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Efficiency in broadcasting
Definition and measurement of transmitter efficiency

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White Paper
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1 Introduction

Broadcast network operators face the challenge of reducing operating expenses even as the cost of electricity increases. This situation has fueled the demand for energy-efficient transmitters over the past few years. Several methods to increase transmitter efficiency are available (see [1]). Doherty technology in particular is an extremely effective measure.

Responding to this situation, various transmitter manufacturers advertise the efficiency of their transmitters. Network operators need both transparency with respect to efficiency values and a means of comparing efficiency across manufacturers. Also of interest are a true assessment of transmitter efficiency during operation as well as an understanding of the many ways state-of-the-art transmitters can optimize efficiency for specific requirement profiles.

In Section 2, this white paper therefore first discusses the various transmitter system levels and parameters that can affect efficiency values. Section 3 addresses application-related aspects of transmitter efficiency measurements. Section 4 briefly summarizes the aspects outside the transmitter that affect efficiency by viewing the system as a whole. Section 5 rounds off the discussion with a historical overview of the continuous improvements made in transmitter efficiency.

2 Different reference levels to define efficiency

In real-world systems, the supplied energy is not fully delivered as usable energy. There is a certain amount of dissipation in the form of mostly unwanted heat. Transmitters generate both the desired RF output power and heat, particularly in the RF power components.

Fig. 1 shows this relationship. Transmitter efficiency is defined as the ratio of average RF output power to the consumed AC effective power.

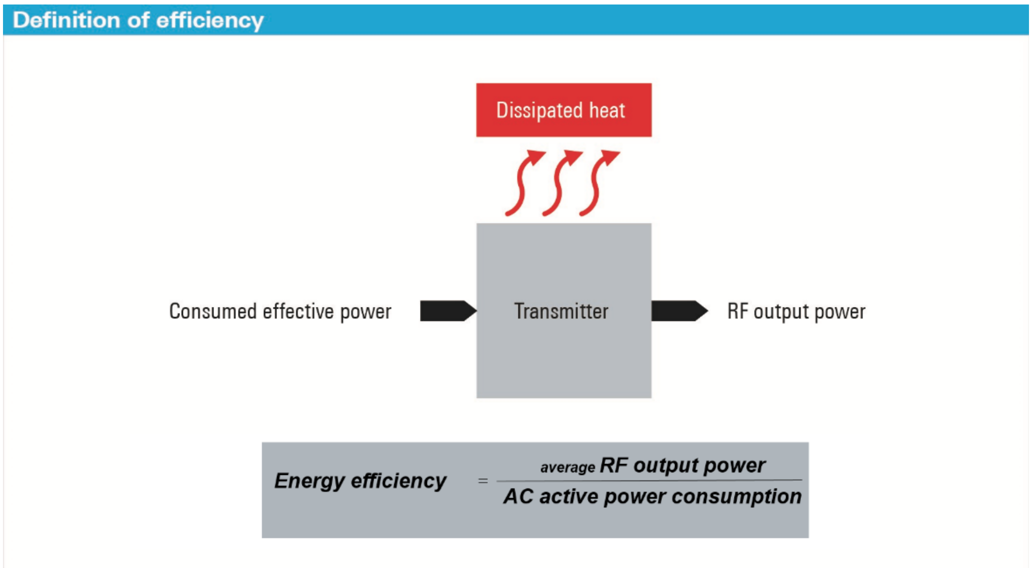

Fig. 1: Definition of transmitter efficiency.

Note that energy efficiency calculation is always a ratio of active powers. The reactive power component of the electrical input is not used in this formula, even though it causes losses in the electrical supply cables. A low reactive power, i.e. a high power factor, is therefore important in practice. However, it is not a key factor in transmitter efficiency.

Efficiency ratings depend a great deal on the considered system components and their related signal parameters, which is explained in more detail in Sections 2.1 and 2.2.

2.1 Influence of considered system components on efficiency values

In a transmitter system, different components are involved in the generation of the broadcast signal. Fig. 2 illustrates these components, starting with signal generation in the exciter, the system control and cooling system and continuing with the RF amplifier modules and RF combiner with a harmonics filter and RF rigid line, and finally the transmitter output. This figure also shows how the calculated efficiency values will have a different point of reference depending on the components considered in the calculation and their power consumption. The figure shows the step-wise extension of the reference levels when specifying efficiency values.

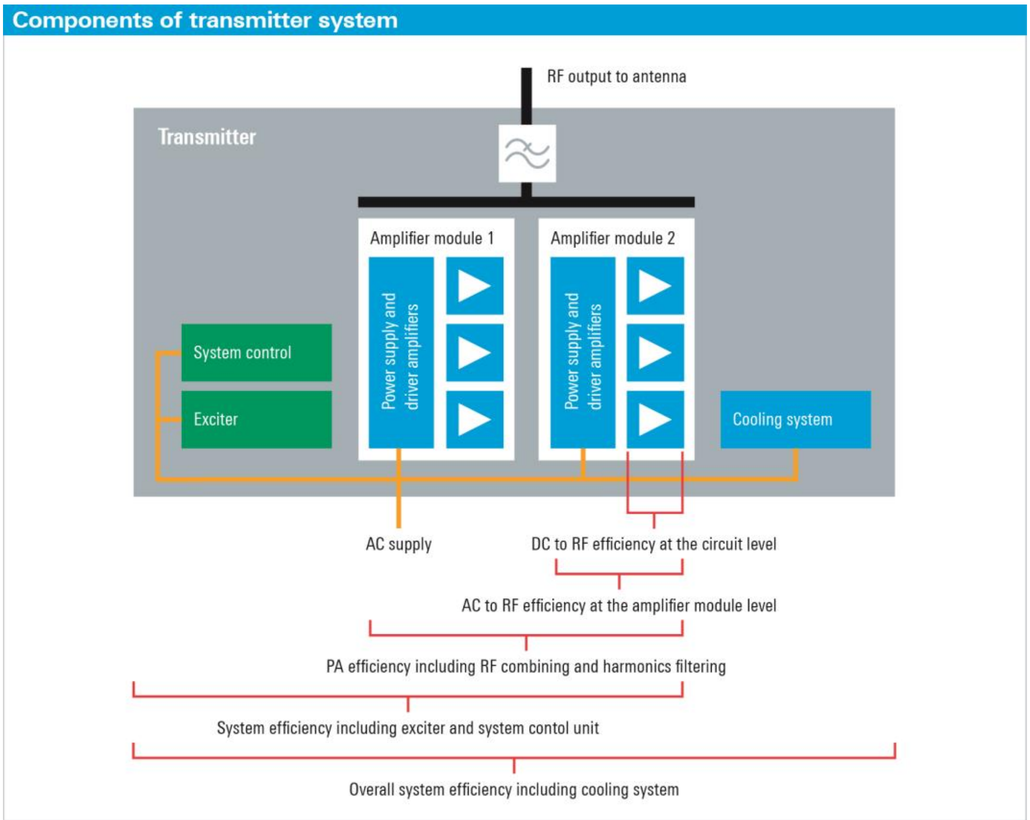

Fig. 2: Efficiency definition related to different system levels

The lowest level is the DC-to-RF efficiency at the circuit level. This value references the smallest unit in the amplifier, typically consisting of a pair of output-stage transistors including the impedance matching network, but not considering the power necessary for control and without any conversion losses from the amplifier power supply. An efficiency value for this level, usually called drain efficiency, offers the highest values because no losses are taken into consideration outside of the impedance matching network and of course the losses in the power transistors themselves. Rohde & Schwarz Doherty UHF amplifiers achieve an efficiency value of up to 52 % at the circuit level for OFDM standards. All efficiency values in this white paper refer to OFDM standards in the UHF band unless otherwise specified.

One level above, the AC-to-RF efficiency at the amplifier module level describes the efficiency of the entire amplifier module. The power of multiple output-stage transistors (transistor pairs) is combined using combiners that are fed via a preamplifier and drivers. Because the generated preamplifier and driver power contributes to the output power to small amount only, the supply power of these components is a significant contributor to amplifier losses. The power is supplied from one or several, usually switch mode, power supplies. The typical efficiency of these supplies is 90 % to 96 %. The conversion losses of the power supplies in the amplifier must also be considered here.

These values can differ significantly depending on the system. This is because many transmitter manufacturers generate the driver power in a separate module for all output stages, and in some cases the power supplies are not part of the output stage. This must be taken into consideration when comparing values. The current generations of Rohde & Schwarz Doherty amplifiers, including the control circuit, driver power and the power supplies, have an overall efficiency of up to 42 %.

Depending on the desired output power, multiple amplifier modules are cascaded via combiners. A highly optimized combiner structure, as found in Rohde & Schwarz transmitters, leads to minimal attenuation. The amplifiers are docked directly to the combiner inputs, so no additional, loss-prone RF connections are needed in between. The PA efficiency, including RF combining and harmonics filtering, for a transmitter with four amplifier modules is about 40 %.

The typical power consumption of an exciter module and a system control module in the transmitter system lies at 200 W. If these components are included in the calculation, then a transmitter with 4.65 kW output power (four amplifier modules) has an efficiency of up to 39 %.

In the final analysis, the complete system must also include the cooling. The power consumption of the cooling system depends on the climatic environmental conditions and the operating conditions for the transmitter. Under normal conditions, the power consumption of the cooling system is about 300 W for a Doherty transmitter with 4.65 kW output power (four amplifier modules). The overall system, including cooling system, therefore has an efficiency of up to 38 %. Fig. 3 graphically shows the relative power losses in the individual system components.

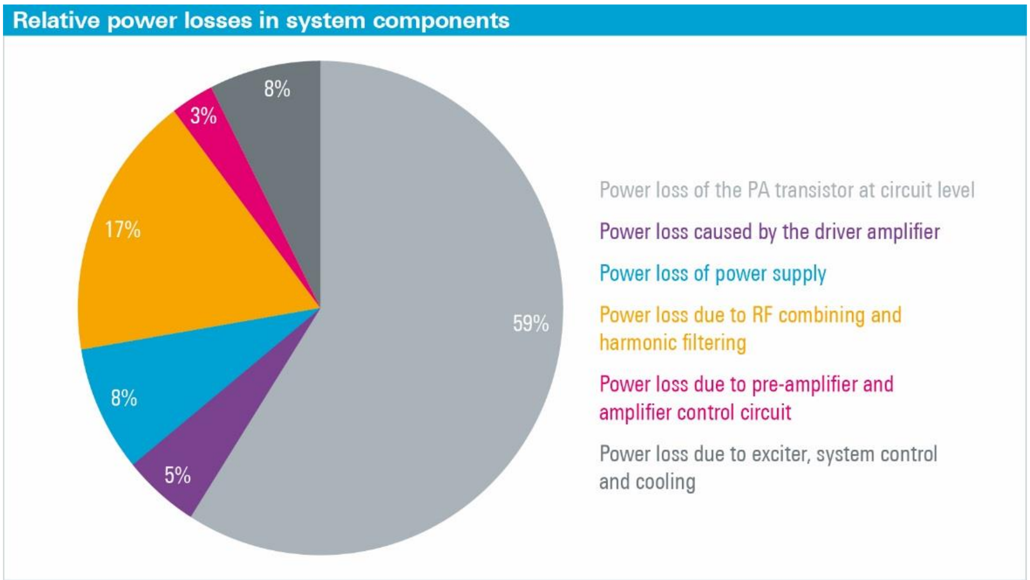

Fig. 3: Relative power losses in system components.

All efficiency values in this section refer to a UHF transmitter, which at nominal power generates a CODFM signal with 37 dB shoulder attenuation and 34 dB MER.

When considering efficiency values, it is important to know what transmitter system components are included. Unless specified otherwise, efficiency values for Rohde & Schwarz transmitters typically are given to the complete system, including cooling.

2.2 Influence of signal parameters on efficiency values

Signal frequency and power level

As indicated in the previous section, various signal parameters influence the efficiency value of a transmitter. Generally speaking, power transistors are more efficient at lower frequencies than at higher frequencies. In addition, the skin effect leads to higher RF losses as the frequency increases. As a result, transmitters for VHF Band III are typically more efficient than transmitters for UHF Bands IV and V. Even within the individual bands, the efficiency is dependent on the frequency. Efficiency can vary by a few percentage points from one channel to the next.

The output power level of the amplifier has a significant effect on efficiency. Maximum efficiency of a conventional amplifier is achieved at maximum output power, when the amplifier is driven in compression. At reduced output power, the efficiency decreases. The goal is therefore to operate the amplifier in the compression range, as it is the case for FM radio with a constant signal amplitude (constant envelope). A DC to RF efficiency of around 80 % is achieved there.

Signal characteristics and transmission standard

In the digital operating modes (DVB-T, ATSC, etc.) on the other hand, the amplitude (i.e. the envelope of the modulated signal) continuously changes. The amplifier must be able to cover the maximum power peaks in order to ensure that the signal is not distorted. This requires, that the amplifiers are operated with an average power far below compression level, leading to significantly lower efficiency compared to FM. For conventional amplifiers, the DC to RF efficiency for digital operating modes is in the range of 30 %. The optimal efficiency is achieved only at the signal peaks, which are relatively rare.

To improve the efficiency, Doherty designs can be used. With a Doherty amplifier, modulation of the load impedance allows optimum efficiency even at a power level well below compression (see [2]). Doherty designs allowed a large improvement in transmitter efficiency compared to a conventional design. An R&S Doherty transmitter has an overall DC to RF efficiency of 52% at circuit level.

The ratio of peak to average power of a signal is specified by the crest factor (see [3] and [4]), which is a key parameter influencing amplifier efficiency. The crest factor of a signal reflects the dynamic range in the amplitude of the signal. To achieve distortion-free amplification, the range in which the power amplifier delivers a linear characteristic must increase as the dynamic range increases. However higher requirements on the linearity of the amplifier mean, that the power transistors must be operated further below the saturation point. This means that for distortion-free amplification of the amplitude response, the efficiency will decrease as the crest factor of the signal increases. Because an ATSC signal exhibits a lower crest factor than an OFDM signal, the efficiency values for ATSC are typically higher. ATSC 3.0 in contrast will be also OFDM-based.

Signal quality requirements

When looking at the signal quality of digital transmitters, the primary parameters taken into consideration are the modulation error ratio (MER) and the shoulder distance. However, the MER and the shoulder distance have influence on the crest factor. A higher MER or a higher shoulder distance also result in a higher crest factor for the signal. This relationship always leads to a compromise between signal quality and efficiency. The MER requirement should therefore not be higher than necessary for a desired coverage area. High signal quality in form of a high MER can be achieved by a high amplifier supply voltage. However, a higher amplifier supply voltage leads to a higher energy consumption and a lower energy efficiency.

A high supply voltage generates greater headroom, which increases the signal quality but leaves much of the energy unused. (The range in which the power transistors provide linear amplification is increased, which means however that they also operate less in saturation.) It is therefore fundamentally desirable to reduce the headroom as far as possible while maintaining the signal quality requirements in order to optimize energy consumption. Fig. 4 shows this relationship graphically. As mentioned in the previous section, Rohde & Schwarz efficiency values for OFDM TV signals are typically given for a 34 dB shoulder distance and 37 dB MER unless otherwise noted. These values represent the typical requirements of network operators. For more information on the definition of the MER, see [3].

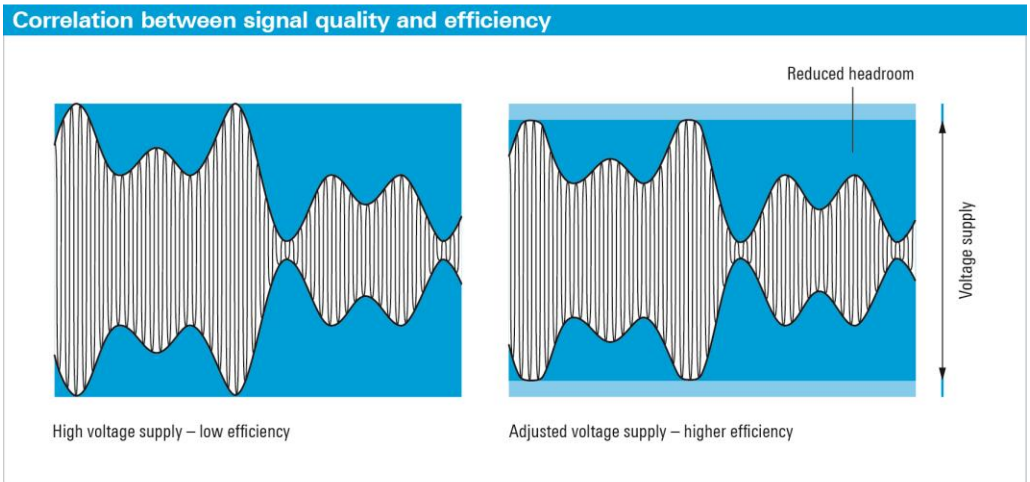

Fig. 4: Correlation between signal quality and efficiency.

Another consideration in the context of the signal quality parameters is operating a transmitter at reduced power. Operating the amplifiers below nominal power provides more headroom and signal quality is improved. However, the amplifier is not operating at its maximum efficiency then. Advanced transmitters such as the R&S Tx9 generation of transmitters allow network operators to adjust the amplifier parameters according to the power level and signal quality requirements. In this way optimal efficiency can be achieved regardless of the requirements. The next section discusses how to measure transmitter efficiency.

3 Conducting efficiency measurements

When measuring efficiency, it is critical that the appropriate T&M instruments be selected to obtain meaningful results. The measurement should be started after the transmitter has warmed up fully. Due to the high thermal time constants, about an hour warm-up time at nominal power is reasonable. The efficiency is determined using the following formula:

$$\textit{Energy efficiency} = \frac{\textit{average RF output power}}{\textit{AC active power consumption}}$$

Using conventional diode sensors to measure RF power with a high crest factor and rapidly changing envelope, e.g. for OFDM-modulated signals, can lead to substantial measurement errors. Sensors that capture the thermal power and have a low fault tolerance are therefore preferred.

Rohde & Schwarz offers the R&S®NRPxx family of sensors that meet these requirements and can be conveniently adapted for connection to a laptop or a tablet. As an example, the measurement uncertainty for an R&S®NRP-Z51 is < 0.082 dB. However, even the sample port itself influences the results. When measuring transmitter efficiency, the directional coupler should lie directly at the transmitter output and the coupling factors of the sample ports must be precisely known.

The AC power consumption should be measured using a mains power analyzer that is able to capture the AC active power with a tolerance of < 1%. Because high-power transmitters typically supply power via a fixed connection, the individual line conductors should be tapped using rigid AC current clamps or for more convenience, flexible Rogowski type AC current probes can be placed directly on the transmitter input connection. Only qualified personnel may perform this measurement because it requires access to the mains connection. In all cases, the instructions in the service manual must be followed. Smaller transmitters can also be measured directly via the power plug.

4 Outlook: efficiency beyond transmitter output

Besides the transmitter itself the remaining components such as channel combiners, mask filters and the antenna interface also impact the system efficiency.

The higher the transmitter efficiency, the more the other system components contribute to the total losses. The mask filters also contribute a sizable percentage of the total losses. An apparent CAPEX savings gained by using a smaller, less expensive filter will result in energy costs many times that of the savings over the service lifetime because the filter's increased insertion loss must be compensated by increasing the output power of the transmitter.

Especially in the case of very exposed transmitter systems with long distance to the antenna, a significant portion of the costly RF power is converted into heat through attenuation in the antenna cable. The losses in the RF cables alone can cost half of the generated transmitter power.

In some cases, the high power density achieved by modern transmitter systems can be used to bring the transmitter closer to the antenna. This can further reduce the transmitter power and increase the overall efficiency.

The formula below can be used to calculate the how much the system efficiency decreases due to insertion loss (IL) between transmitter output and antenna:

$$\eta_{system} = \frac{\eta_{transmitter}}{10^{(IL/10)}}$$

As an example, an insertion loss of 1 dB due to channel combiner, mask filter and cable losses reduces a good overall transmitter efficiency of e.g. 38 % to 30 % efficiency of the complete setup until the antenna.

Fig. 5 graphically illustrates this relationship based on a transmitter efficiency of 38 %.

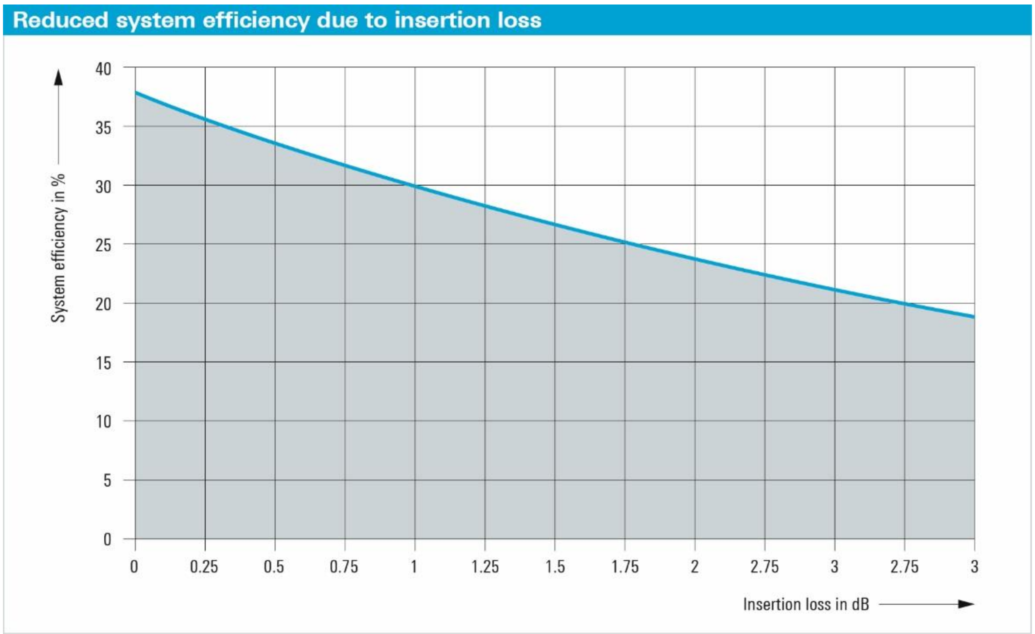

Fig. 5: Reduced system efficiency due to insertion loss.

Instead of considering the investment costs alone, an overall approach that includes the operating costs over the planned service lifetime can show that it pays off to invest in low-loss channel combiners, filters and cables.

5 Progress of efficiency improvements in the broadcasting industry

Efficiency has increased greatly over the past decade as a result of continuous circuit optimizations, and especially due to the rapid advances made in semiconductor technology and new, computationally intensive, predistortion algorithms. The first semiconductor based transmitters in the UHF frequency range were implemented using bipolar transistors with a gain of about 8 dB and a peak power of about 80 W. The required drive power was accordingly high. As a consequence the number of transistors and thus the number of power combiners with their associated losses was much higher than it is for current amplifier technology. State-of-the-art LDMOS transistors have ten times as much gain and ten times as much power capability.

The rising cost of energy is a constant incentive to strive for even better values. The last major leap forward in recent years was achieved by using load modulation, known as Doherty amplifiers. The development of robust LDMOS transistors with high gain combined with cutting-edge circuit topologies has made it possible for this technology – known since the days of the vacuum tube – to experience a successful rebirth in state-of-the-art transmitters.

Fig. 6 shows the increase in efficiency over the years. As mentioned previously, Rohde & Schwarz Doherty transmitters achieve up to 38 % efficiency for OFDM standards, including cooling. Other manufacturers state efficiency values of about 30 % without providing more information about the basis for this value. (see [5])

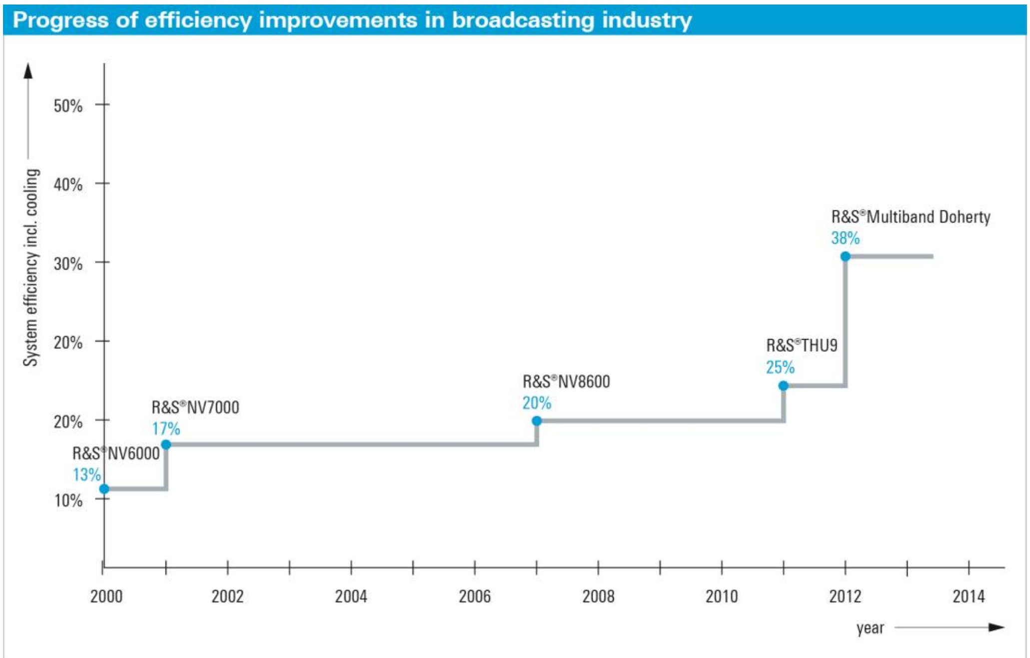

Fig. 6: Progress of efficiency improvements in the broadcasting industry.

6 Conclusion

When comparing efficiency values, it is always important to note which system components are included in the assessment. Even the signal parameters have a considerable influence on the efficiency. The efficiency of today's transmitters can be optimized by adjusting the amplifier parameters to meet the necessary requirements profile. Rapid technological advances have brought about remarkable improvements in efficiency over the past few years. Your local Rohde & Schwarz subsidiary would be happy to help you determine the efficiency of your existing transmitters and show you how much you could save in operating costs by using state-of-the-art transmitter technology. For more information, go to https://www.rohde-schwarz.com/tx9.

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