

Machine Learning for the Detection and Identification of Internet of Things (IoT) Devices: A Survey

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Abstract—The Internet of Things (IoT) is becoming an indispensable part of everyday life, enabling a variety of emerging services and applications. However, the presence of rogue IoT devices has exposed the IoT to untold risks with severe consequences. The first step in securing the IoT is detecting rogue IoT devices and identifying legitimate ones. Conventional approaches use cryptographic mechanisms to authenticate and verify legitimate devices' identities. However, cryptographic protocols are not available in many systems. Meanwhile, these methods are less effective when legitimate devices can be exploited or encryption keys are disclosed. Therefore, non-cryptographic IoT device identification and rogue device detection become efficient solutions to secure existing systems and will provide additional protection to systems with cryptographic protocols. Non-cryptographic approaches require more effort and are not yet adequately investigated. In this paper, we provide a comprehensive survey on machine learning technologies for the identification of IoT devices along with the detection of compromised or falsified ones from the viewpoint of passive surveillance agents or network operators. We classify the IoT device identification and detection into four categories: device-specific pattern recognition, Deep Learning enabled device identification, unsupervised device identification, and abnormal device detection. Meanwhile, we discuss various ML-related enabling technologies for this purpose. These enabling technologies include learning algorithms, feature engineering on network traffic traces and wireless signals, continual learning, and abnormality detection.

Index Terms—Internet of Things, Security, Physical-layer Security, Malicious Transmitter Identification, Radiometric signature, Non-cryptographic identification, Physical-layer identification.

I. INTRODUCTION

AS a rapidly evolving field, the Internet of Things (IoT) involves the interconnection and interaction of smart objects, i.e., IoT devices with embedded sensors, onboard data processing capabilities, and means of communication, to provide automated services that would otherwise not be possible [1]. Trillions of network-connected IoT devices are expected to emerge in the global network around 2020 [2]. The IoT is becoming pervasive parts of everyday life, enabling a variety of emerging services and applications in cities and communities [3], including in health [4], transportation [5], energy/utilities, and other areas. Furthermore, big data

analytics enables the move from the IoT to real-time control [6]–[9].

However, the IoT is subject to threats stemming from increased connectivity [10], [11]. For example, rogue IoT devices, *defined as devices claiming a falsified identity or compromised legitimate devices*, have exposed the IoT to untold risks with severe consequences. Rogue IoT devices could conduct various attacks: forging the identity of trusted entities to access sensitive resources, hijacking legitimate devices to participate in distributed denial of service (DDoS) attacks [11], and etc. The problem of rogue devices becomes even more hazardous in wirelessly connected IoT, as the network traffic is easier to be intercepted, falsified, and broadcast broadly. Hence, from the perspective of network operators, the first step in securing the IoT from risks due to rogue devices is identifying known (or unknown) devices and detecting compromised ones. This survey defines the term *Device Detection and Identification* to contain two perspectives: *a) Identity verification of known devices. b) Detection of falsified or compromised devices.*

Conventional cryptographic mechanisms use message authentication code, digital signatures, challenge-response sessions, and etc. to authenticate legitimate peers or verify the identities of message senders. These methods make it mathematically impossible for the malicious to forge the legitimate ones' identities. Even though cryptographic mechanisms are effective as long as critical keys are securely protected, security requirements may not be fully satisfied in pervasively distributed IoT. Reports have shown that it is possible to use reverse engineering to access encryption keys or conduct further exploitations [12]–[16]. Moreover, it is impossible to install cryptographic protocols into the huge amount of insecure systems or devices in a short time. Some of them have already become part of critical infrastructures [17]–[22]. Finally, cryptographic approaches become less effective in dealing with hijacked devices. Therefore, as a supplementary to existing cryptography mechanisms, non-cryptographic Device Identification with Rogue Device Detection functions are needed to secure the IoT ecosystem especially from the perspective of network operators and cybersecurity surveillance agents.

Non-cryptographic device identification and rogue device detection have emerged as essential requirements in safety-critical IoT [23]–[25]. Compared with cryptographic approaches, non-cryptographic approaches aim to identify known devices and detect rogue devices by exploiting device-specific

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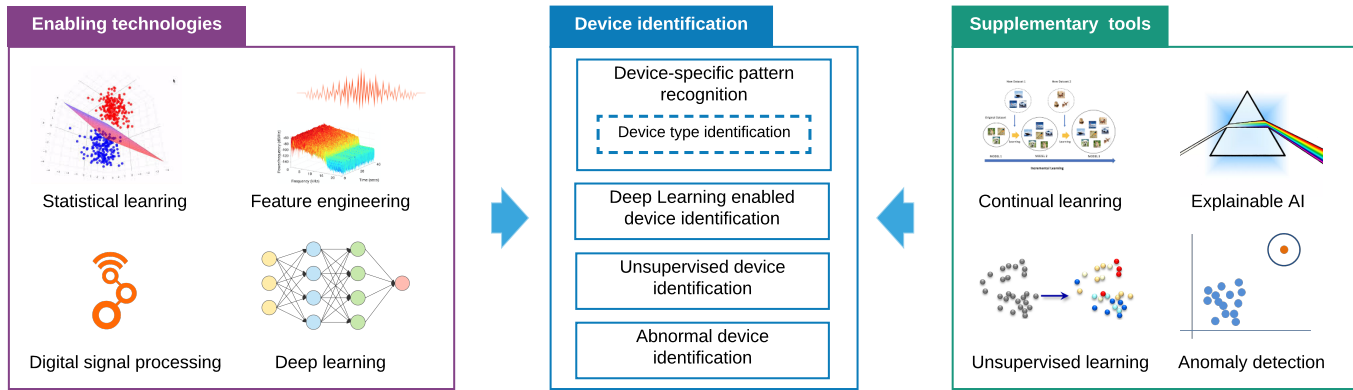


Fig. 1. Overview of ML for the Detection and Identification of Rogue IoT Devices

signal patterns or behavior characteristics [26]. More importantly, non-cryptographic approaches do not require modifications to existing systems that can not be upgraded easily, e.g., ADS-B [27], AIS [28] and etc.

Non-cryptographic device identification and detection are still challenging. Firstly, the flexible deployment scenarios and diverse specifications of devices make it challenging to provide a general guideline to derive distinctive features from signals or network traffic. Moreover, even though machine learning (ML) and Deep Learning (DL) have the potential to automatically discover distinctive latent features for accurate device identification, state-of-art algorithms require intensive modifications to be utilized in IoT [29]. Therefore, this domain is not yet thoroughly investigated and motivated us to conduct a comprehensive survey as a summary of existing works and anticipate the future development of this domain from the perspective of machine learning.

The scope of this paper and related surveys are compared in Table I. In general, existing surveys focus on presenting broad overviews of threats and countermeasures in IoT. In this paper, we focus on a more specific point by providing a comprehensive survey of machine learning for the detection and identification of devices in IoT using passively collected traffic traces and wireless signals, which are easily accessible to network operators and surveillance agents. Figure 1 presents an overview of ML for the detection and identification of IoT devices with relations between key concepts in Figure 2. We classify the IoT device identification and detection into four categories: device-specific pattern recognition, Deep Learning enabled device identification, unsupervised device identification, and abnormal device detection. We identify various ML-related enabling technologies and tools for this purpose, including statistical learning, feature engineering, digital signal processing, and deep learning. These tools include continual learning, unsupervised learning, and anomaly detection.

The remainder of this paper is structured as follows. Section II presents a general threat model and attack chain of rogue devices in IoT. In Section III, we review device type identification (Section III-A) and statistical learning on device-specific feature identification (Section III-B), including conventional radiometric signature and statistical learning. In Section III-C

TABLE I
A COMPARISON WITH EXISTING SURVEYS

Surveys	Year	FD	DL	DT	UD	RD
[30]	2020	•	•			•
[31]	2019	•		•		•
[32]	2017	•	•	•		
[33]	2012	•				•
[34]	2010	•			•	•
This paper	2021	•	•	•	•	•

FD: Feature-based specific device identification; DL: Deep Learning enabled specific device identification; DT: Device type identification; UD: Unsupervised device identification; RD: Rogue device detection.

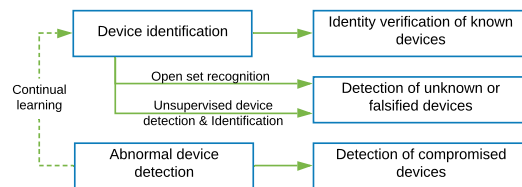


Fig. 2. Key concepts in this survey.

we review state-of-the-art Deep Learning (DL) based methods for device identification with a focus on emerging issues such as continual learning, abnormality detection, hyperparameter, and architecture search. A novel emerging approach, unsupervised device detection, is reviewed in Section III-D. In Section IV, we present methodologies to detect compromised wireless devices using anomaly detection algorithms, which is complementary to device-specific identification. Section V pinpoints the challenges and future research directions with discussions on enabling technologies. Section VI concludes this paper.

II. THREAT MODE OF ROGUE DEVICES IN IOT

This section briefly reviews the threat modes of rogue devices along with countermeasures in IoT. We analyze the attack chain and identify the essential requirements of IoT device detection and identification: verifying legitimate devices' identity, detecting unknown or falsified devices, and detecting compromised (hijacked) devices with abnormal behaviors.

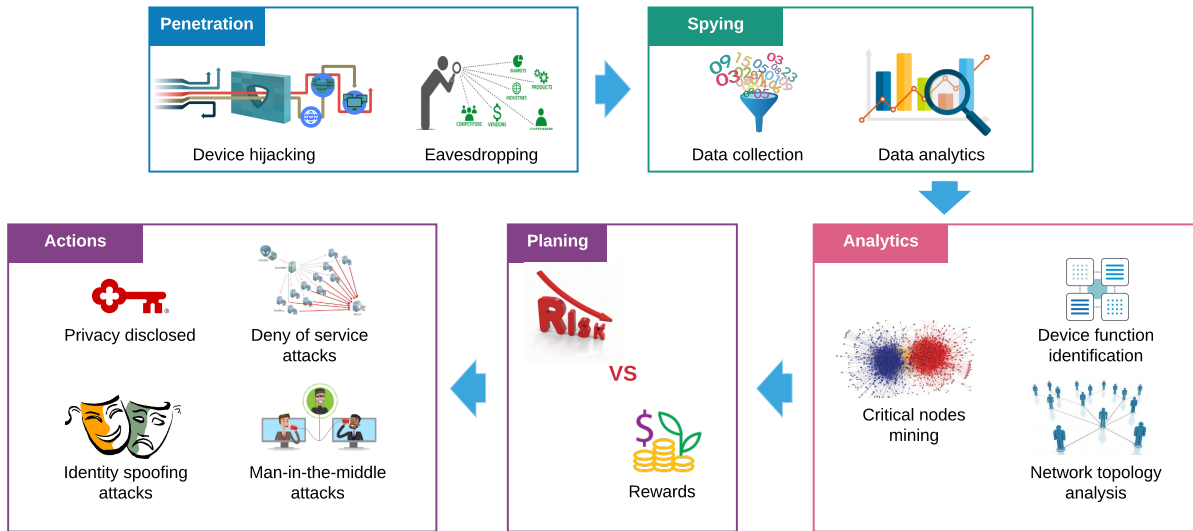


Fig. 3. Attack chain in the IoT.

The cyberinfrastructure of IoT allows sharing information and collaborating among devices with different capacities and vulnerabilities. On the one hand, this scheme cultivates a large open system with low entry restrictions. On the other hand, adversaries can conduct rogue activities with great convenience [35]. Generally, the attack modes of adversaries in IoT are in two folds: passive attack and proactive attacks. In a passive attack, adversaries do not cause damage or performance degradation for a long time. Still, they passively analyze devices' communication and activity patterns, providing road maps for proactive attacks in the future. If we regard passive attackers as spies secretly and peacefully gathering intelligence, the proactive attackers do whatever possible to degrade performances or exploit devices to conduct malicious activities. In practical attacks, proactive and passive attacks are combined. A typical attack chain to IoT systems is shown in Figure 3 with a more specific demonstration of identifying spoofing attack depicted in Figure 4. We divided the whole attack chain into five stages, as follows:

1) *Penetration*: In this stage, the rogue IoT devices try to eavesdrop on communication channels or attain the control privileges of vulnerable peers for further actions. Research in [36] shows that using ARP (Address Resolution Protocol) spoofing, the malicious can easily

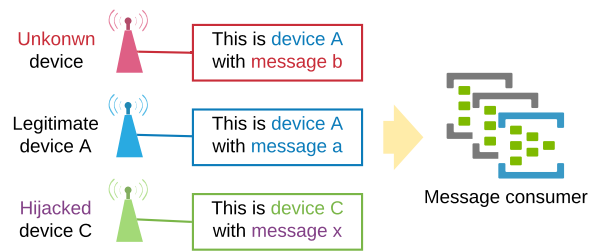


Fig. 4. Identity spoofing attacks.

observe ongoing traffic generated by connected IoT devices from more than 20 manufacturers. Nowadays, it is still challenging to develop software stacks with assured security [37].

- 2) *Spying*: In this stage, the malicious will observe the ongoing activities by exploiting penetrated devices as its agents. As in [36], more than 50% of tested popular smart home IoT devices contain at least one vulnerable ports.
- 3) *Data analytics*: The malicious analyses the behaviors and evaluate the vulnerabilities of the IoT from multiple perspectives. An example in [38] reveals that even if

TABLE II
COMPARE OF CRYPTOGRAPHIC AND NON-CRYPTOGRAPHIC COUNTERMEASURES

Methods	Principles	Advantages	Challenges
Cryptographic	Use shared secrecy to mathematically make the decryption of sensitive information and forge of identity computationally expensive.	<ul style="list-style-type: none"> • Device independent • Protects both confidentiality and can verify identity 	<ul style="list-style-type: none"> • Disclosure of secret keys. • Re-distribution of secret keys. • Needs special adaption to existing systems.
Non-cryptographic	Extract and verify device-specific features from received messages to assure that messages are from known sources.	<ul style="list-style-type: none"> • Device-specific. • Can identify Hijacked devices with abnormal behaviors. • compatible with existing IoT 	<ul style="list-style-type: none"> • Computationally expensive. • Identity disclosure.

encryption mechanisms are employed, an attacker can still extract sensitive information, such as manufacture, device functionality, and etc.

- 4) *Planning*: In this stage, the adversaries perform strategic planning and wait for the best time to minimize their risk while maximizing the rewards.
- 5) *Attack*: In this stage, prevalent attacks are in action.

Among these stages, passive and proactive attacks are combined in the penetration stage. From the perspective of network operators or cybersecurity surveillance agents, if we can prevent the adversaries from successfully impersonating legitimate devices in the first stage (penetration) or can identify hijacked devices in the second stage (spying). Network operators and surveillance agents can destroy the whole attack chain.

Various countermeasures can be applied to secure IoT systems for IoT device identification and detection. Both cryptographic and non-cryptographic methods can be applied. A brief comparison of them is presented in Table II. Cryptographic methods are widely used in computer networks and telecommunication systems. However, special modifications are needed to deploy cryptographic protocols to existing systems without cryptographic protocols such as ADS-B, AIS, and etc. Non-cryptographic methods require higher computational capacities to derive device-specific fingerprints, but they are transparently compatible with existing systems.

III. LEARNING-ENABLED DEVICE IDENTIFICATION IN IOT

This section reviews methods to recognize devices' identities and types in IoT. Most of them are based on network traffic and wireless signal pattern recognition. We first review device type identification methods, which are widely used in identifying commercial IoT devices. We then discuss and compare corresponding signal feature-based device recognition approaches. Especially, We discuss Deep Learning in device identification with emerging issues extensively. Finally, we review the unsupervised device identification and its open issues.

A. Device type identification

Even though device types are not directly related to devices' identities, they still provide essential information for network management and risk control. A brief diagram of typical IoT devices is in Figure 5, and comparisons of their Physical Layer, Data Link Layer as well as aggregated data transmission characteristics are presented in [39], [40] and [41], respectively. As in Figure 5, WiFi is pervasively utilized in smart homes while smart cities prefer reliable cellular networks. Device type identifications are frequently performed on network, transportation, and application layers and implemented in Software Defined Network (SDN) controllers or Software Routers [42]–[44]. Device types reveal functionalities and activity profiles. A taxonomy of features for device type identification is presented in Figure 6.

As in Figure 6, remote service is a popular attack surface to disclose the device type or even identity. The reason is that the IoT devices communicate with remote service providers

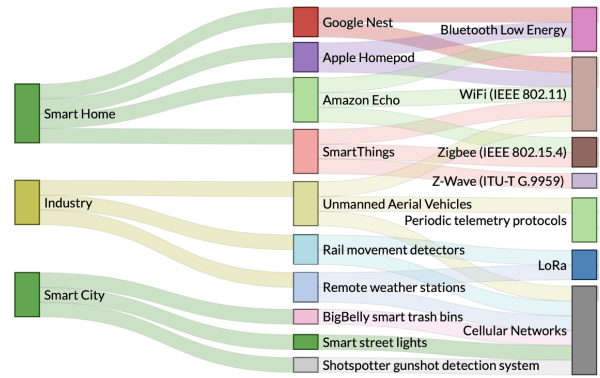


Fig. 5. Typical IoT devices and protocols.

through the REST API [45]. Even though sensitive data are encrypted, some unique strings in their Web requests can still be exploited to infer device types. Authors in [46] present that using only port numbers, domain names, and cipher suites, a Naive Bayesian classifier can reach high accuracy in classifying 28 commercial IoT devices.

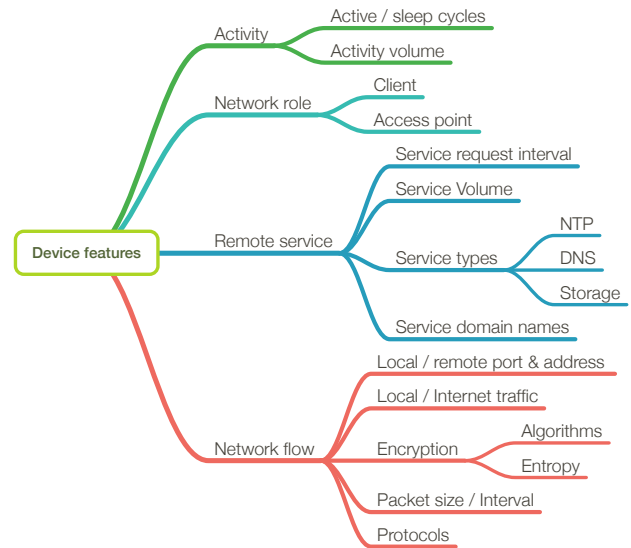


Fig. 6. Features for device type identification.

Even though modeling devices' remote service requests provides promising results in device type identification, these solutions may not work if they interact with anonymous service providers. For alleviation, their activity and data flow patterns can be utilized. Authors in [47] propose that their Random Forest classifier reaches a high accuracy of 95% in identifying 20 IoT devices when features of activities, network data flows, and remote service requests are utilized simultaneously. In [48], devices' types are identified based on the periodicity of activities. The authors first use the Discrete Fourier Transform (DFT) and discrete autocorrelation to find the dominant periods in protocol-specific activities. They then use statistical and stability metrics to model devices' behaviors. Finally, the Bayesian-optimized k-Nearest Neighbor

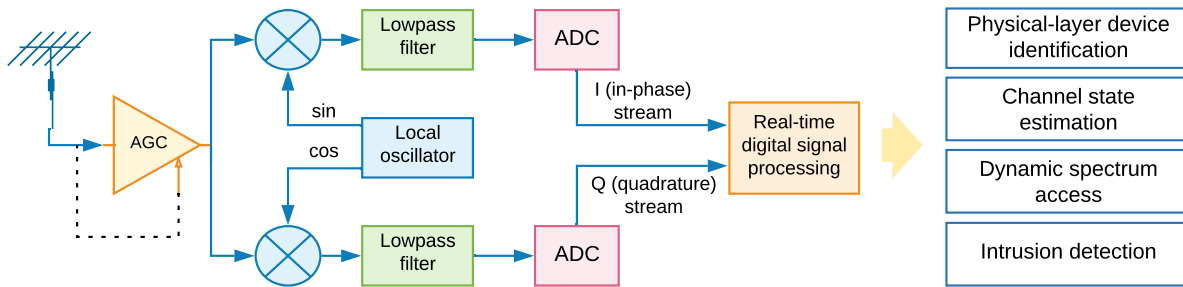


Fig. 7. General pipeline of Software-Defined wireless signal identification.

algorithm is employed for classification. In [49] and [50], the authors extract the protocols and network flow properties within a sliding window to generate fingerprints of devices. They use one-versus-rest classifiers to identify commercial devices. In [51], The authors first provide a Random Forest classifier using TCP/IP stream features. They incorporate confidence thresholds and averaged decisions within a sliding window to identify known or unknown device types. Similar research is presented in [51] and [52]. In [53], the authors also present that network traffic, device types, and their operation states (boot, active, and idle) can be inferred simultaneously.

To automate the processes to derive useful features, in [52], the authors propose a Genetic Algorithm (GA) enabled feature selector. Furthermore, a Deep Neural Network approach, which does not require complicated feature engineering, is presented in [54].

An extra benefit of modeling device activity patterns is increasing the chances of identifying behavioral variations. Such benefit directly contributes to the detection of compromised devices or network attacks, which will be discussed in section IV.

Deriving devices' benign flow characteristics is nontrivial, therefore, the IETF standard Manufacturer Usage Description (MUD) profile [55] is proposed as an initial static profile to describe IoT device network behavior and support the making of security policies. A collection of MUD profiles from 30 commercial devices in [56]. The MUD profiles can be used to either verify device types or detect devices under attack or being compromised [57]. However, one issue of using the static profiles is that longer observation time is needed to make decisions.

Device identifiers based on network flow and activity patterns may encounter emerging issues. First, IoT devices are becoming smart devices where new extensions can be installed, and firmware upgrades can happen periodically, thereby changing activity patterns or network flow statistics, as suggested in [58], [59] and [46]. Second, device types do not necessarily correlate to their identities. Therefore, behavior-independent specific device identification is of great significance.

B. Feature-based statistical learning for specific device identification

IoT device identification can be formalized as a classification problem. In this section, we first introduce the generic pipeline for signal reception and then focus on feature-based statistical learning approaches for specific device identification from raw signals and their open issues.

1) *Generic wireless signal reception pipeline for device identification:* Software-Defined Radios (SDR) are multipurpose front-ends to deal with various modulation and baseband encoding schemes in wireless device identification. Fundamental technologies in SDR are quadrature modulation and demodulation [60].

Generally, wireless signals of IoT devices can be represented as: $S(t) = \mathbf{I}(t) \cdot \cos[2\pi(f_c + f')t] + \mathbf{Q}(t) \cdot \sin[2\pi(f_c + f')t]$, where $\mathbf{I}(t)$ and $\mathbf{Q}(t)$ are denoted as in-phase and quadrature components, respectively. The key idea is use $\mathbf{I}(t)$ and $\mathbf{Q}(t)$ to represent different modulation schemes.

A brief quadrature demodulation pipeline is given in Figure 7. We denote the reconstructed version of $\mathbf{I}(t)$ and $\mathbf{Q}(t)$ as $\hat{\mathbf{I}}(t)$ and $\hat{\mathbf{Q}}(t)$, respectively. We can derive the signals instantaneous amplitude, phase, and frequency by $\hat{m}(t) = \sqrt{\hat{I}^2(t) + \hat{Q}^2(t)}$, $\hat{\phi}(t) = \tan^{-1}(\hat{Q}(t)/\hat{I}(t))$ and $\hat{f}(t) = \partial\hat{\phi}(t)/\partial t$. Manufacturing imperfections and channel

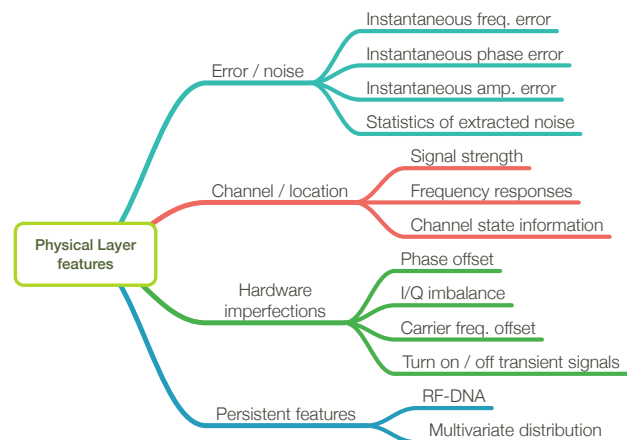


Fig. 8. Physical Layer device-specific features.

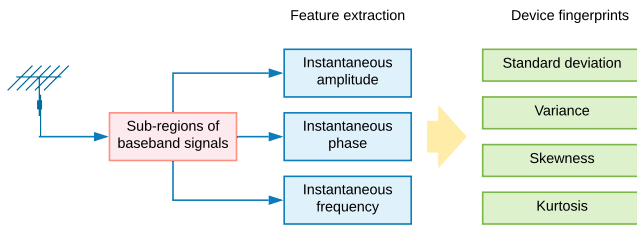


Fig. 9. A brief dataflow of RF-DNA.

characteristics can cause $\hat{m}(t)$, $\hat{\phi}(t)$ and $\hat{f}(t)$ to deviate from its original form, providing side channels to identify wireless devices. A brief overview of features for IoT device identity verification using wireless signals in Physical Layer is given in Figure 8. The features for wireless device identification are also named Radiometric Fingerprints.

2) *Hardware imperfections*: Heterogeneous imperfections exist in IoT devices' wireless frontends. These imperfections do not necessarily degrade the communication performance but influence signal waveforms, thereby providing a side channel to identify different devices. Such features enclosed in transmitted signals are named Physical Unclonable Features (PUF) [61], [62] since regular users can not clone or forge the characteristics of these manufacturing imperfections.

a) *Error / noise patterns*: The errors between expected rational signals and actual received signals can disclose useful device-specific information. In [63] and [64], the authors use phase errors of Phase Lock Loop (PLL) in transmitters as a distinctive feature. Their simulations indicate promising results even with low SNR (Signal-to-Noise Ratio). In [65], the authors use the instantaneous differences between received I/Q signals and theoretically expected templates to construct error vectors. They then combine error vectors' statistics and time-frequency domain statistics to synthesize the fingerprints of RF transmitters.

In [66]–[68], the authors use the differential constellation trace figure (DCTF), carrier frequency offset, phase offset, and I/Q offset to identify different Zigbee devices. They develop a low-overhead classifier, which learns how to adjust feature weights under different SNRs. The behaviors of their classifiers are similar to k-NN algorithms. Authors in [69] use odd harmonics of center frequencies as fingerprints for RFID transmitters. Their classification (k-NN) test on 300 RFID cards shows zero error.

b) *Persistent patterns*: Persistent pattern recognition assumes that the statistics of consecutive sub-regions in received signals can disclose identity-related information. A typical method is named as RF-DNA (Distinctive Native Attributive [70], [71]. The basic idea is to use the statistical metrics of signals' consecutive subregions to form device fingerprints. A brief dataflow of RF-DNA is given in Figure 9. In [72]–[74], the authors capture the preamble of WPAN (Wireless Personal Area Network) signals and extract the variance, skewness, and kurtosis of signals' subregions (bins) as signatures. Research in [75] also shows that the idea of RF-DNA can be applied in the Fourier transform of messages' signals.

From the perspective of the Random Process, a sequence of signal symbols can be regarded as a sample from some multivariate distributions. The parameters of such distribution represent the unique fingerprints of devices' wireless transmitters. With this idea, authors in [76] use the Central Limit Theorem and proposed a repetitive stacking symbol-based algorithm. They model preamble of each packet as a sample from a specific multivariate distribution. They extract statistics from preambles of ZigBee devices and employ Mahalanobis Distance and nearest neighbor algorithm to identify 50 ZigBee devices.

Regional statistic vectors from complete messages can unintentionally embed protocol-dependent features and result in unreliable device identification models. Therefore, if we only extract persistent features from the protocol-agnostic part of signals (e.g., preambles), the resulting device identification model will only focus on signal features rather than communication protocols.

c) *Transient patterns*: Compared with persistent statistics of signals' subregions, transient patterns are more difficult to forge in terms of wireless channels [77]. An example of transient periods in wireless communication is given in Figure 10. Transient periods are commonly seen at the beginning and end of wireless packet transmission. In [78], the authors employ the nonlinear in-band distortion and spectral regrowth of the received signals (potentially caused by power amplifiers of transmitters) to distinguish the masquerading device. In [79], the authors derive the energy spectrum from transmitters' turn-on transient amplitude envelopes to classify eight different devices. Their experiment shows that frequency-domain features are more reliable than time-domain features. In [80] and [81], the time-domain statistical metrics and wavelet features of transmitters' turn-on transient signals are transformed into devices' RF fingerprints. Finally, it is notable that the authors in [82] capture the turn-on transient signal of Bluetooth devices and extract 13 time-frequency domain features (via Hilbert-Huang spectrum) to construct devices' fingerprints. Their experiments show that well-designed fingerprints provide promising results even without using complicated machine learning models.

The merit of transient features is that an adversary could not forge such nonlinear features unless they can accurately forge the coupled characteristics of pair-wise wireless channels and RF front-ends between victims and surveillance agents. In other words, the transient features can be influenced by the locations of devices, as different locations can result in variation of RF channel characteristics, e.g., transient responses,

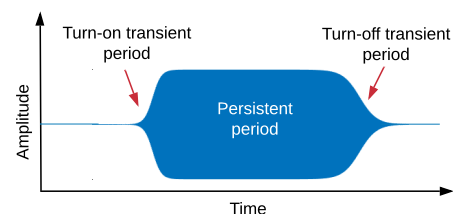


Fig. 10. Transient periods during wireless communication.

machine learning algorithms can produce accurate but unreliable device identification results by exploiting RF channel characteristics rather than learning device-specific features.

3) *Channel state features*: From the perspective of signal propagation, the nonlinear characteristics of radio channels can cause recognizable distortions to received signals. Those distortions can become unique profiles of transmitters. Therefore, the channel state recognition approach's basic idea is to: a) mathematically or statistically describe the nonlinear characteristics of the propagation channel within receivers and transmitters. b) Estimate whether a wireless device's signals' distortions comply with specific channel characteristics. Typical work is presented in [89], the authors use a kernel regression method to model the nonlinear pattern of signals' propagation channels. Their basic idea is that the combination of frequency offsets and special channel characteristics may not be forged easily, and therefore, can be used as a profile for wireless devices.

Channel state features are commonly seen in Orthogonal Frequency-Division-Multiplexing OFDM modulated communication systems. In the OFDM and MIMO schemes of wireless communication, the channel state information (CSI) [90], [91] can provide rich information on the time-varying characteristics of radio channels. IEEE 802.11 receivers estimate CSI during the reception of each packet's preamble. For each packet, its CSI is expressed as a complex-valued T_n by R_m by K matrix \mathbf{H} along with a noise component $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \mathbf{S})$, where T_n denotes the number of transmitter's antennas, R_n denotes the number of receivers' antennas, K denotes the number of sub-carriers and n denotes the complex-valued Gaussian random variable with mean zero and covariance matrix \mathbf{S} . Each complex-valued element in \mathbf{H} provides instantaneous phase and amplitude response of antenna-wise channels at specific subcarriers.

Channel state information directly reveals the phase, frequency, and amplitude responses of radio channels and has been utilized to identify fixed-position wireless transmitters. Specifically, CSI is affected by propagation obstacles, signal reflections, and even baseband data patterns [91]. In [92], a CSI based device identification scheme is proposed. The authors use averaged CSI to construct an SVM based profile for each legitimate device to prevent and identify spoofing attacks. They compare CSI and RSS based approaches and demonstrate the superiority of CSI. Another merit of their solution is utilizing the two-cluster k-means algorithm to detect the presence of rogue IoT transmitters when constructing legitimate devices' profiles. Similar research is presented in [93], legitimate devices' CSI from multiple locations are collected to train a more robust device identification model. Comparably, in [94], the authors use the information from CSI to model the radiometric signatures of obstacles within the signals' propagation path. They provide an iterative differentiation approach to derive the weights and factor out the multipath components in received signals. The weights of reflection signals can be used as a location-based signature of transmitters.

Except for wireless channel characteristics, CSI can disclose RF transmitter-specific information for persistent feature-based

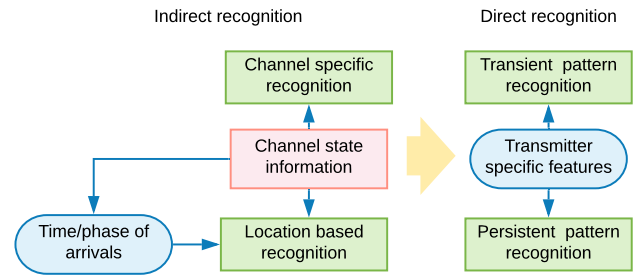


Fig. 11. A brief overview of channel state recognition and related approaches.

device identification. Related researches are as follows:

- *Carrier Frequency Offsets (CFOs)*: In [95], the authors propose to derive Carrier Frequency Offsets (CFOs) from CSI as devices' fingerprints. Their primitive hypothesis is that the constant CFOs can cause a linearly varying trend in instantaneous phases in received signals. Specifically, the authors first use phase measurements on specifically selected subcarriers to eliminate phase shifts at the receiver of the device identification oracle. They then use the differentiated phases from adjacent packets to eliminate the phase shifts introduced by the relative positions of transmitters. Finally, they derive the carriers' frequency offsets by the slope (relative to the time intervals of adjacent packets) of the purified instantaneous phase.
- *Phase errors*: Authors in [96] use summation of selected subcarriers' instant phases to extract the rationale arrival phases of subcarriers. They then estimate and subtract the rationale arrival phases and receivers' insertion phase lag to derive the phase error caused by transmitters' internal imperfections. A drawback of their approach is they need to estimate the Time of Flight (ToF) of received packets.

A summary of device identification based on channel state features is in Figure 11. The drawbacks of channel state features are apparent. For one thing, researches show that channel state features can even be influenced by the motions of obstacles in subcarriers' propagation path [97]–[99]. On the other hand, the channel characteristics are environment-oriented. Therefore, using channel state features based device identifier in indoor or mobile environments with human activities is still challenging [100], [101].

It should be noted that a great majority of CSI enabled researches depend on limited categories of Network Interface Cards (NICs) for data collection, owing to the limitation of CSI Tools [90]. However, the authors in [102] provide a new way. They use generic SDR transceivers to extract the Long Training Sequences (LTS) in the preambles of IEEE 802.11n pilot carriers to identify more than 50 Network Interface Cards. They show that by exploiting the frequency offsets and comparing LTS frequency responses of adjacent pilot carriers, they can even derive a location-agnostic device identification model.

4) *Cross domain features*: Many researchers convert signals to other domains that are more distinguishable. A straight-

TABLE III
INFLUENTIAL FACTORS FOR FEATURE-BASED SPECIFIC DEVICE IDENTIFICATION

Influential factors ¹	Persistent feature recognition	Transient feature recognition	Channel status recognition	Cross-domain recognition	Hybrid approaches	Countermeasures	Reference
Stationary noise	Median (Exc. noise pattern)	Median	Low	Median	Low	<ul style="list-style-type: none"> • Denoise filtering. • Data argumentation 	[76], [83]
Rx imperfections	Median	Median	Median	Median	Median	<ul style="list-style-type: none"> • Adaptive filtering. • Calibrations 	[84], [85]
Co-channel devices	High	High	Low	High	High	<ul style="list-style-type: none"> • MIMO receivers. • Blind signal separation 	[86], [87]
Channel features	Median	Median	High	Low	Low	<ul style="list-style-type: none"> • Adaptive filtering 	[84]
Baseband patterns	Median (Exc. noise pattern)	Low	Median	Low	Low	<ul style="list-style-type: none"> • Message-independent features 	[88]

¹ High: solutions include hardware modifications; Median: solutions are software-based but require high capacity processors; Low: Software-based optimal solutions are available and compatible with regular processors;

forward way is to remap signals into the time-frequency domain [103]. In [104], the authors use the STFT (Short-Time Fourier Transform) with the SVM algorithm to identify four different transceivers. This research is comparable to [105], where Discrete Gabor Transform (Gaussian windowed STFT) is employed.

Other domains can also be utilized as long as they can model devices' signal patterns. In [106], [107], the authors utilize the wavelet transform as well as classifiers (SVM and Probabilistic Neural Network) to construct a device identifier, compared with [104], they further use the PCA algorithm to reduce the redundancy of the extracted data. In [108], the authors provide a normal frequency-based method along with PCA and SVM to distinguish devices in the GSM band. They compare their methods with Hibert-Huang Transform based method in [109]. Similar work presented in [110], shows that Variation Mode Decomposition theoretically provides even better performance than the conventional EMD method even for relaying scenarios.

It is notable that Bispectrum is also widely utilized. In [111], the energy entropy and color moments of the Bispectrum combined with Support Vector Machine (SVM) are employed to simulate the possibility of device identification. Their results indicate that higher-order statistics can theoretically improve the performance of identification under low SNR. However, other authors [112] claim that compared to Bispectrum, the squared integral bispectra (SIB) is more robust to noise while providing the same amount of information as the Bispectrum. In [113], the authors employed singular values of the Axial Integrated Wigner bispectrum (AIWB) feature to identify spoofing signals from genuine signals in navigation satellite systems (GNSS).

5) *Hybrid methods*: A large number of device-specific features have been discovered along with different signal transform techniques. Hybrid methods aim to find the optimized combinations of features from different domains to derive robust identification models. In [114], the authors extract the signals' energy distribution from wavelet coefficients, and marginal spectrum [115] and use k-NN and SVM to identify eight devices. Their tests show that this k-NN requires higher SNR than SVM. In [116], the authors apply Intrinsic

Time-Scale Decomposition (ITD) [117] to input signals. They extract factual, bispectrum, and energy features to all subchannels of ITD decomposition sub-signals, their test on SVM shows that more features can significantly improve device identifiers' performance.

Although integrating signals' features from multiple domains can provide promising device identification results, the redundant information within the integrated features requires complicated models and considerable processing capacity. Therefore, automatic feature selection is introduced and becomes an indispensable part. Research in [72] demonstrates that properly selected features, particularly from the F-test and MLF methods, enable a significant (80%) reduction of redundancy. In [118], the authors capture the pilot tones of the OFDM signals and extract a series of features relative to the rational signal. They use an information-theoretic approach to select useful features for device identification. In [119], four types of features, scramble seed similarity, carrier frequency offset, sampling clock offset, and transient pattern, are suggested for the physical layer fingerprints of WiFi devices. The authors also claim that by combining all these features, their device identification accuracy reaches 95%.

A comparison of device-specific feature-based approaches in Table III, hybrid approaches have superior performance under various influential factors, since the automatic feature selection methods can remove irrelevant information and pro-

TABLE IV
A BRIEF COMPARE OF CLASSIFIERS IN DEPLOYABLE WIRELESS TRANSMITTER IDENTIFICATION SYSTEMS

Approach	Application overhead	Continual learning	Abnormality detection
k-NN	Depends on the size of fingerprint library.	Natively supported	Clustering or statistical models
SVM	Depends on the number of feature dimensions	Knowledge replay	One-class SVM
Random forest	Depends on the number of decision trees.	Knowledge replay	Isolation forest
Neural network	Depends on structural complexity	Section III-C2d	Section III-C2c

vide an optimal combination of features. However, hybrid features could bring side effects, especially in statistical learning algorithms: a) The complicated combination of a large number of features can result in a highly accurate identifier with its internal mechanism not interpretable. b) High dimension features can potentially result in complicated models that are computationally difficult to retrain for operational variations. We can make better use of hybrid features in Deep Neural Networks, which will be discussed in Section III-C.

6) *Open issues*: In general, the following issues need to be investigated in feature-based statistical learning for specific device identification:

- 1) These methods require efforts to manually extract features or high-order statistics, the quality of handcraft features dominates device identification performances. E.g., authors in [124] show that the combination of permutation entropy [125] and K-NN even surpasses combination of bispectrum [126] and SVM in [111].
- 2) Experiments are conducted in rational environments with a limited number (less than 30) of IoT devices. Therefore, publicly available datasets containing signals from a larger number of IoT devices are needed to provide a reliable benchmark. Currently, publicly available datasets for IoT device identification from wireless signals are still limited. Some small datasets are provided in [127], [128] and [129] while a larger dataset but with only ADS-B signals is in [130].
- 3) There's no guarantee whether a specific type of feature is time-invariant. Therefore, this type of system should incorporate wireless channel estimation approaches to identify real device-specific patterns.
- 4) A brief comparison of the device-specific feature-based wireless device identification with influential factor is given in Table III, co-channel devices have the most significant impacts among all solutions. Unfortunately, there's limited research in dealing with it.
- 5) A deployable wireless device identification system should have the capacity to report unknown abnormalities and continually evolve and adapt to operational variations. A comparison of frequently employed statistical learning algorithms on continual learning and abnormality detection is in Table IV. Among these algorithms, only k-NN provides intuitive and native supports for continual learning and abnormality detection. However, k-NN is insufficient in handling complicated features. Though SVM or Random Forest could handle more complicated features, they lack the continual learning and abnormality detection abilities and explainability.

C. Deep Learning enabled specific device identification

The feature-based statistical learning approaches require manual selection of useful transforms or features. In contrast, deep neural networks (DNN) can incorporate existing features or directly deal with raw inputs and derive latent distinctive features. Therefore, Deep Learning enabled device identification mechanisms are increasingly investigated. A brief comparison of device-specific feature-based statistical learning

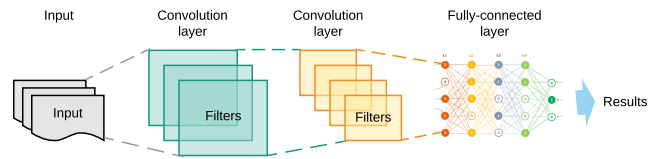


Fig. 12. Typical architecture of deep neural network classifiers

and deep learning based approaches are presented in Table VII. In this section, we discuss typical deep learning enabled wireless device identification solutions and then focus on open issues that impede the application of deep learning in IoT device identification.

1) *Case studies and comparisons*: A typical Deep Neural Network enabled classifier is depicted in Figure 12. Generally, It employs convolutional layers to extract latent features and uses fully connected dense layers to produce final results. Deep Neural Networks with convolutional layers are also referred as Convolutional Neural Networks (CNN).

Deep neural networks can be seamlessly integrated with existing feature engineering methods. In [122], the authors use the differential error between re-constructed rational signals and received signals to train Deep Neural Networks to distinguish Zigbee transceivers. In [131], the authors compare the effects of short-time Fourier features and wavelet features for device identification, and their results show that wavelet features can outperform Fourier features. In [121], the authors extract the 1-D Regions of Interest (ROIs) from 54 Zigbee devices' preambles under different SNRs and then resample signals within ROIs into various substreams with different sample rates. Finally, the substreams are fed into a convolutional neural network for identification. Similar ideas are proposed in [120], [132] and [133].

Compared with the conventional fully-connected neural network, convolutional layers apply filters (a.k.a. kernels) with much fewer parameters to obtain distinctive information. In [83], the authors propose a combined solution to denoise signals and identify devices simultaneously using an autoencoder and a CNN network. The authors use their encoder to automatically extract relevant features from the received signals and use the derived features to train another deep neural network for device identification. Similar methods are presented in [134]. In [123], the authors provide an optimized Deep Convolutional Neural Network approach to classify wireless devices in 2.4 GHz channels and compare the performance with SVM and Logistic Regression. Their results show that, even by using raw I/Q digital baseband signals, CNN can achieve high accuracy and surpass the best performance of SVM and Logistic Regression. In [127], neural networks were trained on raw IQ samples using the open dataset¹ from CortexLab. Their results also show that CNN can achieve promising results even on raw I/Q signals, but the movement of devices and the varying amplitudes will degrade CNN's performance.

An extensively discussed topic for Deep Learning based de-

¹<https://wiki.cortexlab.fr/doku.php?id=tx-id>

vice identification is preventing the network from learning only trivial features, such as protocol identifiers, unique identifiers, etc. Generally, three types of countermeasures are applied, and their comparisons are provided as in Table V.

Compared with feature-based device identification approaches, Deep Learning methods usually require a much larger dataset to initialize the network. To know how large the training data is needed. In [135], CNN models are used to classify different devices' signals with controlled difficulty levels. The classification accuracy of a fixed CNN network with different dataset sizes is predicted using a power-law model and the Levenberg-Marquardt algorithm. Their results show that the dataset size should be at least 10,000 to 30,000 times the number of devices to be identified. However, this conclusion is only a rough estimation.

New architectures in Deep Learning are emerging and can significantly influence the performance of device identification systems. In [120], the authors use Convolutional Deep Complex-valued Neural Network (CDCN) and Recurrent Deep Complex-valued Neural Network [136] to address the device identification problem. Their networks utilize fragments of raw I/Q symbols as input, and their test is conducted on both WiFi and ADS-B datasets. Their experiments show that the Complex-valued neural networks surpass regular real-valued deep neural networks. In [137], [138], a zero-bias dense layer is proposed. The authors show that their solution enables deep neural networks' final decision stage to be interpretable. Their solution maintains equivalent identification accuracy and outperforms regular DNN and one-class SVM in detecting unknown devices.

2) *Open issues in Deep Learning for IoT device identification*: Deep Learning is becoming a promising technology in this domain. However, as in other domains, Deep Learning encounters several challenges. Although researches in IoT device identification rarely cover the issues, we briefly discuss their current states and solutions.

a) *Hyperparameter searching*: One critical problem for using deep neural networks is hyperparameter tuning. Hyperparameters such as learning rate, mini-batch size, dropout rate, etc. are used to initialize the training process. Hyperparameters can significantly impact the performance of deep neural networks. For instance, in [146], the authors compare the performance of Deep Neural Networks, Convolutional Neural

Network, and the LSTM (Long Short Term Memory) in device identification using the raw I/Q signals directly. Their results show that CNN has the best performance, followed by DNN and LSTM. They point out that the hyper-parameters of Deep Learning, especially for network architectural parameters, significantly influence the upper bound of performance.

Obtaining optimized hyperparameters is computationally expensive. Several strategies are proposed for efficient hyperparameter searching, such as grid search, random search, prediction-based approaches, and evolutionary algorithms. Their characteristics are as follows:

- **Grid search**: Grid search divides the whole parameter space into identical intervals and performs brute-force trials to find optimal parameter combinations. However, this strategy is inefficient since useless combinations of parameters can not be pruned rapidly.
- **Random search**: In random search, sample points are distributed uniformly in search space. This strategy increases the variation and outperforms the grid search when only a small number of parameters can impact the network performance.
- **Prediction-based**: In prediction-based approaches, the algorithms first perform random trials at the beginning to model the relation between the network performances with hyperparameters. Then the algorithms perform new trials based on parameters that are more probable to yield better results. Such trial-model-predict paradigm is conducted repeatedly [147]. A typical prediction strategy is the Bayesian optimization process [148], in which the algorithms model the target outcome space as Gaussian processes.
- **Evolution based**: In evolutionary algorithm based approaches, the heuristic searches are performed as in other nonlinear optimization problems. In [149], the authors utilize the Genetic Algorithm to find the optimal hyperparameters of a neural network. Compared with prediction-based approaches, evolutionary algorithms provide the best-guess with bio-inspired strategies. However, there is no guarantee for the performances of evolutionary algorithms.

b) *Neural network Architecture search*: Network Architecture Search (NAS) is another challenging task in designing neural networks. Network architecture defines the flow of

TABLE V
COUNTERMEASURES TO PREVENT LEARNING FROM TRIVIAL FEATURES

Reference	Methodology	Description	Challenges
[120]	Fragmenting	The raw I/Q signals are split into small signal fragments whose duration is shorter than the duration of trivial parts or just use the preambles of packets..	Long range dependent features will be destroyed after fragmenting
[121]	Masking	One can directly mask or remove the trivial parts in raw signals.	The position and length of the masking bits or discontinuity can leak protocol information
[122], [123]	Randomization	One can let transmitters send random contents	One has to gain the access of large number of transmitters to train a reliable classifier.

tensors and could significantly affect the complexity and performance of neural networks [150], [151]. At the current stage, most network architectures are specified manually or with trial-and-error.

Architecture searching algorithms are provided by several Automatic Machine Learning (AutoML) platforms. A brief comparison of their functionality and performance on different datasets is in [152]. A collection of recent literature and open-source tools are given in [153] and [154] respectively. These efforts can be classified into three categories: (i) network pruning [155], (ii) progressively growing [156], and (iii) heuristic network architecture search [157]. Their features are as follows:

- **Network pruning:** Network pruning algorithms use group sparsity regularizers [158] to remove unimportant connections from a regularly trained network. Then the pruned network will be retrained to fine-tune the weights of the remaining connections [159], [160]. A key benefit of network pruning is that it can greatly compress neural networks and make them suitable to deploy in low capacity IoT devices.
- **Progressively growing:** This strategy grows a neural network architecture during training. It is effective in simple networks with only one hidden layer [161], [162]. More recent advances employ growing strategies to progressively add nodes and layers to increase the network's approximation ability [163], [164].
- **Heuristic network search:** In heuristic network search, the architecture of the Deep Neural Network (can either be block-wise [165] or element-wise [166]) can first be represented in a high dimension space with billions of parameters. Next, heuristic searching algorithms are applied to transverse this search space to find optimal solutions. Examples are given in [157], [167] and [168]. The authors make use of the Genetic Algorithm to find the possible structure of neural networks. Notably, the Genetic Algorithm fits perfectly in NAS problems since it allows using length-varying variables (genes) to encode the candidate solutions. An empirical example is the NeuroEvolution of Augmenting Topologies (NEAT) algorithm [167].

- **Reinforcement Learning:** Reinforcement learning (RL) has become a popular strategy in NAS [169]–[171]. Its basic idea is to let a deep learning-enabled agent explore network architectures' representative space and use validation accuracy or other metrics as rewards to adjust the agents' solutions. Ideally, as an RL process moves on, an agent can find an optimal searching strategy and discover a novel architecture. Intuitively, evolution algorithms use a fixed strategy to discover the optimal architecture while RL agents learn their own strategies and have better capabilities in avoiding bad solutions.
- **Differentiable space search:** Aforementioned, NAS strategies use discrete space to encode the architecture of neural networks, which is not differentiable and lacks efficiency. Therefore, differentiable spaces to represent the Neural Networks' architectures are proposed, in which efficient off-the-shelf optimization algorithms can be used. Typical solutions are given in [172], [173]. The algorithm, DART (Differentiable Architecture search), is presented. The authors use the Softmax function to represent discrete selections in a numerically continuous domain. They then use a gradient descent algorithm to explore the search space. Similar work with an enhanced stochastic adaptive searching strategy is presented in [174]. Block-wise representations of the neural network and differentiable searching space together are bringing NAS to practice.

Network architecture search has become an emerging topic for deep neural network research with publicly available benchmarking tools in [175] and [176], respectively.

c) Openset recognition: A critical problem for learning based device identification is that classifiers only recognize pretrained devices' signals but can not deal with novel ones that are not in the training dataset. In [145], the authors address it as a semi-supervised learning problem. They first train a CNN model with the last layer as a Softmax output on a collection of known devices. They then remove the Softmax function and turn the neural network into a nonlinear feature extractor. Finally, they use the DBSCAN algorithm to perform cluster analysis on the remapped features of raw I/Q signals. Their results show that such a semi-supervised learning method

TABLE VI
METHODS FOR UNKNOWN DEVICE RECOGNITION

Methods	Description	Complexity	Memory	Pros & Cons	Reference
GAN	Use the discriminator from GAN model as an outlier detector.	High ¹	Depends on final network	<ul style="list-style-type: none"> • Can catch deep latent features. • Hard to design and train. 	[132], [139]
Autoencoder	Train a deep Autoencoder on known signals and use its reconstruction error to judge outliers.	High ¹	Depends on final network	<ul style="list-style-type: none"> • Can catch deep latent features. • Easier than GAN to design and train 	[140], [141]
Statistic metrics	Measure the confidence of whether a signal or its fingerprint is generated by a given category.	Low	Low	<ul style="list-style-type: none"> • Provide explainable results. • Accuracy depends on the fingerprinting methods. 	[138], [142]–[144]
Clustering	Perform clustering analysis on known signals' fingerprints to judge whether it is in identical cluster as known ones.	Median ²	Depends on the number of existing fingerprints.	<ul style="list-style-type: none"> • Provide explainable results • Accuracy depends on the fingerprinting methods. 	[142], [145]

¹ Needs to specify both network architecture and hyperparameters.

² Needs to specify the clustering algorithms to use.

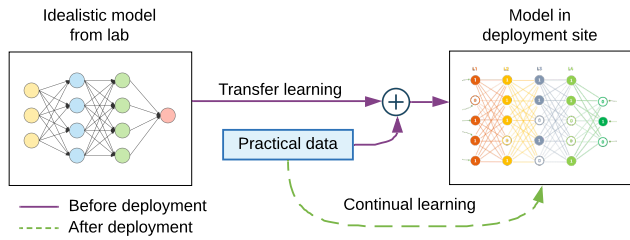


Fig. 13. Transfer learning and continual learning.

has the potential of detecting a limited number of untrained devices. Comparably, in [177], the authors use an incremental learning approach to train neural networks to classify newly registered devices.

From the perspective of Artificial Intelligence, this issue is categorized to the Open Set Recognition [178], [179] and the Abnormality Detection problem. The taxonomy of existing approaches is given in table VI. In [132], the authors use the Generative Adversarial Network (GAN) to generate highly realistic fake signals. Then they exploit the discriminator network to distinguish whether an input is from an abnormal source. In [142], the authors provide two methods to deal with unknown devices: i) Reuse trained convolutional layers to transform signals to feature vectors, and then use Mahalanobis distance to judge the outliers. ii) Reuse pretrained convolutional layers to transform signals to feature vectors, and then perform k-means ($k = 2$) clustering to group outliers.

d) Continual learning: In practical scenarios, deep neural networks would have to evolve to adapt to operational variations continuously. Intuitively, a deep learning enabled IoT device identifier has to learn new devices' characteristics during its life cycle. Therefore, such functionalities are defined as lifelong learning. Generally, there are two ways to achieve this goal: Transfer Learning (TL) and Continual Learning (CL). In Transfer Learning, neural networks are pre-trained in the lab and then fine-tuned for deployment using practical data [181]. In continual learning, neural networks are trained incrementally as new data come in progressively [182]. Continual learning does not allow neural networks to forget what they have learned in the early stages compared with transfer learning. The phenomenon in which a neural network forgets what it has previously learned after training on new data is named Catastrophic Forgetting. Therefore, transfer learning is useful when deploying new signal identification systems, and continual learning is useful in regular software updates and maintenance, as depicted in Figure 13. The strategies to implement continual learning for deep neural networks are as follows:

- **Knowledge replay:** An intuitive solution for continual learning is to replay data from old tasks while training neural networks for new tasks. However, such a solution requires longer training time and larger memory consumption. Besides, one can not judge how many old samples are enough to catch sufficient variations. Therefore, some studies employ data generator networks to replay data from old tasks. For instance, in [183],

Generative Adversarial Network (GAN) based scholar networks are proposed to generate old samples and mixed with the current task. In this way, the deep neural network could be trained on various data without using huge memories to retain old training data.

- **Regularization:** Initially, regularization is employed to prevent models from overfitting by penalizing the magnitude of parameters [184]. In continual learning, regularization is employed to prevent model parameters from changing dramatically. In this way, the knowledge (represented by weights) learned from the old tasks will be less likely to vanish when an old network is trained on new tasks. There are two types of regularization strategies: global regularization and local regularization. Global regularization penalizes the whole network's parameters from rapid change but impedes the network from learning new tasks. In local regularization strategies, such as Elastic Weight Consolidation (EWC) [185], the algorithms identify important connections and protect them from changing dramatically, in which non-critical connections are used to learn new tasks.
- **Dynamic network expansion:** Network expansion strategies lock the weights of existing connections and supplement additional structures for new tasks. For instance, the Dynamic Expanding Network (DEN) [186] algorithm first trains an existing network on a new dataset with regularization. The algorithm compares the weights of each neuron to identify task-relevant units. Finally, critical neurons are duplicated and to allow network capacity expansion adaptively.

Continual learning algorithms, as well as abnormality detection, together provide great potential for deploying the neural networks in complex, uncertain scenarios.

e) Summary: A brief comparison of Deep Learning and other statistical learning methods is given in Table IV. Compared with statistical learning, Deep Learning is not yet an idealistic solution. However, its unified development pipeline, and the capability of dealing with high dimension features are making it easy to use. Furthermore, for practical issues such as continual learning and abnormality detection, deep learning provides better performances than the majority of statistical learning algorithms. In one word, although deep learning is not theoretically novel, it gains its place by providing the most balanced merits.

D. Unsupervised device detection and identification

Feature-based statistical learning and deep learning are supervised learning schemes, where classifiers must learn the features of legitimate devices in advance. Unsupervised device detection and identification are required in scenarios where the identities of devices are not directly available [187]. Generally, the methods in this topic can be divided into two folds, device behavior modeling and signal propagation pattern modeling. *the essence of unsupervised device detection is to map devices' signals or activity profiles into latent representative spaces, where different devices are represented by separated clusters or probabilistic distributions.* If behavior or signal propagation

TABLE VII
BRIEF COMPARE OF IOT DEVICE IDENTIFICATION AND DETECTION METHODS

Device identification approaches	Technology branch	Feature requirement	Model explainability	Continuous learning	Anomaly detection	Challenges
Feature based device identification	Supervised learning	High ¹	Strong (k-NN) / median (SVM)	Easy (k-NN) / median (PCA-SVM)	Low (k-NN) / Median (k-Means)	Can not discover latent feature.
Deep learning enabled device identification	Supervised learning	Low	Weak ²	Hard (EWC) ³	High (Autoencoder) / Median (clustering)	Learning from trivial features
Unsupervised device detection and identification	Unsupervised learning	High ¹	Strong	N/A	Low	Can not be applied to complex environment

¹ Requires an extra feature engineering process.

² Please refer to Explainable AI (XAI) in [180]

³ Please refer to section III-C2d

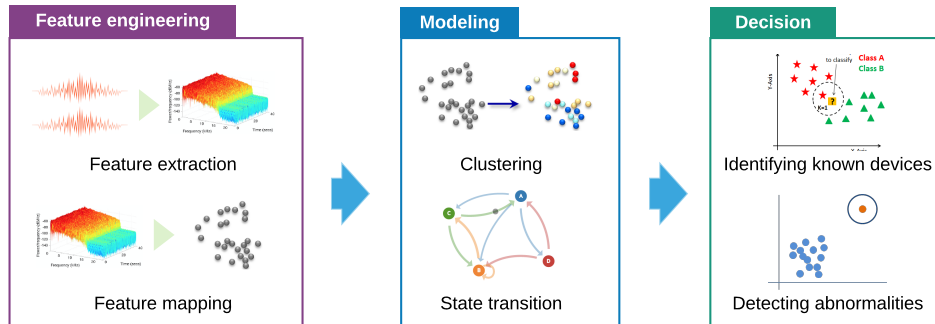


Fig. 14. Unsupervised device detection and identification

patterns are strictly correlated with specific devices, extracted behavior or signal features can be used to verify the identity of devices. Comparisons of supervised and unsupervised learning based device identification are (also in Table VII):

- The training data does not directly indicate device specific information (device identifier, device type, and etc.).
- The number of devices may not be known in advance.

As depicted in Figure 14, the work flow of unsupervised learning enabled device detection and identification is made up of three steps: a) Feature engineering on IoT devices' signals or behavior profiles, including feature selection and mapping. b) Modeling the latent spaces, this step finds out cluster centers, probabilistic distributions, related decision boundaries, or state transition models. c) Matching of input signal or behavior profiles to the most likely clusters or report abnormalities.

1) *Device behavior modeling:* Device behavior modeling extracts distinctive features from the input data and finds out the number of different devices using unsupervised learning algorithms. However, the physical layer does not provide much information for device behavior modeling. Therefore, the methods are more frequently employed in the upper layers with related techniques employed are unsupervised feature engineering, clustering, and Software-Defined Networking [44].

In [188] and [189], the data traffic attributes are obtained from flow-level network telemetry to recognize different IoT devices. The authors utilize Principle Component Analysis along with an adaptive one-class clustering algorithm to find the optimal representative components and cluster centers for each device. They provide a conflict resolution mechanism to

associate different types of devices to corresponding cluster centers in the representative spaces. A similar approach using Deep Learning is presented in [190]. The authors use TCP data traffics for each device to train an LSTM-enabled autoencoder to map inputs into a representative feature space. They then use a clustering algorithm to divide the training samples into their natural clusters. Finally, they use probabilistic modeling to associate new data with known clusters for device identification. Unfortunately, their experiments show that unsupervised behavior identification may not work once there are devices from an identical model.

2) *Signal propagation pattern modeling:* In the Physical Layer, signal propagation patterns provide information for device identification. On the one hand, if devices positions are unique and known in advance, we may directly use wireless localization algorithms to specify whether a received data packet is from its claimed identity. Corresponding surveys on wireless device localization are given in [195]–[197], and we provide a brief comparison of the widely employed methods in Table VIII.

On the other hand, signal propagation modeling derives the path loss or attenuation patterns of received signals to detect different devices using unsupervised learning algorithms [34]. In [198], the authors use the signals' propagation path effect, and they discover that the received signal strength from transmitters in the same location would have very similar varying trends. They convert signal strength metrics into time series and incorporate the Dynamic Time Warping algorithm to align and find differences between received signals. Finally, they apply a clustering algorithm to identify signals from active transmitters. In [199], the authors assume that the received

TABLE VIII
COMPARISON OF DEVICE LOCALIZATION METHODS IN IOT

Methods	Requirements	Unit cost ¹	Precision	Weakness	References
Signal propagation modeling	Multiple collaborative transmitters to construct signal strength map.	Low	Depends on environmental features and refresh rate of respondent data.	<ul style="list-style-type: none"> • Depends highly on signal propagation models of certain area. • Results do not directly indicate certain device types or identities. 	[191]
Coherent TDoA	At least 4 coherent receivers and 5 receivers are recommended to linearize computational process.	Median	Depends on the estimation of signals' Time of Arrival (ToA).	<ul style="list-style-type: none"> • Receivers needs to be strictly synchronized. 	[192]
Sync-free TDoA	At least 4 receivers and receivers are able to communicate mutually.	Median	Same as coherent TDoA	<ul style="list-style-type: none"> • Needs specific hardware with known response latency. 	[193], [194]

¹ Low: Does not require extra RF receivers; Median: Requiring commercially available RF receivers with unit cost less than \$1000; High: Requiring special hardware and specific processing stacks. ² Requiring multiple distributed receivers.

signals' Power Spectrum Density coefficients of each device, in a specific time window, form a mixture model dominated by a weighted sum of Gaussian distributions and propagation path related Relay distributions. In this way, they use the Expectation-Maximum algorithm to estimate the composition (different transmitters) of received signals.

Signal propagation pattern modeling only provides an indirect evaluation on whether specific signals come from devices in close locations or with similar propagation paths. Although related methods are not widely utilized in commercial IoT devices owing to their complicated deployment environments, the methods provide a useful solution in preventing identity spoofing attacks in ADS-B systems [200], [201].

3) *Open issues*: Unsupervised device identification provides a novel solution when the identities of devices are not directly available. In essence, the unsupervised device identification and detection are similar to automatic knowledge discovery with the following issues to be addressed:

- 1) **Feature engineering**: Unsupervised device identification relies on feature engineering since representative vectors of devices are supposed to form distinctive clusters. Feature selection is still conducted manually, and there is no guarantee on whether the outputs of the mapped feature can form distinctive clusters.
- 2) **Clustering**: Clustering in the latent space can be challenging if the number of devices is unknown. Although one may use adaptive algorithm such as DBSCAN [202], Optics [203] or X-Means [204], the proper configurations of these algorithms to adapt to the latent space are still difficult, similar obstacles are seen in setting hyperparameters in Deep Neural Networks (section III-C2a).
- 3) **Decision boundaries** Even if we know the number of devices, we can still get clusters with uncertain shapes or density, in which decision boundaries between different devices are difficult to define, as indicated in [188].
- 4) **Direct identity verification**: Researches on unsupervised device identification using behavior-independent and location-agnostic device specific features are still limited. Although unsupervised behavioral modeling has shown promising results in identifying different types of devices, whether these methods are still effective in distinguishing devices from the same model needs

further investigation.

Therefore, we believe learning-based unsupervised device detection is promising with great novelty, but the topic needs substantial investigation.

IV. LEARNING-ENABLED ABNORMAL DEVICE DETECTION

Previous sections discussed methods to identify specific IoT devices. Except for device identity verification, detection of compromised devices with abnormal behaviors is needed to alert ongoing attacks and discover system vulnerabilities.

In general, abnormal device detection algorithms are deployed in network and application layers. The detection algorithms first collect a certain amount of normal operation data from devices to create reference models (or signatures). Then IoT devices' operational data are collected and compared with reference models to judge whether significant deviations appear. Compared with device-specific identification schemes, the key idea is abnormality detection with both unsupervised learning approaches [205] and supervised learning with confidence thresholds [206].

A. Statistical Modeling

Statistical modeling aims to judge whether devices are in abnormal situations. In [207], Markov models are utilized to judge whether IEEE 802.11 devices are compromised by calculating the probabilities of its sequential transitions of the protocol state machines. In [208], the authors model the Electronic Magnetic (EM) harmonics peaks of medical IoT devices as probabilistic distributions to assess whether a specific device is under attack. They assume that when devices are operated under an abnormal scenario (with rogue shellcodes executing), its EM radiometric signals can deviate from known scenarios. However, statistical modeling requires manual selection of potentially informative features and define their importance.

To reduce the cost of modeling IoT devices' normal behavior, Manufacturer Usage Description (MUD) profile [55] is proposed. A collection of MUD profiles for 30 commercial devices is provided in [56]. The MUD profiles enable operators to know devices' network flow patterns and dynamically monitor their behavioral changes. Several open-source tools

are provided to dynamically generate, validate, and compare IoT devices' MUD profiles in [57]. Besides, the authors presented that by comparing the deviation of devices' runtime MUD profiles with static ones, we can identify their behavioral deviations or even identify device types. In [209], MUD profiles of devices are translated into flowtable rules and contribute to select appropriate features. The authors then use PCA to map each device's data traffic from side windows into its own representative one-class space, where X-Means [204] and Markov chains are used to partition the space and model the state transition in cluster centers. Finally, an exception is triggered by a specific detector on either the mapped traffic pattern is out of boundaries or the state transitions do not comply with the reference model. Their experiments show the accurate detection of several types of volumetric attacks.

B. Reconstruction Approaches

Reconstruction approaches aim to learn and reconstruct domain-specific patterns from devices' normal operation records. In other words, we need to develop a model to "memorize" the normal schemes of IoT devices by producing low reconstruction errors. Simultaneously, the model is supposed to produce high reconstruction errors for unknown scenarios or encounters behavioral deviations. This goal is generally achieved using deep autoencoders. Since an encoder removes a great amount of information, a decoder needs to reconstruct lost information according to domain-specific memories. Consequently, once abnormal inputs are given to a well-trained autoencoder, its decoder would not be able to reconstruct such unknown inputs and yields a high abnormal score (reconstruction error). In [210]–[212], the authors utilize autoencoder to detect abnormal activities by modeling the data traffic and content of IoT devices once abnormal activities are detected. In [213], the authors show that compared with other anomaly detection methods (one-class SVM [214], Isolation Forest [215] and Local Outlier Factor [216]), deep autoencoder yields the best result in terms of reliability and accuracy.

C. Prediction Approaches

Prediction approaches utilize temporal information in devices' operation records. Corresponding methods model each IoT device's operational data as multi-dimension time series. Then, device-specific prediction models are trained using time series from normal schemes. When devices are hijacked for rogue activities, they are not supposed to behave as predicted, causing the corresponding time series predictors to output high prediction errors.

In [217], the authors employ a CNN based predictor to analyze the abnormal behaviors in devices' network traffics. They show that predictors trained without abnormal data are sensitive (yield high prediction error) to anomalies. Similar work is shown in [218], and the authors use an autoregression model to capture the normal varying trend of devices' traffic volumes. However, modeling a single variable can not be sufficient in dealing with complicated scenarios. Recent studies combine deep Autoencoder with Long Short Term Memory (LSTM) to derive abstracted representations of complex scenarios and

make predictions. In [219] and [220], Deep Predictive Coding Neural Network [221] is used to predict consecutive frames of time-frequency video streams of wireless devices. They can even specify the type of attacks using the spatial distribution of error pixels in the reconstructed frames.

D. Open issue

Methods in this topic overlap with the methods of open set recognition in Deep Learning. We briefly list several open issues in this topic:

- **Selection of behavioral features:** Many researches use manual feature selection along with dimension reduction. A concern is that we can not guarantee the selected features are sensitive to unknown intrusions in the future.
- **Processing of abnormality metrics:** Generally, intrusion detection approaches provide metrics corresponding to the degree of deviation. However, the output error metrics require a posterior process, e.g., selecting appropriate decision thresholds or aggregation window length, which balances between the true positive, false negative, and response latency. One solution is to regard the corresponding parameters as hyperparameters and use cross-validation to tune them. The processing of error metrics remains a case-specific open issue.

V. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Our literature review has shown that device detection and identification provide another layer of security features to IoT. However, the existing solutions are still far from perfect. This section summarizes the existing challenges of IoT device identification and detection as well as future research directions.

A. Challenges in machine learning models

1) *Unknown device recognition:* Existing works focus on the accuracy they can obtain using a fixed dataset with all devices labeled, in which Black-Box models (e.g., Deep Learning and SVM) are commonly employed. In practical scenarios, these models can produce wrong answers when encountering novel devices. Additional mechanisms are needed to identify unknown signals. Although we can use the one-versus-rest technique to train a group of classifiers and avoid producing results on unknown devices. However, once we have new devices to register, all classifiers in the group are supposed to be retrained from scratch. Therefore, we need to provide a solution to verify the known devices. Meanwhile, we need to identify:

- Devices that are exactly not in the scope of the identification system.
- Unknown devices that are from identical manufacturers. Devices of the same model from an identical manufacturer can share similar behavior patterns, e.g., network flow characteristics. Such similarities can impede identity verification in the network, transportation, or application layers.

The latter is more challenging and requires extracting behavior-independent characteristics. We believe that without the capability of unknown device recognition, these types of systems are still far from practice.

2) *Continual learning on new devices*: Continual or incremental learning [182] in this domain emphasizes that an identification or detection model should be able to learn newly registered devices without retraining on a large dataset containing new and old devices. Because retaining the old dataset or deriving generators for knowledge replay is computationally expensive. This topic faces several challenges:

- Knowing the capacity or the maximum number of devices a model can memorize, especially for the Black-Box models, e.g., the Deep Neural Networks.
- Expanding models dynamically as new devices are being added. Continual learning is natively supported in Nearest Neighbor algorithms but is challenging to implement in Deep Neural Networks.

3) *Deployment of device identification models*: The deployment sites and model providers' lab can differ dramatically, in which identification accuracy can be impaired. This issue is more severe in device identification models using wireless signals due to the difference of wireless channel characteristics. For alleviation, extra works are needed:

- Deriving features that are independent of wireless channels or deployment sites. Researches in [222], [223] suggest that neural networks can only learn about channel-specific features rather than device-specific features.
- Occasional site fine-tunes are needed with the help of continual or transfer learning to adapt to variations.
- Model providers need to use data augmentation methods to simulate operational variations during lab training, as suggested in [224].
- Model providers can use multi-domain training to derive multi-purpose feature extractors, which will be utilized as building blocks for domain-specific device identification models. Diverse training from different domains could provide more robust feature extractors.

4) *Reliable benchmark datasets*: The IoT device identification is a pattern recognition problem on signals or behaviors. A common benchmark dataset is critical for comparing various methods in device identification and rogue device detection reliably. However, by the end of this survey, we only find a limited number of datasets providing devices' raw signals or network traffic traces in diverse scenarios. Some datasets are provided in [127], [128] and [129], respectively. For physical layer device identification, a larger dataset containing raw signals from more than 100 airborne transponders are provided in [130], but it only contains ADS-B protocol. Another dataset containing more than 30 IoT devices' traffic traces under volumetric attack and benign scenarios are in [56]. Such dataset are important because they provide fair comparisons between algorithms. Additionally, models trained on large datasets can be efficiently transferred to more specific applications [225], [226].

B. Challenges in feature engineering

1) *The robustness of features*: Although many existing works claim the effectiveness of their discovered features, only very few evaluate the features' robustness under various scenarios in terms of device mobility pattern, temperature, obstacles, etc. Feature robustness has a limited influence on device type identification in the network or higher layers. However, in the Physical Layer identification of wireless devices, the robustness of features would severely impair the final model. Currently, a popular way to enforce robust feature discovery is through data augmentation to simulate various scenarios. Besides, in neural networks, regularization and dropout methods can encourage models to make full use of input data and discover robust latent features, but their effectiveness needs further study.

2) *Making use of time-varying features*: Some device detection and identification models make use of protocol-agnostic and behavior-independent features from physical layer wireless signals. However, in mobile environments, devices' movements can result in time-varying channel conditions, in which device identification methods based on static channel characteristics can be impaired. On the other hand, varying patterns of channels, signal strength, etc. also encode valuable features, e.g., locations, distances, to describe IoT devices [227], [228]. Therefore, both discovering time-invariant features and making use of time-varying features are still an open issue in device identification and detection.

3) *Challenges from deep generative attackers*: The utilization of GAN brings challenges to device identification, especially in the Physical Layer. Using GAN models, an attacker can train highly realistic signal or data packet generators to mimic its victims' signal characteristics. Research in [229] shows that GAN can increase the success rate of spoofing attacks from less than 10% to approximately 80%. Fortunately, a simple remedy is to use MIMO receivers and wireless localization methods to estimate whether a transmitter is from a reasonable location. Additionally, controlled imperfections can be dynamically imprinted into the devices' signals or data flows, with a Pseudorandom Noise Code driven time-varying manner [223] which is cryptographically impossible to predict.

C. Future research trends

1) *Deep identification models with explainable behaviors and assured performances*: The conveniences of Deep Neural Network make it a versatile tool to implement IoT device identification and rogue device detection systems, but more efforts have to be made, especially for model explainability and performance assurability. On the one hand, we have limited knowledge of the decision process, especially on how a deep neural network makes its final decisions and corresponding decision boundaries. Without knowing the decision process and decision boundaries, there is no way to assure its performance. On the other hand, researches on the explainability of Deep Neural Networks focus on explaining models' behaviors but do not provide guidelines on deriving assurable performance.

Without explainability, we can not assure the performances of models.

2) *Unsupervised and continual learning enabled deep identification model*: With a large number of devices being connected to IoT, device identification and detection models need to continually adapt to operational variation in real-time. A solution can be the seamless integration of the feature abstraction capability of deep neural networks, continual learning and unsupervised learning. The knowledge of using deep neural networks to perform unsupervised learning for IoT device identification and detection is currently limited. Meanwhile, continual learning in deep models for device identification and detection is also rarely investigated.

3) *Controlled imprinting of verifiable patterns*: Compared with passive non-cryptographic device identification and detection methods in this survey, a proactive way is imprinting verifiable patterns into devices' transmitted signals or activity patterns. As suggested in [230], controlled imperfections are utilized as verifiable patterns. Embedded these patterns in signals could significantly enhance the performance of device identification. However, a critical concern is how to prevent the adversaries from collecting and learning about the imprinted identity verification information. As suggested in [222], a possible solution is to dynamically change the identity verification patterns according to a pair of synchronized pseudorandom code generators, where the initialization keys are only shared among the device and corresponding device identifiers. Methods are still limited in imprinting verifiable patterns that are difficult to learn.

VI. CONCLUSION

This survey aims to provide a comprehensive on the existing technologies on IoT device detection and identification from passively collected network traffic traces and wireless signal patterns. We discuss existing non-cryptographic IoT device identification mechanisms from the perspective of machine learning and pinpoint several key developing trends such as continual learning, abnormality detection, and deep unsupervised learning with explainability. We found that a multi-perspective IoT wireless device detection and identification framework is needed. Future research for rogue IoT device identification and detection needs to cope with challenges beyond signal processing and borrow ideas from advanced topics in Artificial Intelligence and Knowledge Discovery.

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