EtherCAT® Master Stack

Technical Presentation

Features according to ETG.1500 Master Classes

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Master Core Features (1)

Feature name	Master Class A	Master Class B
Basic Features		
Service Commands, IRQ field in datagram, Slaves with Device Emulation, EtherCAT State Machine, Error Handling, EtherCAT Frame Types	✓	✓
Sophisticated error detection and diagnosis: Lost cable connection, missing/wrong, slave response, slave operation monitoring, Ethernet link layer debug messages, > 200 error codes	✓	✓
VLAN	✓	--
Process Data Exchange		
Cyclic PDO (High performance up to 50 us cycle time), Multiple Tasks	✓	✓
Network Configuration		
Online scanning, Reading ENI, Compare Network configuration, Explicit Device identification, Station Alias Addressing, Read and Write to EEPROM	✓	✓

Master Core Features (2)

Feature name	Master Class A	Master Class B
Mailbox Support		
State change check: Logical and physical polling	✓	✓
Resilient Layer (repeating mailbox communication)	✓	✓
Multiple mailbox channels (multiple protocols in parallel)	✓	✓
CoE Mailbox Protocol		
SDO Up- and Download, Normal, Expedited and Segmented Transfer, SDO Info service (Read Object Dictionary), Complete Access, Emergency Message	✓	✓
EoE Mailbox Protocol		
Services for tunneling Ethernet frames. includes all specified EoE services Virtual Switch	✓	✓
EoE Endpoint interface to Operating Systems	FP	--
FoE Mailbox Protocol		
FoE Services	✓	--
Firmware Up- and Download	✓	--
Boot State	✓	--

Master Core Features (3)

Feature name	Master Class A	Master Class B
SoE Mailbox Protocol		
SoE Services	✓	✓
AoE Mailbox Protocol		
AoE Services	✓	--
VoE Mailbox Protocol		
VoE Services	✓	--
Synchronization with Distributed Clock (DC)		
Initial propagation delay measurement, Offset compensation, Set start time, Continuous drift compensation, Sync window monitoring	✓	--
Master must synchronize itself on the reference clock. DC master synchronization (DCM).	✓	--
Slave-to-Slave Communication		
via Master, required for safety devices	✓	✓

EtherCAT Network Timing

Interaction between application and EtherCAT network traffic

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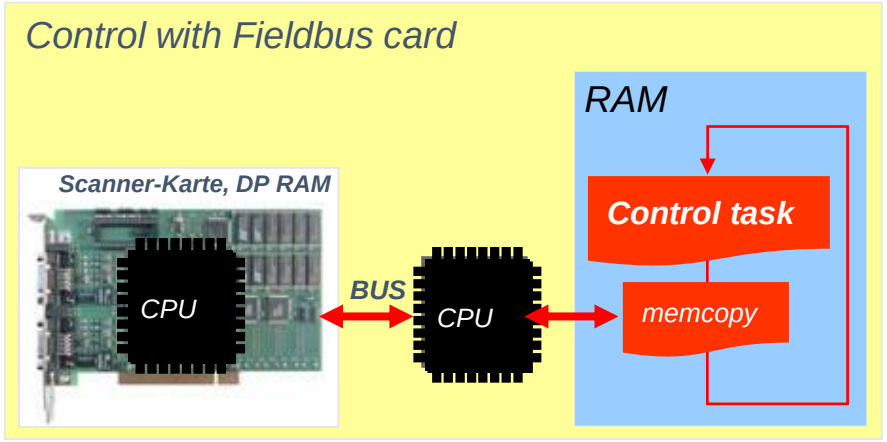
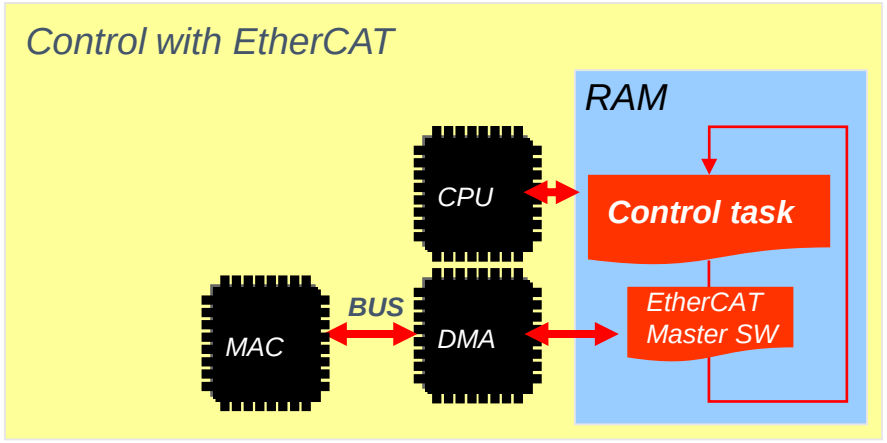
EtherCAT Master and application on a single CPU



Classic solution with cpu-powered fieldbus card:

→ Fieldbus software and application tasks running on different CPUs

→ Real-Time is guaranteed by fieldbus card



EtherCAT Master as software solution:

→ No extra CPU required. EC-Master consumes low CPU time.
→ Master is integrated in control loop
→ Real-Time OS or Real-Time Extension required for application and EtherCAT Master

EC-Master without internal tasks

EtherCAT Master has no internal tasks:

From the application side it looks like a driver, which is activated by calling some simple functions (Read, Write, Admin).

- Benefits:
- No synchronization issues between application and EtherCAT Master.
- Consistent process data without using any locks.
- The application decides, what shall be done at which time
- Cyclic part may run within Interrupt Service Routine (ISR)
- Easy to integrate

Cyclic jobs

I

EtherCAT Master: Refresh Inputs

eUsrJob_ProcessAllRxFrames: Process all received frames

O

EtherCAT Master: Write Outputs

eUsrJob_SendAllCycFrames: Send cyclic frames

MT

EtherCAT Master: Administration

eUsrJob_MasterTimer: Trigger master and slave state machines

AS

EtherCAT Master: Send acyclic datagrams/commands

eUsrJob_SendAcycFrames: Transmit pending acyclic frame(s).

App

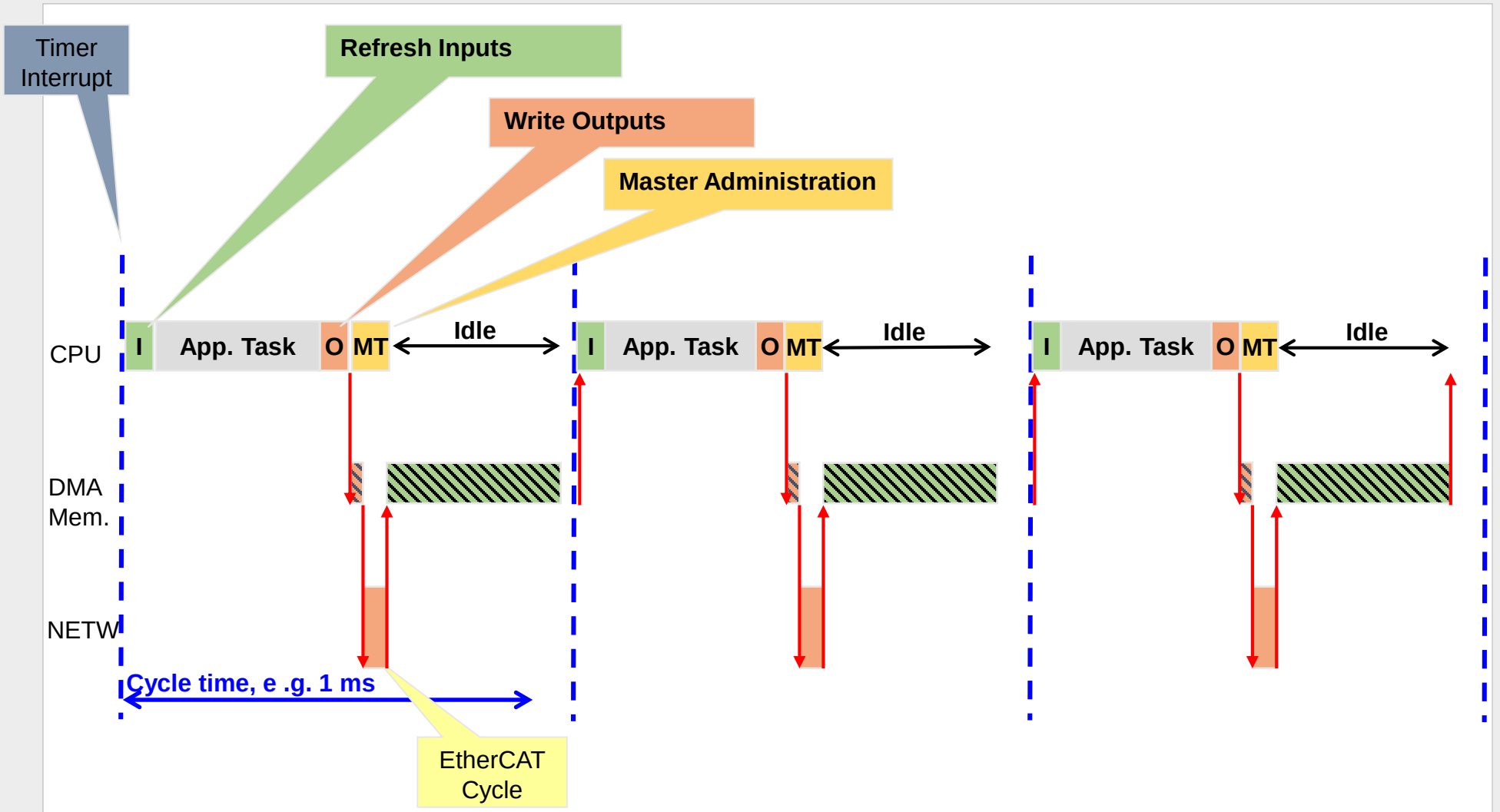
Application: Work on inputs and create output values

Cyclic and acyclic EtherCAT frames

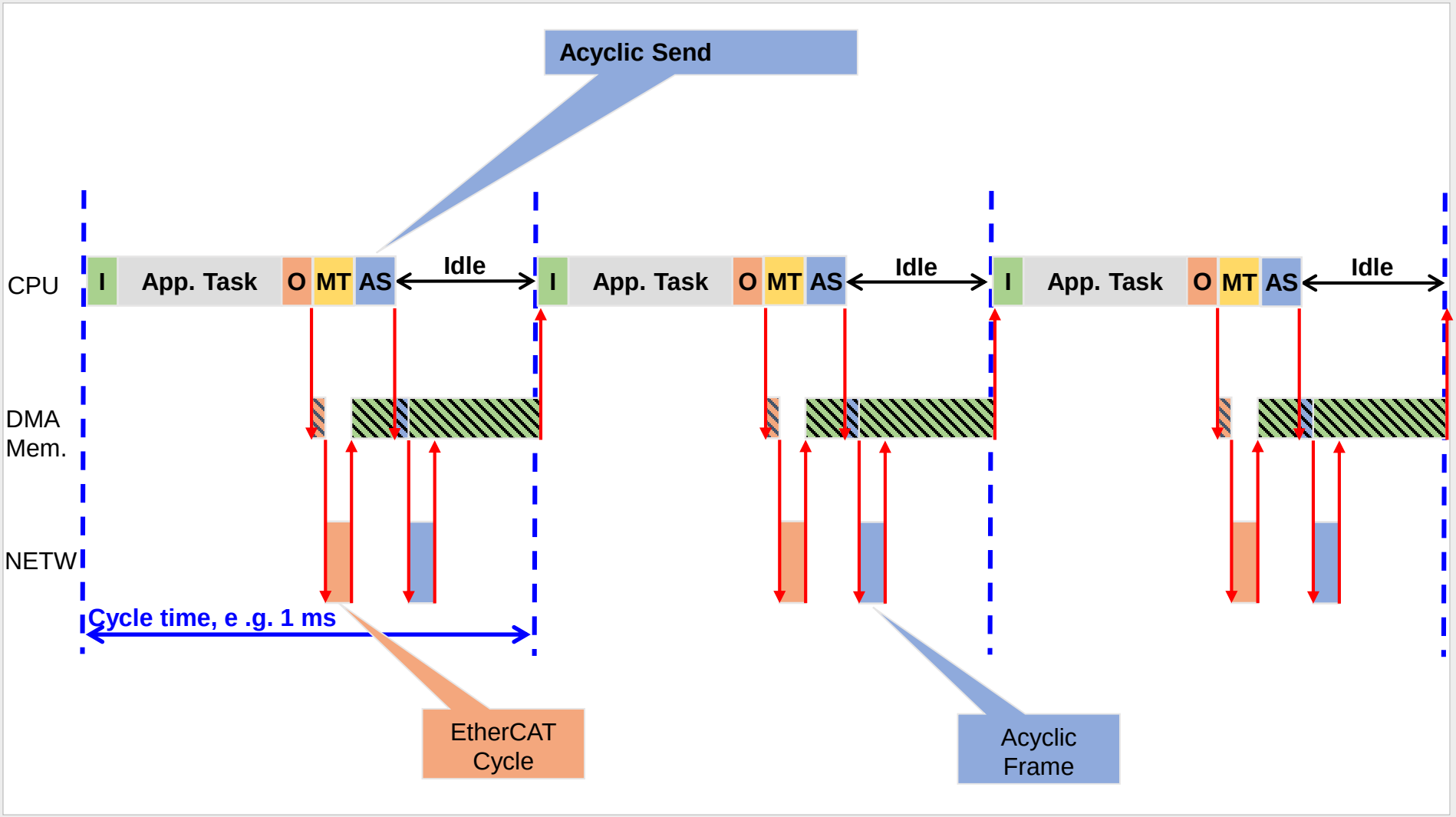
- Cyclic frames:
  - Contain process output and input data
  - Distributed Clocks (DC): Contain datagram to distribute network time
  - Typically sent by master in every cycle
  - Defined by the configuration tool (which data to read and to write)

- Acyclic frames:
  - Asynchronous, event triggered communication
  - Mailbox communication (CoE, FoE, EoE)
  - Status requests (e. g. read slave state information)
  - Raw EtherCAT datagrams requested by application

Network Timing: Cyclic frames
No interrupt from network controller



Network Timing: Cyclic and acyclic frames
No interrupt from network controller



Feature Pack: Split Frame Processing

EC Master

- Split I/O data processing into several application tasks
- Split processing of acyclic communication into a separate task

P

Master: Refresh Inputs

eUsrJob_ProcessRxFramesByTaskId: Process received data related to a specific task ID

S

Master: Write Outputs

eUsrJob_SendCycFramesByTaskId: Send cyclic frames related to a specific task ID

MT

Master: Administration

eUsrJob_MasterTimer: Trigger master and slave state machines

AS

Master: Send acyclic datagrams/commands

eUsrJob_SendAcycFrames: Transmit pending acyclic frame(s).

App

Application: Work on inputs and create output values

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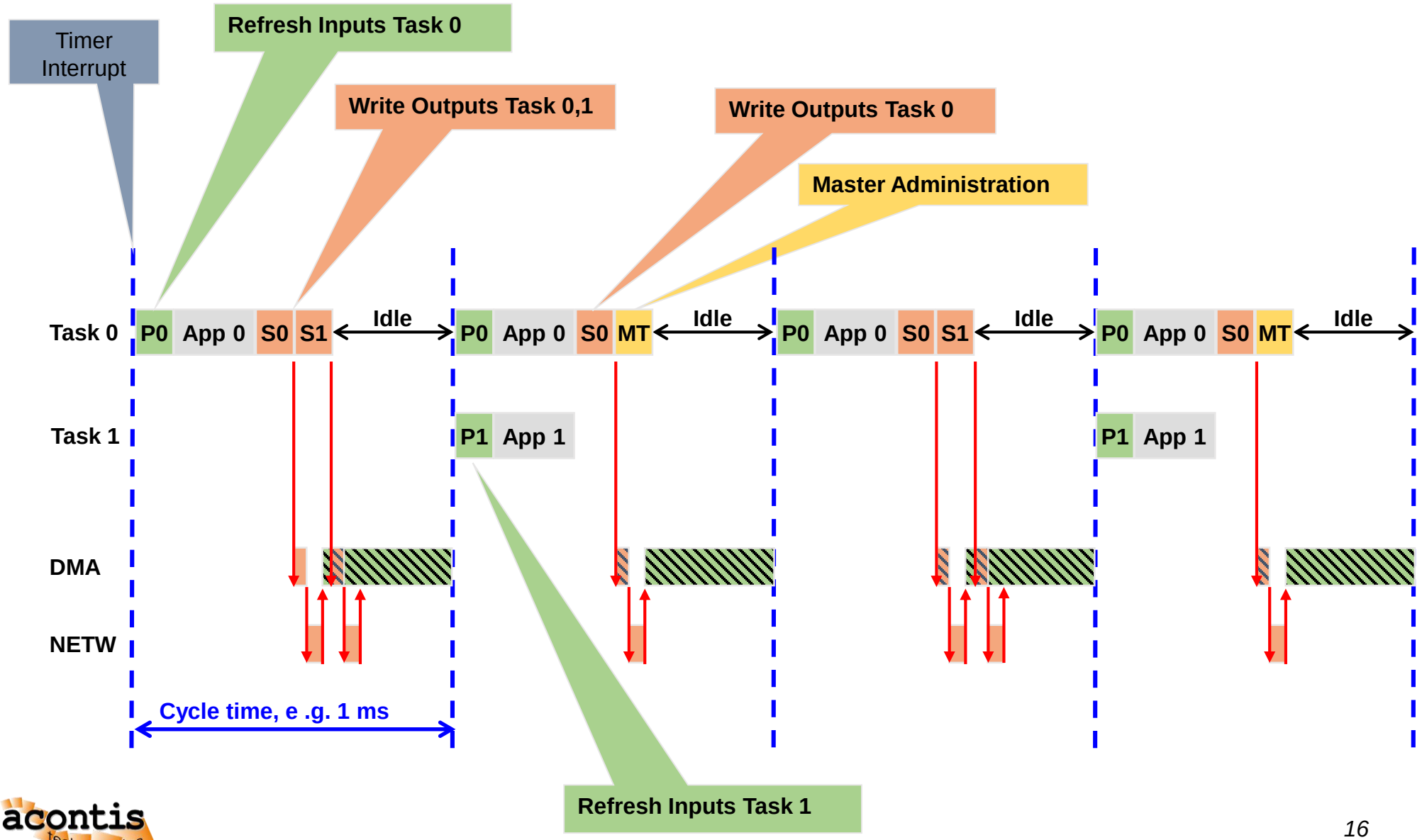
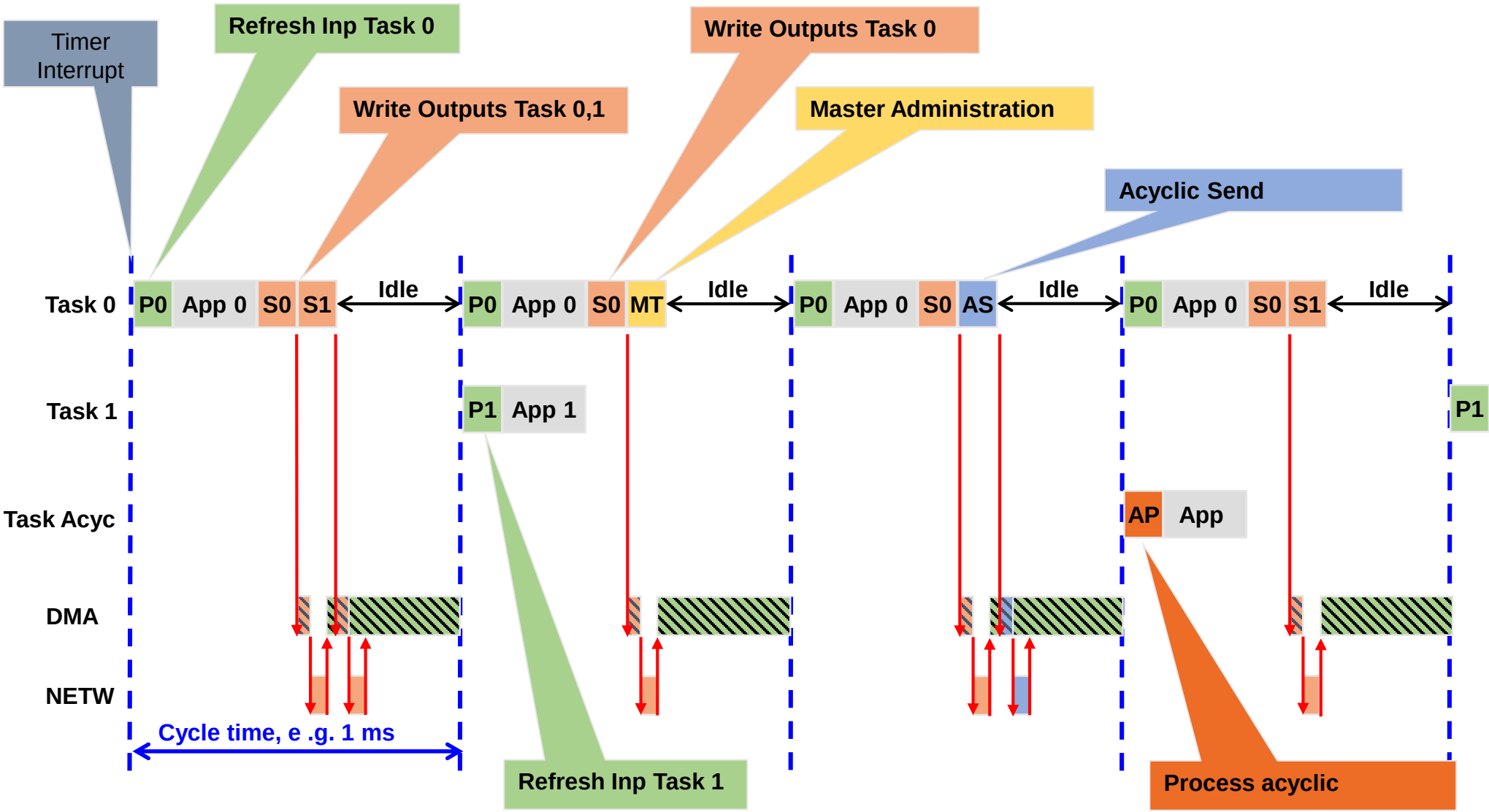
Feature Pack: Split Frame Processing
Network Timing: Split cyclic frame processing

EC Master



Feature Pack: Split Frame Processing
Network Timing: Split cyclic and acyclic frame processing

EC Master



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EtherCAT Synchronization

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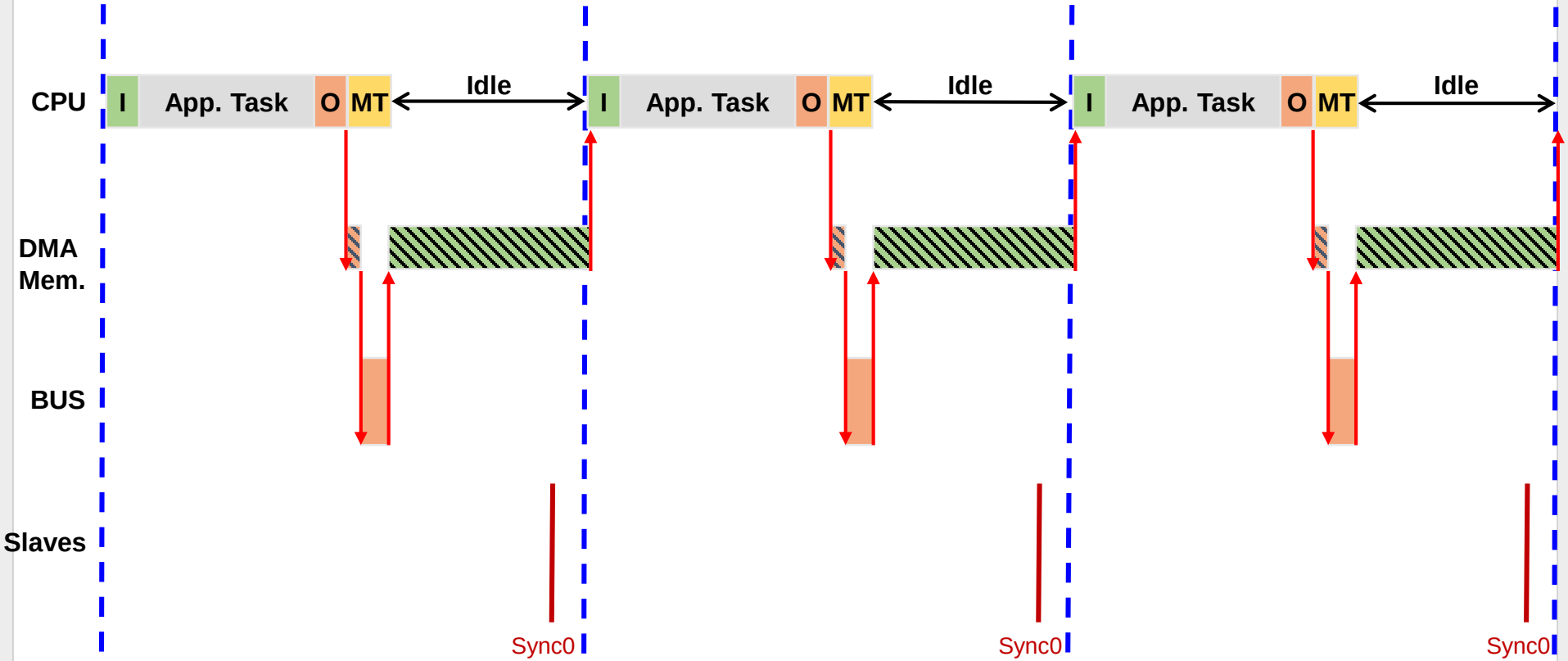
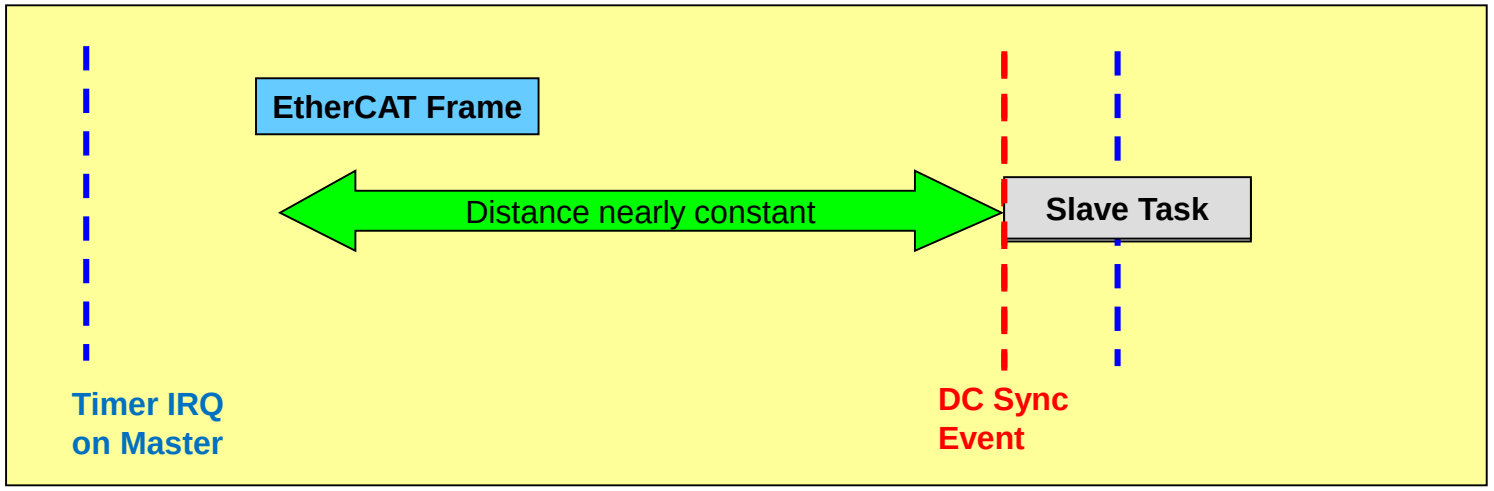
Network Timing: Cyclic Frames with DC Sync Signals
No interrupt from network controller



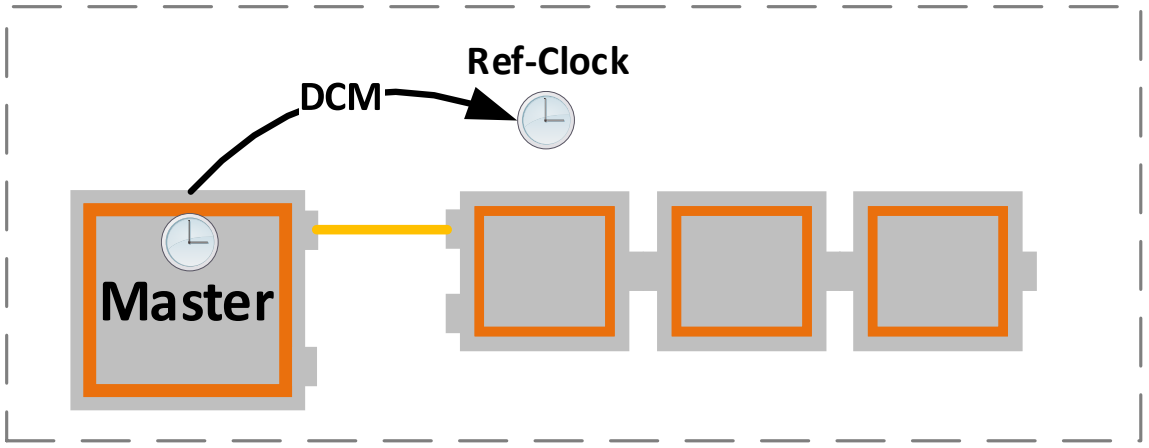
Distributed Clocks Master Synchronization



Without DCM

With DCM

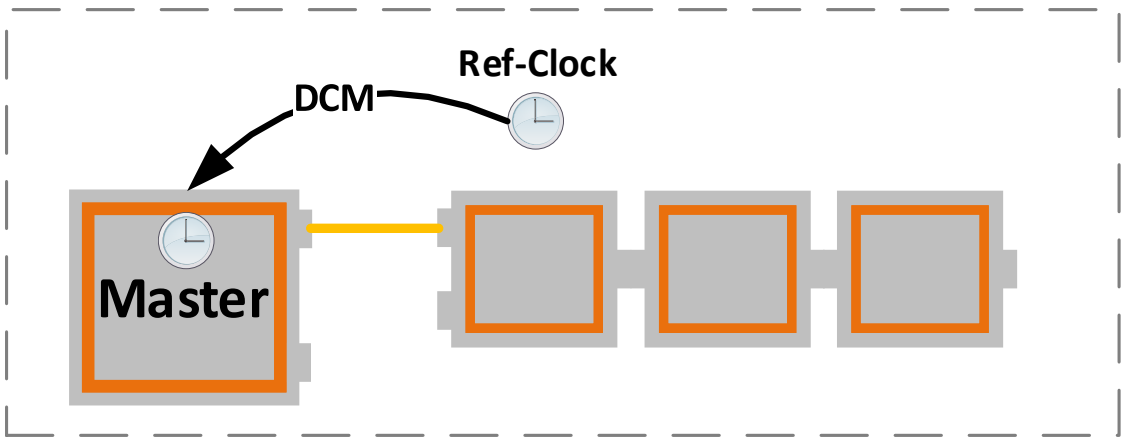
Bus Shift Mode
Reference Clock controlled by Master/Controller Time



Bus Shift: DC Reference Clock follows the Master Clock/Timer

- Adjust the Bus Time Register of the DC Reference Clock.
- The DC slaves converge to this time.
- Frame send time used for drift measurement (time is related to master timer)

Master Shift Mode
Master/Controller Time controlled by Reference Clock



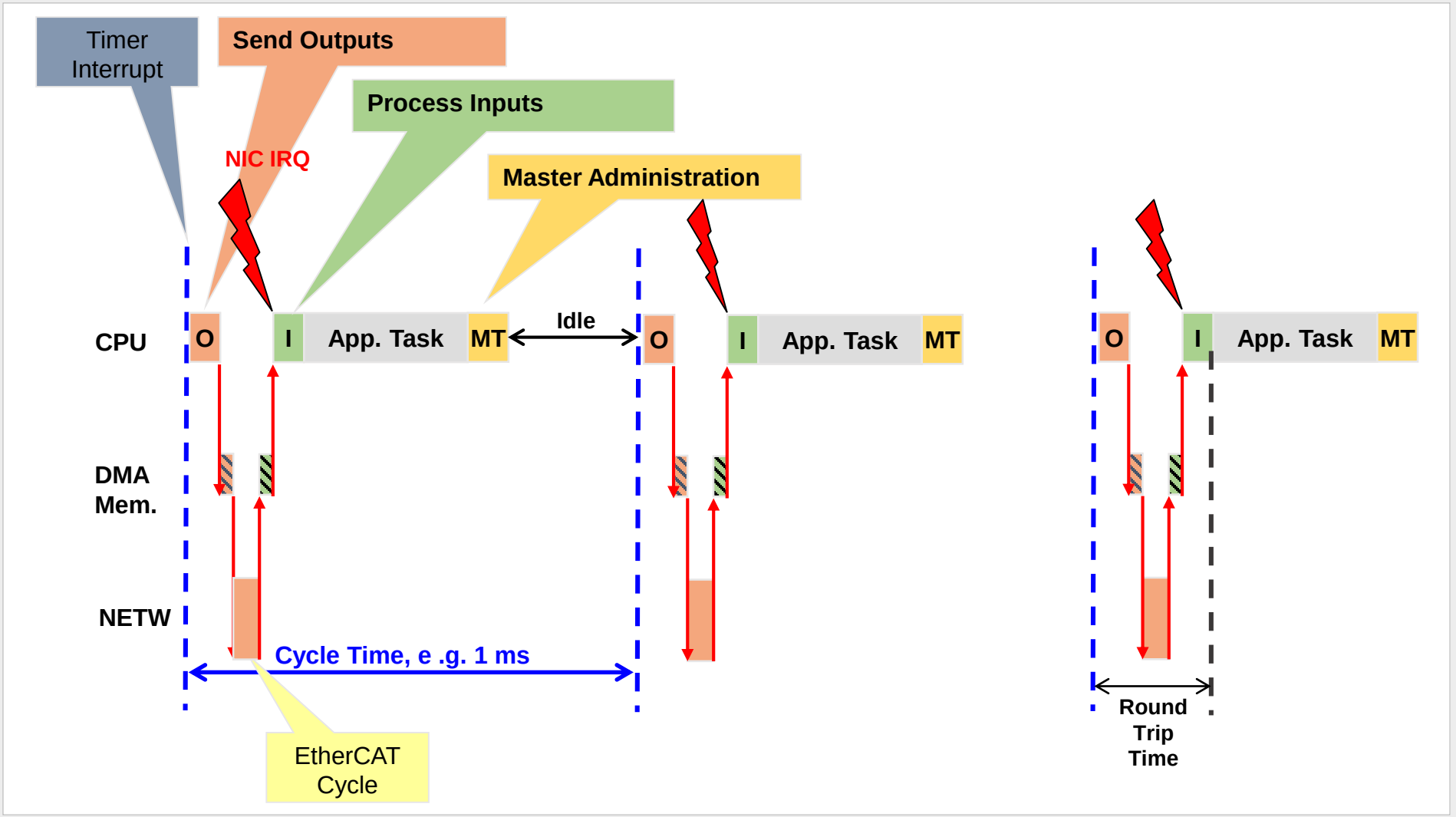
Master Shift: Master Clock/Timer follows the DC Reference Clock

- The timer (reload value) on Master control system (Host) is adjusted.
- E. g., if the Host is to fast, increase the reload value for one tick and then switch back to the default value.
- Interface to adjust timer required. Not available on all operating systems!

Distributed Clocks Master Sync
DCM Mode Selection Criteria

Criteria	Bus Shift Mode	Master Shift Mode
Accuracy of SYNC Signals	+/- 1000 nanosec jitter	+/- 20 nanosec jitter
Maximum acceptable drift between master and reference clock	600 ppm → very precise timer in control system required	no physical limitation
Multiple EtherCAT networks	possible	not possible
Implementation	possible	not possible on all operating systems

Network Timing: Sync Manager (SM) Synchronization With Interrupt from network controller



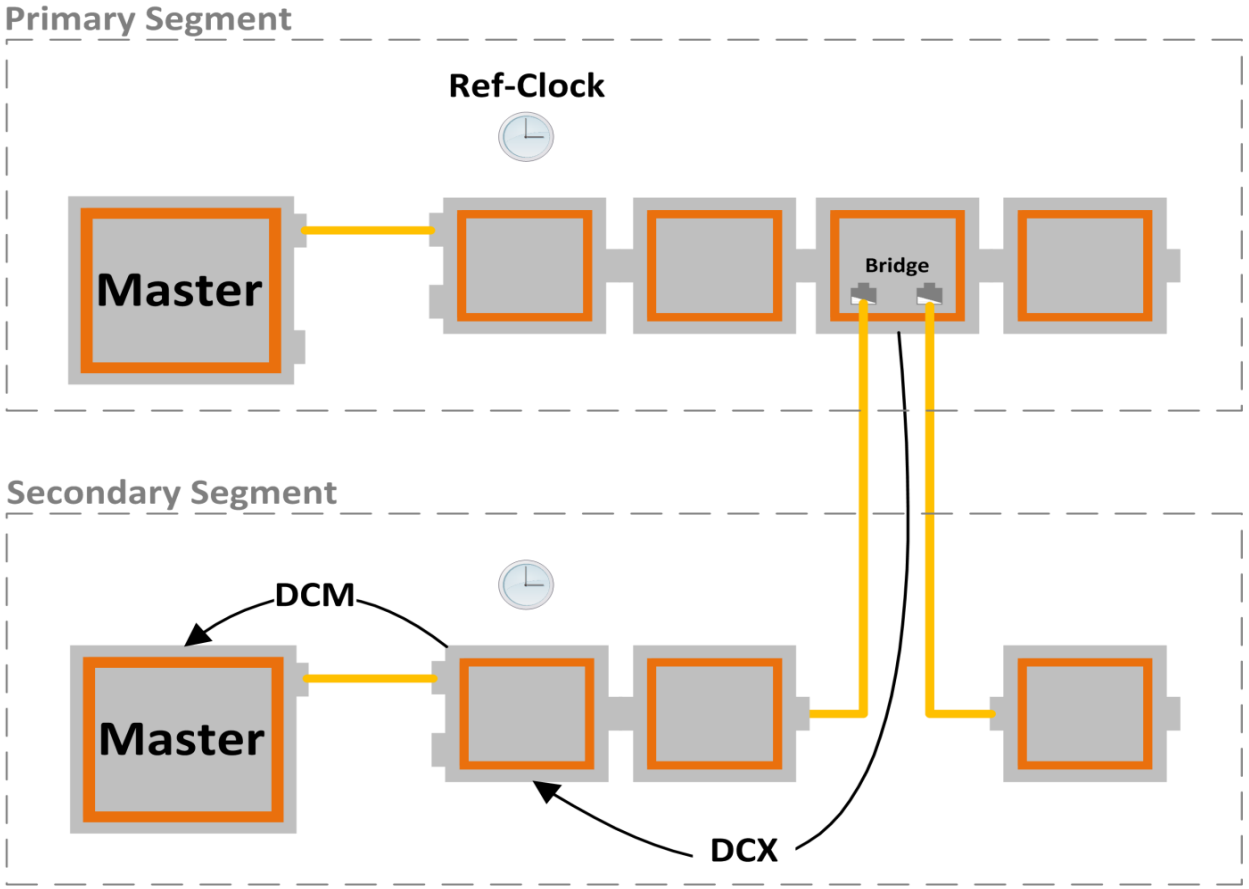
Network Timing: Sync Manager (SM) Synchronization

- Alternative synchronization instead of using DC, much simpler to implement
- Drawback: slave delay time not compensated
- Drawback: slave timing related to master frame send time jitter
  - minimum send time jitter is required
    - send frames immediately after timer irq on master
- Immediate slave reaction on new data (update when frame is received)

Feature Pack: External Synchronization (1)

EC Master

The external synchronization feature pack allows the synchronization of two or more EtherCAT segments by a Bridge device, e. g. Beckhoff EL6695



The synchronization process is divided in two parts; DCM and DCX.

- DCM: Synchronize Master timer to slave. (MasterShift)
- DCX: Synchronize slaves to bridge device. (BusShift)

Feature Pack: External Synchronization (2)

- The Bridge has two EtherCAT connections. The primary port is connected to the primary segment; the secondary port is connected to the secondary segment. The Bridge provides an internal (primary port) and an external (secondary port) time stamp which is used by the Master to adjust the Ref-Clock.

- The Bridge device must support the “External Synchronization Status” PDO 0x10F4 see document ETG.1020 chapter “21.1.2 Synchronization by a Bridge device”.

- During startup the two segments can be powered-on at different times. That means that there will be an absolute time difference between the two segments.

EtherCAT® over Ethernet (EoE)

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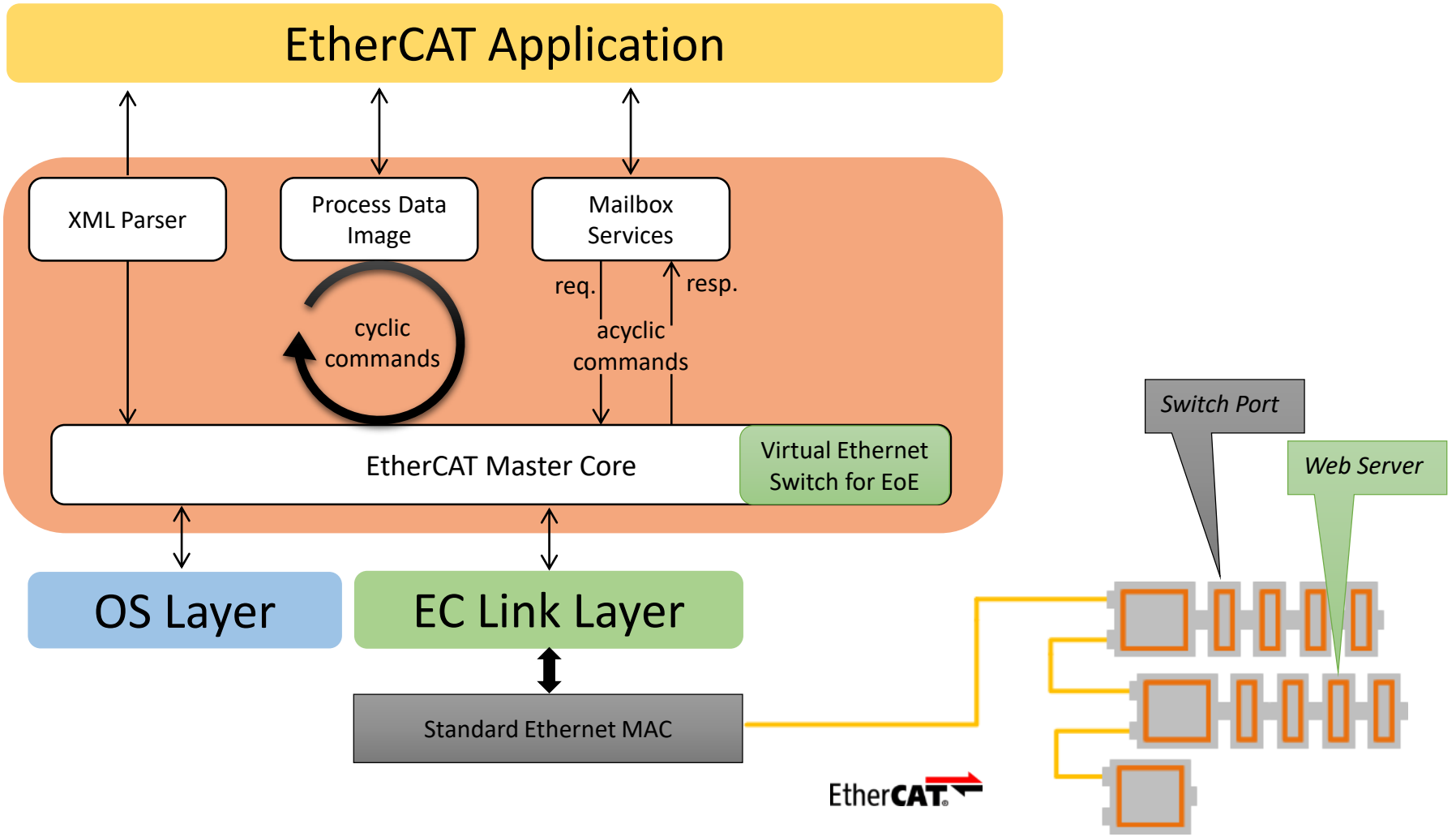
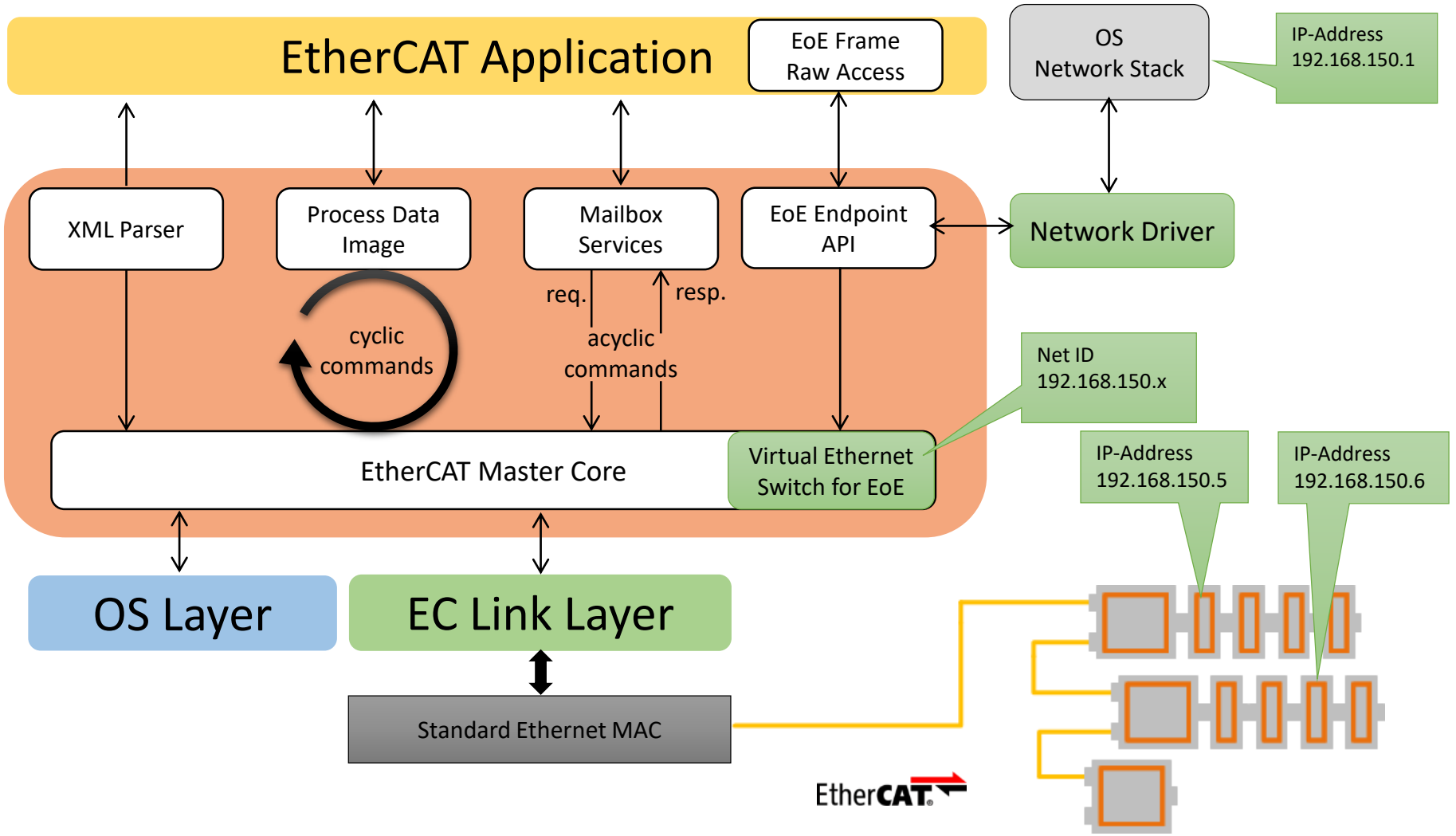
Class A: Includes Virtual Ethernet Switch for EoE

EC Master



Class A: Includes Virtual Ethernet Switch for EoE

EC Master



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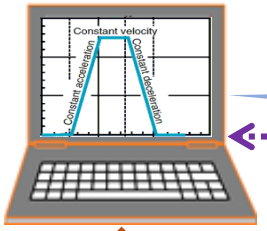
Configure drives connected to the EtherCAT network without additional cables

User Input



Third Party drive tool can be used in parallel to standard application

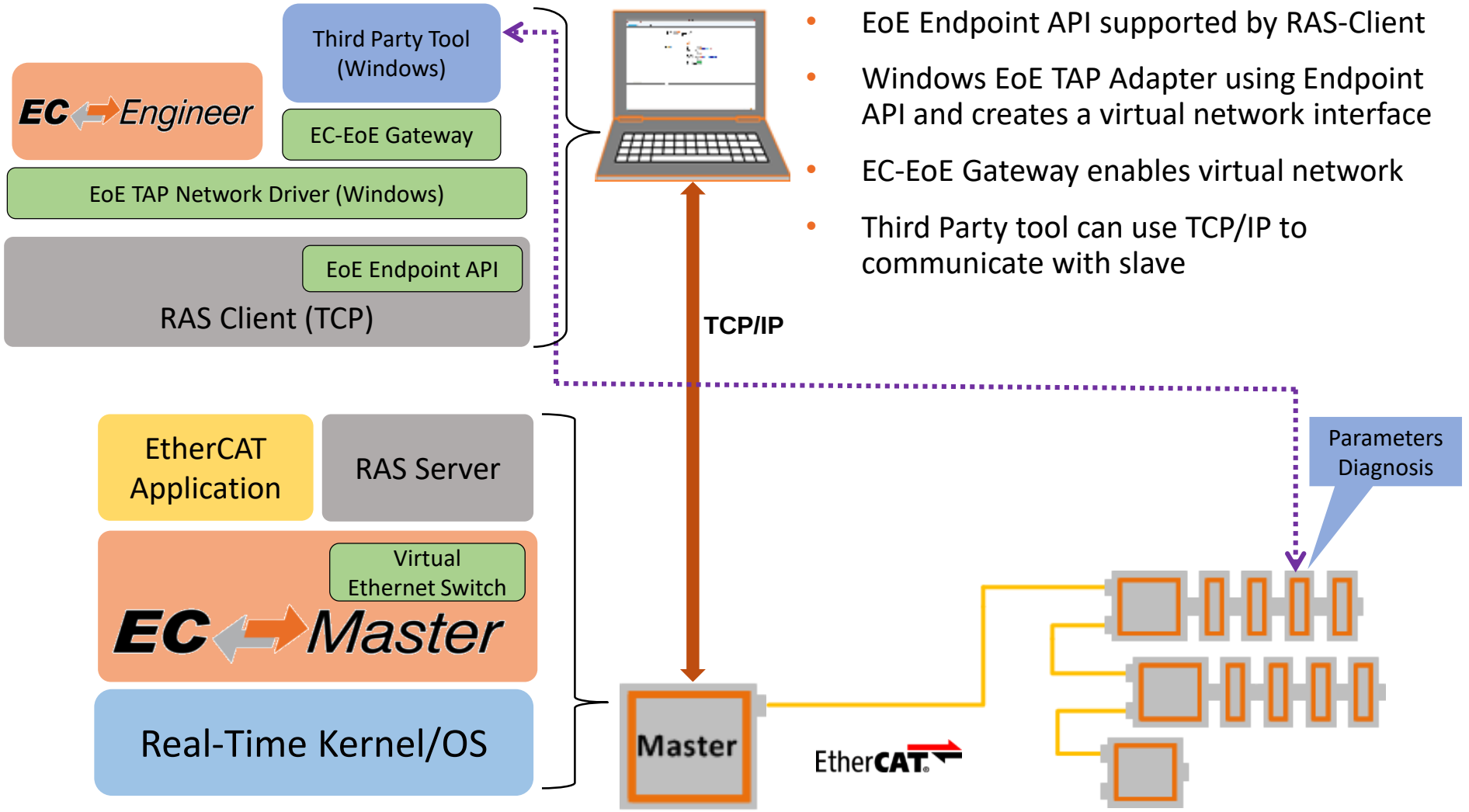
TCP/IP

Parameters + Diagnosis

Master

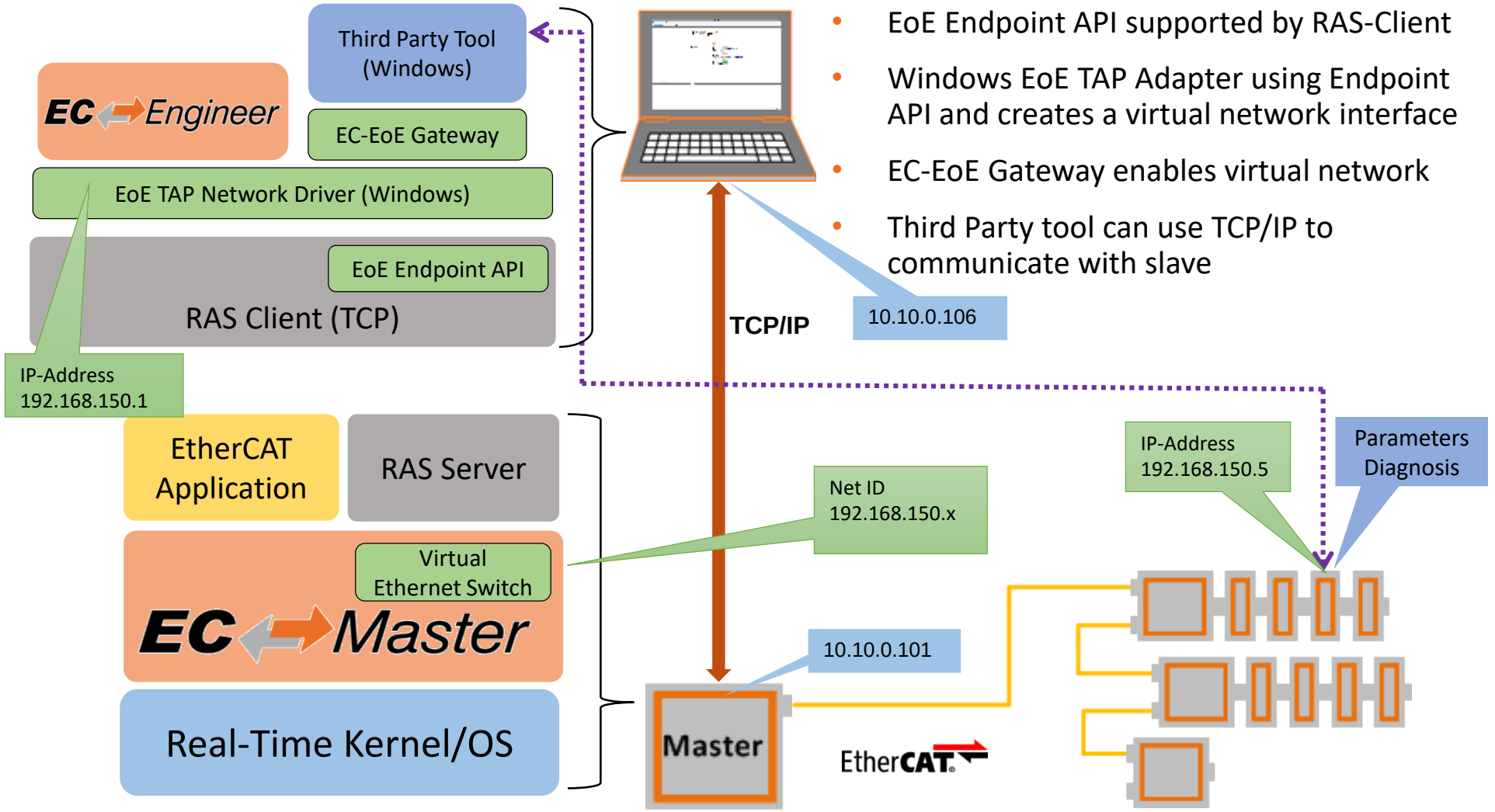
Tunneling Ethernet traffic through EtherCAT network (EoE protocol)

Windows Network Driver for EoE Endpoint with RAS



- EoE Endpoint API supported by RAS-Client
- Windows EoE TAP Adapter using Endpoint API and creates a virtual network interface
- EC-EoE Gateway enables virtual network
- Third Party tool can use TCP/IP to communicate with slave

Windows Network Driver for EoE Endpoint with RAS



- EoE Endpoint API supported by RAS-Client
- Windows EoE TAP Adapter using Endpoint API and creates a virtual network interface
- EC-EoE Gateway enables virtual network
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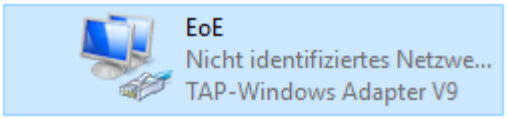
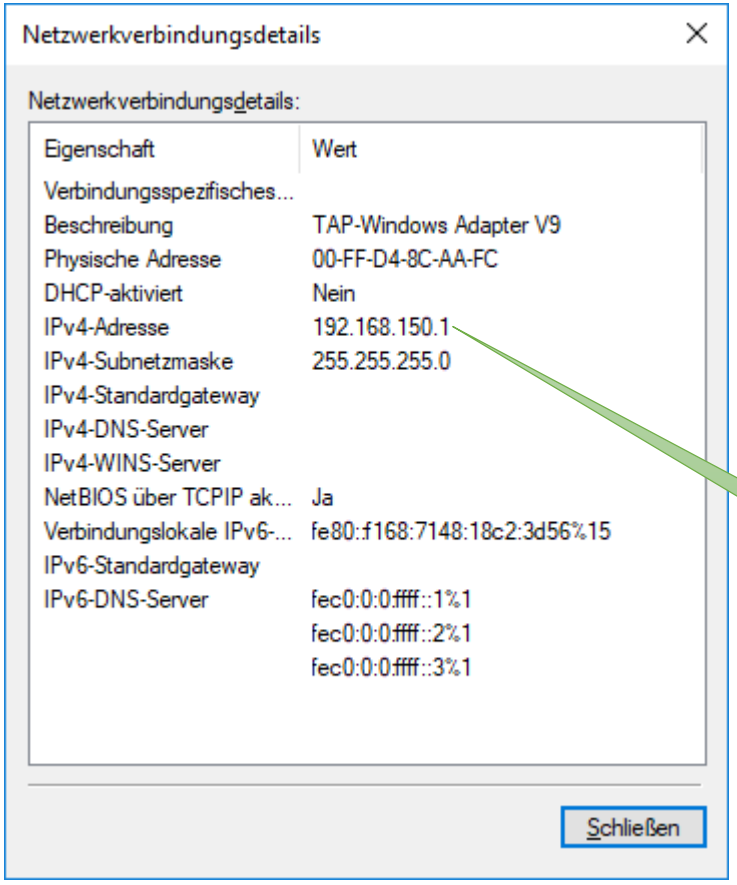
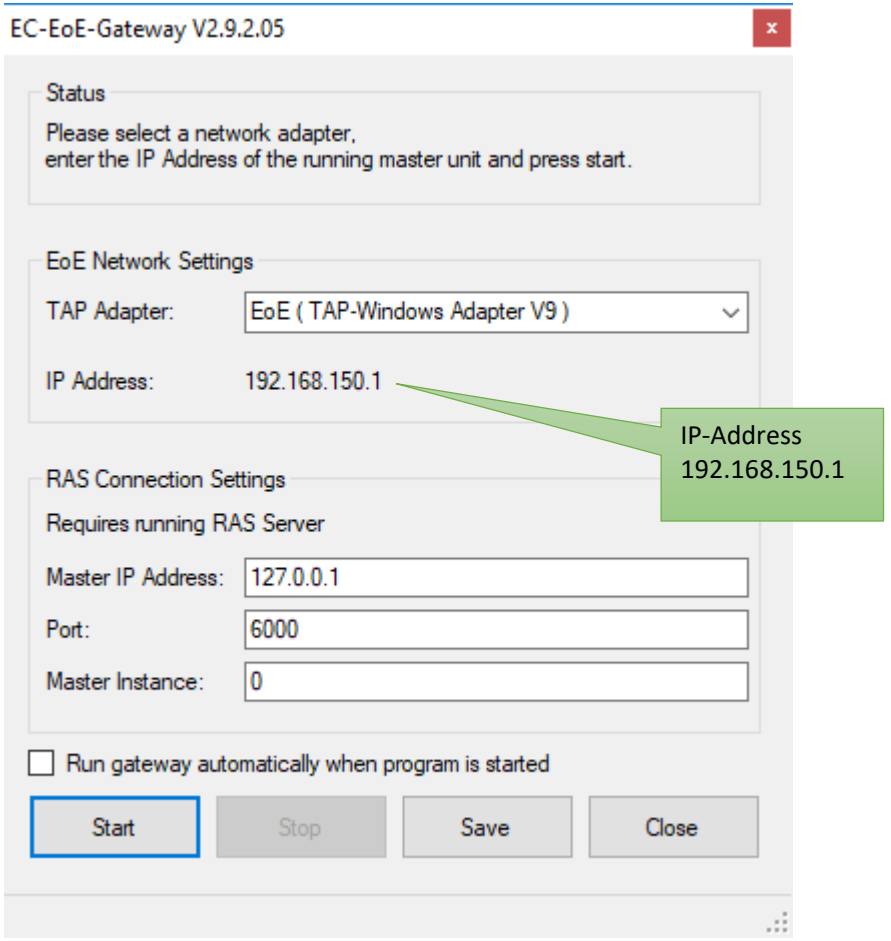
EoE TAP Network Driver (Windows)





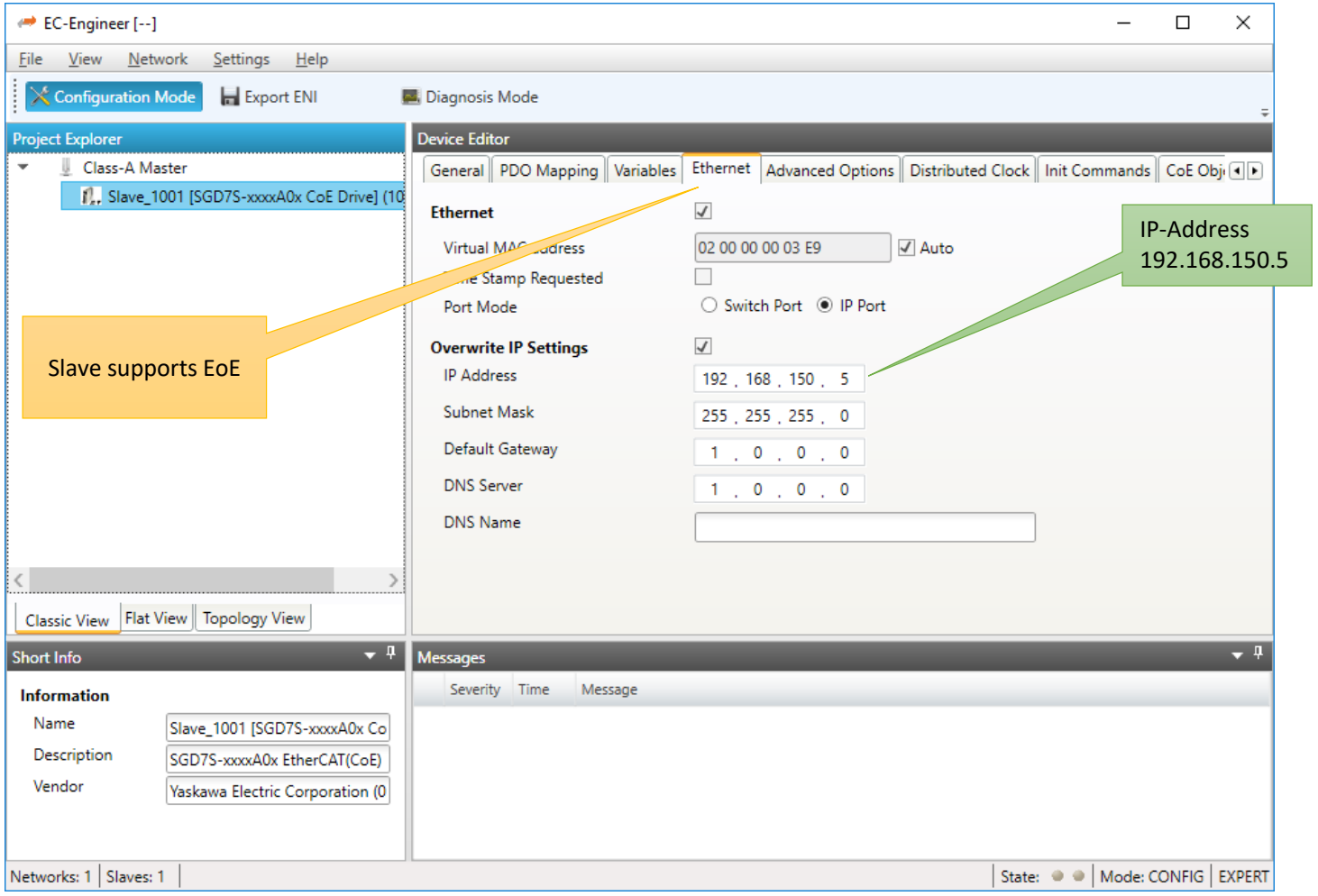
IP-Address
192.168.150.1

EC-EoE-Gateway



- Select TAP adapter used
- Select Master to connect to
- Start
  - EoE Gateway connects to remote master and enables the TAP adapter
  - IP-connection to remote system is available
  - Any tool can then use slave devices which support EoE

Setting IP address in EC-Engineer



Performance Measurements

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CPU load on different systems

7 Slaves: EK1100 + 2xEL2004 + 2xEL1004 + EL4132 + EK1110

Load: One cyclic frame (Size=579 Bytes) with 512 Bytes Process Data and mailbox transfer to EL4132

		x86: Intel Atom 1600 MHz NIC: Realtek 8111 Windows CE 6.0		TI Sitara AM3359 720 MHz NIC: Internal without OS		PowerPC e500v2 1200 MHz NIC: Realtek 8111 VxWorks	
Nr.	EC-Master Funktion	Avg µsec	Max µsec	Avg µsec	Max µsec	Avg µsec	Max µsec
1	Process Inputs	2.4	7.2	8.7	20.5	5.1	7.8
2	Send Outputs	5.2	7.6	6.1	9.3	6.3	7.5
3	Administration	5.5	24.9	3.3	15.7	3.7	7.3
4	Send Acyclic Frame	0.9	4.4	0.6	8.0	1.1	5.1
	Total CPU Time	14.0	44.1	18.7	53.5	16.2	27.7

Round-Trip Time on different systems

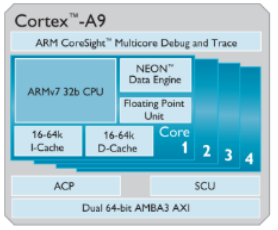
- 7 Slaves: EK1100 + 2xEL2004 + 2xEL1004 + EL4132 + EK1110
- Load: One cyclic frame (Size=579 Bytes) with 512 Bytes Process Data and mailbox transfer to EL4132

		x86: Intel Atom 1100 MHz NIC: Realtek 8111 Windows CE 6.0		x86: Core2Quad 2400 MHz NIC: Intel Pro/1000 IntervalZero RTX		PowerPC e500v2 1200 MHz NIC: Realtek 8111 VxWorks	
Nr.	EC-Master Funktion	Avg µsec	Max µsec	Avg µsec	Max µsec	Avg µsec	Max µsec
1	Round-Trip (Out+Inp)	94.4	112.2	67.0	82.1	74.6	88.1
2	Administration	7.0	10.2	0.8	2.5	3.1	4.7
3	Send Acyclic Frame	1.5	6.4	1.1	3.6	1.1	5.1

CPU load depending on number of slaves

Device: IXXAT Econ 100,
CPU: Xilinx Zynq SoC - Dual-Core Cortex-A9, 666 MHz

Software: Linux with EC-Master V2.6.2, Link Layer GEM



Number of Slaves	16	32	64
Network cycle time	250 usec	500 usec	1000 usec
Payload	128 Bytes	256 Bytes	512 Bytes
EC-Master Function			
Process Inputs [usec]	33.7	34.1	36.1
Send Outputs [usec]	17.0	17.9	18.8
Administration [usec]	13.8	21.0	49.4
Send Acyclic Frame [usec]	13.6	15.4	15.6
Total Time [usec]	78.1	88.4	119.9
CPU Load [percent]	31 %	18 %	12 %

Quality Assurance
Success Stories

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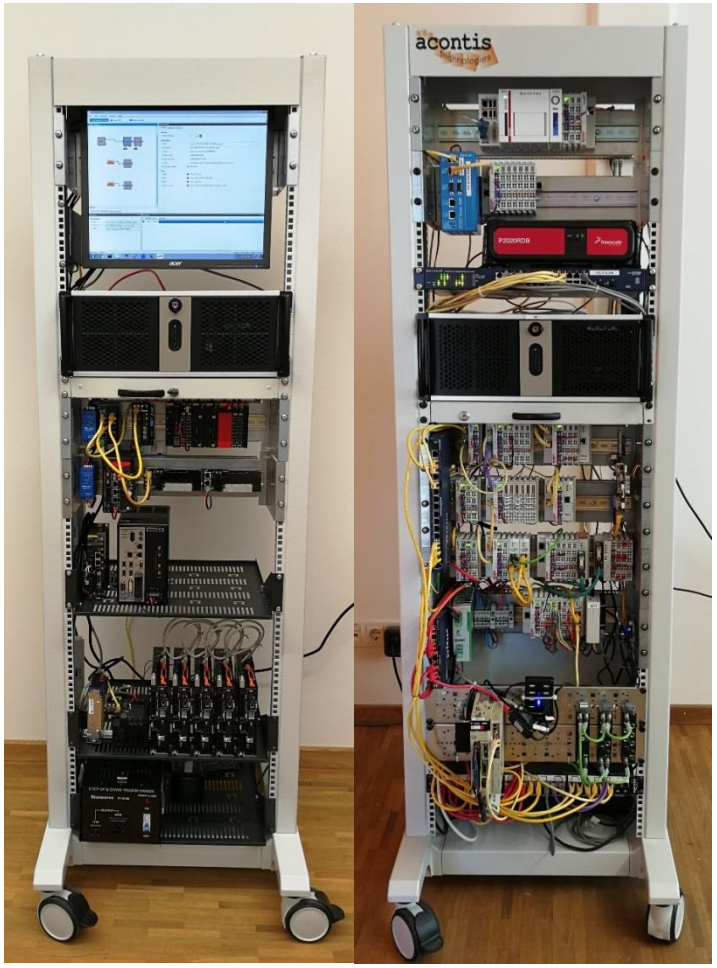
High Quality - Software Quality Assurance

- Source code management software, Configuration Management
- Automatic build process for all supported operating systems
- Well defined release process with regression tests
- Deep knowledge in various real-time OS
- Long term experience with real-time systems
- Acceptance test with integrated frame loss simulation
- Acceptance test with many different EtherCAT slaves

- EtherCAT conformance assurance
  - Attendance in all ETG Technical Committee Meetings
  - Plug Fests
  - Active, Leading Member in several ETG Working Groups (e.g. EAP)
  - Very good and close contacts to ETG, Beckhoff and Hilscher

Test Equipment - I/O



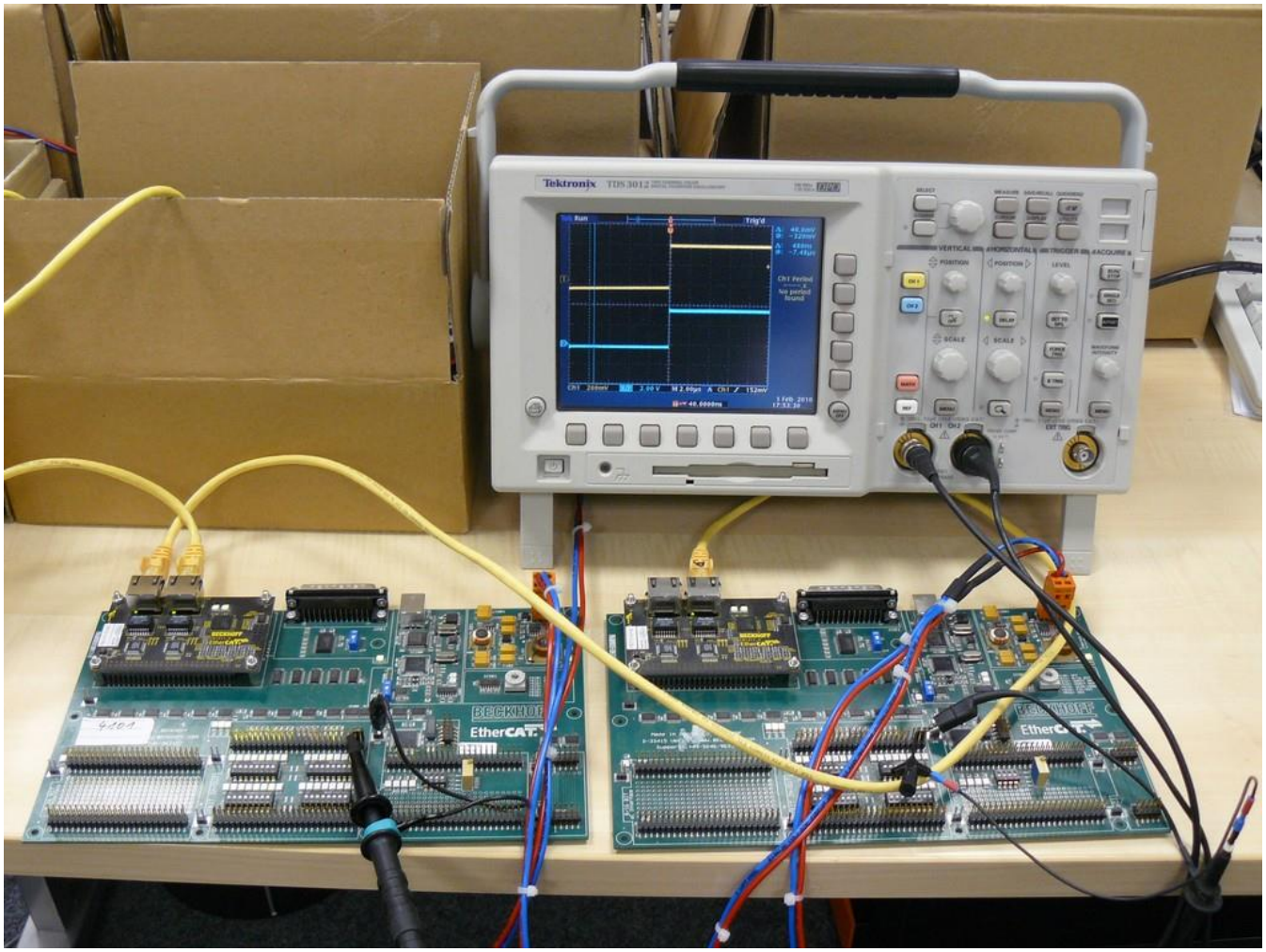
Master systems:

- Different operating systems
- Different CPU architectures
- Different performance classes

Slaves:

- Various manufacturers
- Digital/analog I/O
- Drives (Copley, Omron, Yaskawa, etc.)
- Safety (FSoE) devices
- In total >400 slaves (not just in these racks)

Test Equipment - Distributed Clocks



EtherCAT® and GPL

EC-Master on Linux

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EtherCAT® Licensing

What is necessary to use EtherCAT?

- Member of the EtherCAT Technology Group (ETG)
- Recommended:
  Beckhoff "**ETHERCAT MASTER LICENSE AGREEMENT"**
- **Whereas**, Licensor is the owner of all intellectual property rights pertaining to the EtherCAT Technology, including but not limited to (a) the following German patent applications and patents: EP1590927, EP1789857, DE102004044764, DE102007017835 with corresponding applications or registrations in various other countries, and (b) the trademarks "EtherCAT" and "Safety over EtherCAT", with applications or registrations in the European Community (CTM003122736, CTM006350029, CTM005460563) and corresponding registrations or applications in various other countries.
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- **Whereas,** Licensee acknowledges Licensor's commercially reasonable efforts to keep the number of those EtherCAT Technology products in the market sold under the trade name "EtherCAT" and not being fully compatible with the then current version of the EtherCAT Technology at a minimum.

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- The GPL is the first copyleft license for general use, which means that derived works can only be distributed under the same license terms.
- GPL:

  6. Each time you redistribute the Program (or any work based on the Program), the recipient automatically receives a license from the original licensor to copy, distribute or modify the Program subject to these terms and conditions. **You may not impose any further restrictions** on the recipients' exercise of the rights granted herein. You are not responsible for enforcing compliance by third parties to this License.
  http://www.gnu.org/licenses/gpl-2.0.html
- The Linux kernel is released under the GNU General Public License version 2.

What does this mean for EtherCAT?

ETG web site: http://www.ethercat.org/en/faq.html#790

3.4 How about Open Source? EtherCAT technology itself is not Open Source.
→ EtherCAT cannot be licensed in conjunction with ANY Open Source License!

Backed by the standardization of EtherCAT by IEC, ISO and SEMI, access to EtherCAT technology is available to everyone to non-discriminatory terms. Additionally, Master Licenses are free of royalties. Maintenance and all further development of the technology is available to all users by membership within the ETG, the user group for EtherCAT technology. If you have questions regarding implementing or using EtherCAT in conjunction with shared source or open source systems please contact ETG headquarters or Beckhoff, the EtherCAT technology licensor.

EC-Master Architecture on Linux