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Federated Radio Frequency Fingerprinting with Model Transfer and Adaptation

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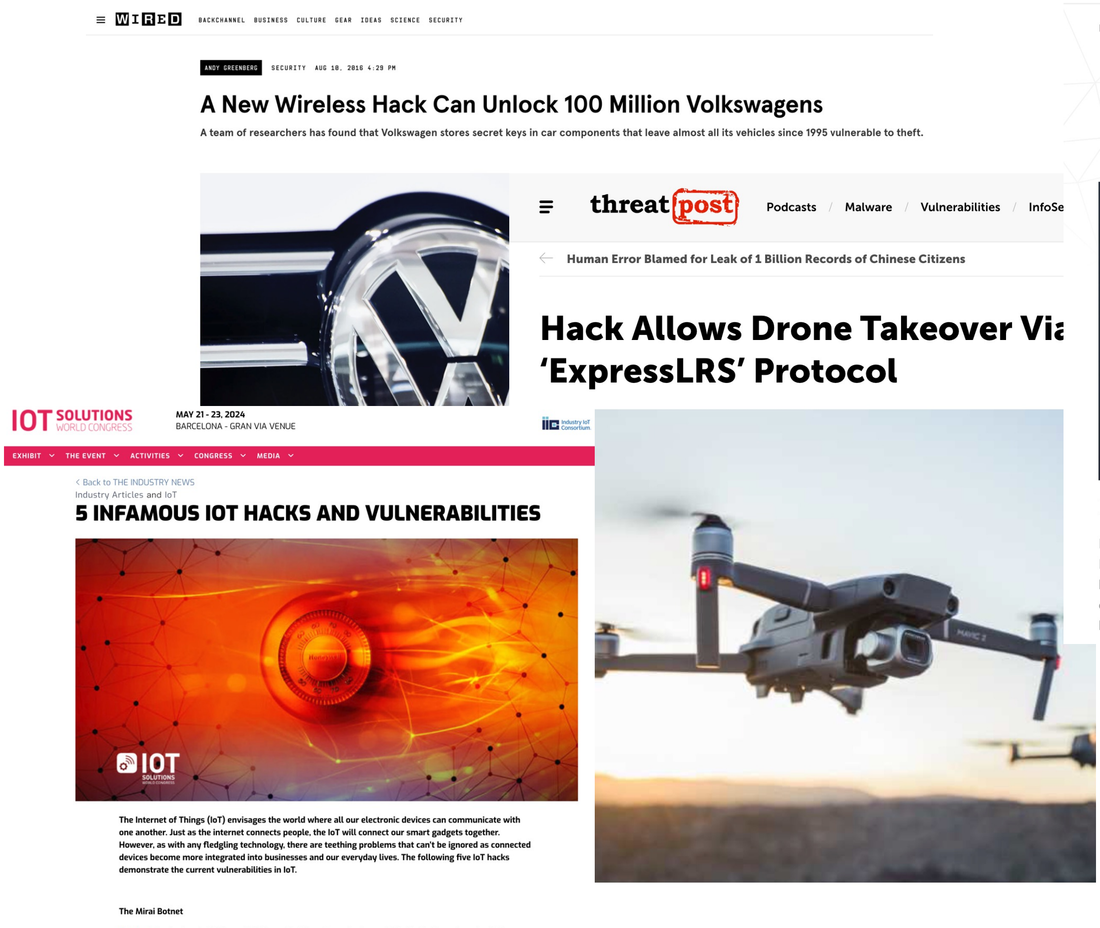
Content

- Background on Security and RF Fingerprinting
- Current Approaches and Challenges
- Our Proposed Method
- Experimental Results
- Conclusion

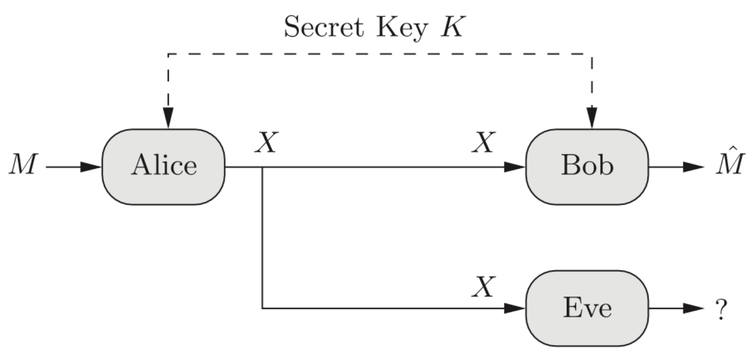
Wireless security threatens

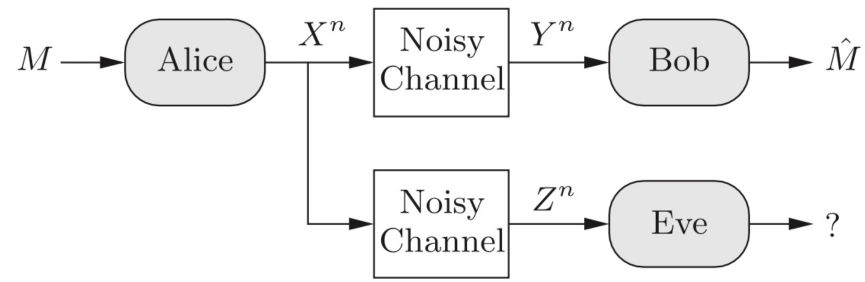
- Cyber attack happens almost everywhere in many fields.



How to achieve security

- Two fundamental primitives for any security systems.
  - **Secure transmission**

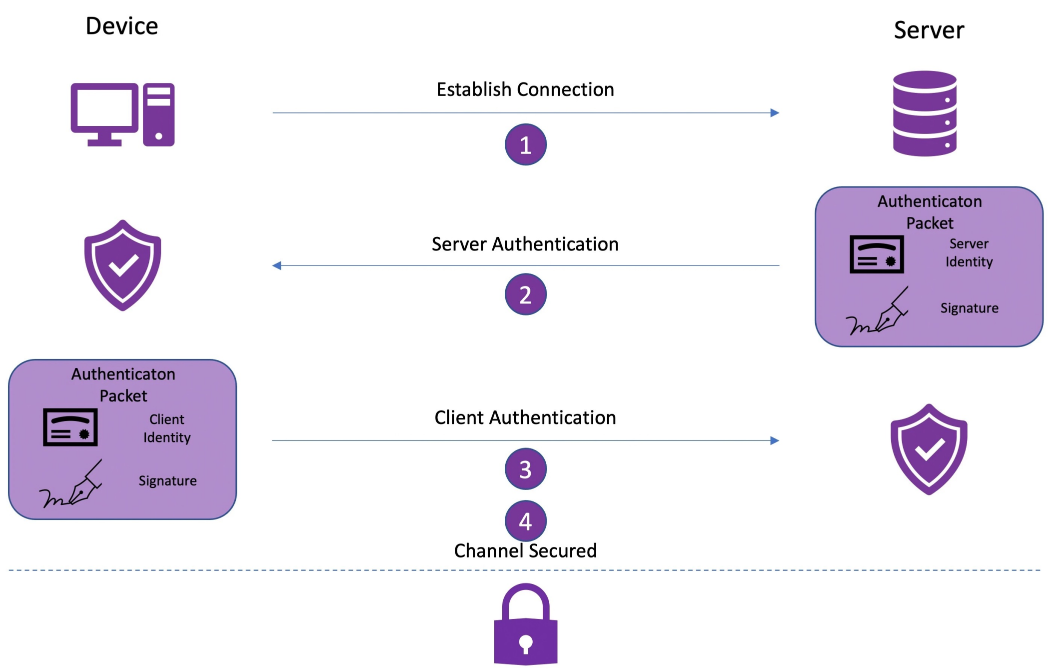




- H. V. Poor, R. F. Schaefer, “Wireless physical layer security,” in Proceedings of the National Academy of Sciences, 2017, 114(1): 19-26.
- L. Lai, H. El Gamal and H. V. Poor, "Authentication Over Noisy Channels," in IEEE Transactions on Information Theory, vol. 55, no. 2, pp. 906-916, Feb. 2009.

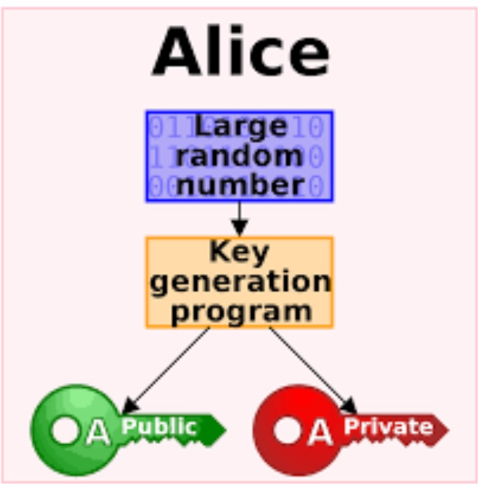
How to achieve security

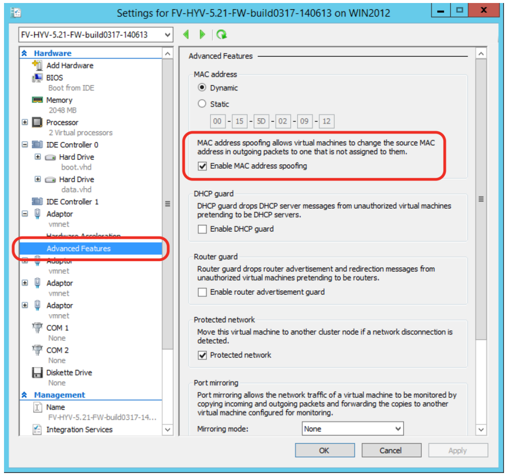
- Two fundamental primitives for any security systems.
  - **Secure transmission**
  - **Authentication/Identification**



Device identification and authentication

- Traditional schemes are mainly based on techniques stemming from **cryptography** such as encryption or solely based on **MAC address**.





Security is not guaranteed if keys are compromised

MAC address can be easily manipulated

RF fingerprinting

- RFF: An emerging physical layer security technique that helps with **device identification by exploiting hardware impairments** that are hidden in the electromagnetic waves of the transmitter;
- Recent research has found that **every transmitter has its unique RF fingerprint** resulting from imperfections of analog components, which are **non-reproducible** by attackers.

RF fingerprinting

- Consider a signal $s_t = I_t + jQ_t$.

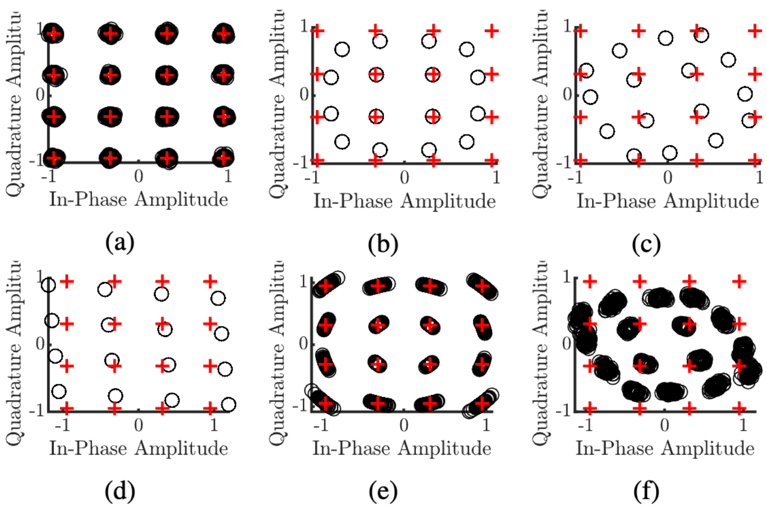
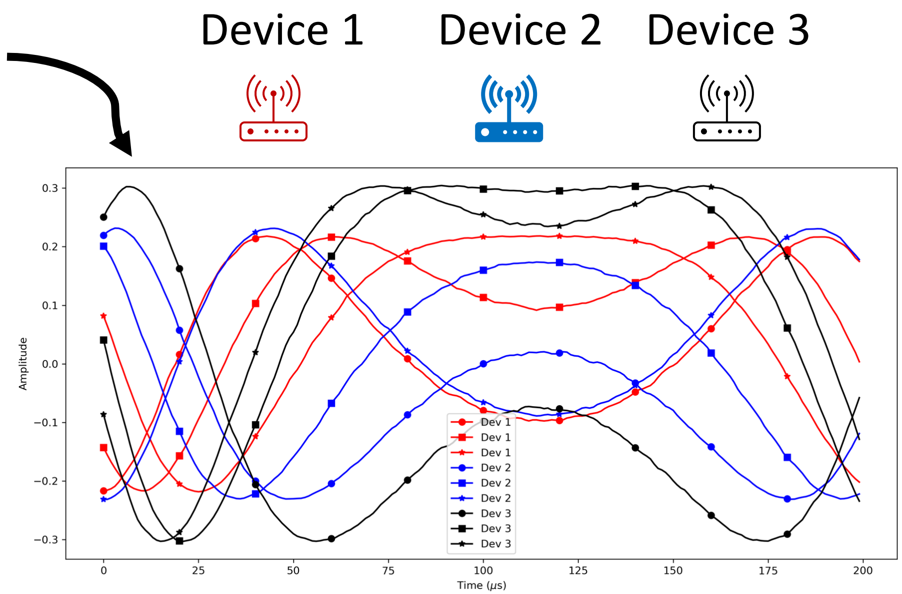


Fig. 1: RF impairments simulation. (a) Signal vs signal with AWGN noise; (b) Signal vs signal with amplifier distortion; (c) Signal vs signal with AM/PM conversion; (d) Signal vs signal with phase imbalance; (e) Signal vs signal with phase noise; (e) Signal vs signal with phase noise; (f) Signal vs signal with multiple impairments.



These hardware impairments are hidden in the signal emitted by different devices. RFF is identifying which device this signal belongs to by using a user-defined function $f(\cdot)$

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How to design $f(\cdot)$?

- State-of-the-art RFF learning models.

$$\theta^* = \arg\min \mathcal{L}(f(x; w), y)$$

True **labels** of the corresponding dataset, for example, 1, 2…

Loss function measuring the goodness of our learning function f, e.g., **cross-entropy**, **triplet loss**

The **parameters** of function f

Dataset stored in a **centralized** server

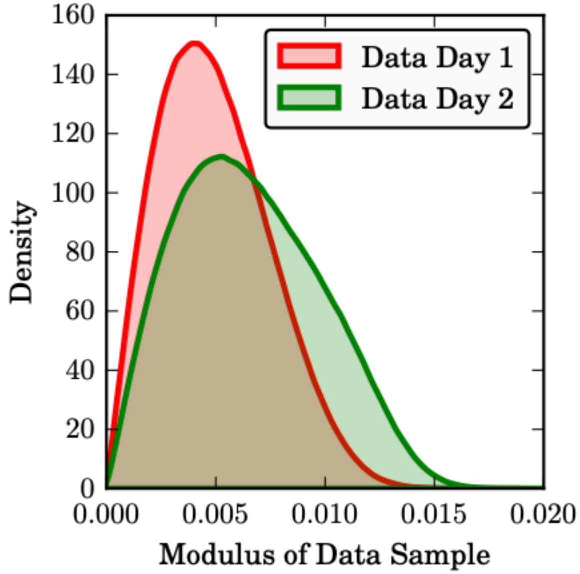
Target model/function, e.g., **CNN**, **MLP**

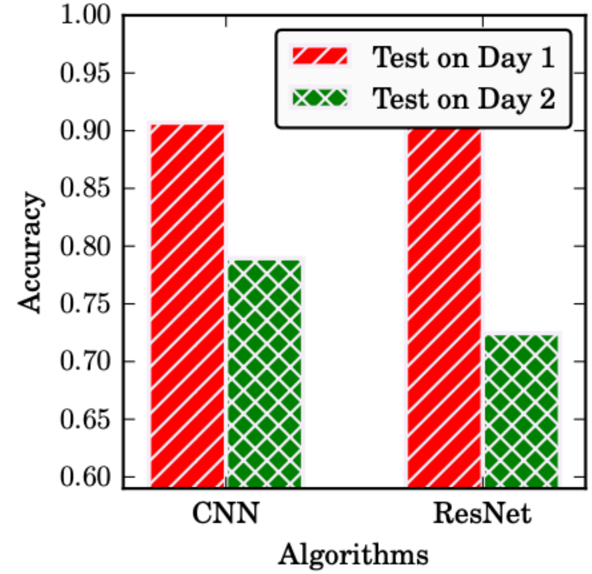
Challenges of centralized RFF

- Centralized RFF is inappropriate when **data privacy and protection** is a must; users are not incentivized to share data to a centralized entity (server) since their **data may contain private information**;
- Unrealistic to assume that a centralized dataset is always updated with signal collections as **new devices are continuously entering the market**;
- **Data distribution mismatch** between training and test if wireless environment changes.

■ T. Jian et al., "Radio Frequency Fingerprinting on the Edge," in IEEE Transactions on Mobile Computing, vol. 21, no. 11, pp. 4078-4093, 1 Nov. 2022.

Data distribution mismatch

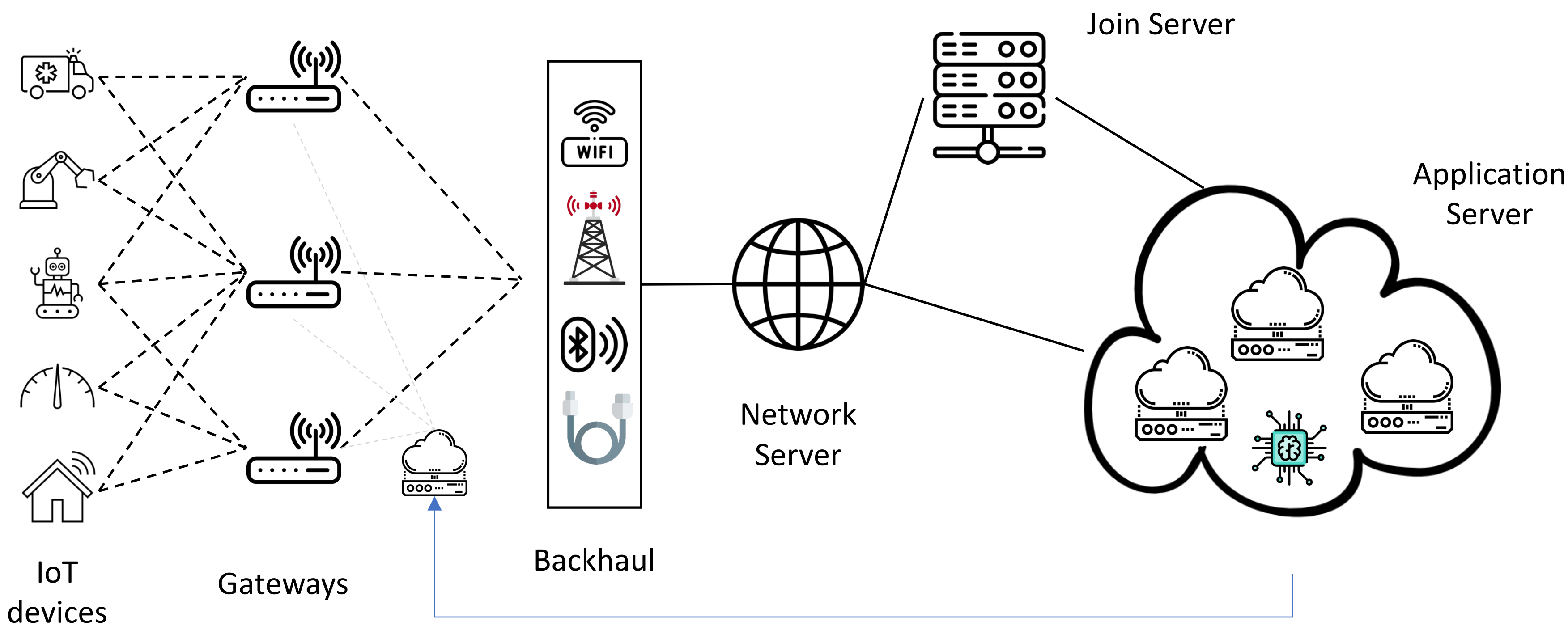




Train a model using data day 1 and test the model on the data of day 2, leading to a considerable performance degradation.

Solutions

- Push RF fingerprinting to the network edge and solve the data distribution mismatch using transfer learning.



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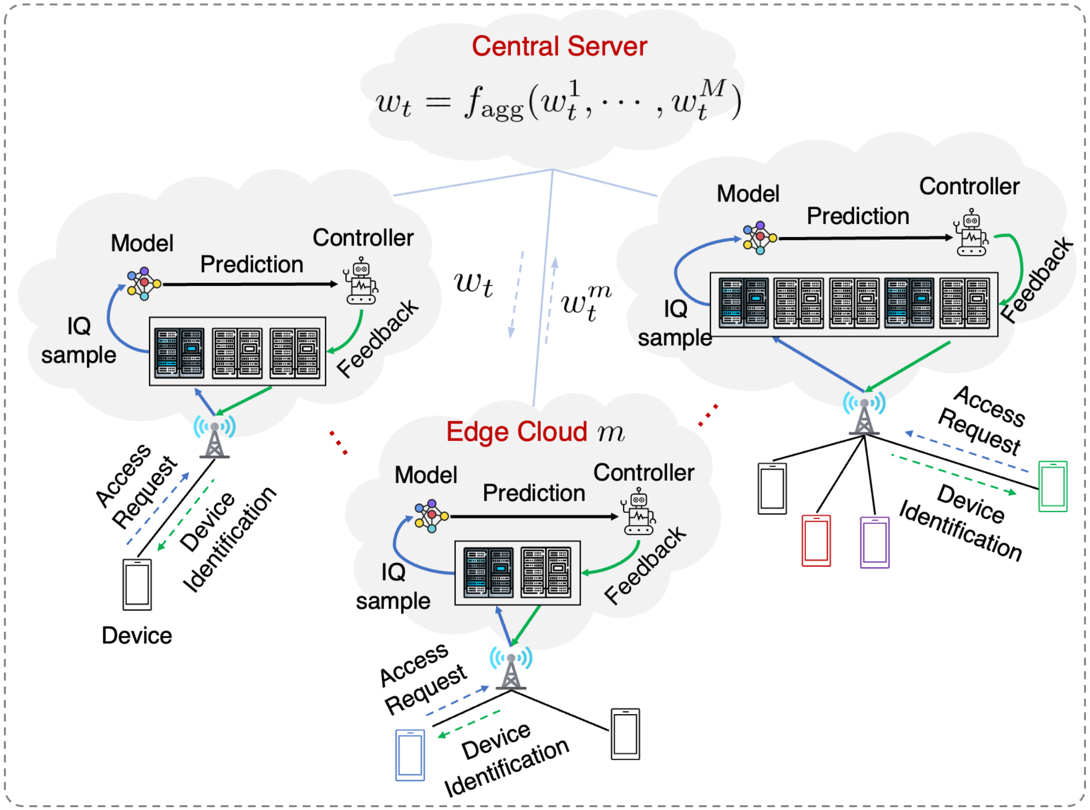
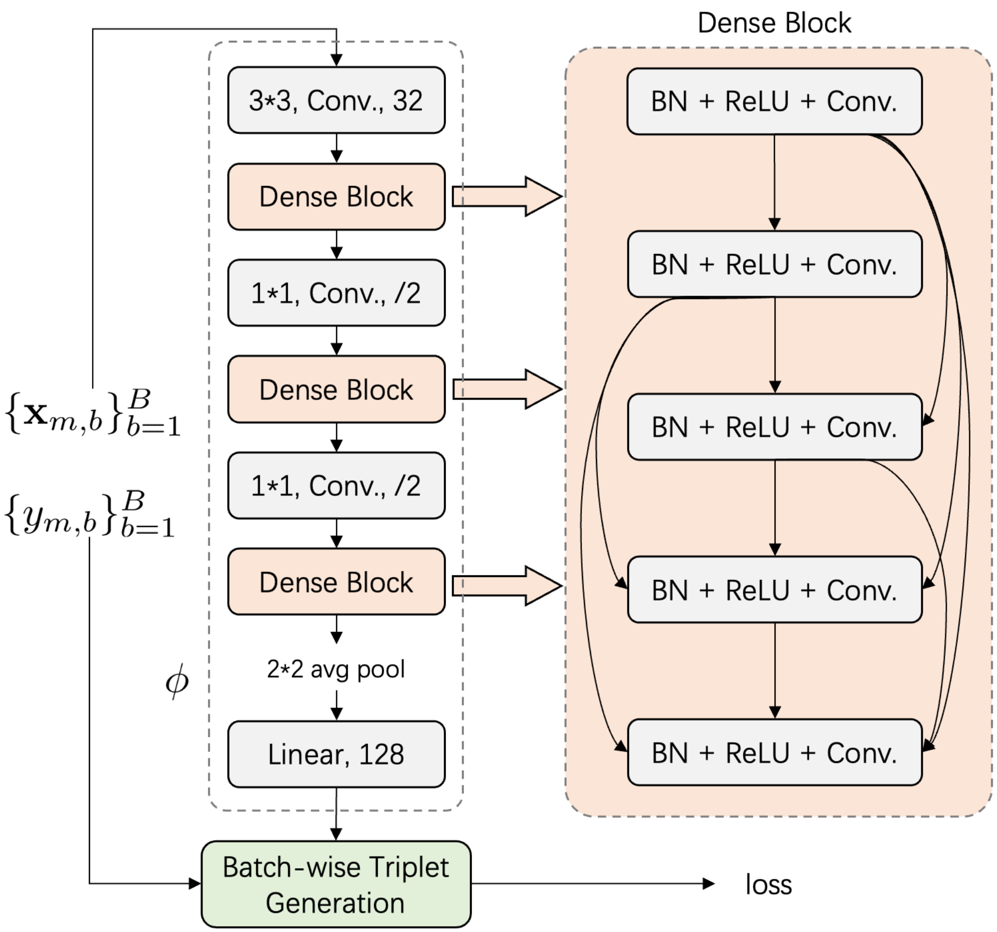
System model

- An RFF model is collaboratively trained by multiple edge nodes in a federated way.



Learning framework



- We introduce **dense connectivity** into RFF, making our framework **easy to train** (no gradient explosion or vanishing) and of **low complexity** (less parameter);
- We adopt **triplet loss** as our objective to **reinforce feature separation**

Transfer learning inspired model enhancement

- **Data distribution mismatch** between training samples and test samples will dramatically lower device identification accuracy;
- We propose **model transfer and adaption** (MTA) to solve the above challenge;
- Key idea: use the **pre-trained model** of one channel environment as the **initialization** of other environments (transfer) and **update it** using **very limited several data samples** to yield a new model (adaption).

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Setups

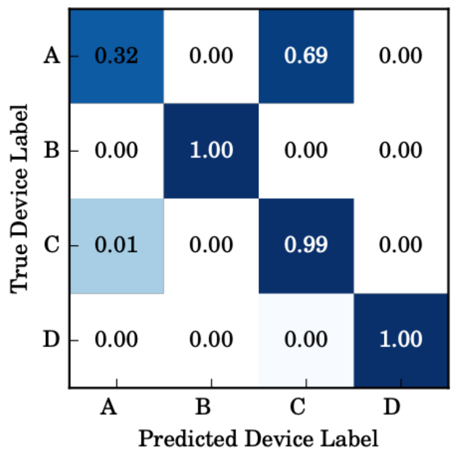
- We test our algorithm on a real world data, which is publicly available. The dataset contains **four devices' three different kinds of IQ samples**, i.e., Wi-fi, 4G LTE, 5G NR, logged in **two different days;**
- The first day's data (12000 samples) is used for training. For the second day's data (12000 samples), **ρ samples are used to perform MTA**, and others will be used to test performance;
- A federated learning scenario is mimic with **100 edge nodes**, the model is trained **50 rounds**, each round performs **10 local epochs** using **Adam** optimizer with a learning rate of 0.0001. The local batch size is 10.

Overall prediction performance

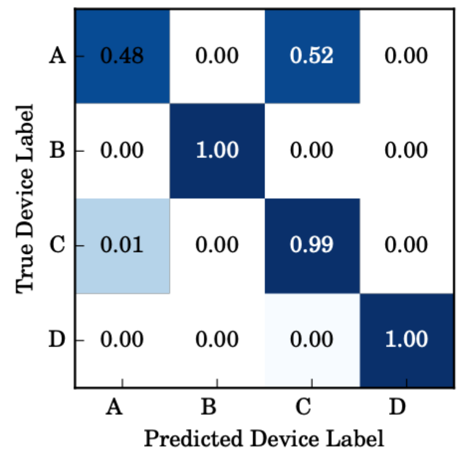
		Centralized ResNet	Federated MLP	Federated CNN	Federated ResNet	Proposed-Basic	Proposed-MTA
Notes	# of Parameters	157.54 K	1.58 M	1.19 M	157.54 K	79.95 K	
	Privacy-Preserved	✘	✔	✔	✔	✔	
Signals	4G	0.8257	0.7110	0.7895	0.7245	<u>0.8683</u>	**0.9343**
	5G	0.8375	0.7123	0.7725	0.7448	**0.9105**	<u>0.9100</u>
	WiFi	<u>0.9690</u>	0.7205	0.8213	0.7688	0.7508	**0.9800**
	Hybrid	0.7268	0.6923	0.7553	0.7692	<u>0.7721</u>	**0.9003**

- We compare our algorithm with **several baselines**, i.e., centralized ResNet, federated MLP, federated CNN, federated ResNet.
- Two versions of our algorithm: **proposed-basic** and **proposed-mta**. The former means the model is trained without using MTA strategy while the latter using MTA strategy.
- Findings
  - Our algorithm achieves **much better prediction performance** than baselines, even without MTA strategy
  - Our algorithm has the **least parameter complexity**

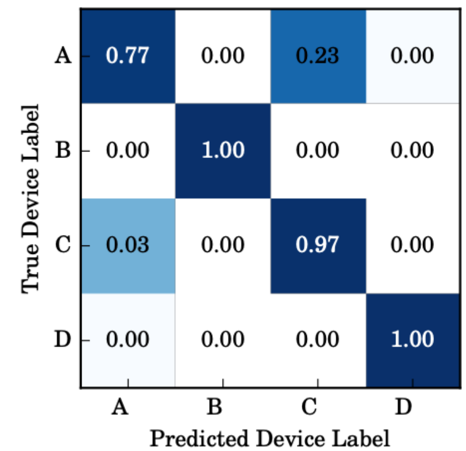
Per-device prediction performance



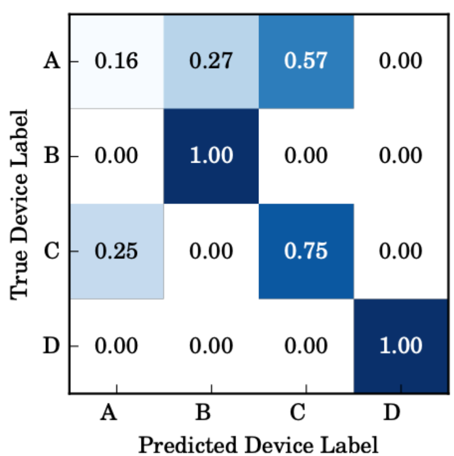
(a) Centralized ResNet (4G).



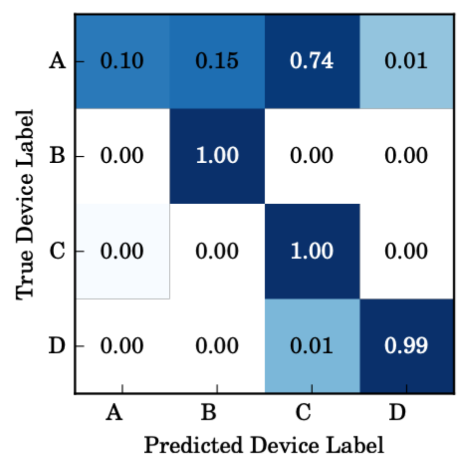
(b) Proposed-Basic (4G).



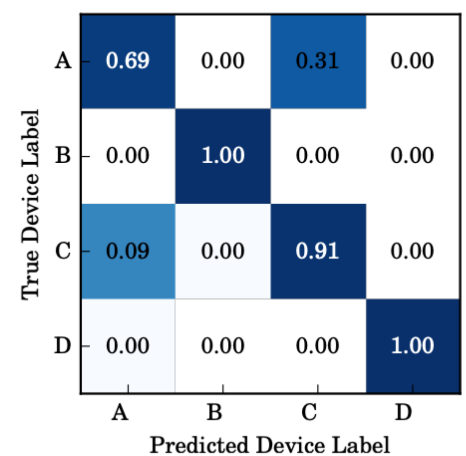
(c) Proposed-MTA (4G).



(d) Centralized ResNet (Hybrid).



(e) Proposed-Basic (Hybrid).



(f) Proposed-MTA (Hybrid).

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Conclusion

- We considered the **RF fingerprinting problem in the scenario of federated learning** for edge networks;
- We proposed **a novel CNN framework** by introducing dense connectivity into RF fingerprinting;
- We designed **a strategy named model transfer and adaption (MTA)** to overcome the data distribution mismatch problem brought by time-varying wireless environments.

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Thanks for your time!

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