Key Update for OSCORE (KUDOS)

draft-ietf-core-oscore-key-update-01

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Content Recap

- OSCORE (RFC8613) uses AEAD algorithms to provide security
  - Need to follow limits in number of encryptions and failed decryptions, before rekeying
  - Excessive use of the same key can enable breaking security properties of the AEAD algorithm*

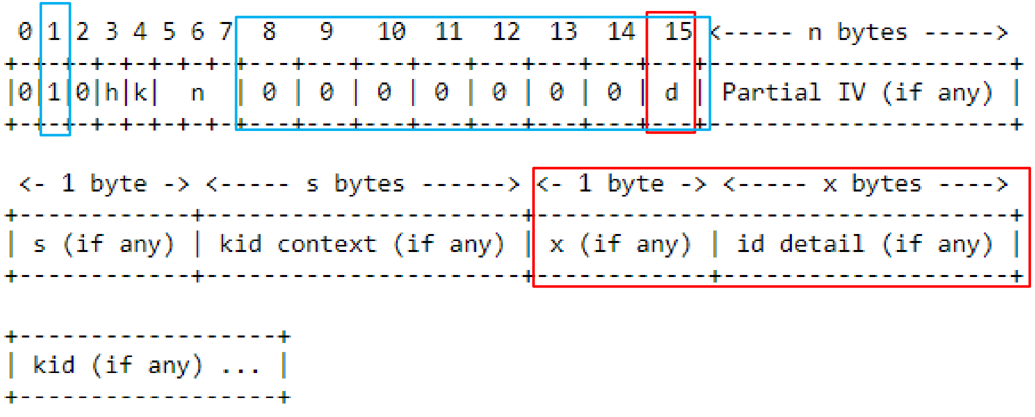
- (1) AEAD Key Usage Limits in OSCORE
  - Defining appropriate limits for OSCORE, for a variety of algorithms
  - Defining counters for key usage; message processing details; steps when limits are reached
  - Now recommends (q, v, l) = (2^20, 2^14, 2^8) for AES 128 CCM 8; details in Appendix A

- (2) Defined Key Update for OSCORE (KUDOS) ← MAIN FOCUS OF TODAY
  - Loosely inspired by Appendix B.2 of OSCORE
  - Goal: Renew the Master Secret and Master Salt; derive new Sender/Recipient keys from those
  - Achieves Forward Secrecy

*See also draft-irtf-cfrg-aead-limits-03

Key Update Recap

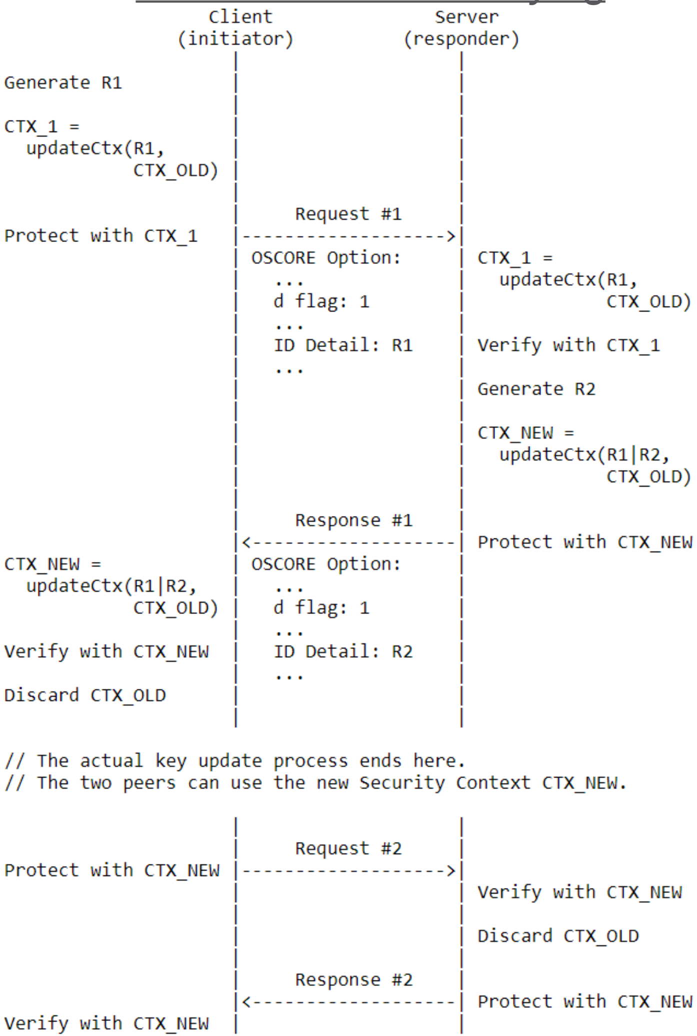
- Method for rekeying OSCORE
  - Key Update for OSCORE (KUDOS)
  - Client and server exchange nonces R1 and R2
  - *UpdateCtx()* function for deriving new OSCORE Security Context using the nonces



```
 0 1 2 3 4 5 6 7  8   9   10  11  12  13  14  15 <----- n bytes ----->
+-+-+-+-+-+-+-+-+---+---+---+---+---+---+---+---+---------------------+
|0|1|0|h|k|  n  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | d | Partial IV (if any) |
+-+-+-+-+-+-+-+-+---+---+---+---+---+---+---+---+---------------------+

 <- 1 byte -> <----- s bytes ------> <- 1 byte -> <----- x bytes ---->
+------------+----------------------+---------------------------------+
| s (if any) | kid context (if any) | x (if any) | id detail (if any) |
+------------+----------------------+------------+--------------------+

+------------------+
| kid (if any) ... |
+------------------+
```

Figure 3: The OSCORE option value, including 'id detail'

Client-initiated rekeying



```
                  Client               Server
               (initiator)          (responder)
                    |                    |
Generate R1         |                    |
                    |                    |
CTX_1 =             |                    |
  updateCtx(R1,     |                    |
            CTX_OLD)|                    |
                    |                    |
                    |     Request #1     |
Protect with CTX_1  |------------------->|
                    | OSCORE Option:     | CTX_1 =
                    |   ...              |   updateCtx(R1,
                    |   d flag: 1        |             CTX_OLD)
                    |   ...              |
                    |   ID Detail: R1    | Verify with CTX_1
                    |   ...              |
                    |                    | Generate R2
                    |                    |
                    |                    | CTX_NEW =
                    |                    |   updateCtx(R1|R2,
                    |                    |             CTX_OLD)
                    |                    |
                    |     Response #1    |
                    |<-------------------| Protect with CTX_NEW
CTX_NEW =           | OSCORE Option:     |
  updateCtx(R1|R2,  |   ...              |
            CTX_OLD)|   d flag: 1        |
                    |   ...              |
Verify with CTX_NEW |   ID Detail: R2    |
                    |   ...              |
Discard CTX_OLD     |                    |
                    |                    |

// The actual key update process ends here.
// The two peers can use the new Security Context CTX_NEW.

                    |                    |
                    |     Request #2     |
Protect with CTX_NEW|------------------->|
                    |                    | Verify with CTX_NEW
                    |                    |
                    |                    | Discard CTX_OLD
                    |                    |
                    |     Response #2    |
                    |<-------------------| Protect with CTX_NEW
Verify with CTX_NEW |                    |
```

Key Update without FS (1/2)

- Added alternative KUDOS mode without Forward Secrecy in Appendix E
  - Initially raised on the CoRE mailing list in [1]
  - It allows stateless key update on loss of state (e.g., rebooting)
    - Needed for constrained devices that cannot store information to persistent memory

- Extension to KUDOS, enabling the selection of a no-FS mode through a new bit ‘p’
  - 'p' set to 0 ==> run KUDOS in FS mode (original mode)
    - Devices capable of writing to persistent memory should initiate the procedure with ‘p’ set to 0
  - 'p' set to 1 ==> run KUDOS in no-FS mode

- New concepts defined
  - Latest Master Secret and Latest Master Salt
    - From the latest derived OSCORE Security; should be stored on disk by a device capable to do so
  - Bootstrap Master Secret & Bootstrap Master Salt
    - If provisioned they are stored on disk, and they are never changed by the device

[1] https://mailarchive.ietf.org/arch/msg/core/EL0yHxQrP2DQwHxo6ojnQedvFbY/

Key Update without FS (2/2)

- Running KUDOS in no-FS mode
  - Before starting KUDOS, the current OSCORE Context CTX_OLD is modified to ensure that
    - Master Secret = Bootstrap Master Secret ; Master Salt = Bootstrap Master Salt
  - Thus forward secrecy is sacrificed, but all other properties of KUDOS remain!

- This mode of KUDOS requires that both peers have Bootstrap Master Secret/Salt

- <u>Agreed</u> downgrading of mode is possible
  - If the initiator sets 'p' to 0, the responder might be unable continue (if it cannot write to disk)
    - Server responder: Return a protected 5.03 error response to Request #1, with 'p' set to 1
    - Client responder: Send a protected Request #2, with 'p' set to 1
    - In either case, abort KUDOS
  - Then, the initiator may retry with 'p' set to 1, to support the best possible common thing

- Reasonable approach? Comments? Good to move to the draft main body?

Keeping Observations (1/2)

- Scenario description:

1. The client starts an observation Obs1 by sending a request Req1 with req_piv X
2. The two peers run KUDOS and reset their Sender Sequence Number (SSN) to 0.
3. Later on, while Obs1 is still ongoing, the client sends a new request Req2 also with req_piv X. This is not necessarily an observation request.

- Problem: A notification sent by the server for Obs1 or a response to Req2 would both cryptographically match against Req1 and Req2

- Now Appendix C defines
  - A method for “long-jumping" beyond PIVs already in use for observations (more on next slide)
  - A new bit ‘b’ to signal interest in keeping observations
    - If there is no mutual interest, delete observations after key update

Keeping Observations (2/2)

- "Long-jumping” method
  - When wishing to send a first request after a KUDOS execution, the client determines the PIV* as the highest req_piv among all the ongoing observations.
  - The client updates its SSN to be (PIV* + 1)

- Issue: Client needs explicit confirmation from server to remove an ongoing observation
  - What if the client cannot get this confirmation?
  - A peer maintains a counter EPOCH for each ongoing observation it participates in, incrementing the EPOCH for every KUDOS execution
  - When EPOCH reaches MAX_EPOCH (same for both peers) the associated observation is deleted by both peers

- MAX_EPOCH
  - Need good default value to recommend

Comments?

Admit negotiation of MAX_EPOCH in KUDOS?

Renew Sender/Recipient IDs (1/3)

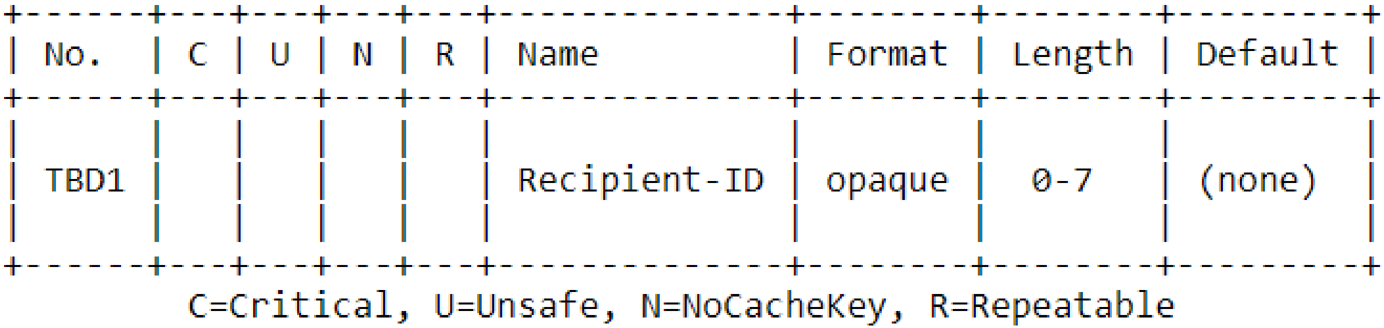
- Appendix D defines a method to update peers’ Sender and Recipient IDs
  - Based on earlier discussions on mailing list [1][2]

- Properties
  - Each peer specifies its own new Recipient ID (similar to EDHOC)
  - Accepting to update the Sender/Recipient IDs is optional; explicit confirmation is needed
  - **This procedure can be embedded in a KUDOS execution or run standalone**
  - Possible for both client and server to initiate this procedure
  - Changing IDs practically triggers derivation of new OSCORE key material
  - Must **not** be done immediately following a reboot (e.g., KUDOS must be run first)

[1] https://mailarchive.ietf.org/arch/msg/core/GXsKO4wKdt3RTZnQZxOzRdIG9QI/
[2] https://mailarchive.ietf.org/arch/msg/core/ClwcSF0BUVxDas8BpgT0WY1yQrY/

Renew Sender/Recipient IDs (2/3)

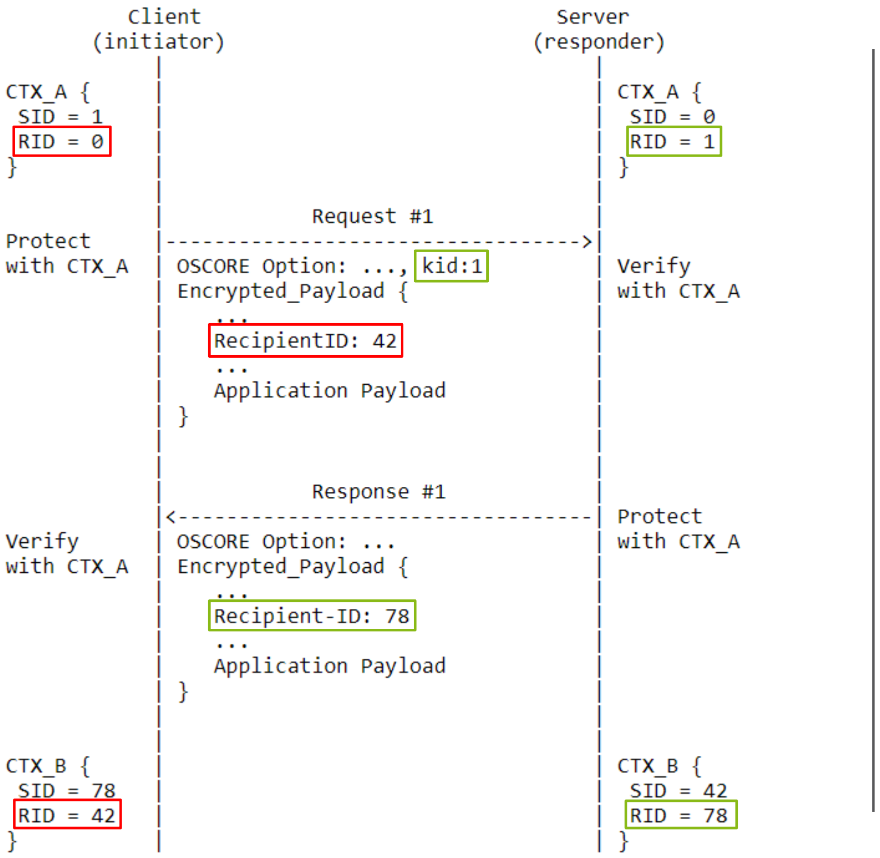
- Defined new CoAP Option to carry the desired Recipient ID
  - Proposed option number 24 (00011000)
  - The option value is the selected new Recipient ID of the message sender
  - The peer selects and offers a free Recipient ID for the used ID Context
  - Class E option for OSCORE processing



No.	C	U	N	R	Name	Format	Length	Default
TBD1					Recipient-ID	opaque	0-7	(none)

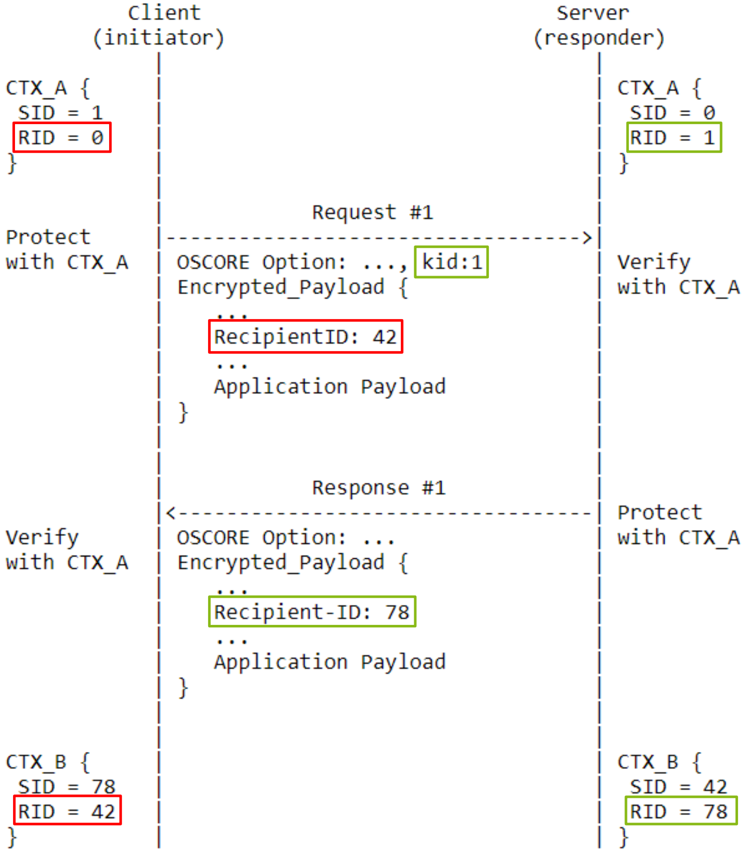
C=Critical, U=Unsafe, N=NoCacheKey, R=Repeatable

Renew Sender/Recipient IDs (3/3)

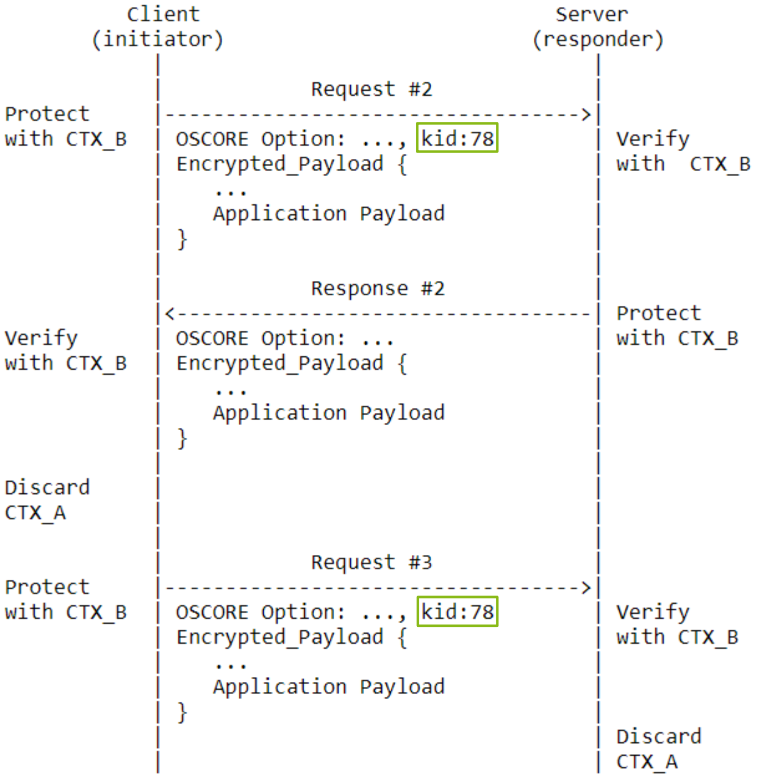


```
         Client                               Server
       (initiator)                          (responder)
            |                                    |
CTX_A {     |                                    | CTX_A {
 SID = 1    |                                    |  SID = 0
 RID = 0    |                                    |  RID = 1
}           |                                    | }
            |                                    |
            |            Request #1              |
Protect     |----------------------------------->|
with CTX_A  | OSCORE Option: ..., kid:1          | Verify
            | Encrypted_Payload {                | with CTX_A
            |    ...                             |
            |    RecipientID: 42                 |
            |    ...                             |
            |    Application Payload             |
            | }                                  |
            |                                    |
            |            Response #1             |
            |<-----------------------------------| Protect
Verify      | OSCORE Option: ...                 | with CTX_A
with CTX_A  | Encrypted_Payload {                |
            |    ...                             |
            |    Recipient-ID: 78                |
            |    ...                             |
            |    Application Payload             |
            | }                                  |
            |                                    |
CTX_B {     |                                    | CTX_B {
 SID = 78   |                                    |  SID = 42
 RID = 42   |                                    |  RID = 78
}           |                                    | }
```

Renew Sender/Recipient IDs (3/3)



```
          Client                            Server
        (initiator)                       (responder)
             |                                 |
CTX_A {      |                                 | CTX_A {
 SID = 1     |                                 |  SID = 0
 RID = 0     |                                 |  RID = 1
}            |                                 | }
             |                                 |
             |            Request #1           |
Protect      |-------------------------------->|
with CTX_A   | OSCORE Option: ..., kid:1       | Verify
             | Encrypted_Payload {             | with CTX_A
             |    ...                          |
             |    RecipientID: 42              |
             |    ...                          |
             |    Application Payload          |
             | }                               |
             |                                 |
             |            Response #1          |
             |<--------------------------------| Protect
Verify       | OSCORE Option: ...              | with CTX_A
with CTX_A   | Encrypted_Payload {             |
             |    ...                          |
             |    Recipient-ID: 78             |
             |    ...                          |
             |    Application Payload          |
             | }                               |
             |                                 |
CTX_B {      |                                 | CTX_B {
 SID = 78    |                                 |  SID = 42
 RID = 42    |                                 |  RID = 78
}            |                                 | }
```



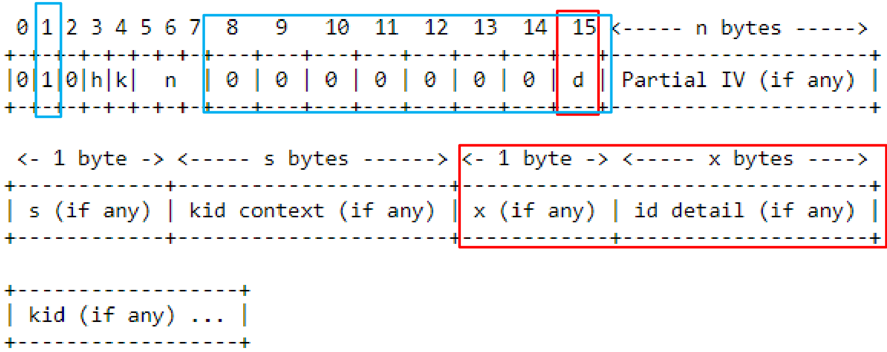
```
          Client                            Server
        (initiator)                       (responder)
             |                                 |
             |            Request #2           |
Protect      |-------------------------------->|
with CTX_B   | OSCORE Option: ..., kid:78      | Verify
             | Encrypted_Payload {             | with  CTX_B
             |    ...                          |
             |    Application Payload          |
             | }                               |
             |                                 |
             |            Response #2          |
             |<--------------------------------| Protect
Verify       | OSCORE Option: ...              | with CTX_B
with CTX_B   | Encrypted_Payload {             |
             |    ...                          |
             |    Application Payload          |
             | }                               |
             |                                 |
Discard      |                                 |
CTX_A        |                                 |
             |                                 |
             |            Request #3           |
Protect      |-------------------------------->|
with CTX_B   | OSCORE Option: ..., kid:78      | Verify
             | Encrypted_Payload {             | with CTX_B
             |    ...                          |
             |    Application Payload          |
             | }                               |
             |                                 | Discard
             |                                 | CTX_A
```

Objections? Alternatives?

Alternatives for signaling

- **Currently 3 bits are defined**
  - "ID Detail Flag", 'd'
    - Signals inclusion of ID Detail in OSCORE option
  - "No Forward Secrecy", 'p'
    - Signals the use of the no-FS mode
  - "Preserve Observations", 'b'
    - Signals preservation of CoAP Observations

- **Where to put bits 'b' & 'p', and integrity protect them?**
  - In the 1 byte 'x' following 'kid context', originally encoding the size of 'id detail'
  - Recommended size of nonces R1 & R2 (carried in 'id detail') is 8 bytes → Number of bits available in the 'x' byte is still sufficient to indicate the size of 'id detail'
  - The 'x' value is taken as input in the derivation of the new OSCORE Security Context



```
 0 1 2 3 4 5 6 7  8   9   10  11  12  13  14  15 <----- n bytes ----->
+-+-+-+-+-+-+-+-+---+---+---+---+---+---+---+---+---------------------+
|0|1|0|h|k|  n  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | d | Partial IV (if any) |
+-+-+-+-+-+-+-+-+---+---+---+---+---+---+---+---+---------------------+

 <- 1 byte -> <----- s bytes ------> <- 1 byte -> <----- x bytes ---->
+------------+----------------------+-------------------------------+
| s (if any) | kid context (if any) | x (if any) | id detail (if any) |
+------------+----------------------+------------+------------------+

+------------------+
| kid (if any) ... |
+------------------+
```

Figure 3: The OSCORE option value, including 'id detail'

```
updateCtx(R1, CTX_OLD)     ——▶ updateCtx(X1|R1, CTX_OLD)
updateCtx(R1|R2, CTX_OLD)  ——▶ updateCtx(X1|X2|R1|R2, CTX_OLD)
```

Comments?

Summary and next steps

- Latest updates
  - Suggested key update **without forward secrecy** (Appendix E)
  - Suggested method for **preserving observations** across key updates (Appendix C)
  - Suggested procedure to **update OSCORE Sender/Recipient IDs** (Appendix D)
  - Proposed alternative placement for signaling bits
  - Improvements in message processing
  - Optional storing optimization for ‘count_q’ (Appendix B)

- Address open points and issues – Feedback is welcome!
  - Improve the suggestions above, move to document body
  - Clarify which KUDOS messages can contain actionable payload

- Implementation
  - To build on existing implementation of OSCORE in Java Californium

Thank you!

Comments/questions?

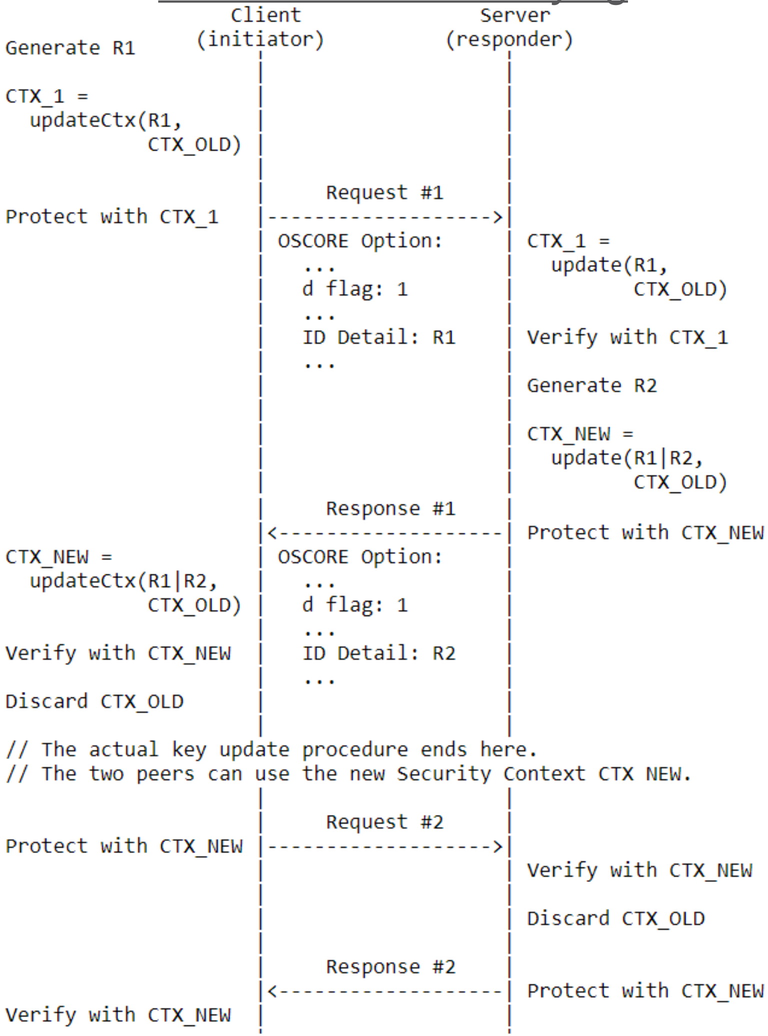
https://github.com/core-wg/oscore-key-update

Key update overview

- Defined a new method for rekeying OSCORE
  - Key Update for OSCORE (KUDOS)
  - Client and server exchange nonces R1 and R2
  - *UpdateCtx()* function for deriving new OSCORE Security Context using the nonces

- Properties
  - Can be initiated by either the client or server
  - Completes in one round-trip (after that, the new Security Context can be used)
  - Only one intermediate Security Context is derived
  - The ID Context does not change
  - Robust and secure against peer rebooting
  - Compatible with prior key establishment using the EDHOC protocol
  - NEW › Mode with PFS (stateful) and without PFS (stateless)
  - NEW › Possibility to update Recipient/Sender IDs

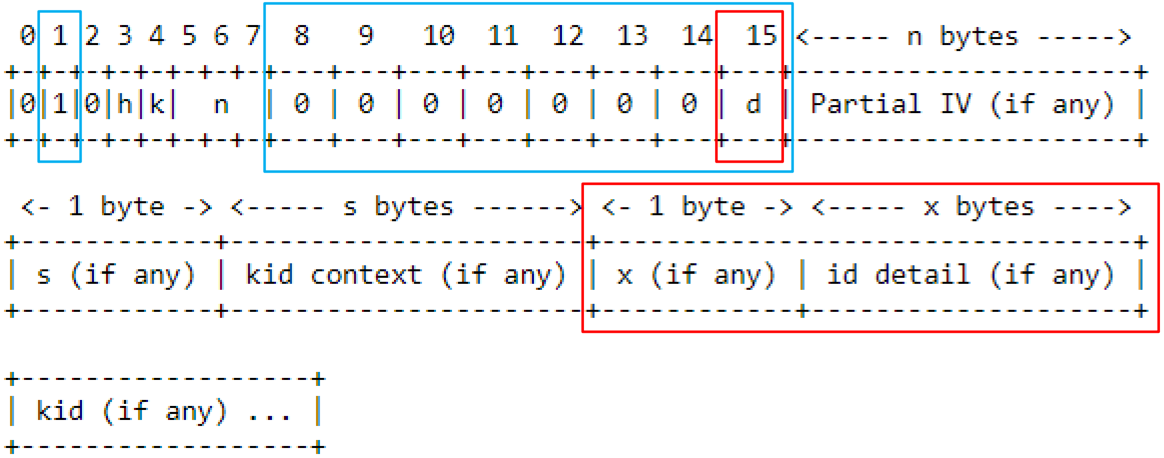
Client-initiated rekeying



```
                   Client               Server
Generate R1     (initiator)         (responder)
                     |                    |
CTX_1 =              |                    |
  updateCtx(R1,      |                    |
            CTX_OLD) |                    |
                     |                    |
                     |     Request #1     |
Protect with CTX_1   |------------------->|
                     | OSCORE Option:     | CTX_1 =
                     |   ...              |   update(R1,
                     |   d flag: 1        |          CTX_OLD)
                     |   ...              |
                     |   ID Detail: R1    | Verify with CTX_1
                     |   ...              |
                     |                    | Generate R2
                     |                    |
                     |                    | CTX_NEW =
                     |                    |   update(R1|R2,
                     |                    |          CTX_OLD)
                     |     Response #1    |
                     |<-------------------| Protect with CTX_NEW
CTX_NEW =            | OSCORE Option:     |
  updateCtx(R1|R2,   |   ...              |
            CTX_OLD) |   d flag: 1        |
                     |   ...              |
Verify with CTX_NEW  |   ID Detail: R2    |
                     |   ...              |
Discard CTX_OLD      |                    |
                     |                    |
// The actual key update procedure ends here.
// The two peers can use the new Security Context CTX_NEW.
                     |                    |
                     |     Request #2     |
Protect with CTX_NEW |------------------->|
                     |                    | Verify with CTX_NEW
                     |                    |
                     |                    | Discard CTX_OLD
                     |                    |
                     |     Response #2    |
                     |<-------------------| Protect with CTX_NEW
Verify with CTX_NEW  |                    |
```

OSCORE Option update

- OSCORE Option: defined the use of flag bit 1 to signal presence of flag bits 8-15
- Defined flag bit 15 -- 'd' -- to indicate:
  - This is a OSCORE key update message
  - "id detail" is specified (length + value); used to transport a nonce for the key update



```
 0 1 2 3 4 5 6 7  8   9   10  11  12  13  14  15 <----- n bytes ----->
+-+-+-+-+-+-+-+-+---+---+---+---+---+---+---+---+---------------------+
|0|1|0|h|k|  n  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | d | Partial IV (if any) |
+-+-+-+-+-+-+-+-+---+---+---+---+---+---+---+---+---------------------+

 <- 1 byte -> <----- s bytes ------> <- 1 byte -> <----- x bytes ---->
+------------+----------------------+------------+--------------------+
| s (if any) | kid context (if any) | x (if any) | id detail (if any) |
+------------+----------------------+------------+--------------------+

+------------------+
| kid (if any) ... |
+------------------+
```

Figure 3: The OSCORE option value, including 'id detail'

Key limits (1/3)

Confidentiality Advantage (CA): Probability of breaking confidentiality properties

Integrity Advantage (IA): Probability of breaking integrity properties

- Recap on AEAD limits
  - Discussed in **draft-irtf-cfrg-aead-limits-03**
  - Limits key use for encryption (q) and invalid decryptions (v)
  - This draft defines fixed values for ‘q’, ‘v’, and ‘l’ and from those calculate CA & IA probabilities
    - IA & CA probabilities must be acceptably low

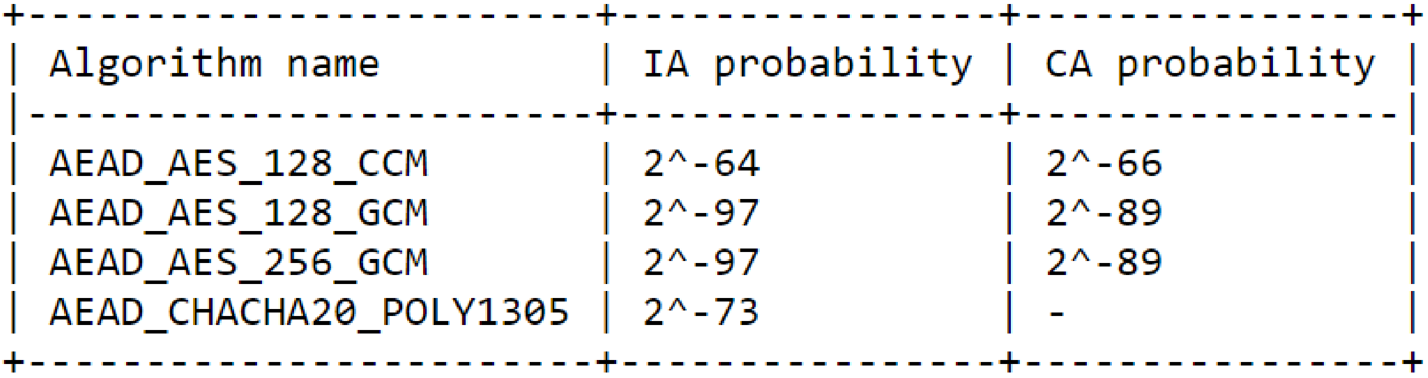
- Now explicit size limit of protected data to be sent in a new OSCORE message
  - The probabilities are influenced by ‘l’, i.e., maximum message size in cipher blocks
  - Implementations should not exceed 'l', and it has to be easy to avoid doing so
  - New text: *the total size of the COSE plaintext, authentication Tag, and possible cipher padding for a message may not exceed the block size for the selected algorithm multiplied with 'l'‘*

- New table (Figure 3) showing values of ‘l’ not just in cipher blocks but actual bytes

Key limits (2/3)

- Increased value of ‘l’ (message size in blocks) for algos except AES_128_CCM_8
  - – Increasing ‘l’ from 2^8 to 2^10 should maintain secure CA and IA probabilities
  - – draft-irtf-cfrg-aead-limits mentions aiming for CA & IA lower than to 2^-50
    - They have added a table in that document with calculated ‘q’ and ‘v’ values

q = 2^20, v = 2^20, and l = 2^10

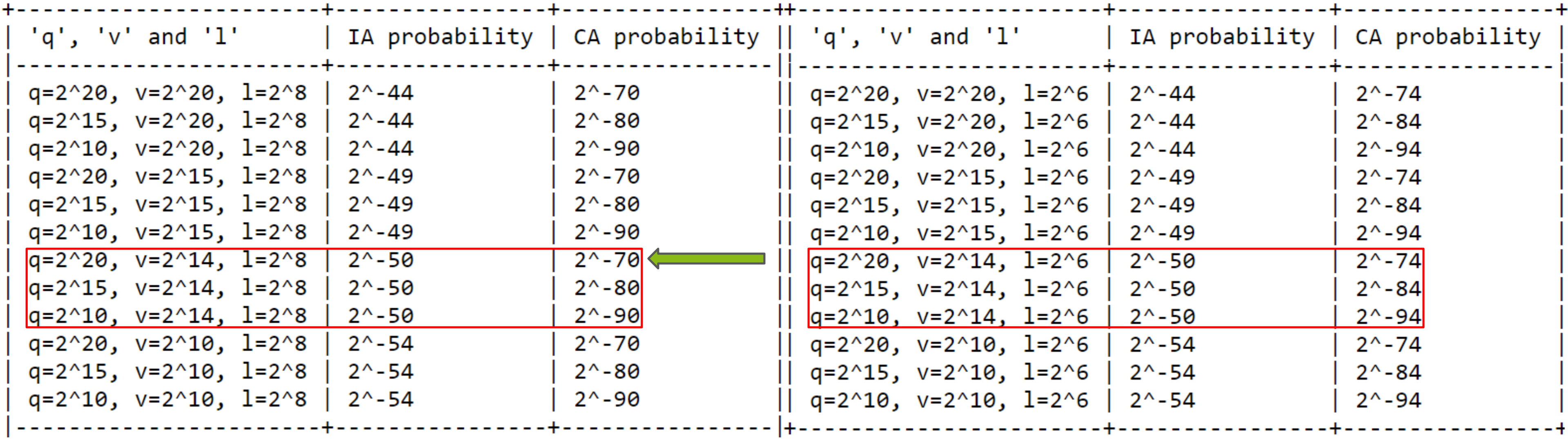


Algorithm name	IA probability	CA probability
AEAD_AES_128_CCM	2^-64	2^-66
AEAD_AES_128_GCM	2^-97	2^-89
AEAD_AES_256_GCM	2^-97	2^-89
AEAD_CHACHA20_POLY1305	2^-73	-

- Intent is to increase 'q', 'v' and/or 'l' further. Should we?
  - – Since we are well below 2^-50 for CA & IA currently

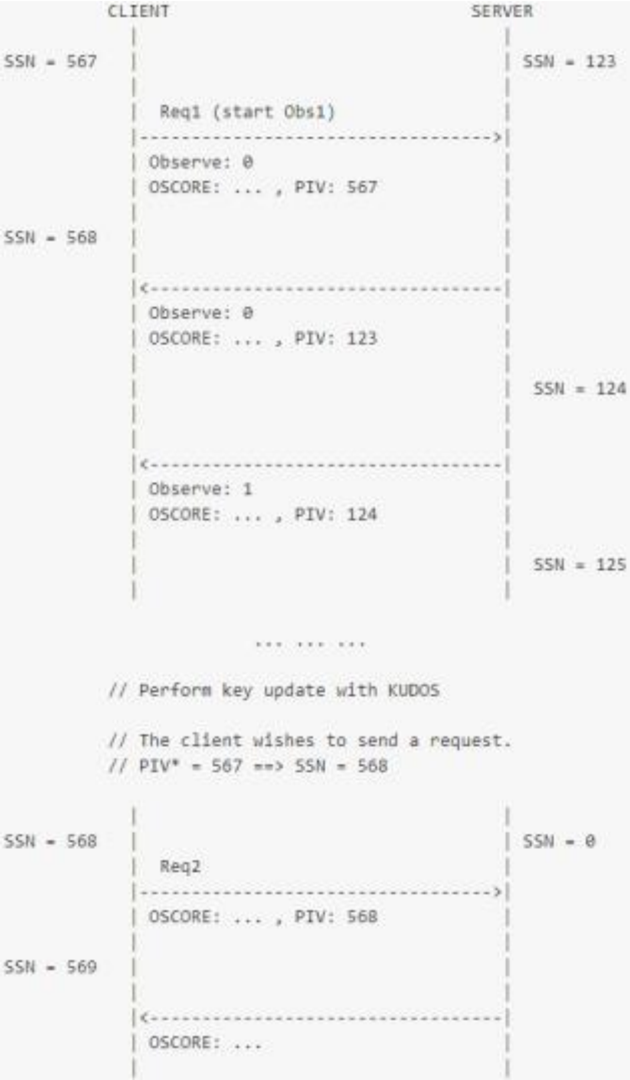
Key limits (3/3)

- Updated table of ‘q’, ‘v’ and ‘l’ for AES_128_CCM_8
  - Added new value for ‘v’, still leaving CA and IA less than 2^-50
  - Is it ideal to aim for CA & IA close to 2^-50 as defined in the CRFG document?



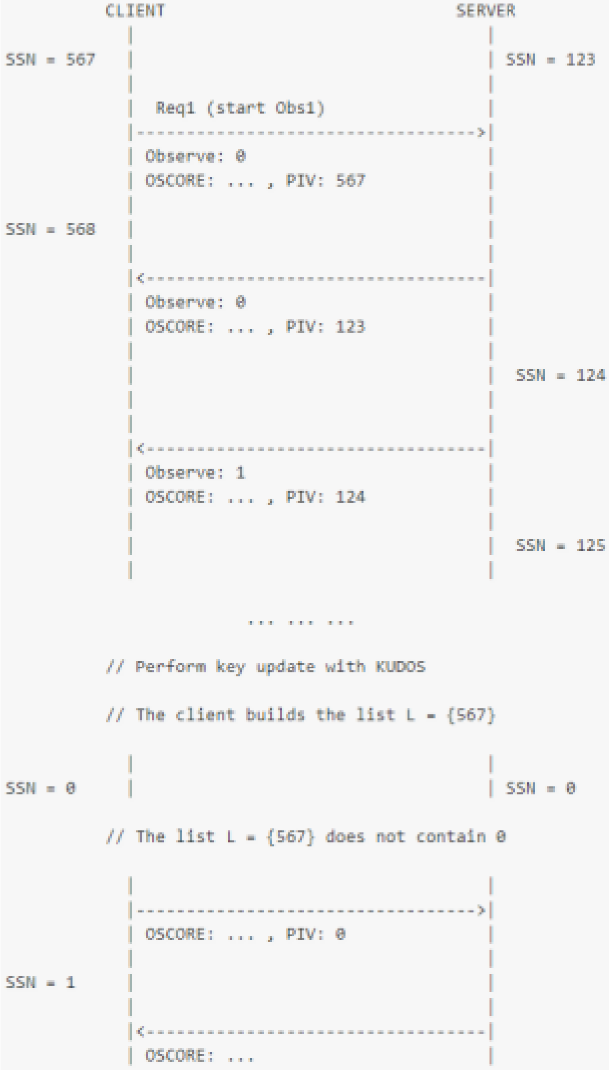
```
+------------------------+----------------+----------------++------------------------+----------------+----------------+
| 'q', 'v' and 'l'       | IA probability | CA probability || 'q', 'v' and 'l'       | IA probability | CA probability |
|------------------------+----------------+----------------||------------------------+----------------+----------------|
| q=2^20, v=2^20, l=2^8  | 2^-44          | 2^-70          || q=2^20, v=2^20, l=2^6  | 2^-44          | 2^-74          |
| q=2^15, v=2^20, l=2^8  | 2^-44          | 2^-80          || q=2^15, v=2^20, l=2^6  | 2^-44          | 2^-84          |
| q=2^10, v=2^20, l=2^8  | 2^-44          | 2^-90          || q=2^10, v=2^20, l=2^6  | 2^-44          | 2^-94          |
| q=2^20, v=2^15, l=2^8  | 2^-49          | 2^-70          || q=2^20, v=2^15, l=2^6  | 2^-49          | 2^-74          |
| q=2^15, v=2^15, l=2^8  | 2^-49          | 2^-80          || q=2^15, v=2^15, l=2^6  | 2^-49          | 2^-84          |
| q=2^10, v=2^15, l=2^8  | 2^-49          | 2^-90          || q=2^10, v=2^15, l=2^6  | 2^-49          | 2^-94          |
| q=2^20, v=2^14, l=2^8  | 2^-50          | 2^-70          || q=2^20, v=2^14, l=2^6  | 2^-50          | 2^-74          |
| q=2^15, v=2^14, l=2^8  | 2^-50          | 2^-80          || q=2^15, v=2^14, l=2^6  | 2^-50          | 2^-84          |
| q=2^10, v=2^14, l=2^8  | 2^-50          | 2^-90          || q=2^10, v=2^14, l=2^6  | 2^-50          | 2^-94          |
| q=2^20, v=2^10, l=2^8  | 2^-54          | 2^-70          || q=2^20, v=2^10, l=2^6  | 2^-54          | 2^-74          |
| q=2^15, v=2^10, l=2^8  | 2^-54          | 2^-80          || q=2^15, v=2^10, l=2^6  | 2^-54          | 2^-84          |
| q=2^10, v=2^10, l=2^8  | 2^-54          | 2^-90          || q=2^10, v=2^10, l=2^6  | 2^-54          | 2^-94          |
|------------------------+----------------+----------------|+------------------------+----------------+----------------+
```

“Long-Jumping”

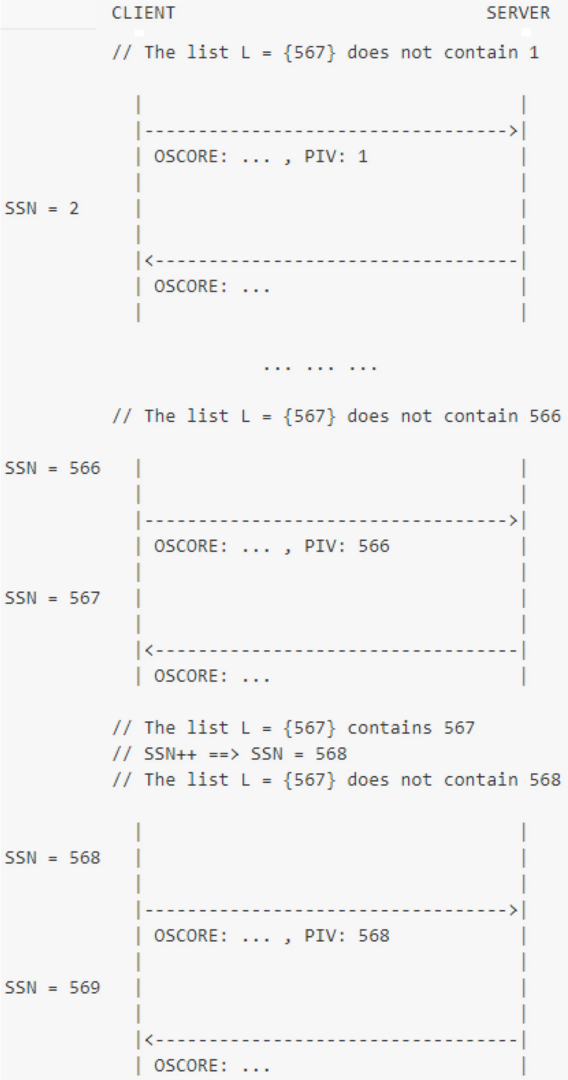


```
            CLIENT                                 SERVER
              |                                       |
SSN = 567     |                                       | SSN = 123
              |                                       |
              |  Req1 (start Obs1)                    |
              |-------------------------------------->|
              | Observe: 0                            |
              | OSCORE: ... , PIV: 567                |
              |                                       |
SSN = 568     |                                       |
              |                                       |
              |<--------------------------------------|
              | Observe: 0                            |
              | OSCORE: ... , PIV: 123                |
              |                                       |
              |                                       |  SSN = 124
              |                                       |
              |                                       |
              |<--------------------------------------|
              | Observe: 1                            |
              | OSCORE: ... , PIV: 124                |
              |                                       |
              |                                       |  SSN = 125
              |                                       |

                         ... ... ...

          // Perform key update with KUDOS

          // The client wishes to send a request.
          // PIV* = 567 ==> SSN = 568

              |                                       |
SSN = 568     |                                       | SSN = 0
              |  Req2                                 |
              |-------------------------------------->|
              | OSCORE: ... , PIV: 568                |
              |                                       |
SSN = 569     |                                       |
              |                                       |
              |<--------------------------------------|
              | OSCORE: ...                           |
              |                                       |
```

“Skipping”



```
           CLIENT                                    SERVER
             |                                          |
SSN = 567    |                                          | SSN = 123
             |                                          |
             |  Req1 (start Obs1)                       |
             |----------------------------------------->|
             | Observe: 0                               |
             | OSCORE: ... , PIV: 567                   |
             |                                          |
SSN = 568    |                                          |
             |                                          |
             |<-----------------------------------------|
             | Observe: 0                               |
             | OSCORE: ... , PIV: 123                   |
             |                                          |
             |                                          |  SSN = 124
             |                                          |
             |                                          |
             |<-----------------------------------------|
             | Observe: 1                               |
             | OSCORE: ... , PIV: 124                   |
             |                                          |
             |                                          |  SSN = 125
             |                                          |

                         ... ... ...

       // Perform key update with KUDOS

       // The client builds the list L = {567}

             |                                          |
SSN = 0      |                                          | SSN = 0

       // The list L = {567} does not contain 0

             |                                          |
             |----------------------------------------->|
             | OSCORE: ... , PIV: 0                     |
             |                                          |
SSN = 1      |                                          |
             |                                          |
             |<-----------------------------------------|
             | OSCORE: ...                              |
```



```
          CLIENT                                     SERVER
          // The list L = {567} does not contain 1

             |                                          |
             |----------------------------------------->|
             | OSCORE: ... , PIV: 1                     |
             |                                          |
SSN = 2      |                                          |
             |                                          |
             |<-----------------------------------------|
             | OSCORE: ...                              |
             |                                          |

                         ... ... ...

          // The list L = {567} does not contain 566

SSN = 566    |                                          |
             |                                          |
             |----------------------------------------->|
             | OSCORE: ... , PIV: 566                   |
             |                                          |
SSN = 567    |                                          |
             |                                          |
             |<-----------------------------------------|
             | OSCORE: ...                              |

          // The list L = {567} contains 567
          // SSN++ ==> SSN = 568
          // The list L = {567} does not contain 568

             |                                          |
SSN = 568    |                                          |
             |                                          |
             |----------------------------------------->|
             | OSCORE: ... , PIV: 568                   |
             |                                          |
SSN = 569    |                                          |
             |                                          |
             |<-----------------------------------------|
             | OSCORE: ...                              |
```