Challenges of Using Phased Array Antennas in Commercial Backhaul Equipment at 26 GHz

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Abstract. Software Defined Network is one of the key enabling technologies for the upcoming 5G networks. Both the fronthaul and the backhaul of the network must be reconfigurable for SDN to work properly. Phased Array Antennas could add to the backhaul/fronthaul wireless equipment beamsteering capabilities to make it reconfigurable. This paper summarizes feasibility considerations resulting from the desire of replacing the current reflector antenna with phased arrays in the backhaul segment. Energy consumption and compliance with regulatory radiation masks are analyzed and found to represent challenging requirements. Several techniques are also identified as possible solutions to comply with such stringent demands and future research steps are described. AQ1

Keywords: Phased array antenna · mmWave · Backhaul · 5G

1 Introduction

Current point-to-point micro-wave and millimeter-wave communications are today required to guarantee multi-Gbps capacities with average availability often in excess of 99.995%, accounting for fading due to rain and all other propagation phenomena. As a consequence, directive antennas are needed, in turn implying large reflectors with very narrow beamwidths. The primary practical problem arising from this is the critical sensitivity to misalignments due to external agents such as wind and thermal deformations.

Phased Array Antennas (PAA) provide inherent beamsteering capabilities and thus represent a promising solution not only to solve this problem, but also to add reconfiguration functionalities to the wireless backhaul network. This constitutes an important feature in the upcoming 5G network. Therefore, this provides an important reason to investigate the integration of PAAs with commercial wireless backhaul equipment.

This paper presents the main challenges of replacing the current reflector antennas with a PAAs in today equipment, with the constraint that the total System Gain (SG) should be preserved after the replacement.

M. E. Auer and T. Tsiatsos (Eds.): IMCL 2019, AISC 1192, pp. 1–8, 2021.
https://doi.org/10.1007/978-3-030-49932-7_103

In the market and in the literature there are several works regarding phased array antennas at 26–28 GHz [1–3]. However, these are mainly focused on the mobile access instead of the backhaul and are not compatible with the total SG required. On the other hand, the duplexing scheme of these works is Time Division Duplexing (TDD) that is the technique employed by access stations at millimeter wave frequencies, instead of using Frequency Division Duplexing (FDD) favored by the studied backhaul scenario.

The study has been developed first by calculating the array size and power consumption. Then, simulations of the array pattern were performed in order to test the beam steering capabilities and the fulfillment of the Radio Pattern Envelope (RPE) requirements of the ETSI specifications.

Power consumption and compliance with regulatory radiation masks were found as the main problems. The optimum output power of the power amplifiers (PAs) that minimizes the power consumption in PAA was analytically calculated.

The next sections of the paper are organized therefore as follows. Sections 2 and 3 describe the objectives and the methodology followed. Sections 4 and 5 present the results and discussions. Finally, Sect. 6 shows the conclusions.

2 Objectives

The objective of this work is to identify the main challenges of using PAAs to replace the reflector antenna used in conjunction with commercial point-to-point backhaul equipment at 26 GHz manufactured by SIAE Microelettronica. Considering the previous, the PAA must meet the following requirements:

1. The radiation pattern must comply with RPE class 2 of ETSI [4].
2. The SG must be maintained. It is defined by:

$$SG = P_{\text{tx}} \times G_{\text{tx}} \times G_{\text{rx}} \quad . \tag{1}$$

   The current equipment has an output power P_{tx}=30 dBm@P1dB, the antenna gain is $G_{\text{tx}}=G_{\text{rx}}=G$=36 dBi. Thus, the SG needed is 102 dBm.
3. The energy consumption must be as low as possible, considering that the current equipment has a power consumption lower than 100 W.
4. The PAA should be designed to work in a FDD system.

3 Methods

The PAA architecture consists of N active components connected to M antennas. Each active component has two phase shifters (PS), one connected to a power amplifier (PA), the other to a low noise amplifier (LNA) . Considering the previous, the approach is as follows:

1. The single antenna element of the PAA was designed and simulated.

2. Adjusting (1) to PAA, the array size (N, M) can be estimated by:

$$SG = (P_{\mathrm{tx}} \times N) \times (G \times M)^2 \quad . \tag{2}$$

where P_{tx} is the output power of each of N PAs and G is the gain of each of M patch antennas. Considering that $M = k \times N$, where k is the number of antennas that are grouped and handled by one active element, therefore:

$$SG = P_{\mathrm{tx}} \times G^2 \times k^2 \times N^3 \quad . \tag{3}$$

3. A simulation of the radiation pattern of a rectangular planar array was performed by using the results of the previous steps. Phased Array Antenna Toolbox™ of Matlab® was used for this purpose. The inputs of the simulations are the radiation pattern of the antenna element, the array size, the separation between antenna elements and the shape of the array.
4. The DC power consumption of N active components was estimated by [5]:

$$P_{\mathrm{DC}} = N \times \left(\frac{P_{\mathrm{tx}}}{\eta_{\mathrm{PA}}} + P_{\mathrm{TxOH}} + P_{\mathrm{DC-LNA}} + P_{\mathrm{RxOH}} \right) \quad . \tag{4}$$

where η_{PA} is the drain efficiency of the PAs. $P_{\mathrm{DC-LNA}}$, P_{TxOH} and P_{RxOH} are the power consumption of the LNAs, and of the overhead components (e.g. PS) respectively.

3.1 Approaches to Minimize the Power Consumption

Since one of the requirements is to minimize the power consumption of the PAA as much as possible, the following approaches were followed:

1. Subarrays: given a SG, (3) shows that if k increases, N decreases and according to (4), P_{DC} also decreases. However, because there is no phase control on each radiating element, a decrease in the performance of the beam steering is expected. The possibility of reusing the PA of the current equipment ($\eta_{\mathrm{PA}} = 15\%$, $P_{\mathrm{tx}} = 30$ dBm @P1dB) is used for the sake of an assumption.
2. PAs with an ad-hoc output power: this approach refers to the possibility of devising a PA with an optimum P_{tx}, where the optimum is such that it minimizes P_{DC}. In contrast to the previous approach, here all the antennas are considered active ($k = 1$) with the aim to have control over all of them.

4 Results

A microstrip patch was selected as antenna element due to its low profile, easy design and fabrication. The width and length of the antenna are 4.6×3.5 mm^2 respectively, using the substrate RT/duroid® 5880 ($\epsilon_{\mathrm{r}} = 2.2$, h = 0.508 mm). The resulting gain and bandwidth ($|S_{1,1}| < -10$ dB) were 6 dBi and 1 GHz respectively.

4.1 First Approach to Minimize the Power Consumption

Figure 1 was computed by using the results of the designed antenna, (3), (4) and the subarray approach described in the previous section. All the points along the dashed curve constitute valid combinations of (k,N) fulfilling the required 102 dBm of overall SG. On the leftmost end, 100 active elements ($N = 100$) would be needed if only one antenna is connected to each active element ($k = 1$). This amount of active elements leads to a huge power consumption (∼700 W) compared with the current consumption of the equipment.

The power consumption could be reduced to 280 W or even to 110 W if the subarray size k is increased to 4 or 16 respectively. This reduction is possible because the number N of active elements becomes 40 or 16 respectively.

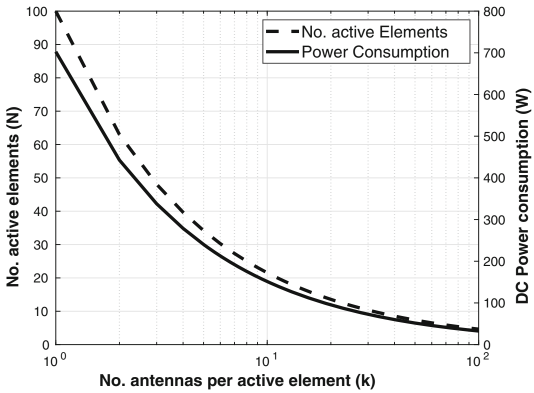
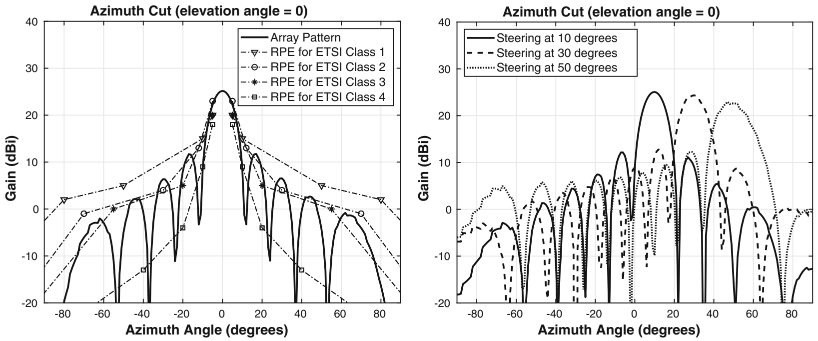


Fig. 1. Analytical trade-offs to achieve a given SG using PAAs. Assumptions: $SG = 102$ dBm, $P_{\text{tx}} = 30$ dBm, $G = 6$ dBi, $\eta_{\text{PA}} = 15\%$, $P_{\text{DC-LNA}} = 340$ mW, $P_{\text{TxOH}} = P_{\text{RxOH}} = 10$ mW.

Now that several possible pairs (M, N) can be chosen, the next step is to simulate the array pattern to validate the compliance of the RPE class and the beam steering capabilities.

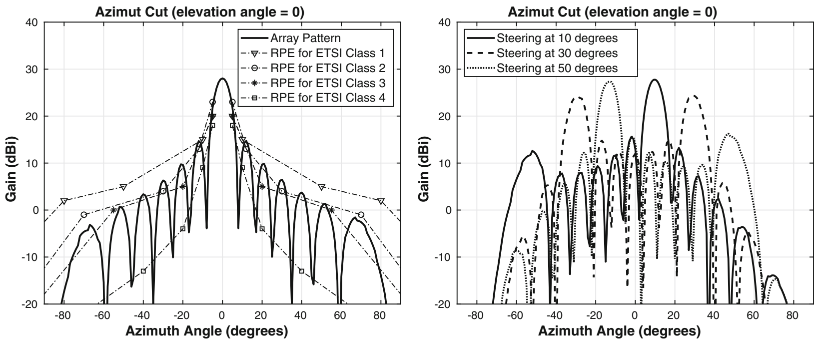
Figure 2 shows the simulated array pattern in the azimuth plane when $k = 1$ and $M = N = 100$. The shape of the array is a square of 10×10 antenna elements. Figure 2a, shows that RPE class 2 is not fulfilled. Figure 2b shows the beam-steering capabilities without any undesirable grating lobe up to $+50°$ of steering.

On the other hand, Fig. 3 shows the simulated radiation pattern in the azimuth plane when $k = 4$ and $N = 49$ (N was changed just to make a square array). The subarray shape is a square of 2x2 elements. The array shape is square of a 7x7 subarrays. Just like the previous case, Fig. 3a shows that the radiation pattern simulated also does not meet the RPE class required. Furthermore, Fig. 3b shows the appearance of grating lobes when beam-steering is applied. It is important to remark that the behavior is even worse when k increases more.



(a) Radiation Pattern (b) Beam-Steering Capabilities

Fig. 2. Simulation result of PAA. Array size : $M = N = 100$. Antenna element: patch antenna. Array illumination: uniform. Inter-antenna distance: $\lambda/2$.



(a) Radiation Pattern (b) Beam-Steering Capabilities

Fig. 3. Simulation result of PAA. Array size: $N = 49$, $k = 4$, $M = 196$. Antenna element: patch antenna. Array illumination: uniform. Inter-subarray distance: λ.

4.2 Second Approach to Minimize the Power Consumption

In contrast with the first approach, here the subarray size is always $k = 1$, therefore $M = N$. This assumption was chosen due to the degradation in the performance of beam steering when $k > 1$. The objective is to find the P_{tx} that minimize P_{DC}. A further assumption is that the efficiency of this ad-hoc PA remains the same η_{PA} of about 15%, since only a technological leap would alter this value significantly.

Figure 4 shows the numerical results using the aforementioned assumptions, (3) and (4). The solid line shows that if P_{tx} decreases, P_{DC} also decreases up to a minimum point. That point will be denoted as (P_{TxOP}, P_{DCmin}).

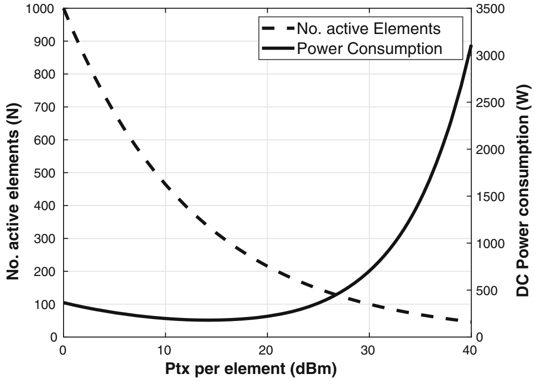


Fig. 4. Analytical result concerning PAAs. Assumptions: $SG = 102\,\text{dBm}$, $N = M$, $G = 6$ dBi, $\eta_{\text{PA}} = 15\%$, $P_{\text{DC-LNA}} = 340$ mW, $P_{\text{TxOH}} = P_{\text{RxOH}} = 10\,\text{mW}$.

According to Fig. 4, P_{TxOP} is around 15dBm with a P_{DCmin} estimated at 181 W approximately. Now, following the same approach of [5], this point is analytically calculated. Merging (3) and (4) we have:

$$P_{\text{DC}}(N) = \frac{SG}{N^2 \times G^2 \times \eta_{\text{PA}}} + [N \times (P_{\text{TxOH}} + P_{\text{DC-LNA}} + P_{\text{RxOH}})] \quad . \tag{5}$$

Minimizing (5) , therefore N_{OP}, P_{TxOP} and P_{DCmin} are respectively:

$$N_{\text{OP}} = \sqrt[3]{\frac{3 \times SG}{G^2 \times \eta_{\text{PA}} \times (P_{\text{TxOH}} + P_{\text{DC-LNA}} + P_{\text{RxOH}})}} \quad . \tag{6}$$

$$\frac{P_{\text{TxOP}}}{\eta_{\text{PA}}} = \frac{P_{\text{TxOH}} + P_{\text{DC-LNA}} + P_{\text{RxOH}}}{2} \quad . \tag{7}$$

$$P_{\text{DCmin}} = \frac{3}{\eta_{\text{PA}}} \times \sqrt[3]{\frac{SG \times P_{\text{TxOP}}^2}{G^2}} \quad . \tag{8}$$

Using the previous equations the optimal output power of each PA is $P_{\text{tx}} = 14$ dBm approximately. The corresponding optimum number of antenna elements is $N_{\text{OP}} = 342$ and the power consumption estimated is $P_{\text{DCmin}} = 180$ W. It is important to remark that all these values fit perfectly with Fig. 4.

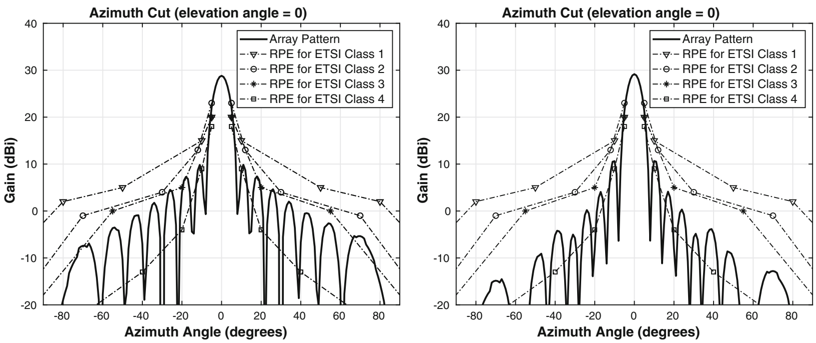
5 Discussion

As evident on the previous section, power consumption is one of the main problems arising with PAAs. To overcome this problem two approaches were studied. The first proposed approach to tackle the issue regarded the possibility of grouping antenna elements in active components in order to reduce the energy consumption. However, in spite of considerably reducing the energy consumption, a limitation with respect to beam-steering capabilities was evidenced.

On the other hand, in the second approach all antennas were fed by active elements. The P_{DC} can be reduced by carrying P_{tx} up to the optimum value P_{TxOP} that in this case is 14 dBm. It is important to recall that (7) shows that P_{TxOp} does not depend on the required SG or on the gain of the antenna element, it only depends on its efficiency and on the power consumption of the other elements in the active component. Furthermore, it is also important to highlight that this is a reference theoretical point. For practical implementations, it is better to work for instance at 18 dBm consuming 196 W instead of 180 W, but the number of elements is 252 instead of 342, which makes the design less complicated.

Even if the power consumption is reduced to acceptable levels and steering capabilities are provided without grating lobes, the fulfillment of the RPE specifications is still a problem. To overcome this problem, the radiation pattern can be tapered by a non-uniform illumination of the rectangular array or, instead, using a circular array. Figure 5 shows the compliance with RPE class 2 by using these two proposals. The drawback with a non-uniform illumination is that the gain of the antenna and the total output power are reduced. The first due to the efficiency of the illumination and the second because the antennas are fed with less power at the edges. In the particular case of Taylor illumination the reductions are 0.4 and 4 dB respectively.

Reflecting on the duplexing scheme, for FDD support, two separate arrays for Tx and Rx are required due to the difficulty to get enough Tx-Rx isolation (i.e. 65 dB from equipment specification) with a diplexer in such a small space (i.e. in the order of λ). However, even in this case, a filter is necessary to ensure the isolation and the compliance of the out-of-band emissions requirements [6].



(a) Square array with Taylor illumination with -18 dB of Sidelobe level.

(b) Circular array with uniform Illumination

Fig. 5. Simulation result of PAA. Array size : $M = N = 256$. Antenna element: patch antenna. Inter-antenna distance: $\lambda/2$.

6 Conclusions and Future Work

A study to identify the main challenges of using PAA in a commercial wireless backhaul equipment at 26 GHz has been carried out. An acceptable DC power consumption and the fulfillment of the RPE requirements were found as the biggest hurdles.

The RPE problems can be fulfilled by using nonuniform illumination in the array or by using a circularly shaped array. The best option is the second because it does not imply gain and power losses.

To get the best performance in terms of beamsteering capabilities all the antenna elements have to be fed by an active component at the expense of a high power consumption. To minimize it, a new amplifier has to be designed with an output power around the optimum point (i.e., from 14 dBm to 18 dBm), unless future technological advances allow higher efficiencies.

Despite the challenges encountered, the benefits of PAAs however outnumber such issues and thus demand further research for convenient adoption in commercial applications. Further research will also include: co-design of the antenna element with a low-order filter, integration issues with the equipment and fabrication techniques.

Acknowledgment. This work is funded by the H2020 research program 5G STEP-FWD under grant agreement No. 722429. For the advice throughout this research I thank Goran Biscevic from SIAE Microelettronica, Michele D'Amico and Gian Guido Gentili from Politecnico di Milano.

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