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Simulation Framework for Misbehavior Detection in Vehicular Networks

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Abstract—Cooperative Intelligent Transport Systems (C-ITS) is an ongoing technology that will change our driving experience in the near future. In such systems, vehicles and Road-Side Unit (RSU) cooperate by broadcasting V2X messages over the vehicular network. Safety applications use these data to detect and avoid dangerous situations on time. MisBehavior Detection (MBD) in C-ITS is an active research topic which consists of monitoring data semantics of the exchanged Vehicle-to-X communication (V2X) messages to detect and identify potential misbehaving entities. The detection process consists of performing plausibility and consistency checks on the received V2X messages. If an anomaly is detected, the entity may report it by sending a Misbehavior Report (MBR) to the Misbehavior Authority (MA). The MA will then investigate the event and decide to revoke the sender or not. In this paper, we present a MisBehavior Detection (MBD) simulation framework that enables the research community to develop, test, and compare MBD algorithms. We also demonstrate its capabilities by running example scenarios and discuss their results. Framework For Misbehavior Detection (F²MD) is open source and available for free on our github.

Index Terms—Cooperative Intelligent Transport Systems (C-ITS), MisBehavior Detection, Simulation

I. INTRODUCTION

The field of Intelligent Transport Systems (ITS) is advancing at much faster pace in the last couple of years. Autonomous vehicles are a reality now with vehicles gaining up to level-4 driving capabilities i.e. without much human intervention [1]. A plethora of technologies has been applied and/or invented to support the future of ITS. Sensors such as RADAR, LIDAR and camera are heavily used for applications such as Advanced Driver Assistance System (ADAS), lane keeping, forward collision warning, etc. However, the aforementioned sensors only work in line-of-sight conditions. For non-line-of-sight applications, technologies such as Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X) have been under research and development.

DSRC and C-V2X support the next generation of vehicles known as Connected Vehicle (CV). Connected Vehicles broadcast their kinematic information (e.g., position, speed, heading, etc.) on an ephemeral network known as Vehicular Ad hoc NETwork (VANET). This enables CVs to “see” beyond

the line-of-sight, but it also brings with it an attack surface. An actively participating entity in a VANET can lie about its kinematics, causing disruption in the network and indirectly causing safety issues on the road. Such an action is known as a misbehavior in VANETS. Misbehavior in VANETS includes malfunctioning entities unintentionally sending faulty information and malicious entities intentionally transmitting false information in a V2X attack.

MisBehavior Detection (MBD) in VANETS is an active field of research that concentrates on developing mechanisms to detect anomalous behavior pertaining to vehicle movement, transmission, etc. MBD algorithms could be sensor-based or V2X-based. In this paper, we concentrate on V2X-based MBD. In order to perform substantial research, these techniques have to be implemented on a large scale, in different scenarios, with a variety of vehicle densities and many other variations. Currently, there are only a few widespread deployments of CVs [2], [3]. A variety of problems still exist with these deployments such as the limited number of use cases and the strict regulations on the generated data. Obtaining raw, untouched data is difficult due to regulations that require anonymization and stripping of information that may be helpful in designing detection algorithms. Also, finding a suitable subset of data for analysis warrants spending huge amounts of time that could be used in actually designing MBD algorithms. Hence, there is a crucial need to simulate VANETS and evaluate MBD algorithms in those simulations.

Simulators such as Vehicles In Network Simulation (VEINS) [4] provide a platform for MBD algorithm development. In this paper we propose our Framework For Misbehavior Detection (F²MD). F²MD provides a singular framework with which one can:

- Implement a set of new V2X attacks,
- Implement several MBD algorithms for easy comparison,
- Evaluate effectiveness of attacks (we provide 6 attacks and 9 faulty behaviors with our framework),
- Assess performance of MBD algorithms (we provide 15 algorithms with our framework), using 8 metrics,
- Visualize in real-time the MBD algorithms performance,
- Generate dataset to feed the common attack dataset

VeReMi [5], [6],

- Evaluate multiple misbehavior report formats and global MisBehavior Detection algorithms.

The structure of this paper is as follows. We discuss the related work in Section II. In section III we detail the system model. In section IV we explain our proposed framework in detail. In section V, we run multiple examples with our framework to demonstrate the extent of results one can get from it. Section VI presents our conclusion and future work.

II. RELATED WORK

In this section we give an overview of the related work about MBD techniques ranging from generic, physical layer to machine learning based. We also discuss work related to simulation of these techniques, the metrics used to evaluate their performance, and attacks considered in each work.

Van der Heijden et al. [7] did a survey on MBD in C-ITS. They provided a taxonomy of node-centric and data-centric detection techniques, and compared them according to their scope, security, privacy, ability to generalize and resources required. The survey showed that no perfect techniques exist yet. The survey concluded with open challenges: definition of thresholds, protection against Sybil attack, and reporting to back-end to name a few. The F²MD framework proposed here aims at finding solutions to these open challenges.

Kamel et al. [8] investigated MBD algorithms feasibility with respect to current standards, law compliance, as well as hardware/software requirements. The authors showed that some MBD algorithms do not comply with current regulations (laws or standards). Most of the challenges discussed in the study originated from privacy protection regulations. The F²MD framework could help with finding privacy-preserving MBD solutions by integrating various Pseudonym Change Policies (PCP) (the current privacy solution for C-ITS). MBD algorithms could thus be tested against different PCPs.

Sun et al. [9] explored verifying an attacker's location and mobility using features available at the application and physical layer of Vehicle-to-Vehicle communication (V2V) communication. In their attacker model, the attacker transmits dubious locations inside the Basic Safety Messages (BSMs). This attacker can be a "lone-wolf" or can collude with other attackers who will corroborate the false data. The authors consider only a straight highway scenario with at least one honest vehicle in the communication range of the ego vehicle. They verify the attacker's location and mobility information using Angle of Arrival estimation (AoA), Doppler Speed measurement (DS), extended Kalman filter (EKF) and input from neighboring vehicles. They evaluate their mechanism in terms of true-positive rate, false-positive rate, true-negative rate and false-negative rate. The authors implemented their framework in MATLAB and performed evaluation in the same environment.

In [10], the authors proposed an MBD mechanism based on a support vector machine (SVM) and Dempster-Shafer theory (DST) of evidence to detect false message injection. The SVM-based classifier is used to detect false messages based on message content and vehicle attributes. Another SVM-based

classifier is used to evaluate whether the vehicle is credible based on its behavior in terms of message propagation. Then, DST is used by a trusted third party, which aggregates multiple trust assessment reports about the same vehicle and derives a comprehensive trust value. The authors evaluate their system's performance based on true-positive rate, false-positive rate, and accuracy. They performed their simulations in VEINS. Putting their proposal into our framework, the DST would be part of the MA. Our F²MD contains a stress attack on the MA that generates a large number of fake reports. As noted by the author, this type of attack would be helpful to test and improve this DST algorithm.

So et al. [11] proposed a framework to use plausibility checks as feature vector for evaluating two machine learning models (SVM and KNN). They evaluated the performance of these models in terms of their classification accuracy and precision-recall characteristics. They scored their location plausibility, movement plausibility and other quantitative features to feed into SVM and KNN models. The authors considered location spoofing attacks from the VeReMi dataset [5]. The attacks and detection were performed on the LuST scenario [12]. Their simulation data was generated using VEINS and evaluation was performed in MATLAB. Although, their study was comprehensive, the attack type was limited to location spoofing attacks.

It is safe to assume that simulations are a crucial part of evaluation of MBD algorithms. For V2V simulations, a simulator should consist of network and mobility models that simulate real-world V2V scenarios. Simulators such as NS3 and OMNET++ provide feature-rich environments for network simulations. However, these simulators do not simulate a crucial aspect of VANETs, a vehicle's mobility model. Simulations performed in MATLAB require a readily available dataset on which MBD algorithms can be run for conducting evaluations.

In C-ITS research, one commonly used network and mobility simulator is VEINS [4]. VEINS combines OMNET++ and SUMO (traffic mobility simulator) to create a layer for V2X simulation. VEINS provides APIs to create custom applications that run locally on a vehicle. These applications can react on receiving a beacon from another vehicle and/or on changing its own position among other features. VEINS also provides the capability to generate custom datasets for different road networks. However, it does not include MBD algorithms or the capability to evaluate them.

To the best of our knowledge, there is only one simulation framework that allows evaluation of MBD algorithms in VANET, namely Vehicular Reference Misbehavior (VeReMi) [5]. VeReMi is an extension to VEINS and consists of two main components: (i) a dataset containing transmission data from misbehaving and genuine vehicles for evaluation of MBD algorithms offline; (ii) five position-based attacks and four basic MBD algorithms.

In this paper, we introduce our proposed simulation framework F²MD which is also based on VEINS and consists of a comprehensive list of feature sets, from basic to advanced as discussed in Section IV. F²MD allows conducting studies on a large set of vehicles simulated in a large road network [12].

These road networks can be switched for evaluations on different types of road networks. Attacks can be programmed into attacker vehicles in F²MD, this feature makes sure of no bias in the attacks. It contains a comprehensive list of position-based and mobility-based attacks. It provides MBD algorithms ranging from basic plausibility checks to advanced algorithms based on thresholds, value aggregation and behavioral analysis. F²MD also supports addition of machine learning models for MBD. All MBD algorithms can be extended for further enhancements or new ones can be easily added to the F²MD framework. F²MD gives the ability to generate misbehavior reports to be sent to an MA. These reports can be chosen to range from a basic report to a report with evidence included to help the MA in its decision. Finally, F²MD provides a visualization feature that generates graphs online and in real-time to analyze the performance of MBD algorithms.

In conclusion, each aforementioned related work uses various methods for evaluating performance of their MBD algorithms and are hardly comparable. F²MD offers a free and open-source unified platform to implement attacks on VANETs, implement MBD algorithms and evaluate their performance using common metrics.

III. SYSTEM MODEL

A. C-ITS System Model

Cooperative Intelligent Transport Systems (C-ITS) are composed of mobile (e.g. passenger vehicle, trucks, aftermarket device, hand-held devices) and static entities (e.g. Road Side Unit (RSU), electric vehicle charging station, traffic management center). Each vehicle is equipped with an On-Board Unit (OBU) that enables it to broadcast mobility data (e.g. telematics, motion, maneuvers) to neighboring entities or to the Internet for cloud-based services. The primary goal is to improve road safety by broadcasting frequently (i.e. up to 10Hz as described in the American standard [13]) local beacons (called Basic Safety Message (BSM) in US, or Cooperative Awareness Message (CAM) in Europe). The BSM/CAM contains location, speed, acceleration, brake status and other optional fields [13], [14]. Receiving vehicles will use the BSM/CAM to understand the scene (by fusing its sensor data in the context of automated vehicle) and act upon it (e.g. notify operator, perform maneuver).

One example of safety application using BSM/CAM is the Emergency Electronic Brake Light (EEBL). In EEBL [15], vehicles performing an emergency brake (i.e. decelerating at a level greater than 0.4g) broadcast messages with corresponding fields indicating its greater deceleration (e.g. field in BSM). On the receiver side, the EEBL application warns the driver in the case of a hard-braking event by a vehicle that is ahead and in the same lane or in an adjacent lane. The EEBL application is expected to function in both straight and curved roadway geometries. The C-ITS safety applications are put in place to improve the road safety and prevent fatal accidents. Therefore, attacks that result in failure of such systems could lead to catastrophic results. The C-ITS system could be subject to external and internal attacks. However, a security architecture is put in place to mitigate the effects of both these attacks.

B. C-ITS Security Architecture

In the current C-ITS system, two types of attackers are possible: External attackers (i.e. without valid credentials) and insider attackers (i.e. with valid credentials). External attacks are treated with a Public Key Infrastructure (PKI) whereas insider attacks are mitigated by a MisBehavior Detection system. Figure 1 shows the various stages of the C-ITS security architecture.

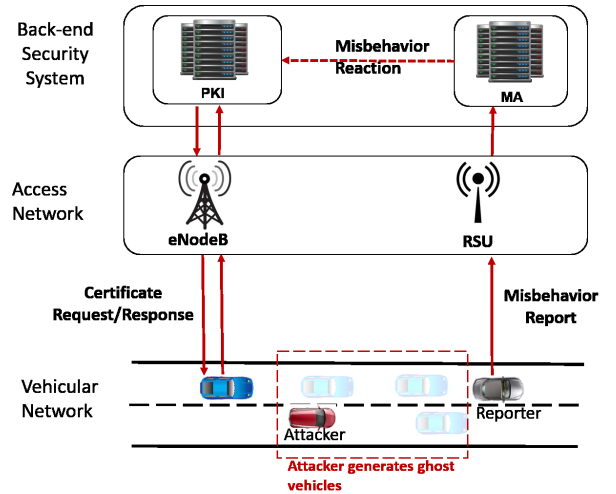


Fig. 1. C-ITS security architecture

External C-ITS attackers, i.e. without valid credentials, are prevented by authenticating every message sent on the medium using digital signature as specified in [16], [17]. Indeed, device authentication relies on a PKI that manages cryptographic material (i.e. generation, provisioning, update, revocation). In the US, the PKI is called the Security Credential Management System (SCMS) [18] and uses asymmetric cryptography, namely ECDSA, as the authentication algorithm. Moreover, to reduce a vehicle's trackability, each vehicle uses short-term cryptographic credentials—called pseudonyms—and regularly changes it [19]. Therefore, as discussed in the next section, we assume that cryptographic verification will take care of external attacker and focus on insider attacker.

Insider attackers in C-ITS are handled by a MisBehavior Detection mechanism. As we demonstrate in this paper, the MisBehavior Detection process is divided into four steps:

- 1) **Local MisBehavior Detection:** Every C-ITS entity will have to run a MisBehavior Detection system in order to cope with insider attackers.
- 2) **Misbehavior reporting:** After detection, the entity will have the opportunity to signal the misbehavior by sending a report to a MA.
- 3) **Global MisBehavior Detection:** The MA will investigate the event and potentially trigger revocation of the misbehaving entity.
- 4) **Misbehavior reaction:** The MA will issue the appropriate reaction to protect the system (e.g. perform certificate revocation request to the PKI).

C. Attacker Model

In this paper, we consider the following attacker model:

- 1) **Insider:** The attacker has the required cryptographic credentials to communicate in a C-ITS.
- 2) **Active:** The attacker actively participates in C-ITS communication and sends bogus data.
- 3) **Message payload modification:** We assume that the attacker can modify any fields in its outgoing BSMs/CAMs. This is possible if an attacker has complete access to his vehicle's CAN bus. The attacker can mount a man-in-the-middle attack and modify any sensor data.
- 4) **Transmission rate modification:** We assume that the attacker can modify the transmission rate of her on-board unit. We assume that the attacker has modified the on-board unit in his vehicle, allowing faster or slower transmission rate depending on the type of attack.
- 5) **Pseudonym certificates access:** We assume that the attacker has complete access over the usage of pseudonym certificates. We use the same premise as above that the attacker has modified her on-board unit. It should allow the usage of pseudonym certificates as the attacker pleases. This would enable mounting Sybil attacks.

The attacker will perform attacks described in Section IV-F. Following the EEBL example presented in Section III-A, an attacker would send wrong deceleration value (potentially along with corresponding mobility data) in order to force sudden braking by the victim(s). Attacker without valid credentials won't be able to properly sign the message, and verification will fail at the receivers. However, an internal attacker will send authenticated messages and the only way to not be fooled by them is to perform MBD algorithms.

IV. FRAMEWORK

In this section we describe the different components of F²MD. All parts of the framework that are described in the following section are also available for download in open source format [20].

A. General Framework Characteristics

This framework provides complete solution for real time simulation and evaluation of an MBD system. It extends VEINS with a large panel of MBD, evaluation and other general C-ITS modules. One of the main characteristics of F²MD is its modularity. The architecture is organized in several functional levels: *input data*, *local detection*, *local visual output*, *report data output* and *global detection*. According to the misbehavior evaluation level, the complexity of the scenario, the attacks and the detection method may be chosen. Additionally, F²MD is extensible. Besides the implemented MBD mechanisms and attacks, it offers the possibility to extend the framework with additional modules through the existing API. A key characteristic of our framework is its integration with non-simulated modules such as external Machine Learning modules for advanced MBD and external packet reporting logging. Figures 2 and 3 summarize this idea while showing the different modules of the architecture. These modules are detailed in Sections IV-C to IV-H.

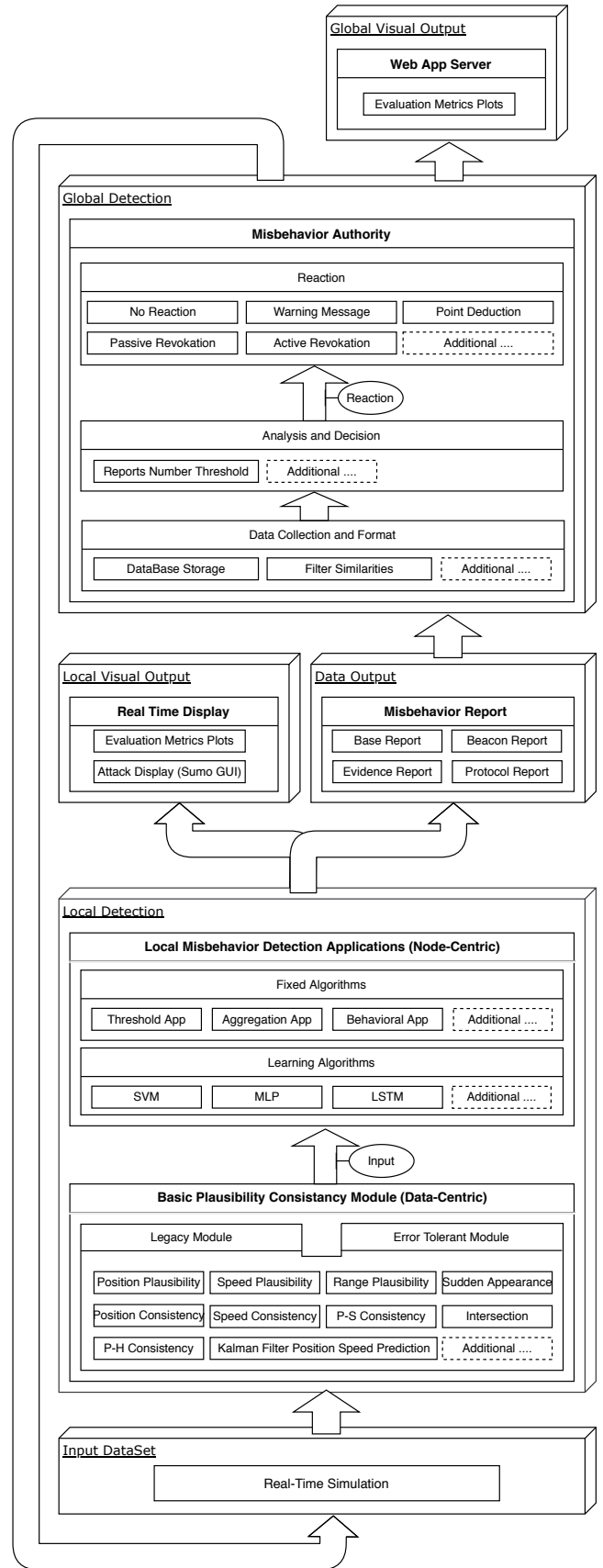


Fig. 2. Diagram representation of the main modules

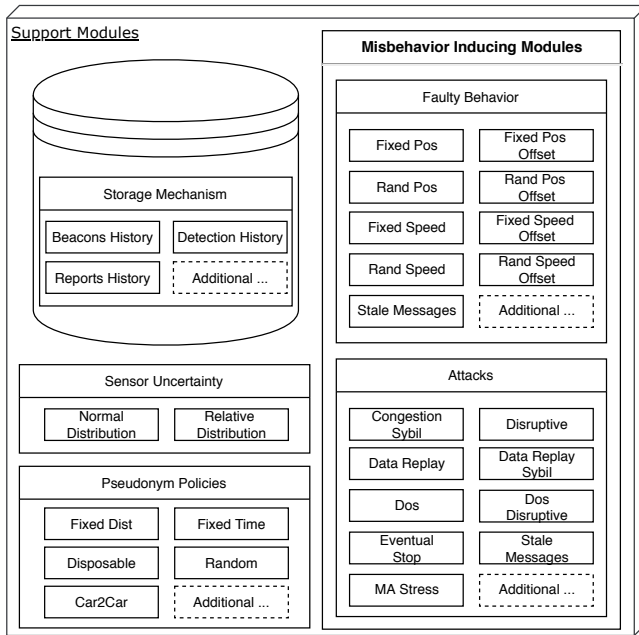


Fig. 3. Diagram representation of the secondary modules

B. Framework Input Data

The first input required for the framework is a sumo scenario. We do provide two scenarios out-of-the-box. The first scenario is from Paris-Saclay area. This network combines some suburban-like grid and some organic network properties. It is a relatively small network for which we generate a variable vehicle density. We use it as our test bench for calibration and fine tuning since it provides fast and predictable results. The second scenario is the LuST SUMO network [12]. This scenario is a SUMO network based on population census data and a real traffic information of Luxembourg. This scenario is much slower to run but is more valuable for final simulation results. In addition to SUMO scenario, the VEINS simulation requires an OMNeT++ configuration. The OMNeT++ configuration includes beacon parameters such as the header bit length and the beacon interval. It also includes the Network Interface Card (NIC) settings such as the txPower, bitrate, Recall and thermalNoise. We strongly recommend leaving these settings as the VEINS defaults. The values could be found in the OMNeT++ configuration file on our github. Finally, our framework requires specific inputs like the attack types, the attacker density, the report format and the PCP. This list is not exhaustive but gives a general idea of what types of input is expected. Some inputs are even specific to the type of attack or the PCP. For example, if we choose a periodical pseudonym change, then we have to set the mean change period. A full list of inputs is included in our github.

C. Local Detection

In this framework, we provide a rich module for local MBD. This module provides simple methods to customize and test different algorithms using a simple methodology. The local detection logic goes as follows. The system runs

basic plausibility and consistency checks on every received message. The results are transmitted to the local misbehavior application that decides whether or not to send a report to the MA. Therefore, the local detection could be customized in two locations: the basic plausibility (often called detectors) and the more intelligent detection application (often referred to as data fusion). For this reason, we have implemented multiple versions of the basic checks and multiple misbehavior applications. We also provide a method for real-time machine learning based MBD applications.

1) *Plausibility Checks*: Inspired by the literature, we extracted a set of basic MBD checks. The following checks or detectors were implemented in their legacy version and in an Error-Tolerant (ET) version. The legacy version is much faster to compute the plausibility checks and returns a binary output to show whether a certain aspect of the message is plausible or not. The ET version is generally slower to compute the plausibility checks but returns an uncertainty factor that reflects the scale of the message implausibility [21].

Here is the list of all the local plausibility checks that are implemented:

- **Range plausibility**: Check if the position of the sending ITS Station (ITS-S) is inside of the ego ITS-S maximum range (predefined value mapped on the ego ITS-S maximum radio coverage).
- **Position plausibility**: Check if the position of the sending ITS-S is at a plausible place (e.g. on a road, no overlaps of physical obstacles, etc.).
- **Speed plausibility**: Check if the speed advertised by the sending ITS-S is less than a predefined threshold.
- **Position consistency**: Check if two consecutive beacons coming from a same ITS-S have plausible separating distance.
- **Speed consistency**: Check if two consecutive beacons coming from a same ITS-S have plausible acceleration or deceleration.
- **Position speed consistency**: Check if two consecutive beacons coming from a same ITS-S have consistent speed and separating distance.
- **Beacon frequency**: Check if the beacon frequency of a sending ITS-S is compliant with the standards.
- **Position heading consistency**: Check if the positions in two consecutive beacons coming from a same ITS-S correspond to the heading advertised by that ITS-S.
- **Intersection check**: Check if no two beacons coming from two different ITS-S have overlapping locations (i.e. both ITS-S overlap each others).
- **Sudden appearance**: Check if no ITS-S suddenly appeared within a certain range.
- **Kalman filter tracking**: Check if the ITS-S advertised information is within a plausible range of the Kalman filter predicted values. This check is proposed in [22].

2) *Advanced MisBehavior Detection*: The MBD applications are the decision making part of the detection logic. They are also referred to as fusion applications since the decision is often based on fusion of multiple factors (the results of the plausibility checks, the node history, etc.). We implemented multiple simple examples. Some of them use a

fixed algorithms and others are based on artificial intelligence. The fixed algorithms were implemented directly into VEINS while the learning applications were implemented in python and accessed through a specific API. The followings are the applications based on fixed algorithms:

- **Threshold App:** A node is reported if a certain message fails at least one of the plausibility checks. A fail is determined if the result of the check falls below a certain threshold.
- **Aggregation App:** This application is based on the node history. The checks results of certain messages are aggregated with the last n results. A node is reported if the aggregated results falls below a certain threshold.
- **Behavioral App:** This application is based on the gravity of the misbehavior event. According to the gravity of the misbehavior, the node is put in timeout and all the data it sends are reported to the MA. The gravity is deduced from the results of the basic plausibility checks.

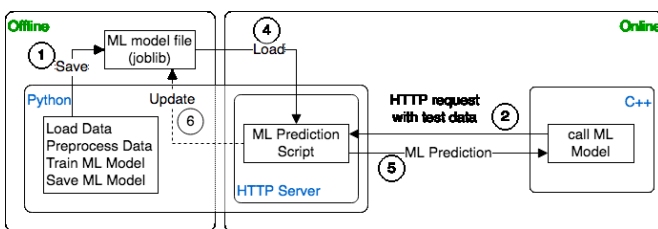


Fig. 4. Python-C++ interface for machine learning modeling

3) Python-C++ Interface for Machine Learning Modeling:

One of the most used programming ecosystems for Machine Learning (ML) and Deep Learning (DL) is Python. We designed this part of the framework such that anyone could extend the framework with their own ML/DL models. We have developed an interface between Python and C++ parts of our framework. This interface allows any developer to implement their ML models in Python and let the core framework call their models during simulations.

Figure 4 represents the Python-C++ interface design. The interface is designed around a typical ML model development process. As shown in Figure 4, the interface is divided into offline and online phases. All files are represented as separate modules in the figure. This means that an ML model is divided into two files. One file for each phase.

In the offline phase, a developer can design, train and save her ML model. We support scikit-learn [23] for ML modeling and the joblib library [24] for saving ML models. joblib is much more efficient in saving ML models than NumPy [25] than Python's built-in module pickle.

In the online phase, the ML model runs inside an HTTP server (PyMLServer) listening on a user-defined port. The simulation core (written in C++) calls the ML model (written in Python). As shown in Figure 4, the simulation core sends data to be tested against the ML model in an HTTP request. PyMLServer calls the ML prediction script which performs operations as follows:

- Load the data from HTTP request that needs to be processed for prediction.

- Load the ML model saved during offline phase. We use joblib again to load the ML model.
- Respond to the HTTP request with prediction from the ML model.
- Optionally, the prediction script could update the ML model and save it back to the loaded model. Models that use back-propagation may need such functionality.

Finally, simulation core reads the prediction output from the HTTP response to perform further investigation. Based on the previous interface we implemented the following techniques:

- **Support Vector Machines (SVM) Classifier:** A two-class SVM model was trained on features extracted from the plausibility checks similarly to [11] and as described in previous sections. This SVM classifies Genuine vehicles from Misbehaving ones with accuracy largely dependent on the scenario (Network, Density, Attacks, etc.). For extended results on supervised machine learning, we refer the reader to [11].
- **Multi-Layer Perceptron (MLP) Classifier:** An MLP based neural network was trained on the same data as for SVM. We found the MLP's accuracy is generally better than SVM. However, remember that the comparison of techniques is not the objective of this paper.
- **Long Short-Term Memory (LSTM) Classifier:** An LSTM was also trained on the same data as for SVM. LSTM is part of the Recurrent Neural Network (RNN) family of ML algorithms adequate for the treatment of time dependent data. LSTM's accuracy was generally the best out of the tested algorithms. However, it is also the slowest algorithms to compute.

D. Reporting

One important goal of the local MBD is to send a report to a central MA for post-processing. In this framework, the MBD algorithm could decide to generate a misbehavior report. The reports are pushed to a global MA via HTTP connection. Additionally, the reports can be collected in json or xml format in a local folder.

We propose a misbehavior report inspired by the protocol described in [26]. The report is composed of three containers: *Header Container*, *Source Container* and *Evidence Container*. The *Header Container* contains the basic information that should be included in every report: generation time, sender id, reported id and report type. The *Source Container* consists of the results of the plausibility and consistency checks on the reported beacon, granted that a vehicle is reported only after a received beacon shows some implausibilities. The *Evidence Container* should help the MA in its investigation and to support its conclusion. The *Evidence Container* can be composed of messages from the reported or the reporter or any neighboring vehicles if deemed helpful. It could also include some other data like a Local Dynamic Map (LDM), or direct sensor data from the reporter. The Evidence required by the MA is further detailed in [26].

The report format is however not yet standardized and is still a subject of scientific research. For this reason, we deemed

useful to provide multiple formats of the misbehavior report to facilitate further investigation and testing. The following versions are implemented in the framework:

- **Base Report:** This format includes only the *Header Container* and the *Source Container* with no evidence.
- **Beacon Report:** This version includes a base report and the reported beacon in the *Evidence Container*.
- **Evidence Report:** This version contains a more complete *Evidence Container* depending on the type of plausibility checks failure. For example, if the vehicle failed the *Speed Consistency*, we include both inconsistent beacons as evidence.

In the current state of the framework, every message flagged as misbehaving is reported. However, not every message should be reported individually. This would generate a significant network overhead especially when the vehicle is misbehaving because of a faulty component in its system. Consequently, the report format allows for omitted reports, which means that the vehicle is not constantly reported for the same behavior. Instead of that, the local vehicle refrains from reporting the same behavior after a certain time while collecting evidence. The evidence is then sent to the MA in a single report. This protocol assumes an intelligent MA that prioritizes the content of the received reports instead of their number.

E. Global MisBehavior Detection

The Misbehavior Authority (MA) is the global entity that receives the reports sent by the vehicles. The MA should then decide on the suitable reaction to make. We defined three main components of the MA:

- **Collection and Format:** The collected report is added to a database. This action would enable to access reports using certain criteria. For example, we can get all the reports accusing a certain pseudonym or all the reports from a certain region. Those requests could be helpful in the analysis phase. We also have a filtering system, if enabled, that could aggregate all reports signaling the same implausibly (e.g. sets of two messages with a speed inconsistency).
- **Analysis and Decision:** The MA analyzes the reports and outputs the correct level of reaction. We have implemented a simple non intelligent method that has a threshold on the number of reports for every reaction level. The number of reports required to reach every level is modifiable. We set the output as levels so it would be compatible with our reaction mechanism. However, other outputs could be developed. Please note that this component will evolve into a more complex element in future versions of the framework.
- **Reaction:** The misbehavior reaction is still a widely debated subject. We propose a level-based solution with 5 levels of reaction:
 - level 0: no reaction
 - level 1: a warning message is sent to the vehicle
 - level 2: a warning point is deducted from the vehicle's score

- level 3: passive revocation where the vehicle cannot request more certificates
- level 4: active revocation where the current certificates of the vehicle are revoked.

Currently, the reactions do not cause a change in the behavior of the vehicle, however we expect to have a more intelligent system where the vehicle would change its behavior according to the reaction level (e.g. a vehicle with a faulty sensor would re-calibrate upon a warning from the MA).

F. Misbehavior Mechanisms

In order to assess the quality of different detection methods we need to generate misbehavior into the system. For this reason, we implemented two categories of misbehavior: Faulty behavior and Attacks. Faulty behavior acts on one sensor data, and Attacks are more elaborate schemes. The framework inserts a predefined percentage of misbehaving vehicles. These vehicles could all present one type of misbehavior or could mix multiple types. Details of all the implemented misbehavior mechanisms are presented below.

1) *Faulty Behavior:* Each vehicle should include an on-board treatment of the data to ensure plausibility before transmission. However, this preventive system could possibly lack some use cases and is prone to failure, especially in the case of budget vehicles. Here, we consider the case where such an on-board data pre-treatment system fails. We extracted from the literature a set of possible faulty behaviors [27]. The following set was implemented in the framework:

- **Fixed Position:** The vehicle broadcasts the same position (X,Y) each beacon.
- **Fixed Position Offset:** The vehicle broadcasts its real position with a fixed offset ($\Delta X, \Delta Y$).
- **Random Position:** The vehicle broadcasts a random position from the playground.
- **Random Position Offset:** The vehicle broadcasts its real position with a random offset limited to a max value ($\Delta(0 \mapsto X_{max}), \Delta(0 \mapsto Y_{max})$).
- **Fixed Speed:** The vehicle broadcasts the same speed (V_x) each beacon.
- **Fixed Speed Offset:** The vehicle broadcasts its real speed with a fixed offset (ΔV_x).
- **Random Speed:** The vehicle broadcasts a random speed with an upper limit ($0 \mapsto V_{max}$).
- **Random Speed Offset:** The vehicle broadcasts its real speed with a random offset limited to a max value ($\Delta(0 \mapsto V_{max})$).
- **Stale Messages:** The vehicle broadcasts its real information after adding a predefined delay (Δt).

2) *Attacks:* Our attack schemes vary in complexity. The following list details what is currently implemented in our framework:

- **DoS:** In order to deny the other vehicles access to the network, the attacking vehicle increases the beaconing frequency by a certain factor. In our implementation the vehicle could also choose to send valid message or random data. The attacker could also choose to more

frequently change and alternate between his pre-loaded pseudonyms in order to avoid detection.

- **Disruptive:** This attack aims to disrupt the system by flooding the network with old beacons data. The attacker chooses a random beacon from the received history and replays its data. Simultaneously, the attacker is able to increase the beaconing frequency to maximize the effect. It is worth noting that the data was originally generated by genuine vehicles, thus making it plausible on some levels. As a result, this attack severely deteriorates the quality of the C-ITS. Similarly to the DoS Attack, the attacker could also choose to alternate between his pre-loaded pseudonyms.
- **Data Replay:** The attacker chooses a target and replays its data with a certain delay. Consequently, it could seem to an observer that there are two vehicles following each other. The attacker could chose to change his pseudonym when changing the target vehicle to avoid detection.
- **Eventual Stop:** After a certain random delay, the attacker stops updating the beacon position and sets the speed to zero, thus simulating a sudden stop.
- **Congestion Sybil:** One type of Sybil attack consists of generating ghost vehicles. To this end, the following actions are performed:
 - The position, speed and heading of the ghost vehicles are calculated according to the data of the attacking vehicle or a chosen target vehicle.
 - A list of pseudonyms is generated and maintained, one pseudonym per ghost vehicle.
 - The beaconing frequency of the attacker is increased according to the number of ghost vehicles.
 - The ghost vehicles beacons are multiplexed such that every vehicle is sending one beacon per cycle.

This attack demonstrates the ability to use the framework to (i) manipulate pseudonyms, (ii) increase the beacon frequency on-the-fly and (iii) intelligently calculate the data to serve a specific objective.

- **MA Stress:** This attack does not target local vehicles. Instead, it targets the global entity (i.e. the MA) by sending a large number of fake reports. The reports contain the identities of the attacker's neighboring vehicles. The attacker could choose to change its identity for every report. The attacker could also increase the frequency by which the reports are sent to the MA.

G. Privacy

The use of pseudonyms have been included in the IEEE and ETSI standards [16], [19], [28]. However, when and how a pseudonym change happens is still a research challenge. Scientific studies have suggested multiple methods to determine the location and rate of change of pseudonyms [29].

Node-centric MBD mechanisms rely on a consistent identity of the treated vehicles. This approach is greatly affected by privacy-preserving mechanisms based on pseudonyms. For this reason, we have implemented the following Pseudonym Change Policies (PCP) in our framework:

TABLE I
DEFINITION OF POSITIVE / NEGATIVE

	Misbehaving	Genuine
Detected	True Positive (TP)	False Positive (FP)
Undetected	False Negative (FN)	True Negative (TN)

- **Periodical:** The vehicle changes its pseudonym after a predefined period of time.
- **Distance:** The vehicle changes its pseudonym after predefined number of kilometers.
- **Disposable:** The pseudonym is used for a fixed number of messages (including beacons and warnings).
- **Random:** The pseudonym has predefined chance of change at every sent message.

H. Evaluation and Visualization

In a given scenario, a *vehicle* transmitting messages could be misbehaving or genuine, and a local detection mechanism could classify *messages* as misbehaving or genuine. Therefore, as illustrated in Table I, the evaluation of detection mechanisms starts by deciding what is true positive / negative, and false positive / negative.

The *Recall* (1) measures the proportion of correctly identified misbehaving messages out of all received misbehaving messages. The *Precision* (2) measures the proportion of messages correctly flagged as misbehaving out of all flagged messages. The *F₁score* (3) is the harmonic mean of *Recall* and *Precision*. It could be used as a single metric to evaluate the system's performance if we attribute the same importance to the *Recall* and *Precision*. If needed, we can attribute more weight to one metric by calculating an *F_βscore*. This metric could be interesting since one could argue that *Recall* is more important than *Precision* in some cases. The *Accuracy* (ACC) (4) is the rate of positive agreement, which in our case refers to the ratio of true detection in the system. The *Bookmaker Informedness* (BM) (5) characterizes the probability of an informed decision. It shows how much the decision of this system is better than a random guess. The *Markedness* (6) is the probability that the detection is ascertained by the classification as opposed to by chance. The *Matthews Correlation Coefficient* (MCC) (5) is the geometric mean of the *Informedness* and the *Markedness*. It is especially useful when the measured classes are of very different sizes, which is often the case with C-ITS attackers. *Cohen's kappa* (κ) (8) is a measure of the positive agreement, similar to the *Accuracy*, but where we subtract the agreement by chance.

$$Recall = \frac{TP}{TP + FN} \quad (1)$$

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

$$F_1score = 2 \times \frac{Recall \times Precision}{Recall + Precision} \quad (3)$$

$$ACC = \frac{TP + TN}{TP + FP + TN + FN} \quad (4)$$

$$BM = \frac{TP}{TP + FN} + \frac{TN}{TN + FP} - 1 \quad (5)$$

$$MK = \frac{TP}{TP + FP} + \frac{TN}{TN + FN} - 1 \quad (6)$$

$$MCC = \frac{TP \times TN + FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}} \quad (7)$$

$$\kappa = \frac{ACC - \frac{(TP + FN) \times (TP + TN) + (TN + FP) \times (TN + FN)}{(TN + TP + FP + FN)^2}}{1 - \frac{(TP + FN) \times (TP + TN) + (TN + FP) \times (TN + FN)}{(TN + TP + FP + FN)^2}} \quad (8)$$

One of the goals of our framework is to facilitate the evaluation of any detection mechanisms or any changes that could affect the detection rate. In order to achieve that, the simulator writes a snapshot of the current state of the running mechanisms at every time interval. Then, a script parses the data, calculates, and plots the aforementioned evaluation metrics in real-time. To further facilitate the evaluation and comparison of mechanisms, the simulator and the script support running two simultaneous mechanisms on the same system. Figure 5 shows a real-time comparison between the *Threshold App* running on binary basic plausibility checks and the *Behavioral App* running on the Error-Tolerant plausibility module.

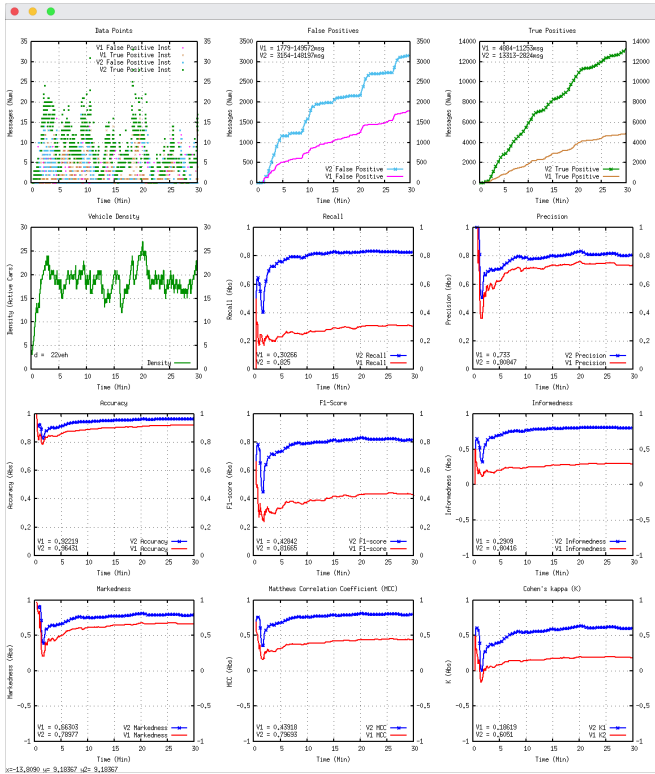


Fig. 5. F^2MD GUI: Real-Time Evaluation Metrics Plots (Data Points, TP, FP, Density, Recall, Precision, Accuracy, F_1 score, BM, MK, MCC, κ)

However, the visualization is not limited to the detection results. The attacks and detection system are also visualized in SUMO's GUI. The simulator uses SUMO's Traffic Control

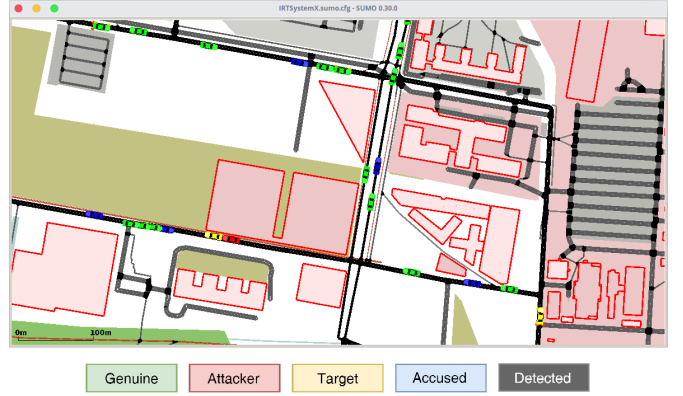


Fig. 6. Sumo GUI with F^2MD Vehicle Color Profiles

Interface (TraCI) [30] to color the vehicles according to the intended role as specified in Figure 6.

Finally, since the MA is implemented as an HTTP server, we provide a web interface. The web interface runs in real time and serves as a display of different metrics and evaluations on the current state of the MA (Figure 7). We currently display three metrics:

- Cumulative and instantaneous prediction accuracy,
- Number of received reports per pseudonym for some of the most relevant identifiers,
- Radar chart of the cumulative percentage of the issued reactions.

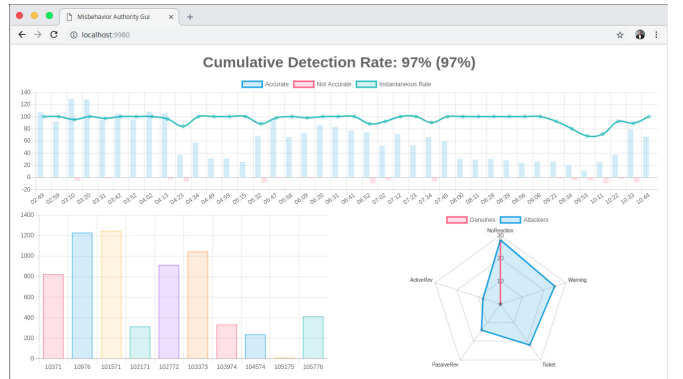
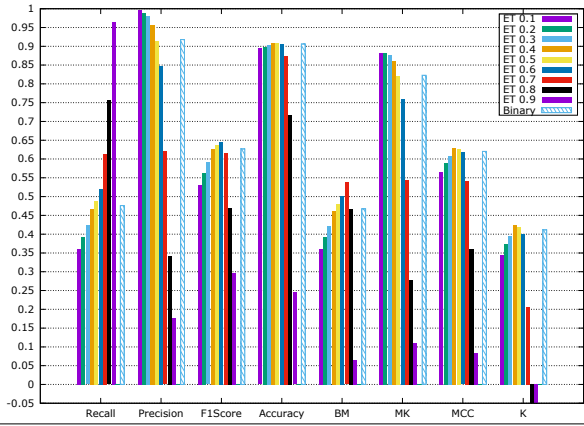


Fig. 7. Misbehavior Authority Web Interface

V. EXAMPLES

In order to demonstrate the capabilities of the framework, we run multiple example scenarios. Each example is based on showcasing the capabilities of a different module of the framework. In the following scenarios we use our benchmarking network described in Section IV-B. We introduce misbehaving entities with an density of 0.1. Each misbehaving vehicle introduced to the system chooses its type of attack as detailed in Section IV-F2. The following results are reproducible using the implementation and scenarios provided on our Github [31].



Misbehavior Types	Evaluation Metrics							
	Rec	Pre	F1s	Acc	BM	MK	MCC	K
ET 0.1	0.36	1.00	0.53	0.89	0.36	0.88	0.56	0.35
ET 0.2	0.39	0.99	0.56	0.90	0.39	0.88	0.59	0.37
ET 0.3	0.42	0.98	0.59	0.90	0.42	0.88	0.61	0.40
ET 0.4	0.47	0.96	0.63	0.91	0.46	0.86	0.63	0.42
ET 0.5	0.49	0.91	0.64	0.91	0.48	0.82	0.63	0.42
ET 0.6	0.52	0.85	0.64	0.90	0.50	0.76	0.62	0.40
ET 0.7	0.61	0.62	0.62	0.87	0.54	0.54	0.54	0.21
ET 0.8	0.76	0.34	0.47	0.72	0.47	0.28	0.36	-0.35
ET 0.9	0.96	0.18	0.30	0.24	0.07	0.11	0.08	-0.08
Binary	0.48	0.92	0.63	0.91	0.47	0.82	0.62	0.41

Fig. 8. Variable threshold evaluation plot

A. Plausibility detectors example

As discussed earlier, we implemented two versions of the detectors. The legacy version outputs a binary value while the ET version assigns a factor in uncertain scenarios. The plausibility factor is a score assigned to the each plausibility check done on the message. This score is calculated using the value and the error range advertised for each field in a certain message. The score varying between completely implausible (0) and definitely plausible (1).

To better understand the effect of this value, we run both versions of the detectors simultaneously coupled with a threshold-based detection application. We vary the threshold between 0.1 and 0.9. As we can see in Figure 8, we can see a clear trade-off between precision and recall for the ET version of the detectors. This validates our hypothesis that the uncertainty factor quantifies the plausibility of a certain message.

The plausibility factor thus provides a more informative view of the implausible scenario. This could prove useful to an intelligent application trying to detect an attack. Therefore, for the same previous scenario, we trained an Multi-Layer Perceptron (MLP) to classify a single message plausibility check result. Table II shows that the ET model have better results than the Binary one.

However, this improvement comes at the cost of higher processing time. In fact the binary detectors are 8 times faster than their ET counterparts as shown in Table III.

B. Local application example

Next, we demonstrate the capabilities of the MBD applications module. We tested all the applications provided with our

TABLE II
COMPARING ET AND BINARY DETECTORS USING AN MLP

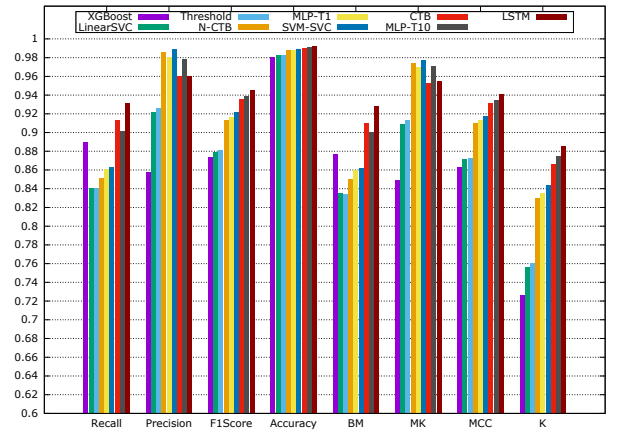
Misbehavior Types	Evaluation Metrics							
	Rec	Pre	F1s	Acc	BM	MK	MCC	κ
Binary	0.48	0.92	0.63	0.91	0.48	0.83	0.63	0.42
ET	0.64	0.93	0.76	0.93	0.63	0.86	0.73	0.56
Δ	+31%	+1%	+19%	+3%	+32%	+4%	+17%	+32%

TABLE III
PROCESSING TIME OF MLP USING BINARY OR ET

Detector Version	Binary	ET
Time (μ s)	17.117	140.581

framework. Our fixed algorithm apps: Threshold, Aggregation and Behavioral Analysis. Our machine learning models: SVM and MLP. The results of the plausibility checks are used as the input features for the learning models. We also created models with multiple plausibility check results as features. We call the number of checks used to create the features: the *depth* of the model. We show here models trained with a depth of 5 and 20 messages, marked by D5 and D20 accordingly. Figure 9 shows the evaluation metrics of the different detection scenarios. These metrics are collected from plots of the GUI described in Section IV-H.

Although the detection rate is important, the local application has to also be light on resources. Arguably, the main goal of a local detection application is to alert a global entity. This means a trade-off of lower detection rate for faster processing could be considered. For this reason we also provide the mean processing time of every application. The application processing time for the previous scenarios is shown in Table IV. Looking at the evaluation metrics and the processing



Misbehavior Types	Evaluation Metrics							
	Rec	Pre	F1s	Acc	BM	MK	MCC	K
Aggre	0.35	0.99	0.52	0.89	0.35	0.88	0.56	0.34
Thre	0.49	0.91	0.64	0.91	0.48	0.82	0.63	0.42
SVM	0.51	0.95	0.66	0.91	0.50	0.86	0.66	0.46
MLP D1	0.64	0.93	0.76	0.93	0.63	0.86	0.73	0.56
MLP D5	0.70	0.94	0.80	0.94	0.69	0.88	0.78	0.63
MLP D20	0.74	0.97	0.84	0.95	0.74	0.92	0.82	0.69
Behav	0.78	0.94	0.85	0.95	0.77	0.90	0.83	0.70

Fig. 9. Detection evaluation by local app

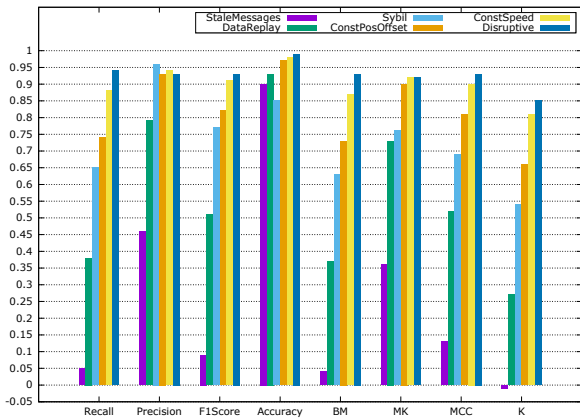
TABLE IV
MEAN PROCESSING TIME

App Version Time (μ s)	Aggre	Thre	SVM	MLP	Behav
	4.86	1.13	373.1	233.7	1.99

time, one could conclude that the Behavioral Analysis app is the best choice overall. This application assigns a trust value for every pseudonym and updates this value over time. Theoretically, this approach would be strongly affected by changing pseudonyms. However, the scenarios tested here have the pseudonym change disabled.

C. Attacks example

Until now, our evaluations were based on an even mix of misbehavior types. However, the detection rate is strongly dependent on the type of misbehavior. To demonstrate this fact, we tested the ability of the MLP, trained with a depth of 20 messages, to detect individual attacks. Figure 10 shows that the stale messages misbehavior type is somewhat hard to detect with our detectors. This result is in line with our expectations since the messages transmitted here are plausible and just sent a few seconds later. Therefore the stale messages do not have many implausible features. One should note that the SAE J2945/1 [15] specifies that BSM generated 30 seconds in the past (and in the future) pass time relevance check. On the other hand, we see that the Disruptive attack is the easiest to detect. That is due to the fact that this type of attack replays a mass of messages without data consistency. Consequently, there is a large amount of implausible features that were easily fingerprinted by the neutral network.



Misbehavior Types	Evaluation Metrics							
	Rec	Pre	F1s	Acc	BM	MK	MCC	K
StaleMessages	0.05	0.46	0.09	0.90	0.04	0.36	0.13	-0.01
DataReplay	0.38	0.79	0.51	0.93	0.37	0.73	0.52	0.27
Sybil	0.65	0.96	0.77	0.85	0.63	0.76	0.69	0.54
ConstPosOffset	0.74	0.93	0.82	0.97	0.73	0.90	0.81	0.66
ConstSpeed	0.88	0.94	0.91	0.98	0.87	0.92	0.90	0.81
Disruptive	0.94	0.93	0.93	0.99	0.93	0.92	0.93	0.85

Fig. 10. Detection evaluation by attack

D. Reporting and global detection example

Finally, we demonstrate the reporting and the global detection of the framework. We start by examining the different

TABLE V
AVERAGE REPORT SIZE COMPARISON

Report Type	Report Size (Bytes)	
	Uncompressed	Izma Compressed
Base	512.45	313.27
Beacon	1090.00	479.73
Evidence	1979.84	545.89

type of reports. Our different report formats have different containers and should vary in size. Using the same scenario as in Section V-C, we measure the size of the reports transmitted to the MA in JSON. This measurement is done for each of the formats described in Section IV-D. Table V shows the average sizes of the different reports. We can see that the sizes are consistent with the reports format, and the differences are smaller when the information is compressed. Please note that the sizes are only used for comparison purposes, however, these are not to scale with a real eventual report. All C-ITS messages of European Telecommunications Standards Institute (ETSI) and Institute of Electrical and Electronics Engineers (IEEE) have a security header a signature and multiple other layer that are not included here [13], [17].

for the global detection, our current simple MA is still based only on the number of received reports for a certain pseudonym. Consequently, a PCP would dramatically affect the result. To show this effect, we enable a periodical PCP. We then simulate the same scenario with multiple pseudonym change periods. Figure 11 shows the average number of reports received by the MA for genuine and misbehaving nodes per pseudonym. We can see that the number of reports is significantly affected by more frequent pseudonym change. Indeed, the MA does not receive enough reports with the same reported ID, certainly affecting the detection quality.

In order to mitigate this effect, the MA can analyze the contents of the report. A report with *Evidence Container* is advantageous for this process. Additionally, currently proposed reporting protocols do not send a report for each message [26]. Instead, to reduce overhead, the vehicle collects evidence and then sends a more complete report. This process would make the global detection based on the number of reports obsolete. The need for an intelligent MA is therefore paramount.

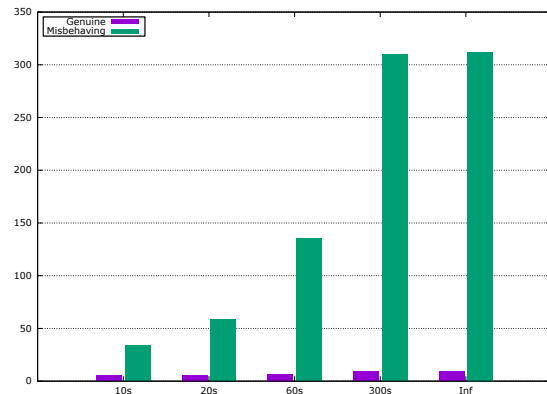


Fig. 11. Average number of reports by pseudonym received by the MA for different pseudonym change period

VI. CONCLUSION

Cooperative Intelligent Transport Systems are susceptible to false data injection attacks that could jeopardize road users safety. In this paper, we proposed a simulation framework and source code called F²MD, which enables the research community to develop, test, and compare MBD algorithms. We implemented in the framework (i) a comprehensive list of attacks, (ii) a extensive set of basic and advanced detection algorithms, (iii) a Python/C++ bridge to allow import of artificial intelligence algorithms, (iv) basic Pseudonym Change Policies, (v) a visualization tool to analyze real-time performance of the MBD system, and (vi) a Misbehavior Authority and Misbehavior Report formats. We demonstrated its full capabilities by running example scenarios and discussed their results.

As future work, we are planning to expand the pseudonym change strategies (e.g. addition of a silent period [32]), attacks and detectors. The framework will also be extended with a intelligent Misbehavior Authority in order to evaluate global misbehavior investigation (and the effects of misbehavior reporting policies and its report format), and detection performance at the MA. We will also extend the attacker model by considering colluding attackers and false misbehavior report injection. The addition of a Public Key Infrastructure module is also considered.

VII. ACKNOWLEDGMENTS

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