TeRFF: Te e a e-a a e Radi F e e c Fi ge i g f S a h e

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E ai : { ia _g , j , g ai , h 2021, ab g, a g g2002, he g, j }@ e .ed .c

***Abstract*—In recent years, radio frequency (RF) fingerprinting has attracted more and more attention. Many different types of RF fingerprints have been proposed, such as carrier frequency offset (CFO), sampling frequency offset and error vector magnitude. Among them, the CFO fingerprint is recognized as a promising RF fingerprint. However, for commonly used smartphones, we find that its CFO fingerprint is unstable, because the temperature of crystal oscillator varies greatly and large fluctuations of temperature significantly affect its CFO fingerprint. Therefore, the solutions of CFO-based fingerprinting will no longer be effective for smartphones if the temperature of crystal oscillator is not involved. To this end, we propose a more reliable and applicable CFO-based fingerprinting approach called temperature-aware radio frequency fingerprinting (TeRFF). First, we construct a dataset by extracting crystal oscillator's temperature and the corresponding CFO value on multiple smartphones over a period. In the dataset, the extracted temperature values constitute a set of temperature values, and each registered temperature value corresponds to a group of CFO samples. On this basis, we train multiple Naive Bayes models, each tagged with a registered temperature value. Moreover, since there are many temperature values which are not in the temperature set, we design a CFO estimation method to estimate the CFO fingerprint at the unregistered temperature. Finally, the experimental results demonstrate that our proposed solution TeRFF makes the CFO fingerprinting still effective for smartphone identification, and its performance is better than other existing RF fingerprinting schemes.**

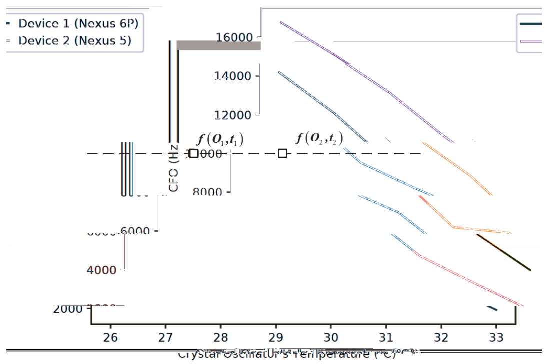
***Index Terms*—Smartphones, Radio frequency fingerprinting, Carrier frequency offset, Crystal oscillator's temperature**

I. INTRODUCTION

A he Wi-Fi ech i e de e g ad a , he be f Wi-Fi de ice i c ea i g i ece ea , a d he g ba Wi-Fi a ke i e i jec ed g f USD 9.4 bi i i 2020 USD 25.2 bi i b 2026 [1]. he ca e f a ge- ca e Wi-Fi de ice , he a he ica i bec e e a d e ig ca f he ec i f Wi-Fi de ice . C - e i a Wi-Fi de ice a he ica i i ba ed IP add e , MAC add e a d e- ha ed ec e f a i [2]. B he e f a i a e ea i f ged b a ici e e f a acki g he i e a e k. M i a ed b he ab e, c g a hic i ba ed de ice ide ca i a e ed ece . F de ice ide ca i , Radi F e c (RF) ge i g i a e iab e a d ec e a ach beca e RF ge ha e de ice- e a ed cha ac e i ic i Wi-Fi de- ice . F a acke , i i e di c a e i h had a e i e fec i c e cia Wi-Fi de ice . The ef e RF ge i g ha a ac ed he a e i f a e ea che .

RF ge i g ca be e i a e a i-c a ca i be . C e , RF ge i g f Wi-Fi de ice ca be di ided i dee ea i g-ba ed a d ha dc af ed fea e-ba ed e h d e a a e . Dee ea i g-ba ed e h d ca a a ica e ac effec i e a d de i g fea e f a i e e ce ed I/Q ig a i h e i g he k edge f i ee c ica i . addi i , he d a i de a i ed ig a ca be k i ad a ce. CNN [3] [5] a d MLP [6] ha e bee ed i Wi-Fi de ice ide ca i . H e e dee ea i g de a be deg aded a ge b i e e cha e [4]. The ef e he dee ea i g-ba ed e h d i a icab e i he ac ica ce a i . O he he ha d, he ide ca i e h d ba ed ha dc af ed fea e de e d e e k edge a d he e ha dc af ed fea e ca i dica e ec c i e fec i i i e e de ice . The e ha dc af ed fea e ca a be di ided i a ie [7], [8] a d d a i [2], [9], [10] fea- e . T a ie fea e ca be e ac ed i he a ie age f he a i e, hich e e a a i fac e f a ce. H e e , he ac i i i f he e fea e eed e e i e RF ecei e i h high a i g a e i he de f gigab e . Thi ake he e h d i ib e de a a ge ca e. B c a , d a i fea e ike ca ie f e e c ff e (CFO), a i g f e e c ff e a d e ec ag i de ig a e f d a i e a d he e ca be e ac ed b f a e-de ed ecei e ike USRP N210 i he edi ice a ge. A g he d a i fea e , CFO ge i i c ide ed be e effec i e i [9], [11].

He ce, CFO ge i i a effec i e fea e i RF - ge i g. H e e , i i f d ha e i g k a e ha he e ea e f c a ci a i he Wi-Fi de ice i e a i e ab e. i ea i , he a h e i a a e f Wi-Fi de ice, b c a ci a ' e ea e i he a h e ha a age a ia ce beca e i i ea i affec ed b i e c i . Be ide , e ea e i e f he i a fac hich affec he c a ci a i a RF f -e d [12]. The f i g i ake ib cc , hich a e h i Fig. 1: he a e a h e ha diffe e ge i , a d diffe e a h e ha e i i a ge i . We e he b f e e e a f c i f he c a ci a e **O** CFO e **C**. H e e , i e e f c i f^{-1} d e ' e i . T be ec c, CFO y ha c e di g a e i he c a ci a e **O**: c a ci a O_1 a d O_2. A a e , i i ead he i ake



Device 1 (Nexus 6P)
Device 2 (Nexus 5)
16000
14000
12000
8000
6000
4000
2000
CFO (Hz
$f(O_1,t_1)$
$f(O_2,t_2)$
26
27
28
29
30
31
32
33

f e en c i n g e a ed he c a ci a , hich i an e en ia c n en f he a h n e. I gen e a e an e ec- ica ign a i h a c n an f e en c . Acc din g diffe en age ch a i e ackin g, -c n e i n , d n -c n e i n an d n , he f e en c i ie e e age he ci a a a ba ic f e en c ce gen e a e a i f e en cie a diffe en e e . H e e , an e e n a fac i affec he abi i f he c a ci a . The e e a e i a ign n can fac hich can affec he n e n a f e en c f he c a ci a c n ide ab [12]. In de ai , he in e n a c a in he c a ci a ha a f e en c -e ea e cha ac e i ic e e en ed b he f in g e a i n :

$$\frac{\Delta f}{f_0} = A_1 (T - T_0) + A_2 (T - T_0)^2 + A_3 (T - T_0)^3 \quad (4)$$

he e f_0 i a efe en ce f e en c f he c a hen i i a e ea e T_0. $\frac{\Delta f}{f_0}$ efe e a i e f e en c chan ge i h he a ia i n f e ea e. Be ide , he c effi cien A_1, A_2 an d A_3 a e c n an hich ha e a e c e e a i n hi i h h ica e ie f he c a .

B. CFO Extraction in Smartphones

The c n a h n e 802.11a/g/n /ac c . The e c e e age OFDM echn g en han ce da a a e [13]. A Wi-Fi OFDM f a e ha a c n c e a n g e e a 802.11 c ab e. A h n in Fig. 3, he OFDM f a e in c de f n ed hich a e Sh T ain in g Fie d (STF), L n g T ain in g Fie d (LTF), Sign a Fie d (SIG) an d Da a Fie d e eci e .

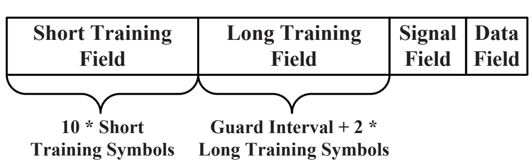


Fig. 3. Wi-Fi OFDM F a e S c e

1) Packet Detection: When a a h n e ecei e RF ign a , i c n e high adi f e en c ign a ba eban d digi a ign a b a RF f n en d. F he e, i i n ece a de e in e he he OFDM f a e cc in he ecei ed ign a a e . T be ecn c, STF i e e en ed b 12 bca ie in he f e en c d ain . F he eci e f i e d ain , STF i a e i dica ign a hich c n ain 10 e ea ed h ain in g b . A a e , ign a a c e a i n can in dica e he he i i e i dica . If he a c e a i n i e i dica , an OFDM f a e i de ec ed. B he a , he c a e CFO α_i can be e i a ed ick b he h ain in g b i an d $i+1$ f he n e ce in g e . I can be ca c a ed a he f in g e a i n :

$$\alpha_i = \frac{1}{16} arg(\sum_{n=(i-1)*16}^{N_s-1+(i-1)*16} x[n] \times x^*[n+16]) \quad (5)$$

he e arg in dica e he ha e f ign a , N_s i he en g h f in d in STF an d $x^*[n]$ e e en c e c n j ga e f $x[n]$.

2) Symbol Alignment: Af e he acke de ec i n an d c a e CFO c ec i n , b a ign en n eed be ca ied in g LTF. LTF i e e en ed b 53 bca ie in f e en c d ain . F he ie f i e d ain , LTF c n i f 2 e-ea ed ain in g g b an d a g a d in e a . A a a e a e f 20 MHz, LTF can be a ed a 160 di c e e a in g in . The eak f c -c e a i n be een n kn n ign a an d LTF efe en ce ign a c e n d he acc a e a in f da a f e d in an OFDM f a e.

3) Average CFO Estimation: A h gh c a e CFO i e i-a ed in he e i d f acke de ec i n , i ha a a ge an d e . T c ec he an d e , a h ain in g b can be ed ca c a e a e eci e a e $\bar{\alpha}$:

$$\bar{\alpha} = \frac{1}{9} \sum_{n=0}^{8} (\frac{1}{16} arg(\sum_{k=0}^{N_s-1} x[16 \times n + k] \times x^*[16 \times (n+1) + k])) \quad (6)$$

In de i if he de c i n , he CFO in he f -in g ec i n in dica e he a e age CFO $\bar{\alpha}$ ca c a ed b E a i n 6.

III. Smartphone Identification

We n in d ce he cen a i f RF n ge in in g f de-ice a hen ica i n , hen he gen e a ce f de ain in g an d a h n e iden n ca i n i e en ed. In addi i n , e f -c n he CFO-ba ed c a n ca i n a egi e ed e e a e an d CFO e i a i n a n egi e ed e ea e .

A. System Model

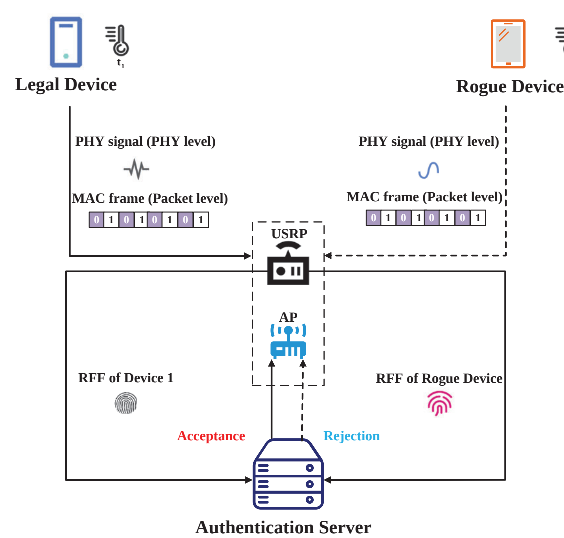
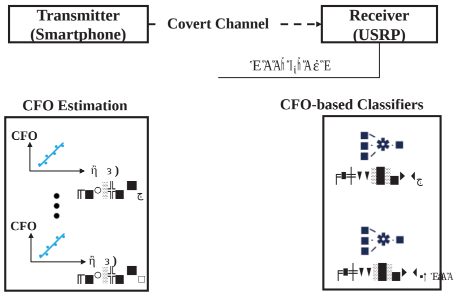


Fig. 4. Scen a i f RF n ge in in g f a h n e in de ice a hen ica i n

RF n ge in in g f a h n e i ed in de ice a hen i-ca i n . In he de ice a hen ica i n , e a e ha a acke ha e an abi i a e ade a a ega e a he acke e e b he d n f ge RF ign a a he PHY e e . A i a ed in Fig. 4, he a ici a acke a e f ge n g iden n e ike MAC add e an d en c i n /dec i n


Transmitter
(Smartphone)
Covert Channel
Receiver
(USRP)
CFO Estimation
CFO
CFO
CFO-based Classifiers

2) The e ea e f he c a ci a i ch e ha ha f he CPU he he a h e a c e- e i e a ica i .

Acc di g he e ab e, e ca ch e a a e a i e e ea e e i he a h e e e e he e e- a e f he c a ci a a i a e . T be ec c, he e i f he e ea e e achie e i g e digi ha he e ea e i a e i a di c e e e ege . T c ec RF a e a high e e a e i hi 40 60°C, e ake he a h e ac i e c a i a i e i e g a a d e d acke AP a he a e i e. B c a , he a e f c a ci a a e ea e i ab e hich i dec ea e he be f RF a e a e ea e. T eed he c ec i f RF a e a e e a e i hi 20 40°C, e e e age he PID a g i h [15] hich c he acke e di g a e a a ica kee he e ea e f c a ci a c a . F he e f aki g a i g a e ba a ced, a fa c ec i f he a h e' RF ge i a high a d e e- a e ca be acc i hed. I addi i , he e e a e i a i g e i d a e added e e a e e S_{temp}. We ca he e ea e i S_{temp} a egi e ed e ea e a d he e ea ea egi e ed e ea e.

D. Temperature-aware Classification Based on CFO

The CFO f e e f a e i ca c a ed f STS. I i f d ha he CFO i Ga ia di ib i . A i e f i gi e a f :

Property 1. *The distribution of $\bar{\alpha}$ is Gaussian Distribution.*

Proof. I i a ed ha e e c a e CFO a d a iab e i STS i de e de a d ide ica di ib ed. I addi i , α_{c_n} e e e he c a e CFO ca c a ed b h OFDM b n a d $n+1$. Acc di g ce a i i he e (CLT) [16], he a iab e α_{c_n} i Ga ia di ib ed e a a e a d $\bar{\alpha}$ i ca c a ed a f :

$$\bar{\alpha} = \frac{\sum_{n=0}^{8} \alpha_{c_n}}{9}, \quad \alpha_{c_n} \sim N(\mu_n, {\sigma_n}^2) \tag{7}$$

De e di g he Le -C a e he e [17], i i ed ha CFO $\bar{\alpha}$ i a Ga ia di ib ed.

$$\bar{\alpha} \sim N(\frac{\sum_{n=0}^{8} \mu_n}{9}, \frac{\sum_{n=0}^{8} {\sigma_n}^2}{81}) \tag{8}$$

□

T ed ce c ai a c f a i g de , Nai e Ba e ca e i ed ake a ca ca i f Wi-Fi de ice .

Si ce CFO i a c i a iab e, i i ea ab e ha babi i de i f c i f CFO i e e aged e e e he babi i f CFO' cc e ce a i a e . I he a i g e i d, he ea μ_i^j a d a ia ce $(\sigma_i^j)^2$ ca be e i- a ed f a a f CFO a g f a h e d_i i h e ea e t_j. I addi i , he e ea e i he a h e i a c ce e a iab e. He ce, he he de ice i a e ea e t_j, he i babi i f CFO α i h a be :

$$P^j(C=\alpha|D=d_i) = \frac{1}{\sqrt{2\pi}\sigma_i^j} e^{-(\alpha-\mu_i^j)^2/2(\sigma_i^j)^2} \tag{9}$$

Whe a CFO α_c i e ac ed b he e ab e i Sec i II, i i ed ca c a e a e i babi i f he a h e d_i i h e ea e t_j:

$$P^j(D=d_i \mid C=\alpha_c) = \frac{P^j(C=\alpha_c \mid D=d_i)P^j(D=d_i)}{P^j(C=\alpha_c)} \tag{10}$$

The , a e i a ed de ice $\hat{d}$ i h he a ge e i babi i i ea ched i he de ice e S_d. I i a ed ha $P^j(D)$ i if di ib i , a d $P^j(C)$ i e a ed a de ice i e f. I he d , a c a i be ee e i babi i ie i e i a e a c a i be ee i babi i ie . A a e , he ide ed de ice i de e ed a be :

$$\begin{aligned}\hat{d} &= \underset{d\in S_d}{argmax}\, P^j(D=d \mid C=\alpha_c)\\ &= \frac{P^j(D=d)}{P^j(C=\alpha_c)} \underset{d\in S_d}{argmax}\, P^j(C=\alpha_c \mid D=d)\\ &= \underset{d\in S_d}{argmax}\, P^j(C=\alpha_c \mid D=d)\end{aligned} \tag{11}$$

E. Estimation of CFO at Unregistered Temperatures

I he age f ge i c ec i , a idea ca e i ha CFO a a e ea e eached b he a h e a e a ca ed. H e e, he e ea e f he a h e i affec ed b a ki g c di i f he a h e a d he a bie e e a e. I i b i ha he ki g c di i ca be adj ed b a bie e e a e ca be c ed a a . The ef e i i e di c f a h e a e e a ibe e e a e i he age f a e c ec i .

F a e , i i f d ha he CFO f each a h e i dec ea e i h he e ea e i ac ica e e i e . The ef e a e ia e a i hi be ee CFO a d e ea e ca be ed f he e i a i f a h e ge i . T be ec c, he CFO a egi e ed e e a- e ca be gh e i a ed h gh eg e i a a i .

The ce f TeRFF i h i A g i h 1. I de ai , i i a ed ha he ge i d a a e $FP = \left\{\left(\mu_i^j, \sigma_i^j\right) \mid d_i \in \boldsymbol{D}, t_j \in \boldsymbol{T_r}\right\}$, he e $\boldsymbol{D}$ a d $\boldsymbol{T_r}$ e e e he e f a h e a d egi e ed e ea e e a a e . The a ia e f c i e ca dida e f c i e e $\boldsymbol{F} = \{f_1, f_2, ...,$

$$\theta_i^j = \min \sum_{t_k \in \boldsymbol{T_{c_1}}} \left(\mu_i^k - f_j(t_k, \theta)\right)^2 \tag{12}$$

he e ce , he be f c i e $\boldsymbol{F}$ i ch i e he e f a ce f CFO e i a i . Mea Ab e E (MAE) i a c k d f e a a i e ic e i a i , hich i e i a ie f CFO a g he ge da a e . addi i , $\boldsymbol{X_{d_i,t_j}}$ dica e he ea CFO e f he de ice d_i a he e e a e t_j. The ef e he be f c i e i decided b he f g e e i :

$$f_{best} = \min \sum_{d_i \in \boldsymbol{D}} \sum_{t_j \in \boldsymbol{T_{r_2}}} \sum_{x \in \boldsymbol{X_{d_i,t_j}}} \left| f_k(\theta_i^k, t_j) - x \right| \tag{13}$$
$$s.t. \quad f_k \in \boldsymbol{F}$$

hi a e, f c i e e $\boldsymbol{F}$ c de ea - ia , ec d-deg ee ia a d hi d-deg ee ia . The he ea ia a d c e d g a a e e a e ch e e i a e he CFO a egi e ed e a e .

Algorithm 1 The ce f TeRFF

Input: ge da a e FP, CFO a e x, e e a e t, de ice e $D\{d_0, d_1, ..., d_n\}$, be f c i e f, egi e ed e e a e e T_r, egi e ed e e a e e T_o, a a e e e Θ f f c i e f, de ea ch g f c i $f' : \mathbb{Z} \rightarrow \mathbb{N}$

Output: ide ed de ice d_i

```
if t ∈ T_r then
    d ← d_0, p ← 0, m ← f'(t)
    for μ_i^m, σ_i^m in FP do
        if p > pdf(μ_i^m, σ_i^m, x) then
            p ← max(p, pdf(μ_i^m, σ_i^m, x)), d ← d_i
        end if
    end for
else if t ∈ T_u then
    dis ← +∞
    for θ_i in Θ do
        if |f(θ_i, t) − x| < dis then
            dis = |f(θ_i, t) − x|
            d ← d_i
        end if
    end for
end if
```

Af e de e g he a a e e a d e f f c i , e ca e i a e he ea a e f he de ice' CFO a egi e ed e e a e a g de ice hich ca be ed a he efe e ce ge . C a ed h he ge c ec ed di ec a he egi e ed e e a e , he e i a ed CFO achie e e acc ac . Beca e he e i a ed f c i ca c a e a ea a e f CFO hich ca de c ibe he CFO c ehe i e . The ef e i e e iab e e e age he Ga ia di ib i f CFO ha e a ea a e f CFO f a h e ide ca i . H e e , ac ica e e i e be ha e c ed ha he e e i a ed CFO a e i effec i e a h e ide ca i .

IV. Evaluation

A. Experiment Setup

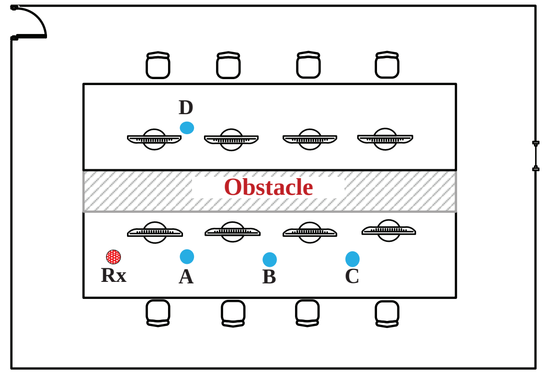


Fig. 6. Thi i e e i e a ce a i he e R i USRP N210. Be ide , A, B, C a d D dica e f de e ca i f a - h e .

The e e i e a e i e i a ce i e i , hich i f f e ec ag e ic e fe e ce. Be ide , i i a ica d e i e . The a f he ce i h Fig. 6. The de e a d a i ie f a h e a e h Tab e I, c d g i e de f a h e a d i e a h e de e de . Each a e a i e e f e ac g c a ci a ' e e a e a a h e i a i ed Tab e I. addi i , he f -e d f he ecei e i USRP N210 a f , a d g -ieee802-11 [18] jec ba ed GNU Radi i d ed e ac CFO f Wi-Fi ig a .

TABLE I
THE LIST OF SMARTPHONES AND THEIR ALTERNATIVE SENSORS

Device Model	Alternative Sensor	Device Number
Ne 5	a_he 0	9
H a ei Ne 6P	a_he 1	1
Ne 5X	a_he 0	1
H a ei P9	a_0	1
Vi X9	a_he 0	1
O eP 3	a_he 0	1
H a ei H 7	a_0	1

Gi e a RF a e f a h e , acc ac efe he i f c ec ide ed RF a e a RF a e .

$$Accuracy = \frac{N_{right}}{N_{all}} \tag{14}$$

B. Effects of Temperature

We e iga e he i ac f he he c ide g e e - a e i ece a . The RF a e f a a h e a e ca ed a egi e ed e e a e be ee 26°C a d 33°C. de ai , he be f RF a e e i ed b each a h e a each egi e ed e e a e i 3000. The e i e a e a e i a g a d e e 2:1 a ca i a i . T i if he e e i e , e a e a c ca e: he e i d f a g a e c ec i i h a d he e e a e f he a h e a ie i e. The ef e, he ca e i a ed b a g a e a a ce a e e a e. Fi , e a eigh c a ca i de eigh e e a e e a a e . Whe he e e a e f de ice i c ide ed, he c e di g de ca be e ec ed f a h e ide i- ca i . O he he ha d, he a h e' e e a e i de c ide a i , he e e a e c e di g e g a e i ib e a he e e a e f Nai e Ba e de ha he e f a ce f a h e ide ca i i deg ade. A i i h Fig. 7, i i f d ha he ide ca i e h d i h e e a e (i.e. TeRFF) i b i g ea e ha ha i h e e a e (i.e. Nai e Ba e a ach). The e e i e i a e ha e e a e i e f he ig ca fac hich ca e ce a h e ide ca i . The ef e he ide ed a h e d e i e e a e he a he ica i e e f a be e e f a ce.

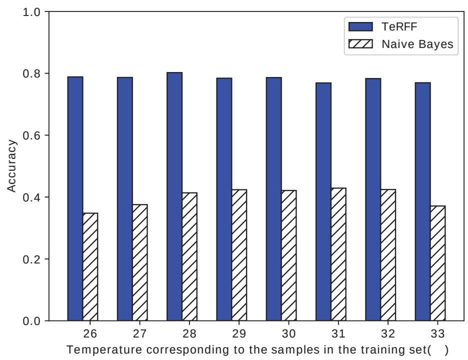
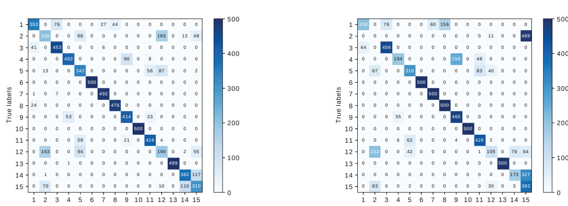


Fig. 7. Acc ac f TeRFF

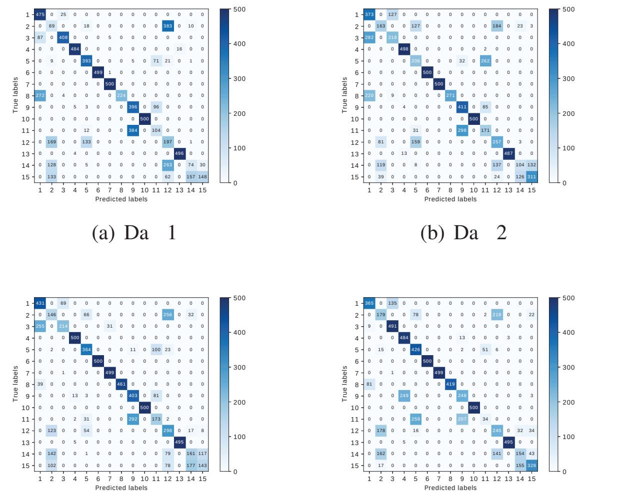


(a) Rea CFO (b) E i a ed CFO

Fig. 8. Effec i e e f e i a ed CFO

C. Effectiveness of Estimated CFO

We a ida e he effec i e e f e i a ed CFO a egi - e ed e e a e . A Fig. 8 h , he acc ac f a - h e ide ca i a egi e ed e e a e achie e a 69.59%. C a ed he CFO-ba ed e h d a egi e ed e e a e h e acc ac eache 79.10%, ha a - egi e ed e e a e ha a e e f a ce. H e e, i i b i ha he e i a ed CFO i a effec i e a h e ide ca i he he a h e' e e a e i a egi e ed e a e.



(a) Da 1 (b) Da 2

(c) Da 3 (d) Da 4

Fig. 9. F - e i d(da) e e i e a e

D. Stability over Time

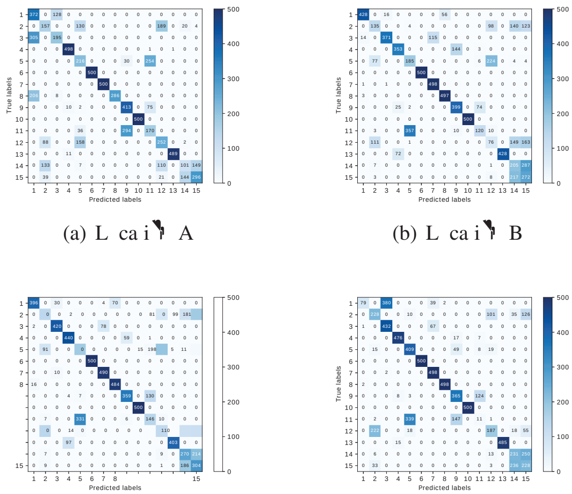
We c ec RF a e f da be ee Dece be 2021 a d Ja a 2022. F he e, 500 a e a e c - ec ed e da . The e f a ce f a h e ide ca i diffe e da i h Fig. 9. I i f d ha he acc ac f a h e ide ca i f da i 66.49%, 66.27%, 70.51% a d 71.49% e a a e . I i h ha he acc ac ca e a ab e a d ca achie e a e ab e acc ac .

E. Effects of Different Locations

T f he e if he effec i e e f ed e h d, e e he he he ca i cha ge f a h e i de- g ade he acc ac f a h e ide ca i . T be eci c, ca i A i he fa he f he USRP ecei e , ca i B i he e , a d ca i C i he c e . The di a ce be ee he c e ca i ab e i a i a e 0.5 e . Be ide , We f he he a h e ca i D e iga e he i ac f he b ac e he e f a ce f he a h e ide ca i e h d. A i a ed Fig. 10, he acc ac f a h e ide ca i ca i A C a e 65.93%, 66.23% a d 68.77% hich a e e c e. addi i , e a d ha he b ac e d e ' deg ade he e f a ce f ed e h d hich ca achie e 68.36% ca i D. The ef e ed e h d i b ca i .

F. Multiple Consecutive Samples in the Network Traffic

We a e e he he i i g i e c ec i e a e a e k a c i e he e f a ce f a h e ide ca i . The c ec i e a e a e ca ed da . The ide ca i e f a a c i de e ed b he aj i f ide ca i e i e c ec i e a e . I i f d ha he di e i f RF ge i i he e f a ce f a - h e ide ca i . T be eci c, he CFO f de ice 14 a d



(a) L ca i A (b) L ca i B

(c) L ca i C (d) L ca i D

Fig. 10. E e i e a e diffe e ca i

15 ca be di g i hed ea i . The ef e, he acc ac f a h e ide ca i i c ea e f 68.39% 69.80%, hich d e h a iceab e e f a ce b .

G. Comparison with Baseline RF Fingerprinting

Fi a , e c a e ed e h d i h a e- f-a e h d c di g LTF-ba ed [6] a d e ec a de i (PSD)-ba ed [10] e h d . We a d c ec e f a I/Q da a a he a i g e a d e e e- ec i e . F he e, e e ed e h d a d he e h d ide if a h e . I Fig. 11, i i f d ha ed e h d ca achie e he highe acc ac a g h ee e h d . We i fe he e f a ce f he he e h d i ea i deg aded b i e e cha e . T be eci c, LTF-ba ed e h d a e he cha e f e e c e e a f a e a a i c a . H e e , i i a a i a i f de d a i a d dec di g f Wi-Fi ig a , hi e he e i- ead fea e be ee LTF a e ea i e he ed b he cha e a ia i i h he d a i f a f a e. Be ide , he PSD-ba ed e h d i i e f e c -d ai cha ac e i ic f RF ig a hich ca e ec he RF f -e d i ai e .

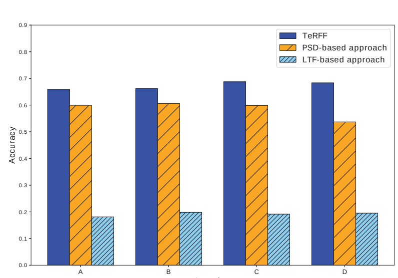


Fig. 11. C a i f TeRFF a d e i g a h e ide ca i e h d

V. Related Work

A. Device Fingerprinting

De ice Fi ge i g i a ig i ca a ach hich i f e ed a h e ide i ca i a d a he ica i . Beca e i i e e i a f ge a ack ha adi i a g ide i -ba ed e h d , a e ea che ha e de ed hei a eff ide if i g de ice b c c i g i e ge f f a e ha d a e. e f he f a e-ba ed ge , he a e e ac ed f e k a c he a ica i a e . T be eci c, he c bi a i f di c c e eb i e b e , chi e , a e a d d i e ca be ed a de ice ge . addi i , he d a ic fea e ch a a c a e a d i g e a be e e a e a ed ide if de ice i e . H e e , he e ge ab e ca be di ed ea i b a ici a acke . The ef e, ha d a e-ba ed ge ha e bee ed ece ea . The i e f e ec i f eadi a ai abe c i API f c i [19] a d ag e ic d c i ig a e i ed f he CPU chi a d a ia ed e ci c i [20] e e e h ica cha -ac e i ic f CPU de ice . Be ide , he a ib e f e he face f ed h ica bjec a e de e ed b he feede , i i e a d h e d, hich ca be ed a h e ide ca i [21]. addi i , c ck ke f 802.11 beac be e e f a e ca be ed a a k d f de ice ge [22]. addi i , he RF ge RF f -e d f Zigbee [23] a d L a [24] de ice ca be e ac ed f a h e ide ca i d g ee- - ee e k c ica i .

B. Temperature Effects on the Circuit

The e ec ica e ie f a ci c i a e ce ib e a i-a i he e e a e, hich e ia h ea he a e a i f he ci c i . I i di c f a fac e c e e e i a e he ega i e effec ca ed b a ia-i f e i e a e e a e e ec ic c he ci c i . The ef e e e a e c e a i died f ci c i ' abi i . A e CMOS e a e i h e e a e c e a i de ig ed f e g he a ia i f ga [25]. Be ide , f e c f a 7-MH c ck ci a a 0.25-μ ce kee c a b a age c [26]. A h gh a ia i f e e a e de e i a e he e f a ce f ci c i , hi ee ega i e h ica e a ca e e a ica i a a g a . S e e ea che ha e e i ed he e e a e- e i i e cha ac-e i ic f ci c i ha e e de ig ed f e e a e e g ac a a - eci i he e e. A Ga ia ce de i de ig ed eg e he e a i hi be ee ha e a d e e a e, hich ca e i a e he e e a e i h 5°C e [27]. Be ide , f e acc ac f e e a e ea e e , he he e i e a effec a e ca ce ed b g a ai f RFID ag i h diffe e i e [28]. addi i , e a e ec ica c e f RFID ci c i a e ed ea e he e e a e i h he e ec ic c e ' a i a ce [29].

VI. Conclusion

n hi a e, e e an en han ced CFO-ba ed n ge - n n g i TeRFF e c e he cha en ge ha he CFO n ge n f a h n e i n abe n de diffe en c a ci a ' e ea e. Fi , e e abi h a da a e c n an n g c a ci a ' e ea e an d he c e n d- n g CFO a e n i e a h n e e a e i d. T be ecn c, a e f e ea e a e i c bn ed i h he e ac ed e ea e a e, an d he a a h n e i a he egi e ed e ea e, i c e n din g CFO a e a e ed n he da a e. On hi ba i, e an i e Nai e Ba e de , each agged i h a egi e ed e ea e a e. M e e, n de e he be ha he e ea e a e a e n n he e ea e e d n g he a h n e iden n ca i n, e de ign a CFO e i a i n e h d e i a e he CFO n ge n a he n egi e ed e ea- e. Fin a , i i de n a ed b ac a e e i en ha ed i n TeRFF ake he CFO n ge n n g i effec i e f a h n e iden n ca i n, an d TeRFF ha a be e e f an ce han he e i n g RF n ge n n g che e.

VII. Acknowledgment

Thi k a a ia ed b he Na i n a Ke R&D P g a f Chin a (N . 2018YFB2100300); he Na i n a Na - a Scien ce F n da i n f Chin a (N . 62072102, 62132009, 62072103, 62022024, an d 61972088); Jian g P n cia Na - a Scien ce F n da i n f E ce en Y n g Sch a (N . BK20190060); Jian g P n cia Ke Lab a f Ne - k an d In f a i n Sec i (N . BM2003201); he Ke Lab a f C e Ne k an d In f a i n In egra i n f he Min i f Ed ca i n f Chin a (N . 93K-9), he F n da en a Re ea ch F n d f he Cen a Un i e i ie (N . 2242022k30029).

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