11 Security-oriented mechanisms

Clause 11 introduces the security-related mechanisms, focusing in particular on ONU identity and various aspects of access management (see 11.2) and data encryption / decryption (see 11.3), achieved in an interoperable manner.

11.1 Overview of threats and mitigation measures

11.1.1 Threat model

The security threat model in PONs encompasses various risks and vulnerabilities that need to be addressed to ensure a secure and reliable network infrastructure:

— **Broadcast of downstream data**:
One of the inherent vulnerabilities in PONs is the broadcast nature of downstream data transmission. As downstream data is broadcasted to all ONUs attached to the OLT's PON port, a malicious user who gains control of an ONU or attaches an un-authorized device could intercept and access downstream data intended for all connected users. This poses a significant risk to the confidentiality and privacy of user data.

— **Impersonation and service theft**:
Due to the nature of upstream data transmission in PONs, where data can originate from any ONU attached to the ODN, a malicious user with control over an ONU could forge packets to impersonate a different ONU. This "theft of service" attack allows the attacker to masquerade as a legitimate ONU, potentially gaining unauthorized access to network resources or services.

— **Infrastructure Tampering**:
An attacker could compromise the security of the PON infrastructure by physically tampering with street cabinets, spare ports, or fiber cables. By connecting a malicious device at various points within the network, the attacker could intercept and manipulate network traffic. Depending on the location of the malicious device, it could impersonate the OLT, allowing unauthorized access and control over the network, or impersonate an ONU to intercept and tamper with data.

— **Packet Replay and Bit-Flipping Attacks**:
In PONs, a malicious user who successfully captures network packets transmitted on the PON could store and replay them at a later time. This replay attack poses a threat to data integrity and can lead to unauthorized access or service disruption. Additionally, an attacker could conduct bit-flipping attacks, altering the content of transmitted packets, potentially compromising the integrity and accuracy of the data.

— **Data Capture and Offline Decrypt**:
In PONs, a malicious user who successfully captures network packets transmitted on the PON could store and attempt to decrypt them at a later time if/when the private key(s) of the peers is cracked or compromised – gaining access to any encryption keys derived from the public key exchange. This attack could compromise tremendous amounts of data retroactively – even if/when compromised public/private key pairs are taken out of service.

11.1.2 Physical protection of security data in the ONU

The physical protection measures outlined in this sub-clause collectively ensure the secure storage and protection of certificates and keys within ONUs in PON networks, safeguarding against unauthorized access and potential security breaches.

11.1.2.1 Secure non-volatile storage

ONUs shall implement the requirements outlined in SECv3.0 for secure non-volatile storage of certificates and their associated public/private keys. This ensures that sensitive cryptographic information remains protected from unauthorized disclosure and modification.

11.1.2.2 Protection against unauthorized access

ONUs should employ measures to prevent unauthorized access to the ONU certificate private key, particularly in production devices. One recommended approach is to restrict or block physical access to the memory that contains the private key. This prevents unauthorized individuals from using debugger tools to read the key.

11.1.2.3 Use of One-Time-Programmable (OTP) Memory

To enhance security and make it more challenging to replicate a valid ONU, ONUs should use one-time-programmable (OTP) memory for storing certificates and keys. OTP memory is designed to prevent alteration or cloning of the stored data, thereby bolstering the overall security of the ONU.

11.1.2.4 Compliance with FIPS-140-2 Security Requirements

The ONU shall meet the security requirements specified in the Federal Information Processing Standard (FIPS) 140-2 for all instances of permanent private and public key storage. FIPS-140-2 provides a rigorous set of cryptographic security standards, ensuring the confidentiality and integrity of the stored keys.

11.1.2.5 Compliance with FIPS-140-2 Security Level 1

The ONU shall also comply with FIPS-140-2 Security Level 1. This level requires minimal physical protection and shall be achieved through the use of production-grade enclosures. The enclosures for ONUs shall meet production-grade quality standards, including standard passivation sealing. The circuitry within the ONU shall be implemented as a production-grade multi-chip embodiment, typically in the form of an IC printed circuit board. The ONU itself should be contained within a metal or hard plastic enclosure, which may include doors or removable covers.

11.1.3 Security mechanisms

The physical security and tamper-proof installation of the ODN, optical splitters, and ONUs can enhance the overall security of the PON infrastructure. By implementing physical security measures, such as those listed in 11.1.2, the risk of unauthorized access or tampering can be significantly reduced.

However, the specific threat landscape of PON installations requires deployment of specific security measures, such as robust authentication protocols, encryption mechanisms, network monitoring systems, and intrusion detection systems, to mitigate the identified threats effectively. By adopting a comprehensive and multi-layered security approach, PON operators can ensure the confidentiality, integrity, and authenticity of data transmitted over the network, even in scenarios where physical security measures are compromised or absent.

11.1.3.1 Establishment of security mechanisms

The process of adding a new ONU to a PON follows a series of defined steps, ensuring secure ONU integration and subsequent operation. Figure 11-4 illustrates these steps:

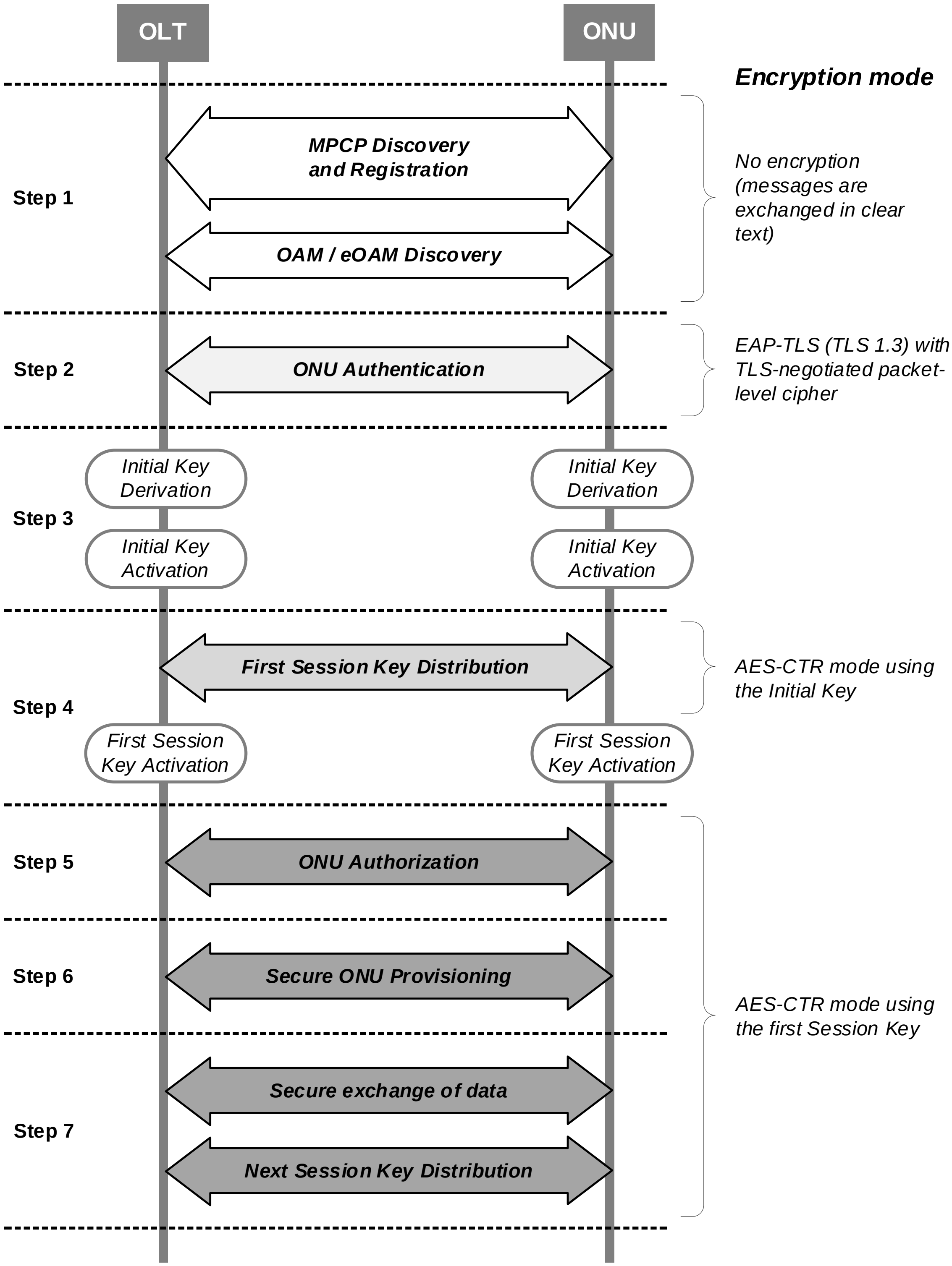


Figure 11-4–Sequence of steps to establish secure ONU operation

Step 1 – ONU Discovery and Registration:

Upon completion of the boot/restart sequence, the ONU completes the MPCP. OAM, and eOAM discovery processes as specified in 13.3.1 and 13.3.2. At this time, ONU is assigned two logical links: PLID for exchanging the GATE and REPORT MPCPDUs and MLID for exchanging the OAM control messages (OAMPDUs). The MPCP and OAM discoveries are performed in the clear, i.e., using unencrypted MPCP and OAM messages.

Step 2 –ONU authentication:

Upon completion of eOAM discovery, the ONU and OLT proceed with ONU authentication using the method defined in 11.2.2. This step cryptographically verifies the ONU identity within the network. If the ONU fails to authenticate, the OLT may retry the authentication procedure with a different ONU's credential. The OLT does not provision user services to an ONU that has failed to authenticate using any of its available certificates.

Step 3 – Establishment of the initial key:

Once the ONU and OLT have completed the authentication exchange, both the OLT and ONU independently derive the initial symmetric encryption key. The key derivation and activation methods are specified in 11.3.2.

Step 4 – Secure distribution and activation of session keys:

The OLT/NMS distributes the first session key to the ONU using the session key distribution protocol (see 11.3.3). The messages exchanged under the session key distribution protocol are encrypted using the initial key obtained in Step 3. After the encryption key is distributed to the ONU, the OLT initiates a switch to the new key (i.e., key activation by both the OLT and the ONU), using the procedure described in 11.3.4.

Step 5 – ONU authorization

ONU authorization refers to the verification of ONU's eligibility to operate on the operator's network. ONU authorization is initiated by the NMS/AAA server after the ONU has successfully authenticated and symmetric encryption has been established for secure communication between the OLT and the ONU. The ONU authorization procedure is specified in 11.2.3. The exchange of information between the OLT and ONU pertaining to the ONU authorization is carried over the encrypted MLID logical link.

Step 6 – Secure provisioning of additional logical links:

If the NMS determines that the ONU is authorized to operate on a given PON network, it proceeds with the provisioning of the additional bidirectional and unidirectional (multicast) logical links for this ONU. The additional logical links are provisioned using the extended action *acConfigLlid* (see 14.6.2.8).

Note that no additional encryption configuration steps are needed for the newly-provisioned bidirectional links. These links automatically begin operating with the ONU's currently active session encryption key. However, this is not the case for the newly provisioned unidirectional (multicast) logical links. As explained in 11.3.3.3, each of multicast logical link uses a unique encryption key that is shared among all members of this multicast group. Therefore, before the ONU is able to process the data frames received on the multicast logical link, it needs to obtain the specific encryption key for that multicast group. The multicast keys are distributed using the same extended action *acConfigEncrKey* (see 14.6.5.1) as is used for the unicast keys.

The control messages that provision additional logical links (*acConfigLlid* actions) and the messages that convey encryption keys for the multicast LLIDs (*acConfigEncrKey* action) are securely exchanged between the OLT and an ONU via the encrypted MLID link.

Step 7 – Exchange of encrypted data and control messages:

With the session keys distributed by the OLT and additional ULIDs provisioned for carrying the subscriber data, the OLT and the ONU can securely exchange data frames over the PON. The data frames are encrypted using the session key to ensure confidentiality and integrity during transmission. The cryptographic method is defined in 11.3.5. The OLT can also provide credential and trust store updates to the ONU for future authentication as described in TBD.

11.2 ONU identity and access management

Before an ONU is allowed access to the operator's network and symmetric encryption keys established for secure communication between the OLT and the ONU, the ONU's identity needs to be determined and verified. The authenticated ONU identity can then be used by the NMS to reliably establish what level of access the ONU is granted. This subclause defines how this authentication is performed.

11.2.1 ONU identity

The SIEPON.4 system uses the ONU MAC address associated with the ONU's PON port as the identity of the ONU (see 14.4.1.2). However, the ONU identity cannot be trusted until the ONU has successfully completed the Authentication procedure (see 11.3.4).

When an ONU is powered on, it reports its MAC address to the OLT through the MPCP Discovery process, as defined in IEEE Std 802.3, Clause 144.

The OLT shall use the ONU MAC address associated with PON port as the identity of the ONU.

11.2.2 ONU authentication

The OLT shall initiate the ONU authentication procedure immediately after the completion of OAM/eOAM discovery (see Figure 11-4). At this time, the ONU's access to the network is restricted; it has only two "system" logical links assigned to it: PLID used for providing connectivity (carries GATE and REPORT MPCPDUs) and MLID used for ONU management (carries OAMPDUs). The ONU cannot support any data services at this time.

ONU authentication in SIEPON.4 is accomplished using EAP-TLS 1.3 (see RFC-9190) with the OLT operating as the "EAP Authenticator"/"EAP-TLS Server" and the ONU operating as the "EAP Supplicant"/"EAP-TLS Client" (see RFC-3748). By utilizing TLS 1.3 as described in this clause, the TLS handshake is encrypted and authenticated using an ephemeral key that provides a shared secret to both parties while ensuring privacy and perfect forward secrecy (PFS). The shared secret is then used by both the OLT and ONU to independently derive the SIEPON.4 initial traffic encryption key, as described in 11.3.2.

The OLT may consult NMS/AAA servers for assistance with the ONU's authentication. The mechanism of communication with the NMS/AAA servers or the nature of information passed between the OLT and the servers is outside the scope of this standard.

The OLT shall restrict access to the network to the following categories of ONUs:

- An ONUs that failed authentication;
- An ONU whose identity matches that of another authenticated ONU;

— An ONU that has been administratively prohibited from connecting to the given network (i.e., an ONU on a "Deny list").

Several possible methods to restrict ONU's access to the network are described in 11.2.4.

11.2.2.1 ONU authentication credentials

The ONU may be authenticated using the built-in credential (the Device Authentication Credential) or an operator-provided credential (the Network Authentication Credential). In either case, the ONU identity is attested via the built-in keypair (the Device Authentication Keypair). When properly used, these credentials provide the ability for an NMS to cryptographically verify the identity of the ONU attempting to access the PON and determine what access the ONU is granted.

11.2.2.1.1 The Device Authentication Keypair (DAK) requirements

The Device Authentication Keypair (DAK) facilitates robust identification and authentication of ONUs on the PON network.

All SIEPON.4 ONUs and OLTs shall have a unique DAK of type *Curve P-384* (see FIPS 186-4, D.2.4) generated in accordance to NIST ST SP 800-57 Part 1R5 section 8.1.5.1. The DAK shall persist across device power cycles and factory resets.

Requirements for securing the DAK private key can be found in 11.1.2.

11.2.2.1.2 Credential Identification and Selection

In order to provide the NMS/OLT the ability to select the particular ONU credential to use for authentication, the TLS 1.3 CertificateRequest extension "SIEPON.4 Credential Type" is defined in the IEEE namespace as OID 1.3.111.2.1904.4.1.1 with the following definition:

```
enum {
    undefined(0),
    dac(1),
    nac(2),
    reserved(3..255)
} SIEPON4CredentialType;
```

11.2.2.1.3 The Device Authentication Credential (DAC) Requirements

The DAC is a data structure containing the DAK public key, metadata identifying the ONU device (including the *aOnuId* attribute), and a cryptographic signature(s) used to verify the authenticity of the DAC. The DAC shall neet the following requirements:

— Formatted in accordance to X.509v3 (see X.509/RFC-6818).

— Contains the *SIEPON4CredentialType* extension with a value of "1" (dac). (see 11.3.3.2)

— The Subject Common Name (CN) field conforms to the PrintableString definition as described in RFC-5280 and contains the *aOnuId* attribute value encoded into 12 hexadecimal digits preceded by the string "SIEPON4_ONU_". For example, "`CN=SIEPON4_ONU_0A7FB49E2CF1`" (see RFC-4648, section 8)

— The public key field contains the DAK public key of the device encoded according to RFC-5480, section 2.1.

— The DAC be is signed using the device's DAK private key producing an ECDSA signature with a SHA-256, SHA-384, or SHA-512 HMAC according to RFC-5480, section 2.1.

— The Key Usage Extension indicates the certificate's public key usage is "Digital Signature" and "Key Encipherment". (see RFC-5280, section 4.2.1.12).

— The total size of the DAC does not exceed 1491 octets.

— The certificate does not include any extensions marked "critical" unless required by RFC-5280 or required above.

The DAC may also be signed using a device manufacturer's CA private key producing an ECDSA signature with a SHA-256, SHA-384, or SHA-512 HMAC according to RFC-5480, section 2.1.

An example DAC is provided in Annex 11A, TBD.

11.2.2.1.4 The Network Authentication Credential (NAC) Requirements

The Network Authentication Credential (NAC) is an end-entity certificate (see RFC-5280) containing the DAK public key, operator-defined metadata, and a cryptographic signature used to verify the authenticity of the NAC.

The network operator may create a NAC for an ONU to contain network operator-defined metadata. The NAC is signed using an operator-defined Certificate Authority (CA) – enabling the ONU to be validated using a network operator-defined Public Key Infrastructure (PKI) system. For example, a network operator may create an NAC containing a unique serial number, an alternate operator-defined identify for the ONU, identify the customer or management entity associated with the ONU, the ONU's assigned service level, and/or the network locale the ONU can operate within. An example NAC is provided in Annex 11A, TBD.

A NAC may be pre-installed into an ONU before the ONU's deployment/installation, or it may be installed remotely after the ONU has successfully authenticated using the built-in DAC (see 11.2.2.1.3).

To ensure that ONUs do not operate with expired NACs, a network operator may revoke the existing NAC and/or install a new NAC in the ONU at any time using the *eOAM_Install_NAC_Request* eOAMPDU (see 13.4.6.7.1). Intermediate CA certificates and the root CA can also be uploaded along with the NAC as long as the total size of the certificate chain does not exceed the specified maximum NAC length. NAC creation is facilitated by the *eOAM_Retrieve_DAC_Request* eOAMPDU (see 13.4.6.7.3), which allows for on-demand retrieval of the ONU's DAC, containing the DAK public key.

The OLT shall not generate the *eOAM_Install_NAC_Request* eOAMPDU containing the NAC that

— Is not formatted in accordance with the RFC-5280

— Has size exceeding 1489 octets

— Is not signed using an ECC Named Curve as defined in RFC-5480, section 2.1.1.1.

The ONU shall set the field `CertificateStatus` in the *eOAM_Install_NAC_Response* eOAMPDU (see 13.4.6.7.2) to the value `Invalid Format (0x03)`, if the received NAC

— Is not formatted in accordance with the RFC-5280

— Contains a public key that does not match the ONU's DAK public key

— Does not contain the SIEPON4CredentialType extension with a value of “2 (nac)”. (see 11.3.3.2)

An example NAC is provided in Annex 11A, TBD.

11.2.2.1.5 Network Authentication Credential (NAC) Intermediate Certificates

The Network Authentication Credential (NAC) may reference intermediate certificates. The NMS may install the intermediate certificates together with the NAC certificate into an ONU for the purposes of authenticating the NAC. For example, intermediate certificates can be included to enable the authentication of NACs signed by intermediate CAs with AAA servers that only have root certificates in their trust store. NAC intermediate certificates are formatted and authenticated in accordance to RFC-5280.

Note that the OLT is able to include the intermediate certificates in the *eOAM_Install_NAC_Request* eOAMPDU (see 13.4.6.7.1) only if the total size of the encoded certificate chain (i.e., the NAC certificate and all the intermediate certificates) does not exceed 1489 octets.

11.2.2.2 ONU authentication procedure

In order to perform EAP-based authentication, the OLT and ONU exchange EAPOL (Extensible Authentication Protocol over LAN) frames over the MLID (see IEEE Std 802.1X, Clause 11,). The authentication procedure is illustrated in Figure 11-5.

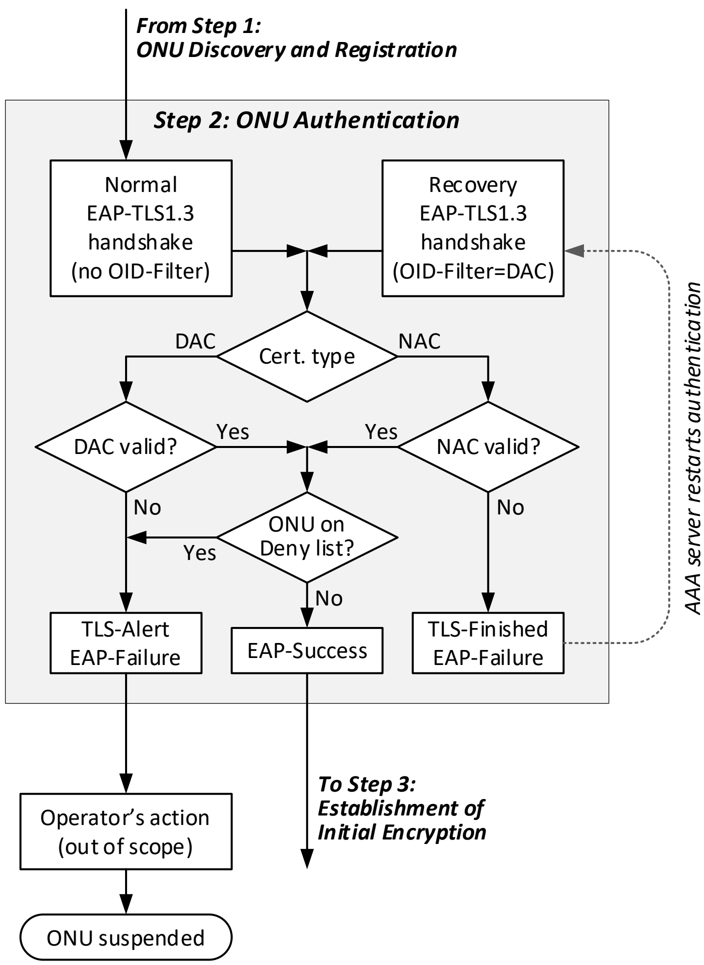


Figure 11-5 — ONU authentication procedure

The EAP authentication procedure is performed according to the following requirements:

- The OLT and ONU shall support EAP-TLS 1.3 as defined in RFC-9190 and use EAP type EAP-TLS (type 13) in all EAP-Request and EAP-Response messages. EAP-Request/Response for Identity (type 1) are not to be used by the ONU or OLT and the ONU shall return an EAP-Response/Nak to any EAP-Request/Identity messages.

- The OLT and ONU shall only advertise TLS 1.3 in their respective TLS `ClientHello` and `ServerHello` messages (exchanged via EAP), as defined in RFC-8446. The `legacy_version` field shall be set to `0x0303` and the `supported_versions` extension shall include TLS 1.3 (`versions` value `0x0304`).

- The OLT and ONU may utilize any TLS 1.3 supported and negotiated DHE key exchange method. Session resumption using PSK-based key exchange methods are not defined for use in SIEPON.4 at this time but may be supported in the future.

- In order to support ONU authentication, the OLT shall issue and the ONU shall honor the `CertificateRequest` message, as described in TLS 1.3, section 4.3.2.

- The ONU shall support TLS 1.3 OID Filters extension as described in TLS 1.3 (see RFC 8446, section 4.2.5). The NMS/OLT may use this to perform credential selection, When a `SIEPON4CredentialType` is present in the TLS 1.3 `CertificateRequest` OID Filters extension (see RFC-8446, section 4.2.5), the filter shall only be considered matched against an ONU credential if the ONU has an authentication certificate containing the `SIEPON4CredentialType` extension with the same value as the one in the `CertificateRequest`.

- If the ONU is not configured with a NAC, or the DAC is matched via the TLS `CertificateRequest` OID Filter (see 11.2.2.1.2), the ONU shall include the DAC in its TLS 1.3 Certificate message as the "end-entity" certificate in the `certificate_list`. Requirements for the DAC can be found in 11.2.2.1.3.

- If the ONU is configured with an NAC, and the DAC is not explicitly selected via a TLS `CertificateRequest` OID Filter (see 11.2.2.1.2), then the ONU shall include the NAC in its TLS 1.3 Certificate message as the `end-entity` certificate with any intermediate certificates following the NAC in the `certificate_list`. Requirements for the NAC and associated intermediate certificates can be found in 11.2.2.1.4 and 11.2.2.1.5, respectively.

- If the ONU is not configured with a credential that is explicitly selected via the TLS `CertificateRequest` OID Filter (see 11.2.2.1.2), the ONU shall abort the handshake with an "unsupported_certificate" alert.

The OLT initiates the EAP authentication process by issuing an EAP-Request with an EAP-Type of EAP-TLS (type `13`). The OLT shall not initiate another EAP authentication session until any ongoing authentication session has been completed with either Success or Failure, per RFC-3748, section 2.1.

11.2.3 ONU authorization

ONU authorization refers to the verification of ONU's eligibility to operate on the operator's network. The determination of ONU's eligibility is based on a reasonable assurance that the ONU is compatible and interoperable with the rest of equipment used in the operator's network, that the user served by this ONU is eligible to receive service, and that the ONU operates within the limits established by the operator.

ONU authorization is initiated by the NMS/AAA server after the ONU has successfully authenticated and symmetric encryption has been established for secure communication between the OLT and the ONU. Only two “system” logical links (PLID and MLID) are configured at the ONU at the time of the ONU’s authorization. Any exchange of information between the OLT and ONU pertaining to the ONU authorization is carried over the encrypted MLID logical link.

Subject to operator’s policies, the ONU authorization procedure maybe modified or bypassed altogether.

11.2.3.1 Authorization procedure

The ONU authorization procedure generally comprises the verification of ONU properties and capabilities (see 11.2.5.1.1), the verification of user account / service eligibility (see 11.2.5.1.2), and the verification of ONU’s operational parameters (see 11.2.5.1.3). If an ONU fails the get authorized, its access to the network shall be restricted, as described in 11.2.4. The authorization procedure is illustrated in Figure 11-6.

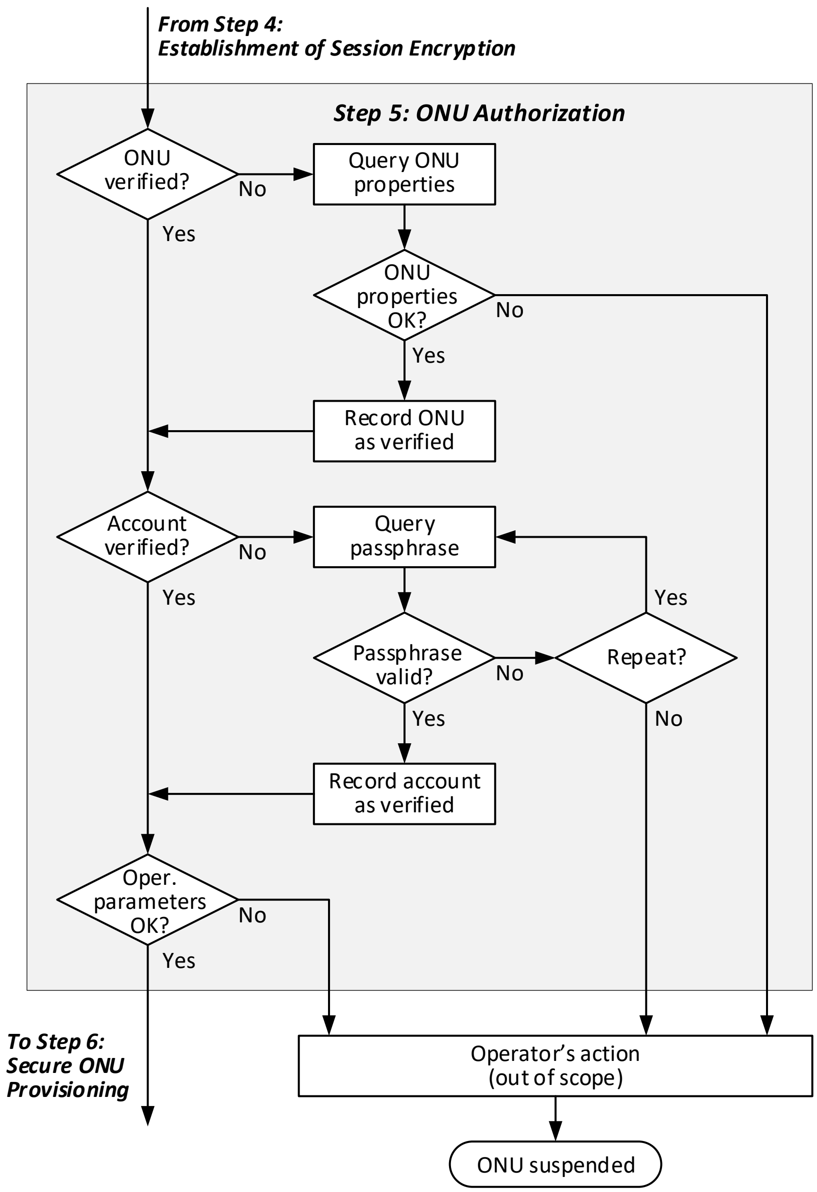


Figure 11-6 — ONU authorization procedure

11.2.3.1.1 Verification of ONU properties and capabilities.

This step ensures that the ONU device is compatible and interoperable with the rest of equipment used in the operator's network. The verification typically involves checking ONU's manufacturer and/or model to confirm that it belongs to the class of ONUs that were pre-qualified to operate on a given network. Various ONU capabilities may also be queried and checked to ensure that the ONU is able to support the necessary services.

The ONU properties and capabilities are immutable characteristics of the device. Therefore, this step is generally performed only once, in the process of onboarding of a new ONU (see 11.2.3.2). It is also possible to perform this step offline, prior to ONU deployment, as explained in 11.2.3.2.1.2.

11.2.3.1.2 Verification of user account / service eligibility.

This step associates the identity of the ONU device with a user account and verifies the eligibility of the ONU to be provisioned to service user data. The association between the ONU with the user account needs to be established only once, in the process of onboarding of a new ONU (see 11.2.3.2). There could be various operator-specific methods of establishing such association, for example:

- The ONU's serial number / MAC address can be scanned/retrieved from the ONU and associated with a known customer account at the time of installation by either a technician or customer, facilitated by the use of an external device with Internet access.

- A unique activation/association passphrase can be generated by the NMS and conveyed to the customer prior to ONU installation. During the ONU onboarding phase, the user is prompted to enter the passphrase via the CPE device connected to the ONU. The passphrase together with the ONU identity is delivered via the eOAM channel to NMS, allowing the association to be established (see 11.2.3.2.2). This method may be particularly necessary in situations where no Internet connectivity is available, except through the ONU being deployed.

It is also possible to associate ONU identity with a user account offline, prior to ONU deployment, as explained in 11.2.3.2.1.3.

11.2.3.1.3 Verification of ONU's operational parameters.

Optionally, operators may desire to analyze various operational characteristics of the ONU to determine its eligibility to access the PON and connected resources. For example, OLT may verify that given ONU is authorized for the particular OLT PON port on which it is discovered (i.e., a port-based access control). Alternatively, or in addition to the PON port verification, the OLT may compare the ONU's round-trip time to the previous measurement and deny access to the ONU that has unexpectedly relocated.

The verification of ONU's operational parameters is performed every time the ONU is restarted, not just during the initial onboarding.

11.2.3.1.4 ONU authorization requirements

The OLT shall be able to support port-based access control and should be able to support RTT-based access control.

If port-based access control is enabled, the OLT shall verify that given ONU is authorized for the particular OLT PON port on which it is discovered.

If RTT-based access control is supported and enabled, the OLT shall keep track of ONU's RTT value measured during previous ONU registration and it shall compare the newly-measured RTT to the previous RTT value.

The OLT shall restrict network access to the following categories of ONUs:

- The ONU whose properties and capabilities were found unacceptable for the given network;
- An ONU that could not be associated with a valid user account;
- The ONU that has been re-discovered on a PON port different from the one on which it is authorized (only if PON port-based authorization is enabled);
- The ONU that has unexpectedly relocated, i.e., whose measured round-trip time is significantly different from the previous measurement (only if RTT-based authorization is supported and is enabled).

Several possible methods to restrict ONU's access to the network are described in 11.2.4.

The OLT may consult NMS/AAA servers to determine the ONU's authorization to access the network resources. The mechanism of communication with the NMS/AAA servers or the nature of information passed between the OLT and the servers is outside the scope of this standard.

11.2.3.2 Onboarding of a new ONU

Within the context of this standard, the term *onboarding* refers to the process of integrating a newly-installed ONU into the established operator's network. A number of steps related to ONU authorization to operate on a given network are performed only once, during the ONU onboarding. However, an operator has the ability to repeat the onboarding procedure for any ONU, even after the ONU has already been onboarded.

11.2.3.2.1 ONU deployment scenarios

The steps required during the ONU onboarding are determined by the ONU deployment scenario adopted by the network operator. Several typical ONU deployment scenarios are described in sub-clauses 11.2.5.2.1.1 through 11.2.5.2.1.4, although other scenarios are also possible.

11.2.3.2.1.1 Unknown/generic ONU

The unknown/generic ONU deployment scenario refers to deployment of an ONU that has not been in the possession of the network operator prior to deployment, as is the case of a customer-procured ONU. In other words, this is a scenario where the operator has no apriori information about the ONU properties and capabilities or about which user account the ONU is associated with.

In this scenario, the ONU authorization includes all of the following steps: the verification of ONU properties and capabilities (see 11.2.3.1.1), the verification of user account / service eligibility (see 11.2.3.1.2), and the verification of ONU's operational parameters (see 11.2.3.1.3).

11.2.3.2.1.2 Pre-validated ONU

The *pre-validated ONU* deployment scenario refers to deployment of ONUs whose properties and capabilities have been verified by the operator prior to deployment. An individual ONU is selected for the installation from a pool of verified ONUs, although it is not known which exact ONU will be deployed to a specific customer until the installation time.

In this scenario, the AAA server maintains a list of identities of the pre-verified ONUs. During the ONU authorization, the AAA server recognizes the ONU identity as pre-verified. Therefore, the ONU authorization includes only the following steps: the verification of user account / service eligibility (see 11.2.3.1.2) and the verification of ONU's operational parameters (see 11.2.3.1.3).

11.2.3.2.1.3 Pre-validated user account

The *pre-validated user account* refers to a deployment scenario where the customer is required to register its customer-procured ONU before the ONU's installation. The registration would typically involve a submission of the ONU's serial number (or some other form of ONU identity) along with the customer account number (or some other form of customer identity, such as a unique activation code or a passphrase provided by the operator). The information submitted by the customer is used to associate the ONU identity with customer identity and this association is recorded in the AAA server. However, no information is available to the operator regarding the ONU's properties and capabilities.

During the ONU authorization procedure, the AAA server finds the record of a verified user account associated with the identity of the ONU being authorized. Therefore, the ONU authorization includes only these steps: the verification of ONU properties and capabilities (see 11.2.3.1.1 and the verification of ONU's operational parameters (see 11.2.3.1.3).

11.2.3.2.1.4 Pre-authorized ONU

The *pre-authorized ONU* refers to a deployment scenario whereby an operator selects a specific ONU to be deployed to a specific customer. Before the ONU shipment / deployment, a record is made and stored in the AAA server reflecting the fact that the ONU is pre-validated (see 11.2.3.2.1.2) and the associated user account is also pre-validated (see 11.2.3.2.1.3).

During the ONU authorization procedure, the AAA server finds the record matching the identity of the new ONU, and confirming the verification status of the ONU as well as the verification status of the user account associated that ONU. Therefore, the ONU authorization procedure includes only the verification of ONU's operational parameters (see 11.2.3.1.3).

11.2.3.2.2 Passphrase-based user account verification

As explained in 11.2.3.1.2, operator may rely on a customer-unique passphrase as a method to associate ONU identity with a customer account or service profile. In this method, during the ONU onboarding phase, the user is prompted to enter the passphrase via the CPE device connected to the ONU. The passphrase together with the ONU identity is delivered via the eOAM channel to NMS, allowing the association to be established (see 11.2.3.2.2).

The passphrase-based account verification method relies on the extended action *acPassphrasePrompt* (see 14.6.5.3) and the extended read-only attribute *aPassphrase* (see 14.4.5.2), and is performed over an encrypted MLID logical link.

The *acPassphrasePrompt* action displays an NMS-specified prompt to the user and also resets the value of any stored passphrase to a zero-length string. The *aPassphrase* action allows the retrieval of the user-entered string. As the time required for a user to manually enter the passphrase is expected to be much longer than the OAMPDU response timeout (see 13.2.3), it is expected that *aPassphrase* attribute is queried multiple times before the input is received, as illustrated in Figure 11-7.

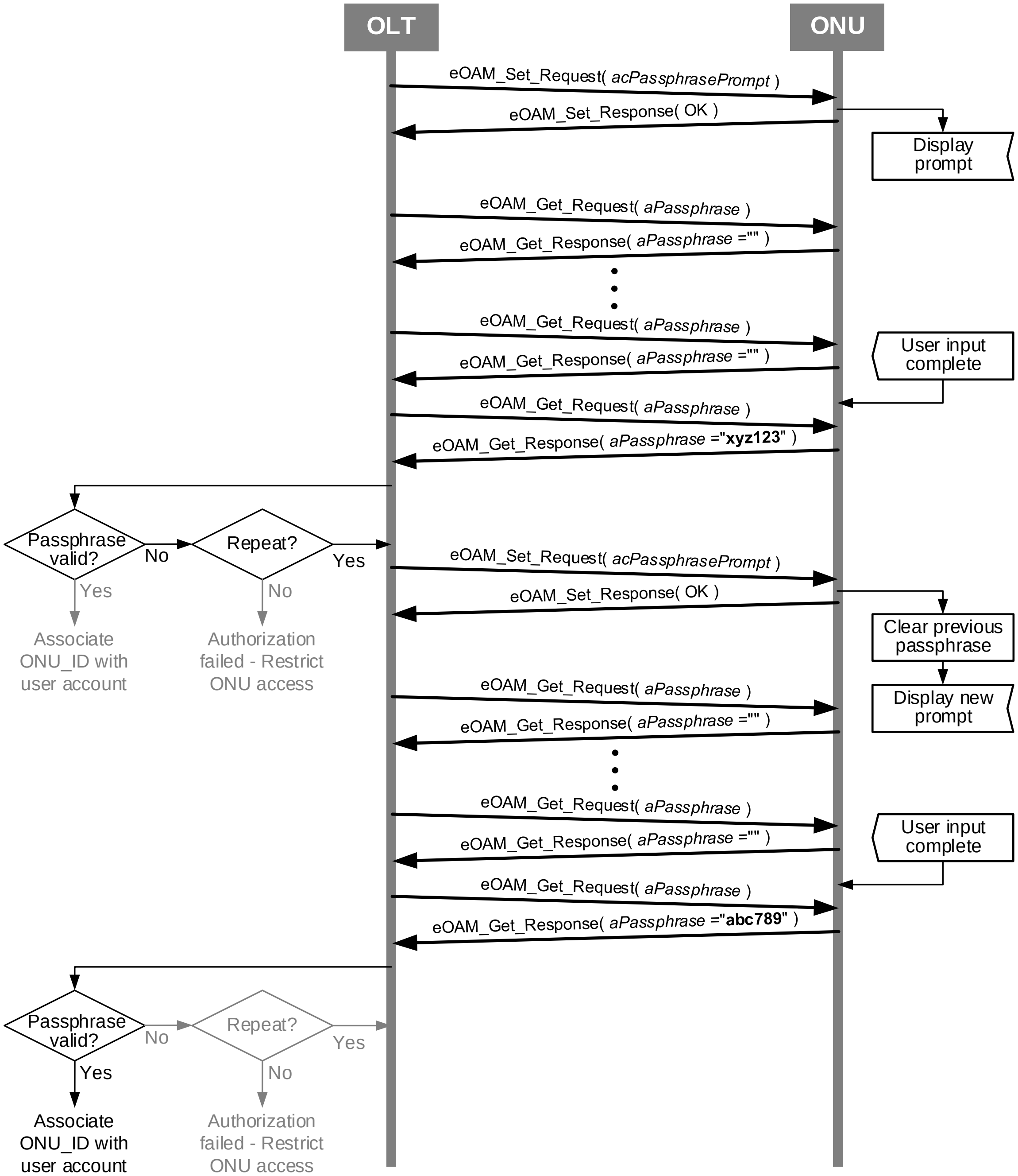


Figure 11-7 — Passphrase query protocol

11.2.4 ONU access restriction

The ONU that failed the authentication is unable to derive the initial encryption key, and as a result, is unable to establish the symmetric encryption with the OLT. Correspondingly, the NMS does not initiate the authorization procedure for such ONU. The ONU that has successfully authenticated may fail the subsequent authorization.

An operator may resort to different actions in response to ONU's failure to get authenticated or authorized.

One possible action is to withhold service configuration/provisioning to the ONU. Such ONU remains registered with two active LLIDs: primary PLID and primary MLID. The ONU is able to process GATE MPCPDUs and generate REPORT MPCPDUs, and it is able to exchange OAMPDUs with the OLT, but is unable to service any user data. Such ONU does consume a small amount of PON transmission capacity.

Alternatively, the operator may suspend the ONU. The suspended ONU is deregistered and does not attempt to register again, until instructed to do so. The ONU suspension method is described in 11.2.4.1.

11.2.4.1 Suspension and resumption of ONU operation

The ONU registration status is controlled via the REGISTER MPCPDU (see IEEE 802.3, 144.3.6.4). The specific ONU behavior is determined by the value of the *Flag* field. Per IEEE 802.3, 144.3.7:

> If the *Flag* field in the REGISTER MPCPDU has the value of ACK, the ONU performs a fast registration sequence where it simply responds with the REGISTER_ACK MPCPDU, while remaining registered at all times.

> If the *Flag* field in the REGISTER MPCPDU has the value of NACK, the ONU deregisters and goes through a complete discovery sequence, as outlined above.

This standard extends the definition of the *Flag* field by adding an additional value SUSPEND (2) as defined in Table 11-xx. The Table 11-xx replaces the table 144-5 in IEEE 802.3:

Table 11-xx—REGISTER MPCPDU *Flag* field

Value	Indication	Notes
0	ACK	The ONU's requested registration is successful or a registered ONU is asked to re-register
1	NACK	The registration request is denied or a registered ONU is asked to deregister and register again.
2	SUSPEND	The ONU is requested to deregister and to not attempt to register again.
3 to 255	Reserved	Ignored on reception

The REGISTER MPCPDU with the *Flag* field value equal to SUSPEND shall be transmitted to the destination ONU in an envelope with unicast PLID assigned to this ONU.

The ONU that receives REGISTER MPCPDU with the *Flag* field value equal to SUSPEND shall deregister (i.e., release its assigned PLID and MLID values). The suspended ONU shall begin to receive and process the envelopes sent to the DISC_PLID logical link, but it shall not attempt to register until either of the following events has occurred:

— The ONU was factory-reset. (The factory-reset procedure is outside the scope of this standard.)

— The ONU received a unicast DISCOVERY MPCPDU (see IEEE 802.3, 144.3.6.6), i.e., a DISCOVERY MPCPDU sent to DISC_PLID with a unicast MAC DA matching the identity of the given ONU (11.2.1).

The ONU shall maintain its suspension state across the restart or reboot. The ONU may remain in the suspended state for an unlimited period of time.

11.3 Encryption

11.3.1 Overview of encryption architecture

11.3.1.1 Encryption entity

An encryption entity is a distinct logical element within a communication system that is responsible for maintaining the confidentiality of data exchanged within the communication system. It achieves this by applying encryption algorithms to prevent unauthorized access and eavesdropping of sensitive information.

Each encryption entity operates independently from other encryption entities within the system and utilizes its distinct set of cryptographic parameters, including encryption keys, initialization vectors (IVs), and cryptographic configurations.

11.3.1.1.1 Mapping between the encryption entities and logical links

As explained in 4.5.1, all logical links of an ONU (whether provisioned or assigned during registration) are categorized as either bidirectional or unidirectional. The ONU is capable of receiving data from all provisioned logical links, while it can only transmit data through bidirectional links.

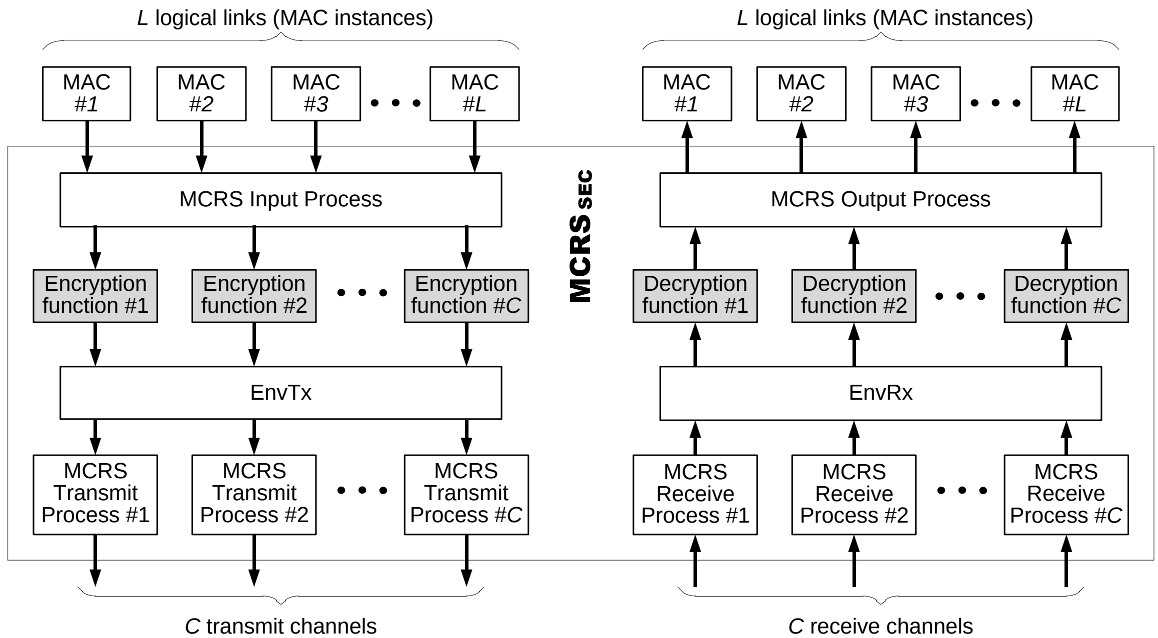
All bidirectional links terminated at a specific ONU are mapped to a single encryption entity. Correspondingly, the traffic on all bidirectional links terminated at a specific ONU is encrypted using a single ONU-wide encryption key. When a key switch event occurs, it affects all bidirectional links, although for 50G-EPON ONUs, this event may happen at different times on different channels.

The unidirectional logical links are typically provisioned as point-to-multipoint (P2MP) links and carry downstream multicast traffic. Each envelope transmitted by the OLT is delivered to multiple ONUs. Therefore, the encryption key used to encrypt the multicast traffic needs to be shared among all ONUs that are part of the multicast group. Consequently, each unidirectional LLID is mapped to a separate encryption entity.

Overall, a SIEPON.4 system that includes *U* ONUs and is provisioned to use *M* multicast LLIDs instantiates $U + M$ encryption entities.

11.3.1.2 Location of encryption/decryption functions

The Multi-channel Reconciliation Sublayer (MCRS) reconciles *L* logical links (i.e., MAC instances) above the sublayer with *C* physical layer channels below it. The MCRS is defined in IEEE Std 802.3, Clause 143. When security mechanisms are implemented within the MCRS sublayer, such enhanced sublayer is referred to as Secure MCRS ($MCRS_{SEC}$) sublayer. The encryption function is located in the transmit path of the $MCRS_{SEC}$ sublayer, as illustrated in Figure 11-1(a), and the decryption function is located in the receive path of the $MCRS_{SEC}$ sublayer, as illustrated in Figure 11-1(b).



a) Transmit Path **b) Receive Path**

Figure 11-1–Location of encryption/decryption function within MCRS_{SEC}

In the MCRS_{SEC} transmit data path, a separate instance of the encryption function is located within every channel between the MCRS Input Process and the *EnvTx* buffer. In the MCRS_{SEC} receive data path, a separate instance of the decryption function is located within every channel between the *EnvRx* buffer and the MCRS Output Process.

11.3.1.3 Encryption function block diagram

Each instance of the encryption function includes the Encryption Key Activation process (see 11.6.2.4 and 11.6.2.6) and the Encryption process (see 11.7.2). The block diagram of the encryption function is illustrated in Figure 11-2.

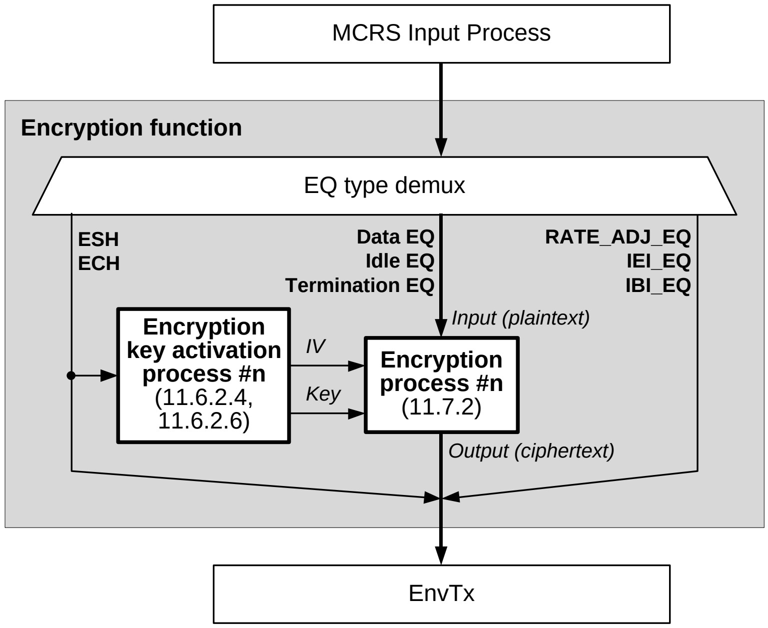


Figure 11-2–Encryption function block diagram.

The Encryption Key Activation process detects the transmission of either the envelope start header (ESH) or the envelope continuation header (ECH) and uses the data inside the header to generate an initialization vector IV and the encryption key. These two parameters are passed to the Encryption process, which encrypts the given envelope as one cryptographic message.

The encryption function encrypts the envelope payload, which consists of data EQs, idle EQs, and termination EQs. The envelope header itself bypasses the Encryption process and is transmitted unencrypted (see 11.7.5.2).

The inter-envelope control EQs include rate adjustment (RATE_ADJ_EQ), inter-envelope idle (IEI_EQ), and inter-burst idle (IBI_EQ) (see 11.7.5.1). These control EQs bypass the Encryption process and are transmitted unencrypted.

11.3.1.4 Decryption function block diagram

Each instance of the decryption function includes the Decryption Key Activation process (see 11.6.2.5) and the Decryption process (see 11.7.3). The block diagram of the decryption function is illustrated in Figure 11-3.

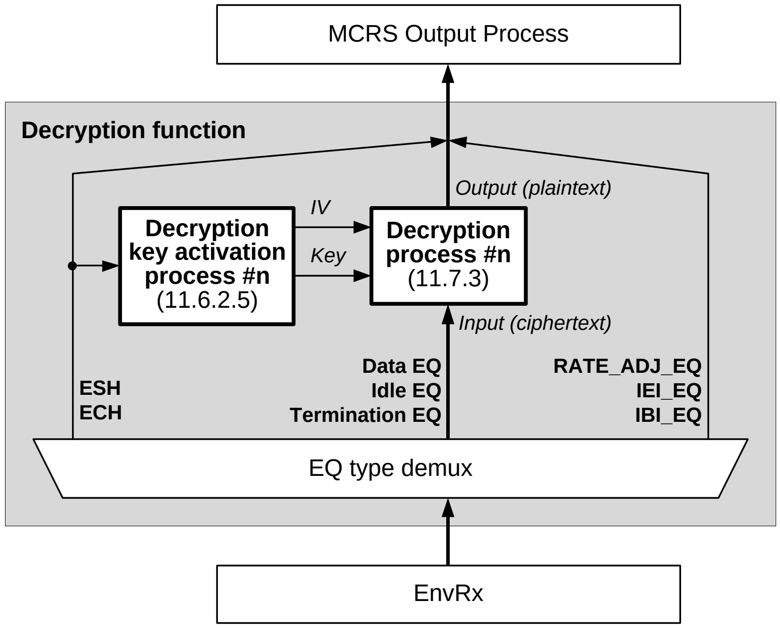


Figure 11-3–Decryption function block diagram.

The Decryption Key Activation process detects the reception of either the envelope start header (ESH) or the envelope continuation header (ECH) and uses the data inside the header to generate an initialization vector IV and the decryption key. These two parameters are passed to the Decryption process, which decrypts the given envelope as one cryptographic message.

The decryption function decrypts only the envelope payload, which consists of data EQs, idle EQs, and termination EQs. The envelope header itself is received unencrypted and bypasses the Decryption process (see 11.7.5.2).

The inter-envelope control EQs include rate adjustment (RATE_ADJ_EQ), inter-envelope idle (IEI_EQ), and inter-burst idle (IBI_EQ) (see 11.7.5.1). These control EQs are received unencrypted and bypass the Decryption process.

11.3.1.5 Latency requirements

The latency introduced into the MCRS transmit path by the encryption function (see Figure 11-1(a)) shall remain constant (to within 1 EQT), regardless of whether the encryption is enabled or disabled.

The latency introduced into the MCRS receive path by the decryption function (see Figure 11-1(b)) shall remain constant (to within 1 EQT), regardless of whether the decryption is enabled or disabled.

11.3.2 Initial key establishment

The initial key is used by the OLT to encrypt the MLID channel for subsequent distribution of the first session key to the ONU (see step 4 in Figure 11-4). The establishment of the initial key involves the derivation of the initial key value (see 11.3.2.1) and the activation of the initial key (see 11.3.2.2).

11.3.2.1 Initial key derivation

Once the ONU and OLT have completed the authentication exchange, the initial AES-128 encryption key shall be established by both parties from the least-significant 128 bits (16 octets) of the MSK, which is derived from the TLS 1.3 ephemeral session key as described in RFC-9190, section 2.3.

11.3.2.2 Initial key activation

The initial key is activated using the same procedure as defined for the session key activation (see 11.3.4). The ONU stores the derived value of the initial key in the key memory The OLT stores the derived value of the initial key in their local key memories, in the location `keys[ee][0]` (see 11.6.2.1), where `[ee]` is an index of the encryption entity associated with the bidirectional logical link(s) between the OLT and the ONU.

For the ONU to be able to decrypt the encrypted envelopes, its cipher clocks need to be synchronized with that in the OLT, as detailed in 11.3.5.4.1. The cipher clock synchronization relies on an OAMPDU containing the *Sync Cipher Clock* TLV sent form the OLT to the ONU. Before activating the encryption in the downstream direction, the OLT shall receive a positive acknowledgement form the ONU, indicating that the cipher clocks have been synchronized.

11.3.3 After the initial key is written into the key memory and a positive acknowledgement of cipher clock synchronization is received, the OLT sets the `initialKeyReady[ee]` variable to `true`. The initial key is activated in the downstream direction first, when the OLT transmits an envelope encrypted with this key (see 11.3.4.1). Session key distribution protocol

11.3.3.1 Protocol overview

The session key distribution protocol is a function of the OAM client at the OLT (see 4.7.2) and the ONU (see 4.8.2).

After the initial key exchange (defined in 11.3), all the subsequent keys are generated by the OLT and are distributed using the *acConfigEncrKey* action (see 14.6.5.1). The OAMPDU carrying the next key is transmitted within the MLID envelope encrypted using the current key. The OLT shall not transmit the OAMPDU carrying the *acConfigEncrKey* action over an unencrypted MLID channel.

Figure 11-6 illustrates the process of updating the session key (hereinafter referred as "key") and the subsequent activation of that key, first by the OLT and then by the ONU.

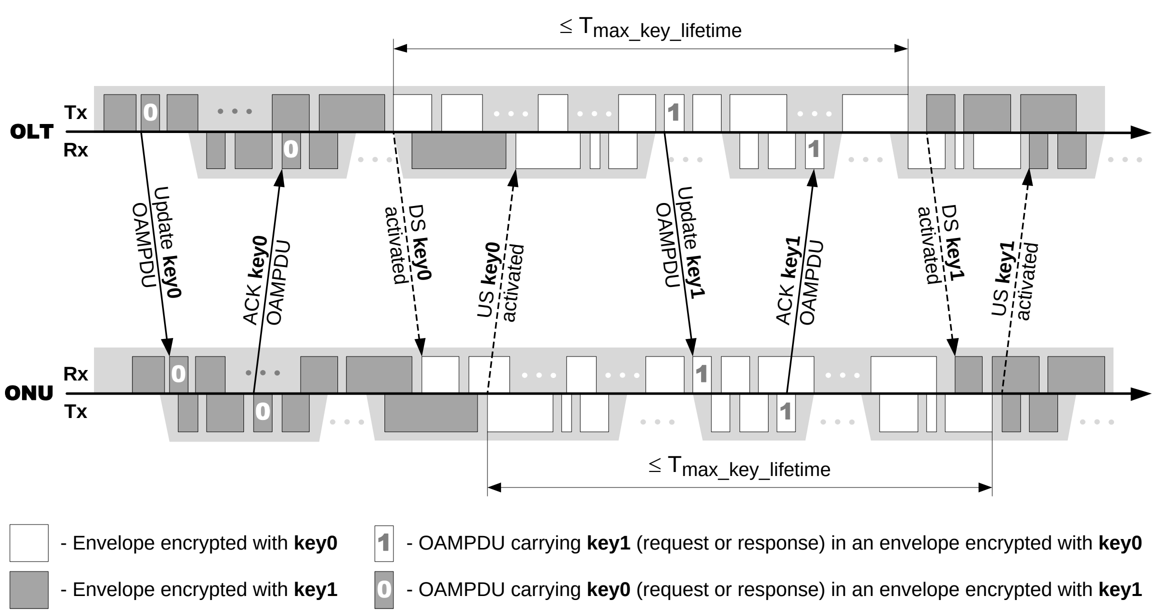


Figure 11-6–Key update and subsequent key activation time diagram

The next key may be distributed at any time within the lifetime of the currently-active key. In case multiple keys were distributed for the same encryption entity (i.e., under the same context object, which can be either the ONU or a multicast LLID), the last-distributed value is saved.

For each encryption entity, the OLT maintains the key lifetime timer and activates the next key upon the timer's expiry. The OLT shall distribute the next key to an ONU sufficiently in advance of the expiration time of the current key in order to allow possible retransmission attempts in case of OAMPDU delivery failure (either the OAM request or the OAM response).

The OLT may issue different key sizes to different ONUs. Different multicast LLIDs may also use different key sizes, even if these multicast LLIDs are received by the same ONU.

11.3.3.2 Distribution of keys for unicast LLIDs

All unicast LLIDs provisioned at a given ONU are encrypted using the same key value in both upstream and the downstream directions. Therefore, only a single OAMPDU containing the *acConfigEncrKey* action is used to distribute the next key for all unicast LLIDs at the ONU.

A unique unicast key value is distributed to each ONU via an encrypted downstream unicast MLID channel and each ONU generates an individual response OAMPDU, also transmitted using the encrypted upstream unicast MLID channel.

If the ONU's unicast key distribution acknowledgement is not received by the OLT within the OAM message timeout (see `timeoutOLT` definition in 13.3.2.3.1), the OLT shall repeat the key distribution attempt. The maximum number of key distribution attempts is an implementation design choice, but it shall be not less than 3.

ONU's failure to update the key before the expiration of the current key is a critical link condition. It causes the ONU to lose downstream connectivity and leads to OAM and MPCP timeouts and a consequent ONU deregistration.

11.3.3.3 Distribution of keys for multicast LLIDs

The term *multicast LLID* represents an LLID value provisioned into multiple ONUs (see 7.4.2.1). This term collectively refers to *multicast PLID*, *multicast MLID*, or the *multicast ULID*.

A key for a multicast LLID is used by all ONUs that are members of the given multicast group to decrypt the traffic associated with this LLID. ONUs use the multicast keys only for decrypting the multicast data.

A multicast key is distributed to each member of the multicast group via an encrypted unicast MLID channel. The OLT generates a separate OAMPDU carrying *acConfigEncrKey* to each member ONU and each member ONU generates an individual response OAMPDU (i.e., ACK or NACK). The sequence of the key distribution and key activation events is as shown in Figure 11-6, however the OLT distributes the multicast key to every group member before activating this key.

As is the case with the unicast key distribution, the OLT shall distribute the next multicast key to all member ONUs sufficiently in advance of the expiration time of the current key in order to allow possible retransmission attempts in case of OAMPDU delivery failures.

In case the multicast key distribution acknowledgement from any ONU in the multicast group is not received by the OLT within the OAM message timeout (see `timeoutOLT` definition in 13.3.2.3.1), the OLT shall repeat the key distribution attempt. The maximum number of multicast key distribution attempts to each ONU in the multicast group is an implementation design choice, but it shall be not less than 3. Each subsequent key distribution attempt may distribute the key to all group members or only to the ONUs that failed to acknowledge the key reception in the previous attempt(s).

Note however that the failure of some ONUs to receive or acknowledge the new multicast encryption key is not a sufficient reason for the OLT to deregister the said ONU or to delete the multicast group. The ONUs that failed to update the key will be unable to decrypt the multicast traffic subsequent to the OLT switching to the new key.

11.3.3.3.1 Distribution of keys for multicast MLIDs

The distribution of encryption keys for the multicast MLIDs allows for a somewhat more optimized approach. The distribution of the initial multicast key require an individual OAMPDU with *acConfigEncrKey* action to be sent to each member ONU via an encrypted unicast MLID channel, as described in 11.5.3.

However, once the encrypted multicast MLID channel is established, the subsequent multicast keys may be distributed sending a single OAMPDU carrying *acConfigEncrKey* action over this multicast channel. This method only requires a single OAMPDU to distribute the next key to the entire multicast group, no matter the group size. It must be noted however that the OLT expects an individual response OAMPDU (over a unicast MLID) from every member ONU.

11.3.3.3.2 Multicast distribution of multicast keys

The multicast distribution of a multicast MLID keys described in 11.5.3.1 can also be extended to multicast non-MLID channels, such as multicast PLID or multicast ULID.

This approach involves provisioning of a multicast LLID (PLID or ULID) together with a multicast MLID into each member ONU (i.e., creating an MLID multicast group that mirrors the membership of the intended PLID or ULID multicast group). The initial key for the MLID multicast group is distributed by individual OAMPDUs, as described in 11.5.3.

Once the initial key is established, the subsequent keys may be distributed by transmitting a single OAMPDU carrying *acConfigEncrKey* action over the encrypted multicast MLID channel.

This approach requires distribution of two keys each time: a key for the multicast MLID and a key for the multicast PLID/ULID. Both *acConfigEncrKey* actions carrying these keys typically can be placed into the same OAMPDU. Therefore, this method only requires a single OAMPDU to distribute the next MLID key and PLID/ULID key to the entire multicast group, no matter the group size.

As mentioned above, the OLT expects an individual acknowledgement message (over a unicast MLID) from every member ONU. The acknowledgement of the multicast MLID key and the acknowledgement of the multicast PLID/ULID key may be packed into the same OAMPDU, requiring only a single OAM response message transmitted upstream by each ONU.

The benefits of multicast distribution of keys for multicast non-MLID flows are mostly realized with long-lived multicast groups (i.e., groups with expected lifetimes much longer that the lifetime of a single session key).

11.3.4 Session key activation protocol

11.3.4.1 Protocol overview

The key activation protocol defines a procedure of switching from the current encryption key to a new encryption key that has been previously distributed by the OLT to one or more ONUs using the session key distribution protocol (see 11.5).

The key activation protocol relies on encryption signaling fields embedded in envelope headers. These fields include the encryption enabled flag (*EncEnabled* field) and encryption key index (*EncKey* field). The *EncEnabled* and *EncKey* fields are described in IEEE Std 802.3, 143.3.2 and 143.3.3.4. The *EncKey* field takes on values of only 0 and 1.

11.3.4.1.1 Activation of a unicast (bidirectional) key

The unicast (bidirectional) key activation procedure consists of four sequential steps, as illustrated in Figure 11-7.

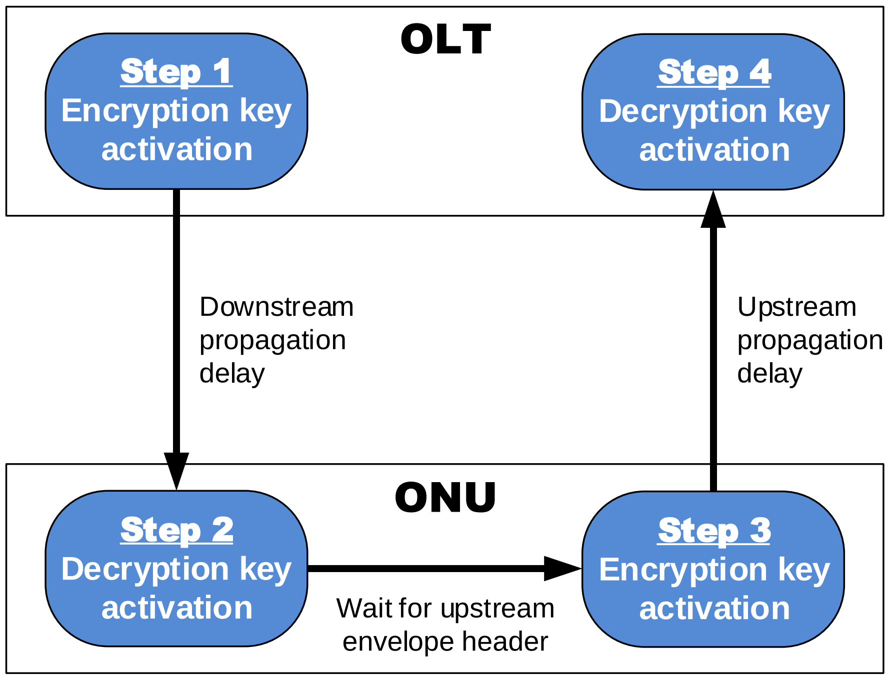


Figure 11-7–Four steps comprising the key activation procedure

Each of the above four steps is represented by an independent process that runs continuously within the secure Multi-Channel Reconciliation Sublayer (MCRS$_{SEC}$).

Step 1 — Encryption key activation at the OLT:

> The process of encryption key activation at the OLT is defined in 11.6.2.4. The OLT activates the new encryption key upon the expiration of the key activation timer.
>
> Generally, every encryption entity (i.e., ONUs and multicast LLIDs) maintains its own key activation timer and these timers may have different intervals and/or be set to expire at different times. However, for practical considerations, it is allowed for all encryption entities to share the same key activation timer.
>
> Once the key activation timer expired, the OLT waits for the next envelope header destined to the given encryption entity. The OLT indicates switching to the new key by toggling the value of the *EncKey* field in the envelope header. The envelope payload following this envelope header is encrypted using the new key.

Step 2 — Decryption key activation at the ONU:

The process of decryption key activation at the ONU is defined in 11.6.2.5. For every received envelope, the ONU retrieves a key associated with the given encryption entity, identified by the LLID field in the envelope header, and the key index, identified by the *EncKey* field. Thus, toggling of the *EncKey* value by the OLT in Step 1 above caused the ONU to also retrieve the new key after it parsed and processed this envelope header.

Step 3 — Encryption key activation at the ONU:

The process of encryption key activation at the ONU is defined in 11.6.2.6. ONU's activation of a new decryption key in Step 2 also serves as a trigger for activating the same key for the encryption of its upstream transmission. The ONU waits for the next envelope header from to the given encryption entity. The ONU indicates switching to the new key by toggling the value of the *EncKey* field in the envelope header. The payload following this envelope header is encrypted using the new key.

Step 4 — Decryption key activation at the OLT:

The process of the decryption key activation at the OLT is identical to that process at the ONU, and is, in fact, described by the same state diagram (see 11.6.2.5). For every received envelope, the OLT retrieves a key associated with the given encryption entity, identified by the LLID field, and the key index, identified by the *EncKey* field. Thus, toggling of the *EncKey* value by the ONU in Step 3 above caused the OLT to also retrieve the new key after it parsed and processed this envelope header.

Optionally, the OLT may implement additional safety check of comparing that the retrieved decryption key matches the previously used encryption key. If implemented, such check shall be performed not earlier than a round-trip time after the activation of the new encryption key in step 1.

11.3.4.1.2 Activation of a multicast (unidirectional) key

The activation of a multicast (unidirectional) key, i.e., a key associated with a multicast LLIDs, involves only step 1 and step 2 (see 0) because the multicast LLIDs carry traffic only in the downstream direction.

The activation of the encryption key by the OLT, as signaled by toggling of the *EncKey* field in the downstream envelope header, is detected by all ONUs that are members of the given multicast group. This causes all member ONUs to activate the new key for the decryption.

11.3.4.1.3 Location of key activation processes

The encryption and decryption key activation processes are located within the secure MCRS (MCRS $_{SEC}$) sublayer, as detailed in 11.3.1.2.

11.3.4.2 Definition of processes comprising the key activation protocol

11.3.4.2.1 Variables

`activeKeyIndex[ee]`

TYPE: 1-bit integer

This variable represents the index of the currently active encryption/decryption key for the encryption entity `ee`. Incrementing this variable by 1 causes its value to toggle between 0 and 1.

`decryptionCounter[ch]`

TYPE: 128-bit sequence

The initial value of the counter (initialization vector) used as an input block to the AES forward cipher in the AES-CTR mode for decryption (see NIST SP 800-38A, 6.5). The `decryptionCounter` is calculated independently for every received envelope header on every channel `ch` and is passed to the decryption function (see Figure 11-1(b)).

`decryptionKey[ch]`

TYPE: sequence of 128 or 256 bits

The value of the key currently used for decryption on channel `ch`. The `decryptionKey` value is fetched for every received envelope header and is passed to the decryption function (see Figure 11-1(b)).

`encryptionCounter[ch]`

TYPE: 128-bit sequence

The initial value of the counter (initialization vector) used as an input block to the AES forward cipher in the AES-CTR mode for encryption (see NIST SP 800-38A, 6.5). The `encryptionCounter` is calculated independently for every transmitted envelope header on every channel `ch` and is passed to the encryption function (see Figure 11-1(a)).

`encryptionEnabled[ee]`

TYPE: boolean

This variable indicates whether the encryption is enabled or disabled for the given encryption entity `ee`.

It the OLT, this variable is set to `true` when the initial encryption key becomes available (calculated or provisioned) to the encryption entity `ee` in both the OLT and an ONU (refer to the definition of variable `initialKeyReady[ee]`). Note that for testing and troubleshooting purposes, the NMS may temporarily disable the encryption for an encryption entity `ee` by overwriting the `encryptionEnabled[ee]` with the value of `false` (see 11.9).

In the ONU, under normal operation, this variable is equal to `receivedEncrypted[ee]`, i.e., an encryption entity `ee` encrypts the outgoing envelopes only if the envelopes this entity receives from the OLT are also encrypted. For testing and troubleshooting purposes, the NMS may force the ONU's encryption to be on or off (via the attribute *aEncryptionMode*, see 14.4.5.1)

`encryptionKey[ch]`

TYPE: sequence of 128 or 256 bits

The value of the key currently used for encryption on channel `ch`. The `encryptionKey` value is fetched for every transmitted envelope header and is passed to the encryption function (see Figure 11-1(a)).

`encryptionMode[ee]`

TYPE: boolean

This variable is an alias of the extended attribute *aEncryptionMode* (0xDB/0x04-04) defined in 14.4.5.1.

`initialKeyDone[ee]`

TYPE: boolean

This variable is used only by the OLT encryption key activation process (see 11.6.2.4), where it causes the replacement of the initial (ephemeral) key by the session key as soon as the first session key is distributed to the ONU (i.e., without waiting for the key lifetime interval to expire).

If the encryption entity `ee` is associated with an ONU object, this variable is set to `true` by the OLT OAM client after the first session key was distributed to the ONU and its reception and processing was acknowledged by the ONU (see step 4 in 11.2.3). This variable is reset to `false` on read.

If the encryption entity `ee` is associated with a multicast LLID object, this variable is equal to `false` at all times.

`initialKeyReady[ee]`

TYPE: boolean

This variable is used only by the OLT encryption key activation process (see 11.6.2.4), where it causes the encryption entity `ee` to start encrypting traffic in the downstream direction.

If the encryption entity `ee` is associated with an ONU object, this variable is set to `true` by the OLT OAM client after the initial (ephemeral) key was calculated and stored in the array `keys` as element `keys[ee][0]`. The derivation of the initial key is described in 11.3. This variable is reset to `false` on read.

If the encryption entity `ee` is associated with a multicast LLID, this variable is set to `true` by the OLT OAM client after the first session key was distributed to all ONUs in a multicast group and its reception and processing was acknowledged by every ONU. This variable is reset to `false` on read.

`keys[E][2]`

TYPE: array of encryption keys

`keys[E][2]` is a two-dimensional array representing the stored encryption keys. The array size is $E \times 2$, where E represents the total number encryption entities, with two values stored for each entity - the currently-active key and the key to be activated next. The value of E for the OLT (E_{OLT}) is defined in 11.8.1 and its value for the ONU (E_{ONU}) is defined in 11.8.2.

The key values are written into the `keys[E][2]` array by the Security function of the OAM Client as the end result of the Session Key Distribution Protocol (see 11.5). The Session Key Activation protocol stat diagrams have a read-only access to this array.

`keyInterval[ee]`

TYPE: integer

This variable represents an interval of time between updating the encryption keys (i.e., a key lifetime) for encryption entity `ee`. The value of this variable is provisioned to the OLT by the NMS, subject to constraints listed in 11.8.3.

`receivedEncrypted[ee]`

TYPE: boolean

This variable indicates whether the received envelope, whose LLID value maps to the encryption entity `ee`, is encrypted or not. In the OLT and in the ONU, the value of this variable is derived from the *EncEnabled* field of the received envelope headers.

`RxEQ[ch]`

TYPE: EQ

This variable represents an envelope quantum (EQ) received and stored in the `EnvRx` buffer of the MCRS on channel `ch` (see IEEE Std 802.3, 143.3.4).

`TxEQ[ch]`

TYPE: EQ

This variable represents an envelope quantum (EQ) being transmitted from the `EnvTx` buffer of the MCRS on channel `ch` (see IEEE Std 802.3, 143.3.3).

11.3.4.2.2 Functions

`calculateIV(ch, eq)`

This function calculates the value of the initialization vector (IV) used as an input block to the AES forward cipher in the AES-CTR (see NIST SP 800-38A, 6.5). The argument `ch` is an index of the channel on which the IV is to be used. The argument `eq` is an EQ that represents an envelope header. The IV construction method is defined in 11.7.4.2.

`isHeader(eq)`

The `IsHeader(eq)` function returns true if the parameter `eq` represents an envelope header. This function is defined in IEEE Std 802.3, 143.3.4.4.

`mapEncrEntity(llid)`

The `mapEncrEntity(llid)` function maps an LLID value to an index of an encryption entity (see 11.2.1.1). Each multicast LLID maps to an encryption entity associated with that multicast LLID. All unicast (bidirectional) LLIDs provisioned on an ONU map to a single encryption entity associated with the given ONU.

11.3.4.2.3 Timers

`keyTimer[ee]`

This timer is used to count down the time remaining until the next key update. There exists a separate instance of this counter for every encryption entity `ee`. A key for encryption entity `ee` may not be used past the expiration of the `keyTimer[ee]`.

Each timer instance `keyTimer[ee]` is associated with an instance of boolean variable `keyTimer_done[ee]`. Upon expiration of the timer, the value of `keyTimer_done[ee]` becomes true (see 3.6.6).

11.3.4.2.4 OLT encryption key activation process state diagram

The OLT shall implement the encryption key activation process as depicted in state diagram in Figure 11-8. There shall be a separate instance of the encryption key activation process for each transmit channel `ch` in the OLT.

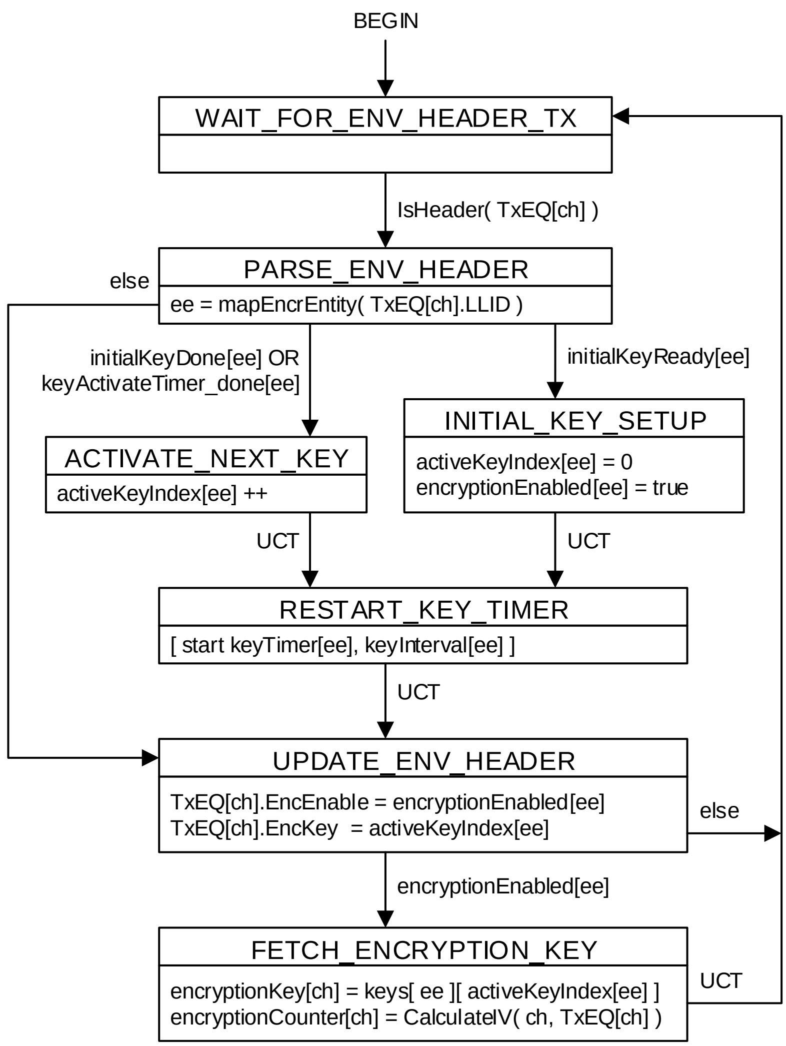


Figure 11-8—OLT encryption key activation process state diagram

11.3.4.2.5 OLT and ONU decryption key activation process state diagram

The OLT and the ONU shall implement the decryption key activation process as depicted in state diagram in Figure 11-9. There shall be a separate instance of the decryption key activation process for each receive channel `ch` in the OLT and in the ONU.

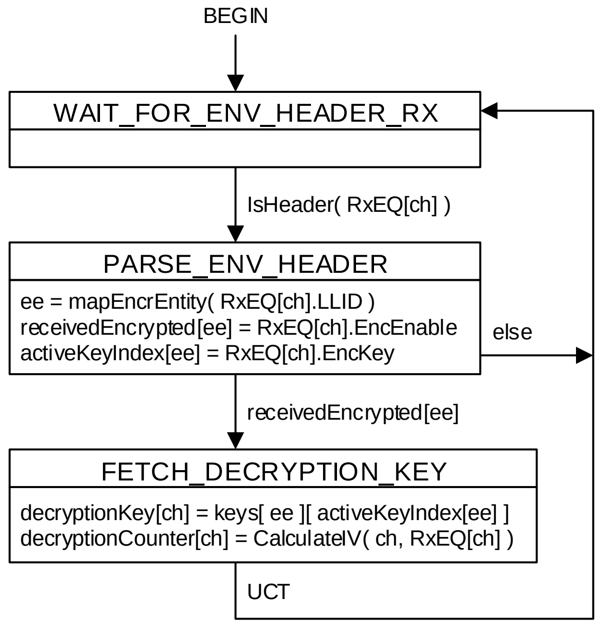


Figure 11-9—OLT and ONU decryption key activation process state diagram

11.3.4.2.6 ONU encryption key activation process state diagram

The ONU shall implement the encryption key activation process as depicted in state diagram in Figure 11-10. There shall be a separate instance of the encryption key activation process for each transmit channel `ch` in the ONU.

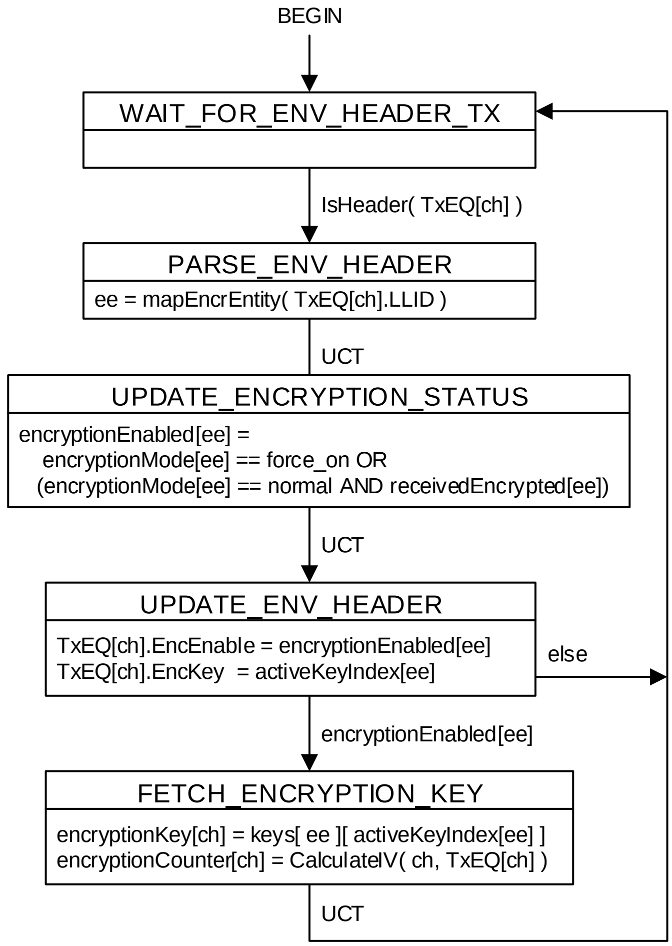


Figure 11-10—ONU encryption key activation process state diagram

11.3.5 Cryptographic method

11.3.5.1 Introduction

In SIEPON.4 systems, the OLT and ONUs encrypt data using the AES Counter mode (AES-CTR). The AES-CTR is a confidentiality mode that applies the forward cipher to a set of input blocks, called counters, to produce a sequence of output blocks that are XOR-ed with the plaintext to produce the ciphertext, and vice versa. The AES-CTR mode requires that all counter values be distinct across all of the messages that are encrypted under the given key. For the detailed specification of the AES-CTR refer to NIST SP 800-38A, 6.5.

11.3.5.1.1 Envelope-based encryption

The concept of transmission envelope is defined in IEEE Std 802.3, 143.2.4.2. An envelope encapsulates continuous transmission by a specific MAC instance (LLID) on one MCRS channel.

In SIEPON.4 cryptographic method, the encryption is based on an envelope structure, i.e., an envelope payload constitutes the plaintext message to be encrypted. The envelope headers themselves are not encrypted. An entire envelope payload is encrypted using the same session key. A new session key may only activate during the reception or transmission of an envelope header (refer to Session Key Activation protocol in 11.6).

The cipher block size is 128 bits. Each block of plaintext includes exactly two EQs. Some plaintext blocks are only partially-encrypted, i.e., the above-mentioned XOR operation is applied to only a portion of the plaintext block. The reason for this is explained in 11.7.2.

11.3.5.1.2 Location of the encryption/decryption functional blocks

The encryption and decryption functional blocks are located within the secure MCRS (MCRS SEC) sublayer, as detailed in 11.2.2.

11.3.5.2 Encryption process

The encryption process applies the forward cipher function to each counter block, and the resulting output blocks are XOR-ed with the corresponding plaintext blocks to produce the ciphertext blocks (see Figure 11-11).

The first counter block in a message (Counter 1) is initialized to the value called Initialization Vector (IV). The IV value used for the encryption is calculated by the OLT encryption key activation process (see Figure 11-8) and by the ONU encryption key activation process (see Figure 11-10). Every subsequent counter block associated with the given message is constructed by incrementing the value of the previous counter block by 1.

If the envelope payload length is odd, the last block will only contain one EQ. In such case, the most significant 64 bits of the last output block are used for the XOR operation and the remaining 64 least significant bits of the last output block are discarded.

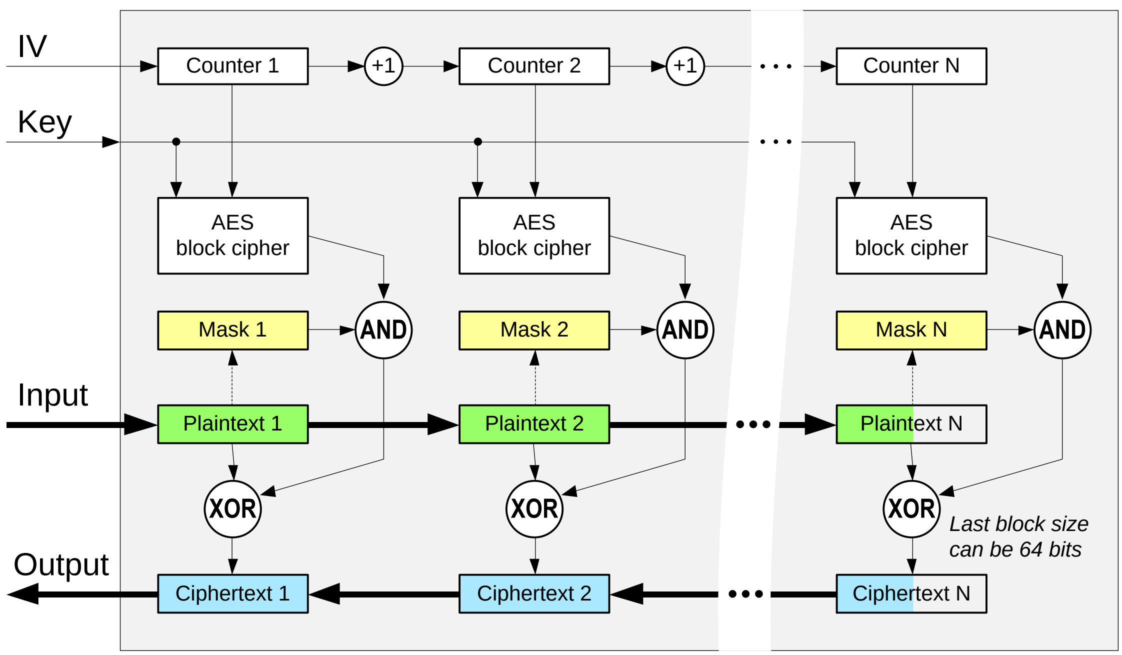


Figure 11-11—Block diagram of the encryption process

For every block of plaintext, a mask is constructed to block-out the control characters (see 11.7.5.2). This mask is AND-ed with the output of the AES block cipher, resulting in the unencrypted control characters being placed in the ciphertext blocks.

In the encryption process, the forward cipher block operations can be performed in parallel. Moreover, the forward cipher functions can be applied to the counters prior to the availability of the plaintext data, if the corresponding counter block values can be determined.

11.3.5.3 Decryption process

The decryption process applies the forward cipher function to each counter block, and the resulting output blocks are XOR-ed with the corresponding ciphertext blocks to recover the plaintext blocks (see Figure 11-12).

Similar to that in the encryption process, the first counter block in a message (Counter 1) is initialized to the value called Initialization Vector (IV). The IV value used for the decryption is calculated by the OLT and ONU decryption key activation process (see Figure 11-9). Every subsequent counter block associated with the given message is constructed by incrementing the value of the previous counter block by 1.

For a given encrypted message (i.e., an envelope), the IV and the subsequent counter block values applied by the decryption process match the IV and the counter values that were previously applied by the encryption process to encrypt the same message.

If the envelope payload length is odd, the last block will only contain one EQ. In such case, the most significant 64 bits of the last output block are used for the XOR operation and the remaining 64 least significant bits of the last output block are discarded.

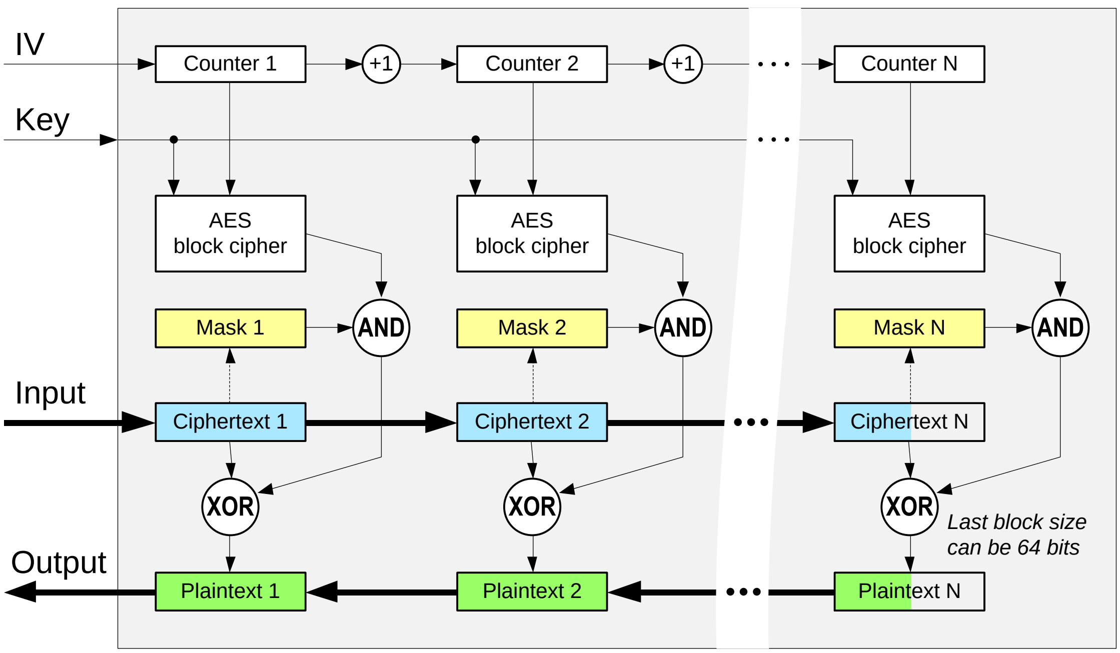


Figure 11-12—Block diagram of the decryption process

For every block of ciphertext, a mask is constructed to block-out the control characters (see 11.7.5.2). This mask is AND-ed with the output of the AES block cipher, resulting in the unencrypted control characters being transferred from the ciphertext blocks into the plaintext blocks.

In the decryption process, the forward cipher block operations can be performed in parallel. Moreover, the forward cipher functions can be applied to the counters prior to the availability of the ciphertext data, if the corresponding counter block values can be determined.

11.3.5.4 Initialization Vector (IV) construction

The sequence of counters must have the property that each block in the sequence is different from every other block. This condition is not restricted to a single message; across all of the messages that are encrypted under the given key, all of the counters must be distinct. This condition is satisfied by ensuring that IV values calculated for every message are distinct for any message (envelope) encrypted with the same key.

To encrypt a message, the IV is calculated by the encryption key activation processes at the OLT (see Figure 11-8) and at the ONU (see Figure 11-10) when an envelope header (ESH or ECH) is observed in the transmit path of the $\mathrm{MCRS}_{\mathrm{SEC}}$ sublayer.

To decrypt a message, the IV is calculated by the decryption key activation processes at the OLT and the ONU (see Figure 11-9) when an envelope header (ESH or ECH) is observed in the receive path of the $\mathrm{MCRS}_{\mathrm{SEC}}$ sublayer.

The data within the envelope header together with the index of the channel on which this envelope header was transmitted or received comprise the input parameters to the `CalculateIV(…)` function that derives the IV values in the above mentioned processes (see 11.6.2.2). It is critical that for any given encrypted message (envelope), the IV calculated by the decryption key activation process matched the IV calculated by the encryption key activation process.

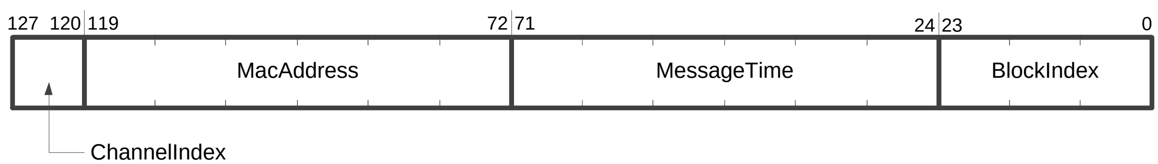


Figure 11-13—Structure of the Initialization Vector

The structure of the IV is illustrated in Figure 11-13. The IV consists of the following four fields:

ChannelIndex – Index of the channel on which the encrypted message is being transmitted or received. The most significant bit (bit 127) represents the direction (0 – downstream; 1-upstream), and bits [126:120] represent the channel number. For example, the value 0x01 represents the downstream channel 1 (DC1) and the value 0x80 represents the upstream channel 0 (UC0). The MCRS channels are explained in IEEE Std 802.3, 143.4.1.1.

The inclusion of this field ensures that in a situation when multiple ESHs to/from the same ONU are transmitted at the same time (i.e., the IVs have the same *MessageTime* filed value) on different channels, their associated IV values would still be distinct.

MacAddress – This is the MAC address of the device that encrypted the given envelope. In the downstream direction, this is the MAC address associated with the PON port of the OLT. In the upstream direction, this is the MAC address associated with the PON port of the transmitting ONU.

To calculate the IV for the decryption, the ONU uses the OLT's MAC address known to it from the MPCP registration step. The OLT also has a prior knowledge of MAC addresses of all connected ONUs, but it needs to determine which specific ONU sourced the given envelope. It does that by first extracting the LLID value from the ESH and then looking up the MAC address associated with this LLID.

MessageTime – This field represents a timestamp of *cipher clock* captured at the moment when the encryption key activation process observes the ESH in the $\mathrm{MCRS}_{\mathrm{SEC}}$ transmit path or the decryption key activation process observes the ESH in the $MCRS_{SEC}$ receive path. The cipher clock runs synchronously with the MPCP clock, but otherwise is a distinct clock, as explained in 11.7.4.1.

This field ensures that all the counter block values used on the same channel (i.e., the IVs have the same *ChannelIndex* values) and with the same session key are distinct.

BlockIndex – The block index field is set to zero when an envelope header is detected. This field is incremented by 1 for every subsequent counter block in the same envelope.

11.3.5.4.1 Cipher clock

The cipher clock is a 48-bit counter that runs synchronously with the MPCP clock (*LocalTime*), but is a distinct clock. The OLT and the ONUs contain versions of this clock that is used as a timestamp source for the IV field *MessageTime*. At the OLT, a single clock, referred to as *CipherClock* is used for IV construction in both the encryption and the decryption functions. At the ONU, there are two instances of the cipher clock: the *TxCipherClock* that is used to construct the IV for the encryption function, and the *RxCipherClock* that is used to construct the IV for the decryption function. The relationship between the OLT's *CipherClock* and the ONU's *RxCipherClock* and *TxCipherClock* is illustrated in Figure 11-14.

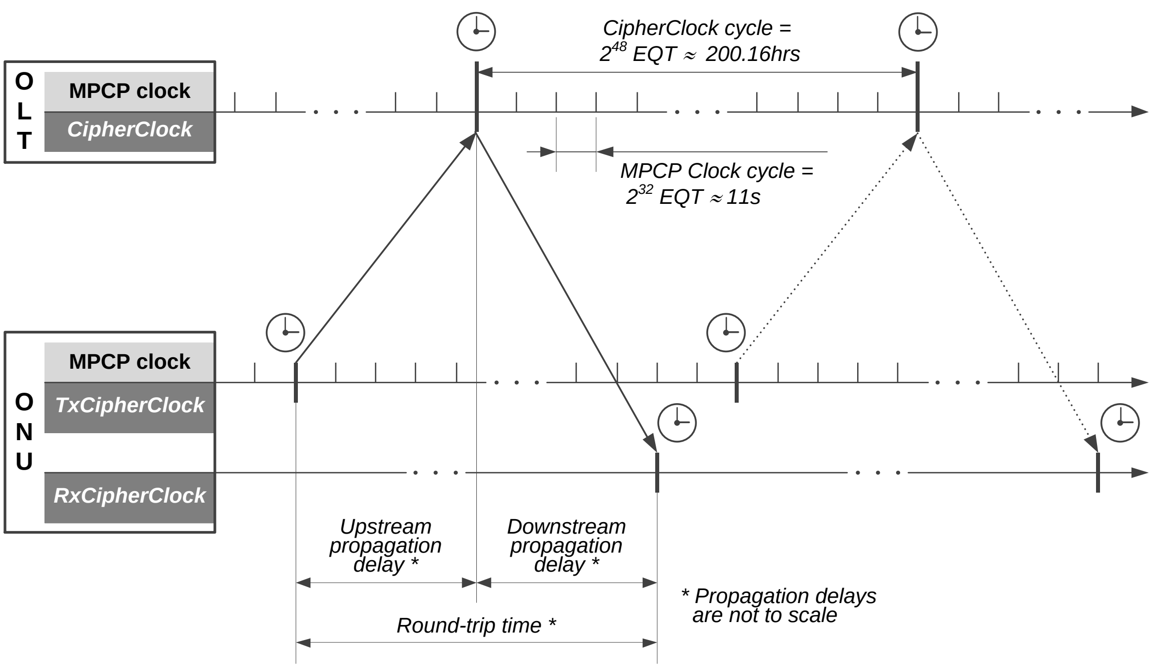


Figure 11-14—Relationship of OLT's *CipherClock* and ONU's *TxCipherClock* and *RxCipherClock*

The MPCP clock is a 32-bit counter that increments by one every EQT. The initial synchronization of the MPCP clock takes place during ONU's MPCP discovery and registration and is described in IEEE Std 802.3, 144.3.1.1.

The origin point of the MPCP clock (counter) at the ONU is advanced relative to the origin point of the MPCP clock at the OLT by the upstream propagation time. The desired effect of such shift is that an envelope header transmitted by the ONU at its local MPCP time T_i is received by the OLT also at its local MPCP time T_i.

The *CipherClock* in the OLT is an extension of the OLT MPCP clock constructed by prepending 16 most-significant bits to the MPCP clock, i.e., `LocalTime` counter (see IEEE Std 802.3, 144.2.1.1). The carry-over bit from the `LocalTime` counter increments the first bit of the 16-bit extension portion (i.e., the bit 32 of the 48-bit *CipherClock* counter).

The *TxCipherClock* in the ONU is an extension of the ONU MPCP clock and is constructed in a manner similar to the OLT *CipherClock* construction. Because the OLT *CipherClock* and the ONU *TxCipherClock* extend their respective MPCP clocks, they preserve their relative shift, ensuring that the *MessageTime* value used to construct the IV for the encryption at the ONU matches the *MessageTime* value used to construct the IV for the decryption at the OLT.

The *RxCipherClock* at the ONU is a separate 48-bit clock increments synchronously with the ONU MPCP clock, but is not an extension of the MPCP clock (i.e., the low 32 bits of the *RxCipherClock* are not equal to ONU's MPCP `LocalTime` value). The origin point of the *RxCipherClock* at the ONU is delayed relative to the origin point of the *CipherClock* at the OLT by the downstream propagation time. The desired effect of such shift is that an envelope header transmitted by the OLT when its *CipherClock* value is T_i is received by the ONU at its *RxCipherClock* value is also T_i.

11.3.5.4.1.1 Cipher clock alignment in the upstream

The MCRS defined in IEEE Std 802.3, Clause 143 ensures that an envelope header (EH) transmitted by the ONU at a specific local time value is received at that exact local time at the OLT. To achieve that, the ONU sets the EPAM field in the EH to equal 6 least significant bits of its MPCP time (`EH.EPAM = LocalTime[5:0]`).

At the OLT, this EH is received (i.e., is written) into the `EnvRx` buffer into row with index equal to `EH.EPAM`. This EH is then read from the `EnvRx` buffer at the exact time when the OLT's `LocalTime[5:0]` are equal to the row index (i.e., when `LocalTime[5:0] = EH.EPAM`). As the 6 LSB are aligned, so are the entire extended MPCP clock values at the ONU and OLT are equal.

Since the *CipherClock* at the OLT and the *TxCipherClock* at the ONU are the extensions of their respective MPCP clocks, it follows that the value of ONU's *TxCipherClock* latched at the moment when the EH is written into `EnvTx` buffer at the ONU matches the value of OLT's *CipherClock* latched at the moment when the EH is read from the `EnvRx` buffer at the OLT.

11.3.5.4.1.2 Cipher clock alignment in the downstream

In the downstream direction, the OLT sets the EPAM field in the EH to equal 6 least significant bits of its MPCP time (`EH.EPAM = LocalTime[5:0]`).

At the ONU, this EH is received (i.e., is written) into the `EnvRx` buffer into row with index equal to `EH.EPAM`. This EH is then read from the `EnvRx` buffer at the exact time when the 6 LSB of the ONU's *RxCipherClock* are equal to the row index. (Note however, that ONU's `LocalTime[5:0] ≠ EH.EPAM` because the ONU's MPCP clock is advanced by the upstream propagation time, see Figure 11-14.)

As the 6 LSB are aligned, it follows that the value of OLT's *CipherClock* latched at the moment when the EH was written into `EnvTx` buffer at the OLT matches the value of ONU's *RxCipherClock* latched at the moment when the EH was read from the `EnvRx` buffer at the ONU.

11.3.5.4.1.3 Initial cipher clock synchronization

While the OLT and ONU MPCP clocks are synchronized as part of the MPCP Discovery and Registration process (see IEEE Std 802.3, 144.3.1.1), the *RxCipherClock* and the *TxCipherClock* require an additional synchronization procedure to synchronize the 16 most-significant bits.

To initiate the cipher clock synchronization at the ONU, the OLT issues a *Set_Request* OAMPDU containing the *Sync Cipher Clock* TLV (see 14.6.5.2). The OLT shall not activate the initial encryption key for an ONU until it receives a positive acknowledgement from that ONU that the *Sync Cipher Clock* TLV was processed successfully.

The OLT shall form the *Sync Cipher Clock* TLV by setting its *RxCipherTimestamp* and *TxCipherTimestamp* fields as follows:

```
RxCipherTimestamp = CipherClock;
TxCipherTimestamp = RxCipherTimestamp + RTT[PLID];
```

The `RTT[PLID]` is the round-trip time value measured for the given ONU (PLID) at the time of its MPCP discovery. Note that adding `RTT[PLID]` may cause the value `TxCipherTimestamp` to wrap around.

It may not be possible to tightly control the transmission time of OAMPDUs, unlike that of MPCPDUs. It is acceptable for the OAMPDU containing the *Sync Cipher Clock* TLV to be transmitted after the time epoch corresponding to the captured value of the OLT's *CipherClock*, but the transmit time (referenced to the ESH of the envelope containing this OAMPDU) shall not lag behind the said time epoch by more than 1 second.

When the ONU receives the *Sync Cipher Clock* TLV, it increments both the `TxCipherTimestamp` and the `RxCipherTimestamp` until the bottom 32 bits of the `TxCipherTimestamp` match the current value of its local MPCP clock (i.e., `LocalTime` variable). The amount of such increment depends on how much the transmission time of *Sync Cipher Clock* TLV lagged behind the captured value of OLT's *CipherClock*. Note that incrementing the `TxCipherTimestamp` or the `RxCipherTimestamp` may cause the values to wrap around.

```
while( TxCipherTimestamp[31:0] != LocalTime)
{
   TxCipherTimestamp ++;
   RxCipherTimestamp ++;
}
```

Once the bottom 32 bits of `TxCipherTimestamp` match the `LocalTime`, the values of *TxCipherClock* and *RxCipherClock* are set by writing the corresponding adjusted timestamps into the *acSyncCipherClock* attribute (see 14.6.5.2):

```
acSyncCipherClock.sTxCipherClock = TxCipherTimestamp;
acSyncCipherClock.sRxCipherClock = RxCipherTimestamp;
```

From this moment on, the *TxCipherClock* and the *RxCipherClock* increment synchronously with the ONU's MPCP clock.

If the *TxCipherClock* and the *RxCipherClock* are synchronized properly, the following holds true:

— The bottom 32 bits of *TxCipherClock* match the local MPCP time at all times (`TxCipherClock[31:0] == LocalTime`).

— The bottom 6 bits of *RxCipherClock* match the value of the EPAM field in any received envelope header.

Implementations may choose to verify the above conditions in order to ensure proper *RxCipherClock* and *TxCipherClock* alignment.

11.3.5.4.1.4 Implementation options (informative)

At the OLT, the *CipherClock* and MPCP clock can share the same 48-bit variable (register), with the MPCP clock occupying the 32 least-significant bits (i.e., `LocalTime[31:0] = CipherClock[31:0]`).

At the ONU, an observation can be made that the time frame reference of *RxCipherClock* lags behind the time frame reference of the *TxCipherClock* by a fixed interval equal to ONU's round trip time. Thus, it is possible to represent the MPCP clock, the *TxCipherClock* and the *RxCipherClock* by the same 48-bit variable (register). The *TxCipherClock* is represented by the full register value, while the ONU MPCP clock is represented by the 32 least-significant bits (i.e., `LocalTime[31:0] = TxCipherClock[31:0]`). The *RxCipherClock* can be derived by subtracting the round-trip time (a fixed constant) from the value of the *TxCipherClock*: `RxCipherClock[47:0] = TxCipherClock[47:0] – RTT`.

11.3.5.4.2 CalculateIV(…) function

The function `CalculateIV(ch, eh)` is used by the encryption and decryption key activation processes in the OLT and ONUs. In each of these processes, the behavior of this function is similar at the high level, but differs in specific minor details, as explained below. This function executes within one MPCP clock cycle (in under one EQT), therefore the 6 least-significant bits of the relevant cipher clock counter match the value of the EPAM field of the EH (see IEEE Std 802.3, 143.3.2).

In the OLT encryption key activation process, the function `CalculateIV(ch, eh)` is called at the moment when an envelope header (EH) `eh` is observed in the MCRS transmit path on channel `ch` (see Figure 11-8). The following is the definition of the function `CalculateIV(ch, eh)` for the OLT encryption key activation process:

```
int128 CalculateIV( ch, eh )
{
       iv.ChannelIndex = ch;                    // Channel index
       iv.MacAddress   = OLT_MAC_ADDRESS;       // Known constant
       iv.MessageTime  = CipherClock;           // Latch OLT's cipher clock
       iv.BlockIndex   = 0;                     // Reset block index
       return iv;
}
```

In the OLT decryption key activation process, the function `CalculateIV(ch, eh)` is called at the moment when an envelope header (EH) `eh` is observed in the MCRS receive path on channel `ch` (see Figure 11-9). The following is the definition of the function `CalculateIV(ch, eh)` for the OLT decryption key activation process:

```
int128 CalculateIV( ch, eh )
{
       iv.ChannelIndex = ch;                    // Channel index
       iv.MacAddress   = MacAddr[eh.llid];      // MAC address table lookup
       iv.MessageTime  = CipherClock;           // Latch OLT's cipher clock
       iv.BlockIndex   = 0;                     // Reset block index
       return iv;
}
```

Note that, in this function, the OLT needs to perform a table lookup to retrieve the MAC address associated with a given LLID value.

In the ONU encryption key activation process, the function `CalculateIV(ch, eh)` is called at the moment when an envelope header (EH) `eh` is observed in the MCRS transmit path on channel `ch` (see Figure 11-10). The following is the definition of the function `CalculateIV(ch, eh)` for the ONU encryption key activation process:

```
int128 CalculateIV( ch, eh )
{
       iv.ChannelIndex = ch;                   // Channel index
       iv.MacAddress   = ONU_MAC_ADDRESS;      // Known constant
       iv.MessageTime  = TxCipherClock;        // Latch ONU’s tx. cipher clock
       iv.BlockIndex   = 0;                    // Reset block counter
       return iv;
}
```

In the ONU decryption key activation process, the function `CalculateIV(ch, eh)` is called at the moment when an envelope header (EH) `eh` is observed in the MCRS receive path on channel `ch` (see Figure 11-9). The following is the definition of the function `CalculateIV(ch, eh)` for the ONU decryption key activation process:

```
int128 CalculateIV( ch, eh )
{
       iv.ChannelIndex = ch;                   // Channel index
       iv.MacAddress   = OLT_MAC_ADDRESS;      // Learned at registration
       iv.MessageTime  = RxCipherClock;        // Latch ONU’s rx. cipher clock
       iv.BlockIndex   = 0;                    // Reset block index
       return iv;
}
```

11.3.5.5 Encrypted envelope format

To encrypt a message, an envelope payload is divided in 128-bit blocks of plaintext and the encryption operation is performed as described in 11.7.2. To decrypt a message, an envelope payload is divided in 128-bit blocks of ciphertext and the decryption operation is performed as described in 11.7.3.

Exactly two EQs form a plaintext or ciphertext block, except in the case of odd payload length, the last block contains a single EQ (see Figure 11-15). In every envelope, the first payload block is aligned to the end of envelope header. The envelope header itself is not encrypted.

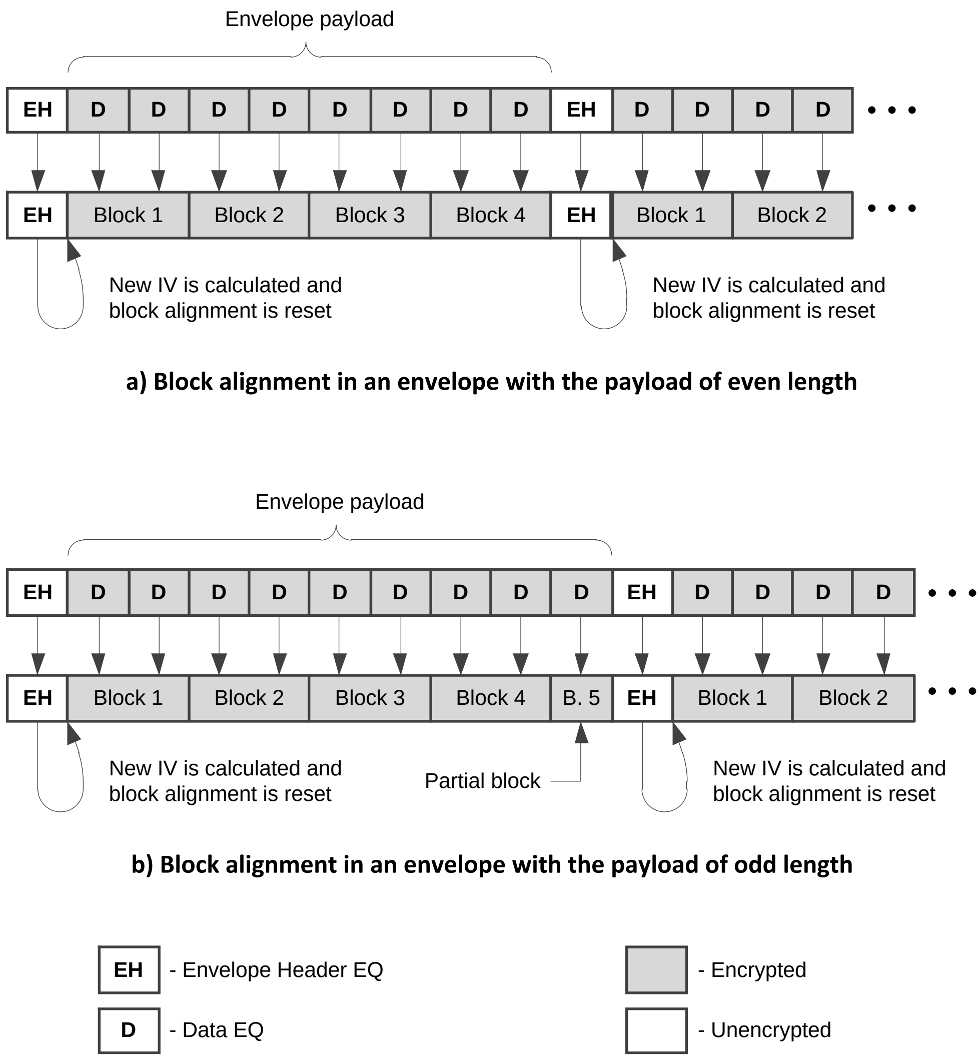


Figure 11-15—EQ-to-block conversion

11.3.5.5.1 EQ types that bypass the encryption and decryption processes

As was shown in 11.2.3 and 11.2.4, there are several types of EQs that can appear in the MCRS data path. Some of the EQ types represent control sequences used to signal frame, envelope, or burst delineation (see IEEE Std 802.3, 143.3.3.6.2). These EQs require special treatment by the encryption and the decryption functions, as illustrated in Figure 11-16 and detailed below:

Rate Adjustment (RATE_ADJUST_EQ):

The MCRS ($MCRS_{SEC}$) periodically inserts a series of 33 RATE_ADJUST_EQs to pace the MAC data rate in order to allow the FEC parity data insertion by the PCS. The position of RATE_ADJUST_EQ insertion is determined by the Input process of the MCRS Transmit function and by the Output process of the MCRS Receive function. The RATE_ADJUST_EQ insertion by the Input and the Output processes may happen at different positions within an envelope.

The RATE_ADJUST_EQs are not considered part of envelope (i.e., they are not accounted in envelope length value). As described in 11.2.3 and 11.2.4, these EQs bypass the Encryption/Decryption processes, i.e., they are not encrypted and they do not affect the plaintext or the ciphertext block alignment. The sequence of RATE_ADJUST_EQs may be inserted in the middle of single plaintext or ciphertext block, as illustrated in Figure 11-16.

Inter-Envelope Idle (IEI_EQ):

The IEI_EQs are inserted when there is no envelope available for transmission, while the transmission channel itself is active. The IEI_EQs are not part of an envelope. However, unlike the RATE_ADJUST_EQs, they cannot appear in the middle of an envelope. Within the encryption and decryption functions, the IEI_EQs bypass the Encryption/Decryption processes, i.e., they are not encrypted and they do not affect the plaintext or the ciphertext block alignment.

Inter-Burst Idle (IBI_EQ):

The IBI_EQs are inserted when the transmission channel is not active, such as between transmission bursts. The IBI_EQs can only appear in the upstream and are not considered part of an envelope. Within the encryption and decryption functions, the /IBI/ characters bypass the Encryption/Decryption processes, i.e., they are not encrypted and they do not affect the plaintext or the ciphertext block alignment.

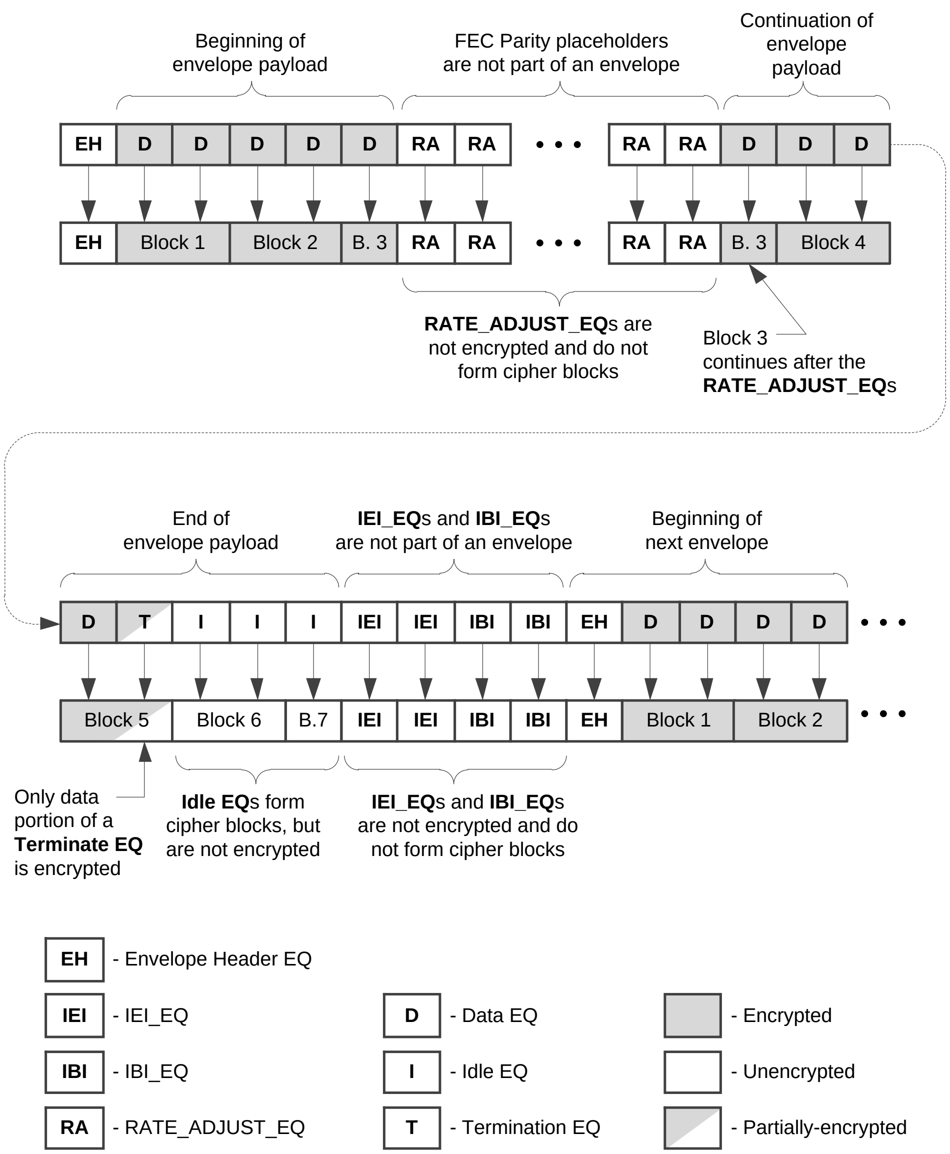


Figure 11-16—Handling of special EQ types by encryption/decryption function

11.3.5.5.2 Handling of the control characters in envelope payloads

There are several EQ types that can appear in the payload portion of an envelope: data EQ, Termination EQ, and (regular) Idle EQ. Some of these EQ types may include control characters /T/ and /I/. In order to support 64b/66b encoding in the PCS, these control characters are passed from the input to the output of the encryption or the decryption process unmodified.

As explained in 11.7.2 and 11.7.3, the control characters are left unencrypted by applying a mask to the output of the AES block cipher, before that output is XOR-ed with the plaintext or the ciphertext blocks.

Within the MCRS, an EQ is represented by a 72-bit structure, consisting of 8 control bits `Ctrl[0:7]` and 8 data octets `Data [0:7]` (see IEEE Std 802.3, 143.2.4.1). If the `Ctrl[i]` bit is 1, then the corresponding `Data[i]` octet represents a control character, which shall be left unencrypted. Otherwise, the `Data[i]` is a data octet, which shall be encrypted. Table 11-1 shows all EQ types that may be encountered in the envelope payload and the associated EQ mask. The masks associated with two EQs that form a plaintext or a ciphertext block are combined to form a 128-bit mask that is to be applied to the output of the AES block cipher.

Table 11-1—EQ types and the associated encryption EQ masks

EQ type	Ctrl[0:7] (bin)	Data[0:7] (hex) [a]	Mask (hex)
Data	00000000	xx-xx-xx-xx-xx-xx-xx-xx	FF-FF-FF-FF-FF-FF-FF-FF
Terminate	00000001	xx-xx-xx-xx-xx-xx-xx-FD	FF-FF-FF-FF-FF-FF-FF-00
	00000011	xx-xx-xx-xx-xx-xx-FD-07	FF-FF-FF-FF-FF-FF-00-00
	00000111	xx-xx-xx-xx-xx-FD-07-07	FF-FF-FF-FF-FF-00-00-00
	00001111	xx-xx-xx-xx-FD-07-07-07	FF-FF-FF-FF-00-00-00-00
	00011111	xx-xx-xx-FD-07-07-07-07	FF-FF-FF-00-00-00-00-00
	00111111	xx-xx-FD-07-07-07-07-07	FF-FF-00-00-00-00-00-00
	01111111	xx-FD-07-07-07-07-07-07	FF-00-00-00-00-00-00-00
	11111111	FD-07-07-07-07-07-07-07	00-00-00-00-00-00-00-00
Idle	11111111	07-07-07-07-07-07-07-07	00-00-00-00-00-00-00-00

[a] `xx` indicates 'any value'

11.3.6 Encryption key management

11.3.6.1 Key storage in the OLT

The OLT encrypts the unicast traffic to each ONUs using a unique key. Every multicast LLID is encrypted using a unique key as well.

Given a PON configuration that includes U ONUs and M multicast LLIDs, the OLT shall be able to support E_{OLT} encryption entities, where $E_{OLT} = U + M$ (refer to use of constant E_{OLT} in the definition of `keys[E][2]` in 11.6.2.1). The OLT shall contain enough storage space for $2 \times E_{OLT}$ keys, with each key being 128 or 256 bits long.

At any time, in the OLT, at most U keys are active for decryption and $U + M$ keys are active for encryption.

11.3.6.2 Key storage in the ONU

The ONU encrypts all unicast LLIDs with the same key in both upstream and the downstream directions. Each multicast LLID provisioned into the given ONU is encrypted using its independent key.

For each encryption key, the ONU stores two key values: the currently-active key value and the key value that will become active on the next key switch event.

Given an ONU configuration that includes any number of unicast LLIDs and m multicast LLIDs, the ONU shall be able to support E_{ONU} encryption entities, where $E_{ONU} = m + 1$ (refer to use of constant E_{ONU} in the definition of `keys[E][2]` in 11.6.2.1). The ONU shall contain enough storage space for $2 \times E_{ONU}$ keys, with each key being 128 or 256 bits long.

At any time, in the ONU, at most $m + 1$ keys are active for decryption and only one key is active for encryption.

11.3.6.3 Key lifetime

One of the requirements of AES CTR mode is that the counter values do not repeat for the duration (lifetime) of a single encryption key (see NIST SP 800-38A, 6.5). Therefore, the construction method of the Initialization Vector (IV) imposes the upper limit on the encryption key lifetime.

The IV construction is defined in 11.7.4. It relies on the extended 48-bit MPCP clock counter. This counter increments every envelope quantum time (EQT), which equals 2.56 ns (see IEEE Std 802.3, 1.4.245c). Thus, the MPCP counter rolls-over every 200.16 hours. The OLT shall maintain the key lifetime of less than or equal to 200 hours ($T_{max\_key\_lifetime}$). Different encryption entities may optionally have different key lifetimes not exceeding the $T_{max\_key\_lifetime}$.

11.3.7 Encryption testing and troubleshooting modes of operation

Under the normal operation conditions, for all encryption entities associated with ONU objects, the encryption is enabled in both downstream and upstream directions, and for all encryption entities associated with multicast LLID objects, the encryption is enabled the downstream direction.

For testing and troubleshooting purposes, the NMS may temporarily disable the encryption for any encryption entity `ee` in the downstream direction and/or in the upstream direction, if applicable.

11.3.7.1 Encryption entities associated with multicast LLID objects

For an encryption entity `ee` associated with a multicast LLID object, the encryption is disabled by setting the variable `encryptionEnabled[ee]` at the OLT to `false` (see 11.6.2.1). Disabling encryption for a multicast ULID or a multicast PLID does not affect the security of traffic or the key updates for other encryption entities. There are special considerations for disabling encryption for an entity `ee` associated with a multicast MLID, as explained in 11.9.3.

Note that disabling the encryption of multicast ULID/PLID does not stop the periodic key updates for these multicast LLIDs. The key updates continue over the unicast or multicast MLID channels, which remain encrypted and secure.

Upon completion of the testing or troubleshooting analysis, the encryption of multicast ULID or a multicast PLID traffic is re-enabled by simply setting the variable `encryptionEnabled[ee]` at the OLT to `true`.

11.3.7.2 Encryption entities associated with ONU objects

An encryption entity `ee` associated with an ONU object carries all the unicast traffic to and from that ONU (i.e., it aggregates all the unicast LLIDs at a given ONU, including the unicast MLID).

Setting the variable `encryptionEnabled[ee]` to `false` at the OLT disables the encryption of downstream traffic associated with encryption entity `ee`. This, in turn, causes the ONU encryption key activation process to disable the encryption of the upstream unicast traffic associated with this encryption entity `ee` (see 11.6.2.6).

NOTE -- The action of disabling the downstream encryption for an encryption entity `ee` associated with an ONU object may expose the encryption keys distributed via the MLID channel. Such action shall never be performed on ONUs carrying live user traffic.

Once this value `encryptionEnabled[ee]` is set to false at the OLT, it cannot be changed back to true via NMS anymore. To re-enable the encryption, the OLT shall initiate the ONU authentication process (see 11.3) and the initial key exchange (see 11.4).

At the ONU, the upstream encryption is controlled via the attribute *aEncryptionMode* (see 14.4.5.1). Under the normal operation, the upstream encryption is enabled if the downstream unicast traffic to this ONU is encrypted. For testing and troubleshooting purposes, the *aEncryptionMode* allows forcing the upstream encryption on or off, regardless of the status of the downstream encryption.

Disabling the upstream encryption is a less disruptive operation than disabling the downstream encryption, since the encryption keys are never transmitted in the upstream direction. Upon conclusion of the troubleshooting analysis, the upstream encryption can be re-enabled by setting the *aEncryptionMode* attribute to `normal`.

11.3.7.3 Encryption entities associated with multicast MLID objects

Special care is required when disabling the encryption for multicast MLIDs, as such MLIDs may be used to distribute the multicast encryption keys (see 11.5.3.1 and 11.5.3.2). The multicast MLID encryption shall never be disabled in systems carrying live user multicast traffic.