Graphical Approach for RF Amplifier Specification in Radio over Fiber System: Maximum Power Issues

Teguh Prakoso, Munawar Agus Riyadi
Dept. of Electrical Engineering, Faculty of Engineering
Universitas Diponegoro
Semarang, Indonesia
e-mail: teguhprakoso@elektro.undip.ac.id

Razali Ngah
Wireless Communication Centre
Universiti Teknologi Malaysia
Johor Bahru, Malaysia
e-mail: razalin@fke.utm.my

***Abstract*—Radio-over-fiber (RoF) technologies address wireless communication's need for high data rate, protocol-transparency, and flexibility. One of challenge in RoF access point design is RF amplifier requirement that match to microwave-photonic link chosen and service range needed. This paper proposes a graphical approach as systematic method to solve the challenge. The method identifies two regions, i.e. (a) scalable region where amplifiers' output 1-dB compression point (OP1dB) improvement can enhance system's maximum input and output power, and (b) saturation region where any improvement on amplifiers' OP1dB cannot improve AP's maximum input and output power. The methods have been verified by system simulations. The errors at scalable and saturation regions are less than 1 dB and the standard deviation is no more than 0.6 dB. The error values around the breakpoint between scalable and saturation regions are around 1 dB. Therefore, the proposed graphical approach can be used in the specification tradeoff between RoF access point input and output power, amplifier's gain and OP1dB.**

***Keywords*—graphical approach; radio-over-fiber; RF amplifier; microwave photonics; access point**

I. Introduction

Future wireless technologies such as 5G are envisioned to deliver 10 Gbps to the end users [1]. This multi-gigabit delivery requires large bandwidth for the radio signal hence must be supported with broadband access network. They also integrates different types of communication technologies, and is characterized by context-aware, environment-adaptive, cognition-based, highly-reconfigurable terminals and networks. Radio over fiber (RoF) based access networks play important role due to their protocol transparency, centralized processing and upgrade, and flexible system [2].

Users access CRoF services through access point (AP). AP consists of analog optical link, RF amplifier, and antenna which must cover broad frequency band. One the most critical step in designing CRoF AP is determining correct RF amplifier that match the chosen microwave-photonic link (MwPh) and system requirement of AP. This process often relies on manual, trial and error efforts which can be very time-consuming. Therefore, a systematic design tool to specify the gain, noise figure (NF), output 1 dB compression point (OP1dB), and output third order intercept point (OIP3) values of the RF amplifiers is urgently needed. This paper proposes a graphical tool to determine the best RF amplifier candidates in simpler and faster manner hence long system simulations or field trials/measurements can be avoided.

Graphical tools have been used in many fields in engineering. Smith-chart is one of the most popular examples. This kind of tool used in the tradeoff among RF gain, noise figure, and third-order spurious free dynamic range for analog photonic link employing Mach-Zehnder modulator [3]. Graphical approaches are also employed in RF budget or architecture analysis [4], PLL design [5], and teaching amplifier design [6].

II. Maximum Power Issues in Two-Stage RF Amplifiers Model

There are two types of RF amplifiers used in RoF AP. Firstly, a post-amplifier following an MwPh link that is used in downlink, and secondly a pre-amplifier preceding an MwPh link used in uplink. Since MwPhs generally are more high-price than RF amplifiers and RF amplifiers are available with more options than MwPhs, the type of MwPh is chosen first and then the pre- and post-amplifiers are optimized for the chosen MwPh.

MwPh can be also modeled as RF amplifier [7, 8] hence commercial RF transistor can be used in MwPh's pre- and post-amplifier circuit as discussed in [9]. This paper deals with a process before MwPh and amplifier circuit design stage, i.e. specification on the pre- and post-amplifiers' required gain, NF, and OIP3 is needed. In system view, an MwPh and its pre- or post-amplifier can be modeled as a two RF amplifiers in cascade. Then the formula of cascaded amplifiers can be applied to calculate its total gain and OP1dB.

Modern communication standards used error vector magnitude (EVM) as performance merit. The total EVM (EVM_t) of cascaded MwPh and pre- or post-amplifier can be expressed as [10]

$$EVM_t = \sqrt{EVM_{MwPh}^2 + EVM_{post}^2} \qquad (1)$$

in downlink part of AP, or

$$EVM_t = \sqrt{EVM_{MwPh}^2 + EVM_{pre}^2} \qquad (2)$$

for uplink microwave-photonic antenna. In (1) and (2), EVM_{MwPh}, EVM_{post}, and EVM_{pre} are individual EVM produced by MwPh, post-amplifier, and pre-amlifier respectively. In dealing with maximum power issues, EVM is dominated by nonlinearity which is indicated by OP1dB or input 1 dB compression point (IP1dB). To achieve certain EVM value, RF amplifiers should be operated some dB lower than their OP1dB (or IP1dB if input power is under concern). This step is known as backoff (Δ_{BO}), e.g. output power backoff (OBO) or input power backoff (IBO). Normally, Δ_{BO} values are different for every modulation and coding scheme. Therefore required backoff values should be known, through measurement or simulation, prior to specification stage.

III. Post-Amplifier

In downlink RoF AP, see Fig. 1, input power to the system ($P_{in,DL}$) equals to the input power to the MwPh ($P_{in,MwPh}$). The total downlink gain (G_{DL}), in dB values, can be expressed as

$$G_{DL} = G_{MwPh} + G_{post} \quad (3)$$

$P_{in,DL} + G_{DL}$ is designed to produce output power ($P_{out,DL}$) that meet the required service distance of the system. The gain of MwPh (G_{MwPh}) is fixed, whereas post-amplifier gain (G_{post}) is subject to be optimized.

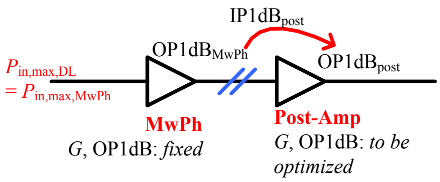

Fig. 1. Active elements in downlink RoF AP mainly consist of MwPh and post-amplifier.

The cascaded OP1dB, in scalar, of the downlink RoF AP ($OP1dB_{DL}$) can be written as

$$OP1dB_{DL} = \frac{OP1dB_{MwPh} G_{post} OP1dB_{post}}{OP1dB_{MwPh} G_{post} + OP1dB_{post}} \quad (4)$$

Taking very high $OP1dB_{post}$ for fixed $OP1dB_{MwPh}$, G_{post}, and G_{MwPh} results in $OP1dB_{post} >> OP1dB_{MwPh}.G_{post}$, then

$$OP1dB_{DL,sat} = OP1dB_{MwPh} G_{post} \quad (5)$$

This equation defines the *saturation region*, see Fig. 2. At low value of $OP1dB_{post}$, $OP1dB_{post} << OP1dB_{MwPh}$, the limit of $OP1dB_{DL}$ tends to value of

$$OP1dB_{DL,lin} = OP1dB_{post} \quad (6)$$

This equation defines the *linearly-scaled (or scalable) region*, see Fig. 2.

The border or breakpoint between these "linearly-scalable" and "saturation" regions is called *corner* $OP1dB_{post}$ ($COP1dB_{post}$). The imaginary intersection point between the two regions can be determined as the $OP1dB_{post}$ value in linearly-scaled region (5) that produces $OP1dB_{DL}$ equals to its saturation region value (6). Mathematically, it can be written as

$$OP1dB_{DL}|_{COP1dB_{post}} = OP1dB_{MwPh} G_{post} \quad (7)$$

Since in linearly-scaled region $OP1dB_{DL} = OP1dB_{post}$, the value of $COP1dB_{post}$ is

$$COP1dB_{post} = OP1dB_{MwPh} G_{post} \quad (8)$$

or its equivalence in dB is

$$COP1dB_{post} = OP1dB_{MwPh} + G_{post} \quad (9)$$

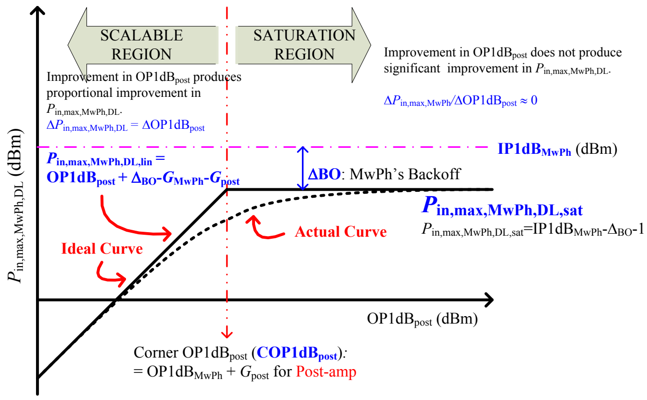

Fig. 2. Design graph for downlink RAP's active elements.

As stated earlier, in order to produce specific EVM_t value, the system should be operated at maximum output power of downlink AP ($P_{out,max,DL}$) of $P_{out,max,DL} = OP1dB_{DL} - \Delta_{BO}$ (in dB). Since $P_{in,DL} = P_{out,DL} - G_{DL}$, maximum input power to the downlink AP ($P_{in,max,DL}$) to obtain the EVM_t value can be written as

$$P_{in,max,DL} = OP1dB_{DL} - \Delta_{BO} - G_{DL} \quad (10)$$

In downlink, $P_{in,max,DL} = P_{in,max,MwPh,DL}$. It also can be noted that in the linearly-scaled region (6), $OP1dB_{DL} = OP1dB_{post}$ therefore maximum input power to MwPh in downlink AP and scalable region ($P_{in,max,MwPh,DL,lin}$) can be expressed as

$$P_{in,max,MwPh,DL,lin} = OP1dB_{post} - \Delta_{BO} - G_{DL} \quad (11)$$

Since $OP1dB_{MwPh} = IP1dB_{MwPh} - 1$, in the saturation region, the maximum power to the downlink AP is

$$P_{in,max,MwPh,DL,sat} = OP1dB_{MwPh} - G_{MwPh} - \Delta_{BO} = IP1dB_{MwPh} - 1 - \Delta_{BO} \quad (12)$$

Based on this discussion, a design graph can be drawn as presented in Fig. 2. Equations (9, 11, 12) are useful to create corner model which is labeled as "Ideal Curve" in Fig. 2. This graph can be employed to determine post-amp specification for an MwPh using these steps. *Firstly*, decide the required output power ($P_{out,req,DL}$) used by the AP. *Secondly*, obtain the value of backoff then calculate the lowest value of $OP1dB_{post}$ equals to the required output power plus OBO, refer to (9). *Thirdly*, the highest input power to the system equals to $P_{in,max,MwPh,DL,sat} = IP1dB_{MwPh} - 1 - \Delta_{BO}$, refer to (12). *Fourthly*, the minimum post-amplifier gain ($G_{post,min}$) the produce the required output power can be calculated as $G_{post,min} = P_{out,req,DL} - P_{in,max,MwPh,DL,sat} - G_{MwPh}$. *Fifthly*, corresponding minimum OP1dB value related with the $G_{post,min}$ is $OP1dB_{post,min} = P_{out,req,DL} + \Delta_{BO} = OP1dB_{MwPh} + G_{post,min} = COP1dB_{post}$.

If a post-amp with $G_{amp} = G_{post,min}$ is chosen in an RoF AP design, it means that it is in the "saturation region." A downlink RAP can be operated at input power below $P_{in,max,MwPh,DL,sat}$. Of course the gain value of the post-amp must be higher than $G_{post,min}$ and the OP1dB value at least equals $\text{OP1dB}_{post,min}$. In this case, it is in the "scalable region."

IV. PRE-AMPLIFIER

The active portion of an uplink microwave-photonic antenna consists of a microwave-photonic link and a pre-amplifier as presented in Fig. 3. The uplink total gain (in dB) can be written as

$$G_{UL} = G_{pre} + G_{MwPh} \tag{13}$$

Here, the input power to the system ($P_{in,UL}$) is the same with the input power at pre-amp ($P_{in,pre}$) and related with input power at MwPh as (in mW)

$$P_{in,UL} = \frac{P_{in,MwPh}}{G_{pre}} \tag{14}$$

or equivalently can be expressed in dBm as

$$P_{in,UL} = P_{in,MwPh} - G_{pre} \tag{15}$$

The microwave-photonic link's gain and OP1dB are fixed whereas the pre-amp's gain and OP1dB are subject to be optimized. The system OP1dB (OP1dB_{UL}) can be written as

$$\text{OP1dB}_{UL} = \frac{\text{OP1dB}_{pre} G_{MwPh} \text{OP1dB}_{MwPh}}{\text{OP1dB}_{pre} G_{MwPh} + \text{OP1dB}_{MwPh}} \tag{16}$$

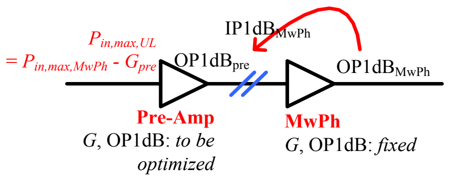

Fig. 3. Active elements in uplink side of RoF AP mainly consist of pre-amplifier and MwPh.

In area where $\text{OP1dB}_{pre} G_{MwPh} >> \text{OP1dB}_{MwPh}$, the value of $\text{OP1dB}_{pre} G_{MwPh} + \text{OP1dB}_{MwPh} \cong \text{OP1dB}_{pre} G_{MwPh}$, thus OP1dB_{UL} can be expressed as

$$\lim_{\text{OP1dB}_{pre} \to \infty} \text{OP1dB}_{UL} = \lim_{\text{OP1dB}_{pre} \to \infty} \frac{\text{OP1dB}_{pre} G_{MwPh} \text{OP1dB}_{MwPh}}{\text{OP1dB}_{pre} G_{MwPh} + \text{OP1dB}_{MwPh}} = \text{OP1dB}_{MwPh} \tag{17}$$

which governs at the saturation region. At the very low value of OP1dB_{pre} such that $\text{OP1dB}_{pre} G_{MwPh} << \text{OP1dB}_{MwPh}$, the value of $\text{OP1dB}_{pre} G_{MwPh} + \text{OP1dB}_{MwPh} \cong \text{OP1dB}_{MwPh}$, and therefore

$$\text{OP1dB}_{UL} = \text{OP1dB}_{pre} G_{MwPh} \tag{18}$$

which determines the linearly-scaled region's characteristics. The border of the two regions called corner OP1dB_{pre} (COP1dB_{pre}) which is defined as

$$\text{OP1dB}_{UL}|_{\text{COP1dB}_{pre}} = \text{OP1dB}_{MwPh} \tag{19}$$

Since in linearly-scaled region $\text{OP1dB}_{UL} = \text{OP1dB}_{pre} G_{MwPh}$, the value of COP1dB_{pre} is

$$\text{COP1dB}_{pre} = \frac{\text{OP1dB}_{MwPh}}{G_{MwPh}} \tag{20}$$

This equation can be written in dB as

$$\text{COP1dB}_{pre} = \text{OP1dB}_{MwPh} - G_{MwPh} = \text{IP1dB}_{MwPh} - 1 \tag{21}$$

In order to produce a specific EVM_t value, the system should be operated at $P_{out,max,UL} = \text{OP1dB}_{UL} - \Delta_{BO}$ (in dB). For fixed G_{UL},

$$P_{in,max,UL} = P_{in,max,MwPh,UL} - G_{pre} = \text{OP1dB}_{UL} - \Delta_{BO} - G_{UL} \tag{22}$$

In the linearly-scaled region, substituting (18) to (22) results in

$$P_{in,max,MwPh,UL,lin} = \text{OP1dB}_{pre} + G_{MwPh} + G_{pre} - G_{UL} - \Delta_{BO}$$
$$G_{in,max,MwPh,UL,lin} = \text{OP1dB}_{pre} - \Delta_{BO} \tag{23}$$

And, substitution of (17) to (22) produces relation in the saturation region which can be written as

$$P_{in,max,MwPh,UL,sat} = \text{OP1dB}_{MwPh} - \Delta_{BO} - G_{UL} + G_{pre}$$
$$P_{in,max,MwPh,UL,sat} = \text{IP1dB}_{MwPh} - 1 - \Delta_{BO} \tag{24}$$

Then, a design graph can be created as presented in Fig. 4. Equations (21, 23, 24) are useful to build corner model which is identified as "Ideal Curve" in Fig. 4.

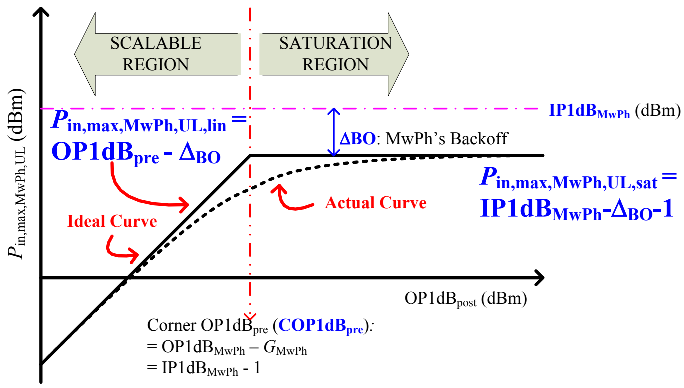

Fig. 4. Design graph for uplink RAP's active elements.

V. PREDICTION MODEL

Figs. 2 and 4 include curves with label "Actual Curve." The curves are expected as result of actual system simulations of measurements. There are large discrepancies between "Ideal Curve" and "Actual Curve" around the corners, i.e. COP1dBpost and COP1dBpre. To improve prediction model's accuracy of the graphical approach, two additional parameters are introduced, namely C1dB and S1dB. Both of the parameters are used to identify 1 dB deviations from ideal linear and saturation lines, respectively. At OP1dB_{amp} values no more than C1dB, (11) and (23) deviate no more than 1 dB. In the saturation region, at $OP1dB_{amp}$ values equals to S1dB and above (12) and (24) deviate 1 dB or less.

The values of C1dB and S1dB for post-amplifier ($C1dB_{post}$ and $S1dB_{post}$, respectively) can be defined as follows. The condition for $C1dB_{post}$ in (6) can be written in dB as

$$OP1dB_{DL} = OP1dB_{post} - 1 \quad (25)$$

Converting this condition into scalar and substituting it into equation (4) produce

$$OP1dB_{post} = (0.2589)OP1dB_{MwPh}G_{post} \quad (26)$$

After substituting (8), the equation can be expressed in dB as

$$C1dB_{post} = COP1dB_{post} - 5.87 \quad (27)$$

S1dB can be derived using similar steps to (4), (5), and (8), resulting in an expression in dB as follows

$$S1dB_{post} = COP1dB_{post} + 5.87 \quad (28)$$

Since the uplink's related equations are also similar, the C1dB and S1dB for pre-amplifier can be written as

$$C1dB_{pre} = COP1dB_{pre} - 5.87 \quad (29)$$

$$S1dB_{pre} = COP1dB_{pre} + 5.87 \quad (30)$$

VI. Model Verification with System Simulation

This graphical approach for post-amplifier specification (Fig. 2) is validated by AWR's Visual System Simulator (VSS) [11] involving PSI-1601 [12] as MwPh and a post-amplifier with 60 dB gain, with $EVM_{t,DL}$ = 3%, as presented in Fig. 5. Here the simulations were done for single channel of IEEE 802.11a-54Mbps signals. The backoff value is 5.1 dB, G_{post} = 60 dB, G_{MwPh} = -30 dB, and $OP1dB_{MwPh}$ = -25 dBm. Input power to MwPh is varied for an $OP1dB_{post}$ value, and then EVM value of the system is recorded and EVM = 3% is identified. The step is repeated for other values of $OP1dB_{post}$. Result of the system simulation is presentd in Fig. 5 with curve labeled "*simulation*."

The *corner model* of $P_{in,max,DL}$ (as presented as $P_{in,max,MwPh,DL}$, the vertical axis in Fig. 5). The curve labeled with "*Ideal"* is built from the saturation value calculated using (12), which is -0.1 dBm, the linearly-scaled value predicted by (11) resulted in $OP1dB_{post}$ = -35.1 dBm, and the $COP2dB_{post}$ = 35 dBm as calculated by (9). The curve with label "*Prediction*" is based on (11, 12, 27, 28). The prediction error is less than 0.2 dB in linearly-scaled region, lower than error in saturation region which reach 0.5 dB and error at around $COP1dB_{post}$ point which is 1 dB. The standard deviations prediction errors are 0.5 dB and 0.6 dB, respectively. With these small errors, it can be suggested that the accuracy and applicability of (9, 11, 12, 27, 28) are confirmed as long as the backoff values are correctly-adjusted.

Simulation and prediction results of an uplink AP are shown in Fig. 6. The errors of ideal line and prediction curve are within 1 dB at $OP1dB_{pre} \leq COP1dB_{pre} - 5$ or $OP1dB_{pre} \geq COP1dB_{pre} - 5$. Whereas at $COP1dB_{pre}$, the errors of ideal line and prediction curve are around -3 dB and ≤-1.5 dB, respectively. The maximum standard deviation of prediction error is 0.6 dB. These small errors can be made by adjusting the OBO values for each number of channels in prediction equation. It can be concluded that prediction is accurate as long as the OBO value is accurate. And also, $COP1dB_{amp}$ is very useful for RoF AP designers to identify the border or breakpoint between scalable and saturation region.

Figs. 5 and 6 also show that the transition of the dominant EVM contributor takes place between C1dB and S1dB. At P_{in} ≤ C1dB, pre- and post-amps dominate the contribution to the total EVM of RoF APs. Hence, it can be said that pre- and post-amps become the performance limiter in this region. The analog photonic link, PSI-1601, starts dominating the total EVM at P_{in} ≥ S1dB and it is a sign that the microwave photonic link now acts as performance limiter of RoF APs system. Therefore, C1dB is a good parameter for maximum value of OP1dB allowing $P_{in,max}$ grows linearly with OIP3 improvement. Whereas C1dB is a good estimator of saturation, where any improvement on pre- and post-amps' OP1dB does not produce any effect to the total EVM. These facts signify the applicability and importance of C1dB and S1dB as performance measures for RoF AP.

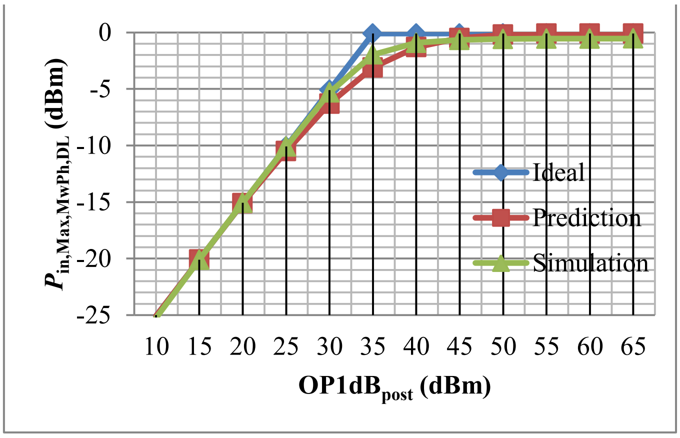

Fig. 5. Input power to downlink BAPRoF as function of OP1dB of RF post-amplifier for EVM ≤ 3% of single channel IEEE 802.11a - 54 Mbps signal. The 60 dB post-amp is preceded by PSI-1601.

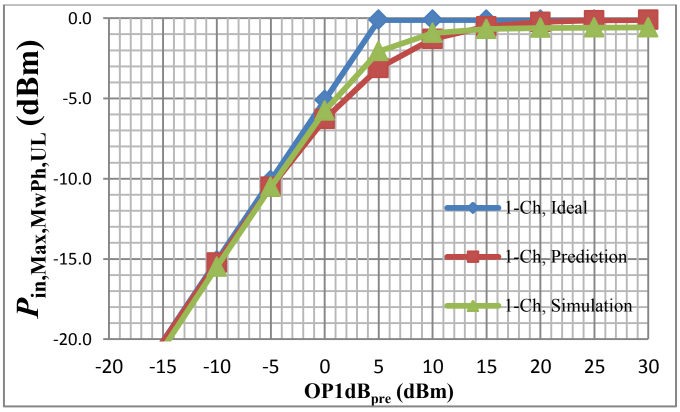

Fig. 6. Input power to uplink BAPRoF as function of OP1dBpre for EVM ≤ 3% of one to four channel IEEE 802.11a - 54 Mbps signals. The pre-amp's gain is 40 dB.

VII. CONCLUSION

This paper deals with graphical-approach for radio-over-fiber access point's pre-amplifiers and post-amp amplifiers requirement. The model identifies two regions, i.e. (a) scalable region where amplifiers' OP1dB improvement can enhance system's maximum input and output power, and (b) saturation region where any improvement on amplifiers' OP1dB cannot improve AP's maximum input and output power. The breakpoint between the two regions is identified as corner OP1dB. The methods have been verified by AWR Visual System Simulations and it is found that both of them are fairly accurate. The errors at scalable and saturation regions are less than 1 dB and the standard deviation is no more than 0.6 dB. The error values around the breakpoint between scalable and saturation regions are around 1 dB. The approaches are developed to be applied for point-to-point RoF AP using simultaneous multi-channel IEEE 802.11a signal. Nevertheless, the methods can be applied for microwave-photonic-link's post and pre-amps in general. The graphical approach helps RoF system designers with a systematic method to find a correct pre-amp and post-amp for their photonic link.

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