Iterative Calibration Method for Integrated Tunable mmW Vector-Sum Phase Shifter

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***Abstract*—An iterative calibration method of 5G mmW vector-sum phase shifter (VSPS) is presented in this paper. The phase and amplitude imbalances of I and Q branches can be tuned. The phase is adjusted with a tunable polyphase filter (PPF) by changing its resonance frequency. The VSPS is equipped with differential amplifiers on each branch which are used to compensate for the amplitude imbalance. The iterative calibration method uses information collected during the measurements and adjusts VSPS parameters towards the optimal operation point. The error vector magnitude (EVM) of VSPS phase constellation decreases fast along the iterations, and the calibration process can be finished with a fraction of the measurement time compared with exhaustive search. Results show that the method can reach an RMS amplitude error of 0.11 dB and phase error of 0.6 degrees on selected frequency points.**

***Index Terms*—Vector modulator, phase shifter, phased array, calibration, millimeter wave.**

I. INTRODUCTION

Phased arrays are used to provide a high and steerable antenna gain in 5G millimeter wave (mmW) and forthcoming 6G communication systems [1] to compensate for significant signal path loss. Antenna arrays require the gain and the phase of the individual antenna elements to be accurately controlled. The phase shifting can be performed by changing the characteristics of the transmission line, either using switches to change the length or the filter parameters of the line [2]. Another method for phase shifting is to split the signal into two orthogonal components and control the relative amplitude of the components before summing up the signals [3]. This type of phase shifter is called vector-sum phase shifter (VSPS), which has the benefit of a smaller required die area compared with the other techniques.

Tunable VSPS [4], [5] enables widening the operating frequency range of VSPS and having amplitude control for example for tapering purposes. With extra gain stage, amplitude control is achieved without reduction in phase resolution. Vector modulator requires calibration to find the optimal control parameters for a certain operating point, ie. center frequency in this case. High frequency phased arrays require numerous antennas to be used [6] to compensate for the small aperture of individual antenna. Large antenna array requires phase shifter in each antenna interface. Hence, an efficient way to calibrate the phase shifters is needed.

In this paper, we present iterative calibrating method for VSPS, which requires significantly fewer measurements compared with exhaustive search procedure. Calibration can be done in many ways, two common techniques are laboratory measurements [7] and build-in-self test (BIST) [8], [9]. The calibration method in this paper is demonstrated with measurements done in laboratory environment. The method can be used for reducing calibration time in manufacturing line but has potential to enhance BIST calibration as well.

II. PHASE SHIFTER TOPOLOGY

A simplified block diagram of VSPS, used in this work, is presented in Fig. 1 [4], which supports 5G mmW 3GPP frequency range 2 operation [10]. The VSPS generates two orthogonal signals, with tunable polyphase filter (PPF). Since PPF can provide perfect quadrature generation only on a narrow band, wider operation range can be achieved by tuning the operation frequency. I/Q branches are equipped with differential amplifiers to compensate for amplitude imbalance, but also to reduce common mode signal after PPF. The actual phase shifter constellation is then generated with quadrature switches, which select the constellation quadrant, and variable gain amplifiers (VGA). In total the VSPS has 10 bit cartesian control and 1024 states for generating phase shifter constellation points. For calibration, 3 bit PPF frequency control (PPF_{freq}), 3 bit differential amplifier bias ($DAmp_{biasI/Q}$) and 4 bit VGA bias control ($VGA_{biasI/Q}$) are used.

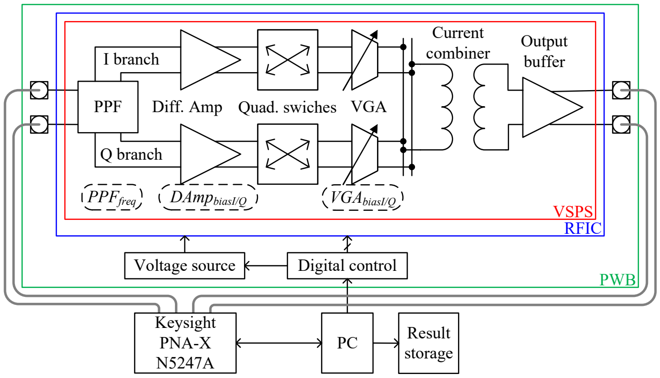


Fig. 1: Topology of vector-sum phase shifter implementation used in this work [4] and measurement setup, controlled parameters highlighted with dashed line.

Fig. 2 depicts non-ideal shape of the entire phase shifter constellation. In the figure, A_I and A_Q are amplitude ranges in I and Q direction, which can differ, causing the phase shifter constellation to squeeze. The angle between I and Q branches can also differ from optimal 90°, which is marked in the figure by α. To calibrate the VSPS, the angle α equal to 90° and matching of A_I and A_Q is desired.

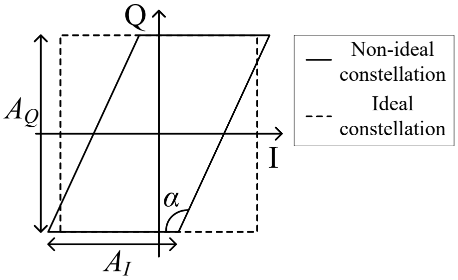


Fig. 2: Contour of phase shifter constellation presenting VSPS non-ideal behaviour, ideal contour presented with dashed line.

III. MEASUREMENT METHODOLOGY

The measurements were done with the setup presented in Fig. 1. VSPS was implemented with 45 nm CMOS SOI technology as part of a 5G mmW RFIC, which was then flip chip bonded to prototype printed wiring board (PWB). Differential input and output signals were routed from VSPS to PWB connectors, which were cable connected to a vector network analyser (PNA-X). The whole measurement setup was automated with a PC running Matlab to control the RFIC, the supply voltages and the measurement equipment.

In optimal VSPS, amplitude and phase between the I/Q branches can be tuned independently. Unfortunately, this is rarely the case in practical realization, and tuning one parameter has effect on the other. This is illustrated, as an example, in Fig. 3, where $DAmp_{biasI}$ has been swept and constellation points $1+0i, 0+1i, -1+0i$ and $0-1i$ are plotted. It can be seen that amplitude control is also rotating the phase of the constellation points. Although only the I branch amplifier is tuned, small effect on Q component is also visible at the bottom-most constellation point. These four points are also used in latter to measure amplitude and phase difference between I and Q branches, since the points are having only either I or Q component. Relationship between four measurement points to full phase shifter constellation is presented in Fig. 4.

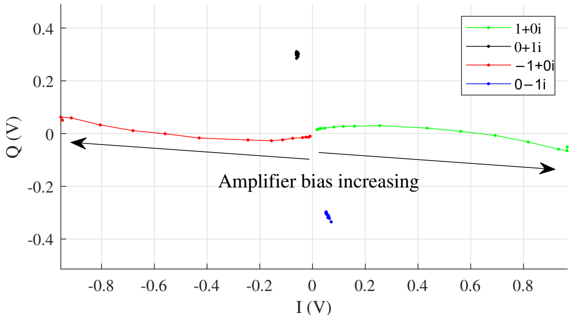


Fig. 3: I/Q plane phase shifter constellation points by sweeping differential amplifier bias control ($DAmp_{biasI}$), showing the non-liner behavior of the control.

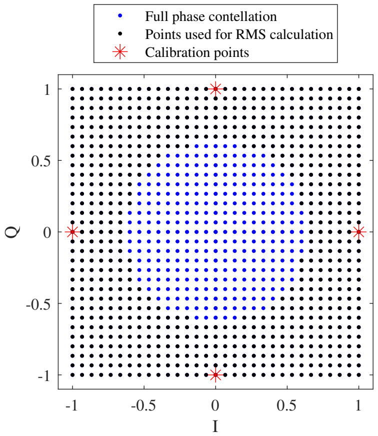
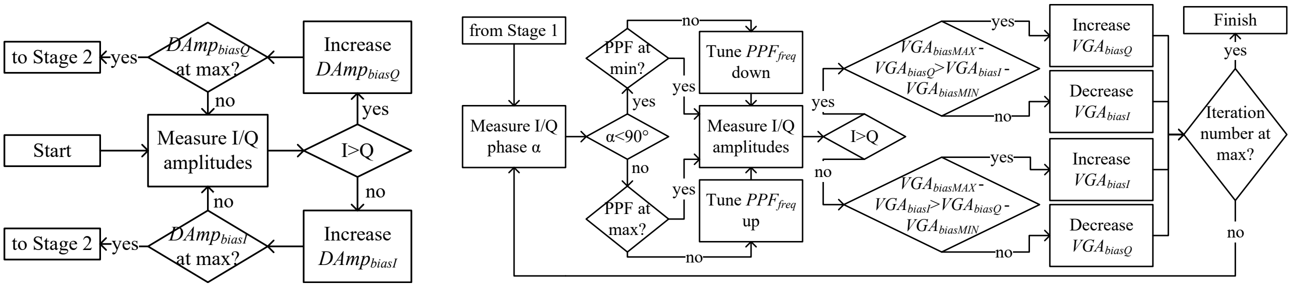


Fig. 4: Normalized ideal phase shifter constellation for VSPS.

Usually, the problem of mutual effect on different control parameters is taken care of by exhaustive search, were every control parameter is swept against every other control combination. The problem with this method is large amount of measurements required to find the best combination. In this work, we propose an iterative calibration method, which employs information from previous iterations to adjust the control parameters for the next one. The method is divided into two stages. In stage one, illustrated in Fig. 5a, I/Q amplitudes are adjusted with $DAmp_{biasI/Q}$ by starting from the lowest control value and after each measurement the control of the branch with lower amplitude is increased. By stepping through the controls to the highest value, the method will go through the control value pairs out of which the pair giving the minimum I/Q amplitude imbalance can be found and is then selected for the next stage. In stage two, illustrated in Fig. 5b, PPF_{freq} is used to adjust I/Q phase α towards optimal $90°$, but because PPF control has effect on amplitude as well, $VGA_{biasI/Q}$ is used to fine tune amplitude imbalance. First, the phase is measured and the result is used to tune PPF parameter to compensate offset. Next, amplitude balance is measured and the amplitude control which is further from its limit ($VGA_{biasMAX/MIN}$) is changed. These two steps are then alternated until the limit on the number of measurements is reached. An example of measurement results from iterative process is presented in Fig. 6.

The number of measurements needed in the proposed calibration method is significantly less compared with exhaustive search. Exhaustive search would take $N_{meas} = 4 * N_{DAmp}^2 * N_{PPF} * N_{VGA}^2$ measurements, where N_{DAmp}, N_{PPF} and N_{VGA} are the number of differential amplifier, PPF and VGA control words respectively. In this VSPS implementation exhaustive search would be impractical with over $524k$ measurements. In the proposed method the maximum number of measurements was limited to 100, corresponding to 25 iterations, but even a lower number could be sufficient, as seen in Section IV. With exhaustive search, one option is to limit search space, but this possibly limits the best control parameters out from the measurement set. The proposed calibration method does not suffer from this limitation as it



(a) Stage 1

(b) Stage 2

Fig. 5: Flow chart of iterative calibration method.

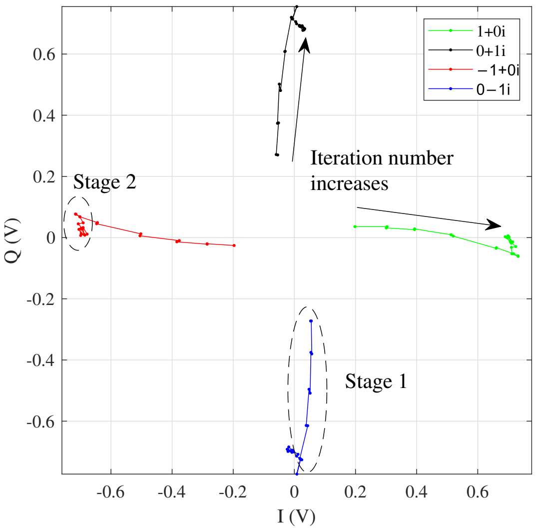


Fig. 6: Measurement results of the iterative method at 28 GHz, presented in I/Q plane.

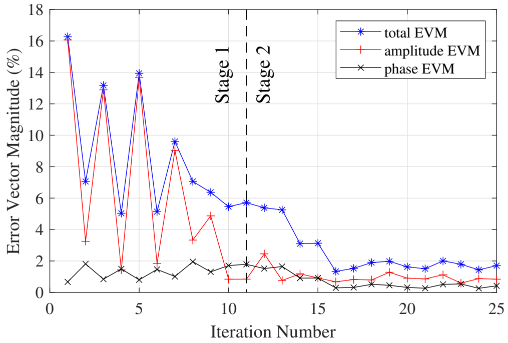


Fig. 7: Convergence of EVMs based on four calibration points at 28 GHz.

can use all possible control values.

IV. RESULTS

Phase shifter constellation points over measurement iterations are presented in Fig. 6, for each iteration we can also calculate error vector magnitude (EVM) for the measurement points. Further EVM value can be divided into amplitude and phase errors. This is presented in Fig. 7, where the convergence of the method is clearly seen, as the error decreases rapidly over iterations. During stage 1, amplitude error steps up and down with every other iteration, this is because amplitude control of I and Q branch has similar step size and once fairly good match is found then the next iteration need to make error larger to go to the next, higher, amplitude control values. In stage 2, phase control is used and so phase error is clearly improved in first few iterations. Method converges to very low error values before the loop is interrupted, but finding the limit for adequate error level was out of the scope of this work.

In Fig. 8, full phase shifter constellation is presented before and after the calibration process at 28 GHz. It can be seen that after calibration the constellation is much closer to the optimal square shape. To see the efficiency of executing calibration measurement with only four constellation points, the root mean square (RMS) error is calculated. The calculation is done over the constellation points located outside of -7 dB circle compared to the maximum constellation point power, this is illustrated in Fig. 4 with black points. RMS phase and amplitude error was calculated after calibration for four frequency points. The results, presented in Fig. 9 and Fig. 10, show that amplitude error under 0.16 dB and phase error under 1.9 degrees was achieved over the whole frequency range.

In Table I, performance is compared with results presented in [4], both the minimum and maximum error level over frequency range of 26-29 GHz are presented. Similar performance levels are reached, even though in this work the VSPS is part of larger design, requiring additional signal routing. In [4], VSPS was independently measured by using an exhaustive search method with reduced search space. The search space was limited by skipping part of the control values. In this work, the reduction of measurements needed to calibrate VSPS is 20 folds even compared with limited search space and compared with full exhaustive search over 5000 folds.

V. CONCLUSION AND DISCUSSION

This paper presented an iterative calibration method for mmW VSPS. The method can minimize EVM calculated from four phase shifter constellation points with under 25 iterations. Effective iteration count can be even lower when multiple frequencies are calibrated. Because amplitude tuning

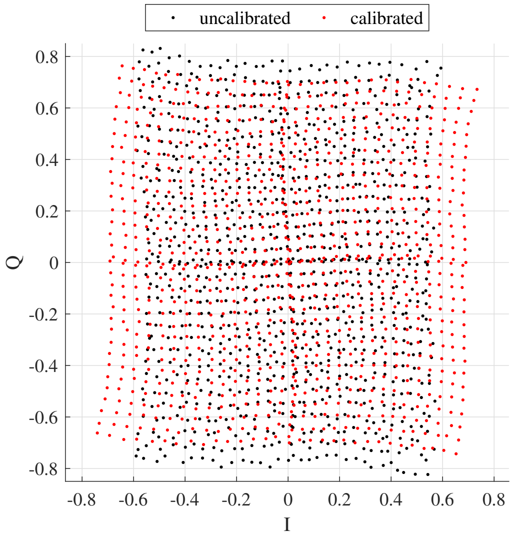


Fig. 8: Measured VSPS constellation before and after calibration at 28 GHz.

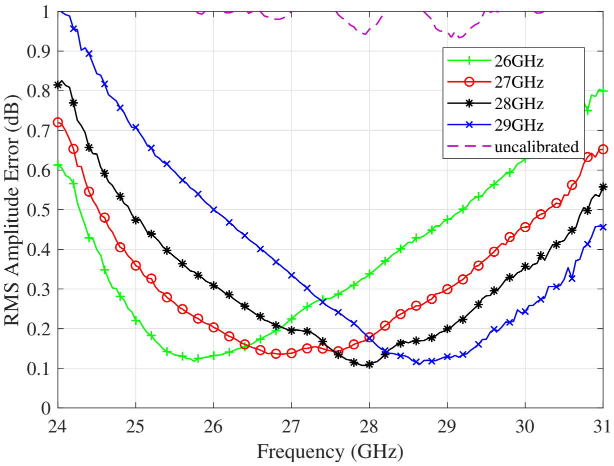


Fig. 9: RMS amplitude errors before and after iterative calibration at four different frequency points.

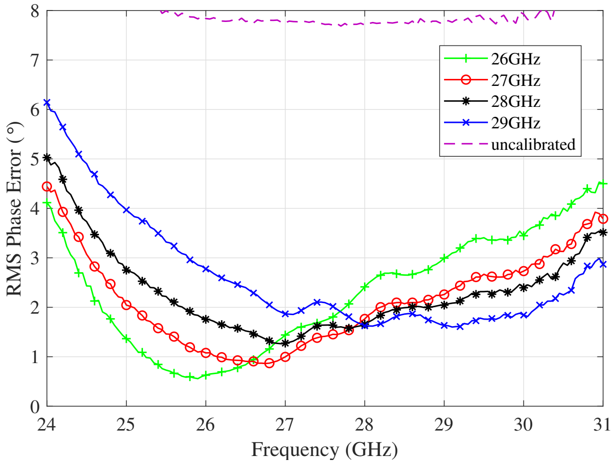


Fig. 10: RMS phase errors before after iterative calibration at four different frequency points.

TABLE I: Calibration performance comparison.

	N_{meas}	RMS ampl. error	RMS phase error
This work	< 100	0.11-0.16 dB	0.6-1.9°
Work in [4]	2048	0.08-0.17 dB	0.6-1.1°
Exhaustive	524k	NA	NA

is wide band, amplitude iterations can be reused for multiple frequency points. The only limitation of the method is that the amplitude and phase controls need to be monotonic, otherwise wrong decisions can be made, breaking the convergence. The method was demonstrated with tunable VSPS measured in lab environment, but the method can be utilized also with BIST implementations. The measurements were done cable connected, but over-the-air measurements are also possible. Results show over 0.8 dB improvement in RMS amplitude error and over 6 degree improvement in RMS phase error compered with the uncalibrated system.

ACKNOWLEDGMENT

Nokia is acknowledged for financing the project, GlobalFoundries for chip processing and Keysight for providing measurement equipment. This work was supported in part by the Academy of Finland, 6G Flagship program under Grant 346208 and Business Finland projects NGmining (44049/31/2020) and RFSampo (3071/31/2021).

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