

From NDSS22 to SP22

This document contains our rebuttal to the reviews, the list of changes between the NDSS version of the paper and the current one and a paper diff.

Changelog since the submission to NDSS'22

- Abstract
 - improve the presentation of the contribution
- Introduction
 - improve the presentation of the contribution
 - update the description of the disclosure
- Background
 - better presentation of BT vs. BLE
- CTKD analysis (Section 3)
 - 3.A more clearly introduces the CTKD argument in Bluetooth v5.1/5.2
 - 3.B better introduce the need to RE CTKD despite the description in the Bluetooth standard
- BLUR attacks (Section 4)
 - 4.E better explain why the unintended session attacks are enabled by CTKD
 - 4.F collects and discusses important attacks' aspects. For example, effectiveness regardless of Bluetooth v5.1/5.2 and pairing association methods
- Evaluation (Section 6)
 - 6.B clearly explain that we empirically verified our claim regarding 5.1 and 5.2 and explain why we are not evaluating 5.1/5.2 peripherals
- Discussion (Section 7)
 - 7.A provides an extended discussion of the countermeasures
 - 7.B reintroduces the lessons learned
- Related work
 - Strengthen comparison with prior work including Table IV
- Conclusion
 - Shortened as requested

Rebuttal

We thank the reviewers for their feedback. Each of the following sections addresses comments raised by a reviewer.

Rev88A

Proposed attacks require considerable programming efforts

We do not agree that a custom attack device makes the attack less practical. *Any* attack on a wireless system needs a certain level of equipment. The programming effort is *close to zero* because we have already written the software, which will

be on GitHub when the paper is published. (It is not public yet because of responsible disclosure).

The manuscript is not discussing and evaluating the mitigation strategies in depth.

The paper proposes *concrete* countermeasures in Section 7 and explains the exact step in the attack that will fail if this countermeasure is in place, In addition, we test the most obvious countermeasure (disable key overwriting) on actual devices.

The paper does not discuss Bluetooth IDS

We are currently not discussing such IDS as we believe that our proposed countermeasures efficiently fix the root issues exploited in the attacks, and an IDS is at best a *probabilistic detection method*. Nevertheless, if the reviewers think the paper would be strengthened by a discussion of Bluetooth IDS, we are happy to add a discussion on this in a revision.

Rev88B

This paper did not perform any user study

The majority of the devices we tested did not require user interaction, not even a confirmation of “do you want to accept pairing with your device”. There were devices that showed a prompt for certain attacks and a user study might indeed be helpful. However there are already a fair number of studies that *inefficacy of security prompts*, e.g., “Alice in Warningland: A Large-Scale Field Study of Browser Security Warning Effectiveness”, and we do not believe that any study we do will add much in terms of new information.

This paper would be more solid if a formal model was built

Building a formal model of Bluetooth is not a simple task, nor is it required to show the nature of the presented attacks or how to effectively prevent them. We consider this out of the scope of our work.

Rev88C

Issues with some citations

If the reviewer is referring to the lines in the Bibliography, those mean that the authors are the same as the paper above. It is not our choice to have those, they come with the conference bibliography-style.

Scalability of the proposed solution by deploying it on small scale IoT devices.

We are not sure what is meant by this comment. We are proposing *protocol-level* attacks and mitigations that work between two Bluetooth devices, *regardless of* the number of other devices in the environment. Moreover, CTKD is *not* a

mechanism adopted by small-scale IoT devices that typically support only BLE or LoRa, or Zigbee.

How JW, address, and public key can be retrieved to perform impersonation?

The attacker only needs to know the Bluetooth address of the victim (that can be gathered by eavesdropping), JW is negotiated by the attacker, and the attacker computes her public key.

Evaluate the proposed solution thoroughly and be tested on various devices

Table 3 in our paper is a list of all the devices we tested this on. All the attacks worked on every single device we tested. We tested a countermeasure on a Linux laptop and Linux represents a considerable portion of the affected Bluetooth devices (i.e., Android smartphones, embedded devices).

Rev88D

Why does the BT SIG say something different about 5.1 and 5.2?

The current situation with the SIG is a bit controversial. In summary, they are convinced that their “key overwrite” mitigation addresses the BLUR attacks. Such mitigation is presented in the paper in Section 3A. On the other hand, we have shown that this is not the case in the paper and we provide a detailed explanation in Section 6B. The same explanation was reported recently to the SIG.

Attacks against three 5.1 or 5.2 slaves, but only against 4.1 and 4.2 masters.

The evaluation demonstrates attacks against 5.1 and 5.2 masters (e.g., smartphones). At the time of writing, there were *very few* (and expensive) 5.1 and 5.2 devices and we were not able to find 5.1 and 5.2 slaves supporting CTKD. We can clarify this point in the paper.

How the RE information relates to the standard.

The problem here is that the standard provides a *limited* description of CTKD that is not sufficient to perform a security analysis. That is why we had to perform experiments with actual devices, capture their traffic, and RE information that are missing from the standard (e.g., CTKD negotiation). As a result, the RE information is *not* implementation-specific, but *extends* what is in the standard. We will clarify it in the paper.

How CTKD makes the unintended session attack possible or more powerful

CTKD enables the unintended session attack because it provides *more ways* to pair with a victim. In a non CTKD scenario there is only one transport active

(and potentially in use) at a time. Instead with CTKD a device stays pairable on *both* BT and BLE while using only one most of the time. In the revision, we will clarify this point.

Several of the countermeasures involve users' transport-specific actions

The user is *not* involved in the countermeasure at all. Our countermeasures act at the protocol level and are transparent to end-users. It would be useful to know which specific countermeasures the reviewer is referring to so we can fix the confusion.

Why are there only two master devices of the same type in the evaluation?

The role column in Table 3 refers to the attacker role, as such, we tested only two *slave* devices. We tested 2 of them because they were the only ones at our disposal and Covid made it difficult to gather devices from colleagues and students.

Rev88E

Missing feedback from the SIG, report the issues to device vendors

The feedback is missing because the SIG has yet to provide any. Device vendors are notified by the SIG when a vulnerability is submitted, so they are aware of the problem.

Overclaiming the attacks' impact

We disagree about overclaiming the impact of the attacks. As it happens for other radio technologies, the range of Bluetooth can be extended *way over 10 meters* with a directional antenna. The fact that the attacks require radio proximity is an implicit constraint of *every* attack on a wireless protocol.

Countermeasures not addressing the issue directly. OS logging and C2.

The countermeasures we present are aimed directly at the *root causes* of the attacks. We are happy to improve the explanation if it seems to be unclear. To clarify, logging the metadata at the OS level (Bluetooth Host) does *not* entail any changes in the Bluetooth threat model, and is already employed for other purposes. C2 does *not* break the link layer as it does not introduce backward-incompatible features but it enforces backward compatible ones.

Just Works as a key requirement. How effective are the CTI's when there are other association mechanisms?

The attack works against *any* association mechanism. This is because the attacker can *downgrade* the association to Just Works even if a victim device supports a stronger association method.

BLURtooth: Exploiting Cross-Transport Key Derivation in Bluetooth Classic and Bluetooth Low Energy

Anonymous Submission

Abstract—The Bluetooth standard specifies two transports: Bluetooth Classic (BT) for high-throughput wireless services and Bluetooth Low Energy (BLE). ~~The two transports have different security architectures and threat models and provide dedicated pairing and session establishment protocols.~~ Traditionally, two devices would for very low-power scenarios. BT and BLE have dedicated pairing protocols and devices have to pair over BT and BLE to use both securely. ~~But in~~ In 2014, Bluetooth the Bluetooth standard (v4.2) addressed this usability issue by introducing Cross-Transport Key Derivation (CTKD). CTKD allows establishing BT and BLE pairing keys just by pairing over one transport of the two transports. While CTKD crosses the security boundary between BT and BLE, little ~~information is known about CTKD internals and no prior work analyzed is known about the internals of CTKD and~~ its security implications.

In this work, we present the first complete description of CTKD obtained by merging the scattered information from the Bluetooth standard ~~and results from~~ with the results from our reverse-engineering experiments. Then, we perform a security evaluation of CTKD and uncover four cross-transport issues in its specification that can be used to cross the security boundary between BT and BLE. We leverage these issues to design four standard-compliant attacks on CTKD enabling ~~to exploit BT from BLE and vice versa. The new ways to exploit Bluetooth (e.g., exploiting BT and BLE by targeting only one of the two).~~ Our attacks work even if the strongest security mechanism for BT and BLE are in place and they, including Numeric Comparison and Secure Connections. They allow to impersonate, man-in-the-middle, and establish unintended sessions with arbitrary devices. We refer to our attacks as *BLUR attacks*, as they *blur* the security boundary between BT and BLE. We provide a low-cost implementation of the BLUR attacks and we successfully evaluate them on 16 devices with 14 unique Bluetooth chips from popular vendors. We discuss the attacks' root causes and present effective countermeasures to fix them. We disclosed our findings and countermeasures to the Bluetooth SIG in May 2020 (CVE-2020-15802), and we reported additional unmitigated issues in May 2021.

Keywords—CTKD, Bluetooth, Cross-Transport Attacks

I. INTRODUCTION

Bluetooth is a pervasive wireless technology used by billions of devices including mobile phones, laptops, headphones, cars, speakers, medical, and industrial appliances [11]. ~~Bluetooth~~ It is specified in an open standard maintained by the Bluetooth special interest group (SIG), and its latest version is 5.2 [10]. The standard specifies two transports: ~~Bluetooth Classic (BT) and Bluetooth Low Energy (BLE)~~ Bluetooth Classic (BT) and Bluetooth Low Energy (BLE). BT is best suited for connection-oriented and high-throughput use cases, such as streaming

audio. BLE is optimized for connection-less and very-low-power use cases such as ~~HCI, fitness tracking, or digital contact tracing~~ fitness tracking.

The Bluetooth standard defines ~~different dedicated~~ different dedicated security architectures and threat models for BT [10, p. 947] and BLE [10, p. 1617]. Each transport provides a ~~pairing and a secure session establishment~~ pairing and a session establishment protocol. Pairing results in the establishment of a long-term pairing key ~~. While secure session that acts as the root of trust. Session establishment allows paired devices to create establish~~ a secure channel through a fresh session key derived from their shared pairing key.

Traditionally, two devices supporting BT and BLE would have to pair ~~over BT and BLE to securely use both separately on each transport.~~ In 2014 ~~Bluetooth~~, the Bluetooth standard (v4.2) introduced *Cross-Transport Key Derivation (CTKD)* to address this usability issue. CTKD enables to pair devices once, either over BT or BLE, and negotiate BT and BLE pairing keys without having to pair a second time ~~and with no extra user interaction~~ [10, p. 1401].

~~Security-wise,~~ CTKD has not received any attention from the research community and the Bluetooth standard ~~hastily~~ describes only some aspects and threats associated with CTKD. ~~On the other hand, CTKD is a very interesting. We believe CTKD provides a significant~~ attack surface, as it is a standard-compliant security feature, is used together used in conjunction with the most secure modes of BT and BLE (i.e., Bluetooth modes (e.g., Secure Connections), allows crossing and is transparent to the end-users. In addition, CTKD allows crossing the security boundary between BT and BLE, and is transparent to the end-user as CTKD forces implicit trust between BT and BLE. For example, if two devices pair over BT and generate a BLE pairing key with CTKD then the security of the BLE transport entirely relies on BT.

In this work, we present a complete description of CTKD obtained by ~~reverse-engineering key information missing from combining the incomplete and scattered information provided in~~ the Bluetooth standard (i.e., CTKD negotiation and usage and our reverse-engineering experiments needed to understand how CTKD is negotiated and used in practice for BT and BLE). Then, we perform ~~a security evaluation the first security evaluation of CTKD~~ and we uncover four cross-transport issues (CTI) with CTKD's specification: cross-transport issues (CTI) with its specification. The issues affect pairing states, role asymmetries, key generation and distribution, and association methods. For example, CTKD ~~enables to (over)write and steal security keys by design enables overwriting trusted keys with~~

malicious ones across transports.

We leverage ~~these vulnerabilities~~ the uncovered CTIs to design four ~~novel cross-transport attacks~~ cross-transport and standard-compliant attacks on CTKD. Our attacks enable ~~to impersonate and take over secure sessions from any BT/BLE master or slave device.~~ Combining master and slave impersonation the attacker can also persistent cross-transport impersonation, man-in-the-middle BT and BLE secure sessions. Furthermore, a bad actor can establish secure, but unintended, and unintended session attacks on BT and BLE sessions with a victim device while remaining anonymous via CTKD. The attacks are effective regardless of the ~~usage of the strongest security mode for BT and BLE including Secure Simple Pairing (SSP), Secure Connections (SC), and strong association~~ employed Bluetooth security mechanisms, including Secure Connections and Numeric Comparison. We name our attacks *BLUR attacks*, as ~~by exploiting CTKD, they~~ blur the security boundary between BT and BLE.

~~In contrast to prior standard-compliant attacks [22], [21], [36], [40], [9], [2], [5], [4], [44], [46], [41], our attacks~~ The BLUR attacks are the first cross-transport attacks as they can break standard-compliant BT and BLE by targeting just one of the two and the first attacks exploiting CTKD. Additionally, our attacks ~~do~~ attacks to not require the attacker to be present when a victim is pairing or establishing a secure session ~~and they result in a persistent compromise of the victim.~~, unlike prior work [22], [21], [36], [40], [9], [2], [5], [4], [44], [46], [41]. In particular, our attacks are the first that can be conducted in absence of one of the victims. The BLUR attacks are also the first that exploit interactions between BT and BLE (via CTKD). For a more detailed comparison to prior work see Section VIII.

~~We implemented~~ To demonstrate that the BLUR attacks ~~using are feasible~~ we present a low-cost hardware implementation of the attacks based on a cheap development board and open-source software ~~and we verified their standard-compliance and large-scale impact. We successfully exploited~~ — We evaluated our attacks on a large and heterogeneous sample of devices. In particular, we exploited 16 unique devices employing 14 different Bluetooth chips from Broadcom, Cambridge Silicon Radio (CSR), Cypress, Intel, and Qualcomm. Our vulnerable device set set of vulnerable devices covers all Bluetooth versions supporting CTKD (i.e., Bluetooth 4.2, 5.0, 5.1, and 5.2) and even a Bluetooth 4.1 device to which CTKD was backported.

We concretely address the BLUR attacks by presenting four ~~countermeasures fixing the four protocol-level countermeasures mitigating the~~ presented CTIs and the related BLUR attacks. Our mitigations can be implemented at the operating system level with low effort. ~~We also evaluated~~ To backup this claim we tested one countermeasure (i.e., disable key overwriting) by implementing it on a Linux laptop.

We responsibly disclosed our findings with the Bluetooth SIG two times. In May 2020 we sent our first report which was tracked with CVE-2020-15802. In September 2020 the Bluetooth SIG unilaterally released a security note ~~at with some recommendations to address the attacks. However, as we detail later in the paper, these recommendations are not~~

~~stopping the BLUR attacks. Hence, in May 2021 we provided (see https://tinyurl.com/vxhwftc2), claiming that Bluetooth 5.1 and later are not vulnerable to the presented attacks. As result, we further analyzed 5.1 and 5.2 devices, and found them to still be susceptible. We explain why this is the case in Section IV-F and experimentally confirm it in Section VI-B. We disclosed those findings to the SIG additional evidence to explain why the BLUR attacks are still effective on all Bluetooth versions supporting CTKD, but have not received a reaction. We note that the SIG is expected to notify vendors of vulnerabilities, so no separate vendor disclosure is required.~~

We summarize our main contributions as follows:

- We present a complete description of CTKD combining public and reverse-engineered information. We perform the first security evaluation of CTKD and uncover four vulnerabilities in its specification. ~~Among others~~ For example, CTKD enables to adversarially pair over unused transports and to tamper with BT and BLE security keys.
- Based on the identified issues we propose four novel and standard-compliant attacks capable of breaking BT and BLE just by targeting one of the two. Compared to related work, our attacks are the first exploiting CTKD and acting across transports. Our attacks enable to impersonate, man-in-the-middle, and establish unwanted and stealthy sessions with arbitrary devices. We name our attacks *BLUR attacks* as they blur the security boundary between BT and BLE.
- We present a low-cost implementation of the BLUR attacks based on a Linux laptop and a Bluetooth development board. We use our implementation to attack 16 different devices employing 14 unique Bluetooth chips and covering all Bluetooth versions compatible with CTKD (e.g., 4.2, 5.0, 5.1, and 5.2). Our evaluation demonstrates that the BLUR attacks are very effective and specification-compliant. To address them, we discuss four countermeasures to address the presented issues and attacks affecting CTKD.

II. BLUETOOTH CLASSIC (BT) AND LOW ENERGY (BLE)

~~We now compare the most relevant features of BT and BLE. To provide precise technical descriptions we follow the Bluetooth standard's master/slave terminology instead of more apt terms like leader/follower.~~

BT and BLE are two wireless transports specified in the Bluetooth standard [10]. These transports are ~~incompatible (e.g., they use different physical layers and link layers) and are~~ designed to complement each other. BT is used for high-throughput and connection-oriented services, such as streaming audio and voice, while BLE is optimized for very low-power and low-throughput services such as fitness tracking and digital contact tracing. High-end devices, such as laptops, smartphones, headsets, and tablets, provide both BT and BLE, while low-end devices such as mice, keyboards, and wearables provide either BT or BLE.

BT and BLE have similar security mechanisms ~~but different (i.e., pairing and session establishment) but different~~ security architectures and threat models. ~~Both transports provide a~~

~~pairing mechanism, named Pairing, also known as~~ Secure Simple Pairing (SSP), ~~to let lets~~ two devices establish a ~~long-term pairing key and authenticate a pairing key that acts as the root of trust~~. BLE SSP is performed over the Security Manager Protocol (SMP) [10, p. 1666], while BT SSP uses the Link Manager Protocol (LMP) [10, p. 568]. During pairing, BLE allows negotiating the entropy of the pairing key while BT does not. ~~Additionally~~

~~While pairing, BT and BLE provide a secure session establishment mechanism to employ similar association mechanisms.~~ For example, *Just Works* association is supported by all Bluetooth devices as it does not require user interaction, but it does not protect against MitM attacks. ~~While Numeric Comparison association protects against MitM attacks by asking the user to confirm a numeric code on the pairing devices' screens.~~ As the Bluetooth standard does not protect the negotiation of the association method, an attacker can always *downgrade* it to *Just Works* even if the victim device has I/O capabilities.

~~Session establishment lets paired devices~~ establish a secure communication channel ~~using a~~. The channel is protected by a *fresh* session key derived from ~~a pairing key the pairing key and some nonces~~. During session establishment, BT allows negotiating the entropy of the session key while the BLE session key inherits the entropy of the associated pairing key.

BT and BLE use the same notion of ~~pairable and discoverable~~ *pairable* and *discoverable* states. If a device is *pairable* then it accepts pairing requests from other devices. If it is *discoverable* it reveals its identity when scanned by other devices. Notably, a device answers to a pairing request even if it is ~~not not~~ *discoverable* [43]. For example, if the user knows the Bluetooth address of her pair of headphones she can complete BT or BLE pairing ~~with her smartphone by sending a pairing request from her laptop~~ without putting the headphones into *discoverable* mode.

BT and BLE provide a ~~“Secure Connections”~~ *Secure Connections* mode which enhances ~~their security primitives without affecting their security mechanisms~~ *the security primitives in use without affecting the underlying protocols*. In particular, *Secure Connections* mandates the usage of FIPS-compliant algorithms such as AES-CCM, HMAC-SHA-256, and the ECDH on the P-256 curve [10, p. 269]. ~~Furthermore, BT and BLE employ similar association mechanisms to authenticate pairing. Two examples of associations are Just Works that does not protect against MitM attack but requires no user interaction. Numeric Comparison instead protects against MitM attacks by forcing the user to confirm that she sees the same numeric code on the pairing devices' screens.~~

Both BT and BLE use a ~~master-slave~~ *master-slave* medium access protocol ~~but define the master and slave roles differently.~~ For BT, ~~the master~~. The *master* (BLE *central*) is the connection initiator, ~~the slave is the connection responder, and roles can be switched dynamically by any party after a radio link is established.~~ For BLE, ~~the master and slave while the slave (BLE peripheral) is the responder. BT allows to switch roles dynamically, while BLE roles are fixed and cannot be switched.~~ The BLE *master* (defined as *central*) acts as the connection initiator and the BLE *slave* (defined as *peripheral*) as the connection responder. High-end devices, such as laptops and

smartphones, support both BLE master and BLE slave modes and are typically used as BLE masters, while low-end devices, such as fitness trackers and smartwatches, support only the BLE slave mode ¹.

III. DESCRIPTION AND SECURITY ANALYSIS OF CTKD

In this section, we present ~~our the first complete description and~~ security analysis of CTKD. ~~In particular, in~~. In Section III-A we describe what is publicly known about CTKD, in Section III-B we complement ~~it by reverse engineering how CTKD works in practice.~~ Finally, ~~in those information with other crucial ones that we had to reverse engineer (e.g., CTKD negotiation for BT and BLE).~~ In Section III-C, we ~~present four security issues with CTKD's specification, which uncover four critical and novel cross-transport issues (CTI) in the specification of CTKD.~~ These issues are the root causes of the *BLUR attacks*. ~~The attacks' implementation is described standard-compliant and cross-transport attacks presented in Section V, while their evaluation is detailed and evaluated in Section VI.~~

A. Public Information about CTKD

~~CTKD is a feature provided by~~ As described in the *Introduction*, CTKD was introduced in the Bluetooth standard to improve the ~~usability~~ *usability* of BT and BLE ~~pairing~~. Before the introduction of CTKD, ~~a user had to pair devices separately devices had to separately pair over BT and BLE before being able to use both transports securely.~~ While with CTKD, ~~introduced in 2014 with Bluetooth version 4.2, two devices, can pair onethe devices pair once,~~ either over BT or BLE, derive a pairing key for each transport and establish BT and BLE secure sessions [10, p. 280].

~~CTKD is Being a standard-compliant feature CTKD has to be supported by all major hardware and software Bluetooth vendors.~~ The list of vendors includes Apple [45], Google [6], Cypress [15], Linux [13], Qualcomm [34], and Intel [23]. Notably, Apple presented it as a core and always-on Bluetooth feature during WWDC 2019.

To use CTKD, a device requires ~~specific capabilities. A device must be few capabilities. It must be a~~ *dual-mode device* (i.e., support both BT and BLE), has to support *Secure Connections* (~~introduced in Section II) and, and implement a~~ Bluetooth version among 4.2, 5.0, 5.1, and 5.2. Examples of devices supporting CTKD are laptops, tablets, smartphones, headsets, speakers, and high-end wearable devices. The number of those devices is steadily growing as dual-mode devices are replacing single-mode ones [12].

CTKD ~~specifies a unique key derivation function (KDF) regardless of which transport is used to pair employs the same deterministic key derivation function (KDF) for BT and BLE~~ [10, p. 1658]. The ~~function~~ *KDF* takes as inputs a 128-bit (16-byte) key and two 4-byte strings and derives a 128-bit (16-byte) key. If CTKD is started from BLE, then the BT pairing key is derived using the “tmp2” and “brle” strings. In the other case, the derivation is performed using the “tmp1” and “lebr”

¹For precise technical descriptions in the rest of the paper we follow the *Bluetooth standard's* master/slave terminology instead of more apt terms like leader/follower.

strings. The key derivation function is deterministic, as using CTKD on the same input key will always generate the same output key. ~~Our implementation of KDF is discussed in We re-implemented KDF to validate our analysis, see Section V-C for more details.~~

The Bluetooth standard lacks a security analysis of CTKD but provides only a *limited and version-specific security argument*. Since version 5.1, ~~the Bluetooth standard addresses a specific key overwrite attack via CTKD with the following statement: “While performing cross-transport key derivation, if the key for the other transport already exists, then the devices shall not overwrite that existing key with a key that is weaker in either strength or MITM protection”~~ the standard states that ~~“While performing cross-transport key derivation, if the key for the other transport already exists, then the devices shall not overwrite that existing key with a key that is weaker in either strength or MITM protection”~~ [10, p. 1401]. ~~This means that In other words, an attacker cannot overwrite a pairing key with CTKD if the overwritten-overwriting key has either a lower entropy (i.e., strength) or a lower MitM protection. We note that the attacker can still While this can be expected to protect against attacks in limited settings, other scenarios and attacks are still possible. For example, an adversary can still overwrite keys with equal-equal strength and MitM protection. It is not clear why such countermeasure is enforced only on-without violating the standard (as we experimentally demonstrate in Section VI-B). In addition to the limited scope of the countermeasure, it is unclear why it was introduced only for 5.1 and 5.2 devices and is not backported to all devices compatible with CTKD.~~

~~The quoted countermeasure is not effective against the key overwrite attack presented in Section IV as the attack is neither lowering the key entropy (i.e., strength) nor the MitM requirements. We experimentally validated this claim by performing our key downgrade attack on-not for all Bluetooth versions supporting CTKD, and how it should be interpreted when one of the devices does not support Bluetooth 5.1 and or 5.2 devices (see Section VI-B for an extended discussion).~~

B. Reverse-Engineered CTKD Protocols

The ~~Bluetooth standard lacks a discussion about public information that we gathered about CTKD, including the ones provided by the Bluetooth standard are not sufficient to perform a security analysis of CTKD. Specifically, from the standard is not clear how CTKD is negotiated and used negotiated for BT and BLE. We had to reverse-engineer (RE) these details to perform our security analysis. In this section, we summarize what we reversed about CTKD negotiation and usage. To ease our description, we abstract the protocols at a message level and we and if the protocols differ. To address this problem, we reverse-engineered the CTKD negotiation protocols for BT and BLE. Here we present them abstracting the description at the message level. We refer to the Bluetooth master and slave as Alice and Bob. Finally, we also to the slave as Bob and in the figure we color-code BLE with light blue and BT with blue. At the end of the section, we detail our RE methodology.~~

a) ~~BLE pairing with CTKD: CTKD from BLE~~ Figure 1 shows ~~what happens when two devices are pairing over~~

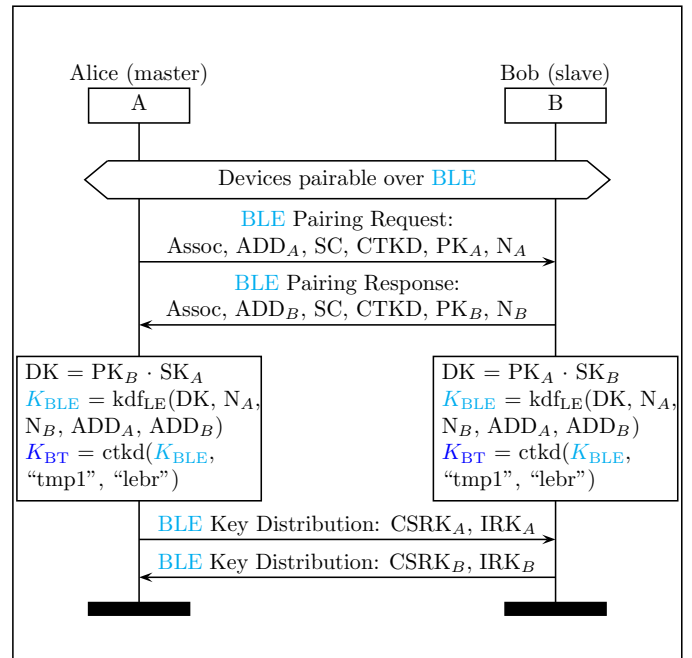


Fig. 1: ~~BLE pairing with CTKD from BLE~~. Alice and Bob negotiate SC and CTKD support during BLE pairing. Then, they compute the BLE pairing key and from that key, they derive the BT pairing key via CTKD (without exchanging any message over BT). Finally, they generate and exchange additional keys for BLE including signature (CSRK) and identity resolving (IRK) keys. After the protocol is completed Alice and Bob can establish secure sessions both for BT and BLE (without having to pair over BT).

~~BLE and using CTKD to derive also the BT pairing key how CTKD is negotiated and used from BLE to derive BLE and BT pairing keys.~~ Alice and Bob are pairable over BLE and BT and discover each other using BLE scanning and advertising. Then, they perform pairing over BLE using the SMP protocol. We found that CTKD is negotiated by setting to one the Link Key flag of the Initiator and Responder key distribution SMP fields [10, p. 1680] and that such negotiation is not protected. Other than the Link Key flag the devices should also declare Secure Connections support (SC) which is also spoofable. The BLE pairing messages also contain an association method (Assoc), a source BLE address (ADD), a public key (PK), and a nonce (N).

After exchanging the pairing messages, the devices compute a Diffie-Hellman shared secret (DK) using the exchanged PK. DK is used to compute the BLE pairing key (K_{BLE}) using BLE pairing key derivation function (kdf_{BLE}). Then, the devices use CTKD’s key derivation function ($ctkd$) to derive the BT pairing key (K_{BT}). To complete BLE pairing, Alice and Bob establish a secure session over BLE and exchange additional keys (e.g., CSRK and IRK). As a result, Alice and Bob share K_{BLE} and K_{BT} , but they only paired over BLE.

a) ~~BT pairing with CTKD: CTKD from BT~~ Figure 2 presents ~~BT pairing with CTKD how CTKD is negotiated and used from BT to derive BT and BLE pairing keys.~~ Alice and Bob are pairable over BT and BLE and discover each

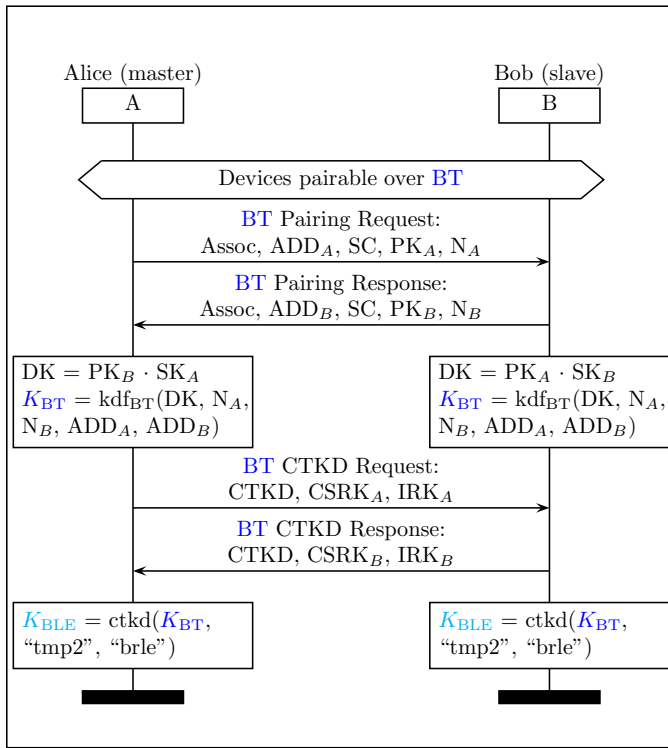


Fig. 2: **BT pairing with CTKD from BT**. Alice and Bob during BT pairing negotiate SC support. Then, they compute the BT pairing key, start a secure session over BT and send BT CTKD messages containing CTKD support and other keying material generated for BLE such as signature (CSRK) and identity resolving (IRK) keys. Notably, the CTKD request and response are encoded as BLE pairing request and response and tunneled over BT. Afterward, Alice and Bob derive the BLE pairing key, via CTKD (without exchanging any message over BLE). After the protocol is completed Alice and Bob can establish secure sessions both for BT and BLE (without having to pair over BLE).

other via BT inquiry. Then, they exchange pairing request and response messages over BT to negotiate several BT capabilities (including SC), and to exchange their BT addresses, keys, and nonces. Then, they compute DK and use it together with their BT addresses and nonces to compute the BT pairing key (K_{BT}) through the BT pairing key derivation function (kdf_{BT}).

Unlike for BLE, BT pairing messages do not include a CTKD flag. What happens is that the devices start a secure BT session and exchange two messages containing the CTKD flag and additional security material needed for BLE such as signature keys (CSRK) and identity resolving keys (IRK). These two messages are peculiar as they are encoded as BLE SMP packets but sent over BT. We are not sure why the Bluetooth standard is not describing such "BLE tunneling" protocol to negotiate CTKD from BT. Once CTKD is negotiated, Alice and Bob use it to derive the BLE pairing key (K_{BLE}) from the BT key and the static strings "tmp2" and "brle".

a) **RE methodology: RE methodology** To RE the negotiation and usage of CTKD we used a Linux laptop connected to a dual-mode development board as a test device. The laptop

runs a patched Linux kernel capable of pairing diagnostic messages from the board. The board acts as the laptop fronted (i.e., the laptop is the BT/BLE Host while the board is the BT/BLE Controller), and is initialized to report to the laptop all sent and received link-layer traffic using HCI diagnostic messages.

To test CTKD from BLE we sent a BLE pairing request from our test device to a pair of dual-mode headphones (Sony WH-1000XM3) and we monitored the HCI log. To check out CTKD from BT we sent a BT pairing request from our test device to an Android smartphone (Pixel 2) and we monitored the HCI log. In each case, we tested that it was possible to establish BT and BLE secure sessions after only pairing on one transport. Notably, CTKD from BT was particularly tricky to reverse as the CTKD negotiation messages over BT are decoded by Wireshark but appear as standard L2CAP messages.

C. CTKD Cross-Transport Issues (CTI)

We isolated four ~~cross-transport issues (CTI)~~ cross-transport issues (CTI) with the specification of CTKD resulting from CTKD bridging BT and BLE without properly enforcing the security boundary between the two. We now describe in detail each CTI.

a) ~~CTI 1: extended pairing~~: CTI 1: extended pairing

CTKD introduces more options to pair two devices as dual-mode devices are pairable over BT and BLE all the time. This enables an attacker to (silently) pair over a transport that is currently unused. The attacker does not need to wait until a victim is in discoverable mode, as, despite common belief, a Bluetooth device in pairable state already accepts pairing requests.

a) ~~CTI 2: role asymmetry~~: CTI 2: role asymmetry

While BT and BLE roles are defined differently, CTKD does not enforce which role was used to pair on which transport. BT roles can be switched even before pairing, while BLE roles are fixed. This is problematic because an attacker can adversarially switch BT role before using CTKD and send a BT pairing request to a victim which expects BT and BLE pairing responses. We note that, issues with role asymmetry have been already proven effective to bypass BT authentication during session establishment [4].

a) ~~CTI 3: key tampering~~: CTI 3: key tampering

CTKD enables to tamper with all BT security keys from BLE and vice versa using only a single run of the pairing protocol. This is a new and powerful attack primitive for Bluetooth. For example, an attacker can use CTKD to write new pairing keys for BT and BLE or even overwrite trusted pairing keys with her own. Furthermore, by using CTKD from BT the attacker can get access to all BLE security keys distributed as part of BLE pairing including identity resolving key usable to de-anonymize a BLE device.

a) ~~CTI 4: association manipulation~~: CTI 4: association manipulation

CTKD does not keep track of which association mechanism was used as part of pairing and the negotiation of the association scheme is not protected. Indeed, an attacker can use CTKD to re-establish pairing keys using an arbitrary association scheme. This includes a weak association to write or substitute authenticated keys with

unauthenticated ones (e.g., by re-pairing using Just Works). Recently, association confusion attacks have been proposed for BT or BLE [41], CTKD extends this issue across transports.

IV. ATTACKS VIA CTKD

We now present our threat model and the design of four novel and standard-compliant attacks on CTKD. Our attacks are the first samples of *cross-transport* exploitation for Bluetooth, as they are capable of exploiting BT and BLE just by targeting either of the two. ~~Our attacks are stealthy as CTKD is transparent to the users, and do not require a strong attacker model as the attacker does not have to be present when the victims are pairing or establishing a secure session. For example, they can be conducted at any time against arbitrary devices (including the ones supporting BT and BLE SC, and SSP with strong association).~~ More-over, they are the first attacks exploiting CTKD. The attacks do not require a strong attacker model as the attacker does not have to be present when the victims are pairing or establishing a secure session. For example, they can be conducted at any time against arbitrary devices (including the ones supporting BT and BLE SC, and SSP with strong association). As our attacks are blurring the security boundary between BT and BLE, we name them *BLUR attacks*.

~~The attacks were discovered by inference from the analysis presented in Section III and the data collected during our experiments with real devices (e.g., BT and BLE link layer and HCI packets).~~

A. System Model

Our system model considers two victims, Alice and Bob, who can securely communicate over BT and BLE. The victims support CTKD, and are using the most secure BT and BLE modes, namely, SC and ~~strong association (e.g., Numeric Comparison if both have the necessary IO)~~ SSP with strong association. This setup ~~should~~ should protect the victims against ~~device impersonation, traffic eavesdropping, and active eavesdropping, impersonation, and man-in-the-middle attacks on BT and BLE~~ as claimed in [10, p. 269]. Without loss of generality, we assume that Alice is the master and Bob is the slave.

Regarding the notation, we indicate a BT pairing key with K_{BT} , a BT session key with SK_{BT} , a BLE pairing key with K_{BLE} , a BLE session key with SK_{BLE} . We indicate a Bluetooth address with ADD, a public key with PK, a private key with SK, a shared Diffie-Hellman secret with DK, a nonce with N, and a message authentication code with MAC.

B. Attacker Model and Goals

Our attacker model considers Charlie, ~~a remote attacker who is in Bluetooth radio range with the victims. The attacker aims to compromise the secure BT and BLE sessions between the victims without tampering with their devices. The attacker's knowledge is limited to what the victims advertise over the air, e.g., full or partial Bluetooth addresses, Bluetooth names, authentication requirements, IO capabilities, and device classes.~~ an attacker in Bluetooth range with the victims. The attacker aims to compromise the secure BT and BLE sessions between the victims without tampering with their devices. The attacker's knowledge is limited to what the victims advertise over the air, e.g., full or partial Bluetooth addresses, Bluetooth names, authentication requirements, IO capabilities, and device classes.

~~The attacker does not know any BT or BLE key shared between the victims, does not have to be present when the victims pair or negotiate a secure session. The attacker and security and IO capabilities. She can scan and discover devices, send pairing requests and responses, use CTKD, propose weak association mechanisms (e.g., Just Works), and dissect and craft~~ she can scan and discover devices, send pairing requests and responses, use CTKD, propose weak association mechanisms (e.g., Just Works), and dissect and craft

Bluetooth packets. However, the attacker does not know any pairing or session key shared between the victims, and does not have to be present when the victims pair or negotiate a secure session. Moreover, she cannot access and tamper with the victim devices.

The attacker has four goals. ~~The first one is to impersonate Alice (to Bob) and potentially take over Alice's secure sessions. The second goal is to impersonate Bob (to Alice) and also take over Bob's secure sessions. By i) impersonate Alice (master) and take over her secure sessions with Bob. (ii) impersonate Bob (slave) and take over his secure sessions with Alice. (iii) man-in-the-middle Alice and Bob's secure session (iv) establish unintended and stealthy sessions with Alice and Bob.~~ The first one is to impersonate Alice (to Bob) and potentially take over Alice's secure sessions. The second goal is to impersonate Bob (to Alice) and also take over Bob's secure sessions. By i) impersonate Alice (master) and take over her secure sessions with Bob. (ii) impersonate Bob (slave) and take over his secure sessions with Alice. (iii) man-in-the-middle Alice and Bob's secure session (iv) establish unintended and stealthy sessions with Alice and Bob.

Let us clarify some aspects of the attackers' goals. By "take over" we mean that after the attack the security bond between the two victims is broken. We note that, Alice and Bob's impersonations are different goals (e.g., when Charlie takes over a session from Alice then Alice will not be able to connect back to Bob). Master and slave impersonation are indicated as different goals, as they require different impersonation techniques (i.e., master and slave impersonations).

~~The attacker's third objective is to establish a man-in-the-middle position in a secure session between two victims and requires combining and synchronizing Alice and Bob's impersonation attacks. The fourth objective is to establish unintended and possibly stealthy sessions with Alice or Bob attack strategies. We define an unintended session as a session established with a victim device as an arbitrary device, without taking over a session and without breaking existing security bonds. An unintended session enables the attacker to access a much broader attack surface than the one exposed in a connection-less scenario (e.g., Charlie silently pairs with Alice as a random device using CTKD and connects with Alice over BT and BLE).~~ The attacker's third objective is to establish a man-in-the-middle position in a secure session between two victims and requires combining and synchronizing Alice and Bob's impersonation attacks. The fourth objective is to establish unintended and possibly stealthy sessions with Alice or Bob attack strategies. We define an unintended session as a session established with a victim device as an arbitrary device, without taking over a session and without breaking existing security bonds. An unintended session enables the attacker to access a much broader attack surface than the one exposed in a connection-less scenario (e.g., Charlie silently pairs with Alice as a random device using CTKD and connects with Alice over BT and BLE).

C. Attack Strategy

We now describe our attack strategy ~~using Alice's impersonation as a reference example and~~ using Alice's impersonation as a reference example and with the help of Figure 3. Let us assume that Alice is a laptop and Bob is a pair of headphones and the victims are already paired and they are running a secure BT session. Since the victims support CTKD, they are also pairable over BLE, even if the transport is not currently in use. Charlie sends a BLE pairing request to Bob (the victim) pretending to be Alice, and claiming ~~to support CTKD CTKD support~~ no input/output capabilities to trigger unauthenticated JW association during pairing no input/output capabilities to negotiate unauthenticated Just Works (JW) association. The attacker also declares ~~no input/output capabilities to trigger unauthenticated JW association during pairing no input/output capabilities to negotiate unauthenticated Just Works (JW) association~~ no input/output capabilities to trigger unauthenticated JW association during pairing no input/output capabilities to negotiate unauthenticated Just Works (JW) association. This last step does ~~not~~ not trigger the key overwrite countermeasure described in Section III-A as the attacker is neither changing the MitM protection flag nor the strength (i.e., entropy) of the pairing key.

Bob, even if running a BT session with Alice, has to answer to Charlie with a BLE pairing response as Charlie's message is compliant with the Bluetooth standard. Then, Charlie (as Alice) and Bob agree on a BLE pairing key and, via CTKD, generate a new BT pairing key that overwrites Alice's key in Bob's BT key store. In doing so, Charlie, wins two prizes with one shot, as he takes over Alice's BT and BLE sessions with

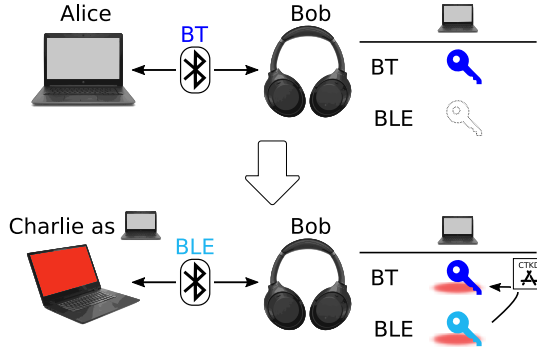


Fig. 3: Attack strategy. Alice and Bob are paired over BT and run a secure BT session. Charlie pairs with Bob as Alice over BLE declaring CTKD support. Then Charlie agrees upon a BLE pairing key with Bob, and, via CTKD, tricks Bob into overwriting Alice’s BT pairing key. As a result, Charlie can establish BT and BLE sessions with Bob as Alice, and takes over the real Alice who can no longer connect to Bob. Using a similar strategy, Charlie can also impersonate Bob to Alice, man-in-the-middle Alice and Bob, and establish unintended BT and BLE sessions as an arbitrary device.

Bob. In other words, Alice can no longer connect to Bob as she does not know the BT and BLE pairing keys (overwritten by the attacker). Furthermore, Charlie also overwrites other security keys that are distributed during pairing, including CSRK (signature key) and IRK (MAC randomization key). We note that the overwrite trick is transparent to the end user as the standard does not mandate to notify the user about CTKD, and works even if Alice and Bob are sharing BT *and* BLE pairing keys before the attack takes place.

Following a similar strategy, Charlie can impersonate Bob to Alice, man-in-the-middle them, and create unintended sessions as an arbitrary device with a victim. We note that our attack strategy is effective because the Bluetooth standard does not enforce important security properties at the boundary between BT and BLE and does not address all cross-transport threats in its threat model (see Section III-C for more details). In the remaining of this section, we describe the technical details of the four BLUR attacks.

D. Impersonation Attacks

a) **Master impersonation:** **Master impersonation** Charlie impersonates Alice and takes over her BT and BLE sessions with Bob as in Figure 4. Bob is already paired with Alice, and can run a BT session with her while Alice’s impersonation takes place. Notably, Bob must be pairable over BT and BLE to support CTKD from BT and BLE. Charlie takes advantage of that and sends a BLE pairing request as Alice by using Alice’s Bluetooth address (ADD_A), Just Works (JW) association while pairing, his public key (PK_C), and CTKD support.

As Charlie’s BLE pairing request is standard-compliant, Bob sends back a BLE pairing response believing that Alice wants to pair (or re-pair) over BLE using CTKD. Then, Charlie and Bob compute K_{BLE} , derive K_{BT} via CTKD, and exchange additional BLE key material (e.g., CSRK, IRK) over a BLE secure session. After the master impersonation attack is

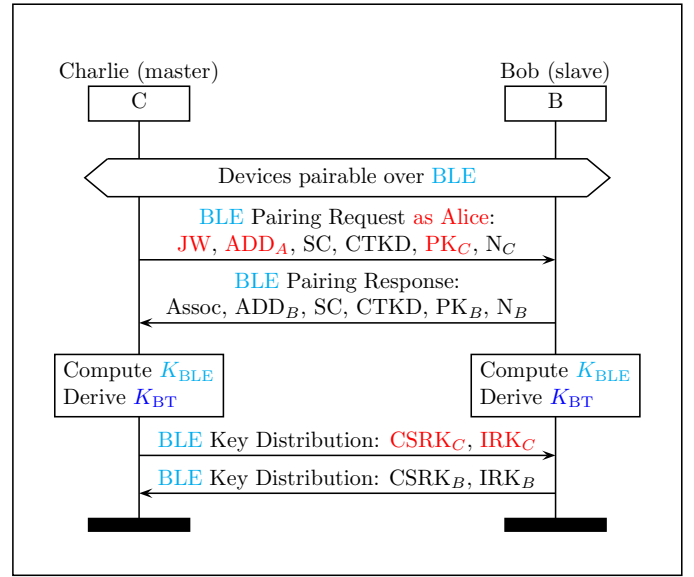


Fig. 4: BLUR master impersonation attack. Charlie sends a BLE pairing request with Alice’s address (ADD_A) including Just Works (JW) association, CTKD, and his public key (PK_C). Bob answers with a BLE pairing response thinking that he is talking to Alice. The attacker and the victim agree on K_{BLE} , and derive K_{BT} , via CTKD and complete BLE pairing by generating and distributing more keys over a secure BLE session. As a result of the master impersonation attack, Charlie tricks Bob into overwriting Alice’s keys with his ones and takes over Alice who can no longer connect back to Bob.

completed Charlie takes over Alice’s BT and BLE sessions by tricking Bob into overwriting Alice’s BT and BLE keys with his ones.

a) **Slave impersonation:** **Slave impersonation** Charlie impersonates Bob and takes over his BT and BLE sessions with Alice as in Figure 5. Alice and Bob have already paired and can run a BLE secure session while the impersonation takes place. Alice has to be pairable over BT and BLE to provide CTKD support from both transports, and Charlie takes advantage of that by sending a BT pairing request to Alice as Bob using Bob’s address (ADD_B), Just Works (JW), and his public key (PK_C). Charlie’s pairing request is still standard-compliant even if Charlie is supposed to be the slave as BT, unlike BLE, enables a slave to switch to a master role before sending a pairing request.

Alice answers with a BT pairing response believing that Bob wants to re-pair over BT, and the two agree on K_{BT} . Then, Charlie starts a secure BT session and sends a tunneled BLE pairing request to Alice still pretending to be Bob. The BLE pairing request includes CTKD support and Charlie’s signature and MAC randomization BLE keys ($CSRK_C$, IRK_C). Alice answers with a BLE pairing response tunneled over BT and the two derives K_{BLE} via CTKD. Once the slave impersonation attack is completed, Charlie takes over Bob’s BT and BLE sessions by tricking Alice into overwriting Bob’s BT and BLE keys with his ones.

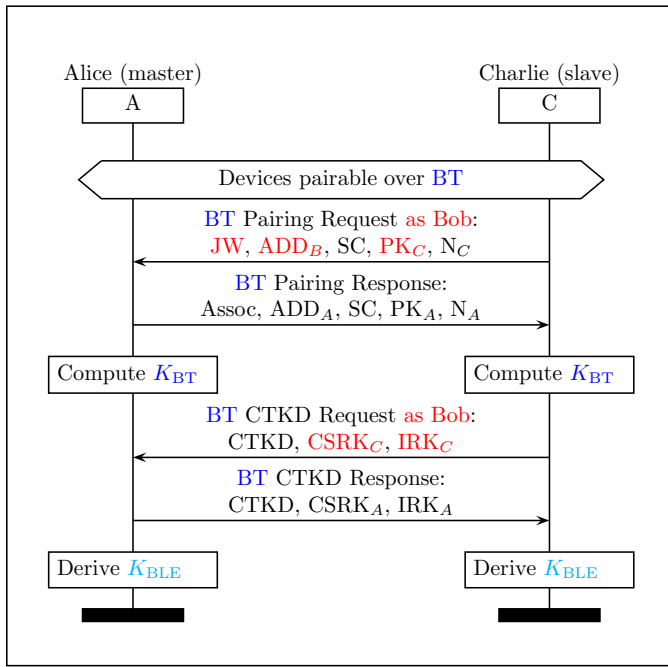


Fig. 5: BLUR slave impersonation attack. Charlie sends a BT pairing request with Bob’s address (ADD_B) including Just Works (JW) association, and his public key (PK_C). The pairing request is valid as BT enables to dynamically switch from slave to master before sending a pairing request. Alice answers with a BT pairing response believing that she is talking to Bob. The attacker and the victim establish K_{BT} , negotiate CTKD and exchange additional keying material for BLE with a BT CTKD request and response messages, and derive K_{BLE} . As a result of the slave impersonation attack, Charlie tricks Alice into overwriting Bob’s keys with his ones and takes over Bob who can no longer connect back to Alice.

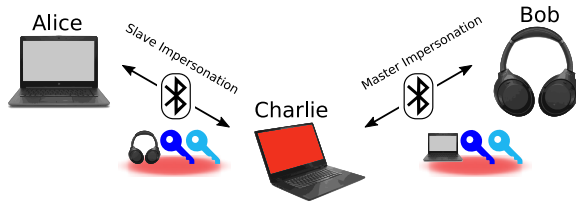


Fig. 6: BLUR MitM attack. Charlie combines the master and slave impersonation attacks presented so far to establish a man-in-the-middle position between Alice and Bob both on BT and BLE.

a) *Man-in-the-middle*: **Man-in-the-middle** Charlie can conveniently combine the described master and slave attacks to launch a cross-transport man-in-the-middle attack as shown in Figure 6. If Alice and Bob are running a BLE session, Charlie starts with the slave impersonation attack presenting to Alice as Bob over BT. Otherwise, he launches a master impersonation attack by targeting Bob as Alice over BLE. After the first impersonation attack, the impersonated victim is taken over and disconnects from the other victim. Then, Charlie targets the impersonated victim with a second impersonation attack and establishes a MitM position between the two victims. As a

result, Charlie controls all BT and BLE secure sessions between Alice and Bob.

E. Unintended Session Attacks

~~BLUR unintended sessions attack. Charlie can take advantage of CTKD to establish unintended BT and BLE session with Bob as a random device with arbitrary capabilities. The same can happen if Charlie targets Alice.~~

~~The attacker can take advantage of CTKD to establish unintended secure sessions as an anonymous device. This attack is valuable for four main reasons. Firstly, the attack is stealthy as the attacker can pretend to be any device and does not have to break existing bonds. Secondly, the attacker can enumerate and tamper with all CTKD enables unintended session attacks as it provides more ways to (silently) pair devices. In particular, two devices supporting CTKD are always pairable over BT and BLE services running on the victim device (including the protected ones) without having to impersonate a trusted device. Thirdly, but typically they use one transport at a time. Hence, the attacker can anonymously gain access to extra key-material including identity resolving keys that de-anonymize BLE devices using random addresses. Finally, the attacker can silently reach more (vulnerable) code including RCE in the pairing and secure session code, which is unreachable by an untrusted device target the unused transport as a stepping stone to establish trusted bonds on BT and BLE via CTKD, while impersonating a random device. To the best of our knowledge, this attack technique is new in the context of Bluetooth.~~

Let us see how an unintended session attack works in a scenario where Alice and Bob are already paired and are running a secure BT session (see Figure 7). ~~As in the impersonation attack scenario, Alice and Bob must also be pairable over BLE to support CTKD.~~ Charlie targets Bob by sending a BLE pairing request using a random Bluetooth address, CTKD support, and Just Works for association. Bob answers to Charlie’s request and the two negotiate K_{BLE} , and derive K_{BT} via CTKD. Now, Charlie can establish secure but unintended BT and BLE sessions with Bob without breaking Bob’s existing sessions (e.g., with Alice) and by using an anonymous identity and arbitrary capabilities. Using a similar strategy, Charlie can reach the same goals targeting Alice.

An unintended session attack is valuable for various reasons. It is stealthy as the attacker can establish a trusted relation with the victim as an anonymous device and with minimal user interaction (e.g., Just Works). Moreover, it allows complete device enumeration as the attacker, being a trusted peer, can access all BT and BLE services, including the protected ones unlike other attacks such as [14]. Additionally, the attack deterministically de-anonymizes BLE devices, as the attacker get access to the identity resolving key distributed during pairing. Finally, it enables the attacker to reach more Bluetooth stack code sections than an untrusted device, including remote code execution bugs in the pairing and secure session code.

~~Table I shows how the~~

F. Attacks Discussion

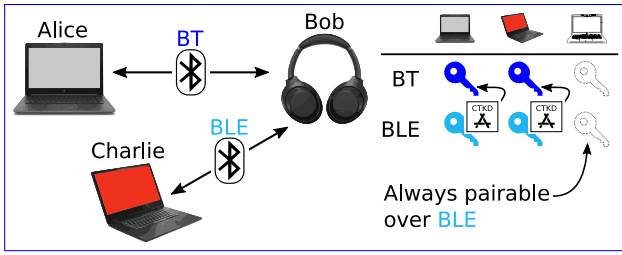


Fig. 7: BLUR unintended sessions attack. Charlie can take advantage of CTKD to establish unintended BT and BLE session with Bob as a random device with arbitrary capabilities. The same can happen if Charlie targets Alice.

We now discuss the attacks' root causes, their effectiveness regardless of the Bluetooth version, association method, and even CTKD support. Finally, we detail how we discovered them.

Root causes (CTIs) The BLUR attacks take advantage of the four ~~cross-transport vulnerabilities that we present~~ CTI presented in Section III-C in different ways. To cover all possible attack scenarios, a. As shown in Table I, a checkmark (✓) indicates that a CTI is required, an "x" if it is not required, and an "*" if it is ~~only needed sometimes~~.

~~All~~ sometimes needed. From the table we see that all attacks exploit extended pairability (CTI 1). The slave impersonation and MitM attacks take advantage of role asymmetries (CTI 2), while some unintended session attacks take advantage of that. Key tampering (CTI 3) is exploited in all attacks as the attacker has to either write or overwrite keys using CTKD. Association manipulation (CTI 4) is required in the first three attacks when the victim expects a strong association mechanism but the attacker negotiates Just Works.

Bluetooth v5.1/5.2 In Section III-A we describe a version-specific key overwrite security argument included in the Bluetooth standard since v5.1. The Bluetooth SIG currently uses this argument to state that the BLUR attacks are *not* effective against Bluetooth 5.1 and 5.2 devices (see <https://tinyurl.com/vxhwftc2>). We disagree with this statement, and we provided them empirical evidence (see Section VI-B) and solid arguments (described below) about why this is not the

| | CTI 1 | CTI 2 | CTI 3 | CTI 4 |
|----------------------|-------|-------|-------|-------|
| Master Impersonation | ✓ | x | ✓ | * |
| Slave Impersonation | ✓ | ✓ | ✓ | * |
| MitM | ✓ | ✓ | ✓ | * |
| Unintended Session | ✓ | * | ✓ | x |

TABLE I: Mapping the BLUR attacks to the CTI presented in from Section III-C. CTI 1: extended pairing, CTI 2: role asymmetry, CTI 3: key tampering, and CTI 4: association manipulation. We use a ✓ if a CTI is required to conduct an attack, a x if it is not required and a * if it is only required in specific cases.

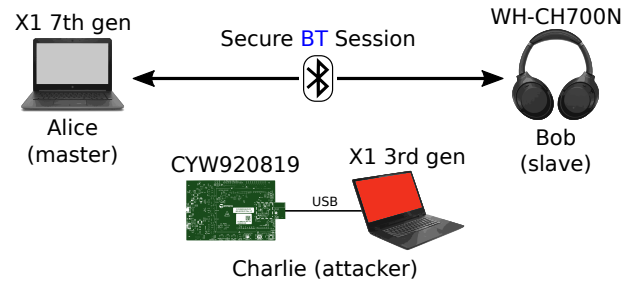


Fig. 8: BLUR Attack Scenario. Alice (master) is a ThinkPad X1 7th gen, Bob (slave) is a pair of Sony WH-CH700N headphones and Charlie (attacker) is a CYW920819 board connected via USB to a ThinkPad X1 3rd gen. Alice and Bob have paired in absence of Charlie, and are running a secure BT session.

case.

In particular, the key overwrite countermeasure is ineffective as it is *out of scope* with our attacks. Firstly, it does not cover *non key overwrite* cross-transport attacks such as the cross-transport unintended session and key writing attacks presented in this work. In addition, it does not protect against key overwrite attacks *not* involving the downgrade of keys' strength and MitM protection. Specifically, our key overwrite attacks declare "no input/output capabilities" to force the usage of Just Works without downgrading key strengths or MitM protections.

Association The BLUR attacks are effective regardless of the association methods supported by a victim, as the attacker can *always* downgrade it to Just Works. Even Just Works might require minimal user interaction (e.g., Yes/No pairing prompt) but remains an *unauthenticated* and vulnerable mechanism (e.g., the user has no way to tell if the remote pairing device is trustworthy).

CTKD support Interestingly our attacks can be launched even if one of the victims does *not* support CTKD. By design CTKD's negotiation is not protected and enforced across pairing sessions. Hence, if the attacker impersonates a device not supporting CTKD, she can still use the BLUR attacks if the victim supports CTKD. For example, the adversary can impersonate BT-only speakers to a BT/BLE (dual-mode) laptop and exploit CTKD.

Discovery We discovered the BLUR attacks by *inference* from the public information and RE details presented in Section III. Our experiments involved actual devices and static and dynamic analysis of the exchanged Bluetooth packets and the CTKD code.

V. IMPLEMENTATION

In this section we describe our attack scenario, our implementation of a custom attack device to perform the BLUR attacks and our re-implementation of CTKD's key derivation function. We will open-source both implementations.

A. Attack Scenario

Our attack scenario follows the example in Figure 8 and includes two victims, Alice (master) and Bob (slave). Alice

| | Alice | Bob | Charlie |
|-------------|------------|-----------------|------------------------|
| Device(s) | X1 7th gen | WH-CH700N | X1 3rd gen / CYW920819 |
| Radio Chip | Intel | CSR | Intel / Cypress |
| Subversion | 256 | 12942 | 256 / 8716 |
| Version | 5.1 | 4.1 | 5.0 |
| Name | x7 | WH-CH700N | x1 |
| ADD | Redacted | Redacted | Redacted |
| Class | 0x1c010c | 0x0 | 0x0 |
| BT SC | True | Only Controller | True |
| BT AuthReq | 0x03 | 0x02 | 0x03 |
| BLE SC | True | True | True |
| BLE AuthReq | 0x2d | 0x09 | 0x2d |
| CTKD | True | True | True |
| h7 | True | False | True |
| Role | Master | Slave | Master |
| IO | Display | No IO | Display |
| Association | Numeric C. | Just Works | Numeric C. |
| Pairable | True | True | True |

TABLE II: Relevant Bluetooth features for Alice, Bob, and Charlie. We redact the devices’ Bluetooth addresses for privacy reasons.

is represented by a 7th generation ThinkPad X1 laptop and Bob by a pair of Sony WH-CH700N headphones. The attacker (Charlie) uses a CYW920819 development board [16] and a 3rd generation ThinkPad X1 laptop as an attack device. The implementation of the attack device is presented in Section V-B. In our evaluation, presented in Section VI, we use the same attack scenario to attack other victim devices.

Table II summarizes the most relevant features of Alice, Bob, and Charlie. Alice and Bob have an Intel Bluetooth chip, while Bob has a Cambridge Silicon Radio (CSR) one. Alice, Bob, and Charlie support respectively Bluetooth 5.1, 4.1, and 5.0. Alice and Charlie support Secure Connections both on the Host and the Controller, while Bob only on the Controller. All devices support BT, BLE, and CTKD. Regarding pairing association methods, the laptops support Numeric Comparison, while the headsets only support Just Works as they lack a display.

B. Attack Device

To conduct our attacks we developed a custom attack device making use of a CYW920819 development board connected to a Linux laptop (see Figure 9). Both devices support BT, BLE, SC, and CTKD. Using standard laptops, smartphones or dongles is not sufficient to implement the BLUR attacks, as they do not allow to modify all device’s identifiers (e.g., BT and BLE address) and all devices’ capabilities advertised over the air (e.g., firmware and controller version) their Bluetooth firmware (Controller) but at most the OS Bluetooth stack (Host). A software-defined radio (SDR) is also out of scope because there is no open-source BT/BLE SDR stack currently available.

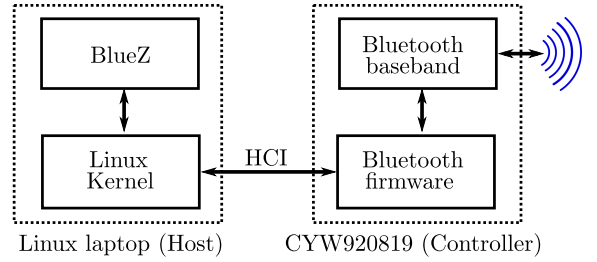


Fig. 9: Attack Device Block Diagram. The attack device is composed of Linux laptop (Host) and a CYW920819 development board (Controller) connected via USB and communicating using the Host Controller Interface (HCI) protocol.

Instead, with our attack device, we can program our development board (Bluetooth Controller) to impersonate any BT/BLE device, we can patch its closed-source firmware to control both BT LMP and BLE LL link layer packets. Moreover, we can alter the laptop’s BT and BLE kernel and user-space code to set Bluetooth Host-specific configuration bits such as negotiating CKTD and Just Works. We now describe in detail how we modify the attack device’s Host and Controller components.

a) Host modifications: Host modifications For the host, we use standard Linux tools to configure an Bluetooth interface (e.g., `hciconfig`), and to discover and pair with a device (e.g., `bluetoothctl`, `hcitool` and `btmgmt`). In particular, `btmgmt` was very useful as it provides handy low-level commands. For example, it includes commands to toggle BT, BLE, SC, scanning, and advertising. Moreover, it allows to easily send custom pairing requests on BT and BLE and to set the related association (e.g., Just Works).

Furthermore, we configured our host to get all link-layer packets sent and received by the controller. This is handy as it enables to monitor both HCI and link-layer packets directly from the host (e.g., using Wireshark). To activate link-layer packet forwarding, we sent a proprietary Cypress HCI command from the host to the controller that switches on an undocumented diagnostic mode in the controller. Then, we added extra C code to the Linux kernel to parse those special HCI packets in the host.

a) Controller modifications: Controller modifications We modified the controller by dynamically patching the development board Bluetooth firmware using a Cypress proprietary mechanisms. To patch the firmware we had to extract it from the board and statically reverse-engineer its relevant parts. In particular, to extract the firmware we used a proprietary HCI command to read and save a runtime RAM snapshot from the board’s SoC. We use the memory maps that we extracted from the board’s SDK to extract the memory segments from the snapshot (e.g., ROM, RAM, and the scratchpad). As expected, the firmware was in the ROM segment and was a stripped ARM binary containing 16-bit Thumb instructions.

To reverse-engineer the firmware, we loaded the ROM, RAM, and scratchpad in Ghidra and statically analyzed them. In our first pass, we isolated the libc functions (e.g., `malloc` and `calloc`) by looking at the signatures and the code patterns

of the functions that are called the most. Then, we found the firmware debugging symbols hidden in the board’s SDK and loaded them into Ghidra. Using these symbols we isolated functions and data structures relevant to the BLUR attacks. Then, we wrote ARM Thumb assembly patches to change their behaviors and we apply those patches at runtime using internalblue [30], an open-source toolkit to manage several Bluetooth devices including our board. Our set of patches allows transforming our board in whatever device we want by changing its identifiers including addresses, names, and capabilities,

C. CTKD Key Derivation Function (KDF)

We implemented CTKD’s ~~key derivation function, following its specification in custom KDF, following~~ the Bluetooth standard [10, p. 1401]. ~~We used our implementation to—This implementation is not required to conduct the attack, but it was used to check that the keys that we observed during our experiments—~~CTKD keys were correctly derived; ~~yet, it is not required to conduct the BLUR attacks.~~ Our implementation is written in Python 3 ~~and~~, uses the PyCA cryptographic module [7]. ~~We tested it against the CTKD, and was successfully tested against the~~ test vectors in the standard [10, p. 1721]. We now describe its technical details.

$$K_{BLE} = \begin{cases} f(f(tmp2, K_{BT}), brle) & \text{if } h7 \text{ is supported} \\ f(f(K_{BT}, tmp2), brle) & \text{otherwise} \end{cases}$$

~~We implemented CTKD’s key derivation for BT deriving and following the equation above. The key derivation~~ The KDF computes K_{BLE} using a function $f(a, b)$ that corresponds to $AES-CMAC(key, plaintext)$. ~~If both pairing devices declare $h7$ support, then K_{BT} , “tmp2” and “brle”, and K_{BT} from K_{BLE} is computed using the equation at the top otherwise the one at the bottom. $h7$ is a, “tmp1” and “lebr”. Each case can be represented by a system of equations (see below). If CTKD is run from BT then the first system of equations is used otherwise the second. Each system has two equations and the top equation is used if both devices support the $h7$ key conversion function defined in the Bluetooth standard and $h7$ is negotiated during pairing using AuthReq the AuthReq flag [10, p. 1634]. All four equations internally use $f(a, b)$ that is implemented as $AES-CMAC(key, plaintext)$.~~

$$K_{BLE} = \begin{cases} f(f(tmp2, K_{BT}), brle) & \text{if } h7 \text{ is supported} \\ f(f(K_{BT}, tmp2), brle) & \text{otherwise} \end{cases}$$

$$K_{BT} = \begin{cases} f(f(tmp1, K_{BLE}), lebr) & \text{if } h7 \text{ is supported} \\ f(f(K_{BLE}, tmp1), lebr) & \text{otherwise} \end{cases}$$

~~We also implemented CTKD’s key derivation for BLE deriving and following the equation above. In this case the derived key is . The equations’ logic is identical to the one explained for BT. What changes are the input parameters. In particular, the computation uses as inputs: , “tmp1”, and “lebr”.~~

VI. EVALUATION

In this section we present how we successfully conducted the BLUR attacks on 16 devices using 14 unique Bluetooth chips. Our results confirm that the BLUR attacks are effective against different device types (e.g., laptops, smartphones, headphones, and development boards), manufacturers (e.g., Samsung, Dell, Google, Lenovo, and Sony), operating systems (e.g., Android, Windows, Linux, and proprietary OSes), and Bluetooth firmware (e.g., Broadcom, CSR, Cypress, Intel, Qualcomm, and Samsung).

A. Setup

The BLUR attacks, presented in Section IV, include master impersonation, slave impersonation, man-in-the-middle, and unintended session attacks. In the next paragraphs, we describe how we conducted each attack using the attack device described in Section V-B.

a) ~~Laptop (master) BLUR impersonation attack:~~ **Laptop (master) BLUR impersonation attack** To impersonate the laptop, we patch our attack device to clone the laptop’s Bluetooth features (e.g., Bluetooth address, name, device class, and security parameters) Then, we send a BLE pairing request from the attack device to the headphones declaring CTKD and Just Works support. The malicious BLE pairing request is sent using `btmgmt`’s text-based user interface (TUI). The headphones accept the pairing request, and the devices agree on K_{BLE} , derive K_{BT} via CTKD and establish a secure BLE session. Then, the headphones terminate the BT session with the impersonated laptop and establish a secure BT session with the attack device. The impersonated laptop cannot connect back with the headphones as it does not possess the correct pairing keys overwritten by the attacker.

a) ~~Headphones (slave) BLUR impersonation attack:~~ **Headphones (slave) BLUR impersonation attack** To impersonate the headphones, we patch our attack device to clone the headphones’ Bluetooth features. Then, we send a BT pairing request from the attack device to the laptop declaring CTKD and Just Works support using `btmgmt`’s TUI. The laptop accepts to pair over BT as a BLE slave can send a BT pairing request as a master. The devices agree on K_{BT} , derive K_{BLE} via CTKD, and establish a secure session over BT. The impersonated headphones cannot connect to the laptop as they do not own the correct pairing keys.

a) ~~BLUR—Man-in-the-middle—attack:~~ **BLUR Man-in-the-middle attack** By using two development boards connected to the same laptop, we can impersonate the laptop and the headphones at the same time, and man-in-the-middle them. In particular, we run the laptop (master) impersonation attack first, and then the headphone (slave) impersonation attack. As a result, the attack device positions itself in the middle between the victims.

a) ~~BLUR—Unintended sessions—attack:~~ **BLUR Unintended sessions attack** For the unintended session attack, we patched our attack device to look like an unknown device to the current victim (e.g., unknown Bluetooth address and name). If the victim is a master, we run the same steps used in the slave impersonation attack otherwise we use the master impersonation attack’s steps. In both cases, the attacker

| Device | | | Chip | | Bluetooth | BLUR Attack | | | |
|----------|-----------------|-------------|----------|-------------|------------------|-------------|-------|------|----|
| Producer | Model | OS | Producer | Model | Version | Role | MI/SI | MitM | US |
| Cypress | CYW920819EVB-02 | Proprietary | Cypress | CYW20819 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Dell | Latitude 7390 | Win 10 PRO | Intel | 8265 | 4.2 | Slave | ✓ | ✓ | ✓ |
| Google | Pixel 2 | Android | Qualcomm | SDM835 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Google | Pixel 4 | Android | Qualcomm | 702 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Lenovo | X1 (3rd gen) | Linux | Intel | 7265 | 4.2 | Slave | ✓ | ✓ | ✓ |
| Lenovo | X1 (7th gen) | Linux | Intel | 9560 | 5.1 | Slave | ✓ | ✓ | ✓ |
| Samsung | Galaxy A40 | Android | Samsung | Exynos 7904 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Samsung | Galaxy A51 | Android | Samsung | Exynos 9611 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Samsung | Galaxy A90 | Android | Qualcomm | SDM855 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Samsung | Galaxy S10 | Android | Broadcom | BCM4375 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Samsung | Galaxy S10e | Android | Broadcom | BCM4375 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Samsung | Galaxy S20 | Android | Broadcom | BCM4375 | 5.0 | Slave | ✓ | ✓ | ✓ |
| Xiaomi | Mi 10T Lite | Android | Qualcomm | 9312 | 5.1 | Slave | ✓ | ✓ | ✓ |
| Xiaomi | Mi 11 | Android | Qualcomm | 10765 | 5.2 | Slave | ✓ | ✓ | ✓ |
| Sony | WH-1000XM3 | Proprietary | CSR | 12414 | 4.2 | Master | ✓ | ✓ | ✓ |
| Sony | WH-CH700N | Proprietary | CSR | 12942 | 4.1 [†] | Master | ✓ | ✓ | ✓ |

[†] CTKD was backported by the vendor to Bluetooth 4.1.

TABLE III: BLUR attacks evaluation results. The first three columns show the device’s producer, model, and OS. The next two columns state the Bluetooth chip’s producer and model. The sixth column tells the Bluetooth version of the target device. The seventh column indicates the attacker role. The last three columns contain a checkmark (✓) if a device is vulnerable to the relevant BLUR attack.

completes pairing using CTKD and can establish secure sessions over BT and BLE with the victim.

B. Results

We ~~evaluated~~ exploited the BLUR attacks against 16 unique devices (employing 14 different Bluetooth chips) ~~and our results are shown and covering all Bluetooth versions supported by CTKD. We show our results~~ in Table III. The ~~table’s~~ first six columns indicate the device’s producer, model name, operating system, chip manufacturer, chip model, and Bluetooth version. The seventh column contains either Slave if the attacker’s role is slave, or Master otherwise. The table’s last three columns ~~contain~~ have a checkmark (✓) if a device is vulnerable to master or slave impersonation attack (MI/SI), MitM, or unintended session (US) attack.

~~From Table III we confirm empirically demonstrates~~ that the BLUR attacks are ~~standard-compliant and very effective. All devices that we tested regardless of their implementation details are vulnerable. Moreover, effective on actual devices and are compliant with the Bluetooth standard. The attacks are effective on~~ all Bluetooth versions supporting CTKD ~~are affected~~ (i.e., Bluetooth 4.2, 5.0, 5.1, and 5.2) ~~and the attacks are even effective on older versions of Bluetooth (e.g., 4.1 devices that backported CTKD).~~ In addition, they succeed regardless of the hardware and software details of the victim device. ~~Interestingly, they work even on older Bluetooth versions to which CTKD was backported.~~

~~Moreover, Table III demonstrates experimentally confirms~~ that Bluetooth 5.1 ~~and 5.2 devices are also~~ are still vulnerable to

~~the BLUR attack despite the key overwrite countermeasure to the BLUR attacks, despite the CTKD key overwrite mitigation in the standard [10, p. 1401] (discussed also in Section III-A). We identified two reasons why this is the case. The countermeasure is too narrow as it does not address all the BLUR attack scenarios but only a specific key overwrite attack. As such, other attack scenarios exploited by the BLUR attacks are not covered (e.g., anonymous unintended sessions; key overwriting without a downgrade, or key writing). And, the countermeasure is not effective against the key overwrite attack that we propose, as during a BLUR key overwrite attack we simply declare the “no input for an introduction and Section IV-F for our explanation about why it is ineffective. We want to evaluate more 5.1/output capabilities” flag to force the usage of “Just Works” but we lower neither the MITM protection nor the strength (i.e., 5.2 devices supporting CTKD, such as speakers and headsets. So far, we were able to find only 5.1/5.2 high-end devices supporting CTKD (e.g., entropy) of the overwritten key Xiaomi Mi 11, Mi 10T Lite, and ThinkPad X1 7th gen).~~

VII. DISCUSSION

~~To effectively~~

A. Countermeasures

~~To concretely~~ address the BLUR attacks and their root causes (CTI ~~presented in Section III-C~~) ~~we now CTIs~~, we present four countermeasures. ~~Each countermeasure addresses its related CTI (e.g., C1 addresses CTI 1). Then, we describe~~

~~how to implement them and how we evaluated one of them on a Linux laptop. As they act at the protocol level, they are effective regardless of the Bluetooth version number, and as they also cover non key-downgrade attacks, they block all BLUR attacks. This is not the case with the Bluetooth SIG's 5.1 key overwrite countermeasure described in Section III-A.~~

~~a) C1: Disable pairing when not needed: C1: Disable pairing when not needed~~ To prevent an attacker from pairing with a device on unused transports, a device should automatically stop being pairable on a transport that is not currently in use. To avoid DoS issues, a device should also allow a user to ~~manually~~ enable and disable pairing ~~manually~~ on a specific transport.

~~a) C2: Align BT and BLE roles: C2: Align BT and BLE roles~~ To fix role asymmetries ~~between BT and BLE~~ when using CTKD ~~from BT or BLE~~, a device should store the transport and the role used while pairing, and enforce it across re-pairings ~~regardless of the transport in use~~. In case of a role mismatch, the device should abort pairing. We note that the BIAS paper [4] also takes advantage of role switching but is not proposing role switch enforcement as a countermeasure.

~~a) C3: Prevent cross-transport key tampering: C3: Prevent cross-transport key tampering~~ To prevent cross-transport key overwrites via CTKD, a device should disable it ~~while pairing if a trusted if a~~ pairing key already exists for the other transport. ~~As a result, to overwrite a trusted To overwrite a~~ pairing key a user should explicitly re-pair on that transport. To mitigate cross-transport key writes, CTKD should be disabled when two devices, who already share a pairing key on a transport, re-pair on that transport with a weaker ~~pairing~~-key (that would be used as input to CTKD). A key is ~~considered~~ stronger than another one if its entropy is higher or if it is established with a stronger association mechanism.

~~a) C4: Enforce strong association mechanisms: C4: Enforce strong association mechanisms~~ To prevent an attacker from manipulating ~~the association mechanisms used when pairing on different associations across~~ transports, a device should keep track of the association mechanism used while pairing for the first time ~~with a device~~ and enforce it for subsequent re-pairings (across BT and BLE). There is no ~~obvious~~ reason why two devices which support strong association would want to ever use a weaker association scheme. If a weaker mechanism than the one stored is proposed, pairing should be aborted.

The four countermeasures ~~not only address the four CTIs but they also stop the ultimately block the~~ BLUR attacks. In particular, C3 prevents impersonation and MitM as the attacker ~~will not be able to write and overwrite key across transports cannot write or overwrite keys across transports,~~ but only target ~~separately~~-BT and BLE ~~separately~~. To stop the unintended ~~sessions attacks~~session attacks, C1 is also needed as the attacker should not be able to pair with CTKD on unused transports. C2 and C4 help ~~to~~ mitigate the attacks by providing more defense-in-depth, but they are not strictly required.

Our countermeasures ~~are easy to implement and do not rely on backward-incompatible features. In particular, they~~ can be implemented in the ~~Bluetooth Host component Bluetooth Host~~ (i.e., ~~device's main OS OS level~~). C2, C3, and C4 can be realized by keeping track of ~~metadata that is already exchanged~~

~~during the pairing protocol~~ extra data that is exchanged during pairing (e.g., device role, association) and aborting the protocol when needed. Logging is already supported and used by the Host (e.g., to store pairing keys). C1 can be implemented with a timer ~~which~~ that disables pairability on a transport when not needed and a simple user interface to monitor and switch on/off pairability for BT and BLE.

~~PoC for C3~~ To verify the effectiveness of C3 ~~we implemented a C3 and show that our mitigations are easy to implement and do not impact normal operations, we developed a proof-of-concept and tested it using a Linux laptop. We paired our laptop with the victim device using CTKD and we deleted the pairing data on the victim device and then used it as the attacker device (PoC) for C3 for Linux. We can evaluate multiple device classes simultaneously by testing Linux, as it is employed by Android smartphones, embedded devices, and laptops. The C3 PoC works as follows. We pair a Linux laptop (victim) with an arbitrary device with CTKD. Then, to disable CTKD key overwrites on the laptop, we unset the write permission bit in the folder and the file storing the of the pairing key file stored at /var/lib/bluetooth. We then use the paired devices normally to demonstrate no impact on benign use. Finally, we run the BLUR impersonation attack and we confirm that it is ineffective as the attacker cannot overwrite the pairing keys. Then we ran the impersonation attack from the attack device and the attack failed as the OS was preventing the Bluetooth Host from (over) writing new pairing keys~~

B. Lessons Learned

~~Specification and modeling~~ Security mechanisms that ~~cross the security boundary between two technologies should be well-specified and tested against a comprehensive cross-transport threat model. On the contrary, the Bluetooth standard provides an incomplete specification for CTKD and only discusses some cherry-picked cross-transport threats.~~

~~Security guarantees~~ Cross-transport mechanisms should be designed such that the mechanisms trusted at the boundary ~~between the two transport (i.e., BT and BLE pairing) have the same threat model and provides equivalent security guarantees. This is not the case for Bluetooth as BT and BLE use different pairing protocols, link layer mechanisms, and threat models.~~

~~Usability vs. Security~~ CTKD was introduced to improve Bluetooth's usability, but, in light of the presented attacks, the usability benefits are not balancing the security issues deriving from CTKD. Indeed, it is paramount to find a good balance between usability and security and ~~not~~ trade off the latter for the former.

VIII. RELATED WORK

Bluetooth provides a royalty-free and widely-available cable replacement technology [20]. ~~Bluetooth standard compliant attacks~~ Standard-compliant attacks on Bluetooth are particularly dangerous as all ~~Bluetooth~~ devices are affected, regardless of version numbers or implementation details. Such ~~standard-compliant attacks have appeared since the first versions of Bluetooth attacks were discovered since Bluetooth v1.0~~ [24], [29]. ~~Standard-compliant~~

| Year | Paper | Target | Attack | | | | Note |
|--|---------------------------|----------|---------|---------|--------|------------|--------------------------------|
| | | | Phase | C I A K | SC/SCO | Persistent | |
| <i>Attacks on BT</i> | | | | | | | |
| 2016 | Albazzraqe et al. [1] | Standard | Any | ●○○○ | x | - | BlueEar Sniffer |
| 2017 | Seri et al. [37] | Impl. | Pairing | ●●●○ | NA | ✓ | BlueBorne |
| 2018 | Sun et al. [40] | Standard | Pairing | ●●●○ | ✓ | - | Passkey (MitM) |
| 2018 | Biham et al. [9] | Impl. | Pairing | ●●●○ | NA | ✓ | Fixed Coordinate Invalid Curve |
| 2019 | Ossmann et al. [32] | Standard | NA | ●○○○ | x | - | Ubertooth sniffer |
| 2019 | Antonioli et al. [2] | Standard | Pairing | ●●●○ | ✓ | - | KNOB (MitM) |
| 2020 | Antonioli et al. [4] | Standard | Pairing | ●●●○ | ✓ | - | BIAS |
| 2021 | Tschirschnitz et al. [41] | Standard | Pairing | ●●●○ | ✓ | - | Method Confusion (MitM) |
| <i>Attacks on BLE</i> | | | | | | | |
| 2016 | Jasek et al. [25] | Standard | NA | ●○○○ | x | - | Black Hat |
| 2019 | Seri et al. [38] | Impl. | NA | ○●○○ | NA | ✓ | Bleedingbit |
| 2020 | Zhang et al. [46] | Standard | Pairing | ●●○○ | ✓ | - | MitM (SCO) |
| 2020 | Wu et al. [44] | Standard | Session | ○○●○ | ✓ | - | BLESA |
| 2020 | Garbelini et al. [19] | Impl. | Any | ●●○○ | NA | - | SweynTooth fuzzer |
| 2020 | Antonioli et al. [5] | Standard | Pairing | ●●○○ | ✓ | - | Downgrade (MitM) |
| <i>Cross-transport attacks on BT and BLE</i> | | | | | | | |
| 2021 | BLUR (this work) | Standard | Any | ●●●○ | ✓ | ✓ | First against CTKD |

TABLE IV: ~~Overview of recent Comparison with related work. The BLUR attacks on are the first cross-transport standard-compliant attacks for Bluetooth and BLE the first targeting CTKD.~~ C = Data Confidentiality, I = Data Integrity, A = Device Authentication, K = Key disclosure. No (○) Partially (◐), Yes (●).

~~The Bluetooth standard evolved over time to include better pairing mechanisms (e.g., SSP, SC) and two transports (e.g., BT, BLE). Recent standard-compliant attacks on BT include attacks on legacy pairing [39], secure simple pairing (SSP) [21], [40], [9], Bluetooth-association [22], [41], key negotiation [2], and authentication procedures [28], [42], [4]. Standard-compliant attacks on BLE include attacks on legacy pairing [36], key negotiation [5], SSP [9], [46], reconnections [44], and GATT [25]. Compared to the mentioned attacks that target either BT or BLE, the BLUR attacks are the~~

~~The BLUR attacks are novel compared to prior standard-compliant attacks. As we can see from Table IV they are the first cross-transport attacks, meaning the first targeting BT from BLE and vice versa. Moreover, no prior attacks targeted (and evaluated the security of) CTKD. Finally, like the BIAS attack [4], they require a weak threat model as the attacker can target a victim at any time. Unlike the BIAS attack, the effect of our attacks is persistent across sessions. Like other standard-compliant attacks targeting the intersection between BT and BLE, the BLUR attacks are effective regardless of the security mode (e.g., SSP with SC), association method (e.g., Numeric Comparison), and Bluetooth version numbers.~~

We have seen attacks targeting specific implementation flaws on BT [37] and BLE [38], [19]. As our BLUR attacks target the specification level, they are effective regardless of the implementation details. Several surveys on BT and BLE security were published [17], [31], [33] but neither of those surveys nor the Bluetooth standard considers CTKD as a threat. We here demonstrate that CTKD is a serious threat and must be included in the standard Bluetooth threat model.

~~Cross-transport Cross-protocols~~ attacks were exploited for proximity technologies using Bluetooth and Wi-Fi. Two prominent examples are attacks on Apple ZeroConf [8] and

~~Google Nearby Connections [3]. Our BLUR attacks are the first cross-transport attacks for BT and BLE. However, no prior attack targeted the BT/BLE combination.~~

The cryptographic primitives used by Bluetooth have been extensively analyzed. For example, the E_0 cipher used by BT was investigated [18] and it is considered relatively weak [33]. SAFER+, used for authentication, was analyzed as well [27]. BT and BLE “Secure Connections” use the AES-CCM authenticated-encryption cipher. AES-CCM was extensively analyzed [26], [35] and it is FIPS-compliant. ~~Our BLUR attacks target key negotiation and not cryptographic primitives, and As our attacks are at the protocol-level, they~~ are effective even with perfectly secure cryptographic primitives.

~~As can be seen from Table IV, compared to other standard-compliant attacks, the BLUR attacks are novel and are enabling impactful attack scenarios. The BLUR attacks are the first cross-transport attacks for Bluetooth and are the first attacks exploiting CTKD. In terms of impact, the BLUR attacks require a weak attacker model as the attacker does not have to observe previous pairing and secure sessions between the victim. On top of that, they break even the most secure BT and BLE mode (i.e., SSP, LESC, SC, and strong association) and their effect is persistent.~~

IX. CONCLUSION

This work presents the first security evaluation of CTKD. ~~CTKD is a feature specified was introduced~~ in the Bluetooth standard ~~that allows two devices compatible with BT and BLE to pair just once on either transport and use both of them securely. Despite CTKD being a dangerous attack surface, little is known about its actual security. In our evaluation we reverse-engineered how CTKD is used from BT and BLE and we uncover four vulnerabilities in its specification. The vulnerabilities affect any device supporting to improve the~~

usability of pairing. With CTKD two devices can pair on BT (or BLE) and generate pairing keys for both transports. CTKD is a novel attack surface as it allows to tamper with BT from BLE and vice versa, and is only partially documented in the Bluetooth standard (without an appropriate security analysis).

To address these issues, we RE the CTKD protocols and analyzed them using a *cross-transport* attacker model. Our analysis uncovers four critical cross transport issues (CTI) in the specification of CTKD. As such, *all* and can be used to exploit BT and BLE just by targeting one of the two Bluetooth devices supporting CTKD are currently affected by those vulnerabilities.

To show the effectiveness of the uncovered vulnerabilities we exploit them to present four We leverage the CTIs to implement four standard-compliant cross-transport attacks for Bluetooth. The attacks allow to impersonate or MitM any master or slave device supporting CTKD. Furthermore, the attacks can be used to establish unintended sessions as an anonymous device. As the attacks are effective regardless of the security mode in use (e.g., SSP, SC, on strong association) they can break the strongest security level of BT and BLE. Collectively our attacks are called BLUR attacks as they blur the security boundary between. Our attacks allow an attacker to impersonate and MitM devices, and allow establishing unintended (anonymous) sessions with a victim to enumerate sensitive data and send malicious packets. The attacks are the first standard-compliant BT and BLE -.

The BLUR attacks are also novel compared to prior standard-compliant attacks in the literature. Our attacks to not require the attacker to be present when a victim is pairing or establishing a secure session, unlike prior work [22], [21], [36], [40], [9], [2], [5], [4], [44], [46], [41]. In particular, our attacks are the first cross-transport attacks for Bluetooth and are the first attacks targeting CTKD. Moreover, unlike prior attacks, such as KNOB or BIAS, they can be executed at any point in time and they achieve a persistent compromise of the victim devices. For example, the attacker does not have to wait until the victims start new pairing or secure sessions, that can be conducted in absence of one of the victims. The attacks are effective regardless of the targeted Bluetooth version and security mode (e.g., SSP, SC, on strong association).

To demonstrate the practicality of the BLUR attacks, we presented a low-cost implementation based on readily available hardware and open-source software. We use our implementation to experimentally empirically confirm that the BLUR attacks are standard-compliant and effective all targeted devices. In particular, we exploit exploited 16 devices from different popular vendors different devices using 14 unique Bluetooth chips and implementing. Our device sample includes all Bluetooth versions supporting CTKD (e.g., 4.2, 5.0, 5.1, and 5.2) - We also exploited a Bluetooth 4.1 device to which CTKD was backported, and BT and BLE devices supporting SC and strong association.

To fix the presented attacks and their root causes, we propose protocol-level countermeasures, we discuss four effective and cross-transport countermeasures. The countermeasures enforce that a device is not pairable when not

needed, that BT and BLE roles are aligned while pairing, that security keys cannot be improperly (over)written or stolen, and that association is not downgraded. Our countermeasures can be implemented at the OS level and to show their feasibility we implemented one of them on the Linux OS and demonstrate the efficacy of the most important one (disable key overwrites) experimentally.

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Lessons Learned

~~In this section we list the main lessons that we learned in the hope that they will be useful for protocol designers who are dealing with cross-transport security mechanisms.~~

~~a) *Cross-transport specification and modeling:* Security mechanisms that cross the security boundary between two technologies should be well-specified and tested against a comprehensive cross-transport threat model. On the contrary, the Bluetooth standard provides an incomplete specification for CTKD and only discusses some cherry-picked cross-transport threats.~~

~~a) *Cross-transport security guarantees:* Cross-transport mechanisms should be designed such that the mechanisms trusted at the boundary between the two transport (i.e., BT and BLE pairing) have the same threat model and provides the same security guarantees. This is not the case for Bluetooth as BT and BLE use different pairing protocols, link layer mechanisms, and threat models.~~

~~a) *Usability vs. Security:* CTKD was introduced to improve Bluetooth’s usability, but, in light of the presented attacks, the usability benefits are not balancing the security issues deriving from CTKD. Indeed, it is paramount to find a good balance between usability and security and not overweight the former.~~