MJEN

MANAS Journal of Engineering
ISSN 1694-7398 | e-ISSN 1694-7398

Volume 7 (Issue 2) (2019) Pages 94-98

Design, fabrication and performance analysis of TTD structures for S-band active phased array RF beamforming networks

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ABSTRACT

In this study an eight-channel active analog beamforming structure is designed and developed in subsystems by using an Applied Wave Research (AWR) simulation program. This structure works in S-band and contains true-time-delay (TTD) systems. The simulation results and the results obtained from the manufactured structure are compared. In the comparison, the TTD values for different time delay steps and phase difference measurements between channels are analyzed and interpreted. The test results show that desired performance is obtained from the designed and manufactured PCB. However, it is observed that feeding each antenna element with single channel beamforming board would be more appropriate.

ARTICLE INFO

Research article

Received: 28.03.2019
Accepted: 15.10.2019

Keywords:
Active phased array, beamforming, true-time-delay (TTD), phase shift, single pole four throw (SP4T).

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1. Introduction

In electronic warfare (EW) systems, electronic scanning featured active phased-array beamforming systems are one of the most important structures necessary for vital functions like: self-protection and counter measure. The performance of these structures directly affects the performance of whole system. To be able to involve targets in different positions, the antenna beam should be directional. EW systems can be classified into two groups with respect to the type of beamforming as: mechanically directed systems [1] and phased array systems [1-5]. A large scaled, mechanically directed antenna and to feed that antenna a high powered RF amplifier is needed to generate a beam in conventional methods [1]. Only one beam can be generated when beamforming is done mechanically which takes milliseconds. On the other hand, in phased array systems the beamforming is done by exciting more than one antenna element in different phases [1]. Since beams are directed electronically with phase shifters in these systems, the time necessary for beamforming is in the order of microseconds. This provides efficiency in comparison to mechanically directed systems.

Phased array structures are divided into two with respect to feeding status of antenna element as: passive phased array and active phased array structures. The advantage of active phased array structures against passive phased array ones is that they are able to control amplitude of each antenna element individually. Compared to passive phased array structures less powered transceiver modules are used to feed these antennas [1].

Photonic TTD beamformers provide solutions to many drawbacks for wireless radar and satellite communication systems. But with the increasing number of antennas, scalability limitations may arise. In [2] a concept of a photonic TTD beamforming network for phased array antennas (PAA) is presented. Rotman lens which increases the capabilities of multibeam antennas and photonic beamforming are compared in [3] for wideband radio frequency (RF) beamforming. In [4] optical phase-lock-loop (OPLL) is used to achieve tunable time delays and laser diodes are used to generate RF signal. This is the first example of an OPLL being used in TTD setup. An optical TTD beamformer is reported in [6, 7, 8] for various systems and in all successful results have been achieved. A compact and high frequency TTD beamformer is applied by using bidirectional reflectance of the fiber gratings in [9]. In [10], a combination of time switching with non-orthogonal multiple access is reported by Gao *et al.* in order to cancel the inter-cluster interference.

In this study, an eight-channel active beamforming structure is designed by using Applied Wave Research (AWR) simulation program. The designed and manufactured beamforming printed circuit board (PCB) operates in the S-band and contains true-time-delay (TTD) systems. A good matching is observed, when the simulation results and the results obtained from the manufactured structure are compared with respect to TTD values for different time delay steps, and phase difference between channels.

2. Analog beamforming

In most of the phased array structures only one beamforming technique is used which is either analog, digital [11] or photonic [12]. On the other hand, there are some examples of hybrid systems in which more than one of these techniques are used [5]. The complexity of RF circuit can be reduced and same performance can be provided with the hybrid beamforming. An investigation is made [5] to prevent reduction in system bandwidth, where long delays are produced digitally and short delays with analog electric circuits.

The phase value necessary for each antenna element is given by analog or digital phase shifters in analog beamforming technique, the block diagram of which is given in Fig. 1. When a breakdown occurs in one of the modules, the system continues to work properly with less performance; since each antenna is fed with a separate module. Phase shifters add a constant phase difference to the signal through the operating frequency band, without changing the signals amplitude. Theoretically, if the signal entering to the phase shifter is Ve^{j0}, then the signal in the output is $Ve^{-j\phi}$ [13]. In phased array systems, phase shifters are used to add proper phases to antenna elements in order to perform beamforming electronically.

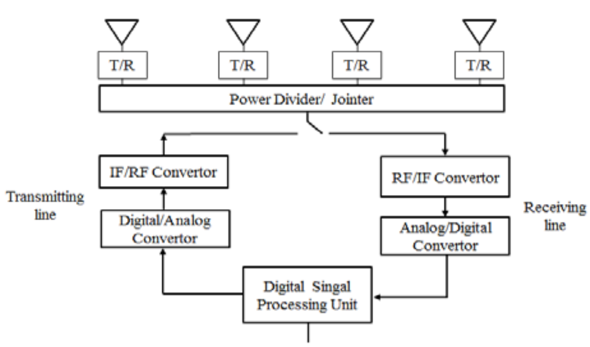


Figure 1. *Block diagram of analog beamforming structure.*

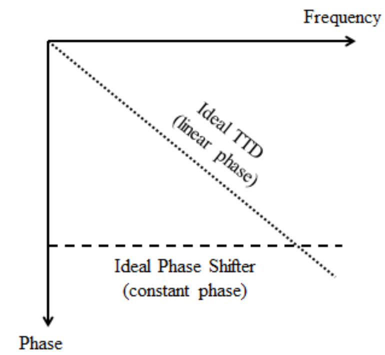


Figure 2. *Comparison between TTD and phase shifter.*

In analog beamforming, if the broadcasting frequency band is wide and the array is formed with multiple elements, TTD structures are used to reduce the loss of earnings caused by beam shifting. As TTD structures are independent of frequency, loss of earnings emerged during beamforming in wide band systems can be removed easily. Unlike phase shifter, there is an inverse relationship between frequency and phase for TTD which can be seen in Fig. 2. TTD expression can be identified in terms of time and phase as [1]:

$$\Delta t = \frac{dsin(\theta)}{c} \tag{1}$$

$$\Delta\phi = 2\pi f \Delta t = \frac{2\pi dsin(\theta)}{\lambda} \tag{2}$$

where θ is the direction or steering angle, c is the speed of light, d is the distance between antenna elements, and f indicates the frequency. Time delay $\tau = \frac{i\times d\times \sin(\theta)}{c}$ indicates that TTD value is independent of frequency [14].

3. Numerical results

In this study, a structure with eight channels is designed and manufactured for beamforming process. The designed and manufactured beamforming PCB is shown in Fig. 3. As seen from the manufactured structure, the components of the beamforming circuit have a physically symmetrical design.

Because of material over-density on the PCB, any short circuit that is possible to occur during alignment process may affect whole operating performance. For beamforming process each channel passes through power divider part of the structure. That is why an RF performance decrease in any channel will affect the overall performance of the system; since the channels are interactive of each other. The HMC594LC3B and HMC232LP4 amplifiers are used to compensate the interruption losses of the phase shifter and attenuator, and also to achieve the desired gain. Moreover, the LFCN3800 filter is used to provide the desired S-band frequency (2-4 GHz). In Fig. 3, the part of the circuit used for phase and amplitude adjustment is given, where the aforementioned phase shifters and adjustable attenuator is implemented.

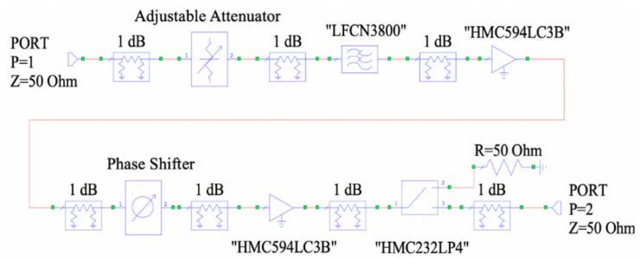


Figure 3. *Circuit schematic for the phase and amplitude adjustment block.*

As seen in Fig. 4, this design study consists of three blocks; which are phase and amplitude setting block, first TTD block and second TTD block. Each TTD block contains two levels in itself and connected to other TTD blocks with a time delay by using single pole four throw (SP4T) switching mechanisms. In switched time delay, when lines of switches are directly connected to each other via transmission lines, there occurs no time delay. This condition is accepted as reference channel, and the calculations are made with respect to this reference channel. In the measurements, some bits are unable to give the expected delays. The reason for that is the coupling effect; which is occurred as lines of switches with same lengths are inclined toward each other.

First TTD block measurements are made for 100, 200, 300 ps time delay steps as shown in Fig. 5. The measurements are made between 2-4 GHz frequency range, since the structure operates at S-band. The maximum difference between measured TTD values and simulation results is 10 ps. Similarly, second TTD block measurements are made for the time delay steps values of: 100, 200, 400 ps. Second block of the system has two levels. First and second level of second block TTD test results are depicted in Fig. 6(a) and (b), respectively. As seen from the graphs, very close results are obtained between measured and simulated values, where the maximum difference is 15 ps. This shows the accuracy and usability of the proposed system.

According to the simulation results, the phase difference between channels is expected to be in the same phase for each channel. On the other hand, when measurement results in Fig. 7 are analyzed, at the end of the band in some of the channels there occurs 20 degrees of phase difference. The line length of each channel is expected to be equal; however, for the manufactured PCB, some lines are not in equal length with a very small difference. This is one of the reasons for the phase difference between channels. Secondly, since RF connectors and other circuit materials are not precisely soldered and contacted to the PCB, it also causes the phase difference between channels.

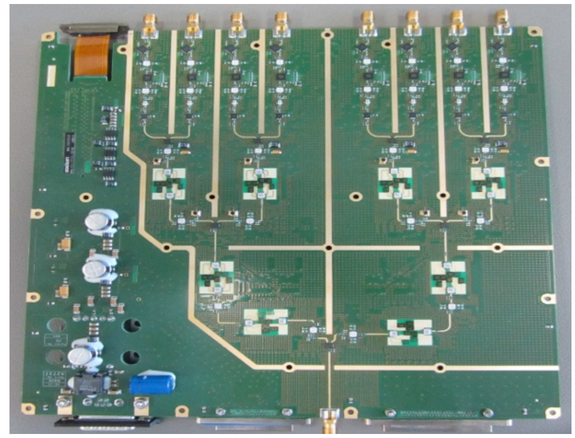


Figure 4. *Manufactured beamforming PCB.*

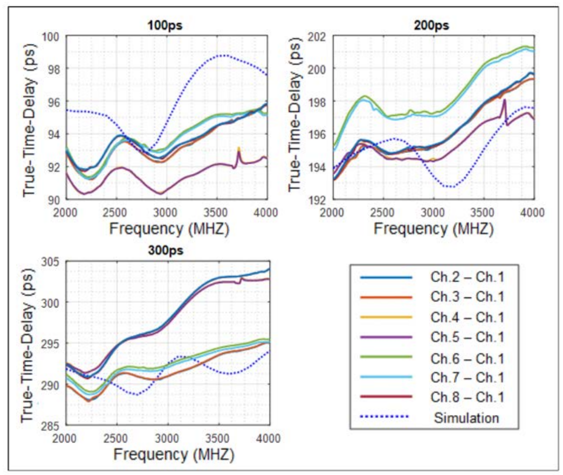
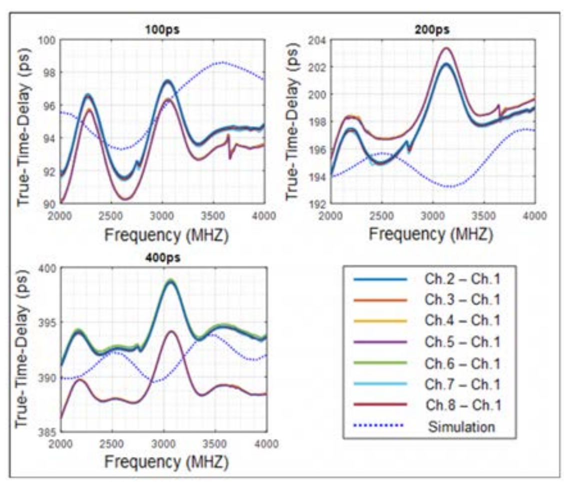
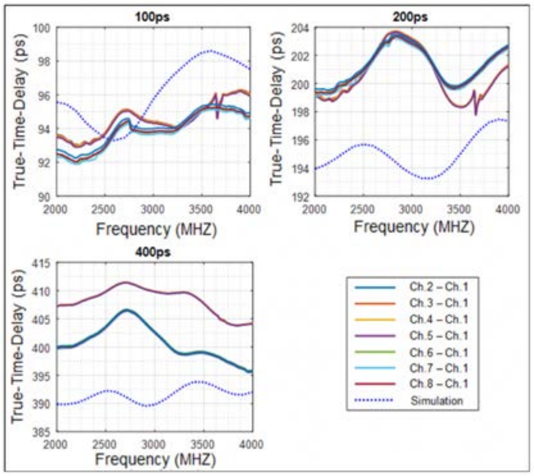


Figure 5. *First block TTD test results.*



(a)



(b)

Figure 6. ***(a)*** *First level of second block TTD test results.* ***(b)*** *Second level of second block TTD test results.*

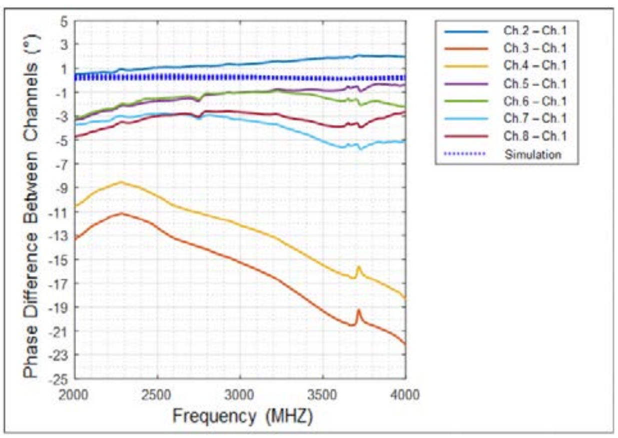


Figure 7. *Phase difference test results between channels.*

4. Conclusion

In this study a novel analog beamforming structure is designed in sub-blocks by using a simulation program, which is also manufactured as a PCB. Measurements of TTD and phase difference between channels are made for different time delay steps. When the simulation results are compared with the measured ones, the maximum time differences between them are: 10 ps for first level TTD with 100, 200, 300 ps time delay steps; 15 ps for each block of second level TTD with 100, 200, 400 ps time delay steps. According to measurement results, 20 degrees of phase difference is observed at the end of the bands for some channels. Test results confirm the success in the performance and accuracy of the manufactured PCB. Furthermore, similar values are obtained for the simulated design and manufactured PCB. However, it is observed that for the reported system, feeding each antenna element with single channel beamforming board would be more appropriate. This helps to achieve more successful results with less time difference between the simulated and fabricated system.

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