Qualcomm's mobile processor lines

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2018 December

(Ver. 3.0)

Contents

1. Qualcomm's role in the mobile segment

1. Qualcomm's role in the mobile segment

Market share of leading companies in supplying modems and transceivers for mobile communication [1]

(Share of Global Revenue)

Q3-12 Rank	Company Name	Percent of Total
1	Qualcomm	52.3%
2	MediaTek	14.9%
3	Intel	8.4%
4	Broadcom	5.6%
5	STMicroelectronics	5.3%
	Top 5 Companies	**86.6%**
	All Others	**13.4%**

Source: IHS iSuppli Research, January 2013

1. Qualcomm’s role in the mobile segment (2)

Broadcom's and Ericsson's exit from the modem market [2]

- In 6/2014 Broadcom announced their decision to discontinue the firm's modem activities and to sell or offload the associated division.

  It came as a surprise since Broadcom only recently (9/2013) acquired Renesas' Mobile division from Nokia.

  The reason is the fact that Broadcom was not able to compete with Qualcomm and others in the 4G space.

- In 9/2014 also Ericsson disclosed their exit from the mobile modem business.
  It resulted from Ericson's failure to develop integrated devices (modems + application processors) in line with OEM's preference.

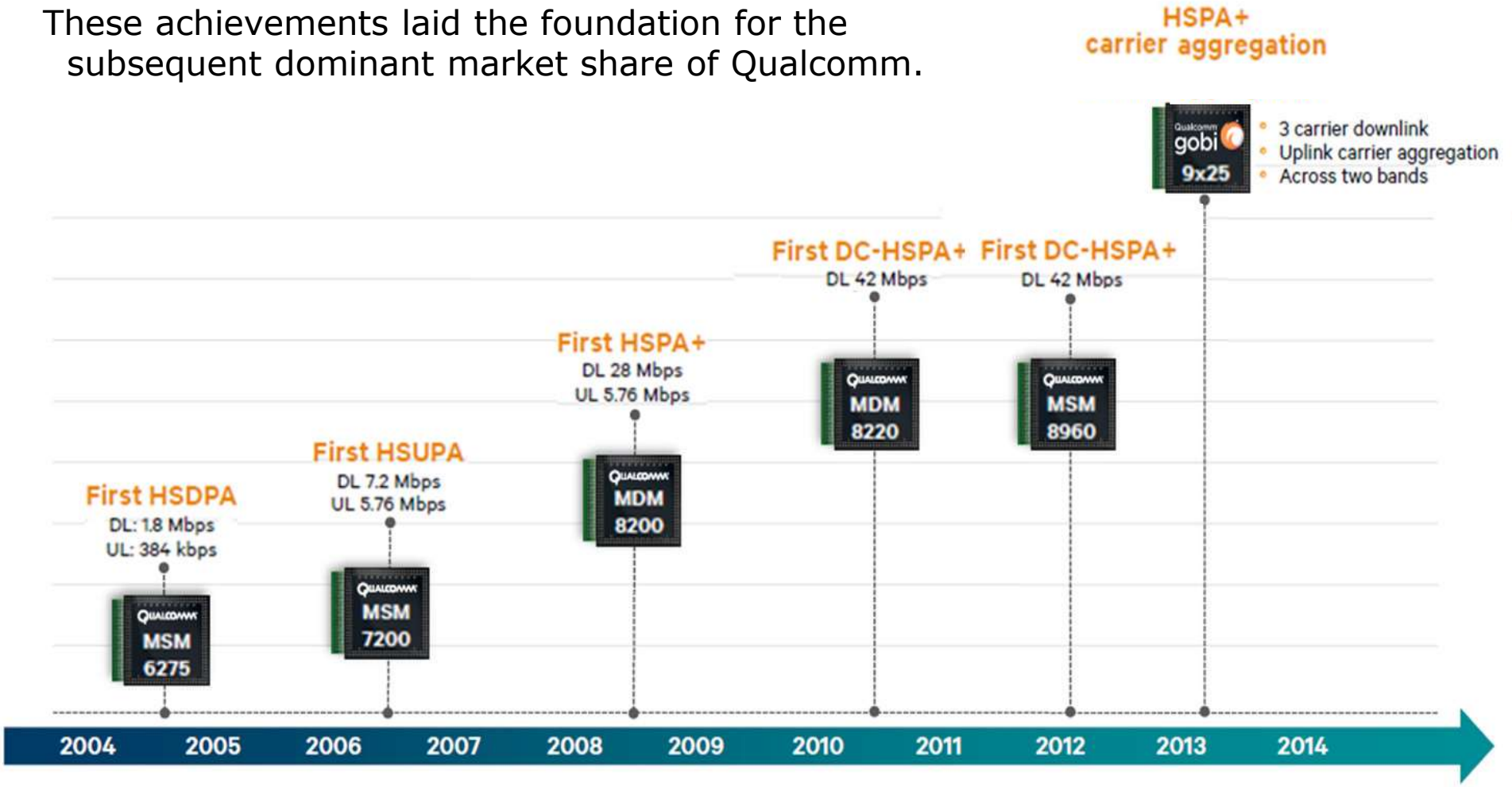
1. Qualcomm's role in the mobile segment (3)

Samsung's plan to enter the integrated modem market [3]

- In 7/2014 Samsung announced their new quad-core Exynos ModAp that will be the firms first generation integrated LTE Modem-Application processor with up to LTE Release 9 (advanced LTE) Cat 4 connectivity.
- The processor is built on a 28 nm HKMG (High-K Metal Gate) process and is said to be faster and more battery friendly than its predecessors.
- ModAp incorporates a powerful internal image signal processor.
- A new Exynos RF transceiver companion chip is also available.
- No shipping dates were revealed.

Qualcomm's eminent role in implementing 3G standards [4]

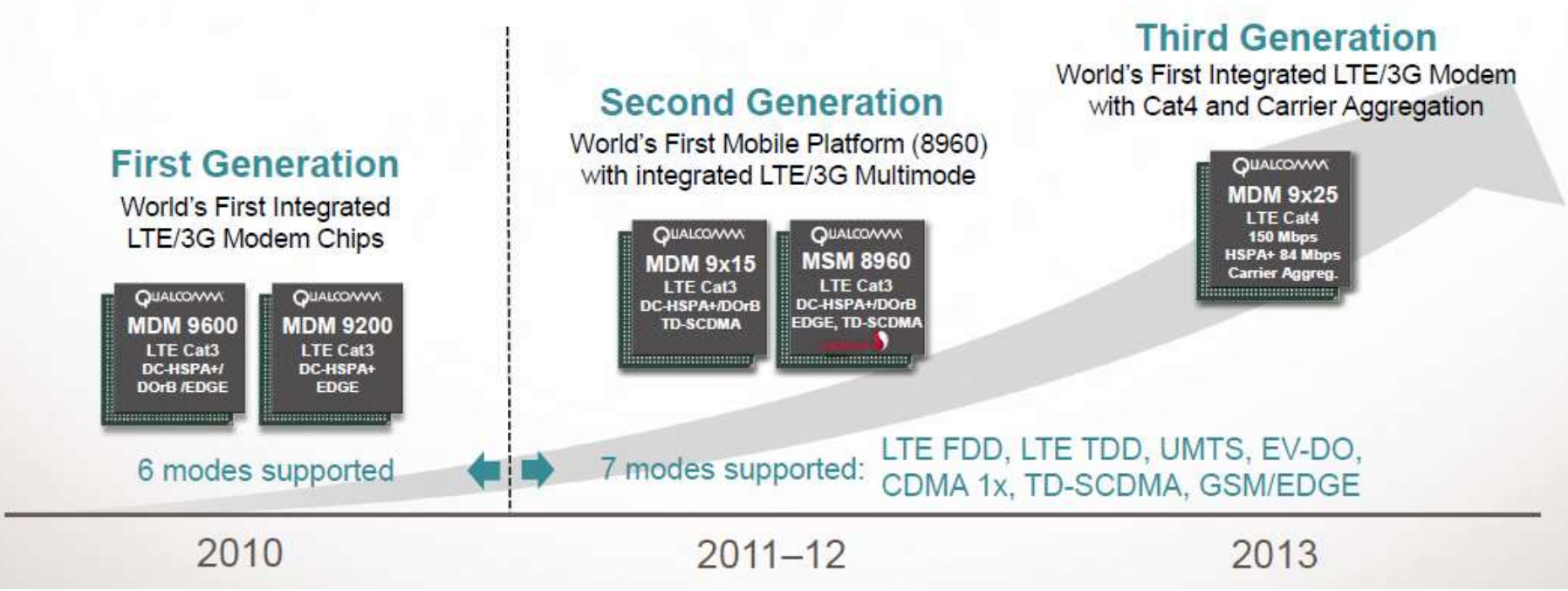
These achievements laid the foundation for the subsequent dominant market share of Qualcomm.



9x25 – LTE-A CA was launched in 2013,
HPSPA+ UL-CA expected to launch in 2014,
HSPA+ DL 3-carrier CA supported but not yet launched

1. Qualcomm's role in the mobile segment (5)

Qualcomm's eminent role in implementing 4G standards [5]



1. Qualcomm's role in the mobile segment (6)

Qualcomm's main product lines designed for mobiles

Qualcomm's main product lines is differentiated by prefixes, as indicated below.

Qualcomm's main product lines designed for mobiles

MSMs	**APQs**	**MDMs**	**QSCs**
(Mobile Station Modems) Previous designation: QSD (Qualcomm Snapdragon SOC)	(Application Processors of Qualcomm)	(Mobile Data Modems)	(Qualcomm Single Chips)
Application processors with an integrated modem	Application processors without an integrated modem	Stand alone RF modems, typically without an RF transceiver	SOCs including an integrated application processor, modem and RF transceiver
Since 2007: **Snapdragon platform**			
Typ. use *Smartphones, tablets*		*WWAN cards , like Gobi WWAN cards, for notebooks, e-readers etc..*	*Feature phones*
Snapdragon S1 – S4 (2007 - 2012) → **Snapdragon S200 – S800** (2013 -)			

2. Introduction to connectivity

2. Introduction to connectivity

Types of connectivity in PCs, laptops, tablets and smartphones [32]

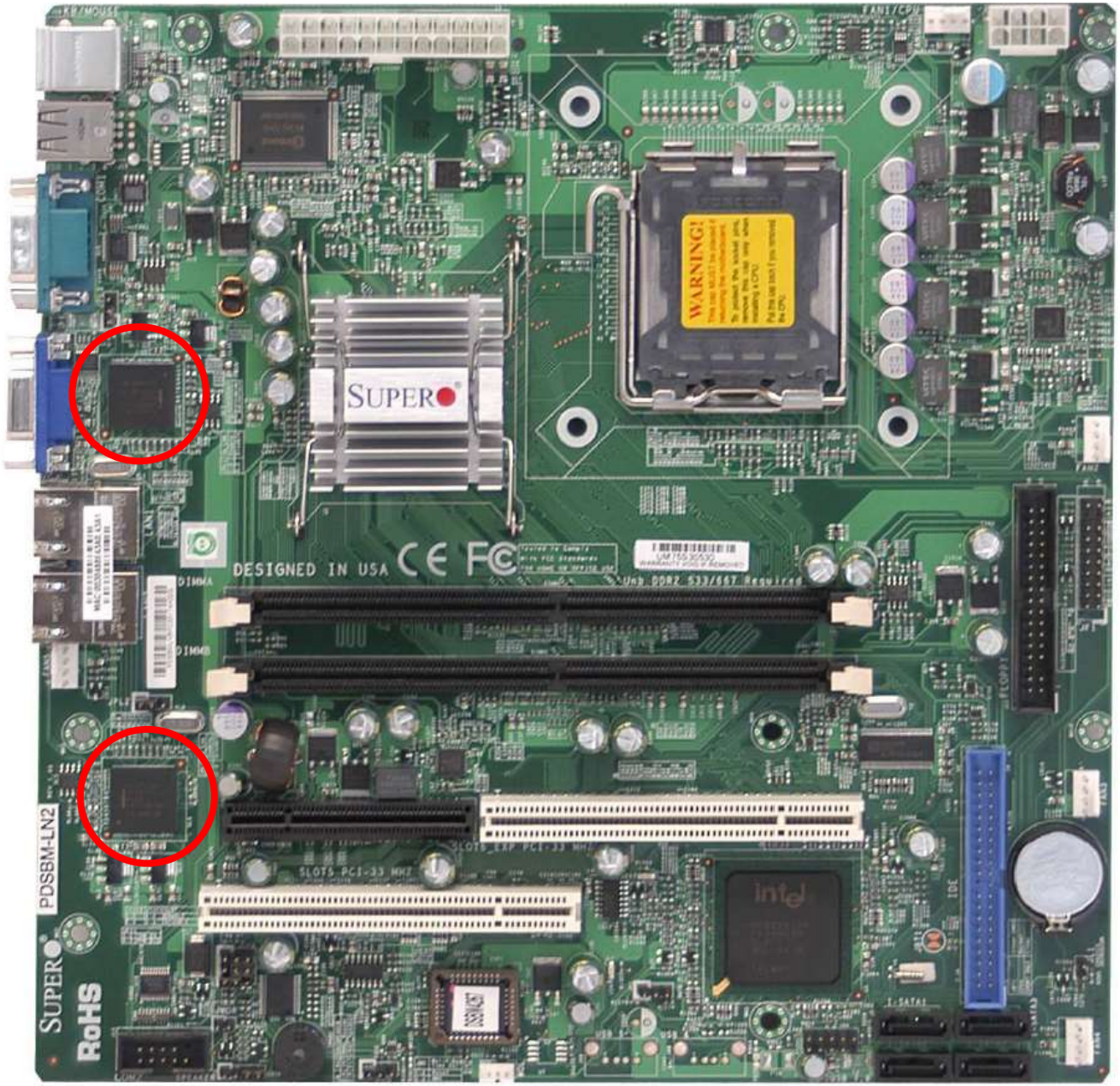
a) LAN (Local Area Network) connectivity

- Implemented typically in PCs and laptops.
- Connectivity over a LAN cable and a LAN controller to a network.
- The LAN controller was implemented earlier on a LAN card (called often Network Interface Card (NIC)), but recently it is usually integrated onto the motherboard.

  There is a wide variety how LAN cards were implemented, this point is however, out of the scope of our interest.
- Accessing contents requires a subscription to a service provider.

Figure: Example for a LAN card
(Dual LAN ports, Gigabit Ethernet Card, PCIe x1 socket [64]

Example for on-board NICs [65]

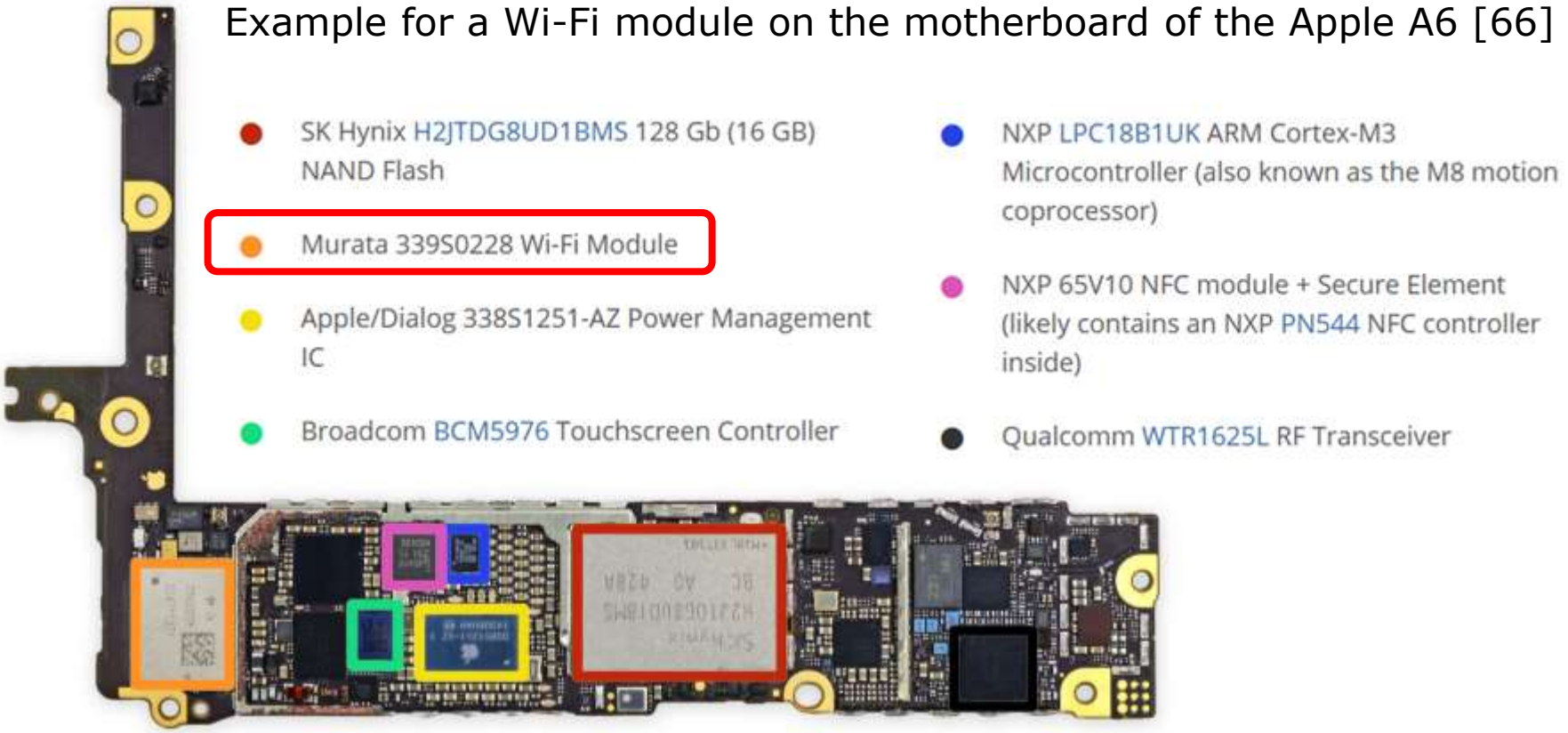


Intel's 82573L Gigabit Ethernet Controllers on a Supermicro Core 2-based motherboard (2009)

b) WLAN (Wireless Local Area Network) connectivity

- Provides connectivity via a Wi-Fi router or wireless router.
- WLAN covers a small area, typically up to hundreds of meters distance.
- WLAN connectivity is commonly provided in homes, offices, hotels etc.
- It needs a WLAN card or a WLAN module (chip).
- WLAN provides connectivity usually for laptops, tablets and smartphones.

Example for a Wi-Fi module on the motherboard of the Apple A6 [66]



2. Introduction to connectivity (4)

c) WWAN (Wireless Wide Area Network) connectivity

- Provides connectivity over a mobile (cellular) network (e.g. LTE).
- WWAN became worldwide available.
- For providing the connectivity for WWAN see the next Table.

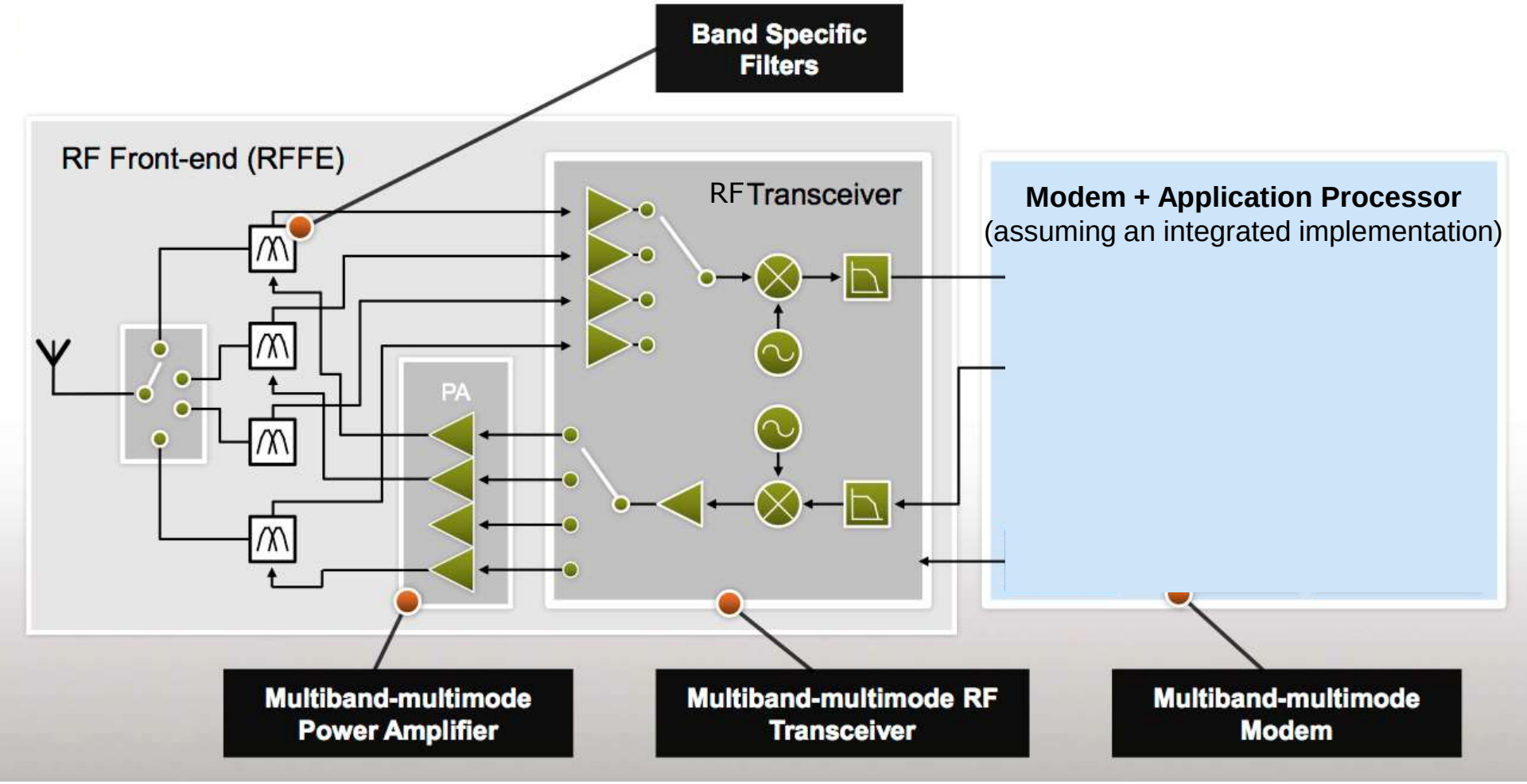
2. Introduction to connectivity (5)

Typical implementation of mobile (cellular) connectivity, called also WWAN (Wireless Wide Area Network) connectivity

<table>
<tr><th></th><th>In desktops</th><th>In notebooks</th><th>In tablets</th><th>In smart phones</th><th>In features phones</th></tr>
<tr><td>WWAN connectivity provided by</td><td colspan="2">WWAN card
The WWAN card includes
• the baseband modem +
• the RF transceiver
E.g. MDMs from Qualcomm (Gobi cards).</td><td colspan="2">Two chips,
• a SOC including
• the appl. processor and
• the baseband modem
+
• RF transceiver
E.g. MSM processors from Qualcomm, or most contemporary processors.
or
Three discrete chips:
• the appl. proc.
• the baseband modem
• the RF transceiver
E.g. processors with discrete modems, like Apple's recent processors.</td><td>SOC including
• a simple appl. proc.
• the baseband modem
• the RF transceiver
E.g. QSCs from Qualcomm-</td></tr>
</table>

Introduction to connectivity

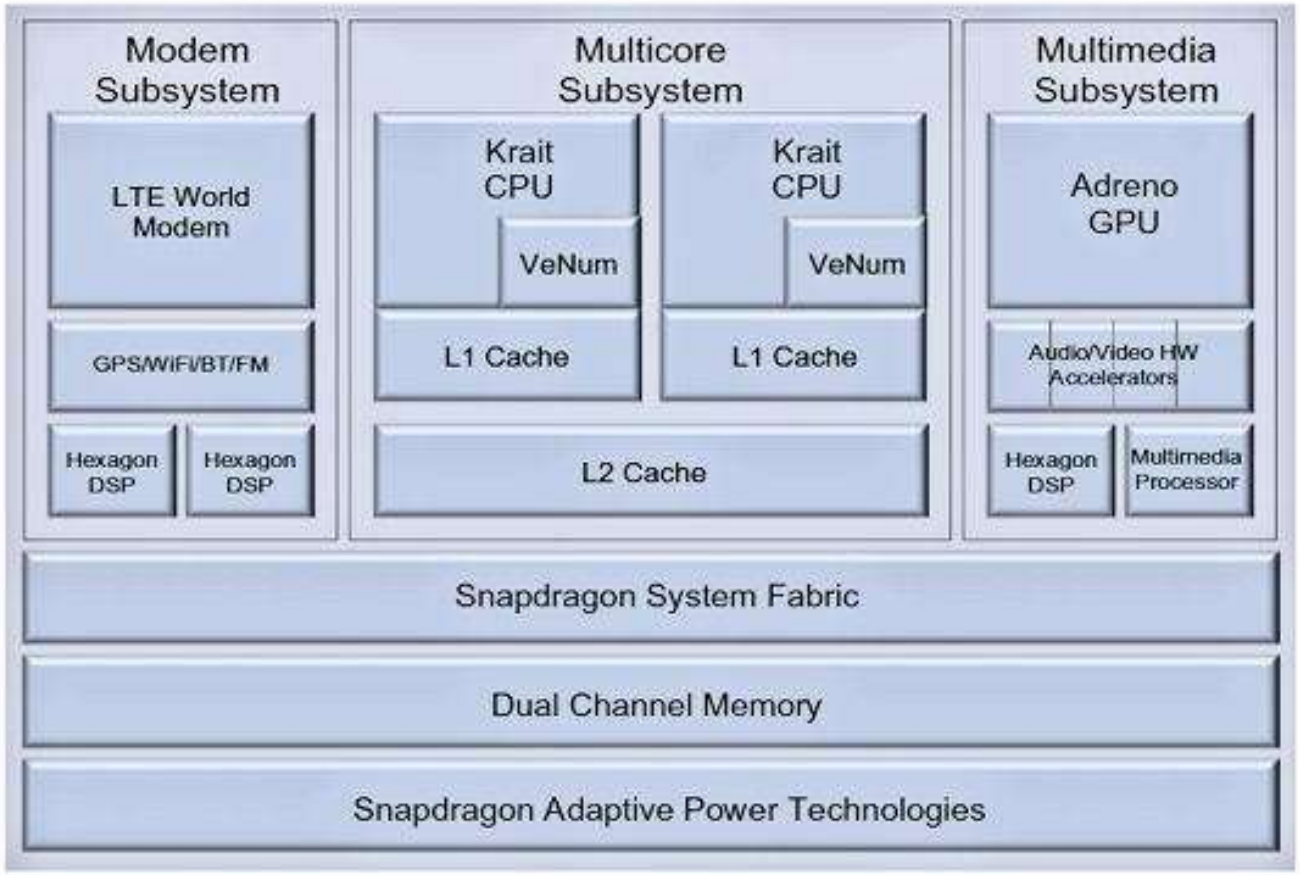
Strongly simplified view of a mobile platform [6]



PA: Power Amplifier

2. Introduction to connectivity (7)

Example for an integrated modem + Application processor
(Actually it is a specific model of Qualcomm's Snapdragon S4 line) [7]



Multimode support

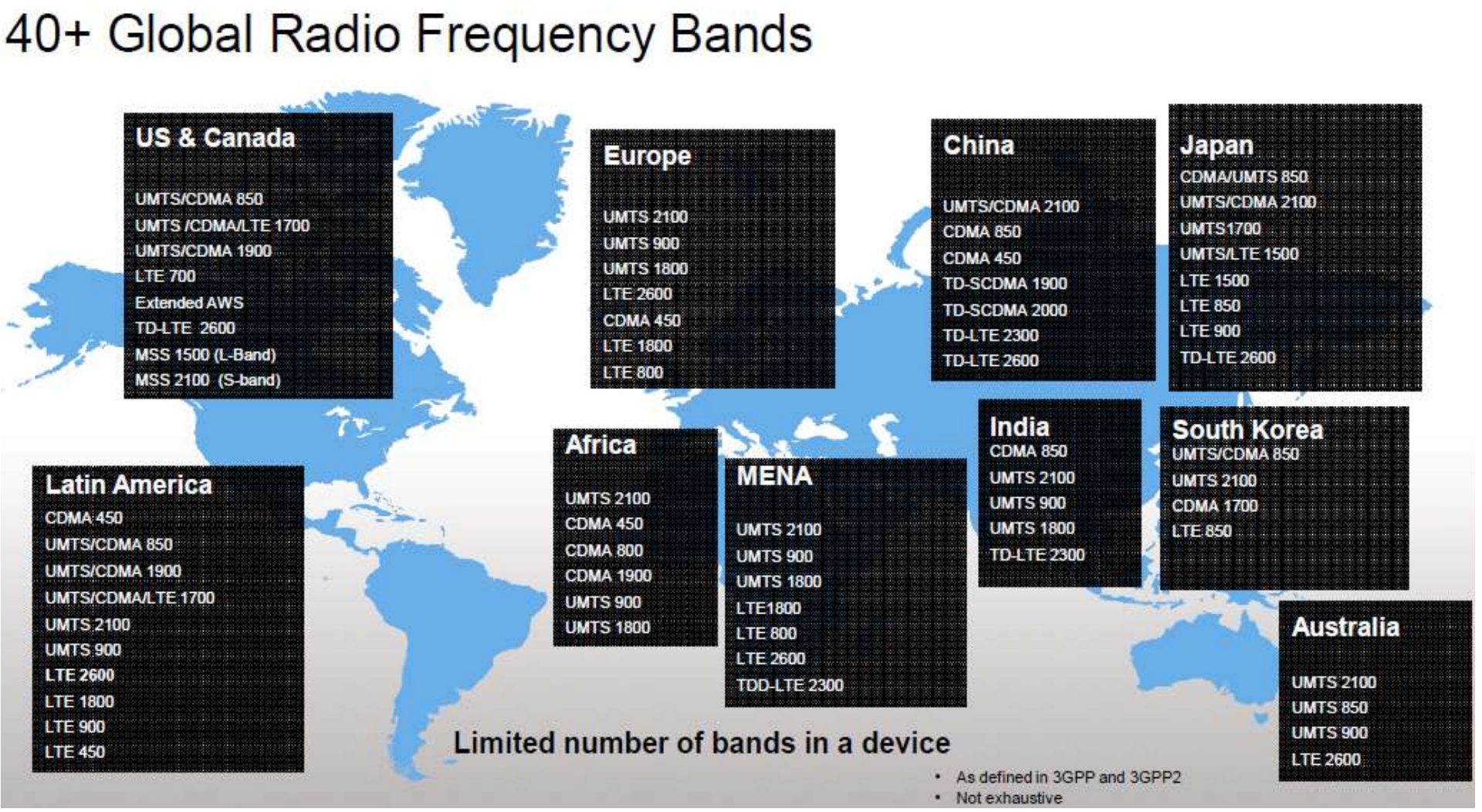
It means support for multiple standards, like in case of the Snapdragon 810, as indicated below.

- LTE Advanced CAT6 supporting LTE FDD, LTE TDD,
- WCDMA (DC-HSPA+, DC-HSUPA),
- CDMA1x,
- EV-DO Rev. B,
- TD-SCDMA and
- GSM/EDGE.

CAT6 speeds are up to 300 Mbps with support for up to 3x20 MHz carrier aggregation on LTE FDD and LTE TDD.

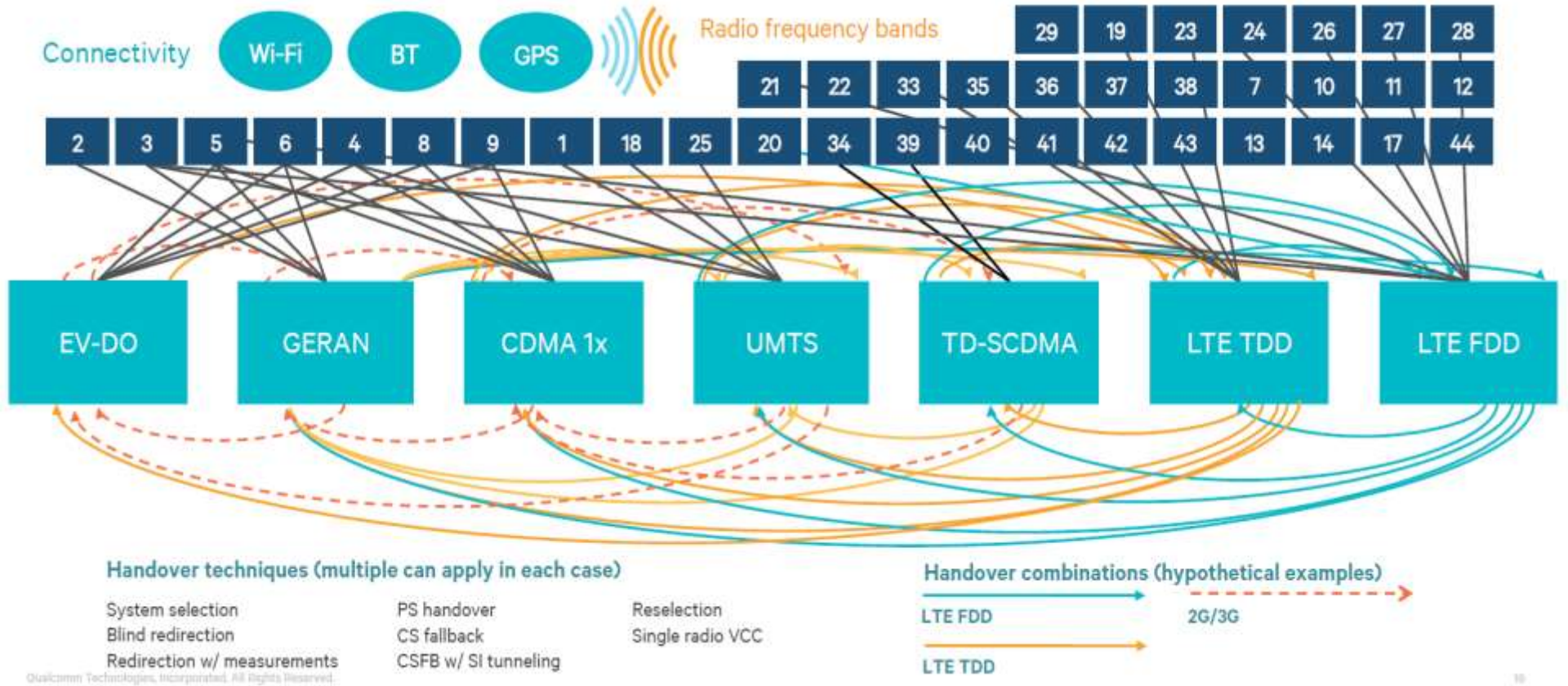
Multiband support – support of world mode bands

Radio frequency bands used over the world in 2012 (40+) [25]



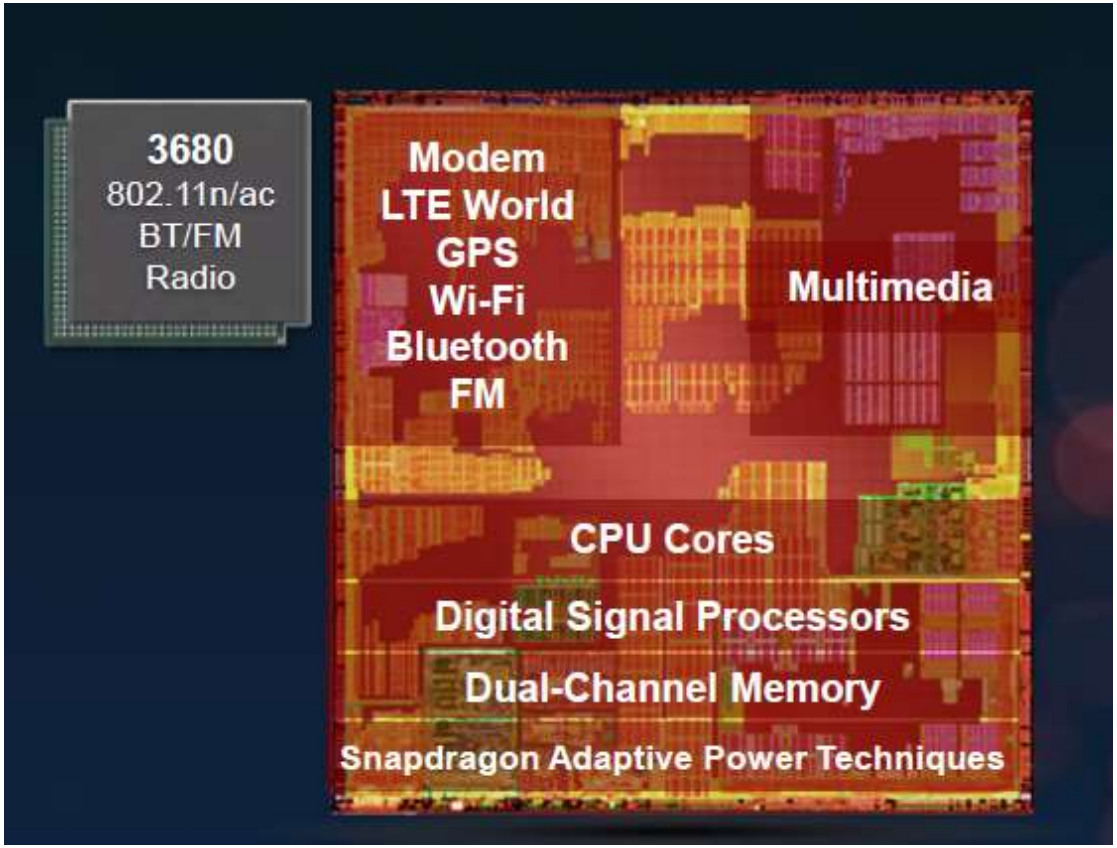
2. Introduction to connectivity (10)

Frequency bands associated with different mobile standards [23]



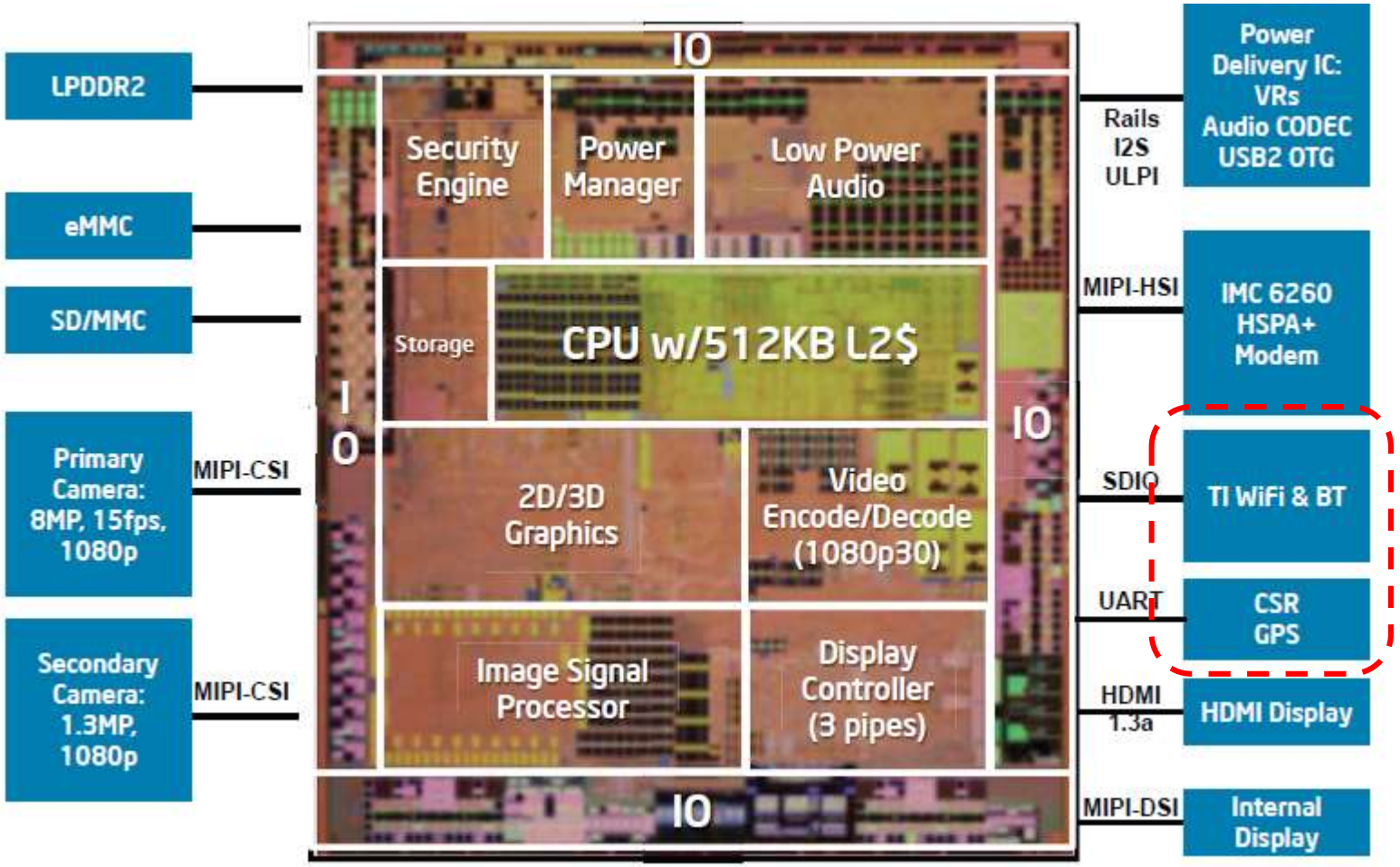
Support of GPS/WiFi/BT by the MSM line in recent implementations [26]

(In 2012 only Qualcomm provided this level of integration)



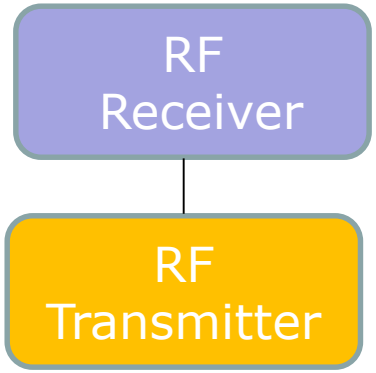
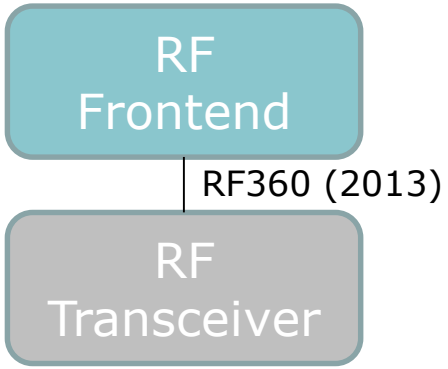
Support of GPS/WiFi/BT by Intel's Medfield (Atom Z2480) [52]

By contrast, we show below the implementation of GPS/WiFi and BT support of Intel's Medfield.

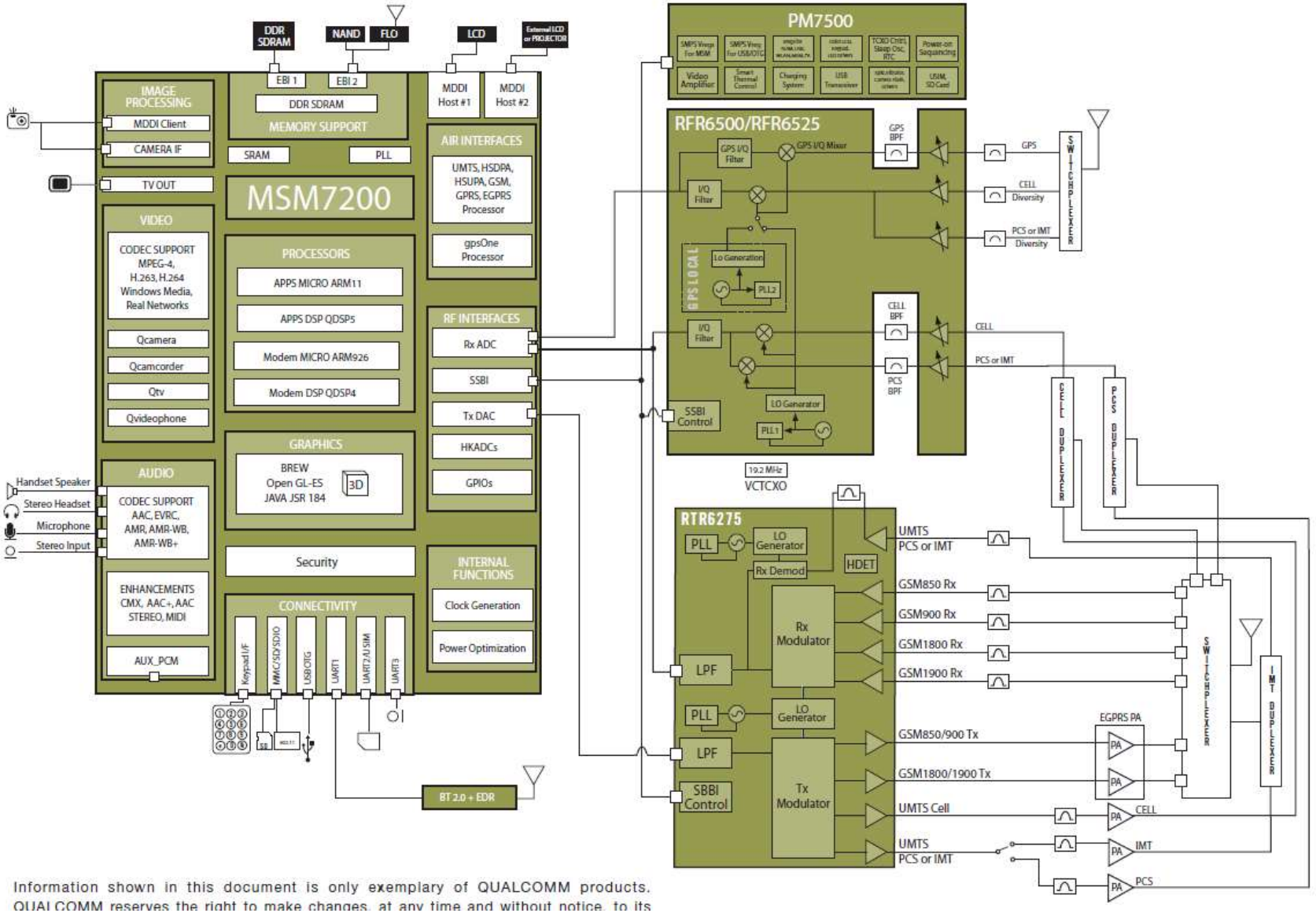


Evolution of Qualcomm's RF receivers and transmitters

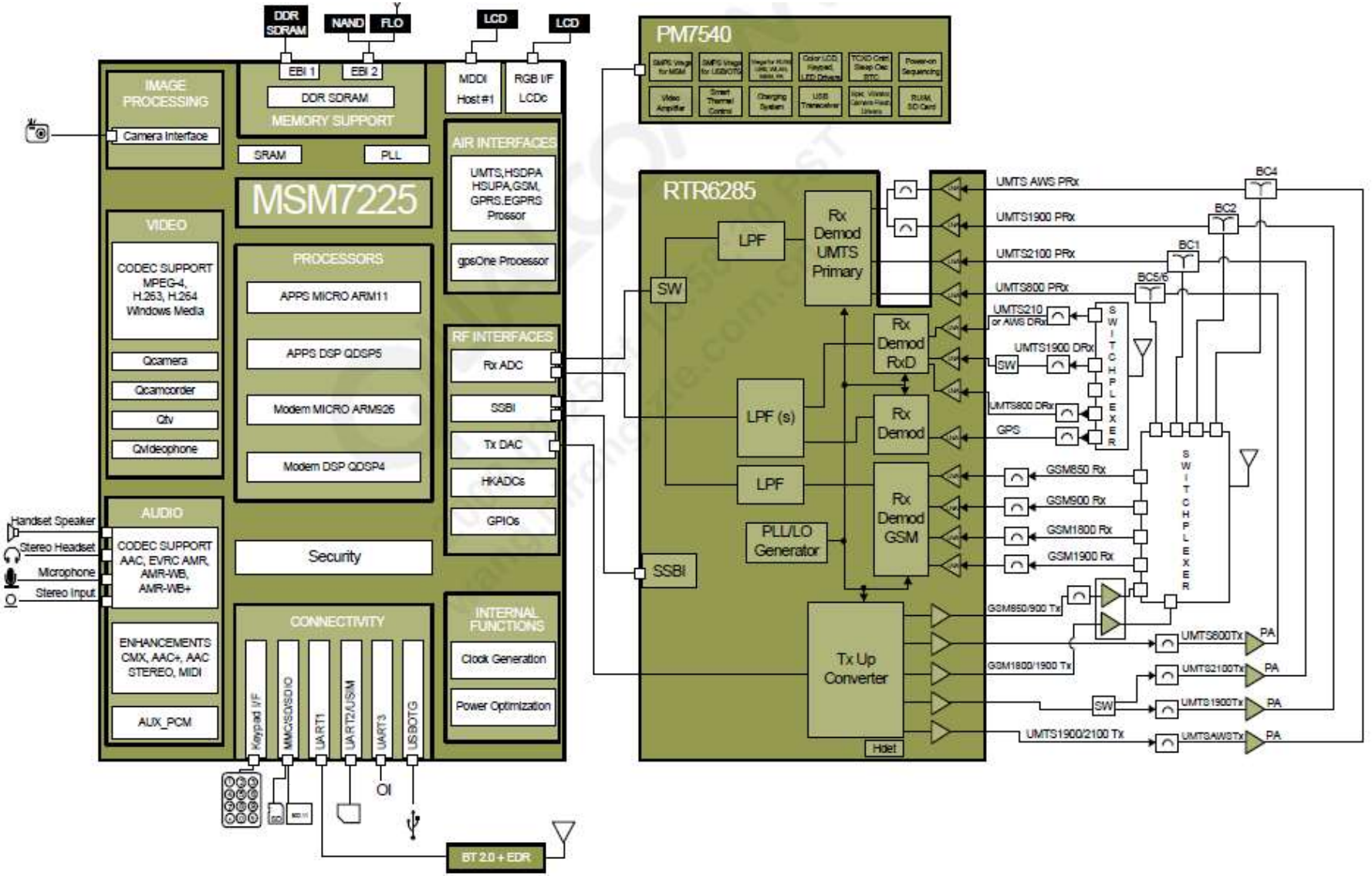
implementation of Qualcomm's RF receivers/transmitters

Separate RF receiver and RF transmitter	**Integrated RF transmitter**	**RF transceiver + front-end**
		
E.g. RFR5200/RFT5200 (2001) RFR6500/RTR6275 (2006)	RTR6285(2007) RTR8600 (2010)	WTR1605L (2013) WTR1625L (2013) WTR3905 (2014) WRT3925 (2014)
Typical use *Before the Snapdragon S1-S4 lines (before 2007)*	*In the Snapdragon S1-S4 lines (2007-2012)*	*In the Snapdragon S200-S800 lines (2013-)*

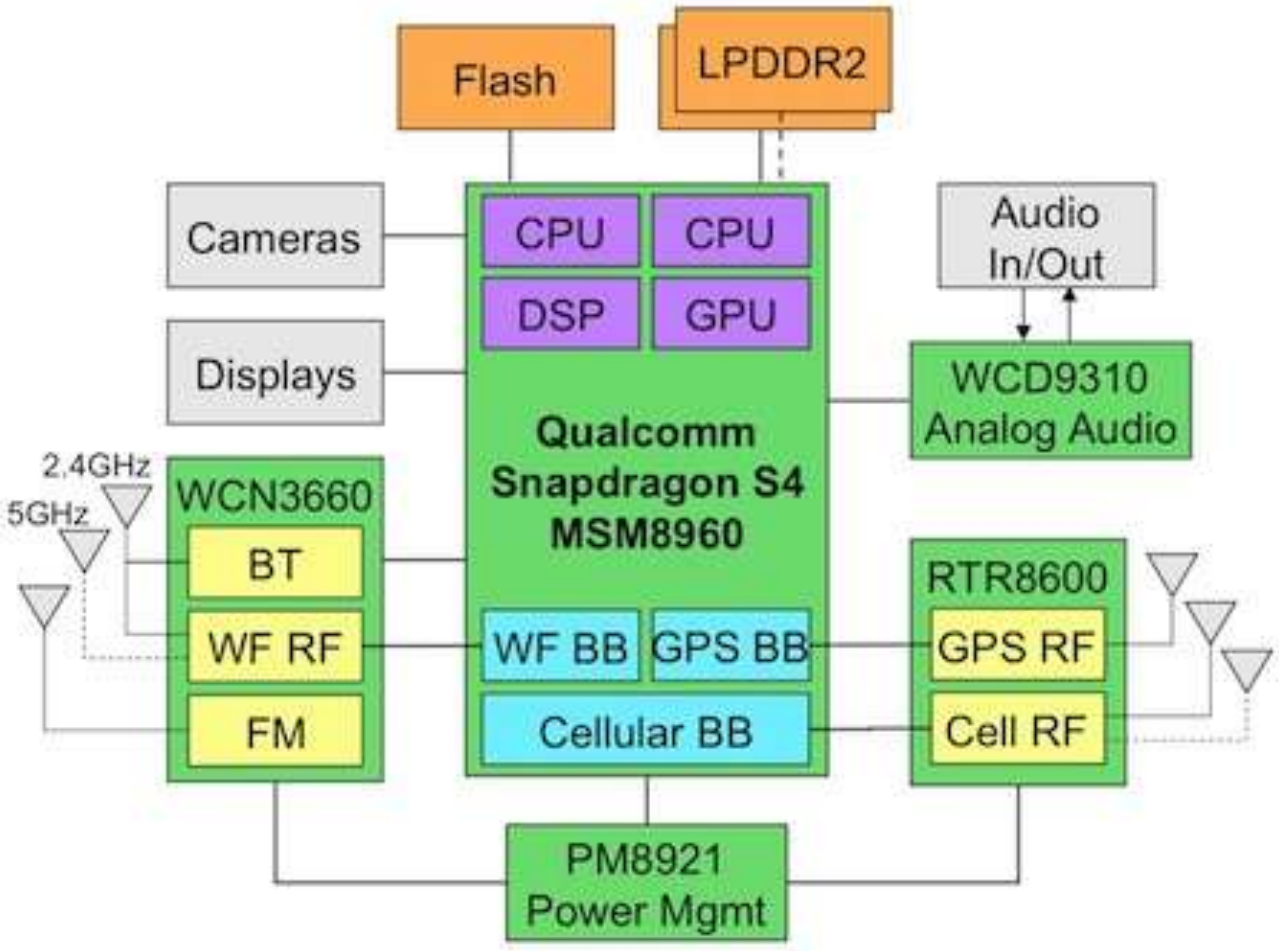
Example for separate RF receiver and transmitter (with MSM7200) (2006) [27]



Example 1 for integrated RF transceiver (with MSM7225 of the S1 line) (2007) [18]

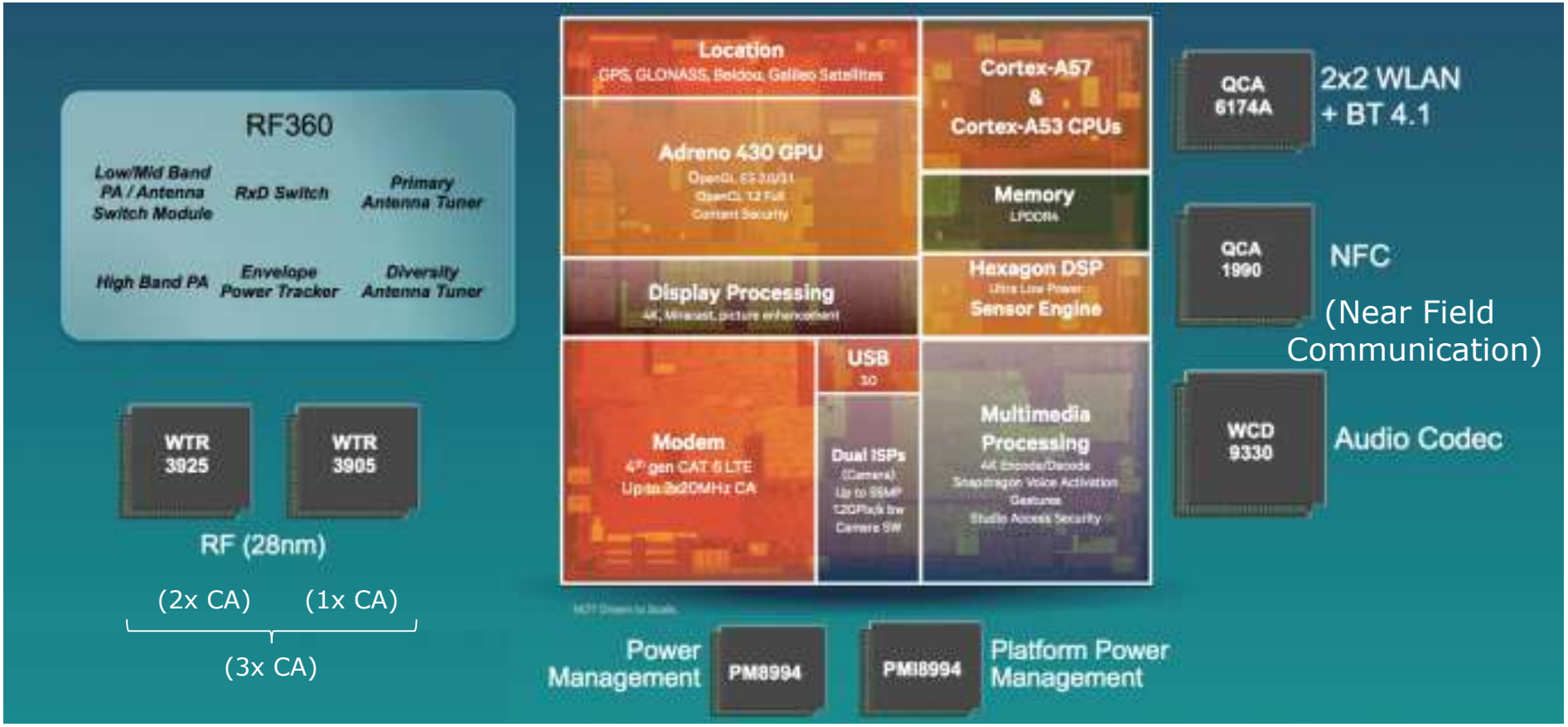


Example 2 for integrated RF transceiver (with MSM8960 of the S4 line) (2007) [28]



RTR8600: RF Transceiver

Example for an RF transceiver and front-end (with MSM8994 of the S810 line) (2015) [24]

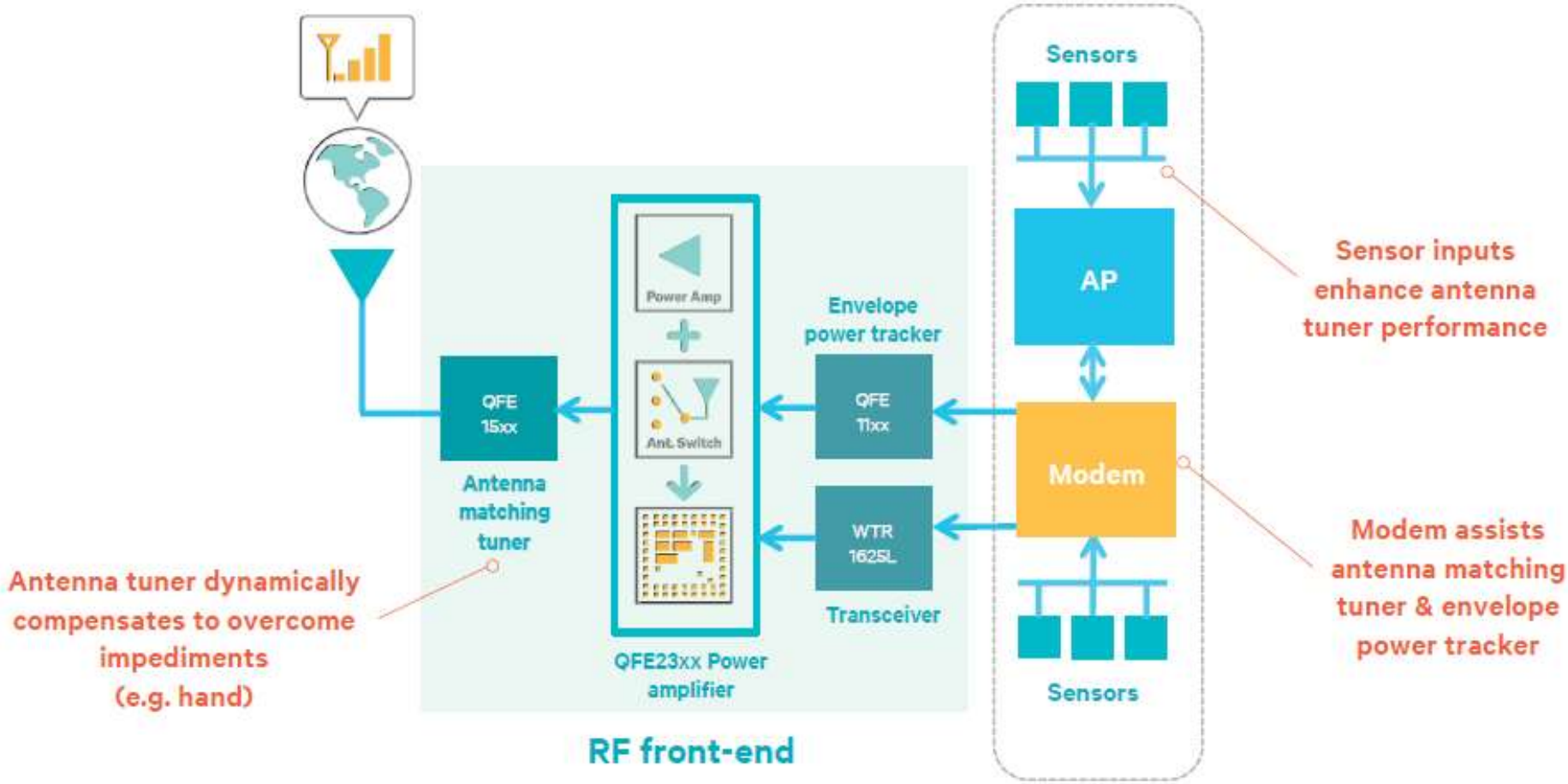


CA: Carrier Aggregation

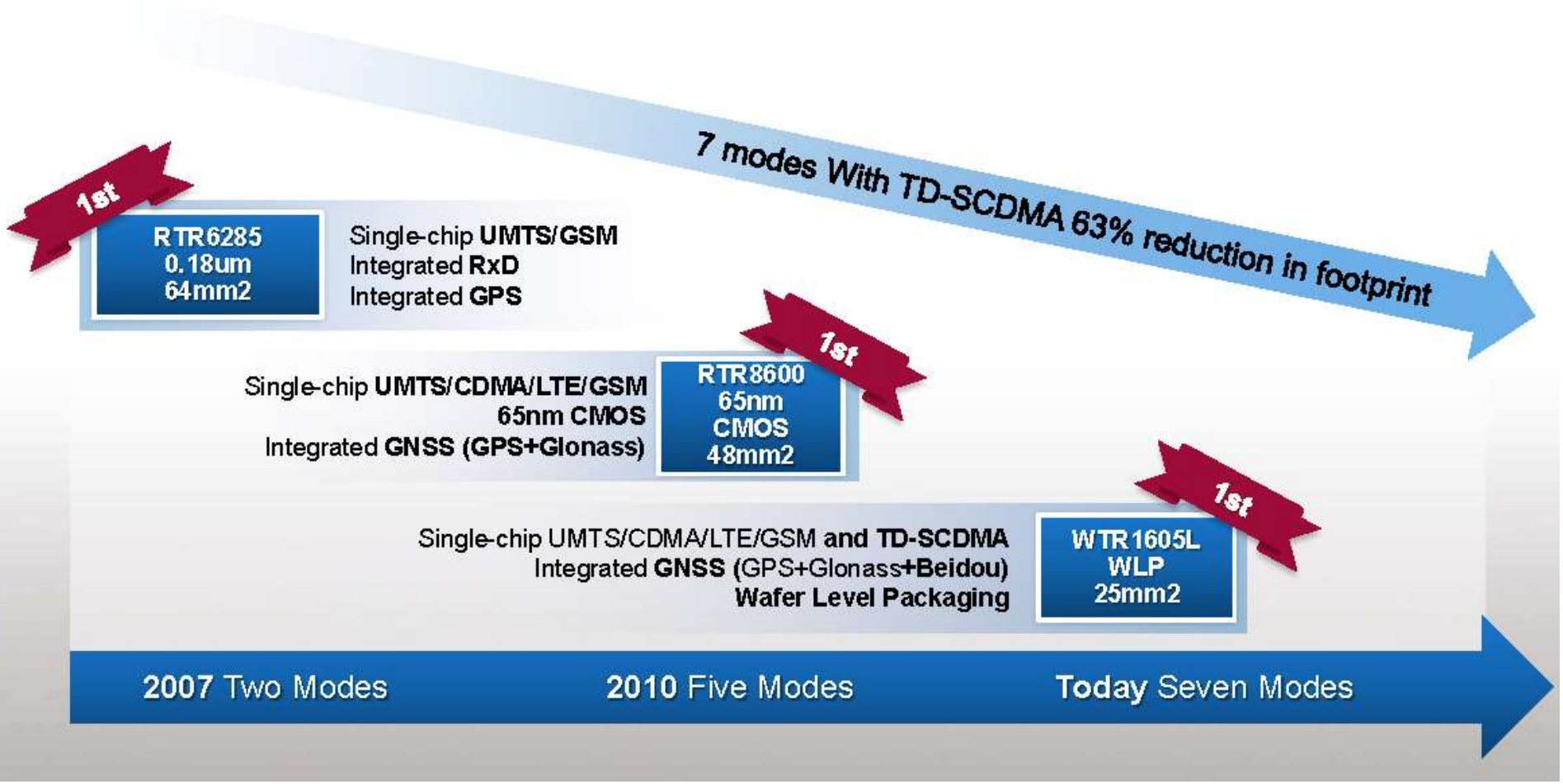
RF360: Front-end

WTR3905/WTR3925: RF Transceivers

The RF360 Front-end [23]



Evolution of the number of supported modes in Qualcomm's RF units [6]



WLP: Wafer Level Package

Overview of Qualcomm's main product lines designed for mobiles

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Qualcomm's main product lines designed for mobiles

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Typ. use	*Smartphones, tablets*	*WWAN cards , like Gobi WWAN cards, for notebooks, e-readers etc..*	*Feature phones*

Snapdragon S1 – S4 (2007 - 2012) → **Snapdragon S200 – S800** (2013 -)

Remark to the naming of Qualcomm's Snapdragon S1-S4 processors

- Qualcomm introduced the S1-S4 branding in 08/2011 and at that time they classified their prior Snapdragon processors (launched between 2007-2011) retrospective as S1-S3 parts.
- As a consequence, Qualcomm designates their application processors prior 08/2011 as Snapdragon processors but thereafter as Snapdragon S1-S3 parts.
- In 08/2011 also the S4 processor class was introduced for the next generation Snapdragon processors.
- For simplicity, in the above Figure we use the S1-S4 designations as if this branding were introduced already along with the Snapdragon platform.

3. Qualcomm’s early MSMs (Mobile Station Modems)

3. Qualcomm's early MSMs (Mobile Station Modems)

MSMs are application processors with an integrated modem.

Brief history of Qualcomm's early MSM chipsets

- In 1993, Qualcomm introduced its first generation multi chip ASICs, called the Mobile Station Modem (MSM) for CDMA phones, based on their outstanding expertize in the CDMA technology.
- Later generations of MSMs became then single chip ASIC implementations mainly in the second half of the 1990's targeting first feature phones and then also smartphones built for CDMA based standards, as indicated in the next Figure.
- We note that baseband modems are implemented as a combination of software and hardware.

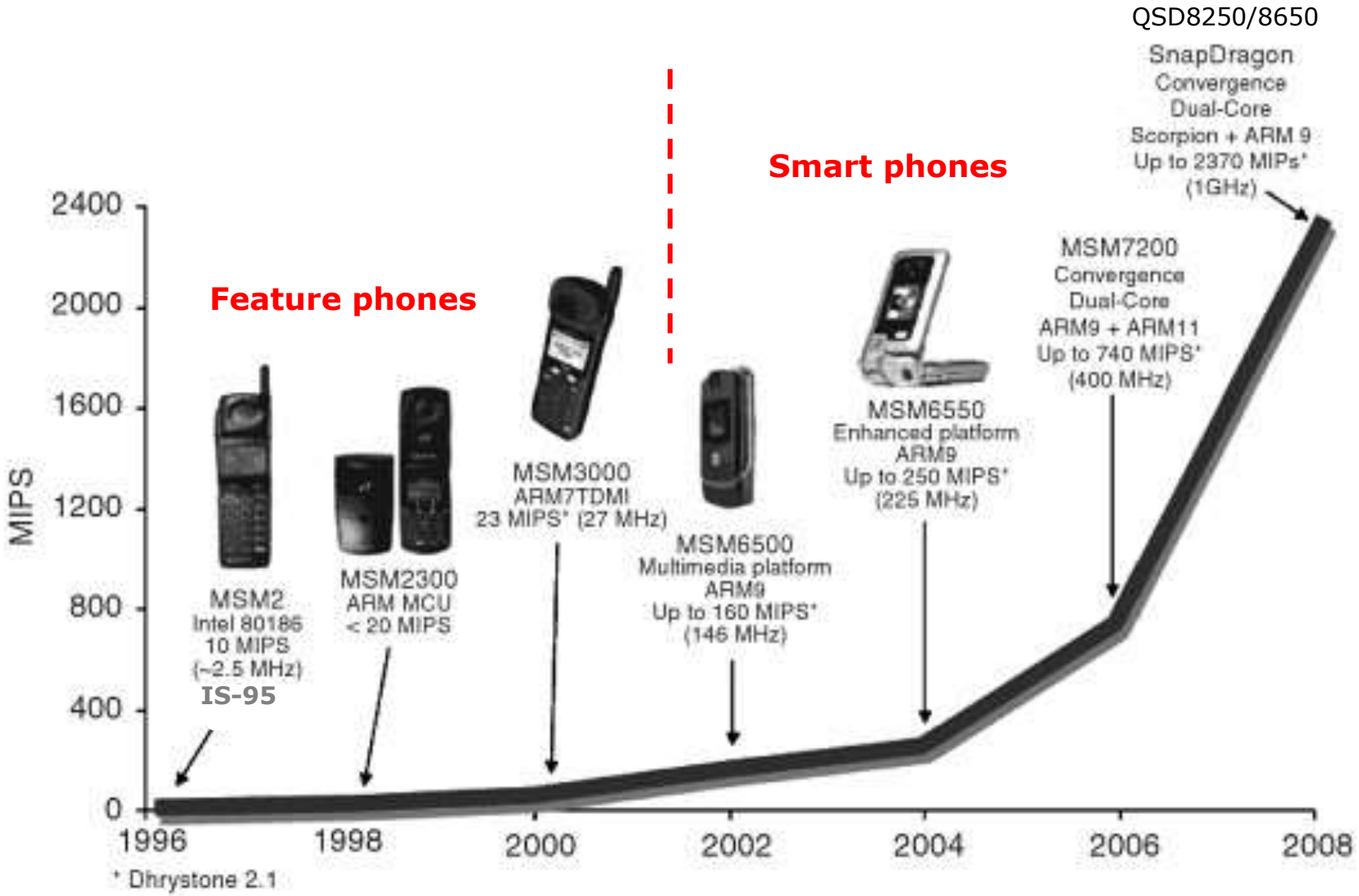
  The partition is done according to aspects like power consumption and reusability.

  As one extreme, Icera (acquired by NVIDIA in 2011) opted for a mostly software based solution, called SDR (Software Defined Radio) used in Tegra 4i.

ASIC: Application Specific IC

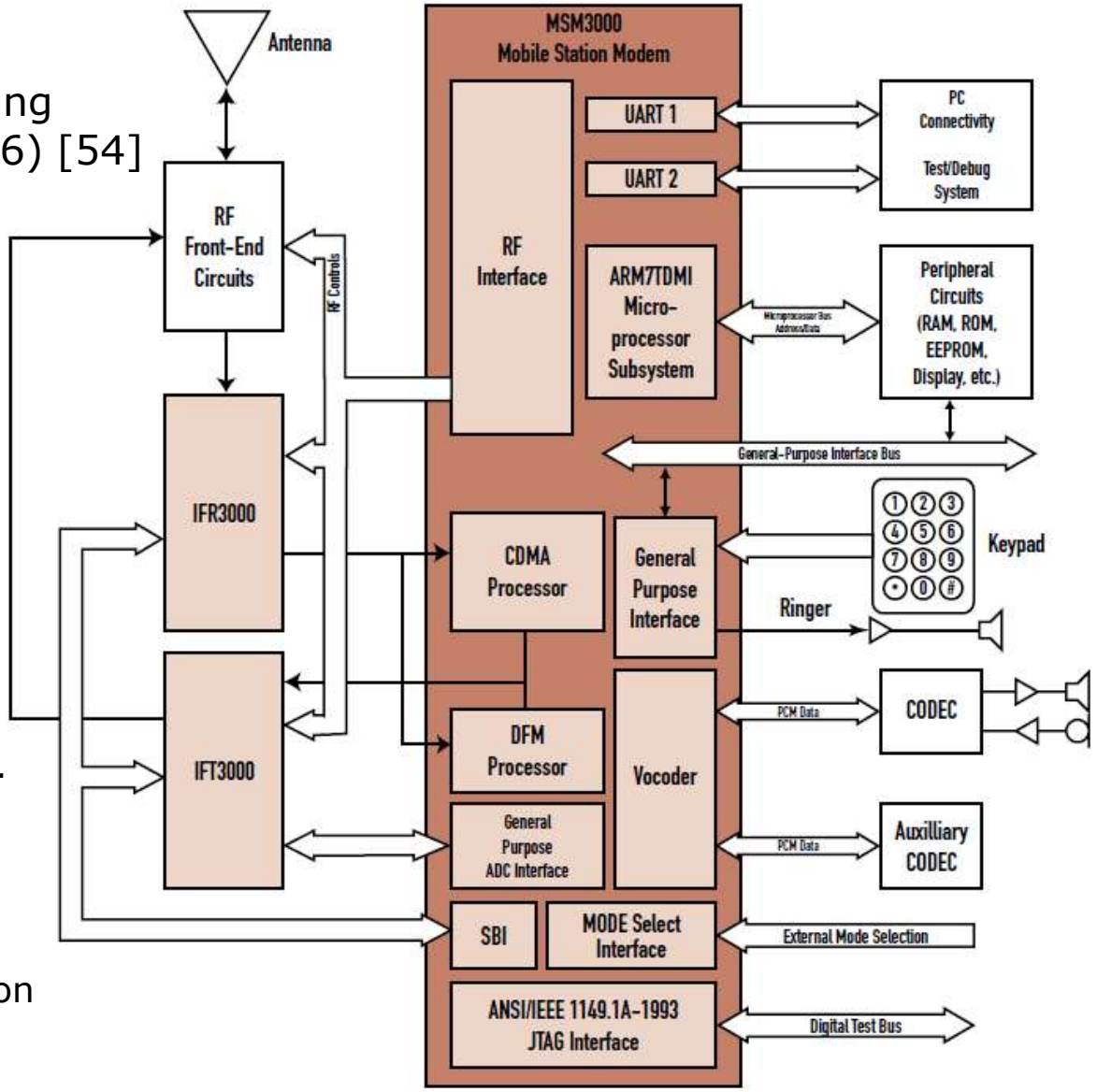
3. Qualcomm's early MSMs (Mobile Station Modems) (2)

Qualcomm's early MSM chipsets [8]



Example of Qualcomm's early MSM ASICs targeting feature phones

Figure: The fourth generation single chip MSM3000 targeting IS-95A feature phones (1996) [54]



DFM: Digital FM for AMPS operation
SBI: Serial Bus Interface
ADC: Analog Digital Converter

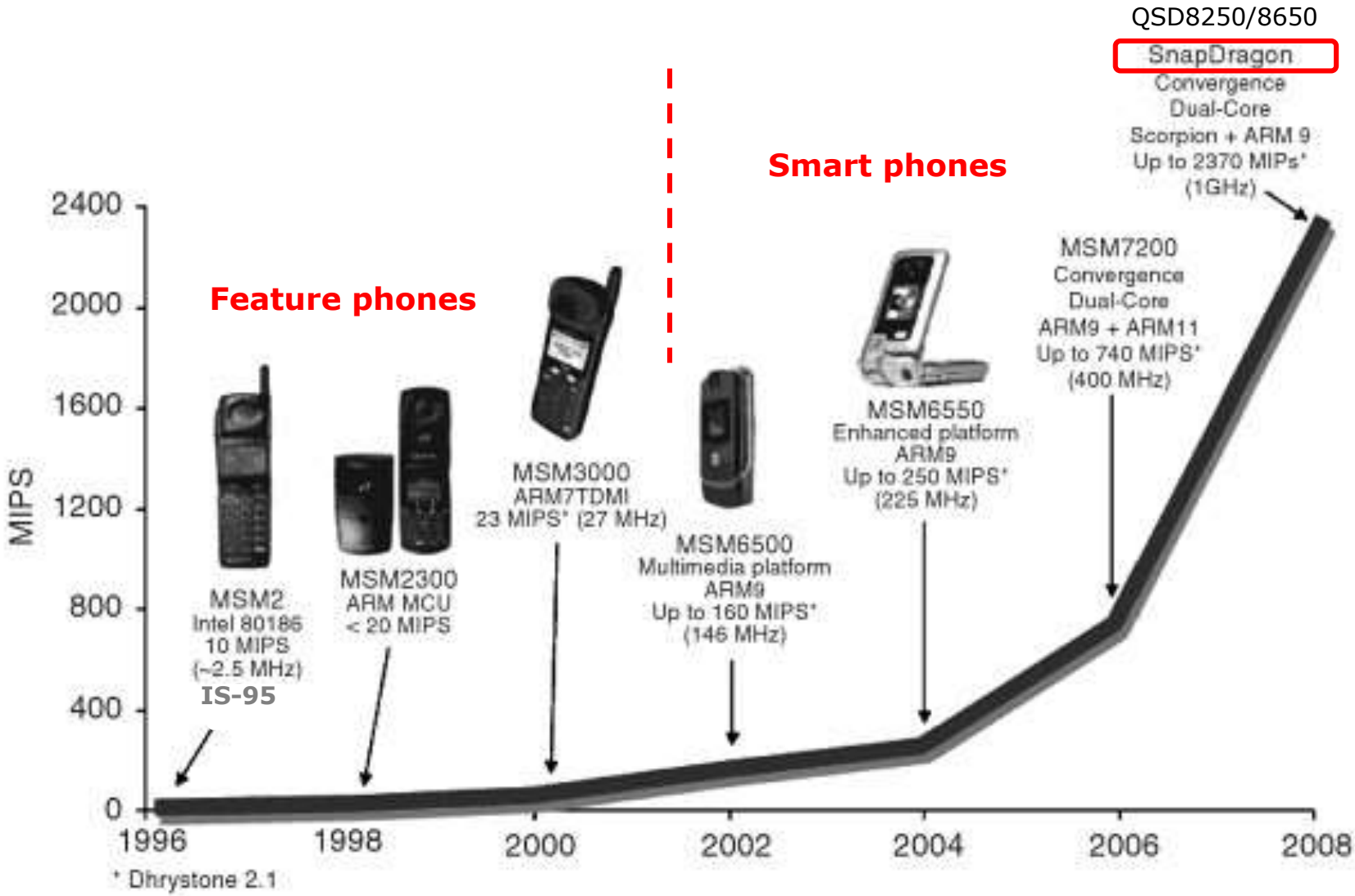
3. Qualcomm's early MSMs (Mobile Station Modems) (4)

Emerging MSMs targeting smartphones

In the first half of the 2000's Qualcomm's upcoming MSMs already began to target smartphones, as the next Figure shows.

3. Qualcomm's early MSMs (Mobile Station Modems) (5)

Qualcomm's early MSM chipsets [8]



3. Qualcomm's early MSMs (Mobile Station Modems) (6)

Example of Qualcomm's early MSM ASICs targeting smartphones

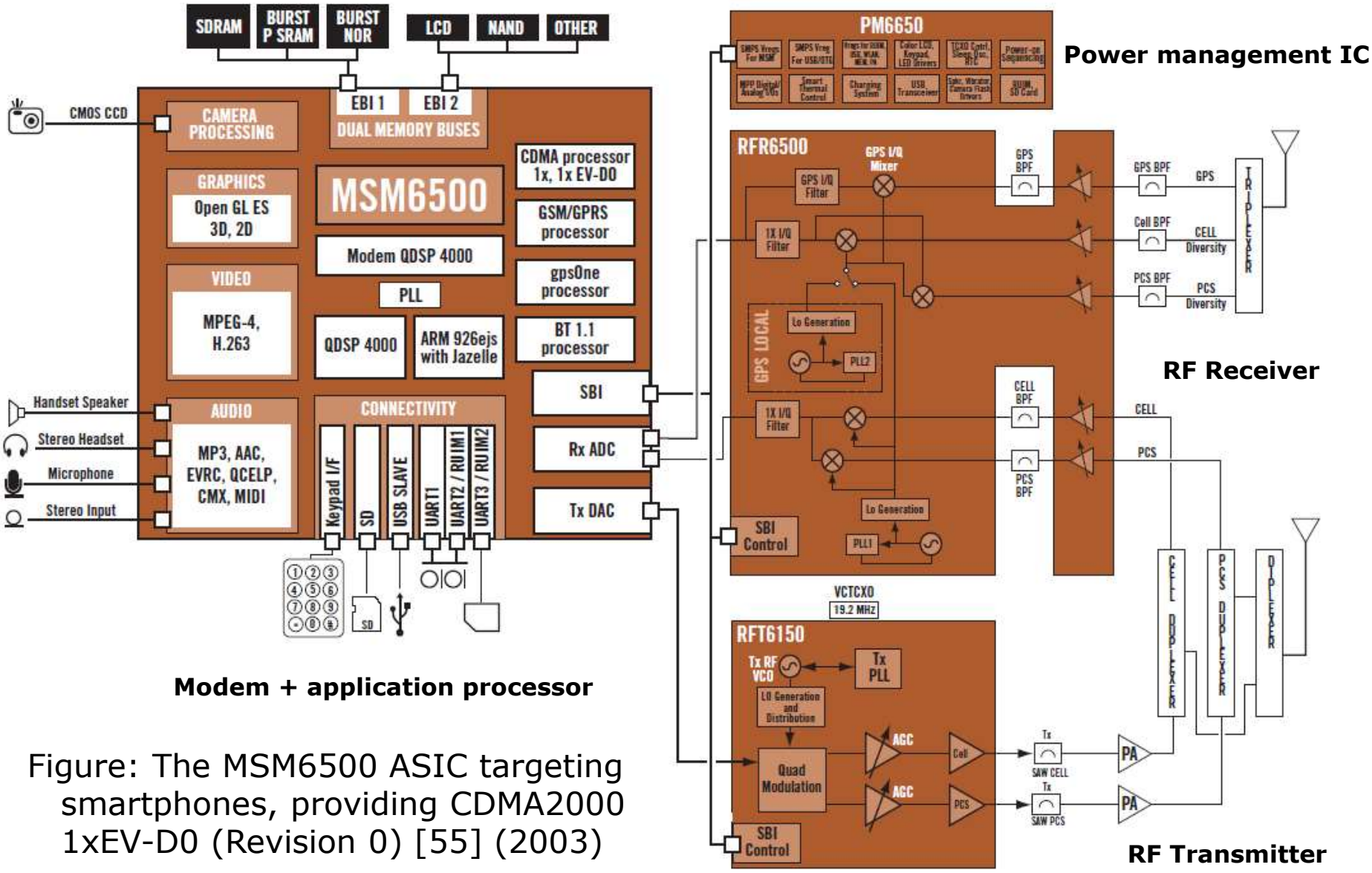


Figure: The MSM6500 ASIC targeting smartphones, providing CDMA2000 1xEV-D0 (Revision 0) [55] (2003)

3. Qualcomm's early MSMs (Mobile Station Modems) (7)

Main features of Qualcomm's mobile processors with integrated modems (called MSMs) preceding the Snapdragon lines between 2006 – 2008 [92]

Typ. model numbers	Feature size	ISA	CPU	fc up to	DSP/	Memory technology	Wireless technologies up to[1]	Sampling available
MSM6245	65 nm	ARMv5	ARM926EJ-S	180 MHz	2x QDSP4000	SCh. SDRAM	GSM, GPRS, UMTS	2006
MSM6250	130 nm	ARMv5	ARM926EJ-S	146 MHz	2x QDSP4000	SCh. SDRAM	GSM, GPRS, UMTS	2003
MSM6260	65 nm	ARMv5	ARM926EJ-S	225 MHz	2x QDSP4000	SCh. SDRAM	GSM, GPRS, UMTS	2006
MSM6275	90 nm	ARMv5	ARM926EJ-S	225 MHz	2x QDSP4000	SCh. SDRAM	GSM, GPRS, UMTS	2004
MSM6280	90 nm	ARMv5	ARM926EJ-S	270 MHz	2x QDSP4000	SCh. SDRAM	GSM, GPRS, UMTS	2005
MSM7200 MSM7600	90 nm	ARMv6	ARM1136EJ-S	400 GHz	Adreno 130	SCh. SDRAM	UMTS UMTS/CDMA	2006
MSM7201 MSM7601	90 nm	ARMv6	ARM1136EJ-S	528 GHz	Adreno 130	SCh. SDRAM	UMTS UMTS/CDMA	2006
MSM7200A MSM7600A	65 nm	ARMv6	ARM1136EJ-S	528 GHz	Adreno 130	SCh. SDRAM	UMTS UMTS/CDMA	2008
MSM7225[1]	65 nm	ARMv6	ARM11	528 MHz	Software rendered	SCh. LPDDR1	HSPA	2007
MSM7625[1]							HSPA/GSM, CDMA2000	
MSM7201A MSM7601A	65 nm	ARMv6	ARM1136EJ-S	528 GHz	Adreno 130	SCh. SDRAM	UMTS UMTS/CDMA	2008

1: Subsequently, the MSM7225 and MSM7625 were classified as Snapdragon S1 processors.

3. Qualcomm's early MSMs (Mobile Station Modems) (8)

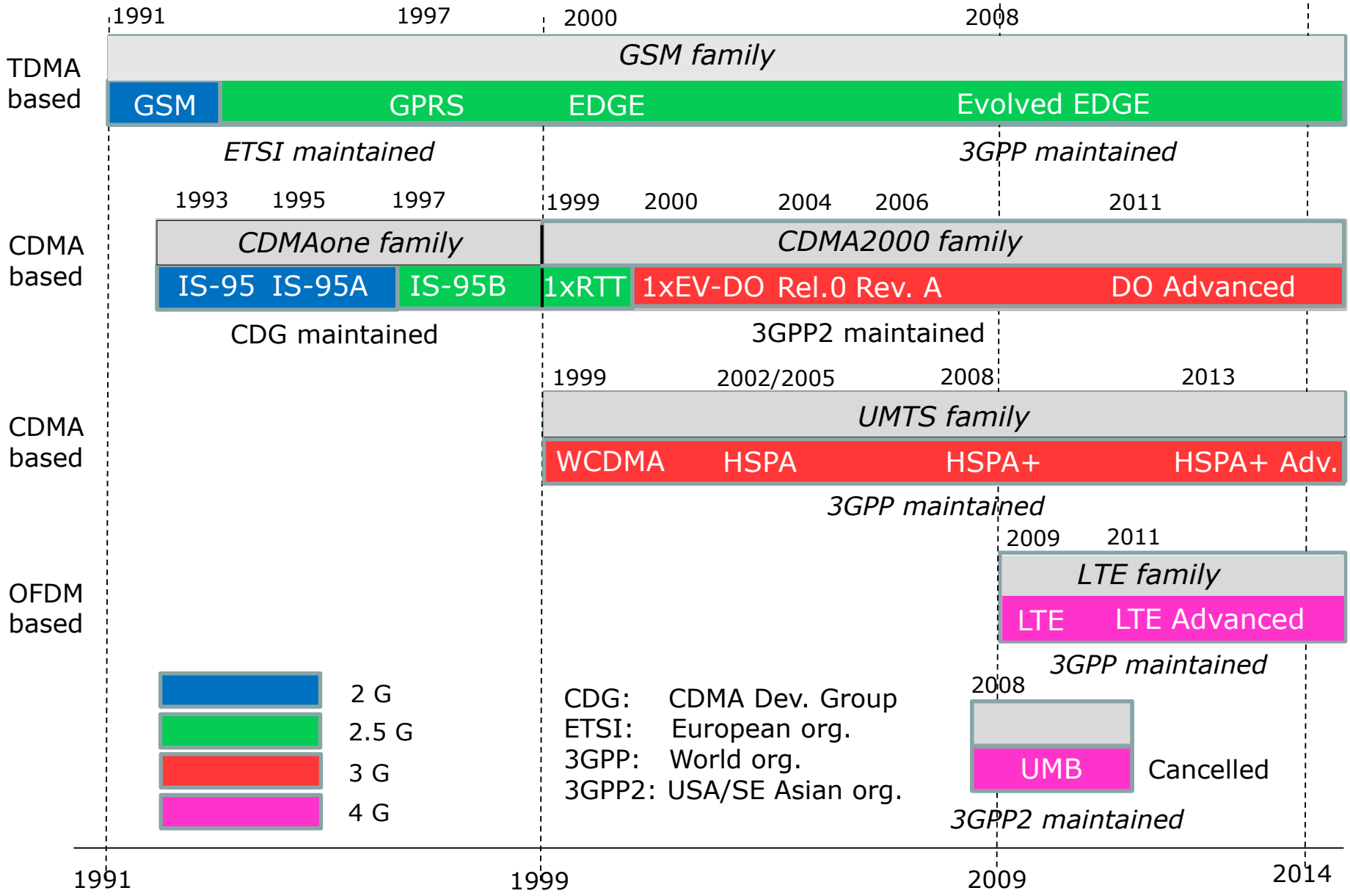
Remarks to Qualcomm's model numbering [91]

Designation of 3G parts

- Qualcomm designs typically two versions of each processor.
- Models with a "2" as the second numerical digit support UMTS, the most popular 3G mobile standard in the world.
- By contrast, processors with a "6" have a dual-mode baseband that adds support for the CDMA protocol as well, which is popular by a number of carriers in the US and also elsewhere.

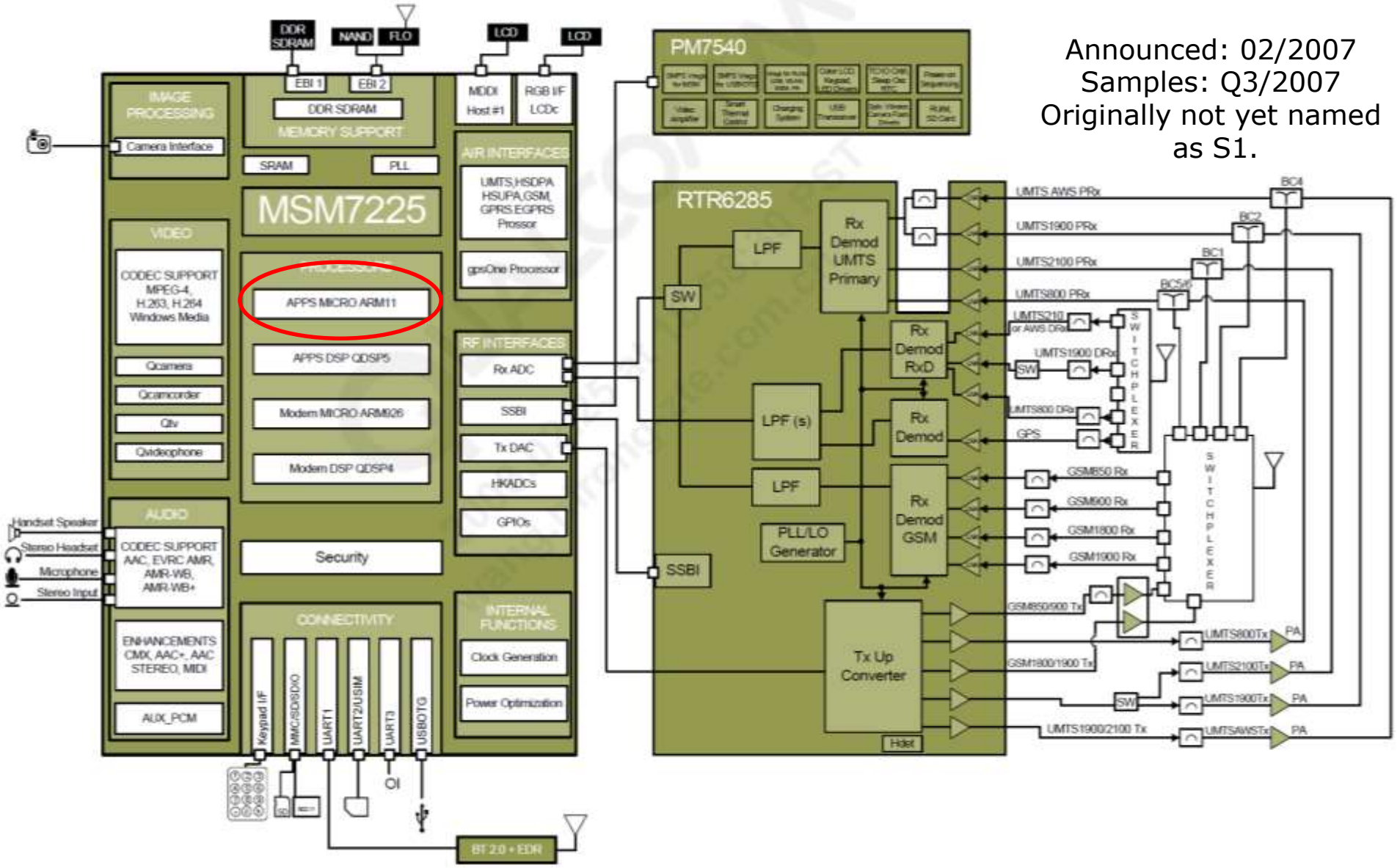
3. Qualcomm's early MSMs (Mobile Station Modems) (9)

Overview of the approved main mobile broadband standards (2G to 4G)



3. Qualcomm's early MSMs (Mobile Station Modems) (10)

Example of Qualcomm's early MSM ASICs targeting smart phones []



Announced: 02/2007
Samples: Q3/2007
Originally not yet named as S1.

3. Qualcomm's early MSMs (Mobile Station Modems) (11)

Remark on the Snapdragon classification of the MSM7225/7625 processors

At its introduction in 02/2007 Qualcomm does not yet designated the MSM7225/7625 processors as belonging to the Snapdragon line.

Only retrospective did Qualcomm classified these processors as Snapdragon 1 devices.

4. The Snapdragon line of processors

- 4.1 Introduction
- 4.2 The Snapdragon S1 - S4 processor lines
- 4.3 The Snapdragon 200 - 800 processor lines

4.1 Introduction

4.1 Introduction

- In 11/2006 Qualcomm announced the Snapdragon platform along with the Scorpion core with first devices scheduled for sampling in Q3/2007.
- The Snapdragon platform covers both application processors with integrated modems, termed MSMs, and application processors without modems, called APQs, as indicated in the Figure.

Figure: Snapdragons (Oroszlánszáj, tátika) [9], [10]

Qualcomm's MSMs (Mobile Station Modems)

Qualcomm's main product lines designed for mobiles

MSMs	**APQs**	**MDMs**	**QSCs**
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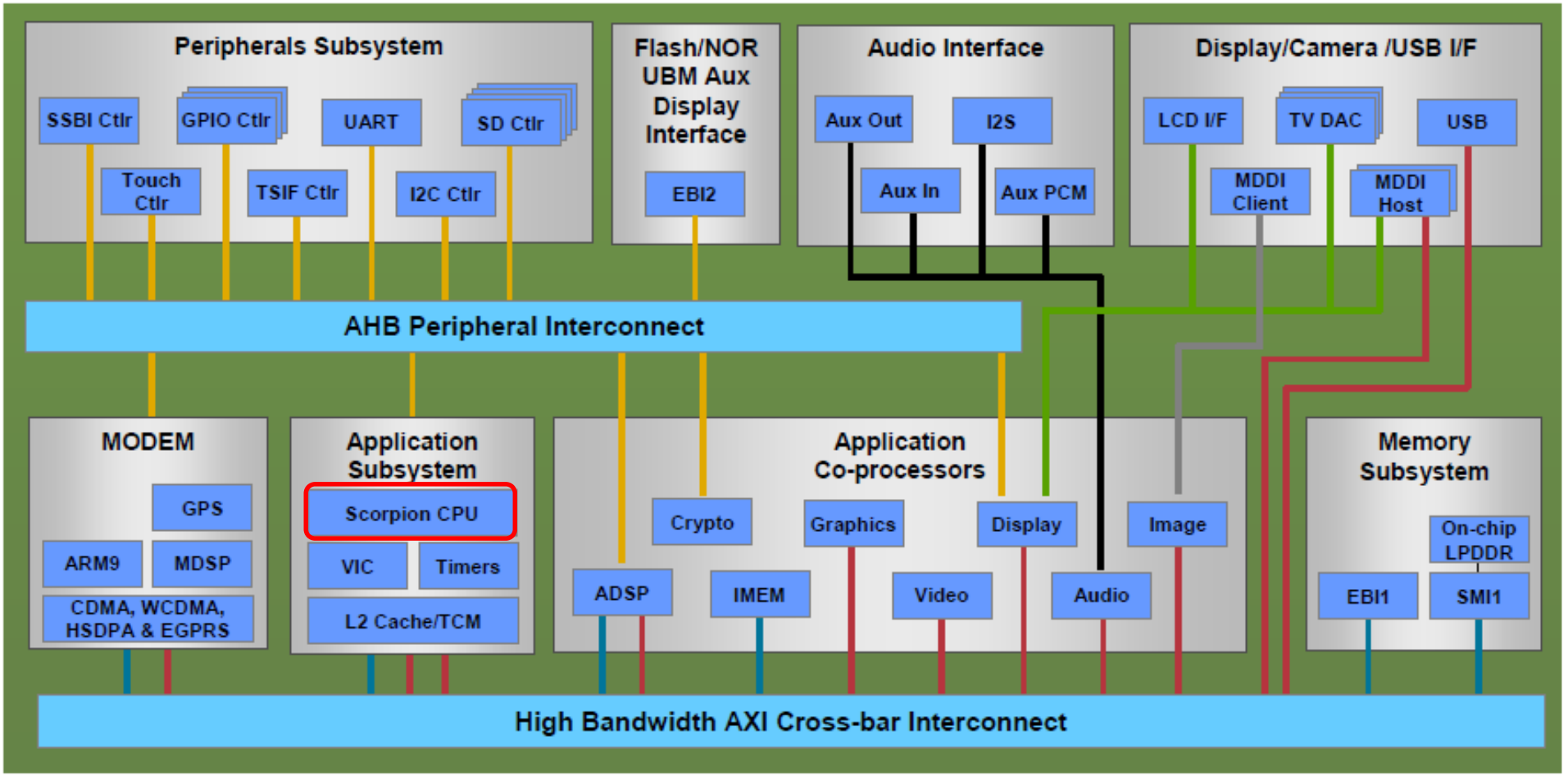
Snapdragon S1 – S4 (2007 - 2012) → **Snapdragon S200 – S800** (2013 -)			

Example for an early Snapdragon platform [11]

- Cross-bar interconnect to enable simultaneous traffic
- Balanced interconnect enabling any master to access any slave
- Tiered bus structure to off-load low bandwidth/latency tolerant traffic



Qualcomm's first Snapdragon processors

- One year after announcing the Snapdragon platform Qualcomm introduced in 11/2007 the first two models of this platform (labeled them as the QSD8250 and QSD8650 for Qualcomm SnapDragon SoC) with immediate availability.

Typ. model numbers	Feature size	ISA	CPU	fc up to	Typ. GPU	Memory technology	Wireless technologies up to[1]	Sampling available
QSD8250 QSD8650	65 nm	ARMv7	SC Scorpion	1 GHz	Adreno 200	SCh. LPDDR1	UMTS (HSPA) + CDMA (1xEVD0 Rel.0 Rev.A	2007

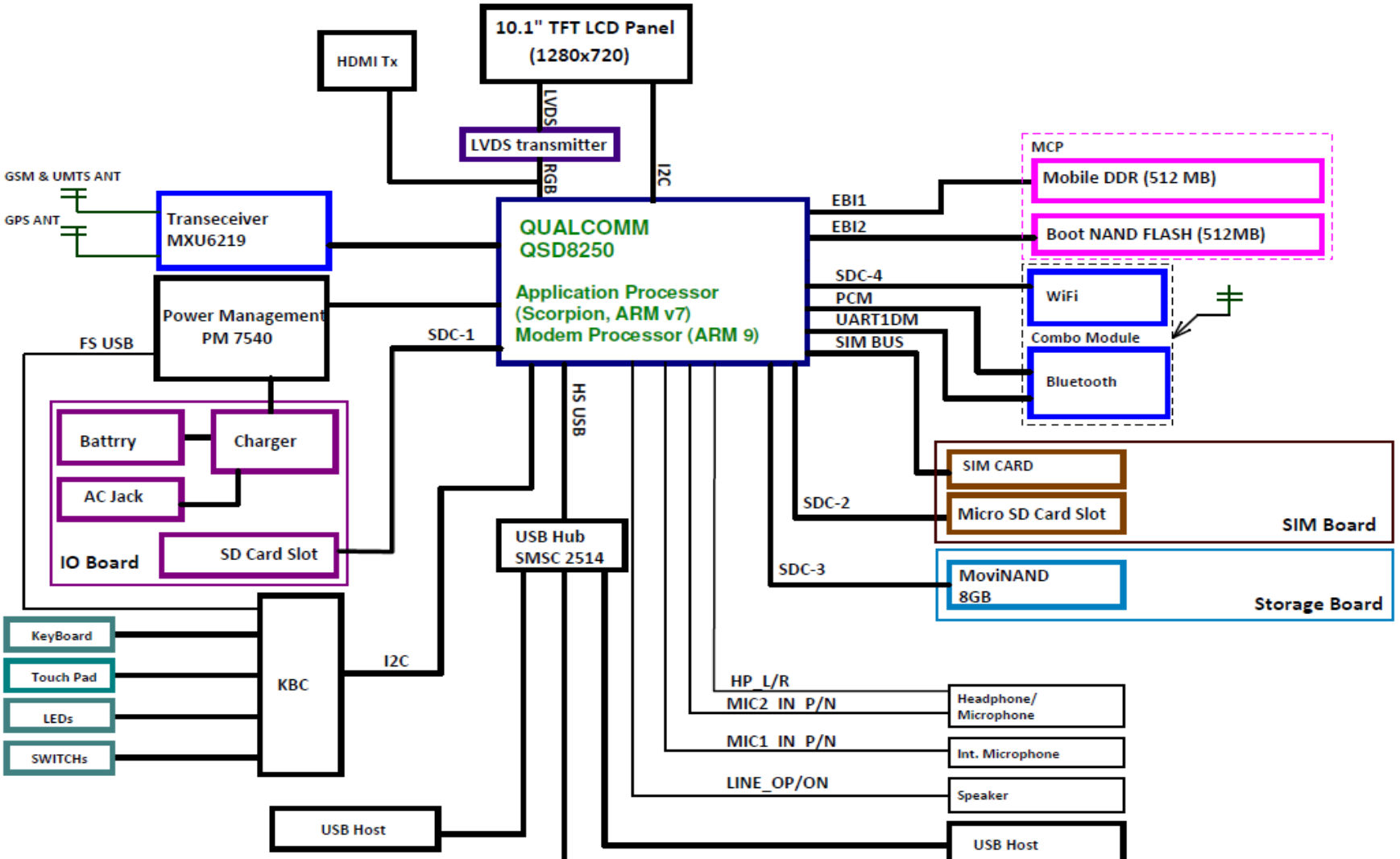
Table: Main features of Qualcomm's first Snapdragon processors

- Subsequently, Qualcomm deprecated the QSD label and replaced it by the previous MSM designation.
- Both models were running under Windows Mobile and Linux.
- At their introduction of the Snapdragon processors Qualcomm did not yet make use of the S1 - S4 brandings.

  But after introducing the S1 – S4 branding in 2011, Qualcomm classified these models retrospective as S1 models.

4.1 Introduction (5)

Block diagram of a Qualcomm QSD8250-based mass market smart phone []

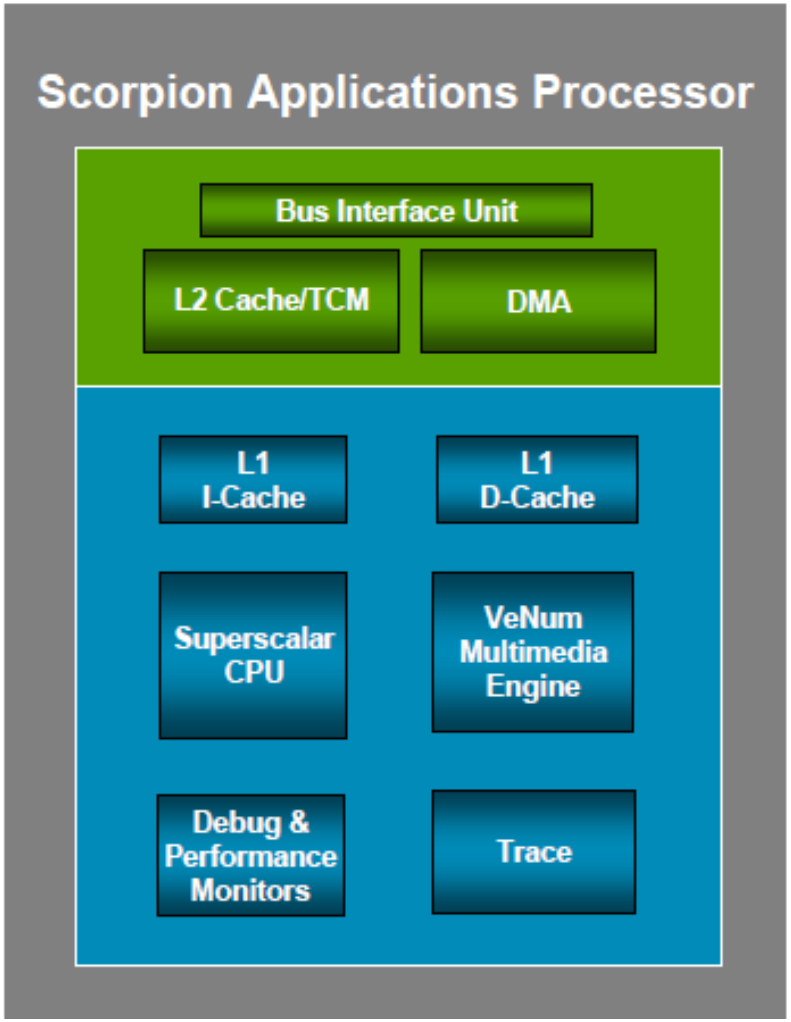


Wistron T-note SC block diagram, Wistron Corporation, Taipei, June 30. 2009
https://wenku.baidu.com/view/6a91206b1eb91a37f1115cdf.html

4.1 Introduction (6)

Introducing the Scorpion core as part of the Snapdragon platform (2007) [11]

- It is based on the ARMv7 ISA,
- has a dual-issue superscalar core, and
- its microarchitecture is similar to the ARM Cortex-A8 processor.



Comparing main feature of Qualcomm's Scorpion core [12]

Architecture Comparison					
	ARM11	ARM Cortex A8	ARM Cortex A9	Qualcomm Scorpion	Qualcomm Krait
Decode	single-issue	2-wide	2-wide	2-wide	3-wide
Pipeline Depth	8 stages	13 stages	8 stages	10 stages	11 stages
Out of Order Execution	N	N	Y	Partial	Y
FPU	VFP11 (pipelined)	VFPv3 (not-pipelined)	Optional VFPv3-D16 (pipelined)	VFPv3 (pipelined)	VFPv3 (pipelined)
NEON	N/A	Y (64-bit wide)	Optional MPE (64-bit wide)	Y (128-bit wide)	Y (128-bit wide)
Process Technology	90nm	65nm/45nm	40nm	40nm	28nm
Typical Clock Speeds	412MHz	600MHz/1GHz	1.2GHz	1GHz	1.5GHz

in S1-S3 in S4

4.2 The Snapdragon S1 - S4 processor lines

4.2 The Snapdragon S1 - S4 processor lines

- In 8/2011 Qualcomm introduced a new branding for their Snapdragon processors and classified their prior processors retrospectively as S1 - S3 classes.
- Qualcomm also introduced the S4 class, typically with a new core (Krait) and partly with LTE support, as follows:

Figure: Target areas and models of the introduced S1 – S4 platform classes [16]

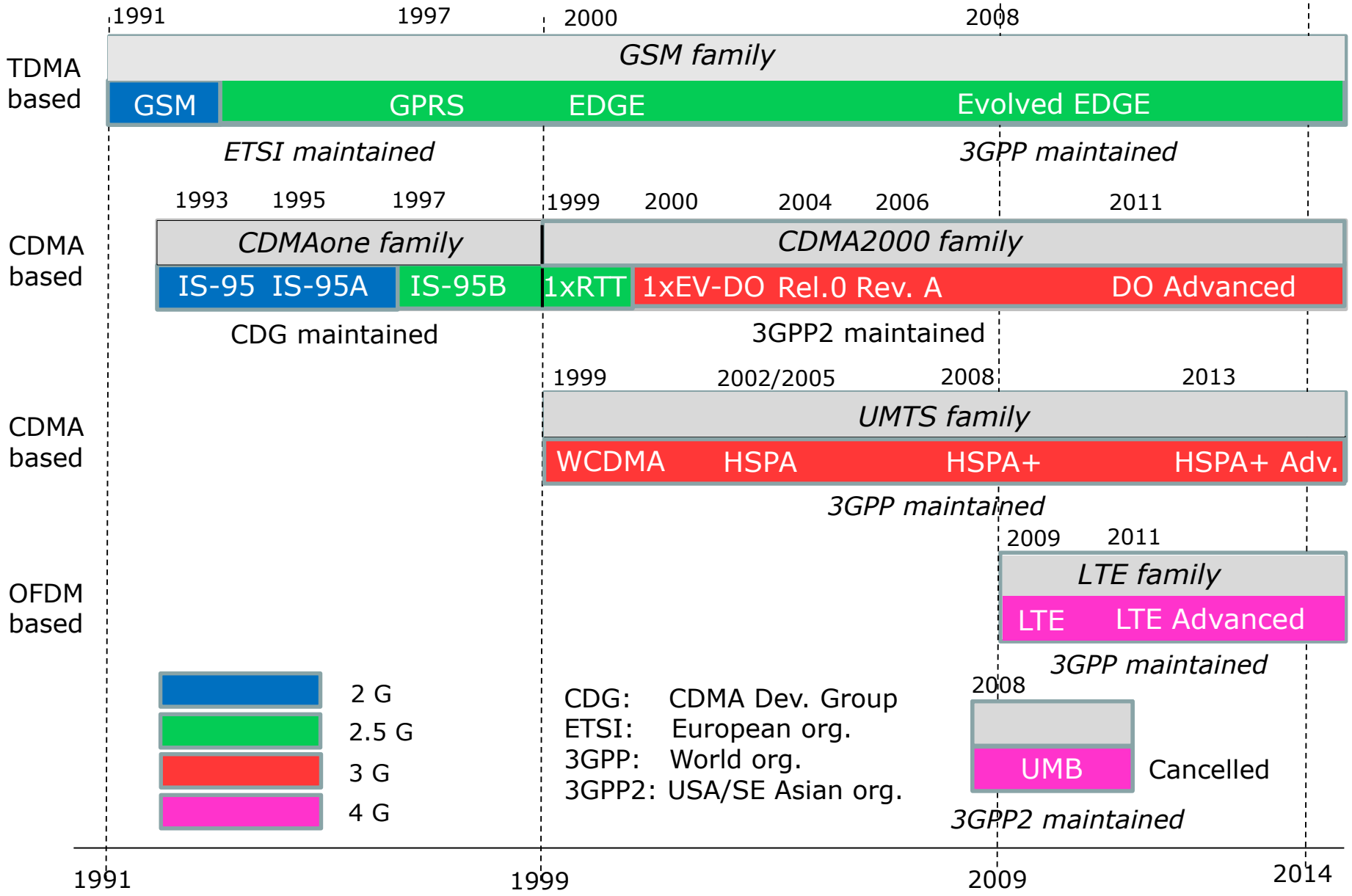
4.2 The Snapdragon S1 – S4 processor lines (2)

Remarks to the designation of Qualcomm's 4G parts

- A "9" in the second numerical digit indicates the support of the 4G family of communication standards, e.g. MSM9816.
- For an overview of the communication standards see next Figure.

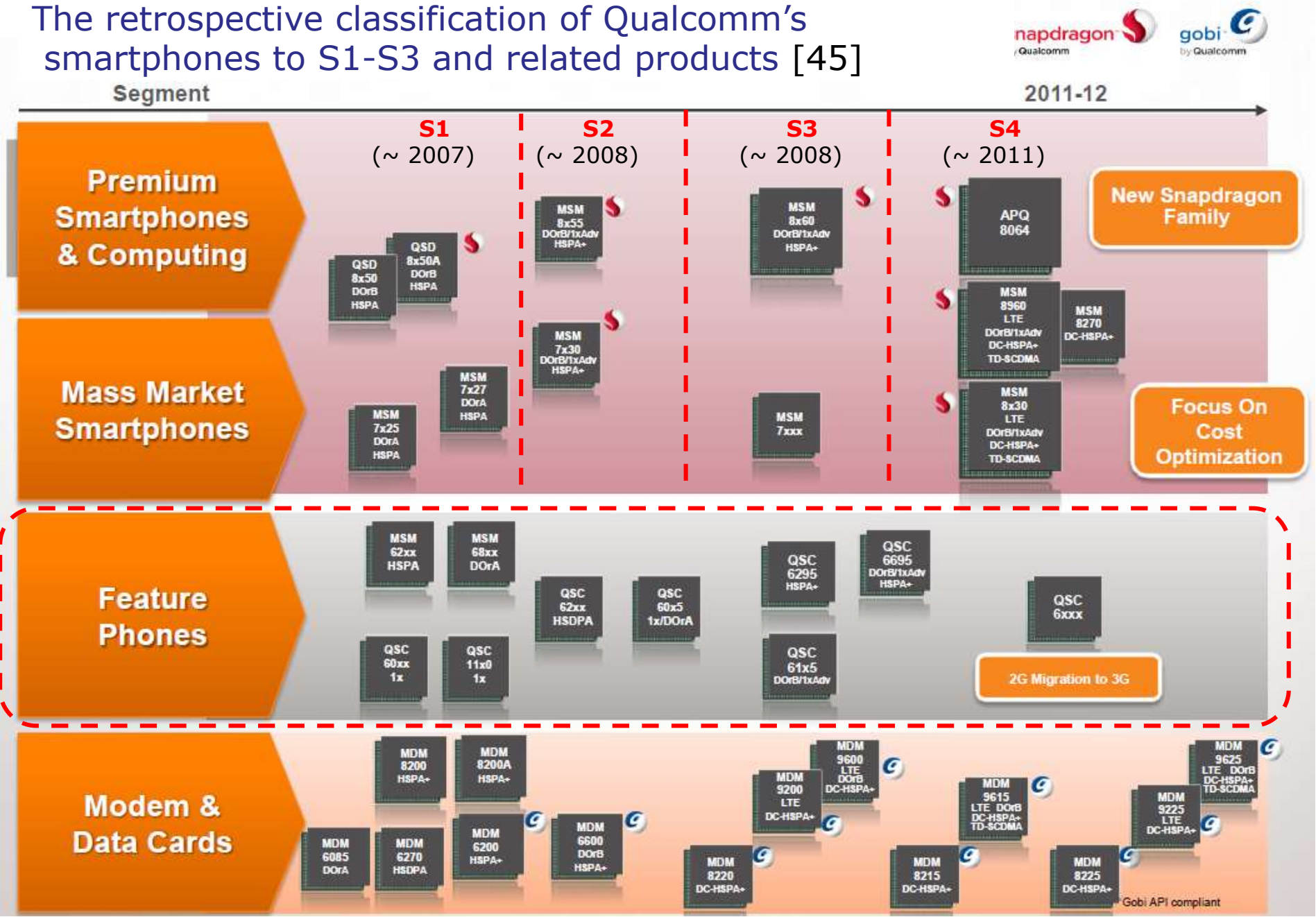
4.2 The Snapdragon S1 – S4 processor lines (3)

Overview of the approved main mobile broadband standards (2G to 4G)



4.2 The Snapdragon S1 – S4 processor lines (4)

The retrospective classification of Qualcomm's smartphones to S1-S3 and related products [45]



4.2 The Snapdragon S1 – S4 processor lines (5)

Remarks to the naming of Qualcomm's smartphones and feature phones

Qualcomm's labeling scheme for their processors is as follows:

- 8xxx: premium smartphones
- 7xxx: mass market smartphones
- 6xxx: feature phones

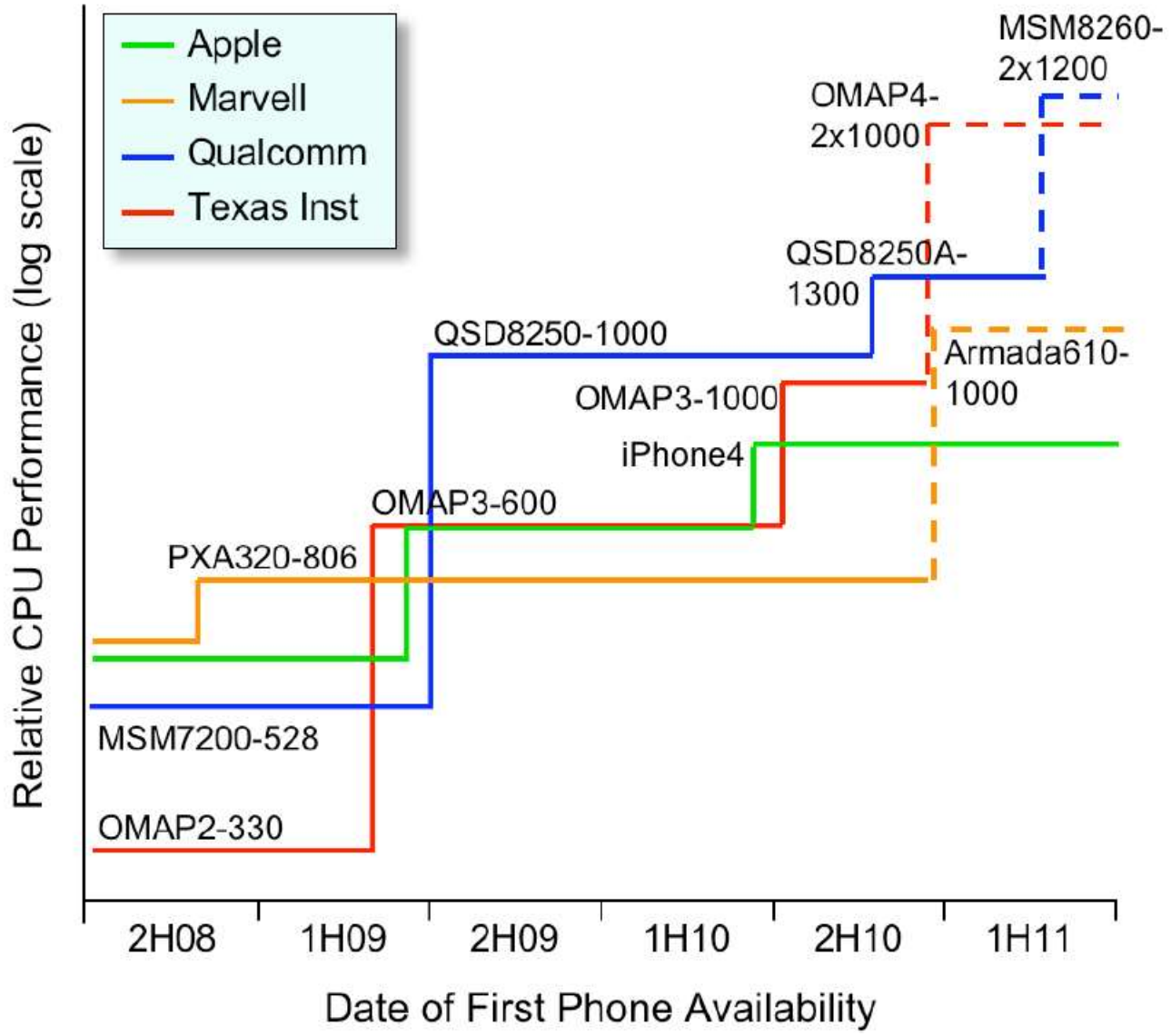
4.2 The Snapdragon S1 – S4 processor lines (6)

Main features of the Snapdragon S1 – S3 lines [14], [15]

Family	Typ. model numbers	Feature size	ISA	CPU	fc up to	Typ. GPU	Memory technology	Wireless technologies up to[1]	Sampling available
S1	MSM7225 MSM7625	65 nm	ARMv6	ARM1136EJ-S	528 MHz	Software rendered	SCh. LPDDR1	UMTS UMTS/CDMA	2007
	MSM7227 MSM7627	65 nm	ARMv6	ARM1136EJ-S	800 MHz	Adreno 200	SCh. LPDDR1	UMTS UMTS/CDMA	2008
	QSD8250 QSD8650	65 nm	ARMv7	SC Scorpion	1 GHz	Adreno 200	SCh. LPDDR1	UMTS UMTS/CDMA	2008
	MSM7225A MSM7625A	45 nm	ARMv7	ARM Cortex-A5	800 MHz	Adreno 200	SCh. LPDDR1	UMTS UMTS/CDMA	2011
	MSM7227A MSM7627A	45 nm	ARMv7	ARM Cortex-A5	1.0 GHz	Adreno 200	SCh. LPDDR1	UMTS UMTS/CDMA	2011
S2	MSM7230 MSM7630	45 nm	ARMv7	SC Scorpion	800 MHz	Adreno 205	DCh. LPDDR2	UMTS UMTS/CDMA	2010
	MSM8255 MSM8655	45 nm	ARMv7	SC Scorpion	1.0 GHz	Adreno 205	DCh. LPDDR2	UMTS UMTS/CDMA	2010
S3	MSM8260 MSM8660	45 nm	ARMv7	DC Scorpion	1.2 GHz in 2011 1.7 GHz	Adreno 220	SCh. LPDDR2	UMTS UMTS/CDMA	2010

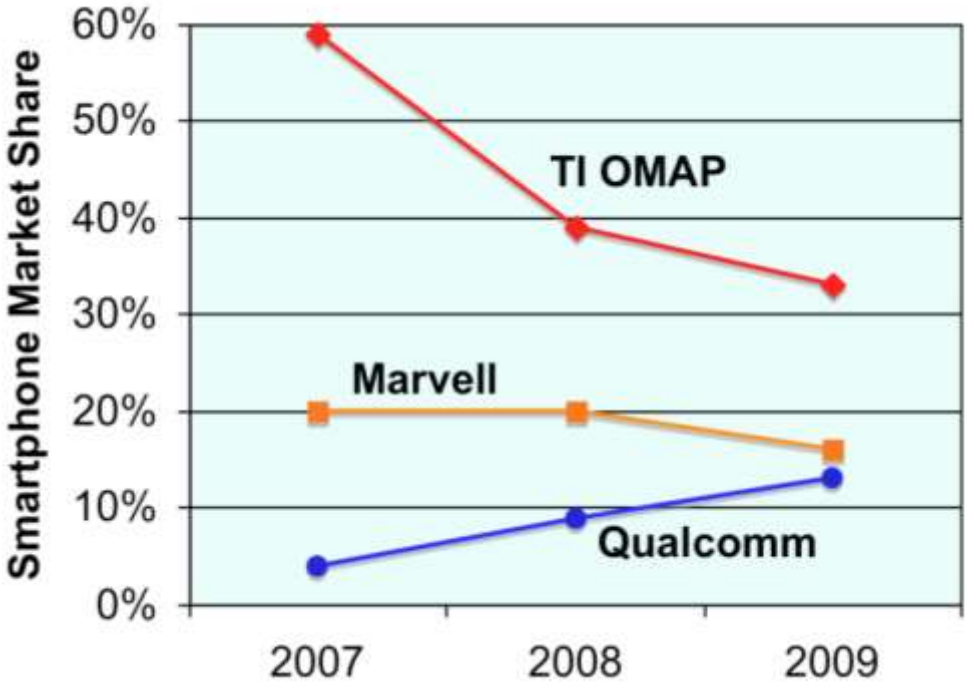
[1] For 3G parts only the UMTS support level and for 4G parts only the LTE support level is indicated.

Raising CPU performance in early mobile processors [91]



4.2 The Snapdragon S1 – S4 processor lines (8)

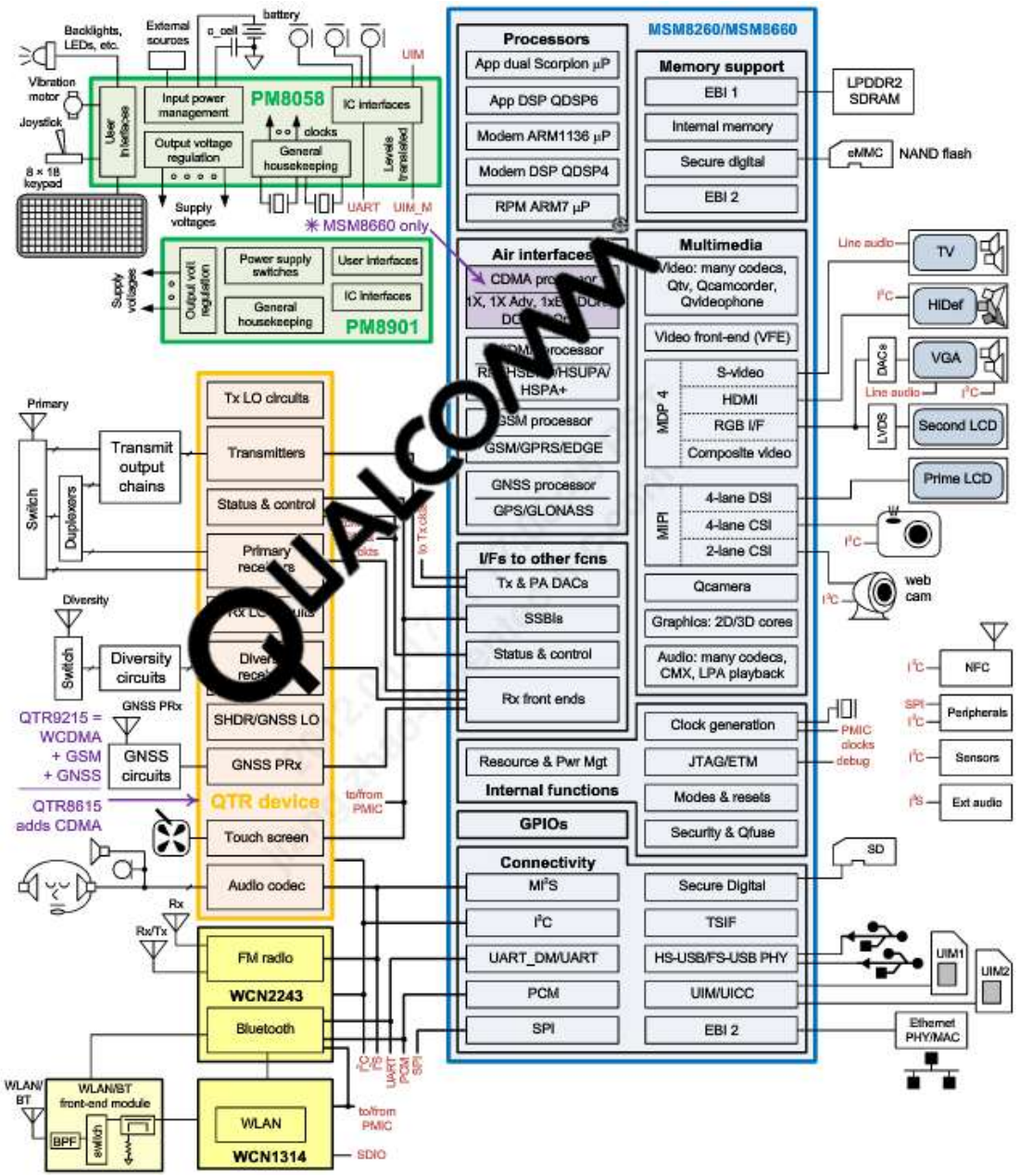
Raising market share of Qualcomm's application processors [91]



Qualcomm's increasing share in the world market of application processors is spurred by their integrated baseband modem and their faster rising performance compared to the competitors.

4.2 The Snapdragon S1 – S4 processor lines (9)

Example: Block diagram of the first dual Scorpion core platform (2010) (MSM8260/MSM8660) [19]



4.2 The Snapdragon S1 – S4 processor lines (10)

Main features of the Snapdragon S4 line [14], [15]

Family	Typ. model numbers	Feature size	ISA	CPU	fc up to	Typ. GPU	Memory technology	Wireless technologies up to[1]	Sampling available
S4	MSM8225 MSM8625	45 nm	ARMv7	DC Cortex-A5	1.2 GHz	Adreno 203	SCh. LPDDR2	UMTS UMTS/CDMA	2012
	MSM8227 MSM8627	28 nm	ARMv7	DC Krait 200	1.0 GHz	Adreno 305	SCh. LPDDR2	UMTS UMTS/CDMA	2012
	MSM8230 MSM8630	28 nm	ARMv7	DC Krait 200	1.2 GHz	Adreno 305	SCh. LPDDR2	UMTS UMTS/CDMA	2012
	MSM8260A MSM8660A	28 nm	ARMv7	DC Krait 200	1.5 GHz	Adreno 305	DCh. LPDDR2	UMTS UMTS/CDMA	2012
	MSM8960	28 nm	ARMv7	DC Krait 200	1.5 GHz	Adreno 305	DCh. LPDDR2	LTE Cat 3	2012
	MSM8960T	28 nm	ARMv7	DC Krait 300	1.7 GHz	Adreno 320	DCh. LPDDR2	LTE Cat 3	2012

[1] For 3G parts only the UMTS support level and for 4G parts only the LTE support level is indicated.

4.2 The Snapdragon S1 – S4 processor lines (11)

Introduction of the Krait core along with the Snapdragon S4 line

Along with the S4 line Qualcomm announced their second generation in-house designed ARMV7 ISA based core, designated as the Krait core in 2/2011.

Technical details followed in 10/2011.

The next Table pinpoints main enhancements of the Krait core vs. the Scorpion core.

Qualcomm Architecture Comparison		
	Scorpion	Krait
Pipeline Depth	10 stages	11 stages
Decode	2-wide	3-wide
Issue Width	3-wide?	4-wide
Execution Ports	3	7
L2 Cache (dual-core)	512KB	1MB
Core Configurations	1, 2	1, 2, 4

Table: Comparing key microarchitecture features of Qualcomm's 1. and 2. gen. processors [12]

4.2 The Snapdragon S1 – S4 processor lines (12)

Processor models and use of the Krait family [20]

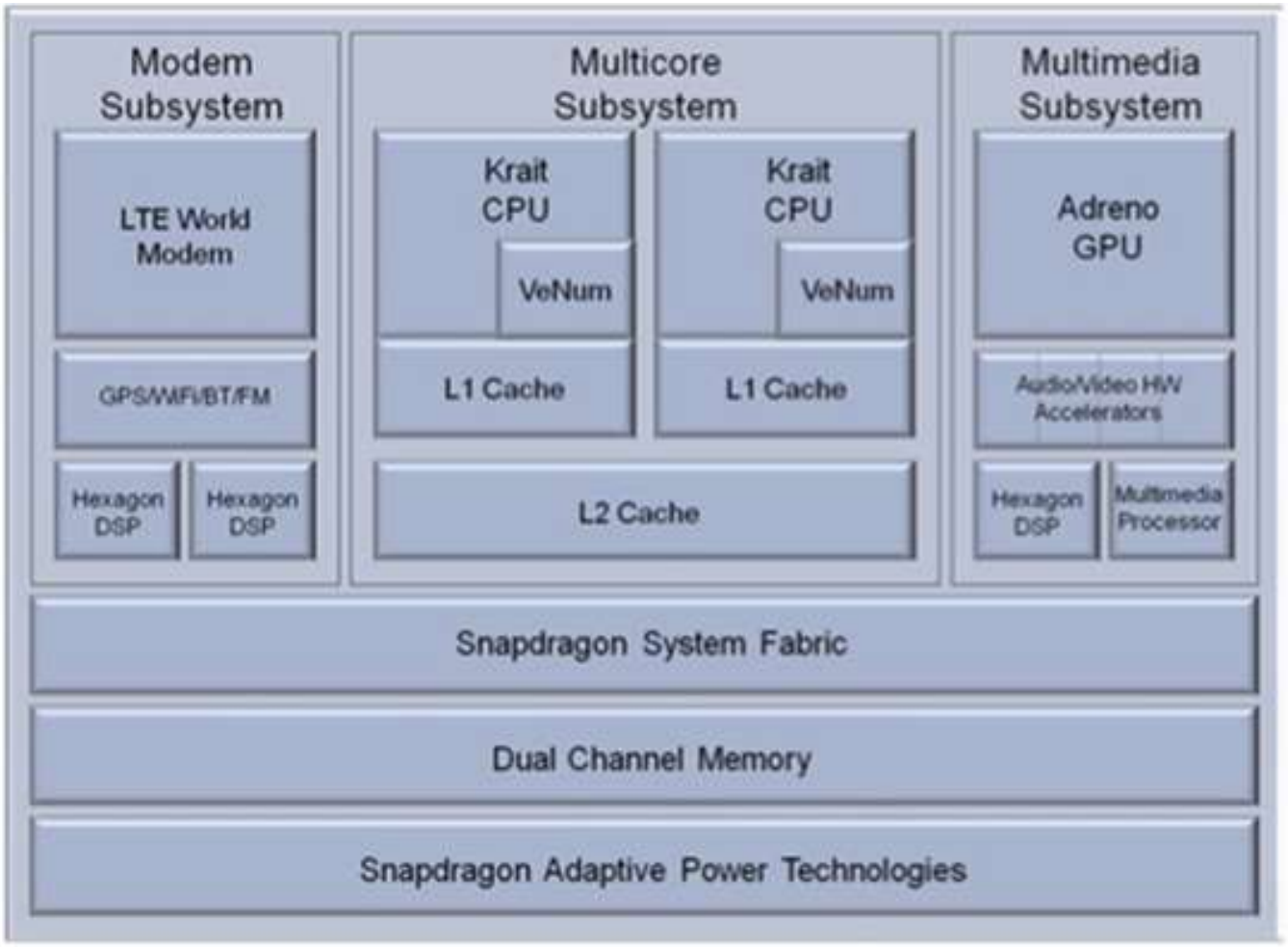
Model	Technology	DMIPS/MHz	Introduced	Used in
Krait 200	28 nm LP	3.3	2012	Snapdragon S4/S400
Krait 300	28 nm LP	3.39	2013	Snapdragon S4/S400/S600/S602a
Krait 400	28 nm HPm	3.39	2013	Snapdragon S800/S801
Krait 450	28 nm HPm	3.51	2014	Snapdragon S805

4.2 The Snapdragon S1 – S4 processor lines (13)

Qualcomm's Asynchronous Symmetric Multi Processing (aSMP) [67], [68]

- Based on customized ARMv7 cores, called Krait cores.
- Introduced in the Snapdragoon S4/S400 lines (DC Krait 200/300) in 2012/2013.
- These processors were dual core symmetric multicores, as indicated in the next Figure.
- Per core DVFS
- Also the L2 can run at separate voltage and clock rate.
- Each core can be operated in a low power mode.
- Power saving of 25 to 40 %.

Example: Block diagram of a Krait 200 based Snapdragon S4 processor (MSM8960) (2012) [17]



4.2 The Snapdragon S1 – S4 processor lines (15)

Comparing key microarchitecture features of select ARMv7 mobile processors [12]

	ARM11	ARM Cortex A8	ARM Cortex A9	Qualcomm Scorpion	Qualcomm Krait
Decode	single-issue	2-wide	2-wide	2-wide	3-wide
Pipeline Depth	8 stages	13 stages	8 stages	10 stages	11 stages
Out of Order Execution	N	N	Y	Partial	Y
FPU	VFP11 (pipelined)	VFPv3 (not-pipelined)	Optional VFPv3-D16 (pipelined)	VFPv3 (pipelined)	VFPv3 (pipelined)
NEON	N/A	Y (64-bit wide)	Optional MPE (64-bit wide)	Y (128-bit wide)	Y (128-bit wide)
Process Technology	90nm	65nm/45nm	40nm	40nm	28nm
Typical Clock Speeds	412MHz	600MHz/1GHz	1.2GHz	1GHz	1.5GHz

4.2 The Snapdragon S1 – S4 processor lines (16)

Comparing key features of competing mobile processors around 2011 [12]

SoC	Process Node	CPU	GPU	Memory Bus	Release
Apple A5	45nm	2 x ARM Cortex A9 w/ MPE @ 1GHz	PowerVR SGX 543MP2	2 x 32-bit LPDDR2	2011
NVIDIA Tegra 2	40nm	2 x ARM Cortex A9 @ 1GHz	GeForce	1 x 32-bit LPDDR2	2011
NVIDIA Tegra 3/Kal-El	40nm	4 x ARM Cortex A9 w/ MPE @ ~1.3GHz	GeForce++	1 x 32-bit LPDDR2	Q4 2011
Samsung Exynos 4210	45nm	2 x ARM Cortex A9 w/ MPE @ 1.2GHz	ARM Mali-400 MP4	2 x 32-bit LPDDR2	2011
Samsung Exynos 4212	32nm	2 x ARM Cortex A9 w/ MPE @ 1.5GHz	ARM Mali-400 MP4	2 x 32-bit LPDDR2	2012
ST-Ericsson NovaThor LP9600 (Nova A9600)	28nm	2 x ARM Cortex-A15 @ 2.5GHz	IMG PowerVR Series 6 (Rogue)	Dual Memory	2013
ST-Ericsson Novathor L9540 (Nova A9540)	32nm	2 x ARM Cortex A9 @ 1.85GHz	IMG PowerVR Series 5	2 x 32-bit LPDDR2	2H 2012
ST-Ericsson NovaThor U9500 (Nova A9500)	45nm	2 x ARM Cortex A9 @ 1.2GHz	ARM Mali-400 MP1	1 x 32-bit LPDDR2	2011
ST-Ericsson NovaThor U8500	45nm	2 x ARM Cortex A9 @ 1.0GHz	ARM Mali-400 MP1	1 x 32-bit LPDDR2	2011
TI OMAP 4430	45nm	2 x ARM Cortex A9 w/ MPE @ 1.2GHz	PowerVR SGX 540	2 x 32-bit LPDDR2	2011
TI OMAP 4460	45nm	2 x ARM Cortex A9 w/ MPE @ 1.5GHz	PowerVR SGX 540	2 x 32-bit LPDDR2	Q4 11 - 1H 12
TI OMAP 4470	45nm	2 x ARM Cortex A9 w/ MPE @ 1.8GHz	PowerVR SGX 544	2 x 32-bit LPDDR2	1H 2012
TI OMAP 5	28nm	2 x ARM Cortex A15 @ 2GHz	PowerVR SGX 544MPx	2 x 32-bit LPDDR2	2H 2012
Qualcomm MSM8x60	45nm	2 x Scorpion @ 1.5GHz	Adreno 220	1 x 32-bit LPDDR2*	2011
Qualcomm MSM8960	28nm	2 x Krait @ 1.5GHz	Adreno 225	2 x 32-bit LPDDR2	1H 2012

4.3 The Snapdragon 200 - 800 processor lines

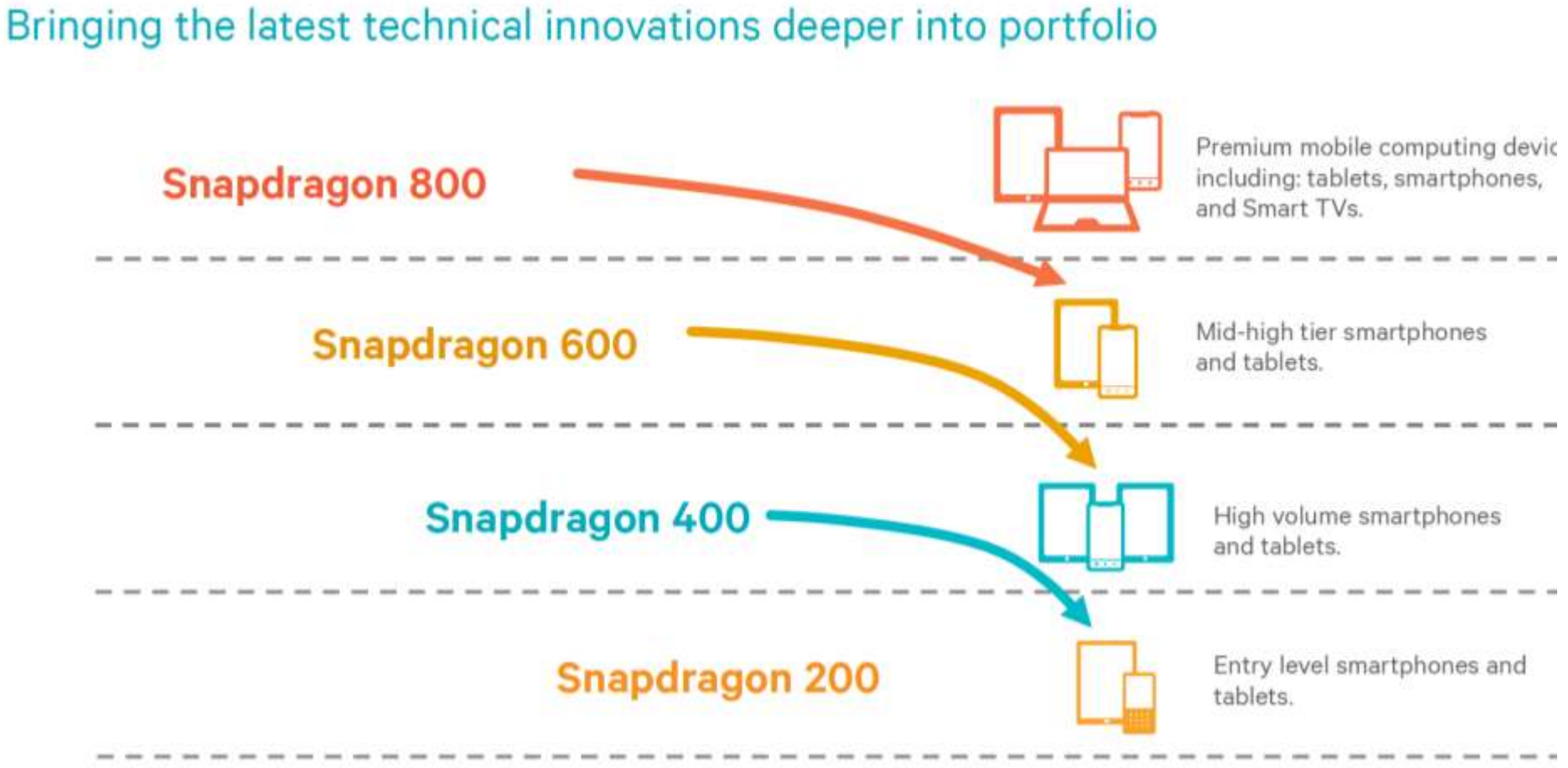
- 4.3.1 Overview of the Snapdragon 200 - 800 processor lines
- 4.3.2 The Snapdragon 820 processor
- 4.3.3 The Snapdragon 835 processor
- 4.3.4 The Snapdragon 845 processor
- 4.3.5 The Snapdragon 850 processor
- 4.3.6 The Snapdragon 855 processor
- 4.3.7 The Snapdragon 8cx processor

4.3.1 Overview of the Snapdragon 200 - 800 processor lines

4.3.1 Overview of the Snapdragon 200 - 800 processor lines

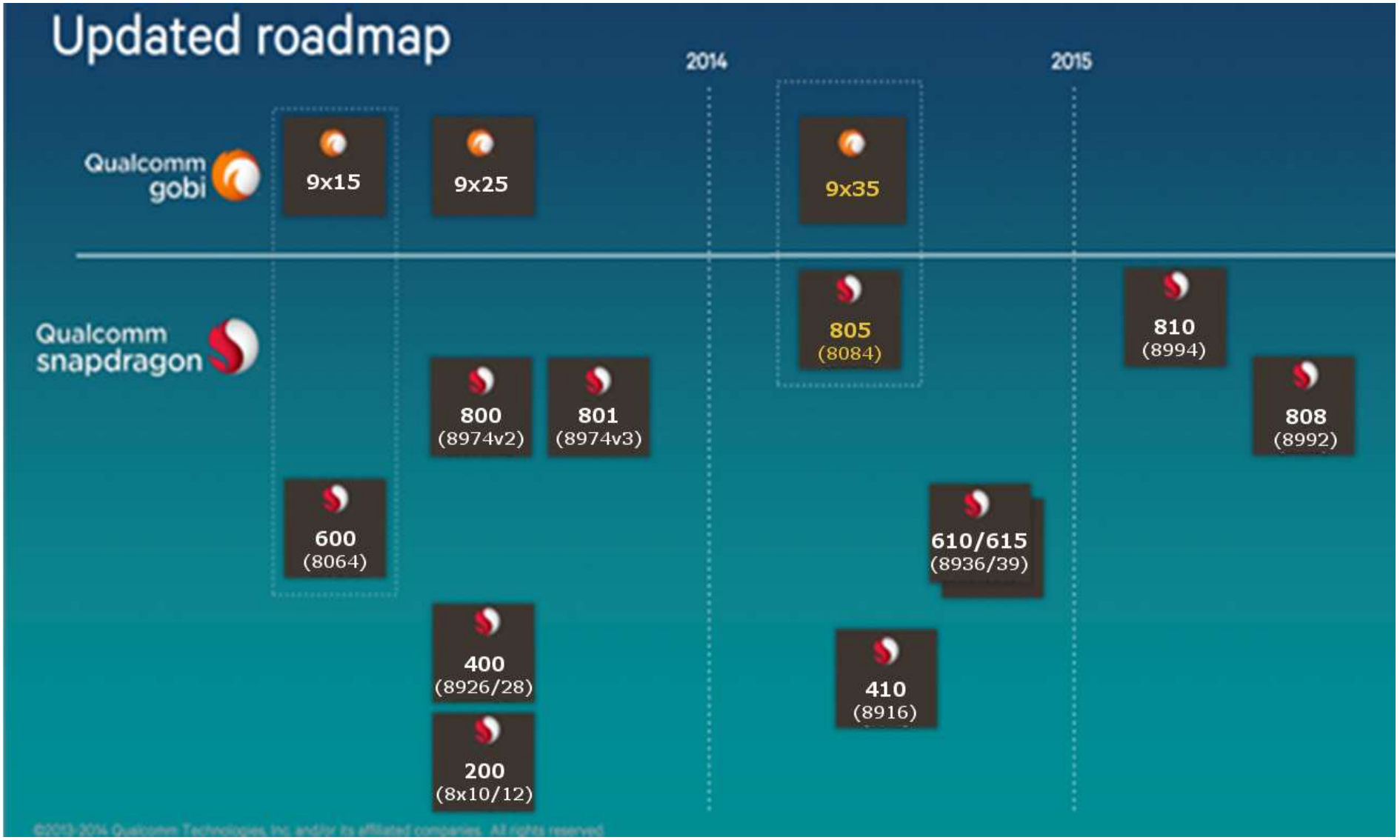
New categorization of Qualcomm's processors in 2013 [23]

In 1/2013 Qualcomm introduced a new categorization for their processors as follows:

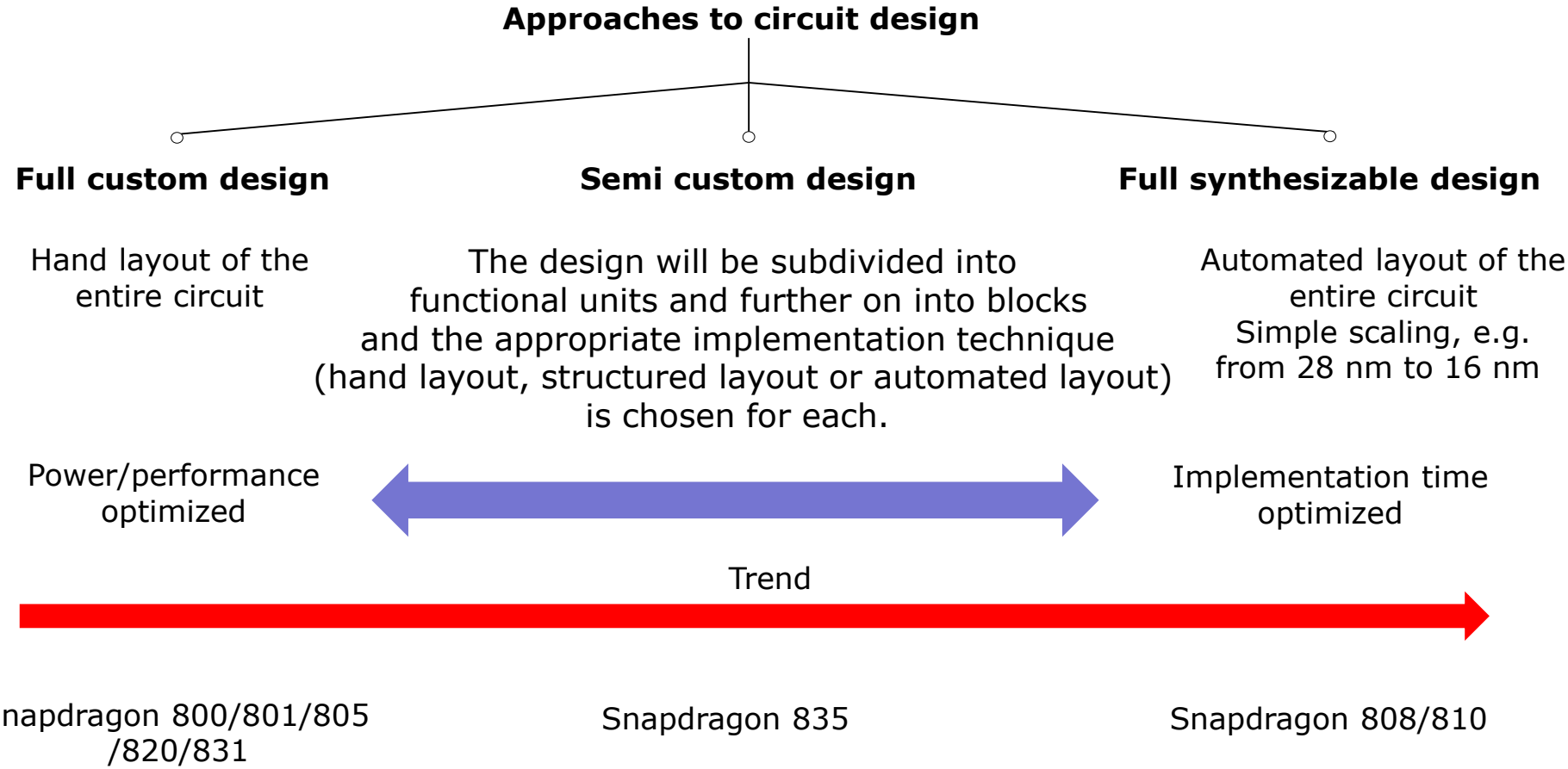


4.3.1 Overview of the Snapdragon 200 – 800 processor lines (2)

The Snapdragon S200 – S800 roadmap from 2014 [22]



Evolution of the approaches used to circuit design -1 [1]



4.3.1 Overview of the Snapdragon 200 – 800 processor lines (4)

Design approaches used by Qualcomm in developing recent processors [69]

810	820	835
Stock ARM (Full synthesizable design)	Custom	Semi-Custom : Built on ARM Cortex® Technology
Rapid 64-bit deployment	High performance with improved power	Higher performance with extreme power efficiency
Limited System Integration	Tight system integration	Tight system integration
4xA53 2.0+ 4xA57 1.55	2xKryo 2.15+ 2xKryo 1.59	4xKryo 280 2.45+ 4xKryo 280 1.9
20 nm (2015)	14 nm (2015)	10 nm (2016)

4.3.1 Overview of the Snapdragon 200 – 800 processor lines (5)

Key features of Snapdragon S200 – S400 family models [14], [15]

Family	Typ. model numbers	Feature size	ISA	CPU	fc up to	Typ. GPU	Memory technology	Wireless technologies up to[1]	Sampling available
S 200	8225Q 8625Q	45 nm	ARMv7	ARM Cortex A5	1.4 GHz	Adreno 203	SCh. 16-bit LPDDR2	HSPA+	2013
S 200	8210/12 8610/12	28 nm	ARMv7	ARM DC Cortex-A7	1.2 GHz	Adreno 302	SCh. 16-bit LPDDR2	HSPA+	2013
S 208		28 nm	ARMv7	ARM QC Cortex-A7	1.1 GHz	Adreno 304	SCh. 16-bit LPDDR2/3	HSPA	2014
S 210		28 nm	ARMv7	ARM QC Cortex-A7	1.1 GHz	Adreno 304	SCh. 16-bit LPDDR2/3	LTE Cat 4	2014
S 400	8226/28 8626/28	28 nm	ARMv7	ARM QC Cortex-A7	1.2 GHz	Adreno 305	SCh. LPDDR2/3	HSPA+	2013
S 400	8926/28	28 nm	ARMv7	ARM QC Cortex-A7	1.6 GHz	Adreno 305	SCh. LPDDR2/3	LTE Cat 4	2013
S 400	8230/8630/ 8930	28 nm	ARMv7	DC Krait 200	1.2 GHz	Adreno 305	SCh. LPDDR2	HSPA+	2013
S 400	8x30AA/AB	28 nm	ARMv7	DC Krait 300	1.4 GHz	Adreno 305	SCh. LPDDR2	LTE Cat 4	2013
S 410	MSM8916	28 nm	ARmv8	ARM QC Cortex-A53	1.4 GHz	Adreno 306	SCh. LPDDR2/3	LTE Cat 4	2014

[1] For 3G parts only the UMTS support level and for 4G parts only the LTE support level is indicated.

4.3.1 Overview of the Snapdragon 200 – 800 processor lines (6b)

Key features of Snapdragon S600 – S800 family models [14], [15] -1

Family	Typ. model numbers	Feature size	ISA	CPU	fc up to	Typ. GPU	Memory technology	Wireless technologies up to[1]	Sampling available
S 600	APQ8064T	28 nm	ARMv7	QC Krait 300	1.9 GHz	Adreno 320	DCh. LPDDR3	--	2013
S2602a	APQ8064 AU	28 nm	ARMv7	QC Krait 300	1.5 GHz	Adreno 320	DCh. LPDDR3	--	2014
S 610	MSM8939	28 nm	ARMv8	QC Cortex-A53+ QC Cortex-A53	1.6 GHz 1.0 GHz	Adreno 405	SCh. 32-bit LPDDR3	LTE Cat 4	2014
S 615	MSM8936	28 nm	ARMv8	QC Cortex-A53+ QC Cortex A53	1.7 GHz 1.0 GHz	Adreno 405	SCh. 32-bit LPDDR3	LTE Cat 4	2014
S 800	MSM 8x74AA	28 nm	ARMv7	QC Krait 400	2.26 GHz	Adreno 330	DCh. LPDDR3	LTE Cat 4	2013
S 801	MSM 8x74 AB/AC	28 nm	ARMv7	QC Krait 400	2.5 GHz	Adreno 330	DCh. LPDDR3	LTE Cat 4	2013?
S 805	APQ8084	28 nm	ARMv7	QC Krait 450	2.7 GHz	Adreno 420	DCh. 64-bit LPDDR3	--	2014
S 808	MSM8992	20 nm	ARMv8	DC Cortex-A57+ QC Cortex-A53	1.82 GHz	Adreno 418	DCh. 32-bit LPDDR3	LTE Cat. 6	2015
S 810	MSM8994	20 nm	ARmv8	QC Cortex-A53+ QC Cortex-A57	2.0 GHz	Adreno 430	DCh. 32-bit LPDDR4	LTE Cat 6	2015
S 820	MSM8996	14 nm FinFET	ARMv8	DC Kryo 2.15 GHz DC Kryo 1.59 GHz	2.15 GHz	Adreno 530	QCh. 16-bit LPDDR4	LTE Cat 12/13	2015
S 821	MSM8996 Pro	14 nm FinFET	ARMv8	DC Kryo 2.34 GHz DC Kryo 1.6 GHz	2.34 GHz	Adreno 530	QCh 16-bit LPDDR4	LTE Cat 12/13	2016

[1] For 3G parts only the UMTS support level and for 4G parts only the LTE support level is indicated.

4.3.1 Overview of the Snapdragon 200 – 800 processor lines (6)

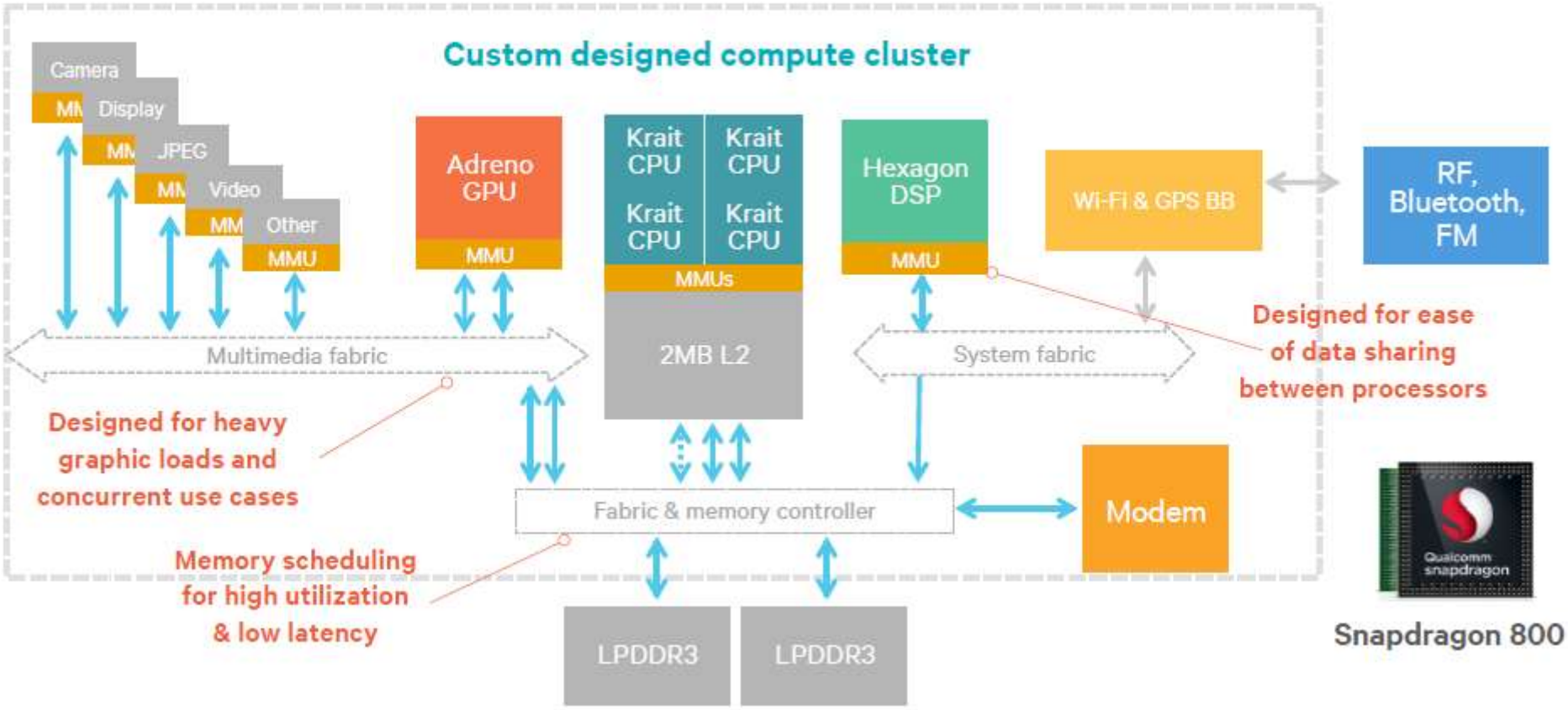
Key features of Snapdragon S600 – S800 family models [14], [15] -2

Family	Typ. model numbers	Feature size	ISA	CPU and Clock frequency (up to)	L3 shared	Typ. GPU	Memory technology	Wireless technologies up to[1]	Available
S 835	MSM8998	10 nm FinFET	ARM V8.0	4x Kryo 280 Gold (A73-based) @ 2.45GHz 2MB L2 (shared) 4x Kryo 280 Silver (A53-based) @ 1.90GHz, 1MB L2 (shared)	--	Adreno 540	4x16-bit LPDDR4-1866	LTE Cat 16/13	Q1/2017
S 845	SDM845	10 nm FinFET	ARM V8.2	4x Kryo 385 Gold (A75-based) @ 2.8GHz 4x256KB L2 4x Kryo 385 Silver (A55-based) @ 1.80GHz 4x128KB L2	2 MB	Adreno 630	4x16-bit LPDDR4-1866	LTE Cat 18/13	Q1/2018
S 850	SDM850	10 nm FinFET	ARM V8.2	4 x Kryo 385 Gold (A75-based) @ 2.95 GHz 4 x 256 KB L2 4 x Kryo 835 Silver (A55-based) @ ? GHz 4x128 KB L2	2 MB	Adreno 630	4x16-bit LPDDR4x	LTE Cat 18/13	Q3/2018
S 855	SDM855	7 nm FinFET	ARM V8.2	1x Kryo 485 Gold (A76-based) @ 2.84GHz 1x512KB L2 3x Kryo 485 Gold (A76-based) @ 2.42GHz 3x256KB L2 4x Kryo 485 Silver (A55-based) @ 1.80GHz 4x128KB L2	2MB	Adreno 640	4x16-bit LPDDR4-2133	LTE Cat 20	Q1/2019
S. 8cx	n.a.	7 nm FinFET	ARM V8.2	4x Kryo 485 Gold (A76-based) @ ?? GHz 4x256KB L2 4x Kryo 485 Silver (A55-based) @?? GHz 4x128KB L2	2 MB	Adreno 680	8x16-bit LPDDR4x	LTE Cat 24	Q3/2019

[2]Kryo 280

4.3.1 Overview of the Snapdragon 200 – 800 processor lines (7)

Example 1: Block diagram of the Snapdragon 800 SOC [23]



4.3.1 Overview of the Snapdragon 200 – 800 processor lines (8)

Example 2: Snapdragon 810 based platform [24]

Remark

Enabling 3x LTE CA requires two RF transceivers: Qualcomm's **WTR3925** and **WTR3905**.
WTR3925 is a 2x CA RF transceiver and WTR3905 adds another carrier.

4.3.2 The Snapdragon 820 processor

4.3.2 The Snapdragon 820 processor

- It is a custom designed processor that is based on a new core, called the Kryo core.

  The Kryo core runs the ARMv8 ISA rather than the ARMv7 ISA as Qualcomm's previous cores (Scorpion, Crait) did.
- Announced in 03/2015, sampled about 06/2015.
- It is a 2 + 2 core design with
  - 2x Kryo clocked at 2.15 GHz
  - 2x Kryo clocked at1.59 GHz and
- Manufactured on 14 nm technology (FinFET LPP (Low Power Plus)).
- Along with the Snapdragon 820 and Kryo, Qualcomm introduced also
  - the Hexagon 600 DSP that is a significantly enhanced version of the Hexagon line of DSPs (6. version) targeting AI and
  - the Symphony System Manager.

4.3.2 The Snapdragon 820 processor (2)

Main features of select Snapdragon 800 processors [70]

	Snapdragon 810	Snapdragon 820	Snapdragon 821	Snapdragon 835
CPU Core	Stock ARM Cortex-A	Custom design Kryo	Custom design Kryo	Semi-custom ARM Cortex design Kryo 280
Sampling	2015	2015	2016	2017
CPU Config	4x Cortex-A57 4x Cortex-A53	2x Kryo 2.15 GHz 2x Kryo 1.59 GHz	2x Kryo 2.35 GHz 2x Kryo 1.6 GHz	4x Kryo 280 2.45 GHz 4x Kryo 280 1.9 GHz
GPU	Adreno 430	Adreno 530	Adreno 530	Adreno 540
DSP	Hexagon V56	Hexagon 680 with HVX	Hexagon 680 with HVX	Hexagon 682 with HVX
RAM	2x 32-bit LPDDR4 1600 MHz	2x 32-bit LPDDR4X 1866 MHz	2x 32-bit LPDDR4X 1866 MHz	2x 32-bit LPDDR4X 1866 MHz
Flash	eMMC 5.0 / UFS 1.0	eMMC 5.1/ UFS 2.0	eMMC 5.1/ UFS 2.0	eMMC 5.1/ UFS 2.1
Process	20nm HPm	14 nm FinFET	14nm FinFET LPP	10nm FinFET LPE

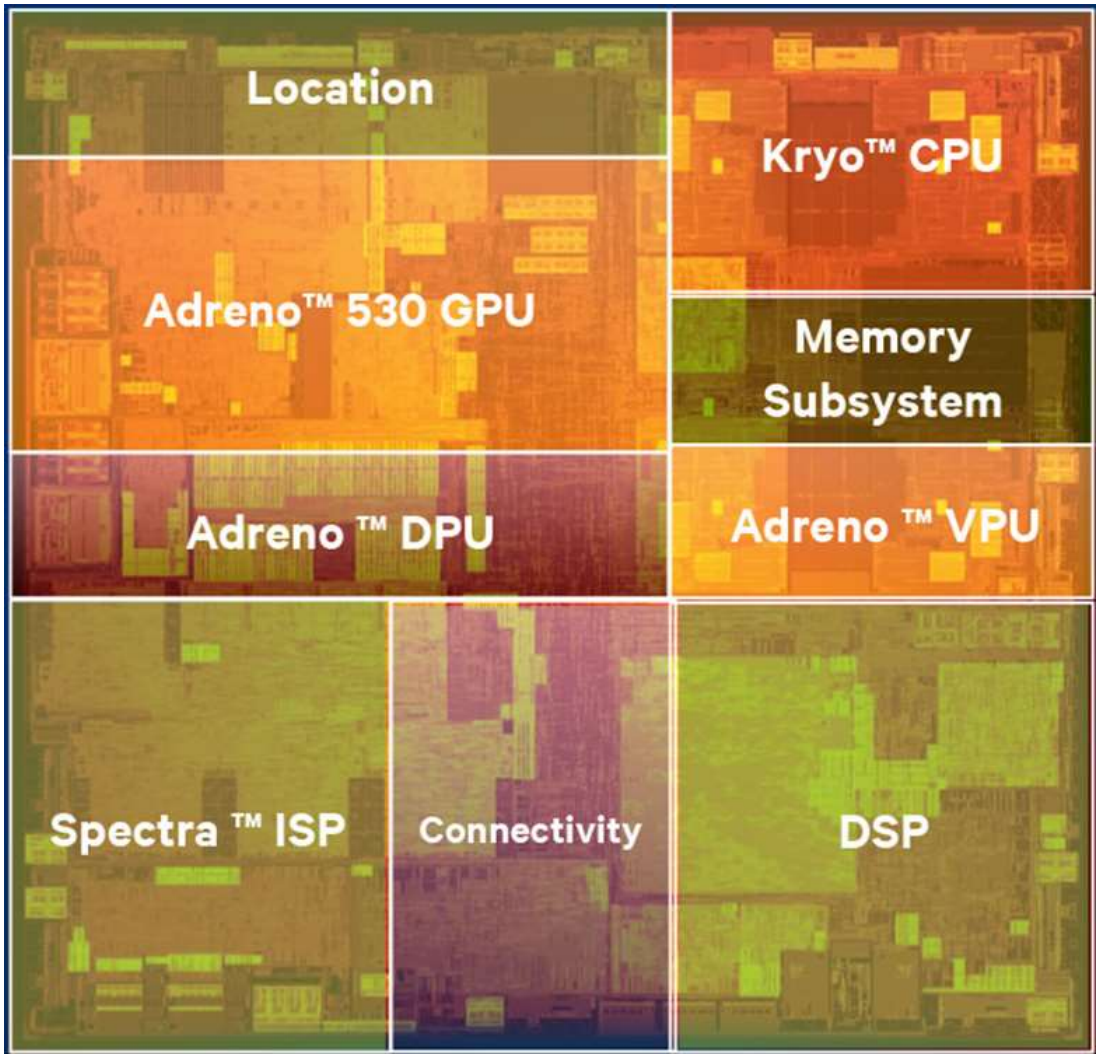
4.3.2 The Snapdragon 820 processor (3)

Main features of the Kryo core vs. the previous ones [71]

Qualcomm CPU Core Comparison			
	Snapdragon 800	Snapdragon 810	Snapdragon 820
CPU Codename	Krait	ARM Cortex-A57	Kryo
ARM ISA	ARMv7-A (32-bit)	ARMv8-A (32/64-bit)	ARMv8-A (32/64-bit)
Integer Add	1	2	1
Integer Mul	1	1	1
Shifter ALUs	1	2	1
Addition (FP32) Latency	3 cycles	5 cycles	3 cycles
Multiplication (FP32) Latency	6 cycles	5 cycles	5 cycles
Addition (INT) Latency	1.5 cycles	1 cycle	1 cycle
Multiplication (INT) Latency	4 cycles	3 cycles	4 cycles
L1 Cache	16KB I$ + 16KB D$	48KB I$ + 32KB D$	32KB I$ + 32KB D$?
L3 Cache	N/A	N/A	N/A

4.3.2 The Snapdragon 820 processor (4)

Main functional blocks of the Kryo core [72]



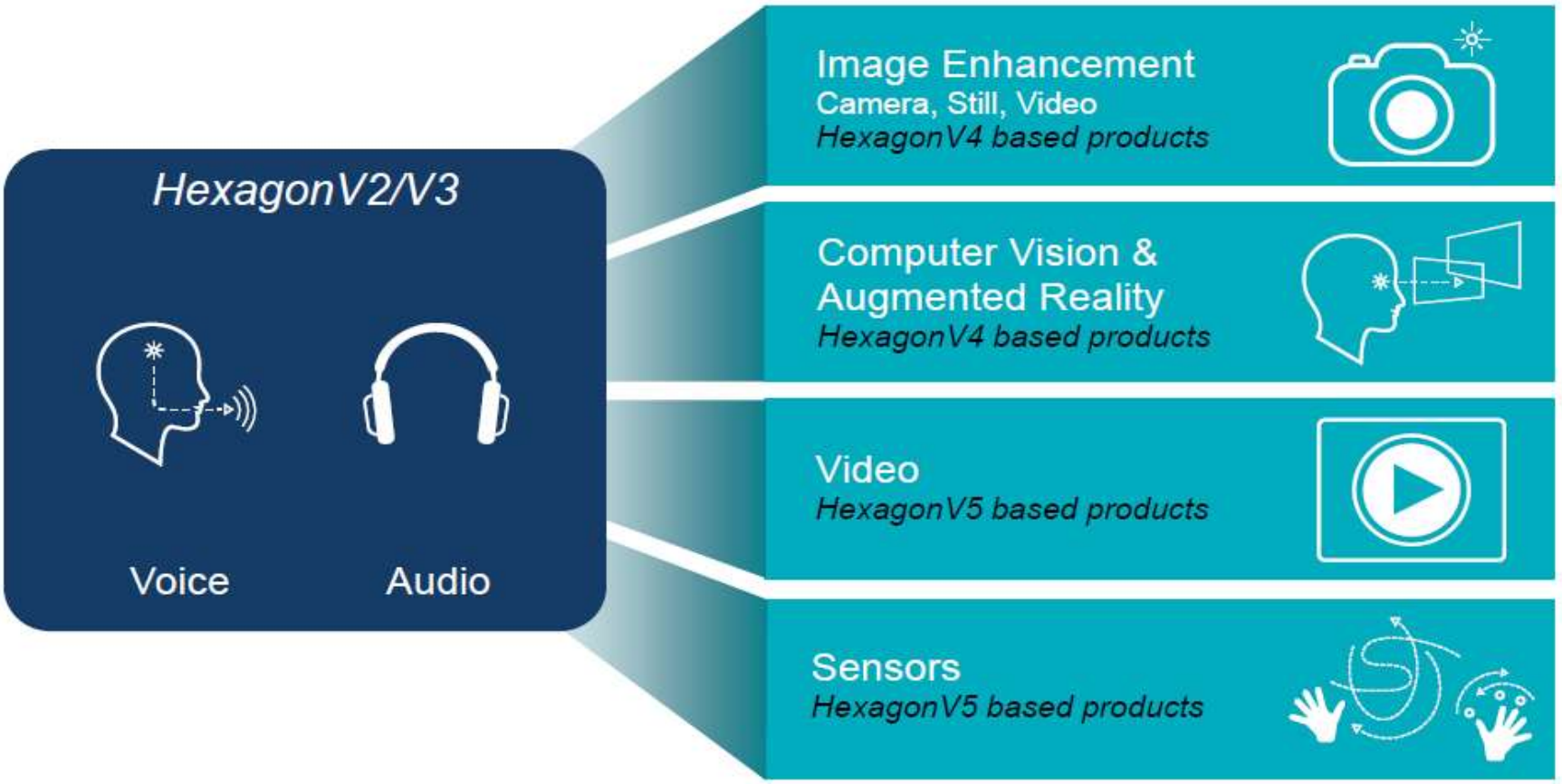
4.3.2 The Snapdragon 820 processor (5)

The Hexagon 680 DSP

- It is the 6. version of the Hexagon DSP line that is introduced along with the Snapdragon 820 model.
- Originally the Hexagon DSP line supported only audio processing, subsequent
- versions expanded the supported applications areas continuously, as indicated in the next Figure.

4.3.2 The Snapdragon 820 processor (6)

Enhancements of subsequent Hexagon DSP versions [73]

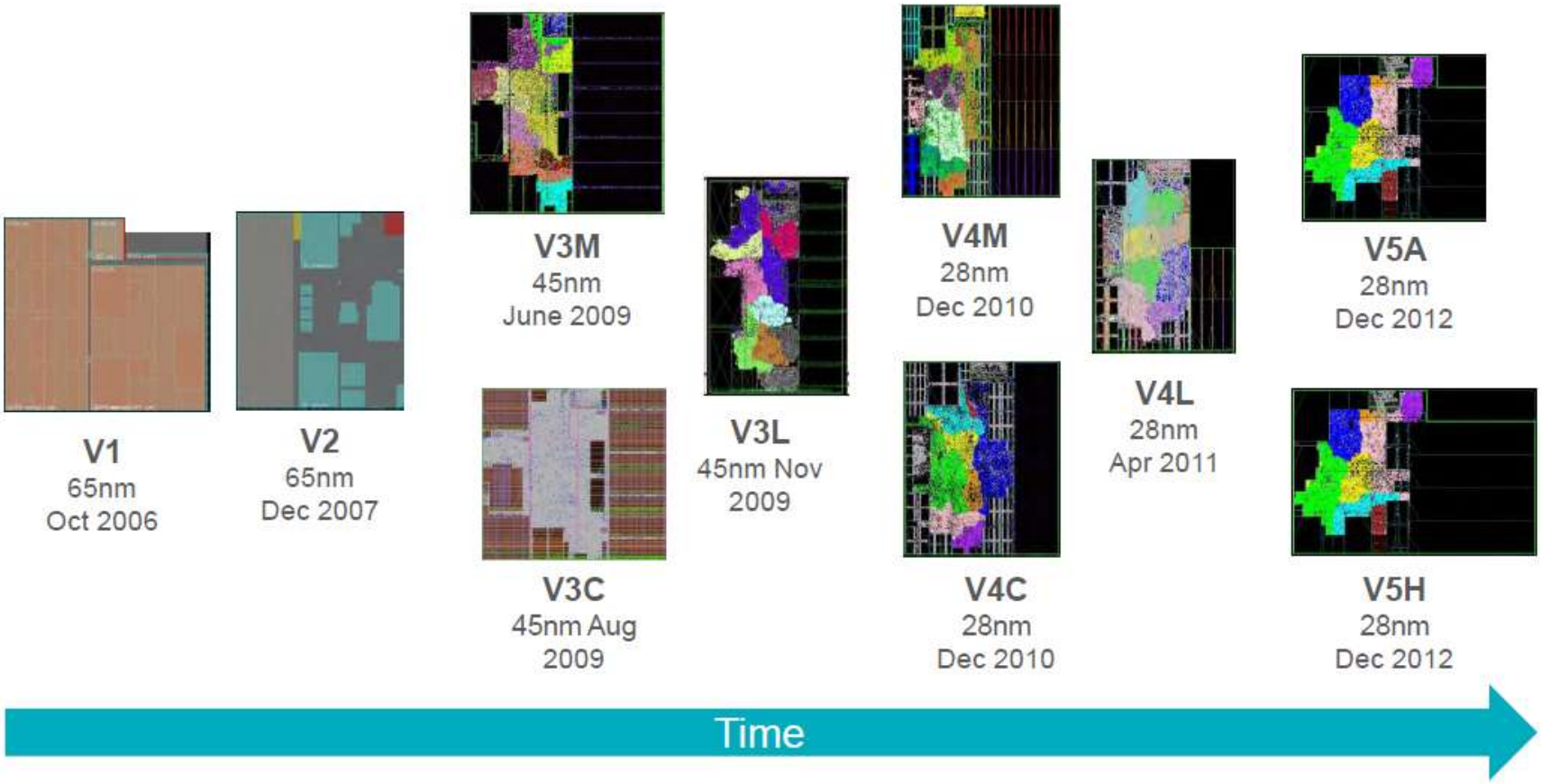


- Subsequently, Hexagon V6 expanded its scope also for artificial intelligence.

4.3.2 The Snapdragon 820 processor (7)

Release history of Hexagon DSPs (v1–v5) used in Snapdragon processors [73]

Generational improvements in performance and power efficiency driven by both architecture and implementation



4.3.2 The Snapdragon 820 processor (8)

Major enhancements of the Hexagon version 6 (6xx implementations) vs. the 5. version (Hexagon 5xx implementations) of the Hexagon DSP line

- V5 is based on a 32 x 32-bit register set, it supports both FX and FP operations, whereas
- V6 is based on a 32x1024-bit register set, it supports only FX operations,
- V6 is the first Hexagon implementation that supports already the HVX (Hexagon Vector eXtension) ISA enhancement that aims at AI.

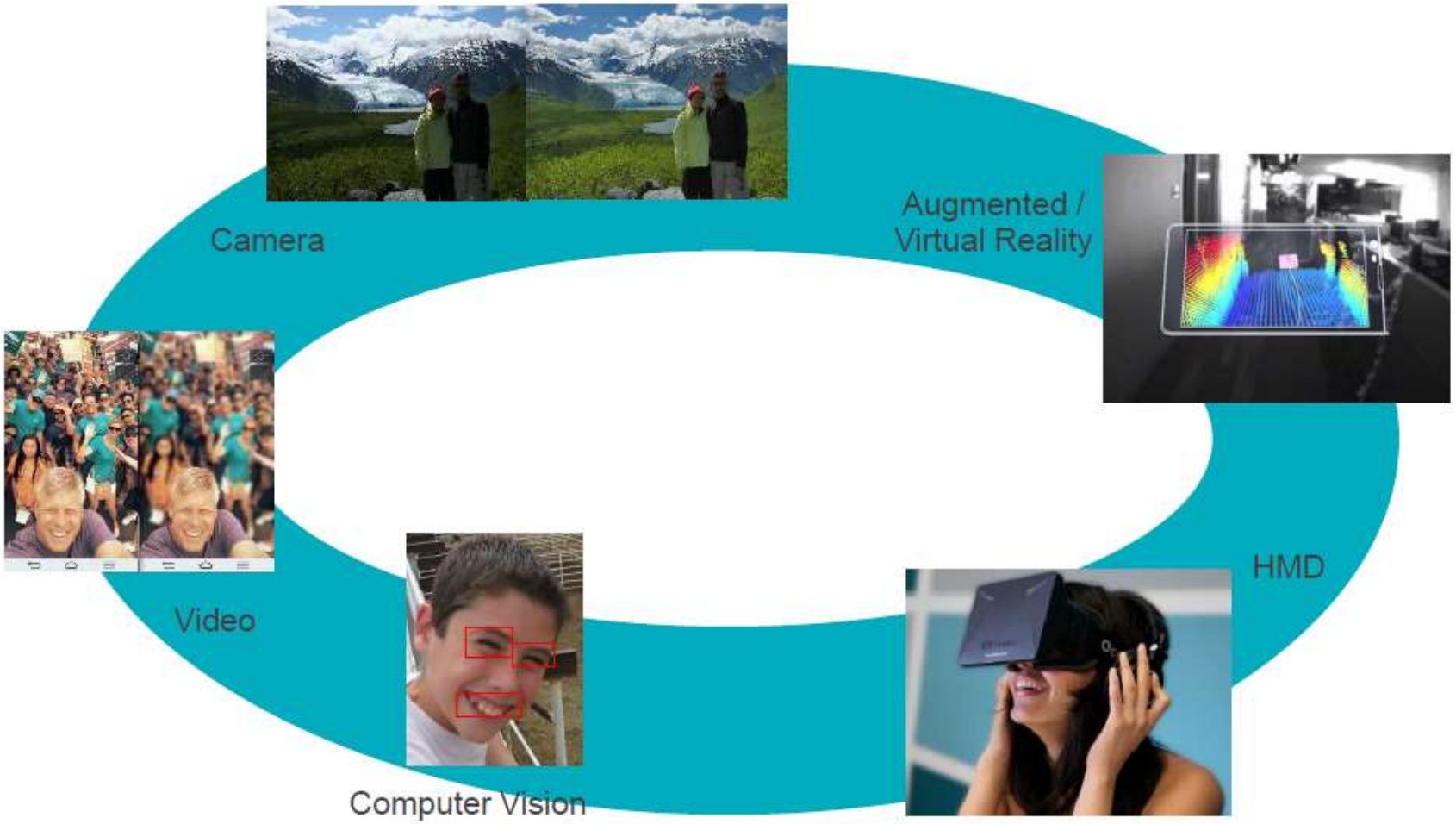
4.3.2 The Snapdragon 820 processor (9)

Use of Hexagon 400 to 600 DSPs (versions 4-6) in Snapdragon processors [74]

		Hexagon Core Architecture		
		Hexagon 400 (version 4)	Hexagon 500 (version 5)	Hexagon 600 (version 6)
	Key Attributes	Fixed Point	Floating Point	Hexagon Vector eXtensions (HVX)
Snapdragon Chipsets (SDxxx)	Premium Tier		801, 805, 808, 810	820, 821, 835, 845
	High Tier	602A	615, 161, 617, 625, 650, 652	
	Mid Tier		410, 412, 415, 430	
	Low Tier		208, 210, 212	
	SDK Version	AddOn_600	SDK 2.0	SDK 3.0
	Command Line Tools	5.0, 5.1	5.0, 5.1, 6.2, 6.4	7.2, 7.3
	RTOS	QuRT	QuRT	QuRT

4.3.2 The Snapdragon 820 processor (10)

Main application areas of Hexagon DSPs [75]



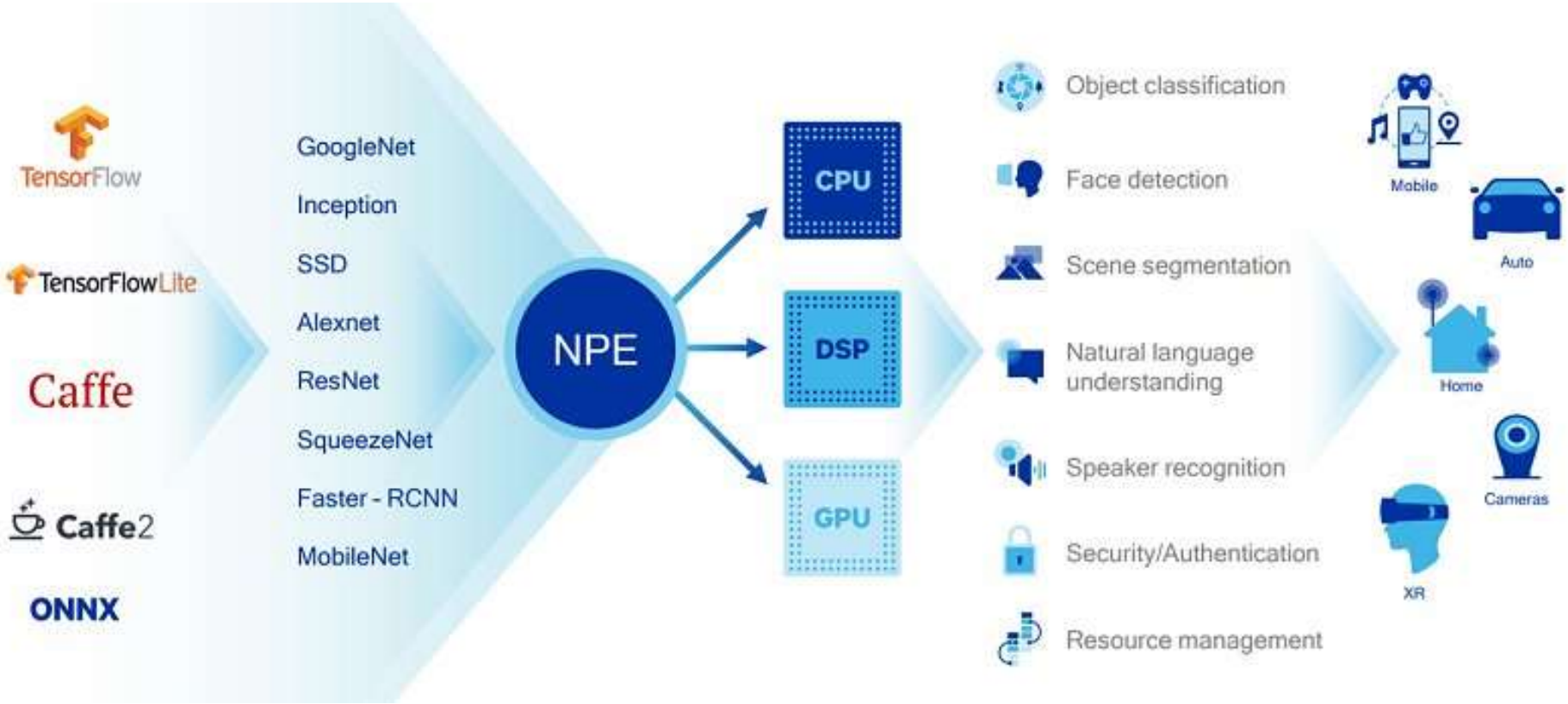
Benefit of using Hexagon DSPs: Higher performance at lower power consumption.

4.3.2 The Snapdragon 820 processor (11)

Example: AI execution resources on the Snapdragon 845 processor [76]

HVX: Hexagon Vector eXtensions

Principle of executing AI-like tasks supported by the NPE SDK [76]



NPE: Neural Processing Engine SDK, available since 07/2017.

The NPE is also capable enough to control which computational resource

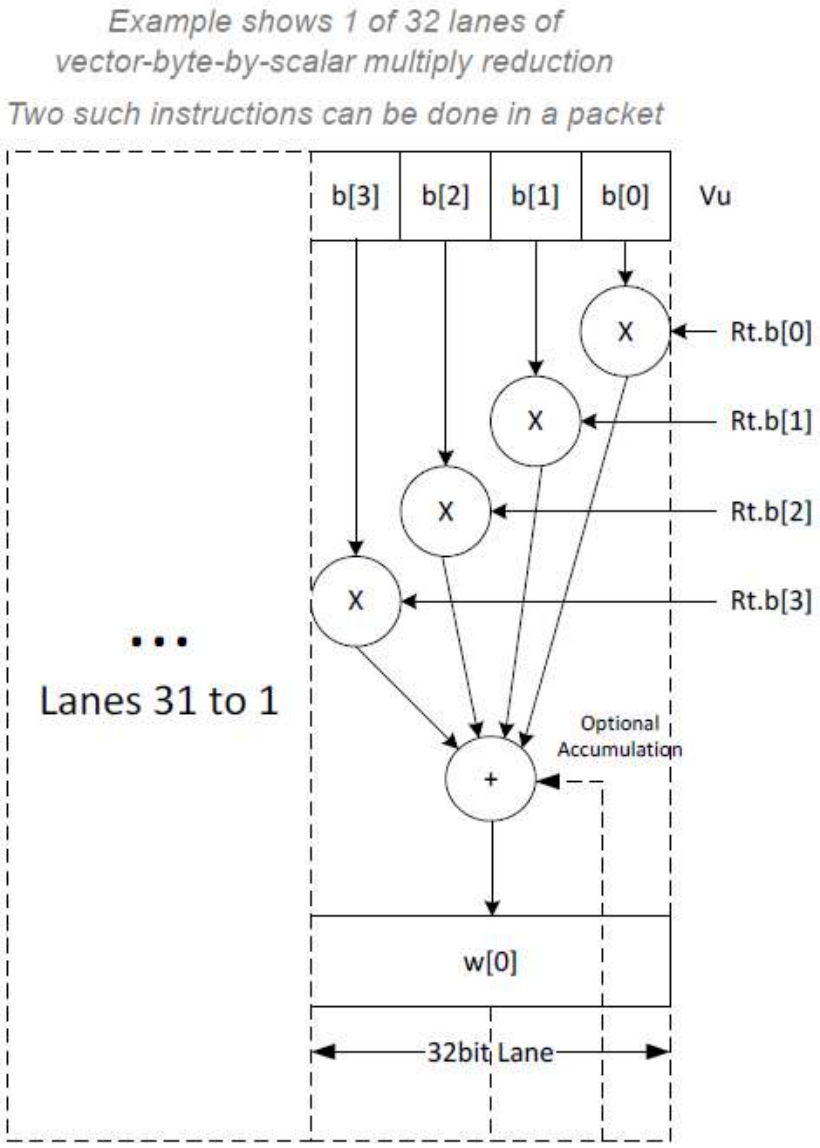
4.3.2 The Snapdragon 820 processor (13)

The HVX (Hexagon Vector eXtension) ISA enhancement

Introduced in the Hexagon 600 (version 6) release along with the Snapdragon 820 in 2015.

The HVX ISA extension: SIMD extension [75]

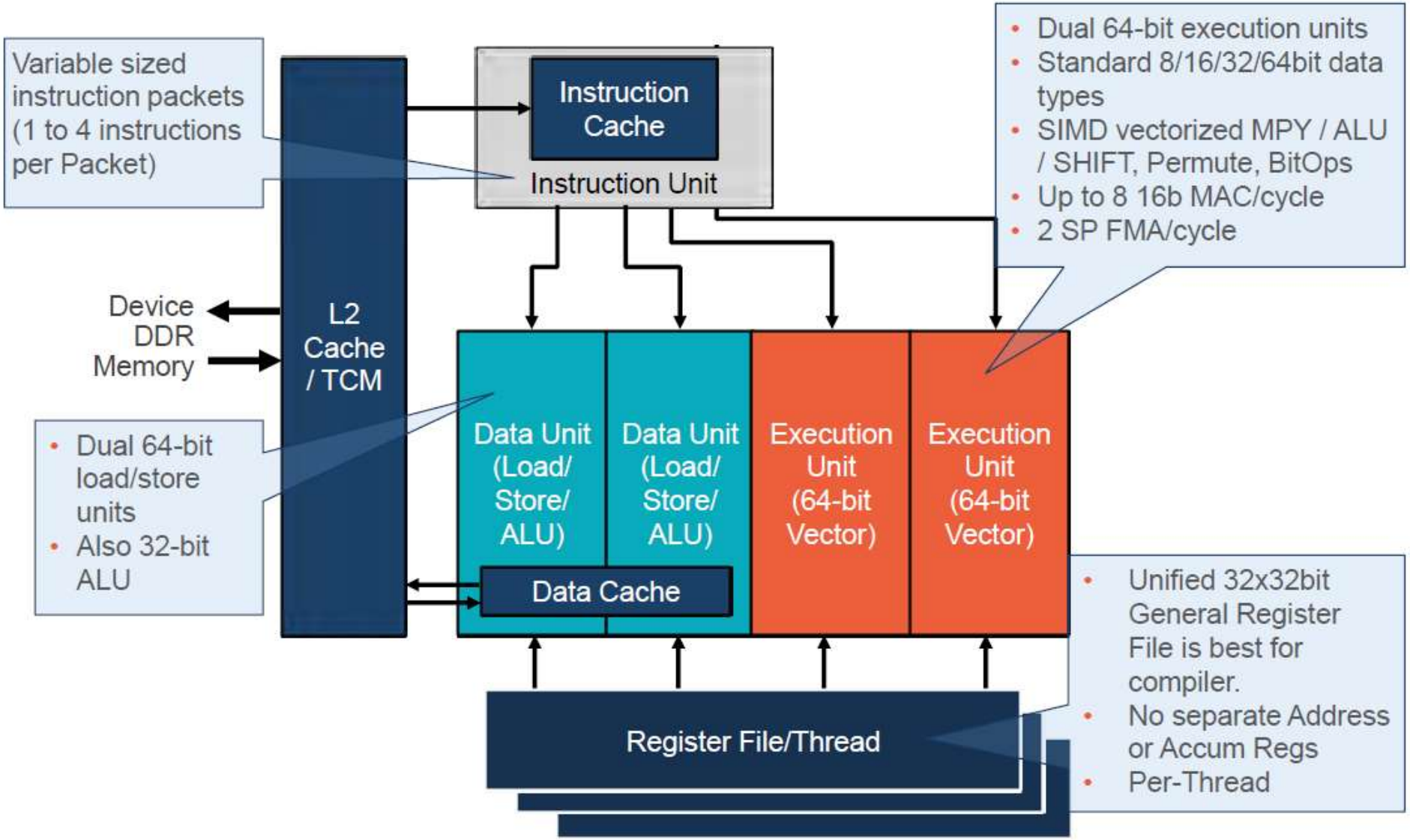
- Large SIMD Extensions
  - 1024b SIMD * 4 vector-slot VLIW
  - 4096 result bits / cycle
- 256 8x8 mpy, 64 16x16 mpy
- 32 1024-bit vector registers
- 8/16/32 bit fixed point
- *NO floating-point*
  - *Smaller & Lower Energy Design*
  - *Algorithmically not needed for majority of CV/Imaging Apps*
- Special ISA: Sliding window filters, LUTs, Histograms
- Performance is sufficient for UHD video post-processing, 20Mpix camera burst mode processing … and more



4.3.2 The Snapdragon 820 processor (15)

Principle of operation: VLIW4 execution

Example VLIW4 execution on Hexagon 500 (version 5) DSP [73]



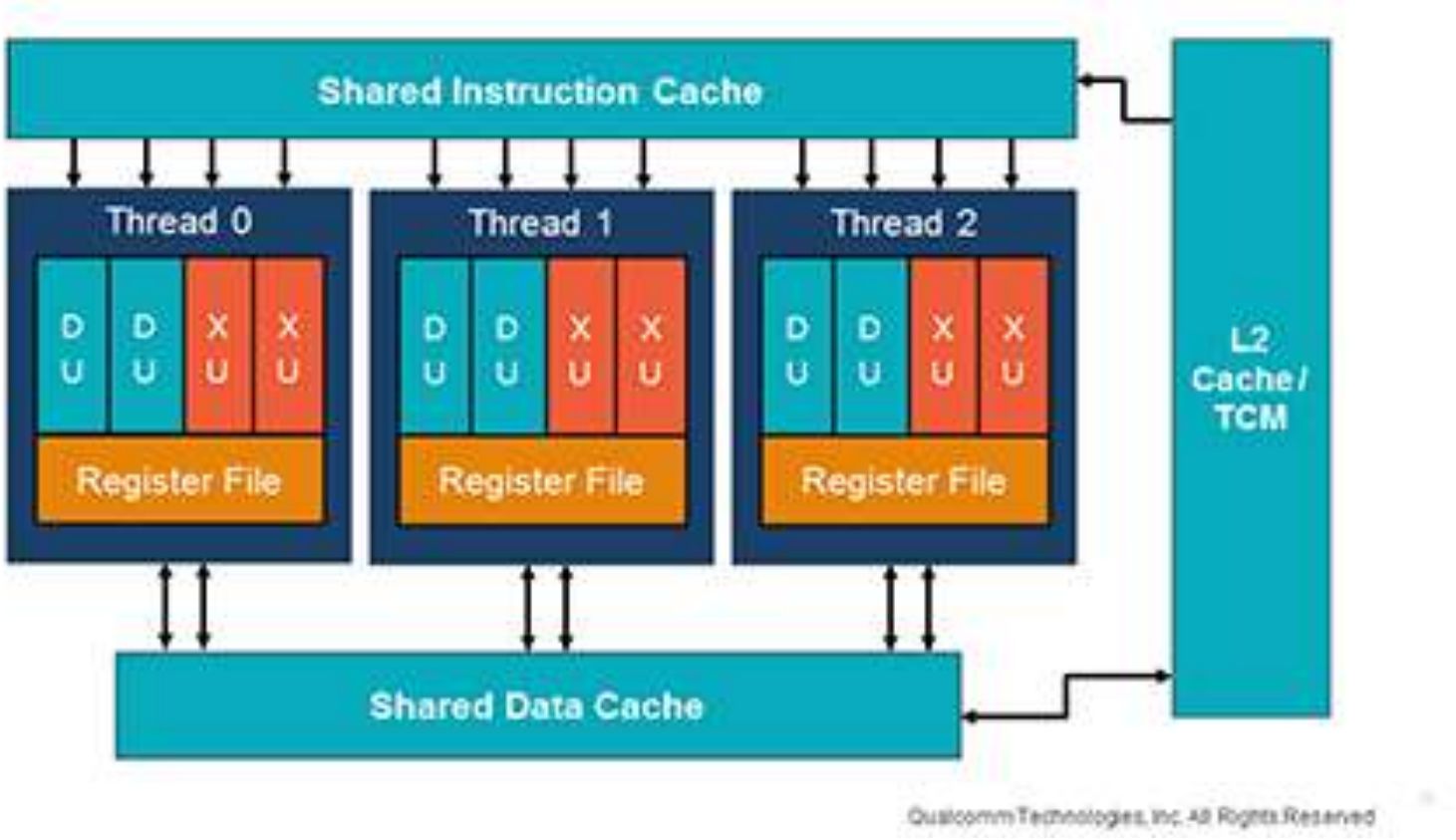
4.3.2 The Snapdragon 820 processor (16)

Support of multithreading in the Hexagon DSP line

- Hexagon DSPs support multithreading.
- The number of ways of multithreading is however different in particular versions, like
  - 6 in version 2
  - 3 in version 4 and 5 or
  - 4 in version 6.

4.3.2 The Snapdragon 820 processor (17)

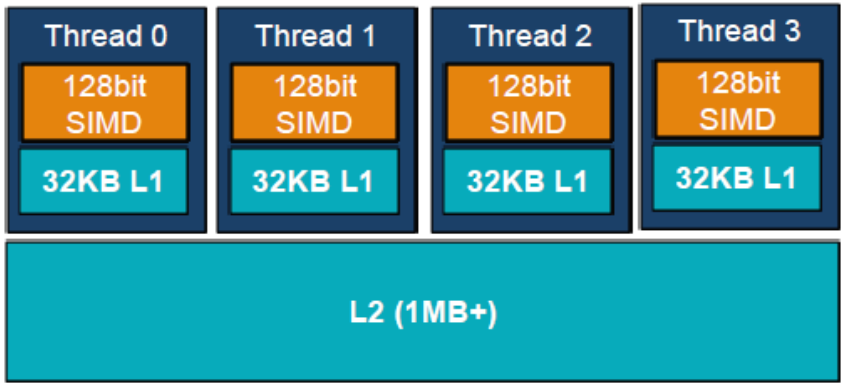
Example: DSP operation on a Hexagon 5xx (V5) implementation [74]



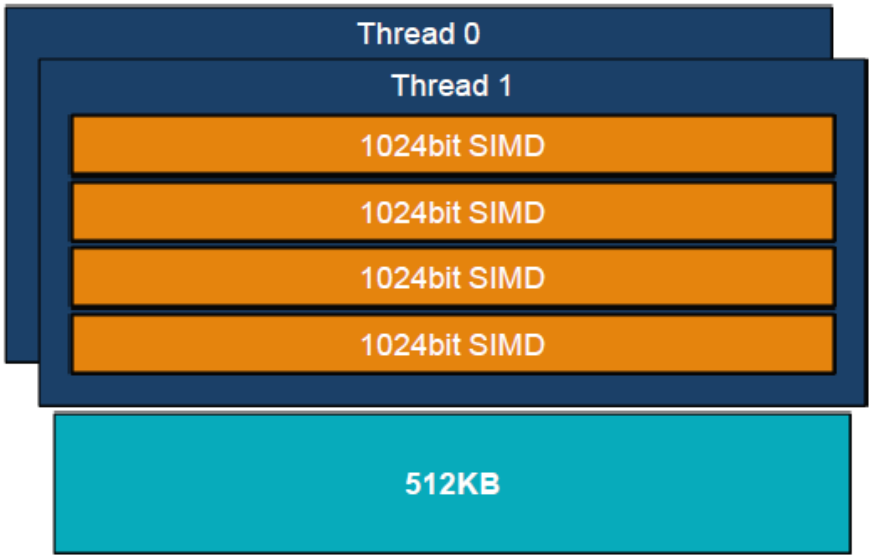
Note: Version 5 doesn't yet support the AVX ISA extension.

Principle of AVX execution vs. quad CPU execution with NEON support on Hexagon 6xx (version 6) DSPs [75]

Quad CPU with Neon	Hexagon DSP with HVX	HVX Advantage
128 bit SIMD with 1 SIMD pipeline/CPU is common	1024 bit SIMD, 4 Pipelines	8x compute/cycle
SIMD thread on 32KB L1	SIMD threads share 512KB "L1"	8x more "L1" memory/thread Efficient Data Sharing
Floating-Point in SIMD	Only Fixed-Point in SIMD	Lower area & power



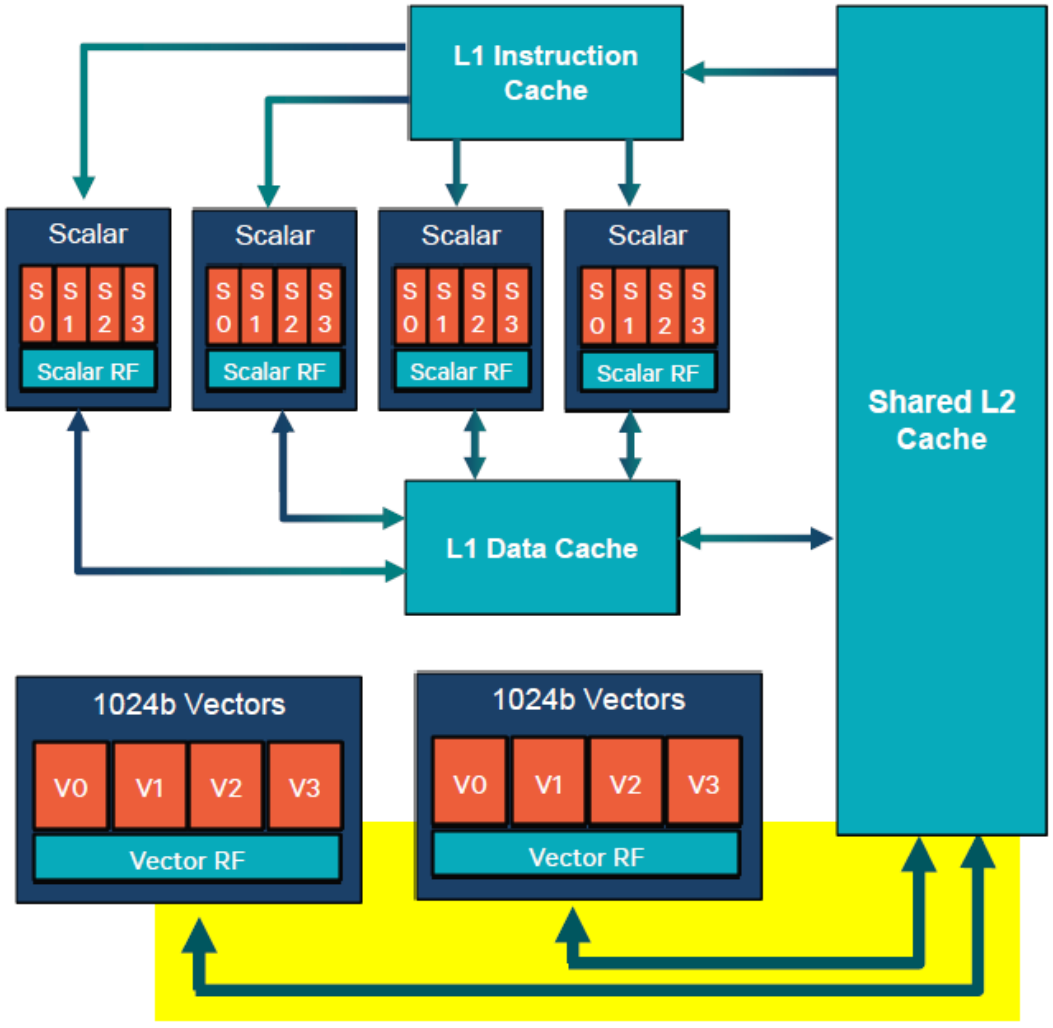
Quad CPU



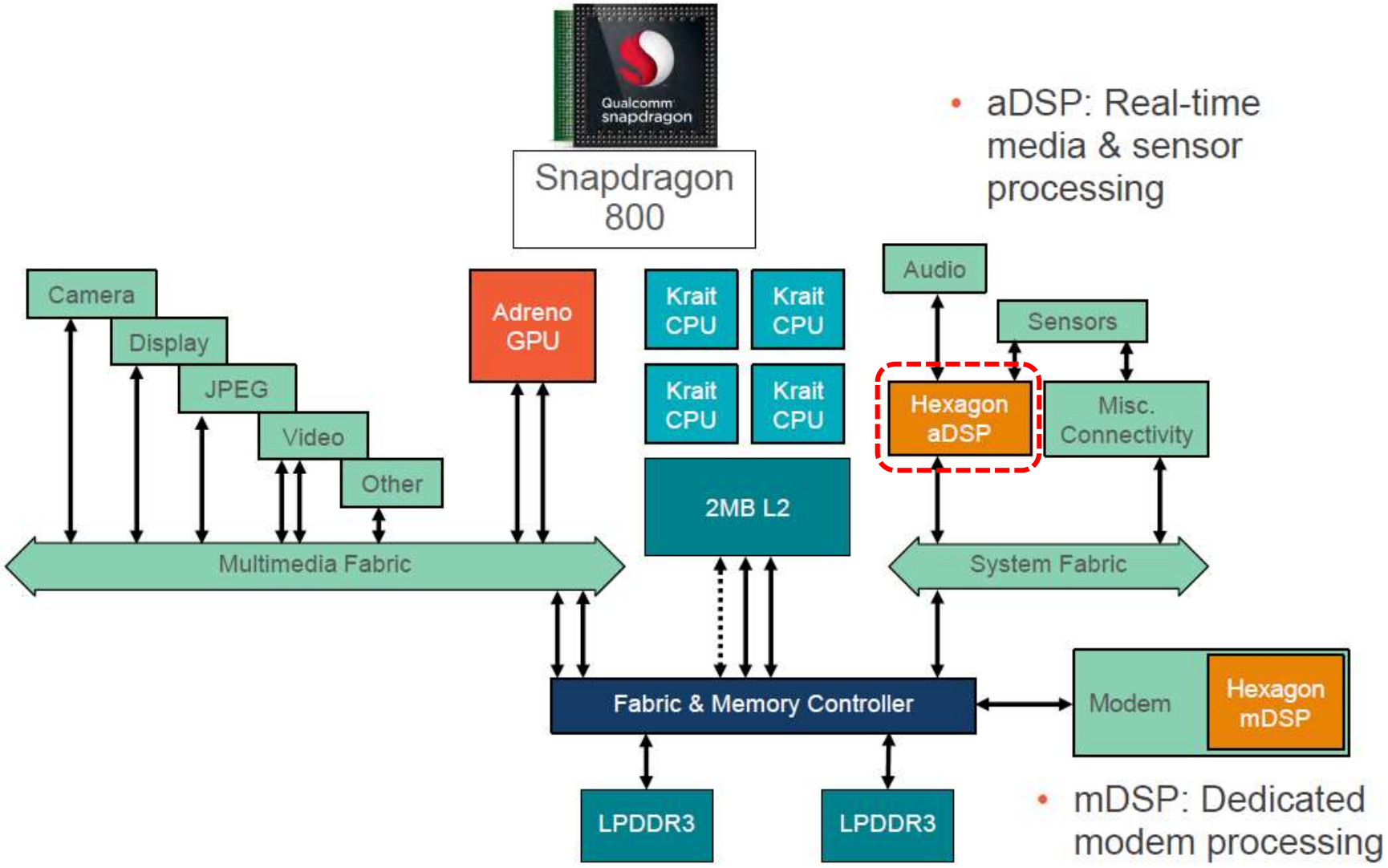
Hexagon DSP with HVX

AVX execution on a Hexagon 6xx (V6) implementation [75]

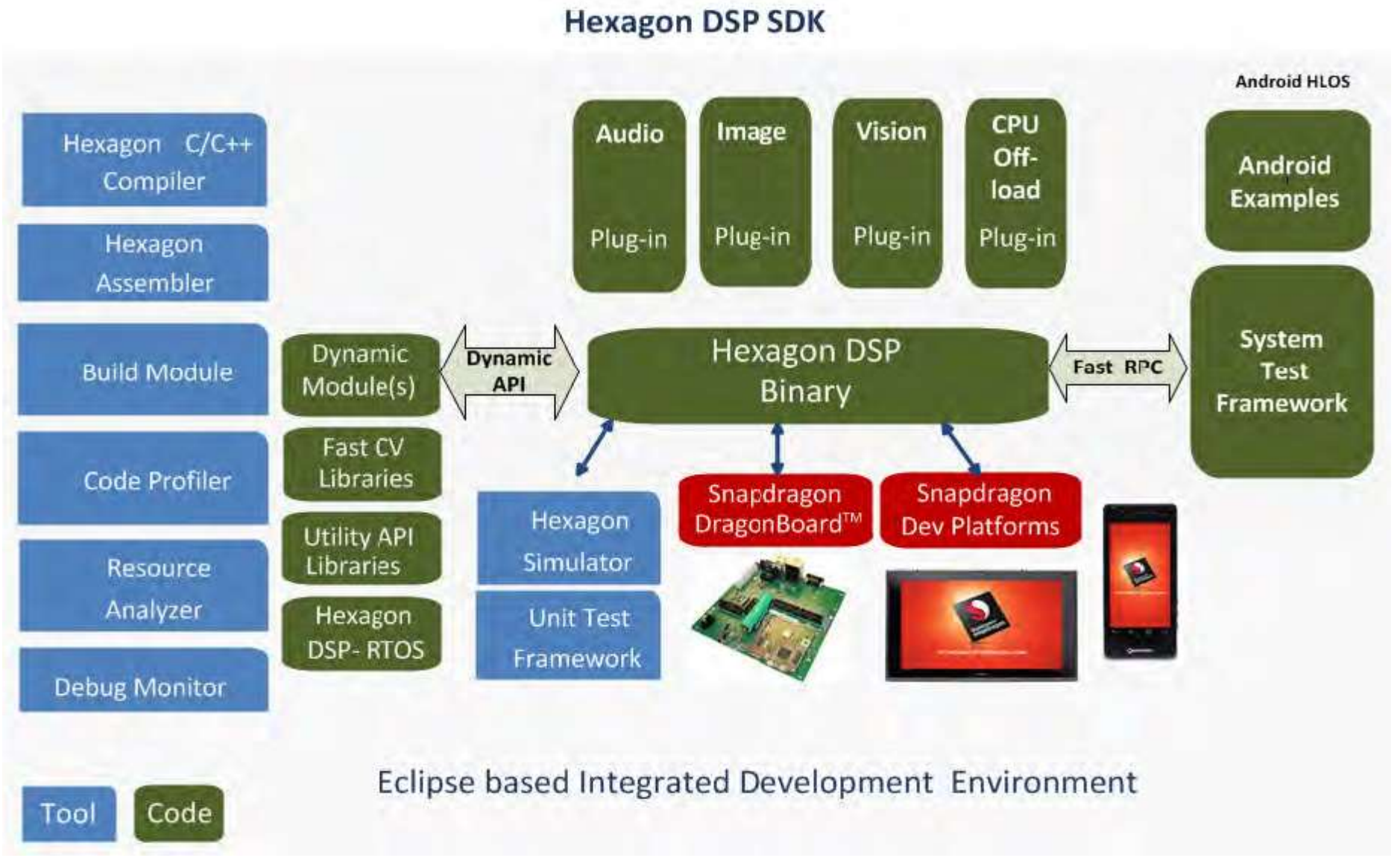
- L2 is the first level memory for the vector units
  - Large primary memory to hold image data reduces tiling overheads seen on small L1
  - Single cycle Load to Use
  - Supports full BW
  - Simplifies programming
- L1/L2 is kept HW coherent
- Streaming prefetch from DDR to L2
- Vector units support variety of Load/Store instructions:
  - Unaligned
  - Per-Byte Conditional



Example for incorporating a DSP in a Snapdragon processor [73]

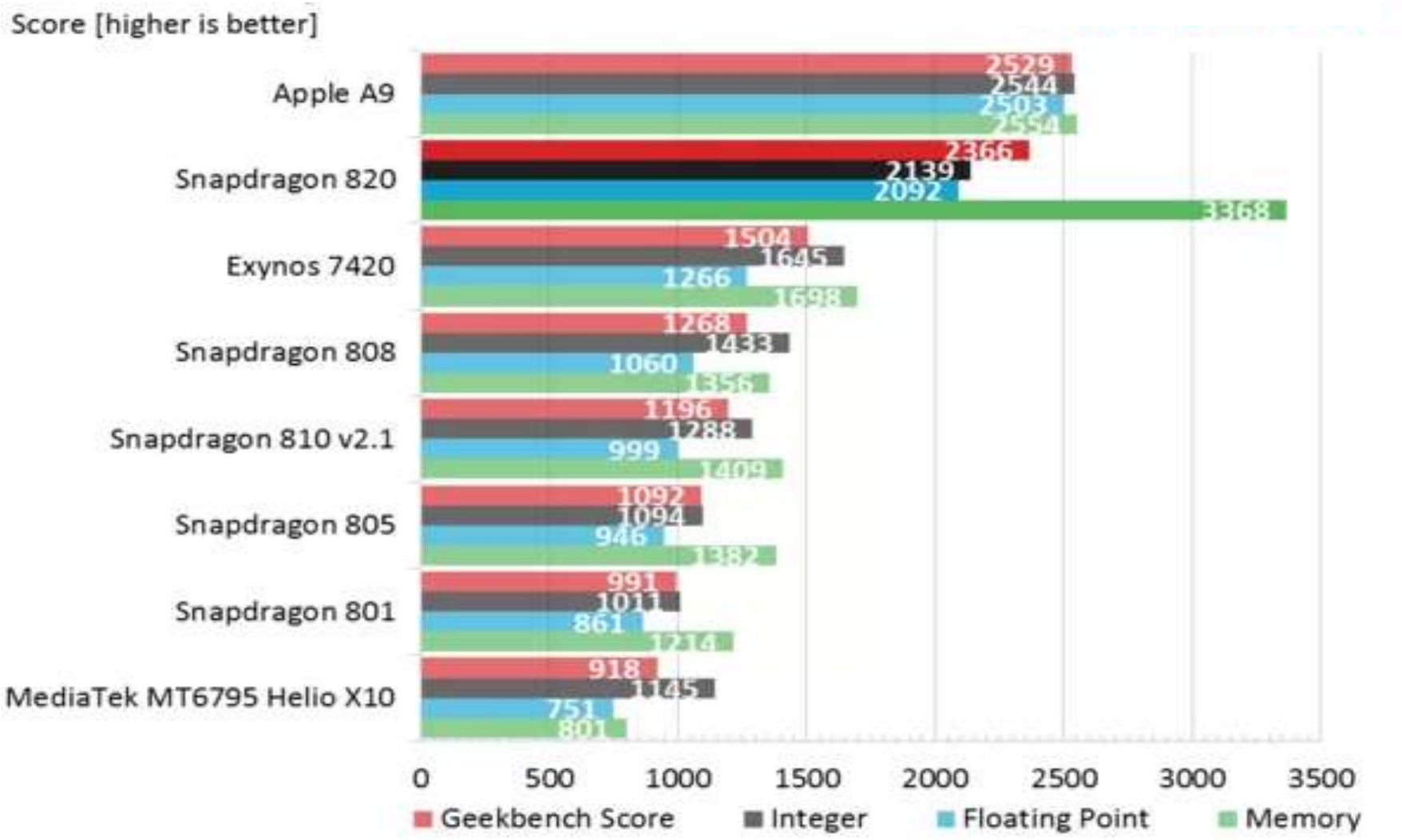


Example for programming DSPs by the Hexagon DSP SDK 2.0 (supporting Hexagon version 5) [73]

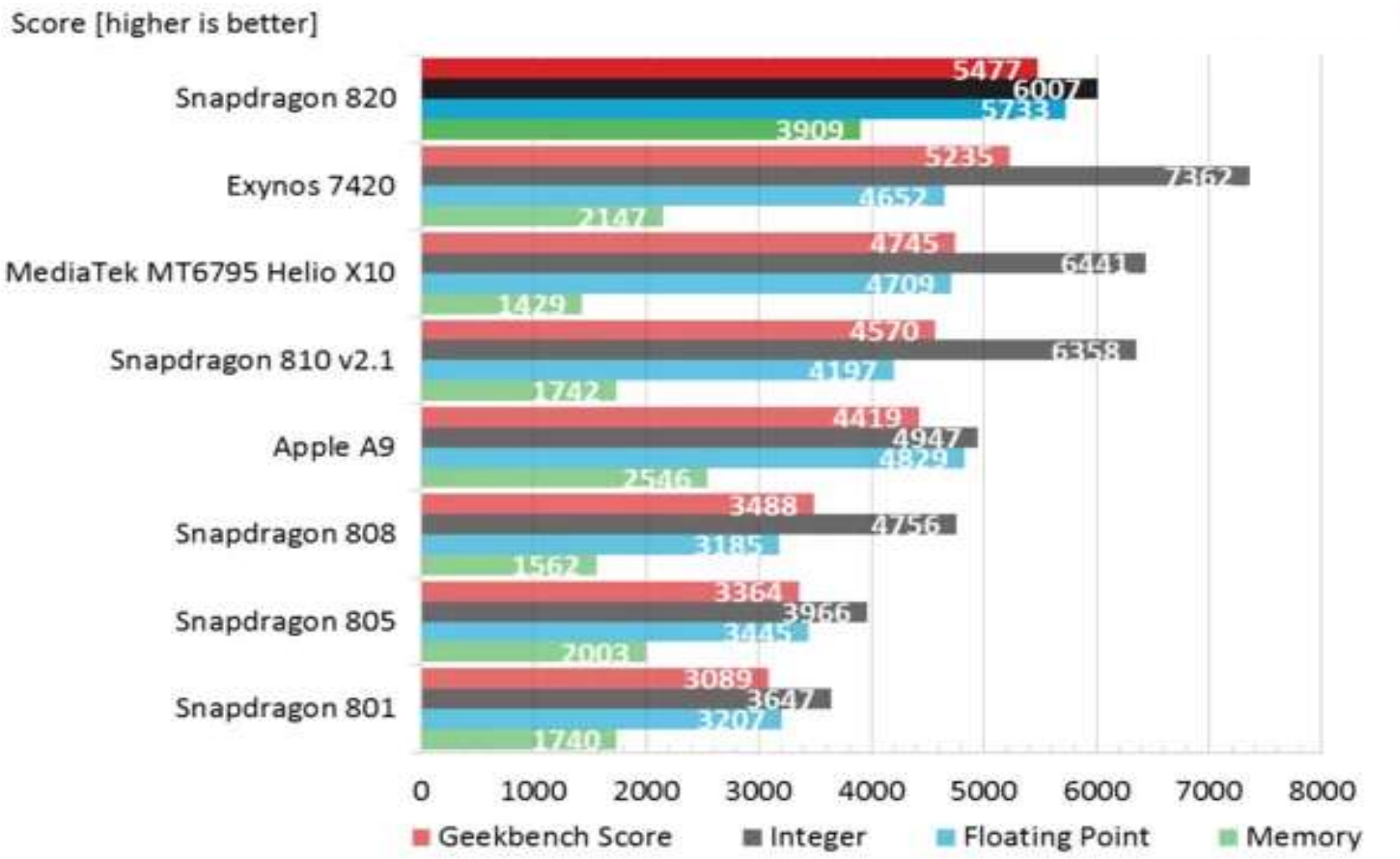


4.3.2 The Snapdragon 820 processor (22)

Geekbench 3 Pro v3.3.1 benchmark single core results [77]

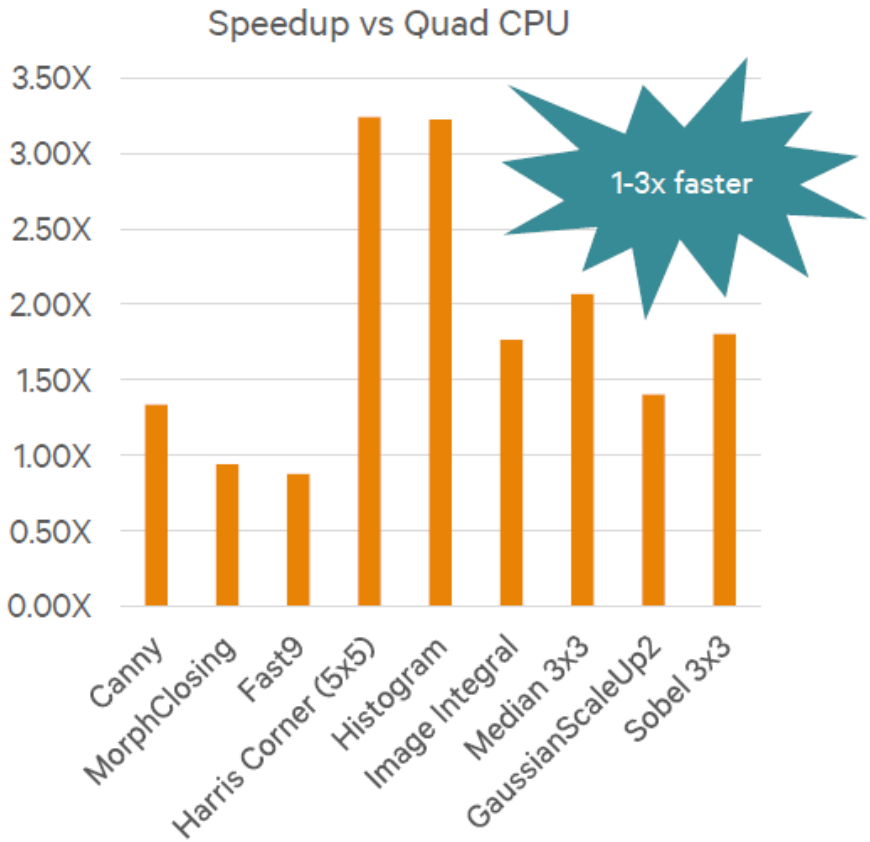


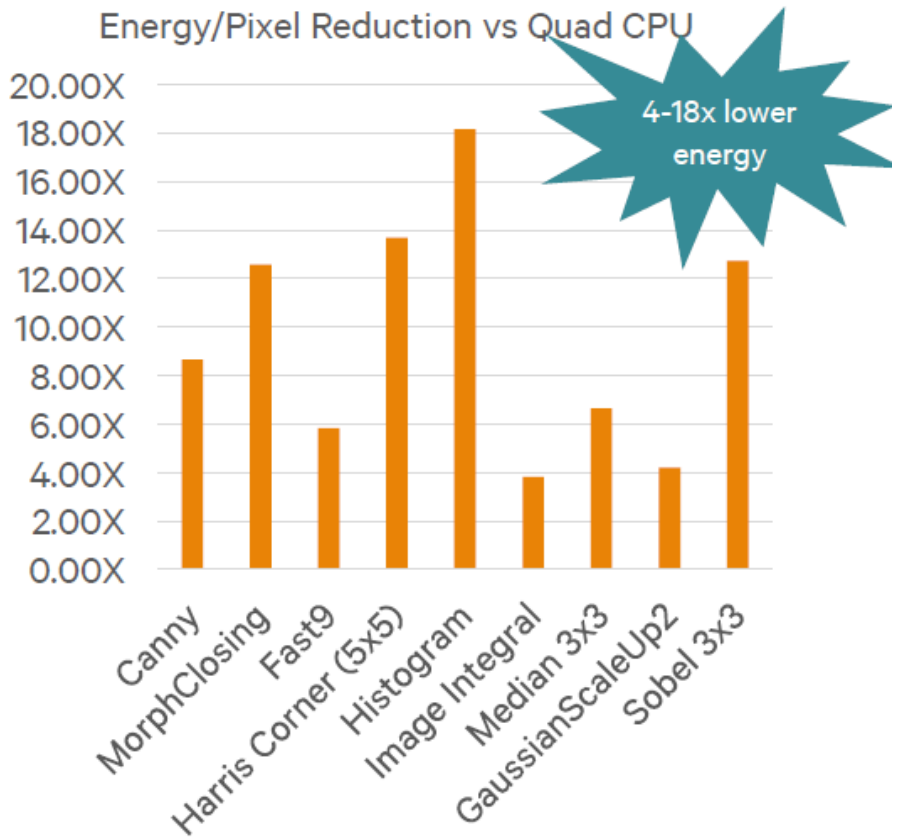
Geekbench 3 Pro v3.3.1 benchmark multi-core results [77]



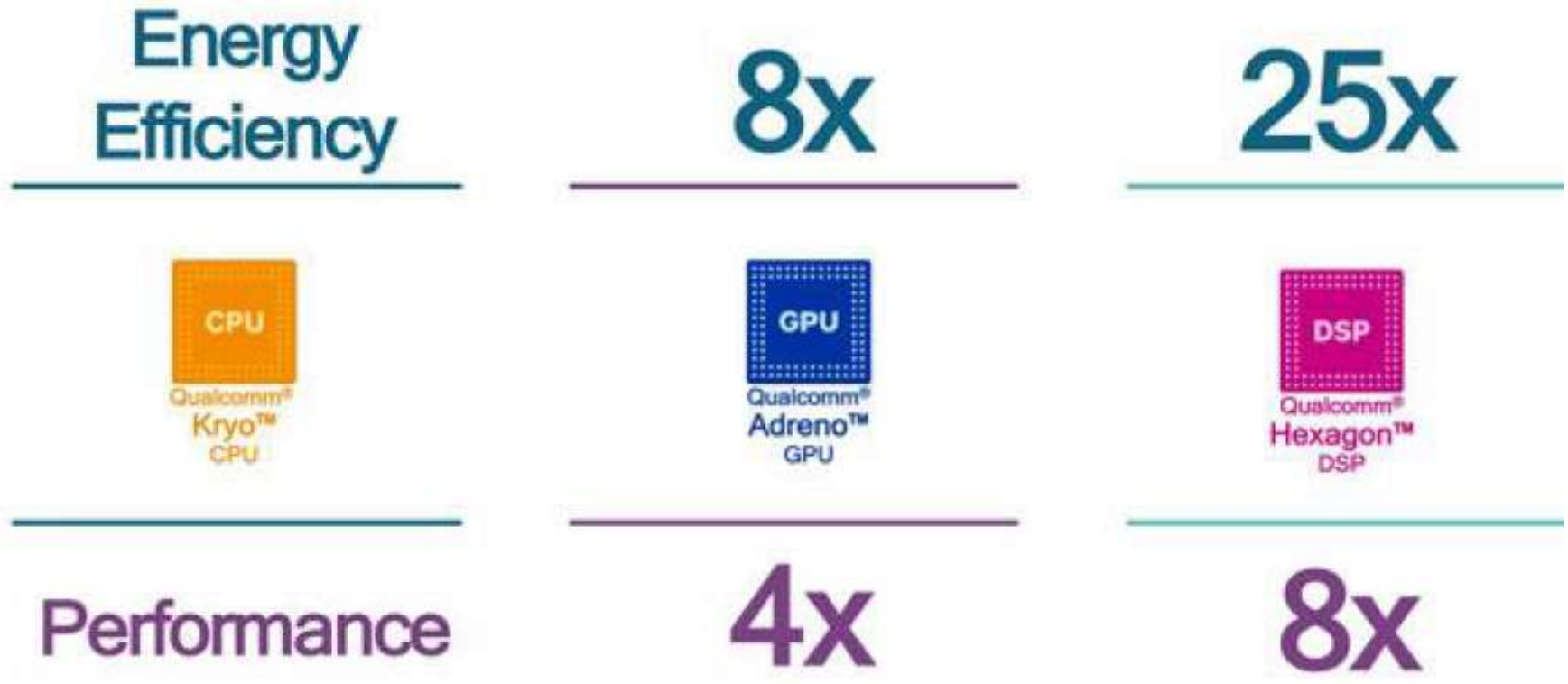
Imaging and vision kernel benchmarks [75]

- DSP with HVX vs Quad Krait CPU *with full Neon-Optimization*
  - Quad Krait CPU clocked at 2.65GHz
  - Single DSP/HVX clocked at 725MHz
  - Core power only excluding SoC infrastructure, DDR, etc.





Speeding up machine learning applications by GPUs and DSPs in Qualcomm's Snapdragon 845 [78]



According to Qualcomm machine learning apps run 25 times more power-efficiently than on non-Hexagon devices.

Main tasks of the Symphony SDK [79]

- It provides C++ APIs for parallelizing and assigning tasks to the Symphony runtime.
- It includes C++ APIs for lowering power consumption.
- Its user-level library runs on Android devices and allows application prototyping on x86 Linux and Windows.

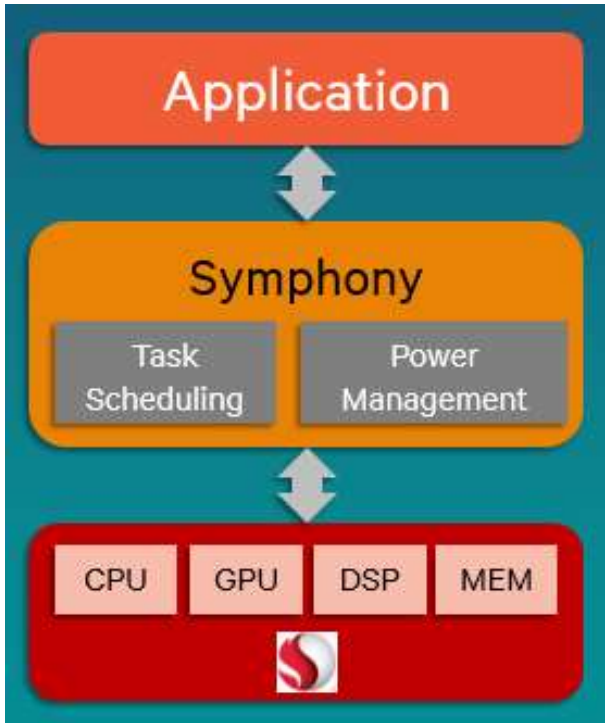
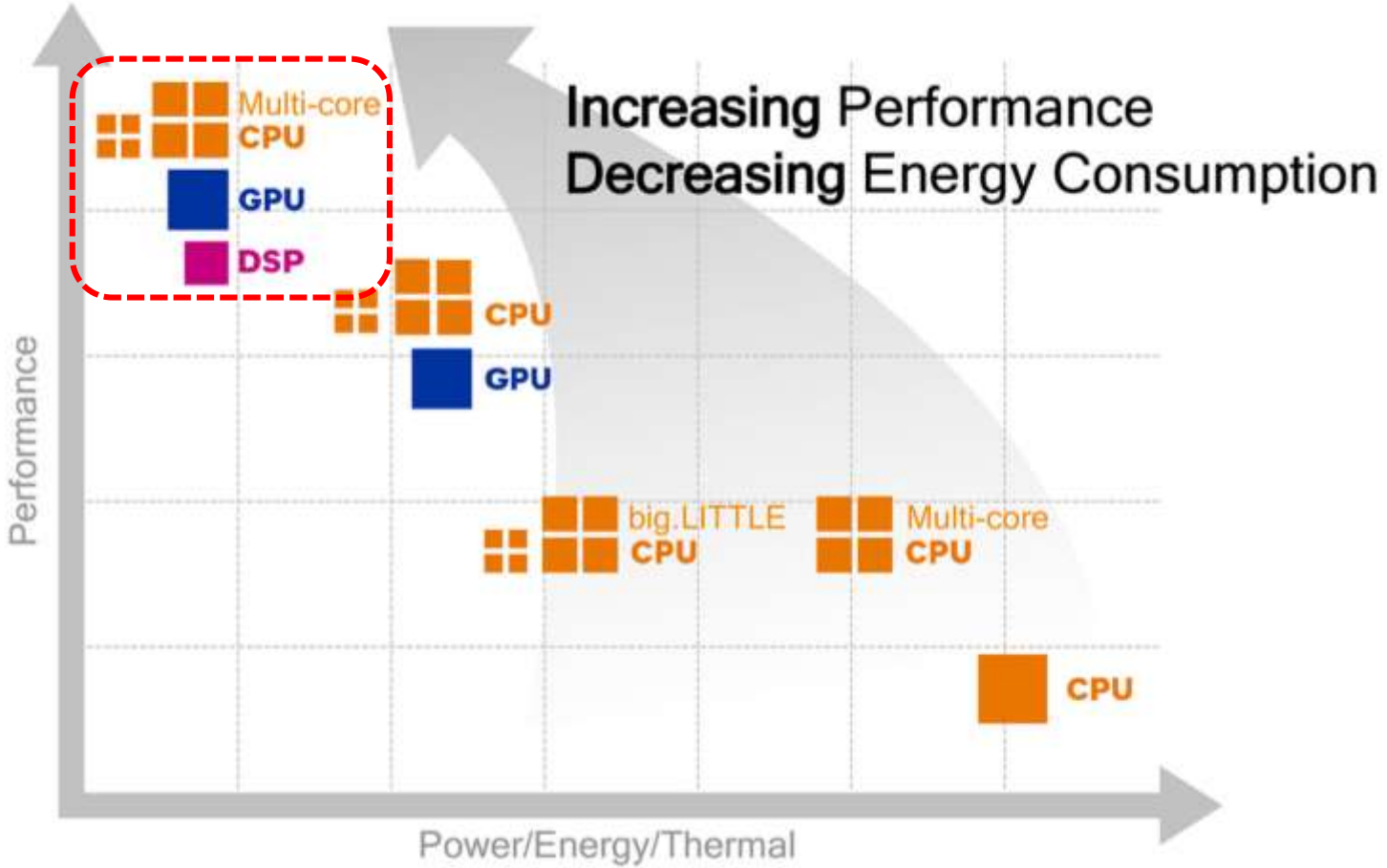


Figure: Main tasks of the Symphony SDK [79]

Benefit of using Symphony [69]



4.3.3 The Snapdragon 835 processor

4.3.3 The Snapdragon 835 processor (1)

The Snapdragon 835

- Announced in 11/2016, sampled about Q1/2017.
- The Snapdragon 835 is Samsung's first processor that is manufactured on 10 nm LPE (Low Power Early) process.
- It is a semicustom design that is based on an enhanced core, called the Kryo 280 core.
- It is a 4+4 core design, rather than a 2+2 design as the previous 820 with slightly increased clock speeds:
  - 4x Kryo 280 clocked at 2.45 GHz and
  - 4x Kryo 280 clocked at 1.9 GHz.
- The Snapdragon 835 is a Tick type processor with small improvements of its constituting units.
- Designing laptops on the Snapdragon 835 will result in extended battery life and fan-less light devices.
- It is the first ever ARM processor that is designed to support Windows 10.

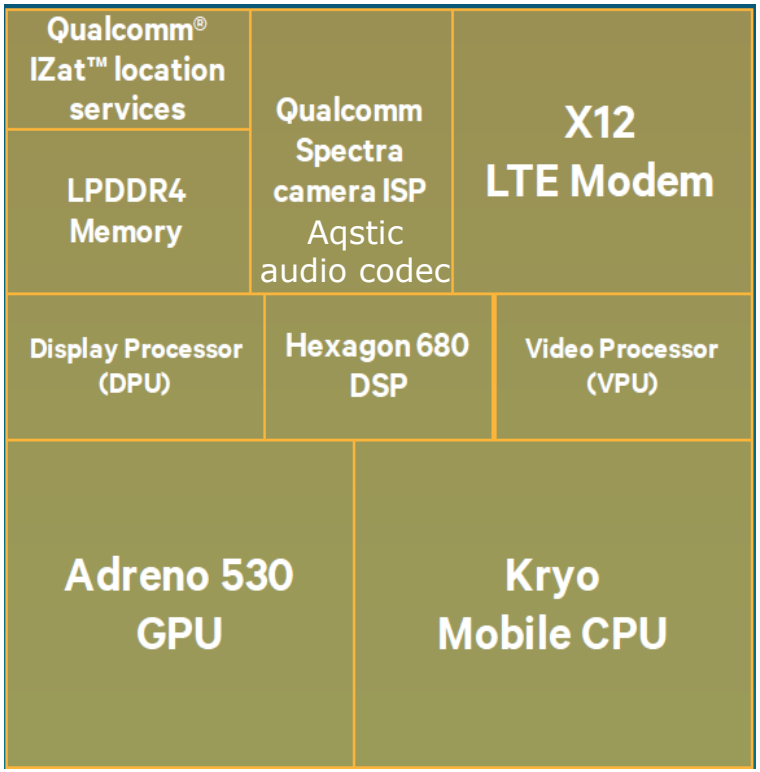
4.3.3 The Snapdragon 835 processor (2)

Main features of the Snapdragon 835 [70]

	Snapdragon 810	Snapdragon 820	Snapdragon 821	Snapdragon 835
CPU Core	Stock ARM Cortex-A	Custom design Kryo	Custom design Kryo	Semi-custom ARM Cortex design Kryo 280
CPU Config	4x Cortex-A57 4x Cortex-A53	2xKryo 2.15 GHz 2xKryo 1.59 GHz	2xKryo 2.35 GHz 2xKryo 1.6 GHz	4x 2.45 GHz Kryo 280 4x 1.9 GHz Kryo 280
GPU	Adreno 430	Adreno 530	Adreno 530	Adreno 540
DSP	Hexagon V56 (version 5)	Hexagon 680 with HVX	Hexagon 680 with HVX	Hexagon 682 with HVX
RAM	2x 32-bit LPDDR4 1600 MHz	2x 32-bit LPDDR4X 1866 MHz	2x 32-bit LPDDR4X 1866 MHz	2x 32-bit LPDDR4X 1866 MHz
Flash	eMMC 5.0 / UFS 1.0	eMMC 5.1/ UFS 2.0	eMMC 5.1/ UFS 2.0	eMMC 5.1/ UFS 2.1
Process	20nm HPm	14 nm FinFET	14nm FinFET LPP	10nm FinFET LPE

4.3.3 The Snapdragon 835 processor (3)

Main functional units of the Snapdragon 835 vs. the 820 [80], [70]



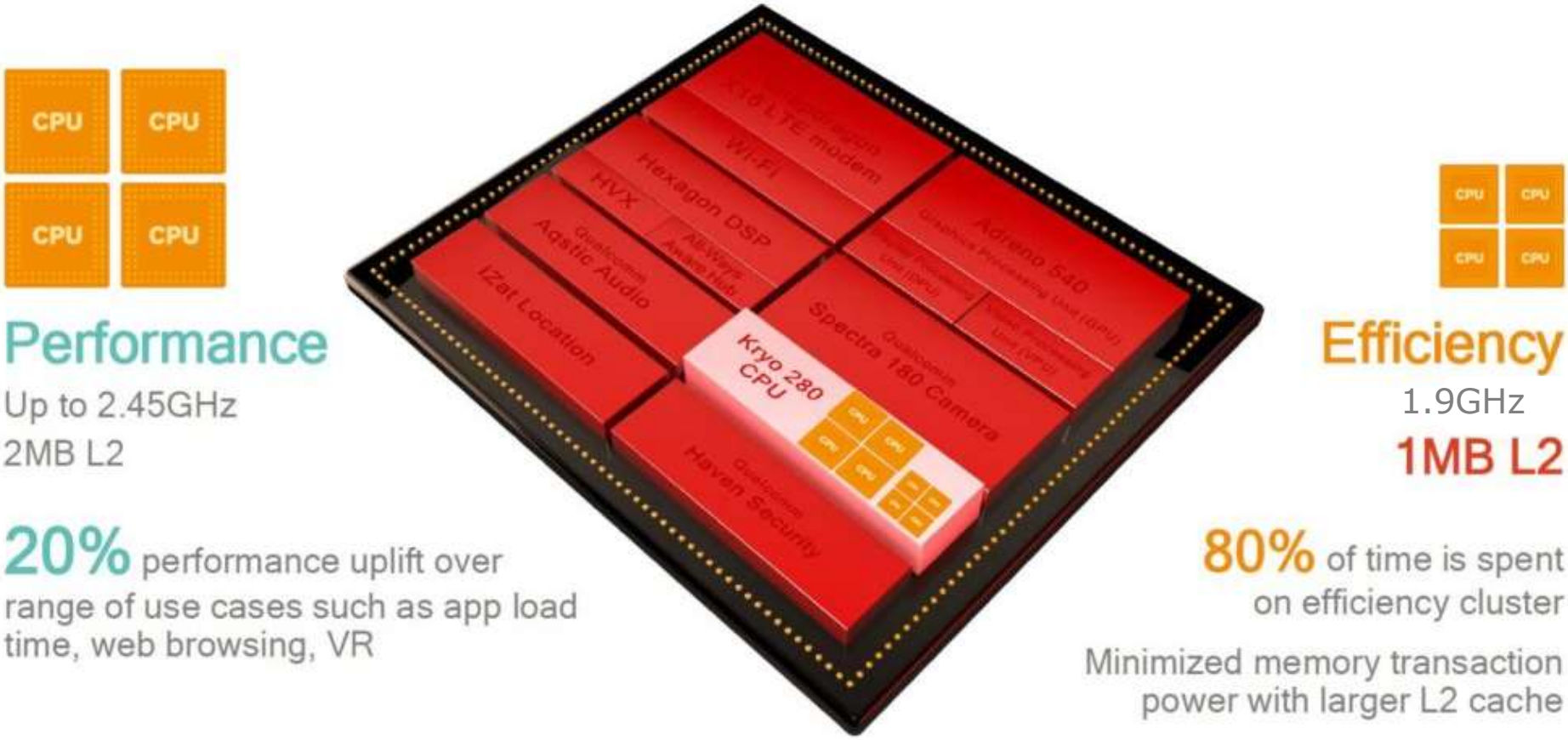
Snapdragon 820

Snapdragon 835

Izat: Qualcomm's indoor location technology

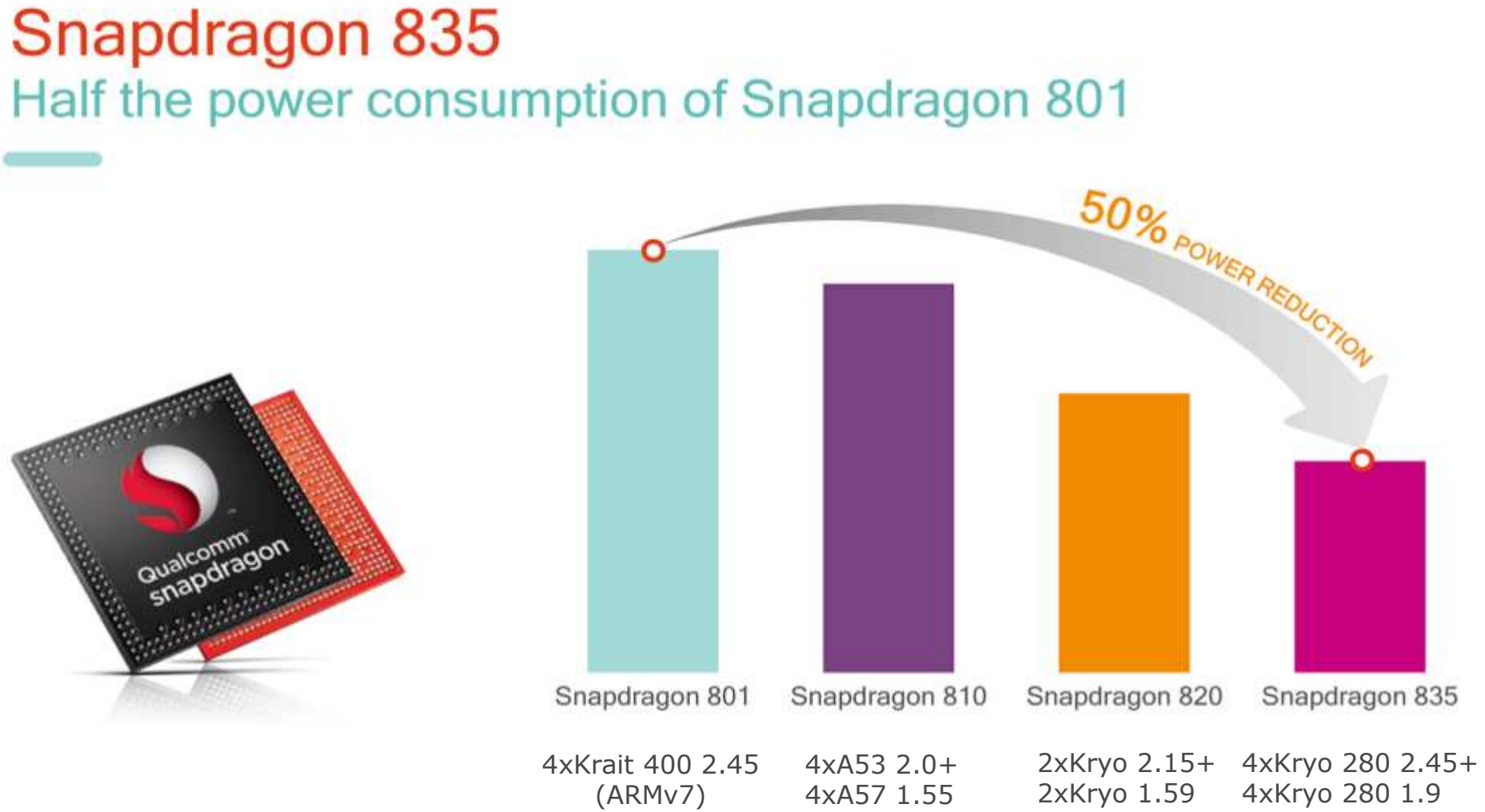
4.3.3 The Snapdragon 835 processor (4)

The Kryo 280 CPU [81]



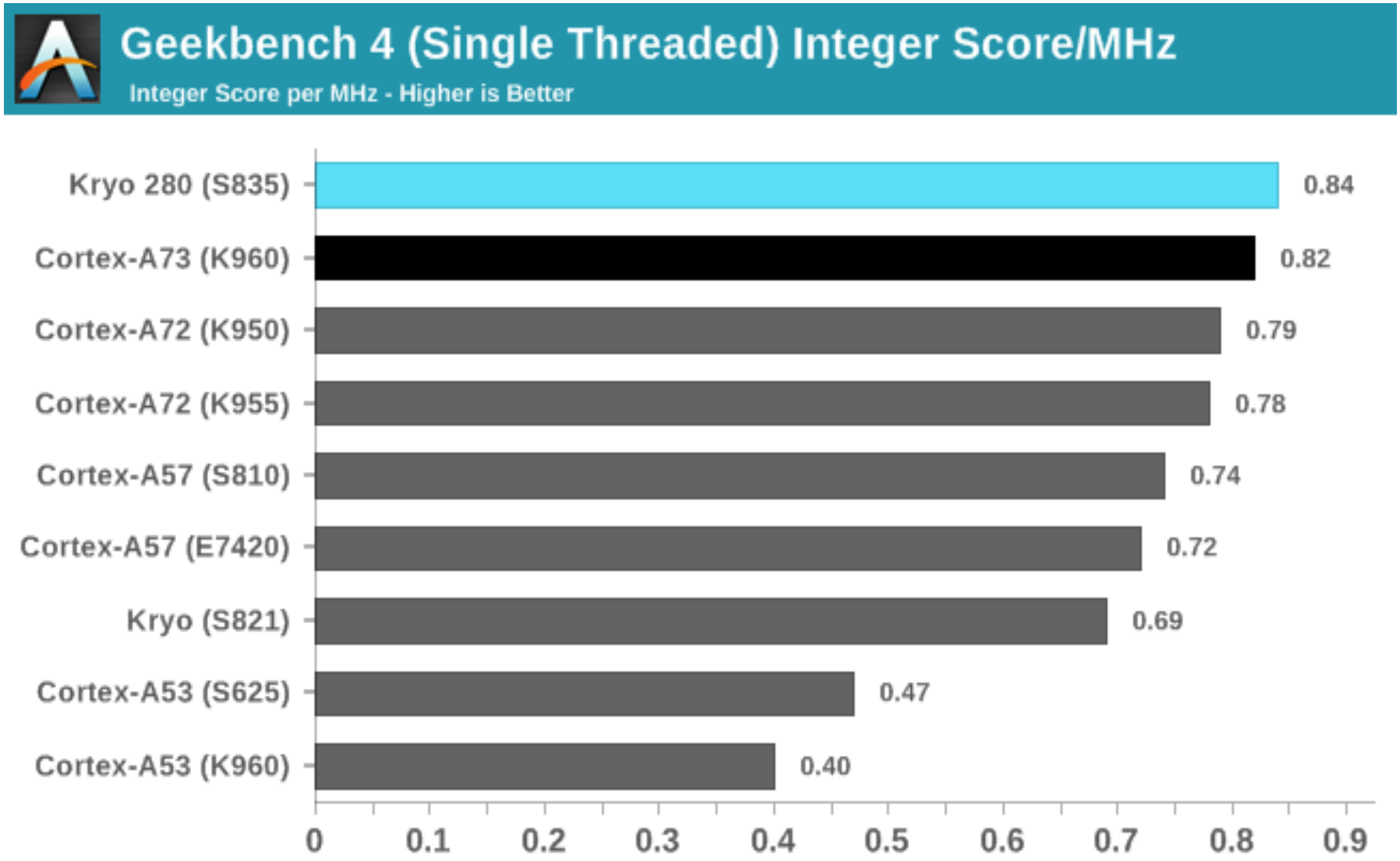
4.3.3 The Snapdragon 835 processor (5)

Reducing power consumption in Snapdragon's 800 models [69]



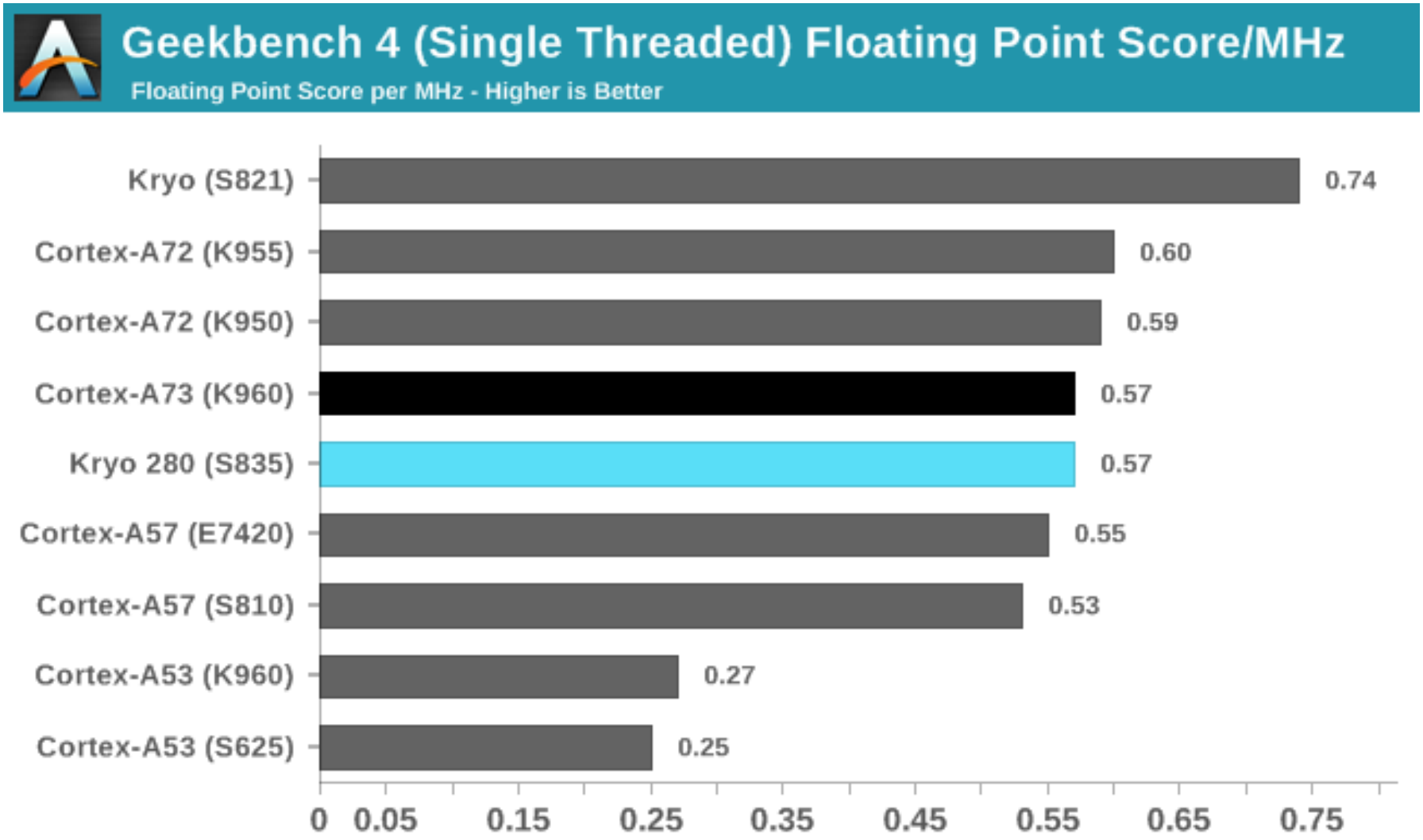
4.3.3 The Snapdragon 835 processor (6)

Geekbench 4 single threaded results (integer score/MHz) [82]



4.3.3 The Snapdragon 835 processor (7)

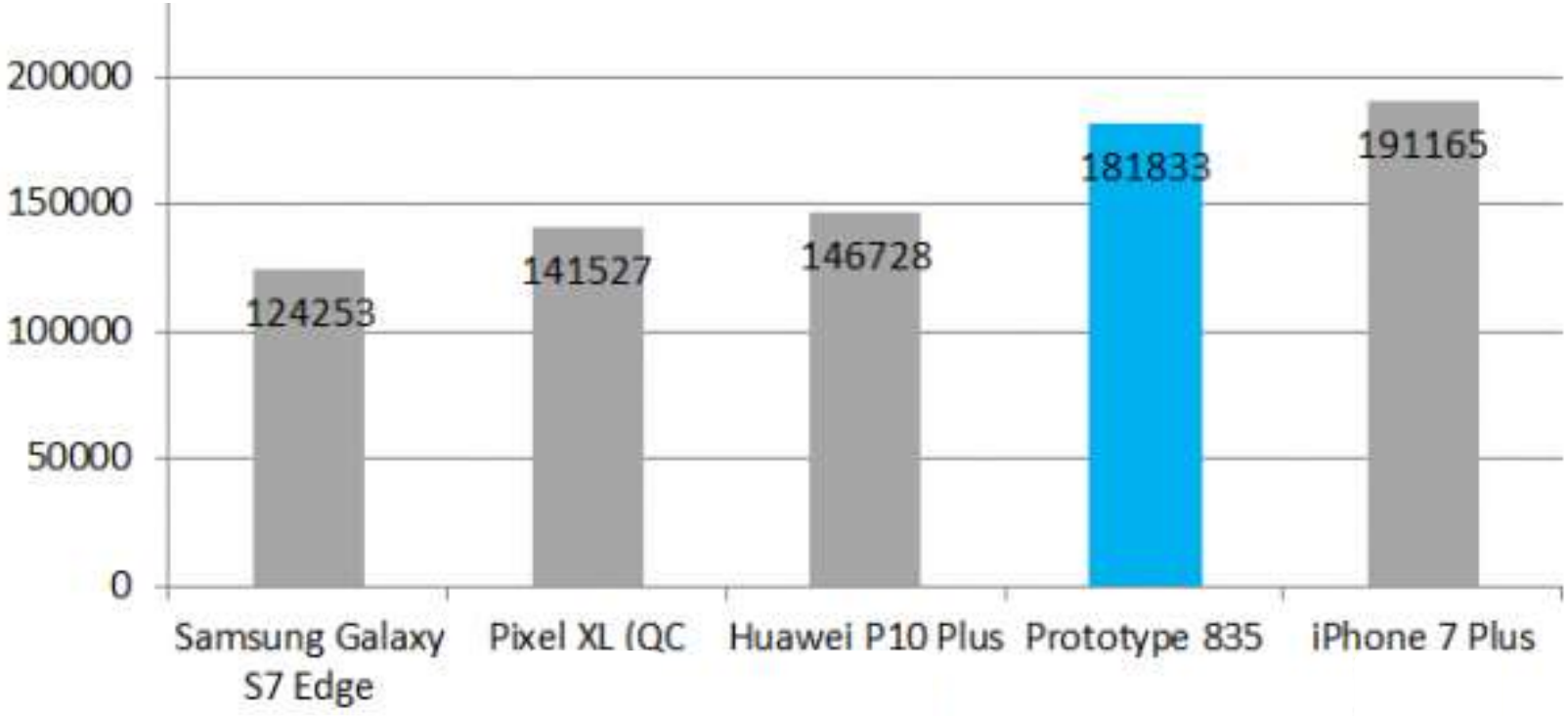
Geekbench 4 single threaded results (floating point score/MHz) [82]



4.3.3 The Snapdragon 835 processor (8)

Antutu overall score [83]

(AnTuTu is a Chinese benchmarking tool commonly used to assess the performance of phones and tablets.)



Exynos 8890	Snapdragoon 821	Kirin 960	Snapdragoon 835	Apple A10
	2x Kryo 2.34 GHz 2x Kryo 1.6 GHz		4x Kryo 280 2.45 GHz 4x Kryo 280 1.9 GHz	
4xM1 2.6 GHz 4xA53 1.6 GHz		4x A73 2.36 GHz 4x A53 1.84 GHz		2x Hurricane 2.34 GHz 2x Zephyr ?? GHz

4.3.3 The Snapdragon 835 processor (9)

Running Windows 10 and x86 apps on the ARM ISA based Snapdragon 835

- The Snapdragon 835 is the first ever ARM processor that is designed to support Windows 10.
- On the 2017 Snapdragon Technology Summit (12/2017) Qualcomm has announced the first Windows 10 laptops powered by the Snapdragon 835, these are the ASUS NovaGo and HP's Envy x2 [84], see the next slide.

  These devices provide all day battery life (e.g. 15 or 20 hours).

4.3.3 The Snapdragon 835 processor (10)

Snapdragon 835 based Windows 10 devices [85]

HP Envy x2

ASUS NovaGo

Lenovo MIIX 630

4.3.3 The Snapdragon 835 processor (11)

Running Windows and x86 apps on the ARM ISA-based Snapdragon 835 [86]

- While running Windows 10 or x86 apps on the ARM ISA-based Snapdragon 835 the code to be executed apps needs to be emulated.
- In this case the Snapdragon 835 processor passes code through additional steps, including an emulator and abstraction layer.
- Obviously, emulation will slow down code execution.
- Furthermore, when Windows 10 and x86 apps are running on the ARM-based Snapdragon 835 processor there are some limitations, as discussed next.
- Nevertheless, according to Qualcomm there are supposedly little differences in day-to-day use.

Remark

HP's Envy x2 runs under Windows 10 S, this causes further limitations, e.g. only apps downloaded from the Windows Store may be used unless the OS becomes upgraded.

4.3.3 The Snapdragon 835 processor (12)

Main limitations when Windows 10 and x86 apps are running on the ARM-based Snapdragon 835 processors [87]

- Only 32-bit apps can be run, support of running 64-bit x86 apps is planned in a future release.
- x86 drivers can not be used, only native ARM64 drivers.

  This greatly limits hardware support vs. mainstream x86-based Windows 10 PCs.
- Older games and graphics apps may not work.

  Windows 10 on ARM supports only DirectX 9 to DirectX 12 thus apps/games that are using older versions will not work.
- Certain classes of apps will not run, like shell extensions or cloud storage apps.

4.3.4 The Snapdragon 845 processor

4.3.4 The Snapdragon 845 processor

- Announced in 12/2017, to be shipped in devices in Q1/2018.
- Its official designation is SDM845.

  This is why Qualcomm renamed their processors including an integrated modem from MSMxxxx to SDMxxx, beginning with the Snapdragon 845.

  Accordingly, the Snapdragon 845 is officially called SDM845 rather than MSM9xxx.
- It is built up on 8 Kryo 385 CPU cores.
- The Kryo 385 is a semicustom design and is the first chip that is based on the ARMv8.2-based Cortex-A75 and A-55 cores and ARM's DynamIQ core technology.

  (The second one is Samsung's Exynos 9810, announced a few weeks later).
- It is a 4 + 4 core design with
  - 4x Kryo 385 cores clocked at 2.8 GHz
  - 4x Kryo 385 cores clocked at 1.8 GHz
- Manufactured on Samsung's 2. gen 10 nm technology, called LPP (LP Plus).
- The Snapdragon 845 is used in a large number of premium mobiles, like Samsung Galaxy S9/S9+, LG G7, HTC U12+, Google Pixel 3 XL, LG V40 ThinQ, Sony Xperia X23 or OnePlus's OnePlus 6/6T.
- It is the second ARM processor that supports Windows 10, but apparently no Windows 10 tablets or laptops appeared on the market.

4.3.4 The Snapdragon 845 processor (2)

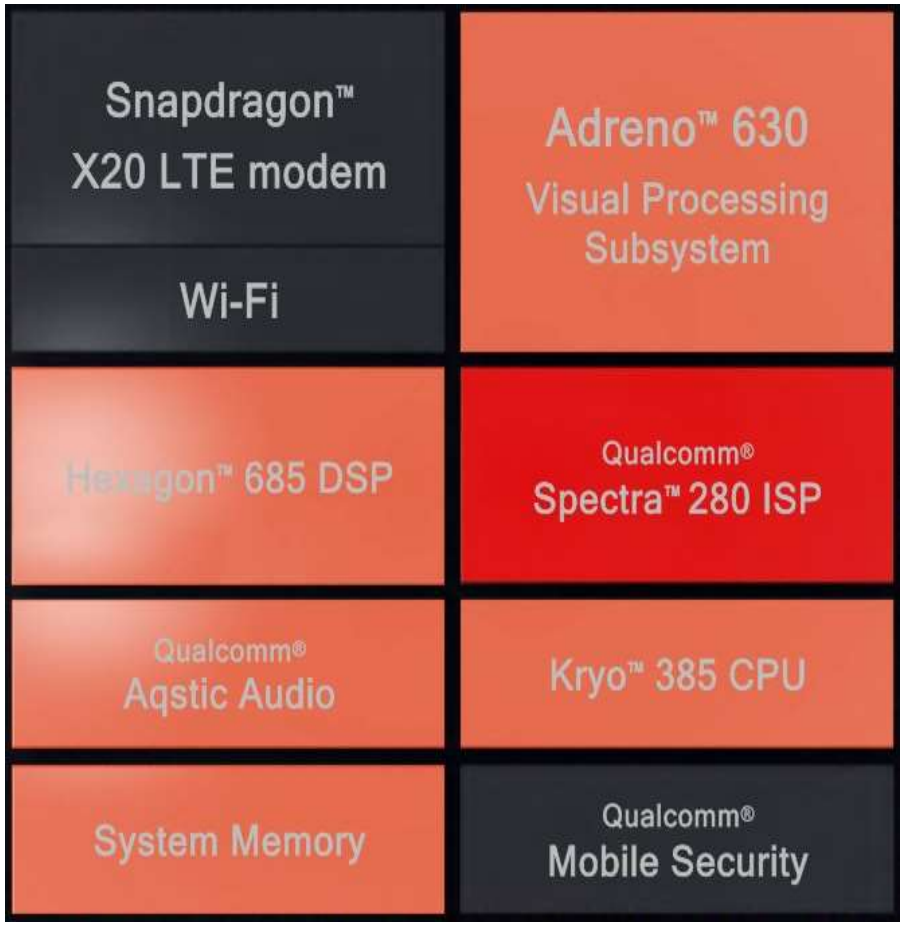
Main features of the Snapdragon 845 vs. that of Snapdragon 835 [88]

Qualcomm Snapdragon Flagship SoCs 2017-2018		
SoC	Snapdragon 845	Snapdragon 835
CPU	4x Kryo 385 Gold (A75 derivative) @ 2.8GHz 4x256KB L2 4x Kryo 385 Silver (A55 derivative) @ 1.80GHz 4x128KB L2 2MB L3	4x Kryo 280 Gold (A73 derivative) @ 2.45GHz 2MB L2 4x Kryo 280 Silver (A53 derivative) @ 1.90GHz 4x1MB L2 No L3
GPU	Adreno 630	Adreno 540 @ 670/710MHz
Memory	4x 16-bit CH @ 1866MHz LPDDR4x 29.9GB/s 3MB system cache	4x 16-bit CH @ 1866MHz LPDDR4x 29.9GB/s
ISP/Camera	Dual 14-bit Spectra 280 ISP 1x 32MP or 2x 16MP	Dual 14-bit Spectra 180 ISP 1x 32MP or 2x 16MP
Encode/ Decode	2160p60 10-bit H.265 720p480	2160p30 (2160p60 decode), 1080p120 H.264 & H.265
Integrated Modem	Snapdragon X20 LTE (Category 18/13) DL = 1200Mbps 5x20MHz CA, 256-QAM UL = 150Mbps 2x20MHz CA, 64-QAM	Snapdragon X16 LTE (Category 16/13) DL = 1000Mbps 3x20MHz CA, 256-QAM UL = 150Mbps 2x20MHz CA, 64-QAM
Mfc. Process	10nm LPP	10nm LPE

4.3.4 The Snapdragon 845 processor (3)

Main functional units of the Snapdragon 845 vs. the Snapdragon 835 [76], [80]

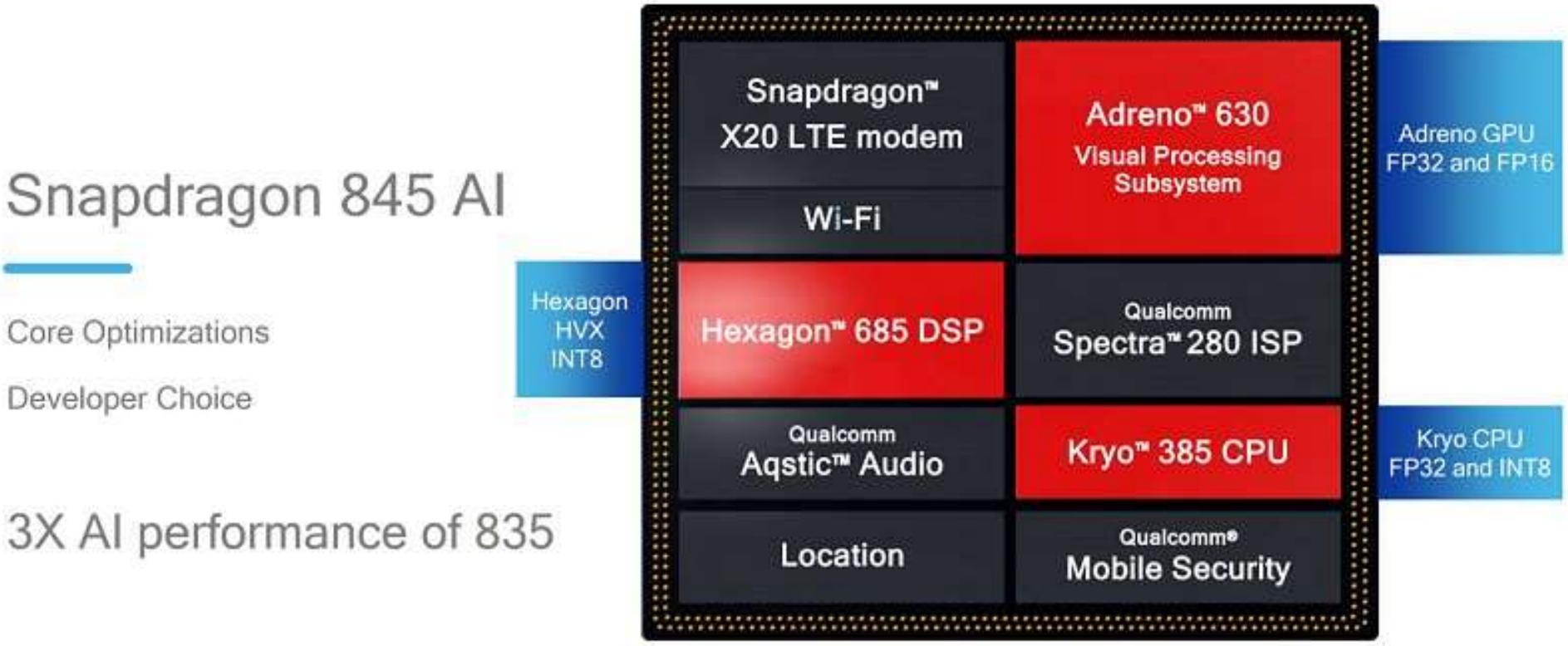
Snapdragon 845 [76]



Snapdragon 835 [80]

4.3.4 The Snapdragon 845 processor (4)

AI execution resources on the Snapdragon 845 processor [76]



HVX: Hexagon Vector eXtensions

4.3.4 The Snapdragon 845 processor (5)

The Kryo 385 CPU [76]

Instead of designing fully customized Kryo cores, Qualcomm based the Kryo 385 on ARM's DynamIQ core technology and the stock Cortex A75 and A55 cores, as shown below.

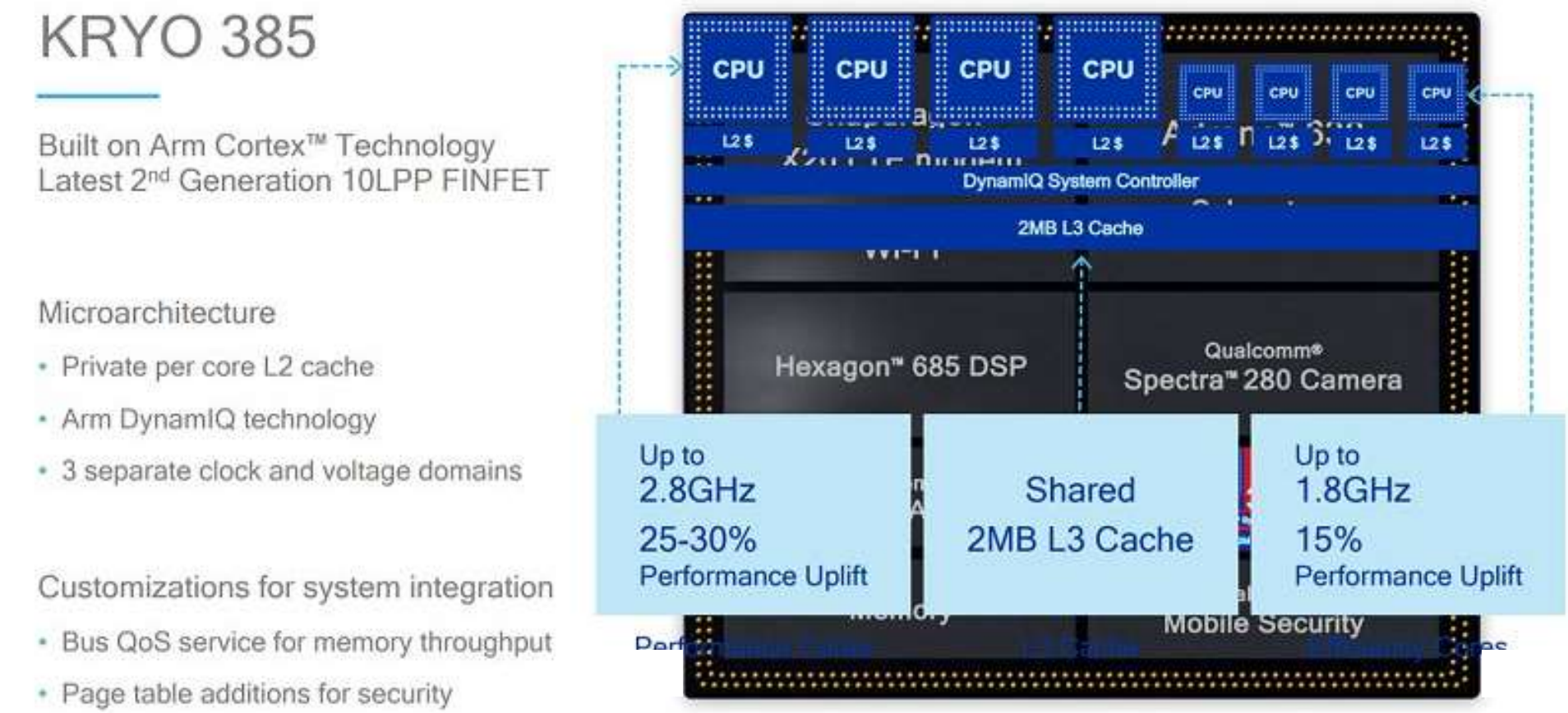
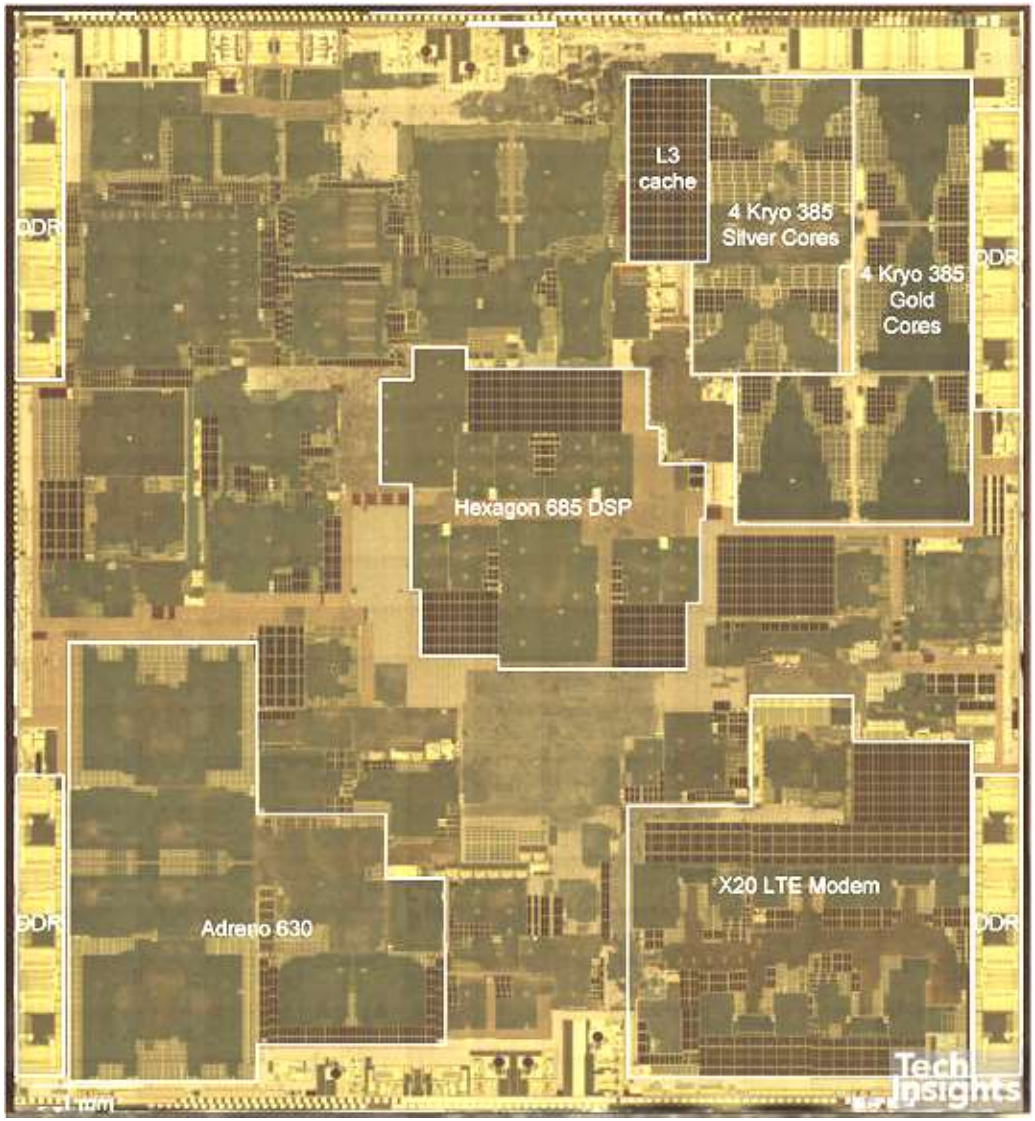


Figure: The Kryo 385 processor [76]

4.3.4 The Snapdragon 845 processor (5b)

Floorplan of the Snapdragon 845 [93]



4.3.4 The Snapdragon 845 processor (6)

Optimizations on the Snapdragon 845 SOC

The Snapdragon 845 is optimized mainly in two aspects:

a) enhancements for the efficient execution of AI tasks and
b) enhancements for the efficient execution of non-ARM code (under emulation).

4.3.4 The Snapdragon 845 processor (7)

a) Enhancements for the efficient execution of AI tasks

It is achieved by

- Enhancing the Hexagon line of DSPs for key AI application areas power consumption and performance for AI
  and imaging and
- Introducing the Snapdragon™ Neural Processing Engine (NPE) software development kit (SDK) (already before launching the Snapdragon 845 in 7/2017).

4.3.4 The Snapdragon 845 processor (8)

Enhancing the Hexagon line of DSPs for key AI application areas [76]

The enhancements relate both to power consumption and performance while running AI and imaging tasks.

2015
SDM820
Hexagon 680

2016
SDM835
Hexagon 682

2017
SDM845
Hexagon 685

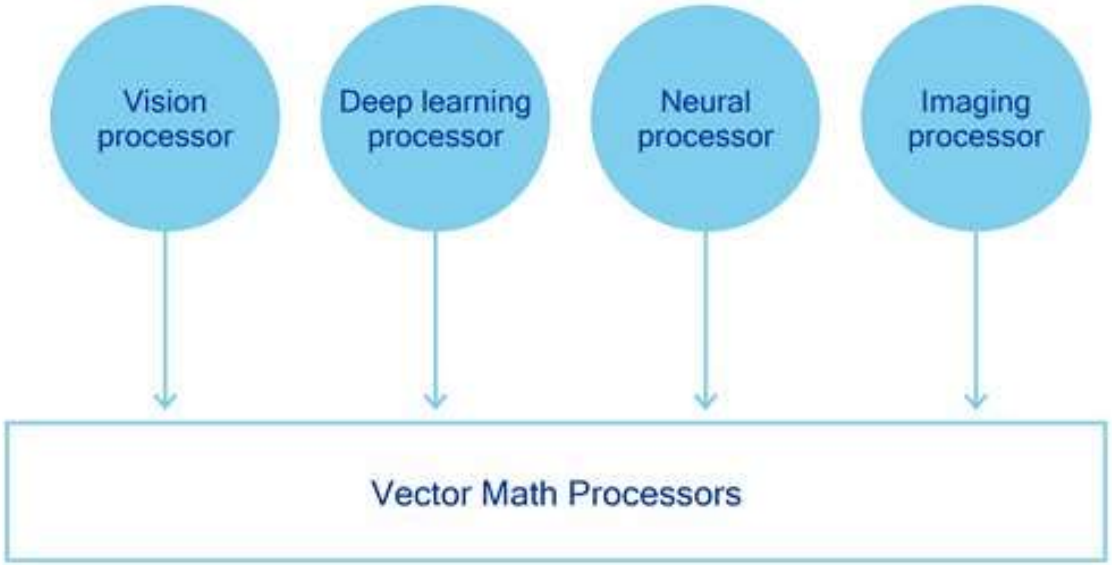


Figure: Release history of Hexagon DSPs (2015-2017)

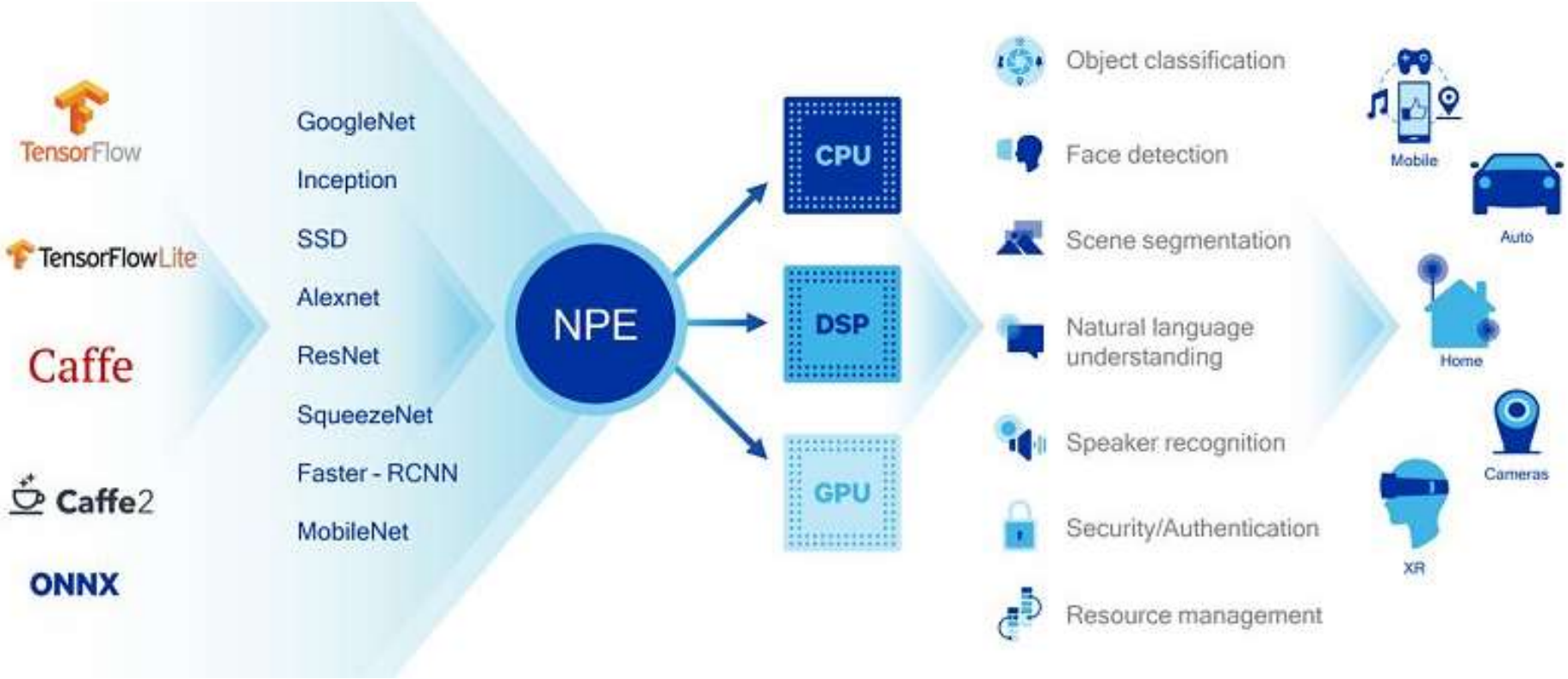
4.3.4 The Snapdragon 845 processor (9)

Introducing the Snapdragon Neural Processing Engine (NPE) software development kit (SDK) [89]

- The Snapdragon NPE is designed to provide developers with software tools to accelerate running deep neural network workloads on mobile and other edge devices that are based on Snapdragon processors.
- NPE targets on-device neural networks-driven apps in multiple industries, including mobile, automotive, healthcare, security and imaging.
- Developers can choose the optimal Snapdragon core including Qualcomm's Kryo CPU, the Adreno GPU or the Hexagon DSP.

4.3.4 The Snapdragon 845 processor (10)

Executing AI tasks on the Snapdragon 820-845 processors while using the NPE SDK [76]



NPE: Neural Processing Engine SDK

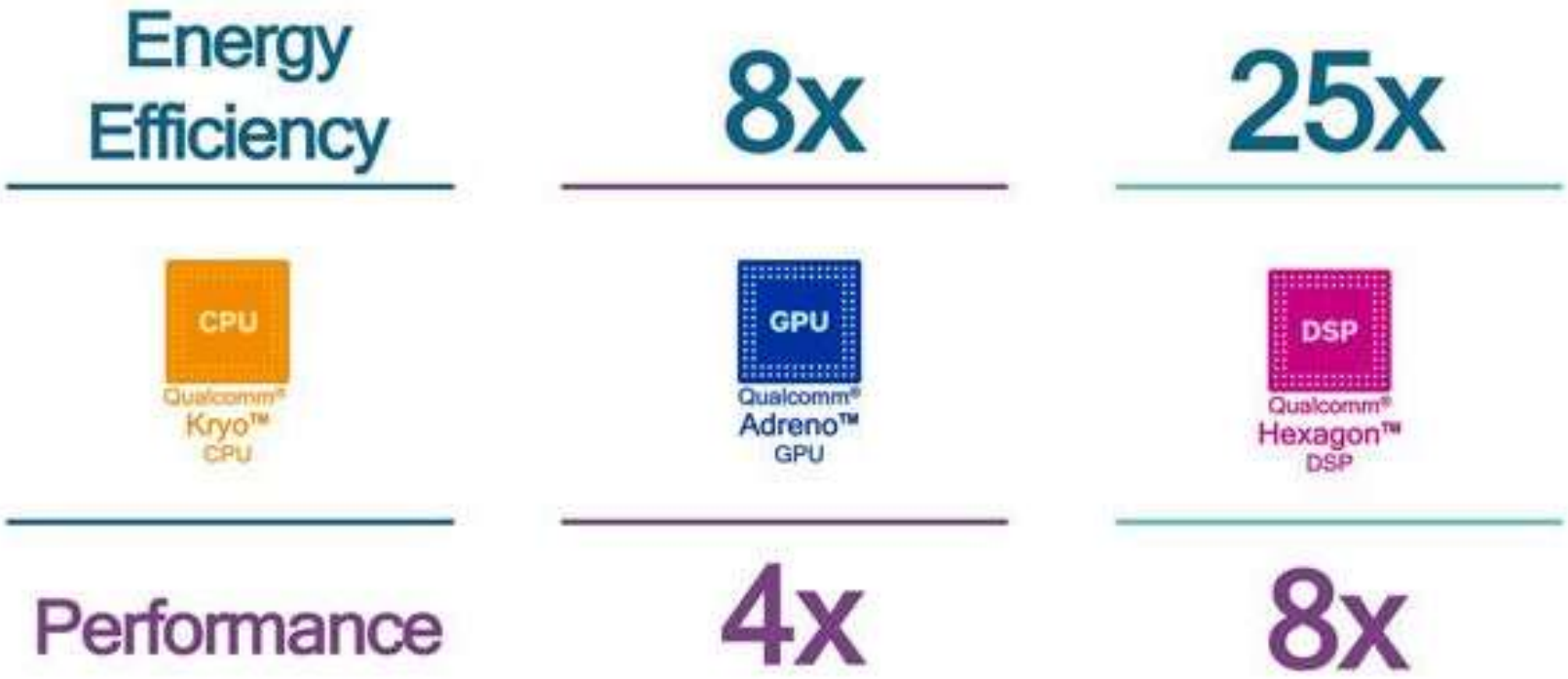
Note that the NPE is capable to allocate the appropriate computational resources to AI tasks.

TensorFlow/TensorFlow Lite are Google's frameworks, Caffe/Caffe2 are Facebook's frameworks whereas ONNX is the new Open Neural Exchange framework available on GitHub.

Expected Benefits of introducing the Snapdragon NPE SDK [76]

4.3.4 The Snapdragon 845 processor (12)

Performance and energy efficiency improvements when using TensorFlow and the Hexagon 685 DSP) rather than non-Hexagon devices [78]



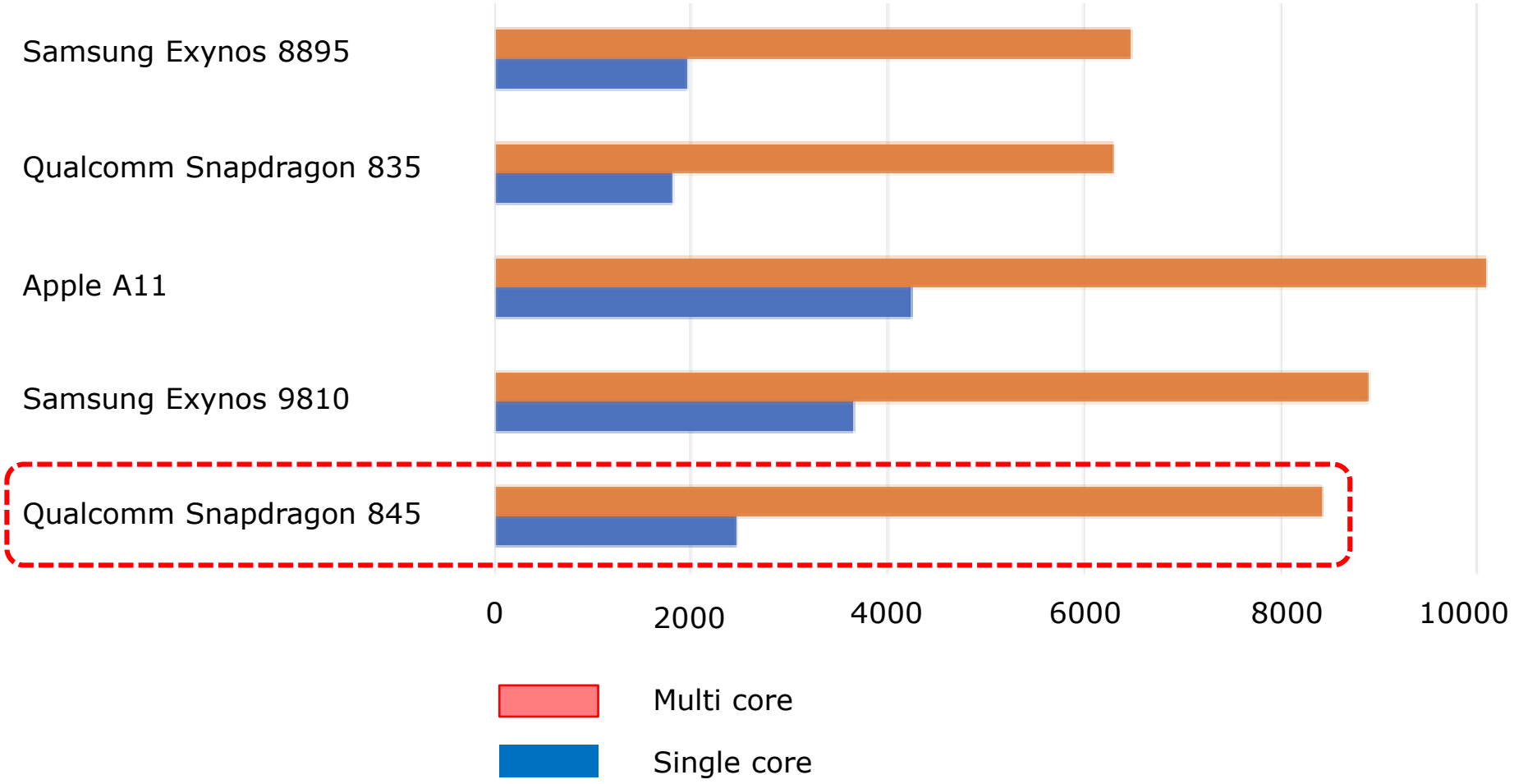
TensorFlow: (Google's machine learning platform (SDK))

4.3.4 The Snapdragon 845 processor (13)

b) Enhancements for the efficient execution of non-ARM code

Qualcomm worked with Microsoft over two years to ensure there are no perceivable penalty issues while executing Windows 10 OS and its legacy apps.

Geekbench 4 scores [90]



Geekbench is a cross-platform benchmark that simulates real-world scenarios.
Geekbench 4 scores against a baseline of 4000 provided by Intel's Core i7-6600U @ 2.60 GHz.

4.3.5 The Snapdragon 850 processor

4.3.5 The Snapdragon 850

- Announced in 6/2018, shipped in devices in Q3/2018.
- It is the first chip built specifically for Windows 10 devices.
- It basically has the same silicon as the Snapdragon 845 with a few enhancements, resulting in ~5 frequency increase of the big cores (actually 2.95 GHz vs. 2.80 GHz).

4.3.5 The Snapdragon 850 processor (2)

Contrasting main features of the Snapdragon 850 vs. the 845 and 835 [101]

Qualcomm Snapdragon 850 vs 845 vs 835				
SoC		Snapdragon 850	Snapdragon 845	Snapdragon 835
CPU	Large Cores	4 x Kryo 385 Gold (A75-based) @ 2.95 GHz 4 x 256 KB L2	4x Kryo 385 Gold (A75-based) @ 2.8GHz 4 x 256 KB L2	4x Kryo 280 Gold (A73-based) @ 2.45GHz 2MB L2
	Small Cores	4 x Kryo 835 Silver (A55-based) @ ? GHz 4 x 128 KB L2	4 x Kryo 385 Silver (A75-based) @ 1.77 GHz 4 x 128 KB L2	4 x Kryo 280 Silver(A73-based) @ 1.90 GHz 1 MB L2
DSU		2 MB L3	2 MB L3	--
GPU		Adreno 630	Adreno 630	Adreno 540 @ 670/710MHz
Memory		?	4x 16-bit CH @ 1866MHz LPDDR4x 29.9GB/s 3MB system cache	4x 16-bit CH @ 1866MHz LPDDR4x 29.9GB/s No L3
ISP/Camera		Dual 14-bit Spectra 280 ISP	Dual 14-bit Spectra 280 ISP 1x 32MP or 2x 16MP	Dual 14-bit Spectra 180 ISP 1x 32MP or 2x 16MP
Encode/ Decode		2160p 10-bit H.265 720p480	2160p60 10-bit H.265 720p480	2160p30 (2160p60 decode), 1080p120 H.264 & H.265
Integrated Modem		Snapfragon X20 LTE Cat 18/13	Snapdragon X20 LTE Cat 18/13	Snapdragon X16 LTE Cat 16/13
Mfc. Process		10nm LPP	10nm LPP	10nm LPE

4.3.5 The Snapdragon 850 processor (3)

Benefits of the Snapdragon 850 platform vs. the 835 platform [101]

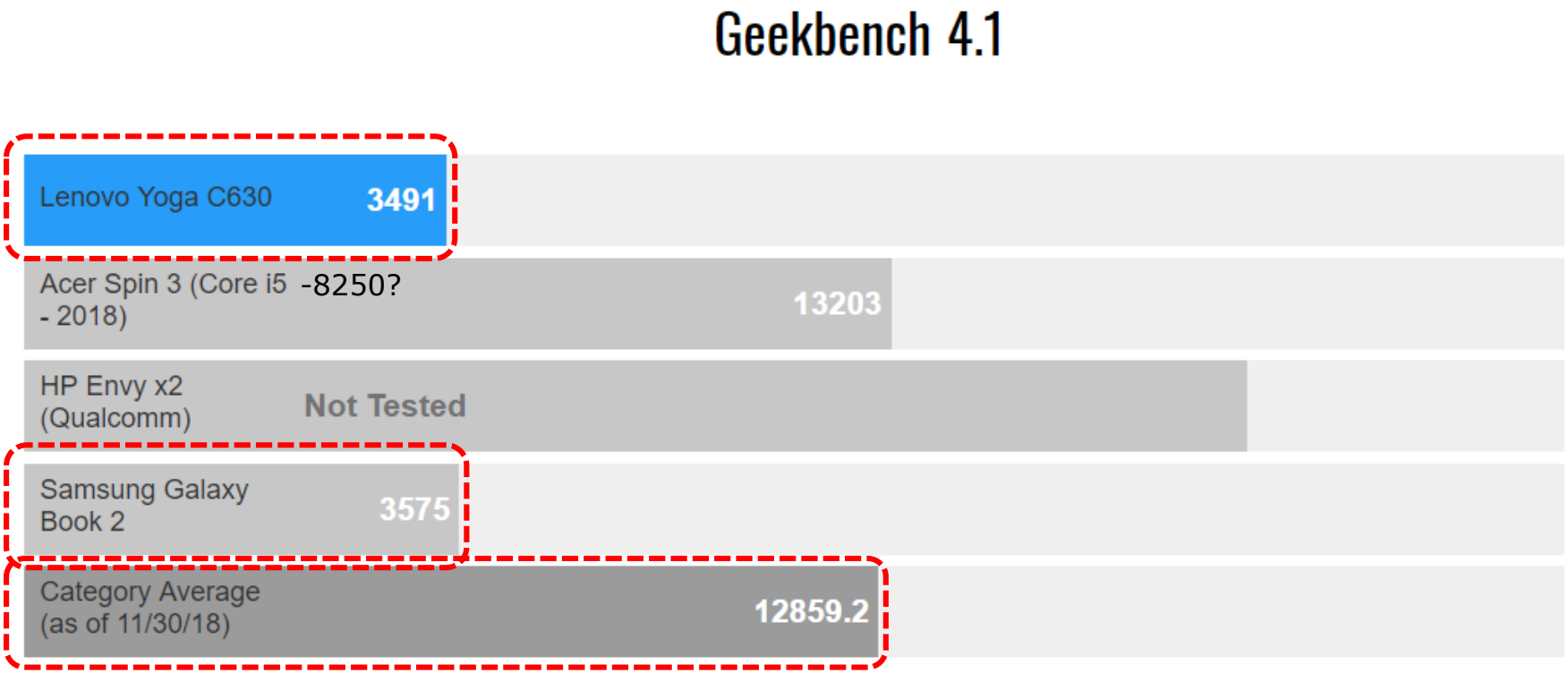
Snapdragon 835 Mobile PC Platform	Snapdragon 850 Mobile Compute Platform
Always On Always Connect Thin/light	+Entertainment +AI +Innovative form factors
Beyond all-day Battery life	Multi-day Battery life
Gigabit speeds (1Gpbs)	2nd Gen Gigabit speeds (1.2Gpbs)
Kryo 280 CPU up to 2.6GHz	Kryo 385 CPU up to 2.95GHz

4.3.5 The Snapdragon 850 processor (4)

Improvements of the Snapdragon 850 platform vs. the 835 platform [101]

4.3.5 The Snapdragon 850 processor (5)

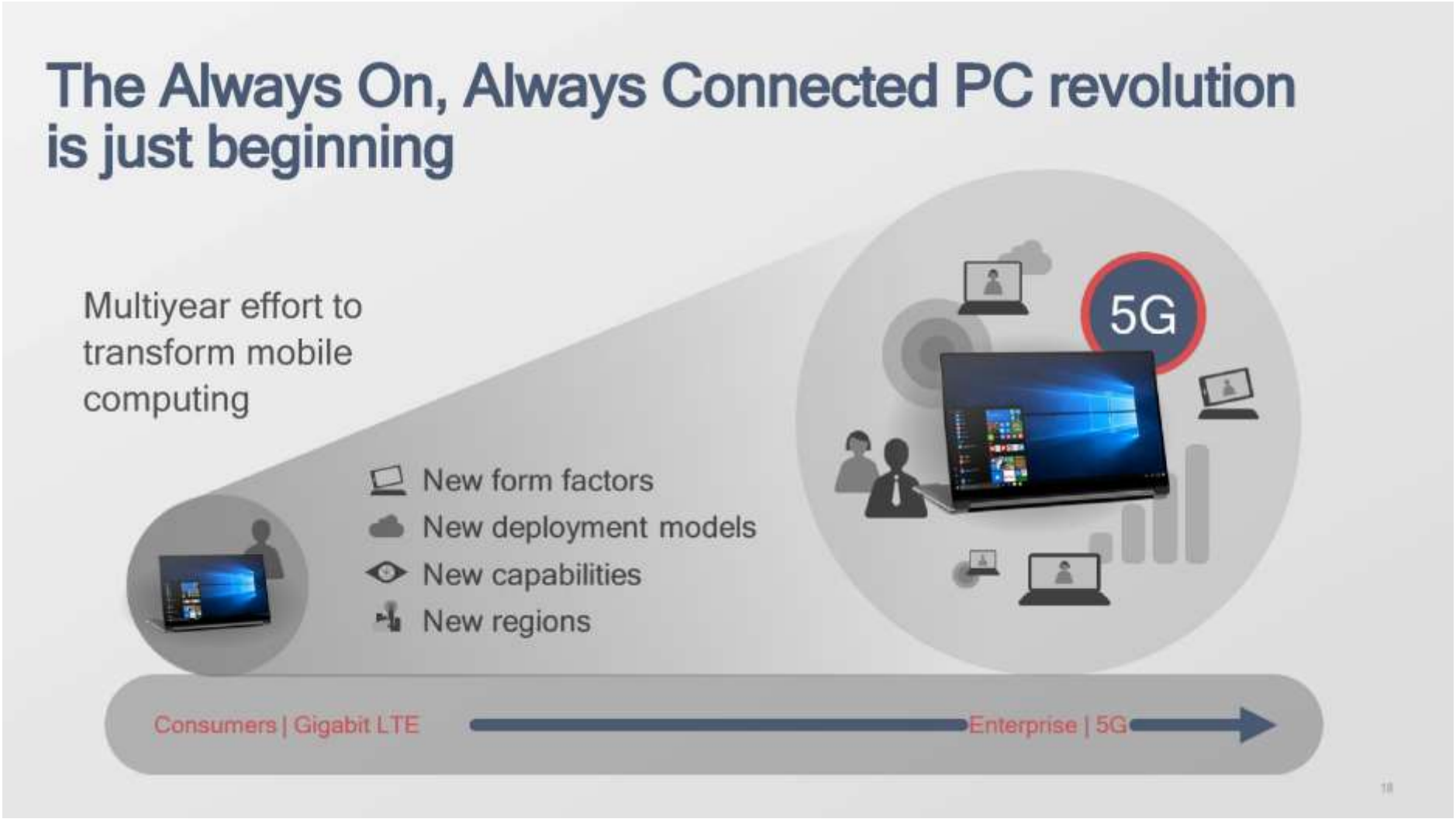
Geekbench 4.1 scores of Snapdragon 850-based 2-in-1 PCs vs. category average [102]



4.3.5 The Snapdragon 850 processor (6)

Improvements related to Snapdragon 850-based devices [101]

The new "Always On, Always Connected PC" (ACPC) category [101]



4.3.5 The Snapdragon 850 processor (8)

First “always connected 2-in-1 PCs” (ACPCs) built on the Snapdragon 850

The 12” Samsung Galaxy Book2 (10/2018)[102]

(It ships with Windows 10 in S Mode, which limits the apps to those available in the Microsoft Store by default).

The ‘13,3” Lenovo Yoga C630 WOS (09/2018) [104]

It runs Windows 10 S out of the box, but can be upgrade to Windows 10 Home for free if third-party programs should be installed.

4.3.5 The Snapdragon 850 processor (9)

Increasing software support for Snapdragon 850-based devices [105]

- With the Windows April 2018 update Snapdragon based systems will be compatible with Windows machine libraries compiled for Arm based processors.
- Cortana is accelerated using the Hexagon DSP.
- Microsoft Edge will also be re-optimized for the platform.
- In 05/2018 Qualcomm has implemented a 64-bit SDK for developers intending to optimize their code on the Snapdragon 850.
- In 10/2018 work on 64-bit emulation is still in progress, however Qualcomm has stated that a fair amount of software is already compiled in 64-bit mode even if the devices cannot take advantage of it.

4.3.5 The Snapdragon 850 processor (10)

Assessment of Snapdragon 850-based 2-in-1 PCs by reviewers e.g. [102], [106]

Reviewers reassure the progress in software support and improving in performance as well as they are very pleased with the long (> 20 hours) battery life, but they are not yet satisfied with the overall performance of 850-based devices compared to Intel-based premium laptops (as indicated in the Geekbench scores shown before).

4.3.6 The Snapdragon 855 processor

4.3.6 The Snapdragon 855 processor

- Announced in 12/2018, to be shipped in devices in Q1/2019.
- It includes 8 Kryo 485 CPU cores.
- It is a 1 + 3 + 4 core design, as follows:
  - 1x Kryo 485 Gold (A76 derivative) @ 2.84GHz 1x512KB L2$
  - 3x Kryo 485 Gold (A76 derivative) @ 2.42GHz 3x256KB L2$
  - 4x Kryo 485 Silver (A55 derivative) @ 1.80GHz 4x128KB L2$
- Manufactured on TSMC 7 nm technology.

4.3.6 The Snapdragon 855 processor (2)

Die size and transistor count of select processors [95]

Die Size and Transistor Counts					
AnandTech	Process Node	Die Size (mm)	Die Area (mm2)	Tr	Density (MTr/mm2)
Snapdragon 8cx	7nm TSMC	8.3 x 13.5	112*	> 5.3b < 10.6b	> 56.4 < 94.6
Snapdragon 855	**7nm TSMC**				
Snapdragon 845/850	10LPP Samsung		94	5.3 b	56.4
Snapdragon 835	10LPE Samsung		72.3	3.0 b	41.5
Kirin 980	7nm TSMC		74.13	6.9 b	93.1
Kirin 970	10nm TSMC	9.75 x 9.92	96.72	5.5 b	56.9
Kirin 960	16nm TSMC	10.77 x 10.93	117.72	4.0 b	34.0
Apple A12 Bionic	7nm TSMC	9.89 x 8.42	83.27	6.9 b	82.9
Apple A12X Bionic	7nm TSMC		122	10 b	
Exynos 9810	10LPP Samsung	10.37 x 11.47	118.94	?	?
8-core Ryzen	14nm GloFo	22.06 x 9.66	192	4.8 b	25.0
Skylake 4+2	14nm Intel	13.31 x 9.19	122	1.75 b	14.3
*Upper Bound					

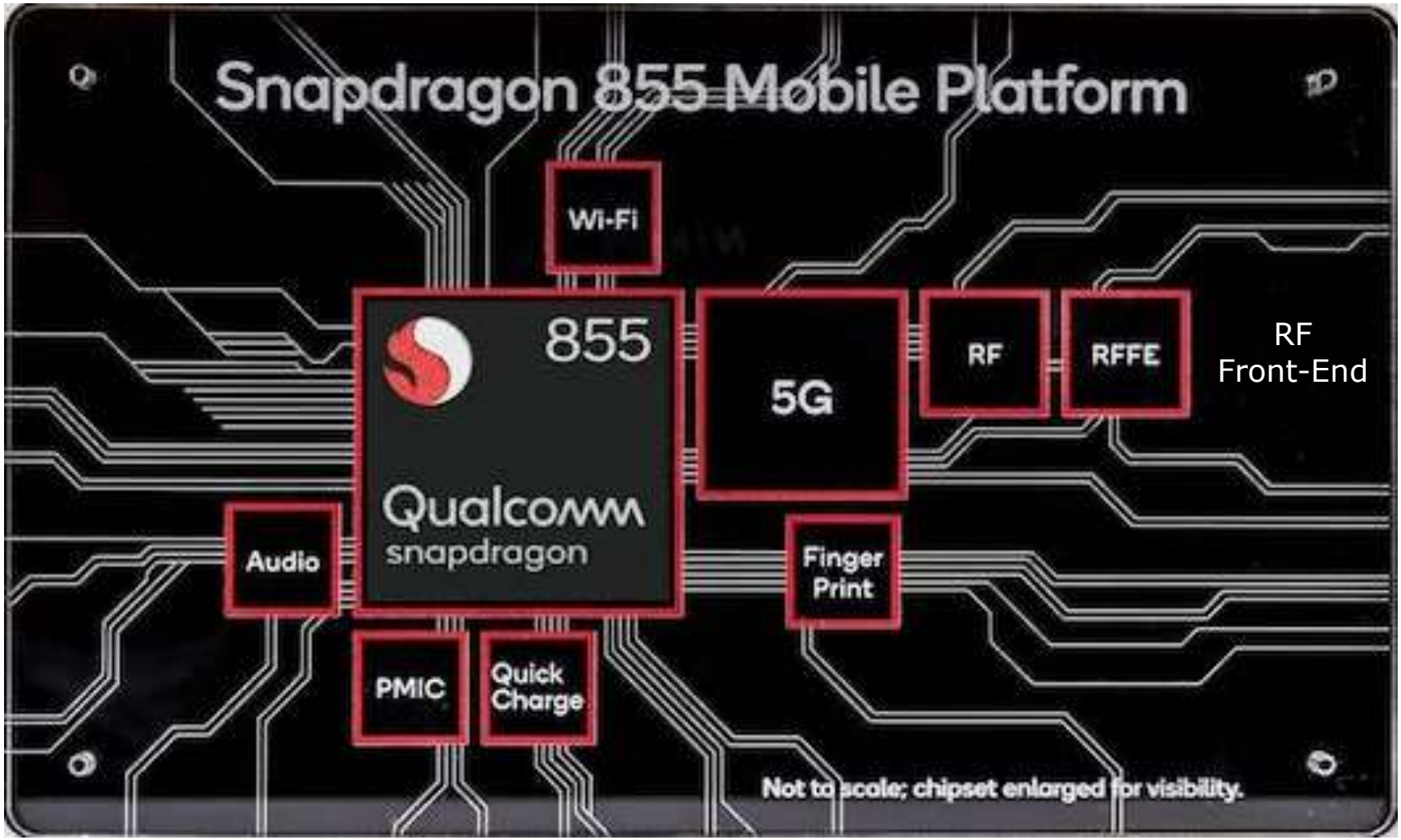
4.3.6 The Snapdragon 855 processor (3)

Contrasting main features of the Snapdragon 855 and 845 processors [94]

Qualcomm Snapdragon Flagship SoCs 2018-2019		
SoC	Snapdragon 855	Snapdragon 845
CPU	1x Kryo 485 Gold (**A76** derivative) @ 2.84GHz 1x512KB pL2 3x Kryo 485 Gold (**A76** derivative) @ 2.42GHz 3x256KB pL2 4x Kryo 485 Silver (A55 derivative) @ 1.80GHz 4x128KB pL2 2MB sL3	4x Kryo 385 Gold (**A75** derivative) @ 2.8GHz 4x256KB pL2 4x Kryo 385 Silver (A55 derivative) @ 1.80GHz 4x128KB pL2 2MB sL3
GPU	Adreno 640 @ ?MHz	Adreno 630 @ 710MHz
Memory	4x 16-bit CH @ 2133MHz LPDDR4x (34.1GB/s) 3MB system level cache	4x 16-bit CH @ 1866MHz LPDDR4x (29.9GB/s) 3MB system level cache
ISP/Camera	Dual 14-bit Spectra 380 ISP 1x 48MP or 2x 22MP	Dual 14-bit Spectra 280 ISP 1x 32MP or 2x 16MP
Encode/ Decode	2160p60 10-bit H.265 HDR10, HDR10+, HLG 720p480	2160p60 10-bit H.265 720p480
Integrated Modem	Snapdragon X24 LTE ((Category 20) DL = 2000Mbps 7x20MHz CA, 256-QAM, 4x4 UL = 316Mbps 3x20MHz CA, 256-QAM	Snapdragon X20 LTE (Category 18/13) DL = 1200Mbps 5x20MHz CA, 256-QAM, 4x4 UL = 150Mbps 2x20MHz CA, 64-QAM
Mfc. Process	7nm (N7)	10nm LPP

4.3.6 The Snapdragon 855 processor (4)

Chips of a Snapdragon 855 mobile platform [96]



4.3.6 The Snapdragon 855 processor (5)

Main components of the Snapdragon 855 processor [96]

4.3.6 The Snapdragon 855 processor (6)

Main features of Kryo 485 cores [94]

Kryo 485

Built on Arm Cortex Technology

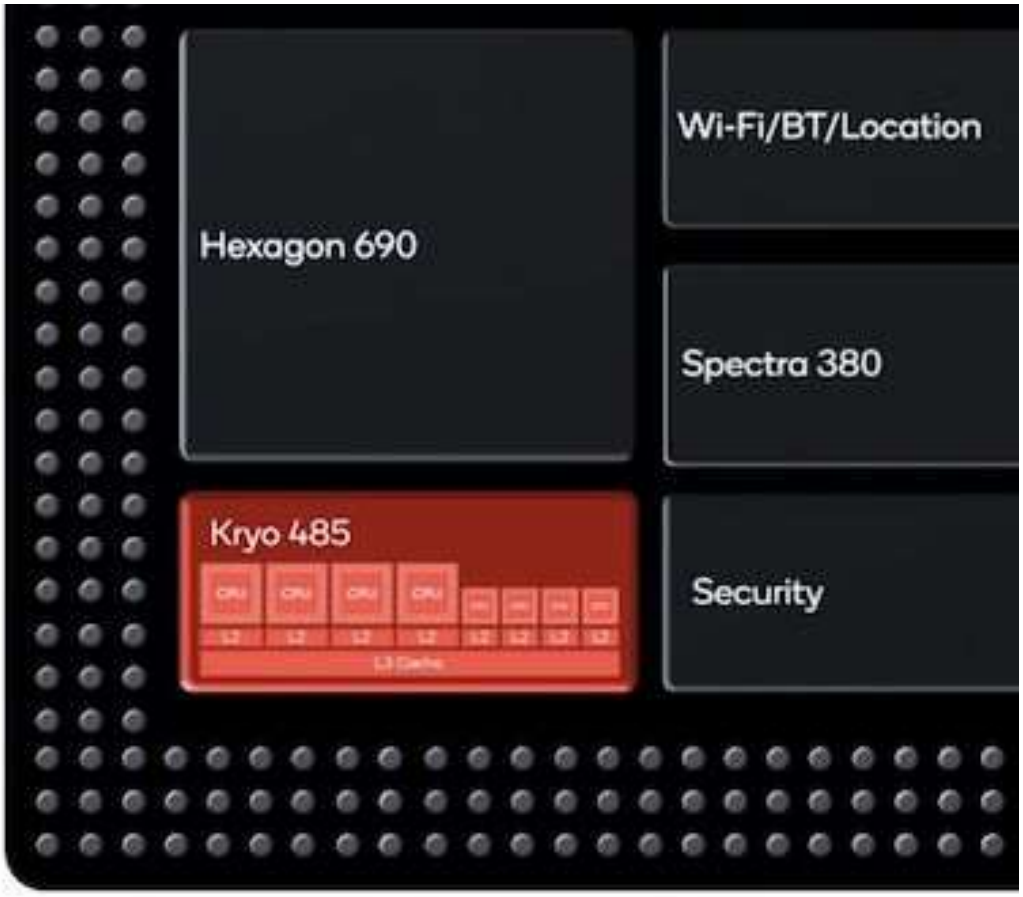
45% performance uplift

1 x 2.84GHz Prime Core
3 x 2.42GHz Performance Cores
4 x 1.80GHZ Efficiency Cores

Customized design for Snapdragon

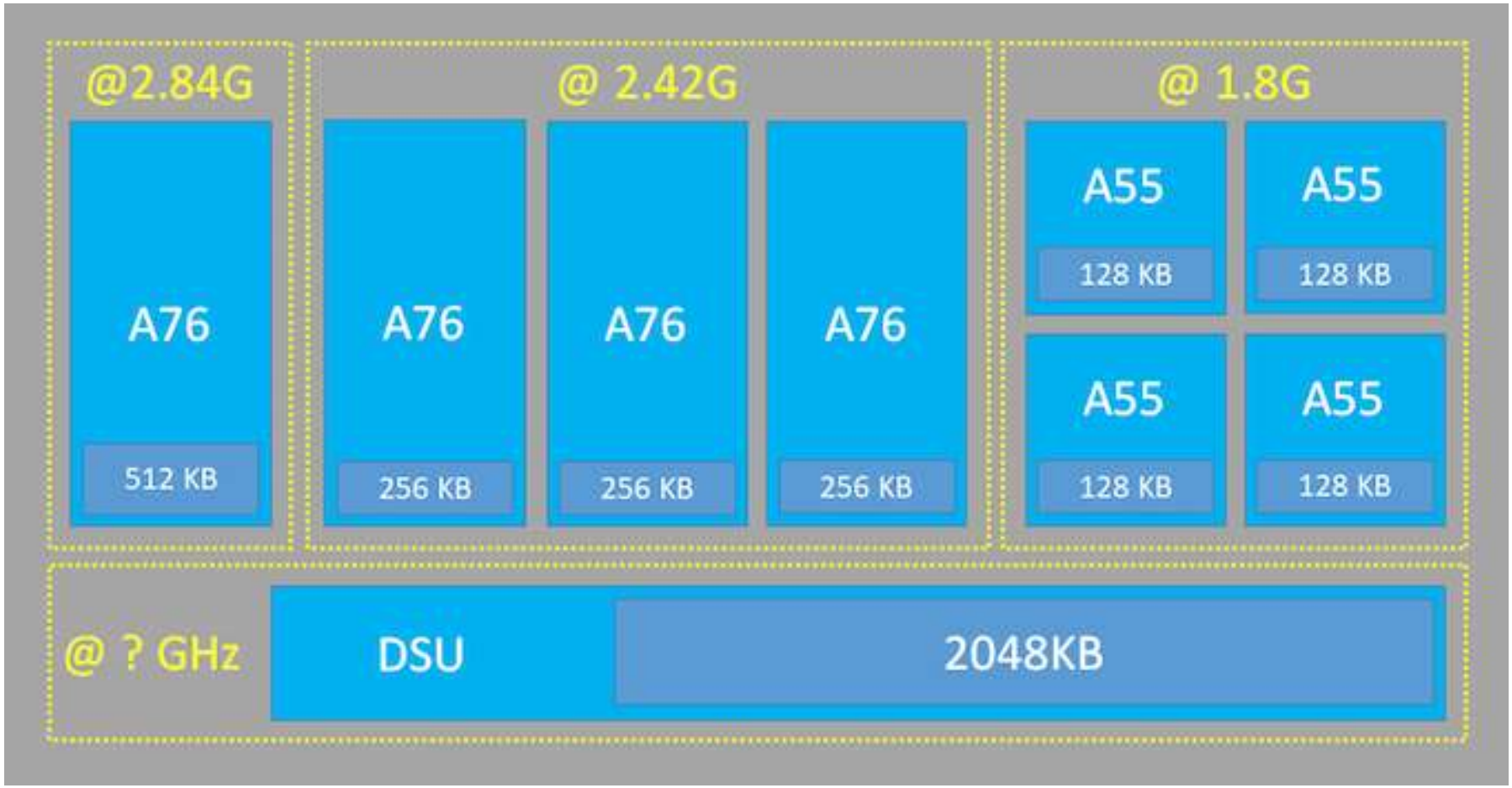
- Larger Out-of-order execution window
- Optimized data prefetch for better efficiency

Private per core L2 cache + Shared L3 Cache + System Cache

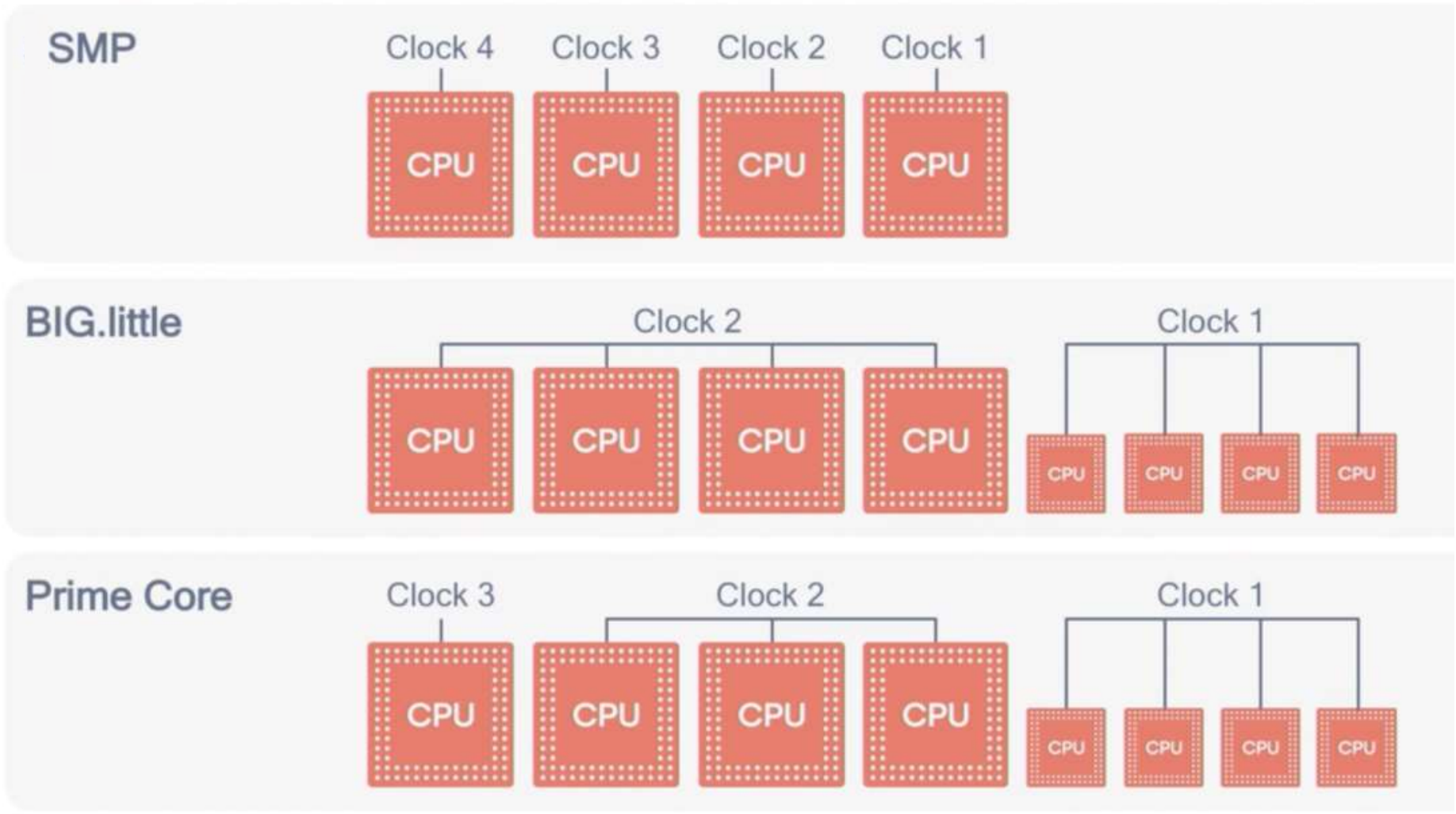


4.3.6 The Snapdragon 855 processor (7)

Core clusters (1 + 3 + 4) of the Snapdragon 855 processor [94]

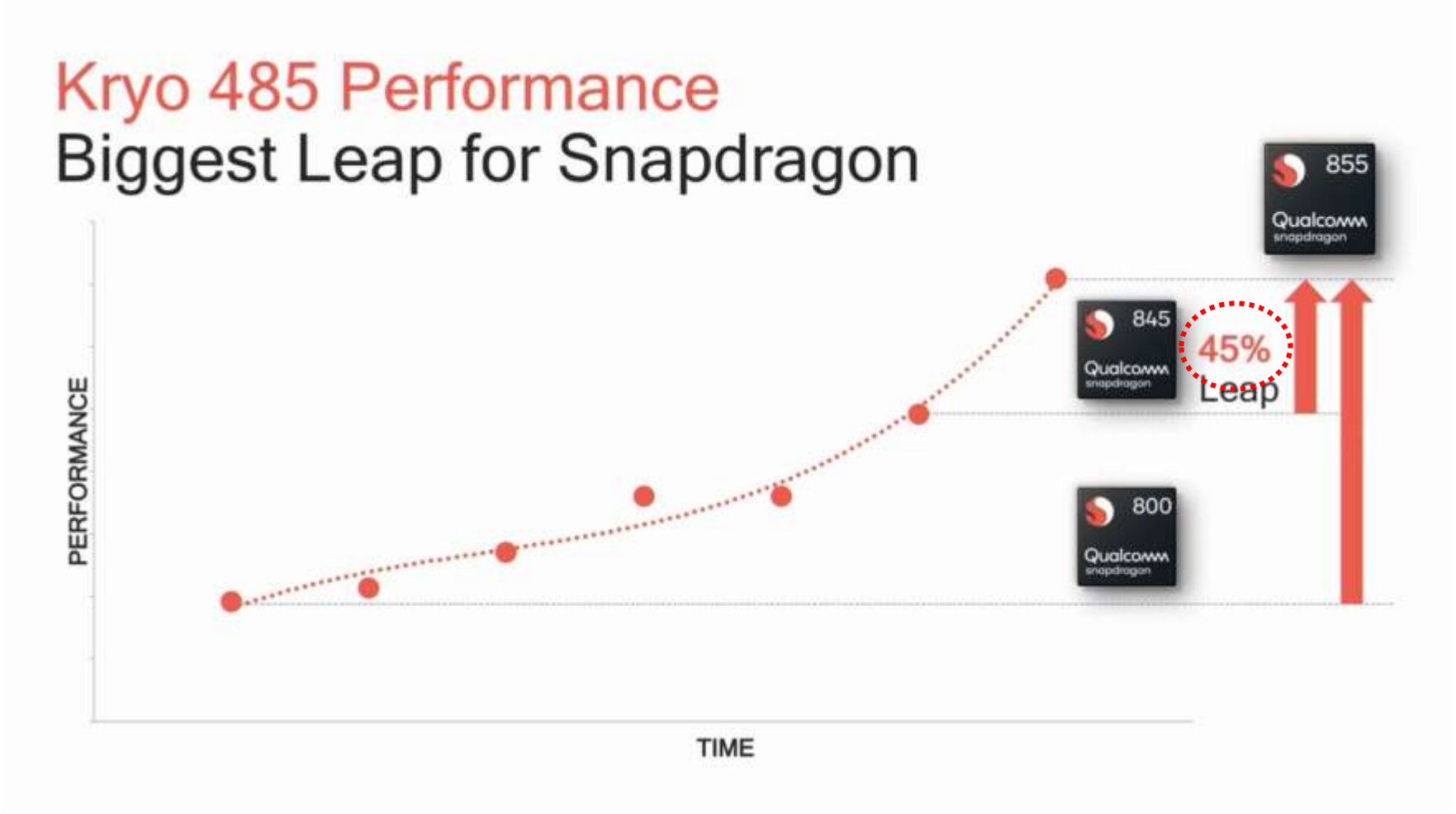


Evolution of core arrangements [117]



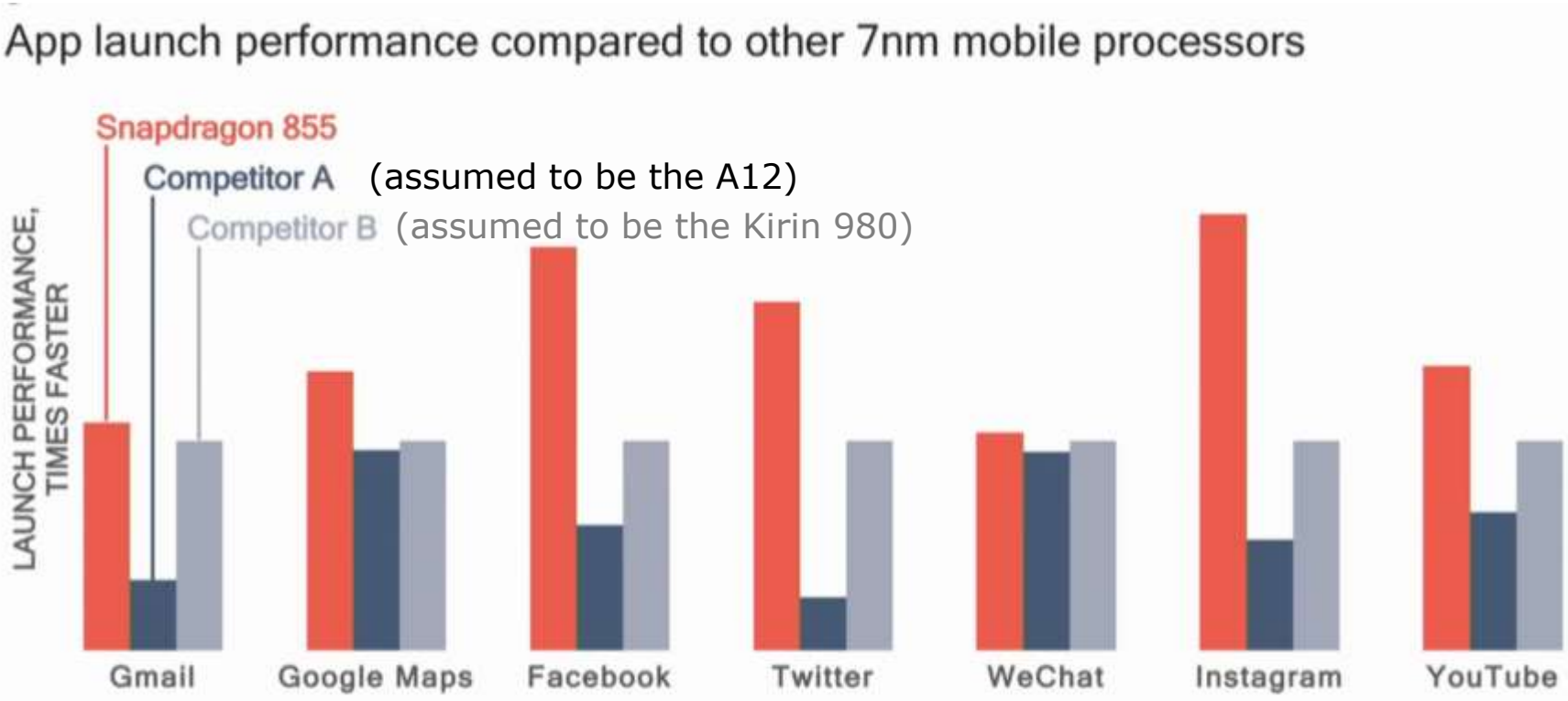
4.3.6 The Snapdragon 855 processor (8)

Performance leap of the Snapdragon 855 vs. the 845 [94]



4.3.6 The Snapdragon 855 processor (9)

Comparing the performance of 7 nm mobile processors [94]



The Adreno 640 GPU [94] -1

Adreno 640

Qualcomm designed GPU

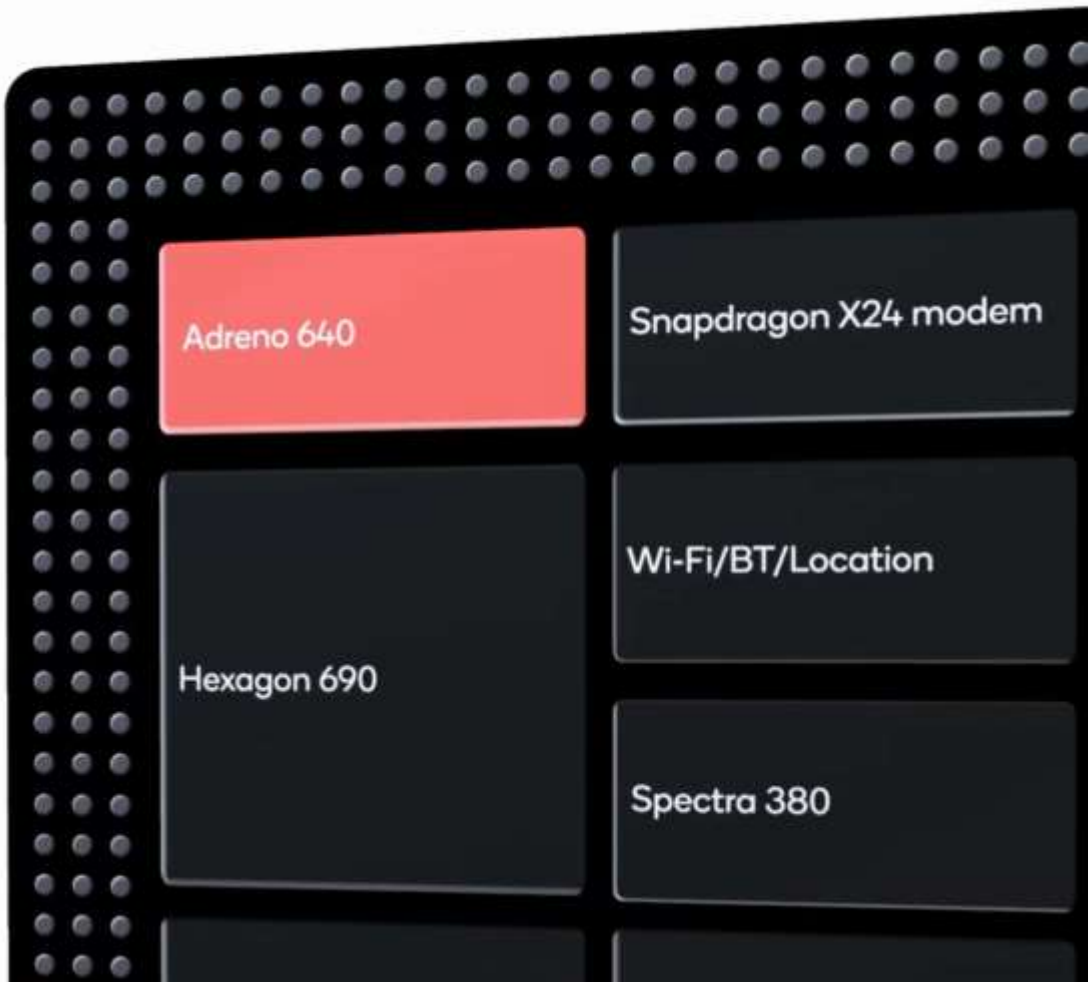
20% faster graphics rendering

Industry leader in performance/watt

- Integrated microcontroller for power management
- Lowest driver overhead for less CPU power

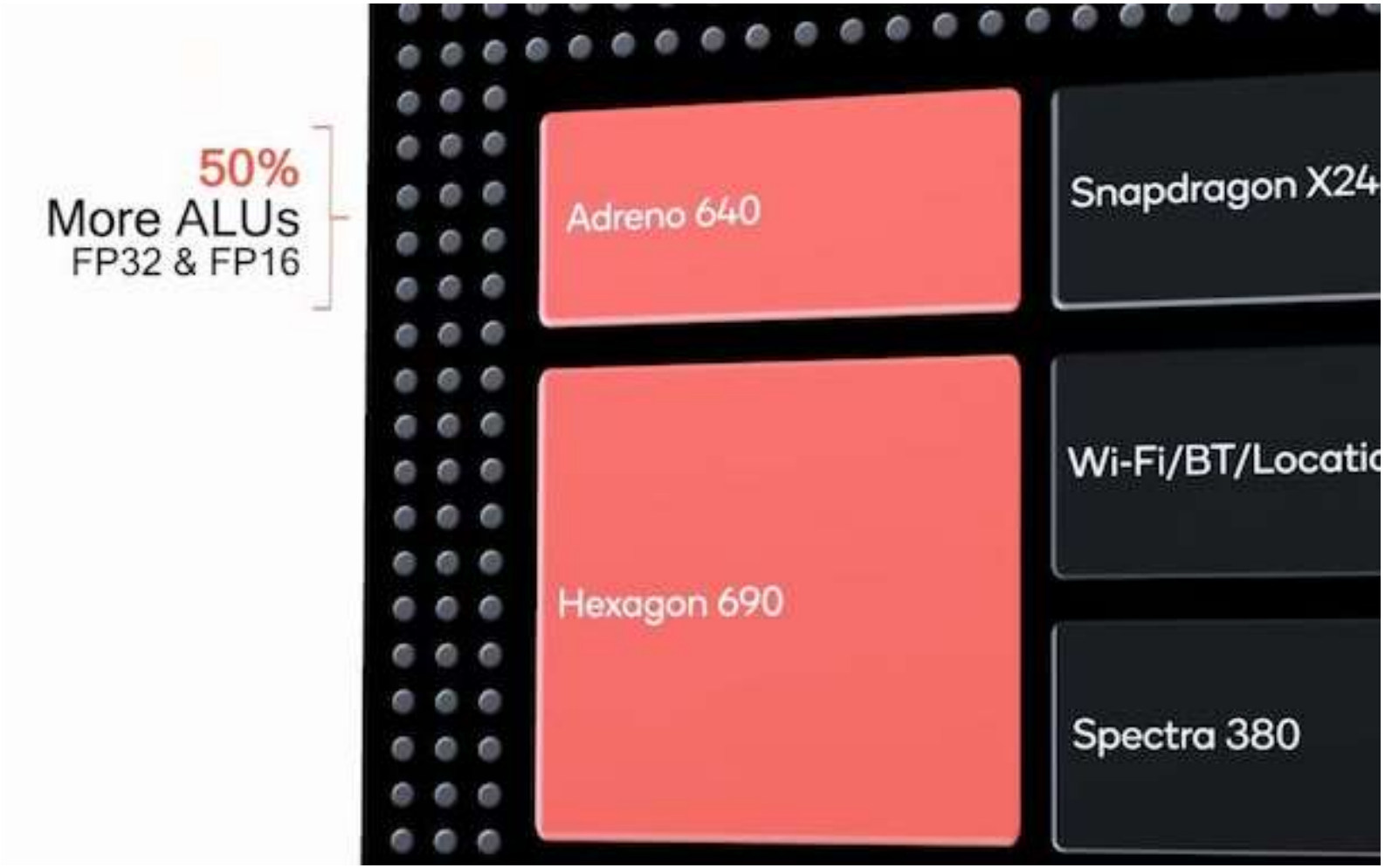
Industry leader in graphics feature set

- First to mobile with Vulkan 1.1



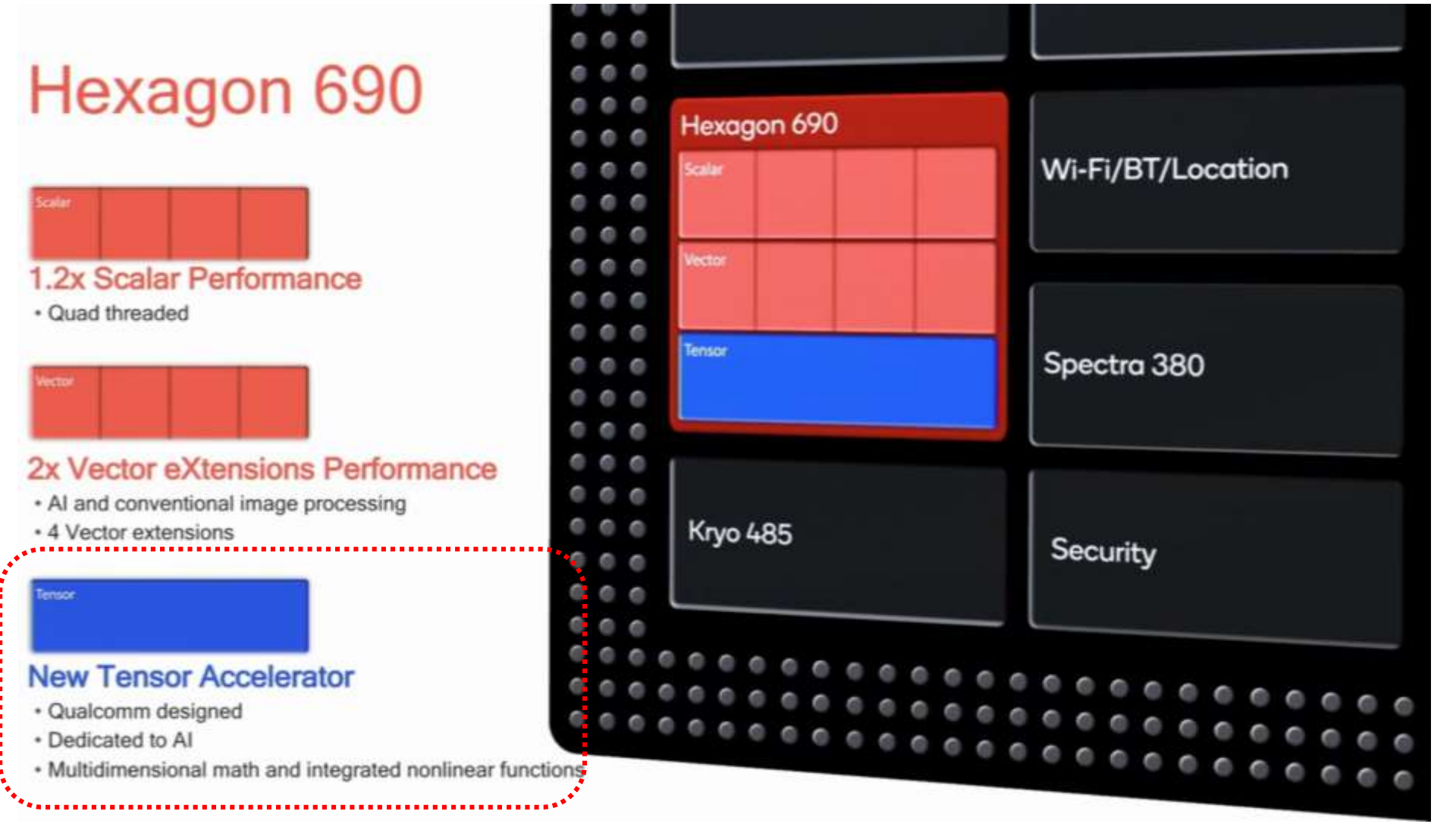
4.3.6 The Snapdragon 855 processor (11)

The Adreno 640 GPU [94] -2



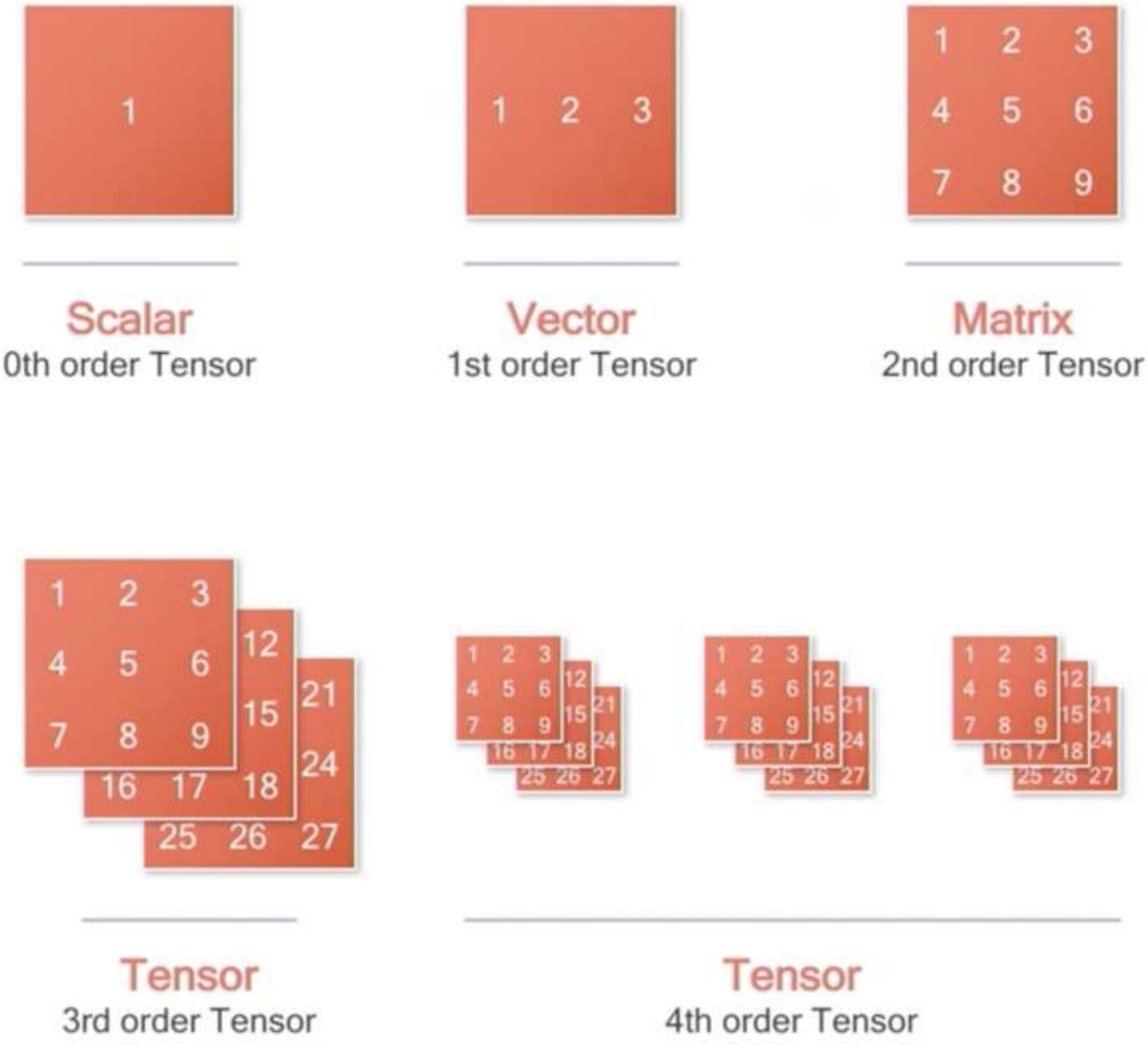
4.3.6 The Snapdragon 855 processor (12)

The Hexagon 690 DSP [94]



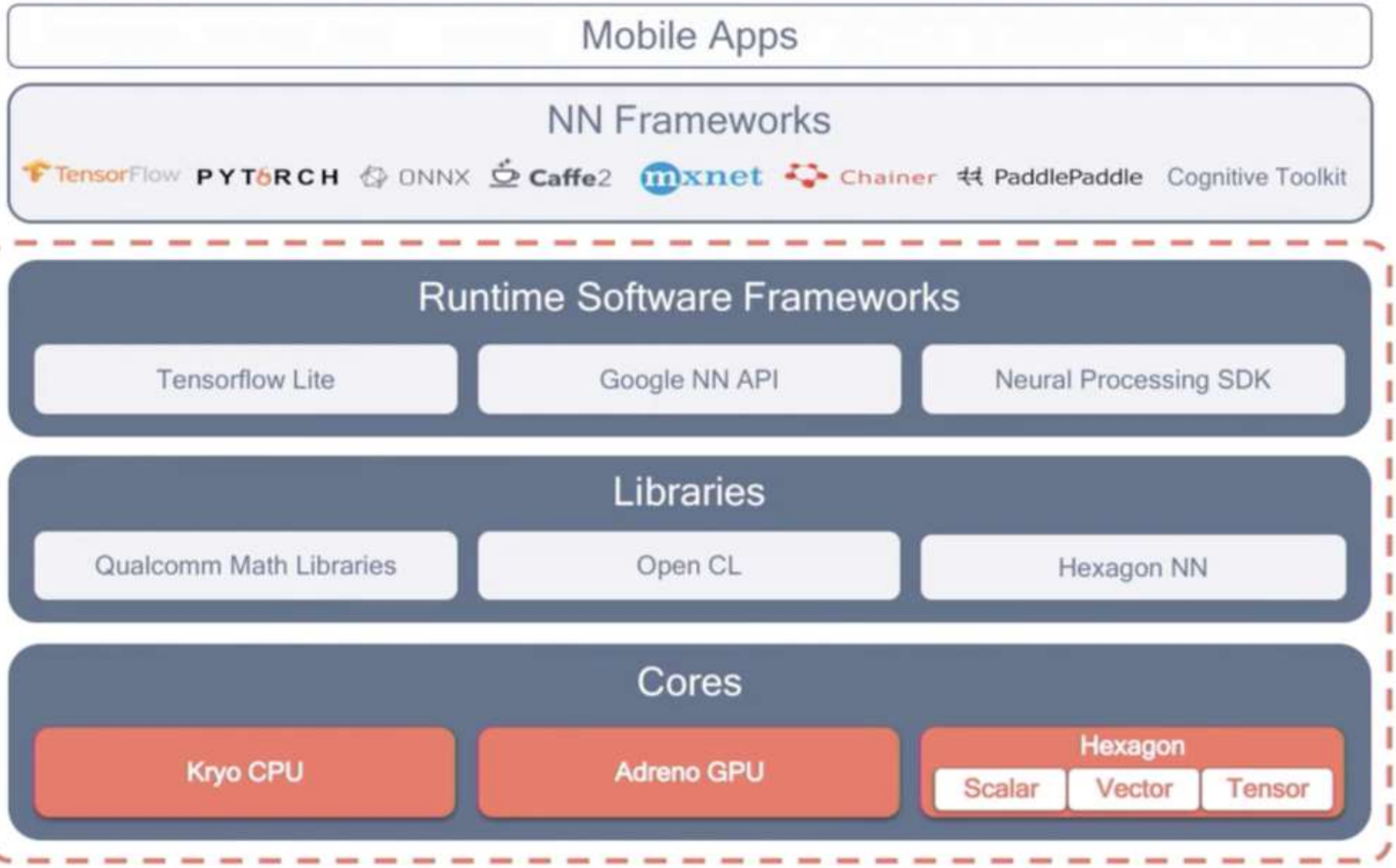
4.3.6 The Snapdragon 855 processor (12b)

Snapdragon 855's 4th gen. AI Engine, based on the Hexagon 690 DSP [117]



Performance of Snapdragon 855's 4th gen. AI Engine [117]

NN Frameworks and Runtime Software Frameworks of Snapdragon 855's 4th gen. AI Engine [117]



4.3.6 The Snapdragon 855 processor (13)

The Spectra 380 ISP (Image Signal Processor) [94]

World's
First
CV-ISP

Extreme
Speed Boost

Up to 4x
Power Savings

Computer Vision

Multi-object Classification

Multi-Object Tracking

Object Segmentation

Depth Sensing at 60fps

6DoF XR Body Tracking

CV Stabilization

4.3.6 The Snapdragon 855 processor (14)

Support of Wi-Fi 6 standards: (802.11ax and 802.11ay [94]

It needs an external Wi-Fi chipset, e.g. the IPQ8074 SoC that is Qualcomm's first chipset that supports the 802.11ax standard.

4.3.6 The Snapdragon 855 processor (15)

4G LTE and 5G connectivity of the Snapdragon 855 processor [94]

Provided by the
X24 modem
implemented
on the processor die

Provided by the
X50 modem
placed
onto the mainboard

4.3.6 The Snapdragon 855 processor (16)

Main features of LTE categories [98]

Downlink			Uplink			
DL UE Category	Max data rate in Mbps	DL MIMO Layers	**UL UE Category**	Max data rate in Mbps	64QAM Support	256QAM Support
M1	~ 1 Mbps	1	M1	~ 3 Mbps	No	No
M2	~ 4 Mbps		M2	~ 7 Mbps		
0	~ 1 Mbps		0	~ 1 Mbps		
1bis	~ 10 Mbps		1bis	~ 5 Mbps		
4	~ 150 Mbps	2	3	~ 50 Mbps		
6	~ 300 Mbps	2 or 4	5	~ 75 Mbps	Yes	
7	~ 300 Mbps		7	~ 100 Mbps	No	
9	~ 450 Mbps		8	~ 1500 Mbps	Yes	
10	~ 450 Mbps		13	~ 150 Mbps		
11	~ 600 Mbps		14	~ 9500 Mbps		
12	~ 600 Mbps		15	~ 220 Mbps		
13	~ 390 Mbps		16	~ 100 Mbps		Yes
14	~ 3900 Mbps	8	17	~ 2100 Mbps		
15	~ 800 Mbps	2 or 4	18	~ 210 Mbps		
16	~ 1050 Mbps		19	~ 13500 Mbps		
17	~ 25000 Mbps	8	20	~ 315 Mbps		
18	~ 1200 Mbps	2, 4 or 8	21	~ 300 Mbps		No
19	~ 1600 Mbps					
20	~ 2000 Mbps					
21	~ 1400 Mbps	2 or 4				

4.3.6 The Snapdragon 855 processor (17)

Remark: 5G NR [97]

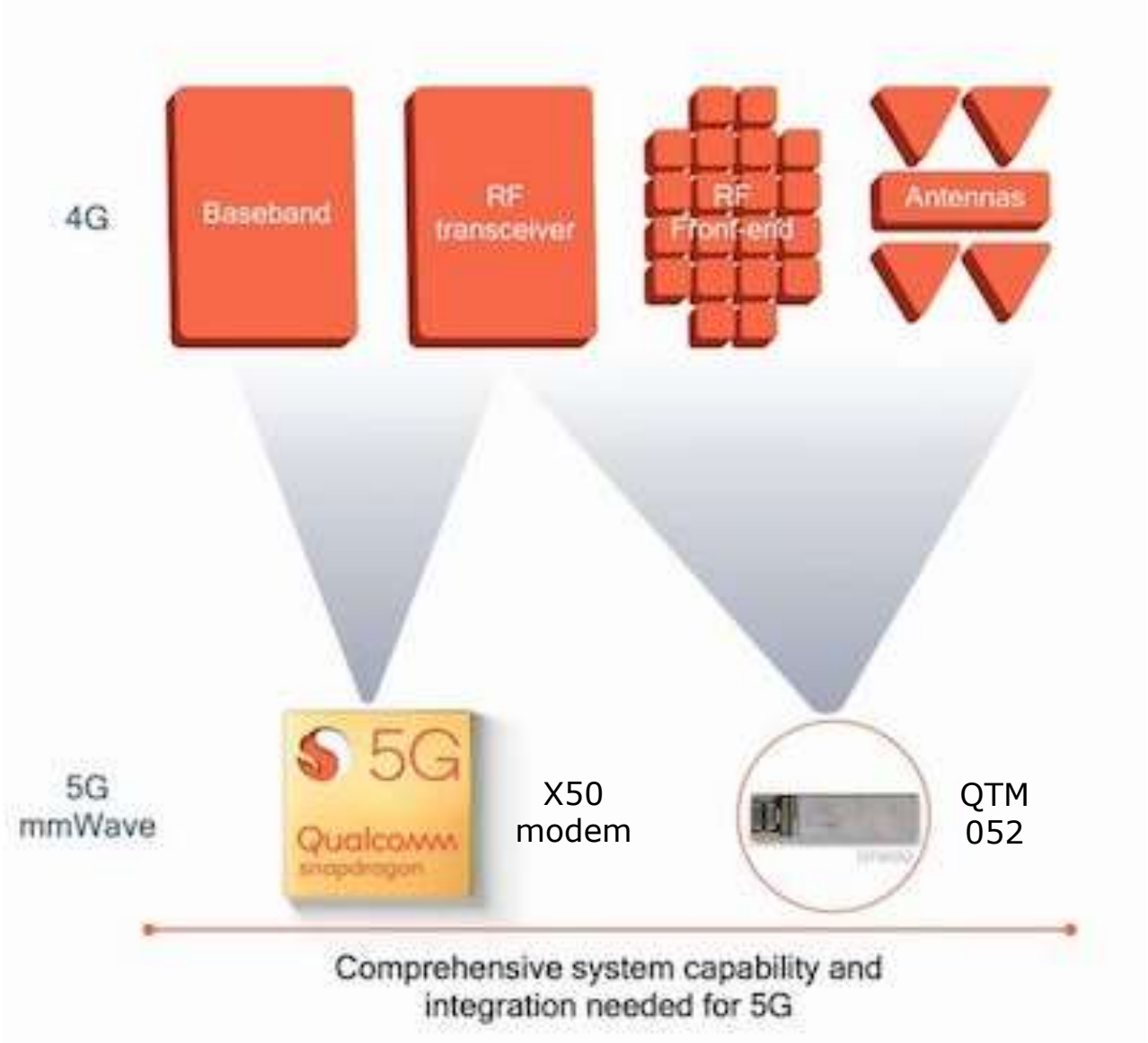
- 5G NR (New Radio) has been developed to provide significant enhancements in areas like scalability and efficiency, both in terms of power usage and spectrum.
- 5G New Radio provides
  - very high bandwidth communications, like streaming video,
  - low latency communications for remote control vehicle communications and
  - low data rate low bandwidth communications for machine type communications.
- mmwaves operate in the spectrum between 30GHz and 300GHz, e.g. 5G NR will operate in the future also in ranges of 60-64 GHz & 76-81 GHz.
- 5G NG can also operate in sub 6 GHz ranges, e.g. in the ranges of 3.3 GHz to 3.8 GHz and 4.4 GHz to 5.0 GHz.

5G standards [99]

- 5G standards are worked out by the 3GPP organization (3rd Generation Partnership Project) that unites seven telecommunications standard development organizations ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC).
- The first approved 5G standard is release 15 from 3GPP, approved in 06/2018.

4.3.6 The Snapdragon 855 processor (19)

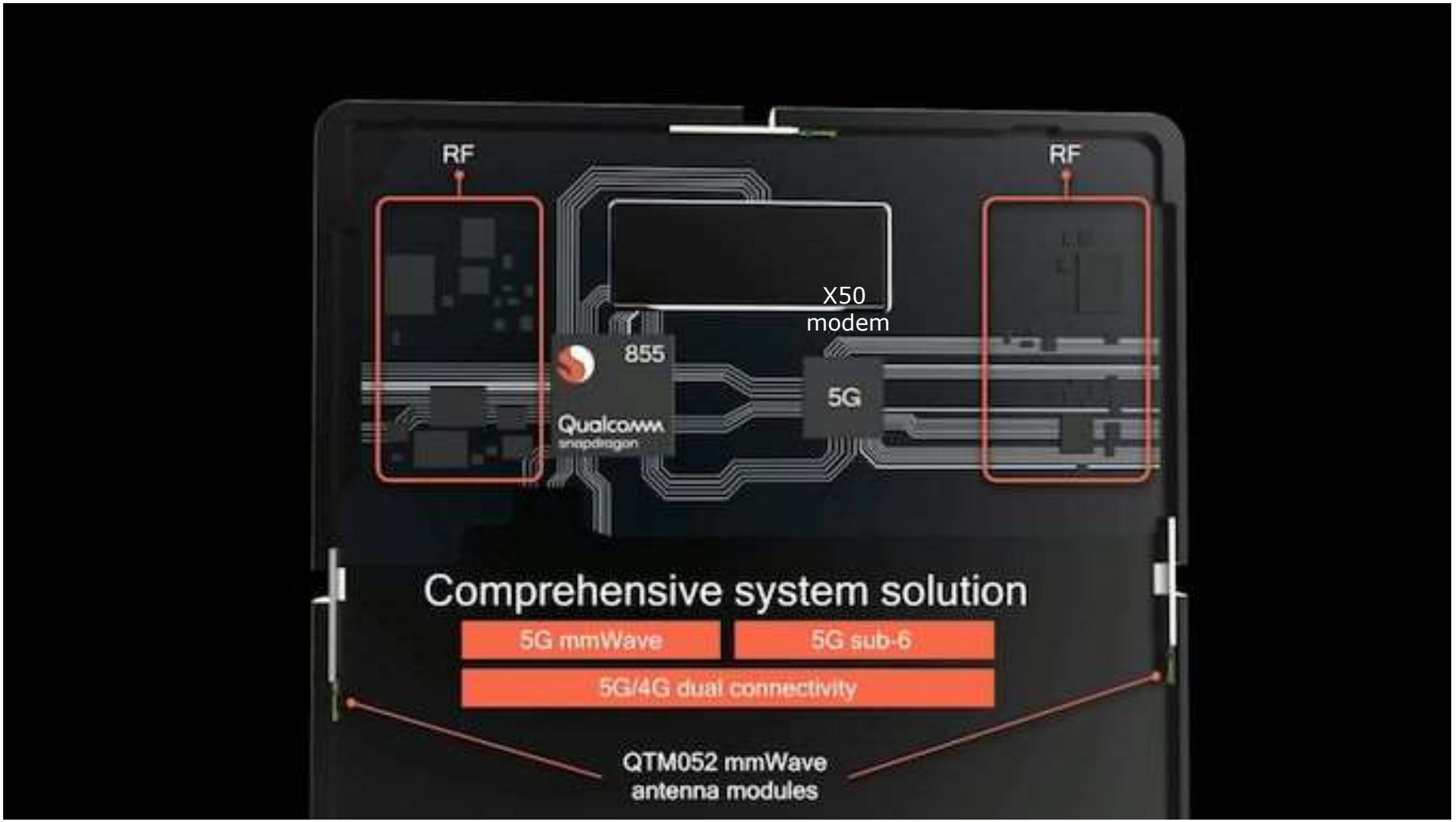
Principle of 5G NR mmwave implementation in the Snapdragon 855 [94]



https://www.anandtech.com/show/13680/snapdragon-855-going-into-detail

4.3.6 The Snapdragon 855 processor (20)

X50 modem and RF antenna modules (QTM052) on the Snapdragon 855 platform []



https://www.anandtech.com/show/13680/snapdragon-855-going-into-detail

4.3.7 The Snapdragon 8cx processor

4.3.7 The Snapdragon 8cx processor

- Announced in 12/2018, to be shipped in devices about Q3/2019.
- It includes
  - 4 Cortex-A76-based big cores and
  - 4 Cortex-A55-based LITTLE cores.
- Manufactured on TSMC 7 nm technology
- Die size is ~112 mm^2, transistor count ~10b.
- The Snapdragon 8cx Qualcomm's first processor that is designed exclusively for Windows 10 devices.
- It is Qualcomm's highest performance processor to date.
- In the designation "c" means: compute, "x": eXtreme.
- The sustained power consumption of the Snapdragon 8cx is 7 W and this low power consumption allows to build fanless systems with multi-day battery life.
- Qualcomm stated that the 8cx will represent a new higher power category above the 850 rather than directly replacing it.

4.3.7 The Snapdragon 8cx processor (2)

Evolution of fabrication technology of mobile processors of major vendors

	20/22 nm	14 /16 nm	10 nm	7/8 nm
Apple	A8 (2014) A8X (2014)	A9 (2015) A9X (2015) A10 (2016)	A10X (2017) A11 (2017)	A12 (2018) A12X (2018)
Qualcomm Snapdragon	808 (2015) 810 (2015)	820 (2015) 821 (2016)	835 (2017) 845 (2017) 850 (2018)	855 (2015) 8cx (2019)
Huawei Kirin	—	940 (2015) 950 (2015) 955 (2016) 960 (2016)	970 (2017)	980 (2018)
Samsung Exynos	5430 (2014) 5433 (2014)	7420 (2015) 8890 (2016)	8895 (2017) 9810 (2018)	9820 (2019)

4.3.7 The Snapdragon 8cx processor (3)

Die size and transistor count of more recent processors [95]

Die Size and Transistor Counts

AnandTech	Process Node	Die Size (mm)	Die Area (mm2)	Tr	Density (MTr/mm2)
Snapdragon 8cx	7nm TSMC	8.3 x 13.5	112*	> 5.3b < 10.6b	> 56.4 < 94.6
Snapdragon 855	7nm TSMC				
Snapdragon 845/850	10LPP Samsung		94	5.3 b	56.4
Snapdragon 835	10LPE Samsung		72.3	3.0 b	41.5
Kirin 980	7nm TSMC		74.13	6.9 b	93.1
Kirin 970	10nm TSMC	9.75 x 9.92	96.72	5.5 b	56.9
Kirin 960	16nm TSMC	10.77 x 10.93	117.72	4.0 b	34.0
Apple A12 Bionic	7nm TSMC	9.89 x 8.42	83.27	6.9 b	82.9
Apple A12X Bionic	7nm TSMC		122	10 b	
Exynos 9810	10LPP Samsung	10.37 x 11.47	118.94	?	?
8-core Ryzen	14nm GloFo	22.06 x 9.66	192	4.8 b	25.0
Skylake 4+2	14nm Intel	13.31 x 9.19	122	1.75 b	14.3

*Upper Bound

4.3.7 The Snapdragon 8cx processor (4)

Elucidation of the design goal of Snapdragon 8cx: Windows 10 devices [107]

4.3.7 The Snapdragon 8cx processor (5)

Main functional units on the Snapdragon 8cx die [108]

4.3.7 The Snapdragon 8cx processor (6)

Contrasting main features of the Snapdragon 8cx, 850 and 835 [109]

	Snapdragon 8cx	Snapdragon 850	Snapdragon 835
CPU Core	Semi-custom ARM Cortex - Kryo 495	Semi-custom ARM Cortex - Kryo 385	Semi-custom ARM Cortex - Kryo 280
CPU Config	4x (Cortex-A76) 4x (Cortex-A55)	4x 2.96GHz (Cortex-A75) 4x 1.7GHz (Cortex-A55)	4x 2.45GHz (Cortex-A73) 4x 1.9GHz (Cortex-A53)
GPU	Adreno 680 Extreme	Adreno 630	Adreno 540
DSP	Hexagon 690	Hexagon 685 with HVX	Hexagon 682 with HVX
RAM	16GB LPDDR4x	8GB LPDDR4x	8GB LPDDR4x
Storage	UFS 3.0, NVME SSD	UFS 2.1	UFS 2.1
Process	7nm FinFET	10nm LPP FinFET	10nm LPE FinFET
Camera support	32MP single / 16MP dual Hybrid AF, HDR video. multi-frame noise reduction	32MP single / 16MP dual Hybrid AF, HDR video. multi-frame noise reduction	32MP single / 16MP dual Hybrid AF, HDR video
Video capture	4K UHD, HDR @ 30fps	4K UHD @ 30fps	4K UHD @ 30fps
Video playback	360 degree, 4K up to 120fps, 10-bit, H.265 and VP9 video decode	4K UHD @ 60fps, 10-bit H.264 (AVC) and H.265 (HEVC)	4K UHD @ 60fps, 10-bit H.264 (AVC) and H.265 (HEVC)
Wireless	Wi-Fi 802.11a/b/g/n/ac/ad 2.4, 5, and 60GHz Bluetooth 5.0	Wi-Fi 802.11a/b/g/n/ac/ad 2.4, 5, and 60GHz Bluetooth 5.0	Wi-Fi 802.11a/b/g/n/ac/ad 2.4, 5, and 60GHz Bluetooth 5.0
Modem	x24 LTE 2000Mbps down 316Mbps up	x20 LTE 1200Mbps down 150Mbps up	X16 LTE 1000Mbps down 150Mbps up

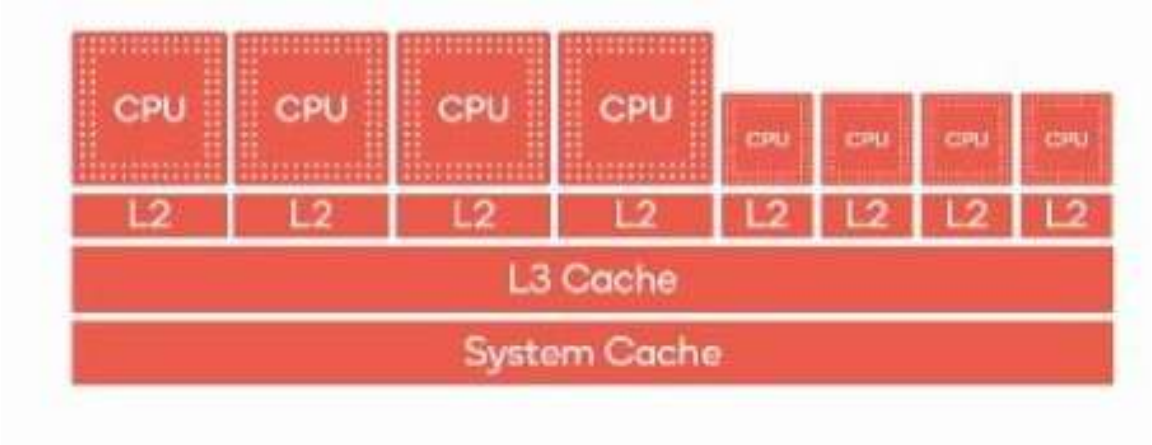
4.3.7 The Snapdragon 8cx processor (7)

Main enhancements of the Snapdragon 8cx vs. the 855

	8cx	855
CPU big cores	Kryo 495	Kryo 485
GPU	Adreno 680	Adreno 640
ISP	Spectra 390	Spectra 380
Memory	8x16-bit LPDDR4x	4x16-bit LPDDR4x
Storage	UFS 3.0, NVMe	UFS 2.1

4.3.7 The Snapdragon 8cx processor (8)

Main features of the Kryo 495 CPU [110]



Fastest Snapdragon ever

7nm process technology

Larger system cache and L3 cache

Total of 10MB cache available

4.3.7 The Snapdragon 8cx processor (9)

Performance and power efficiency improvements of the Cortex-A76 core vs. the A75 core (used in the Snapdragon 855) [100]

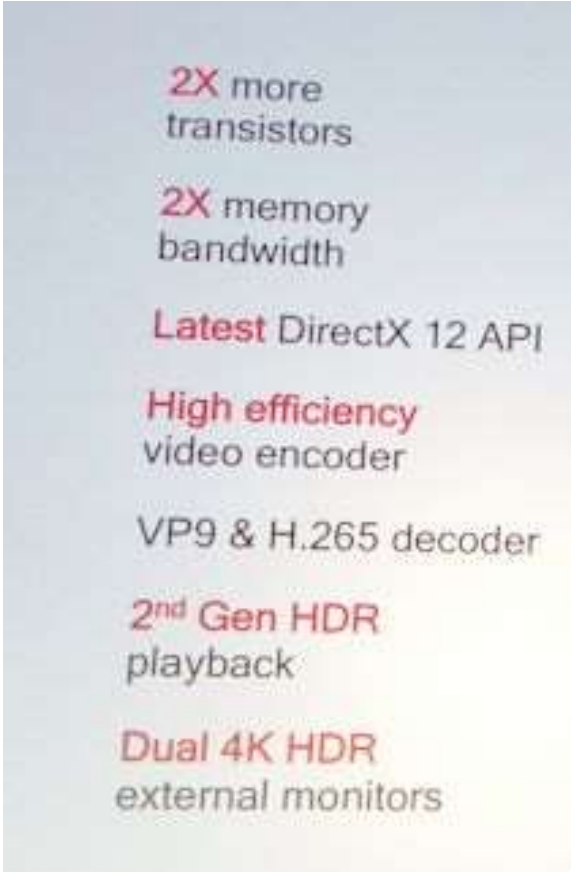
Figure: Performance and power efficiency of a 3.0 GHz 7 nm Cortex-A76 vs. a 2.8 GHz 10 nm Cortex-A75 [100]

Remarks

- The Cortex-A76 has a brand new, wider microarchitecture (4-wide, up from 3) compared to the preceding A75.
- It has an enhanced, 2. gen. DynamIQ core cluster.

4.3.7 The Snapdragon 8cx processor (10)

The Adreno 680 GPU of the Snapdragon 8cx vs. the Adreno 630 (of the Snapdragon 850 [113]

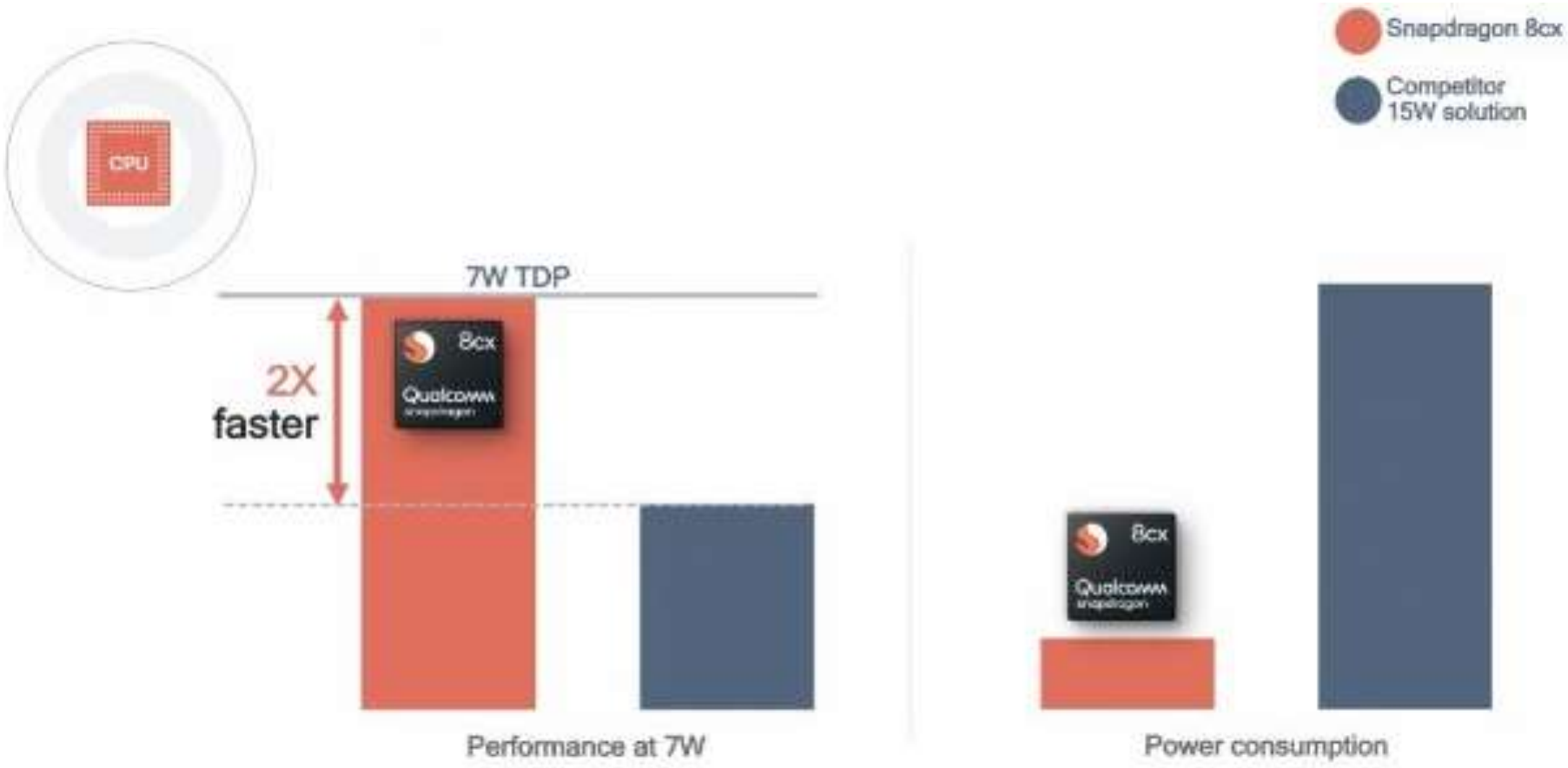


HDR: High-Dynamic-Range imaging (greater dynamic range of luminosity)

It preserves details in darkest or brightest regions of a picture that became lost using traditional techniques and provides more natural colors.

4.3.7 The Snapdragon 8cx processor (11)

Performance and power consumption of Snapdragon 8cx vs. a competitor [108]



It can be presumed that the referenced competitor is a model of Intel's 15 W U-series processors, like the i7-8565U or the i5-8265U.

4.3.7 The Snapdragon 8cx processor (12)

Geekbench 4 scores of Intel's 15 W i7-xxxxU processors [116]

Model	CPU cores	Launched	GB 4 SC max	GB 4 MC max	Family	Techn.
I7-4500U	2C	6/2013	3854	6854	Haswell	22 nm
I7-4600U	2C	9/2013	4202	7592	Haswell	22 nm
i7-5600U	2C	1/2015	4217	8018	Broadwell	14 nm
I7-6600U	2C	9/2015	4775	9010	Skylake	14 nm
I7-7560U	2C	8/2016	5000	10182	Kaby Lake	14 nm
I7-7660U	2C	1/2017	5128	10389	Kaby Lake	14 nm
I7-8565U	4C	8/2018	5576	17813	Coffee Lake	14 nm

4.3.7 The Snapdragon 8cx processor (13)

Geekbench 4 scores of Apple's A series processors [114]

Model	CPU cores	Launched	GB 4 SC max	GB 4 MC max	Techn.
A8	2C	9/2014	1663	2855	20 nm
A8X	3C	10/2014	1798	4214	20 nm
A9	2C	9/2015	2524	4391	14/16 nm
A9X	2C	11/2015	3057	5114	16 nm
A10	2+2C	9/2016	3480	5928	16 nm
A10X	3+3C	6/2017	3915	9339	10 nm
A11	2+4C	9/2017	4224	10185	10 nm
A12	2+4C	9/2018	4797	11260	7 nm
A12X	4+4C	10/2018	5006	17925	7 nm

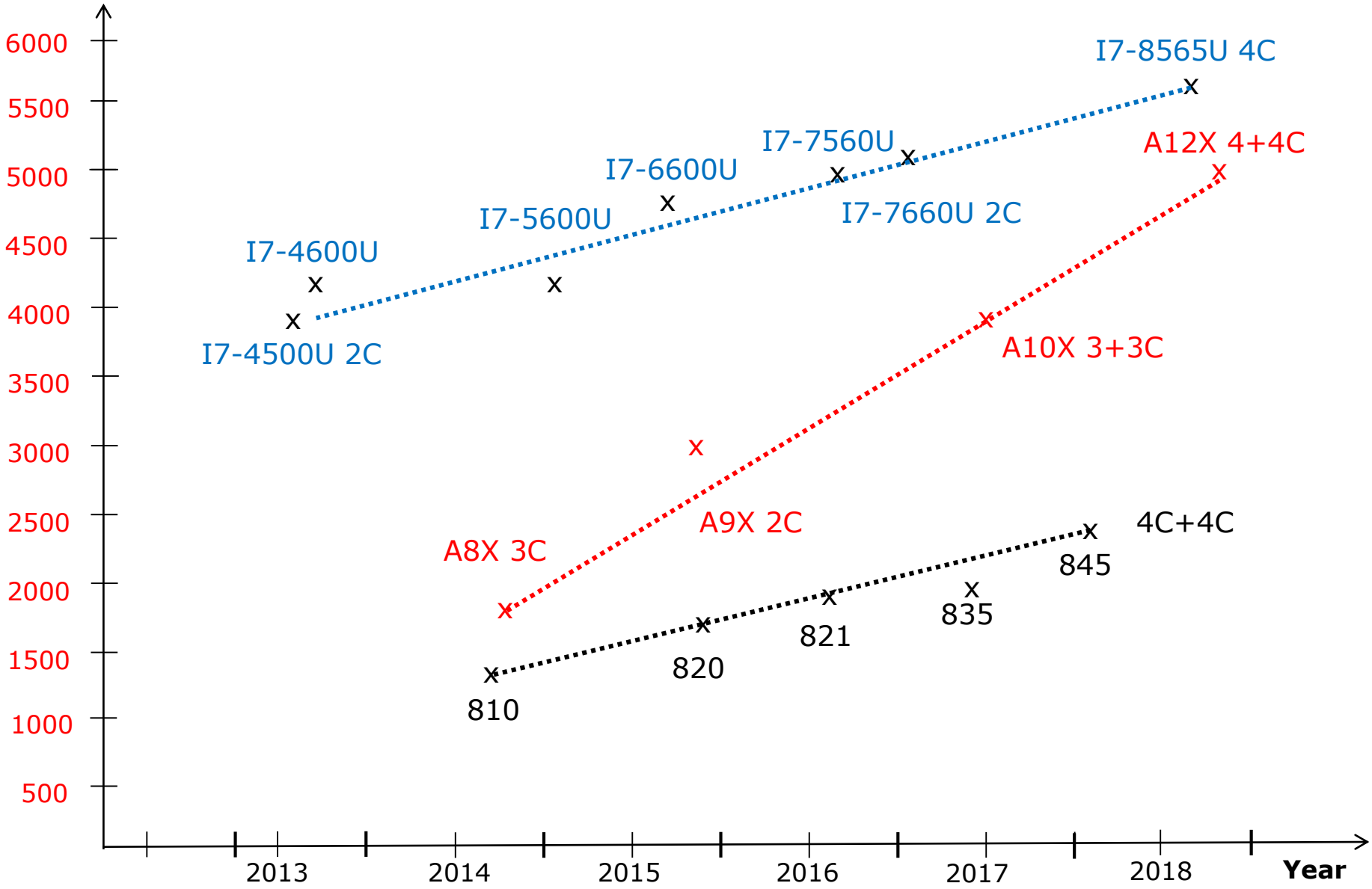
4.3.7 The Snapdragon 8cx processor (14)

Geekbench 4 scores of Qualcomm's Snapdragon processors [115]

Model	CPU cores	Launched	GB 4 SC max	GB 4 MC max	Techn.
808	2+4C	Q3/2014	1152	2813	20 nm
810	4+4C	Q3/2014	1351	3446	20 nm
820	4+4C	Q4/2015	1702	3955	14 nm
821	4+4C	Q3/2016	1880	4430	14 nm
835	4+4C	Q2/2017	1947	6624	10 nm
845	4+4C	Q1/2018	2415	8689	10 nm
850	4+4C	Q3/2018			10 nm
855	1+3+4C	Q1/2019			7 nm

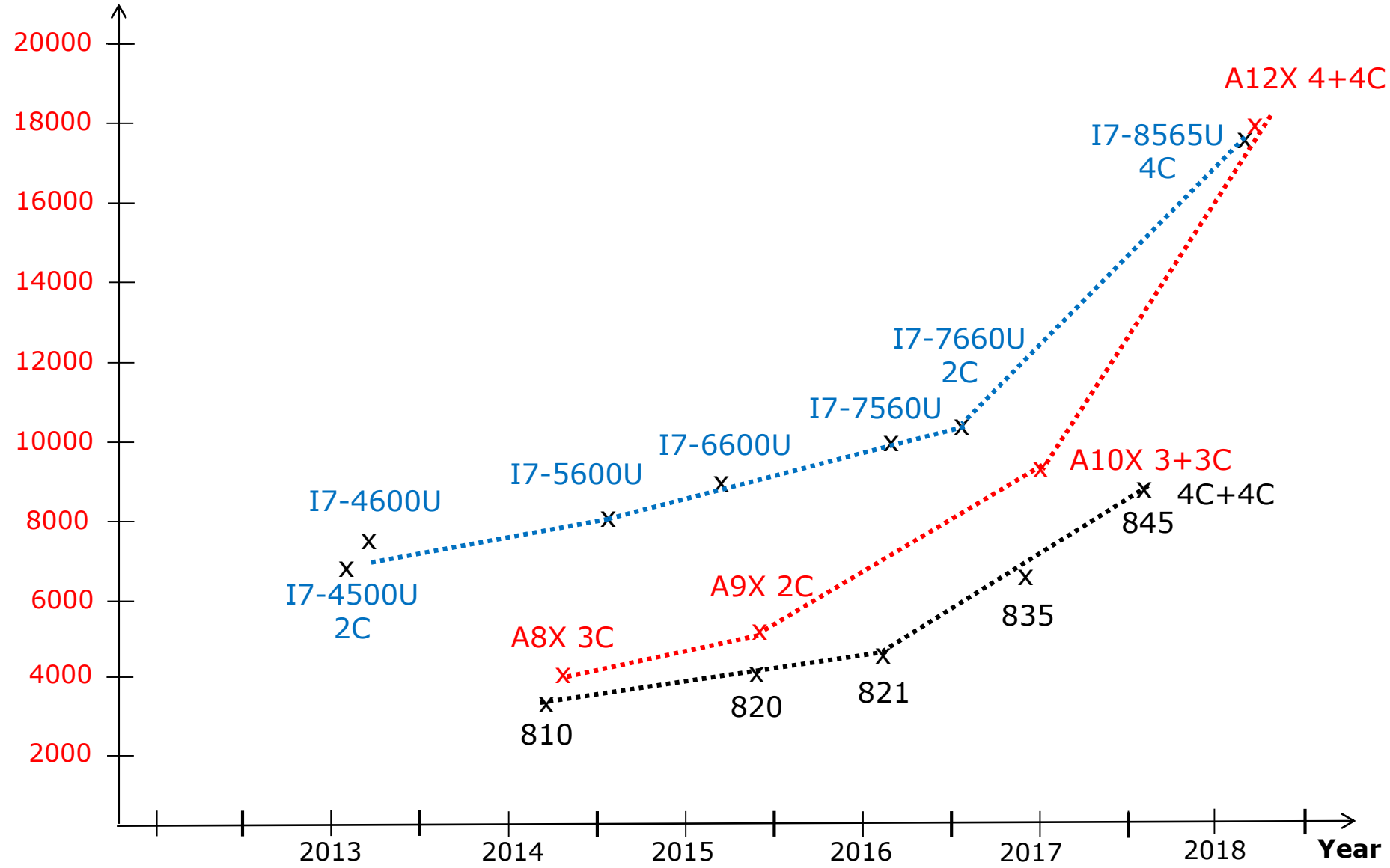
4.3.7 The Snapdragon 8cx processor (15)

Geekbench 4 SC scores of Intel's, Apple's and Qualcomm's processors



4.3.7 The Snapdragon 8cx processor (16)

Geekbench 4 MC scores of Intel's, Apple's and Qualcomm's processors



4.3.7 The Snapdragon 8cx processor (17)

Microsoft's and Qualcomm's support for porting native applications to the Microsoft Store [87], [111], [112] -1

- First Snapdragon 835-based Windows 10 devices had a number of software limitations, like
  - these devices run under Windows 10 S which restricted users to the Edge browser,
  - only 32-bit apps could be run,
  - only DirectX 9 to DirectX were supported thus apps/games that are using
  - older versions wont work.
- For Snapdragon 8cx-based devices software support will greatly improved.
  - 8cx's devices will be able to run Windows 10 Enterprise rather than only Windows 10 S,
  - In 05/2018 Microsoft released an SDK for coding 64-bit ARM apps that can then be ported to the Microsoft Store,
  - Microsoft begun working with enterprises to port their apps.
  - Qualcomm also released an LLVM compiler,
  - Qualcomm has been working with Google and Firefox and already showed off fully working versions of both the Chromium and Firefox browsers working in native ARM64 code.

4.3.7 The Snapdragon 8cx processor (18)

Microsoft's and Qualcomm's support for porting native applications to the Microsoft Store [111] -2

- Most other apps from outside the Microsoft Store will still need emulation by an extra layer of software translating the code for the Snapdragon chip but, at the launch event Qualcomm demonstrated that the extra power of the 8cx allows apps to run in this way more faster and responsive than before.

5. Qualcomm’s APQs (Application Processors of Qualcomm)

5. Qualcomm's APQs (Application Processors of Qualcomm) -1

Qualcomm's main product lines designed for mobiles

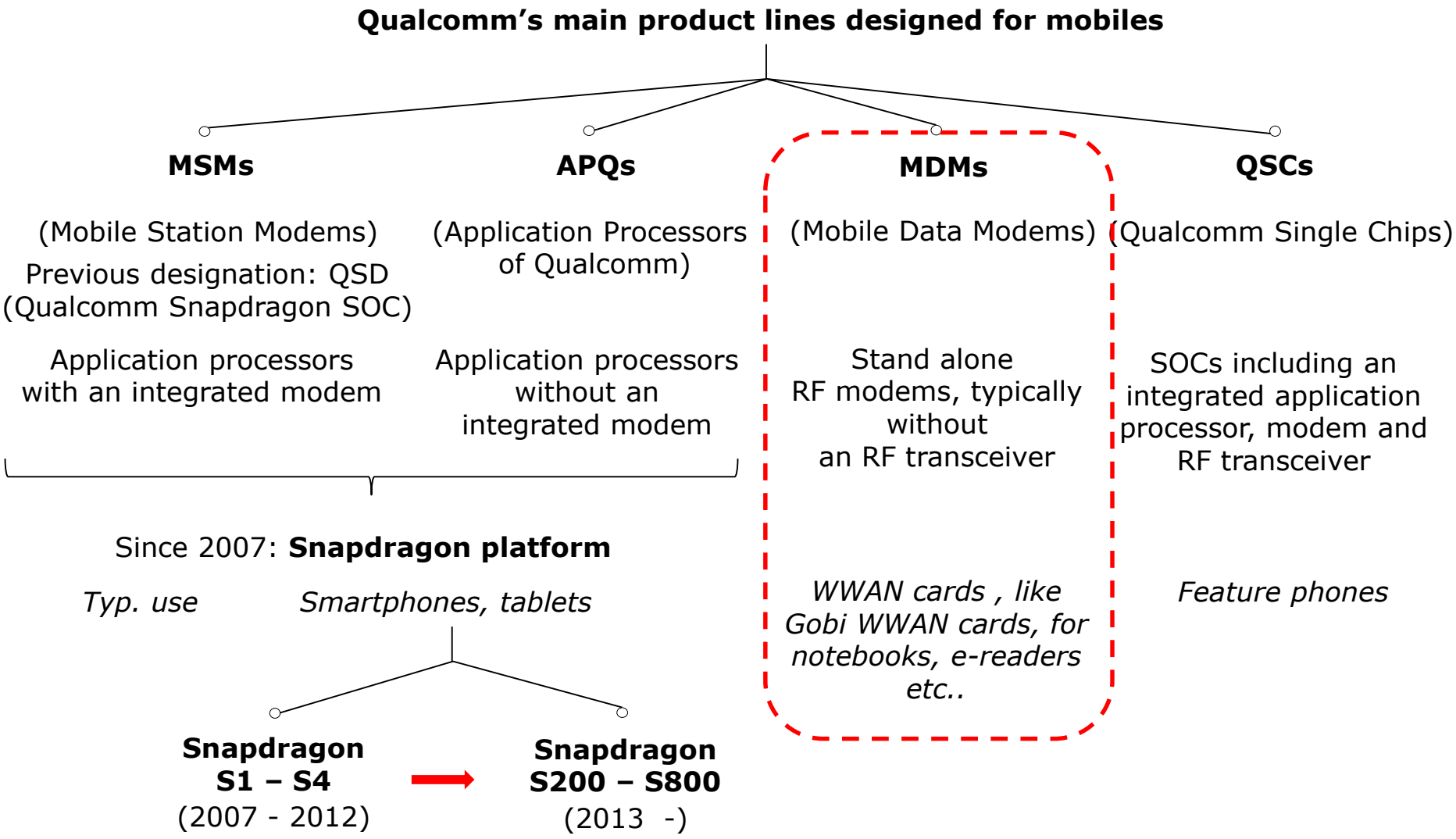
MSMs	**APQs**	**MDMs**	**QSCs**
(Mobile Station Modems) Previous designation: QSD (Qualcomm Snapdragon SOC)	(Application Processors of Qualcomm)	(Mobile Data Modems)	(Qualcomm Single Chips)
Application processors with an integrated modem	Application processors without an integrated modem	Stand alone RF modems, typically without an RF transceiver	SOCs including an integrated application processor, modem and RF transceiver
Since 2007: **Snapdragon platform**			
Typ. use *Smartphones, tablets*		*WWAN cards, like Gobi WWAN cards, for notebooks, e-readers etc..*	*Feature phones*
Snapdragon S1 – S4 (2007 - 2012) → **Snapdragon S200 – S800** (2013 -)			

Qualcomm’s APQs (Application Processors of Qualcomm) -2

These devices do not include RF modems just the “traditional processor”, thus in this Section we are not going to discuss them.

6. Qualcomm’s MDMs (Mobile Data Modems)

6. Qualcomm's MDMs (Mobile Data Modems)



Qualcomm’s Mobile Data modems (MDMs)-2

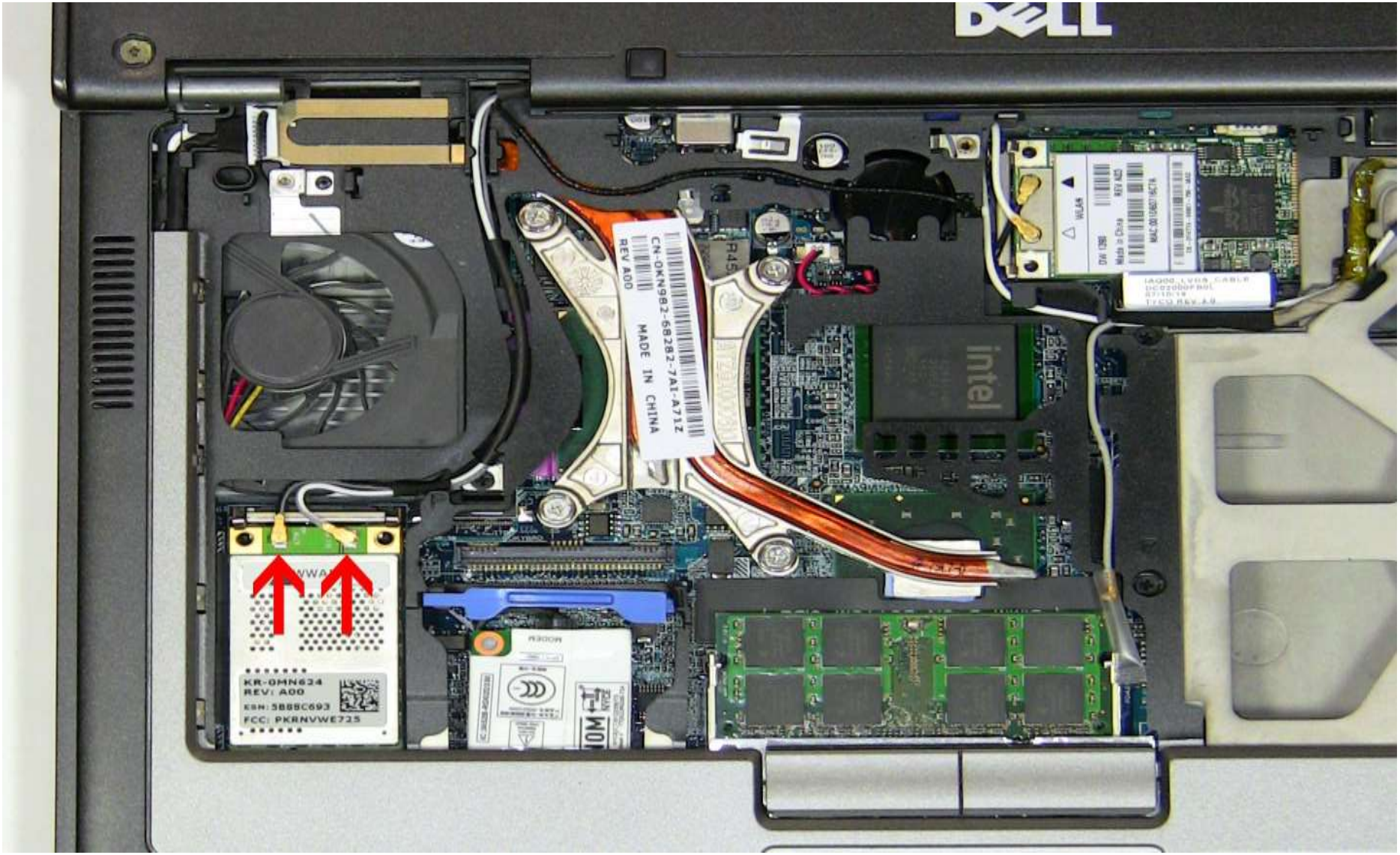
MDMs are stand alone RF modems to be used in WLAN cards etc. to be inserted into mobile devices, first mostly into notebooks, later on also into e-book readers, smartphones (e.g. in iPhones) etc., to provide wireless connectivity, as the next Figures illustrates.

6. Qualcomm's MDMs (Mobile Data Modems) (3)

Example WWAN cards [29]

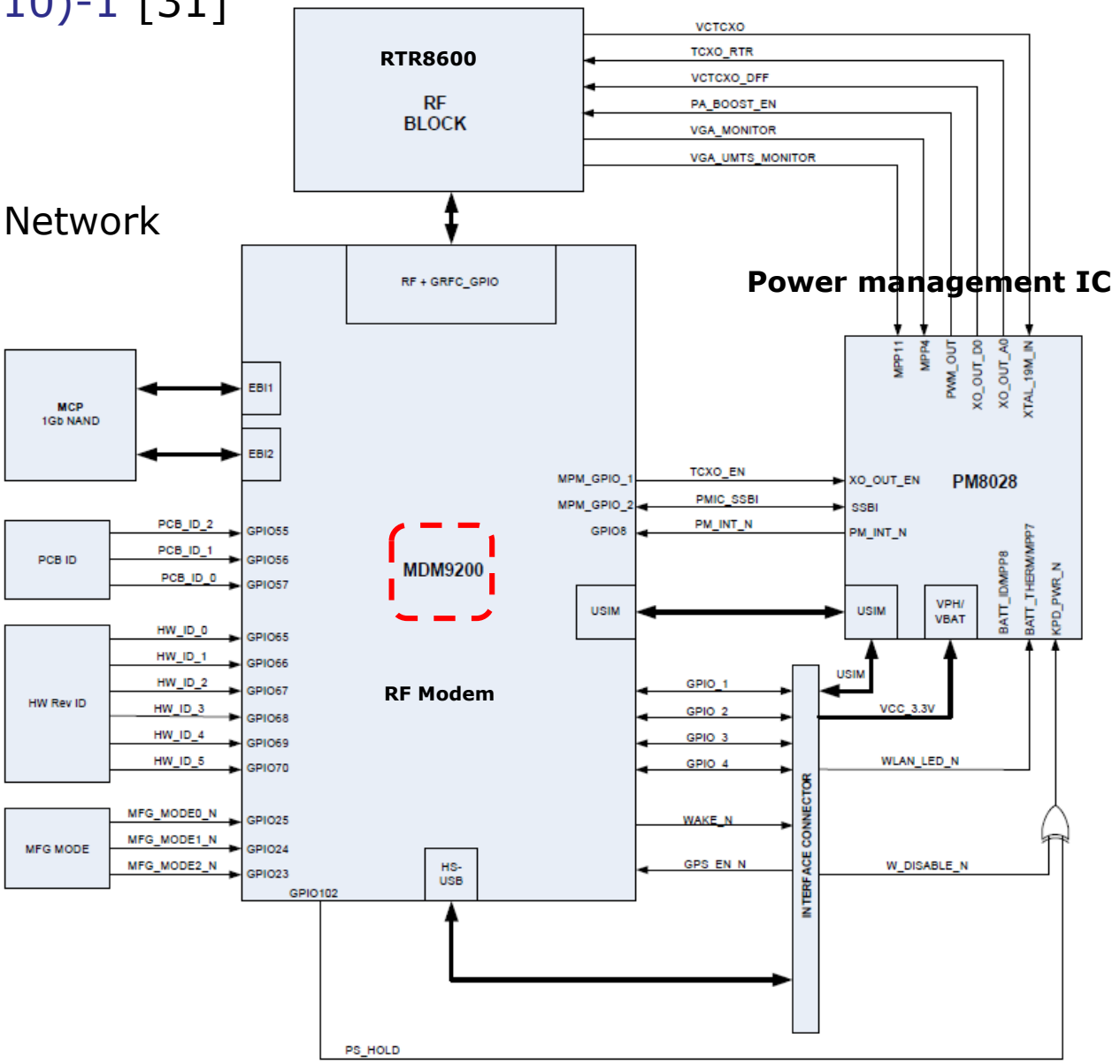
6. Qualcomm's MDMs (Mobile Data Modems) (4)

WWAN card in a Dell notebook [56]



Example block diagram of a WWAN card (the MCM7710)-1 [31]

WLAN: Wireless Local Area Network



6. Qualcomm's MDMs (Mobile Data Modems) (6)

Contrasting WLAN and WWAN (based on [32])

WLAN: Wireless Local Area Network

- Provides connectivity over an Internet Service Provider (ISP) and a wireless router
- WLAN coverage is small, up to hundreds of meters.
- WLAN connectivity is commonly provided in homes, offices, hotels etc.
- It needs a WLAN card in the mobile device, such as a notebook and subscription to the service provider.

WWAN: Wireless Wide Area Network

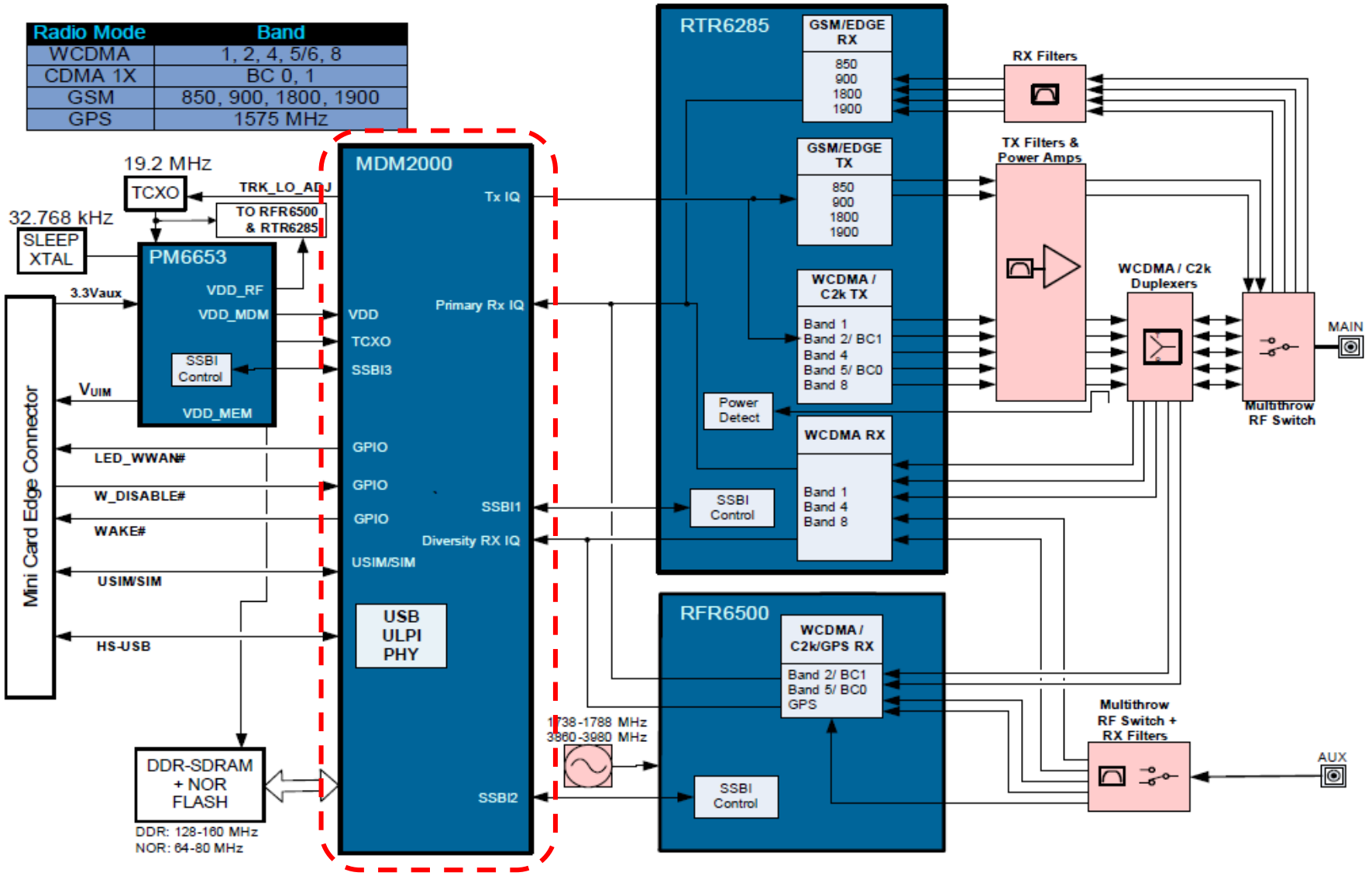
- Provides connectivity over a cellular network (e.g. LTE).
- WWAN has a large, regional coverage over the cellular network.
- It needs a WWAN card and in the mobile device, such as a tablet and appropriate subscription to the service provider.

MDMs (Mobile Data Modems)-2

MDMs are typically RF modems without the RF transceiver, as the next example illustrates.

6. Qualcomm's MDMs (Mobile Data Modems) (8)

Example of an MDM (Qualcomm's MDM2000 of the Gobi family (2008)) [33]

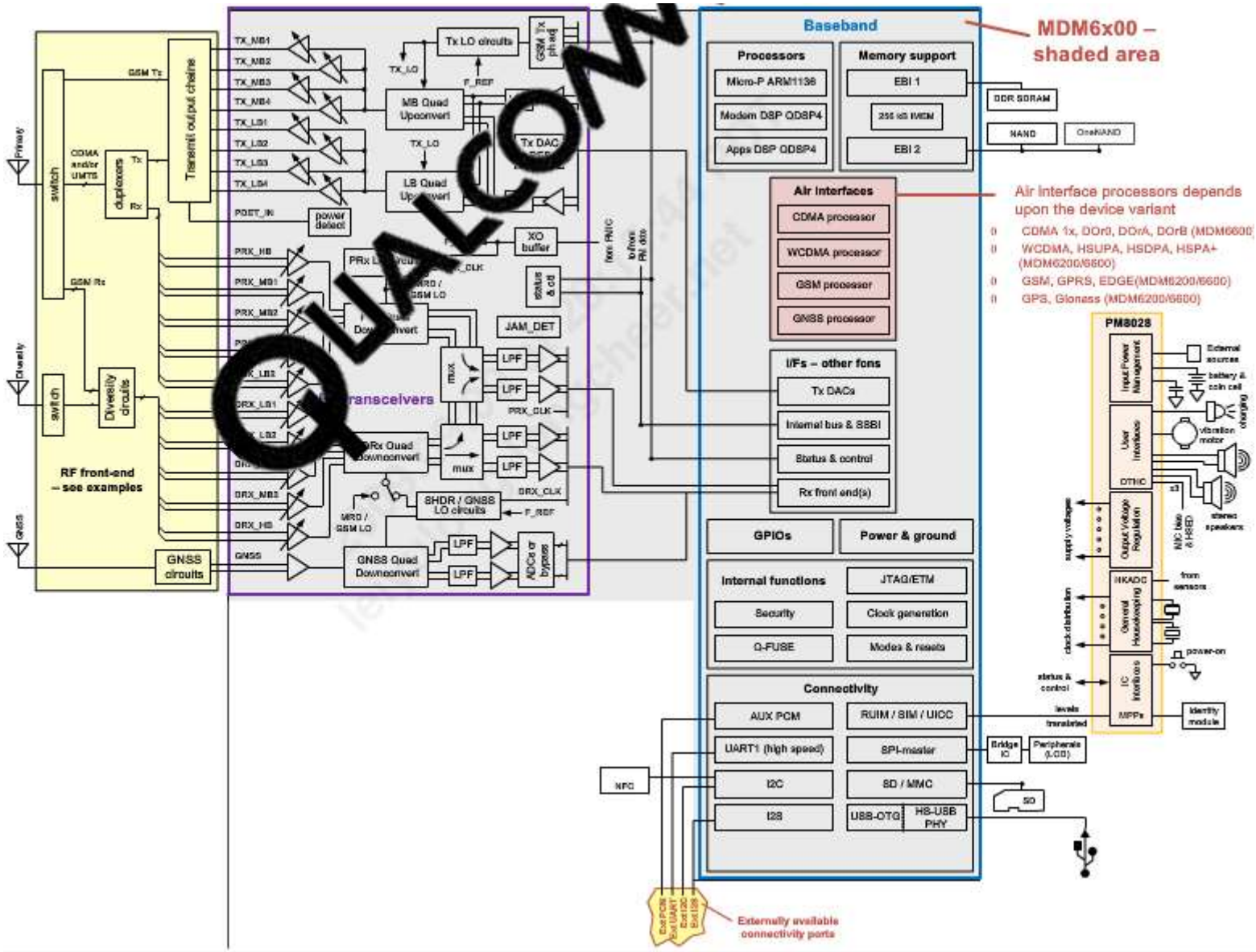


Single chip implementation of the MDM 6200/6600 models [34]

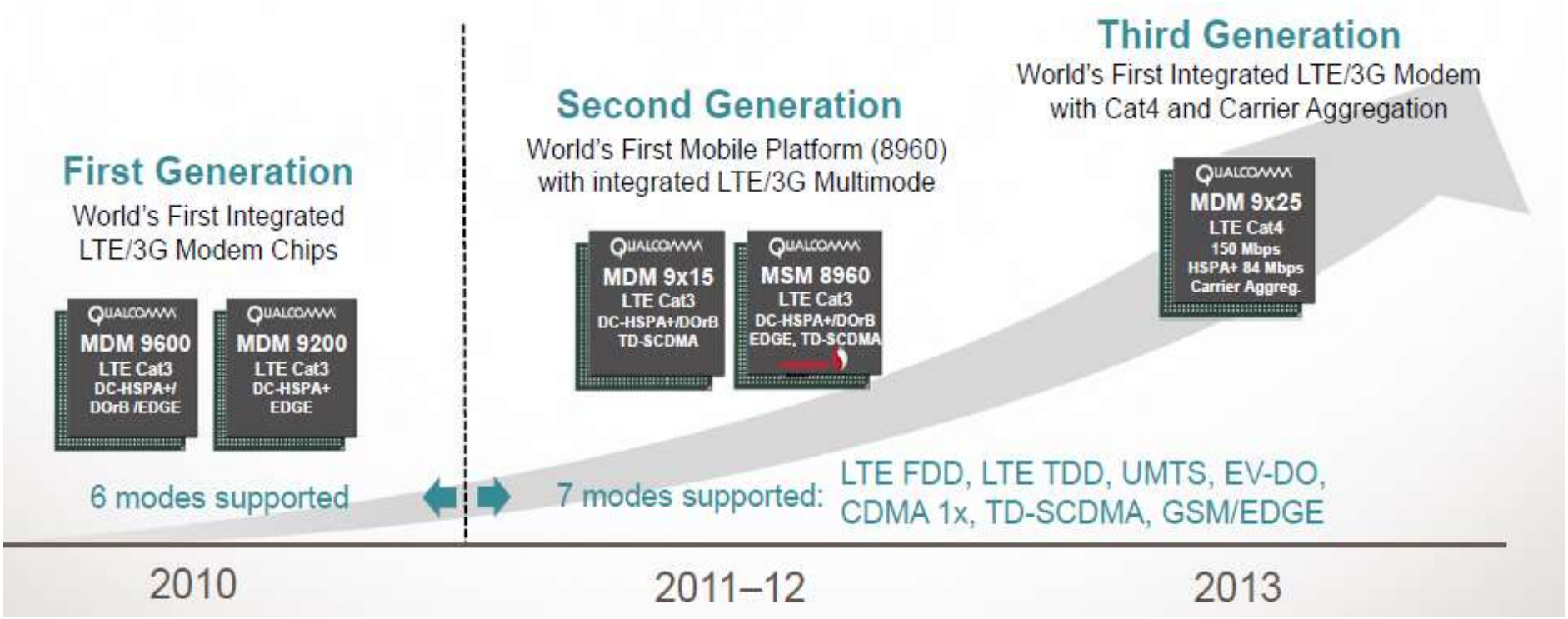
The MDM 6200/6600 models (2009) represent an exception, as these models, it integrates both the RF modem and the RF transceiver, as shown in the next Figure.

6. Qualcomm's MDMs (Mobile Data Modems) (10)

The MDM 6200/6600 models (2009) [34]



Evolution of Qualcomm's LTE modems [35]



Introduction of the Gobi modem family

- In 10/2007 Qualcomm introduced the Gobi family of mini PCIe modules providing broadband wireless connectivity for mobiles.
- These modules are based on Qualcomm's MDM modems and the firm also provides the drivers needed for specific OSs (like Windows XP, Windows 7 etc.)

Figure: Qualcomm's UNDP-1 mini PCIe module providing wireless connectivity for laptops [36]

Generations of Gobi modems

Until now there are three generations of Gobi modems, as shown below.

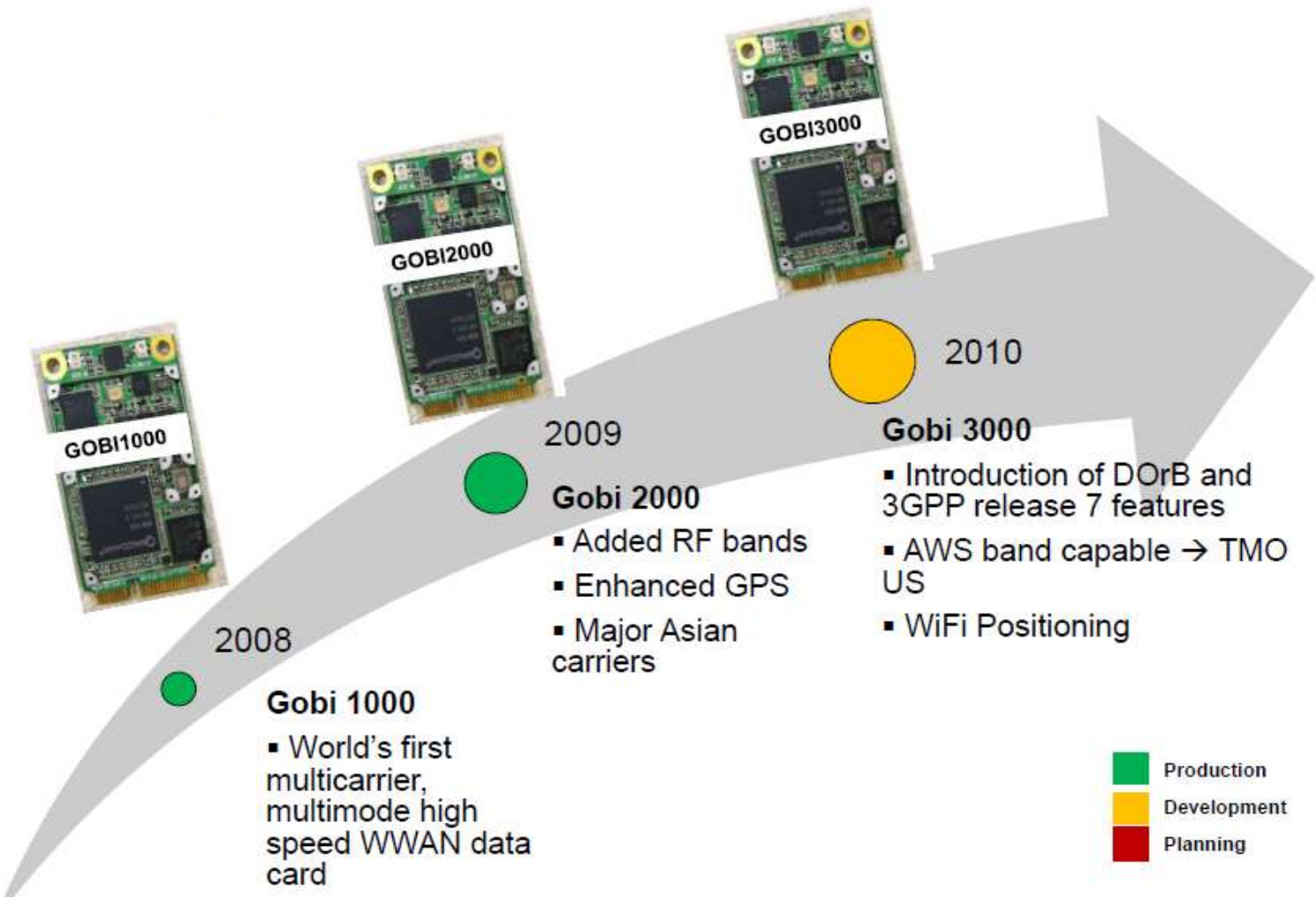


Figure: Three generations of Gobi modems [53]

Main features of the Gobi generations [53]

Features	Gobi 1000	Gobi 2000	Gobi 3000
Package	PCI Express Mini Card – Full Mini	PCI Express Mini Card – Full Mini	PCI Express Mini Card – Full Mini
Modem (2)	CDMA 1x, 1xEVDO Rev A, WCDMA, GSM, GPRS, EDGE, DTM, HSDPA / HSUPA	CDMA 1x, 1xEVDO Rev A, WCDMA, GSM, GPRS, EDGE, DTM, HSDPA /HSUPA	CDMA 1x, 1xEVDO, 1xEVDO Rev A, WCDMA, GSM, GPRS, EDGE, DTM, HSDPA /HSUPA, 1xEVDO Rev B
3G Protocols	3GPP Release 6 DOrA	3GPP Release 6 DOrA	3GPP Release 7: DTX, DRX, Enhanced F-DPCH, Enhanced CELL_FACH DOrB
3G Data Throughput (3)	HSPA: 7.2/2.0 Mbps DOrA: 3.1/1.8 Mbps	HSPA: 7.2/5.76 Mbps DOrA: 3.1/1.8 Mbps	HSPA: 14.4 / 5.76 Mbps DOrB: 9.3 /5.4 Mbps
4G Data Throughput (3)			
Connectivity	USB 2.0 HS Peripheral UICC	USB 2.0 HS Peripheral UICC	USB 2.0 HS Peripheral UICC
GPS (1)	Standalone	Standalone, XTRA, Assisted (V2, SUPL)	Standalone, XTRA, Assisted (V2, SUPL)
OS Support (4)	MS Windows XP, Vista, Linux (limited), Windows 7	MS Windows XP, Vista, Linux, Windows 7	MS Windows XP, Vista, Linux, Windows 7

Notes:

1. Assisted GPS availability varies by network operator
2. 1xEV-DO devices utilize Qualcomm's hybrid mode alternative solution
3. Peak rates: DL/UL
4. Various common Linux distributions available

Designation of the chips underlying the Gobi modem generations

Gobi generation	Gobi designation	Underlying chip
First generation	Gobi1000	MDM1000
Second generation	Gobi2000	MDM2000
Third generation	Gobi3000	MDM3000

Example: The UNDP-1 Gobi 1000 Module (2008)

- This is the first implementation of the Gobi 1000 family of mini PCIe mobile broadband (WWAN) modules.
- It was specifically developed for HP laptops.
- It is based on Qualcomm's MDM 1000 chip and supports all actual 2G to 3G standards, such as
  - EV-DO Rev.A/1xRTT
  - HSPA and
  - GSM/GPRS/EDGE,

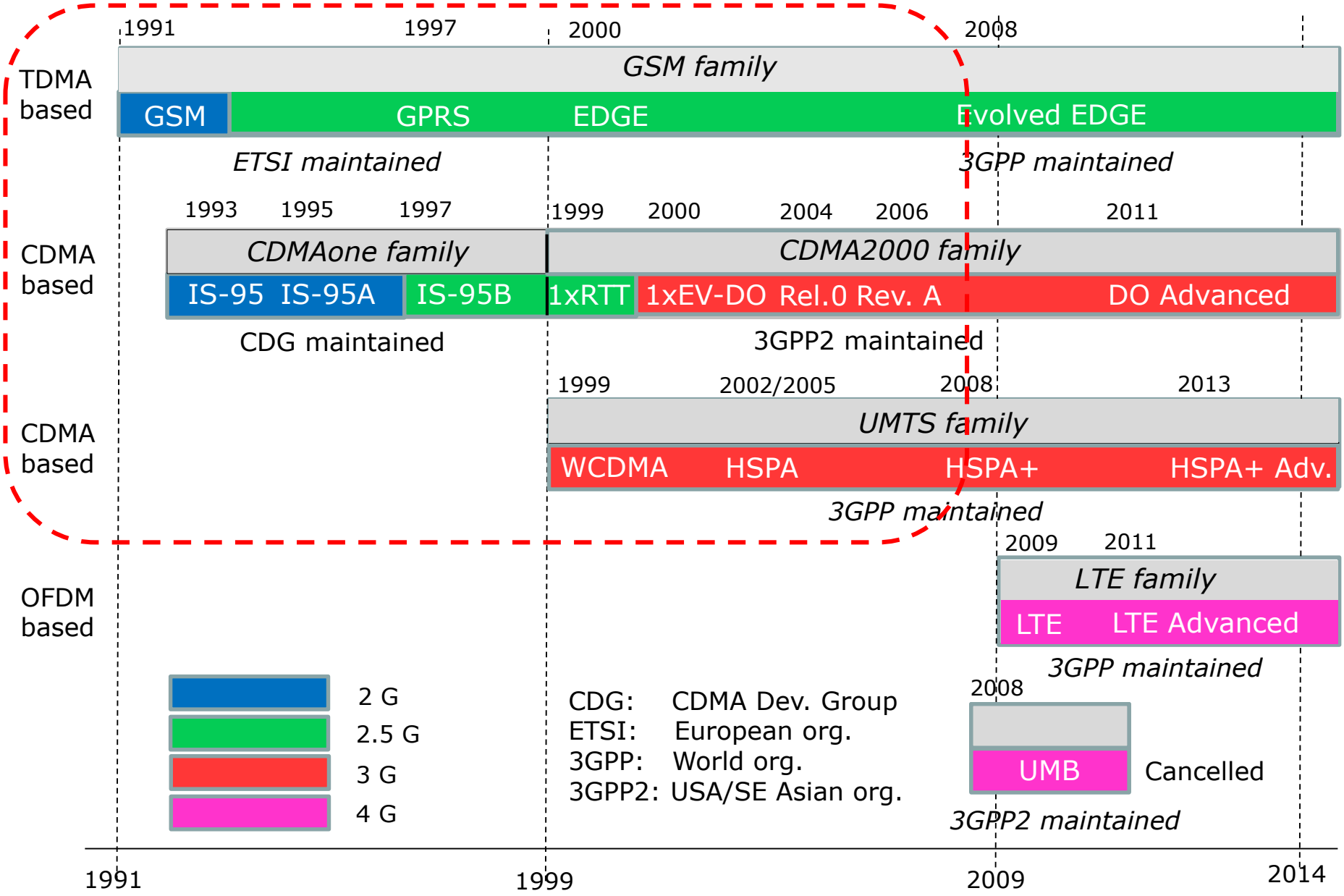
  as indicated in the next Figure.

Figure: Qualcomm's UNDP-1 mini PCIe module providing wireless connectivity for laptops [36]

UNDP: Universal Notebook Data Platform

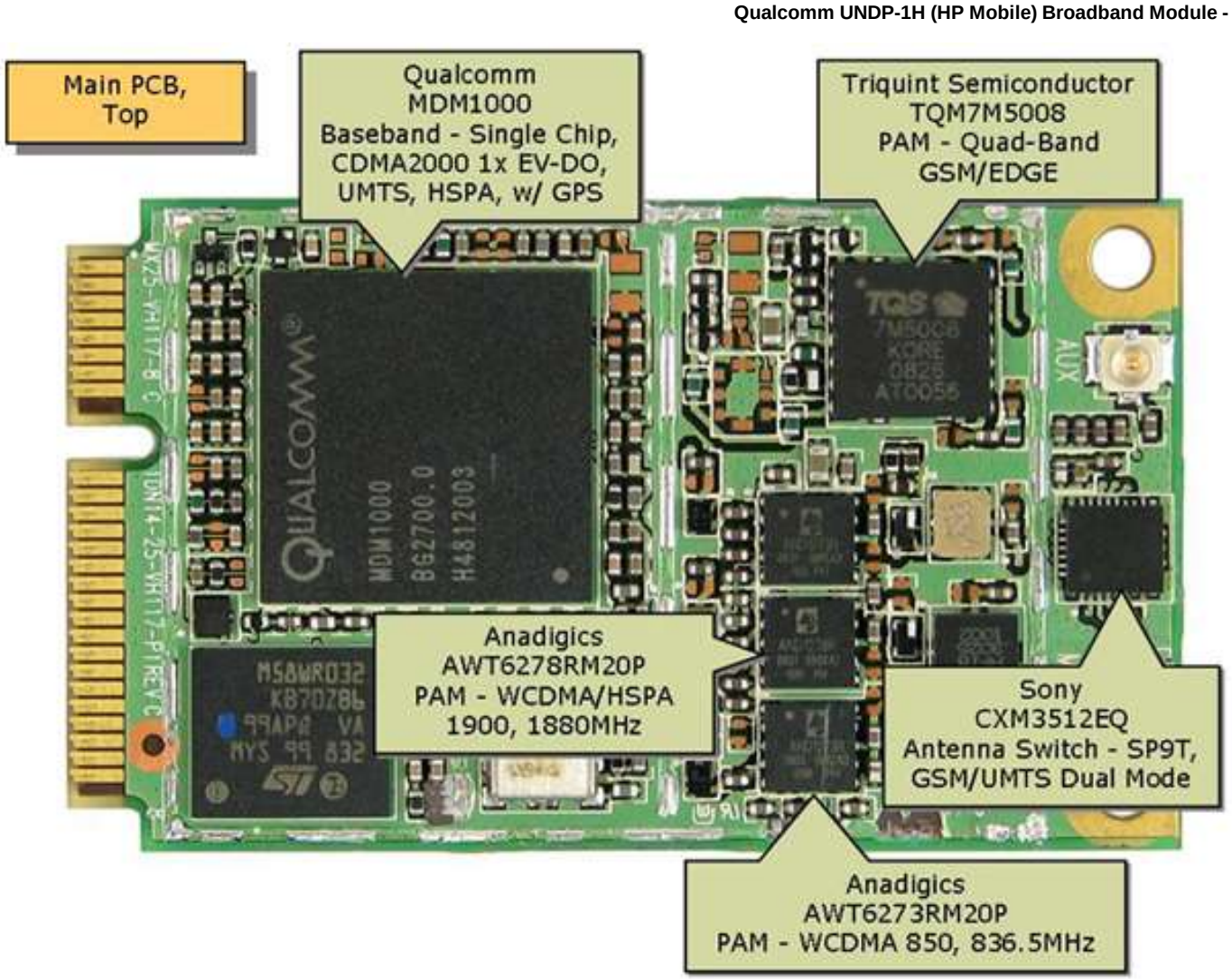
6. Qualcomm's MDMs (Mobile Data Modems) (17)

Overview of the approved main mobile broadband standards (2G to 4G)



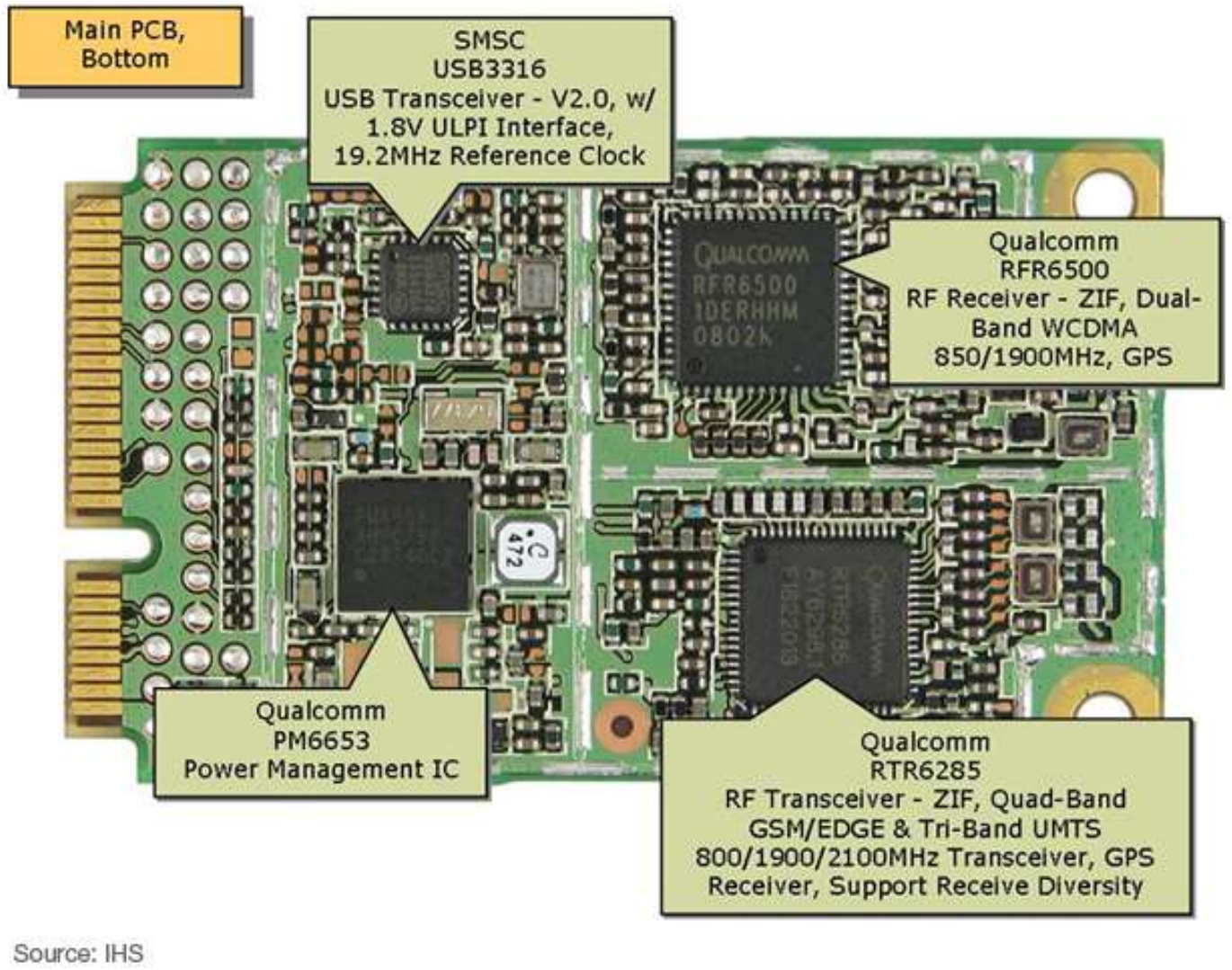
6. Qualcomm's MDMs (Mobile Data Modems) (18)

Top view of the UNDP-1 mobile broadband module of the Gobi1000 line [36]



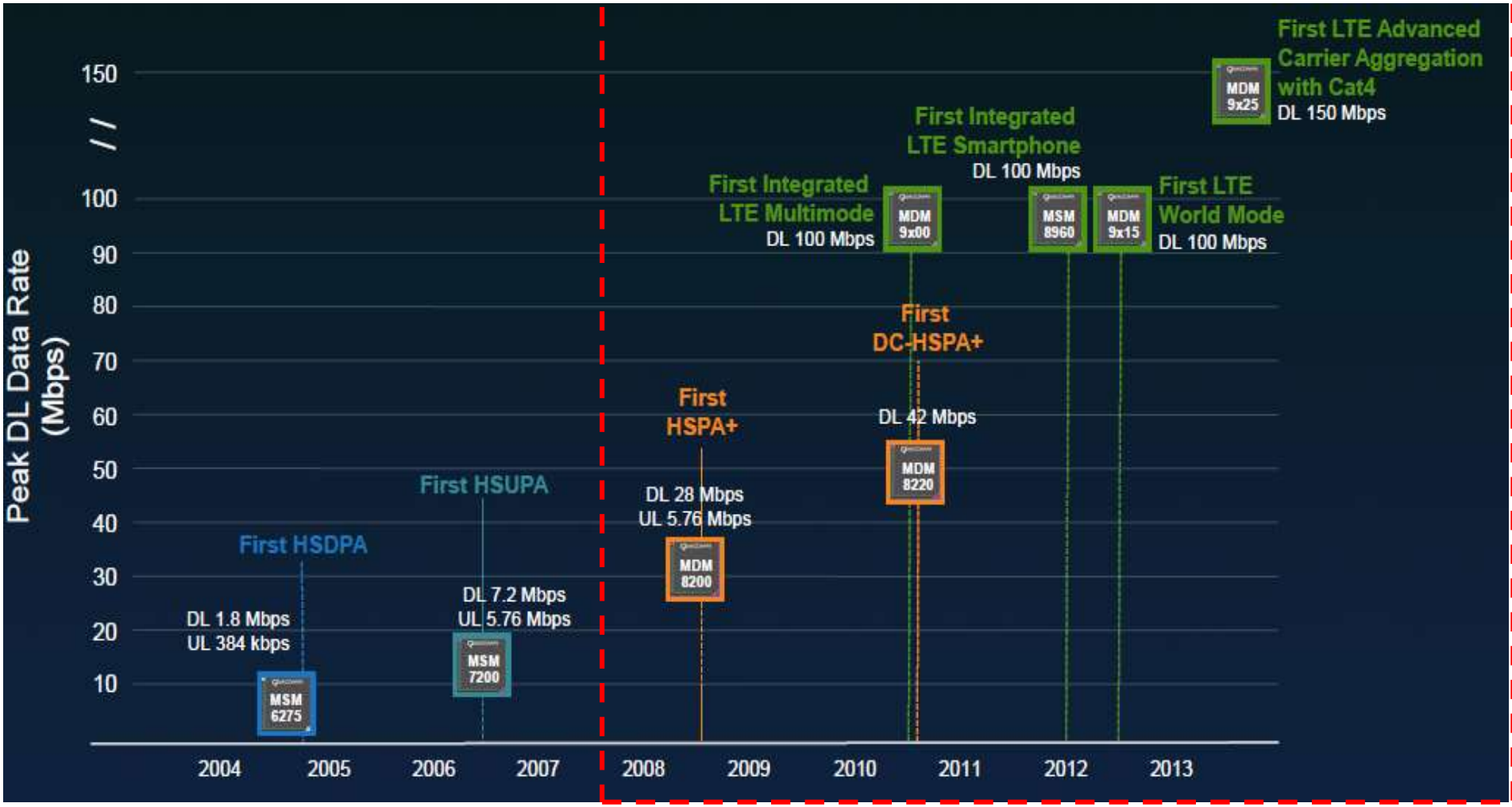
6. Qualcomm's MDMs (Mobile Data Modems) (19)

Bottom view of the UNDP-1 mobile broadband module of the Gobi1000 line [36]



6. Qualcomm's MDMs (Mobile Data Modems) (20)

Subsequent evolution of the Gobi modems [26]



6. Qualcomm's MDMs (Mobile Data Modems) (21)

Main features of Qualcomm's Gobi modem chips [37]

3G	Modem	Peak Data Rates
MDM6600	HSPA+, GSM/GPRS/EDGE, CDMA 1x, EV-DO Rev. A/B	Up to 14.4Mbps
MDM6270	HSPA, GSM/GPRS/EDGE	Up to 3.6Mbps
MDM6200	HSPA+, GSM/GPRS/EDGE	Up to 14Mbps
MDM8200A	HSPA+, GSM/GPRS/EDGE	Up to 28Mbps
QSC6270	HSPA, GSM/GPRS/EDGE	Up to 3.6Mbps
QSC1105	CDMA 1x, EV-DO, GSM/GPRS/EDGE	Up to 153Kbps

3G+/4G	Modem	Peak Data Rates
MDM8225	Release 9 HSPA+, GSM/GPRS/EDGE, EGAL	Up to 84Mbps
MSM8215	Release 8 DC-HSPA+, GSM/GPRS/EDGE	Up to 42Mbps
MDM8220	Release 8 DC-HSPA+, GSM/EGPRS	Up to 42Mbps

4G LTE	Modem	Peak Data Rates
MDM9615	World Mode (LTE FDD/TDD CAT 3, SVLTE-DB, Release 8 DC-HSPA+, TD-SCDMA, GSM/GPRS/EDGE, EGAL, 1x Adv., EV-DO Rev. A/B)	Up to 100Mbps
MDM9215	LTE FDD/TDD CAT 3, SVLTE-DB, Release 9 DC-HSPA+, TD-SCDMA, GSM/GPRS/EDGE, EGAL	Up to 100Mbps
MDM9600	World Mode (LTE FDD/TDD CAT 3, SVLTE-DB, Release 8 DC-HSPA+, GSM/GPRS/EDGE, EGAL, 1x Adv., 1x EV-DO Rev. A/B)	Up to 100Mbps
MDM9200	LTE FDD/TDD CAT 3, SVLTE-DB, Release 8 DC-HSPA+, GSM/GPRS/EDGE, EGAL	Up to 100Mbps

4G LTE Adv	Modem	Peak Data Rates
MDM9625	World Mode (LTE Adv. Cat 4, LTE FDD/TDD CAT 3, SVLTE-DB, Release 10 HSPA+, TD-SCDMA, GSM/GPRS/EDGE, EGAL, 1x Adv., EV-DO Rev. A/B)	Up to 150Mbps
MDM9225	LTE Adv Cat 4, LTE FDD/TDD CAT 3, SVLTE-DB, Release 10 HSPA+, TD-SCDMA,GSM/GPRS/EDGE, EGAL	Up to 150Mbps

6. Qualcomm's MDMs (Mobile Data Modems) (22)

Qualcomm's latest Gobi model [57]

- In 11/2014 Qualcomm announced its fifth-generation LTE solution, called the Gobi 9x45, along with the second generation RF Frontend, the QFE3100.
- The 9x45 is the first announced Category 10 LTE cellular modem.
- It provides a download speed of up to 450 Mbps and an upload speed of up to 100 Mbps for both TDD and FDD mode.
- The 9x45 is sampled in 11/2014, and will commercially available in 2015.

7. Qualcomm’s QSCs (Qualcomm Single Chips)

7. Qualcomm’s QSCs (Qualcomm Single Chips)-1

Qualcomm’s main product lines designed for mobiles

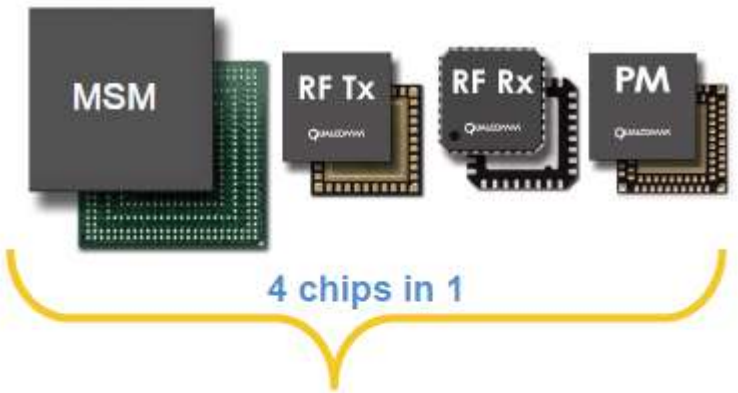
MSMs	**APQs**	**MDMs**	**QSCs**
(Mobile Station Modems) Previous designation: QSD (Qualcomm Snapdragon SOC)	(Application Processors of Qualcomm)	(Mobile Data Modems)	(Qualcomm Single Chips)
Application processors with an integrated modem	Application processors without an integrated modem	Stand alone RF modems, typically without an RF transceiver	SOCs including an integrated application processor, modem and RF transceiver
Since 2007: **Snapdragon platform**			
Typ. use	*Smartphones, tablets*	*WWAN cards , like Gobi WWAN cards, for notebooks, e-readers etc..*	*Feature phones*
Snapdragon S1 – S4 (2007 - 2012) →	**Snapdragon S200 – S800** (2013 -)		

Qualcomm's QSCs (Qualcomm Single Chips)-2

- Typically, Qualcomm provides
  single chip solutions for feature phones,
  termed as QSCs (Qualcomm Single Chips)

- QSCs integrate the functions of
  - MSMs
  - RF Transmitters (RF Tx)
  - RF Receivers (RF Rx) and
  - Power manager ICs (PM)

as illustrated on the Figure left [38].

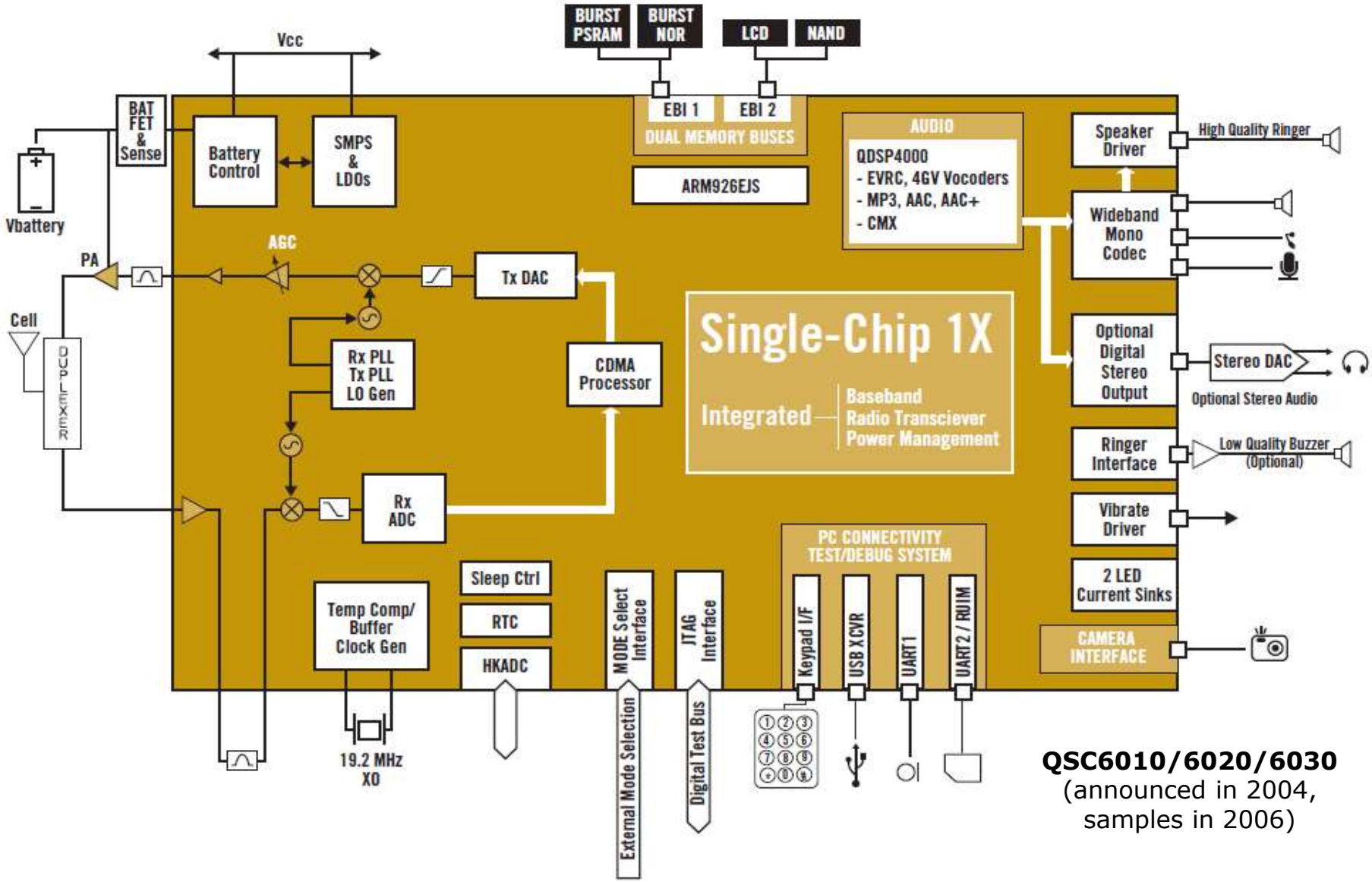


Qualcomm’s QSCs (Qualcomm Single Chips)-3

- Here we do not want to go into details just show an example.
- The example chosen is the Industry’s first CDMA2000 1x single chip solution for the 800 MHz CDMA band (the QSC6010/620/6030), see the next Figure.

7. Qualcomm's QSCs (Qualcomm Single Chips) (4)

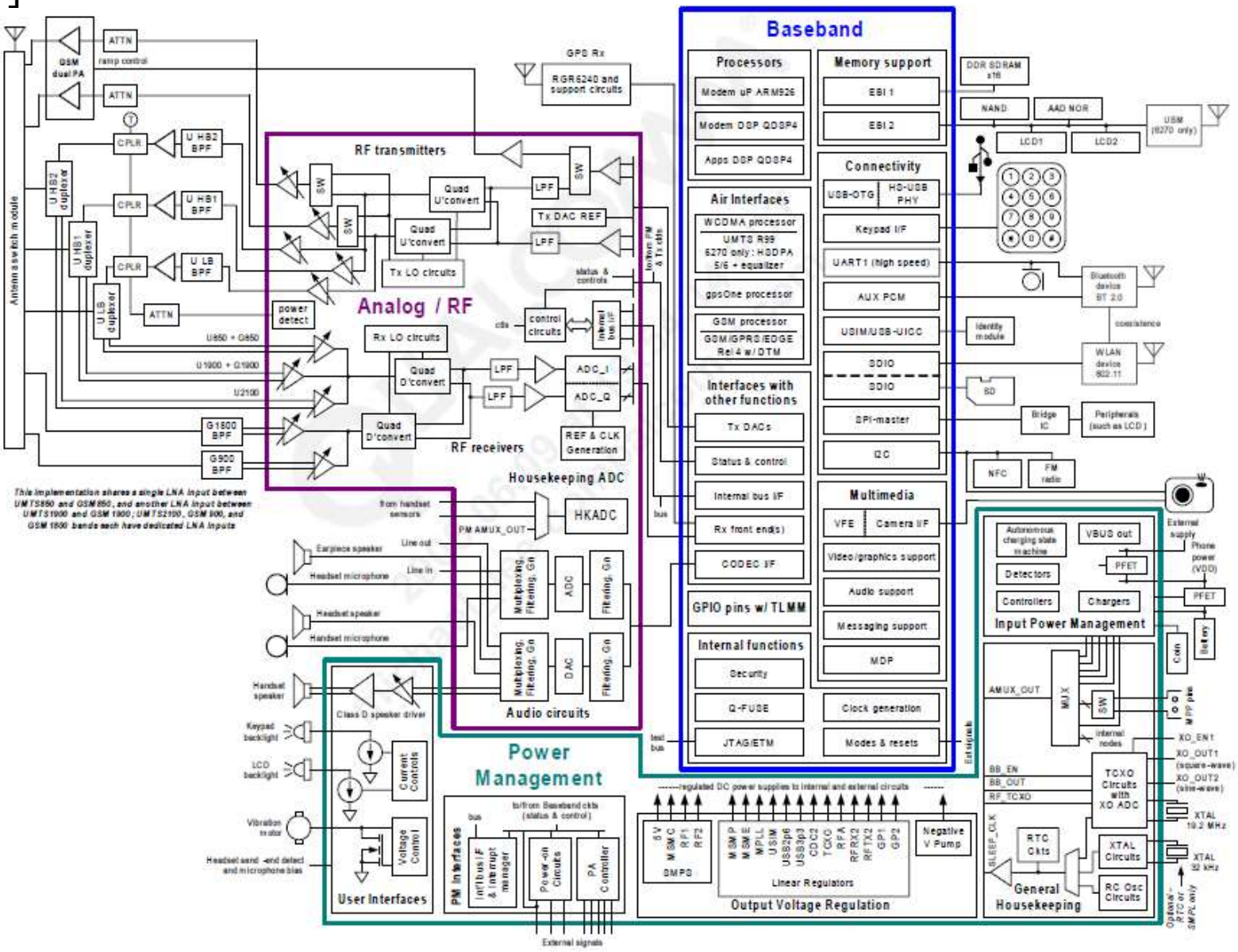
Example 1: Qualcomm's first gen. single chip solution for feature phones (the QSC60x0) (2006) [39]



QSC6010/6020/6030
(announced in 2004, samples in 2006)

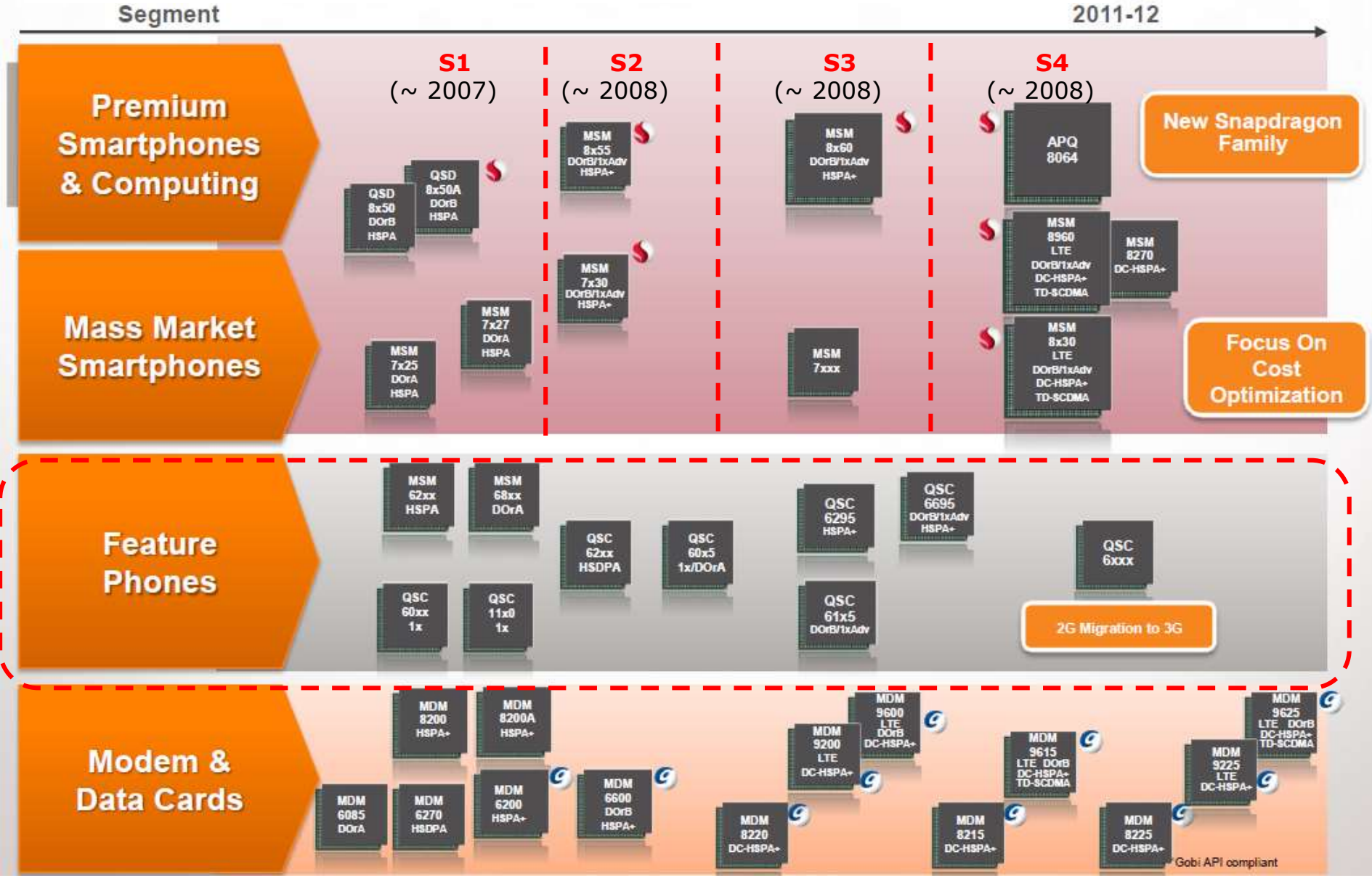
7. Qualcomm's QSCs (Qualcomm Single Chips) (5)

Example 2: Single chip feature phone based on the fourth gen. QSC6240 (2007) [40]



7. Qualcomm's QSCs (Qualcomm Single Chips) (6)

Qualcomm's early QSCs for single chip feature phones [45]



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