STARTING UP MACSEC FOR AUTOMOTIVE ETHERNET.

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TECHNICA ENGINEERING

STARTING UP MACSEC

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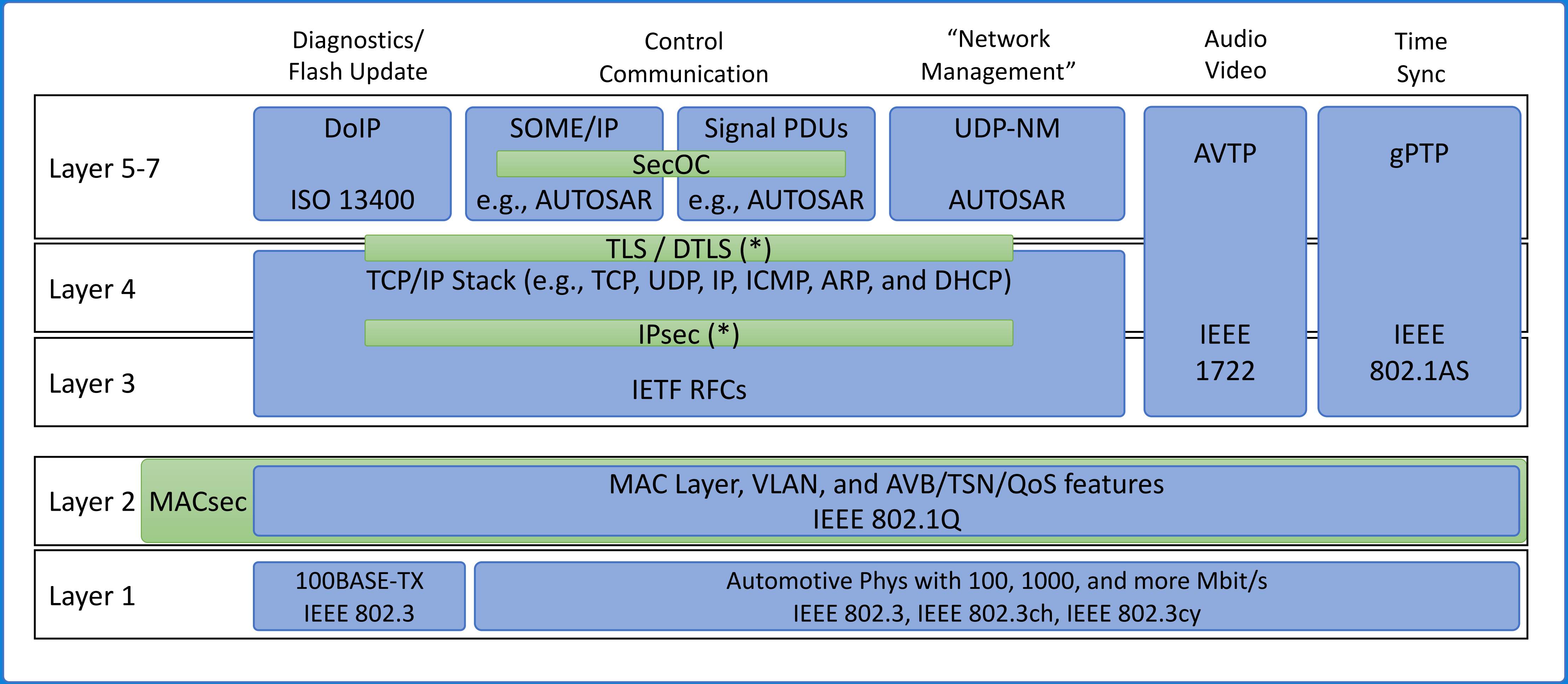
1 CHAPTER.
MACSEC INTRO.

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.

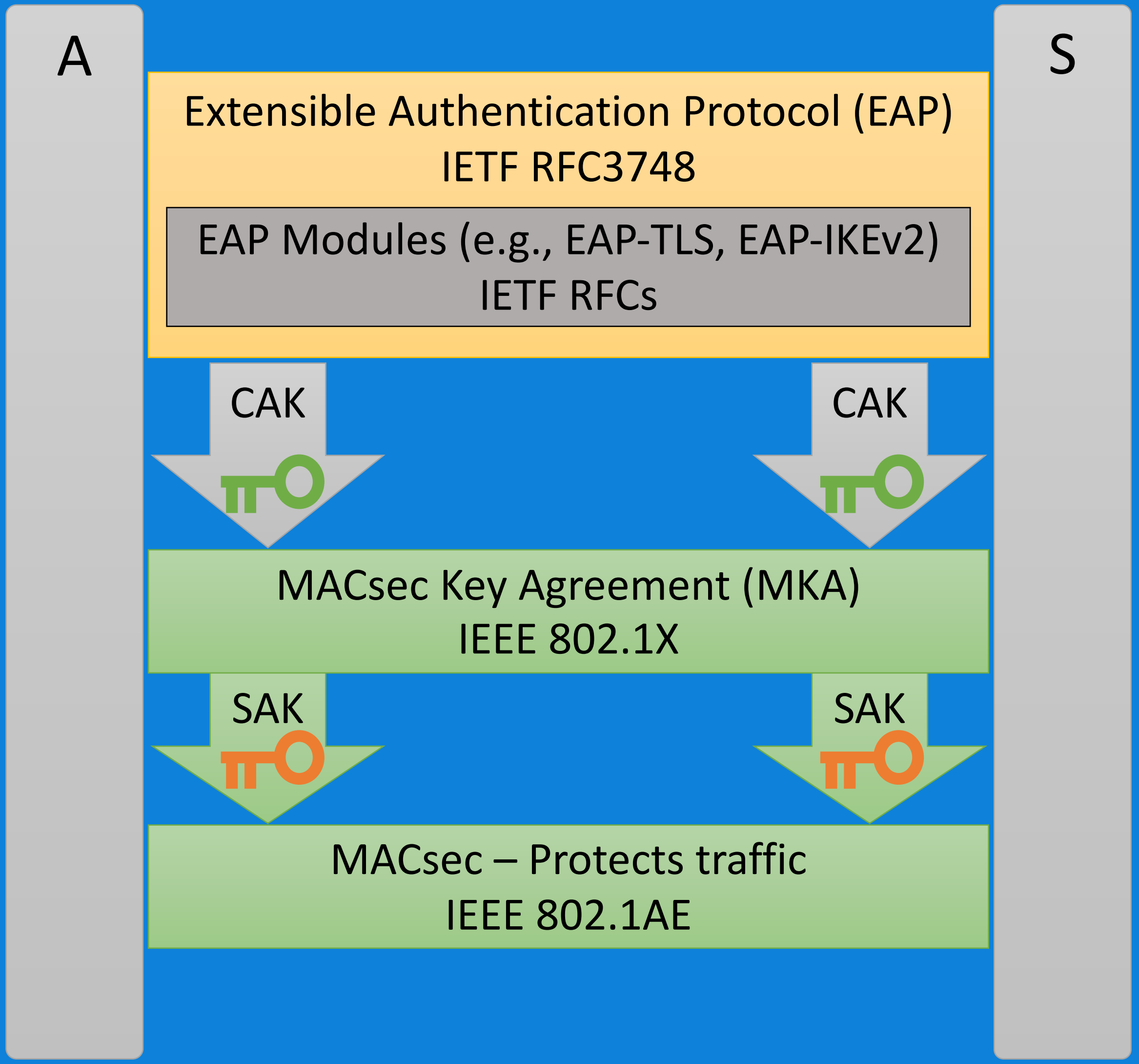
3
- MACsec can protect all traffic on a link with one association.
  - Less keys and key exchanges required (better than SecOC, (D)TLS, IPsec).

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.).



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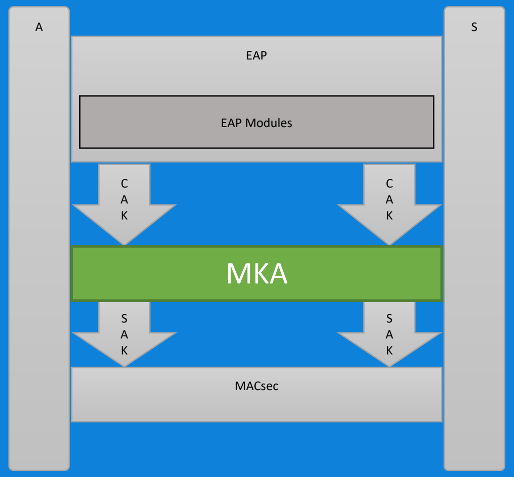
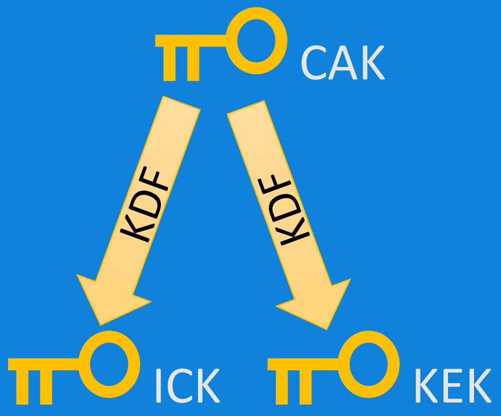
MKA OVERVIEW.

- 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.

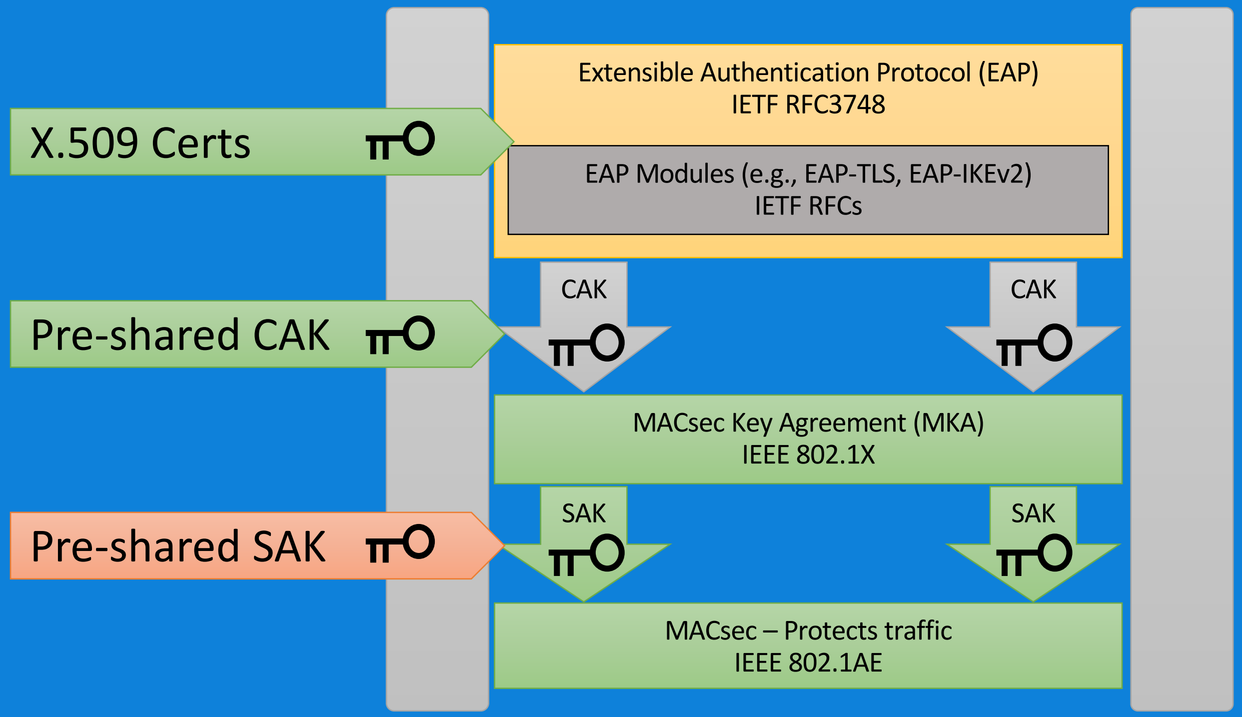
- MACsec/MKA + EAP can support almost every authentication option:
  - Passwords, PSKs, certificates, hardware tokens, …
- Current automotive options in series production:
  - Symmetric keys (e.g., for AES or hash functions).
  - Certificates (e.g., X.509).
- Aspects to keep in mind:
  - Replay attacks.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



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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

EAP-IKEV2

29ms

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).

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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

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Thank you all!