A Formal Analysis of IEEE **802.11**'s **WPA2**

Countering the Kracks Caused by Cracking the Counters

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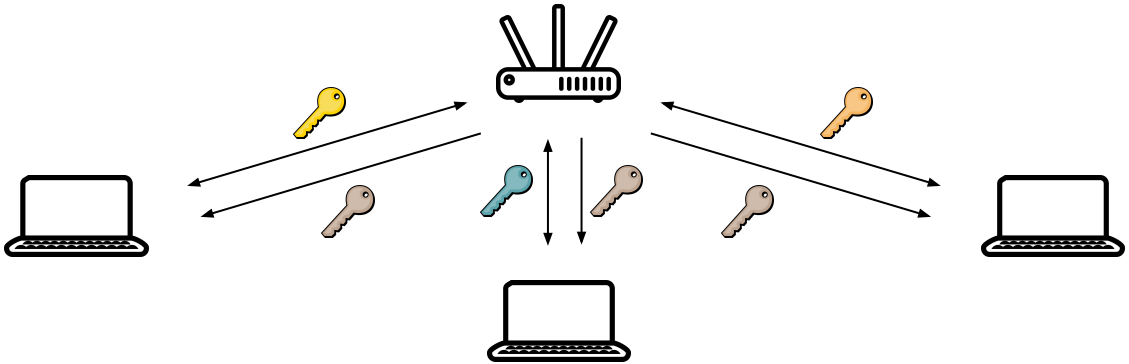
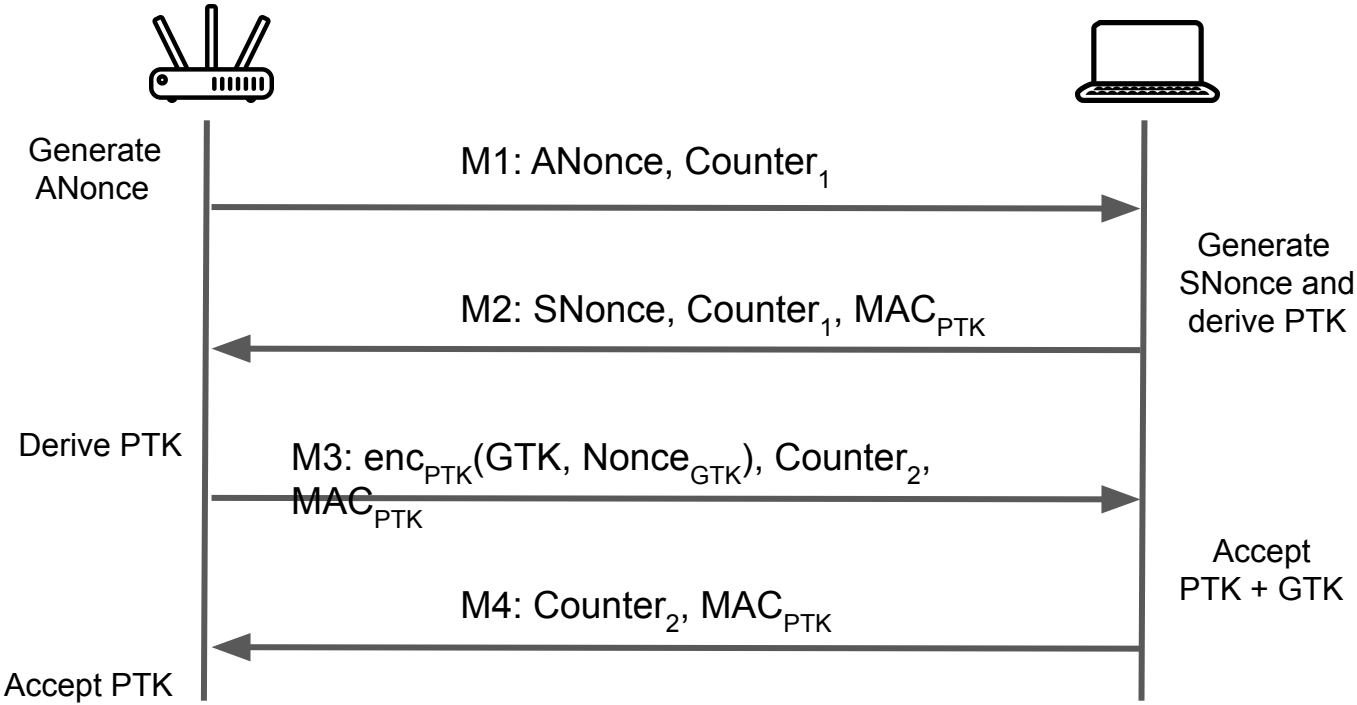
What is **WPA2**?

- **Purpose:** Enable secret communication over wireless networks
- **How:** Establish secret keys for encryption
  - **Pairwise transient keys (PTK)** for protecting WiFi traffic (different for each client)
  - **Group transient keys (GTK)** for protecting broadcast messages (same for each client)

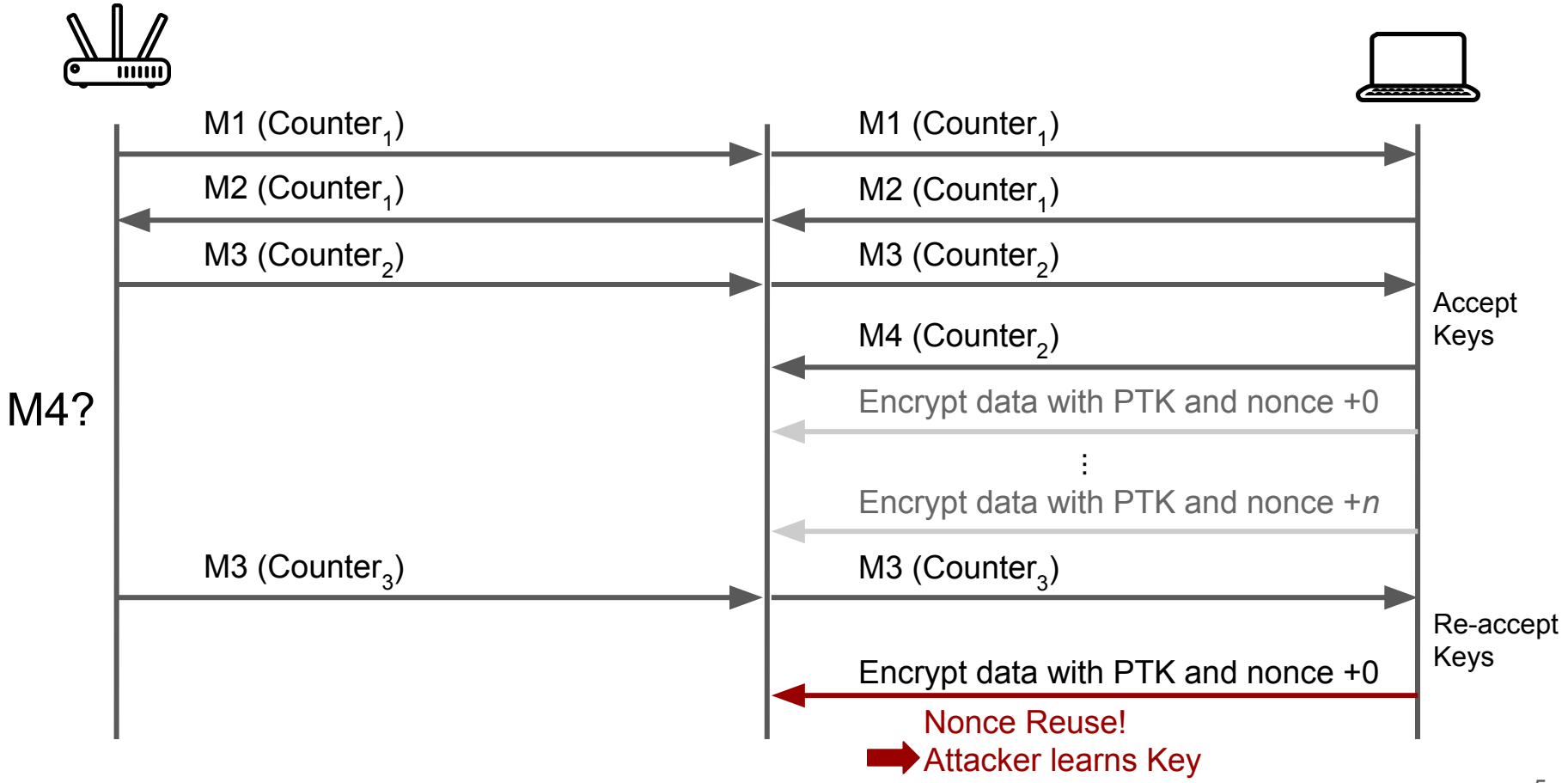


The Four-Way Handshake



What can go wrong?

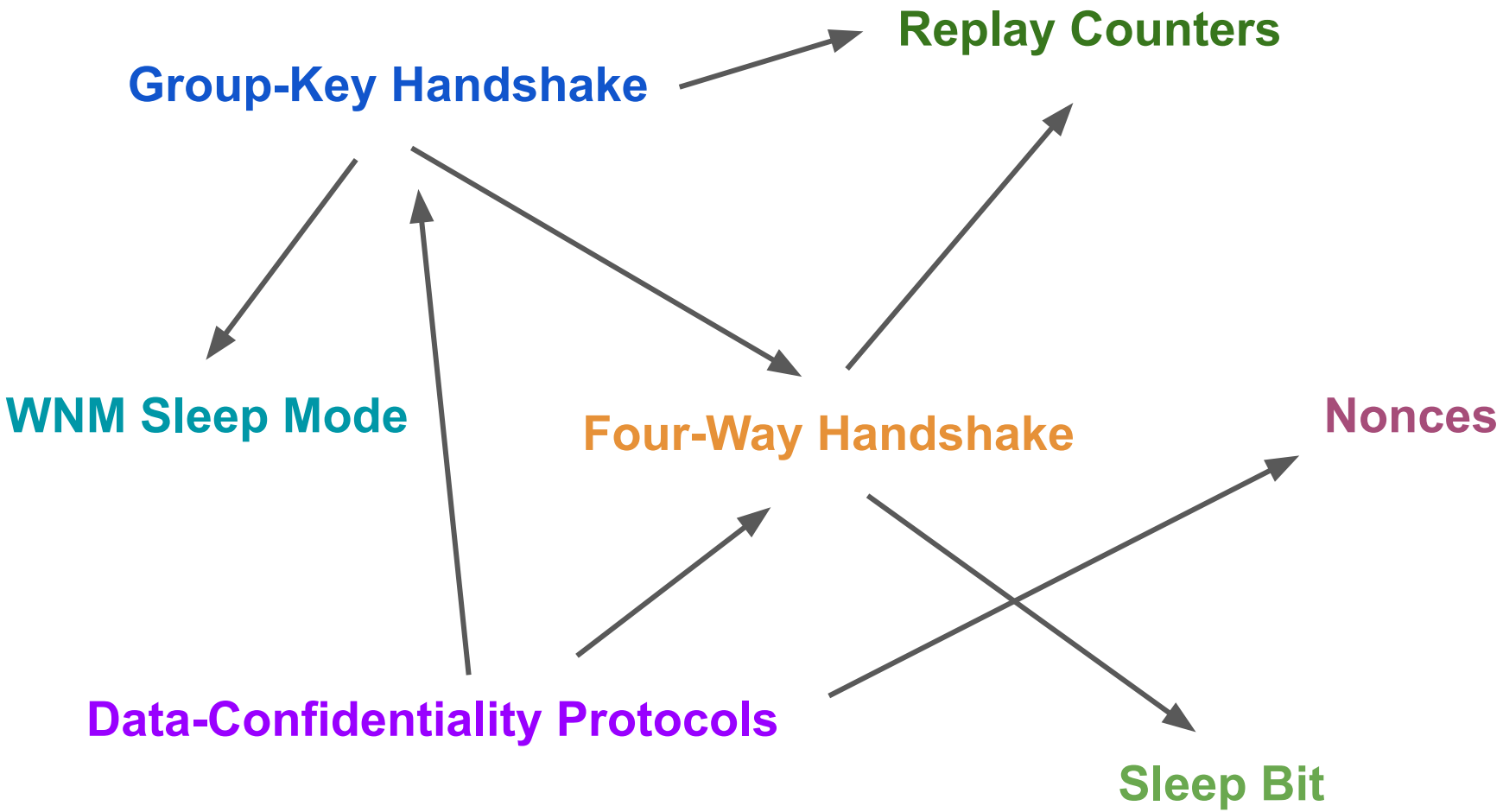
- WPA2 had been considered secure (apart from offline attacks)
- **Big shock** in 2017: **Vanhoef and Piessens** break WPA2 by exploiting subtle behavior of the protocol => **KRACK attacks**
  - Message **retransmissions** are exploited to achieve **key reinstallations**
  - Key reinstallations lead to **nonce reuse** in WPA2's authenticated encryption schemes
  - Nonce reuse **leaks the key** used for encryption


M1 (Counter1)
M1 (Counter1)
M2 (Counter1)
M2 (Counter1)
M3 (Counter2)
M3 (Counter2)
Accept Keys
M4 (Counter2)
M4?
Encrypt data with PTK and nonce +0
Encrypt data with PTK and nonce +n
M3 (Counter3)
M3 (Counter3)
Re-accept Keys
Encrypt data with PTK and nonce +0
Nonce Reuse!
Attacker learns Key

Breaking... and Fixing?

- **Vanhoef and Piessens** proposed **intuitive countermeasures**
- However, in 2018 Vanhoef and Piessens found **new attack variants…**

  ...that circumvent **their own** countermeasures.
- They then proposed new **improved countermeasures**


Replay Counters
Group-Key Handshake
WNM Sleep Mode
Four-Way Handshake
Nonces
Data-Confidentiality Protocols
Sleep Bit

Formal Model using Tamarin

- We created a **formal model** of WPA2 with the **Tamarin prover**
- Modeled 7 state machines for the major mechanisms specified in the standard
- Created a more **accurate model** of the authenticated encryption schemes where nonce reuse leads to key leakage
- This took around **12 person-months** of work
- A lot of time spent on **understanding the WPA2 standard**

Analysis Results

- We proved...
  - **...security** of the **pairwise transient keys** and of the **group keys**
  - **...authentication** of 4-way-handshake (“injective agreement”)
- Verification was **not** fully automatic
- Tamarin required **many** intermediate statements

Analysis Results

- Previous analysis **did not cover** mechanisms such as
  - **Key leakage** through **nonce reuse**
  - **WNM sleep mode** and **sleep bit**
- Our analysis covers a **large class of attacks** including these mechanisms
- **No attacks** on the pairwise keys in the twice patched WPA2 protocol.

Conclusion

- We provide the **first formal security argument** for **WPA2** that covers the major mechanisms.
- **Highly complex** protocols can now be verified **formally**.
- **Read** our paper! **Check out** our Website[1]! **Build** on our model!

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[1] https://cispa.saarland/group/cremers/tools/tamarin/WPA2/index.html