Definitions of RF receiver channels and coil density

Mathias Blasche, MSc.

Siemens Healthineers, Erlangen, Germany

Introduction

The number of RF receiver channels is one of the key purchasing criteria. Multi-channel RF systems offer clear clinical benefits with regard to coverage, image quality, and speed. Multi-channel RF technology started in the early 1990s with typically 4 RF channels. Nowadays, systems with 16 to 32 independent channels are seen as "standard mid-class", while even 128 independent channels are available for high-end research scanners.

In the past, there used to be a common understanding about the definition of a "receiver channel". Unfortunately, this is no longer the case. There are numerous different definitions from different vendors, and many of them are not comparable. For example, the number of ADCs (analog-to-digital converters) is not a relevant definition for "channels" if many of the digitized signals are discarded and are not used for the reconstruction of the final image. As another example, the broadband capabilities of fiber optic cables are not relevant if there are limitations in the number of channels that can be processed in the given architecture and especially if there are limitations in the number of available coil connectors.

We therefore want to propose two definitions for RF receiver channels that should be considered relevant in this context. The definitions are relevant because they are clearly connected to relevant clinical benefits. These definitions will be explained in chapters 1) and 2).

From a clinical perspective, the RF system is only as good as the coils that utilize the available receiver channels. Also for coils, we are seeing different definitions for the "channel count" from different vendors. In the third chapter, we will therefore look at meaningful definitions of "coil density" that are linked to the relevant clinical benefits.

1. Channels that can be connected simultaneously

Definition 1:
Number of channels[1] that can be connected simultaneously.

This definition mainly depends on the available coil connectors:

- How many coil connectors are available?
- How many coil channels can be plugged into each coil connector?

The number of channels that can be connected simultaneously via the available coil connectors is important for the clinical benefits of coverage and flexibility.

[1] A coil consists of coil elements. If the signal from each coil element is processed via a separate channel, i.e. if there is a 1-to-1 relationship between elements and channels, one can also call it "channels". Note that it is in principle possible to combine several coil elements to fewer channels, but then most clinical benefits are lost.

[2] This definition of independent receiver channels was inspired by a definition by Allen D. Elster: "Channels are independent, complete electronic chains required for processing information received from a coil segment. Channels include amplifiers, filters, analog-to-digital conversion circuitry, demodulation/mixer devices, and image processing capability. The output of each channel is generally a partial view of the entire anatomy being imaged, subsequently combined with output from the other channels to produce the final MR image." (http://mriquestions.com/array-coils.html)

[3] SNR = signal-to-noise ratio. A higher number of independent channels (i.e. partial images) will increase the average SNR of the image, due to higher SNR in the image periphery close to the coil windings. When using parallel imaging, the SNR gain will be even more pronounced, as the g-factors (also in the center of the coil) will be better. Coil geometry will also play a major role for the SNR but is independent of channel count and therefore not discussed here.

[4] This includes the possibility to achieve higher acceleration factors in SMS (Simultaneous Multi-Slice) scanning.

[5] Note: There is no need for a separate reconstructor for each signal, but the designated reconstructor must be scaled with the available number of channels to be able to handle the image reconstruction load of the multiple receive channels in an acceptable time.

Clinical benefits:

- **Coverage:** Multiple coils can be connected for large anatomical coverage, for multi-station imaging with an extended field of view (e.g. thorax-abdomen-pelvis), up to whole-body imaging
- **Flexibility** in the choice of coils. Multiple coils can be connected also when using high-density coils.

2. Channels that can be used simultaneously

Definition 2:
Number of independent receiver channels that can be used simultaneously in one single scan and in one single FOV, each generating an independent partial image[2].

The important aspect of this definition is that the whole receiver chain is taken into account, from the coil element to the "partial image". Only this definition is tied to the relevant clinical benefits.

Clinical benefits:

- **Higher image quality**, i.e. higher SNR[3] due to the simultaneous (!) use of multiple independent channels in one single FOV and in one single scan
- **Higher speed** due to higher possible PAT factors (higher acceleration factors[4]) – the g-factors are better when multiple independent channels are used simultaneously

Figure 1 shows a coil with one element (and integrated preamplifier) connected to the whole receiver chain of one individual receive channel. The complete receiver channel consists of:

- the ADC (analog-to-digital converter) for the digitization of the signal that comes from the coil
- a digital receiver for further processing of the signal in the digital domain
- the reconstructor[5], i.e. the computer that calculates the final image
- the resulting partial image for each independent channel

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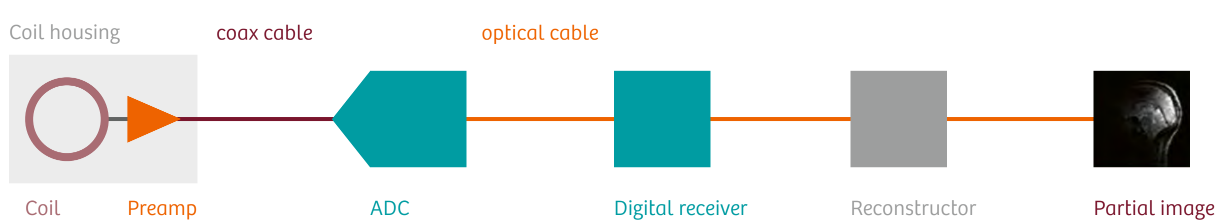

Figure 1:
Complete receiver chain from the coil element to the generation of an independent partial image per coil element.

All the partial images from a multi-channel coil are combined to produce the final image as illustrated in Figure 2 for the example of a Head/Neck 64 coil with 64 independent channels.

It should be noted that the ADC is only a part of the whole receiver chain. If many digitized signals (from coils outside the FOV) are discarded after digitization and do not result in partial images, they do not provide any clinical benefit.

The higher the number of independent receiver channels (according to definition 2), i.e. the higher the number of partial images, the higher the clinical benefits (image quality and speed) will be.

Both channel definitions, by the way, are covered in the "Tim nomenclature" that we have been using since 2003 to describe our RF system configurations. Tim [204x48], for example, means that we can connect up to 204 coil elements/channels[6] simultaneously (according to definition 1), and that up to 48 independent receiver channels can be used simultaneously (according to definition 2).

[6] With most Tim 4G systems, there is a clear 1-to-1 relationship between coil elements and independent receiver channels; each coil element is processed via a separate independent channel. For these systems, the terms "coil elements" and "coil channels" can be used interchangeably. For Tim systems with a Mode Matrix, the highest mode also results in an identical number of coil elements and independent receiver channels.

2

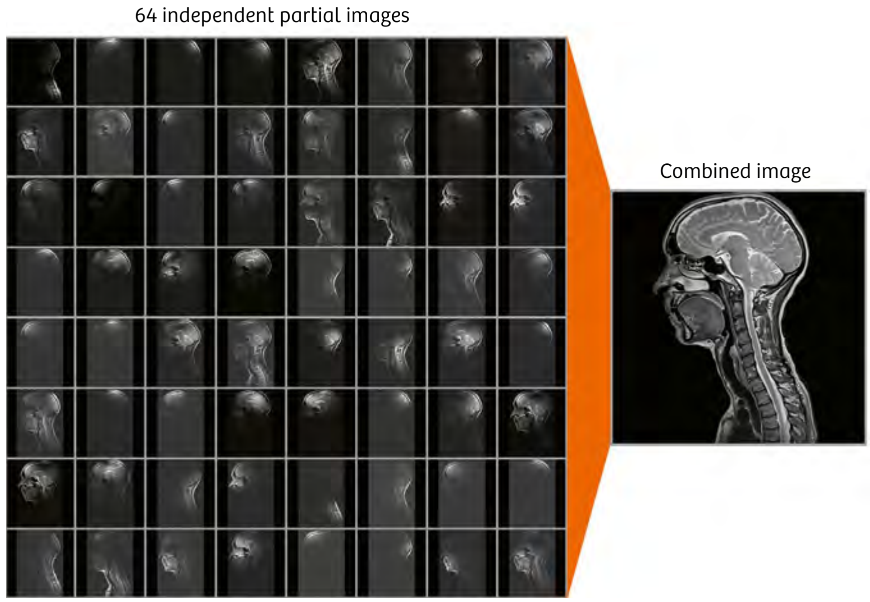

Figure 2:
Depiction of the 64 partial images obtained with the Head/Neck 64 coil. Measured with a Tim [204x64] system with 64 independent receiver channels that can be used simultaneously in one single scan and in one single FOV, each generating an independent partial image.

Figure 3 shows the two channel definitions and the respective clinical benefits in a summary.

An additional benefit which is often seen in a high number of independent receiver channels (right side in Figure 3) is **future security** – having no limitations by the number of independent channels for purchasing (future) high-density coils. This is a valid point. However, some additional aspects are relevant in the context of future security:

- In the past, RF channels used to be extremely expensive, while low-density coils were relatively cheap in comparison. This has changed: An ultra-high-density coil (such as a 64-channel coil) can actually be more expensive than a channel upgrade. Therefore, the coils themselves (and their respective coil densities, see chapter 3) should not be neglected in comparison to the channel count of the system.
- The coil connectors (see chapter 1) present a natural limitation for the maximum coil density. Only the connectors on one side of the patient table can be used for a single coil, otherwise the coil would require long cables to both ends of the patient table. This is not feasible for clinical use due to patient safety and workflow requirements. If there is not a sufficient

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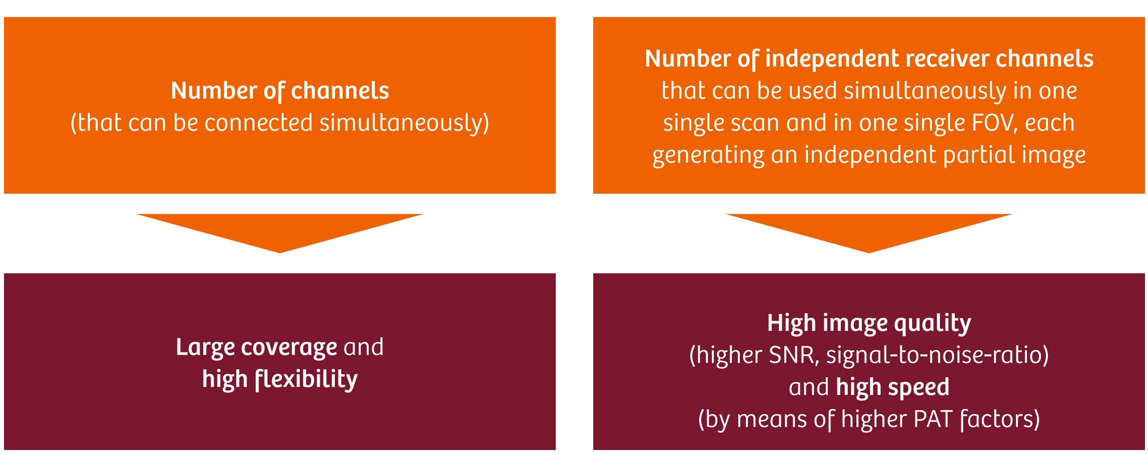


Figure 3:
Summary of the clinical benefits of the two channel definitions.

number of coil connectors, a high-density coil will block too many connectors and will prohibit the use of additional coils for extended coverage.

It should be noted that an exchange of coil connectors will most probably require a change of the whole patient table, besides changes in the overall RF architecture. This would most probably be much more expensive than a channel upgrade. Therefore, the number of connectable channels, as defined in chapter 1, also plays a significant role regarding future security.

3. Coil density

The number of independent receiver channels, as defined in chapter 2, is the upper limit of channels that can be used simultaneously. However, the actual usage of the receiver channels depends on the coils/coil combinations that are available for the diversity of clinical applications.

Therefore, the channel number of the available coils (and coil combinations) is also an important specification for the MR system.

As previously mentioned for the definition of "channels", also the channel count of the coils is defined differently among the vendors, making a fair comparison virtually impossible. Various definitions are used, for example

A. the number of channels of the coil alone, as a hardware entity ("box")

B. the number of channels of the coil in combination with other coils

C. the number of channels of the coil in combination with other coils, adding up multi-station examinations

These different definitions are often non-transparent and can vary by factors, for coils that are actually comparable in clinical use. The clinically most relevant specification is the **coil density** which is closely related to the definition of independent RF channels in chapter 2:

Definition of coil density:
Number of independent channels of a coil (or coil combination) that can be used simultaneously in one single scan for imaging a particular anatomy of interest, each generating an independent partial image.

Only relevant coil channels that contribute significant signal for the anatomy of interest should be counted. Examples for anatomies of interest would be:

- Brain only (without counting channels from a spine coil)
- Head-neck imaging with a specified FOV (up to max. FOV)
- Abdominal imaging with a specified FOV (up to max. FOV)
- Knee imaging (with a knee coil)
- etc.

As an example[7] for the different definitions for the channel count, let's have a look at the Body 18 coil, see Figure 4.

A. The coil alone, as a hardware entity ("box"), has 18 elements = 18 channels.

[7] Example for MAGNETOM Vida with Tim [204x64]. Other systems with a different max. FOV and/or different coil portfolio may result in different numbers.

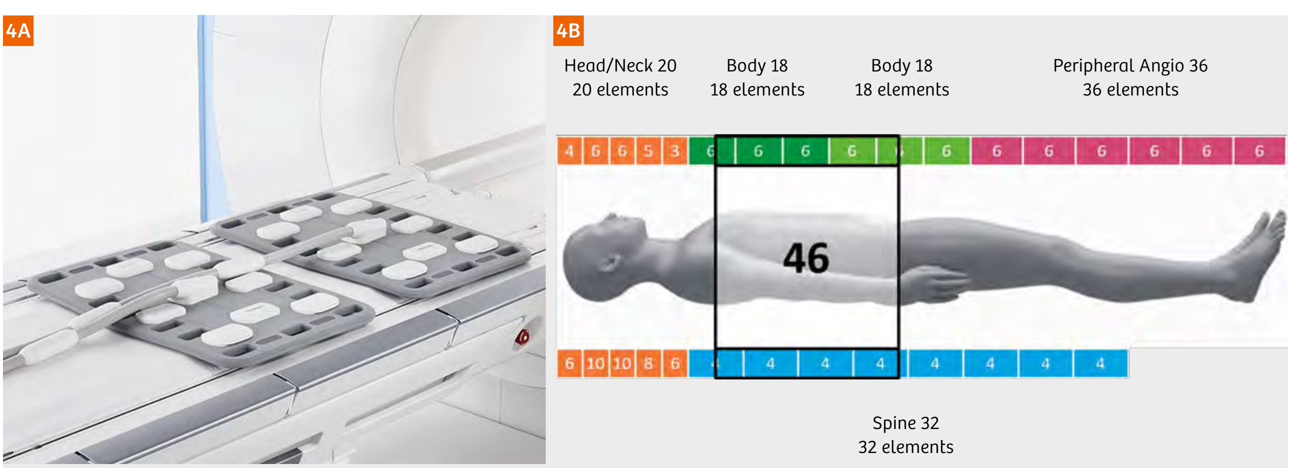


Figure 4:
(4A) Picture of two Body 18 coils on top of the integrated Spine 32 coil. **(4B)** Depiction of the 46 independent channels used in body imaging with max. FOV, as described under B.

B. The Body 18 coil is typically used in combination with the Spine 32 coil: One Body 18 coil in combination with 12 channels from the Spine 32 coil result in 30 channels for a FOV of approx. 35 cm. For the max. FOV of the scanner, 1 ⅔ Body 18 coils and 16 channels from the Spine 32 coil can be used simultaneously in one single scan, resulting in a total of 46 channels.

C. For multi-station examinations, the Body 18 coil can be combined with various other coils, e.g. the Spine 32 coil, the Head/Neck 20 coil or Head/Neck 64 coil, and the Peripheral Angio 36 coil. A multi-step whole-body examination will use up to 168 channels in total (without counting overlaps).

As a second example[8] for the different definitions for the channel count, we show the Head/Neck 20 coil, see Figure 5.

A. The coil alone, as a hardware entity ("box"), has 20 elements = 20 channels, 16 in the head region and 4 in the C-spine/neck region.

B. The Head/Neck 20 coil can be used in combination with the Body 18 coil and the Spine 32 coil: For the max. FOV of the scanner, the Head/Neck 20 coil, 6 channels from the Body 18 coil and 4 channels from the Spine 32 coil can be used simultaneously in one single scan, resulting in a total of 30 channels.

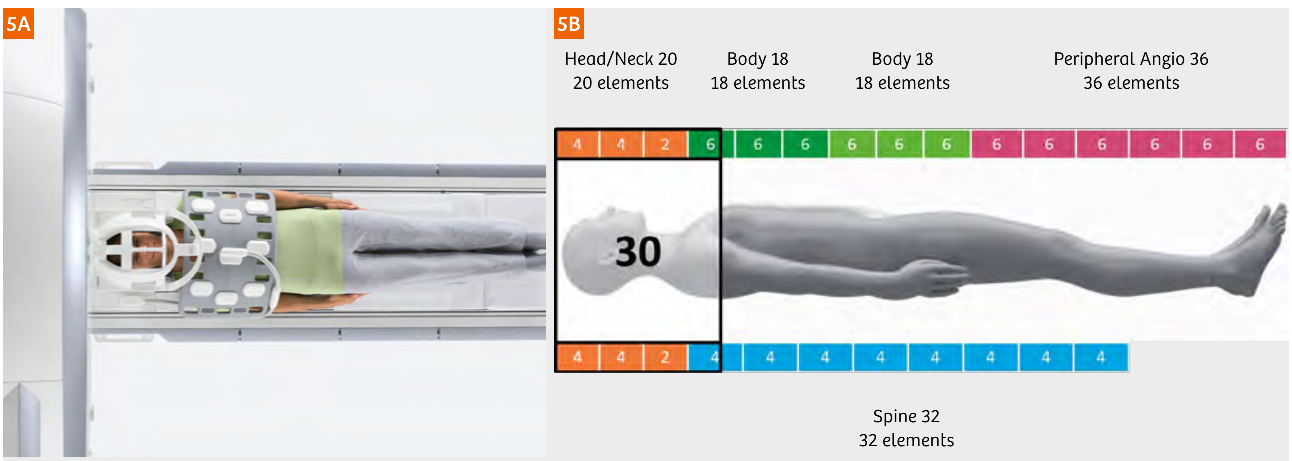
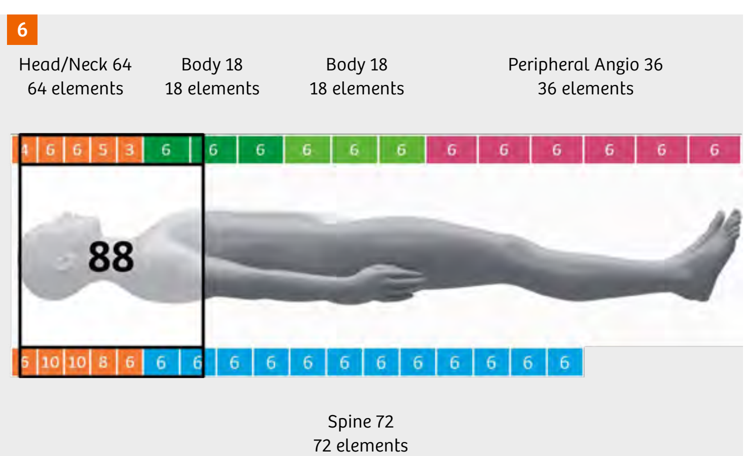


Figure 5:
(5A) Picture of the Head/Neck 20 coil and the Body 18 coil on top of the integrated Spine 32 coil. **(5B)** Depiction of the 30 independent channels used in head/neck imaging with max. FOV, as described under B.

Figure 6:
Depiction of the 88 independent channels used in head/neck imaging with max. FOV, as described under B.



C. For multi-station examinations, the Head/Neck 20 coil can be combined with various other coils, e.g. the Spine 32 coil, 2–3 Body 18 coils, and the Peripheral Angio 36 coil. A multi-step whole-body examination will use up to 124 channels in total (without counting overlaps). Adding a third Body 18 coil (e.g. for obese patients, positioning two Body 18 coils side by side), even 142 channels can be used for a multi-step whole-body examination.

As a third example[9] for the different definitions for the channel count, we look at the Head/Neck 64 coil, see Figure 6.

A. The coil alone, as a hardware entity ("box"), has 64 elements = 64 channels, 55 in the head region and nine in the C-spine/neck region.

B. The Head/Neck 64 coil can be used in combination with the Body 18 coil and the Spine 72 coil: For the max. FOV of the scanner, the Head/Neck 64 coil, 2 x 6 channels from the Body 18 coil and 2 x 6 channels from the Spine 72 coil can be used simultaneously in one single scan, resulting in a total of 88 channels.

C. For multi-station examinations, the Head/Neck 64 coil can be combined with various other coils, e.g. the Spine 72 coil, 2–3 Body 18 coils, and the Peripheral Angio 36 coil. A multi-step whole-body examination will use up to 208 channels in total (without counting overlaps).

All these definitions (A.–C.) for the channel count in the example above are meaningful, but they differ by a factor of close to ten. Transparency is of utmost importance when comparing coils, otherwise it will be a comparison of apples and oranges.

An even better metric would be the **"specific coil density"**, i.e. the number of channels per length of the coil (in z-direction). Examples (both for the anterior coil only):

- For the Body 18 coil, with a length of 38.5 cm, this is **4.7 channels / 10 cm.**
- For the Body 30 coil, with a length of 46 cm, this is **6.5 channels / 10 cm.**
- For the Head/Neck 20 coil, with an "electrical" length of 35 cm, this is **5.7 channels / 10 cm.**
- For the Head/Neck 64 coil, with an "electrical" length of 35 cm, this is **18.3 channels / 10 cm.**
- For the Spine 24 coil, with a length of 120 cm, this is **2.0 channels / 10 cm.**
- For the Spine 32 coil, with a length of 120 cm, this is **2.7 channels / 10 cm.**
- For the Spine 72 coil, with a length of 120 cm, this is **6.0 channels / 10 cm.**

This "specific coil density" is the most relevant measure that should be specified for a coil, being least ambiguous and clearly related to the clinical benefits of image quality and speed.

Summary

We have defined meaningful and relevant definitions for the terms "RF channels" and "coil density" that are clearly related to clinical benefits. This standard should help to achieve a better comparability of RF systems and coils across different vendors.

[8] Example for MAGNETOM Aera and MAGNETOM Skyra with Tim [204x48]. Other systems with a different max. FOV and/or different coil portfolio may result in different numbers.

[9] Example for MAGNETOM Vida with Tim [228x128]. Other systems with a different max. FOV and/or different coil portfolio may result in different numbers.

Contact

Mathias Blasche
Siemens Healthcare GmbH
Karl-Schall-Str. 6
91052 Erlangen
Germany
mathias.blasche@siemens-healthineers.com