F28HS Hardware-Software Interface: Systems Programming

Hans-Wolfgang Loidl

School of Mathematical and Computer Sciences,
Heriot-Watt University, Edinburgh

Semester 2 — 2025/26

[0]No proprietary software has been used in producing these slides

Outline

HERIOT WATT UNIVERSITY

Lecture 2.
Systems Programming with the Raspberry Pi

HERIOT WATT UNIVERSITY

SoC: System-on-Chip

- A **System-on-Chip** (SoC) integrates all components of a computer or other electronic system into a single chip.
- One of the main advantages of SoCs is their low power consumption.
- Therefore they are often used in embedded devices.
- All versions of the Raspberry Pi are examples of SoCs

Note: In this course we are using the Raspberry Pi 2 or 3 Model B. The low-level code will only work with these versions.

Note: Raspberry Pi 4 works with a different GPIO memory base address.
Note: Raspberry Pi 5 will **NOT** work with the sample source code.

The Raspberry Pi Foundation: https://www.raspberrypi.org/
UK registered charity 1129409

HERIOT WATT UNIVERSITY

Raspberry Pi 2

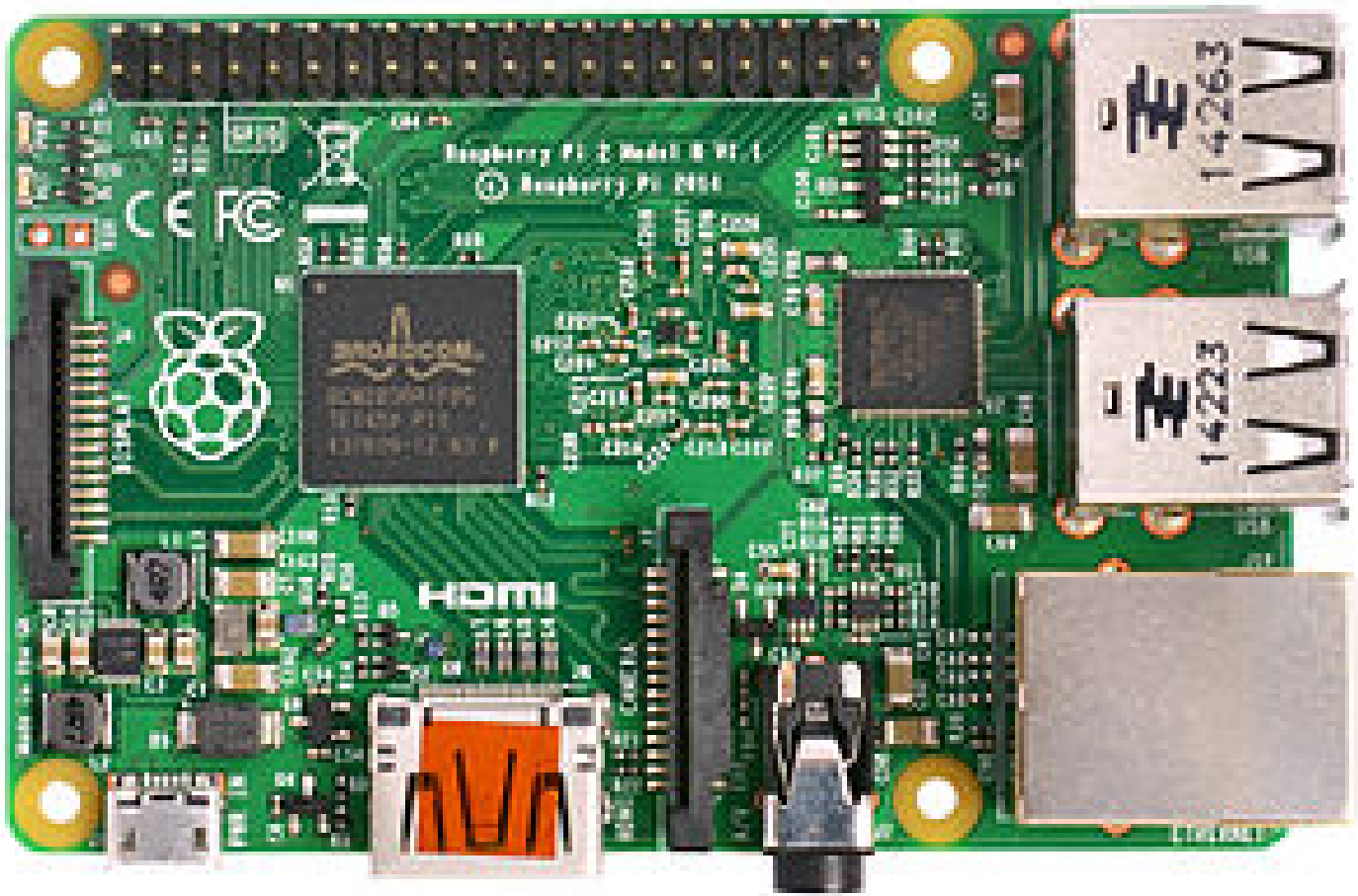
The main components of the RPi2 are:

- the BCM2836 SoC (System-on-Chip) by Broadcom
- an ARM-Cortex-A7 CPU with 4 cores (clock frequency: 900MHz)
- 1 GB of DRAM
- a Videocore IV GPU
- 4 USB ports (sharing the one internal port together with the Ethernet connection)
- power supply through a microUSB port

NB: The A-series of the ARM architectures is for "application" usage and therefore more powerful than the M-series, which is mainly for small, embedded systems.
It is possible to *safely* over-clock the processor up to 950 MHz.

[0] Material from Raspberry Pi Geek 03/2015

Raspberry Pi 2



[0]Source: https://en.wikipedia.org/wiki/Raspberry_Pi

Raspberry Pi 4

Specification:

- **ARMv8, BCM2837B0, ARM Cortex-A72 CPU 64-bit quad-core @ 1.5GHz**
- Up to 1GB, 2GB or 4GB RAM (LPDDR4)
- On board dual-band 802.11.b/g/n/ac wireless LAN
- On board Bluetooth 5.0, low-energy (BLE)
- **Gigabit Ethernet**
- **2 $\times$ USB 3.0 ports**, 2 $\times$ USB 2.0 ports
- Extended 40-pin GPIO header
- **2 $\times$ micro-HDMI ports** (supporting up to 4Kp60)

[0] See data-sheets on official Raspberry Pi pages and RPi 4 spec on NewIT pages

Raspberry Pi 5

Chipset:

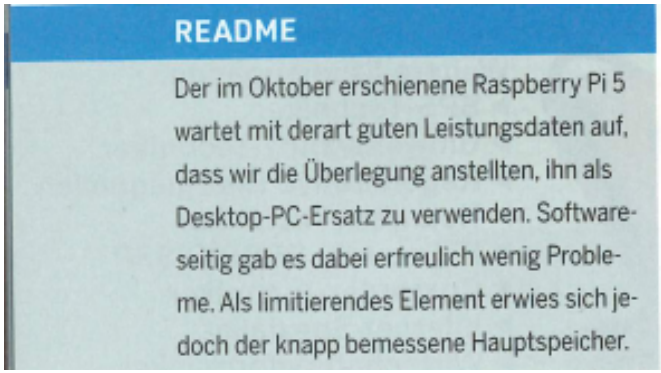
- **ARM Cortex-A76 (quad-core) 2.4 GHz**
- Broadcom BCM2712 chipset
- Broadcom Video Core VII
- 4GB or 8GB DDR4 RAM
- 2 MIPI interfaces (Camera / Display Serial Interface)

Interfaces:

- 40 GPIO pins, PCIe 2.0 MicroSD slot
- 2 USB 2.0 ports, 2 USB 3.0 ports
- 10/100/1000 MBit/s Ethernet
- WLAN IEEE 802.11b/g/n/ac, Bluetooth
- 2 HDMI ports
- USB-C power

[0] From Raspberry Pi Geek 12/23

Raspberry Pi 5 as Desktop



README

Der im Oktober erschienene Raspberry Pi 5 wartet mit derart guten Leistungsdaten auf, dass wir die Überlegung anstellten, ihn als Desktop-PC-Ersatz zu verwenden. Softwareseitig gab es dabei erfreulich wenig Probleme. Als limitierendes Element erwies sich jedoch der knapp bemessene Hauptspeicher.

- RPi5 is suitable as a desktop alternative
- Main limitation is main memory:
  use the 8GB option
- Graphics apps, streaming (YouTube) work fine
- Standalone and browser-based CAD apps work fine
- Avoid running web-browsers all the time, though
- **PCIe interface for NVMe-SSD memory!**
- PCIe data transfer rate: ca 500 MB/s
- **New RP1 controller for interfaces to e.g. GPIO memory**
- $\Longrightarrow$ **probably not compatible with code in our course**

[0] From Raspberry Pi Geek 1/24

HERIOT WATT UNIVERSITY

Software configuration

- RPi supports several major Linux distributions, including: Raspberry OS (former Raspbian; Debian-based), Ubuntu, Arch Linux, etc
- The main system image provided for RPi can boot into several of these systems and provides kernels for both ARMv6 (RPi1), ARMv7 (RPi2/3), ARMv8 (RPi4), and probably more recent versions
- The basic software configuration is almost the same as on a standard Linux desktop
- To tune the software/hardware configuration call

```
> sudo raspi-config
```

HERIOT WATT UNIVERSITY

Updating your software under Raspbian

We are using the latest version of Raspbian (now called Raspberry OS), which is a fork from the Debian distribution of a Linux OS.

To update the software under Raspbian, do the following:

```
> sudo apt-get update
> sudo apt-get upgrade
> sudo rpi-update
```

To find the package `foo` in the on-line repository, do the following:

```
> sudo apt-cache search foo
```

To install the package `foo` in the on-line repository, do the following:

```
> sudo apt-get install foo
```

HERIOT WATT UNIVERSITY

Virtualisation

- In this powerful, multi-core configuration, a RPi can be used as a server, running several VMs.
- To this end RPi2 under Raspbian runs a **hypervisor** process, mediating hardware access between the VMs.
- Virtualisation is hardware-supported for the ARMv6 onwards
- The ARMv7 instruction set includes a richer set of SIMD (single-instruction, multiple-data) instructions (the **NEON** extensions), to use parallelism and speed-up e.g. multi-media applications
- The NEON instruction allow to perform operations on up to 16 8-bit values at the same time, through the processor's support for 64-bit and 128-bit registers
- Performance improvements in the range of $8 - 16\times$ have been reported for multi-media applications
- The usual power consumption of the Ri2 is between $3.5 - -4$ Watt

CPU Performance Comparison: Hardware

Rechenleistung im Vergleich				
Plattform	**RAM**	**Chip**	**Technologie**	**Architektur**
Raspberry Pi				
Raspberry Pi 1	512 MByte	Broadcom BCM2835	65 nm	ARM1176JZ-F
Raspberry Pi 2	1 GByte LPDDR2	Broadcom BCM2836	28 nm	Cortex A7
Banana Pi				
Banana Pi	1 GByte	AllWinner A20	40 nm	Cortex A7
Banana Pro	1 GByte	AllWinner A20	40 nm	Cortex A7
Banana Pi M2	1 GByte	AllWinner A31S	40 nm	Cortex A7
Andere Single Board Computer (SBC)				
Beaglebone Black	512 MByte	TI Sitara AM3358/9	45 nm	Cortex A8
Hummingboard-i2	1 GByte	Freescale i.MX6 DualLite	40 nm	Cortex A9
Cubox-i4Pro	2 GByte	Freescale i.MX6 Quad	40 nm	Cortex A9
Odroid C1	1 GByte DDR3	Amlogic S805	28 nm	Cortex A5
Smartphones				
Galaxy S3 Mini (GT-I8190)	1 GByte	ST-Ericsson NovaThor U8500	45 nm	Cortex A9
iPhone 5	1 GByte	Apple A6	32 nm high-k metal gate	ARMv7s Swift [Apple]
Spielekonsolen				
Playstation 2	36 MByte	EmotionEngine	250 nm	RISC, basiert auf MIPS R5900
Apple-Computer				
Apple][e	64 KByte	MOS Technology 6502	8000 nm	MOS Technology
Apple Macintosh 128 K	128 KByte	Motorola 68000	3500 nm	CISC
iMac G3	32 MByte	PowerPC 750 G3	260 nm	PowerPC G3
Intel- und AMD-PCs				
No Name PC 1	64 MByte	Pentium II, 300 MHz	350 nm	x86 Intel
No Name PC 2	384 MByte	AMD Duron, 800 MHz	180 nm	AMD Spitfire
Dell Inspiron 7520	8 GByte	Intel Core i7-3632QM	22 nm	Intel Core i7
Hetzner EQ-4 Server	32 GByte	Intel Core i7-3770	22 nm	Intel Core i7

CPU Performance Comparison: Measurements

DMIPS/MHz	Kerne	MHz	DMIPS	Vgl. RPi 1	Vgl. RPi 2
1,25	1	700	875	100%	13%
1,90	4	900	6840	782%	100%
1,90	2	1000	3800	434%	56%
1,90	2	1000	3800	434%	56%
1,90	4	1000	7600	869%	111%
2,00	1	1000	2000	229%	29%
2,50	2	1000	5000	571%	73%
2,50	4	1000	10000	1143%	146%
1,57	4	1500	9420	1077%	138%
2,50	2	1000	5000	571%	73%
3,50	2	1300	9100	1040%	133%
20,34	1	295	6000	686%	88%
0,43	1	1	0,43	0,05%	0,01%
0,23	1	6	1,4	0,16%	0,02%
2,25	1	233	525	60%	8%
0,91	1	300	273,6	31%	4%
2,81	1	800	2250	257%	33%
14,19	4	2200	99750	11400%	1458%
14,19	4	3400	106530	12175%	1557%

HERIOT WATT UNIVERSITY

CPU Performance Comparison: Measurements

DMIPS/MHz	Kerne	MHz	DMIPS	Vgl. RPi 1	Vgl. RPi 2
1,25	1	700	875	100%	13%
1,90	4	900	6840	782%	100%
1,90	2	1000	3800	434%	56%
1,90	2	1000	3800	434%	56%
1,90	4	1000	7600	869%	111%
2,00	1	1000	2000	229%	29%
2,50	2	1000	5000	571%	73%
2,50	4	1000	10000	1143%	146%
1,57	4	1500	9420	1077%	138%
2,50	2	1000	5000	571%	73%
3,50	2	1300	9100	1040%	133%
20,34	1	295	6000	686%	88%
0,43	1	1	0,43	0,05%	0,01%
0,23	1	6	1,4	0,16%	0,02%
2,25	1	233	525	60%	8%
0,91	1	300	273,6	31%	4%
2,81	1	800	2250	257%	33%
14,19	4	2200	99750	11400%	1458%
14,19	4	3400	106530	12175%	1557%

Note

RPi2 ca. **7.82× faster** than RPi1

Banana Pi M2 is **1.11× faster** than RPi2

Cubox i4Pro is **1.46× faster**
ODroid C1 is **1.38× faster**

Intel i7 PC is **15.5× faster** than RPi2

High-performance Alternatives

- There are several single-board computers that provide a **high-performance** alternative to the RPi.
- These are of interest if you have applications with high computational demands and you want to run it on a low-cost and low-power device.
- It's possible to build for example a **cluster** of such devices as a parallel programming platform: see The Glasgow University Raspberry Pi Cloud
- Here we give an overview of the main **performance characteristics** of three RPi alternatives:
  - the Rock 5 by OKdo
  - the CuBox i4Pro by SolidRun
  - the Banana Pi M3 by Sinovoip
  - the Lemaker HiKey by Lemaker

Core Specs of the OKdo Rock

- Rockchip RK3588
- Quad-core ARM Cortex-A76 MPCore processor and quad-core ARM Cortex-A55 MPCore processor (**big.LITTLE**)
- Embedded ARM Mali-G610 MP4 3D GPU
- 4GB / 8GB / 16GB RAM ; 4224Mhz memory bus frequency
- **WLAN** (802.11b/g/n), Bluetooth 4.1
- several USB ports
- 40 GPIO pins (not compatible with RPi2)
- HDMI connectors
- Price: 135£

A good high performance alternative to but more expensive than the Raspberry Pi 4.
See: https://wiki.radxa.com/Rock5/hardware/5b

Core Specs of the CuBox i4-Pro (older)

- Freescale i.MX6 (SoC) quad-core, containing an **ARM Cortex A9** (ARMv7 instruction set) with **4 cores**
- GC2000 GPU (supports OpenGL etc)
- 4 GB RAM and a micro-SD card slot
- 10/100/1000 Mb/s Ethernet (max 470Mb/s)
- **WLAN** (802.11b/g/n)
- Bluetooth 4.0
- 1 USB port and eSATA (3Gb/s) interface
- Price: 124£

Software

- Debian Linux, Kodi Linux, XBMC Linux

HERIOT WATT UNIVERSITY

Core Specs of the CuBox i4-Pro (older)

- Freescale i.MX6 (SoC) quad-core, containing an **ARM Cortex A9** (ARMv7 instruction set) with **4 cores**
- GC2000 GPU (supports OpenGL etc)
- 4 GB RAM and a micro-SD card slot
- 10/100/1000 Mb/s Ethernet (max 470Mb/s)
- **WLAN** (802.11b/g/n)
- Bluetooth 4.0
- 1 USB port and eSATA (3Gb/s) interface
- Price: 124£

Software

- Debian Linux, Kodi Linux, XBMC Linux

HERIOT WATT UNIVERSITY

Core Specs of the Banana Pi M3 (older)

- Allwinner A83T (SoC) chip, containing an **ARM Cortex-A7** (ARMv7 instruction set) with **8 cores**
- PowerVR SGX544MP1 GPU (supports OpenGL etc)
- 2 GB LPDDR3 RAM plus 8 GB eMMC memory and a micro-SD card slot
- **Gigabit Ethernet**
- **WLAN** (802.11b/g/n)
- Bluetooth 4.0
- 2 USB ports and SATA interface
- 40 GPIO pins (not compatible with RPi2)
- Price: 90€

Software

- BPI-Berryboot (allegedly with GPU support), or Ubuntu Mate

Experiences

- SATA shares the USB bus connection and is therefore slow
- Problems accessing the on-board micro-phone

Core Specs of the Banana Pi M3 (older)

- Allwinner A83T (SoC) chip, containing an **ARM Cortex-A7** (ARMv7 instruction set) with **8 cores**
- PowerVR SGX544MP1 GPU (supports OpenGL etc)
- 2 GB LPDDR3 RAM plus 8 GB eMMC memory and a micro-SD card slot
- **Gigabit Ethernet**
- **WLAN** (802.11b/g/n)
- Bluetooth 4.0
- 2 USB ports and SATA interface
- 40 GPIO pins (not compatible with RPi2)
- Price: 90€

Software

- BPI-Berryboot (allegedly with GPU support), or Ubuntu Mate

Experiences

- SATA shares the USB bus connection and is therefore slow
- Problems accessing the on-board micro-phone

Core Specs of the Banana Pi M3 (older)

- Allwinner A83T (SoC) chip, containing an **ARM Cortex-A7** (ARMv7 instruction set) with **8 cores**
- PowerVR SGX544MP1 GPU (supports OpenGL etc)
- 2 GB LPDDR3 RAM plus 8 GB eMMC memory and a micro-SD card slot
- **Gigabit Ethernet**
- **WLAN** (802.11b/g/n)
- Bluetooth 4.0
- 2 USB ports and SATA interface
- 40 GPIO pins (not compatible with RPi2)
- Price: 90€

Software

- BPI-Berryboot (allegedly with GPU support), or Ubuntu Mate

Experiences

- SATA shares the USB bus connection and is therefore slow
- Problems accessing the on-board micro-phone

Core Specs of the Lemaker Hikey (older)

- Kirin 620 (SoC) chip with **ARM Cortex A53** and **8 cores**
- ARM Mali450-MP4 (supports OpenGL etc) GPU
- 1 or 2 GB LPDDR3 RAM plus 8 GB eMMC memory and a micro-SD card slot
- **WLAN** (802.11b/g/n)
- Bluetooth 4.1
- 2 USB ports
- 40 GPIO pins (not compatible with RPi2)
- Audio and Video via HDMI connectors
- Board-layout matches the 96-board industrial standard for embedded devices
- Price: 120€

Software

- Android variant (part of 96-board initiative)
- Linaro (specialised Linux version for embedded devices)

Latest version: HiKey 960, with Kirin 960 chipset and a BIGlittle CPU (Cortex A74 quad-core + Cortex A53 quad-core)

Raspberry Pi 3 and Lemaker Hikey: Performance

Performance as runtime (of `sysbench` benchmark) and network bandwidth (using `lperf` benchmark):

	Perf. (runtime) number of threads			Max power	Network bandwidth	
	1	4	8		Ethernet	WLAN
Raspberry Pi 2	297s	75s	—			
Raspberry Pi 3	182s	45s	—			45 Mb/s
Cubox i4Pro	296s	75s	—			
Banana Pi M3	159s	40s	21s	1.1A	633 Mb/s	2.4 Mb/s
Lemaker Hikey	**12s**	**3s**	**2s**	1.7A	—	37.3 Mb/s

Summary: In terms of performance, the Lemaker Hikey is the best choice (of these devices).

[0] Material from Raspberry Pi Geek 04/2016

Raspberry Pi 3 and Lemaker Hikey: Performance comparison

Benchmark-Ergebnisse			
	1 Thread	4 Threads	8 Threads
Raspberry Pi 3	182 Sekunden	45 Sekunden	–
Banana Pi M3	159 Sekunden	40 Sekunden	21 Sekunden
Lemaker Hikey	12 Sekunden	3 Sekunden	2 Sekunden

To run the (CPU) performance benchmark on the RPi2 do:

```
> sudo apt-get update
> sudo apt-get install sysbench
> sysbench --num-threads=1 --cpu-max-prime=10000 --test=cpu
    run
```

[0] Material from Raspberry Pi Geek 04/2016

Core Specs of Odroid-XU4

- Exynos 5422 (SoC) Octa big.LITTLE ARM with an ARM Cortex-A15 quad-core and an ARM Cortex-A7 quad-core
- Mali-T628 MP6 GPU
- 2 GB LPDDR3 RAM plus eMMC memory and a micro-SD card slot
- **Gigabit Ethernet**
- 1 USB 2.0A and **1 USB 3.0** port
- Video via HDMI connectors
- 40 GPIO pins (not compatible with RPi2)
- Price: 95€

The CPU is the same as in high-end smartphones such as the Samsug Galaxy S5.
The big.LITTLE architecture dynamically switches from (faster) Cortex-A15 to (slower) Cortex-A7 to save power.
Software: Ubuntu 14.04 or Ubuntu 16.04; Android 4.4.4; **OpenMediaVault 2.2.13**, Kali Linux, Debian.

HERIOT WATT UNIVERSITY

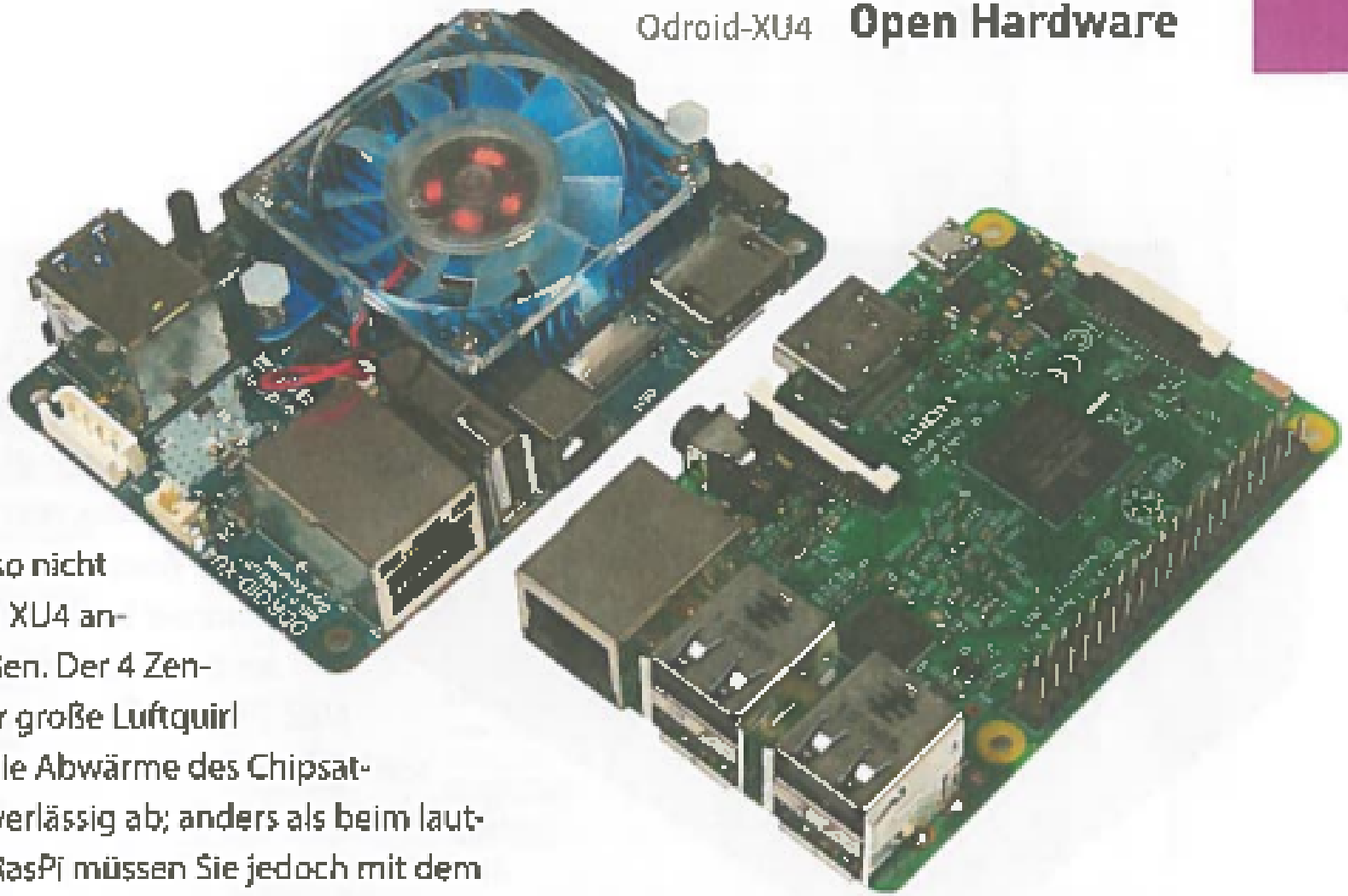
RPi3 vs Odroid-XU4: Specs

Odroid-XU4 vs. Raspberry Pi 3		
	Odroid-XU4	**RasPi 3**
SoC	Exynos 5422 Octa big.LITTLE ARM	Broadcom BCM2837
CPU	Cortex-A15 (2.0 GHz) Quad-Core und Cortex-A7 Quad-Core	ARM Cortex-A53 Quad-Core (1,2 GHz)
GPU	Mali-T628 MP6	Broadcom Dual Core VideoCore IV
RAM	2 GByte LPDDR3 (933 MHz)	1 GByte LPDDR2 (900 MHz)
Speicher	Micro-SD, eMMC 5.0	Micro-SD
Netzwerk	10/100/1000-Mbit/s-Ethernet	10/100-Mbit/s-Ethernet, WLAN 802.11b/g/n
USB	USB 2.0 A, 2 USB 3.0	4 USB 2.0 (über Hub)
Videoausgang	HDMI	HDMI
Schnittstellen	I2S, I²C, GPIO	SPI, I²C, UART
Größe	83 x 59 x 18 mm	85,6 x 56 x 21 mm
Preis (ca.)	95 Euro	35 Euro

[0] Material from Raspberry Pi Geek 02/2017

Odroid-XU4

Odroid-XU4 **Open Hardware**



ich also nicht
n den XU4 an-
chließen. Der 4 Zen-
meter große Luftquirl
ührt die Abwärme des Chipsat-
es zuverlässig ab; anders als beim laut-
ɔsen RasPi müssen Sie jedoch mit dem
aufgeräusch leben. Laut Angaben des
lerstellers springt der Lüfter jedoch nur
ei hoher CPU-Auslastung an – da haben

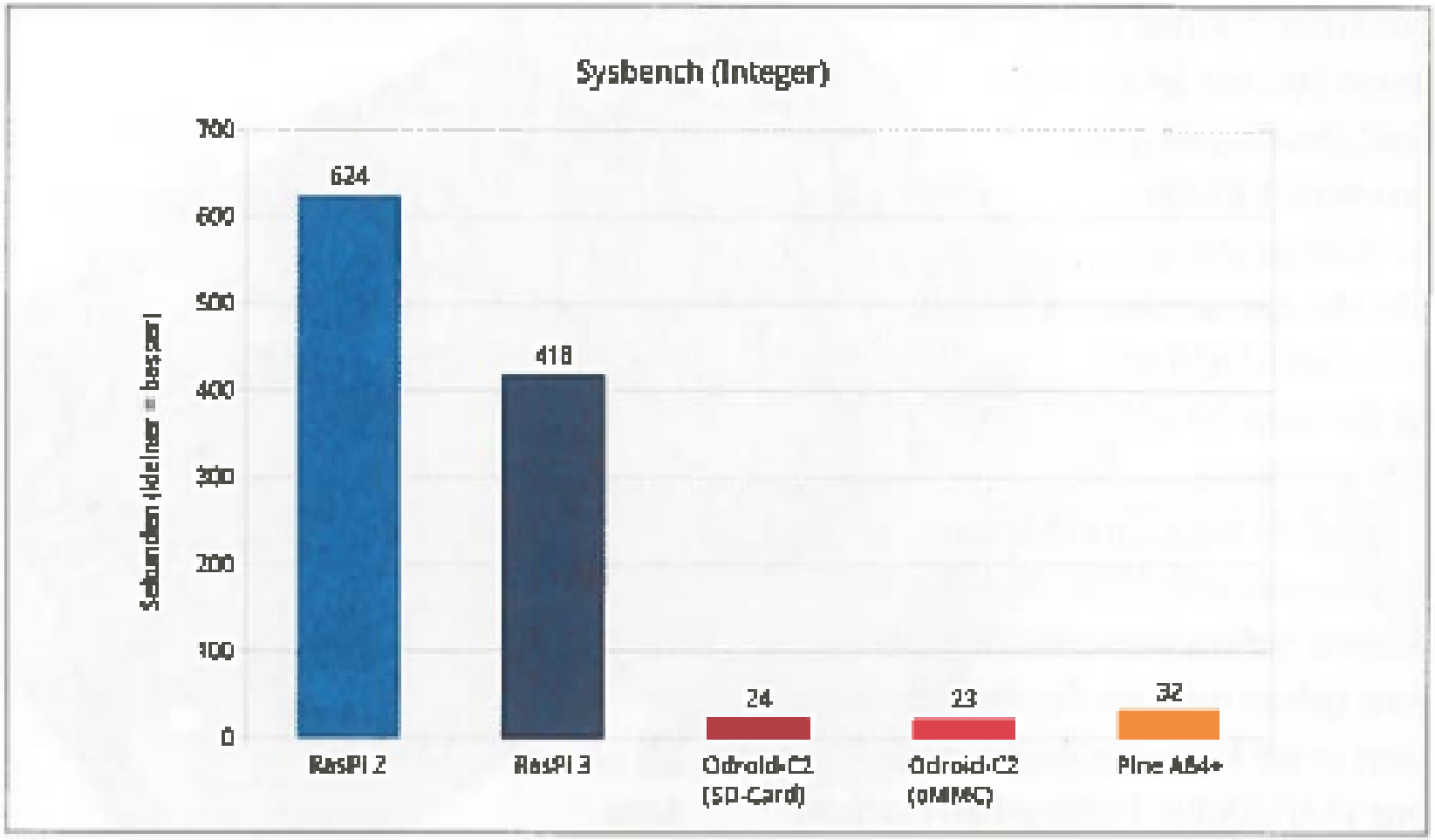
1 **In den Dimensionen unterscheiden sich Odroid-XU4 und Raspberry Pi 3 kaum.**

Network performance: RPi3 vs Odroid-XU4

Datenraten im Vergleich		
	Raspberry Pi 3	Odroid-XU4
Samba		
Datenrate (Upload)	87,80 Mbit/s	418,68 Mbit/s
Datenrate (Download)	89,63 Mbit/s	469,45 Mbit/s
FTP		
Datenrate (Upload)	84,14 Mbit/s	404,15 Mbit/s
Datenrate (Download)	86,18 Mbit/s	439,46 Mbit/s
SSH		
Datenrate (Upload)	86,90 Mbit/s	305,34 Mbit/s
Datenrate (Download)	88,91 Mbit/s	299,59 Mbit/s
Iperf		
Datenrate	94,73 Mbit/s	511,33 Mbit/s
Sämtliche Übertragungsraten über drei Versuche gemittelt.		

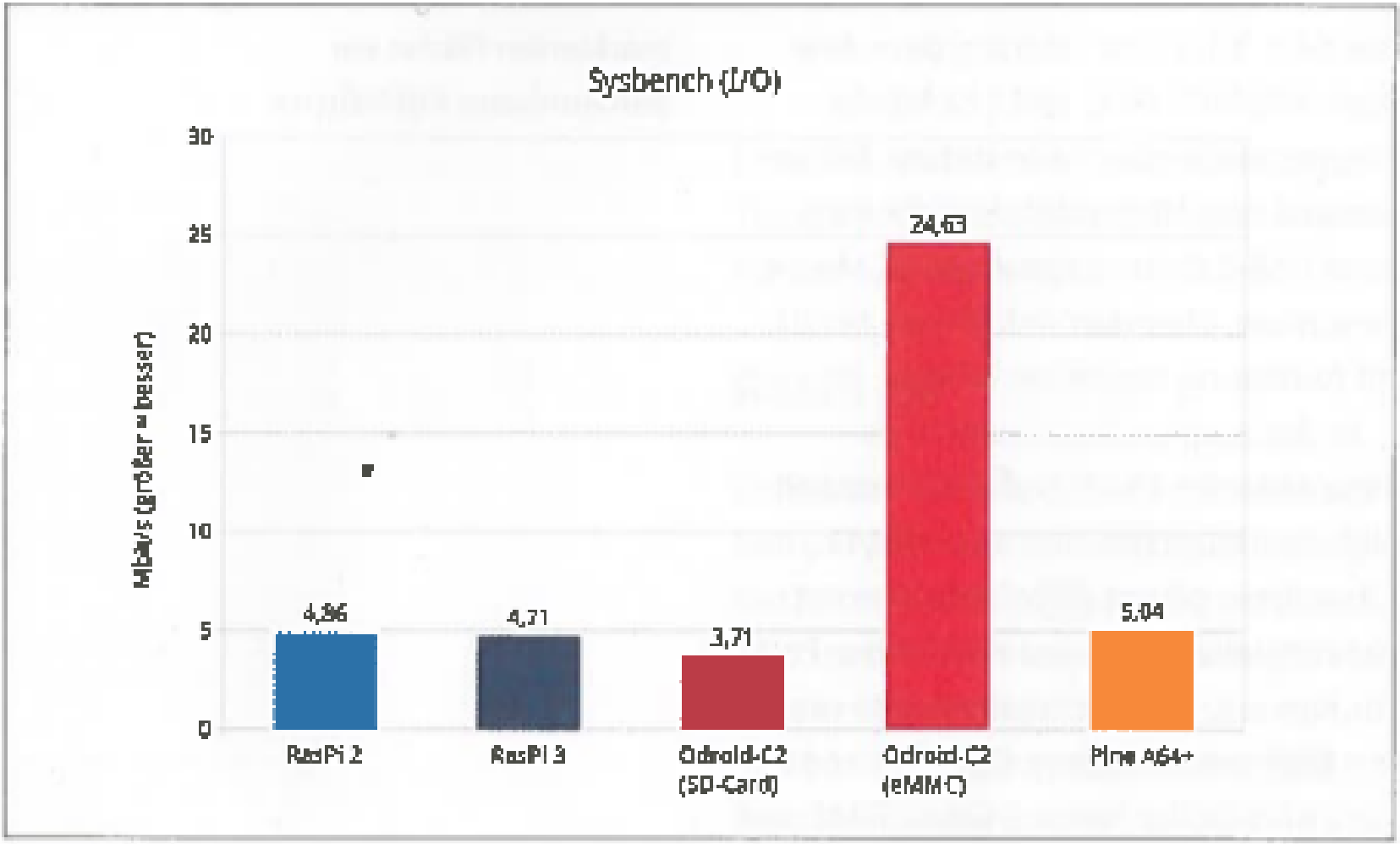
Note: Raw network performance is ca. **5× faster** on the ODroid-XU4!

Raspberry Pi 3 and ODroid C2: CPU Performance Comparison



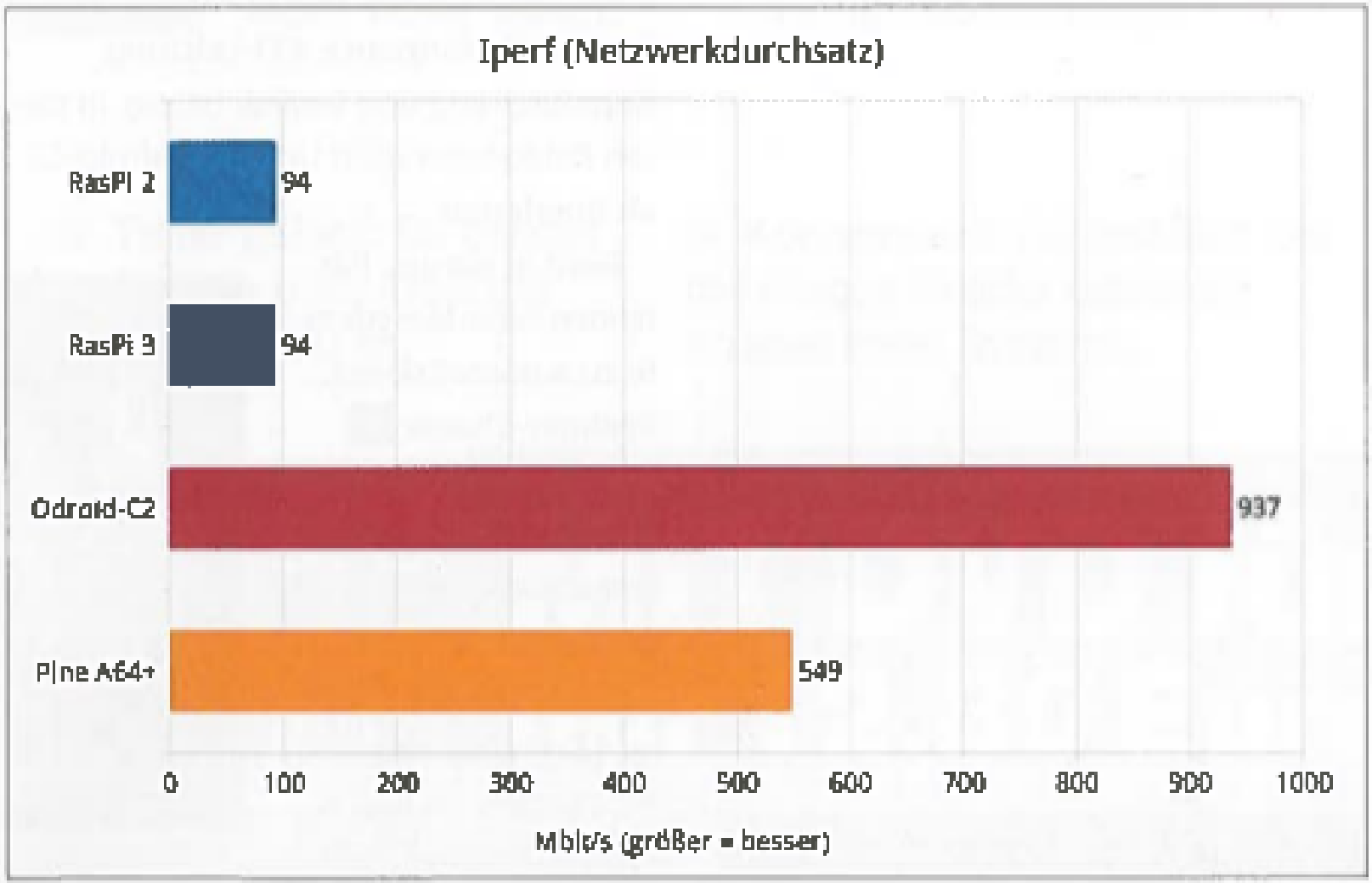
[0] Material from Raspberry Pi Geek 04/2016

Raspberry Pi 3 and ODroid C2: I/O Performance Comparison



[0] Material from Raspberry Pi Geek 04/2016

Raspberry Pi 3 and ODroid C2: Network Performance Comparison



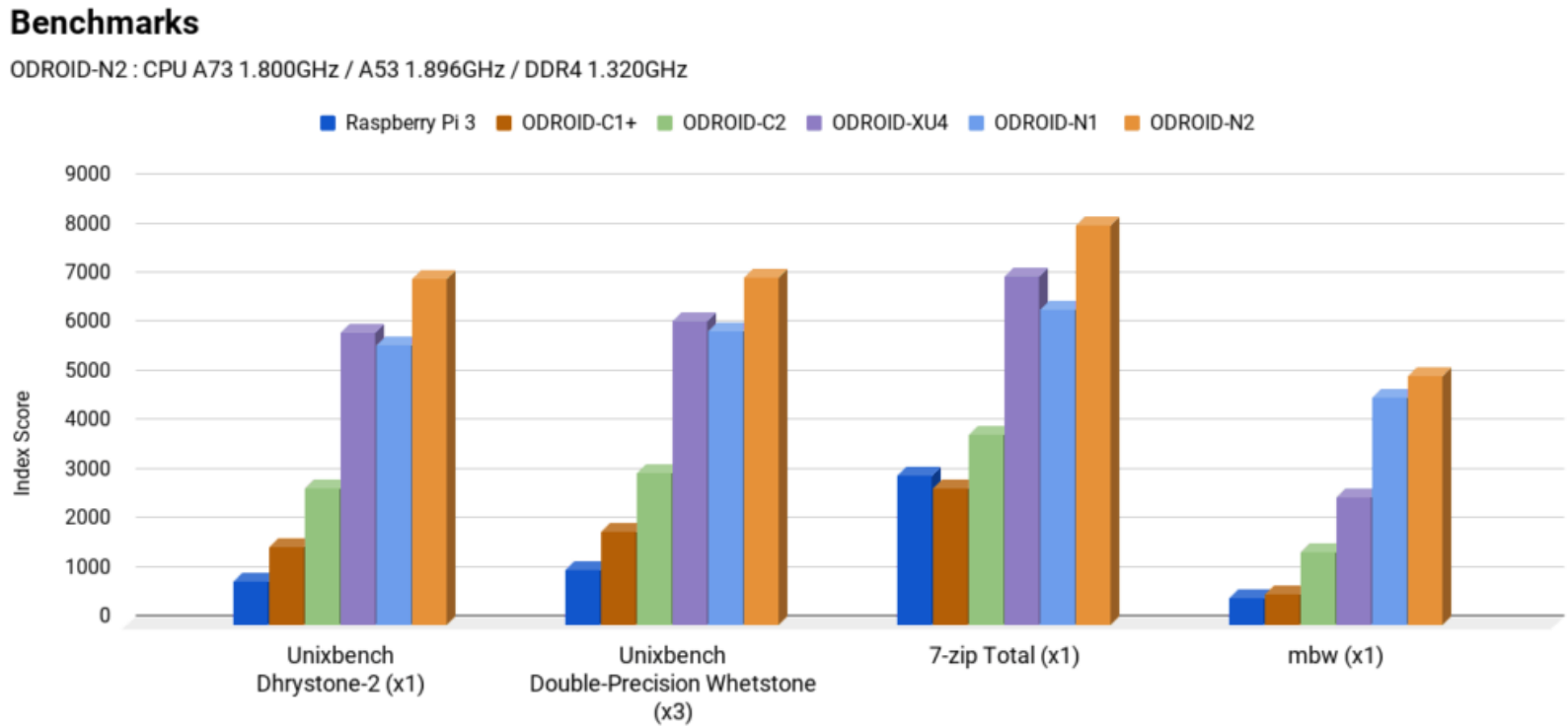
Mit ihrer Fast-Ethernet-Schnittstelle können die Raspberry Pis gegen die Gigabit-

RPi3 vs Odroid-XU4: Experience

- In terms of network-performance, the ODroid-XU4 is much faster.
- It is a good basis for a NAS (Network attached Storage).
- In terms of CPU-performance, the Odroid is slightly faster: Cortex-A15 (2.0 GHz) vs Cortex-A53 (1.2 GHz).
- However, in practice, the **GUI is much slower**.
- Based on the `gtkperf` GUI benchmark, the ODroid is ca. **3× slower**.
- The reason for this difference is more optimisation in the device drivers for RPi's VideoCore IV GPU (compared to ODroid's Mali GPU).
- **Note:** To assess performance and usability, one has to consider the entire software stack, not just the raw performance of the hardware!

HERIOT WATT UNIVERSITY

Performance comparison: Odroid vs RPi4



[0] From RPi4 vs Odroid on MightyGadget pages

Orange Pi (slightly older)

- Allwinner H3 Soc: Quad-core Cortex-A7 H.265/HEVC 4K
- Mali 400MP2 GPU @ 600MHz
- 1GB DDR3 memory (shared with GPU)
- 8GB EMMC Flash
- 10/100 Ethernet RJ45
- 40 Pins Header,compatible with Raspberry Pi B+
- Runs: Android, Lubuntu, Debian, Raspbian

Beware of stability and performance of the software!

Orange Pi 5 (latest)

- Rockchip RK3588 8-core 64-bit processor with 4 Cortex-A76 (2.4GHz), 4 Cortex-A55 (1.8GHz)
- ARM Mali-G610, built-in 3D GPU (OpenGL)
- embedded NPU supporting INT4/INT8/INT16/FP16 hybrid computing (6TOPS)
- up to 16GB LPDDR5 memory (shared with GPU)
- EMMC Flash socket
- one M.2 M-Key slot (PCIe 3.0 4-Lane) for NVMe memory
- 40 Pins Header,compatible with Raspberry Pi B+
- Runs: Orange Pi OS, Ubuntu, Android 13, Debian and other operating systems.

[0] See Orange Pi 5 Spec

Orange Pi RV2

This is a **RISC-V** based alternative (**Open Hardware**):

- Ky X1 8-core **RISC-V** AI CPU
- NPU (2TOPS)
- up to 8GB LDDDR4 memory
- eMMC module (up to 128GB)
- 2× M.2 M-Key SOCKET: PCIe2.0 2 Lane **NVMe** SSD
- 2× Gigabit Ethernet
- 26 GPIO Pins Header
- Runs: Ubuntu24.04

Applications: NAS, Home automation, Intelligent Robotics, Edge computing.

Summary

- The Raspberry Pi is one of the most widely-used single-board computers.
- The RPi comes in several version (1,2,3,4,5); we are using the **Raspberry Pi 2 or 3 model B**.
- The Raspberry Pi 5 is performant enough to serve as a desktop replacement (but GPIO controller is different!)
- There is a rich software eco-system for the RPis and excellent, detailed documentation.
- A good high-CPU-performance alternatives is: Okdo Rock 5 (new) or Lemaker HiKey (older)
- A good high-network-performance alternative is: Odroid-XU4 (old)
- Check out the Raspberry Pi projects available online.

HERIOT WATT UNIVERSITY