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# Device re-identification in LoRaWAN through messages linkage

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## ABSTRACT

In LoRaWAN networks, devices are identified by two identifiers: a globally unique and stable one called DevEUI, and an ephemeral and randomly assigned pseudonym called DevAddr. The association between those identifiers is only known by the network and join servers, and is not available to a passive eavesdropper.

In this work, we consider the problem of linking the DevAddr with the corresponding DevEUI based on passive observation of the LoRa traffic transmitted over the air. Leveraging metadata exposed in LoRa frames, we devise a technique to link two messages containing respectively the DevEUI and the DevAddr, thus identifying the link between those identifiers. The approach is based on machine learning algorithms using various pieces of information including timing, signal strength, and fields of the frames. Based on an evaluation using a real-world dataset of 11 million messages, with ground truth available, we show that multiple machine learning models are able to reliably link those identifiers. The best of them achieves an impressive true positive rate of over 0.8 and a false positive rate of 0.001.

## CCS CONCEPTS

• Security and privacy → Privacy protections; • Computer systems organization → Sensor networks; • Networks → Link-layer protocols.

## KEYWORDS

LoRaWan, re-identification attack, IoT, privacy

## ACM Reference Format:

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## 1 INTRODUCTION

LoRaWAN is a technology allowing for long-range and low bandwidth communications. It is particularly suited for devices with low energy resources such as sensors running on battery for extended period of time. It is used in domain such as health, well-being, and smart city [11]. As of today, it is estimated that there are hundreds of millions of devices<sup>1</sup> and 166 LoRaWAN network operators<sup>2</sup> deployed worldwide.

In LoRaWAN, end-devices (e.g., sensors) are identified by two elements, the DevEUI and the DevAddr. The DevEUI is a globally unique identifier (similar to a MAC address) tied to the device but only exposed in a single message during the join procedure. The DevAddr is an identifier assigned to the device by the network as part of the join procedure. After the join procedure, only the DevAddr is used and the DevEUI is never observed again. As part of security features of LoRaWAN, the assignment of the DevAddr is done via an encrypted message, thus the association between a DevEUI and a DevAddr is never exposed in cleartext over the air. The DevAddr can be renewed, via `rejoin-request` [7], to a new random value. The various DevAddr assumed by a device are thus equivalent to unlinkable pseudonyms from the point of view of an external observer.

Linking multiple identifiers used by a wireless device is a problem that has been mainly studied in Wi-Fi [23] and Bluetooth/BLE [5, 15] where address randomization is becoming the norm. For LoRaWAN, we conducted a preliminary work linking DevAddr with DevEUI by leveraging the timing closeness between the associated messages [2].

In the present work, we propose a consolidated method to find the association between a DevEUI and a DevAddr. After a passive observation of the LoRa traffic over the air, similarly to [2], the DevEUI/ DevAddr association is obtained by linking `join-request` messages with the following `uplink` messages, this time leveraging a large set of metadata such as relative timing, signal reception indicators (RSSI, SNR, etc.), and values included directly inside the headers.

The contributions of this paper are the following:

- We introduce a machine learning approach to re-identify devices by linking `join-request` with `uplink` messages.
- We identify pieces of information found in LoRaWAN traffic that can be leveraged for message linking.

<sup>1</sup><https://www.semtech.com/lora>

<sup>2</sup><https://lora-alliance.org/>

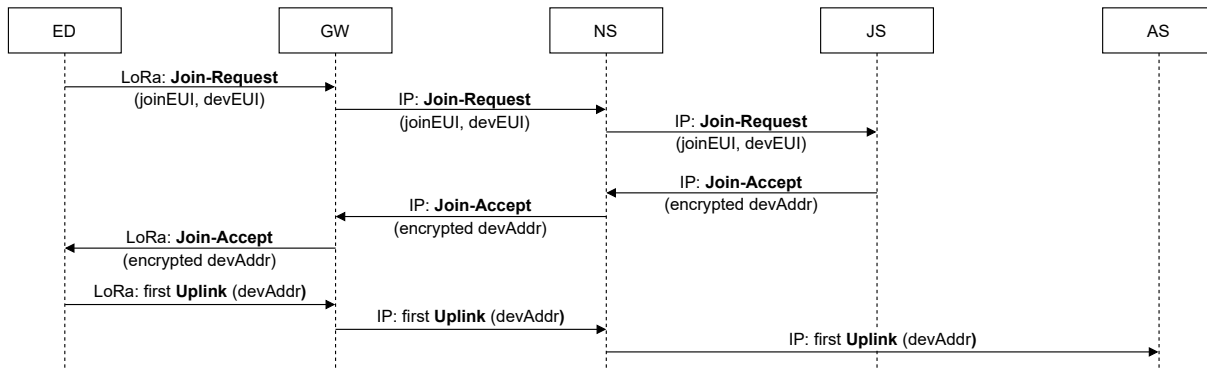


Figure 1: Join procedure using OTAA

- We demonstrate through experimentation on a representative dataset that our approach is able to reliably re-identify devices.
- We discuss several countermeasures that could be deployed to thwart our attack.

## 2 BACKGROUND

Standardized by the LoRa Alliance, LoRaWAN is an open source protocol [7] used as a MAC layer to connect end-devices to servers through gateways (GW). The physical link between the end-device and GW leverages LoRa, a proprietary radio frequency modulation. Thus, the role of the gateway is to translate the LoRa traffic to IP and forward it to or from the server. More precisely, there are three types of servers:

- The Join Server (JS) is responsible of the enrollment of the end-device into the network;
- The Network Server (NS) routes the traffic to the relevant Application Server;
- The Application Server (AS) holds the actual application’s logic.

In numerous implementations, the NS, AS and JS are all located on the same node, but they can be physically separated. In any case, a message going from the end-device to a server is called uplink and, in the opposite direction, downlink.

### 2.1 Addressing

Each end-device owns a unique IEEE EUI64 identifier named DevEUI, provided by the manufacturer and constant over its lifetime. The first 3 bytes contain the OUI of the end-device (Organizationally Unique Identifier, registered to the IEEE).

Apart from this static address, LoRaWAN also uses a new dynamic DevAddr every time an end-device is activated or re-joins the network. Generated by the NS by concatenating the variable length network identifier (7 to 24 bits) and random data, this 32 bits identifier is not bound to a unique device. Multiple end-devices can theoretically use the same DevAddr at the same time. Thus, the JS keeps track of the association between DevEUI and tuples containing the DevAddr as well as a the network’s session key.

### 2.2 End-Device activation

A newly deployed end-device must follow a linking procedure to be able to communicate with the NS. Two methods exist: Over-the-Air Activation (OTAA) and Activation By Personalization (ABP). They mainly differ in where cryptographic information is stored: in ABP, the various keys as well as the DevAddr are saved directly on the end-device before the activation, whereas OTAA derives them during the join procedure.

In this work, we only consider OTAA, the standard procedure (see figure 1). The end-device first sends a join-request message containing notably the DevEUI and JoinEUI, an IEEE EUI64 unique identifier corresponding to the targeted JS. This is the only time the DevEUI is available unencrypted on the air.

Then, the relevant JS answers with a join-accept message, providing additional information to finalize the generation of the keys required to setup a secure session with the AS, as well as a DevAddr. However the join-accept is encrypted, and the following uplink messages are the only ones that provide the DevAddr in clear text. This mechanism is meant to avoid linking the unique identifier of the end-device, the DevEUI, with the traffic containing its ephemeral identifier, the DevAddr.

## 3 MOTIVATIONS AND THREAT MODEL

Being able to link the DevAddr with the DevEUI of an end-device, known as a re-identification attack, can be leveraged to threaten the security and privacy of LoRaWAN networks. And since join and rejoin procedures are similar [7], it is also possible to link the permanent DevEUI with *multiple* DevAddr following the various rejoin-request.

From the security viewpoint, which is not the main objective of this work, this attack can be exploited to target specific devices with reactive and selective jamming [4, 18].

From the privacy viewpoint, since the notion of privacy varies through context and time [9], reducing it to basic questions is beneficial. In our context, privacy applies to three categories of information: identity (*who?*), activity (*what/when?*) and location (*where?*) [10]. By design, LoRaWAN separates the identity (via the DevEUI) from the activity (via the DevAddr). Linking them provides more accurate information about the end-device and its potential applications, both exploitable by an attacker to map it with an

233 already known identity, activity or location. For example, parking  
 234 lot end-device data could help inferring the activity of a household  
 235 [14], leading to a privacy leakage that involves both activity and  
 236 location. Another example, the OUI part of the DevEUI can be used  
 237 to infer the manufacturer, or even the end-device model [16], and it  
 238 can help mapping a type of end-device with a company or person.

239 In any case, eavesdropping LoRaWAN traffic is straightforward.  
 240 Any attacker knowing which band to listen to can eavesdrop the  
 241 communication [22]. To do so, one can use a cheap LoRa device  
 242 to listen on a specific channel [19] or a more expensive but still  
 243 affordable gateway to monitor multiple channels<sup>3</sup>.

244 Then, LoRa benefits from a wide transmission range by design,  
 245 meaning that the attack does not require a physical proximity but  
 246 can be conducted from kilometers away. This is a major difference  
 247 with eavesdropping attacks in wireless protocols such as Bluetooth  
 248 or WiFi [3, 8]. It also means that the eavesdropping device can  
 249 listen for long periods of time without being detected, and can thus  
 250 collect a significant amount of messages.

251 **Threat model:** Our threat model relies on several assumptions.  
 252 First, we assume that the encryption layer is robust: it is impossible  
 253 to access the content of encrypted payloads. Then, we assume a  
 254 passive attacker: the traffic is left untouched and only listened  
 255 to, without injecting or altering messages. This is a reasonable  
 256 assumption as the messages benefit from an integrity protection.  
 257 Likewise, we assume the end-device is left unmodified, and the  
 258 attacker cannot physically access it. Finally, we assume that the  
 259 attacker controls several receivers in the targeted area, silently,  
 260 potentially over extended periods of time. As commercial gateways  
 261 cost a few hundreds euros (see above), achieving good coverage in  
 262 a citywide area is realistic.

## 264 4 LINKING JOIN REQUESTS AND UPLINK 265 MESSAGES

266 In this section, we present the process and the various pieces of  
 267 information used to link the `join-request`, containing a DevEUI  
 268 and the following first `uplink` message. In machine learning, such  
 269 pieces of information are called *features*.

270 Two specificities can be leveraged for this matching. The first  
 271 one is inherent to the protocol itself: a `join-request` is generally  
 272 closely followed by an `uplink` with a fresh DevAddr. There is no  
 273 obligation for the end-device to use the newly acquired DevAddr  
 274 right after receiving it; however, it makes sense in general for a  
 275 sensor either to ask for its configuration or to start sending data as  
 276 soon as possible.

277 The second one is the fact that each end-device has a form of  
 278 fingerprint relative to a group of gateways: its distance to them and  
 279 the terrain in between both affect the radio features. Although LoRa  
 280 end-devices can be mobile, many of them are static (e.g., a water  
 281 metering sensors). Likewise, the emitted signal of an end-device  
 282 remains constant through time: its hardware is built to broadcast  
 283 data with a specific power and should not significantly vary through  
 284 time. Thus, two messages coming from the same static end-device  
 285 should have physical similarities when received by a given gateway.  
 286

287 <sup>3</sup>For example, The Things Gateway costs 300€: <https://www.thingsnetwork.org/docs/gateways/gateway/>. A smaller version is even cheaper, costing 70€ <https://www.thingsnetwork.org/docs/gateways/thingsindoor/>

291 Based on these assumptions, we analyze the variation of features  
 292 among messages in our dataset by separating known first `uplink`  
 293 messages from other `uplink` messages. The distribution of the  
 294 data according to each feature is then analyzed to spot differences  
 295 between the two sets. If the discrepancies are important enough,  
 296 the studied feature can be used to distinguish valid from invalid  
 297 links. A complete list is available in table 1.

298 The most basic form of feature is directly extracted from the  
 299 unencrypted header of the message. For example, each `uplink`  
 300 message contains a 2-bytes frame counter (FCnt), starting at zero  
 301 following a `join` or `re-join` procedure and incremented by 1 with  
 302 each subsequent `uplink`.

303 Alternatively, it is possible to extract more complex features  
 304 based on the transmission itself. As LoRa frames are broadcast, they  
 305 can be received by multiple gateways. This is not a problem when  
 306 working with header fields such as the frame counter. However,  
 307 physics-based features vary from gateway to gateway and cannot  
 308 easily be converted to a single value. Thus, we use various vectors,  
 309 with each index corresponding to a gateway from the dataset. When  
 310 a message is received by a gateway, the relevant value is placed at  
 311 the corresponding index and it is then possible to compute various  
 312 distances. For example, by setting a 1 if a gateway received the  
 313 message and a 0 if it did not, we can compute a vector coding the  
 314 message reception patterns by gateways. Then, we compute the  
 315 euclidean distance ( $GW_{dist}$ ) between the vector of a `join-request`  
 316 and the ones of `uplink` messages. Another example, for a `join`  
 317 request  $j$  and an `uplink`  $u$  received by  $n$  gateways, the ESP distance  
 318 is computed as follows:

$$299 \quad ESP_{dist}(j, u) =$$

$$300 \quad \sqrt{(j_{ESP1} - u_{ESP1})^2 + (j_{ESP2} - u_{ESP2})^2 + \dots + (j_{ESPn} - u_{ESPn})^2}$$

321 The closest the vectors are, the most likely the same end-device  
 322 sent both the `join-request` and the corresponding `uplink`. This  
 323 process is followed for all features with the *dist* suffix.  
 324

## 326 5 METHODOLOGY

327 In this section, we consider a machine learning approach to link  
 328 `join-request` with `uplink` messages, and therefore DevEUI with  
 329 DevAddr, based on the features presented in section 4 (see figure 2).  
 330 The process can be seen as a binary classification problem, as we  
 331 need to distinguish pairs of messages that are actually linked from  
 332 pairs that are not.  
 333

334 **Dataset:** To conduct our experiments, we use a real-world dataset  
 335 including 740 000 `join-request` and 10 570 000 `uplink` messages  
 336 of LoRaWAN 1.0. They were received by a set of a hundred gateways  
 337 deployed in various places in the city of Grenoble (France), listening  
 338 to the EU 868MHz band, from the 23th June 2020 to the 3rd January  
 339 2022.<sup>4</sup>

340 As we control the LoRaWAN network server, we have access to  
 341 the content of the payloads as well as the ground truth for links  
 342 between 211 known DevEUI and 1024 known DevAddr identifiers.  
 343

344 <sup>4</sup>More precisely, only the 868.1, 868.3, 868.5, 868.3, 867.1, 867.3, 867.5, 867.7 and  
 345 867.9MHz frequencies for `uplink` messages as well as 869.525MHz for downlinks are  
 346 listened to. The carrier-grade frequencies used by specific operators are not received  
 347 by the gateways. Thus, some portions of a communication can be lost because the  
 348 end-device changes to a frequency not monitored. This does not affect our experiments  
 349 as it is only relevant to traffic coming from uncontrolled operators.  
 350

Name	Description
FCnt	Frame counter
plen	uplink payload length
OUI	OUI extracted from the DevEUI
Datarate	Datarate
SF	Spreading Factor
$t_{s_{diff}}$	Time of arrival difference between the join-request and the studied uplink
$ESP_{dist}$	Estimated Signal Power euclidean distance
$RSSI_{dist}$	Received Signal Strength Indication euclidean distance
$SNR_{dist}$	Signal to Noise Ratio euclidean distance
$t_{s_{dist}}$	Timestamps euclidean distance
$DevAddr_{diff}$	Time of arrival difference between two uplink messages with identical DevAddr
$GW_{dist}$	Euclidean distance based on gateways receiving the messages

Table 1: Features used by the linking process

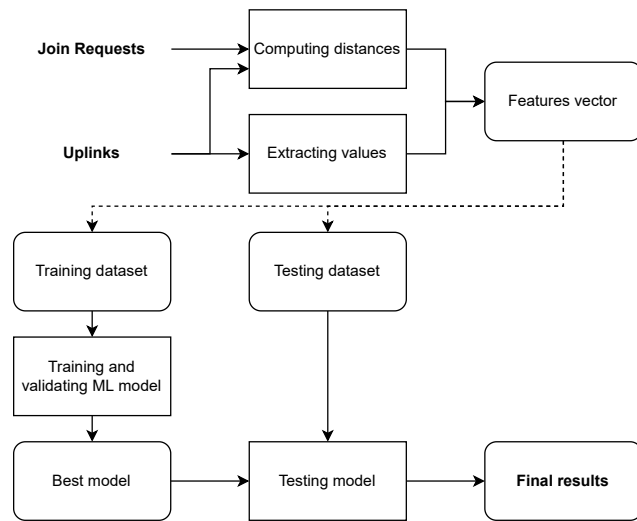


Figure 2: Overview of the methodology

This network is operated by the university and the end-devices are managed by a community of researchers for experimental purposes. Although the end-devices are used in research settings, their implementation and deployment aim at recreating a realistic real-world LoRaWAN network.

**Performance metrics:** In order to evaluate the classification efficiency, we use the following metrics:

- True positive (TP): the link found is valid;
- False positive (FP): the link found is invalid;
- True negative (TN): no link was found, correctly;
- False negative (FN): no link was found, erroneously;
- True Positive Rate (TPR);
- False Positive Rate (FPR);

- Matthew correlation coefficient (MCC)<sup>5</sup>.

**Data preparation:** The machine learning models are built with two sets: a set of join-request messages  $\mathcal{J}$  and another of uplink messages  $\mathcal{U}$ . Note we only deal with the ground truth: messages received from other operators were previously removed. More precisely, a subset of known links  $\mathcal{K}$  is used to detect the unique valid pairs  $(j, u_v) \in \mathcal{K}$ , representing the first class. The second class is built by using the randomly selected leftover uplink messages to create invalid pairs  $(j, u_i) \notin \mathcal{K}$ . This ensures the second class is heterogeneous and contains a vast variety of associations.

Both types of pairs are converted into vectors  $v$  containing a list of features  $f$  such as  $v(j, u) = f_1, f_2, \dots, f_n$  with the last value  $f_n$  being an integer corresponding to the link state between  $j$  and  $u$ . Thus,  $f_n$  is equal to 1 for valid links  $(j, u_v)$  and 0 for invalid links  $(j, u_i)$ .

**Considered classifiers:** Following the works of Acar et al. [1], we choose to study seven classifiers (CLF): Decision Tree (DT), Naive Bayes (NB), Logistic regression (LR), K-Nearest Neighbours (kNN), Random Forest (LR), AdaBoost (AB), and LightBGM (LBGM).

We replaced XGBoost [1] by LightBGM, a faster alternative for gradient boosting. Instead of sorted continuous values, it leverages histograms to build the internal trees, reducing the number of splitting points to analyse [12].

**Training:** Once the data has been transformed into the expected format, we use the scikit-learn Python library<sup>6</sup>, which provides many algorithms [17]. In our work, we consider several of them with the goal to identify the most efficient one.

**Validations methods:** In order to produce robust models against unseen data, the dataset is split into two subsets: 75% is used for training and validation, and the remaining 25% is only exploited during the testing phase. We also use 5-fold cross validation: the dataset is divided into 4 subsets training a model and the last one is used to test it. More precisely, we leverage a stratified k-fold cross validation to preserve the proportion of each class inside the subsets. Using such method improves results, minimizing the bias and variance [13] at the cost of higher computing resources [24]. It also proves an attacker does not need to listen for communications for years before being able to link the traffic. This process is repeated 5 times to further reduce the bias and variance [20].

## 6 EXPERIMENTAL RESULTS

In this section, we present the evaluation of the machine learning classifiers and data presented in section 5. We select a subset that ranges from September 1st, to December 31st, 2021. This equals to 1086 valid links and 165 534 invalid links.

The frame counter is an obvious indicator to detect the first uplink message, and obfuscating it is a potential mitigating solution for the re-identification attack (see section 7). So, in order to further assess the importance of this feature for the success of the attacks, we considered two versions of the dataset: one including it, and one without.

<sup>5</sup>As the two classes are imbalanced, we specifically use the Matthew correlation coefficient (MCC) to compare models. Contrary to accuracy or F1-score, it correctly leverages all data from the confusion matrix and provides a score taking into account both the positive and negative cases [6].

<sup>6</sup><https://scikit-learn.org/stable/index.html> (version 1.0.2)

**Stability against unseen data:** The MCC remains stable for models across the 5-fold cross validation and testing phases<sup>7</sup>. More detailed results are available as artefacts (see section 10).

**Performances with the frame counter:** A comparison between the various classifiers in table 2 shows that Random Forest presents the best results while including the frame counter in the features, with a true positive rate of 0.7939 and a false positive rate of 0.001. Multiple classifiers show high performances, with Decision Tree, AdaBoost, LightGBM and Random Forest all above a 0.79 MCC value. Thus, an attacker has a high confidence in the links obtained: an overwhelming majority of them is correctly detected and the number of false positives remains low.

CLF	TP	FP	TN	FN	TPR	FPR	MCC
<b>RF</b>	235	42	41317	61	0.7939	0.001	<b>0.8195</b>
DT	239	49	41310	57	0.8074	0.0012	0.8173
AB	236	56	41303	60	0.7973	0.0014	0.8013
LGBM	239	68	41291	57	0.8074	0.0016	0.7913
kNN	187	64	41295	109	0.6318	0.0015	0.684
LR	24	33	41326	272	0.0811	0.0008	0.1824
NB	284	10002	31357	12	0.9595	0.2418	0.1398

Table 2: Comparison of classifiers, using the frame counter

CLF	TP	FP	TN	FN	TPR	FPR	MCC
RF	133	29	41330	163	0.4493	0.0007	0.6054
DT	175	115	41244	121	0.5912	0.0028	0.5944
AB	144	70	41289	152	0.4865	0.0017	0.5696
<b>LGBM</b>	191	41	41318	105	0.6453	0.001	<b>0.7272</b>
kNN	171	81	41278	125	0.5777	0.002	0.6237
LR	4	1	41358	292	0.0135	0.0	0.1034
NB	33	797	40562	263	0.1115	0.0193	0.0554

Table 3: Comparison of classifiers, without the frame counter

**Performances without the frame counter:** When the frame counter is ignored (see table 3), most classifiers lose in performance. For example, the true positive rate of the Random Forest classifier decreases from around 0.80 to 0.45. However, for all models, the false positive rate remains close to its previous value and only the number of true positives decreases. Thus, the linking attack can still work with a high confidence on the results, albeit with fewer links found.

**Importance of the features:** In order to assess the importance of the features, we extracted the weights leveraged by the RF classifier (see table 4). The frame counter is confirmed essential with a weight of 0.3685, followed by the various distances and the payload’s length, which amounts for around 13% of the weights without the frame counter<sup>8</sup>.

**Impact of the number of receivers:** Finally, we measure the impact of the number of eavesdropping nodes controlled by the attacker in a specific area. As they are geographically close to each other, they receive a significant subset of messages in common. We selected various sets of three nodes and ran tests with 1, 2, or 3

<sup>7</sup>For example, the Random Forest classifier demonstrates a 0.871 average MCC for 5-fold cross validation and a 0.88 during the final test.

<sup>8</sup>We also tested the ACK and ADR flags[7], which seemed promising based on their distributions, but results were inconclusive.

Feature	With FCnt	Without FCnt
FCnt	0.3685	N/A
$t_{s_{diff}}$	0.115	0.1838
$ESP_{dist}$	0.0866	0.1284
$SNR_{dist}$	0.0765	0.1106
$DevAddr_{diff}$	0.0744	0.1178
$RSSI_{dist}$	0.0613	0.0956
$t_{s_{dist}}$	0.0584	0.0746
plen	0.0546	0.1339
OUI	0.0379	0.0731
Datarate	0.0241	0.0295
SF	0.0237	0.0261
$GW_{dist}$	0.0191	0.0295

Table 4: Weights of each feature for the Random Forest model

nodes to compare the impact of the number on the models. Contrary to our intuition, adding new nodes does not necessarily provide better results. Based on our observations, it seems to highly depend on the amount of traffic captured by the node, the higher the better. Exploring further what would improve the global re-identification efficiency is left to future works.

## 7 COUNTERMEASURES

Since the re-identification attack is effective, as soon as an attacker eavesdrops a join-request and the following uplink message(s), the question of counter measures naturally arises.

**Obfuscating the frame counter:** Tests of section 6 highlight the importance of the frame counter, FCnt, ranked first in table 4 with a 0.37 coefficient. A first possibility is to hide it, for instance by encrypting a part of the header, or using a random offset instead of starting with value 0 in case of a new end-device joining the network. However, both approaches imply a change of the specifications, although the second one remains easier to implement.

In any case, the benefits would be limited as we also proved that in the absence of the FCnt, the attacker can still leverage other features, reaching a reasonable true positive rate of 0.65 (with LGBM) and high confidence on the results. The following question is whether this can be achieved with minimal implications, notably in terms of backward compatibility, without changing the specifications.

**Introducing randomness:** Introducing randomness in parameters influencing physics-related features, such as ESP, is an option. However, it may not be possible without compromising the correct reception of messages, or greatly modifying the end-devices as well as increasing their energy consumption.

Other possibilities that do not impact LoRaWAN standard are: introducing a random delay before sending the first uplink message; padding the payload to hide its actual length; sending multiple first uplink messages with false DevAddr as decoys.

**Obfuscating device identifiers:** More disruptive solutions, that require an update of the LoRaWAN standard, in addition to those centered around the FCnt feature already discussed, include: sharing a DevAddr for multiple end-devices and identifying the devices by their network session key [2]; and using resolvable addresses as in BLE[5].

## 8 RELATED WORKS

Linking multiple pseudonym identifiers used by devices has been studied in other wireless technologies that use address randomization methods, such as Wi-Fi and Bluetooth-Low-Energy. Methods leveraging the content of the wireless frame as well as their timing have both been presented to correlate frames and identifiers [5, 15, 23].

Physical-layer fingerprinting of LoRa devices has been demonstrated in [19], and could be used to single-out a device. However, this fingerprinting requires specialized hardware (USRP), works with physical-layer and not LoRaWAN itself, and has not been demonstrated in a real-world network.

Privacy considerations for LoRa traffic has been discussed in [14]. More specifically, this work focuses on the inference of information based on traffic metadata, and how it can be obfuscated.

Finally, the linking of DevAddr and DevEUI in [21] is done by framing the DevEUI between two sets of consecutive DevAddr with the same behavior. First, their dataset is more homogeneous with 130 end-devices, all deployed for the same application. Then, contrary to our contribution, their method does not take new, unknown end-devices into account and can only link a DevEUI effectively framed between two DevAddr. Lastly, it only leverages the frame counter as well as the timestamp and obtains a 0.936 accuracy, against 0.9975 for our best model.

## 9 CONCLUSION

We show it is possible to reliably link two DevEUI and DevAddr, and thus re-identify devices, by applying machine learning algorithms. Although the frame counter plays a major role in obtaining a 0.8 TPR and 0.001 FPR for the best model, solely obfuscating it is not enough to protect users from this attack, as we obtain a 0.65 TPR and 0.001 FPR by compensating its absence by other pieces of information. We discuss potential countermeasures that require to act on several pieces of information at the same time, with negative consequences for some of them (e.g., backward compliance). Although mitigating the re-identification attack is feasible, it seems there is no easy, perfect solution.

Future works will include fine-tuning the parameters of the models to increase their efficiency, as well as evaluating our approach on other datasets.

## 10 RESEARCH ARTIFACTS

The (anonymized) data and Python code necessary to build the models and reproduce results are published in a public Git repository: <https://gitlab.inria.fr/spelissi/wisec-2022-reproductibility>.

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