Research Article

Analysis of single and multiple on-chip antenna for intra-chip wireless communication with four antenna transceiver model

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Abstract
The Radio Frequency (RF) wireless interconnect is one way to improve the performance of multi-core chips that is limited by high power dissipation in the form of heat in conventional metal wired connections. This paper examined the suitability of various existing on-chip antennas, as well as the performance of four such antennas located symmetrically at the four edges of the chip substrate for short-range millimeter-wave intra-chip communication. In order to simulate the scenario of RF transceiver, millimeter-wave antenna on-chip models were developed using the CST MWS software tool. The simulation is carried out for mm-wave range of 10-75 GHz. In the first scenario, zig-zag antenna, planar triangular monopole antenna, bowtie antenna and rectangular meander antenna were designed for the specified frequency range. Different parameters were observed and compared to the same. The approximate resonating frequency and return loss (S11) are 75 GHz and -17 dB, respectively for the meander and zig-zag antenna. In case of bowtie, it was -46 dB, which is acceptable, but -6.81 dB for the triangular monopole which is insignificant. In the second scenario, multiple antenna transceiver models were designed using the combination of these antennas. Meander antenna was found to perform better, with a lower reflection coefficient and a good Voltage Standing Wave Ratio (VSWR). The transmission coefficient of the side antenna is 4 to 16 dB higher than the oppositely placed antenna in the four-antenna model where antennas are kept at the edge centre. Most of the designs have a VSWR between 1 and 2 at their resonant frequency which is satisfactory.

Keywords
On-chip antenna, WiNoC, Meander antenna, Zig-zag antenna, Short-range communication, Intra chip communication.

1.Introduction
A communication channel can be wire-line or wireless. A channel can be used for unicast, multicast or broadcast systems. Wireless communication refers to the electromagnetic transfer of data between two or more points. Communication over radio waves requires an antenna [1−3]. An interconnect connects two electronic devices or networks. Some of the non-wired technologies are RF wireless interconnects, optical interconnects, 3D chips, Alternating Current (AC) coupling, etc. Generally, interconnects are low frequency metal wired connections. An unlicensed spectrum in the range of 60 GHz frequency has gained much more attention in the last few years due to increased demand for very high-speed multimedia wireless short-range communications [5−8].

The 60 GHz systems have become feasible for mass production with the development of silicon technology and have paved the way for the integration of Radio Frequency (RF) components with analog and digital circuitry on a single chip, like System on Chip (SoC) with a much more compact size.

Modern communication systems require the transmission of very high bit rates, due to which the traditional metal wiring interconnects technology brings with it serious problems such as signal integrity, increased latency, and power dissipation, which is a major hurdle to improve the efficiency of the Very Large-Scale Integration (VLSI) system [9−14]. Therefore, future Integrated Circuits (IC) require non-wired interconnections. In order to make the interconnects wireless, the antenna plays a major role. In addition, it is necessary to consider the placement of the antenna and the type of antenna in such a scenario. This study compares the behaviour of four antenna models placed in the edge centers. RF transceiver with on-chip antenna technique has been increasingly researched in the past years. On-chip

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antennas are primarily used as wireless interconnects for intra-chip/inter-chip communications.

This research focuses on constructing various millimeter-wave on-chip antennas of different geometries using CST MWS software. The frequency range covered from 10-70 GHz. The performance parameters covered in this study were return loss (S11), Voltage Standing Wave Ratio (VSWR), polar plot, directivity and radiation pattern of a various simulated single antenna. To study the channel behaviour between the transceiver antennas, four antenna transceiver model using the single antennas designed were constructed and analysed using the S-parameters. Based on the investigation of the past work, four antennas were chosen which are zig-zag antenna, planar triangular monopole antenna, bowtie antenna and rectangular meander antenna. The antennas were remodelled, if the deviation from expected results were obtained and appropriate results were recorded.

In 3D ICs, circuits are divided into smaller parts and placed in layers as stacks, avoiding the long wires, but this method has still not gone commercial because of the complicated etching and fabrication process involved in this method. Heat removal is a challenging task with respect to the increase in power density in 3D chips. Optical interconnects offer transmission at the speed of light without the challenges of frequency, dispersion and losses associated with the conventional electrical wiring. The transformation of the electrical signal to optical signal requires the use of special devices such as optical modulator and demodulator for which special packaging process and technology are required. All these requirements lead to a costly and complex fabrication process. The interconnect system based on mainly capacitive and inductive coupling, also known as AC Coupling doesn't require any extra manufacturing and packaging process as compared to the 3D chips and optical interconnect technology. However, there is a constraint on the implementation of this technology due to the inability to support larger distances and the requirement of accurate alignment for good performance. Radio Frequency (RF) transceiver based wireless communication avoids the problem of complex packaging and the technology involved in using optical signals and the constraints of distance in case of AC coupling interconnects.

The organization of the research paper is as follows. In Section 2, related work was discussed. The construction, working of single and 4 antenna models were discussed in Section 3 followed by results and performance of channel models in Section 4. Finally, conclusions and future scope were drawn in Section 5.

2.Related work
The shrinking of antennas and transceivers supports the improvement of Wireless-Networks-on-Chip (WiNoC), in which chip-scale communication is employed to surge the computing performance of multi-core architectures. Traditional wired interconnects have many limitations and to overcome these limitations wireless interconnect systems have been employed. Wireless interconnection systems recognize intra-chip interconnection at light speed through electromagnetic waves [1]. The electromagnetic modeling and designing of on-chip dipole antenna were presented in [2]. The obtained results prove that the practicability of this approach and opens opportunities for antenna integration on a chip and the fabrication of totally integrated single-chip wireless systems. In reference [3] the requirements and performance of some of the proposed non-wired interconnect technologies such as optical interconnects, Through-Silicon-Via (TSVs), AC coupling and RF transceiver based wireless interconnects are discussed and compared. The Radio Frequency Wireless Interconnect (RFWI) method was further analysed by modelling in the Simulink environment, and efficient communication between transceivers was obtained. The results point out the possible reliability and feasibility of the intra-chip and inter-chip communication system by using an integrated RF transceiver and antenna to replace the existing interconnecting metal wiring. In the succeeding research carried out by Chang et al. [4], a metallic zig-zag antenna was demonstrated to provide the best power gain for the smallest area overhead. A 3-dB bandwidth of 16 GHz having a center frequency of 57.5 GHz was obtained by using the chip model. A triangular monopole antenna of high gain and low area using a standard Complementary Metal Oxide Semiconductor (CMOS) process was discussed in [5]. Optimization over a modified rectangular Artificial Magnetic Conductor (AMC) which acts as a guard between the Antenna-on-Chip (AOC) and the lossy CMOS substrate was also discussed in [5]. The design of an on-chip Planar Log-Periodic Antenna (PLPA) [6] was proposed in 2014. The PLPA antenna was designed to enhance the signal transmission features of wireless interconnections, then a two-port antenna network was also simulated for 60GHz in High-Frequency Structure Simulator (HFSS) tool and the radiation pattern and the scattering matrix parameters were achieved. In the year 2016, a simplified Wireless Inter/Intra-Chip (WIIC) communication system [7]

prototype was studied using an innovative metamaterial Printed Circuit Board (PCB) absorber propagation channel. Simulation modeling that predicts Bit Error Rate (BER) in High-Speed Interconnect (HIS) systems are presented in reference [8]. The solution offers a practical method for analyzing the system using a novel 3D bathtub curve [8]. The on-chip wireless channel and the effect of antenna positioning and directionality on channel characteristics are described in recent research studies [9]. Analysis of the intra-chip environment reveals that it differs greatly from free space and creates small-scale fading effects from various propagation paths from both chip layers and chip edges. Elaiyabharathi et al. [10] presented a design of the meander line antenna for wireless application for the operating frequency of 3.4 GHz like Worldwide Interoperability for Microwave Access (WiMAX). The antenna performance was improved based on the reflection coefficient of the antenna, radiation pattern, VSWR, and return loss. The return loss was calculated by using the S (1,1) port of reflection coefficient & it was found to be -14 dB. In reference [15] the communication capabilities of short range millimeter wave in network-on-chip based on multi-core processors is investigated along with transmission capabilities between on-chip antennas for both inter and intra chip communication in multi-chip computing systems. The abilities of the wireless hubs existing in WiNoC to institute a post-silicon validation model for communication networks is discussed in [16]. A vertical top hat monopole positioned in Silicon Dioxide (SiO_2) as the wireless interconnect is presented in [17] and tried to achieve better radiation efficiency and impedance matching.

An implementation of a transmission channel for WiNoC applications is discussed considering integrated dipole antennas in Ka band using two antenna model in [18]. An effort is made to improvise the gain by shaping the chip packaging operating around 71GHz [19]. An extensive study of various aspects of chip scale wireless communications, including wave propagation, channel modelling, on-chip Electromagnetics in millimeter wave and THz range is discussed in [20−23]. The influence of placement of the antenna and directionality on channel characteristics in the on-chip wireless channel analysis for multicore processors is discussed in [24] and analysis is extended to THz in [25]. Some of the related existing work for the analysis of on chip wireless link is summarized in *Table 1*. By and large, single and two antenna models have been generally examined from previous studies. The range of the frequencies varied between 20-70 GHz. We chose the 60-75 GHz band for the investigation since the frequency allotment for 60 GHz wireless systems is becoming more popular. The focus of this research is on a four-antenna model for assessing the channel behaviour and receiving ability of three antennas when one of them is excited. In addition, we investigated the alignment and orientation of antenna positioning on a substrate using several antenna models. Based on the findings, we noticed that positioning the antenna in the edge center produces better results, which is discussed in this article. The results include a comparison of four antenna models in terms of receiving ability, as well as directivity and VSWR.

Table 1 Summary of associated existing works for analysis of the on-chip wireless link

Reference	Observations	Frequency/ Antenna	Remarks
[9]	The effects of antenna placement and directionality in the chip plane, as well as signal loss, dispersion, and delay properties, are discussed.	55−65 GHz, folded dipole antenna and planar log periodic antenna	Analysis between pair of antennas
[15]	Short-range mm wave communication capabilities among network-on-chip based multi-core processors, integrated on a board were investigated.	30 GHz, zig-zag antenna	The analysis is available only with zig-zag antenna
[18]	Transmission channel analysis of WiNoC applications	Ka band (26-40 GHz), Integrated dipole antennas	The analysis is only between two antennas
[22]	3D models based on measurements in Ka band	20-50 GHz, Dipole Antenna	Highlights the performances and trade-offs of different parameters such as power output and amplifier's gain
[23]	The implications on WiNoC design are presented using a three-dimensional model that captures essential chip components that influence wireless transmission.	55–65 GHz, zig-zag, planar log periodic antenna	Analysis of individual and pair of antennas

3.Materials and methods

Construction and working of models

Based on the investigation, triangular monopole, zig-zag, meander and bowtie antennas were among the antenna models considered for analysis of intra-chip wireless communication and simulation using CST microwave Studio [11]. The steps for constructing the above-mentioned antennas are depicted in *Figures 1 to 4*, respectively.

Single antenna models with chip dimensions of 1.75 mm × 1.72 mm × 0.49 mm [10] were considered and placed (various antennas) on it. The chip comprises two layers, with silicon used as a substrate in the bottom layer which is 0.36mm thick and silicon dioxide used as a dielectric layer of thickness 0.12mm with a thin copper plate as the ground plane at the bottom with the thickness of 0.01mm. *Figure 1* depicts the overall block diagram.

Figure 2 to *Figure 4* shows the detailed construction of a planar triangular monopole antenna [12] positioned on the chip's edge center, as well as the dimension and positioning of the antenna for simulation.
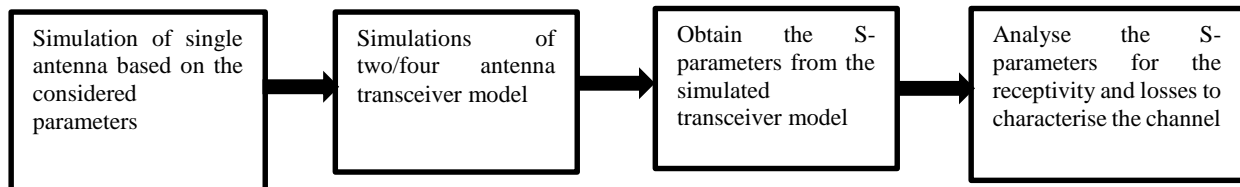
Figure 1 Overall block diagram
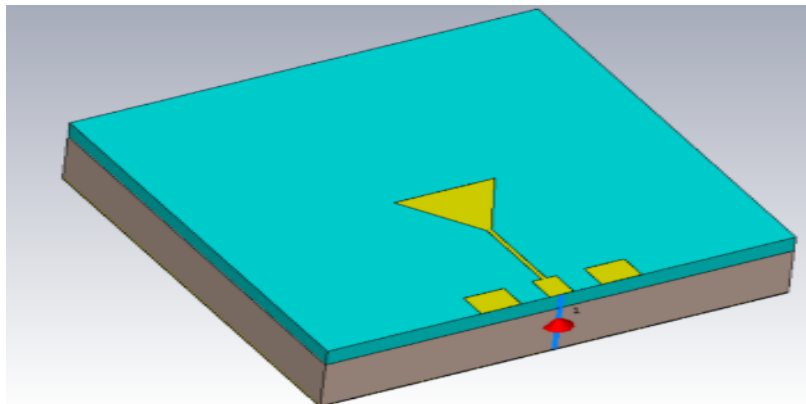
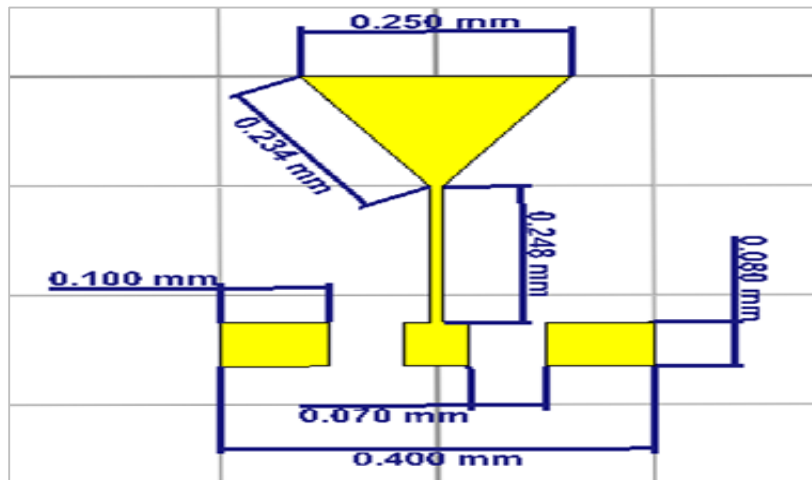**Figure 2**   Single planar triangular monopole antenna

Figure 3 Dimensions of single planar triangular monopole antenna
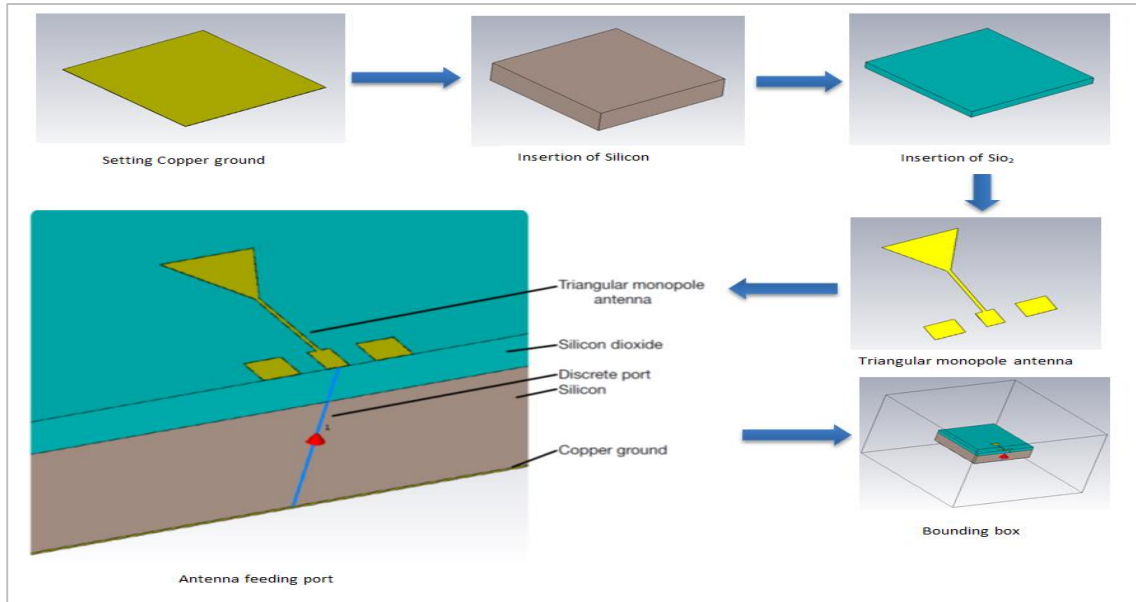
Figure 4 Construction of triangular monopole antenna

Similarly, the remaining three antennas were reconstructed as illustrated in *Figure 4,* using the dimensions of the zig-zag antenna [13], rectangular meander antenna, and the bowtie antenna [14] as shown in *Figure 5* to *Figure 7*. The rectangular meander antenna is designed by taking the total length of the antenna from the dipole calculation, then bending it into 24 arms of equal length and varying the antenna dimensions to achieve the desired results. The bowtie antenna is excited by applying a port to the extended arm.

Figure 5 Dimensions of zig-zag antenna
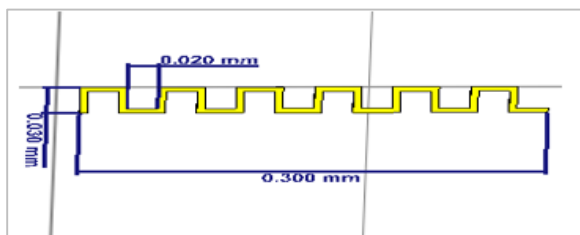

Figure 6 Dimensions of rectangular meander antenna

Figure 7 Dimensions of bowtie antenna

4.Results and discussions

The Gaussian signal shown in *Figure 8* was used as the input signal for all of the models in this research to analyze the models over a range of frequencies. This signal is applied to the discrete port which has 50 ohms matched impedance.

The results of all four single antenna were compared and presented in *Table 2*. It is indicated from the results that the bowtie antenna gives the best result with a S11 value of -46.02 dB and a VSWR value of 1.01. The resonant frequency of the single antenna model simulated is close to 75 GHz. The single antenna models were used to create four on-chip antenna transceiver system models. For on-chip antenna, the antenna is kept in far-field as this boundary is considered at a distance of $(\lambda/2\pi)$ from the antenna.
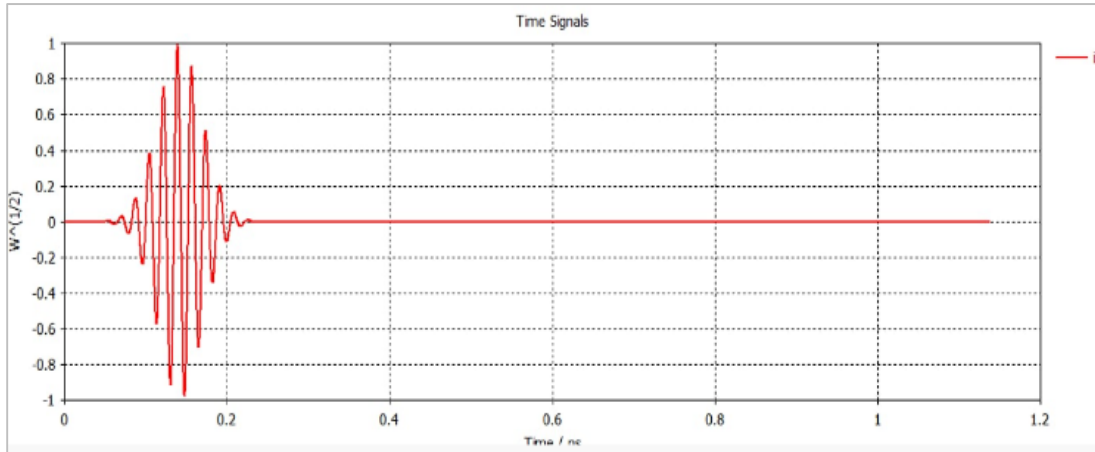
Figure 8 Gaussian input signal

Table 2 Results for various single antenna models

Antenna used	Resonant frequency (GHz)	S_{11} (dB)	VSWR
Triangular Monopole	75.08	-6.81	2.68
Rectangular Meander	75.95	-17.19	1.32
Bowtie	74.04	-46.02	1.01
Zig-Zag	75.56	-17.05	1.33

4.1 Construction of four antenna Transceiver system model using a bowtie antenna

The construction and description of bowtie four antenna transceiver system is depicted in *Figure 9*. The dimensions of the chip used for four antenna model were 5 mm × 5 mm × 0.633 mm as illustrated in *Figure 10*. Here port 1 serves as the source port which acts as a transmitter and the rest of the ports act as receivers. Silicon is used as substrate of 0.633 mm thickness. At top SiO$_2$ layer is placed with a thickness of 0.002 mm. A copper plate of 0.001mm thickness is used as ground plane reference to ports.
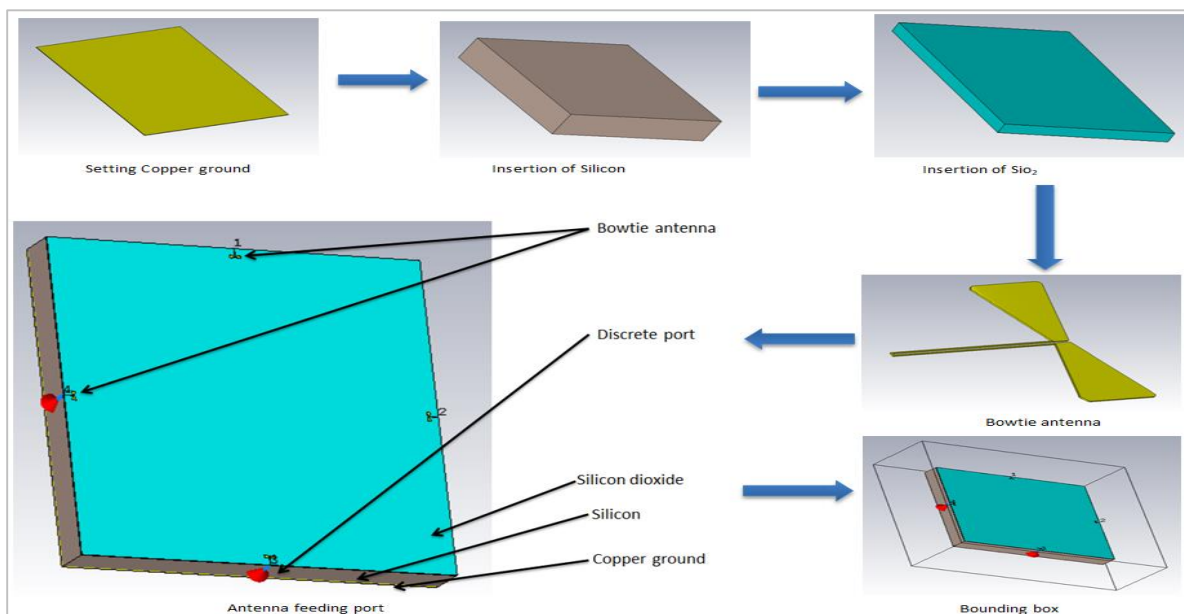

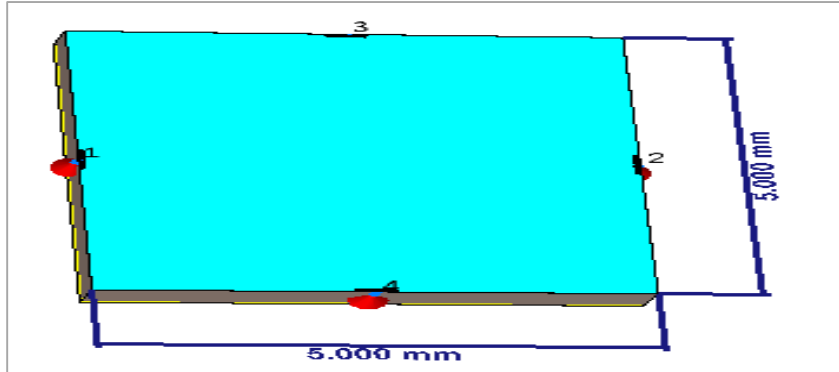**Figure 9** Construction of four antenna transceiver system

Figure 10 Dimensions of chip used for four antenna system

All of the antennas were positioned at the edge center of the model and their dimensions are identical to those of a single antenna system. *Figure 11* depicts the directivity of a bowtie antenna, which shows a more directive beam towards antenna-2 and antenna-4 than antenna-3. *Figures 12* and *13* depict the S parameters as well as the VSWR. Here port-1 is exited while all other ports are receiving. The value of S11 is -17.22 dB at 65.18 GHz. S21, S31, S41 shows the receptivity of other antennas when antenna-1 is transmitting.
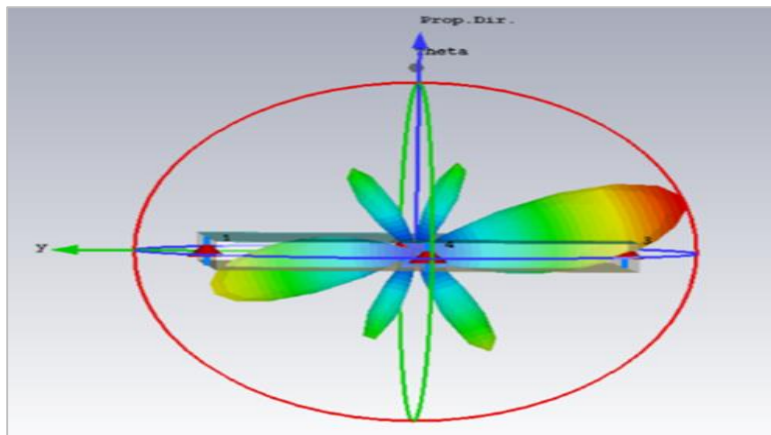

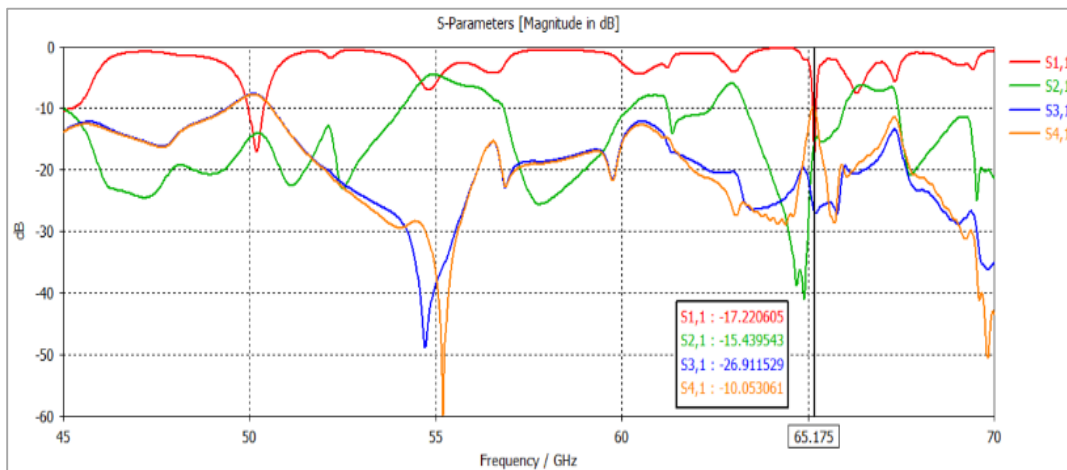**Figure 11**   Directivity of bowtie antenna used in four antenna system

Figure 12 S parameters of a bowtie antenna used in four antenna system
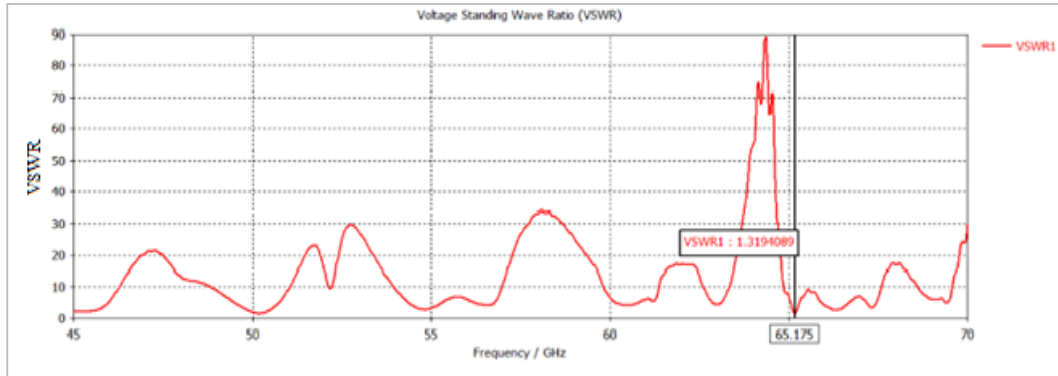
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Figure 13 VSWR of bowtie antenna used in four antenna system

4.2 Planar triangular monopole transceiver system with four antennas

The placement and directivity of planar triangular monopole are shown in *Figure 14* and *Figure 15*. All the antennas are located on the chip's edge center and their dimensions are the same as in a single antenna system. The S parameters are shown in *Figure 16* and VSWR in *Figure 17*. VSWR for this configuration is around 2 which is not so good compare to other antenna models. As depicted in *Figure 15*, the receptivity of all three antennas which are placed at sides and opposite to source port is approximately equal. It does not radiate backwards, which is a major benefit. When considering the S-Parameters, the S11 is not ideal, but the receptivity of other antennas placed to the sides and opposite of the radiating antenna is good.
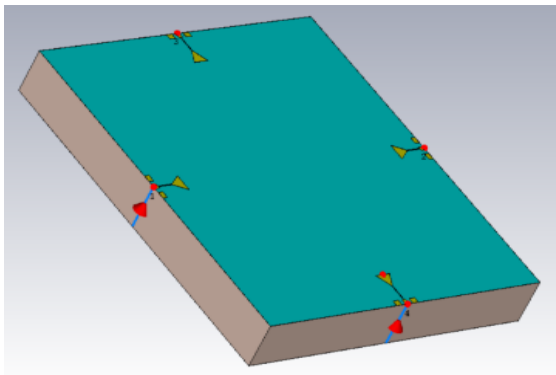

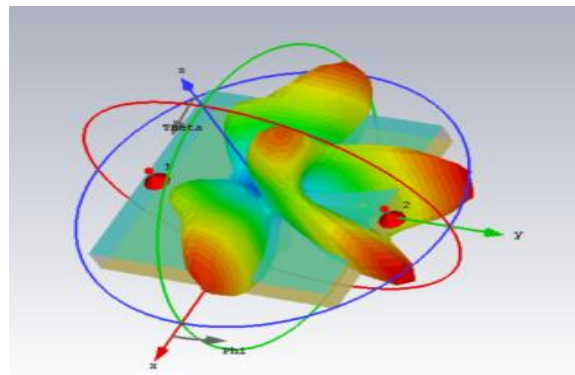**Figure 14** Placement of triangular monopole antenna system

Figure 15 Directivity of triangular monopole antenna in four antenna in four antenna system
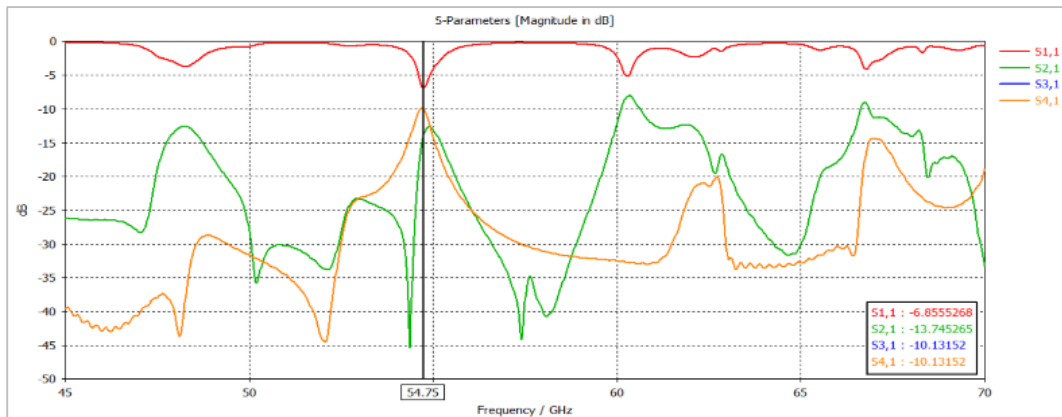

Figure 16 S parameters of triangular monopole antenna used in four antenna system
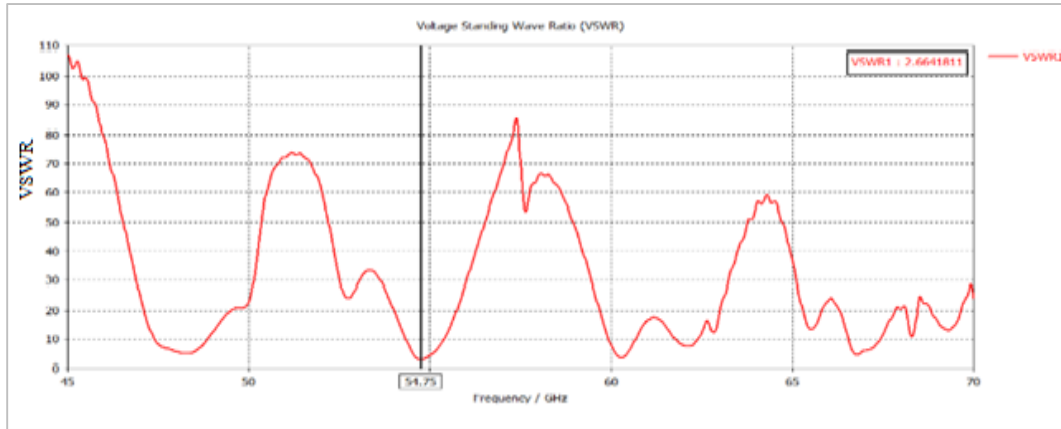
Figure 17 VSWR of triangular monopole antenna used in four antenna system

4.3 Zig-zag transceiver system with four antennas

The placement of four zig-zag antennas on the chip's edge center is shown in *Figure 18*. The antenna's dimensions are identical to those of a single antenna system. *Figure 19* depicts the S parameter analysis. S11 shows the return loss which is -10.31 dB at 54.9 GHz. When Port 1 is excited, S21, S31, and S41 show the receptivity of other antennas. Antennas-3 and 4 have superior results since they are located on the sides, however, antenna-2 has less receptivity because it is placed on the other side, as illustrated in *Figure 20*. At 54.9 GHz, the VSWR is 1.88, which is acceptable.
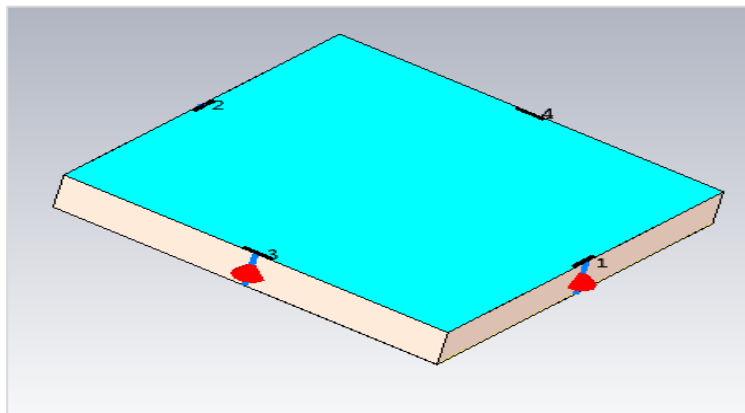

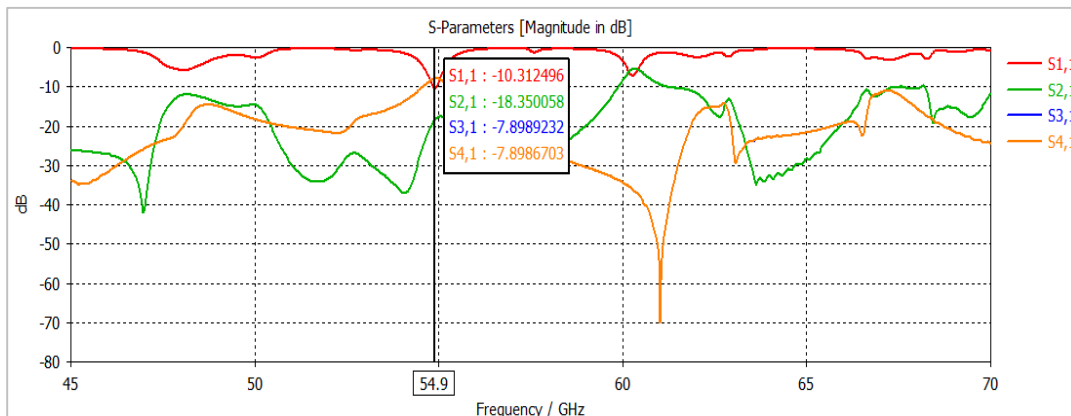**Figure 18** Placement of zig-zag antennas used in four antenna system

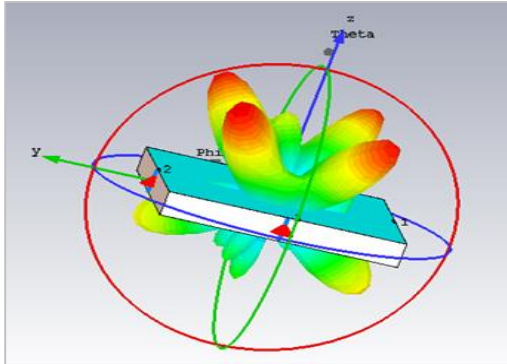**Figure 19** S parameters of zig-zag antennas used in four antenna system

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Figure 20 Directivity of zig-zag antenna used in four antenna system

4.4Rectangular meander transceiver system with four antennas

Figure 21 depicts the positioning of four antennas on the chip's edge center, while *Figure 22* depicts their directivity. All antenna dimensions are same as in a single antenna system. In the analysis of S parameters presented in *Figure 23*, the S11 at 55.1GHz is approximately -15.81 dB, which is within acceptable limits. The receptivity of three antennas can be seen in the directivity plot, where the radiation is directed more to the sides than the opposite as indicated by major lobes. The VSWR is 1.39, which is considered to be satisfactory.
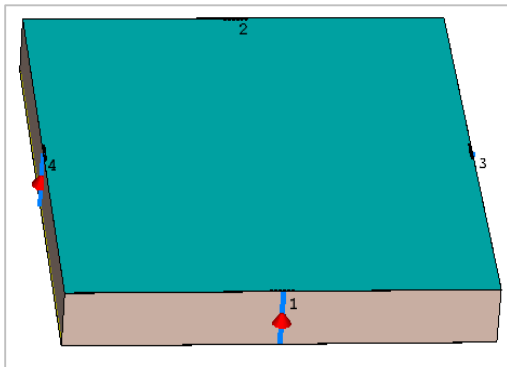

Figure 21 Placement of rectangular meander antenna in 4 antenna system
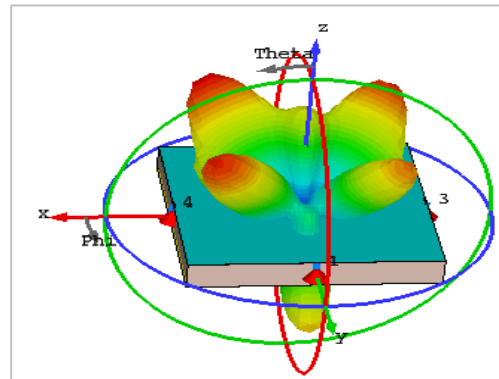

Figure 22 Directivity of rectangular meander antenna used used in four antenna system
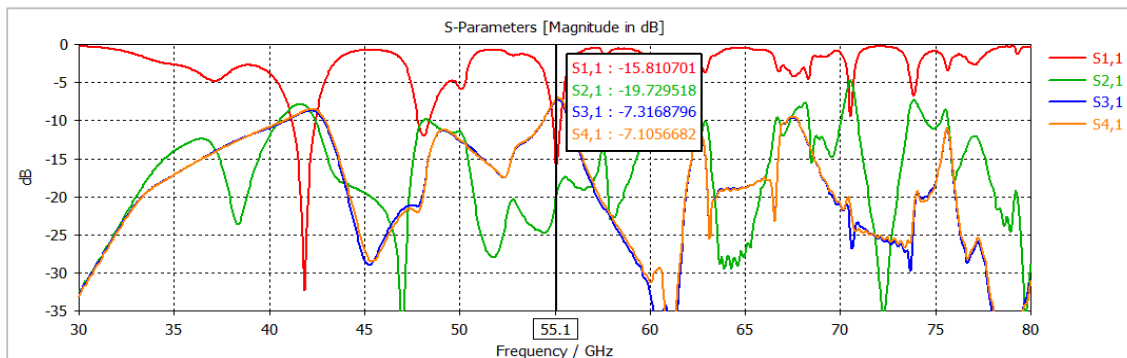

Figure 23 S parameters of the rectangular meander antenna used in 4 antenna system

Table 3 shows the results for four different antenna models with antennas located on the edge centre. The bowtie antenna has a better reflection coefficient S11 at -17.22 dB. The receptivity of the antenna 2 and 4 are marginally better, but very less receptivity shown by antenna 3. VSWR 1.32 is satisfactory. In the case of a zig-zag antenna, the value obtained for S11 at -10.31 dB is reasonable. It is observed that the sidelobes have more directivity, resulting in transmission coefficients S31 at -7.9 dB, S41 at -7.9 dB of antennas-3 and 4 on the sideways being

significantly higher than S21 at -18.35 dB of antenna 2 on the opposite side of the source port. The obtained resonance frequency is 54.90 GHz. VSWR of 1.88 is also satisfactory. The results obtained for the rectangular meander antenna are similar to that of zig-zag antenna configuration with slightly better reflection loss S11 at -15.81 dB and VSWR with 1.39. However, the main lobe directivity S21 at -19.73 dB is marginally less than zig-zag configuration. The transmission coefficients S31 at -7.32 dB, S41 at -7.11 dB of antenna 3 and 4 placed in the sideways has better

receptivity compared to the antenna placed opposite to the source port. The obtained resonant frequency is 55.10 GHz. The performance of the triangular monopole is the least of all considering the S11 at -6.85 dB, which is less than the required value. However the directivity of main and sidelobes are quite satisfactory which results in good receptivity of transmitted signal to the opposite and sideways antenna. It is observed that the resonant frequency for this configuration is 54.75 GHz. *Table 4* compares this study to earlier work on zig-zag antenna models. The achieved findings are respectable when compared to

the overall response of the simulated models. Complete list of abbreviations is shown in *Appendix I.*

Limitations of the Study
In this work, analysis is carried out under ideal conditions. However, the actual scenario of intra chip wireless communication includes the effect of other metal interconnects. The influence of various materials on wireless communication in intra chip is also an important issue that can be taken up by the research community.

Table 3 Results of various four antenna models with antennas on edge center

Antenna	Resonant Frequency (GHz)	S11 (dB)	S21 (dB)	S31 (dB)	S41 (dB)	VSWR
Bowtie	65.18	-17.22	-15.44	-26.91	-10.05	1.32
Triangular Monopole	54.75	-6.85	-13.74	-10.13	-10.13	2.66
Zig-Zag	54.90	-10.31	-18.35	-7.90	-7.90	1.88
Rectangular Meander	55.1	-15.81	-19.73	-7.32	-7.11	1.39

Table 4 Comparison with previous work

Reference[15]			Present work
Parameters	**Simulated**	**Measured**	**Simulated**
Frequency	30-32GHz	20GHz to 30GHz	50-70GHz
Transmission Coefficients	-31 dB to -38 dB	-35 dB to -60 dB	-7.90 dB to -18 dB
Zig-zag Antenna	4	-	4
Distance	10mm	10mm	5mm
Simulating Tool	ANSYS HFSS	Hardware	CST

5.Conclusions and future scope
Four on-chip antenna geometries are analyzed in multi-antenna models and their results are compared. In case of the single antenna model, bowtie antenna is found to provide better performance in terms of efficiency and reflection coefficient. Meander antenna has the better values of reflection coefficient and transmission coefficient for receiving antenna 2 placed opposite to transmitting antenna among all the four antenna models tested. In the zig-zag four antenna model, the transmission coefficient for receiving antennas-3 and 4 placed on adjacent sides of the transmitting antenna is significantly higher than that of the antenna placed opposite to the source port. If VSWR and S11 are critical then the use of triangular monopole is not recommended.

The future scope of the work includes the performance analyses of different antenna geometries and antenna placements. To obtain even better outcomes, the results from CST Microwave Studio can be integrated into MATLAB Simulink. Further analysis can be carried out with other metals like silver and gold instead of copper. Various other semiconductor substrate materials such as Graphene, InAs, etc. can also be tried.

Conflicts of interest
The authors have no conflicts of interest to declare.

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Appendix I

S.No.	Abbreviation	Description
1	AC	Alternating Current
2	AOC	Antenna-On-Chip
3	AMC	Artificial Magnetic Conductor
4	BER	Bit Error Rate
5	CMOS	Complementary Metal Oxide Semiconductor
6	HFSS	High-Frequency Structure Simulator
7	HIS	High-Speed Interconnect
8	IC	Integrated Circuits
9	PCB	Printed Circuit Board
10	PLPA	Planar Log-Periodic Antenna
11	RF	Radio Frequency
12	RFWI	Radio Frequency Wireless Interconnect
13	S11	Return Loss
14	SiO_2	Silicon Dioxide
15	SoC	System On Chip
16	TSV	Through-Silicon-Via
17	VLSI	Very Large Scale Integration
18	VSWR	Voltage Standing Wave Ratio
19	WIIC	Wireless Inter/Intra-Chip
20	WiNoC	Wireless-Networks-on-Chip
21	WiMAX	Worldwide Interoperability for Microwave Access