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**Agenda item: 9.4**

**Source: Nokia**

**Title: Realistic power amplifier model for the New Radio evaluation**

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# 1 Introduction

An objective of the new radio (NR) study item [1] is to identify and develop technology components being able to use any spectrum band ranging at least up to 100 GHz. The goal is to achieve a single technical framework addressing all usage scenarios, requirements and deployment scenarios defined in TR38.913 [2].

RAN1 started discussion on evaluation assumptions for new radio interface in RAN1#84bis. RAN4 received an LS requesting guidance on PA models that RAN1 should adopt for NR waveform link level evaluation for sub 6GHz and above [3].

This contribution discusses the power amplifier model that can be utilized for evaluation of the new RAT. We also make a concrete proposals of PA models to be used in the NR waveform evaluations.

# 2 Discussion

In RAN1 #84bis meeting, it was agreed that RF nonlinearity is considered in RAN1 link level simulation for NR waveform evaluations in four evaluation cases defined in R1-163558 [4]. In addition, RAN1 has agreed on the following:

*Consider the RF nonlinearity in the evaluation cases of R1-163558 [4]*

* *RAN1 can consider the following models for PA modelling, i.e. Rapp model [5] (AM/AM, AM/PM) and/or Clipping model with different thresholds*
  + *Companies should provide the model parameters (operating point, back-off value etc.) and justification (e.g., EVM, OOBE/PSD)*

In [3] RAN1 asked RAN4’s guidance and views on the following questions:

* *The applicability/fidelity of the models above for both UE and BS, different carrier frequency (for sub 6GHz and above) and signal bandwidth, and recommended parameters (operating point and back-off value in case of OFDMA and/or SC-FDMA, etc.) to be used in the models.*
* *Alternative realistic PA models that RAN1 should adopt for NR waveform link level evaluation for sub 6GHz and above.*

In the following sub-sections we try to find answers to RAN1’s questions and try to find concrete proposals that RAN4 could provide to RAN1.

## 2.1 PA impact on performance

The nonlinear power amplifier have significant impact on performance with respect to:

- Transmit spectrum characteristics and mask

- Multiuser Interference between FDM separated UE’s

- The transmit power that can be used for a given modulation and waveform

PAPR and cubic metric (CM) can been used as a rough indication of the PA back-off required. However, while they are valuable as rough figures of merit, PAPR and CM alone do not comprehensively describe the waveforms performance and their unqualified use can lead to unrealistic expectations about the actual performance of certain waveform. Therefore it is seen important to account realistic PA model in evaluations.

The nonlinear power amplifier models can be classified roughly to three categories; memoryless nonlinear models, quasi-memoryless nonlinear models and nonlinear models with memory. The memoryless and quasi-memoryless models aim to characterize the power dependent non-linear behaviour by AM/AM (amplitude to amplitude modulation) and AM/PM (amplitude to phase modulation) distortion curves. In the memoryless nonlinear modelling approach the PA model is presented through narrowband AM/AM transfer function, while in quasi-memoryless models, both AM/AM and AM/PM functions are applied. The instantaneous gain (AM/AM) distortion corrupts the envelope of the signal and relative static phase (AM/PM) distortion corrupts the phase causing distortion for the signal constellation/envelope. Nonlinear models with memory aim also to capture the effects that are manifested not only by the instantaneous input signal magnitude but also the frequency dependent characteristics of the signal envelope e.g. making AM/AM and AM/PM functions non static and dependant on the past input levels. Memory effects in PAs are attributed to various sources, thermal and electric [12][13]. These effects are more elevated in high power PA’s, but also appear as the signal bandwidth is increased.

This nonlinearity phenomena leads to in-band performance degradation and spectral regrowth causing adjacent channel interference. For in-band signal these distortions can be quantified by EVM (Error Vector Magnitude) at the transmitter causing increased BER at the receiver. PA nonidealities have especially noticeable impacts on small devices and thus for especially important for UL transmission but for higher mmWave frequencies PA could also impact and set constraints to DL transmission. The dynamic long term memory effects in PA introduce asymmetry in sidebands (ACLR) or IMD variation due to envelope frequency [12][13][14].

Volterra series are well-known method to model nonlinear systems with memory accurately. The main drawback of it is the high complexity of the model. One common derivative of Volterra series is Memory Polynomial (MP) model [10][11], providing good modelling accuracy with somewhat reduced complexity. MP model (and other derivatives of Volterra series) have widely been used in predistortion studies of wideband high power amplifiers. Other common industry adopted approach is to use the quasi-memoryless nonlinear model e.g. characterise the PA non-linear behaviour through AM/AM and AM/PM functions. This approach, while not necessarily capturing the possible asymmetry, offers reasonable accuracy and merits in simulation simplicity. Furthermore memoryless models have been used extensively in earlier evaluations carried out in RAN4, including CA related studies. In addition it could be expected that finalizing MP type models for NR studies could require some non-significant effort and time (extraction, verification and aligment) causing some undesirable delay to evaluations. Therefore it is felt that at least for initial evaluations for NR waveform selection it is most feasible to focus on quasi-memoryless nonlinear models that have been used in RAN4 earlier (e.g. in LTE CA studies) and considered also in RAN1 LS [1]. MP type models could be considered further on later stage for example to fine tune the requirement definition.

## 2.2 Realistic PA modeling

The LS [1] mentions two possible PA modelling for RAN1 work; “modified Rapp model” including both AM/AM and AM/PM distortions (quasi-memoryless) and clipping model (memoryless) with different thresholds as illustrated in the figure below. below shows an example for amplitude and phase distortions caused by PA models as modified Rapp or simple clipping. As we can see from the clipping model means linear dependence between input and output signal levels up to PA’s saturation level and after that constant signal output level. In the clipping model there is no phase distortion i.e. no AM/PM distortion is modelled. In modified Rapp, which resembles more closely to realistic PAs, both amplitude (AM/AM) and phase (AM/PM) distortions are modelled. Furthermore signal’s amplitude levels after PA is distorted also below PA’s saturation point. In RAN4 studies even more realistic PA models than the modified Rapp have been used and typically they are based on measurements on PAs used in the devices like LTE devices.



Figure : Power Amplifier AM/AM and AM/PM distortions for clipping (only AM/AM distortion) and modified Rapp model (including both AM/AM and AM/PM distortions)

As discussed in the previous section, PA performance and thus also realistic modelling of PA have noticeable impact on the performance of New Radio and its candidate waveforms. Since the simple clipping model has linear amplitude dependence up to PA’s saturation point and no phase distortions, the degradations caused by PA to in-band and adjacent channel performance are not realistic and may cause wrong decisions in waveform evaluations and decisions making. As we can see from Figure 1, clipping model has ideal AM/AM curve up to PA’s saturation level and no AM/PM distortion on any input signal levels. Some waveform, modulation and coding combinations are sensitive to AM/AM and AM/PM distortions whereas some others are not. Typically higher order modulations and OFDM type of waveforms are more sensitive to AM/PM distortions than low order modulations and single carrier waveforms.

For instance from the EVM (in-band) results of [5] we can see that BPSK modulation combined either with OFDM or single carrier based waveform is not very sensitive to PA distortions. On the other hand higher order modulations like 16QAM and especially when combined with OFDM based waveform is sensitive to PA distortions and it makes noticeable difference if realistic AM/AM and AM/PM modelling are used for PA instead of simple clipping model without any AM/PM distortions. We can also see from the results of [5] that power spectrum impacts caused by clipping PA model and more realistic PA model like modified Rapp (including realistic AM/AM and AM/PM distortions) are rather different. It is also worth noting that it is not always easy to estimate in advance which waveform and modulation combinations are sensitive to realistic AM/AM and AM/PM distortions and what is realistic level of performance degradation e.g. in terms on EVM (in-band distortions) or in power spectrum performance.

The absolute level of needed power back-off is important factor in the waveform evaluations as it will provide more accurate information on PA efficiency and thus, power consumption. Furhtermore, since higher order modulations and various variants of OFDM waveforms are currently studied for NR, it would seem important to ensure that all the relevant PA distortions (both AM/AM and AM/PM) are realistically modelled in the waveform evaluations.

In [5] “Rapp’s p=100” in practice is simple clipping model and “IEEE p=1.1” is modified Rapp including both AM/AM and AM/PM distortions. Difference in the EVM results between the clipping (“Rapp’s p=100”) and the modified Rapp (“IEEE p=1.1”) is not linear between different waveform and modulation combinations as expected. Similarly in the power spectrum plots differences between clipping and more realistic PA models are not linear and therefore, it is not easy to estimate what would be real PA impacts and thus, needed Tx power reductions, EVM and SEM performance if only clipping model is used in the simulation. Since the Rapp model will practically become a simple clipping model with the right parameterization, it would be better if RAN1 used the modified Rapp model including AM/AM and AM/PM model and if companies additionally want to check the impacts with simple clipping model that could be done by using the right parameterization as discussed also in [5].

The modified Rapp model for AM/AM and AM/PM distortions could be presented as follows based on [8] & [9].





Where

x is an amplitude of the input signal

G is small signal gain

VSAT is saturation level

p is the smoothness factor

and A, B and q are fitting parameters

The modified Rapp model with AM/AM and AM/PM distortions have been used in studies for radio systems at 60 GHz carrier frequencies with wide bandwidths e.g. ~ 2 GHz bandwidth. RAN4 has been using realistic and even real measured PA models e.g. for its LTE and NB-IoT investigations. Therefore, we propose that at least initially RAN1 would use the modified Rapp model including both AM/AM and AM/PM distortions as the primary PA model for carrier frequencies above 6 GHz e.g. cm and mm wave carrier frequencies like 30 GHz and 70 GHz with BW up to 1 GHz as agreed for the RAN1 simulations in [15].

For carrier frequencies below 6 GHz like 4GHz as agreed for the RAN1 simulations in [10] we propose that RAN1 would use real measurement based PA models with AM/AM and AM/PM distortions similarly as RAN4 has done earlier. In Section 2.3.2 we will provide further details for the proposed measurement based realistic PA model for carrier frequencies below 6 GHz.We see that these proposed PA models are especially suitable for small devices and very small base stations where PA’s impacts are also more significant. As typically there are more constraints e.g. in terms of power consumption, cost and complexity in small devices and very small base stations, we would recommend that realistic PA models would especially used for such studies in the beginning.

## 2.3 PA model proposals

In the following sub-sections we propose details for the PA models to be used in the NR waveforms studies for above and below 6 GHz.

### 2.3.1 PA model for carrier frequencies above 6 GHz

For the RAN1 evaluations and simulations above 6 GHz and especially at the carrier frequencies 30 GHz and 70 GHz as agreed for the RAN1 simulations [15], we propose the following modified Rapp model with AM/AM and AM/PM distortion models:

AM/AM:



AM/PM:



x is an amplitude of the input signal in voltages

G = 16

VSAT = 1.9 V

p = 1.1

A = -345

B = 0.17

q = 4

### 2.3.2 PA model for carrier frequencies below 6GHz

PA models for lower LTE frequency bands are widely available, and have been extensively used in RAN4 RF requirements specification work. A typical model is based on measured AM/AM and AM/PM data. PA measurements done in a lab however rarely find the worst case operating point, when considering manufacturing process yield and operating temperature and voltage. It is typical in RAN4 models to scale down the measured gain of the PA slightly, so that to achieve the wanted output power, the PA must be driven with a slightly higher input signal. This means that the PA model is operating deeper in saturation than the measured PA, to approximate the worst case realistic conditions. The typical RAN4 assumptions allow 4 dB of post-PA losses to account for filters, switches, diplexers, etc. Therefore the PA output power for 23 dBm UEs is actually 27 dBm.

For the New Radio waveform studies below 6 GHz, we provide a 4 GHz PA model that is based on a measured PA. We have measured AM/AM and AM/PM data from a commercial 3.5 GHz LTE UE PA.

For easier modelling purposes and cross-checking, the measured AM/AM and AM/PM curves were scaled so that   
-1 dBm 20 MHz QPSK fully populated LTE uplink signal at the PA input will generate 26 dBm PA output, which just meets the minimum ACLR requirements (i.e. 30, 33, and 36 dB for E-UTRA, UTRA1, and UTRA2 respectively). This takes into account the allowed MPR (1 dB in this case) and the post-PA losses (4 dB). The reference PA input level is   
0 dBm without MPR.

Further, the measured AM/AM and AM/PM curves were approximated using 9th order polynomials, also for easier modelling and cross-checking. The difference in simulation to original unfiltered curves was observed to be negligible in the own channel, adjacent and alternate adjacent channels. The polynomial approximation does smoothen out any measurement noise, which tends to increase the simulated unwanted emissions at larger offsets from the carrier frequency, as can be seen in the following figure.

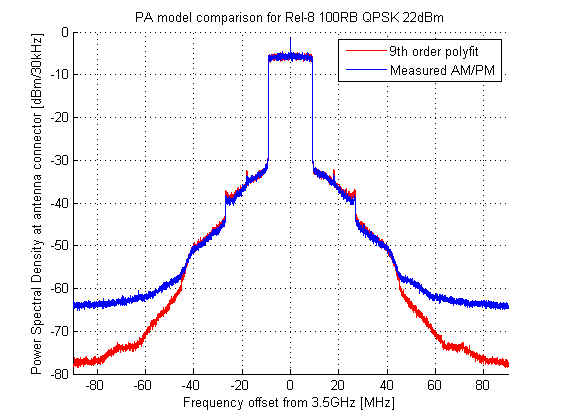


Figure 2: Simulated difference in unwanted emissions between unfiltered AM and PM data vs. polynomial curve fit.

The resulting PA model using AM/AM and AM/PM polynomial approximation is shown in the next figure.

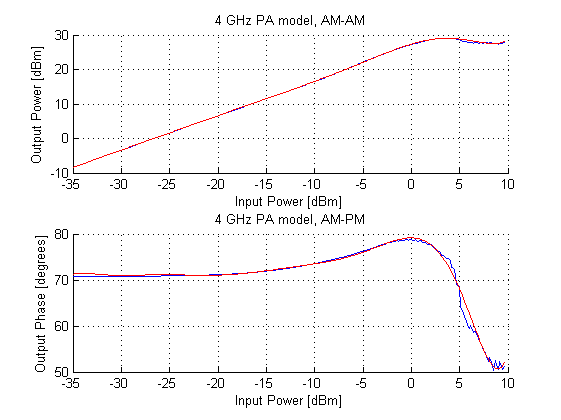


Figure 3: AM/AM and AM/PM curves for the proposed PA model. Measured data in blue, polynomial approximation in red.

The polynomial data in dBm domain is also given below. The format can be directly copied to Matlab. The coefficients are organized as follows: [*p*9 *p*8 *p*7 … *p*0] and the PA output *y*(*t*) can be computed from input *x*(*t*) using the formula  
*y*(*t*) = p0 + *p*1∙*x*(*t*) + *p*2∙*x*(*t*)2 + *p*3∙*x*(*t*)3 + …

p\_am = [7.9726e-12 1.2771e-9 8.2526e-8 2.6615e-6 3.9727e-5 2.7715e-5 -7.1100e-3 -7.9183e-2 8.2921e-1 27.3535];

p\_pm = [9.8591e-11 1.3544e-8 7.2970e-7 1.8757e-5 1.9730e-4 -7.5352e-4 -3.6477e-2 -2.7752e-1 -1.6672e-2 79.1553];

The validity of the polynomial model deteriorates below input power -35 to -30 dBm, and it is suggested that fully linear model is applied below such input levels. Also extremely deep in compression, e.g. at input power above 9 dBm, the model does not provide realistic results. This should be fine since the signal peaks would anyway be limited to a reasonable value before entering the PA.

# 3 Conclusion

Based on discussion in this document we propose following PA models to be used in the NR waveform evaluations:

***Proposal 1: For the RAN1 evaluations and simulations above 6 GHz and especially at the carrier frequencies 30 GHz and 70 GHz as agreed for the RAN1 simulations [15] we propose the following modified Rapp model with AM/AM and AM/PM distortion models:***

AM/AM:



AM/PM:



x is an amplitude of the input signal in voltages

G = 16

VSAT = 1.9 V

p = 1.1

A = -345

B = 0.17

q = 4

***Proposal 2: For the RAN1 evaluations and simulations below 6 GHz we propose the following model based on real measurement using AM/AM and AM/PM polynomial approximation:***

PA output *y*(*t*) to be computed from input *x*(*t*) using the formula  
*y*(*t*) = p0 + *p*1∙*x*(*t*) + *p*2∙*x*(*t*)2 + *p*3∙*x*(*t*)3 + …

The coefficients are organized as follows: [*p*9 *p*8 *p*7 … *p*0] and the

p\_am = [7.9726e-12 1.2771e-9 8.2526e-8 2.6615e-6 3.9727e-5 2.7715e-5 -7.1100e-3 -7.9183e-2 8.2921e-1 27.3535];

p\_pm = [9.8591e-11 1.3544e-8 7.2970e-7 1.8757e-5 1.9730e-4 -7.5352e-4 -3.6477e-2 -2.7752e-1 -1.6672e-2 79.1553]

***Proposal 3: Send response LS to RAN1***

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