Advancing Security and Privacy of Bluetooth IoTs via Formal Protocol Analysis

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Outline

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What is Bluetooth Low Energy

Power Consumption: High
Communication Distance: Short (10+ m)

Power Consumption: Low
Communication Distance: Long (100+ m)

Bluetooth Low Energy Applications

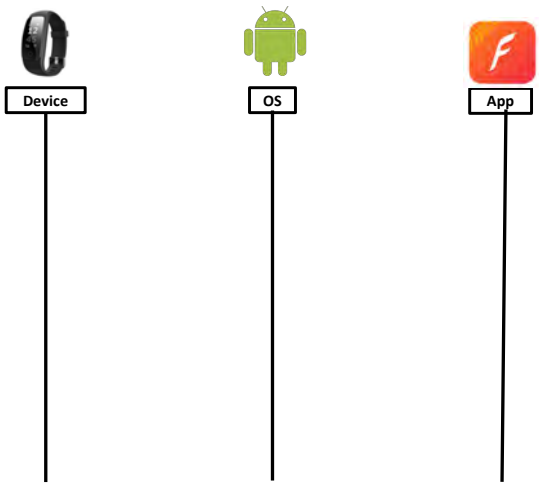








Bluetooth Low Energy Communication



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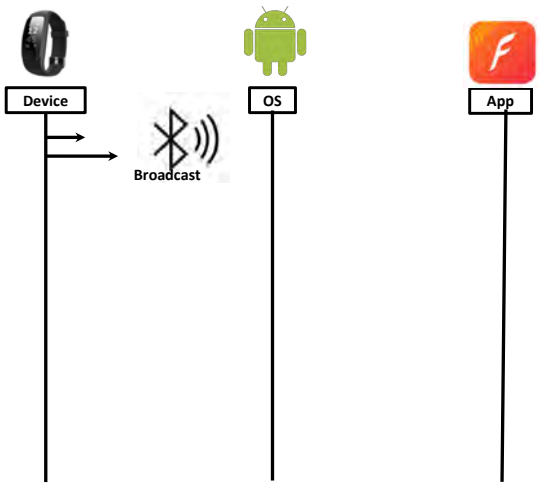

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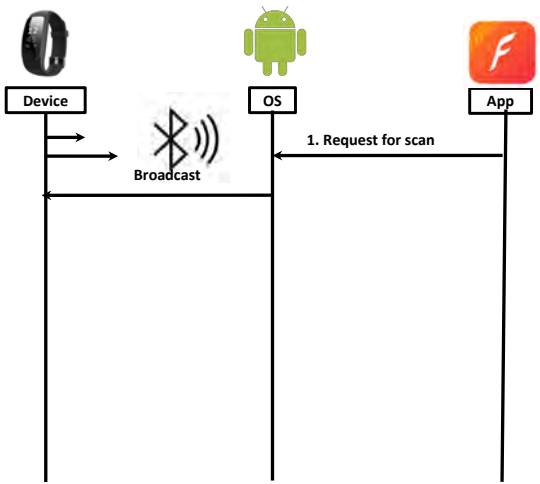

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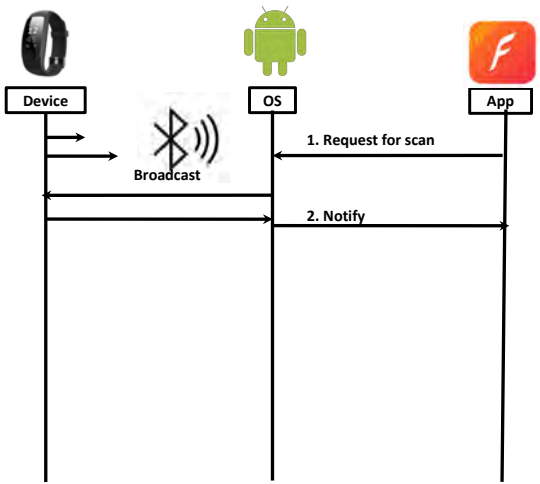

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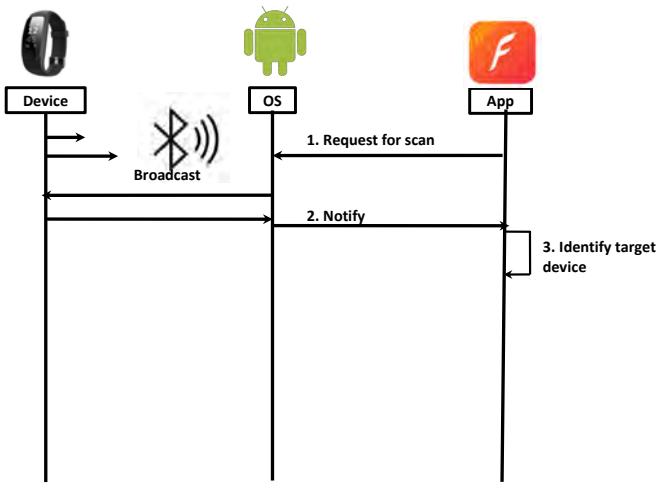

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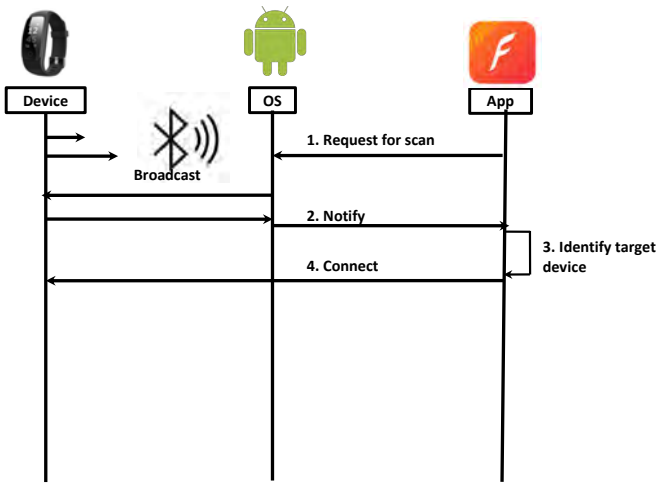

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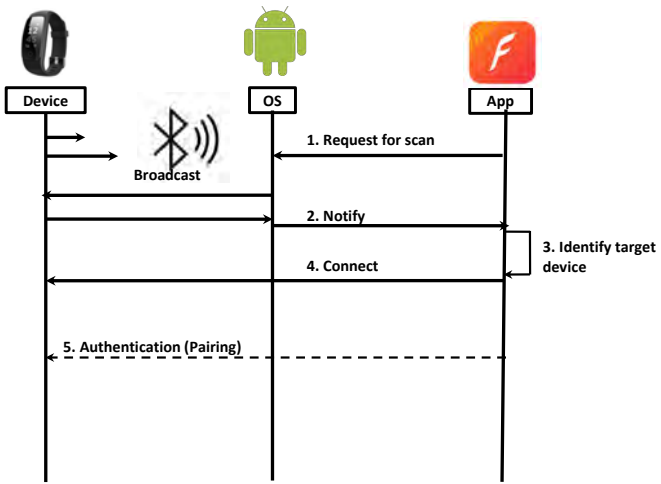

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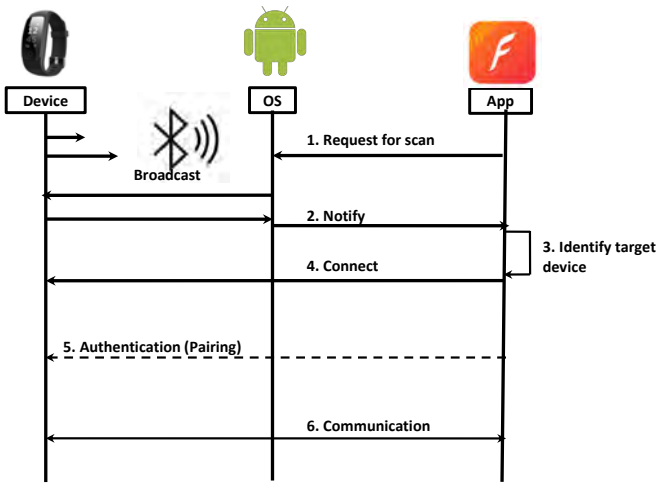

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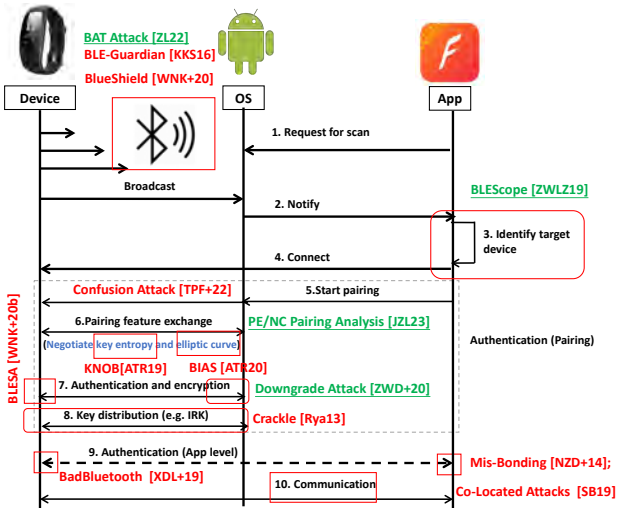

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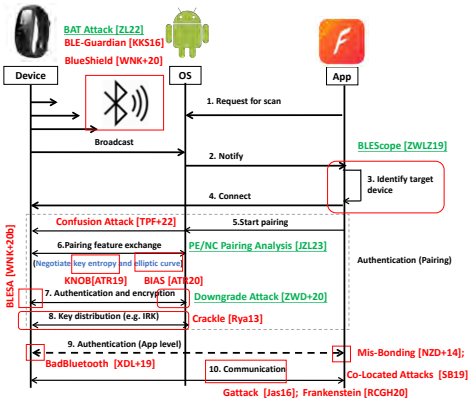


The goal of this project is to systematically uncover the attacks via formal methods

Outline

Mathematical Proof: A Simple Example

Assume a set of even integers
$E = \{..., -2, 0, 2, 4, ...\}$

And a set of odd integers
$O = \{..., -1, 1, 3, 5, ...\}$

Property (Lemma)

P = "Elements of E and O are distinct"

Mathematical Proof: A Simple Example

Math Algebra

$E = 2x \; for \; x \in Integer$
$O = 2y + 1 \; for \; y \in Integer$

Proof by Contradiction

not P = "There exist some common elements among E and O"

Mathematical Proof: A Simple Example

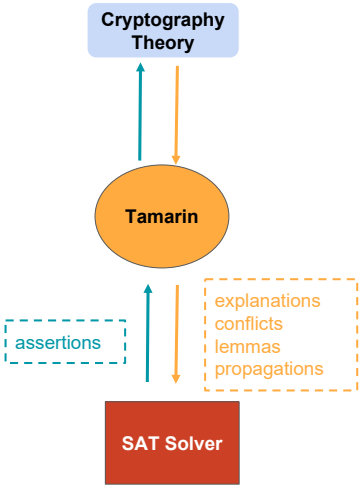
Proof

Start with assuming for some x and y
$2x = 2y + 1$ holds true
$\Rightarrow 2(x - y) = 1$

Mathematical Proof: A Simple Example

Possible Sub-Cases of X-Y	**Generally known axioms (Generalized Constraint Resolution Methods)**	**applying axioms to 2(x-y) = 1**	**Conclusion (Contradicting all not P system states)**
0	0 is the only neutral difference of Integers	2*0=1	Contradict
negatives	all negatives differences of integers are -1 or less {..., -3, -2, -1}	2*(-1 or less)= 1	Contradict
positive	all positive differences of Integers are 1 or more {1, 2, 3, ...}	2*(1 or more)= 1	Contradict

How does Protocol Verification (Tamarin) Work?



- **Dec**(**Enc**(msg, key)) = msg
- **Sign**(msg, privKey) = **Verify**(msg, pubKey)
- Adversary Replay

…

- Find next proof requirements
- Choose which SAT problems to solve first
- Convert problem algebra theory into SAT problems

…

$$x_1 \wedge x_2 \wedge x_3$$

- Does SAT problem have a solution?

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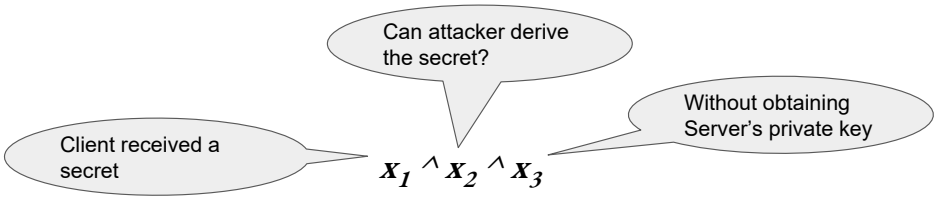
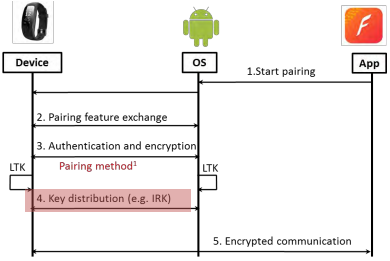


(Privacy) How to Avoid Being Tracked: MAC Address Randomization

Identity Resolving Key (irk_p)

Identity Resolving Key (irk_c)



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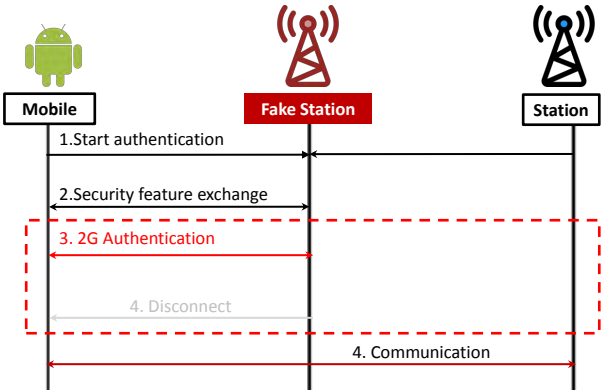
Our Downgrade Attacks against Bluetooth Low Energy [USENIX'20]



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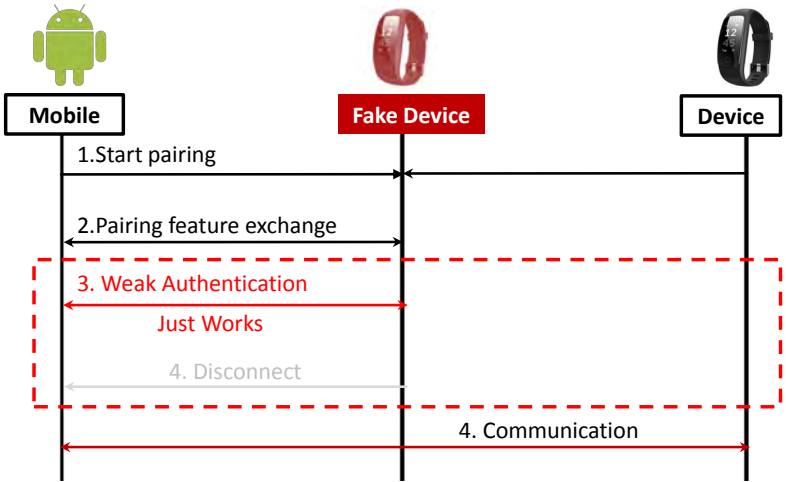

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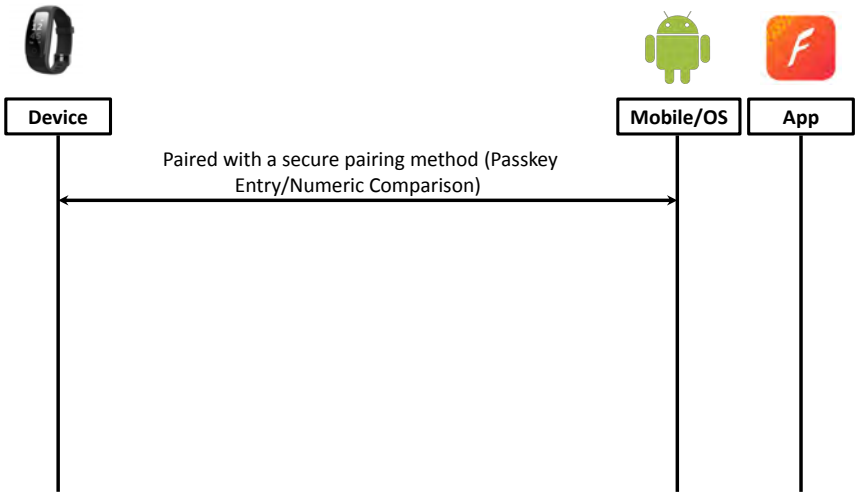

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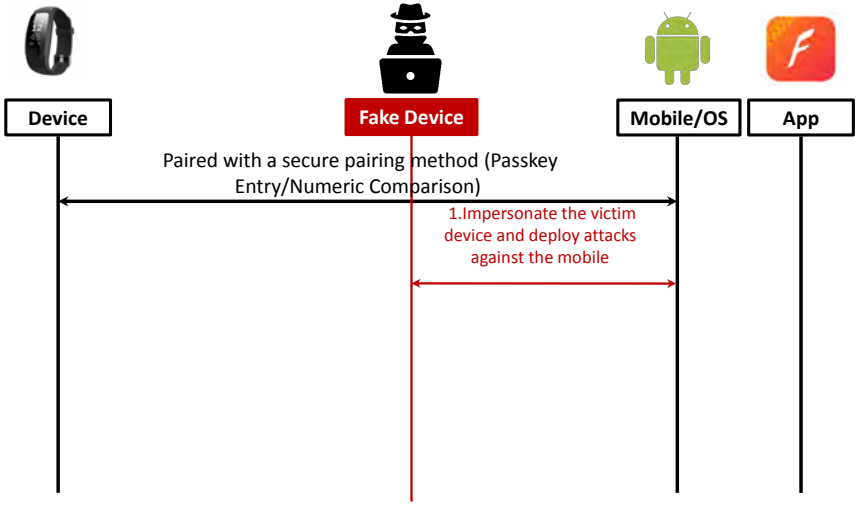

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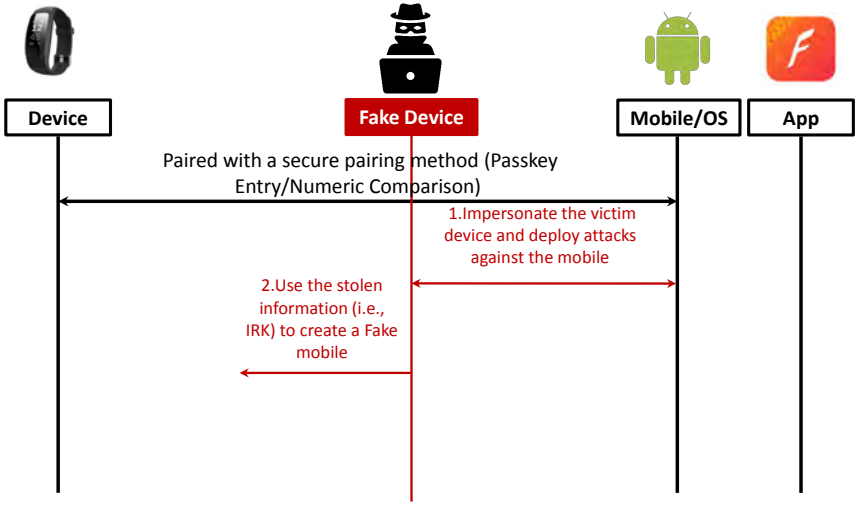

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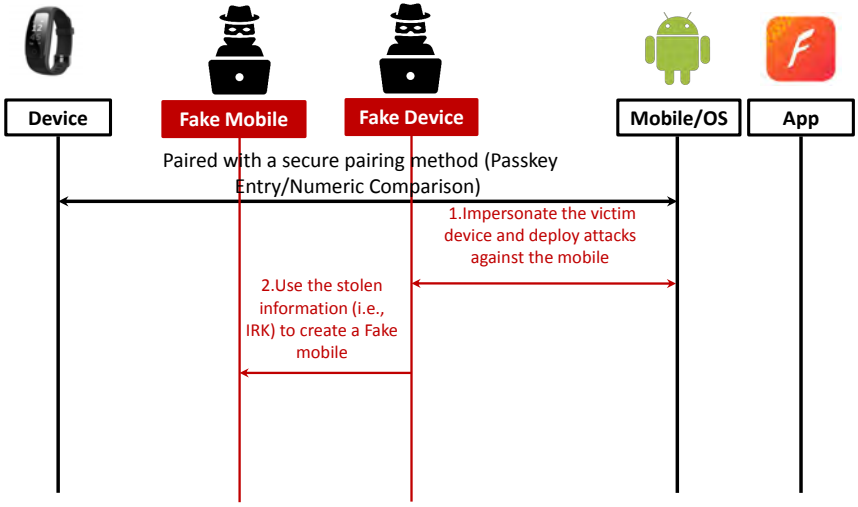

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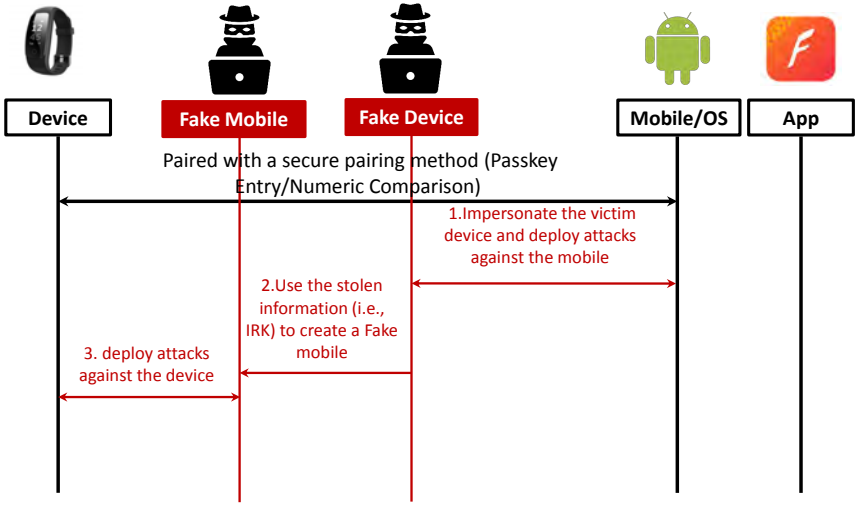

Our Downgrade Attacks against Bluetooth Low Energy [USENIX'20]

The Tested BLE devices

MITM attack against BLE keyboards

CVE-2020-9770

Our BAT Privacy Attacks [CCS'22]: Allowlist-based Side Channel

58:D7:8E:C7:8e:31

NO.	Time	Source	Destination	TYPE
1	00:00:04	58:D7:8E:C7:8e:31	Broadcast	ADV_IND

Our BAT Privacy Attacks [CCS'22]: Allowlist-based Side Channel

58:D7:8E:C7:8e:31

7e:D7:8E:C7:8e:51

NO.	Time	Source	Destination	TYPE
1	00:00:04	58:D7:8E:C7:8e:31	Broadcast	ADV_IND
2	00:00:08	7e:D7:8E:C7:8e:51	58:D7:8E:C7:8e:31	SCAN_REQ
3	00:00:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP

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4	00:00:16	4f:b7:8E:C7:8e:38	58:D7:8E:C7:8e:31	SCAN_REQ
5	00:00:24	58:D7:8E:C7:8e:31	Broadcast	ADV_IND

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5	00:00:24	58:D7:8E:C7:8e:31	Broadcast	ADV_IND

.....

200	00:15:08	73:D7:8E:C7:8e:45	58:D7:8E:C7:8e:31	SCAN_REQ
201	00:15:12	58:D7:8E:C7:8e:31	Broadcast	SCAN_RSP

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1. Cache
2. Timing
3. Power
4. Votage
5. Electromagnetic
6. Acoustic
7. Allow-list
8. ...

Our BAT Privacy Attacks [CCS'22]: MAC Address Replay

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rpa_p

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RPA Replay (rpa'$_p$)

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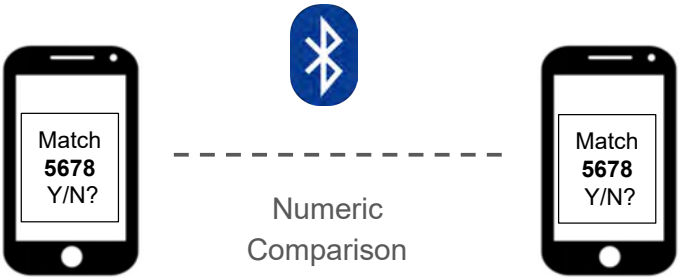
rpa$_p$

rpa'$_p$

Using Protocol Verification to Identify Confusion Attacks [NDSS'23]



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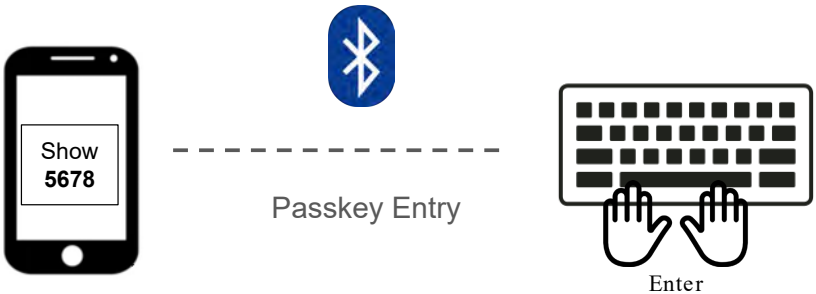

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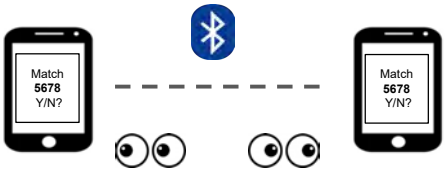
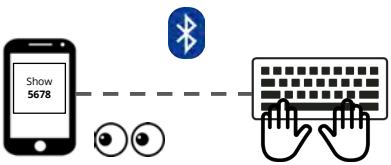


Numeric Comparison



Passkey Entry

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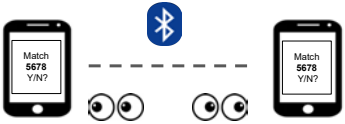

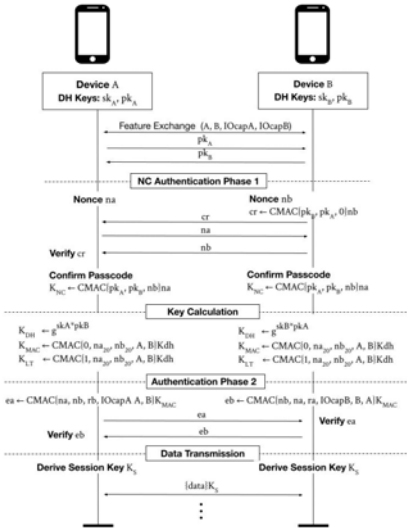

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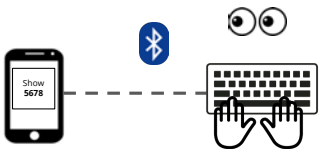

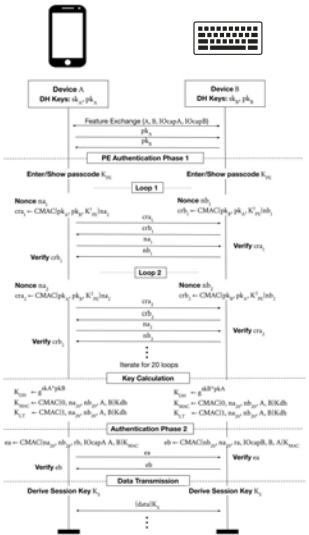

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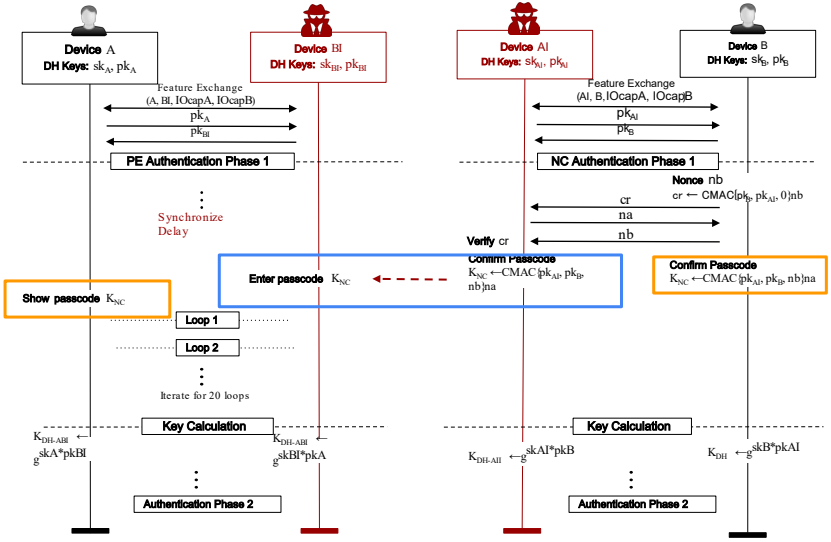

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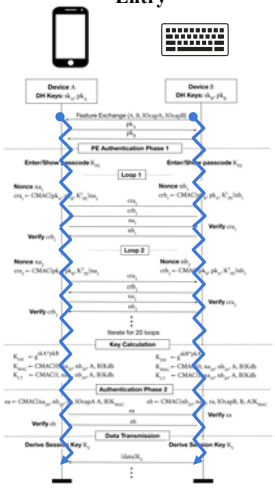

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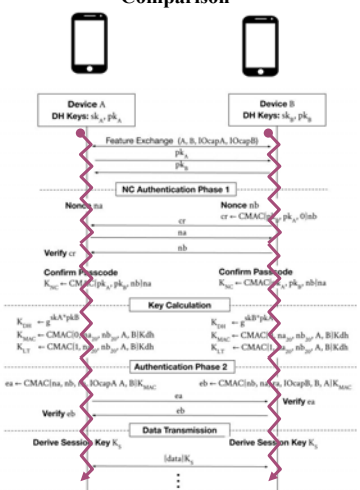
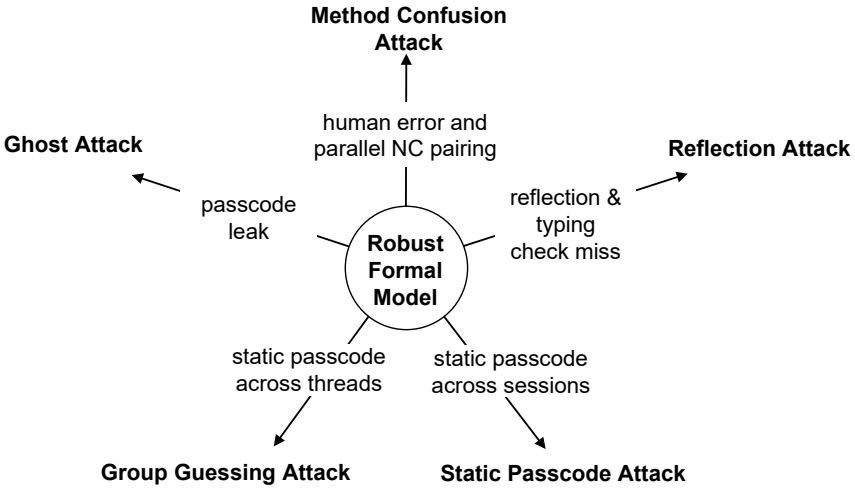
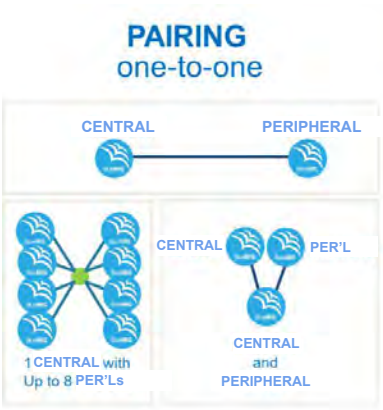


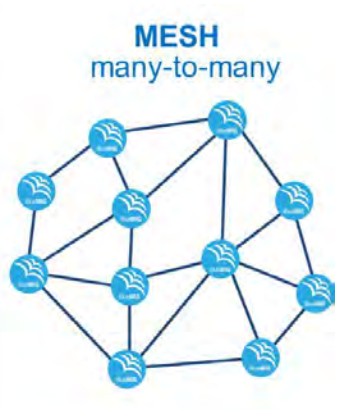
Using Protocol Verification to Identify Confusion Attacks [NDSS'23]



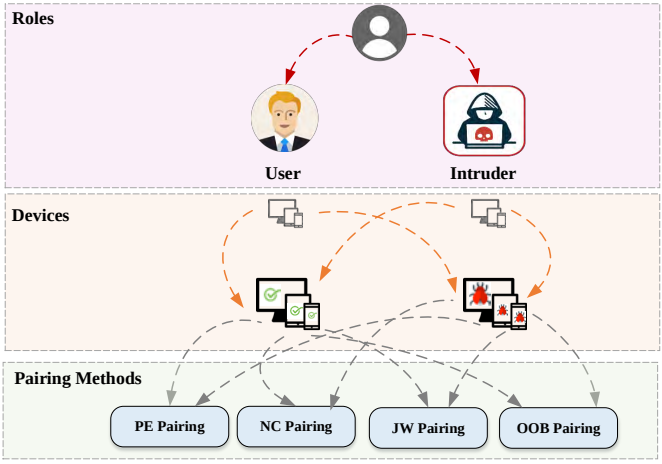
Outline

Task 1: Developing a Formal Model for Full Spectrum of the Protocols

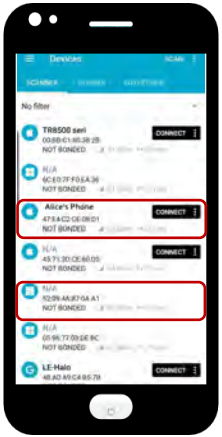




Task 2: Developing a Formal Model for All Pairing Methods (Security)



Task 3: Modelling Linkability of BLE Devices for **Privacy**



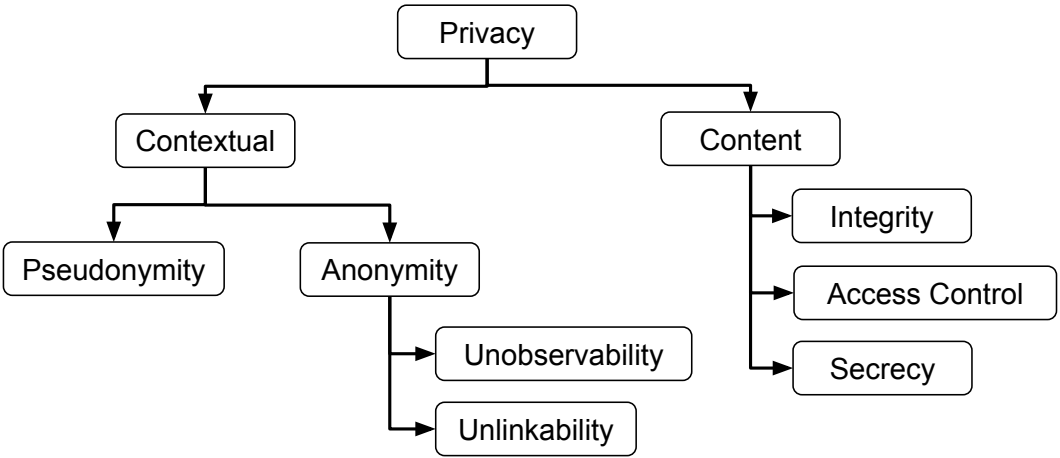
Alice's phone

Bob's phone

T1: 52:09:4A:87:0A:A1

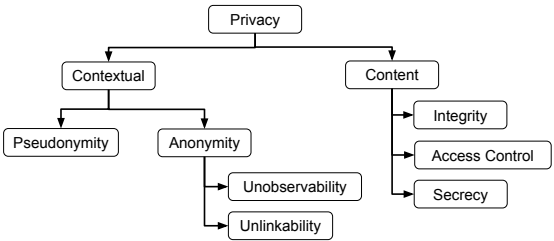
T2: 52:09:4A:87:0A:A1

Task 3: Modelling Linkability of BLE Devices for **Privacy**

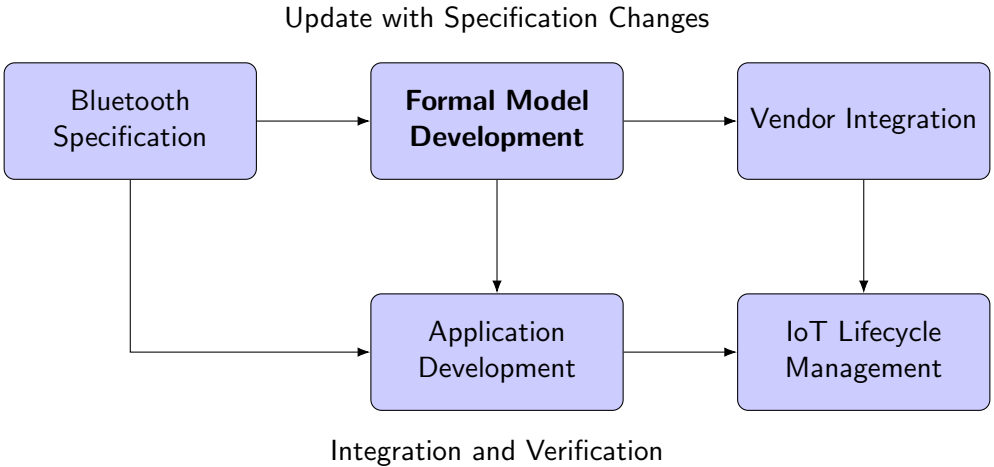


Task 3: Modelling Linkability of BLE Devices for **Privacy**

- **Unlinkability** implies that an attacker cannot relate multiple observations of user actions.
- Proposed Solution: Using Observational Equivalence
  - Finding differences between all possible execution traces of two annotated systems: left and right.



Task 4: Integrating Formal Verification into the Supply-chain



Deliverables

1. **Formal models of the Bluetooth protocol:** Complete formal models for the Bluetooth Low Energy protocol, covering its various aspects, including device pairing, authentication, and communication.
2. **Analysis of the discovered vulnerabilities:** A report detailing the identified vulnerabilities in Bluetooth, based on the formal models developed.
3. **Open-source implementation:** A prototype implementation of the proposed security enhancements for the Bluetooth protocol, released as an open-source project for the community.
4. **Research publications:** Publish findings in peer-reviewed venues to contribute to the global knowledge base on Bluetooth IoT security and privacy.