ESL-IC-10-10-26

Antenna Beam Steering For Wireless Sensors Using Real Time Phase Shifter

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***Abstract*— As part of the increasing demand for accurate, secure and robust short range wireless sensors for Smart Grid systems, we present the design and the simulation of phased array transmitter with variable delay based phase shifters. Multiple antennas are used to achieve beam steering using active beamforming technique. Our design exploits the multiple signal paths. In addition, the transmitter will provide feasible directional point-to-point communication networks via transmitting the signal to the preferred receiver with the desired coverage. The sensitivity and the accuracy of the system are enhanced in terms of object identification and location, respectively. This wireless sensor appears well suited for use in Smart Grid technologies operating at 2.4GHz ISM band with 250kbps data rate capacity where minimum cost and high integration are valued.**

***Index Terms*—** Analog Integrated Circuit, Antenna Beam Steering, Beamforming, Delay Locked Loop (DLL), Phase-Shifter, Phased-Array, Radio-Frequency (RF), Wireless Sensor.

I. INTRODUCTION

A wireless sensor network consists of spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions. The development of such wireless sensors was motivated by military applications. They are now used in many civilian applications like Smart Grid systems. Wireless sensors using phased array transmitter based directional antenna are becoming very popular. They can offer significant increases in data rates without additional bandwidth. In addition, phased array transmitters allow electronic beam steering and interference reduction at the receiver. Hence, spatial directivity and array gain properties of such systems can increase the spectral efficiency and channel capacity. This is illustrated in Figure1.The integration of directional antenna in such a system reduces power consumption in energy constrained wireless sensor networks.

A key component in a phased array system is phase shifters to adjust the phases of the multiple antennas in order to generate multiple beams for spatial multiplexing. Various implementations of variable phase shifters have been reported. The first technique is the distributed-type (DT) phase shifters [1-3].This technique requires transmission lines with lengths proportional to the signal wavelength, which would result in prohibitively large die sizes for applications in the 2.4-GHz band. The second technique utilizes a vector sum of two or more RF signals with orthogonal phases termed as vector-modulator phase shifters. Depending on the signal directions, this technique can be divided into a) forward-type phase shifters (FTPS) [4, 5] and b) reflective-type phase shifters (RTPS) [6, 7]. The use of wavelength-proportional passive couplers in this technique would also result in a large die size at 2.4GHz and limits its applications. The third category uses all-pass network (APN) [8, 9]. However such designs are prone to varying insertion loss in the phase-shift tuning range.

In this paper, we propose delay locked loop (DLL) based phase shifters to solve the problems mentioned above at 2.4GHz band applications. A DLL provides a process, voltage, and temperature (PVT)-compensated delay that can be used to phase shift the reference clock. We designed a simple programmable delay based digital phase shifter to achieve the phase shifting functionality within the DLL. Such digital phase interpolators are very suitable for low-voltage CMOS process yielding low power solutions. Also, we have incorporated analog feedback mode to

calibrate for errors occurring in the desired phased shifts.

The paper presents the derivation of the phase shift requirement between individual antenna elements to steer the beam in a particular direction in section II. In section III, beamforming properties of phase array transmitters are discussed. The system architecture of our proposed DLL based phase shifter along with analog feedback correction circuit is discussed in section IV. Next we describe in details the circuit design of functional blocks in section V. In section VI we provide the simulated results and conclude with section VII.

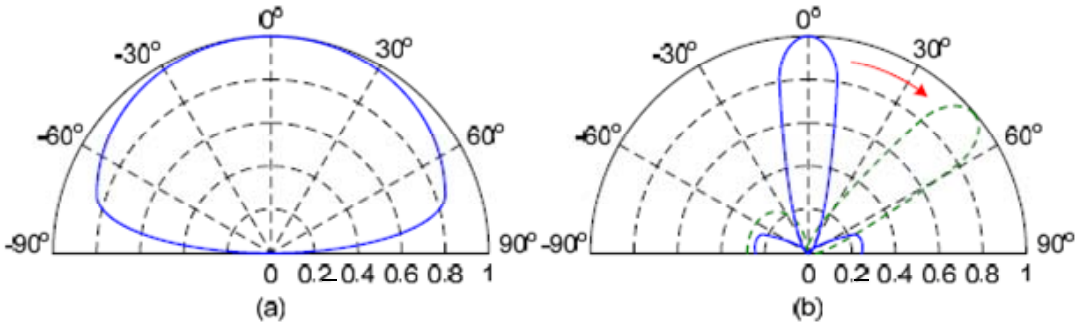


Figure 1. Rotation pattern of (a) individual antenna (b) antenna array with beam-steering and interference reduction capability

II. ANTENNA BEAM STEERING USING PHASED ARRAY TRANSMITTER

The phase shift between individual antenna array elements can be designed for the major lobe or beam being pointed in one direction or more. If all the elements of a linear array or plane array are in phase, the beam will be directed broadside in which the main beam direction is normal to the line of the array. On the other hand, if the phases of the elements of a linear array progressively change by an amount per element that is equal, in radians, to 2πd/λ, where 'd' is the element spacing and 'λ' is the wavelength, the beam direction will be parallel to the line joining the elements termed endfire. Furthermore by progressive phase changes, beams may be directed at intermediate angles. To illustrate this point, we consider a linear array of four radiating elements as shown in Figure 2. In order to point the array to (θ_0, Φ_0) general expression for phase progression as follows:

Array Factor:

$$= F_Y(\theta,\Phi) = \sum_{n=1}^{4} a_n e^{j2\pi\frac{nd}{\lambda}(\sin\theta\sin\Phi-\sin\theta_0\sin\Phi_0)}$$

This is achieved via designing relative phase shift between array elements as

$$\alpha_Y = \frac{-n2\pi d}{\lambda}\sin\theta_0\sin\Phi_0$$

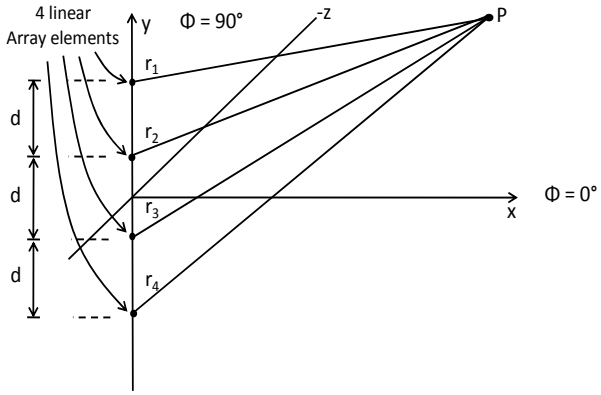


Figure 2. Linear array of four radiating elements

III. ACTIVE BEAMFORMING USING PHASED ARRAY TRANSMITTER

The beamforming properties of phased-array transmitters provide two significant advantages over isotropic transmitters. Firstly, for the same total transmit power, the power of the receiver is increased. The improvement comes from the coherent addition of the electromagnetic fields in the desired direction and attenuation in other directions. Secondly, the interference at receivers that are not targeted are reduced.

The operation principle of electronically controlled beamformer is shown in Figure 3(a). With n paths spaced a distance 'd' apart, excess delay 'τ_k' experienced by k^{th} part is

$$\tau_k = (n-1)\frac{d\sin\theta}{c} = (n-1)\tau$$

where

τ_k is spatial phase shift, 'c' is speed of light and 'θ' is signal transmission angle

The delay in each path essentially indicates spatial phase difference. The signals transmitted by the first and k^{th} path are given by

$$S_0(t) = A(t)\cos[\omega_c t + \Phi(t)]$$

$$S_k(t) = S_0(t - \tau_k)$$

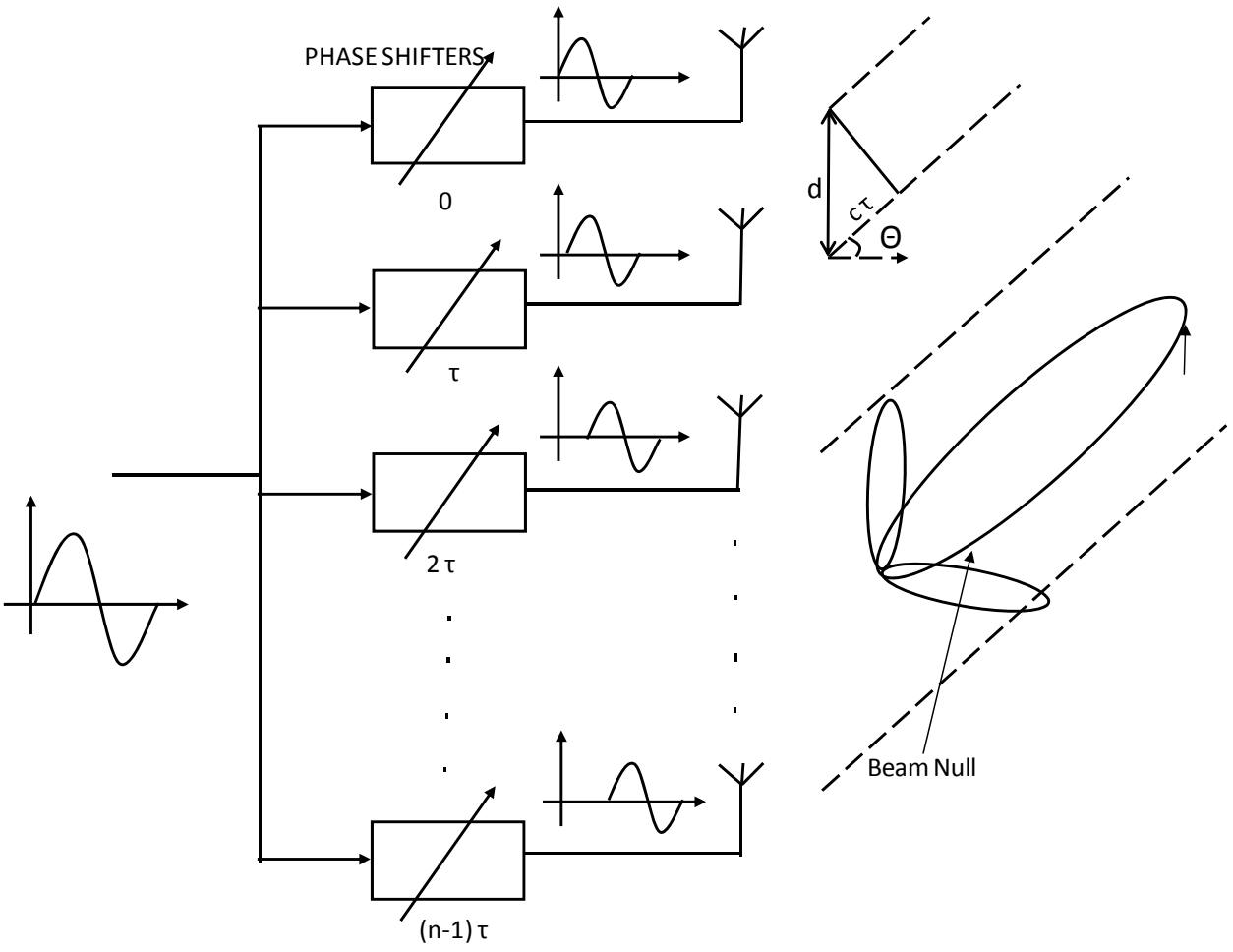


Figure 3(a). n-path Beamforming Transmitter

In order to compensate the signal delay and spatial phase difference arising out of it, ajustable time-delay elements τ_k‘ is introduced. This indicates intrinsic phase difference between array elements.
The combined signal is expressed as

$$S_{sum} = \sum_{k=0}^{n-1} S_K(t-\tau_k') = \sum_{k=0}^{n-1} S_0(t-\tau_k'-\tau_k)$$

$$= \sum_{k=0}^{n-1} [A(t-\tau_k'-\tau_k)\cos\{\omega_c(t-\tau_k'-\tau_k)+$$

$$\phi(t-\tau_k'-\tau_k)\}]$$

If $\tau_k' = \tau_k$, signals from a particular direction can be added coherently while signals from other directions are added destructively. The total output signal strength in the desired direction can be expressed by

$$S_{sum}(t) = nA(t)\cos[\omega_c t + \Phi(t)]$$

Figure 3(b) shows RF-phase shifter based transceiver circuit forming a steerable beam pattern usable in wireless sensor applications. The architecture uses one digital-analog converter (DAC), one RF mixer (MX), N RF phase shifters (PS) and N Power Amplifiers (PA) in the transmitter. The receiver implements N low noise amplifiers (LNA), N RF phase shifters, one RF mixer and one analog-digital converter (ADC). There is one RF signal that is copied and phase-shifted for each antenna in the transmitter. In the receiver, each antenna’s incoming signal is phase-shifted to align them all.

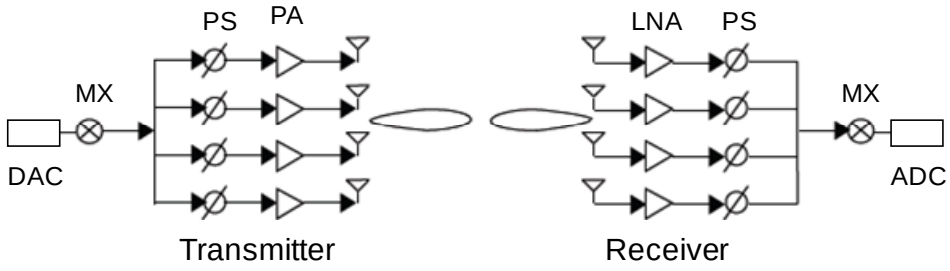


Figure. 3 (b)

IV. SYSTEM ARCHITECTURE DESCRIPTION

The designed system will vary the phase fed to the individual elements of the array in discrete steps to enhance the directivity and the beam steering of the array.

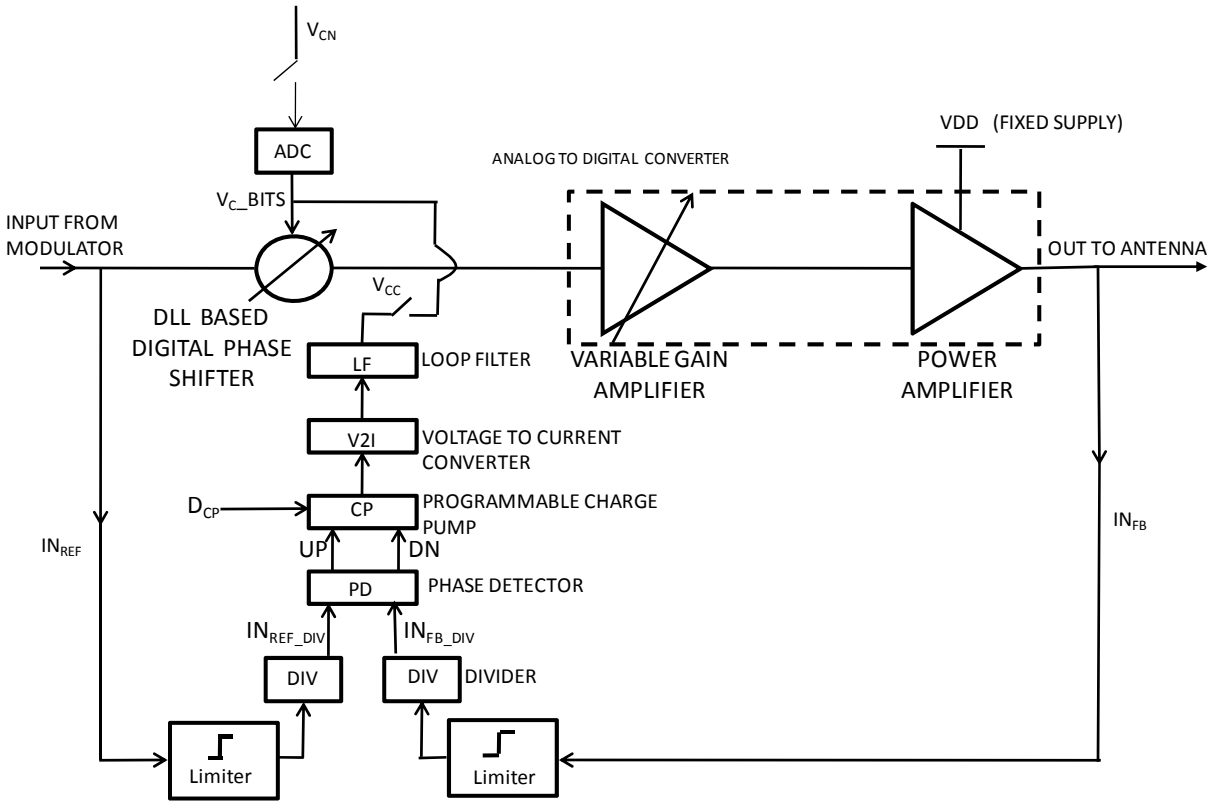
It consists of DLL based digital phase shifter, variable gain amplifier, power amplifier feeding to antenna array as shown in Figure 4.

In this paper the circuit design of DLL based digital phase shifter and error correction feedback loop is done. The remaining components are shown in dotted lines for illustration purpose.

The system has 2 modes of operation: (i) Normal transmit mode (ii) Error correction mode.

In the normal transmit mode the digital control voltage for the phase shifter is applied via Analog to Digital Converter. The I/Q modulator applies the modulated signal to the input and the phase shifter applies the desired phase shift. The phase shift is achieved via internal programmable delay block. This in turn sets relative phases between array antennas for beam-steering in a particular direction. In this mode the feedback loop is disconnected. The design will employ beam-scanning range of 180 degrees in several discrete steps which will lead to wide scanning range with less scanners being employed, bringing down the system cost.

In the error correction mode, feedback circuitry monitors the round-off phasing errors of the phase shifters, and alters the settings at certain times in order to compensate for and eliminate the effects of the accumulated round-off phasing errors. Thus, improvements in beam-steering accuracy and other characteristics are obtained. The system is simplified and the cost is minimized because fewer (and coarser) steps of selectable phase shifts can be employed.



NOMENCLATURE:

IN_{REF} = Input Single Tone Carrier (Calibration Mode)
= Input Modulated, Up-converted Carrier (Transmit Mode)

$D_{CP} = I_{UP} / I_{DOWN}$ control bits

IN_{REF_DIF} = Input reference signal after it has passed through limiter and divider

IN_{FB_DIV} = Phase shifted output signal after it has passed through limiter and divider

IN_{FB} = Phase Shifted and Amplified signal

V_{CN} = Phase shift control voltage (Transmit Mode)

V_{CC} = Phase shift control voltage (Calibration Mode)

V_{C}_BITS = Digital Phase shift control bits

UP/DN = Up and Down pulses from phase detector output

Figure 4. System Architecture

V. CIRCUIT DESCRIPTION OF FUNCTIONAL BLOCKS

A) Delay-Locked Loops (DLL) based digital phase shifter: A Delay Lock Loop is the circuit that synchronizes the final output phase of the signal with the reference input signal so that the output time period is exactly equal to the reference signal time period. It also ensures that all the consecutive delay block phases are equally spaced despite process and temperature variations. The basic block diagram of our designed DLL block along with programmable delay is shown in Figure 5.

The DLL consists of three basic functional blocks a) Voltage Controlled Delay Line (VCDL) (Figure 6) b) Phase Detector (Figure 7) c) Charge Pump (Figure 8). The phase difference between final output phase, FB_CLK and the reference signal, REF_CLK is sensed by the phase detector, a proportional average voltage, Vctrl, is generated, and the delay of the stages is adjusted with negative feedback.

Thus, in the locked state, the phase difference between REF_CLK and FB_CLK is almost 180° i.e. the reference signal is delayed by exactly half clock duration by the delay cells in the VCDL thereby establishing precise edge spacing between the consecutive phases. The charge pump is used to achieve a very high loop gain. Reset mechanism is implemented to initially set the control voltage to the supply voltage to set minimum delay between the edges. This will prevent *false locking phenomenon.*

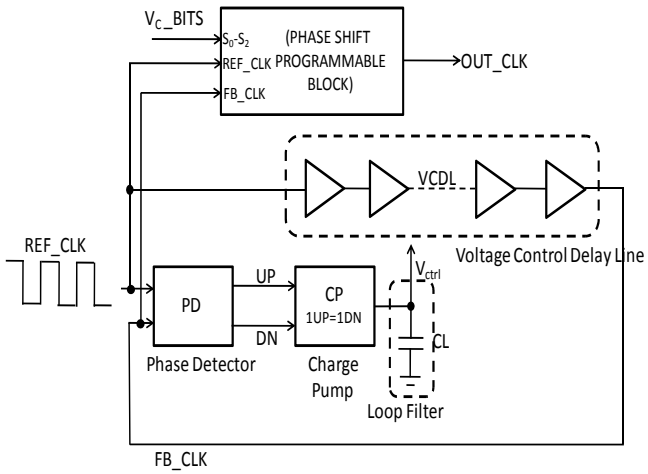
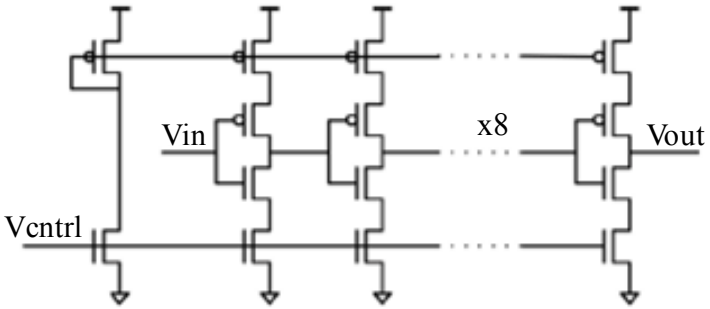
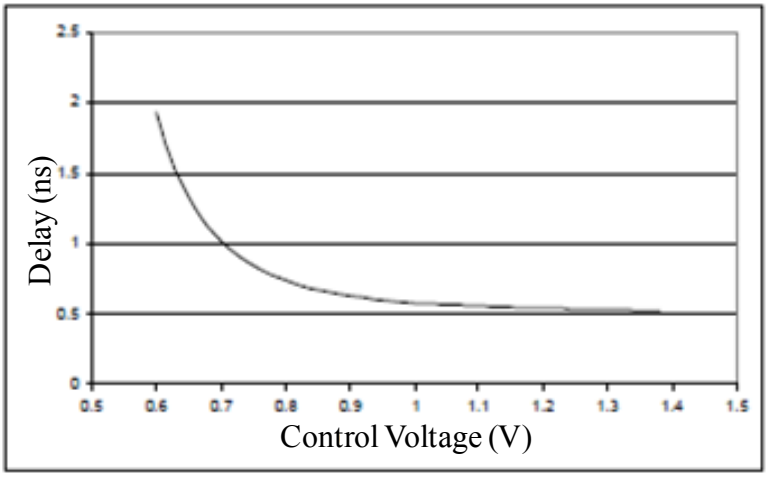


Figure 5. DLL based Digital Phase Shifter



(a)



(b)

Figure 6. Delay Cell used in Voltage Controlled Delay Line

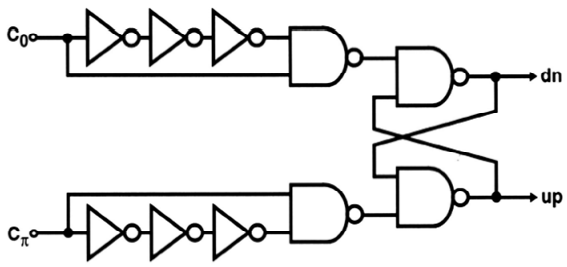


Figure 7. Phase Detector circuit

Additionally *charge sharing problem* due to finite capacitance at the drains of the current sources is avoided using "bootstrapping" circuit in the charge pump as shown in Figure 8.

Different phase shift with respect to REF_CLK is achieved using a nand delay based programmable block as shown in Figure 9. The REF_CLK and FB_CLK can be digitally programmed to be delayed corresponding to phase shift requirements of individual array elements. The relative phase shifts between antenna array elements can thus be programmed to steer the main lobe towards the required direction.

B) Phase Shift error correction mode via negative feedback: In the error correction feedback mode, the input signal is compared to the phase shifted signal at the output. Both signals are amplified by the limiter and divided down before applying to the phase detector input. The charge pump is designed to have variable I_up currents controlled via digital input Dcp as shown in Figures 4, 13 and 14. If I_up and I_dn are set equal to each other, the reference input and feedback input must be offset from each other by 180degrees. This is because in each cycle the charge added by charge pump with Up current must be equal to the charge removed with the Down current. If the relative Up and Down currents are changed, the phase offset between the input and output signals changes as well. We exploit this inherent property to compensate for the phase shift errors appearing due to changes in the operating conditions.

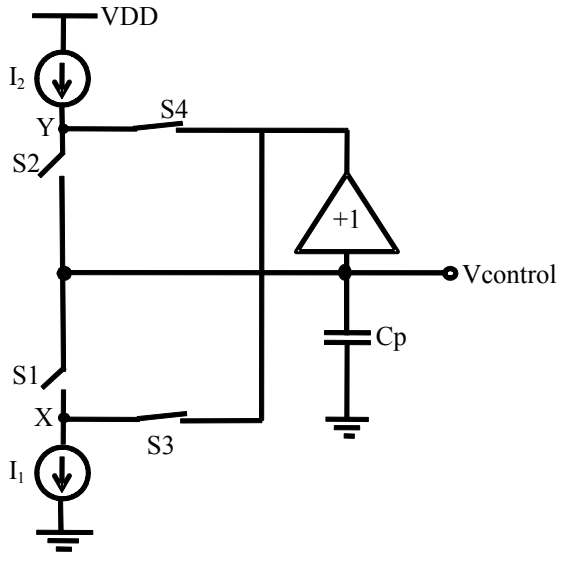


Figure 8. Charge Pump circuit

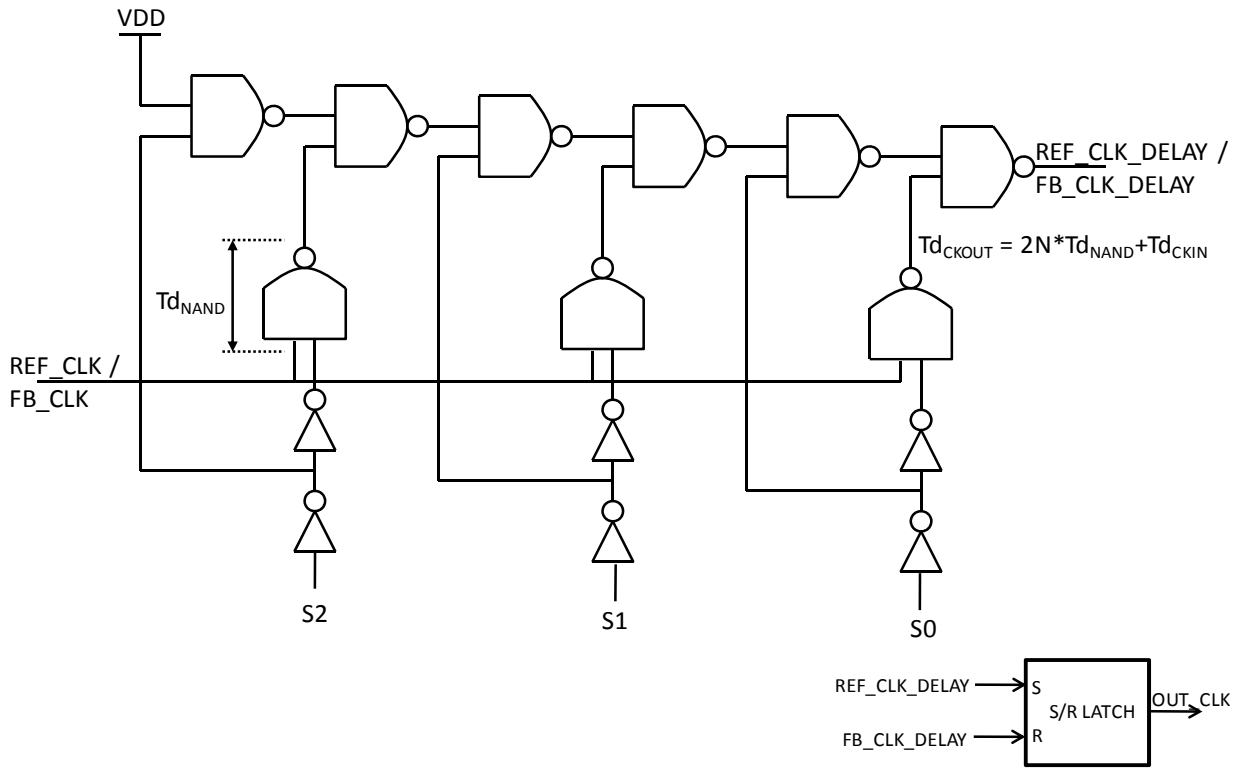


Figure 9. Programmable Delay block for adjusting Phase Shifts

VI. SIMULATION RESULTS

The complete DLL circuit is implemented using *Cadence Spectre* tools. Fig.10 shows the comparing clock phases i.e. REF & FB<4> (reference and feedback signals), the pulses UP & DN generated by the phase detector and the change in control voltage BIASNA as the time progresses. At the onset, reset pulse is applied and the circuit starts with minimum delay. We get DN pulses broader compared to UP pulses that leads to slowing down the delay cells via decrease in control voltage BIASNA as time progresses. As time progresses, the two clock phases shift reaches 180 degrees .When this happens, the UP & DN pulses have equal width and the control voltage stabilizes leading to lock condition as shown in Fig.11. At lock conditions the REF & FB<4> clock phases are half-time period apart & are passed through phase shift digital programmable block to generate relative phase shifts between individual array elements. Fig.12 shows one particular relative phase shift of 7 degrees settings between individual array elements.

In the error correction mode, the input signal is compared to the phase shifted signal at the output. Fig.13 shows the phase shift fixed at 180 degrees for I_up = I_dn (up and down currents from charge pump). The charge pump current is changed via control bits for different settings. In case of I_up > I_dn, phase shift is controlled at less than 180 degrees as shown in Fig.14. Radiation pattern for antenna arrays is shown in Fig.15 (a) and (b) via Matlab plots. Planar antenna array main lobe is scanned via changing relative phase shift between array elements using our DLL based digital phase shifter.

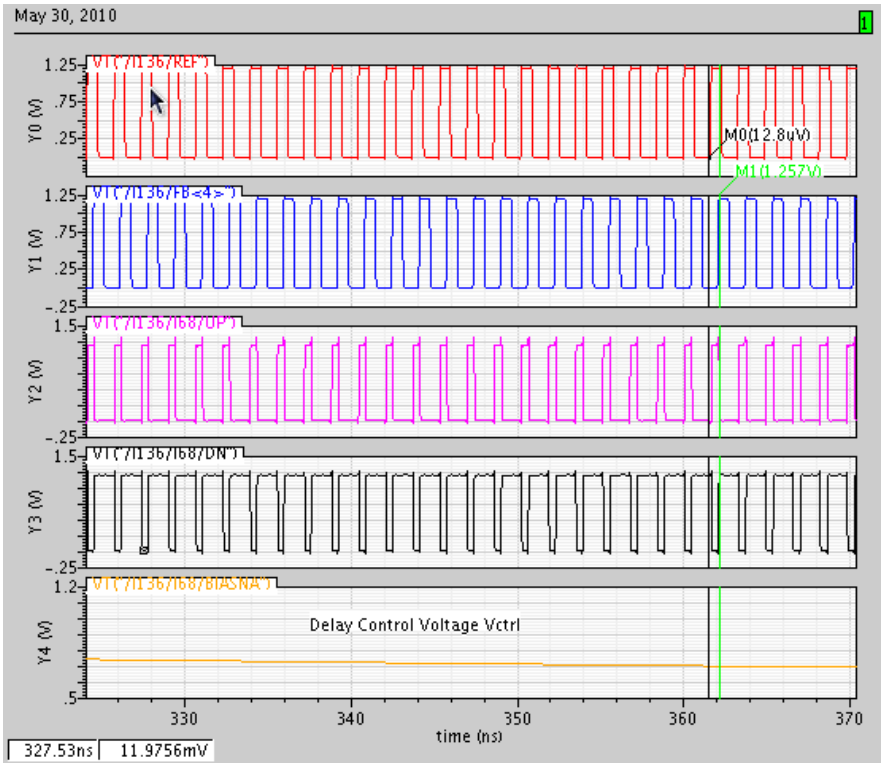


Figure 10. DLL Internal Signals initially as time progresses

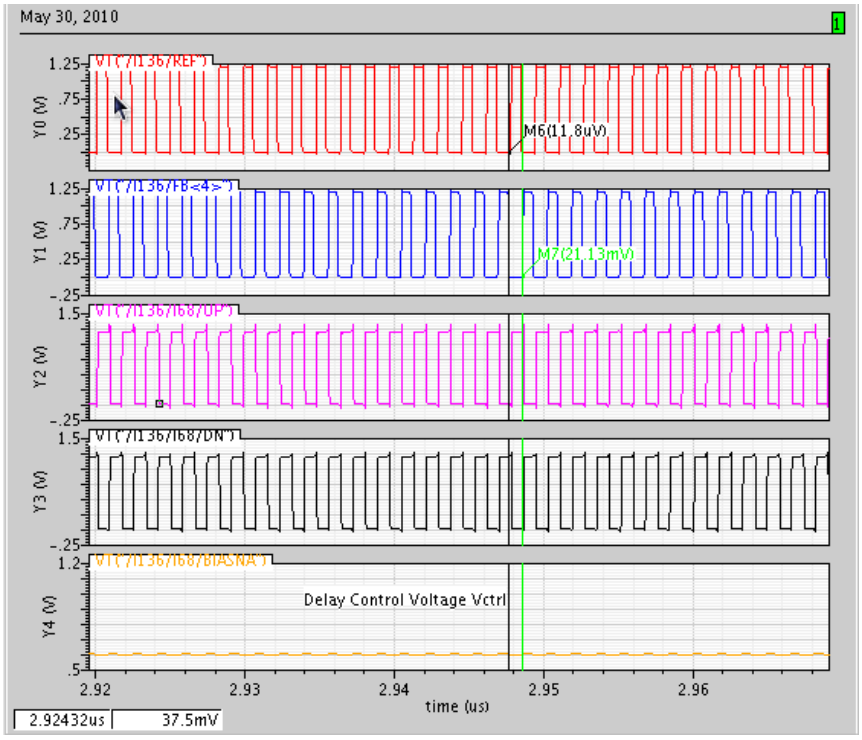


Figure 11. DLL Internal Signals at Lock Condition

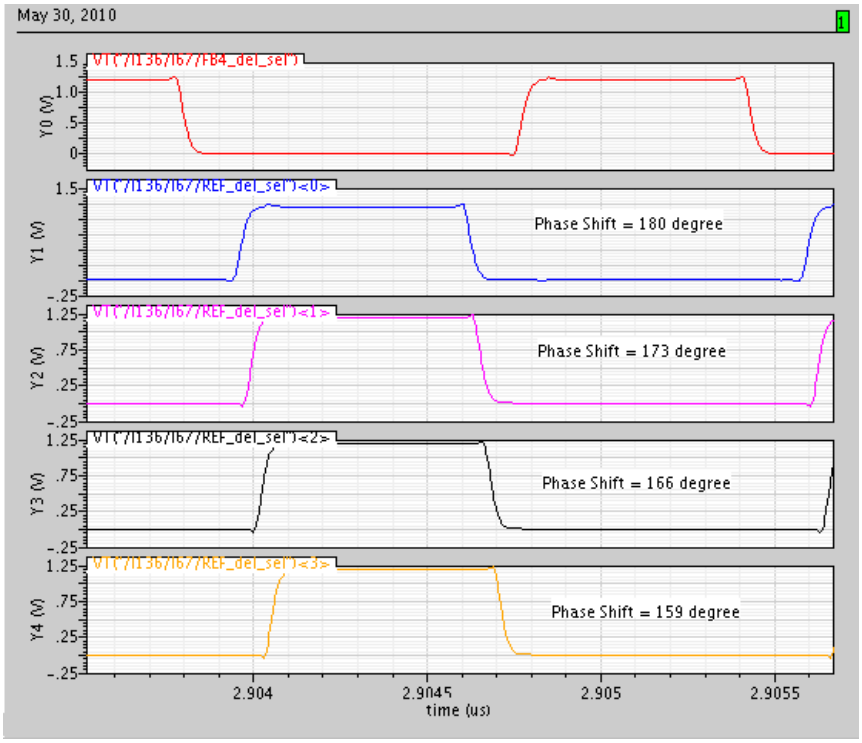


Figure 12. DLL based phase shift generation with relative phase shift of 7 degrees between individual array elements

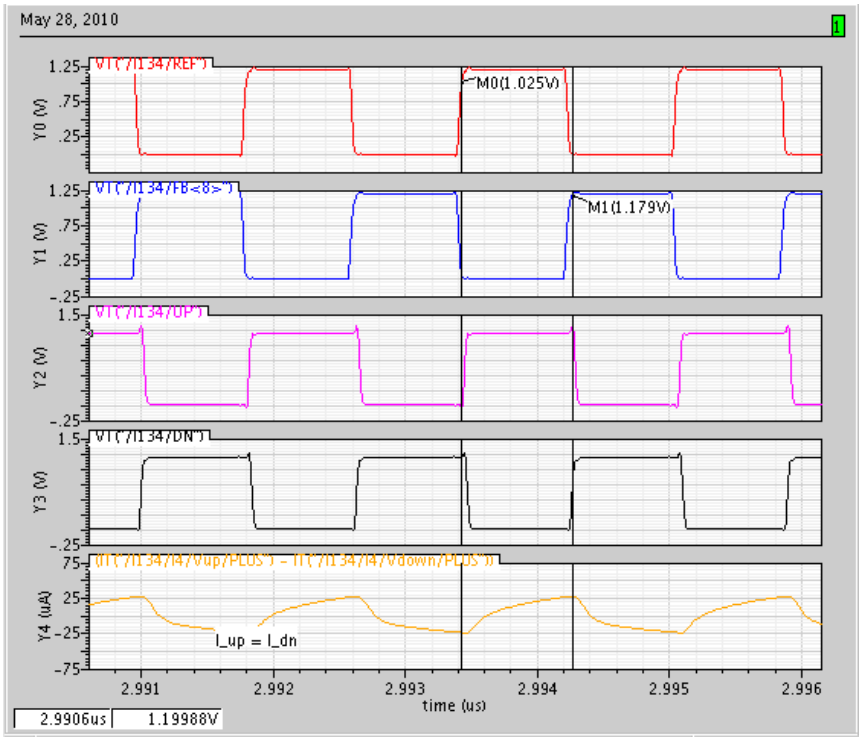


Figure 13. Phase Shift is fixed at 180 deg for I_up = I_dn

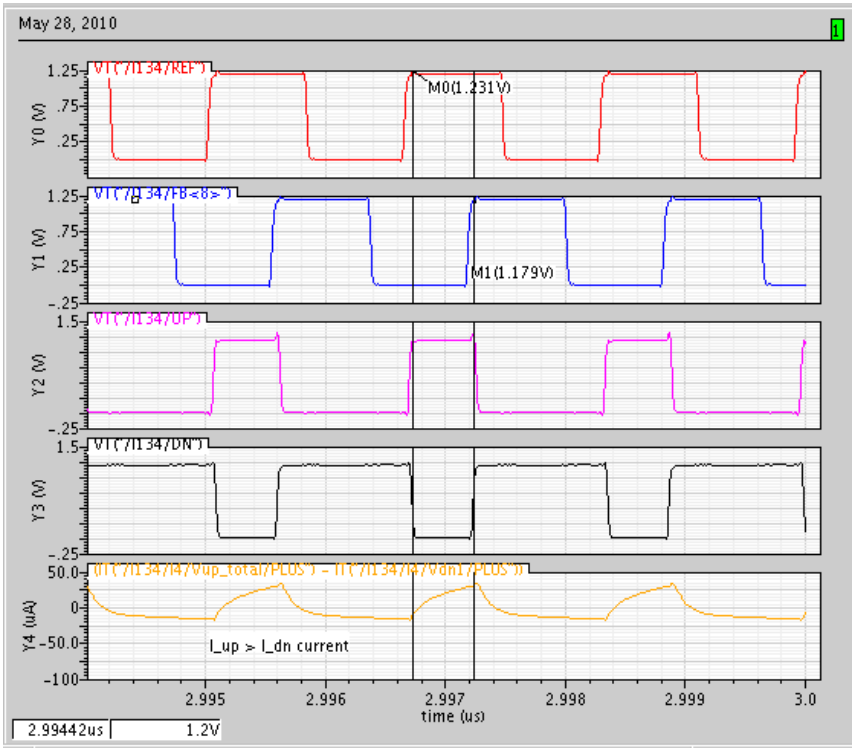


Figure 14. Phase Shift is controlled at less than 180 deg for I_up > I_dn

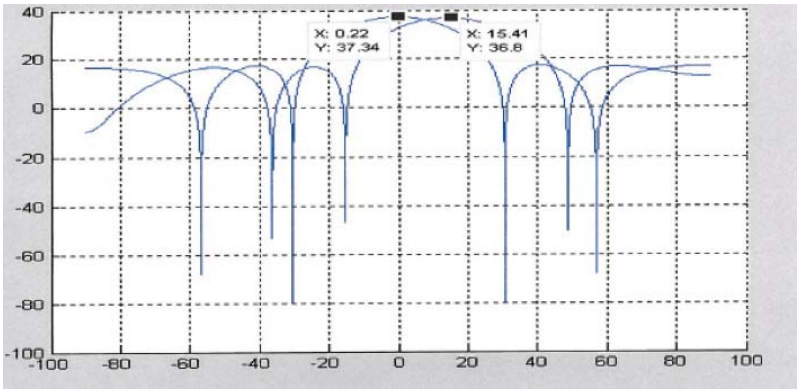


Figure 15 (a). Planar Antenna Array Factor pattern when main beam is scanned for 15 degrees

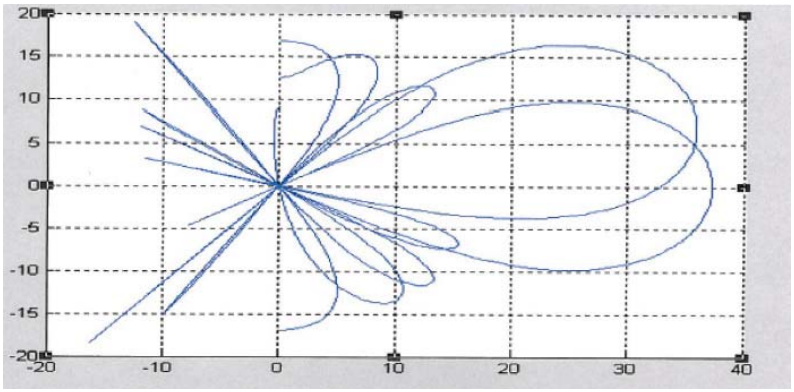


Figure 15 (b). Planar Array Factor pattern for Φ=0 degree cut when beam is scanned from (θ,Φ) = (0,0) to (15°,20°) via change in intrinsic phase shift between array elements

VII. CONCLUSION

In this paper, a DLL based digital phase shifter has been presented with compact design and low power implementation due to its all-active integration using CMOS technology. The variable phase shifter can adjust relative phase shifts between array elements thereby enabling antenna beam steering. Also, we have incorporated real time analog feedback mode to calibrate for errors occurring in the desired phase shifts. The phase shifter described here is suitable for wireless sensor application in Smart Grid technologies in the 2.4-GHz ISM band.

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