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# An Analysis Framework for Steganographic Network Data in Industrial Control Systems

Tom Neubert, Bjarne Peuker, **Eric Schueler**, **Henning Ullrich**, Laura Buxhoidt, Claus Vielhauer

Gefördert durch:

Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz

aufgrund eines Beschlusses des Deutschen Bundestages

The research in this work has been performed in context of the project ATTRIBUT (https://omen.cs.uni-magdeburg.de/itiamsl/deutsch/projekte/attribut.html) jointly by a the teaching project at “Brandenburg University” in term 2023/2024. This comprises in particular the conceptional design of of the experimental analysis framework and embedding method $EM_3$ , software realization in Python of all algorithms for embedding and feature extraction in Section 3. It was further supported by the evaluation dataset (Section IV-B) generously contributed by the project “SYNTHESIS”, funded by the German Federal Min- istry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV, project no. 1501666B) in the framework of the German reactor safety research program.

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I. Introduction + Contribution

II. Basics + State-of-the-Art

III. The Analysis Framework

IV. Evaluation Setup

V. Evaluation Results

VI. Summary and Future Work

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# Introduction

- Stealthy malware is increasingly used by attackers [1]
- It uses unobstrusive data to create hidden channels → utilized to embed malicious code or hidden information
- Since the Stuxnet-Attack in 2010, is has been clear that also ICS are under attack with stealthy malware
- Currently, several attack vectors with steganographic embedding methods and potential defense mechanisms are introduced [5],[6],[7]

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# Introduction

- To analyze and compare steganographic embedding methods to identify potential similarities, differences and effects on the cover data and to derive defense mechanisms an analysis framework is needed

- A comprehensive analysis could for example enable the possibility to distinguish between analyzed embedding methods after a detection which can lead to the opportunity to identify potential attackers → Attribution

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# Contribution

- Thus, this work contributes:
  - a novel **analysis framework** for network steganography in ICS and it offers the possibility to:
    - **compare** and **analyze multiple** network steganographic **embedding methods**
    - with only a single uncompromized network traffic capture from an exemplary ICS
  - validation of novel framework and an extensive evaluation of three exemplary selected embedding methods (2 State of the Art, 1 Novel Method) to find out if we can differntiate between embedding methods and embedded types of message (invariant and heterogenous) with machine learning based approach

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# Basics in Network Steganography in ICS

- *"Steganography is the art and science of concealing the existence of information transfer and storage"* [8]
- network steganography targets the transfer & storage of hidden information in network communication traffic
- stealthy malware should be inconspicuous in a sense that a warden would not be able to differentiate between genuine communication and communication with hidden information embedding [5]
- In ICS its special, due to lower amount of available data for potential embedding than in traditional IT-networks
- Additionally, transmitted network packets are usually smaller in ICS since only meta-data or few values (e.g., from sensors) are transferred per packet.
- ICS specific protocols like OPC-UA [10] or Modbus-TCP [11] are often encapsulated in TCP/IP
- often transmitted unencrypted, because ICS are considered as closed networks and not subject to attacks.

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# State-of-the-Art

- Synthetic Steganographic Data Generation Concept used to generate steganographic network data from [13]:
    - Offers opportunity for fast and easy generation of data for comparison and analysis with the framework
    - The concept synthesizes only the type and characteristics of steganographic channel while the rest is taken directly from an uncompromised ICS-setup
- Embedding Method $EM_1$ [5] & $EM_2$ [6] *are recent and relevant attack vectors in ICS with timestamp modulations which are analyzed and compared in this work with framework*

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# The Analysis Framework

- For **comparison** and **evaluation** of steganographic **embedding methods**
- To enable the possibility to distinguish between methods and to classify attackers (Attribution)

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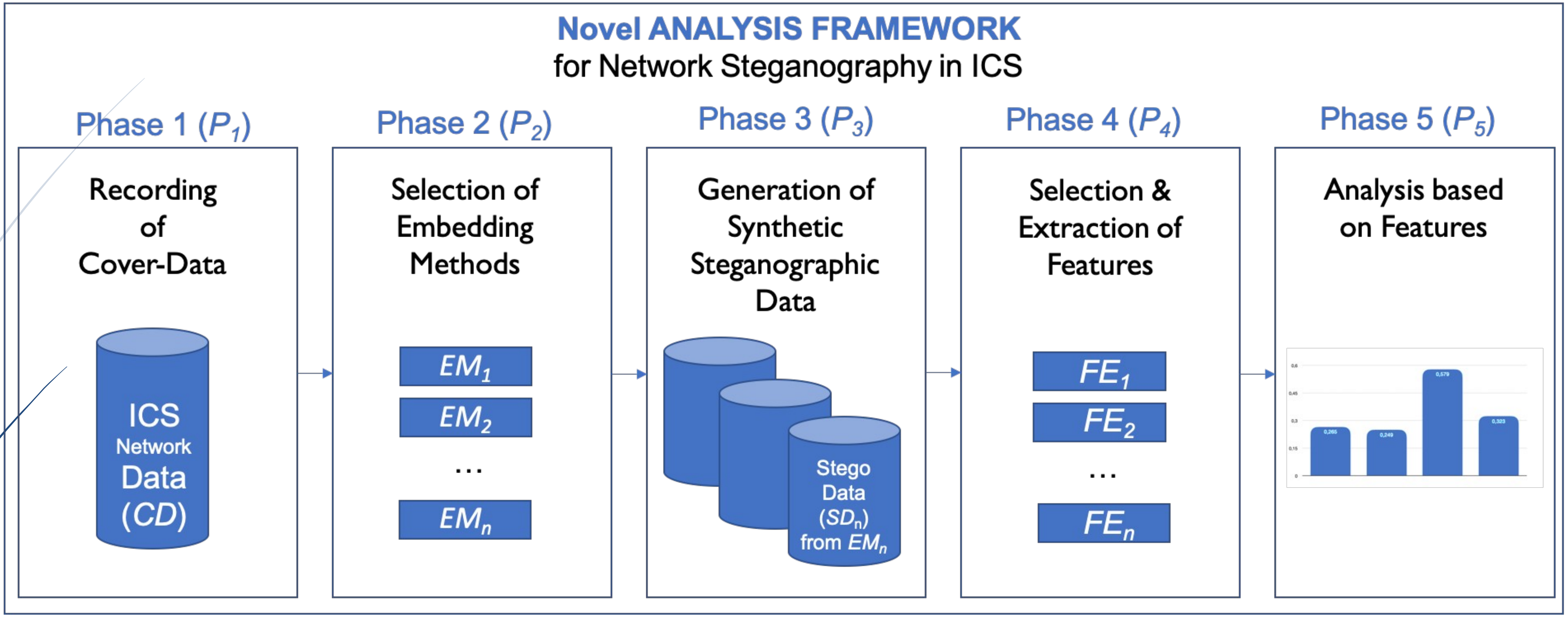
# The Analysis Framework





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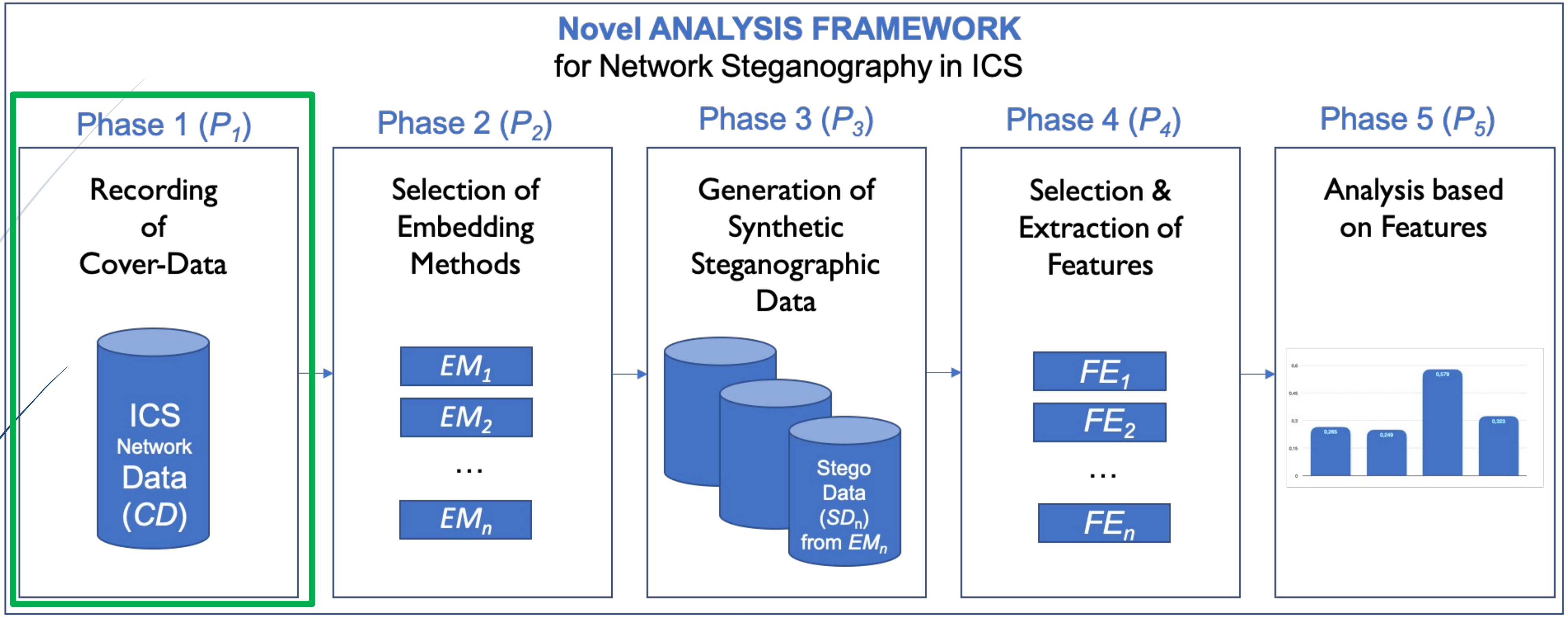


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**$P_1$: Recording of Cover-Data:**

- **C**over **D**ata (**CD**) has to be recorded from an uncomprimized laboratory ICS setup
- *Wireshark* is used, .pcap(ng) file is provided

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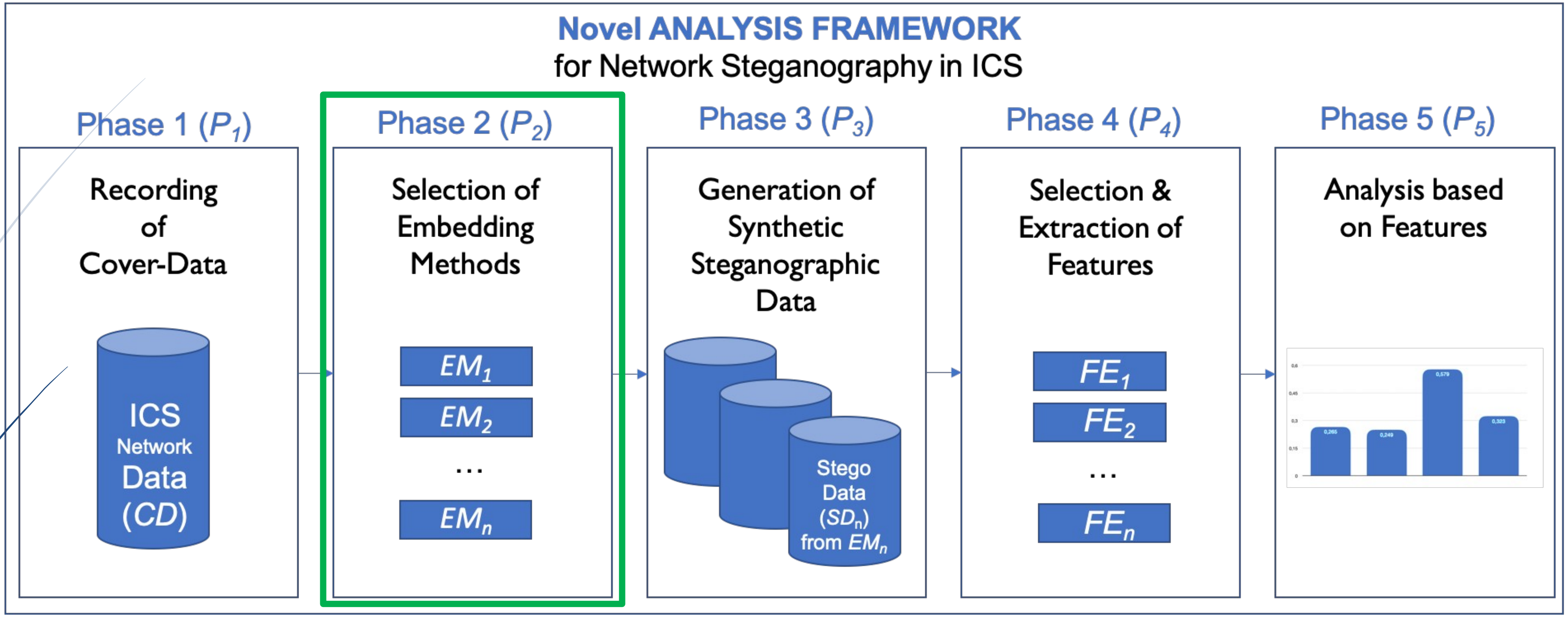
# The Analysis Framework




## $P_2$: Selection of Embedding Methods (for Analysis)

- Selection and Formalization of Embedding Methods $EM_n$ (in this work for validation)
    - $EM_1$ from [5], $EM_2$ from [6] and novel $EM_3$ → *all EM are* **Timestamp Modulations**
- Formalization of $EM_n$ in pseudo code representation for better comparison and comprehensibility of methods

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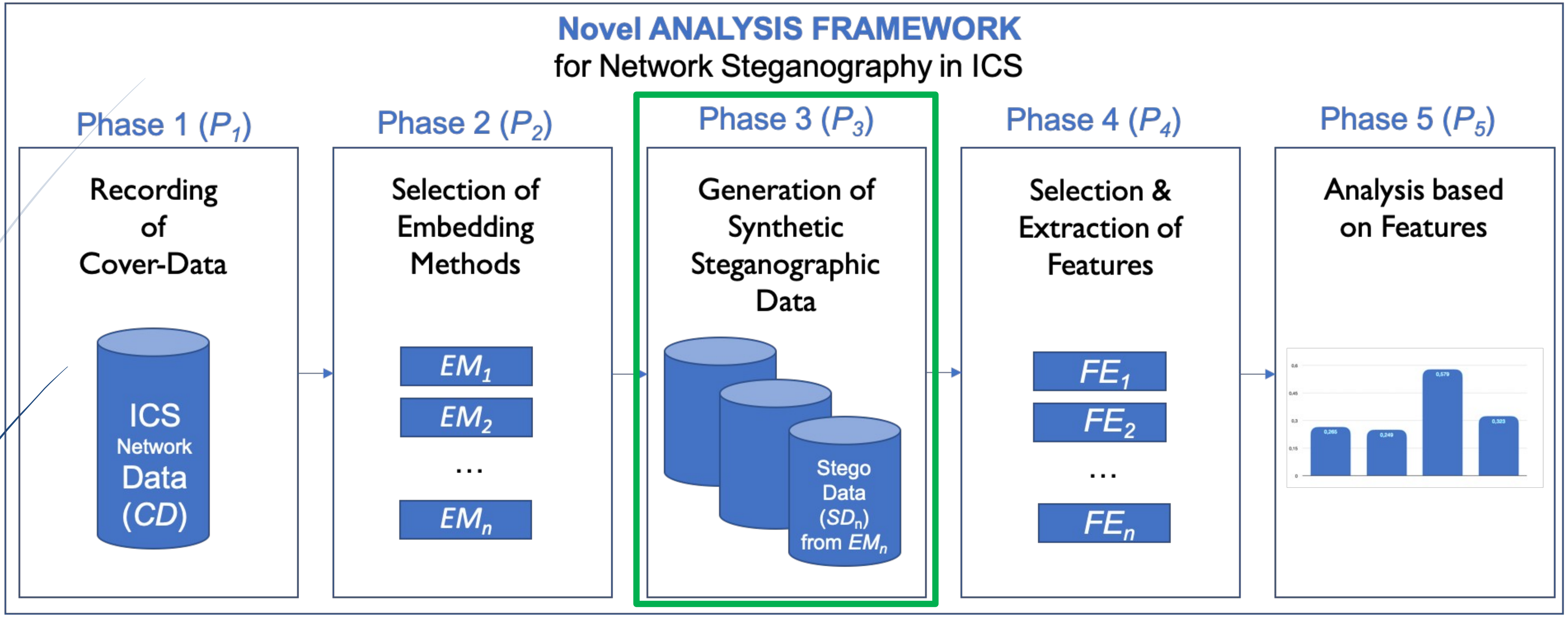


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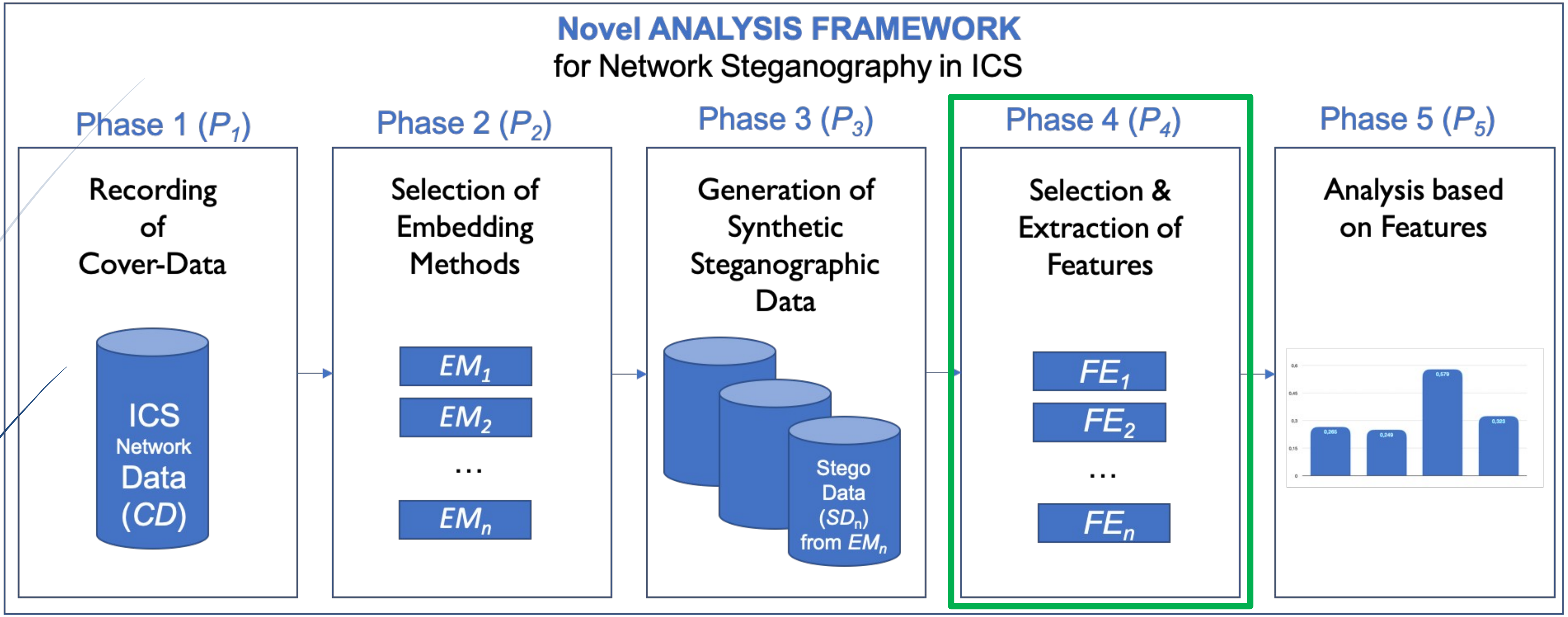
**$P_3$: Generation of Synthetic Steganographic Data** (with all $EM_n$):

- SSE-Concept from [13] is used for easy and fast generation of steganographic data
- No need of physical ICS setup for all embedding methods → very time consuming and complex to elaborate corrupted ICS setup

# The Analysis Framework

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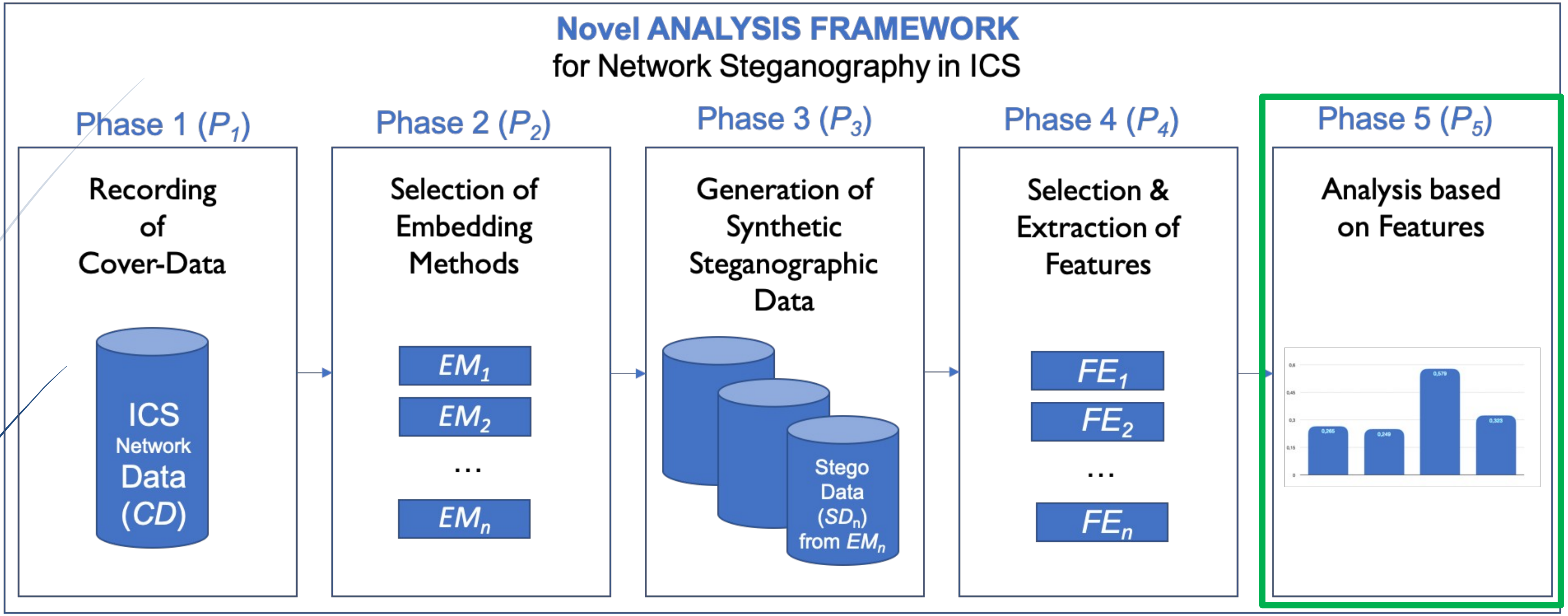
## $P_4$: Selection & Extraction of Features:

- for feature extraction from .pcap recordings, relevant structural elements of network packets should be converted to .csv or .txt (more details in paper)
- handcrafted feature space with discriminatory power should be used for successfull analysis
- we use handcrafted feature space from state-of-the-art [15]

# The Analysis Framework

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**$P_5$: Analysis:**

- Based on extracted features a statistical analysis can be carried out
- Generally, the analysis can focus different use case specific aspects, for example: detectability, attributability, embedding scheme and more depending on goals and objectives of a study

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# Evaluation Setup - Goals

- In our evaluation, we presented framework to analyze the introduced embedding methods $EM_1$, $EM_2$ and $EM_3$ with the following **GOALS**:

  - **$G_1$:** Analysis of the three exemplary embedding methods ($EM_1$, $EM_2$ & $EM_3$) based on the extracted features (slide 5.4, see paper for briefly description) to determine whether a potential **distinction between the methods** is possible for a potential detection of attackers.

  - **$G_2$:** Analysis of different **message types** (invariant {'a'} and heterogeneous {'*securware2024*'}) embedded with $EM_1$, $EM_2$ & $EM_3$ to determine whether a potential distinction between embedded messages is possible.

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# Evaluation Setup - Data

- Uncompromized laboratory ICS setup with lean server-client-communication
  - Siemens S7-1500 **P**rogrammable **L**ogical **C**ontroller (Server)
  - **H**uman-**M**achine-**I**nterface (Client)
  - Exemplary automation tasks running on PLC (traffic light control, temperature measuring)
  - Packets requested from HMI every 100 ms
  - → *Cover Data* ***$REC_{CD}$***: 61 Minutes of recording → 31,189 packets (half requests, half responses)

- Attack Scenario:
  - PLC corrupted via Supply-Chain-Attack and sends corrupted packets via timing delay to embed steganographic message (thus only server responses from PLC are relevant packets)
- Steganographic Embedding with $EM_1$, $EM_2$ & $EM_3$ in **$REC_{CD}$** with synthetic steganographic embedding concept (SSE-concept)

| Name | Type of Recording | Embedding Method | Message Type | Hidden Message | No. of relevant Packets |
|---|---|---|---|---|---|
| $REC_{CD}$ | Cover Data Recording | - | - | - | 19,094 |
| $REC_{EM1_{IV}}$ | Steganographic Data | $EM_1$ | invariant | $a$ (repeated) | 19,094 |
| $REC_{EM1_{HE}}$ | Steganographic Data | $EM_1$ | heterogenous | $securware2024$ (repeated) | 19,094 |
| $REC_{EM2_{IV}}$ | Steganographic Data | $EM_2$ | invariant | $a$ (repeated) | 19,094 |
| $REC_{EM2_{HE}}$ | Steganographic Data | $EM_2$ | heterogenous | $securware2024$ (repeated) | 19,094 |
| $REC_{EM3_{IV}}$ | Steganographic Data | $EM_3$ | invariant | $a$ (repeated) | 19,094 |
| $REC_{EM3_{HE}}$ | Steganographic Data | $EM_3$ | heterogenous | $securware2024$ (repeated) | 19,094 |

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# Evaluation Setup

- We iterate through every recorded network data set and extract a feature vector after 100 relevant packets, which results in 190 samples per data set

- Used to train machine learning based approach

- For **$G_1$** a Multi Layer Perceptron ($MLP_{4C}$) with **4-classes** (CD, *$EM_1$*, *$EM_2$*, *$EM_3$*) is trained to identify **Embedding Method** of sample

- For **$G_2$** a Multi Layer Perceptron ($MLP_{7C}$) with **7-classes** (CD, *$EM_{1IV}$*, *$EM_{2IV}$*, *$EM_{3IV}$*, *$EM_{1HE}$*, *$EM_{2HE}$*, *$EM_{3HE}$*) is trained to identify **Message Type** of sample

| Name | Label of Vectors | In $MLP_{4C}$ included vectors: extracted from: | Number of Vectors | Goal |
|---|---|---|---|---|
| $VEC_{CD}$ | $CD$ | $REC_{CD}$ | 190 | $G_1$ |
| $VEC_{EM1}$ | $EM_1$ | $REC_{EM1_{IV}}$, $REC_{EM1_{HE}}$ | 380 (2x190) | |
| $VEC_{EM2}$ | $EM_2$ | $REC_{EM2_{IV}}$, $REC_{EM2_{HE}}$ | 380 (2x190) | |
| $VEC_{EM3}$ | $EM_3$ | $REC_{EM3_{IV}}$, $REC_{EM3_{HE}}$ | 380 (2x190) | |
| | | In $MLP_{7C}$ included vectors: | | |
| $VEC_{CD}$ | $CD$ | $REC_{CD}$ | 190 | $G_2$ |
| $VEC_{EM1_{IV}}$ | $EM1_{IV}$ | $REC_{EM1_{IV}}$ | 190 | |
| $VEC_{EM1_{HE}}$ | $EM1_{HE}$ | $REC_{EM1_{HE}}$ | 190 | |
| $VEC_{EM2_{IV}}$ | $EM2_{IV}$ | $REC_{EM2_{IV}}$ | 190 | |
| $VEC_{EM2_{HE}}$ | $EM2_{HE}$ | $REC_{EM2_{HE}}$ | 190 | |
| $VEC_{EM3_{IV}}$ | $EM3_{IV}$ | $REC_{EM3_{IV}}$ | 190 | |
| $VEC_{EM3_{HE}}$ | $EM3_{HE}$ | $REC_{EM3_{HE}}$ | 190 | |

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# Evaluation Setup

- **5-fold Cross Validation** performed to evaluate MLPs and achieve $\mathbf{G_1}$ and $\mathbf{G_2}$


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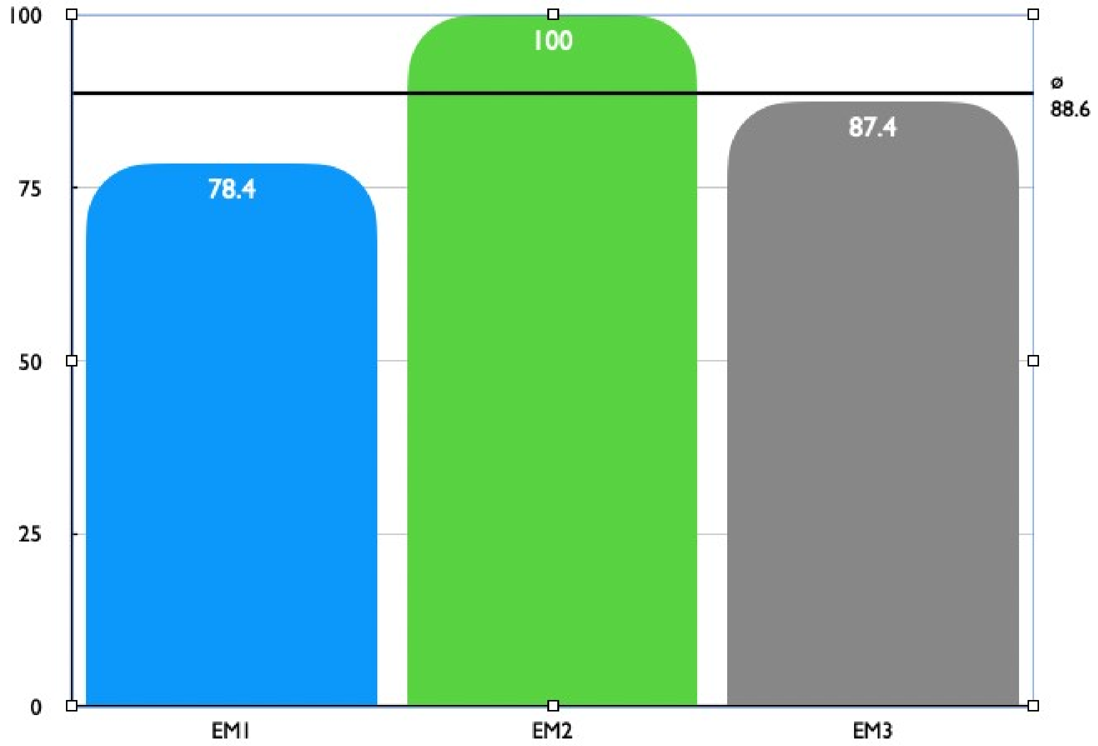
# Evaluation Results - $G_1$

- $MLP_{4C}$ classifies ~77% of samples correctly
- It can distinguish between Embedding Methods with accuracy of 88.6%
- Challenge: distinction between Cover Data (CD) and $EM_1$ (due to sophistication of $EM_1$)

| classified as −> Actual | $CD$ | $EM_1$ | $EM_2$ | $EM_3$ |
|---|---|---|---|---|
| $CD$ (190) | **12** | 150 | 0 | 28 |
| $EM_1$ (380) | 78 | **298** | 0 | 4 |
| $EM_2$ (380) | 0 | 0 | **380** | 0 |
| $EM_3$ (380) | 27 | 21 | 0 | **332** |

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# Evaluation Results – $G_2$

- $MLP_{7C}$ can distinguish between Embedding Methods comparable to $MLP_{4C}$
- The Message Type can be distinguish for $EM_2$ with accuracy of **61.3%**
- Challenge: for $EM_1$ and $EM_3$ most samples are misclassified due to the embeddings
  - The formalizations of these embeddings show, that the embedded message (type) should not result in statisticially measuable differences with our features

| classified as −> / Actual ($\sum$) | $CD$ | $EM1_{IV}$ | $EM1_{HE}$ | $EM2_{IV}$ | $EM2_{HE}$ | $EM3_{IV}$ | $EM3_{HE}$ |
|---|---|---|---|---|---|---|---|
| $CD$ (190) | **80** | 7 | 8 | 19 | 20 | 39 | 17 |
| $EM1_{IV}$ (190) | 66 | **18** | *28* | 16 | 17 | 31 | 14 |
| $EM1_{HE}$ (190) | 58 | *23* | **22** | 16 | 16 | 38 | 17 |
| $EM2_{IV}$ (190) | 9 | 0 | 5 | **126** | *35* | 15 | 0 |
| $EM2_{HE}$ (190) | 2 | 0 | 4 | *68* | **107** | 9 | 0 |
| $EM3_{IV}$ (190) | 36 | 2 | 7 | 23 | 26 | **62** | *34* |
| $EM3_{HE}$ (190) | 38 | 1 | 7 | 29 | 22 | *69* | **24** |

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# Summary and Future Work

- **Summary**:
  - Novel Analysis Framework to compare and analyze network stego embedding methods in ICS
  - Exemplary Analysis of 3 *EM*
  - With a MLP as classification engine based on a state-of-the-art feature space we are able to distinguish between 3 embedding methods with an accuracy of 88.3%
  - The classification of embedded message types is challenging for $EM_{1,3}$, but decent for $EM_2$
- **Future Work:**
  - Analysis of various embedding methods from state-of-the-art with framework
  - Additionally, we would like to analyze the opportunity to differentiate between message types more accurately with for a example a novel handcrafted feature space
  - Can improved features spaces lead to a attribution of attackers with different types of embeddings and message types that are not involved into training

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# Appendix

**Algorithm 1** Steganographic Embedding Method $EM_1$

$AM \leftarrow A$
$i \leftarrow 0$
$K \leftarrow 4\ Digit\ Key$
$I \leftarrow 4\ Digit\ Initialization\ Vector$
**while** $i < Length(A)$ **do**
  $D \leftarrow Hour\ value\ of\ T_i$
  $E \leftarrow Minute\ value\ of\ T_i$
  $F \leftarrow Second\ value\ of\ T_i$
  $G \leftarrow Value\ of\ digit\ 1\ after\ floating\ point\ of\ T_i$
  $H \leftarrow Value\ of\ digit\ 2{-}6\ after\ floating\ point\ of\ T_i$
  $S \leftarrow G \oplus DigitSum(K)\ mod\ 2$
  $O \leftarrow D \times E \times F\ mod\ 10000$
  $K' \leftarrow \sum_{n=0}^{3}((K_n \oplus (G + I_n))\ mod\ 10) \times 10^n$
  $K'' \leftarrow O \oplus K'\ mod\ 10000$
  $c \leftarrow m \oplus K''\ mod\ 8192$
  **if** $S == 0$ **then**
    $H_0, H_1, ..., H_3 \leftarrow c$
  **else if** $S == 1$ **then**
    $H_1, H_2, ..., H_4 \leftarrow c$
  **end if**
  $AM[i] \leftarrow T_i$
**end while**

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# Appendix

**Algorithm 2** Steganographic Embedding Method $EM_2$

$AM \leftarrow A$
**for** $Bit$ in $Bitstream$ **do**
  **for** $i \leftarrow 1$ to $3$ **do**
    **if** $Bit_i$ is 0 **then**
      $T_i[\mu_{i \ mod \ 3}] \leftarrow 4$
    **else if** $Bit_i$ is 1 **then**
      $T_i[\mu_{i \ mod \ 3}] \leftarrow 9$
    **end if**
    $AM[i] \leftarrow T_i$
  **end for**
**end for**

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# Appendix

**Algorithm 3** Steganographic Embedding Method $EM_3$

$AM \leftarrow A$
$i \leftarrow 0$
$K \leftarrow "SyntheticStegoKey"$
**for** $Bit$ in $Bitstream$ **do**
  **for** $i \leftarrow 1$ to 3 **do**
    $C_0 \leftarrow 0$
    $C_1 \leftarrow 0$
    **while** $C_1 == C_2$ **do**
      $C_0 \leftarrow Random(K)\ mod\ 9$
      $C_1 \leftarrow Random(K)\ mod\ 9$
    **end while**
    $j \leftarrow C_0 + C_1\ mod\ 3$
    **if** $Bit_i$ is 0 **then**
      $T_i[\mu_j] \leftarrow C_0$
    **else if** $Bit_i$ is 1 **then**
      $T_i[\mu_j] \leftarrow C_1$
    **end if**
    $AM[i] \leftarrow T_i$
  **end for**
**end for**

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