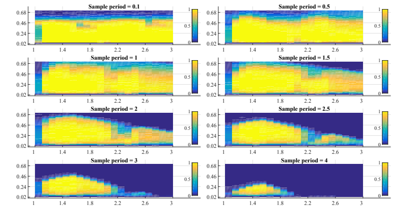

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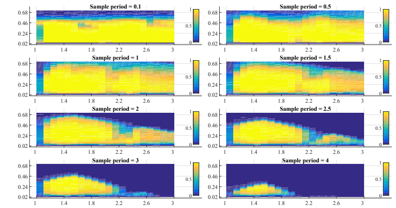

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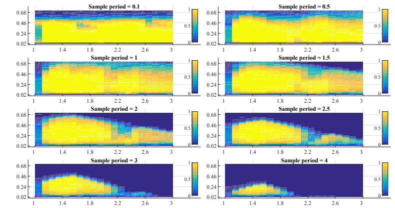

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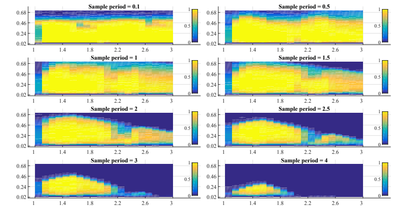

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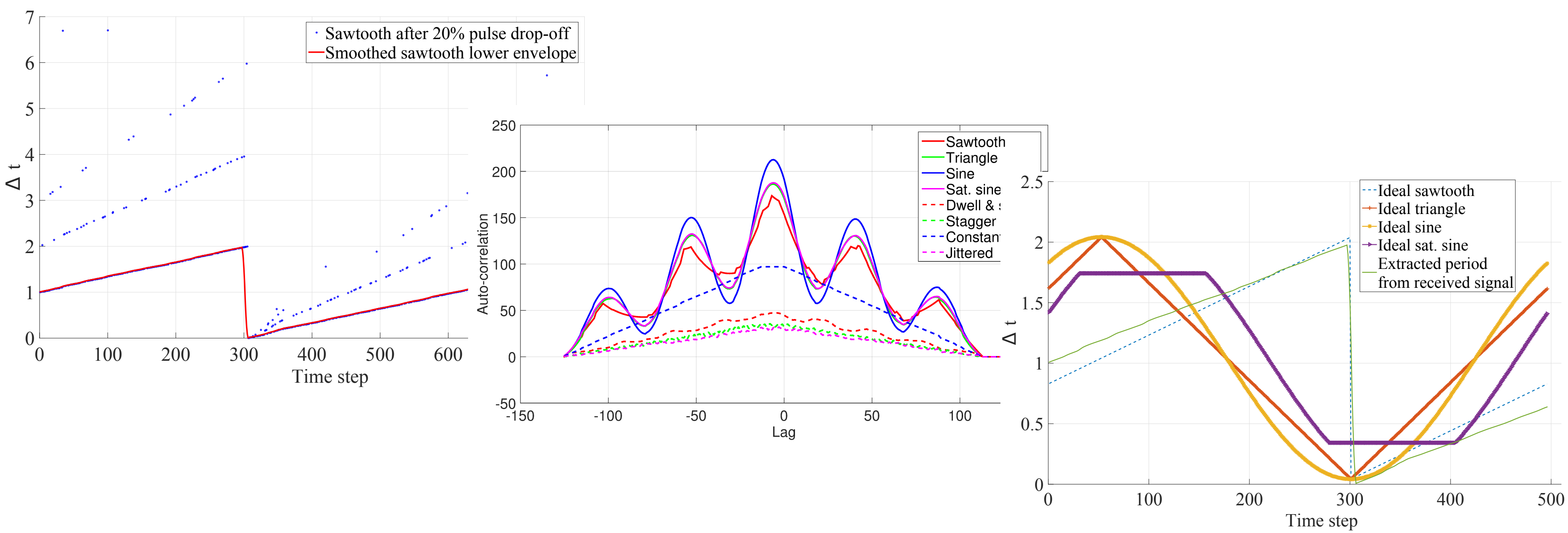
- First algorithm in the open literature that classifies complex PRI modulation types
- Classification of complex PRI modulation with good statistics under varying signal reception conditions
- Information from an emitter database plays a crucial role
- Almost complete rejection of signals having non-complex PRI modulation
- Low computational complexity algorithm



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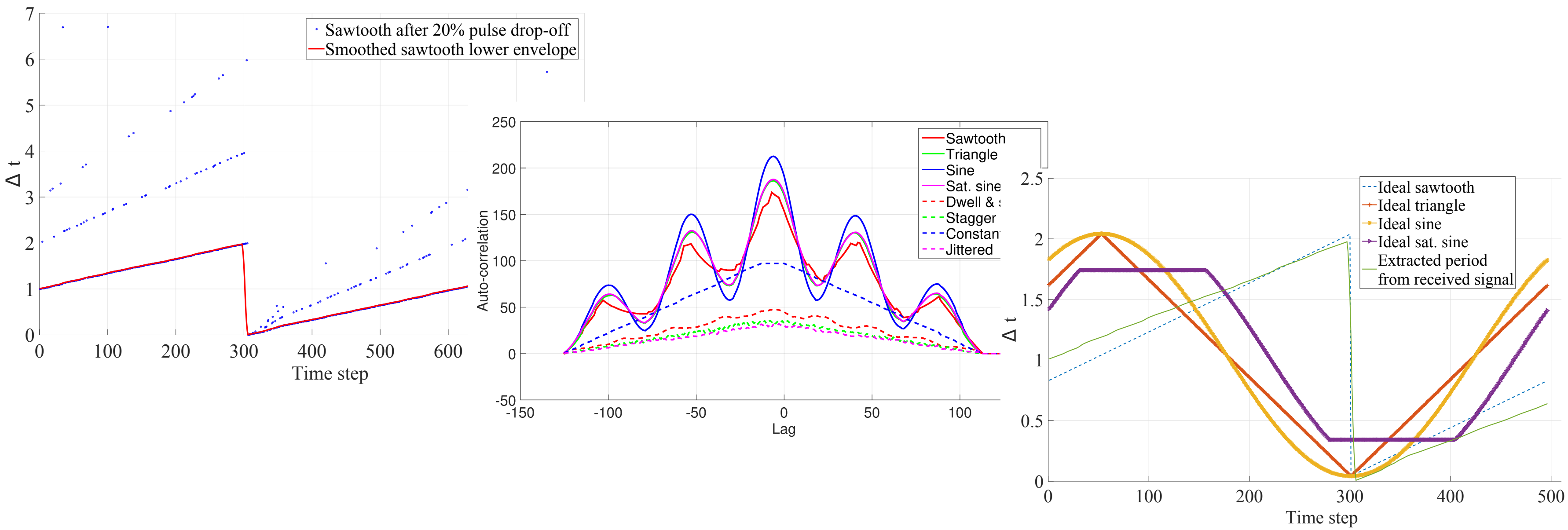

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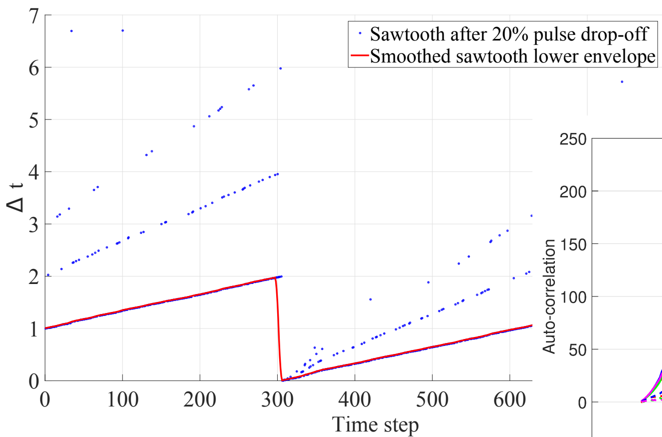

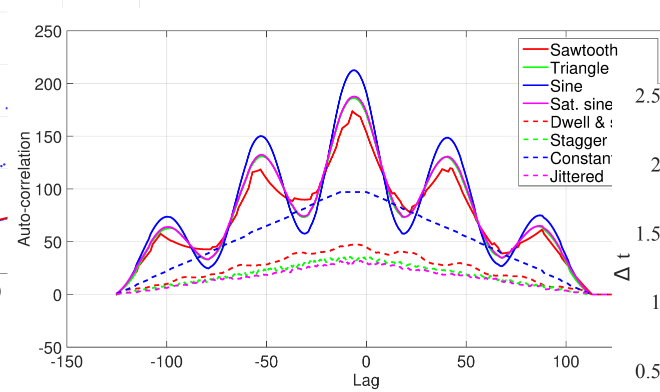

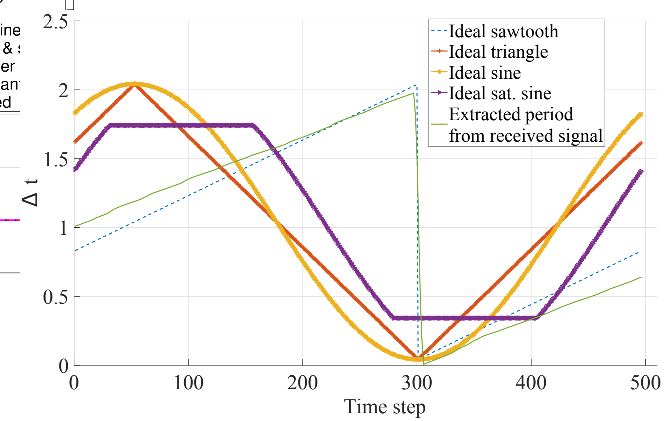

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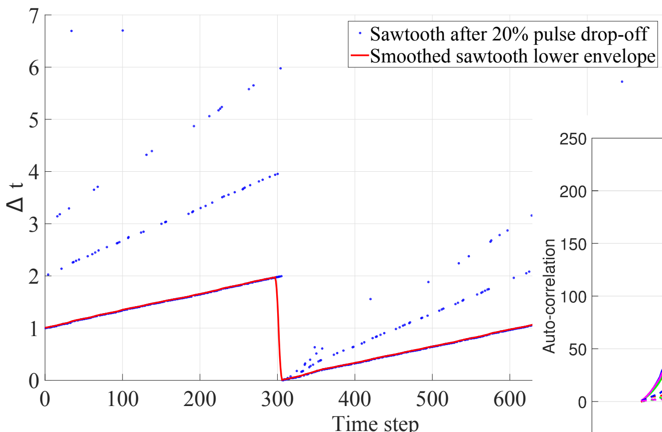
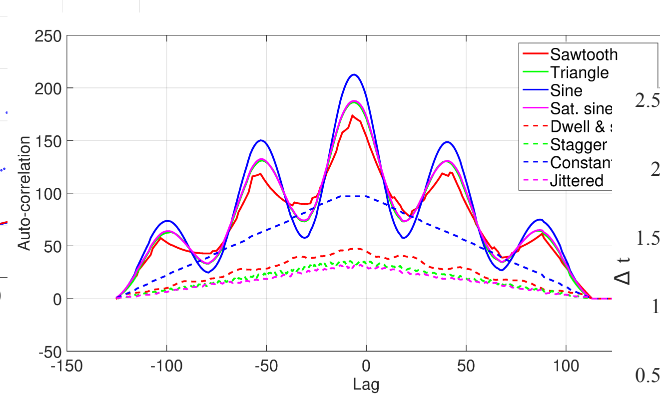
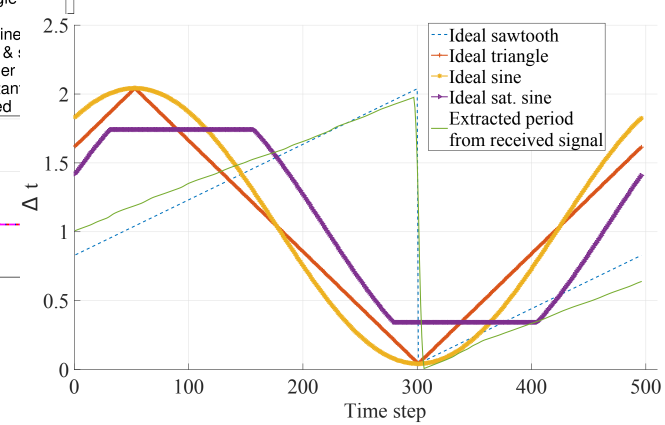
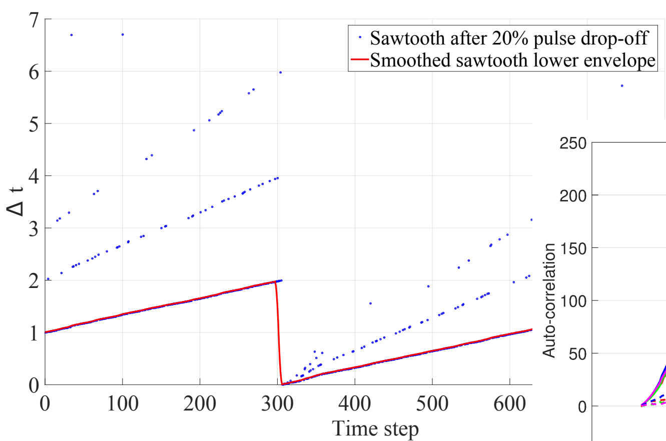


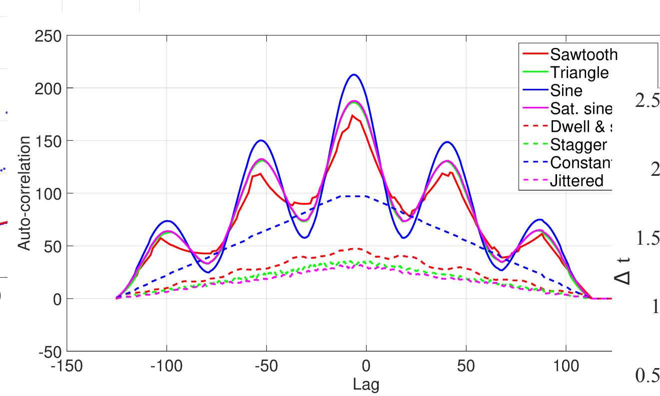


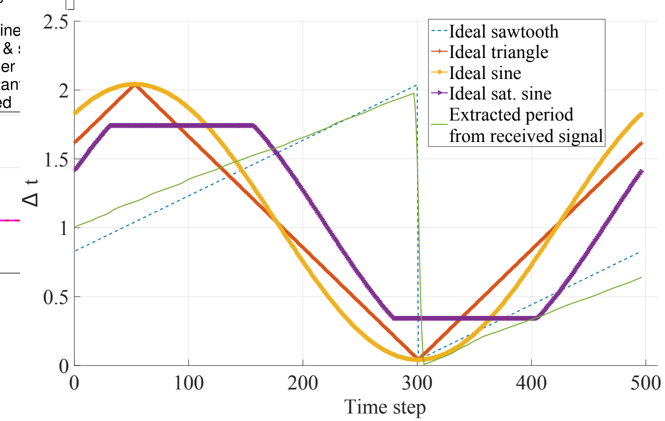


Summary

- First algorithm in the open literature that classifies complex PRI modulation types
- Classification of complex PRI modulation with good statistics under varying signal reception conditions
- Information from an emitter database plays a crucial role
- Almost complete rejection of signals having non-complex PRI modulation
- Low computational complexity algorithm







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Thank you
for your attention!

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