Happy MitM – Fun and Toys in Every Bluetooth Device

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ABSTRACT
Bluetooth pairing establishes trust on first use between two devices by creating a shared key. Similar to certificate warnings in TLS, the Bluetooth specification requires warning users upon issues with this key, because this can indicate ongoing Machine-in-the-Middle (MitM) attacks. This paper uncovers that none of the major Bluetooth stacks warns users, which violates the specification. Clear warnings would protect users from recently published and potential future security issues in Bluetooth authentication and encryption.

CCS CONCEPTS
• Security and privacy → Mobile and wireless security: Security protocols; Key management.

KEYWORDS
Bluetooth, Machine-in-the-Middle, Usable Security

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1 INTRODUCTION
Attacks on Bluetooth pairing often lead to two separate keys, as shown in Figure 1. Such attacks are either enabled by vulnerabilities in the specification and implementation [11, 25, 26] or the insecure Just Works mode used by most IoT devices and headsets [7, p. 985]. In practice, an attacker faces the following barriers:

1. Presence during the initial pairing or forcing a new pairing.
2. Presence in all future connections to re-encrypt traffic.

In other network protocols, such as TLS, continuous presence can be achieved by placing a MitM on, e.g., a router close to the target. Bluetooth is used on devices that move and have varying signal strength. A permanently successful attacker must be omnipresent and immediately reply with a strong signal to all connection attempts. If the attacker only fails once—which is very likely in a mobile environment—devices under attack would use incompatible keys, resulting in an authentication or encryption failure. According to the Bluetooth 5.2 specification, the user shall be notifies of security failures [7, p. 1314]. We find that all major Bluetooth stacks skip warning the user, thereby violating the specification. Warnings are independent from the underlying pairing method and technology, since pairing and connection dialogues are implemented on top. We test user interfaces on a large variety of devices, ranging from Bluetooth 2.1 + EDR to 5.2, including Bluetooth Classic (BT) and Bluetooth Low Energy (BLE) as well as the pairing extensions Google Fast Pair and Apple MagicPairing [13, 14]. More precisely, the following platforms are affected:

• Both tested Android flavors (Google and Samsung) do not indicate authentication failures to the remote device.
• Google Android further silently removes the pairing, which opens the door for enforcing new pairings.
• iOS, Samsung Android, and Windows display a message that they could not connect without explaining why, and macOS as well as Ubuntu Gnome indicate a failed connection via user interface button colors. The original key stays valid.
• Various gadgets do not indicate any error and keys stay valid.

We demonstrate stack and user interface failures against both BLE and BT, using PIIIDA [21] to dynamically hook the iOS and Android Bluetooth stacks and substitute keys in Host Controller Interface (HCI) commands. In contrast to existing tools, this allows conditional interaction with the Bluetooth stack by altering commands and events. These scripts are now part of the InternalBlue framework [19], as they will be valuable for further Bluetooth-related research.

This paper is structured as follows. Section 2 explains Bluetooth pairing and security fundamentals. Then, Section 3 continues with details on how to hook into Bluetooth stacks to test for security issues. All identified vulnerabilities are detailed in Section 4. Section 5 concludes this paper.

2 BACKGROUND
The following section explains Bluetooth pairing basics, recent attacks, and expected failures in case of MitM presence.

2.1 Bluetooth Pairing Modes
Bluetooth pairing modes and warnings in user interfaces are separate components on all stacks researched in this paper. However, security vulnerabilities in Bluetooth pairing or encryption enable MitM attacks, and, thus, motivate clear warnings in user interfaces.
The early BT versions had a very flawed pairing, now termed Legacy Pairing, since it is still implemented for backwards compatibility [24]. BT 2.1 introduced Secure Simple Pairing (SSP), which was formally verified [10]. Despite this verification, the specification is unclear about certain aspects of SSP and the follow-up encryption, resulting in various practical attacks [3, 5, 6, 11, 16, 26].

With the Bluetooth specification version 4.0, BLE was introduced, featuring low-energy connections for IoT gadgets and medical devices. Instead of using exactly the same pairing mechanism, a lightweight pairing was added, which is fundamentally broken and now called LE Legacy Pairing [23]. Newer versions use Secure Connections (SC), which are very similar to SSP. Thus, attacks on SSP typically also apply to SC. Even worse, the key format in BT and BLE devices is rather similar, and there is a cross-transport key derivation for both protocol variants, which also is vulnerable [4].

From a user perspective, the underlying pairing mechanism is opaque. No matter if SSP, SC, or LE Legacy Pairing is used, they all feature a Just Works mode, which is vulnerable to active MitM attacks [7, p. 985]. They also have a Numeric Comparison and Passkey Entry mode, which can prevent active MitM attacks—assuming that all known vulnerabilities are fixed. The Out Of Band mode is not affected by these attacks, since it uses a non-Bluetooth channel for exchanging keys. Its vendor-specific implementation may or may not have flaws, and attacks on stages after pairing such as session key entropy reduction [5] apply either way.

This attack history without possibility to secure the Just Works mode led to manufacturers implementing independent pairing solutions. Apple uses so-called MagicPairing, which is undocumented but has been reverse-engineered [14]. Google has a similar protocol called Fast Pair [13]. Both protocols bind Bluetooth keys to cloud accounts and share them across devices. Users only pair a headset once and then can access it via all devices logged into the same cloud account. This is not only more convenient but also reduces the amount of pairing attempts during which MitMs could be present.

### 2.2 Attacks Resulting in Different Keys

The majority of attacks on Bluetooth pairing results in a setup with different keys. This applies to all devices using Just Works mode as well as attacks downgrading a pairing to this mode [16], mixing pairing modes [26], and reflecting messages [11]. Besides direct attacks on protocols, implementation details such as a weak random number generator can also enable MitM attacks [25].

Even a successful attack on the pairing requires a MitM to be omnipresent during all follow-up connections. Otherwise, inconsistent keys lead to authentication and encryption errors. These errors can and should be used to detect attack attempts according to the Bluetooth specification, as described in the following.

#### 2.2.1 Expected Authentication Failure Behavior

If authentication fails, the host terminates the connection [7, p. 1599]. Moreover, the user should—in most cases—be warned [7, p. 1314]. The Bluetooth specification has a way more sophisticated decision process, as shown in Table 1. A Combination key is meant for BT and BLE, thus, initiating either SSP or SC upon a failure is valid. Unauthenticated keys are the result of Just Works mode pairing [7, p. 1306], as it does not protect against MitM. In contrast, an Authenticated key requires Numeric Comparison, Passkey Entry, or Out Of Band pairing. Bonded devices permanently store the keys established during the initial pairing to create a trusted relationship.

If a key is Unauthenticated and does not protect against active MitM, the recommended option is to automatically initiate a new SSP for non-bonded devices. This violates the trust on first use concept and MitM attacks can successfully be launched without any user interaction. This is also the default option for non-bonded Combination keys as well as the alternative option for non-bonded Authenticated keys.

Authentication might legitimately fail if one of the devices deleted the according key. This requires the user to manually reset a device, meaning that the user is aware and can act accordingly.

#### 2.2.2 Expected Encryption Failure Behavior

BLE devices activate encryption using the LE_Enable_Encryption HCI command [7, p. 2322]. Then, the BLE link layer tries to initiate encryption. After finishing this step, an Encryption Mode Change event is sent to the host, indicating if encryption is on or still off. When replacing BLE keys, this results in encryption being reported as off [7, p. 2299]. The specification considers encryption failures in BLE in case that the remote device does not support encryption [7, p. 3141], and there is no differentiation to having an invalid key. Thus, for BLE encryption failures, the overall behavior is not specified in detail.

### 3 BLUETOOTH STACK TEST FRAMEWORK

As explained in the following, over-the-air BT MitM setups are still rather expensive. To facilitate testing BT and BLE security, we instead dynamically hook into HCI.

#### 3.1 Over-the-Air Setups

As of now, Bluetooth Low Energy (BLE) MitM setups can be realized with the bt1e jack toolsuite and three Micro:Bits [9]. This makes a BLE setup as cheap as USD 45. There is still no similar open-source tool for Bluetooth Classic (BT), which has a more complex modulation scheme making eavesdropping harder. Just in 2020, the first full-band BT sniffer for Software-Defined Radios (SDRs) and more recent Bluetooth specifications was released [12]. This sniffer supports synchronization, dethreading, decoding, as well as an algorithm to deanonymize.

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**Table 1: Authentication failure actions as defined by the Bluetooth 5.2 specification [7, p. 1314].**

| Link Key Type | Bonded | Action                                      |
|---------------|--------|---------------------------------------------|
| Combination   | ×      | Option 1: Automatically initiate pairing.   |
|               |        | Option 2, recommended: Notify user and ask if pairing is ok. |
| Combination   | ✓      | Notify user of security failure.            |
| Unauthenticated| ×      | Option 1, recommended: Automatically initiate SSP. |
|               |        | Option 2: Notify user and ask if SSP is ok. |
| Unauthenticated| ✓      | Notify user of security failure.            |
| Authenticated  | ×      | Option 1: Automatically initiate SSP.       |
|               |        | Option 2, recommended: Notify user and ask if SSP is ok. |
| Authenticated  | ✓      | Notify user of security failure.            |
addresses. This setup requires two USRP B210, totaling in approxi-
mately USD 3000. For an active MitM setup, even this advanced
testing is insufficient, since it does not support sending packets.

Nonetheless, it is reasonable to assume that strong attackers
have a working MitM setup. From a technological standpoint a
MitM only needs a recent SDR with 80 MHz bandwidth—and move
significant parts of the implementation into an FPGA to fulfill real-
time requirements. Given the current progress of SDRs, it is to
be expected that there will be affordable BT MitM setups soon,
meaning that devices should be proactively secured against them.

3.2 Hooking into Bluetooth Stacks

Analyzing device behavior upon authentication failures due to
changed keys only requires changing the key locally on one of
the paired devices. By changing the key back and forth, it can
even be tested if the original key is still trusted after in between
authentication failures. There are two options to change a key:

(1) Change the key within the host’s file system.

(2) Substitute the key within HCI commands.

The first option usually requires to restart the Bluetooth daemon.
Moreover, changing the key on the file system while Bluetooth is
still running might corrupt the local key database.

Replacing key information within HCI commands, the second
option, is more flexible. Most Bluetooth chips only have a ROM
and need to request the key either on first usage or whenever
they establish a connection, depending on the implementation.
Apple MagicPairing and Google Fast Pair use this property [13, 14]:
They manage keys bound to accounts separately, but still use
the encryption mechanisms provided by the Bluetooth chip.
Thus, substituting keys as they are requested even allows testing
vendor-specific protocol additions. Key change behavior can be
tested by replacing the HCI_Link_Key_Request_Replay command
for BT [7, p. 720], respectively the LE_Enable_Encryption command
for BLE [7, p. 2322].

Table 2 persisted after an authentication failure. Interestingly, while
some responders only see a disconnect event with the reason
User Terminated Connection. We further analyze this by connecting
the device address of the controller and
/var/lib/bluetooth/mac1/mac2/info
in
On
3.2.1 Linux.

The
Linux
BlueZ
[8] stack stores connection properties in separ-
ate files per connection, making the first option suitable. The
HCI-based alternative on Android and iOS enables us to also test
vendor-specific additions, which are not implemented on Linux.

3.2.2 Android. The Android Fluoride Bluetooth stack is open-source.
The HCI implementation is contained in the file system/bt/hci
/src/hci_layer.cc [2]. Commands to the controller are sent us-
ing the transmit_command function, and events from the con-
troller pass the filter_incoming_event function. After compila-
tion, these functions end up in the llibbluetooth.so binary.

Despite having source code access, recompiling the stack to
swap the key would not be a flexible solution for more generic HCI
analysis. Instead, we hook the stack using Frida [21] on a rooted
Samsung Galaxy Note20 5G with the January 2021 patch level.
On this device, llibbluetooth.so does not contain symbols. Thus, we
locate the relative address of transmit_command manually using
IDA Pro 7.5 [15]. Based on this initial IDA database, the address
of this function can be found automatically using BinDiff [27] if
llibbluetooth.so was compiled for the same architecture.

3.2.3 iOS. The closed-source iOS Bluetooth stack can be reverse-
engineered using debug strings, which even contain some of the
original function names. The part of the Bluetooth stack responsible
for HCI is contained in the Bluetooth daemon bluetoothd itself
instead of using a separate library. Since functions implementing
HCI play an important role, they all contain debug strings. Every
command passes the function O1_HciIfc_CopyPayload to the
HCI engine using debug strings, which even contain some of the
function names required for the functionality we need stayed the
same since various iOS releases, at least since iOS 13.5, meaning
that it should be easy to port the hook to future iOS versions.

4 VULNERABLE STACKS

We find that under some circumstances controllers do not indicate
authentication failures (see Section 4.1). Even if the controller issues
such a failure, the user is not notified on all tested stacks, but they
show varying behavior as shown in Table 2 (see Section 4.2–4.8).
While testing popular peripherals, we discover that they use danger-
ously outdated Bluetooth versions (see Section 4.9). We disclosed
all issues to the vendors (see Section 4.10).

4.1 Bluetooth Controllers and LMP

While running the attacks, we capture traces using the Apple Packet-
Logger for iOS and macOS, Wireshark on Linux, and extract the
bluetooth HCI.log from Android devices. All traces show that initi-
ating BT controllers issue an Authentication Failure event and BLE
controllers issue an Encryption Failure event. This means that the
underlying Bluetooth chips are specification-compliant.

Upon an authentication failure, the host shall terminate the
connection [7, p. 1959]. The packet traces indicate that the Bluetooth
hosts indeed follow this procedure—none of the connections in
Table 2 persisted after an authentication failure. Interestingly, while
the BT initiator always receives an Authentication Failure via HCI,
some responders only see a disconnect event with the reason Remote
User Terminated Connection. We further analyze this by connecting
the Samsung Galaxy Note20 5G to a Google Nexus 5. The Nexus 5 is
rather old, but supports Link Management Protocol (LMP) sniffing
via InternalBlue [19] and features SSP with BT 4.1.
Table 2: User notifications upon authentication and encryption failures due to invalid keys.

| Key Fault Injector         | Device Under Test         | Invalid Key Effect |  |
|----------------------------|---------------------------|-------------------|---|
|                            |                           | No indication, key stays valid. |  |
|                            |                           | Button color or symbol indication, key stays valid. |  |
|                            |                           | Connection error text message, key stays valid. |  |
|                            |                           | Pairing is removed without user notification. |  |
|                            |                           | Connection type not supported. |  |

During the secure authentication phase, the initiator and responder can both end the connection with an LMP_DETACH packet containing the error code Authentication Failure [7, p. 622]. The LMP description of handling authentication errors is not in line with the HCI part of the specification. LMP is only accessible by the controller and not the host, but if the host terminates the connection, it needs to issue an HCI command towards the controller. If authentication fails on the initiator, the controller correctly issues an HCI event to the host indicating an Authentication Failure. Then, the host sends an HCI command to terminate the connection, falsely using the error code Remote User Terminated Connection. Thus, the follow-up LMP_DETACH packet falsely contains the same error code. **As a result, the disconnect event on the responder does not indicate an authentication failure.** This affects at least devices with Android versions 6.0.1–11.

In addition, the host shall notify the user of a security issue upon an Authentication Failure [7, p. 1314]. When looking at popular user interfaces, we avoid that Android will not notify the responder of authentication failures by testing both ends in the initiator role.

### 4.2 Android (Google)

The **Pixel 5** on the March 2021 patch level shows the most unexpected behavior. Upon an authentication failure, the pairing entry is deleted. This happens without an additional explanation—the user taps the device they want to connect to and next it disappears from the list of paired devices. Under certain circumstances, deleting keys is legitimate. Following Table 1, the specification states:

> “Non-bonded authenticated or unauthenticated link keys may be considered disposable by either device and may be deleted at any time.” [7, p. 1314]

The grammar in the previous sentence is unclear, but we assume that non-bonded link keys, no matter if authenticated or not, can be deleted. All devices under test were paired with the **Pixel 5** using the Numeric Comparison method. The BT link keys were authenticated and bonded. Deleting bonded keys enables MitM attackers to remove existing pairings with minimal user interaction—and then launch an attack on the initial pairing. The **Nexus 5** shows the same behavior on **Android 6.0.1**, meaning that this issue is consistent throughout Google-flavored **Android** versions.

### 4.3 Android (Samsung)

Using a **FIDDA**-based Proof of Concept (PoC) on the **Samsung Galaxy Note20 5G** on a January 2021 patch level, we test key change behavior over-the-air against all devices. The **Samsung**-flavored user interface looks differently than the **Google** user interface, including menu structures and texts. When a BT connection fails due to a changed link key, the message “Couldn’t connect.” is displayed. In case the paired device supports a special protocol or capability, this is added to the text. For example, when using tethering with an **iPhone**, the message “Couldn’t connect. Turn on Bluetooth tethering on iPhone.” is shown, as depicted in Figure 2a. This **error message is the same as when the paired device was switched off**, meaning that harmless connection issues and security-critical authentication errors are indistinguishable for users.

![Samsung-flavored Android error message when the tethering AP changes its key.](image)

(a) Samsung-flavored Android error message when the tethering AP changes its key.

![iOS error message when the tethering AP changes its key.](image)

(b) iOS error message when the tethering AP changes its key.

![Windows error message when the tethering AP changes its key.](image)

(c) Windows error message when the tethering AP changes its key.

![Windows error message when the tethering AP is off.](image)

(d) Windows error message when the tethering AP is off.

Figure 2: Error messages with an iPhone for tethering.
Google’s Fast Pair protocol substitutes pairing [13]. Only a limited subset of devices supports this protocol, such as the Bose QC35 II headphones. Fast Pair boils down to setting a link key via HCI. Thus, we can use the same PoC to replace the key. The internal logic of key management is the same, independent from Fast Pair, and the user is displayed the same “Couldn’t connect.” message.

On Android, BLE devices usually require using the according app by the vendor, since BLE is mostly used by IoT devices and has very diverse use cases. Vendor apps do not provide insights on the current pairing state. Thus, we use the nRF Connect app [20], which allows connecting to BLE devices and control the bonding state. The nRF Connect app uses the Android Bluetooth API, meaning that some error messages are displayed by the system upon errors. For example, when changing the BLE long-term key for encryption during the initial pairing, the message “Couldn’t pair with MI Band 2. Make sure that it’s ready to pair” is displayed. When changing the encryption key later on in the LE_Start_Encryption command, the following Encryption Mode Change event indicates that the encryption could not be switched on while using the wrong encryption key. Thus, Android terminates the connection but does not display any error message.

### 4.4 iOS

We hook the Bluetooth daemon with a FIAIDA-based PoC on an iPhone 8 on iOS 14.4. After installing a Bluetooth debug profile, we can use PacketLogger to observe all HCI packets. This provides us with a powerful debug tool for the Apple ecosystem, supporting devices like AirPods that only function with other Apple devices.

When connecting to a BT device, the error message is always “Connection Unsuccessful”, as shown in Figure 2b. This error message is the same no matter if the other device is turned off or if the link key changed. When switching back to the original key, connections are successful again. The same error message is shown when porting the PoC to a jailbroken iPhone 12 on iOS 14.1 and connecting it to another iPhone 12 on iOS 14.6 Beta, because the issue is anchored in the user interface and not the hardware.

Apple uses MagicPairing for AirPods [14]. It leverages the same mechanism as Fast Pair—exchanging a cloud-based key and then setting it via an HCI command. When substituting the key in this command, the same error message is shown.

iOS does not directly support third-party BLE devices, and does not show them in the scan results. The nRF Connect app for iOS does not support bonding. Thus, we are not able to test non-Apple BLE devices on iOS in a comparable fashion.

The Bose QC35 II send BLE advertisements and usually pair using BLE followed by a cross-transport key derivation to switch to BT. However, after receiving the first BLE advertisement from a Bose QC35 II, iOS requests further information via a BT extended inquiry and directly pairs or connects using BT.

### 4.5 macOS

We test the macOS stack by connecting it to devices that switch their key. The version under test is macOS 11.2.1 on a 2020 MacBook Pro. No matter if connecting to a device via the menu bar on top or via the full settings dialogue, buttons temporarily change their color to blue, similar to a connect and disconnect action, for 2–3 s. As on iOS, this dialog does not support non-Apple BLE devices.

### 4.6 Ubuntu with Gnome

A default Ubuntu 20.10 installation uses Gnome as user interface on top of the BlueZ Bluetooth stack. We use a ThinkPad X240 with these packages: gnome-control-center (1:3.38.3-3ubuntu1), bluez (5.55-0ubuntu1.1), and linux-kernel (5.8.8-44-generic). Instead of hooking into the Bluetooth daemon itself, we change keys within the file system.

For BT, only button colors change to blue for a short moment. We use the same ThinkPad X240 as for the Windows setup, with the only exception being the test between Linux and Windows, for which we use a ThinkPad X1 Yoga with BT 4.2 as Linux device. When testing BLE with the Mi Band 2, the initial pairing works, but even without changing the key, reconnecting later on is not supported. Thus, we could not test the BLE behavior of this user interface, even though the underlying BlueZ stack supports arbitrary BLE devices.

The BlueZ stack is by far the most unreliable Bluetooth stack. While testing the listed devices, we observed one crash in the kernel module and two crashes in the Bluetooth daemon.

### 4.7 Windows

We use the most recent Windows 10 Internal Build as available in March 2021. Windows has two menus that can connect to devices. First, the connect side bar is reachable via ■ + K. This is primarily meant for audio devices and other devices are only shown as connection information. The Linux laptop is detected as audio device. Upon a key change, audio devices in this menu show the following message: “That didn’t work. Make sure your Bluetooth device is still discoverable, then try again.”

To connect Windows to one of the smartphones that change their key, we need to pair them via the Settings menu, go to Control Panel → Hardware and Sound → Devices and Printers, right-click the paired smartphone, and connect to it using the AP option. When connecting to a smartphone with a changed key, the message “An unexpected error occurred. Please contact your system administrator.” is shown (see Figure 2c). The authentication failure error message is not helpful to determine the root cause of not being able to connect to the smartphone. Interestingly, Windows has the only interface where the message is different from the case of not being able to connect to switched off device (see Figure 2d).

### 4.8 Peripherals

We test various types of peripherals: headphones, keyboards, and a BLE fitness tracker. AirPods indicate connections with sounds, the Bose QC35 II even reads out the currently connected devices and pairing state, the Xiaomi Mi Band 2 vibrates during the initial pairing, the Mini Keyboard indicates pairing states with an LED, and the MagicKeyboard lacks any kind of feedback mechanism.

Given these limited user interaction capabilities of peripherals, notifying the user of a security failure, as suggested by the Bluetooth specification [7, p. 1314], requires special solutions. While error sounds or status lights would be possible, none of these devices indicate an error when using a wrong key. When switching back to the correct key, they accept the connection again.
4.9 Outdated Bluetooth Versions

Smartphones tend to have new Bluetooth chips supporting the most recent specification. Yet, peripherals that require less throughput have surprisingly old chips. The device labeled as Mini Keyboard is the cheapest keyboard in the Adafruit store sold for USD 12.95 [1]. It is using Bluetooth 2.1 + EDR, which has been released in 2007. At least, this keyboard implements Passkey Entry authentication. Even popular recent devices such as standalone MagicKeyboard sold by Apple in 2021 only has Bluetooth 3.0 + HS, dating back to 2009. On Broadcom chips, as used in this device, the firmware patching capabilities are rather limited [22]. Issues that stem from the outdated Bluetooth version in this chip cannot be fixed in software. Most likely due to usability reasons, the MagicKeyboard does not use numeric verification during wireless pairing.

Keyboards are low-throughput, meaning that old chips do not have any noticeable effect for users. However, security of keyboards is essential—users type confidential texts and passwords. In addition to adding warnings on authentication failures as already required by the Bluetooth specification, we suggest that users **should be warned about outdated Bluetooth versions**.

4.10 Responsible Disclosure

We contacted the Bluetooth SIG, Apple, Google, and Samsung on February 27th 2021. After building further PoCs and testing more devices, we contacted Microsoft, Bose, Xiaomi, and Gnome on March 13th. The Bluetooth SIG will address the issue. Moreover, Apple, Google, and Samsung will integrate warnings in a future release, but classified the issue as feature request. Microsoft stated that they will not change their warnings. Xiaomi misunderstood the report despite multiple clarifications. Bose and Gnome did not reply.

5 CONCLUSION

While many researchers looked into cryptographic aspects of Bluetooth security, little has been done to raise the bar for practical MitM attacks. Patching the newest cryptographic bugs within operating systems does not structurally improve Bluetooth security, as peripherals remain outdated. Users should be notified of security failures as proposed by the Bluetooth specification. This will make the life of wireless attackers much harder, as it significantly reduces attack stealthiness. In addition, users should be warned if security-sensitive peripherals like keyboards use a 10 year old Bluetooth version, vulnerable to various known issues. On a long-term perspective, this would prevent vendors from selling outdated peripherals. Such structural improvements require everyone to contribute, admit flaws, and indicate them towards the users—even if this might be inconvenient.

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