# A Unified Symbolic Analysis of WireGuard

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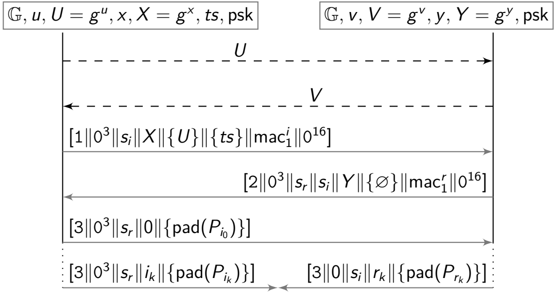
WIREGUARD

FAST, MODERN, SECURE VPN TUNNEL

# The *WireGuard* protocol

*Without cookie*




- $u, U = g^u, v, V = g^v \rightsquigarrow$ static keys, $x, X = g^x, y, Y = g^y \rightsquigarrow$ ephemeral keys, psk $\rightsquigarrow$ pre-shared key
- $ts$ timestamp, $s_i, s_r \rightsquigarrow$ session identifiers, $i_* \rightsquigarrow$ counters, $P_* \rightsquigarrow$ plaintexts
- $\{\cdot\} \rightsquigarrow$ encryption
- $\rho \rightsquigarrow$ nonce, $\tau \rightsquigarrow$ cookie

# Current symbolic analyses

**Symbolic**

- 2018: J. A. Donenfeld and K. Milner, “Formal verification of the WireGuard protocol” *WireGuard*
- 2019: N. Kobeissi, G. Nicolas, and K. Bhargavan, “Noise explorer: Fully automated modeling and verification for arbitrary Noise protocols” *IKpsk2*
- 2020: G. Girol, L. Hirschi, R. Sasse, D. Jackson, C. Cremers, and D. A. Basin, “A spectral analysis of Noise: A comprehensive, automated, formal analysis of Diffie-Hellman protocols” *IKpsk2*

**Threats**

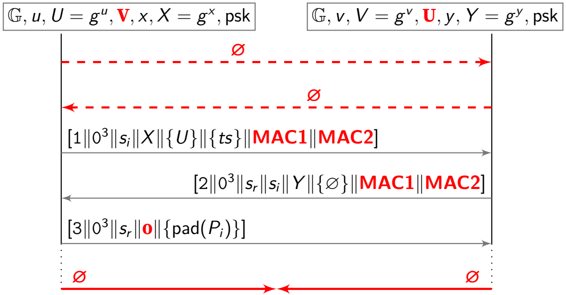
- Static private key reveal / set
- Ephemeral private key reveal / set
- PSK reveal / set
- Static key distribution corruption

**Security Properties**

- Message agreement
- Key secrecy (incl. PFS)
- Anonymity

# Symbolic analyis of *WireGuard* (TAMARIN)

**2018: J. A. Donenfeld and K. Milner, "Formal verification of the WireGuard protocol"**




### Threats

- Static private key reveal ✓ / set ✗
- Ephemeral private key reveal ✓ / set ✗
- PSK reveal ✓ / set ✗
- Static key distribution corruption ✗

### Security Properties

- Message agreement ✓
- Key secrecy ✓ (PFS ✗)
- Anonymity ✓

# Our target threat model for *WireGuard*

### Threats

- Static private key reveal ✓ / set ✓
- Ephemeral private key reveal ✓ / set ✓
- PSK reveal ✓ / set ✓
- Static key distribution corruption ✓
- New! Pre-computation reveal ✓ / set ✓

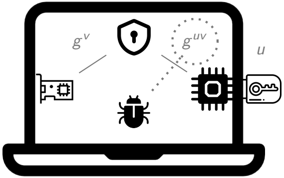
### Pre-computation ?

- Static-static key :
  - Initiator $V^u = g^{uv}$
  - Responder $U^v = g^{uv}$

  *before* session begins, hence WireGuard maintains it.

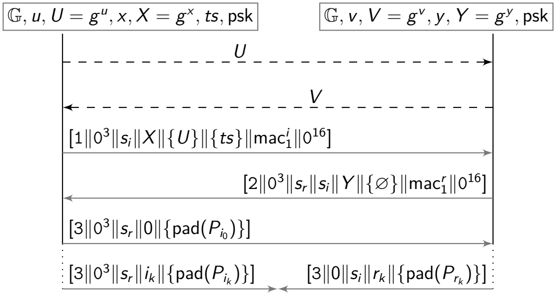
Compromise of $g^{uv}$ is **weaker** than compromise of $u$ or $v$:

- $u \wedge g^v \implies g^{uv}$
- however $g^v \wedge g^{uv} \not\Longrightarrow u$

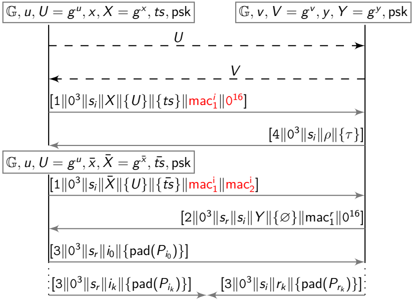


# Our symbolic models of *WireGuard* (Tamarin, ProVerif, Sapic$^+$)

*Without cookie*




*With cookie*

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**Security Properties**

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# Our results : necessary and sufficient conditions

- $D_u, D_v$: adversary corrupts public keys distribution
- $R_u, R_v, R_x, R_y, R_s, R_c$: adversary gets private keys $(u, v, x, y)$, psk $(s)$ or pre-comp. value $(c)$
- $R_u^*, R_v^*, R_s^*, R_c^*$: adversary gets private keys $(u, v)$, psk $(s)$ or pre-comp. value $(c)$ after protocol execution (for PFS)

**Results**

- agreement of `RecHello` and `TransData` (R to I) messages hold ***unless***
  $(D_v \wedge R_s) \vee (R_s \wedge R_v) \vee (R_c \wedge R_s \wedge R_x) \vee (R_s \wedge R_u \wedge R_x)$
- agreement of `TransData` (I to R) messages hold ***unless***
  $(D_u \wedge R_s) \vee (R_s \wedge R_u) \vee (R_c \wedge R_s \wedge R_y) \vee (R_s \wedge R_v \wedge R_y)$
- Key Secrecy from Initiator's view, including PFS hold ***unless***
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- Key Secrecy from Responder's view, including PFS hold ***unless***
  $(D_u \wedge R_s) \vee (R_s \wedge R_u) \vee (R_c \wedge R_s \wedge R_y) \vee (R_s \wedge R_v \wedge R_y) \vee (R_s^* \wedge R_u^* \wedge R_x) \vee (R_s^* \wedge R_v^* \wedge R_y) \vee (R_c^* \wedge R_s^* \wedge R_x \wedge R_y)$

# Our results : interpretation

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## Key distribution corruption

Agreement and key secrecy hold ***unless*** adversary:

- compromises $U$ distribution **AND** gets psk
- **OR** compromises $V$ distribution **AND** gets psk

$\Longrightarrow$ **Shall not be eluded !**

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## Pre-shared key

psk compromise is *necessary* to break all properties.
$\Longrightarrow$ **Shall be mandatory (and not optional) !**

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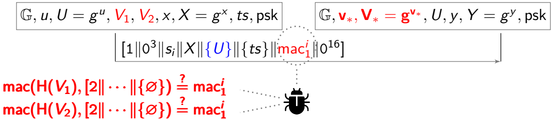
## Pre-computation

In some cases, $R_c$ has same impact as $R_u$ or $R_v$, although *weaker*.
$\Longrightarrow$ **Shall be removed !**

# Anonymity

**Claim:** ***Wireguard guarantees Identity Hiding***

*(Identity hiding proven in 2018 model with* TAMARIN*)*




- `InitHello` message is $[1\|0^3\|s_i\|X\|\{U\}\|\{ts\}\|\mathsf{mac}_1^i\|0^{16}]$
- $\mathsf{mac}_1^i = \mathsf{mac}(\mathsf{H}(V), [1\|\cdots\|\{ts\}])$, where $V$ is public $\Longrightarrow$ Responder's Identity can leak !

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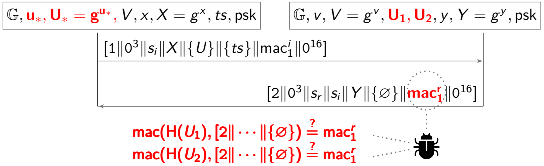


**However issue is the same for `RecHello` message !** **(explained in "A mechanised cryptographic proof of the WireGuard VPN protocol")**

- `RecHello` message is $[2 \| 0^3 \| s_r \| s_i \| Y \| \{\varnothing\} \| \mathbf{mac}_1^r \| 0^{16}]$
- $\mathsf{mac}_1^r = \mathsf{mac}(\mathsf{H}(U), [2\| \cdots \| \{\varnothing\}])$, where $U$ is public $\Longrightarrow$ Initiator's Identity can leak !

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**Claim:** ***Wireguard guarantees Identity Hiding***

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⇝ Reality: WireGuard does **not** provide anonymity at all (key compromise is not necessary) ...

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## Proposed fixes

- Remove **mac** (i.e. use `IKpsk2`)
- Change **mac** computation :
  - $\textbf{mac}_1^r = \mathsf{mac}(\mathsf{H}(U \| g^{uv}), [2\| \cdots \|\{\varnothing\}])$
  - $\textbf{mac}_1^r = \mathsf{mac}(\mathsf{H}(U \| \mathsf{psk}), [2\| \cdots \|\{\varnothing\}])$

$\Longrightarrow$ With these fixes anonymity is **verified** with PROVERIF

# Conclusion

- Currently WireGuard ensures:
  - Agreement
  - Key secrecy and PFS

- Recommandations for end users:
  - Use pre-shared key
  - Care about static key distribution
  - Do not rely on WireGuard for anonymity
- Recommandations for stakeholders:
  - Remove pre-computation
  - Fix anonymity

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- Complete model of WireGuard
- **Fix** for anonymity property
- Precise threat model, including initial key distribution and **pre-computations**
- Necessary and sufficient conditions
- Process with SAPIC$^{+}$, PROVERIF, TAMARIN

Artifact Evaluated
NDSS SYMPOSIUM
Available
Functional
Reproduced

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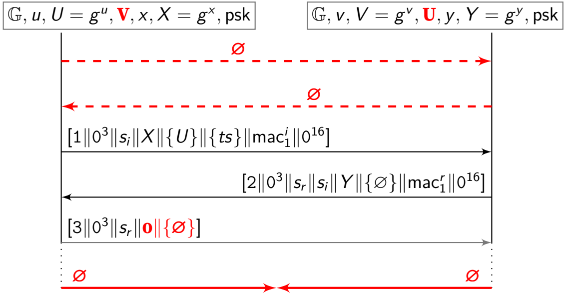
- Thanks for your attention !
- Do you have questions ?

# Computationnal analysis of *WireGuard* (manual)

**2018: B. Dowling *et al.*, “A cryptographic analysis of the WireGuard protocol”**




### Threats

- Static private key reveal ✓ / set ✗
- Ephemeral private key reveal ✓ / set ✗
- PSK reveal ✓ / set ✗
- Static key distribution corruption ✗

### Security Properties

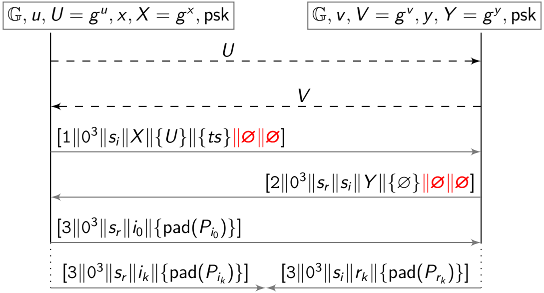
- Message agreement ✓
- Key secrecy ✓ (PFS ✗)
- Anonymity ✗

### Verified Combinations

- ✗

# Computationnal analysis of *WireGuard* (CryptoVerif)

**2019: B. Lipp *et al.*, "A mechanised cryptographic proof of the WireGuard VPN protocol"**




## Threats

- Static private key reveal ✓ / set ✓
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- PSK reveal ✓ / set ✓
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## Security Properties

- Message agreement ✓
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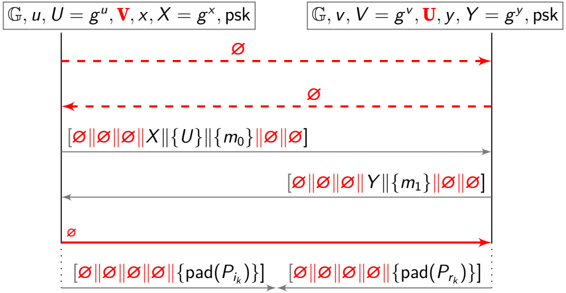
- Anonymity ✗

## Verified Combinations

- ✗

# Symbolic analysis of IKpsk2 (ProVerif)

**2019: N. Kobeissi *et al.*, “Noise explorer: Fully automated modeling and verification for arbitrary Noise protocols”**




### Threats

- Static private key reveal ✓ / set ✗
- Ephemeral private key reveal ✗ / set ✗
- PSK reveal ✓ / set ✗
- Static key distribution corruption ✗

### Security Properties

- Message agreement ✓
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- Anonymity ✗

### Verified Combinations

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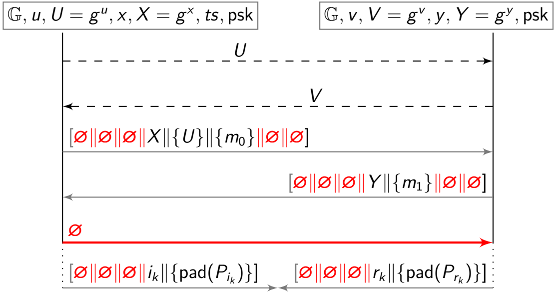


## Threats

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- Ephemeral private key reveal ✓ / set ✓
- PSK reveal ✓ / set ✓
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## Security Properties

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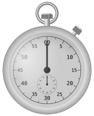
## Verified Combinations

- ✓

# Benchmarks



**With a dedicated 256 cores server**

- Evaluation of agreement and secrecy properties (ProVerif, Tamarin, Sapic$^+$) : 9 hours
- Evaluation of fix for anonymity, based on $g^{uv}$ (ProVerif) : 12 hours
- Evaluation of fix for anonymity, based on psk (ProVerif) : 2 hours

# Combinations

**With pre-computation**

Adversary can

- get $u, v, x, y$, psk, $g^{uv}$ before / after protocol execution
- set $u, v, x, y$, psk, $g^{uv}$ for Initiator and $g^{uv}$ for Responder
- compromise $U$ and $V$ distribution
- and combine ($2^{6+6+7+2} = 2^{21} = 2097152$ combinations per property) !