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# Stabilizing the RF power of transmitters operating in ISM bands

## Application Note

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## **1 Requirements and solutions for stabilizing the RF output power**

Radio links operated in the sub-gigahertz ISM bands are usually subjected to significant field-strength level fluctuations at the receive site, even if the RF power, radiated by transmitter antenna would be held at a steady level. This fluctuation is due to multipath propagation, variations of the path attenuation (at their turn due to changes of the atmospheric conditions), variable antenna to ground distance in case of mobile applications and many other factors like rotation of the antenna polarization plane (especially by handheld applications) or position of the Fresnel zone height (associated to the radio link) versus the ground.

Taking in account the expected magnitude of possible fluctuations a robust radio link should be designed with a certain field-strength margin at receive site.

On the other hand, to avoid strong interferers in the already congested UHF bands and for sake of efficient spectrum usage practically every national and international regulatory specification states a set of requirements for maximum radiated power of intentional transmitters, which have to comply with certain in-band power limits and mandatory spectrum mask or sets of masks (some regulatory specifications take in account the duty cycle of the transmission and apply a certain correction factor for transmissions with low duty cycle, i.e higher pulse peak power is allowed at the cost of the average power, which must be kept however under a prescribed threshold.

At the same time maxima thresholds for the power of unintentional (out of band) radiations are set.

Spurious emissions (harmonics) of the carrier signal and upmixing components (intermodulation products) fall in the class of unintentional transmissions.

To achieve a higher grade of RF output power stability of an RF power amplifier as that subjected to variation of

- load impedance value
- supply voltage
- RF drive level (i.e. the power and voltage level delivered by the RF preamplifier to input of the RF final stage)

there are several means for stabilization of the RF output power.

This may be of particular interest in case of simple reference signal generators, based (as building block) on a low-power RF transmitter, and all those radio links or signal sources, which demand a medium or high-grade stability of the RF power, delivered to load.

This material gives an overview of the feasible methods used for RF power stabilization, with focus on ISM-band transmitters, manufactured by Infineon Technologies AG, but without sole exclusivity on the origin of the transmitter parts. In other words, the described methods and solutions may be applied to third-party transmitters as well.

## **2 General requirements**

Some regulatory standards, like Japan specific ARIB regulatory documents T93; T67; T96 put strict demands on maxima of radiated RF power. Thus RF-power stabilization may have importance for OEMs with focus on Japan in automotive field.

The most popular standard in Japan for RKE and TPMS is the T93 which allows up to -6dBm output power in a frequency band from 312 to 315.05 MHz.

The allowed RF output power is not that impressive in absolute figures but still good enough for the system. Tight link budget restrictions may impose the regulation of the RF-power instead of setting it well below the maxima threshold with a comfortable margin.

For intentional radiators conforming to ARIB T93 regulation only an output power tolerance of +20% or 0.8dB is allowed. Therefore there are strong demands to keep the output power as constant as possible. The decrease of the output power is not regulated within this standard.

Within T67 standard (426 MHz) dealing mainly with non automotive applications, a higher output power is allowed, but center frequency accuracies of 4 ppm or better are required, coupled with tough restrictions regarding adjacent channel emissions. The output power tolerance is in a range of +20% and -50% (+0.8 dB and -3 dB).

Within T96 standard (954 MHz) the output power tolerance of +20% and -80% (+0.8 dB / - 7 dB) is specified, this being a more relaxed requirement.

On the other hand, ISM-band mobile transmitter and transceiver applications are supplied quite often from batteries, which are subjected to

- Gradual decrease of supply voltage (delivered by battery) during battery lifetime.  
This is an irreversible process for the majority of battery types which are in widespread usage recently (lithium, manganese and silver-oxide).
- Temperature dependence of the battery voltage.
- Drop of battery voltage under load conditions (current sourcing) versus non-load condition, due to internal resistance. The internal resistance tends to increase with ageing, i.e. a “used” battery has usually noticeably higher internal resistance as a new one. The ageing is a complex phenomenon and influenced by battery type, storage temperature, remnant capacity (expressed in mAh, as part or percent of initial capacity) and nature of current sourcing load (constant load or short, but more intensive current bursts).

### 3 Feasible solutions

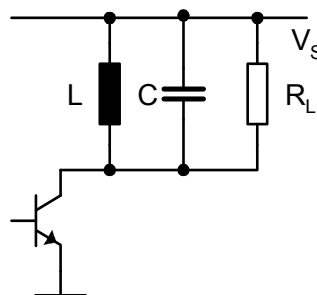
For start let's assume that the RF-power amplifier operates in highly efficient class C mode, as shown in [Figure 3-1](#)

The class C mode is characterized by a pulsed operation of the power amplifier transistor at a current flow angle of  $\varphi \ll \pi$ .

A frequency selective network at the amplifier output passes the fundamental frequency component of the collector current pulse to the load. The higher order components contained in the spectrum of the pulse (harmonics) are attenuated by the mentioned network, but usually not completely suppressed.

The procedure of transforming the load impedance into an equivalent value, as “seen” from the collector circuit of the power amplifier can be generalized based on the equivalent circuit as shown in [Figure 3-1](#).

The tank circuit  $L \parallel C \parallel R_L$  connected in parallel with the output impedance of the transistor should be in resonance at the operating frequency of the transmitter (or on the mean value of the channel frequencies in case of multichannel operation, as in this case different channels have different frequencies assigned).



**Figure 3-1** RF-power amplifier, equivalent tank circuit



The optimum load at the collector of the power amplifier for “critical” operation under idealized conditions at resonance is:

$$R_L = \frac{(V_S^2)}{2 \times P_O} \quad (3.1)$$

The theoretical value of  $R_L$  for an RF output power ( $P_{OUT}$ ) of -6 dBm (0.25 mW) is of 18 kOhms. Keeping in mind the formula [3.1] it is self-understanding that a variation of the supply voltage by a ratio of 2:1 would caused a variation of the RF-power with a ratio of 4:1, if for the transistor in **Figure 3-1** an ideal model is considered.

Referring to class C operation, the critical mode is characterized by the RF peak voltage swing at the collector of the RF power amplifier transistor just reaching the supply voltage ( $V_S$ ) value.

The high degree of efficiency under “critical” operating conditions can be explained by the low power loss at the transistor level itself. During the conducting phase of the transistor, its collector - emitter voltage is very low. This way the power loss in the transistor itself, equaling  $i_C \cdot u_{CE}$  is minimized.

This is particularly true for low conduction angles ( $q \ll p$ ).

In practice the RF-saturation voltage of the PA transistor and other parasitics reduce the “critical”  $R_{LC}$ .

The output power  $P_{OUT}$  is reduced by operating in an “overcritical” mode characterized by  $R_L > R_{LC}$ .

The power efficiency (and the bandwidth) increase when operating at a slightly higher  $R_L$ , as shown in **Figure 3-2**. The collector efficiency  $E$  is defined as:

$$E = \frac{P_O}{V_S \times I_C} \quad (3.2)$$

where  $P_{OUT}$  denotes the RF output power,  $V_S$  the DC supply voltage and  $I_C$  (or  $I_D$ ) the collector current (of bipolar) or the drain current (of CMOS) RF power amplifier stage.

The values shown by **Figure 3-2** have been measured directly at the PA output at  $V_S = 3$  V. Losses in the matching circuit decrease the output power by about 1.5 dB. As can be seen from the diagram in the mentioned example, 250 Ohms is the optimum impedance for operation at 3 V supply voltage.

For an approximation of optimum load impedance ( $R_{OPT}$ ) and RF output power ( $P_{OUT}$ ) at other supply voltages those two formulas may be used:

$$R_{OPT} = K_R \times V_S \quad (3.3)$$

$$P_{OUT} = K_P \times R_{OPT} \quad (3.4)$$

where  $K_R$  and  $K_P$  are mere scaling factors.

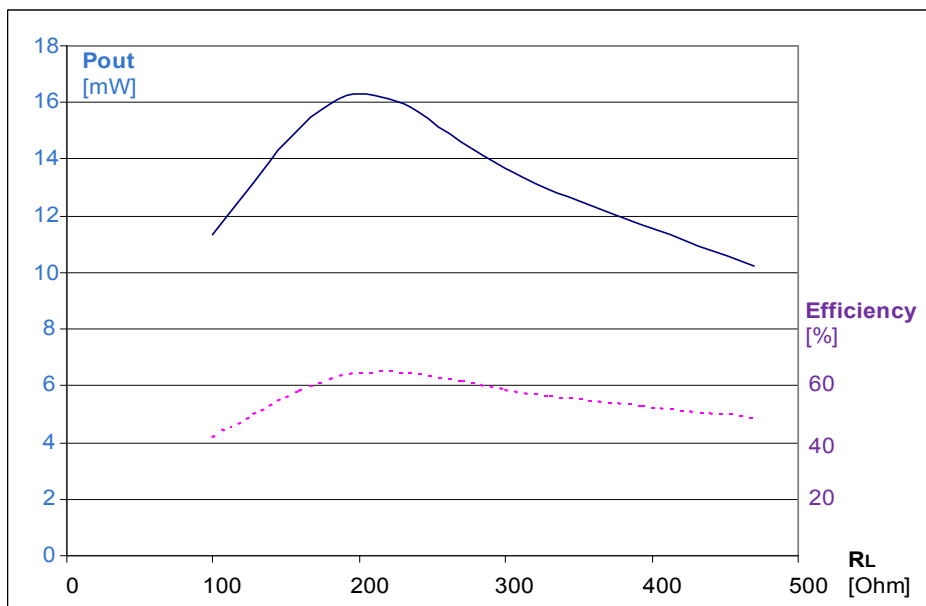


Figure 3-2 RF output power and efficiency of a C class power amplifier, with 10mW nominal output



### 3.1 Regulated supply for the RF power amplifier

This is the most simple solution, based on the assumption that

- if the RF power amplifier is fed by a regulated (stable) supply voltage, and
- the load impedance is constant (i.e. does not change under influence of environmental variations or close-field coupling)

then the RF power delivered by the power amplifier to load is constant, according to [3.1].

The solution is simple and may be very effective in terms of simplicity, especially by low or moderate RF power.

The main drawbacks of the solution are

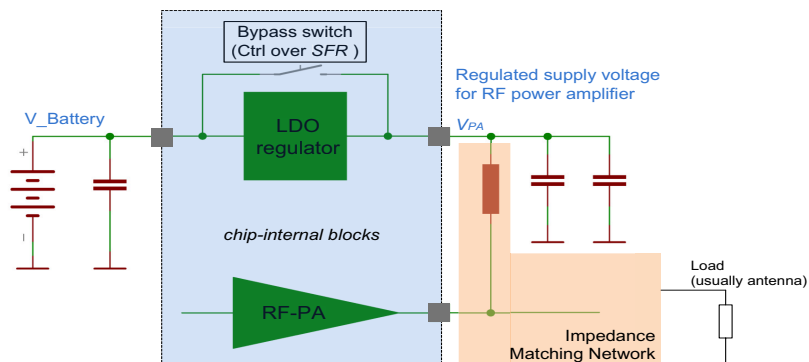
- the regulator (usually a low voltage drop version, denoted LDO in [Figure 3-3](#) causes a voltage drop, decreasing the total efficiency of the system. This may lead to shorter battery life, but for any case diminished battery efficiency.

As a trade-off, the LDO can be either bypassed by a switching element (bipolar or CMOS) actuated by firmware over a Special Function Register bit (SFR) or it can be simply steered into saturation below a certain battery voltage threshold (by a chip internal comparator)

- the solution can not compensate directly for the variation of gain due to thermal dependencies (in RF power amplifier and the driver stage, preceding the PA) thus even if the RF power amplifier is fed by regulated supply voltage, there may be noticeable temperature dependent variations of the output power over the full temperature range.

The variation may be of importance for high-power RF amplifiers operating in a wide temperature range.

For instance a typical C class RF power amplifier with nominal +10 dBm (10 mW) output power may show a variation of  $\pm 1.3$  dBm output power over the  $[-40^{\circ}\text{C}...+110^{\circ}\text{C}]$  temperature range, in other words a total variation of almost 3 dB.



**Figure 3-3 Stabilizing the output power of an RF amplifier by supply voltage regulation**

### 3.2 Closed loop feedback solution with directional coupler

A directional coupler may be connected between the RF-amplifier output and the load, as shown in [Figure 3-4](#).

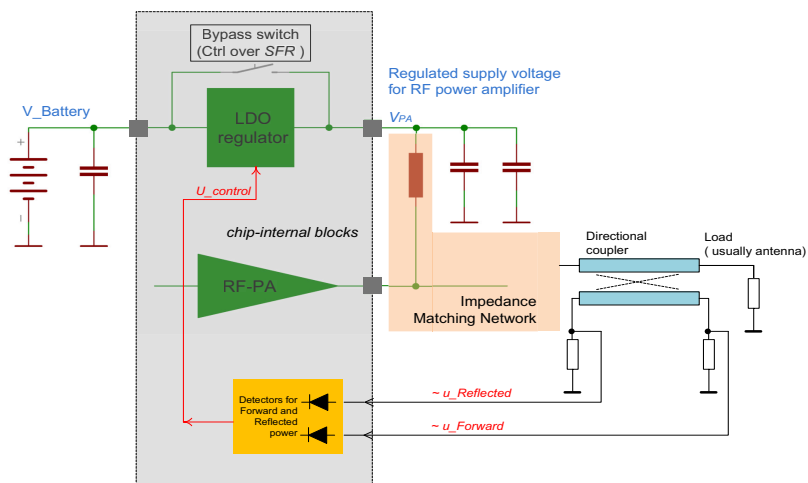
The coupler delivers a voltage for the forward wave (denoted  $F$ ) traveling from the RF power amplifier toward load on one arm, and another, denoted  $R$  for the power reflected from load toward the RF amplifier.

Thus by measuring the forward wave the supply voltage of the RF amplifier can be regulated in such a way, to keep at constant value the “forward” power part.

The reflected wave ( $R$ ) may be used for extraction of information about the degree of mismatch (antenna detuning for instance).

The solution shown in [Figure 3-4](#) is widely used by high power transmitters, where if reflected to the RF amplifier, even a small percentage of the total power may cause significant dissipation and overheating (of the elements in the amplifier stage), but may be of too high complexity for low power applications. The directional coupler itself will add extra cost to system if implemented as a lumped element (discrete) part, but realization is feasible as striplines on PCB for operating frequencies beyond (over) 800 MHz.

RF power regulators based on directional coupler(s) are suitable for accurate systems with tight limits (of the regulated RF power range).



**Figure 3-4 Directional coupler for RF power measurement and regulation feedback**

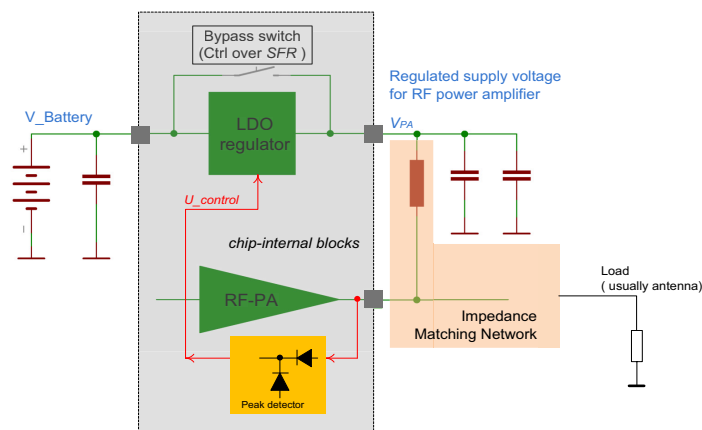
### 3.3 Closed loop feedback solution with peak detector

A peak detector is monitoring the RF signal voltage at the output of the RF power amplifier, as shown in [Figure 3-5](#) and steering either the supply voltage of the RF power amplifier itself, or the supply voltage of the driver stage in such a way, to keep the voltage at the peak detector's output at a constant level.

As this voltage is a "sum" resulting from

- the forward wave (traveling from RF power amplifier toward the load) and
- the reflected wave (the power component reflected from load towards the amplifier, if there is any mismatch)

and taking in account that the peak detector, as a scalar device cannot separate the two voltages corresponding to the two waves one from another, the accuracy of this solution is not as good as if a directional coupler should have been used, but good enough to keep the RF power at compliant level with the above mentioned ARIB standards for instance.



**Figure 3-5 RF power measurement with peak detector**

## 4 Indirect RF power regulation solutions

Open loop systems implement the power regulation by means of a computational method, usually a code segment, executed by a host which adjusts:

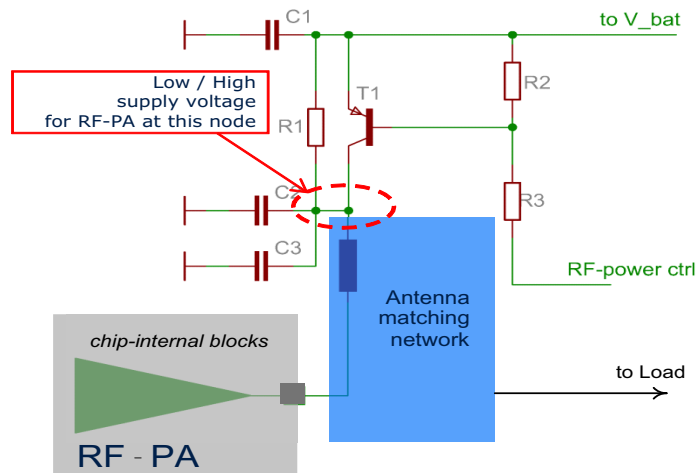
- either the supply voltage of the RF power amplifiers
- or the number of active RF power amplifier stages
- or both of them, using the supply voltage control for instance for fine steps and the stage switching as a coarse means of regulation and stabilization.

This solution can be implemented efficiently by the PMA5110; PMA7110; PMA7105 family and TDA5150 as all of those have multi-stage RF power amplifiers, configured over Special Function Registers (SFRs).

### 4.1 Indirect RF regulation by power amplifier supply control

A simple solution with a high- and a low-power stage is shown in [Figure 4-1](#). If the control voltage applied to resistor  $R3$  is high, the transistor  $T1$  is off and the RF power amplifier is supplied over resistor  $R1$ . The voltage at the common node of  $C2$  and  $R1$  is significantly lower as the supply voltage ( $V_{bat}$ ) thus yielding a reduced RF output power (i.e low-power setting).

If the control voltage applied to resistor  $R3$  is low, the transistor  $T1$  will be in saturation, thus the potential on the common node of  $C2$  and  $R1$  will be approximately the  $V_{bat}$  supply voltage (minus the  $V_{CE}$  saturation voltage of  $T1$ , which is quite low, in the order of  $\sim 50\text{mV}$ ). This is the high-power setting.



### Figure 4-1 Two stage (Low / High) RF power control

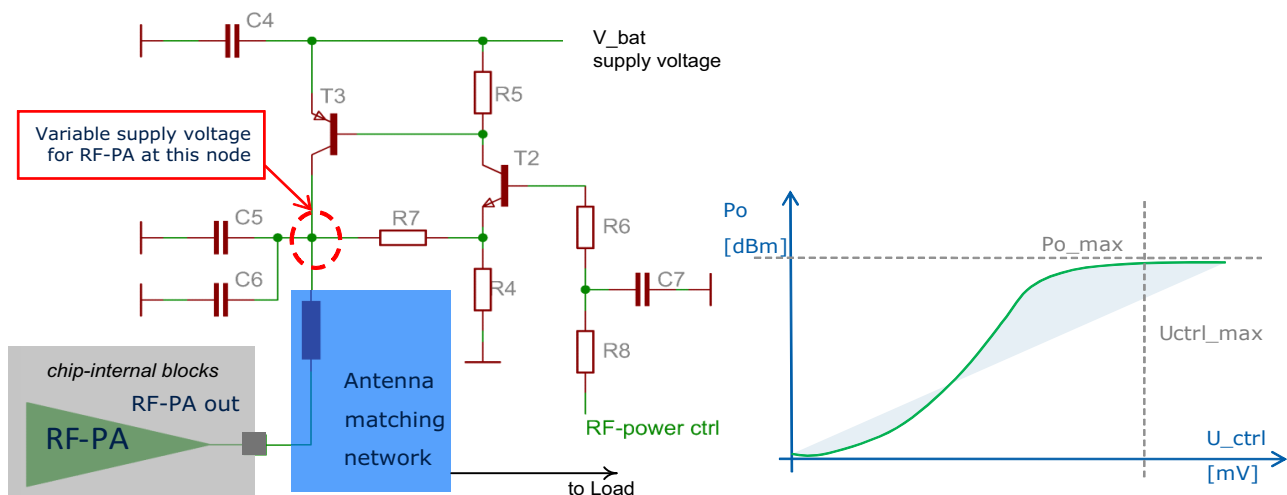
A more elaborate solution is shown by [Figure 4.2](#) with a tracking amplifier. Compared with the solution in [Figure 4-1](#) it is a more elaborate version, allowing fine adjustment of the RF output power via a variable voltage, obtained

- either by integration of a PWM signal, or
- a voltage derived from a D/A converter

Assuming 8 bit resolution for the PWM modulator or the DAC, the output power can be controlled in 255 steps, a more than satisfactory value with regard to RF-power control accuracy.

The control voltage delivered for instance by the PWM modulator is applied to the integrator group C7 and R8. A DC signal (with some ripple) is obtained and used as bias for T2, which at its turn controls the current flowing over T3. The negative feedback (R4 & R7) contributes to linearization of the tracking amplifier (T2 & T3).

An approximate relation between the voltage at the common node of *R8* & *C7* (integrator) and the output power is shown on right side of **Figure 4.2** (plot, simulation result).



**Figure 4-2 Tracking amplifier for RF power control and typical control voltage vs. RF power curve**

## 4.2 Hybrid solutions controlling the supply voltage and stage switching

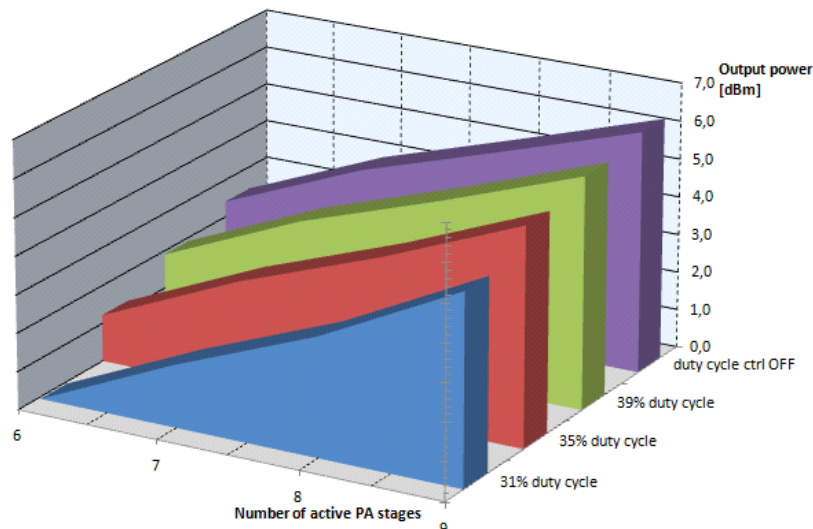
Implementation of power control in a dynamic range exceeding 10 dB is not practical based alone on supply voltage variation, as the efficiency of the end stage (RF PA) may degrade significantly, according to formulas [3.1] and [3.2].

In this case it is more practical to control at the same time the RF power amplifier's supply voltage (for fine steps) and the number of active RF amplifier stages.

This solution suits well to following Infineon Technologies transmitters

- SmartLEWIS<sup>™</sup> MCU transmitters PMA5110; PMA5105; PMA7110; PMA7107, PMA7105; PMA7105 family. The transmitters of this family have software configurable, multi stage RF power amplifier with nominal power settings of +5dBm; +8dBm and +10 dBm
- SmartLEWIS<sup>™</sup> multichannel transmitter TDA5150 with software configurable, multi stage RF power amplifiers with programmable duty-cycle

As shown in [Figure 4-3](#) even a well chosen combination for the number of active RF PA stages and duty cycle settings yield a fine resolution for RF power settings, suitable for compensation of supply voltage variations.

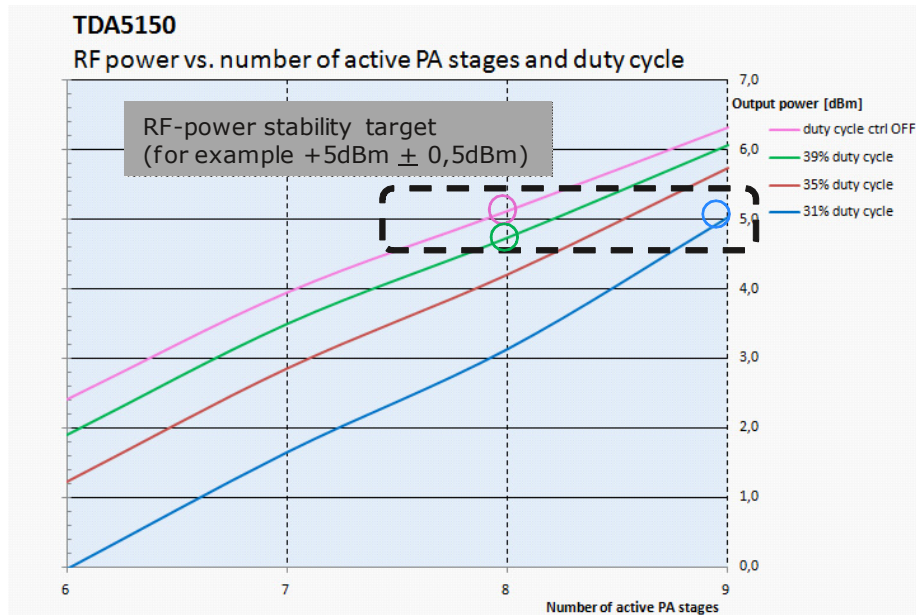


**Figure 4-3 RF power as function of duty cycle and number of active RF PA stages.**  
**Example based on multichannel transmitter TDA5150.**

If the solution of duty cycle control and variable number of active RF power amplifier stages is combined with supply voltage regulation, the power-added efficiency of the (active) RF power amplifiers can be held in the region which yields high efficiency values for the available supply voltage and required RF power.

*Note: a certain RF output power requirement by a given supply voltage yields an optimum generator impedance for the best efficiency. By proper choice for number of active RF PA stages the efficiency can be thus optimized.*

*The only serious limitation is the impedance of the chip-external matching network, which is usually a fixed value and not tunable. The TDA5150 chip has two banks of software-selectable tuning capacitors, which can be used for tuning purposes successfully in the two low ISM bands (315 MHz and 434 MHz).*



**Figure 4-4** RF output power as function of active stage number and duty cycle.  
Observe that 3 settings satisfy the +5 dBm  $\pm$  0.5 dBm criterium in this example.

## References

- [1] Varta AG *Primary Lithium button cell batteries for reliable applications* [weblink](#)
- [2] Duracell *Technical / OEM primary systems* [weblink](#)



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