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Implementation of High-Level Cryptographic Protocols using a SoC Platform

Mémoire présenté en vue de l'obtention du diplôme
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Abstract

by Quentin Delhaye, Master in Computer Science and Engineering, Professional Focus, Université Libre de Bruxelles, 2014–2015.

Implementation of high level cryptographic protocol using a SoC platform

This is an abstract. Yep.

Résumé

par Quentin Delhaye, Master en ingénieur civil en informatique, à finalité spécialisée, Université Libre de Bruxelles, 2014–2015.

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Chapter 1

Introduction

Altera and Xilinx are trying to push those SoC plateforms to the market to popularize the FPGAs.

Power is critical nowadays, esapcially in datacenters. Several solutions exists: abandonning general purpose processors altoghether and turn towards ARM cores, or add an FPGA to the processor for example. Intel proposed the latter solution in 2014 [**?**] and is on its way to expand that market with the merger with Altera [**?**].

1.1 Challenge

1.2 Network security

Chapter 2

Technical background

This chapter will address the technical ground inherent to this work. First comes an overview of Linux operating systems, the distinction between user and kernel mode, and the design of device drivers.
Follow a quick presentation of FPGAs and how they can be driven from the operating system.
Next comes An overview of the cryptographic field with the main primitives: message digests, symmetric ciphers and asymmetric ciphers.
Finally, the ground necessary to understand the inner working and challenges of some VPNs implementations will be covered with SSL/TLS and IPsec.

2.1 Operating system

2.1.1 Device Driver

Userspace I/O [19]

There are two ways to get the results from a hardware device: either by using interruption, or by actively polling the device, relentlessly asking it if it finished its operations. The first case is the cleanest and the most common: when the device has something to send to the driver, or if anything unexpected happened, it sends an interruption request (IRQ) to the processor, which will in turn execute the interruption routine registered by the driver [9, chap. 10]. The second case is the easiest and is always guaranteed to work, but won't let go off the processor willingly, loading it at 100%, and avoiding any other task to be executed. Hopefully, modern monolithic kernels such as the Linux kernel from 2.6 provide preemptive scheduling [30], that is the scheduler interrupts the running task and assigns the processor ressources it used to an other one. Hence, systems with a lot of processes in need for CPU ressources would not be stalled, but it would not change anything if the only process heavily requesting processor time is the one using the driver.

2.2 FPGA

Driving from the OS: basically, they will need to share some memory. That memory can be directly mapped and accessed from the user-space using `/dev/mem`, or can use a direct memory access module (DMA). From the operating system, we build a bunch of scatterlist in the kernel-space memory, then map those pages to memory descriptor that have a physical address on the DMA. They can be mapped three different ways: `DMA_BIDIRECTIONAL`, `DMA_TO_DEVICE` or `DMA_FROM_DEVICE`. When the CPU write something in those descriptors and synchronize them with the DMA, it does not have to care about them anymore, the DMA in now in charge to send them to the device where registers are ready to read the incomming data. The same goes from the device to the CPU: when the device wants to communicate data to the OS, it writes it on the DMA that will transfer them to the CPU, triggering a flag on the way to notify it.

2.3 Cryptography

Cryptography is the corner stone of security. The four main goals are the following, as defined in [24]:

Confidentiality keeping information secret from all but those who are authorized to see it.

Integrity ensuring information has not been altered by unauthorized or unknown means.

Source Authentication corroborating the source of information.

Non-repudiation preventing the denial of previous commitments or actions.

In order to achieve those, four cryptographic primitives are needed: symmetric and asymmetric ciphers, message digests and digital signatures.

2.3.1 Message digest

A message digest is the result of a one-way mathematical function of a fixed size. Those hash functions are of two types [21]: manipulation detection codes (MDC) to guarantee integrity and message authentication codes (MAC) to guarantee both integrity and source authentication.

An MDC $h(x)$ can follow an iterative construction for a message x including t blocks:

$$\begin{cases} H_0 = \text{initial value} \\ H_i = f(H_{i-1}, x_i), \text{with } i \in [1, t] \\ h(x) = H_t \end{cases}$$

Based on this design and adding a key to the process, the RFC 2104 [20] defines a MAC:

$$HMAC(k, x) = h((k \oplus opad)|h((k \oplus ipad)|x))$$

with a key k, and two padding block added for security concerns: an outer pad $opad$ and an inner pad $ipad$.
There exist a wide varety of MDCs, ranging from block cipher based such as Miyaguchi-Preneel, customized such as MD5, SHA-1 and SHA-2, or built using modular arithmetic such as MASH-1.

In both schemes, data integrity can be guaranteed because the flip of one bit will irremediably change the digest. However, only a MAC can ensure source authentication since it is the only one based on a shared secret key.

Now rises the question of what and when authenticating. Bellare and Namprempre [5] prooved that the most secure solution is to encrypt then compute the MAC from the ciphertext. We will see in section 2.4 that if IPsec follows this recommandation, SSL/TLS does not and MAC first the plaintext then encrypt the message.

2.3.2 Symetric cryptography

Talk about encryption, integrity and authentication.

Look in depth into AES, NIST approved five modes [11]: CBC (Cipher Block Chaining), ECB (Electronic CodeBook), CFB (Cipher FeedBack), OFB (Output FeedBack) and CTR (Counter).

AEAD => Encryption and authentication: GCM.

2.3.3 Asymetric cryptography

Asymetric cryptography relies on a pair of keys: one private known only to the owner of the certificate, and one public available to anyone. Such cryptography uses two kinds of operations: encryption using the public key of the recipient and digital signature, which is an ecnryption using the private key of the sender.

2.3.3.1 RSA

RSA is a public-key scheme proposed in 1978 by three MIT researchers who gave it their name [27]. A few years later, they founded RSA Laboratories, which is now in charge of maintaining its standards, alongside many others, as the first Public-Key Cryptography Standards, *aka* PKCS #1. The last version of the standard is the version 2.2 [29] and is defined as a precise key generation protocol allowing encryption and decryption. The keys can be generated by respecting a few steps:

1. randomy choose two large primes p and q;
2. compute the modulus $n = pq$, and consequently we have $\phi(n) = (p-1)(q-1)$, with $\phi(n)$ as the Euler function;
3. randomly choose the public exponent $e \in]1, \phi(n)[\ s.t. \ GCD(e, \phi(n)) = 1$;
4. compute $d \in]1, \phi(n)[\ s.t. \ e \cdot d \equiv 1 (mod \ \phi(n))$

With those parameters, we can form a public key with the pair (n, e) and a private key with the pair (n, d).

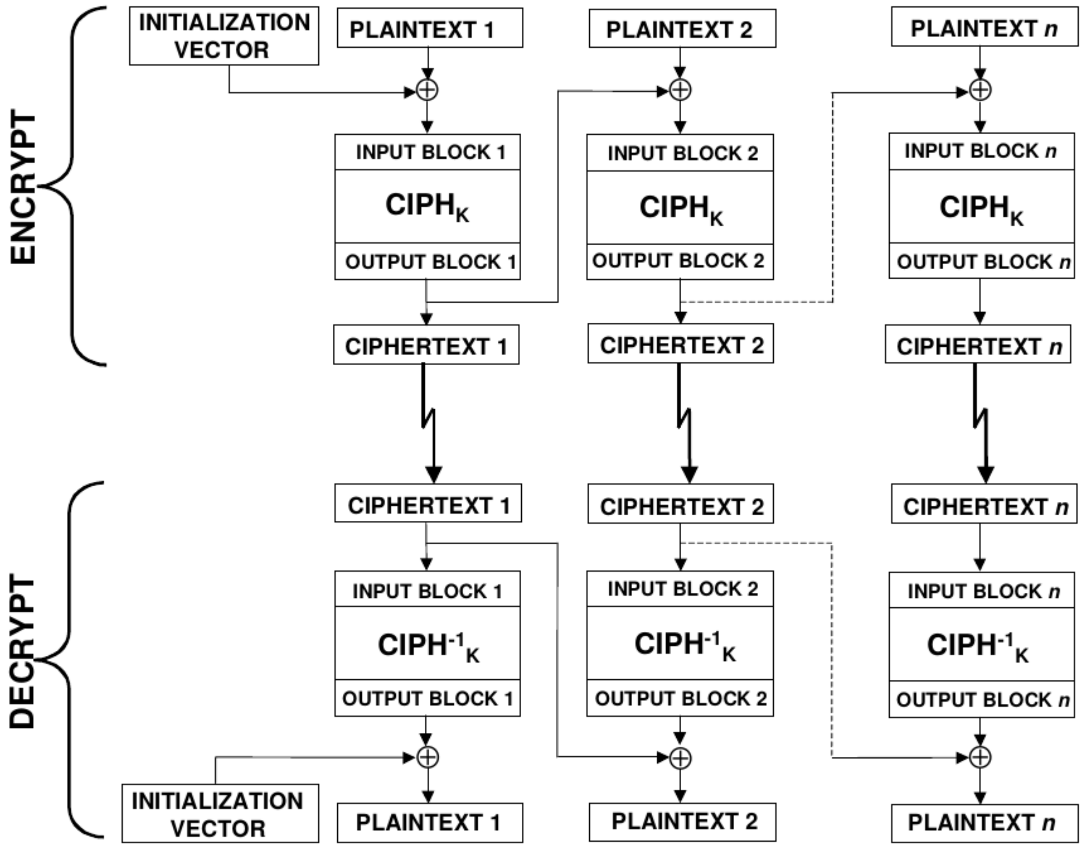


Figure 2.1 – **CBC encryption and decryption diagram:** taken from the NIST recommendation [11].

The encryption and decryption of a given message $m \in \mathbb{Z}_n$ are defined as follows:

Encryption $c = m^e \ mod \ n$
Decryption $m = c^d \ mod \ n$

2.3.3.2 Diffie-Hellman

Diffie-Hellman is a secret key exchange protocol: two parties compute a shared secret ZZ that can be used as a symetric key during the following exchanges. It uses the same kind of operation as RSA, that is modular exponentiation. The protocol can be one of two type ([26], [12]):

- Static: the actors use their authenticated certificate to compute the shared secret.
- Ephemeral: the actors create a new pair of public/private keys from which the secret key is derived.
- Anonymous: same as ephemeral, but without signing anything, hence not identifying neither of the actors. This mode is not advisable since it's vulnerable to main-in-the-middle attack.

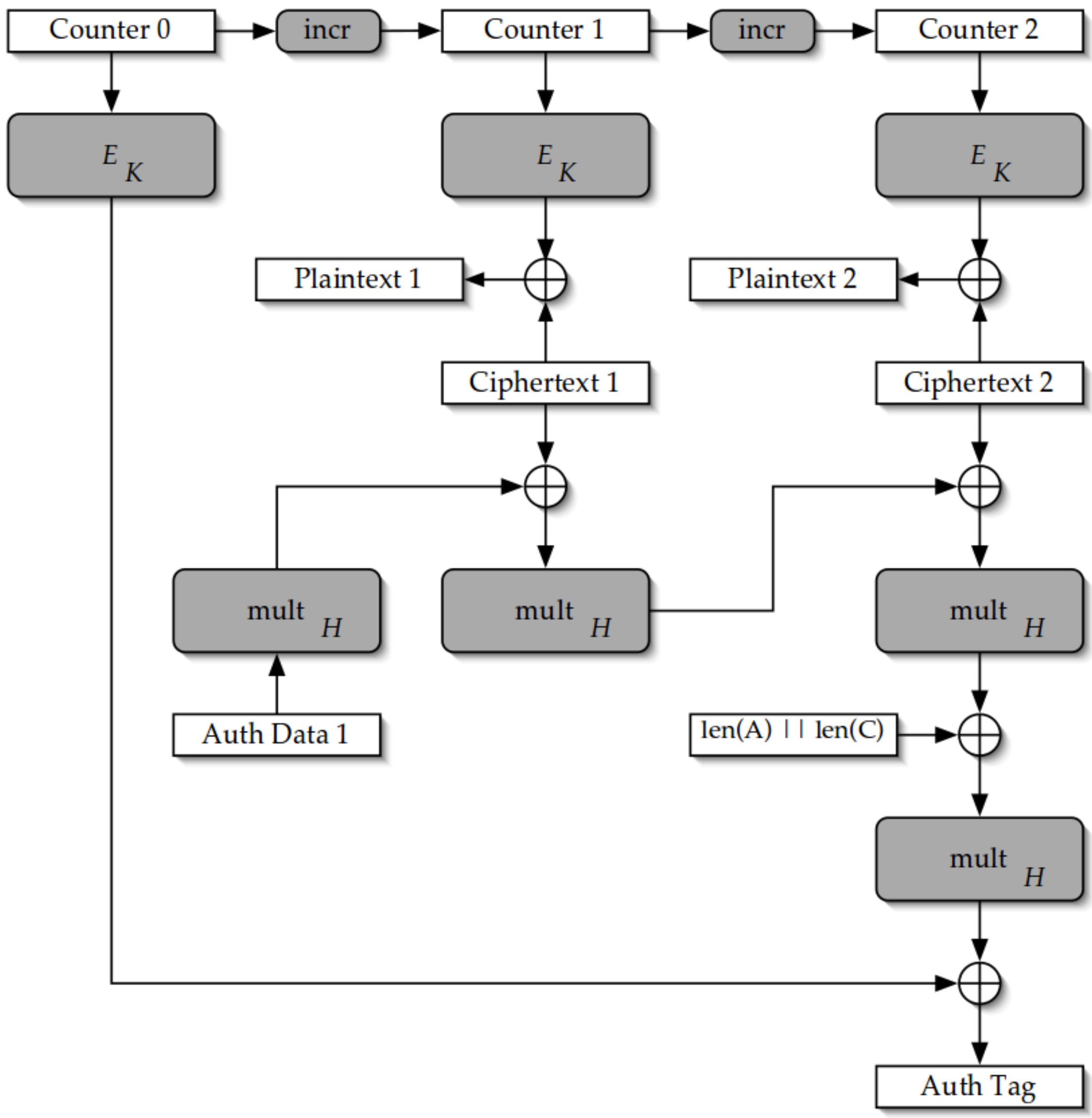


Figure 2.2 – **GCM encryption diagram:** taken from the NIST specification [23]. The ciphertext blocks are formed by *xor*-ing the encrypted counter and the plaintext. The tag is generated by a chain of ciphertext *xor*-ing with Galois field multiplicated data. The decryption works excatly the same way, except the plaintext and ciphertext are swapped.

A static scheme is easier to implement and requires much less operations, but using ephemeral keys is essential to ensure perfect forward secrecy. Imagine that somehow, an opponent lays his hand on the shared secret. If that secret has already been used, he can decipher all data transfered during past connections. However, if the secret is new for every new connection, the compromission of the shared secret des not jeopardize past communications. This is perfect forward secrecy: using a new key to protect the past.

Hereunder is the generation of an ephemeral shared secret. For a static secret, Alice and Bob will simply use their static certificate, sparing the modular exponentiation of the ephemeral public key generation.

1. Alice generates once p and g (using precomputed parameters):
   p large prime number
   g a generator of $\mathbb{Z}_p^*$
2. Alice picks a random integer x_a and computes $g^{x_a} mod\ p = y_a$.
3. Alice sends p, g and y_a to Bob, signing everything using her private certificate.
4. Bob checks the signature and picks x_b.
5. Bob computes $y_a^{x_b} mod\ p = g^{x_a x_b} mod\ p = ZZ$, the shared secret to use as a premaster key from which will be derived the symetric key for further communications.
6. Bob sends $y_b = g^{x_b} mod\ p$, signing everything with his private certificate.
7. Alice checks the signature and computes the same shared secret: $ZZ = y_b^{x_a} mod\ p = g^{x_a x_b} mod\ p$

If the server is Alice, it has to do at least one signature, one signature verification and two modular exponentiations. Note that the client, B in our case, could have one signature less because RFC 5246 [34] leave it as an optional feature, and the server would then have one verification less. However, any sane configuration will have both actors signing their ephemeral public key. If the certificate use RSA, we end up with four modular exponentiations, which can become quite heavy computing wise for certain sizes of prime numbers. We will see in chapter 5 that while a 1024-bit prime is easily manageable by full software implementation, hardware offloading become a necessity for 4096-bit primes. Moreover, 1024-bit parameter size, both RSA and Diffie-Hellman, are disallowed by the NIST recommandations since 2013 [4].

2.4 Network and VPN implementation

The RFC 1122 [6] defines the TCP/IP and OSI stack as in the table 2.1. The main difference between the two is the application layer of the TCP/IP stack which corresponds to the three upper layers of the OSI model. Some references, such as Tanenbaum and Wetherall [32], conceptually split the TCP/IP link layer into an additional physical layer.

There exist several major implementations of VPN: SSL, IPsec, L2TP and PPTP. The later was developped by a vendor consortium leaded by Microsoft and proposed in the RFC 2637 and will not be discussed further.

<table>
<tr><td colspan="2">TCP/IP layering</td><td colspan="2">OSI model</td></tr>
<tr><td>Layer</td><td>Protocols</td><td>Layer</td><td>Protocols</td></tr>
<tr><td rowspan="3">Application</td><td rowspan="3">FTP, SSH</td><td>Application</td><td>FTP</td></tr>
<tr><td>Presentation</td><td>ASCII, JPEG</td></tr>
<tr><td>Session</td><td>RPC, PAP</td></tr>
<tr><td>Transport</td><td>TCP, UDP</td><td>Transport</td><td>TCP, UDP</td></tr>
<tr><td>Internet</td><td>IP, ICMP, IPsec</td><td>Network</td><td>IP, ICMP, IPsec</td></tr>
<tr><td rowspan="2">Data Link</td><td rowspan="2">PPP, MAC, Ethernet, L2TP</td><td>Data link</td><td>PPP, MAC, Ethernet, L2TP</td></tr>
<tr><td>Physical</td><td>USB, DSL, IEEE 802.11</td></tr>
</table>

Table 2.1 – **TCP/IP and OSI model comparison:** They are globaly the same, except for the application layer of the TCP/IP stack which merge togheter the three upper layers of the OSI model. Between parenthsis are examples of protocols resting on each layer.

2.4.1 SSL/TLS

Application level security.

2.4.2 IPsec

IPsec is a modification of the IP stack in the kernel space. It is a network/internet level security; it examines incomming IP packets and checks if there exists a security association with the destination, and decrypt it on-the-fly if necessary.

IPsec consist of three components [33], each defined in their respective RFC:

Traffic protocols Encapsulating Security Payload (ESP, [17]) and Authentication Header (AH, [16]).

Key management Internet Key Exchange (IKEv2, [15]).

Policy Security Policy Database (SPD, [18]) and Security Association (SA [18]).

As Paterson [25] present them, the SAs are used as repository for cryptographic parameters, and the SPD defines the policies to apply. If the SPD can be populated by hand, typically in a configuration file, the SA management should be left to an automated mechanism: the IKEv2.
The IKEv2 protocol uses four different types of exchanges to fulfill its role:

- `IKE_SA_INIT`: The two peers agree on cryptographic parameters to use. Among these is a Diffie-Hellman shared secret from which are derived symmetric keys used for a special IKE SA.
- `IKE_AUTH`: Once the peers are protected by the IKE SA, they can authenticate themselves to each other and add a first SA in the SA database (SADB). The protocol supports three types of authentication methods:
  - Digital signature using a PKI.
  - MAC using a pre-established secret key.

    - Extensible Authentication Protocol (EAP) defined in Aboba et al. [1].

  At this point, the connection is fully established and ready to use.
- `CREATE_CHILD_SA`: Used to create new SAs between the two peers. It may involve new generations of DH secrets to ensure perfect forward secrecy.
- `INFORMATIONAL`: Exchange of management information.

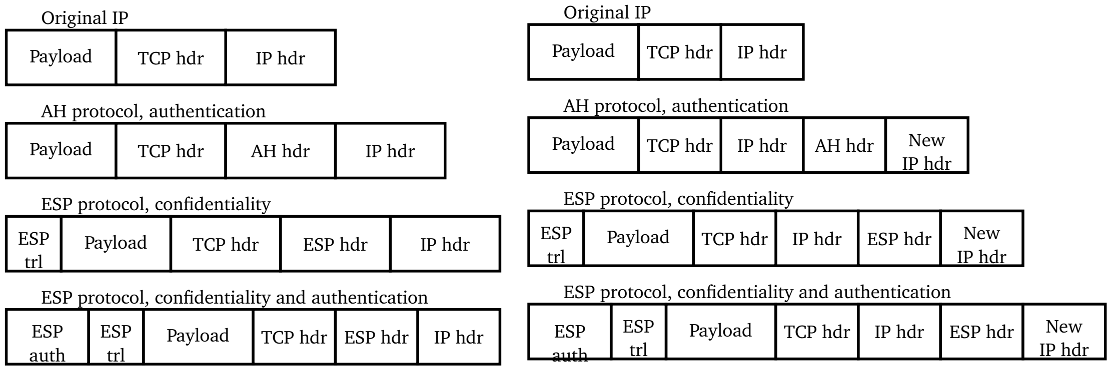
The figure 2.4 shows the structure of an ESP packet. The ESP header includes two fields: a Security Parameter Index (SPI) and a Sequence Number (SN) The SPI is a value on which both actors agreed on during the key exchange protocol, identifying the SA to use for the communication. The SN is an anti-replay feature, an integer incrementing with each packet processed by the SA. This way, the SA will reject any packet that does not have a SN in the current windows, avoiding an intruder to resend a previously captured packet on the network. As the SN is covered by the integrity, the opponent can not change it without having to change the Integrity Check Value (ICV, *a.k.a.* the message digest). This authentication covers the whole packet, whilst the confidentiality excludes the ESP header.
The ESP trailer includes a padding and two 1-byte fields: the padding length and the next header value, which can specify if the packet is dummy or real. The padding is needed when using block ciphers to obtain a payload which length is an integral multiple of the block length.
The ESP payload includes an optional IV and an optional Traffic Flow Confidentiality (TFC) padding. The TFC padding allows to modify the length of the packet with dummy data, somewhat hiding the true nature of the payload. It differs from the standard padding because its length is not limited to 255 bytes like the latter.
AH is the same as ESP, except is does not offer encryption features, only the authentication. Since ESP can use a null cipher, it arguably offers the same features as AH. The existance of AH is actually historical; when the protocol was developped in the 1990s, there were laws in the United States and other countries preventing the export of product including encryption features. Having an authentication only counterparty allowed such product to be exported without encryption capabilities.

IPsec can be deployed in two modes:

- Transport for end-to-end service and protecting the payload. IPsec examines the incomming payload, checks it has not been tampered with and pass it to the next layer.
- Tunnel protects the entire IP packet by encapsulating it into a new IP packet. As the destination contained in the new IP header can be different from the original, this mode can be used to manage gateways.

The figure 2.3 shows the space overhead imposed by AH and ESP in transport and tunnel modes.

Both protocols add 10 bytes of fixed size fields (SPI, SN, pad length and next header). The other fields are of variable length, or even optional, such as the optional authentication field of minimum 12 bytes, the optional IV of minimum 4 bytes and the padding between 0 and 255 bytes long. Xenakis et al. [35] reached the conclusion in their paper that the use of lightweight – and deprecated – encryption schemes (*e.g.* HMAC-MD5 and DES) hardly had any impact on the throughput of the system and on the delay of the packets. Hence, the space overhead of IPsec is negligible when using more serious schemes (*e.g.* AES-256-CBC with HMAC-SHA-256).



(a) Transport (b) Tunnel

Figure 2.3 – **IPsec (a) transport and (b) tunnel overheads:** Tunnel mode adds a custom IP header and moves the AH/ESP header in front of the original IP header. Note: “trl" stands for “trailer", “hdr" for “header", reproduced from [35]

RFC 7321 [22] defines the support for only three AES modes: CBC, CTR and GCM.

```
0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ ----------
|               Security Parameters Index (SPI)                 |      ^Int.
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+      |Cov-
|                      Sequence Number                          |      |ered
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+---   | ----
|                    IV (optional)                              | ^ p  |    ^
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ | a  |    |
|                    Rest of Payload Data  (variable)           | | y  |Conf.
~                                                               ~ | l  |Cov-
|                                                               | | o  |ered*
+               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ | a  |    |
|               |         TFC Padding * (optional, variable)    | v d  |    |
+-+-+-+-+-+-+-+-+         +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+---   |    |
|                         |        Padding (0-255 bytes)        |      |    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+      |    |
|                               |  Pad Length   | Next Header   |      v    v
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+------------
|         Integrity Check Value-ICV   (variable)                |
~                                                               ~
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

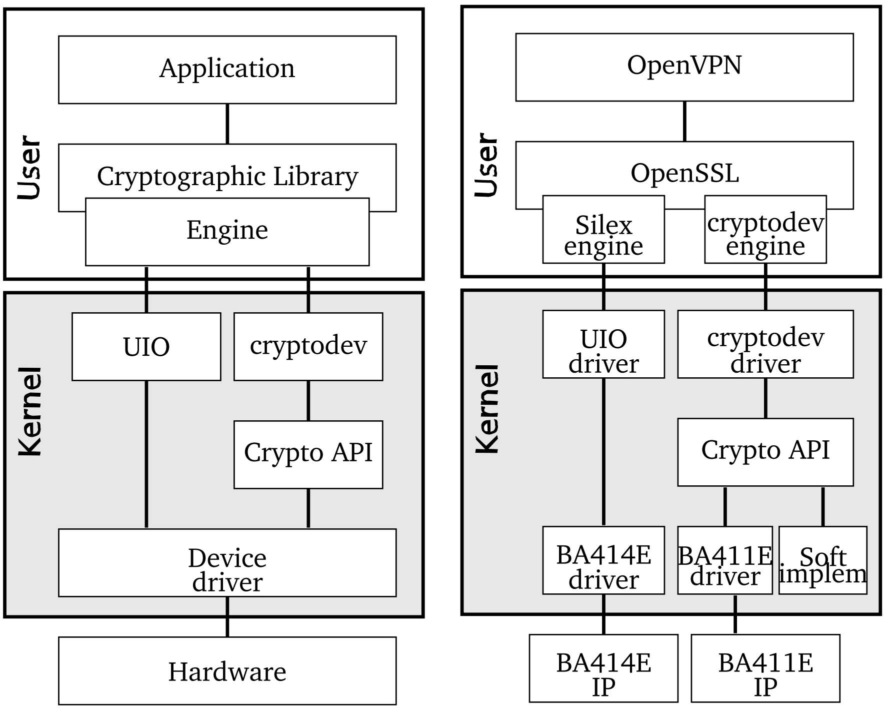
Figure 2.4 – **ESP packet structure:** as defined in RFC 4303 [17].

Chapter 3

Implementation

This chapter will present how we implemented the protocols of chapter 2 on the board. The figure 3.1 shows the generic data flow in the operating system through the user and kernel spaces. We will first detail the software part, with the OpenVPN and openSSH as the applications, and OpenSSL as a cryptographic library on which both applications rely. Then will come strongswan, a user-space abstraction layer giving access to IPsec and we will see how different it is from an OpenVPN implementation. Lastly, the standard Linux cryptographic kernel modules and network drivers will be listed and briefly discussed.

Before closing the chapter, we will present the two main IPs to which the cryptographic operations will be offloaded and the associated drivers.



(a) Generic (b) Specific

Figure 3.1 – **OS data paths:** (a) as a generic abstraction and (b) with some specific blocks replaced with custom implementations.

3.1 Software

3.1.1 OpenVPN

OpenVPN is a very popular VPN solution relying on the application layer of the TCP/IP stack by using the SSL/TLS protocols.

Uses regular TCP/UDP network protocols, which can be an advantage over IPsec if the ISP decides to block the latter.

OpenVPN offers two different TUN/TAP virtual interfaces:

TUN Virtual layer 3 IP tunnel, seen as a point-to-point interface from the kernel point of view.

TAP Virtual layer 2 ethernet tunnel.

Since OpenVPN aims at network security at the application level, it needs virtual network interface to which to push and from which to read the secured data. The `tun` adapter will be used when OpenVPN wants to establish a point-to-point connection between two client, while the `tap` device is used when there is one server acting as a bridge, hence managing lots of clients at the same time.

OpenVPN as two choices when it wants to sends its data over the internet: either encapsulating its IP packet into TCP or UDP packets. The problem of encapsulating IP into TCP is that inside IP packets are already TCP frames. The reason is that IP has been designed to work on unreliable networks, and TCP includes in its standard protocols to retry and drop packets. Hence, encapsulating an IP packet into a TCP packet produces a redundancy by nesting reliability layers. UDP is the unreliable counterparty of TCP, offering a better alternative for encapsulation. If we refer to the figure 3.2, `iperf` would send its regular `IP(TCP)` packet over the virtual `tun` device, which will then compress, fragment and encrypt the frame before encaspulating it into a new UDP packet that will finally be sent through the physical `eth0` interface.
At this point, it is important to note that if the figure 3.2 shows a workflow in which the encryption taking place before the fragmentation, a quick look at the source code proves the opposite. A sample of the said code has been writen down in the listing 3.1.

An other way to look at this workflow is to completely isolate the OpenVPN part from both hosts, and exporting it to an independent device such as a router. The hosts would be stripped off the virtual interface – `tun0` would become physical, and would communicate normally over the internet, at least from their point of view. All their communications would be routed by the router of their local area network, incomming on a physical `tun0` interface and outputed to the internet on the `eth0` interface. Such implementation are used when an adminstrator wishes to secure a whole local area network without bloating each client with a VPN application. In this case, there exist router firmware packages running OpenVPN, such as DD-WRT and OpenWRT. Whatever the method used, the crucial point is that the VPN tunnel usage is transparent to the application.

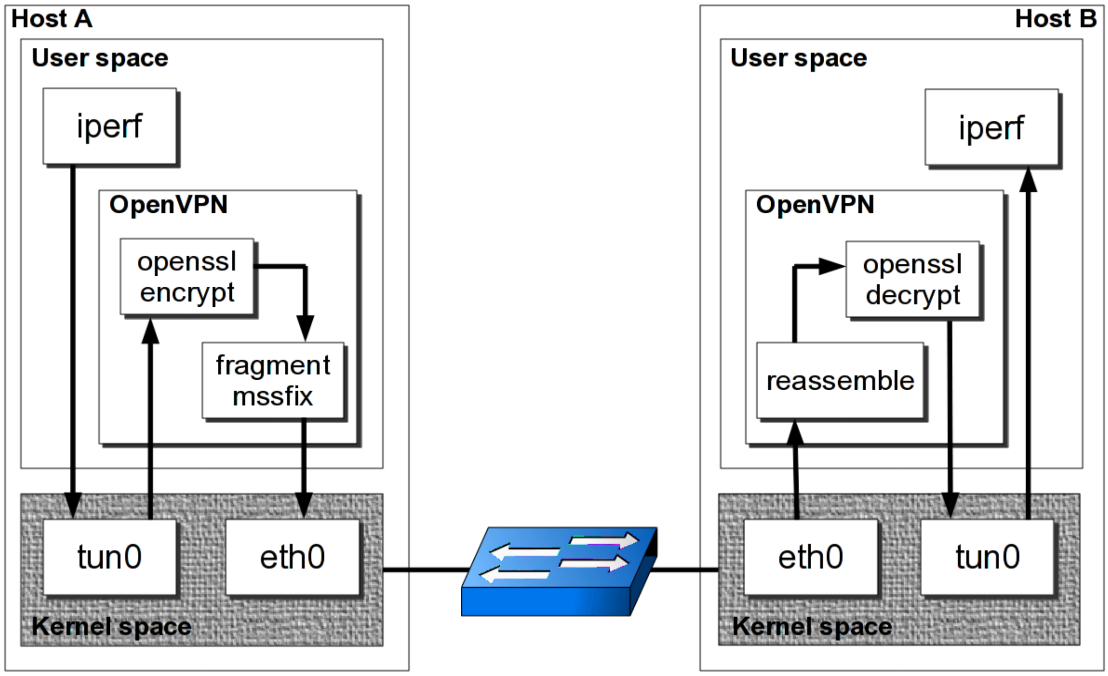


Figure 3.2 – **OpenVPN packet flow:** it shows two hosts using `iperf` inside an OpenVPN tunnel. This figure comes from the OpenVPN documentation [8] and has inverted the encryption and fragmentation.

OpenVPN relies on a cryptographic library, OpenSSL in our case, for all the security operations: encryption, signature, certificate management, etc.
Note that if one wants to use the `none` cipher with a version of OpenVPN ealier than 2.3.7, he would have to update it using a community patch [14].

3.1.2 OpenSSH

OpenSSH relies on an external cryptographic library for all its security operations. Up until the version 6.7 published in october 2014, it had to be compiled against OpenSSL. However, after the infamous security vulnerability heartbleed in april 2014, the developpers took a step to move towards LibreSSL, a fork of OpenSSL managed by OpenBSD developers. Still, there is no official support for any other cryptographic library.

If OpenSSH does support most of OpenSSL ciphers by default, it takes some liberties such as disabling the CBC encryption mode and removing the support of no MAC during a transmission.
The first liberty is a laste[1]. Even if it is not recommended, the user can still enable this mode by explicitly configuring it in the `sshd_config` options.

[1] A vulnerability note as been issued by Carnegie Mellon University Computer Emergency Response Team in early 2009 (last revision) [7], in response to a research of University of London [2] presenting a plaintext-recovering attack against SSH when CBC mode is used, but the OpenSSH update took only place in october 2014.

```c
void encrypt_sign (struct context *c, bool comp_frag)
{
  struct context_buffers *b = c->c2.buffers;
  const uint8_t *orig_buf = c->c2.buf.data;

  if (comp_frag){
  /* Compress the packet. */
    if (lzo_defined (&c->c2.lzo_compwork))
      lzo_compress (&c->c2.buf, b->lzo_compress_buf, &c->c2.lzo_compwork, &c->c2.frame);
  /* Fragment the packet. */
    if (c->c2.fragment)
      fragment_outgoing (c->c2.fragment, &c->c2.buf, &c->c2.frame_fragment);
  }

  /* Encrypt the packet and write an optional HMAC signature. */
  openvpn_encrypt (&c->c2.buf, b->encrypt_buf, &c->c2.crypto_options, &c->c2.frame);
}
```

Listing 3.1 – openvpn compress then encrypt – sample from `forward.c`. It clearly shows that the order of operations in the packet workflow is compression, then fragmentation and finally encryption.

The second liberty has been taken to prevent the user to strip himself from data authenticity and integrity. However, in the case of testing and benchmarking, leaving the MAC behind can be interresting, especially if it is not offloaded in hardware such as the encryption in our case. In order to add this feature to OpenSSH, we wrote a patch to apply on OpenSSH 6.7, available in appendix A.

3.1.3 OpenSSL

Offers an high-level interface called EVP to be used by other applications.

It is to be noted that the present work uses an implementation with all the debug flags activated. Figure 3.3 shows that if it does have an impact on the performance, it is minimal: in the worst case of the benchmark, the throughput drops only by 2.4%. Moreover, the benchmark maximizes this difference by doing only OpenSSL operations. When OpenSSL will have to share the CPU with other applications, the loss will be even less noticeable.

3.1.4 Strongswan

Strongswan is a full implementation of IPsec relying on the kernel drivers for the networking part, on the crypto API for the cryptographic part, and on user space crypto libraries for the connection negociation. An other popular implementation is ipsec-tools, but its development lags behind modern Linux and is not up-to-date with the 3.14 Linux kernel headers, making its cross-compilation painfull. Strongswan as two advantages: it has a tremendous and exhaustive documentation, and its uer interface is straightforward. Once configured, a simple `ipsec`

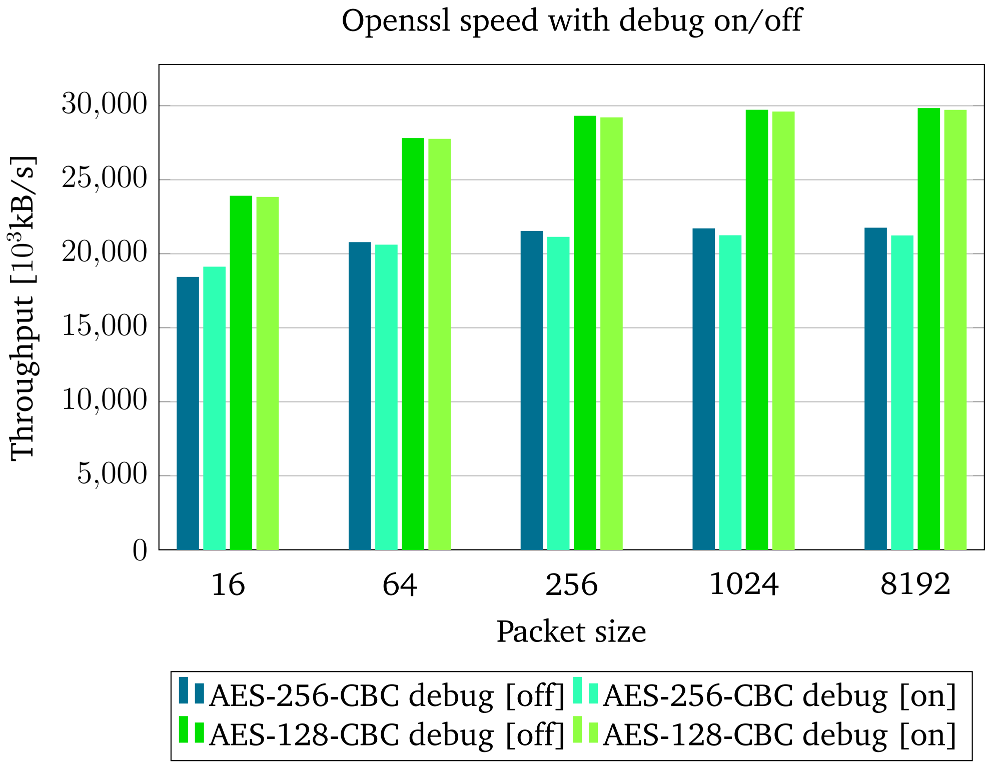


Figure 3.3 – **OpenSSL debugging benchmark:** Software benchmark of Openssl speed for AES mode CBC, with 128- and 256-bit keys, debugging flags (de)activated at compilation (`-fno-inline -g -marm`). The throughput difference ranges from 0.2% and 2.4% , and is more marked for larger keysize, as more debugging data needs to be generated.

`start && ipsec up <connection>` on both sides is enough to create a ready to use VPN.

The figure 3.4 illustrates the workflow of Alice communicating with Bob via an IPsec ESP tunnel. The XFRM, read "transform", framework is implementing IPsec and handles the incomming and outgoing packets for established VPNs [28]. Its name comes from the fact that the kernel transforms packet frames to incorporate IPsec security. Depending on the configuration, XFRM uses the AH or ESP kernel module, which in turn calls the crypto API to encrypt and/or sign the IP packet.

We can also clearly see one of the main advantages of IPsec: it works in the kernel space. Since it does not require a virtual network interface like OpenVPN, the only transfer between the user/kernel space happens when the former wishes to send a packet on the network, passing it to the later – or *vice versa* for incomming packets.

3.1.5 Linux drivers

Several kernel modules are needed to implement the various cryptographic algorithm in software. The GCM alone needs five different modules, and IPsec three

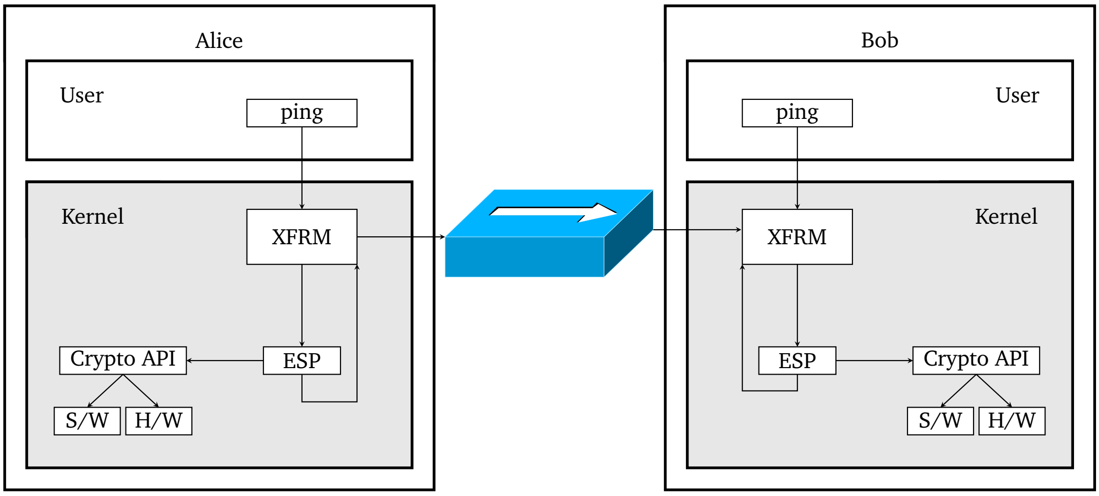


Figure 3.4 – **IPsec user/kernel space workflow, using `ping` as a test case.:**

others. The following description addresses all the kernel modules required to run all the use cases presented in this work.

`aes_arm` Assembly implementation of AES. This version is optimized to use the ARMv7 instruction set.
`sha256-generic` C implementation of SHA-256.
`gfmult128` Multiplication in $GF(2^128)$, needed by the GCM mode.
`ghash` GHASH function needed by the authentication of the GCM mode.
`seqiv` Sequence IV number generator, needed by the CTR and GCM modes.
`cbc` C based CBC mode.
`gcm` C base GCM mode.
`crypto_null` Null cipher. This basically does nothing on the plaintext, but it is still needed to propose the interface in the kernel.
`tun` TUN/TAP network device, needed by OpenVPN.
`xfrm_user` XFRM operations.
`esp4` IPv4 ESP implementation. The AH counterparty is also available in the `ah4` module.
`ipcomp` IP compression module. Needed by IPsec if the option is activated in the configuration.
`cryptodev` Creates `/dev/crypto`, giving access to the crypto API in the user space.
`uio` User-space I/O driver, allowing to access the hardware memory from the user space, needed by our implementation of the BA414E driver.

3.2 Offload

The table 3.1 summarizes the ciphers supported by the two Barco Silex' IPs used in this work.

IP	Ciphers
BA414E	RSA, DH, DSA, EC
BA411E	AES modes CBC, CTR, GCM, CCM, CFB, OFB, CTS, ECB

Table 3.1 – **Summary of the ciphers supported by two of Barco Silex' IPs.:**

3.2.1 BA411E Driver

Takes the rightern path, which is the cleanest because the most versatile. By pluging the driver into the crypto API, we offer a standard kernel interface that can be used by any other kernel driver, such as the ESP driver, or user-space application via the cryptodev driver and OpenSSL engine.

However, at the current state of development, the user-space and the kernel applications do not share the same driver. The former is using an IRQ-based driver, whilst the latter is actively polling the hardware. The reason why the IRQ-based driver can not be used by kernel-space application is because the current implementation uses sleep methods that, when called on other kernel drivers, put the kernel in panic mode and require the system to reboot. An alternative is under development and is further discussed in the last part of this work, in section 6.1.

Be it IRQ or polling, the inner workings are the same and follow the exact same canvas as the default software implementation the different AES modes.

3.2.2 BA414E Driver and Silex engine

At the moment of development, there is no asymetric cryptography interface in the crypto API[2]. The BA414E can thus not be accessed using the same path as the BA411E and a user-space driver will be needed, that is the leftern path of figure 3.1b. As presented in section 2.1.1, we will need to rely on an UIO driver to access the device from the user space.

[2]A request for comment patch as been submitted to the Linux kernel mailing list [31] in late April 2015, proposing a standard interface for public key encryption in the crypto API.

Chapter 4

Test protocol

4.1 Experimental setup

The experimental environment is built around a standard x86 host and an ARM Cortex-A9 alongside an Altera Cyclone V FPGA as the target. Both are linked toghether through a network capped by 100Mbps switches. Both stations have gigabits ethernet interface and could hence be diretly connected to each other, but in that case the communication would be limited by the I/O transfers of the storage units – a hard drive disk in one case, an micro-SD card in the second – on which we can not depend to set a constant throughput limitation, as it is highly influenced by the data block size and general health of the support.

4.1.1 x86 host

The desktop host runs on Windows 7 Professional 64-bit, but a virtual machine using a Linux distribution is used for the developpement and testings.

OS Ubuntu 12.04 LTS, kernel 3.16
CPU Intel Core-i5 (two logical core out of four)
RAM 1GB DDR3

4.1.2 Altera Socrates SoCFPGA

OS Yocto project, kernel 3.14
CPU Dual core ARM Cortex-A9, 800MHz
RAM 1GB DDR3
FPGA Altera Cyclone V

4.1.3 ARM DS-5 Streamline

4.2 TLS Connections

This benchmark is done only with OpenVPN. Since there is no standard support for those operation in the kernel yet, it would not have made sense to use IPsec, since it would have had to fallback to OpenSSL, then following the same path as OpenVPN do. As soon as the public key operations can be plugged into the crypto API, this use case should however be tested.

For this use case, the board is configured in server mode, so that it can accept connections from any client. The virtual machine will then execute then clients in parallel using the script 4.1. The only option differentiating the clients is their IP address and port number. Otherwise, all the clients share the same basic configuration file (see listing **??**), which tell them to renogociate a new connection every second. Hence, if a connection could be made with no delay and if the processes scheduling were ideal, the server would have to address 600 connections per minute.

As this experiment can be very unstable and vastly depends on the operating system scheduling, each test case has been repeated five times to ensure stable results.

```
#!/bin/bash

timeout=120
rsa=1024
remote_ip=150.158.232.208

for i in `seq 1 10`; do
  timeout ${timeout} openvpn --config client_${i}_${rsa}.ovpn --verb 2 --remote
      ${remote_ip} &
done
```

Listing 4.1 – Script starting ten clients in parallel who will stress the server.

The security parameter tested is a standard TLS-DHE-RSA, hence forcing the peers the renogociate a new shared secret and ephemeral Diffie-Hellman parameters at each connection attempt.

4.3 Response time – latency

This use case exchanges ICMP request of various sizes via the `ping` command. The initiating peer sends an ICMP echo request to the remote peer, which then answers with an ICMP echo reply.

For each packet size, 1000 requests were flooded to the board, that is "*outputs packets as fast as they come back or one hundred times per second, whichever is more*", according to the `ping` command manual.

The following loop shows the options used for the test as well as the payload sizes:

```
for i in 56 1000 8000 16000; do
```

```
  sudo ping -f -s ${i} -c 1000 150.158.232.241
done
```

4.4 File transfer

The file transfered is an un compressed block of 128MB of random data generated using the following command:

```
$ head -c $((1024*1024*128)) /dev/urandom > heavy.file
```

For the IPsec use case, the cipher/authentication pair null/null will be used to quantify the overhead of the encapsulation. It should however not be forgotten that it is not to be used as a production configuration. As the RFC 7321 [22, pg. 7] sates: “Note that while authentication and encryption can each be ‘NULL’, they MUST NOT both be ‘NULL’".

We will also use two types of drivers for the BA411E: an interuption-based for OpenVPN and OpenSSH, and a polling-based for IPsec.

All the tests will be conducted with the ESP protocol in tunnel mode, so that we have the worst case scenario; as AH imposes a smaller overhead, the perfomance could only be better.

For OpenSSH, the commmand `scp` will be used to transfer the data securely over an SSH tunnel. As for OpenVPN and IPsec, a tunnel will be established beforehand, and then the simple `ftp` command will allow the client to fetch the file on the server.

Chapter 5

Results and Analysis

This chapter gather the results of the use cases presented in chapter 4. Three use cases are considered: establishing TLS connections, exchanging ICMP requests to compute the latency and transfering a file over a secure channel. Depending on the case, several schemes are analysed: DHE-RSA, AES-CBC, AES-GCM and SHA-256.

It is to be noted that all the CPU usage values are taken from the single one loaded core. Although the platform is dual-core, all applications are used single threaded, either by design, such as OpenVPN, or by choice to obtain comparable results.

5.1 TLS connections

If the ten clients could connect instantaneously to the server every second, the maximum number of connections would be 600 per minute. However, a certain connection time has to be taken into account. Those are summarized in table 5.1.

		Connection time [s]
RSA-1024	soft	0.041921
	BA411E	0.020312
RSA-2048	soft	0.202945
	BA411E	0.039965
RSA-4096	soft	1.436743
	BA411E	0.183533

Table 5.1 – **OpenVPN connection time:** time necessary to establish an aes-256-cbc connection with DHE.

It already shows that the connection latency is divided by 2 for low security RSA, and up to by 7.8 for higher security parameters. The figure 5.1 shows the number of TLS connections per minute for three RSA exponent sizes: 1024-, 2048- and 4096-bit. The higher the exponent size, the higher the performance boost.

For RSA-1024, the results are mitigated: a poor performance increase, but already less than half the CPU usage. It should be noted that at this point, the

	RSA-1024			RSA-2048			RSA-4096		
	Con.		CPU	Con.		CPU	Con.		CPU
Soft	445.4	x1.14	40.32	155.6	x2.70	92.14	19.6	x5.89	81.97
BA414E	509.3		13.29	420.9		4.82	115.5		4.34

Table 5.2 – **TLS connections per minute:** measures obtained with ten clients concurently connecting to an OpenVPN server.

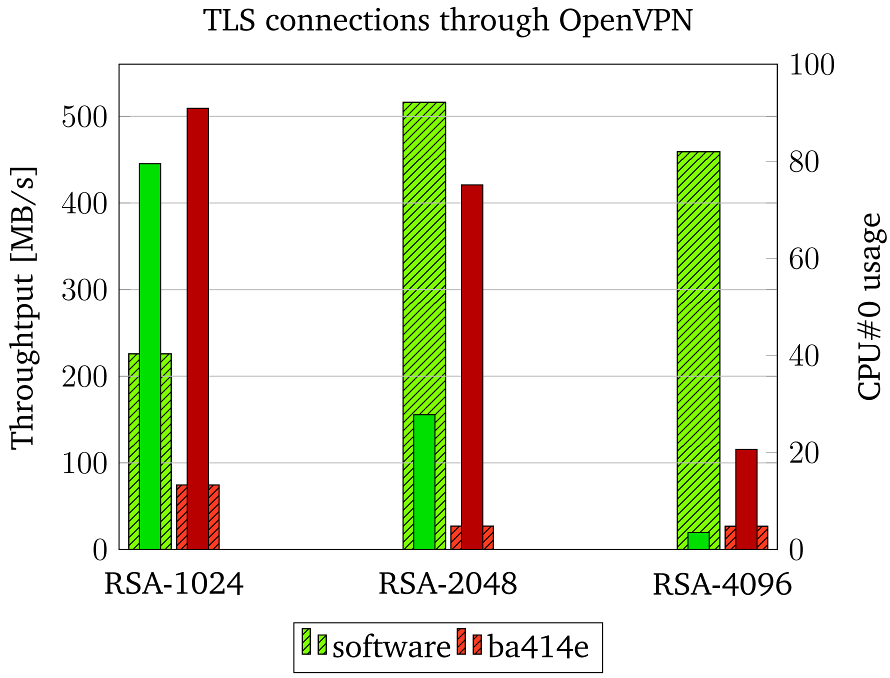


Figure 5.1 – **TLS connections per minute:** The background stripped bars are the CPU usage. Raw data in table 5.2.

number of clients is probably too low to push the configuration to its limits. It is however an interesting comparison case with the next level of security: RSA-2048.
RSA-2048 is a much more common configuration, espacially since the NIST deprecated RSA-1024 in 2013. The full software implementation is visibly affected by the increase of the exponent size: the CPU usage doubles and the server processes three time less connections. At the same time, the hardware loses less than 20% connections for a third of the CPU usage.
The results obtained for RSA-4096 can be interpreted similarly to those of RSA-2048, except that the CPU usage is exactly the same for th hardware configuration. One way too look at those results is to directly compare the raw performance, and the hardware can then process almost six times more connections per minute than the software. However, this is only half of it, since it leaves the CPU usage drop aside. If we look at the efficiency, the software can process 0.24 connection per percentage of CPU usage, whilst the hardware can process 24 of them. The efficiency is thus multipled by a factor 1000.

Such interesting results, particularly regarding the CPU usage, are possible because at least 87% of the operations are RSA and Diffie-Hellman operations, which are entirely offloaded in hardware. Nevertheless, OpenVPN still needs to proceed to some extra computations (such as SHA-1 integrity), and the hardware operations are not instantaneous, so the performance gain can only be that high.

5.2 Response time – latency

The following tests are conducted after the connection has been established, so as the clients do not need to undergo any new key negociation.

5.2.1 OpenVPN

The figure 5.2 shows the results for different payload sizes.

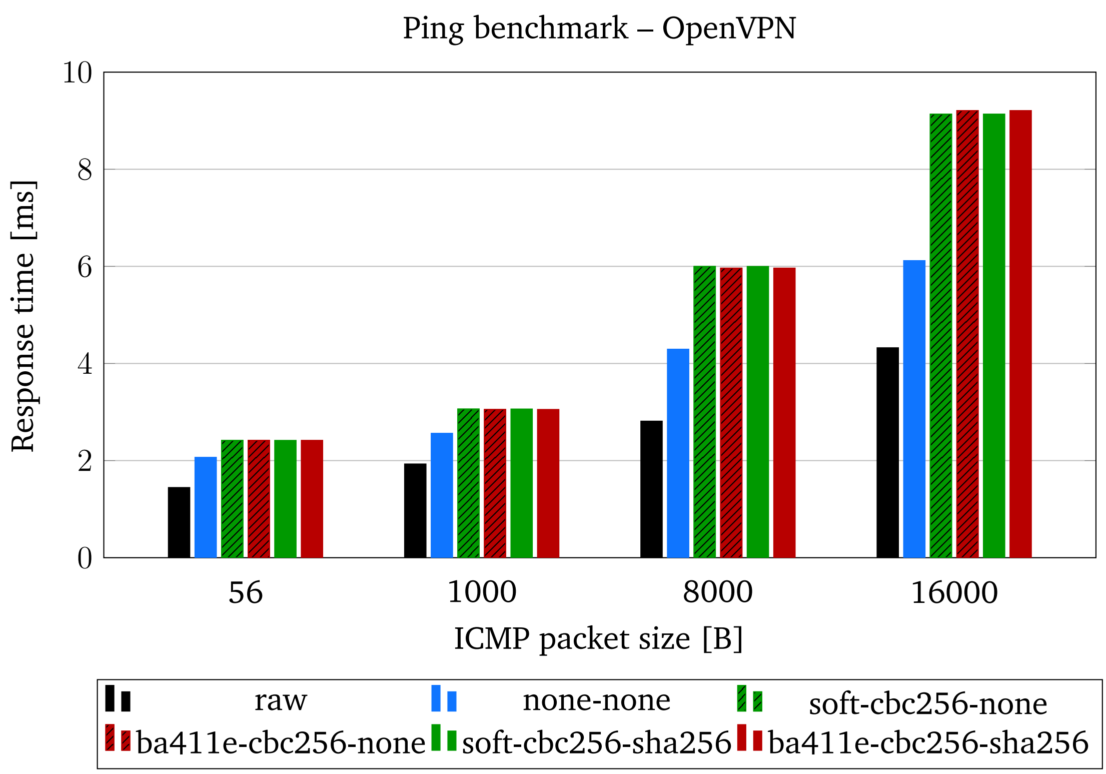


Figure 5.2 – **OpenVN: ping average response time:** OpenVPN adds up to 53% extra delay and offloading the encryption does not improve the latency.

Firstly, is the impact of OpenVPN's operation on the delay: when no encryption nor authentication is used, the exchange is 33% to 53% longer. This is simply because the packet has to go through a virtual interface, hence even without the security time overhead, the latency is much longer.

When combining encryption and authentication, the software and hardware implementation are neck and neck. Eventhough the MAC is not offload, the hardware implementation could have performed better. The reason is not only all the packets have to go through a virtual interface in the kernel, the payload also has to be sent to the hardware through the kernel. In the end, a packet will undergo two full round trips between the user and the kernel space, that is one more than a regular software implementation, plus a final transfer to the physical interface. All those transfer make the offload useless in such a case in term of raw performance. The CPU usage is not even worth mentioning as the operation is only a few milliseconds long.

5.2.2 IPsec

The figure 5.3 studies the same payload size as OpenVPN, but with an extra experimental hardware implementation of AES mode GCM.

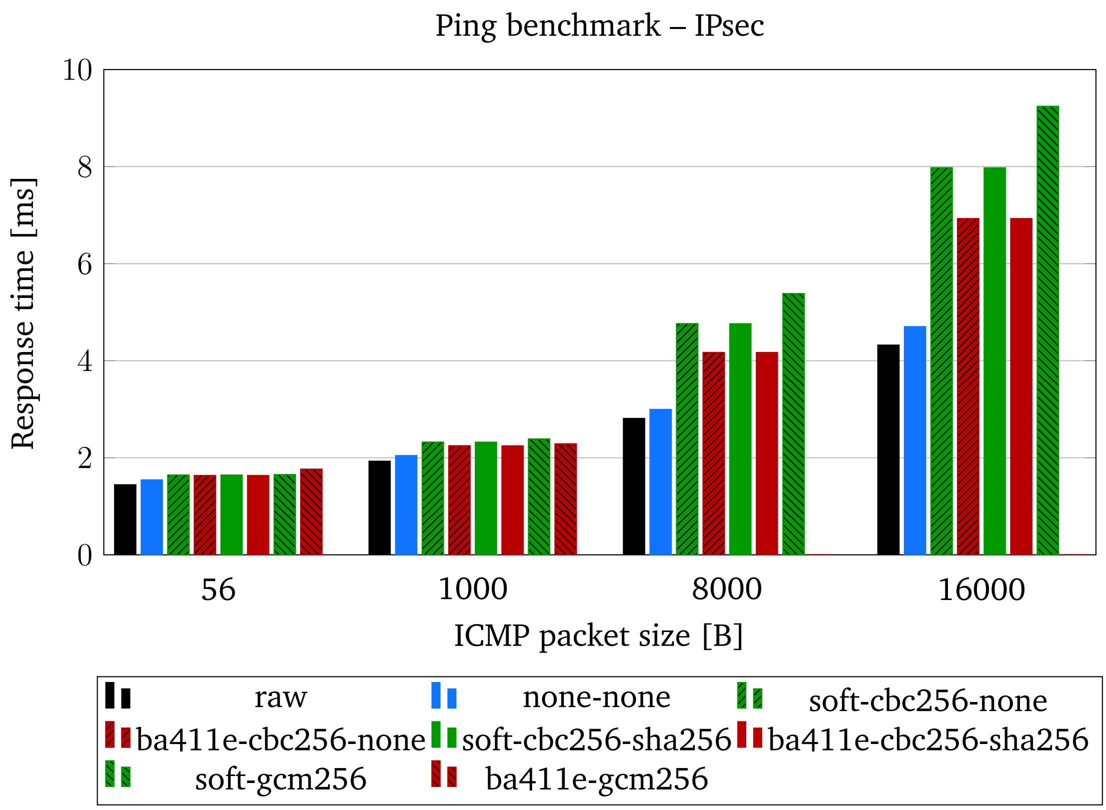


Figure 5.3 – **IPsec: ping average response time:** for different packet sizes.

In this case, the time overhead imposed by IPsec is not larger than 9%, corroborating the results of Xenakis et al. [35].

When combining encryption and authentication, the hardware implementation steadily takes the advantage over the software with the encrease of the payload length. If they both have the same latency at default payload size, the hardware is up to 13% faster for 16000 bytes payloads.

As for the GCM mode, the support in the BA411E driver is highly experimental and takes more of a proof of concept than a real use case. The current implementation could not support payload sizes larger than 1000 bytes, and at this size it is 5% faster than the software. It is not much, but when compared to the 3% improvement the BA411E offers at the same size for AES-256-CBC, we can expect an accelaration exceeding the 20% for larger payload sizes. Aside from the fact that the driver is not fully working yet, it could still be extensively improved. As an example, it still relies on the `seqiv` kernel module, as the software implementation does. Managing the generation of the IV directly in the driver would cut it loose from yet another software boulder.

5.2.3 Comparison

The figure 5.4 summarizes the results for OpenVPN and IPsec for the most realistic use case: the combination of encryption and authentication.

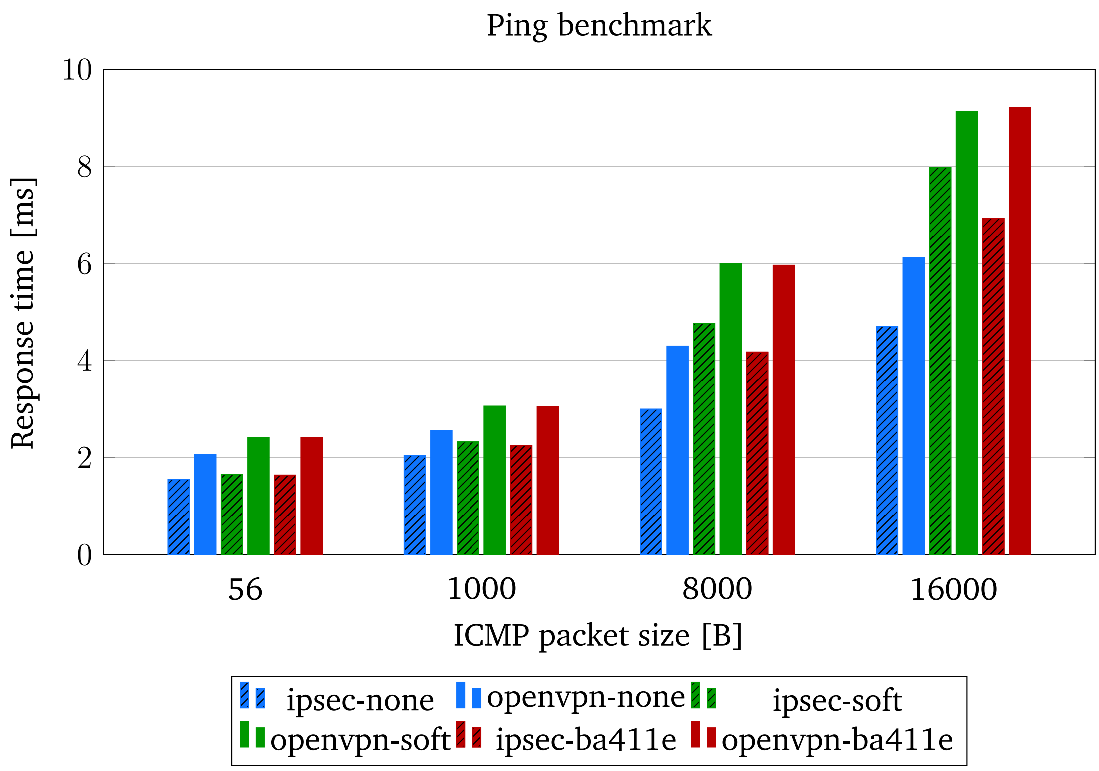


Figure 5.4 – **Ping average comparison:** All values are for AES-256-CBC with SHA-256. Globally, IPsec yields better results and propose the most significant hardware offload. Quick reading: the stripped bars are the IPsec results.

The first main difference is the overhead imposed by each method: 53% for OpenVPN and only 9% for IPsec. Even if those configurations are not realistic, it puts forward the advantage of directly working in the kernel as does IPsec.

As for the combination of encryption and authentication, IPsec is between 13% and 32% faster than OpenVPN. IPsec loses its advantage with the increase of the payload size, the time lost when moving around the data between the user and the kernel space being less important compared to the securoty operations. In hardware, as OpenVPN could not take advantage of the accelaration of the encryption, IPsec is even faster, ranging from 25% to 33% faster than OpenVPN.

5.3 File transfer

This use case studies the performance of a simple file transfer over three different secure implementations: OpenSSH, OpenVPN and IPsec. For each application, three encryption:authentication couples are considered: none:none, AES-256-CBC:none and AES-256-CBC:SHA-256.

5.3.1 OpenSSH

The figure 5.5 shows the results for a file transfer over an SSH tunnel. For this application, there is no none:none couple case inside the tunnel, as it would be the same as a transfer outside the tunnel.

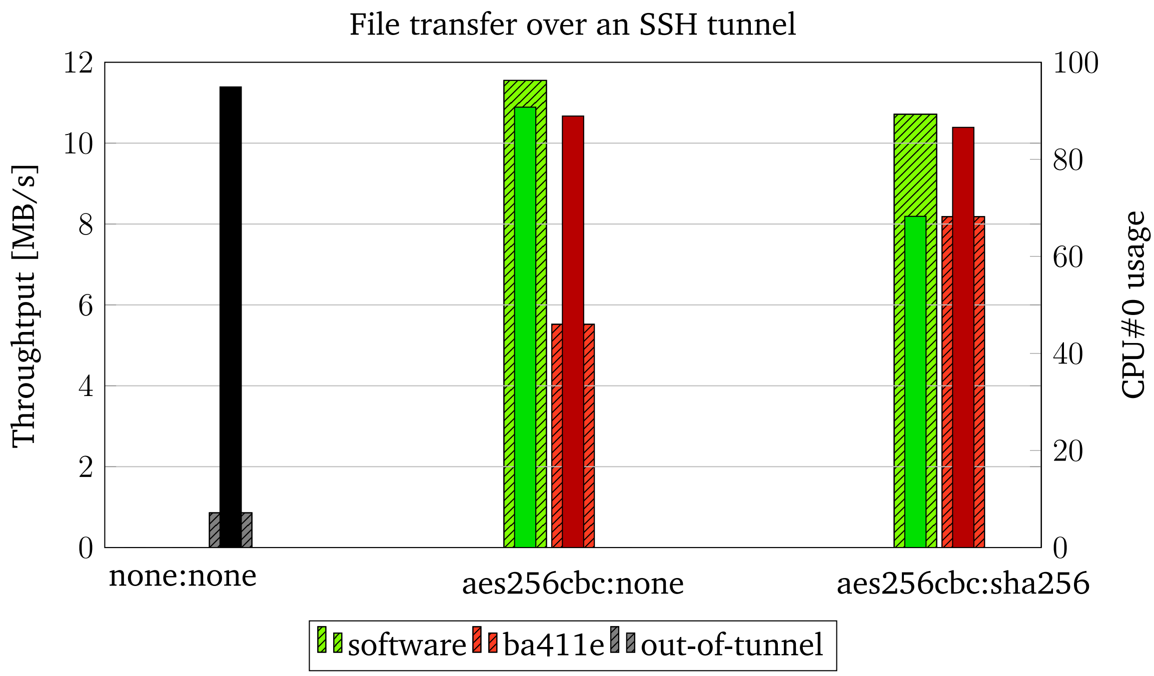


Figure 5.5 – **File transfer over an SSH tunnel.:** The background stripped bars are the CPU usage.

When only encryption is used, both implementation performs almost as well as outside the tunnel, but the software already saturates the CPU, whilst the hardware only uses half the same ressources. About 41% of the operations using the CPU when accelarating with the hardware involve interuptions and kernel memory management.

Adding the authentication makes the software performance drop by 25%, as the CPU was already saturated without those extra operations. The hardware is also consistent, but as there were some ressources available, the throughput is merely affected, even if the MAC is not offloaded in hardware.

5.3.2 OpenVPN

The figure 5.6 shows the performance of the file transfer over an OpenVPN tunnel.

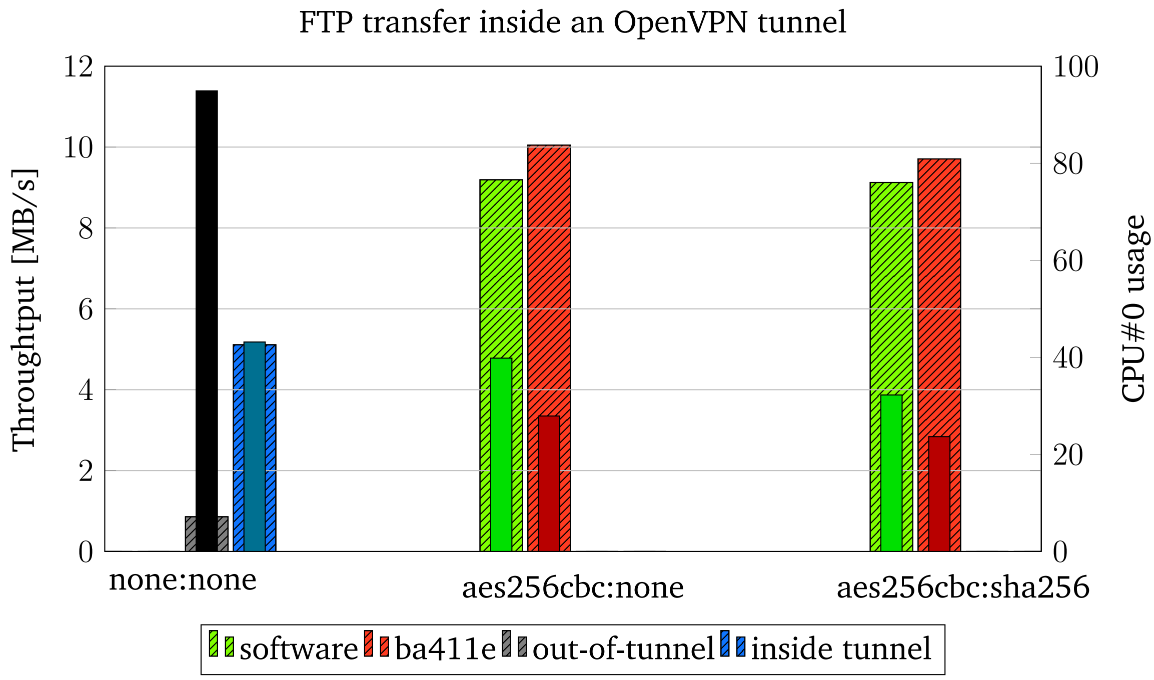


Figure 5.6 – **FTP file transfer over an OpenVPN tunnel.:** The results inside the tunnel with no encryption nor authentication highlights the overhead OpenVPN adds to the transfer. From there, the throughput only change by a small extent. The poor hardware results also shows the heaviness of OpenVPN on hardware offloading. The background stripped bars are the CPU usage.

As it was already the case for the ping benchmark, the overhead imposed by the manipulation of OpenVPN is extremely heavy: the CPU usage jumps from 7.16% to 42.60%, and the throughput drops by 55%, from 11.39MB/s to 5.18MB/s.
Surprisingly enough, encrypting the data only changes the throughput by 8%, but the CPU usage is almost doubled. A fair interpretation would be that the encryption is no the bottleneck, the transfer bewteen the user and kernel mode, as well as the fragmentation, are. However for the hardware, the performance collapse to 3.35MB/s.

Adding a MAC computation aside the encryption lowers the performance in software and hardware by respectively 20% and 15%, for the same CPU usage as without authentication.

5.3.3 IPsec

The figure 5.7 gathers the results of the file transfer over the IPsec tunnel.

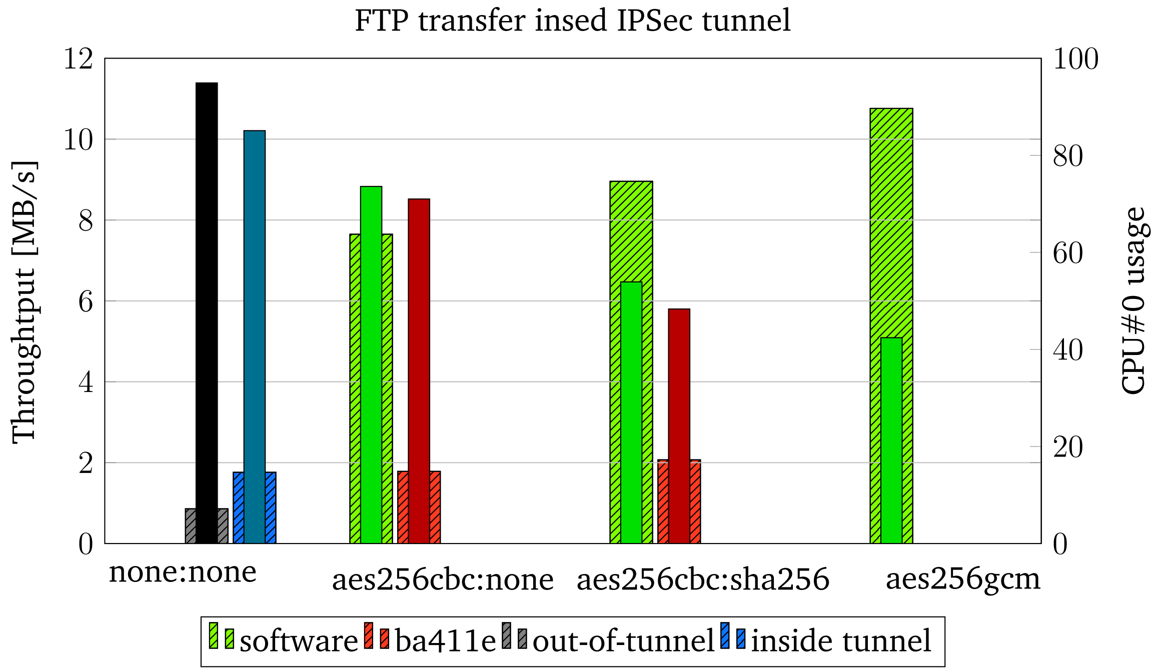


Figure 5.7 – **FTP file transfer over an IPsec tunnel.:** The advantage of the hardware is a lower CPU usage, at the cost of a few percents lower throughput. The GCM mode is also tested to discuss its implementation in hardware. The background stripped bars are the CPU usage.

In this implementation, the IPsec overhead is only of 10%, close to the 9% of the ping overhead, and the CPU usage only double to reach 14.68%.

When encrypting the data, the CPU utilization explodes in the case of the software implementation, but stays at the same level for the hardware. As for the throughput, it lowers respectively by 14% and 17%. What could have been expected for the hardware implementation is a more stable throughput, but an increase of CPU usage for the few operations undergone by the BA411E driver, especially considering the fact that it uses active polling on the hardware. Thus, even if the hardware is the bottleneck, the CPU usage should be higher.
An explanation could be that the operating system prevent the driver to monopolizing the CPU with its polling and preempt it regularly, effectively lowering the ressource usage, but also limiting the performance.

Adding the authentication yields expected results for : an increase of CPU usage and lower throughput. Both implementation lose 2MB/s and a CPU usage increase of 20% and 16%.

In both cases, the hardware implementation exhibited slightly lower performance, but a CPU usage three to four times lower. On embedded platforms, this is as important as the raw performance, because lower CPU usage means underclocked CPU, resulting in a lower power consumption.

The softaware GCM results allows to open a discussion on this mode used in conjunction with IPsec. The GCM performance presented clearly shows a drop of throughput and an increase of CPU usage, illustrating the fact that those operations are hard on the software. With an hardware offload, we could expect not only a drastic drop of the CPU usage, but an increase of throughput as well, since it's CPU-limited in those results. Note that they are achieved using a C-based implementation of galois-field multiplications. As we saw in chapter 2, modern processor designers tend to add specialized instruction sets aimed at AES-GCM enhancement. Should further tests be conducted concerning IPsec paired with GCM, it would be wise to compare with an assembly implementation exploiting ARM NEON instruction set. Some are being developed [13, 10], but none have been committed to the Linux kernel repository yet.

5.3.4 Comparison

The figure 5.8 summarizes the file transfer performance for all the implementations, using the most realistic configuration tested: AES-256-CBC with SHA-256.

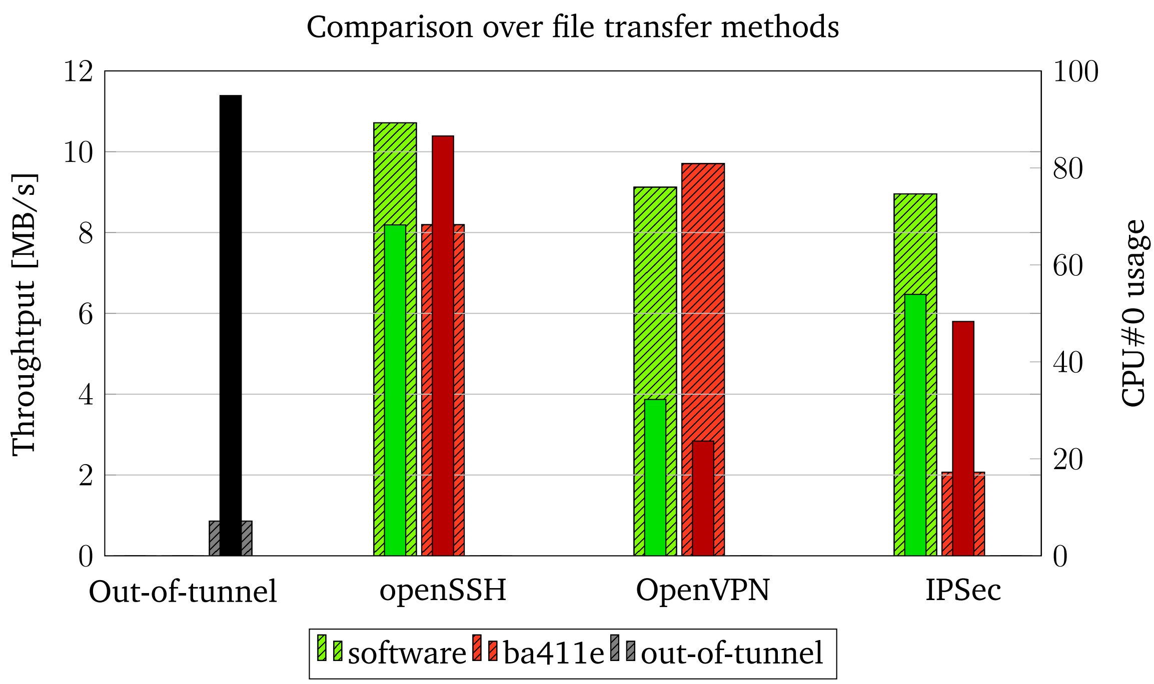


Figure 5.8 – **Comparison of file transfer methods:** Out of the three methods, OpenSSH is to be prefered is the raw performance is the objective, but IPsec offers an higher effeciency. At the same time, OpenVPN is worse on all fronts. The background stripped bars are the CPU usage.

In this work, we have two objectives: the raw performance and the CPU usage. The first objetive is fulfilled by OpenSSH; even if it is a user-space application that needs to transfer the data through the kernel in order to use the hardware, it still outperforms the software by 27%.

The second objective is best fulfilled by IPsec with an efficiency of 0.34MB/s/% of CPU for the hardware, and 0.09MB/s/% of CPU for the software.

	Length	Frequency
OpenVPN	80 – 159	33.04%
	1280 – 2559	66.90%
	other	0.06%
IPsec	80 – 159	9.42%
	1280 – 2559	89.84%
	other	0.74%

Table 5.3 – **Packet size frequency for an FTP transfer:** OpenVPN is less effective in its fragmentation, producing more packets of a smaller size, which perform worse on hardware.

OpenVPN is however losing on all fronts. Not only it has the lowest throughput, but the CPU usage of the hardware is out the roof, especially when compared to the performance.
The table 5.3 shows to what size are fragmented the packets by OpenVPN and IPsec. A look at the figure 5.9 shows that fragmenting at small size is a bad idea, especially when the hardware is reached from the user space. OpenVPN sends one third of its packets at sizes that are highly ineffective, whilst IPsec manages it better and limit the small packets to less than 10%.

Some results have to be put into perspective with the fact that the implementation of SHA-256 is entirely C-based. A more recent one using assembly instructions optimized for the NEON SIMD instruction set of the ARMv7 core could be used and would most probably yield better results. The CPU usage of the software implementation would lower – even if not significantly – as for the hardware, it would be less limited by the software MAC counter part, and if the CPU usage would stay at the same level, we could expect a better throughput.

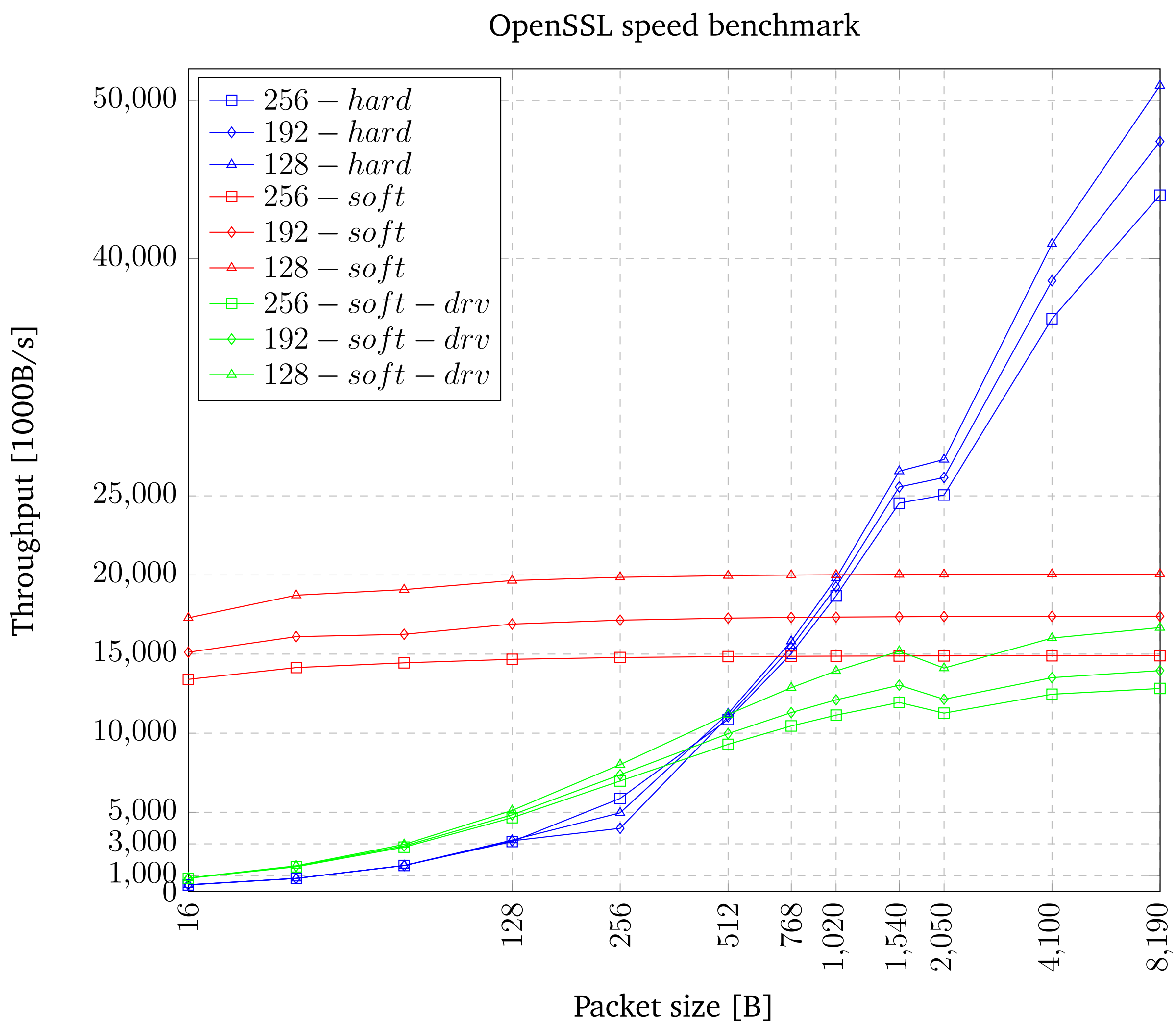


Figure 5.9 – **OpenSSL benchmark for AES-256-CBC:** compare a run of `openssl speed` for three implementation of AES: in software by OpenSSL (soft), in software by the standard Linux kernel module (soft-drv) and in hardware (hard). The last two have to go through cryptodev in order to be reached from the user space.

Chapter 6

Discussion and conclusion

6.1 Future work

Although the present work presents some promising results, the implementation can certainly be improved in several ways and some further experiments should be conducted.

Driver improvement The driver of the BA411E can be made less ressources hungry by improving the initialisation of the descriptors and their linking, but the gain would not be significant enough to justify the time investment at this point. A better alternative would be to avoid descriptors altogether by modifiying the interface with the IP so that it can use the scatterlist directly. We would then spare a lot of DMA mapping instruction and thus some precious cycles on the software side.

As we already remarked in **??**, the use cases involving IPsec were conducted using a previous revision of the driver still activelly polling the IP for its results. A better and cleaner way to proceed is to use interruption routines, as shown in **??**. However, the kernel does not support their current implementation and panics upon usage. If one were to be willing to spend the time replacing the active polling by clean asynchronous interruptions, he should be aware of the overhead imposed by an interruption. In some cases, when the operation is just a few clock cycle long for the IP, an active polling could still be the better way to go. A more thorough comparison of the mutual trade-off deserves some investigation, and as a starting point, the packet size could be treated as a branching point between the two solutions.

Registering public key verification with the crypto API As we saw in **??**, the driver is already capable of offloading a large portion of public key operations to the IP, but only with very specific libraries at the time being – openSSL in our case. The next step is to register the very same operations with the crypto API so it can be used without having to rely on a custom openSSL engine. This feature would require to work very closely to the linux kernel developpement. Indeed, if the signature verification using public key cryptography has been available in the kernel since 2013, a public key encryption API has only been proposed in late April 2015 [31] and is still under request for comments.

Conditional offloading in cryptodev The figure 5.9 clearly shows a threshold on the packet size from which the hardware has a clear advantage, and below which the user mode software implementation is to go for. Using this breakeven point, one could patch the cryptodev cryptodev engine of OpenSSL to branch on the packet size, using the hardware if the packet is large enough, or fallback on the default software implementation otherwise. It would probably not be as trivial and beneficial as it may sound:

- the encryption contexts would need to be synchronized between the hardware and the software;
- as the breakeven point is around 1024kB, the performance for a network application would be very close to those of a full software implementation, knowing that the ethernet frame size, the MTU, is set by default at 1500 bytes.

Such a conditional offloading would be interresting for applications involving mainly very large packets and a few periodic smaller ones, like large data transfer between two hosts on a infrastructure supporting ethernet jumbo frames[1] with periodic ICMP heartbeat.

Disk encryption As the hardware is better used with larger blocks of data, disk encryption could be an interesting application to look into.

Cryptographic libraries OpenSSL is not the only cryptographic library available; GnuTLS is also a very popular alternative and supports cryptodev engines too.

However, one library definitely worth to keep an eye on is mbed TLS, formally known as PolarSSL, recently bought by ARM [3]. We can expect the future releases of this library to be more optimized for ARM platforms, and maybe the software footprint and overhead to be reduced.

Cryptodev If patches adding the GCM support to cryptodev have already been released, those are not compatible with Barco Silex' driver. Adapting the interface would open the GCM hardware offload to the whole user space applications park.

MAC offloading While the symetric and asymetric encryption ciphers IPs are usable from the operating system, the IP computing MACs does not have a usable driver yet. Wherever there is encryption, authentication is also needed. As such, any real day-to-day use case can not be fully offloaded to hardware yet, even if some tricks and patches allowed us to bypass this requirement. The implementation of the GCM mode, combining encryption and authentication, showed us

[1] Jumbo frames have an ethernet MTU of 9000 bytes, whilst standard frames are set to 1500.

that stopping relying on the software implementation of MACs would be a huge step forward.

Appendix A

OpenSSH patch

```
diff -rupN openssh-6.7p1_vanilla/digest.h openssh-6.7p1/digest.h
--- openssh-6.7p1_vanilla/digest.h 2014-07-03 13:25:04.000000000 +0200
+++ openssh-6.7p1/digest.h 2015-02-27 11:59:53.508495697 +0100
@@ -28,7 +28,8 @@
 #define SSH_DIGEST_SHA256 3
 #define SSH_DIGEST_SHA384 4
 #define SSH_DIGEST_SHA512 5
-#define SSH_DIGEST_MAX  6
+#define SSH_DIGEST_NONE  6
+#define SSH_DIGEST_MAX  7

 struct sshbuf;
 struct ssh_digest_ctx;
diff -rupN openssh-6.7p1_vanilla/digest-libc.c openssh-6.7p1/digest-libc.c
--- openssh-6.7p1_vanilla/digest-libc.c 2014-07-02 07:28:03.000000000 +0200
+++ openssh-6.7p1/digest-libc.c 2015-02-27 12:01:48.420494935 +0100
@@ -113,6 +113,16 @@ const struct ssh_digest digests[SSH_DIGE
    (md_init_fn *) SHA512Init,
    (md_update_fn *) SHA512Update,
    (md_final_fn *) SHA512Final
+ },
+ {
+   SSH_DIGEST_NONE,
+   "none@barco.com",
+   0,
+   0,
+   0,
+   NULL,
+   NULL,
+   NULL
  }
 };

diff -rupN openssh-6.7p1_vanilla/digest-openssl.c openssh-6.7p1/digest-openssl.c
--- openssh-6.7p1_vanilla/digest-openssl.c 2014-07-17 01:01:26.000000000 +0200
+++ openssh-6.7p1/digest-openssl.c 2015-02-27 12:00:24.812495489 +0100
@@ -59,6 +59,7 @@ const struct ssh_digest digests[] = {
  { SSH_DIGEST_SHA256, "SHA256",  32, EVP_sha256 },
  { SSH_DIGEST_SHA384, "SHA384", 48, EVP_sha384 },
```

```
  { SSH_DIGEST_SHA512, "SHA512",  64, EVP_sha512 },
+ { SSH_DIGEST_NONE,  "none@barco.com", 0, EVP_md_null },
  { -1,    NULL,  0,  NULL },
 };

diff -rupN openssh-6.7p1_vanilla/mac.c openssh-6.7p1/mac.c
--- openssh-6.7p1_vanilla/mac.c 2014-05-15 06:35:04.000000000 +0200
+++ openssh-6.7p1/mac.c 2015-02-27 12:01:00.204495255 +0100
@@ -87,6 +87,7 @@ static const struct macalg macs[] = {
  { "hmac-ripemd160-etm@openssh.com", SSH_DIGEST, SSH_DIGEST_RIPEMD160, 0, 0,
     0, 1 },
  { "umac-64-etm@openssh.com",  SSH_UMAC, 0, 0, 128, 64, 1 },
  { "umac-128-etm@openssh.com",  SSH_UMAC128, 0, 0, 128, 128, 1 },
+ { "none@barco.com",      SSH_DIGEST, SSH_DIGEST_NONE, 0, 0, 0, 0 },

  { NULL,       0, 0, 0, 0, 0, 0 }
 };
```

Appendix B

Configuration files

B.1 OpenVPN

```
# client.ovpn -- OpenVPN configuration file
lport 11101

dev tap01

ifconfig 10.4.0.101 255.255.255.0

tls-client

ca awesome-ca_4096.crt
cert client_1_4096-cert.crt
key client_1_4096-cert.key

reneg-sec 1

verb 2

#tls-cipher TLS-ECDHE-ECDSA-WITH-AES-256-CBC-SHA
tls-cipher TLS-DHE-RSA-WITH-AES-256-CBC-SHA

# sha256 or none
auth sha256

# AES-256-CBC or none
cipher AES-256-CBC
```

Listing B.1 – OpenVPN client configuration file.

```
# server.ovpn -- OpenVPN configuration file
dev tap1

ifconfig 10.4.0.1 255.255.255.0

tls-server

# dh4096.pem, dh2048.pem or dh1024.pem
dh dh4096.pem
```

```

# Make sure the CA and server certificates/private keys are of the right size:
    1024, 2048 or 4096 bits.
ca awesome-ca.crt
cert server_4096-cert.crt
key server_4096-cert.key

# Server does not renegociate the connection.
reneg-sec 0

verb 2

mode server
```

Listing B.2 – OpenVPN server configuration file.

B.2 Strongswan

```
# ipsec.conf - strongSwan IPsec configuration file

config setup

conn %default
    ikelifetime=60m
    keylife=20m
    rekeymargin=3m
    keyingtries=1
    keyexchange=ikev2

conn host-host
    esp=aes256-sha256!
#    esp=aes256-null!
#    esp=aes256gcm16!
#    esp=null!
    ike=aes256-sha256-modp4096
    left=150.158.232.242
    leftcert=client_1_4096-cert.crt
    leftid="C=AU, ST=Some-State, O=BARCO, CN=client_1_4096" # Should match the '
        subject' field of the certificate. To display it, you can do 'openssl
        x509 -text -in path/to/certificate -noout'.
    leftfirewall=yes
    right=150.158.232.241
    rightid="C=AU, ST=Some-State, O=BARCO, CN=server_4096"
    auto=add
```

Listing B.3 – Strongswan configuration file. Left is the local host, right the remote.

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