# STARTING UP MACSEC FOR AUTOMOTIVE ETHERNET.

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Dr. Lars Völker

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# TECHNICA ENGINEERING

# STARTING UP MACSEC

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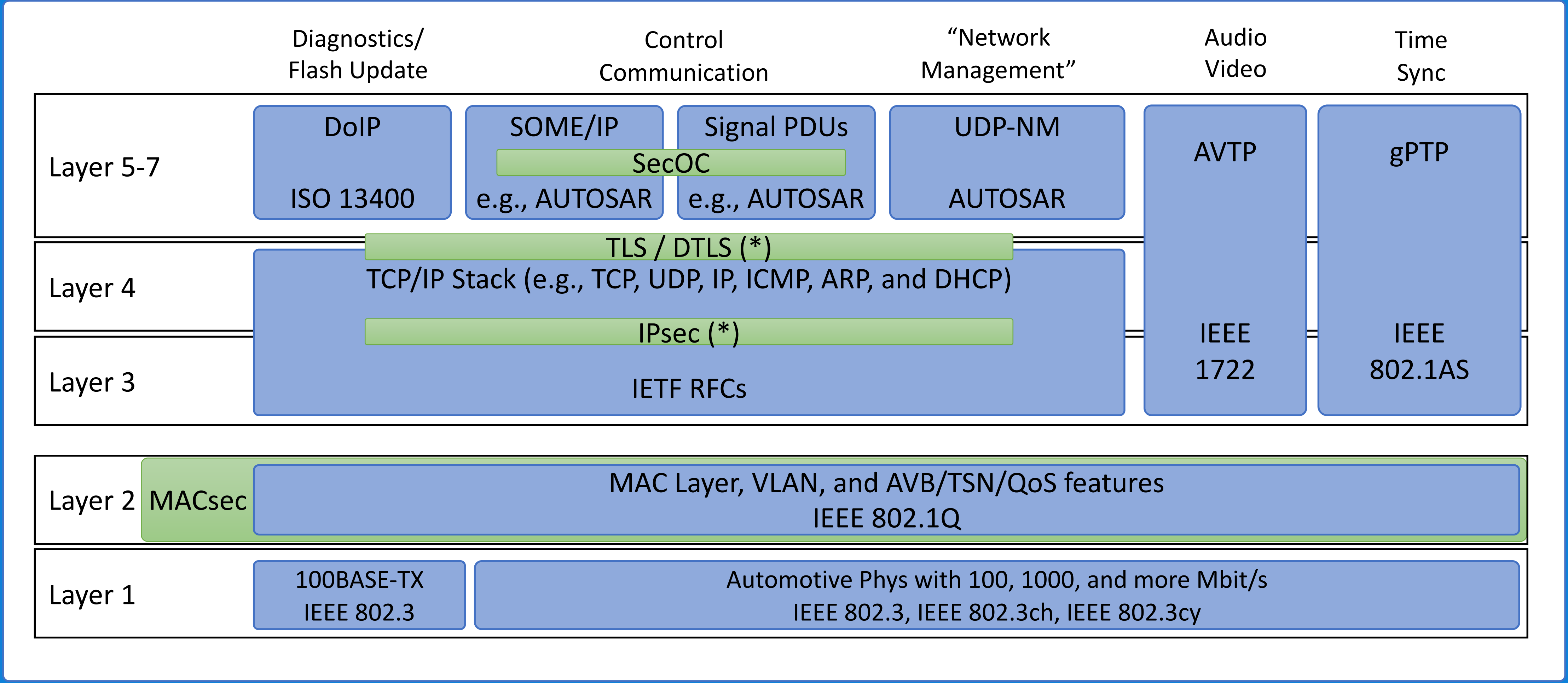
# 1 CHAPTER.
# MACSEC INTRO.

# SIMPLIFIED COMMUNICATION STACK.




(*) Typically unicast only.

# WHY IS MACSEC SO INTERESTING?

1

- MACsec is currently the only solution that can protect all communication on Automotive Ethernet against external attackers.
  - Alternatives (e.g., IPsec, (D)TLS, SecOC) leave many protocols unprotected.

2

- MACsec can protect Multicast and Broadcast communication.
  - Better than (D)TLS and regular IPsec.

3

- MACsec can protect all traffic on a link with one association.
  - Less keys and key exchanges required (better than SecOC, (D)TLS, IPsec).

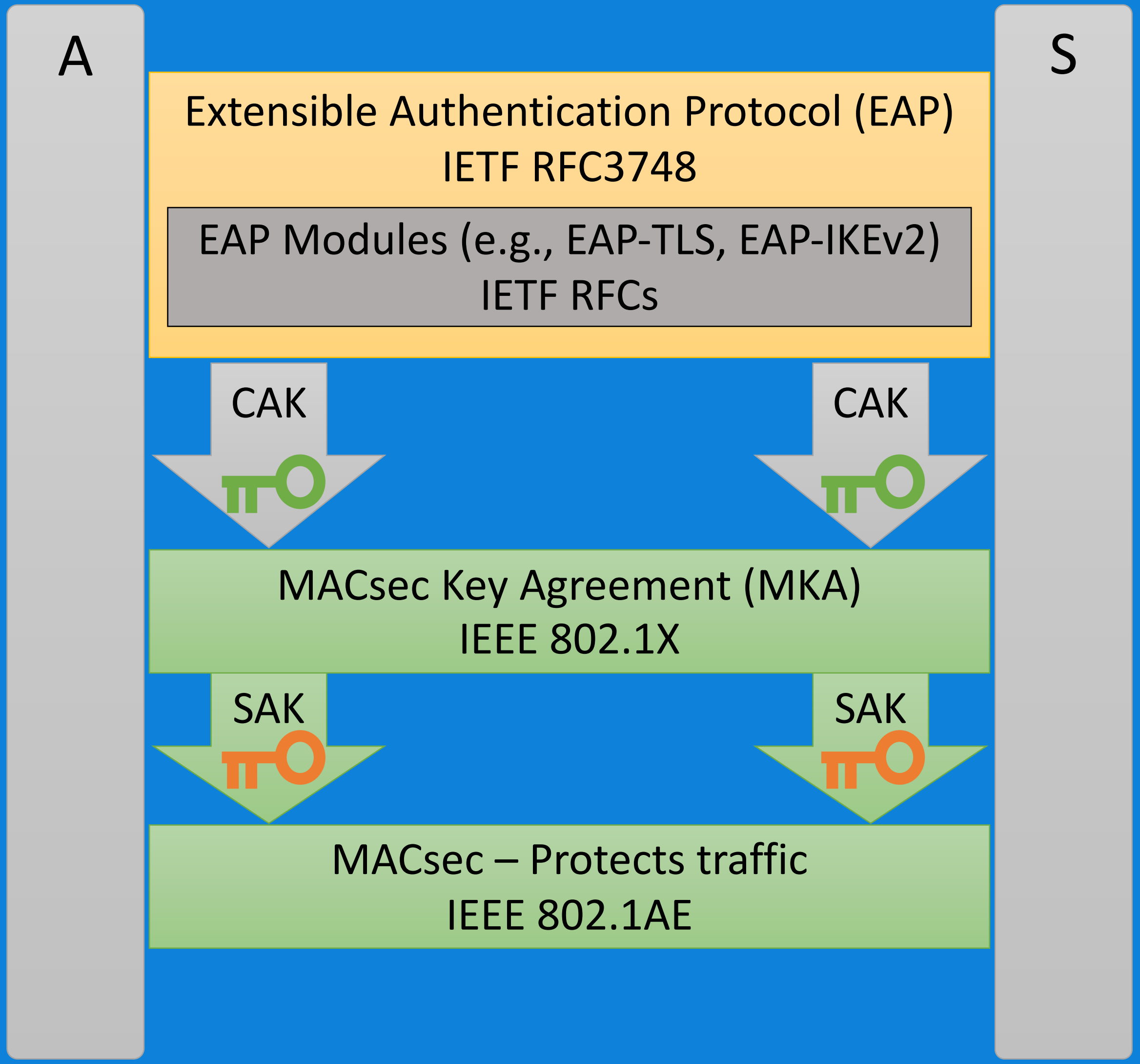
4

- MACsec can be run hop-by-hop:
  - You don’t need to share keys for large groups (better than SecOC).

For further details see:
Dr. Lars Völker, BMW: “Comparing Automotive Network Security for Different Communication Technologies”, Automotive Ethernet Congress, 2018.

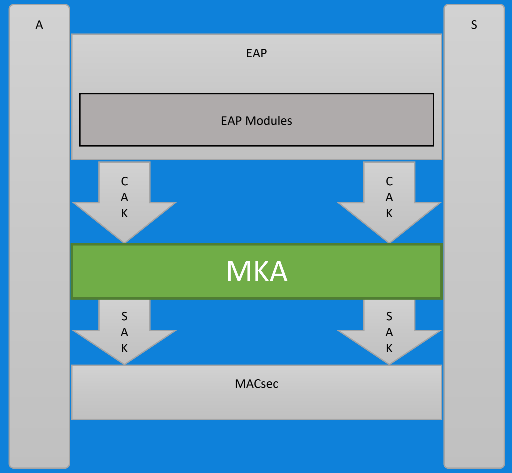
# MACSEC KEY HIERARCHY.

- EAP:
  - The Authenticator (A) controls access of the Supplicant (S).
- EAP modules:
  - Authenticate and authorize supplicant.
  - Agree on Connectivity Association Key (CAK).
  - E.g., EAP-TLS, EAP-IKEv2.
- MACsec Key Agreement (MKA):
  - Distribute Secure Association Key (SAK).
  - Monitoring packet numbers.
  - Rekeying.
- MACsec:
  - Protect communication (auth. or auth.+enc.).

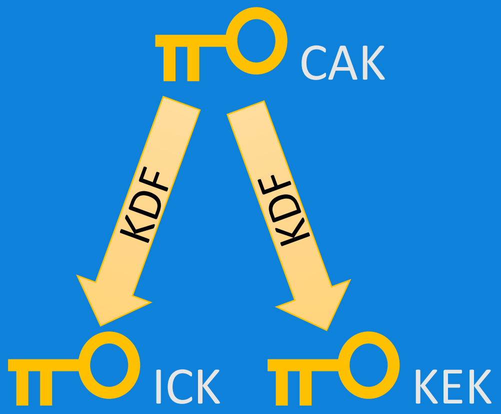


# MKA OVERVIEW.

- Communication partners have the same secret CAK.
- Additional keys are derived via an AES-CMAC KDF:
  - ICV Key (ICK): MKA message integrity protection (AES-CMAC).
  - Key Encryption Key (KEK): encryption of keys in MKA messages.




- Key Exchange process:
  - Find suitable peers and check their liveliness.
  - Elect key server (with EAP obvious).
  - Key server distributes SAK (encrypted by KEK using AES Key Wrap).
  - Activate SAK in MACsec.



# 2 CHAPTER.
# KEY EX OPTIONS.

# AUTHENTICATION OPTIONS.

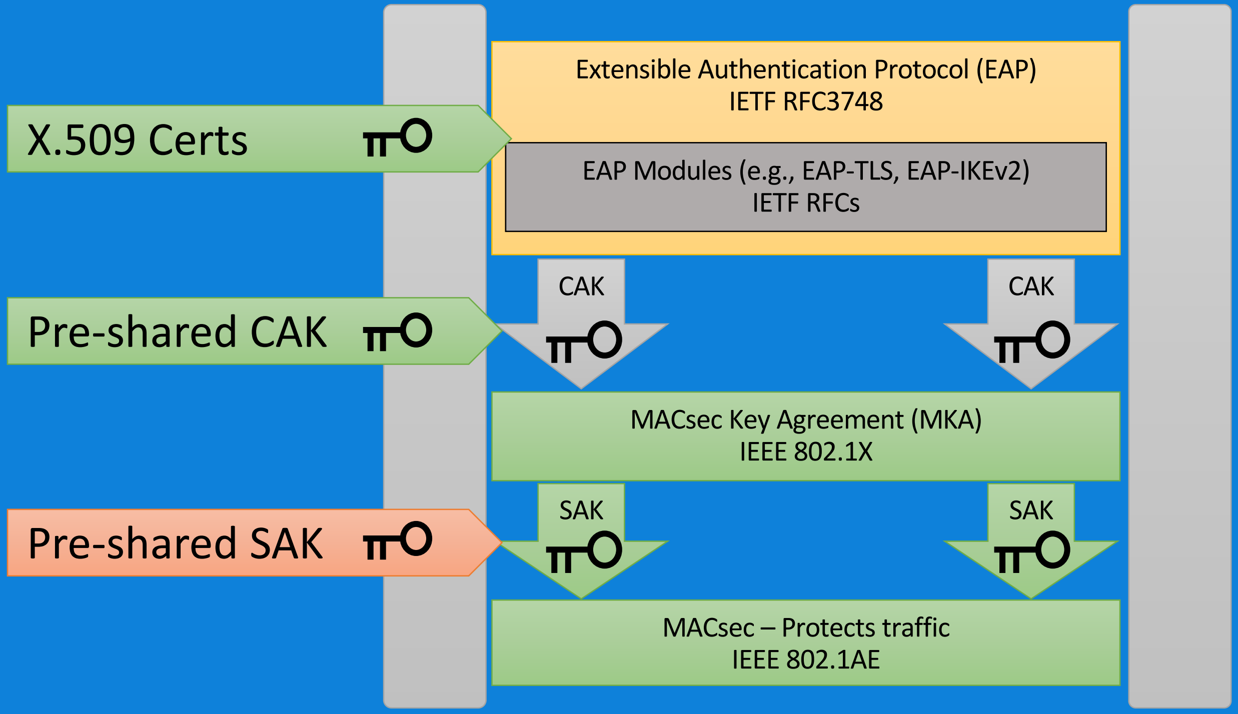
- MACsec/MKA + EAP can support almost every authentication option:
  - Passwords, PSKs, certificates, hardware tokens, …
- Current automotive options in series production:
  - Symmetric keys (e.g., for AES or hash functions).
  - Certificates (e.g., X.509).
- Aspects to keep in mind:
  - Replay attacks.
  - Fast startup requirements for automotive use cases.

# KEY EXCHANGE OPTIONS.

- X.509 certificates:
  - EAP-TLS1.2 (RFC 5216).
  - EAP-TLS1.3 (currently draft only).
  - EAP-IKEv2 (RFC 5106).

- Symmetric keys (128/256 bit):
  - Pre-shared CAKs (MKA).
  - Pre-shared SAKs (MACsec).

  → Key reuse possible! Unsecure!



# 3 CHAPTER. PERFORMANCE.

# MKA OPEN-SOURCE CODE.

- Our team started with an Open-Source implementation.

- First run MKA without EAP: ~3s (sic!):

| No. | Time | Time Delta | Source | Destination | Protocol | Length | Info |
|---|---|---|---|---|---|---|---|
| 1 | 0.000000000 | 0.000000000 | aa:ea:c4:e5:42:cc | 01:80:c2:00:00:03 | EAPOL-MKA | 98 | Key Server |
| 2 | 0.986986779 | 0.986986779 | ce:e9:55:df:c2:5e | 01:80:c2:00:00:03 | EAPOL-MKA | 98 | Key Server |
| 3 | 2.001422945 | 1.014436166 | aa:ea:c4:e5:42:cc | 01:80:c2:00:00:03 | EAPOL-MKA | 118 | Key Server, Potential Peer List |
| 4 | 2.988365546 | 0.986942601 | ce:e9:55:df:c2:5e | 01:80:c2:00:00:03 | EAPOL-MKA | 150 | Key Server, Live Peer List, Distributed SAK |
| 5 | 2.995237588 | 0.006872042 | ce:e9:55:df:c2:5e | 01:80:c2:00:00:03 | EAPOL-MKA | 194 | Key Server, Live Peer List, MACsec SAK Use, Distributed SAK |
| 6 | 2.995736763 | 0.000499175 | aa:ea:c4:e5:42:cc | 01:80:c2:00:00:03 | EAPOL-MKA | 162 | Live Peer List, MACsec SAK Use |
| 7 | 2.996580117 | 0.000843354 | aa:ea:c4:e5:42:cc | 01:80:c2:00:00:03 | EAPOL-MKA | 162 | Live Peer List, MACsec SAK Use |

- Why is this so slow?
  - Both peers send with MKA Hello Time = 2s (see standard) regularly.
  - For election process, peer needs to be found and added to Live Peer List.
  - Only the MACsec SAK Use is send faster (on change).

- Assumptions of IEEE 802.1X are not fully automotive compatible:
  - IEEE 802.1X aims for a bounded time but not a performance target.

# OPTIMIZATIONS.

## 1. Optimize send timings.

- For the peers to find each other, peers should send more frequently.
- Slow down when SAK is established or in Live Peer List of Key Server.

## 2. Configure Key Server priority.

- With PSK, MKA does not assume who is key server (with EAP this is clear).
- Make sure this is configured and no peer waits for election.

## 3. Configure number of peers (“1” in hop-by-hop mode).

- MKA does not assume number of peers; thus, it waits.
- Key Server can generate key as soon as “1” peer is in its Live Peer List.

## 4. ICK and KEK can be precalculated and securely stored to save time.

- Many stacks calculate the AES Key Wraps at startup, but HSM might be busy.

# EXAMPLE: EAP-TLS + OPTIMIZED MKA.

| No. | Time | Time Delta | Source | Destination | Protocol | Length | Info |
|---|---|---|---|---|---|---|---|
| 1 | 0.000000000 | 0.000000000 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 23 | Request, Identity |
| 2 | 0.002054584 | 0.002054584 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAP | 31 | Response, Identity |
| 3 | 0.003316137 | 0.001261553 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 24 | Request, TLS EAP (EAP-TLS) |
| 4 | 0.007923225 | 0.004607088 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | TLSv1.2 | 208 | Client Hello |
| 5 | 0.011259959 | 0.003336734 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 1421 | Request, TLS EAP (EAP-TLS) |
| 6 | 0.012566842 | 0.001306883 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAP | 24 | Response, TLS EAP (EAP-TLS) |
| 7 | 0.013733349 | 0.001166507 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 1421 | Request, TLS EAP (EAP-TLS) |
| 8 | 0.014088112 | 0.000354763 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAP | 24 | Response, TLS EAP (EAP-TLS) |
| 9 | 0.014999081 | 0.000910969 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | TLSv1.2 | 786 | Server Hello, Certificate, Server Key Exchange, Certificate Request, Server Hello Done |
| 10 | 0.020397395 | 0.005398314 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAP | 1426 | Response, TLS EAP (EAP-TLS) |
| 11 | 0.021962444 | 0.001565049 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 24 | Request, TLS EAP (EAP-TLS) |
| 12 | 0.022412434 | 0.000449990 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAP | 1422 | Response, TLS EAP (EAP-TLS) |
| 13 | 0.023837778 | 0.001425344 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 24 | Request, TLS EAP (EAP-TLS) |
| 14 | 0.024133873 | 0.000296095 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | TLSv1.2 | 513 | Certificate, Client Key Exchange, Certificate Verify, Change Cipher Spec, Encrypted Handshake Message |
| 15 | 0.026230843 | 0.002096970 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | TLSv1.2 | 75 | Change Cipher Spec, Encrypted Handshake Message |
| 16 | 0.026966196 | 0.000735353 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAP | 24 | Response, TLS EAP (EAP-TLS) |
| 17 | 0.027921076 | 0.000954880 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 22 | Success |
| 18 | 0.045348454 | 0.017427378 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 82 | |
| 19 | 0.047968715 | 0.002620261 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 82 | Key Server |
| 20 | 0.048169985 | 0.000201270 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 102 | Key Server, Potential Peer List |
| 21 | 0.048263792 | 0.000093807 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 102 | Potential Peer List |
| 22 | 0.048546117 | 0.000282325 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 102 | Live Peer List |
| 23 | 0.049108479 | 0.000562362 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 134 | Key Server, Live Peer List, Distributed SAK |
| 24 | 0.049753040 | 0.000644561 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 178 | Key Server, Live Peer List, MACsec SAK Use, Distributed SAK |
| 25 | 0.049777575 | 0.000024535 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 146 | Live Peer List, MACsec SAK Use |
| 26 | 0.050140095 | 0.000362520 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 146 | Live Peer List, MACsec SAK Use |

28ms

22ms

EAP-TLS

Fragmented!

Fragmented!

MKA

- Key Exchange: ~50ms (with first but not all proposed code optimizations).
  - EAP + EAP-TLS: 28ms (including certificate chain transports).
  - MKA: < 22ms (including 17ms wait times).
  - EAP-TLS, TLS 1.2, ECDH, Certificate chains transported (3k).

# EXAMPLE: EAP-IKEV2 + OPTIMIZED MKA.

| No. | Time | Time Delta | Source | Destination | Protocol | Length | Info |
|---|---|---|---|---|---|---|---|
| 1 | 0.000000000 | 0.000000000 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 23 | Request, Identity |
| 2 | 0.000774654 | 0.000774654 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAP | 33 | Response, Identity |
| 3 | 0.007623369 | 0.006848715 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | ISAKMP | 272 | IKE_SA_INIT MID=00 Initiator Request |
| 4 | 0.012049713 | 0.004426344 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | ISAKMP | 336 | IKE_SA_INIT MID=00 Responder Response |
| 5 | 0.019149714 | 0.007100001 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | ISAKMP | 144 | IKE_AUTH MID=01 Initiator Request |
| 6 | 0.021785272 | 0.002635558 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | ISAKMP | 144 | IKE_AUTH MID=01 Responder Response |
| 7 | 0.026723725 | 0.004938453 | 52:54:00:5c:f9:b1 | 52:54:00:aa:62:b6 | EAP | 22 | Success |
| 8 | 0.030178398 | 0.003454673 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 82 | Key Server |
| 9 | 0.036720458 | 0.006542060 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 82 | |
| 10 | 0.037085717 | 0.000365259 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 102 | Key Server, Potential Peer List |
| 11 | 0.039702837 | 0.002617120 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 102 | Potential Peer List |
| 12 | 0.040614892 | 0.000912055 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 134 | Key Server, Live Peer List, Distributed SAK |
| 13 | 0.041910897 | 0.001296005 | 52:54:00:5c:f9:b1 | 01:80:c2:00:00:03 | EAPOL-MKA | 178 | Key Server, Live Peer List, MACsec SAK Use, Distributed SAK |
| 14 | 0.047462890 | 0.005551993 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 146 | Live Peer List, MACsec SAK Use |
| 15 | 0.053748876 | 0.006285986 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 146 | Live Peer List, MACsec SAK Use |
| 16 | 0.055796143 | 0.002047267 | 52:54:00:aa:62:b6 | 01:80:c2:00:00:03 | EAPOL-MKA | 146 | Live Peer List, MACsec SAK Use |

27ms

29ms

EAP-IKEV2

MKA

- Key Exchange: ~56ms (with first but not all proposed code optimizations).
  - EAP + EAP-IKEv2 (no certs): 27ms (but no certificates transported).
  - MKA: 29ms (including 3.5ms wait time before MKA starts).
  - EAP-IKEv2, DH, no certificate chain transported (not realistic).
- Even after tuning MKA code, results still not stable!

Slow answers of peer (not Key Server).

# FIRST RESULTS.

- After first optimizations: MKA runs in <30ms.
  - MKA timings fluctuate a lot: best cases are <5ms (without wait time).
- ~30ms for certificate-based authentication (EAP-TLS and EAP-IKEv2).
- Platforms (experiments on Raspberry Pi):
  - On a real ECU the asymmetric operations will take longer!
  - Certs: 1 ECDH + 1 ECDSA-sign + (n) ECDSA-verify (n certs in chain).
  - MKA itself should be very fast on embedded ECUs due to AES acceleration.
- Additional optimizations possible.

# 4 CHAPTER. SUMMARY.

# SUMMARY.

- Symmetric keys: static CAK with MKA only → recommended!
- Certificates: EAP-IKEv2 or EAP-TLS (1.3 if possible).
  - Tune algorithm selection.

- MKA uses only AES operations, which can use accelerators.
- Tune the MKA implementations based on automotive assumptions!

- Other recommendations:
  - Choose MACsec algo (e.g., GCM-AES-256 with XPN) and rekey settings.
  - Add mechanisms (e.g., filters) to counter internal attackers too.

# STAY CONNECTED


## Dr. Lars Völker

Technical Fellow
Lars.Voelker@technica-engineering.de
+49 (0) 175 1140982

Technica Engineering GmbH
Leopoldstraße 236
80807 Munich
Germany



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Thank you all!