

# AES 128/192/256 (ECB) AVALON<sup>®</sup>-MM SLAVE

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## 1 Introduction

The Advanced Encryption Standard (AES) is a symmetric block cipher operating on fixed block sizes of 128 Bit and is specified for key sizes of 128, 192 and 256 Bit designed by Joan Daemen and Vincent Rijmen. The algorithm was standardized by National Institute of Standards and Technology (NIST). For more information on the algorithm see [1].

This component implements an AES encryption decryption data path in Electronic Codebook (ECB) mode with either 128, 192 or 256 Bit keys. The key length is determined by generics at compile time. Also the decryption data path can be disabled by generics if it is not needed for the application.

The component provides an Avalon<sup>®</sup> Memory Mapped (Avalon-MM) slave interface to connect to an Altera<sup>®</sup> Avalon<sup>®</sup> switch fabric. The Avalon<sup>®</sup> interface is implemented in a way that it can also be used to connect to a Wishbone master if the signals are correctly mapped, see [2]. For further information about the Wishbone bus refer to [3].

## 2 Interface

The AES core is accessed by the interface described in this section. An Avalon<sup>®</sup> interface was chosen for its simplicity and compatibility with wishbone. Furthermore Avalon<sup>®</sup> defines interrupt request signals for slaves which would be separate signals in a Wishbone implementation. The component can be used both in polling mode or can provide an interrupt for signalling.

Unfortunately Avalon<sup>®</sup> is an Altera<sup>®</sup> proprietary technology. The actual AES core however is a self contained entity and can be embedded into other System on Chip (SoC) bus interfaces as well or used independently.

### 2.1 Configuration Generics

The AES core can be configured by generics shown in table 1, consequently they are provided by the Avalon<sup>®</sup> interface.

Generic name	type	Description
KEYLENGTH	NATURAL	Size of initial user key. Must be 128, 192 or 256 <sup>1</sup> .
DECRYPTION	BOOLEAN	Enables the instantiation of the decrypt data path if true.

Table 1: Component generics

Note: KEYLENGTH of 192 fail synthesis with Xilinx ISE<sup>®</sup> because of division by 6 in key schedule that cannot be mapped to shift operations (`keyexpansion.vhd`).

<sup>1</sup>All other values raise a compilation failure

## 2.2 Signals

The Avalon<sup>®</sup>MM Slave interface is described in [4], the component implements the signals shown in table 2.2. All signals are synchronous, sampled at the rising edge of the clock. The type for all signals is IEEE1164 `std_logic` or `std_logic_vector`. For signals wider than 1 Bit the range is Most Significant Bit (MSB)  `downto`  Least Significant Bit (LSB)

This component has only output signals driven by registers no input signals are directly combinatorially connected to the output signals, thus combinational loops are avoided. All signals are active high. This component does not support burst transfers.

Signal name	Width	In/Out	Description
clk	1	in	Avalon <sup>®</sup> bus clock, also used to drive the core.
reset	1	in	<i>Synchronous</i> reset signal for Avalon <sup>®</sup> bus interface. The core itself is designed without need for reset signals.
writedata	32	in	Input data to write to location designated by address. Bit 31 is most significant Bit.
address	5	in	Word offset to the components base address. The memory map of the component for the respective offset is described in 3. Only full 32-Bit words can be addressed no byte addressing is implemented.
write <sup>1</sup>	1	in	If asserted enable write of data at writedata to location designated by address.
read <sup>1</sup>	1	in	If asserted output data at location designated by address to readdata.
readdata	32	out	Data output port for reading data at the location defined by address. Bit 31 is most significant Bit.
waitrequest	1	out	Asserted if writedata was not accepted, this is the case if the keyexpansion is not yet complete and a new is written to the KEY address range without previous de-assertion of the KEY_VALID Bit
irq	1	out	If Interrupt behavior is enabled IRQ will be asserted when the operation has terminated. For use of interrupt see 4.1

Table 2: Avalon<sup>®</sup> Bus interface signals

## 3 Memory Map

The AES core Avalon<sup>®</sup> slave has an address space of 31 words accessible through the offset described by the signal `address`, see 2.2. This address space is divided into three main sections for the 4-word input data, the 4-word result of the operation and the user key. The actual length of the user key can vary between 4, 6 and 8 words depending on the keysize. For control signals and status information of the component and a control word is provided. The memory mapping

<sup>1</sup>`read` and `write` are mutually exclusive and must not be asserted simultaneously.

is described in table 3.

Offset	Name	Description
0x00-0x07	KEY	Initial user key that will be used for encryption and decryption. The most significant word is written to offset 0x00. This memory section is <i>write-only</i> to the Avalon <sup>®</sup> interface.
0x08-0x0B	DATA	Input data, can be either interpreted as cyphertext for decryption or plain text for encryption. The most significant word shall be written to offset 0x08. This memory section is <i>write-only</i> to the Avalon <sup>®</sup> interface.
0x10-0x13	RESULT	Result of the operation. The most significant word of the result at offset 0x10. This memory section is <i>read-only</i> to the Avalon <sup>®</sup> Interface.
0x14-0x1E	—	reserved
0x1F	CTRL	Control and status word of the component can be read and written. Detailed description see 3.1

Table 3: Memory map of the AES core Avalon<sup>®</sup> slave

### 3.1 Control Register

The AES Core offers the register CTRL to control the function of the core and poll its status. The control register can be accessed in read and write mode. When writing to the register reserved Bits shall be assigned a value of 0. Individual Bits have following functionality described in table 3.1.

In case of a Avalon<sup>®</sup> Bus reset this register is set to 0x00000000 thus invalidating all previously written keys and resetting the AES core.

Offset	Name	Description
31-8	—	reserved
7	KEY_VALID	If asserted key data in the KEY memory range is regarded valid and will be expanded to round keys. When deasserted all keys are invalidated and the current operation of the core is aborted. It must be asserted as long as the key shall be used for either encryption or decryption. This bit must be cleared for one clock cycle to load a new key.
6	IRQ_ENA	Enable use of the interrupt request signal. If asserted the component will set IRQ after completing an operation. If not set the component operates in polling mode only.
5-2	—	reserved
1	DEC <sup>1</sup>	If asserted memory content of the DATA range is regarded to be valid and will be <i>decrypted</i> . This Bit shall only be deasserted externally if a running AES operation is aborted by deasserting KEY_VALID. It will be set 0 by the core to signal completion of the operation.
0	ENC <sup>1</sup>	If asserted memory content of the DATA range is regarded to be valid and will be <i>encrypted</i> . This Bit shall only be deasserted externally if a running AES operation is aborted by deasserting KEY_VALID. It will be set 0 by the core to signal completion of the operation.

Table 4: Bits in the control register

## 4 Protocol Sequence

The AES component appears as memory mapped peripheral. All writes are fundamental slave write transfers, see [4] and take one clock cycle of the Avalon<sup>®</sup> bus clock `clk`. It is not necessary to write all words of a input parameter successively or in one transfer. Bursts are not supported.

Before any AES operation can be started the initial user key has to be written to KEY segment of the memory map. After the user key is transferred to the component the KEY\_VALID Bit must be set to start the key expansion. This Bit can be set simultaneously with DEC or ENC Bit of the control register. To invalidate the previous key and use another key the KEY\_VALID must be deasserted for at least one Avalon<sup>®</sup> bus clock cycle. During this cycle the new key can already be transferred.

Once a key is passed and marked valid data blocks can be transferred to the DATA segment of the memory map. The AES operation is started by asserting the ENC Bit for encryption or DEC Bit for decryption. While asserting ENC or DEC the KEY\_VALID Bit must be kept asserted.

The ENC or DEC Bit respectively is deasserted by the component after completing the requested operation. The result of the operation can be read from the RESULT area of the memory and is not cleared. It will be overwritten by succeeding operations.

The underlying AES core uses the Finite State Machine (FSM) shown in 1 for processing of the data. The signals `data_stable` and `key_stable` are accessible over the control status word CTRL 3.1. `key_ready` is a signal driven by the key generator when all keys are expanded. The signal

<sup>1</sup>ENC and DEC are mutually exclusive and must not be asserted simultaneously.

`round_index` is the counter for the rounds and the address to select a round key.

`NO_ROUNDS` is the total number of rounds the processing takes, a constant defined by the generic `KEYLENGTH` 2.1. The AES standard in[1] defines 10 rounds for 128 Bit key, 12 rounds for a 192 Bit key and 14 rounds for a 265 Bit key.

Thus depending on the key length the processing of a data block needs at maximum 15 clock cycles from `data_stable=1` to completion, if the key is already expanded.

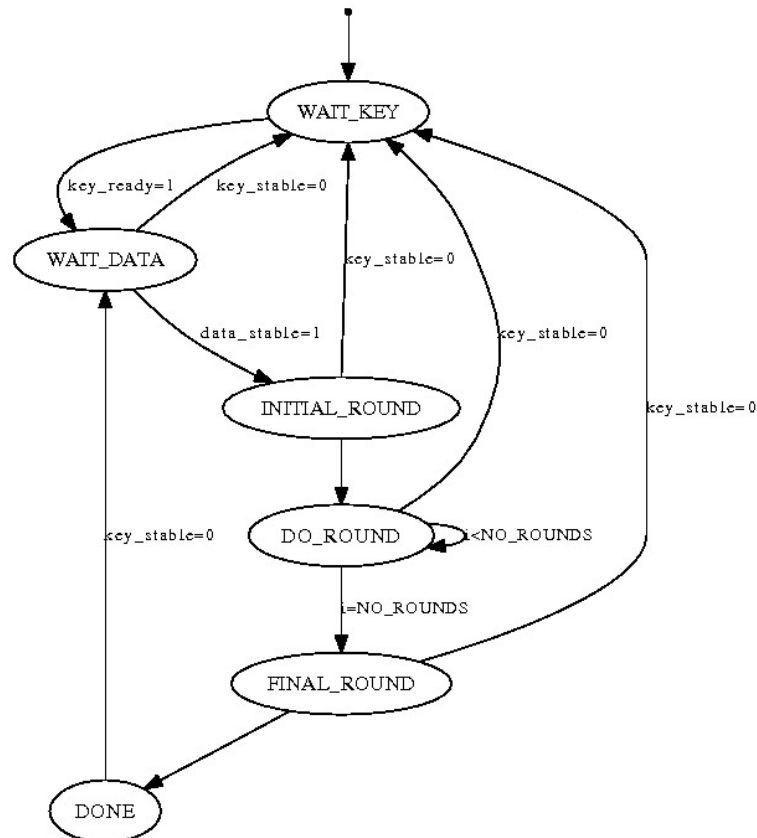


Figure 1: Finite State Machine of encryption and decryption process

## 4.1 Interrupt Behavior

By setting `IRQ_ENA` in the control register 3.1 the component is configured to issue interrupt requests. If `IRQ_ENA` is asserted the interrupt request `IRQ 2.2` will be set when the computation has completed in addition to clearing the `ENC` or `DEC` Bit. The `IRQ 2.2` signal will remain set until clearing `IRQ_ENA` or a read operation on the `RESULT` area of the components address range.

## 5 The Inner Core

The algorithmic core is divided into two separate data paths one for encryption and a second for decryption operation. The two data paths are independent, however they share the keyexpansion component which provides decrypt and encrypt keys (which are the same only in opposite

order). Each data path is controlled by its own FSM if configured by the generic DECRYPTION 2.1 the decryption data path is included and some multiplexers are generated for the shared signals, e.g. `result` or `roundkey_index`.

For reference the encryption data path of `aes_core.vhd` is given in figure 2. The decryption data path is left for the reader or any other author of this document.



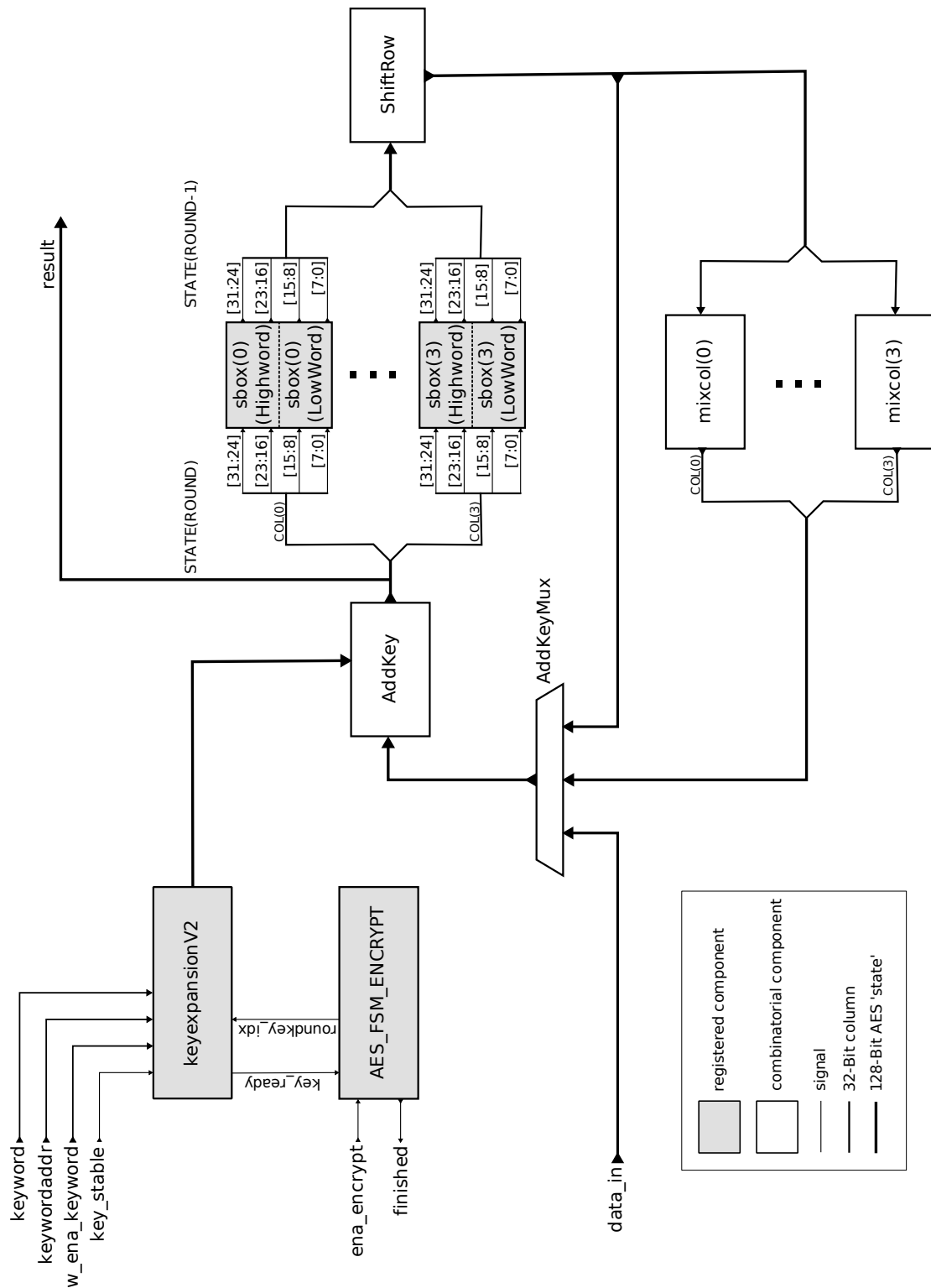


Figure 2: Encrypt data path of the AES core as implemented in aes\_core.vhd

## 6 Throughput Calculation

The Avalon<sup>®</sup> interface communicates a 32-Bit DWORD per clock cycle. Therefore a key is transmitted in 4 to 8 cycles plus one cycle to activate keyexpansion with the control word 3.1. A payload data block or the result consist always of 4 DWORDs, thus it takes 4 cycles to send data to the core, one cycle to activate the computation with the control register 3.1 and 4 cycles to retrieve the data.

The keyexpansion component computes one column of a roundkey each clock cycle. AES takes, depending on the key length, 10, 12 or 14 roundkeys with each 4 columns, see [1]. The keyexpansion therefore takes 40, 48 or 56 cycles until the encryption or decryption can start. The roundkeys are stored until invalidated, see 4 thus this step is only needed once after power-up until the key changes.

The AES core computes one iteration (round) of the Rijndael-Algorithm each clock cycle, thus a 128 Bit data block is encrypted or decrypted in 10, 12 or 14 cycles plus an initial round.

The maximum throughput  $T_{max}[Bits]$  depends on the maximum operation frequency  $f_{max}$  and the key length which influences the number of rounds  $N_{rnd} \in \{10, 12, 14\}$ .

$$T_{max} = \frac{(1 + N_{rnd}) \cdot 128Bit}{f_{max}} \quad (1)$$

Note: Equation 1 assumes that the roundkeys are already generated and does not include the constant of 4+1+4 Avalon<sup>®</sup> bus cycles for transmission of data, activation and result retrieval.

## 7 FPGA implementations

The component has only be implemented and tested on an Altera<sup>®</sup> Cyclone-II EP2C35 FPGA. For this setup a Makefile is provided in `./sys/Altera_Quartus9.1`. All other values in the table are only results of synthesis<sup>0</sup> and are not verified on actual hardware.

The design is kept vendor independent in generic VHDL. AES SubByte component is specially designed using M4K block RAM as dual-port ROM. For non-Altera<sup>®</sup> FPGAs a second VHDL architecture exists also trying to make use of ROM functions of the target chips however the success varies on RTL compiler capabilities. Later versions of Altera<sup>®</sup> Quartus-II<sup>®</sup> show the same results whether M4K blocks are used or the generic version in selected.

Configuration	Target FPGA <sup>1</sup>	LE / Slices	HW RAM	f <sub>max</sub> [Mhz]
256 Bit Key, encrypt + decrypt	Xilinx <sup>®</sup> Spartan3A XC3S1400A-5FG484	- / 1609	18 RAMB16BWE	91
	Xilinx <sup>®</sup> Virtex5 XC5VLX30-3FF324	- / 297	18 18k-Blocks 4 36k-Blocks	224
	Altera <sup>®</sup> Cyclone-II EP2C35F484C8	1937 / -	39912 Bits in 22 M4K-Blocks	65
	Altera <sup>®</sup> StratixII EP2S30F484C5	585 / -	39912 Bits in 22 M4K-Blocks	103
128 Bit Key, encrypt + decrypt	Xilinx <sup>®</sup> Spartan3A XC3S1400A-5FG484	- / 1523	18 RAMB16BWE	91
	Altera <sup>®</sup> Cyclone-II EP2C35F484C8	1776 / -	39912 Bits in 22 M4K-Blocks	65
256 Bit Key, encrypt	Xilinx <sup>®</sup> Spartan3A XC3S1400A-5FG484	- / 680	14 RAMB16BWE	159
	Xilinx <sup>®</sup> Virtex5 XC5VLX30-3FF324	- / 297	10 18k-Blocks 4 36k-Blocks	268
	Altera <sup>®</sup> Cyclone-II EP2C35F484C8	969 / -	22528 Bits in 14 M4K	97
	Altera <sup>®</sup> StratixII EP2S30F484C5	524 / -	22528 Bits in 14 M4K	145
128 Bit Key, encrypt	Xilinx <sup>®</sup> Spartan3A XC3S1400A-5FG484	- / 594	14 RAMB16BWE	159
	Altera <sup>®</sup> Cyclone-II EP2C35F484C8	797 / -	22528 Bits in 14 M4K	95

Table 5: ressource usage on different targets and configuration

All configurations in table 7 use hardware key expansion. Downloading of software generated roundkeys is not yet supported. The decryption and encryption data paths share a common keyexpansion block, multiplexing the address signals is one of the main reasons for regression of the maximum frequency  $f_{max}$  of the configuration compared to encryption only versions.

<sup>0</sup>Synthesized with Altera<sup>®</sup> Quartus-II<sup>®</sup> Web edition Version 9.1 or Xilinx<sup>®</sup> ISE 9.1 Webpack

<sup>1</sup>This table is not meant to be a benchmark between FPGAs of different vendors, it is only a rough estimation for the user of the core. The FPGA families cannot be compared easily, see also [5] and [6]for further details.

## 8 Simulation

### 8.1 Testbench

In `./bench/VHDL/` a “self-checking testbench” is provided which runs tests for a default `TESTKEYSIZE` is 256 Bit . For different key lengths the constant `TESTKEYSIZE` has to be changed appropriately. Expected results for all test cases and key lengths are included. The expected results were generated by AES Calculator applet, written by Lawrie Brown from ADFA, Canberra Australia [7]. The testbench consists of a sequence of 5 test cases:

1. load key1, load data1, encrypt : (basic encryption test)
2. key1, data1, decrypt: (basic decryption test)
3. key1, data1, encrypt: (test if internal state was changed)
4. key1, data2, encrypt: (encryption test with new data)
5. key2, data2, encrypt: (encryption test with new key)

### 8.2 Simulation

The component library is “`avs_aes_lib`”. All files are expected to be compiled into this library as all files depend at least on the package `avs_aes_lib.avs_aes_pkg`.

A Makefile for Mentor Graphics<sup>®</sup> Modelsim<sup>®</sup> is given in `./sim/`. The default make target `simaes` will create the library “`avs_aes_lib`” and a “work” library, compile all files and run a testbench.

## 9 Software Driver

This AES Core Avalon<sup>®</sup> slave was also tested on a NiosII<sup>®</sup> processor. To use it in software a simple driver is provided in `./sw/` among with an example program of the basic usage. The driver consist of the two files `avs_aes.c` and `avs_aes.h`. Find more detailed description in the doxygen documentation in `./doc/sw/html`.

### 9.1 Configuration

To be adapted to different address mappings and key sizes two macros are use in `avs_aes.h`:

<b>define</b>	<b>default</b>	<b>Description</b>
<code>KEYWORDS</code>	8	Key size in 32 Bit words
<code>AES_BASEADDR</code>	0x40000	Base address at which the AES Core is mapped to the Avalon <sup>®</sup> switch-fabric

Table 6: user changeable macros in header

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## List of Acronyms

**Advanced Encryption Standard (AES)**

NIST approved symmetric block cypher

**Electronic Codebook (ECB)**

application of a cypher algorithm without further processing of the blocks

**Finite State Machine (FSM)**

Behavioural Model with finite number of states and transitions

**Least Significant Bit (LSB)**

least value bit in a vector

**Most Significant Bit (MSB)**

highest value bit in a vector

**National Institute of Standards and Technology (NIST)**

US standardisation office

**System on Chip (SoC)**

System of separate functional interacting together implemented on a single chip

## Glossary

**Bit**

Binary Digit, atomic information unit

**Byte**

String of Bits - nowadays mostly a string of 8 Bits, also called oktett

**Master**

Entity initiating and controlling communication.

**memory mapped**

Method of addressing peripheral components like Avalon Slaves via the same address bus as main memory

**Slave**

Entity responding to communication requests by a Master.

**switch fabric**

Interconnect between IP-Cores providing arbitration and glue logic. Altera<sup>®</sup> Avalon<sup>®</sup> term

## References

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## Change History

Rev.	Chapter	Description	Date	Reviewer
0.1	all	initial document	2009/02/01	T. Ruschival
0.2	all	added interrupt	2009/03/25	T. Ruschival
0.3	all	added generics	2009/04/20	T. Ruschival
0.4	all	cleanup for opencores.org	2009/05/20	T. Ruschival
0.5	all	final release	2010/03/07	T. Ruschival
0.6	3,6	fixed memory map, added test-bench description	2010/04/02	T. Ruschival
0.7	3,6	fixed typos	2010/04/03	T. Ruschival